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FOREWORD

This ECFA Large Hadron Collider Workshop is the result of the activity of the Working Groups during the last ten months. It summarizes their continuous studies, and this work will obviously be very useful for the future LHC Experiments. It will be kept track of it in the 3 Volumes of Proceedings:

- Plenary Sessions
- Physics Working Groups
- Detector Working Groups.

These proceedings will also be a most important scientific basis for the decision on the LHC program to be taken by the Council of CERN.

The European Committee for Future Accelerators has the duty to convey to the Council the opinion of the High Energy Particle Physics community, and a recommendation on LHC will be finalized at the Plenary ECFA Meeting on 7 December 1990. On that occasion, a half day summary of this Aachen Workshop will take place at CERN.

The LHC program is the best possible for Europe and it stands very well on its own merits in the International environment. It will allow not only proton-proton collisions at ultra-high energies, but also ion-ion (lead-lead) collisions at unprecedented energies and, together with the existing LEP ring, electron-proton events as well.

As was shown here, proton-proton collisions at LHC will give us the possibility to answer the most fundamental questions in the present status of Particle Physics. We need in Europe to have the means to reach the necessary very high energy domain. LHC does just that, and in a very economic way: LHC will take advantage of the CERN Laboratory - of its existing LEP Tunnel, - of its accelerators, of the SPS as fast injector, - and of the CERN staff of experienced accelerator builders.

This makes it very plausible that LHC is ready before SSC. LHC is designed from the start for a high luminosity. Our studies have shown that this is indeed useful, and that detectors can be built to use it.

There will be competition between SSC and LHC, as has always been the case in the past, for example at the time of the Fermi Lab Accelerator and of the SPS construction. And the common interest of the physicists
on both sides of the Atlantic is to continue the exchange of ideas, students, physicists, and the collaborations which have proven so fruitful in the past. High Energy Particle physicists form a worldwide community, and we here in Europe, besides LHC construction and exploitation, are also interested in a successful completion of SSC.

And there is also complementarity: LHC at CERN will allow to continue the study of Ultra Relativistic ion collisions much beyond what is foreseen for RHIC, at energies where the Quark Gluon Plasma should be fully developed. Eventually, the LEP-LHC electron-proton collisions will open an entirely new energy domain after HERA. This broad range of possibilities will allow the study of a physics domain complementary to the proto-proton one, with a wide range of discovery potential, and this will be a big asset, especially if surprises were encountered at HERA or at RHIC.

This Workshop has also particularly studied the issues in Detector construction. This will be a major effort of the community in the next years. The successful construction of LEP and HERA experiments has shown that we can team efficiently our home Labs for such a task. In fact, the dissemination of the construction of detector components in the institutes and universities is often the occasion to create fruitful links with other university departments, and with the local industry.

But the financing of LHC detectors will need a special effort: even with a very limited number of experiments, I believe that the financial participation needed from the home institutes will be larger than for LEP/HERA. The construction of the LHC detectors will cost more, and this will require a proper increase in the funding of the laboratories and institutes in the home countries.

It is a pleasure to thank the Aachen Organizing Committee led by Günther Flügge for the excellent and impressive organization which has allowed an enlightening and fruitful meeting. They have had to overcome a working Sunday, an ever increasing number of participants, growing demands of meeting rooms, etc... and managed to provide everything, including a memorable Organ Concert in Saint Adalbert!

About 60 persons have taken part, staff, students and workshops, and I cannot name them all. I particularly thank Mr Grant, Mr Geller, Dr Schultz von Dratzig, Dr Graessler, Dr Schulte, Dr Rein, Dr Reithler, very specially Dr Honecker and Ms Lynn Jenkins, who have devoted an enormous dedication to this organization,

and, last but not least, Pr Günther Flügge.

This meeting could not have been organized without the help of our sponsors: The Commission of the European Communities, Deutsche Forschungsgemeinschaft, Deutscher Akademischer Austauschdienst, Bundesministerium fur Forschung und Technologie, Philips Components, and CERN.

Finally, we could all take lessons from this Aachen workshop organization: it might well be even more demanding to arrange a meeting for a "kilo-physicist" collaboration!

Jean-Eudes Augustin
Chairman of ECFA
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Opening Address
Prof. Dr. Klaus Habetha
Rektor der
Rheinisch-Westfälische Technische Hochschule
Aachen

Ladies and Gentlemen!

It is a great honour for me to welcome you to this workshop here in Aachen. Although early for a Sunday morning, I realize that this welcome comes slightly late, as most of you have already spent three days here, combining and refining the results of much work done beforehand in preparing this workshop, but it comes none the less cordially.

You are guests of the Rheinisch Westfälsche Technische Hochschule Aachen, a technical university with approximately 37,000 students, 450 professors and more than 14,000 employees working in 250 institutes. Our university has 10 faculties. The field of research spans from mathematics and natural science over many technical disciplines up to medicine. Besides the traditional emphasis on technical subjects we cover almost all disciplines of a classical university.

This diversity naturally gives rise to many fruitful contacts across the frontiers of the classical institutes, leading to several fields of interdisciplinary research, which contribute to the continuous evolution of our university. Due to this the RWTH Aachen has stayed a modern and young institution, although, had you extended your workshop by just one day, you would have been able to join the celebration of our 150th birthday.

As an example of the high standard of our research potential let me point to the excellent capacity of the computing centre of the RWTH Aachen which offers our students and young scientists unequalled computing possibilities with its IBM 3090-600S and the SIEMENS vector computer. But the standard of a modern university is not only defined by the quality of its teachers and equipment. A really high standard in teaching and research can nowadays only flourish in international contacts and collaborations. Our colleagues of the physics department have been going this way for at least 25 years. They have participated in numerous important experiments in high energy physics at CERN and DESY and thus helped to spread the reputation of the RWTH. This audience by the way gives an excellent example for the international composition of high energy experiments.

Cooperation with industry is essential for trend-setting research and development work. To this aim we have contracts with the Chamber of Industry and Commerce as well as the Chamber of Handicrafts. The success of this policy is documented by the fact, that about 80% of the newly founded enterprises in the Technology Centre Aachen find their origins in our university.

The high tech of our university in mechanical engineering, electronics and computing science, to name only a few examples, gives our physicists many valuable inspirations and help for the design and construction of detectors. This indeed makes Aachen a good place to tackle the problems arising in your instrumentation.

You are here today on invitation of the European Committee for Future Accelerators to the Large Hadron Collider Workshop. Quoting your invitation, "the intention of the workshop is to study in detail the physics potential opened up by the LHC programme at CERN and the requirements and feasibility of detector instrumentation at such a machine". To my understanding this is a modest way of saying that you are preparing the basis for a decision for a future European accelerator. This is certainly a very important task, as at the price of such a machine, the physics community will have to live with it for a long time. It might well determine the physics you can do for several decades.

I look on % as a great compliment for the RWTH Aachen that you are having this workshop here, so let me combine my hearty welcome with the promise, that the RWTH and the local organizing committee will do their best to make your stay as pleasant and fruitful as possible.
Opening Address

Dr. Hans Sterken, MdB
Chairman of the Parliamentary Committee for Foreign Affairs

Magnificenz Habethal!
Honorable Ladies and Gentlemen!

Although this conference is more than an academic celebration – where the chosen address is normal and sufficient – you will probably allow me to be brief. Nevertheless let me express my appreciation to the chairman of the local organizing committee, Professor Flügge, for inviting me. I am also glad to see my colleague of the political stage, Dr. Rembar, and my friends from the Technische Hochschule Aachen. I am delighted to talk to an audience encompassing a Nobel laureate of physics. This is quite a rare event for a Parliamentarian who much more often speaks to other politicians rather than to scientists. So I greet Professor Rubbia.

The very last week – you all have witnessed it – was singular for our country and an outstanding occurrence. I believe, also for many many people around the world. We have recently experienced an enormous growing of mutual confidence and the almost complete disappearance of the East-West conflict which spoiled relations between many neighbouring people for more than 40 years. This is a cause of great relief.

You all remember from previous conferences at Aachen (and elsewhere) that the high energy physicists from Leipzig or from Berlin-Zeuthen - if they were allowed to come at all - appeared as deputies from very far and alien places. Now they come as anybody else does come from Hamburg or from Heidelberg and we have got accustomed to this new normality very fast. What we are also going to be accustomed to is a lot of new problems, mostly of financial kind, and a lot of new responsibilities which tend to keep us occupied for quite some years.

I don't want to question the importance of this intra-german solidarity. I have high respect for solidarity in general, and I have the same respect for Solidarnosc in particular, which, as a model in the wake of Gorbatschow's "Perestrojka", paved the way for many peaceful revolutions. Every participant from Hungary, Czechoslovakia, Poland, Russia has taken advantage from this development. But what I really want to say, is: Let's stay apart from becoming narrow-minded. The long standing problem of German national unity was finally solved by international coherence and cooperation. Thus let us remain sensible for the necessity of international cooperation - in politics as well as in cultural matters and in science.

This conference is an international scientific workshop where new tasks for fundamental research are formulated and new initiatives are going to be brought on the way. I think we have every reason to continue support for successful international laboratories like CERN and for international research projects which challenge the creativity of the most talented and most advanced scientists. In fact we are glad about prospering international collaborations in fundamental research. Because that is one of the investments for the world of tomorrow!

This world will be highly complex, highly interrelated and interdependent. It will need peaceful competition and fruitful cooperation - far beyond national borderlines. Let's take our share, and let's encourage any promising initiative to further reveal the mysteries of nature. I am sure on long terms the present efforts will earn future interests, maybe in unexpected, perhaps in presently unimaginable form. But certainly they are necessary - and cannot be done in isolation.
opened up in our national history. Legally and politically speaking, there is now one Germany only. But, looking closer at our social, economic and also scientific structures, we realize that the union still has to be developed and fully realized. For this, we need the same understanding, advice and support from all over the world as we did immediately after 1945, in particular from the democratic countries "cis et trans atlantica". We are aware of our weakness if left alone, and of our obligations in the community of free states.

2) Particle physics is highly esteemed and supported by both the governments of the 11 West German states (Länder), including Berlin, and by the Federal Government.

The governments of the Länder provide the basic personnel resources and material infrastructure at universities and they share the funding of several national research centres (Grossforschungseinrichtungen), particularly of DESY, and the Max-Planck-Gesellschaft with the Federal Government.

The Federal Government - which means Mr. RIESENHUBER's BMFT - concentrates most of the resources needed in the national research centres, takes care of our contributions to CERN and supports in a subsidiary way academic user groups. In 1990, about 550 million DM are provided for high-energy physics from German public funds.

Recently, 5 East German Länder have joined the Federal Republic of Germany: Brandenburg, Mecklenburg-Vorpommern, Sachsen, Sachsen-Anhalt and Thüringen. Including East Berlin, this means an increase of the German population by about 25% and the German gross national product by about 10%.

An extensive and in-depth review and evaluation of the R & D system of East Germany will be made during the next 12 months in order to prepare the integration of the East German structures with the West German ones. The review is being organized and carried out at the request of the Federal Government by our self-governing organizations of science headed by the Science Council (Wissenschaftsrat) in Köln.

High-energy physics is only one example of the tasks we will have to face in the coming months: experimental research has to return to the universities, the capacities of the big East German Academy of Science (AdW) have to be assigned a new role and employed either at the universities, in industry or in the extra-university governmental research sector. Science in East Germany has to open to peer review, to competition and to world-wide operation. Creativity, independence and responsibility have to be brought back to East German scientists, to groups of researchers and to their institutions.

Internationally speaking, the Federal Republic of Germany has taken over all bilateral and multilateral obligations of the former GDR by signing
the Unification Treaty (Einigungsvertrag). We will consult and negotiate with all partners of the former GDR, in particular with those in socialist or formerly socialist countries, about whether, and if so, how R & D cooperation should continue. We will appreciate the quality of existing cooperation, and we know that our partners abroad need our trust and fairness. Therefore, many of the contacts, scientific exchanges and projects initiated by the former GDR will be continued, if the respective partners so wish.

Tomorrow, BMFT - assisted by German nuclear and particle physicists - will prepare and clarify its future position towards the Joint Institute for Nuclear Research in Dubna, USSR.

3) With CERN and DESY - the two largest West European laboratories for particle physics Germany bears great responsibility for the discipline of particle physics in Europe.

In science as well, responsibility means: identification with the opportunities, achievements and successes, but also with the burdens, particularly the financial burden of scientific work. It is, therefore, evident that in Germany, too, public expenditure on particle physics is critically observed and questioned against the background of the scientific results achieved, the technological importance, social and economic merits and consequences of such expenditure. Particle physics is compared with other scientific disciplines by the scientific community itself in its competition for limited resources, by the public and economic sectors as well as by public administration. Solid and convincing arguments will - as was done in the past - have to be developed and presented in order to provide the necessary funding. As long as "excellence" is a valid argument and criterion there will be no serious problems and difficulties with particle physics.

In looking at the future and prospects of particle physics in Europe, which is what you will do during this workshop, German considerations can not focus on one laboratory or machine, but must refer to the whole network of laboratories, machines and academic user groups.

A new machine is useless, unless there are enough qualified and capable users. An excellent user community would be lost without machines which can compete in the world-wide struggle for scientific excellence.

A project aimed at designing a new machine must, therefore, include plans for new experiments and detectors and for the preparation and qualification of its users. The more unique and outstanding its nature, the more convincing it will be.

The particle physics community in Europe today is faced with the challenge of designing a convincing system of facilities and research capacities for the year 2000 and later years. It must be attractive to researchers as well as to the society. It should have advantages comparable with the US system, without initiating a race between equal programs. It should attract - as it has done for many years - researchers from all over the world, thus demonstrating Europe's role in modern science. It should be oriented to the Eastern part of our European continent, building a true "European House" step by step in the tradition of science, which has always been the pioneer in international cooperation and integration. Bearing this in mind, BMFT is giving its support to the thorough and serious preparation of the next "big machine" in the CERN laboratory, the LHC, and of the relevant experiments. We are joining you on your way to a decision within next year.
1.— Introduction. When delineating the main guidelines for a scientific strategy for the Laboratory, it is important to reflect on the ways Europe contributed in the past to the most important questions in the field of elementary particle physics. This "glorious" past evidences clearly the need for several diversified and complementary experimental paths. There are several reasons for this. Firstly, the very nature of experimental research does not allow one to predict beforehand the outcome of any single approach. Secondly, there are many examples where seemingly diverse experimental phenomena led to a deeper understanding of a same fundamental process.

In its essence, most of our experimental knowledge has come from two complementary methods, namely (1) high-precision studies of particles and forces and (2) hunting for new particles and interactions. In turn, these approaches have determined to a large extent the choice of accelerators and colliders.

The first approach — which I would like to call the "high-precision frontier" — requires machines which can produce chosen particles in copious quantities and under low-background conditions. This is the line pursued today by LEP and other machines. In the future, it will require dedicated "factories", such as H-LEP, B and τ-charm Factories. Within this perspective, LEP will have a renovated role as "Z-factory", with its luminosity upgraded at least tenfold. On a longer time scale, linear e+e- colliders such as CLIC will be needed.

The second, complementary approach relies on pushing much further the so-called "high energy frontier", striving for the highest attainable energies. In recent times, the need for higher energies has brought with it also the need for correspondingly higher luminosities. This is indeed an inescapable consequence of the dimensionality of the cross sections, which goes like $1/E^2$. Such a demand has become nowadays extremely determinant in the choice of the parameters of future colliders which have be-
come the only practical way to reach the highest centre of mass energies. In order to sustain this new experimental environnement, at least for hadronic colliders, a completely new type of detection techniques will have to be invented. Besides the “high energy frontier” we are also witnessing nowadays the emergence of a “luminosity frontier”. In our view, the LHC programme is the correct “next answer” to such a research line for Europe. Indeed with LHC both luminosity and energy have been primed in a balanced way.

In view of the general nature of my talk I would like to indulge a few more moments on what I have called the “glorious” past, eventually just to illustrate the well known principle that “nothing is really new under the Sun”! A first example of this complementarity between approaches can be identified already at the beginning of this century, when the dilemmas leading to the advent of Quantum Mechanics first emerged. At that time, the “low-energy experiments” focused on black body radiation. These were extremely accurate measurements made at energies of about 1/1000th of an eV. At the same time, “high energy” experiments were pursued by physicists such as Hertz, who studied the photo-electric effect at then extraordinarily high energies of 5 to 10 eV.

There are further examples of this complementarity. In the 1920’s, for instance, the interplay between light and matter waves — detected with the first rudimentary accelerators — enabled to develop our understanding of the wave nature of matter. Between 1930 and 1950, the study of both radioactivity and cosmic rays provided us with the first basic notions of elementary particle physics.

The evolution of European particle accelerators has continued over the last decades along the two lines we have described: the relatively low energy but precise experiments at electron-positron colliders such as ADONE, ACO, DORIS and PETRA, and the high-energy frontier explored with proton machines such as the SPS, ISR, and SP̄S. The e+e− machines have provided accurate measurements of vector-meson spectroscopy (ρ, ω, φ, ψ, Y) and QCD observations such as the discovery of gluons. The proton machines have provided neutrino physics, including the discovery of neutral currents, hadron resonance spectroscopy and the understanding of meson decays (π, μ, K, Λ, Σ, Ω, etc.), CP violation, the discovery of QCD jets and, finally, the observation of W and Z particles.
All this underscores the necessity of pursuing simultaneously several, complementary approaches: no matter how effective a given technique or reaction may be, the overall understanding of subatomic phenomena needs experimental measurements from a large variety of different approaches. This is best exemplified by – and it has been the main reason for – the diversity of CERN programmes today, where high and low energies co-exist and where a variety of different projectiles – electrons, protons, heavy ions, etc – are simultaneously exploited.

2.— The role of Europe in the development of Colliding beams. Future plans for CERN are the follow-up of a long and successful tradition in Europe in the field of colliding beam devices. Indeed it has been in Europe that the main breakthroughs were made. Fig. 1 — the contemporary version of the Livingston plot — illustrates how this long and pioneering tradition has contributed to the realization of lepton and hadron colliders. The two lines in this figure represent the two main types of collider, hadron-hadron and e⁺e⁻, and each point represents the start-up date of a new machine. The emergence of the new line of e⁻p colliders is also displayed. Europe initiated hadron colliders with the ISR, followed by the SPPS. Although with TEV 1 the flag is now with our American colleagues, it will presumably return with us when the LHC — the first machine to explore the crucial mass region up to 1 TeV and above — becomes operative.

The electron-positron machines were first operated in the late sixties at Stanford, Novosibirsk, ACO and ADONE. These pioneer machines were followed by others such as DORIS and PETRA at DESY, CESR and PEP in the United States, and TRISTAN in Japan. LEP and SLC currently represent the highest energy e⁺e⁻ colliders. The next step will be LEP 200 which is comparable, in terms of constituent centre of mass energy, to TEV 1. Beyond this, high-energy e⁺e⁻ linear colliders are the probable future option.

In parallel, European laboratories such as CERN and DESY have developed the new and original concept of a series of interconnected machines which have provided a diversified spectrum of experimental possibilities. The CERN machine complex is shown in Fig. 2. The successes and the efficiency achieved through this approach are remarkable: despite ever tighter budgetary constraints in Europe, an impressive series of ma-
chines have been built. Among the CERN machines there are the SPS, LEAR, relativistic heavy ions in the SPS and LEP. At DESY there are PETRA and HERA, the pioneering e-p collider.

This approach has provided as well significant savings in cost, time and manpower. The CERN complex is now operated with half the personnel and yet serves four times the number of users with more facilities than all the of U.S. laboratories combined (Fermilab, SLAC and BNL). The distribution of users of the CERN machines is shown in Fig. 3.

European progress in accelerator R&D and in the related technologies has been the key of this success. For instance, the SPS of Sir John Adams is a most remarkable achievement even by today’s standards. Twenty years after the SPS start-up, the LHC will have a 40-fold increase in the bending power and it will provide 500 times the centre of mass energy. It will cost less than the SPS and it will be designed and built with one half to one third of the staff, in about the same time.

In comparison with the corresponding American facility, the SSC, the LHC is much less expensive and yet it generates a broader range of physics opportunities: it will not only collide p-p, but also ion-ion and e-p. The lower energy of the LHC (16/40 relative to the SSC), is offset by a luminosity as much as fifty times higher.

There is no doubt that the “know-how” developed over the last decades in Europe is by far the best guarantee that the future programmes will be able to deliver on schedule and within cost the ambitious experimental conditions required by elementary particle physicists to make further progress. I will now briefly discuss several major open questions to be addressed by the LHC.

3.— What do we want to learn from the LHC? Accelerator parameters cannot be formulated in isolation but they must be the consequence of specific scientific objectives. Since this is the main question to be addressed by the present workshop, I would limit my presentation to a first outline. The last few years have witnessed remarkable progress in particle physics. Through Gauge Theories, we have achieved a deep understanding of the strong, electromagnetic and weak phenomena. The mediators of the electro-weak and strong interactions — the intermediate vector bosons and the gluons, which were first observed at CERN and DESY, respectively — are now being studied in detail. LEP has shown that the Universe is made
of only three families of standard-model fermions. The basic fermions have all been discovered, with the exception of the τ-neutrino and the Top quark, for which, however, a great deal of indirect evidence has been accumulated. The combined results from p-p colliders, LEP and neutrino-electron experiments have confined the allowed mass range for the Top quark. This has been accomplished within a precise theoretical understanding of the electro-weak radiative corrections. There has also been remarkable progress in the field of strong interactions which, for the first time, can be accurately predicted by calculations.

One of the main problems is the actual mechanism for symmetry breaking in electro-weak phenomenon. This is associated with the nature of the Higgs mechanism, the existence of the Higgs as a particle and the behaviour of the cross sections involving the gauge bosons, W± and Z. The experimental signatures of the Higgs boson are illustrated in Fig. 4. If the Higgs exists with a mass lower than about 1 TeV, it will certainly be detected either at LEP200 or at the LHC (see Fig. 5).

As regards the production of pairs of gauge bosons and the study of the subtle cancellations implied by the Gauge theory, there is an important complementarity between LEP and the LHC. The higher energy of the LHC allows one to test gauge coupling at about the 2% level, which is ten times better than at LEP 200. This is illustrated in Fig 6.

In the case of the phenomenology of the heavy fermions — especially the B- and Top quarks — the LHC offers a very promising field. Figures 7 and 8, for example, show how the mass of the top quark can be measured to an accuracy of a few GeV.

The experimental conditions for exploring CP violation in the B system are compared for several machines in Table I. Assuming the development of suitable detectors, the advantages of the LHC are evident.

The search for new forms of matter — which could eventually explain the dark matter of the Universe — will be vigorously pursued at LHC. These include super-symmetric partners to the known particles, as well as hybrid forms of matter such as lepto-quarks, excited leptons, etc. The composite nature of our present basic particles will be explored to an unprecedented level. For instance the measurement of the single jet, inclusive differential cross section (Figs. 9 and 10) shows how the locality of the theory can be tested down to limits of 10–15 TeV.

Finally, the LHC will allow us to reach a deeper understanding of QCD. The LHC will generate heavy ion collisions at extremely high en-
ergy (≈3.5 TeV/nucleon) with the tantalizing prospect of producing a quark-gluon plasma.

**Table I** — Statistics and backgrounds for B studies at several accelerators

<table>
<thead>
<tr>
<th>Mode</th>
<th>Intensity / Luminosity</th>
<th>$\langle n_c \rangle$</th>
<th>$s_{(bb)} / s_T$</th>
<th>$N_{(bb)} / (10^7 s)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC jet gas target</td>
<td>$10^8 p/s$</td>
<td>~ 17</td>
<td>~ 1 / 25 K</td>
<td>~ 9.6 $10^9$</td>
</tr>
<tr>
<td>SSC</td>
<td>~ 20</td>
<td>~ 1 / 8000</td>
<td>(1 - 5) $10^{10}$</td>
<td></td>
</tr>
<tr>
<td>LHC pp collider</td>
<td>$10^{32}$</td>
<td>~ 80</td>
<td>~ 1 / 550</td>
<td>~ 2 $10^{11}$</td>
</tr>
<tr>
<td>SSC</td>
<td>~ 115</td>
<td>~ 1 / 200</td>
<td>~ 5 $10^{11}$</td>
<td></td>
</tr>
<tr>
<td>CESR e$^+$$e^-$ collider</td>
<td>$10^{34}$</td>
<td>~ 12</td>
<td>~ 1 / 4</td>
<td>1.2 $10^8$</td>
</tr>
<tr>
<td>SLAC</td>
<td>$10^{33}$</td>
<td>~ 12</td>
<td>~ 1 / 4</td>
<td>3.6 $10^7$</td>
</tr>
</tbody>
</table>

4.— **Design parameters for the LHC Project.** Energy and luminosity are the main parameters of a Collider. We shall discuss them in turn. The primary aim of the LHC is to reach collision energies well above 1 TeV at the constituent (quark and gluon) level. This can only be accomplished by a proton collider in the LEP tunnel using bending magnets with the highest magnetic field. The present "state of the art" is represented by the 4 Tesla magnets used at the Tevatron in Fermilab and by the 5 to 6 Tesla magnets being installed in HERA. For LHC we must aim at magnetic fields as high as 10 Tesla. This opens many new, technical challenges which must be solved:

(i) Since the forces grow as the square of the field, the pressure applied on the coils is 500 atmospheres, and yet the coils have to be located with an accuracy better than a micron.
(ii) The allowed current density in the superconducting material sharply decreases at large fields.

(iii) Magnets become bulky, thus increasing the space requirements and costs.

The proposed solution, shown schematically in Fig. 11, is to use the same basic design (namely a cold bore with two \( \cos \theta \) coils, the so-called Rutherford design) but with major changes in technology. In one of the two possible options, NbTi is operated at 1.80 K rather than the "classic" temperature of 4.50 K. At this temperature, helium becomes superfluid; its heat capacity is extremely reduced and risks of leaking are much more serious. Figure 12 shows how such a temperature reduction improves the working field. At 10 Tesla the colder conductor allows about 2000 A/mm\(^3\) – about the same situation as HERA today and one can realize the magnet with a reasonable coil thickness. The other possibility is to use Nb\(_3\)Sn and stay at 4.50 K. This option presents major metallurgical challenges. Both approaches are presently being pursued with prototypes. Estimated costs are compared in Fig. 13, where one can see that significant savings are possible with higher fields and with a more sophisticated cryostat in which both beams are bent by separate coils in the same device ("two-in-one"). This is very relevant in our case since the magnet structure for the LHC represents about 80% of the new investments.

The main features of the magnet, which is shown in Fig. 14, are:

- 50 mm bore, \( \cos \theta \) type with two coils and cold iron yoke;
- "two in one" configuration, for lower cost and compactness.
- different temperatures inside the cryostat, with separate cooling circuits, namely: (i) the beam pipe will have an inner radiation shield at 4-10 0K against synchrotron radiation losses, expected to be as high as 10 KW per ring; (ii) the coils will be at the temperature of superfluid Helium, 1.8 0K; (iii) iron yoke and collars will be at 4.5 0K. We remark that the enthalpy at 1.8 0K is about 10% of the value at 40K.

The realisation of the LHC magnets will require a major effort of Research and Development. Such an effort is already underway through a large collaboration between many European industries and institutes, with the goal to have a full string of magnets ready by 1992.

As already pointed out, a high luminosity is an essential feature at higher energies, mainly for the following reasons:
(i) The cross sections typically decrease as $1/s$. The proton is a broad band beam of quarks, antiquarks and gluons. With a higher luminosity we can make good use of infrequent collisions where the colliding constituents take a relatively large fraction of the energy of the proton. A higher luminosity extends the effective energy in the constituent frame. A factor of 10 in the luminosity is approximately equivalent to a factor of 2 in the energy;

(ii) A high luminosity allows the detection of rare events characterised by unmistakable ("gold-plated") signatures. This is an important feature in view of the huge potential backgrounds. As an example, the process $H^0 \rightarrow 2 Z^0 \rightarrow 4 \mu$ benefits from an extraordinarily beautiful signature. The price, however, is a loss by a factor 1000 in statistics, due to the branching ratio for two $Z^0$ into $4 \mu$ ($R = 0.03 \times 10^{-3}$).

Therefore all possible efforts have been made to attain the highest luminosity. This has resulted in a conceptual limit — usual for electron positron machines but unprecedented in proton machines — related to the emergence of synchrotron radiation (see Fig. 15) which is now particularly difficult to handle, since it must be dissipated inside the (cold) vacuum tube. In particular beam-instabilities may occur reminiscent of the famous "brick-wall" effect which has plagued the ISR, due to outgassing phenomena in the tube, the main source of cryo-pumping. In our design a special sleeve collects this radiation. The choice of its temperature is critical, since a too high value will enhance resistive wall instabilities and a too low temperature will be costly to sustain. Pumping action is achieved separately at 1.8 $^0$K.

In the case of the LHC and other machines of its kind, like the SSC, a careful interplay exists between the rising luminosity — which grows naturally with energy because of adiabatic reduction of the emittance — and the fast acting limitation coming from synchrotron radiation —which goes down like the cube of the energy. This new situation implies a totally new design. The final design figures for the LHC are shown in Table II.

Based on what we know today, we believe that its design parameters for the LHC are sound and the machine can be built. The physics phenomena we have discussed demand that we extend our explorations to a new energy domain, up to 1 TeV in the constituents and perhaps a little beyond.
Table II - LHC design parameters (pp operation). Columns 1 and 3 refer to 1 or 3 interaction points respectively.

<p>| | | |</p>
<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>E (TeV)</td>
<td></td>
<td>7.7</td>
</tr>
<tr>
<td>ε (π 10^{-6} m)</td>
<td></td>
<td>3.8</td>
</tr>
<tr>
<td>K</td>
<td>4725</td>
<td>1575</td>
</tr>
<tr>
<td>Δt (ns)</td>
<td>15</td>
<td>45</td>
</tr>
<tr>
<td>β^* (m)</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>10^{11}</td>
<td>3 10^{11}</td>
</tr>
<tr>
<td>KN</td>
<td>4.710^{14}</td>
<td></td>
</tr>
<tr>
<td>X-ing ANGLE (μrad)</td>
<td></td>
<td>200</td>
</tr>
<tr>
<td>SIMULT. EXP.s</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>FREE SPACE (m)</td>
<td>± 16</td>
<td></td>
</tr>
<tr>
<td>L (cm^{-2} s^{-1})</td>
<td>1.710^{34}</td>
<td>5 10^{34}</td>
</tr>
<tr>
<td>L/x-ing (cm^{-2})</td>
<td>2.510^{26}</td>
<td>2.210^{27}</td>
</tr>
<tr>
<td>P_{SYN} (W)</td>
<td></td>
<td>8800</td>
</tr>
<tr>
<td>W (MJ)</td>
<td></td>
<td>583</td>
</tr>
</tbody>
</table>
At these energies, where a great deal of new phenomena are expected to occur (Higgs, Top, super-symmetry, techni-colour etc.) the difference between 16 and 40 TeV is not significant and our trade-off between luminosity and energy appears both sensible and economical. Indeed, in many instances it appears that luminosity may eventually turn out to be even more important than energy, giving then a decisive advantage to the LHC.

In the choice of the machine parameters one has made full use of the fact that the LEP ring offers the added possibility of accelerating both electron and protons inside the same tunnel and hence e-p collisions. The development of the new Pb ion source will permit to extend at higher energies the ion-ion collision programme. While the importance of e-p collisions at energies higher than what possible today at HERA does not need to be underlined, we would like to touch very briefly the case for ultra-relativistic ion-ion collisions.

5.— Importance of relativistic ion-ion Collisions. In particle physics one is generally looking at simple systems in the hope that their understanding will provide an insight to more complicated ones. For instance the spectroscopy of the hydrogen atom already gives a good basic understanding of much of solid state physics.

Ion-ion collisions, which produce events with a very large number of particles, may show a complexity that is foreign to particle physics. Yet it is the way to approach experimentally a complexity which one cannot avoid, that of the vacuum, as presently described in QCD. The LHC will accelerate and collide lead ions, produced by the source soon to be installed at CERN, at no extra cost. Fig 16 shows in a diagram the rapidity range to be covered by LHC, where about 2000 particles per unit of rapidity are expected to be produced in the central plateau. Since 20 units of rapidity are covered, we can imagine the complexity of the events! The uniqueness of LHC in ion-ion physics is that it is fully complementary to what will be covered soon with the SPS and later with RHIC. To illustrate the complexity of ion events, Fig 17 shows a sulphur-sulphur event recorded at the SPS.
6. — Complementarity of LEP and LHC Programmes. Following a global approach to the basic physics issues which lie ahead of us, LEP and LHC will play parallel and complementary roles. They are each unique instruments and essential elements of a single scientific strategy.

The global aim of this programme is the most cost-effective and successful approach to the TeV energy domain. The schedule (Fig. 18) is foreseen as follows:

(I) In the next few years the priority is for LEP to obtain as many as 5,000,000 Z events for each of the four experiments. This should be achieved by 1993, after raising the luminosity with an 8-bunch "pretzel" scheme.

(II) The accessible energy of LEP should be increased to 180–190 GeV by 1994, and the machine should run intensively for three years in order to accumulate 500 pb\(^{-1}\) above the W pair threshold. The Higgs should be found if its mass is lower than about 80–90 GeV.

(III) The first LHC operation is scheduled for 1998. This will follow a long shut down in 1997.

(IV) After the long shutdown, and in parallel with LHC, a vigorous improvement programme on LEP should be pursued in order to operate at higher luminosities, eventually turning the machine into a "Z factory". In parallel one would satisfy the need for polarized beams. Therefore, LEP may continue to operate well into the next century.

(V) By the time when LEP physics will have largely been explored, one or more crossings could be converted to an e-p interaction region, with energies about 7 times that of HERA and a good luminosity.

(VI) Even further into the future, there may be an electron–positron facility with centre of mass energy larger than 1 TeV. Its actual parameters would crucially depend on the results obtained from colliders such as the LHC.

7.— A Future for High Energy e^+e^- Linear Colliders In this part I will widen the discussion to possible alternatives to the LHC, such as e^+ e^- linear colliders. There is no doubt that for many decades to come, progress in particle physics will be crucially dependent on progress in instrumentation and in particular in accelerator technologies. It is therefore appropriate to investigate the future possibilities of even higher energy e^+ e^- colliders such as CLIC, mnemonically the "Cern LLinear Collider".
The physics potential of such an accelerator operating in the TeV or multi TeV range is considerable. However a cautious optimism prevails concerning the feasibility of such a machine. Clearly we are not yet ready to design and build such "monsters", but R&D is being vigorously pursued at CERN and elsewhere. In this respect, wake-field ideas are apparently being replaced by more conservative approaches. An important milestone is the 50 MW generator operated at a 2 cm wavelength in Novosibirsk. Notice that, typically, one needs a power of 150 MW to achieve fields of 100 MeV/m. A final focus experimentation is ready to be started next year at SLAC. Intense workshop activities are being sponsored by ECFA, ICFA, etc..

My present expectation is that, by the year 2000, we should be ready to start a large-scale facility of that type, likely to be operational by, say, 2010. In this respect, this prospective machine appears to be the logical next step but after the presently planned LHC and SSC. In particular the LHC has to be conceived as a machine precursory to CLIC, since it can be realized (1) more rapidly and (2) at a lower cost than the SSC and it is most active in the energy domain of 1 TeV or slightly beyond which is also aimed at with CLIC. As often in the past a first "exploratory" phase with hadron collisions is a necessary precursory to the second "consolidating" phase using electrons and positrons. We have at present no idea of the phenomenology ahead of us. Such information is essential before planning sensibly the energy of the linear collider. In the past we have learned the hard way that the energy choice in the case of electron colliders is of primordial, strategic importance.

The linear collider in the TeV range will be a big machine, with a totally new structure, and probably on a site of its own. Most certainly its cost will largely exceed the one of LHC and will match the one of SSC. A rough estimate based on non-revolutionary accelerator technology leads to an estimate of about 5-7 MCHF/MeV or about 10,000-15,000 MCHF for a 2 TeV machine, totally out of proportion with the present level of resources of Europe today. Such an effort can only be brought to completion through an adequate world-wide cooperation, which must commence soon and which should hopefully be monitored through ICFA.
8.— Concluding Remarks. LEP has now concluded its first annual cycle collecting over 700,000 Z particles. To date, it is an unchallenged facility world-wide, both because of its luminosity and its future energy upgrades. The addition of an LHC ring in the same tunnel is part of a strategy centred on the LEP–LHC complex in order to explore physics up to the TeV region. The combined efforts of these two activities will provide a definitive exploration of particle physics at energies below 0.1 TeV, and a systematic mapping of the domain from 0.1 to 1 TeV. Finally, they will pave the way to a subsequent exploration of TeV physics with a new $e^+e^-$ linear collider.

Competition for funding with other fields and an overall scarcity of funds will undoubtedly face us. We have therefore followed the approach of operating CERN at an essentially constant budget. With our approach, the addition of LHC in the LEP tunnel has a global added cost equal merely to the scheduled contingency for the SSC. Still, in order to succeed, we need the enthusiastic support of the whole European community.

As a final remark, let me remind you that, a few years ago, a meeting was held here in Aachen to define the goals of LEP 200. It has been a very important meeting in which the strategy of CERN was defined for a number of years to come. It is not of accidental significance that today we are here again to look even further in the future discussing about LHC.
Figure 1 – Livingston Plots for hadron e-p and $e^+e^-$ colliders
Figure 2 – Schematic view of the CERN accelerator complex
Figure 3 – Distribution of CERN users according to the scientific programme
SEARCHING FOR THE HIGGS AT LHC

- $H \rightarrow 2Z \rightarrow 4 \text{jets}$
- $H \rightarrow 2Z \rightarrow 2\nu + 2\mu$
- $H \rightarrow 2Z \rightarrow 4 \text{ leptons} (\mu, e)$
- $H \rightarrow Z^* + Z \rightarrow \text{leptons}$
- $H \rightarrow Z \gamma \gamma$
- $(\text{Lep 200})$

Figure 4 – The primary Higgs signatures at the LHC
Figure 5 – Higgs signals (at masses of 600 and 800 GeV) corresponding to $10^{-4}$ pb$^{-1}$. The solid line corresponds to the expected background.
Figure 6  -- Rate of WZ production as a function of WZ effective mass.
Figure 7 – Top cross-sections as a function of top mass for the channel $pp \to \tilde{t} \tilde{t} + X$ and for the main background ($b\bar{b}$ production). The curves indicate the production cross-sections and the observed cross-sections after applying the top selection criteria.
Figure 8 – Measurement of the top mass: two- and three-jet mass distributions for the channel $t\bar{t} \rightarrow W^+ b W^- b \rightarrow \ell^+ \nu b \, q \bar{q} \, b$. The three-jet mass is shown after the selection of two jets in the $W$ mass region. The signal allows a top mass determination with an uncertainty of 5 GeV for a run of $10^4$ pb$^{-1}$. 
Figure 9  - Single jet inclusive differential cross-section.
Figure 10 – Expected single jet inclusive differential cross-sections for different values of $\Lambda_c$
Figure 11 – Basic geometry of the superconducting dipole magnet.
Figure 12 – Current density ($J_c$) in commercial superconducting wires as a function of the magnetic field intensity $B$. The corresponding coil thickness of the dipole magnets ($w$, see figure 11) is indicated.
Figure 13 – Cost of dipole magnets (50 mm bore) + cryostats as a function of the magnetic field intensity B.
LHC Dipole: standard cross section

Figure 14 – Cross-section of the LHC superconducting dipole magnet
Figure 15 – LHC luminosity as a function of the CM energy. The dashed lines indicate its corresponding synchrotron radiation power.
Figure 16: Rapidity domain covered by several heavy ion machines, as a function of CM energy per nucleon in nucleus-nucleus collisions (A ~ 200)
Figure 17 – View of a Sulphur - Sulphur event at the SPS (NA35 experiment).
Figure 18 – Construction schedule of the LHC
THE LARGE HADRON COLLIDER (LHC) IN THE LEP TUNNEL

LHC Working Group, reported by G. Brianti
CERN, 1211 Geneva 23, Switzerland

1. ABSTRACT

After the remarkable initial operation of LEP, the installation of a Large Hadron Collider, LHC, in the LEP tunnel will open up a new era for the High Energy Physics.

This report summarizes the main LHC parameters and subsytems and describes the more recent studies and developments.

2. INTRODUCTION

The LEP collider after a spectacular start-up in 1989 has already produced fundamental new results, including the highlight of the existence of only three particle families in the Universe. The four LEP experiments have collected to date 750 000 Z⁰ events. LEP will continue to be fully exploited in the coming years, while its beam energy will be progressively increased beyond the W pairs production threshold by means of superconducting cavities.

It is appropriate then to consider a further substantive step of machine construction to enable exploration of matter at an energy level at least ten times the one of LEP. This can be done by installing in the LEP tunnel a double ring of very advanced superconducting magnets capable of handling counterrotating proton beams of app. 8 TeV, known as the Large Hadron Collider (LHC) ¹).

It should be noted that this second installation will also open up the possibility of producing in LEP, in addition to electron-positron collisions, not only proton-proton collisions of 16 TeV in center-of-mass, but also electron-proton collisions up to 1.7 TeV, and eventually Pb-Pb collisions up to 1312 TeV.

CERN could then dispose of the most formidable complex of multipurpose colliders in the world.

It has recently been pointed out that the discovery of a massive Higgs particle (m_H \(< 0.8 \text{ TeV}/c^2\)) seems possible at the LHC, provided a luminosity L higher than \(10^{34} \text{ cm}^{-2}\text{s}^{-1}\) could be reached ²). This could be obtained through the process (H --> ZZ --> 4\mu) using a multi-muon detector. Studies of various limiting phenomena
have shown that for an experiment without central tracking and operating alone, the ultimate luminosity could be as high as $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$.

This paper summarizes the expected performances and limits, the proposed lattice and the status of the various technical systems. The construction carried out in collaboration with National Institutes and European industries is compatible with the completion of LHC within a reasonable budget and time scale.

3. PROTON-PROTON PERFORMANCES

Recent experimental results with dipole models have shown that a magnetic field of $\sim 10$ T can be reached. Since the circumference of the LHC orbit is determined by that of the LEP tunnel, it corresponds to a top energy of app. 8 TeV per beam.

<table>
<thead>
<tr>
<th>Table 1 : List of Main Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference</td>
</tr>
<tr>
<td>Revolution time</td>
</tr>
<tr>
<td>Nominal bending field</td>
</tr>
<tr>
<td>Nominal beam energies</td>
</tr>
<tr>
<td>Injection energy</td>
</tr>
<tr>
<td>No. of interact. regions (initially)</td>
</tr>
<tr>
<td>Full bunch length</td>
</tr>
<tr>
<td>RF frequency</td>
</tr>
<tr>
<td>Min. inter-bunch spacing</td>
</tr>
<tr>
<td>No. of proton bunches/beam</td>
</tr>
<tr>
<td>No. of protons/bunch</td>
</tr>
<tr>
<td>Intensity/beam</td>
</tr>
<tr>
<td>Stored energy/beam</td>
</tr>
<tr>
<td>Total synchro. rad. (two beams)</td>
</tr>
<tr>
<td>Beam radius at $\beta^* = 0.5$ m</td>
</tr>
<tr>
<td>Free space at I.R.</td>
</tr>
<tr>
<td>Luminosity at $\beta^* = 0.5$ m</td>
</tr>
<tr>
<td>(for three simultaneous experiments)</td>
</tr>
</tbody>
</table>

The other important parameter of a collider, the luminosity, is given for round beams of equal sizes by:

$$L = \frac{N^2 f k}{4 \pi \sigma^2}$$

(1)

Here $N$ is the number of protons per bunch, $f$ the revolution frequency, $k$ the number of bunches in each beam and $\sigma$ is the r.m.s beam radius at the crossing points. $\sigma$ is determined by the normalized beam emittance $\varepsilon^*$ expressed in mm.mrad

$$\varepsilon^* = \gamma \sigma^2 / \beta^*$$

(2)
\( \beta^* \) being the beta value at the crossing point and \( \gamma \) the energy in proton rest mass units.

3.1. Beam-beam effects

The main limitation to the collider luminosity is the beam-beam tune shift \( \xi = r.N/4\pi e^* \), where \( r \) is the classical proton radius. The parameter \( \xi \) multiplied by the number of interaction regions must not exceed 0.01. Therefore when the beam-beam limit is reached, the luminosity can be increased:

- by reducing the \( \beta^* \) in the interaction region (I.R). The limits are set by the bunch length, the magnetic strength of the corresponding quadrupole triplets, the beam dynamic aperture and the length of the straight section, \( L^* \), available for Physics experiments. For \( \beta^* = 0.5 \) m, \( L^* = 32 \) m.

- by increasing the number of protons per bunch. Since the ratio \( N/\varepsilon^* \) must stay constant to satisfy the beam-beam limit, the emittance \( \varepsilon^* \) and hence the beam sizes must increase accordingly. Limits are set by collective phenomena for \( N \) and by the available dynamic aperture for \( \varepsilon^* \). A coherent set of parameters in the case of three interaction regions is \( N = 1 \times 10^{11} \) p/bunch and \( \varepsilon^* = 3.8 \) mm mrad. The CERN injector chain is capable of providing such beams with a few improvements.

- by increasing the number of bunches. This allows to increase the luminosity while keeping a small number of events per collision and without changing the beam-beam tune shift. In each interaction region, there is a part with a common vacuum chamber for the two beams where several bunches of the two counter-rotating beams "see" each other. This long range beam-beam effect\(^3\) increases when the interbunch spacing decreases. Limits are also given by the data handling capabilities of the Physics experiments. Since the SPS operates with an RF frequency of 200 MHz, the interbunch spacing in the LHC must be a multiple of 5 ns. The minimum interbunch spacing could be 15 ns, while operation at 30 ns or 45 ns could be provided with minor additions to the R.F. accelerating system of the PS injector.

In order to keep the long range beam-beam effect within tolerable limits, the beam crossing angle, \( \alpha \) has to be increased at high luminosity. This in turn reduces the luminosity according to:

\[
L(\alpha) = L(\alpha = 0)[1 + (\alpha \sigma_L/2 \sigma_T)^2]^{0.5}
\]

where \( \sigma_L, \sigma_T \) are respectively the r.m.s longitudinal and transverse beam sizes.
3.2. Synchrotron radiation

Protons of app. 8 TeV in the LHC emit synchrotron radiation with a critical photon energy of 69 eV. Each beam with an intensity of 4.8\times10^{14} \text{ p} radiates 9 kW. The synchrotron radiation is absorbed by a radiation shield cooled at 4.2 K. Remembering that to extract 1 W at 4.2 K, about 300 W are needed at room temperature, the synchrotron radiation power, \( P_{\text{sync}} \), appears as an important limiting factor in the cost of high luminosity colliders. It is interesting to note that \( P_{\text{sync}} \) of the LHC at very high luminosity is the same as the one of the SSC at \( 10^{33} \text{ cm}^{-2}\text{s}^{-1} \).

3.3. Beam loss

An other limiting factor for high luminosity colliders are beam losses. If protons hit the vacuum chamber of a superconducting magnet, radiated energy is deposited in the coils and can induce a quench. Several processes contribute to systematic losses. While the 2.5 kW of inelastic secondary particles produced in each collision region is more a problem for the detector than for the machine itself, the remaining 2.5 kW of elastic particles per beam produced with small scattering angles in the three collision regions participate in a blow-up of the beam emittance and hence potentially to beam losses\(^4\). Other effects like long range beam-beam effects, non-linearities in the magnetic field, ripple on power supplies also contribute to beam losses. In any accelerator, there are always a few limiting apertures, where some magnets could receive much more radiation than others. Simulations have shown that at 8 TeV a continuous loss of \( \sim 1 \times 10^{7} \text{ p/s} \) can quench a dipole. Therefore a beam cleaning region without superconducting magnets should be designed with a catching efficiency better than 99%.

4. ELECTRON-PROTON PERFORMANCES

An attractive option is the possibility to collide the 8 TeV LHC beam with the LEP electron beam. In the most promising configuration, the electron beam is deviated upwards and collides head-on with the proton beam located about 1 m above the LEP median plane.

Adequate RF power is available from the LEP RF system to compensate the synchrotron radiation losses for an average circulating current of 8.4 mA at 100 GeV. It is assumed that the current scales like \( E^{-4} \) at lower electron energies and that it is
distributed over a number of bunches such that the proton beam-beam limit is not exceeded. This is possible up to a maximum of 540 bunches where the bunch spacing becomes 49.5 m. This is the smallest bunch spacing which is simultaneously a multiple of the LEP and SPS RF wavelengths.

![Graph showing the relationship between electron energy and luminosity in ep collisions](image)

**Fig. 1:** Luminosity for ep collisions (p beam energy app. 8 TeV)

The vertical betatron function at the interaction point for electrons $\beta_{ye}$ is adjusted to the lowest possible value compatible with the required opening angle of the forward detector namely $\beta_{ye} = 0.15$ m. Since the number of bunches in the LHC is much smaller than in the pp mode, the proton injectors are capable of delivering intensities up to $3 \times 10^{11}$ protons per bunch while keeping the same transverse emittance of $3.8 \pi \times 10^{-6}$ rad.m. Other parameters of the electron and proton beams are adjusted so that the beam-beam tune shifts for the protons do not exceed $\xi_p = 0.006$ with one interaction region, and that the beam-beam tune shifts for the electrons do not exceed the LEP design value scaled to three interaction regions, which yields $\xi_e = 0.05$. With the assumptions and the optimization procedures described above, the luminosity obtained in ep collisions strongly depends on the energy of the electron beam, as can be seen in Fig. 1.
5. ION-ION PERFORMANCES

Any beam of fully stripped ions which can be produced by the low energy injectors (Linac, Booster, CPS) can be accelerated in the SPS and in the LHC.

With the oxygen and sulphur ion beams which have already been accelerated in the SPS one could produce a luminosity of respectively $2 \times 10^{26} \text{cm}^{-2} \text{s}^{-1}$ and $3 \times 10^{25} \text{cm}^{-2} \text{s}^{-1}$. Using the lead ion source which is now under consideration for use in the SPS fixed target programme, one would obtain a luminosity of $10^{25} \text{cm}^{-2} \text{s}^{-1}$.

Fundamental limitations in the LHC arise at beam crossings from electromagnetic dissociation and pair production followed by electron capture, as well as intra-beam scattering.

All these effects would limit the luminosity to around $10^{28} \text{cm}^{-2} \text{s}^{-1}$ for lead-lead collisions. However, to reach this luminosity, beam currents 30 times higher than those produced by the lead source presently envisaged would be necessary. This could be obtained by an improvement of the source or through an accumulation system at low energy, or by a combination of both, as discussed in Reference 5).

For a luminosity of $10^{27} \text{cm}^{-2} \text{s}^{-1}$, an increase of the lead beam currents by only a factor 10 would be sufficient. Table 2 gives a list of parameters describing this case.

<table>
<thead>
<tr>
<th>Type of ions</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. c.m. energy ($\sqrt{s}$) for Pb-Pb</td>
<td>1262 TeV</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$1.8 \times 10^{27} \text{cm}^{-2} \text{s}^{-1}$</td>
</tr>
<tr>
<td>Number of I.R.</td>
<td>1</td>
</tr>
<tr>
<td>$\beta^*$ at interaction point</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Free space at I.R.</td>
<td>32 m</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>800</td>
</tr>
<tr>
<td>Inter-bunch distance</td>
<td>105 ns</td>
</tr>
<tr>
<td>No. of ions/bunch</td>
<td>$6.2 \times 10^7$</td>
</tr>
<tr>
<td>No. of ions/beam</td>
<td>$5.0 \times 10^{10}$</td>
</tr>
<tr>
<td>Transverse emittance $\gamma \sigma^2 / \beta$</td>
<td>$1.0 \mu \text{m}$</td>
</tr>
<tr>
<td>Transverse emittance growth times</td>
<td></td>
</tr>
<tr>
<td>• at injection</td>
<td>10 hours</td>
</tr>
<tr>
<td>• at max. energy</td>
<td>15 hours</td>
</tr>
<tr>
<td>Luminosity half-life</td>
<td>11 hours</td>
</tr>
</tbody>
</table>
5.1. **Lattice**

Due to the size of the LEP tunnel cross section, installing two separate cryostats, one for each proton beam, is not possible. The only way is to combine the two beams into the same magnet and the same cryostat. The superconducting coils providing equal but opposite magnetic fields have a common iron yoke and force-retaining structure (Fig 3), the whole being housed in one cryostat. This "two-in-one" solution allows the highest possible field in the restricted space above LEP, and has not only the advantage of compactness but also of lower cost (~30%), compared with that of two independent rings with separate cryostats.

LHC being in the same tunnel as LEP will also have 8 arcs and 8 long straight sections. The two proton beams, horizontally separated by 180 mm in the arcs, alternate from the outside to the inside in the middle of each of the 8 long straight sections, where in principle they could interact.

The evolution in High Energy Physics can lead some existing LEP experiments to be converted into an ep or pp experiment using LHC. In the early stage of the LHC project, it is then mandatory to maintain the maximum of flexibility among the 8 intersection regions, IR. The lattice has then been adjusted in such a way that identical performances can be reached in each IR. To reduce the beam-beam effect, the beams are vertically separated in the crossing regions when the beams are not colliding.

![Diagram of lattice parameters](image)

**Fig. 2. Layout of the standard half-cell**
The LHC lattice of FODO type is constituted by:

- 8 arcs, each of them containing 50 half cells.
  One half of a regular cell (Fig 2) consists of four, ~ 9 m long, dipoles (D), a focusing (or defocusing) main quadrupole (Q). Near each main quadrupole and for each ring stand a beam observation station (BOM), a tuning quadrupole (QT), a vertical or horizontal dipole to correct the closed orbit (COD), a set of multipolar correctors sextupole (S), octupole (O), decapole (D). Lumped correctors (S+O+D) are also foreseen in the middle of the half-cell. All these magnets are superconducting.

- 8 insertions, each of them containing one long straight section and two dispersion suppressors of a type that allows trajectories of identical length for the hadrons in LHC and for the leptons in LEP. Two IRs are reserved, one for the beam dumping system, the other as a beam cleaning region.

Initially up to three IRs can be devoted to Physics experiments. The 'standard' IR can be tuned between $0.5 \, \text{m} < \beta^* < 15 \, \text{m}$, namely in a range between 1 (max. luminosity $1.7 \times 10^{34} \, \text{cm}^{-2}\text{s}^{-1}$) and 30 (min. luminosity $5.5 \times 10^{32} \, \text{cm}^{-2}\text{s}^{-1}$), with a length available for the detector of $\pm 16 \, \text{m}$ and a bunch spacing of 15 ns.

If a specific experiment operating alone can accept a bunch spacing of 45 ns, its maximum luminosity can reach $5 \times 10^{34} \, \text{cm}^{-2}\text{s}^{-1}$.

6. MAGNETS

As far as superconducting magnets are concerned, the LHC enters now in an era of building prototypes in close collaboration with European industry. Results of single aperture NbTi and Nb$_3$Sn dipole models were reported in an other Conference$.^6$)

Four NbTi and one Nb$_3$Sn twin aperture, 1m long dipoles are being built by four different European firms and will be delivered at CERN by end of this year. The first NbTi twin aperture, 10 m long dipole, built with HERA coils (Fig. 4) has been assembled and has been mounted into its cryostat this summer. It will be cooled at 1.8 K and tested at Saclay (F). Two NbTi twin aperture, 10 m long dipole, built with the LHC cables have been ordered by the INFN (I), eight others are being ordered by CERN. Prototypes of the main quadrupole, of tuning quadrupole, of dipole, sextupole and octupole correctors are also under development. The quantities of magnets to be produced are indicated in Table 3.
Table 3: List of Magnets

<table>
<thead>
<tr>
<th>Dipoles</th>
<th>Magnetic Length (m)</th>
<th>Number of magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_0 = 10 \text{T}$</td>
<td>9.00</td>
<td>2 x 1792</td>
</tr>
<tr>
<td>Quadrupoles</td>
<td>$G = 250 \text{T/m}$</td>
<td>3.05</td>
</tr>
<tr>
<td>Tun. quads,</td>
<td>$G = 120 \text{T/m}$</td>
<td>0.72</td>
</tr>
<tr>
<td>Sextupoles</td>
<td>$B'' = 4500 \text{T/m}^2$</td>
<td>1.0</td>
</tr>
<tr>
<td>Orbit corr.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>dipoles</td>
<td>$B_0 = 1.5 \text{T}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Higher-order</td>
<td></td>
<td></td>
</tr>
<tr>
<td>multipoles</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A more detailed review of the LHC magnets is given in Reference 7).

Fig. 3: LHC dipole standard cross-section
Fig. 4. 10 m long dipole

7. CRYOGENICS (FOR NBIT)

The main task of the cryogenic system is to maintain all windings at a temperature below 2 K in steady operation, as well as to cope with slow and fast thermal transients such as cooldown, current ramping and discharge, and resistive transition of the magnets.

In steady operation, the heat sources are those inherent to the cryostat design: in-leak across shields, resistive joints between cables, feedthroughs for signal or heater cables; they are estimated to 0.3 W/metre of dipole cryostat. Another important source is due to the beam: the synchrotron radiation (critical energy < 69 eV) is fully absorbed by the inner radiation shield at about 5 K inside the vacuum chamber; an accidental beam loss can produce a quench if the heat deposit in the dipole exceeds 25 W over 50 m. It is assumed that there is only one such high heat load per half octant.

A cooling scheme based on forced circulation of superfluid helium is being considered. It appears adequate to absorb transient and localized heat loads. A pump
circulates a flow of superfluid helium in a closed loop extending over one half-octant, recooled by heat exchange in a periodic sequence of cooling stations in the machine tunnel.

8. RADIO-FREQUENCY

The basic option of the RF for LHC consist in two independent RF systems, one for each beam. The RF frequency (400.8 MHz) is twice the SPS frequency, to allow single transfer of one SPS turn. The shape of the cavities is such as to keep the 18 cm distance between the two beams. Symmetrical cavities are chosen to avoid transverse magnetic fields. An alternative is to use single-bore cavities acting on both beams and installed around an unused interaction point. Bunch to bunch feedbacks (Bandwidth > 40 MHz) are absolutely necessary in the transverse and longitudinal planes.

To cope with single bunch collective effects at high luminosity (N=1*10^{11} p/bunch), the bucket area must be large enough. A RF voltage of 18 MV corresponding to a 9.25 eV.s bucket area is considered adequate.

For a hadron collider (Φ_s ∼ 0), the RF power is mainly needed to handle the heavy transient beam loading created by the uneven beam structure, mainly due to beam holes required by the injection (~1 μs) and dump kickers (~2 μs).

Only a small fraction (850 kW) of the total installed power (8 MW) is dissipated in the cavity walls.

Each 1 MW power generator drives a multi-cell π mode coupled cavity; this is a favourable arrangement to implement RF feedback needed to handle beam loading.

The PS should be equipped with a 66.8 MHz RF system to bunch the beam at 26 GeV/c flat top with a 15 ns interbunch spacing. The 8 ns bunch length are captured and subsequently compressed to 4 ns with another 66.8 MHz system in the SPS.

With an additional RF system in the PS at 33.4 MHz, one can inject one bunch in every two 66.8 MHz buckets of the SPS, giving an interbunch spacing of 30 ns

9. CONVENTIONAL FACILITIES AND INJECTOR COMPLEX

The great advantage of building the LHC in the LEP tunnel is not only the existence of the tunnel but also of all other conventional facilities such as: access shafts, handling equipments, electrical distribution, ventilation, telecommunication and computer networks.
The cooling plants being installed in the even insertions to increase the LEP energy above 90 GeV are compatible with a future e-p operation at an electron energy of 50 GeV and represent 50% of the cooling power needed for the LHC pp operation.

The existing accelerator complex namely the 50 MeV linac, the 1 GeV Booster, the 26 GeV Proton Synchrotron and the 450 GeV Super Proton Synchrotron, which have operated for many years with world record performance both for beam output and reliability, constitute an excellent injection complex for the LHC (Fig. 5).

Fig. 5. Injector complex

Indeed the present beam characteristics of these injectors with minor additions would enable the LHC to reach an ultimate luminosity of $5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ for proton-proton collisions. The same existing complex, with the inclusion of, respectively, the electron/positron linacs and accumulation ring for the electrons, and of the new front-end for lead ions can provide the other particles for electron-proton and ion-ion collisions. It is appropriate to emphasize that this chain of interlinked machines represents not only a major financial asset, but also integrates decades of human efforts to push its overall performance to the present level of excellency. This is why CERN can be confident that the performance levels discussed for the LHC will be rapidly achieved.
10. EXPERIMENTAL AREAS

This design has not yet been finalized, since it depends on the experiments which are being considered.

It appears that a conceptual design of the standard LEP area, namely a cavern transverse to the beam of somewhat larger diameter, serving also as a garage, could be appropriate.

Another design being considered includes a cavern parallel to the beam, served by two large shafts at both ends for quick installation of large segments of the experiment (2500 tons each).

11. TIME-SCALE

CERN has undertaken a vigorous R&D programme for developing and actually testing on a real scale the advanced superconducting technology on which the LHC is based.

The programme is centred on the fabrication in industry of several full scale superconducting magnets by mid-1992 and finally aims to install in a hall and to fully test (magnetically and cryogenically) approximately 100 m of the complete magnet structure under realistic operating conditions.

If the final executive decision to proceed with the project is taken at that time, the installation of the LHC collider could be completed by 1997 and its commissioning could start at the beginning of 1998.

The LEP energy upgrade by means of RF superconducting cavities will be completed at the beginning of 1994, allowing LEP to be operated at or above the W-pair threshold for three years prior to the shutdown for the installation of the LHC in 1997.

In the years after 1997, when the two colliders coexist in the LEP tunnel, alternate periods of running will be scheduled on a half or full year alternate operation basis.

12. COLLABORATION WITH EUROPEAN INSTITUTES AND INDUSTRIES

The R&D programme for the development of the LHC magnets and cryogenics is based on the best use to be made of the expertise existing outside CERN in the Member States, in order to avoid carrying out in the laboratory work which could be done elsewhere. National Institutes, Universities and Industry were invited to join
forces with CERN in a complementary fashion in order to fulfil the basic aims of the programme.

To date, a number of collaborations have been established and have produced very encouraging results.

Progress so far is a good example of how well Europe can proceed by joining all the available effort and expertise in a common programme and of how an advanced project in particle physics can stimulate technological development.

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STANDARD MODEL PHYSICS AT THE LHC (pp COLLISIONS)

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This is the summary of the work done in the ECFA/LHC Working Groups studying the possibilities for Standard Model physics in pp collisions at the LHC. It is organized as follows:

1. Standard processes:
   - $\sigma_{\text{tot}}$ and $\sigma_{\text{el}}$: minimum-bias event
   - jets and direct photons
   - $W$, $Z$ production; $WZ$, $W\gamma$ pair production

2. B physics:
   - possibilities of observing CP violation
   - collider versus fixed-target mode

3. Top physics:
   - top-quark searches, signal versus background
   - mass determination, branching ratios

4. The Standard Model Higgs:
   - searches for $m_H > 2m_Z$
   - searches for $m_H < 2m_Z$

5. Possibilities for neutrino physics at the LHC:
   - direct observation of the $\nu_\tau$
   - possibilities for $\nu_e$, $\nu_\mu$ studies

6. Conclusion

presented at the
ECFA - Large Hadron Collider Workshop
Aachen, 4 - 9 October 1990.
INTRODUCTION

Within the framework of the ECFA Workshop on physics at the LHC, the study of the Standard Model phenomena in pp interactions at the LHC has been subdivided into four distinct subjects, with corresponding working groups: standard processes, B physics, top-quark physics, and the search for the Higgs boson. The working group on standard processes was in practice subdivided into three subgroups, dealing respectively with i) the determination of the elastic and total cross-sections; ii) the investigation of the possibilities for doing neutrino physics at the LHC; and iii) the study of the hard-collision phenomena: jets, direct photons, W and Z production, intermediate vector boson pair production (WZ, Wγ, ZZ), and heavy-flavour (b̄b and t̄t) production cross-sections – the latter being used in part as an input for the groups studying specifically bottom- and top-quark physics. In the following, we will summarize the work of the various working groups in about the same order, starting with σ_tot and σ_el and finishing with neutrino physics. There was, in addition, a special working group devoted to event generators. Its activity consisted in comparing the various Monte Carlo generators among themselves and in understanding their limitations, fixing some problems, or inserting new mechanisms as the need arose. Although not often quoted in the following, they provided us with a critical understanding and optimization of the models used in the physics simulations. The list of conveners and active participants in each of the working groups is given in Ref. [1]. This summary is complemented by a similar one on physics beyond the Standard Model, by F. Pauss, and by an overview of all the pp/LHC workshop activities given by G. Altarelli, with more emphasis on theoretical issues.

Before summarizing the investigations of the various LHC/pp physics working groups, and to settle the order of magnitude of the various phenomena investigated, Fig. 1 shows the energy dependence of some characteristic cross-sections, and the event rates we expect at the LHC. At a luminosity of 10^{34} cm^{-2} s^{-1}, the expected total cross-section of ~ 100 mb should be responsible for ~ 10 interactions per bunch crossing (every 15 ns). The expected rise of σ_b̄b over the energy range considered shows that, already at a luminosity of 10^{32} cm^{-2} s^{-1}, of the order of 10^{11} b̄b pairs are produced in one year of running (i.e. for 10^{7} s), thus indicating the potential of such machines for B physics. The cross-section for jets of E_T > 250 GeV results in there being > 10^{3} such jets produced per second at a luminosity of 10^{34} cm^{-2} s^{-1}, indicating the need for selective triggers. The production cross-sections for W (or Z) → LLL are expected to be a factor of ~ 20 times greater than at present colliders. Large-<p>T_W, Z production will doubtless provide an interesting test of QCD, but it is also a major source of background for the potential signals looked for at the LHC, such as the top-quark and the Higgs, and has to be well understood. For m_t = 200 GeV, the top-quark is produced at a rate of ~ 10^{6} t̄t pairs per year already at a luminosity of 10^{32} cm^{-2} s^{-1}, where detection is not expected to present particular problems. This makes machines such as the LHC or the SSC into real 'top factories'. It allows a detailed study of t-quark production and decay
properties — and *a fortiori* its discovery, if not yet made. Finally, Fig. 1 also shows that at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ the much-desired Higgs boson is produced at the rate of $\sim 10^5$ events per year for $m_H = 500$ GeV. However, as the Higgs decay mode that provides the best experimental signature, $H \rightarrow ZZ \rightarrow 4\ell\nu$, has a small branching ratio of $\sim 3 \times 10^{-4}$, the Higgs search in this most favourable channel should still be largely limited by statistics.

![Energy dependence of some characteristic cross-sections, from present colliders to the LHC/SSC.](image)

**Fig. 1** Energy dependence of some characteristic cross-sections, from present colliders to the LHC/SSC.
1. STANDARD PROCESSES

Total and elastic cross-sections

Figure 2a shows a compilation of present measurements of $\sigma_{\text{tot}}$ [2], including the latest Fermilab collider result from experiment E710: $72.1 \pm 3.3$ mb [3]. If the present rise is extrapolated to LHC energies according to $\sigma_{\text{tot}} \sim \log^2 s$ (Fig. 2a), we expect $\sigma_{\text{tot}} = 130$ mb at the LHC: if, however, as $s \to \infty$, $\sigma_{\text{tot}}$ tends instead to a constant, then the expectation is $\sigma_{\text{tot}} = 90$ mb (A. Martin). In conclusion, the expectation for the LHC is $\sigma_{\text{tot}} = 110 \pm 20$ mb (see also Ref. [4]).

Figure 2b shows the ratio of $\sigma_{\text{el}}/\sigma_{\text{tot}}$, which rises from $= 0.17$ at the ISR to $= 0.21$ at the Sp $\overline{p}S$ and to $= 0.23$ at Fermilab (0.23 $\pm$ 0.02) [2, 3]. The extrapolation of this behaviour leads us to expect $\sigma_{\text{el}}/\sigma_{\text{tot}} = 0.26$ at the LHC [4]. This ratio is related to the 'grayness of the proton', and its rise is limited by unitarity to the 'black disk limit' of $0.5 - \varepsilon_{\text{diff}}$ (Pumplin's bound), where $\varepsilon_{\text{diff}}$ is the fraction of the diffractive cross-section due to single- and double-diffractive dissociation.

Figure 2c is a compilation of present measurements of the forward elastic slope B ($d\sigma/dt \sim \exp (-B|t| + c|t|^2)$). Extrapolating present parametrizations, the expectation for the LHC is $B = 21$ GeV$^{-2}$ [2]. There is, however, much more to the elastic scattering than just the forward slope; the larger-|t| region $t \sim 1$ GeV$^2$ is very interesting too. Figure 3a shows the expectations for the large-|t| elastic scattering behaviour at LHC/SSC energies according to the impact-parameter model of Bourrely, Soffer and Wu [4]. In this model, the 'edge of the proton' becomes sharper with increasing $\sqrt{s}$, thus resulting in a more pronounced diffractive pattern. The fall-off between the forward maximum and the first secondary maximum is about three orders of magnitude; here the experimental difficulty is not in the event rate or the optics, but rather in the backgrounds present at larger $t$. In this model, no difference is expected between pp and p $\overline{p}$ scattering at LHC energies. This is not the case, however, in the 'odderon model' (Gauron, Leader, Nicolae, D. [5]) shown in Fig. 3b, and for which there are substantial differences between pp and p $\overline{p}$, in particular in the region of the first minimum at $-t = 0.3$ GeV$^{-2}$. This model also predicts that $\sigma_{\text{pp}} > \sigma_{\text{p} \overline{p}}$. If the UA4 result $\rho = 0.24 \pm 0.04$ [6] (Fig. 4) is confirmed by the renewed experiment UA4/2, this would provide strong support for this 'odderon model', as it is the only one to expect such large values of $\rho$ at the Sp $\overline{p}S$ energies, whilst standard expectations are $\rho = 0.10$ to 0.15 [2, 4]. In this case, it would be interesting to check its other predictions concerning differences between pp and p $\overline{p}$, i.e. it would then be important to keep open the possibility of doing also p $\overline{p}$ at the LHC. A luminosity of $\sim 10^{28}$ cm$^{-2}$ s$^{-1}$ would be possible with the present high-$\beta$ insertion discussed below (Scandale); this is sufficient for studying the difference between pp and p $\overline{p}$ in the dip region, it would provide $\sim 10^4$ events per GeV$^2$ in 10 days of running (see Matthiae in Vol. II of these Proceedings). This p $\overline{p}$ option would not be possible at the SSC, where no $\overline{p}$ source is foreseen.

The present (provisional) high-$\beta$ insertion of W. Scandale is shown in Fig. 5. This
Fig. 2  a) Total cross-sections, b) ratio of elastic to total cross-sections, and c) forward elastic slope, with extrapolations to the LHC.
insertion, providing a luminosity of up to \( \sim 1.1 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \), has at the beam crossing point 
\( \beta^* = 750 \text{ m}, \Delta x^* = 300 \mu\text{m} \) for the beam size, and 
\( \Delta \theta_x^* = 0.5 \mu\text{rad} \) for the beam angular divergence. At the detectors — which are about 200 m from the crossing point — at \( \Delta \psi = \pi/2 \) (\( \Delta \psi \) is the betatron phase advance), 
\( \beta_{\text{det}} \sim 5 \text{ m} \) with \( \Delta x \sim 30 \mu\text{m} \), i.e. \( \theta_{\text{min}} \sim 9 \mu\text{rad} \) and 
\( t_{\text{min}} \sim 5 \times 10^{-3} \text{ GeV}^2 \) with a 0.5 mm minimal distance of approach of the detectors (probably fibre detectors in 'Roman pots', see Mondardini and Bernard in Vol. II) to the beams. It would be more favourable to have larger \( \beta \) at the detectors, and this could be remedied (Jeanneret). This \( t_{\text{min}} \) is adequate for the \( \sigma_{\text{tot}} \) measurement (10% extrapolation to the optical point). The total cross-section is then given by the luminosity-independent measurement

\[
\sigma_{\text{tot}} = \frac{16\pi}{(1 + \rho^2)} \left( \frac{dN_{\text{el}}/dt}{N_{\text{el}} + N_{\text{inel}}} \right) = 0,
\]

where \( N_{\text{el}} \) and \( N_{\text{inel}} \) are the total elastic and inelastic event rates, respectively (the effect of \( \rho^2 \) on \( \sigma_{\text{tot}} \) is almost negligible). The size of the beam pipe (4 cm) and the free space around the crossing point makes it possible to cover in a satisfactory way the forward rapidity range for the measurement of the total inelastic rate, with \( \eta \) coverage up to \( = 8.9 \), i.e. \( \theta_{\text{min}} = 0.27 \text{ mrad} \) (\( \eta_{\text{beam}} \) is at 9.7). The exact position and shape of the forward counters measuring the total inelastic rate is not yet determined. However, the \( \eta \)-coverage must be such that the extrapolation uncertainty on \( N_{\text{inel}} \) is not larger than a few per cent (\( \sim 3\% \)), and is considered feasible (for more details, see Matthiae in Vol. II).

If \( \rho = 0.24 \) were confirmed by UA4/2, thus indicating that \( \rho \) continues to grow over the \( S\bar{p} \) \( S\bar{p} \) range, it would be very important to measure it also at the LHC, as it is expected to peak at \( \rho = 0.12 \) to 0.15 and then decrease in any 'reasonable model' (A. Martin): if \( \sigma_{\text{tot}} \rightarrow \log^2 s \), then \( \rho \rightarrow \pi/\log s \); if \( \sigma_{\text{tot}} \rightarrow \log s \), then \( \rho \rightarrow \pi/2 \log s \); if \( \sigma_{\text{tot}} \rightarrow \text{const} \), then \( \rho \rightarrow 0 \) faster, possibly as fast as \( 1/\sqrt{s} \). The measurement of \( \rho \) would, however, require measurements in the Coulomb scattering region, in a \( t \)-range substantially below the \( t_{\text{min}} = 5 \times 10^{-3} \text{ GeV}^2 \) that is accessible with the present (provisional) high-\( \beta \) insertion of Fig. 5. It might be possible either to increase \( \beta^* \) to \( \sim 2 \text{ km} \) or (and) to increase \( \beta_{\text{det}} \) (Scandale, Jeanneret), but here the SSC with its longer straight sections has an advantage.

The minimum-bias event

The properties of the 'minimum-bias event' are not calculable in QCD, thus we have to resort to various models. The understanding of the minimum-bias event, and of the related 'underlying event' in a hard-scattering process, is important, as they can limit or spoil the lepton (or \( \gamma \)) isolation, which is a crucial selection criterion in \( t \)-quark or Higgs searches. The underlying event is part of the hard collision event itself and is thus unavoidable, whilst the minimum-bias events enter through event superpositions during same bunch crossing when
Fig. 3 Elastic differential cross-sections in the large-\( t \) range.

Fig. 4 Compilation of data on \( \rho \); the dashed line is the 'odderon model' prediction, solid line is the standard prediction.
Fig. 5  A provisional high-β insertion for the LHC.

Fig. 6 $<n^{±}>$ and $<p_T>$ in minimum bias events versus $\sqrt{s}$. 
running at high luminosity.

Figure 6a shows the expected $\sqrt{s}$ evolution of the mean charged-particle multiplicity $dn^{\pm}/d\eta$ (in $|\eta| < 2.5$) as predicted by various Monte Carlo generators (ISAJET, PYTHIA, GENCL). The data of UA1 and CDF are also shown. The models, even when tuned to reproduce the current data, present a spread of predictions. The extrapolation to the LHC gives $dn^{\pm}/d\eta \approx 5$ to 6, i.e. $n^{\pm}_{\text{tot}} \approx 80$ charged particles per event on the average. Figure 6b shows the $\sqrt{s}$ variation of $<p_T>$ (for $|\eta| < 2.5$); at the LHC we expect $<p_T> \sim 530$ MeV/c (Di Ciaccio, Ciapetti, Sjöstrand).

**Hard collisions**

**Jet production**

Figure 7a shows the single-jet inclusive $E_T^{\text{jet}}$ production cross-section at $\sqrt{s} = 16$ TeV, as obtained from a lowest-order Monte Carlo (PYTHIA) calculation (Cox). Event rates are also given for a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ in bins of $\Delta E_T^{\text{jet}} = 100$ GeV and $\Delta y = 1$ at $y = 0$. In these conditions we would have a 1 kHz rate for $E_T^{\text{jet}} = 150$ GeV, and still about one event per hour at $E_T^{\text{jet}} = 1.5$ TeV. Thus jets in the TeV range are accessible, and in a year ($10^7$ s) of running, the expected QCD jet differential cross-section fall-off could be followed over 10 to 11 orders of magnitude. Next-to-leading order QCD calculations now exist (Guillet, and Ref. [7]); these, however, require a theoretical jet algorithm/jet-separation-cone definition in terms of, for example, $\Delta R = \sqrt{(\Delta y^2 + \Delta \phi^2)}$, and before comparison with data we must be sure of the experimental and theoretical compatibility of such criteria.

An important goal of jet physics is to look for possible deviations at high-$E_T^{\text{jet}}$ from the expected QCD point-like behaviour, which could reveal a possible composite structure of the quarks, as shown in Fig. 7b. Taking into account the uncertainties in the exact shape of the QCD fall-off due to the various possible choices of structure functions, in a year of running at $10^{33}$ cm$^{-2}$ s$^{-1}$ we would be sensitive, in terms of the usual compositeness scale parameter, to $\Lambda_C = 13$ TeV (Nessi). This can be compared with the present CDF result of $\Lambda_C = 0.95$ TeV [8].

**Direct photon production**

Figure 8a shows the expected inclusive isolated direct-photon production spectrum (Aurenche et al.), with event rates at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$ in $\Delta E_T^\gamma = 100$ GeV and $\Delta y = 1$ at $y = 0$. Again, the rates are large, with about one $E_T^\gamma = 1$ TeV photon per day, and there is the possibility to follow the expected QCD differential cross-section fall-off over 8 to 9 orders of magnitude in a year of running. This would again provide an important test of QCD, in particular as next-to-leading order calculations now exist [9]. These require a theoretical definition of an isolated $\gamma$, and care must be taken that this definition is consistent with the experimental one, needed to extract the direct photon signal. The sensitivity to the quark compositeness scale for a year of running at $10^{34}$ cm$^{-2}$ s$^{-1}$ would be at $\Lambda_C \sim 7$ TeV (for details,
see Werlen in Vol. II).

At the low-\(E_T/\gamma\) end of the spectrum, as \(gq \to q\gamma\) is the dominant production mechanism, direct-photon production allows investigation of the poorly known low-\(x\) behaviour of the gluon structure function. The direct photons are statistically separable from jets for \(E_T/\gamma > 50\) GeV (Werlen), which would allow \(g(x)\) to be directly probed at \(x > 10^{-3}\). The working group has also investigated additional contributions to two-photon production from \(q \bar{q} \to 2\gamma\) and \(gg \to \) quark loop \(\to \gamma\gamma\) (Aurenche et al.; Bonesini, Camilleri, Werlen). As this production mechanism is the main irreducible background to the \(H \to \gamma\gamma\) search, we postpone this discussion to the Higgs section.

Figure 8b compares the inclusive jet, direct photon, single particle (\(\pi^0\)), and 'isolated \(\pi^0\)' \(p_T\) spectra at \(\sqrt{s} = 16\) TeV (Aurenche et al., Guillet et al.). Isolated \(\pi^0\) here means an inclusive \(\pi^0\) with a fragmentation fractional momentum \(z > 0.85\). The \(\gamma/jet\) ratio is \(~2 \times 10^{-4}\) to \(10^{-3}\), increasing with \(p_T\), whilst the 'isolated \(\pi^0/jet\) ratio is \(~10^{-4}\) to \(10^{-5}\) at \(p_T > 150\) GeV/c, rapidly increasing at low \(p_T\). This ratio is an important input, especially at low \(p_T\), when estimating the contamination of direct photon or diphoton samples by jets.

**W, Z production**

The energy dependence of \(\sigma_W^{\text{tot}}\) from present collider to the LHC/SSC energies is shown in Fig. 9 for a number of recent sets of structure functions (Plothow-Besch, and Refs. [10]). The (\(p \bar{p}\)) data of UA1, UA2, and CDF are also shown [11]. At LHC/SSC energies, \(pp\) and \(p \bar{p}\) production cross-sections are the same within a few per cent, and about a factor of 20 larger than at present colliders. The \(Z\) total production cross-section is about a third of the \(W\) one. At the LHC, the expectations for \(\sigma_W^{\text{tot}}\) vary between 90 nb and 270 nb, and for \(\sigma_Z^{\text{tot}}\) between 30 nb and 80 nb, according to the various sets of structure functions. This \(~\pm 50\%\) uncertainty on \(\sigma_W\) and \(\sigma_Z\) expectations makes the \(Z\) production rate unsuitable for a luminosity measurement. At a luminosity of \(10^{33} \text{ cm}^{-2} \text{ s}^{-1}\), these cross-sections correspond to a production rate of \(~10\) \(W \to\) ev events per second and to \(~1\) \(Z \to\) ee event per second, exceeding the LEP rates! This large \(W, Z\) production gives rise to a high rate of hard and isolated single leptons and dileptons, and is a source of a substantial background to \(t\)-quark and Higgs searches, especially at large \(p_T^{WZ}\). Complete order \(\alpha_s^2\) computations of large-\(p_T\) \(W\) and \(Z\) production now exist [10]. The result is a 1 Hz production rate of \(W \to\) ev events at \(p_T^W > 150\) GeV/c and 1 Hz of \(Z \to\) ee events at \(p_T^Z > 60\) GeV/c, at a luminosity of \(10^{34} \text{ cm}^{-2} \text{ s}^{-1}\) (Wood).

**WZ and Wγ pair production and tests of anomalous couplings**

Pair production of intermediate vector bosons provides an essential test of the three-vector-boson couplings characteristic of the electroweak Standard Model. In the case of the \(WZ\) final state, for example, the interesting amplitude is the \(q \bar{q} \to W^* \to WZ\). Figure 10 shows the energy dependence of the \(\sigma_{WZ}^{\text{BR}}(W \to ev)\cdot\text{BR}(Z \to ee)\)
**Fig. 7a** Inclusive jet production at the LHC;

**Fig. 7b** Inclusive jet production at the LHC and expected effects of quark compositeness.

**Fig. 8a** Inclusive direct-photon production at the LHC;

**Fig. 8b** Inclusive jet, photon, single $\pi^0$, and isolated $\pi^0$ spectra at the LHC.
cross-section in pp interactions (Plotnow-Besch). At LHC/SSC energies, this cross-section is \( \sim 0.1 \text{ pb} \), which means the production of \( \sim 10^3 \text{ WZ} \rightarrow (\ell\ell) (\ell\ell) \) events per year for \( L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \). Figure 10 also shows the expected \( p \bar{p} \rightarrow \text{WZ} + X \) cross-section in the Fermilab Collider range; for an integrated luminosity of \( \sim 200 \text{ pb}^{-1} \), this would imply only a few such events produced. This may be enough for a first observation of gauge boson pair-production, but is insufficient for studying the expected gauge cancellations.

From the experimental point of view, it is the WZ channel with W and Z decaying to leptons which is the most convenient one. The WW channel (Mele) is submerged by \( t \bar{t} \rightarrow WWb \bar{b} \) production, and WZ production with either the W or the Z decaying to q \( \bar{q} \rightarrow \) jet-jet is buried under QCD W(Z) + jets production, as can be seen in Fig. 22 discussed later in connection with t-quark physics (Denegri, Rodrigo, Sajot). In contrast, the WZ \( \rightarrow \ell\ell \ell\ell \) channel is essentially background-free, as can be deduced from Fig. 11, showing the inclusive \( p_T \)-integrated three-muon spectrum at \( \sqrt{s} = 16 \text{ TeV} \) (Nisati). Before any cuts, the main background to WZ production is due to c, b and t-quark production. However, c and b production can be suppressed by a factor of \( \sim 10^3 \) to \( 10^4 \) by an \( M_{\ell\ell} = m_Z \pm \delta m_Z \) mass cut and by a lepton isolation criterion. The lepton isolation rejection factor is \( > 10 \) for leptons of \( p_T > 30 \text{ GeV/c} \), and increases with increasing \( p_T \) (for details, see Rodrigo in Vol. II). Similarly, the t-quark background can be reduced by a factor of \( \sim 10^2 \), with again the \( M_{\ell\ell} \) mass cut and an isolation requirement on the third lepton, which in \( t \bar{t} \) production usually comes from the b decay (from \( t \rightarrow Wb \)).

For a comparison with LEP 200 possibilities, note that the rate of WW production at LEP is comparable to the WZ \( \rightarrow \ell\ell \ell\ell \) rate at the LHC at \( 10^{33} \text{ cm}^{-2} \text{ s}^{-1} \). But \( M_{WW} \) is limited to \( \leq 200 \text{ GeV} \) at LEP, whilst \( M_{WZ} \sim 1 \text{ TeV} \) is accessible at the LHC, and the gauge cancellations are largest at large boson-pair invariant masses [12]. This makes the LHC/SSC much more sensitive than LEP 200 to anomalous couplings. Figure 12 shows the expected WZ transverse mass \( M_{T}^{WZ} \) distribution (the directly measurable quantity, since the longitudinal neutrino momentum component is not measurable) according to the Standard Model couplings, and for an anomalous coupling characterized by two values of the parameter, \( \lambda = 0.1 \) and \( \lambda = 0.04 \) (Plotnow-Besch). In the SM, \( \lambda = 0 \), and the rate at large \( M_{T}^{WZ} \) is smallest. The lepton selection cuts are \( p_T > 25 \text{ GeV/c} \) and \( |\eta_{\ell}| < 2.5 \). With an experimental sensitivity of \( 10^5 \text{ pb}^{-1} \) (i.e. \( 10^7 \text{ s at } 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \)), the expected signal and background rates would be: 11240 events for the signal from \( W^+Z + W^-Z \), 550 events from the background of \( Z + b \rightarrow \ell\ell + A \nu c \), and < 2000 events from the \( t \bar{t} \) background, assuming a lepton isolation rejection factor of \( R_{\text{iso}} = 5 \), which is very conservative for leptons of \( p_T > 25 \text{ GeV/c} \), and a Z mass cut rejection factor of 10 against \( t \bar{t} \). The event rates are large enough, so that more stringent rejection cuts could be employed at the expense of some loss in efficiency; thus no problems are expected with backgrounds in this channel, as previously argued (Fig. 11). As a measure of the experimental sensitivity limit, for an integrated luminosity of \( 10^5 \text{ pb}^{-1} \) we expect 10
**Fig. 9** $W$ production cross-section versus $\sqrt{s}$.

**Fig. 10** $WZ$ production cross-section in pp collisions versus $\sqrt{s}$.

**Fig. 11** Inclusive three-muon spectrum versus $p_T$ threshold.
Fig. 12  WZ transverse mass at $\sqrt{s} = 16$ TeV.

Fig. 13  Photon transverse momentum from $W\gamma$ events at $\sqrt{s} = 16$ TeV.
events at \( M_{T}^{WZ} > 1.0 \text{ TeV} \) for the SM, 10 events at \( M_{T}^{WZ} > 1.12 \text{ TeV} \) if \( \lambda = 0.04 \), and 10 events at \( M_{T}^{WZ} > 1.64 \text{ TeV} \) if \( \lambda = 0.1 \) (for details, see Plouchow Besch, Vol. II). The expectation is thus that gauge couplings could be checked at the few per cent level, which is almost an order of magnitude better than at LEP 200.

Another promising channel for studying gauge cancellations and possible anomalous couplings is \( W\gamma \) production [13]. Anomalies in the \( WW\gamma \) coupling would again reveal themselves best at large \( W\gamma \) masses or, equivalently, at large \( p_{T}^{\gamma} \), which is the directly measured quantity. Figure 13 shows the expected \( p_{T}^{\gamma} \) behaviour at \( \sqrt{s} = 16 \text{ TeV} \) if the anomalous coupling \( \lambda \), entering the \( W \) magnetic dipole and electric quadrupole coupling [13], takes a value \( \lambda = 0.1 \), and for the Standard Model value \( \lambda = 0 \). For \( \lambda = 0.1 \) and the following data selection cuts: \( p_{T}^{\gamma} > 100 \text{ GeV/c}, |\eta_{\gamma}| < 2.5, p_{T}^{c} > 25 \text{ GeV/c}, |\eta_{c}| < 2.5, \) and \( |M_{T}^{e\nu} - m_{W\gamma}| < 20 \text{ GeV} \), the total number of events expected would be \( \approx 6900 \text{ W}^{+}\gamma \) and \( \approx 5200 \text{ W}^{-}\gamma \) events, for a luminosity of \( 10^{5} \text{ pb}^{-1} \) (Pepe, Pastore). These numbers of events take into account the electron identification and isolation cuts and efficiency. As can be seen in Fig. 13, the cross-section for \( \lambda = 0.1 \) is about a factor of 2 larger than in the SM, and we would be sensitive up to \( p_{T}^{\gamma} \approx 800 \text{ GeV/c} \) (i.e. 10 events expected at \( p_{T}^{\gamma} > 800 \text{ GeV/c} \) for \( \lambda = 0.1 \)).

Assuming conservatively a jet-to-\( \gamma \) misindentification probability of \( 10^{-4} \) for \( p_{T}^{\gamma} > 100 \text{ GeV/c} \), the background of \( W + \text{jets} \to e\nu + \text{jet} \) events is not negligible, and amounts to \( \sim 20\% \) of the signal. However, the background is more concentrated at low \( p_{T}^{\gamma} \) than the signal, and increased rejection is possible at the expense of efficiency, which can be afforded as the rates are high enough. At \( p_{T}^{\gamma} > 200 \text{ GeV/c} \), for example, and relaxing the \( M_{T}^{e\nu} \) cut, the signal is reduced to \( \approx 2170 \) events and the background to \( \sim 40 \) events. In conclusion, we should be sensitive to values of \( \lambda \) down to \( \sim 0.05 \), and no major difficulties are foreseen for this channel, in particular not in the interesting large-\( p_{T}^{\gamma} \) range (Pepe, Pastore).

The \( ZZ \) pair production has also been studied (Mele). However, as distinct from \( WW, WZ \) and \( W\gamma \), the \( ZZ \) (and \( Z\gamma \)) final state brings no information about the triple-gauge-boson couplings; it does, however, represent an important background in Higgs searches and we postpone its discussion to the Higgs section.

2. B PHYSICS AT THE LHC

Hadron machines are a powerful tool for observing particles containing heavy quarks, when such particles have a measurable decay length. The success obtained with silicon microvertex detectors in the search for charmed particles is evidence that decay-length measurements can indeed be used. The main issue in B physics at the LHC is the observation of CP violation in the B system, and the ultimate goal is to measure the three interior angles of the Cabibbo-Kobayashi-Maskawa (CKM) matrix unitarity triangle [14].

In the small generation-mixing-angle approximation, the CKM matrix can be written as (the Wolfenstein parametrization):
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \lambda^2/2 & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix},$$

where $\lambda = \sin \theta_W = 0.22$, and where the parameter $A$ is determined by the $B$ lifetime, $|A| = 1.0$. In this parametrization, only the elements $V_{ub}$ and $V_{td}$ have a phase, provided $\eta \neq 0$, which implies CP violation in the framework of the SM and vice versa [14,15]. The unitarity of the CKM matrix implies a relation between the elements

$$V_{td} + V_{ub}^* = \lambda V_{cb} ,$$

which can be represented by the 'unitarity triangle' sketched in Fig. 14a, with the three interior angles $\phi_i$ indicated. The values of the parameters $\rho$ and $\eta$, or equivalently of the angles $\phi_i$, are at present poorly determined from the CP measurements in the $K \bar{K}$ system. The allowed domain of variation of $\rho, \eta$ – if we take into account constraints provided by measurements of $\varepsilon, \varepsilon_V/V_{cb}$, and $x_d$ for two values of $m_t$ – is shown in Fig. 14b (shaded area), taken from Ref. [14]. The use of the $B \bar{B}$ system for CP-violation measurements would be much more constraining for the Standard Model, hence the interest in checking in detail the SM scenario for CP violation. The point is that the three angles $\phi_i$ are, in principle, all accessible to direct experimental measurements.

We consider $B^0$ decays to final-state $f$: $B^0 \to f$ and $\bar{B}^0 \to \bar{f}$. In the case where these are CP eigenstates, i.e. $\bar{f} = \pm f$, the experimentally measurable decay-rate asymmetry $A$, defined as

$$A = \frac{N(B^0 \to f) - N(\bar{B}^0 \to \bar{f})}{N(B^0 \to f) + N(\bar{B}^0 \to \bar{f})},$$

depends only on the angles $\phi_i$ of the unitarity triangle with no hadronic physics complications in appropriately chosen channels (Lusignoli, Pich, and Refs. [14,15]). For example:

$$A \sim \sin 2\phi_1 \quad \text{for decays such as } B^0_d \to \psi K^0_S , \ldots,$$
$$A \sim \sin 2\phi_2 \quad \text{for decays such as } B^0_d \to \pi^+\pi^- , \ldots,$$
$$A \sim \sin 2\phi_3 \quad \text{for decays such as } B^0_s \to \rho K^0_S , \ldots.$$

Thus $B^0_{d,s}$ decay channels exist, giving direct access to these angles (Fig. 14). Large CP-violating asymmetries $A$, in the $\sim 5\%$ to $\sim 50\%$ range, are necessarily found in the small branching ratio modes, with typically $BR = 10^{-4}$ to $10^{-6}$. The asymmetry must be substantial
in at least one of these three classes of decays [14]. The $B^0_d \to \psi K^0_S$ is one of the most favourable decays, since from Fig. 14b the angle $\phi_1$ cannot take values of $\approx 0^0$ or $\approx 90^0$ where the asymmetry would vanish; thus a finite asymmetry is guaranteed. For this Workshop, the lower limit of $|\sin 2\phi_1| > 0.08$ from Ref. [14] has been updated to $> 0.20$ (Lusignoli, Prades, Pich), making the situation even more favourable. The branching ratio in this mode is known, $\text{BR}(B^0_d \to \psi K^0_S) \cdot \text{BR}(\psi \to \ell \ell) \cdot \text{BR}(K^0_S \to \pi^+\pi^-) = 3 \times 10^{-5}$, whilst for $B^0_d \to \pi^+\pi^-$ and $B^0_s \to \rho K^0_S$ the expected branching ratio is $\text{BR} \sim 2 \times 10^{-5}$. There is, in fact, a variety of ways in which CP can be violated in the $B$ system [15], but the theoretical predictions are reliable and constraining only in the case of decays to CP eigenstates.

The main issues addressed by the working group were:

i) the best channels for observing the asymmetry – with Lusignoli, Prades and Pich updating the work of Ref. [14] in the light of more recent QCD sum rules and lattice calculations applicable to $B^0_d$ mixing, the range for $f_B$ now being 160 to 250 MeV (see working group report in Vol. II);

ii) the experimental possibilities of triggering, reconstructing and tagging such decays in a collider mode, with a very detailed simulation of an appropriate apparatus and its response (Erhan, Schlein), and the sensitivity it would provide to a measurement of $|\sin 2\phi_1|$;

iii) a discussion of the relative advantages of the various machines for CP-violation measurements (Fridman), and in particular of the possibilities of high-energy pp machines in the collider versus fixed-target mode of operation (Grancagnolo, Lemoigne, Denegri, Zollnerowski), or in a beam-dump type of experiment (Fidecaro); and finally,

iv) the study of the effect of 'fake asymmetries' present in pp machines (and $p \bar{p}$ in each arm independently) owing to the presence of valence quarks (Lusignoli, Pugliese, Steger; Fridman).

The beauty-charmed mesons, a subject not related to CP violation, was also discussed (Lusignoli and Masetti).

**B production at hadron colliders**

i) Collider mode

The expected production cross-section $\sigma_b \bar{b}$ over the LHC/SSC energy range is shown in Fig. 15a [15,16]. There are large uncertainties in the estimate of $\sigma_b \bar{b}$. On the one hand, they are related to the poor knowledge of the gluon structure function at low $x$ ($x \sim 10^{-3}$ to $10^{-4}$ is probed here), used as an input in the calculation. On the other hand, they are due to the questionable applicability of perturbative QCD calculations (at order $\alpha_s^3$) in this regime, where $2m_b^2/s \ll 1$. The perturbative QCD estimate of Nason for $\sqrt{s} = 16$ TeV is $\sigma_b \bar{b}$ in the 0.1 to 0.7 mb range. An independent estimate, based on a quark–gluon string model by Kaidalov [17], is again $\sigma_b \bar{b} = 0.1$ to 0.7 mb, whilst the scaling-law approach of De Rújula and Rückl gives $\sigma_b \bar{b} = 0.5$ mb within a factor of $\sim 2$ [18]. The overall uncertainty is thus about an order of magnitude at $\sqrt{s} = 16$ TeV. In the following, we use $\sigma_b \bar{b} = 0.3$ mb. The fraction of $b \bar{b}$ events is $\sigma_b \bar{b}/\sigma_{\text{tot}} = 1/500$ at the LHC and $1/300$ at the SSC. At a
luminosity of $10^{32}$ cm$^{-2}$ s$^{-1}$ (to avoid multiple interactions per bunch crossing), these cross-sections imply the production of $\sim 3 \times 10^{11}$ b $\bar{b}$ events per year ($10^7$ s).

ii) Fixed-target mode

If the 8 TeV proton beam of the LHC is used in a fixed-target mode, either as an extracted beam on an external target, or as a circulating beam on a gas-jet or wire target, the pp centre-of-mass energy $\sqrt{s}$ is 123 GeV for the LHC (and 193 GeV for the SSC). Figure 15b shows the expected b $\bar{b}$ production cross-section in this fixed-target regime of the LHC/SSC, from a QCD computation by K. Ellis. The UA1 point (in p $\bar{p}$ interactions, $19.3^{+11}_{-8.5}$ µb) is also shown for comparison [19]. The QCD expectations are now somewhat more reliable and lead us to expect $\sigma_{B}$ $\bar{b}$ = 0.3 to 1.5 µb at $\sqrt{s}$ = 120 GeV, with $\sigma_{B}$ $\bar{b}$ (SSC)/$\sigma_{B}$ $\bar{b}$ (LHC) = 3. As $\sqrt{s}$ is much smaller than in the collider mode, there are two significant consequences: $\sigma_{B}$ $\bar{b}$ (collider mode)/$\sigma_{B}$ $\bar{b}$ (fixed-target mode) = 250, i.e. the production cross-section is substantially smaller, and also $\sigma_{B}$ $\bar{b}$ / $\sigma_{tot}$ is now $\sim 10^{-4}$, as compared with $\sim 1/500$ in the collider mode. Nonetheless, for $10^8$ protons per second on a few per cent $\lambda_{int}$ W-target, the above cross-sections would lead to $\sim 5 \times 10^9$ b $\bar{b}$ produced per $10^7$ s of running at the LHC.

Fixed-target versus collider modes

Hadron colliders have very large b $\bar{b}$ production rates, in particular in the collider mode (Table 1). Provided the B's can be isolated – which is not yet proven – these machines give the possibility to study in detail the CP violation sector of the Standard Model [20, 21]. The rates in the fixed-target mode are significantly smaller, which probably would not allow such a comprehensive study, but it should be sufficient to observe CP violation in the most favourable modes, whilst being experimentally simpler and less expensive (Grancagnolo, and Ref. [21]). For comparison, the highest luminosity e$^+$e$^-$ colliders now considered would produce $\sim 10^8$ b $\bar{b}$ pairs per year at a luminosity of 10$^{34}$ cm$^{-2}$ s$^{-1}$ (the CESR project), and in spite of the much more favourable signal-to-background ratio, this event rate seems marginal for detailed CP violation studies, except in the more favourable scenarios [14].

The two disadvantages of the fixed target mode – smaller $\sigma_{B}$ $\bar{b}$ and poorer signal-to-background ratio – are, however, compensated by a number of advantages. At $\sqrt{s}$ = 123 GeV the average event charged multiplicity is $\sim 18$, as compared with $\sim 80$ in the collider mode at $\sqrt{s}$ = 16 TeV. The decay kinematics is also more favourable in the fixed-target mode. The large Lorentz boost gives average B flight-paths of a few centimetres, as compared with a few millimetres in the collider mode. This is illustrated by Fig. 16 (Lemoigne, Zolnierowski). The larger lab. momenta of the B decay products should also substantially ease the problems of triggering and tagging.

Before the goal of making a detailed study of CP violation can be achieved in pp colliders, there are many experimental problems to be solved [20, 21, 22].
Fig. 14  a) the unitarity triangle, and b) the allowed domains of $\rho$ and $\eta$ from Ref. [14].

Fig. 16  B decay length in collider and fixed-target modes for various acceptances on the B.
1) **How to trigger on the interesting decay modes.** The possibilities are to use $\mu$ or $\mu\mu$, or more generally leptons, at large $p$ (E) in fixed-target mode, or large $p_T$ (> 1.5 GeV/c) in collider mode. For $B^0_{d,s} \rightarrow \psi K^0_S$, a trigger on the $\psi \rightarrow \mu\mu$ decay is possible (see Schlein, Grancagnolo and Fidecaro contributions in Vol. II, and Refs. [20, 21, 22]). For $B^0_{d,s} \rightarrow \pi^+\pi^-, K^+K^-, p\bar{p}$, a possibility could be a secondary-vertex trigger and the presence of harder-$p_T$ tracks than in usual minimum-bias events (two-body decays with a large $Q$-value).

With respect to triggering, a fixed-target experiment may have a substantial advantage, as the B-decay tracks are much harder, with $<p> = 100$ to 300 GeV/c for $B^0_d \rightarrow \psi K^0_S$ or $\pi^+\pi^-$ in a fixed-target mode, as compared with $<p> = 20$ to 50 GeV/c in the collider mode, depending on acceptance (Table 1). The geometry of fixed-target experiments should make the trigger easier [20, 21]. With a thin target, it is possible to have a point-like source of B's, and with straight tracks and as little material as possible around the target, events could be selected with tracks not originating from the point source (secondary-vertex trigger à la WA82).

2) **The necessity of tagging the decaying $B^0_{d,s}$ through the B produced in association.** Although some CP violation measurements are possible without tagging, the tagging is an absolute necessity for the decays to CP eigenstates [15]. The possibilities for tagging are the use of: i) the lepton charge from the associated $B(\bar{B}) \rightarrow \ell^{\pm} + X$; ii) the kaons from the $b \rightarrow c \rightarrow s$ sequence [22]; iii) the use of the charge of the associated $B^{\pm}$, through a complete $B^{\pm}$ reconstruction at a secondary vertex.

Here again the fixed-target mode may have an advantage, as long (centimetre) decay lengths may ease secondary-vertex reconstruction, and all decay products are hard (Lorentz boosted), whilst in the collider mode a few-hundred MeV/c pion can more easily be lost at the decay vertex.

3) **There is a need for particle identification.** This is essential for a comprehensive study of CP violation in $B^0_{d,s} \rightarrow \pi^+\pi^-, K^+K^-, p\bar{p}, K\pi$, etc., final states. The interesting modes necessarily have small branching ratios and must be cleanly separated from the dominant decay modes. It is clear that particle identification with B-decay products in the hundreds of GeV/c momentum range will place very great demands on RICH spatial resolution, and in this respect the collider mode may have an advantage.

4) **The need for good $B^0$ mass resolution:** $\delta m_B \ll 200$ MeV (in all-charged decay modes), to distinguish between $B^0_d$ and $B^0_s$ decays to $\pi^+\pi^-$ or $K^+K^-$, and to distinguish between $B^0_d \rightarrow \psi K^0_S$ and $B^0_d \rightarrow \psi K^0_S \pi^0$, where the CP asymmetry may be of opposite sign [14].

These measurements, in both collider and fixed-target mode, are rendered more difficult by various (unavoidable) dilution factors (Steger, Lusignoli, Pugliese, Fridman, and Ref. [20]).

1) Dilution due to oscillations of the decaying $B^0$. This cannot be avoided, since it is precisely
because mixing is present that there is CP violation in the most interesting CP eigenstates, i.e. without mixing there would be nothing to observe.

2) Dilution due to oscillations of the tagging $B^0$. In this respect the $B^\pm$ is the best tagger, if it is clearly recognizable. Here again there may be a potential advantage for a fixed-target mode, if a $B^\pm$ can be fully and reliably reconstructed as a secondary-vertex $B^\pm$ decay. As for the $B^0_s$, it is expected to oscillate so rapidly ($x_s = \Delta m/\Gamma_{B^0_s} \sim 10$ is expected) that it is useless as a tagger. A consequence of the large expected value of $x_s$ is that time-integrated measurements of the asymmetry for $B^0_s \rightarrow pK^0_s, \pi^+\pi^-, K^+K^- \ldots \sim \sin 2\phi_3$ are useless ($A = 0$). The measurement of the angle $\phi_3$ is particularly difficult, as in practice it is accessible only through $B^0_s$ decays, which requires good proper-time (i.e. space and momentum) resolution, in order to study the proper-time evolution of the system.

3) Attention must also be paid to the unavoidable, but small, fake asymmetry resulting from the unequal $B$ and $\bar{B}$ production in hadron collisions, and which is due to valence quarks. It is estimated at the few per cent level (Lusignoli, Pugliese and Steger; Fridman), whilst, for comparison, the expected CP-violating asymmetries in the interesting modes may be at the 5% to 50% level. These fake asymmetries can be measured, either from the difference between production rates of $B^+$ and $B^-$ decaying to CP-non-violating modes, or by measuring the apparent asymmetry $A$ in a $B^0$ decay mode where no CP violation is expected, as in $B^0 \rightarrow \psi \phi$ [14, 20].

In Table 1 (Lemoigne, Fridman, Denegri, Zolnierowski) we attempt to summarize the relative merits of the two pp machine possibilities – collider mode versus fixed-target mode – using as reference experiments, BCD [20] and P238 [22] for the collider mode, the SFT [21] for the fixed-target mode, and the experience gained with NA14. The fixed-target option seems more advantageous, but is ultimately limited by the total production rate. Detailed estimates of achievable sensitivities to $\sin 2\phi_1$ in the fixed-target mode have yet to be made. A study of a crystal channelling extraction scheme by Jeanneret and Scandale shows that, provided outstanding progress can be made in the precise alignment of the atomic planes in the crystal and its surface, about 1 to 2 x 10^8 protons per second could be extracted from the LHC, which is comparable to the flux extracted in the SSC. The possibilities for $B$ physics with an internal target have not yet been looked into; those for a beam-dump type of experiment, according to the suggestion of Kekelidze [24], have been discussed by Fidecaro (see Vol. II for more details). Much more work is clearly needed, but we may expect that a number of questions just raised will be answered in the (near) future: the feasibility of a 'secondary vertex' trigger at colliders by experiment P238 (Schlein and collaborators, Ref. [22]), and in fixed-target mode by the on-going SPS and Fermilab $B$-physics experiments; for the performance of both $\psi$ triggers and microvertex detectors at higher rates, by experiments E771, CDF, etc.
Table 1 Comparison of some experimental conditions in collider and fixed-target mode
(kinematics from ISAJET and/or PYTHIA); stars = quality of merit in each mode;

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<th>Fixed target mode</th>
<th>Collider mode</th>
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<td>20      **</td>
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KINEMATICS

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TRIGGER

- Lepton
  - $p (e\mu) > 100$ GeV/c *
- 2nd vertex
  - possible if thin target **
  - difficult : 1st vertex not stable

TAGGING

- Lepton/$\psi$
  - hard lepton(s) : easier ? *
  - soft lepton(s) : difficult !
- Charge ($B^+/-$)
  - possible ? *
  - not easy !
Detailed simulation of $B^0_d \rightarrow \psi K^0_S$ in the LHC collider mode and sensitivity to $\sin 2\phi_1$

In the framework of the P238 proposal for B physics at the Sp pS (Schlein et al., and Ref. [22]), a detailed study has been made of the possibility to study CP violation at the LHC in the collider mode. Since most of the B production cross-section is at low $p_T$ and forward angles, a large-aperture forward spectrometer is needed. The 'forward beauty detector' envisaged, and Monte Carlo-simulated in detail, is shown in Fig. 17 (Erhan, Schlein). It consists of three spectrometers covering the angular ranges from 2 to 10 mrad, from 10 to 100 mrad, and from 100 to 600 mrad with respect to the beam line. The correlation between the average B-decay product lab. momentum and lab. angle at $\sqrt{s} = 16$ TeV is shown in Fig. 18; the coverage of the spectrometer is indicated also.

The basic problem of collider-mode B-physics experiments is to devise an efficient B trigger. Here a Si microvertex detector is envisaged, with 16 Si planes 4 cm apart, perpendicular to the beam in a fixed-target type of geometry, surrounding the interaction region [22]. A scaled-down (6 planes) version of this vertex detector is now undergoing tests at the p p Collider. For the B trigger, events that are inconsistent with a single vertex would be selected on-line, using just the Si detector information. The trigger algorithm is implemented in a data-driven processor. A detailed software simulation indicates a rejection factor of ~ 500 against minimum-bias events, with a ~ 10% efficiency for $B \bar{B}$ (B to $\psi K$) events.

Assuming a cross-section of $\sigma_B = 300 \mu b$ and $2 \times 10^7 s$ of running time at a (modest) luminosity of $10^{31}$ cm$^{-2}$ s$^{-1}$, and after taking into account the geometrical acceptance, the trigger efficiency, the reconstruction efficiency, and a 15% tagging efficiency using charged kaons, it is found that $\sim 1350 B^0_d$ and $\sim 1350 \ B^0_d \rightarrow \psi K^0_S$, $\psi \rightarrow \ell \ell$, $K^0_S \rightarrow \pi^+ \pi^-$ decays are fully reconstructed and tagged. The tagging dilution factor (good - bad)/(good + bad) is 0.54. The observable asymmetry, in a time-dependent measurement, is then

$$A = \frac{N(B^0 \rightarrow f, t) - N(\bar{B}^0 \rightarrow \bar{f}, t)}{N(B^0 \rightarrow f, t) + N(\bar{B}^0 \rightarrow \bar{f}, t)} = A_{\text{obs}} \sin (x_d \cdot \sqrt{t}) \ ,$$

with

$$A_{\text{obs}} = k_1 \cdot k_2 \cdot \sin 2\phi_1 \ ,$$

where $k_1 = \Sigma f_i/(1 + x_i^2) = 0.73$ is the dilution factor due to oscillations of the tagging B, with $f_i$ the fractions of $B_u$, $B_d$, and $B_s$, respectively, and $k_2$ is the dilution factor due to mistaggings (0.54). The statistical significance of the measurement of $\sin 2\phi_1$ is

$$S = \frac{\sin 2\phi_1}{\delta \sin 2\phi_1} = \frac{0.9 \cdot k_1 \cdot k_2 \cdot \sqrt{2N} \cdot \sin 2\phi_1}{\sqrt{[1 - (\sin 2\phi_1)^2]}} \ ,$$

78
Fig. 17 P-238 spectrometer layout.

Fig. 18 Lab. momentum vs. lab. angle correlation for B decay products at $\sqrt{s} = 0.6$ and 16 TeV.

Fig. 19 Sensitivity to measurements of $\sin 2\phi_1$ from $B^0_d \to \psi K^0_s$ decays for various experiments.
(the factor 0.9 is due to the time-resolution function). The sensitivity of a measurement of \( \sin^{2}\phi_{1} \), expressed in terms of the significance \( S \) versus \( \sin^{2}\phi_{1} \), is shown if Fig. 19. It is compared with similar expectations for the BCD proposal [20] or for an \( e^{+}e^{-} \) B-factory in the ISR tunnel [23]. If \( \sin^{2}\phi_{1} = 0.3 \), for example, it would be measured at a 5\( \sigma \) significance level, and \( \alpha > 3\sigma \) significance measurement would be possible for \( \sin^{2}\phi_{1} > 0.15 \). Ways of optimizing the trigger for the interesting low-multiplicity B-decay modes have to be studied further, as well as possibilities for lepton or \( \psi \) triggers and lepton tags. The ways of measuring simultaneously also \( \phi_{2} \) and \( \phi_{3} \) and the achievable sensitivities have not yet been studied.

3. TOP PHYSICS

Direct searches in collider experiments have so far failed to yield evidence for the top-quark [25]. At present, the most stringent lower limit on \( m_{t} \) is from CDF: \( m_{t} > 89 \text{ GeV} \) [26]. These collider limits depend, however, on the assumed (but very plausible) \( t \to \Lambda b \) semileptonic branching ratio of 1/9. Model-independent lower limits on \( m_{t} \) from LEP or from \( \Gamma_{W} \) are in the 45 to 50 GeV range [27, 28]. As is well known, electroweak radiative corrections to \( m_{Z} \) (and \( m_{W} \)) provide upper limits on \( m_{t} \). The recent LEP precision measurements of \( m_{Z} \), when combined with the measurement of \( \sin^{2}\theta_{w} = 1 - m_{W}^{2}/m_{Z}^{2} \) by UA2 and CDF, imply an upper limit of \( m_{t} \leq 200 \text{ GeV} \) [29]. A comprehensive analysis of all the relevant experimental data, including low-energy processes, yields as a best fit: \( m_{t} = 135 \pm 35 \text{ GeV} \) [29]. If \( m_{t} \leq 150 \text{ GeV} \), it is likely that the top-quark will be found at Fermilab, before the advent of the LHC. With an experimental sensitivity of \( \sim 200 \text{ pb}^{-1} \), the region \( 150 \leq m_{t} \leq 200 \text{ GeV} \) may, however, be more difficult to explore owing to the lack of statistics and to increasing backgrounds. In any case, the observation of the top-quark in this mass range would be limited to few tens of events at best.

The working group devoted to top-quark physics has thus addressed three main questions: i) how to find the t-quark, if it has not yet been found, and how to separate the signal from the backgrounds in order to make detailed studies; ii) how, and with what precision, could \( m_{t} \) be best determined; iii) how to measure the t-quark semileptonic branching ratios, in particular for a check of e/\( \mu/\tau \) universality. This is expected to hold if \( t \to Wb \) is the only decay mode. It might, however, fail if an \( H^{\pm} \) exists with a kinematically allowed and competitive \( t \to H^{\pm}b \) decay mode and a large \( H^{\pm} \to \tau \nu \) branching ratio, as is expected in some region of the SUSY parameter (\( \tan \beta = \nu_{2}/\nu_{1} \)) space. These questions have been studied mostly in the \( t \bar{t} \) production channel, but a study has also been made of the single-top-quark production channel \( Wg \to t \bar{b} \).

*Top-quark production cross-sections*

Figure 20 shows the t-quark production cross-section at hadron colliders (Meng et al.). The QCD \( t \bar{t} \) production cross-sections are now known to order \( \alpha_{s}^{3} \) [30], and have been
computed for the LHC/SSC regime by Nason and by Meng et al. There are uncertainties of the order of $\sim \pm 30\%$ due to various choices of structure functions and to the $Q^2$ scale. Electroweak radiative corrections to $t \bar{t}$ have also been computed and are found to be small (Hollik et al.; for details, see Reya and Zerwas in Vol. II). For $m_t = 200$ GeV, the production cross-section at the LHC (Fig. 20) is larger by a factor of $\sim 300$ than at the Fermilab $p \bar{p}$ Collider. The expected production rate at a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$ is large, with $\sim 10^6$ to $10^7$ $t \bar{t}$ produced per year. The LHC and SSC are in fact 't-quark factories', with a large potential for discovering the t-quark, and for studying it in detail. In the expected Standard Model $m_t$ range, $100 \lesssim m_t \lesssim 200$ GeV, it is the $t \bar{t}$ production mechanism that dominates t-quark production. If, however, the t-quark succeeds in evading the radiative correction upper limit of $\sim 200$ GeV, the mass reach of the LHC for a t-quark, or for a top-like fourth-generation fermion, is in the $\sim 1$ TeV range. In fact, as can be seen in Fig. 21 showing the four different production mechanisms responsible for t-quark production at $\sqrt{s} = 16$ TeV (Phillips, Zerwas, Zunft), for $m_t \gtrsim 300$ GeV the dominant contribution is single-t-quark production through the process $Wg \to t \bar{b}$.

For a t-quark in the 100 to 200 GeV mass range, the top decays to $t \to Wb$ and $t \bar{t}$ production gives $WWb \bar{b}$ final states. Two main search strategies are then possible, with either one or both of the W's decaying to $W \to \ell \nu$ (the purely hadronic modes are overwhelmed by QCD multijet backgrounds, Kleiss and Refs. [31]). The $t \bar{t} \to WWb \bar{b} \to \ell \nu q \bar{q} b \bar{b}$ single-lepton channel has a larger cross-section and may allow the first observation at machine start-up at low luminosity. It can also be used for $m_t$ determination, since the t-quark decay products $t \to q \bar{q} b$ are all observable. The $t \bar{t} \to WWb \bar{b} \to \ell \nu \ell \nu b \bar{b}$ two-lepton mode requires more luminosity. It is, however, less contaminated by backgrounds, as will be discussed in the following.

**Top-quark search in the single-isolated-lepton mode**

In the $t \bar{t} \to WWb \bar{b} \to \ell \nu q \bar{q} b \bar{b} \to \ell \nu + \text{jets}$ single-lepton channel, the main backgrounds to consider are $W+$ jets, electroweak WW, and $b \bar{b}(g)$ production. The $b \bar{b}(g)$ $\to \ell \nu + \text{jets}$ background can be reduced below the unavoidable $W+$ jets background by a number of possible cuts on the lepton $p_T$ threshold, on lepton isolation, on the W mass $M_{jj} = m_W \pm \delta m_W$, on the missing transverse energy, and with a lepton-jet non-back-to-back azimuthal correlation cut (Cavanna, Rodrigo, Unal). For example, with the following cuts on the lepton alone: $p_T^{L} \geq 50$ GeV/c, $\eta^{L} < 1.5$, and an isolation rejection factor of $\sim 50$ (as appropriate for $p_T^{L} > 50$ GeV/c, see Vol. II for details), the signal-to-background ratio is already $\sim 10$. Clearly, less stringent cuts on $p_T^{L}$ or isolation can be required if, in addition, a W-mass cut is applied.

Figure 22 shows the energy dependence of the $t \bar{t}$ signal, of the electroweak WW background, and of the more dangerous $W+$ jets QCD-induced background (Cavanna, Denegri, Rodrigo, Sajot). At $\sqrt{s} = 16$ TeV the electroweak WW pair production is a factor of
10 to 100 – depending on $m_\tau$ – below $t \bar{t} \rightarrow WW b \bar{b}$, and can be neglected. However, the $W + 2$ or 3 jets background is significant, and before any specific background-reduction cuts, it exceeds the signal by a factor of $\sim 2$ to 10, depending on $m_\tau$. The $W + 2, 3$ jets background is obtained from the EKS (Leiden -Wisconsin -Durham group) Monte Carlo. The lowest-order $W + 4$ jets contributions were also computed for this Workshop (Berends, Giele).

The reduction of the $W +$ jets background is possible through various kinematics cuts on the transverse energy and on the rapidity of jets and leptons, since $t \bar{t}$ production with two massive $t$-quarks is more central than $W +$ jets, and exhibits Jacobian-peak-type $E_T$ spectra. Fig. 23 shows the observable $t \bar{t}$ signal as a function of $m_{\tau}$ and the remaining $W +$ jets background, asking for at least three jets of $E_T^{\text{jet}} > 40 \text{ GeV}$ with $\eta_{\text{jet}} < 1.5$, and for a hard and central lepton $p_T^{\ell} > 30 \text{ GeV}$ with $\eta_\ell < 1.5$, cuts optimized for a 150 GeV $t$-quark (Cavanna; for details see Vol. II). The signal-to-background ratio is now $\sim 2$. A further rejection factor of $\sim 3$ is obtained, asking for a jet-jet invariant mass cut $M_{jj} = m_W \pm 20 \text{ GeV}$ (Fig. 22). At a luminosity of $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, the number of observed $t \bar{t}$ events would thus be $\sim 6 \times 10^4$ per year for $m_\tau = 150 \text{ GeV}$. This rate is large enough, so that, if needed, a significant further improvement in the signal-to-background ratio could be obtained, at the expense of efficiency, requiring $b$-tagging. The average $p_T^{b\ell}$ depends on $m_\tau$, but is of the order of $\sim 40 \text{ GeV}$. The possibilities are either to ask for an additional non-isolated muon from the $b$ decays, which is particularly useful at higher luminosity, or to look for displaced vertices with a microvertex detector (limited to lower luminosity). The present experience of CDF with muons in jets is encouraging, and their future experience with a microvertex detector will tell us how useful and realistic the second possibility is.

Owing to its larger cross-section, this single-lepton mode is most profitable at lower luminosity. It requires a well-segmented calorimeter in order to apply a stringent lepton isolation requirement, or a calorimetric coverage that is sufficient to implement an $E_T^{\text{miss}}$ cut, so as to suppress the $b \bar{b}$ ($g$) $\rightarrow \ell \nu +$ jets background below the $W +$ jets background. At higher luminosity, and/or for detailed studies (e.g. mass and branching ratio determinations) requiring little background, the $b \bar{b}$ ($g$) background can be suppressed merely by raising the $p_T^{\ell\ell}$ threshold cut, whilst $b$-tagging with a muon-in-jet is a necessity for suppressing the $W +$ jets background.

Top-quark search in the $t \bar{t} \rightarrow WW b \bar{b} \rightarrow \ell\nu \ell\nu b \bar{b}$ two-isolated-leptons mode

In the two-lepton channel, the main background to worry about is $b \bar{b}$ ($g$) $\rightarrow \ell\nu \ell\nu +$ jets. Figure 24 shows the energy dependence of the $t \bar{t}$ signal and of the $b \bar{b}$ and WW backgrounds up to the LHC energy range (Cavanna, Denegri, Rodrigo, Sajot). The various theoretical expectations for $b \bar{b}$ production discussed in the previous section are shown [16, 17]. The Monte Carlo estimates employed in the simulations are also shown. The initial $b \bar{b}$ background level is 6 to 7 orders of magnitude larger than the $t \bar{t}$ signal. However, as
Fig. 20  $t\bar{t}$ production cross-sections versus $m_t$ and $\sqrt{s}$.

Fig. 21  Various mechanisms contributing to $t$-quark production at the LHC.
Fig. 22 Energy dependence of $t\bar{t}$, $W + $ jets, $WW$ and $WZ$ cross-sections.

Fig. 23 Observable $t\bar{t}$ cross-section versus $m_t$ in the single-isolated-lepton channel.
\[ p_{T}^{b} \sim m_{b} \sim 5 \text{ GeV}, \text{ whilst } p_{T}^{t} \sim m_{t} \sim 100 \text{ GeV}, \] the obvious cut is to select hard (and central) dileptons from the semileptonic heavy-quark decays. The effect of cuts on the two leptons at \( p_{T}^{L} > 50 \text{ GeV/c} \) and \( \eta_{L} < 1.5 \) for both \( t \bar{t} \) and \( b \bar{b} \) is shown also in Fig. 24. With just the \( p_{T}^{L} \) cuts, the signal-to-background ratio has already improved to \( \sim 1/5 \) for a 200 GeV \( t \bar{t} \)-quark.

Figure 25 shows the (integrated) inclusive dilepton spectrum versus the \( p_{T}^{L} \)-threshold (Nisati, Ten Have) for the \( t \bar{t} \) signal and for all the backgrounds investigated: charm and beauty production, \( Z \) and Drell–Yan (DY) pair production. A cut on both leptons at \( p_{T}^{L} > 100 \text{ GeV/c} \) alone would be enough, since the \( Z \) can be eliminated by an explicit mass cut, whilst the DY pairs are concentrated at low masses. Both the \( Z \) and the DY background can also be eliminated by looking at \( e\mu \) final states only. But such a high-\( p_{T}^{L} \) cut would be too costly in terms of event rates. It is more profitable to use a lower \( p_{T}^{L} \)-lepton cut and achieve further background reduction through: i) lepton isolation cuts, and ii) lepton azimuthal correlation cuts.

Figure 26 compares the expected lepton isolation distribution in \( t \bar{t} \) and \( b \bar{b} \) production (any lepton in the \( t \bar{t} \) final state satisfying the \( p_{T}^{L} \) cut is considered). The lepton isolation is measured in terms of the transverse energy flow \( \Sigma E_{T} \) into a \( \Delta R = \sqrt{\Delta y^{2} + \Delta \phi^{2}} = 0.4 \) cone centred on the lepton. Requiring \( \Sigma E_{T} < 10 \text{ GeV} \), for example, has an efficiency of \( \sim 80\% \) per \( t \bar{t} \) lepton and of \( \sim 5\% \) per \( b \bar{b} \) lepton. That is, this is equivalent to a rejection factor \( R_{iso} = 20 \) per lepton of \( p_{T}^{L} > 30 \text{ GeV/c} \) (Rodrigo). An additional way of reducing \( b \bar{b} \) is to use the angular correlation between the two leptons in the transverse plane (azimuthal correlation). This is illustrated by Fig. 27 (Rodrigo). The \( \Delta \phi \) distribution is much flatter for \( t \bar{t} \) than for \( b \bar{b} \), owing to the large Q-value at \( t \bar{t} \)-quark decay. About 60% of \( t \bar{t} \) dileptons are in a \( \Delta \phi \) interval \( 30^{\circ} \) to \( 150^{\circ} \), whilst for \( b \bar{b} \) production this fraction is 12%.

The two peaks in \( b \bar{b} \) at \( \Delta \phi = 180^{\circ} \) and \( 0^{\circ} \) correspond to the two large \( p_{T}^{b} \) production mechanisms, \( gg(q \bar{q}) \rightarrow b \bar{b} \) production and the gluon splitting mechanism \( gg \rightarrow gg \rightarrow g \; b \; \bar{b} \), respectively. Thus a cut on the relative azimuthal angle provides an additional rejection factor of \( \sim 5 \). Figure 28 shows the expected \( t \bar{t} \rightarrow LL \) signal and \( b \bar{b} \) background cross-sections after such selection cuts, as a function of \( m_{t} \) mass (Cavanna, Rodrigo). At \( \sqrt{s} = 16 \text{ TeV} \), the observable \( t \bar{t} \) signal in the two-hard-and-isolated leptons channel is at the level of \( \sim 10^{4} \) events for an experimental sensitivity of \( 10^{4} \text{ pb}^{-1} \), and the signal-to-heavy-flavour background ratio is \( \sim 100 \). Clearly, in this channel less stringent isolation requirements can be applied. At this level, and for \( m_{t} = 200 \text{ GeV} \), the main residual background becomes the electroweak WW production (Fig. 22). The signal-to-background ratio is \( > 20 \) for a \( p_{T}^{L} > 50 \text{ GeV/c} \) cut, and since \( \langle E_{T}^{b} \rangle = 80 \text{ GeV} \) for \( m_{t} = 200 \text{ GeV} \), this background can be further suppressed by asking for two hard and central (b)-jets.

A substantial advantage of this two-lepton channel is that it depends only on locally measurable quantities, such as \( p_{T}^{L} \) and lepton isolation, and does not require selection cuts on
Fig. 24 Energy dependence of the $t\bar{t}$ signal and $b\bar{b}$ (and WW) background cross-sections, with the effects of the various cuts.

Fig. 25 Inclusive dilepton spectrum versus $p_T$ threshold at $\sqrt{s} = 16$ TeV.
Fig. 26 Lepton isolation distribution in $t\bar{t}$ and $b\bar{b}$ production.

Fig. 27 Azimuthal correlation between the two leptons in $t\bar{t}$ and $b\bar{b}$ production.

Fig. 28 Expected $t\bar{t}$ signal versus $b\bar{b}$ background level, in the two-isolated-leptons channel.
a global variable such as the missing transverse energy. In fact, this channel can be exploited for t-quark physics up to the highest luminosity envisaged, as the loss of rejection by lepton isolation due to event superposition can be compensated by a higher $p_T^L$ cut, and at $10^{34}$ cm$^{-2}$ s$^{-1}$, event rates are large enough to afford it. Thus no major difficulties that may hamper the observation of the t-quark at the LHC are foreseen at present.

**Determination of the top-quark mass**

The measurement of $\sigma_1 t\bar{t}$ alone gives $m_t$ with, at best, $\delta m_t \sim \pm 15$ GeV. It is therefore important to study the various ways in which $m_t$ could be determined directly. In the $t \bar{t} \rightarrow WW b \bar{b} \rightarrow \Delta v jj b \bar{b}$ channel, two methods can be used: either the reconstruction of the complete $t \rightarrow Wb \rightarrow jjb$ decay, or the t-quark decaying to $t \rightarrow \Delta vb$. In the latter case, the $L$-v-jet effective mass is computed using, for the non-measurable neutrino longitudinal momentum component, the value reconstructed from the W mass constraint. At high luminosity, if $b$-tagging with a muon-in-jet is applied, still another method can be used. The distribution in the effective mass of the isolated-lepton and the muon (selected in the same hemisphere to favour the same top-quark parentage) is sensitive to $m_t$ and can be used for its determination (Fayard, Unal, Reithler; for details see Vol. II).

Figure 29 illustrates the first mass determination method, which is also the simplest (PYTHIA simulations). The jets are reconstructed in a cone of size $\Delta R = 0.4$, in agreement with GEANT simulations (Unal). The resolutions assumed are: $\Delta E/E = 50%/\sqrt{E} + 2\%$ for jets, $\Delta E/E = 15%/\sqrt{E} + 1\%$ for electrons, and $\Delta p/p = 15\%$ for muons. The selection cuts are the following: $p_T^L > 40$ GeV/c, $E_T^{\text{jet}1} > 50$ GeV, $E_T^{\text{jet}2,3} > 40$ GeV, with jets 1, 2, and 3 chosen in the hemisphere opposite to the isolated lepton. Figure 29a shows the jet-jet effective mass, for jets opposite to the lepton, all combinations included. The W peak is clearly visible. If we now choose events within the W band: $M_{jj} = m_W \pm 20$ GeV, Fig. 29b shows the resulting three-jet effective mass, where the reconstructed t-quark signal at 130 GeV is clearly visible over the event combinatorial background ($m_t = 130$ GeV was generated). B-tagging (with a muon) further increases the significance of the t-quark mass peak. Note that in Fig. 29 the background from W + jets is not included (and signal-to-background ~ 3), but again, if b-tagging is included in the simulation, the W + jets background is much smaller than the signal. After the evaluation of the various sources of errors and uncertainties (b-fragmentation, underlying event, electron-to-hadron calorimeter response ratio, etc.), it is estimated that a precision of $\delta m_t = \pm 8$ GeV can be achieved in this channel, already with a luminosity of $\sim 10^{32}$ cm$^{-2}$ s$^{-1}$.

In the two-isolated-leptons channel, again several methods can be used to determine $m_t$. The lepton-jet effective mass is one possibility. However, the most precise and least background-prone determination is obtained by asking for an additional semileptonic b decay, i.e. in a three-lepton final state. The variable to look at is the effective mass of the hard-and-isolated lepton (from the W decay) and the non-isolated muon from the b decay from
the same parent $t$-quark ($t \to Wb \to \nu b \to \nu L\nu c$). As before, this $\nu L\nu$ two-lepton effective mass distribution is sensitive to the parent $t$-quark mass, although it is not giving $m_t$ directly owing to the missing neutrinos. Taking into account the various uncertainties (b-fragmentation predominantly), the expected statistical errors, and the possible backgrounds in this three-lepton channel, it is estimated that a precision of $\delta m_t = \pm 5$ GeV can be achieved (Unal, Fayard). This method, however, requires $L > 10^{33}$ cm$^{-2}$ s$^{-1}$, as it is penalized by three semileptonic decays (for details, see Fayard in Vol. II).

*Top-quark branching ratios and the search for $H^\pm$*

In the Minimal Standard Model (MSM), $t \to Wb$ is the only decay mode. In models with two Higgs doublets we can have $t \to H^+b$, and if $m_{H^+} < m_t$, then $t \bar{t}$ production is in fact the dominant $H^\pm$ production mechanism (Phillips, Zerwas, Zunft, and Refs. [32]). The $H^\pm$ can be revealed either by a measurement of the branching ratio $BR(t \to Wb) \neq 1$, that is $BR(t \to \mu) \neq 1/9$, or by a direct search for $H^\pm$ decaying to $H^\pm \to c\bar{s}$ or $\tau\nu$, after selecting events through the decay $t \to Wb \to \text{isolated lepton}$ (Felcini).

The $t \to \text{lepton}$ branching ratio can be measured by comparing the number of events in the single-isolated-lepton channel with those in the two-isolated-leptons channel, as this ratio is obviously determined by $BR(t \to Wb)$, since isolated leptons ($e's$ and $\mu's$) can come only from $W$ and not from $H^\pm$ decays. After the uncertainties due to backgrounds ($W + \text{jets}, b \bar{b}$) in the single-isolated-lepton mode have been reduced by requiring a non-isolated $\mu$ tagging the accompanying $b$, the study shows that (for $m_t = 200$ GeV) the attainable precision on $BR(t \to \mu)$ is $\sim 7\%$ for an integrated luminosity of $10^4$ pb$^{-1}$ and the dominant error is statistical. For $10^5$ pb$^{-1}$ the precision is $\sim 5\%$, limited now by systematics (Unal). The expected branching ratios $BR(t \to Wb)$ and $BR(t \to Hb)$ versus $tg\beta$ for $m_t = 200$ GeV and $m_{H^\pm} = 100$ GeV are shown in Fig. 30a (Zerwas, Zunft, and Refs. [32]). In the minimal SUSY model the preferred range of $tg\beta$ is $1 \leq tg\beta \leq m_t/m_b$, and LEP measurements indicate $tg\beta > 1.6$ [33].

Figure 30b shows the branching ratios $BR(H^\pm \to c\bar{s})$ and $BR(H^\pm \to \tau\nu)$ versus $tg\beta$. Note that in the favoured range $tg\beta > 1$, $H^\pm \to \tau\nu$ is dominant. In a direct search of $H^\pm$, the simplest $H^\pm$ signature to exploit is the expected excess of $H^\pm \to \tau\nu$ decays relative to SM expectations. This amounts to looking for the breakdown of lepton universality in the $t$-quark decay $t \to \nu vb$. The starting point of such an analysis is the selection of a sample of single-isolated-lepton ($e$ or $\mu$) $t$-quark events, with a second non-isolated muon tagging the $b$ to reduce backgrounds. This provides a sample of tagged $t$-quarks. In a second step, a search is then performed for an excess of isolated $\tau$'s, as compared with isolated $\mu$'s, in the decays of the second $t$-quark. The key element of the analysis is a good selection of $t \to \tau$ low-multiplicity ($< 4$) charged hadron decays in a collimated ($\Delta R = 0.2$) jet of $E_T > 30$ GeV, with a good rejection of jets from $W \to q \bar{q}$ faking $\tau$'s (Felcini; for details, see Vol. II). Figure 30c shows the expectation for the ratio of $t \to \nu vb$ to $t \to \mu vb$ branching ratios as a
Fig. 29 Determination of $m_t$ from the $t \to W^+ b W^- b$ final state.

Fig. 30 a) $t \to W^+ b$ and $t \to H^+ b$ branching ratio versus $\tan \beta$; b) $H^\pm \to c s$ and $H^\pm \to \tau \nu$ branching ratio versus $\tan \beta$; c) ratio of $t \to \tau \nu b$ to $t \to \mu b$ branching ratios versus $\tan \beta$, and the expected sensitivity limit.

90
function of $\tan \beta$, and the range of $\tan \beta$ that can be explored by this method with a $10^4$ pb$^{-1}$ sensitivity. (In Fig. 30c it is also assumed that the $h^0$ mass is large enough not to allow a $H^\pm \to W h^0$ decay; for details, see Vol. II). The dotted line shows the expected 90% CL limit on the departure from unity in this ratio. The main limitation in this study is statistical, with a 15% stat. error and 6% syst. error for $10^4$ pb$^{-1}$, i.e. $\delta BR(t \to \tau) = 20\%$, since $\tau$ identification, as done in this analysis, is not considered possible at a luminosity higher than $10^{33}$ cm$^{-2}$ s$^{-1}$. None the less, a relatively large region of the $m_t, m_H, \tan \beta$ parameter space can be explored, the LHC being sensitive to $m_{H^+} \leq 150$ GeV for $m_t \leq 200$ GeV (Phillips, Felcini, Zerwas, Zunfit).

4. HIGGS SEARCH AT THE LHC

Higgs production

The search strategies and methods to be employed are rather well defined for the Standard Model Higgs – for if you know its mass, you know nearly everything concerning both its production and decays, up to relatively minor uncertainties related to the mass of the $t$-quark or to the gluon structure functions (see Kunszt and Stirling in Vol. II, and Refs. [31, 34]). At hadron colliders the basic Higgs production mechanisms, sketched in Fig. 31 are gluon–gluon fusion, $WW(ZZ)$ fusion, $t \bar{t}$ fusion, and $W(Z)$ bremsstrahlung production. The Higgs production cross-section at $\sqrt{s} = 16$ TeV according to these various mechanisms is shown in Fig. 32 (Kunszt and Stirling). Figure 32 also gives the expected number of events for an experimental sensitivity of $10^5$ pb$^{-1}$. At the LHC (and SSC) the gluon–gluon fusion mechanism provides the dominant contribution over most of the accessible mass range. At the highest masses $m_H \geq 0.7$ TeV, the $WW(ZZ)$ fusion, labelled $qq \to Hqq$ in Fig. 32, becomes comparable or takes over, depending on the $t$-quark mass. Even if not dominant, this $qq \to Hqq$ mechanism provides an additional event signature, thanks to the two energetic and forward ‘tagging’ jets [35, 31]. At the lower end of the Higgs mass range, the WH (and ZH) associated-production bremsstrahlung mechanism may again provide an additional experimental signature owing to the accompanying $W$ (or $Z$).

The ratio of Higgs production cross-sections at the LHC and SSC varies from values $\sigma_H^{\text{SSC}}/\sigma_H^{\text{LHC}} = 3$ at $m_H = 0.1$ TeV to $\approx 10$ at $m_H = 1$ TeV. The expected Higgs production rates are large at the LHC, from $10^6$ to $10^4$ events per year at $10^{34}$ cm$^{-2}$ s$^{-1}$ for $m_H$ varying from 0.1 to 1 TeV. Unfortunately, the decay channel providing the best experimental signature has a small branching ratio, $\text{BR}(H \to ZZ \to 4 \ell^\pm) = 1.2 \times 10^{-3}$; statistics is thus the limiting factor, and the highest luminosity is desirable.

Higgs decays and experimental signatures

Figure 33 shows the variation of the Higgs total width $\Gamma_H$ with $m_H$ (Kunszt, Stirling); $\Gamma_H$ is a rapidly increasing function of $m_H$. For $m_H < 0.2$ TeV, $\Gamma_H < 2$ GeV, and in this mass range, the experimental mass resolution plays an important role; $\Gamma_H = 60$ GeV for $m_H$
Fig. 31 Higgs production mechanisms at hadron colliders.

\[ p + p \rightarrow H + X \quad \sqrt{s} = 16 \text{ TeV} \]

Fig. 32 Higgs production cross-sections at \( \sqrt{s} = 16 \text{ TeV} \).

Fig. 33 Variation of the Higgs total width versus \( m_H \).
Fig. 34a Higgs decay branching ratios for $m_H > 2m_Z$ and $m_t = 90$ and 200 GeV;

Fig. 34b Higgs decay branching ratios for $m_H < 2m_Z$ and $m_t = 90$ GeV.
= 0.5 TeV and $\Gamma_H = 0.5$ TeV for $m_H = 1$ TeV. For large masses ($m_H \gg m_W$) the width varies as $\Gamma_H = 0.5$ TeV /1 TeV$^3$, and the Higgs broadens and dissolves into the background shape [31, 34].

The Higgs decay branching ratios are shown in Fig. 34a for the 'heavy Higgs' mass range $m_H > 2m_Z$, and in Fig. 34b for the 'intermediate Higgs' mass range $m_Z < m_H < 2m_Z$. For the $m_H > 2m_Z$ regime, the $H \rightarrow WW$ and $ZZ$ partial widths dominate entirely, with $\Gamma(H \rightarrow WW) = 2\Gamma(H \rightarrow ZZ)$. The effect of the t-quark over its entire allowed mass range is only minor (Kunszt, Stirling, Pancheri). For the $m_H < 2m_Z$ mass range (Fig. 34b), the dominant decay mode is $H \rightarrow b \bar{b}$, but this mode is of little use. No practical way has yet been found to exploit it, in face of the overwhelming QCD $b \bar{b}$ pair-production background [36, 37] (see Fig. 1, for example). The decay modes providing the best experimental signature in this mass range are $H \rightarrow ZZ^* \rightarrow 4\phi^\pm$ (Higgs decaying into an on-shell plus an off-shell $Z$), with a rapidly varying branching ratio as a function of $m_H$, and the $H \rightarrow \gamma \gamma$ mode with a BR $\sim 10^{-3}$ for $m_H \leq 150$ GeV [38] (for details, see Kunszt and Stirling in Vol. II). Under some conditions the $H \rightarrow \tau^+ \tau^-$ mode may also be put to use in SUSY Higgs searches (see Kunszt and Zwirner in Vol. II).

The $H \rightarrow ZZ \rightarrow 4\phi^\pm$ channel

This channel is the most convenient Higgs detection mode over the entire mass range $\sim 130$ GeV $\leq m_H \leq 0.8$ TeV. The $\sigma$-BR ($H \rightarrow 4\phi^\pm$) production cross-section and the expected event rate for a sensitivity of $10^5$ pb$^{-1}$ is shown in Fig. 35. At both the lower and upper end of the mass range the experimental search is largely, but not exclusively, limited by statistics. At $m_H = 120$ to 130 GeV, about 100 $H \rightarrow 4\phi^\pm$ events are produced, but acceptance is low; about 1500 $H \rightarrow 4\phi^\pm$ events are expected for $m_H = 200$ GeV; $\sim 200$ $H \rightarrow 4\phi^\pm$ events for $m_H = 0.5$ TeV, and $\sim 10$ events for $m_H = 1$ TeV, where the problem is not only statistics, but also that the signal shrinks owing to the $= 0.5$ TeV total width. The Higgs working group has made a detailed study of the observability of this Higgs signal in the presence of all the possible backgrounds, taking into account reasonable detector performances. As the detection problems and backgrounds are rather different over this entire mass range, we discuss them separately for $m_H$ larger or smaller than 2$m_Z$.

i) The 'heavy Higgs' $H \rightarrow ZZ \rightarrow 4\phi^\pm$ regime.

Figure 36a shows the Higgs signal in the specific $H \rightarrow ZZ \rightarrow 4\mu^\pm$ channel for a sensitivity of $10^5$ pb$^{-1}$. All the known potential $4\mu^\pm$ backgrounds are also shown, $t\bar{t}$ production, $Zb\bar{b}$ production, $ZZ$ continuum production, and two-$Z$-event pile-up at $L = 10^{34}$ cm$^{-2}$ s$^{-1}$ with $\Delta t = 15$ ns time separation— that is, assuming event superposition only from the same bunch crossing (all estimated with ISAJET; Nisati, Della Negra). This is before any background reduction cuts and for a perfect detector. Under these conditions the $t\bar{t}$ background is the dominant one, and at the resonance peak the signal-to-background ratio is $\sim 1$. The ways of reducing backgrounds in $4\phi^\pm$ final states are: i) to require the presence of
two $Z$ — that is, a mass cut $M_{\mu\mu} = m_Z \pm \delta m_Z$, and ii) lepton isolation. Figure 36b shows the effect of the $Z$ mass cuts alone, in a detector of a modest muon momentum resolution of $\Delta p/p = 12\%$, as is expected for an iron toroid in this momentum range (Nisati). The mass cut is $M_{\mu\mu} = m_Z \pm 16$ GeV for both $\mu^+\mu^-$ pairs, and no lepton isolation has yet been required. Now the signal stands out clearly above the background, with the $t \bar{t}$ and $Zb\bar{b}$ backgrounds reduced below the irreducible $ZZ$ continuum background. The $t \bar{t}$ background is not yet entirely negligible at $m_H \sim 200$ GeV, and it can be further suppressed by means of lepton isolation cuts. Notice also that at $m_H \sim 200$ GeV, the limited momentum resolution assumed in the simulation does not make the signal stand out so clearly over the $ZZ$ continuum. However, by applying a $Z$-mass constraint on the two muon pairs, the resolution on the Higgs mass can be rescued and the signal made to stand out more prominently. It is possible, by rescaling the measured muon momenta and forcing $M_{\mu\mu}^{\text{measured}} = m_Z$, whilst keeping the relative space angle between the two muons fixed, to improve the mass resolution to $\delta m_H = 2\%$ (Nisati; for details see Vol. II). This means that even in this Higgs mass range, a modest $M_{\mu\mu}$ mass resolution can do the job.

At the upper end of this mass range the Higgs is broad and the resolution plays no significant role. The ratio of signal to irreducible $ZZ$ background can still be improved by applying cuts on $p_T^Z$ to favour the Jacobian peak from the isotropic $H \rightarrow ZZ$ decay over the continuum $ZZ$ production from $q \bar{q} \rightarrow ZZ$ and $gg \rightarrow$ quark loop $\rightarrow ZZ$ production [31]. Figure 37 shows how, after such an optimization, a high-mass Higgs would stand out above the background in an experiment detecting both electrons and muons with reasonable acceptances and efficiencies, and for an experimental sensitivity of $10^5$ pb$^{-1}$ (Froidevaux). Clearly, the Higgs mass reach is $\sim 800$ GeV, limited by statistics and by the difficulty to recognize an intrinsically broad signal.

ii) The $m_H < 2m_Z$ regime in the $H \rightarrow ZZ^* \rightarrow 4 \ell^\pm$ final state.

Figure 35 shows the $\sigma$-BR cross-section in the $H \rightarrow ZZ^* \rightarrow ZZ+\ell^\pm \rightarrow 4 \ell^\pm$ final state, and the expected number of events. At both the lower end ($\sim 130$ GeV) and around the dip ($\sim 160$ to 170 GeV) the statistics is a limiting factor. In this mass range, the acceptance plays a crucial role. This is visible from Fig. 38 where the effects of the lepton $p_T^\ell$ threshold cut and of the geometrical acceptance are shown; the cuts are applied to all four leptons (Della Negra, Froidevaux). For $m_H < 2m_Z$, a lepton detection threshold at $p_T^\ell = 10$ GeV/c is essential. Note that the two leptons from the on-shell $Z$ are systematically harder, with $\langle p_T^\ell \rangle = 35$ GeV. Figure 38 also shows that a large geometrical acceptance, $\eta_{\ell} \ll 3$, is essential in this mass range, and is still very useful at $m_H \sim 0.3$ TeV.

What are the backgrounds in this mass range? There are irreducible backgrounds such as $q \bar{q}$, $gg \rightarrow ZZ^*$, $Z\gamma^* \rightarrow 4 \ell^\pm$ with isolated leptons, and potentially large but reducible ones due to $t \bar{t}$ and $Zb\bar{b} \rightarrow 4 \ell^\pm$ production. These backgrounds can be reduced by asking for one on-shell $Z$ to suppress the $t \bar{t}$ background, and for lepton isolation to suppress both $t \bar{t}$ and the $Zb\bar{b}$ backgrounds. Figure 39a shows the signal at three mass values
Fig. 35 $\sigma$-BR($H \rightarrow 4\ell^{\pm}$) versus $m_H$ at $\sqrt{s} = 16$ TeV.

Fig. 36 a) Higgs signal in the $H \rightarrow ZZ \rightarrow 4\mu^{\pm}$ channel, and $4\mu^{\pm}$ backgrounds; perfect resolution; b) same as a), but assuming $\Delta p/p = 12\%$ and a $Z$-mass cut on both $\mu\mu$ pairs.
Fig. 37 Expected Higgs signal and ZZ continuum background at $\sqrt{s} = 16$ TeV.

Fig. 38 Number of detected Higgs events versus lepton $p_T$ threshold and geometrical acceptance cuts.

Fig. 39 a) Higgs signal in the $H \rightarrow ZZ^* \rightarrow 4\ell^\pm$ channel and the $4\ell^\pm$ backgrounds, with a $Z$-mass cut; b) same as in a), but with, in addition, a lepton isolation cut.
superimposed on the sum of all backgrounds investigated: $t \bar{t}$ (ISAJET), $Zb\bar{b}$ (Kleiss, QCD computation plus PYTHIA), $ZZ^*$, $Z\gamma^*$ (PYTHIA) (Della Negra, Froidevaux, Kinnunen, Nisati; for details, see Della Negra in Vol. II). (The ISAJET prediction for $Zb\bar{b}$ is also shown, but is not included in the sum of backgrounds). In Fig. 39a the following conditions and cuts have been assumed: $p_T \ell \geq 10$ GeV/c, $|\eta_{\ell}| \leq 3$, efficiency per lepton $\epsilon = 0.9$, a $Z$-mass cut $M_{\ell\ell} = m_Z \pm 10$ GeV (assuming $\Delta E/E = 15%/\sqrt{E + 2%}$), and $M_{\ell\ell} > 12$ GeV to suppress continuum $ZZ^*$ and $Z\gamma^*$, and lepton pairs from the same $b$-decay. No lepton isolation is required in Fig. 39a. Figure 39b shows the signal versus the full background, now asking also for lepton isolation, assuming a rejection factor $R_{\text{iso}} = 7$ and an efficiency $\epsilon_{\text{iso}} = 0.85$ per lepton (these are leptons of $<p_T \ell >$ = 15 to 20 GeV/c). The signal now stands out clearly over the mass range $m_H = 130$ to $2m_Z$. Note, however, that before the isolation cuts (Fig. 39a) the $t \bar{t}$ is the largest background contribution. It can already be reduced at this stage in direct proportion to the $M_{\ell\ell} = m_Z \pm \delta m_Z$ mass-bite applied, this one being directly determined by the lepton-pair mass resolution and limited, of course, by the $Z$ width. So there is here some latitude in the possible experimental apparatus choices, as a trade-off is possible between reliance on mass (momentum) resolution versus lepton isolation (calorimetric granularity). Since in this mass range the event rate is small, it is desirable to function at maximal luminosity, and this consideration could influence the instrumental choices.

The $H \to ZZ \to 4\ell^\pm$ channel thus makes it possible to cover the mass range $\sim 130 < m_H < 800$ GeV. We can now try to extend this mass range at both ends, either using decay modes with larger branching ratios or by providing a different experimental signature. This is particularly important at the lower end in order to close the gap between $m_H = 130$ GeV and the domain that can be explored by LEP 200, which is $m_H = 80$ to 90 GeV. It is also desirable to have some redundancy in the methods of investigation, especially in the lower LHC mass range, where the experiments will clearly be difficult ones.

*The $H \to ZZ \to 4\ell^\pm$ channel*

If we detect both electrons and muons, this decay mode has a branching ratio of 0.8%, i.e. six times larger than for $H \to 4\ell^\pm$. This might allow the $m_H = 1$ TeV region to be probed. The event signature is a Jacobian peak in the $p_T^Z (Z \to \ell^+ \ell^-)$ distribution from the two-body $H \to ZZ$ decay. Figure 40 shows the expected signal for $m_H = 0.8$ and 1 TeV, superimposed on the irreducible $q \bar{q}$, $gg \to ZZ$ electroweak continuum background (Della Negra). The Jacobian peak is very broad, owing firstly to the intrinsic Higgs width, and secondly to the Higgs transverse momentum, which is of the order of $p_T^H = \alpha_s m_H \sim 100$ GeV for $gg \to H$ [39] and $p_T^H \sim m_W \sim 100$ GeV also for $qq \to qqH$ [40], the two mechanisms contributing at high Higgs masses. At $m_H = 1$ TeV, the Higgs signal is not very distinctive, but it could be detected by a change of slope in the continuum $p_T^Z$ distribution. This requires a good knowledge of the background shape and is sensitive to the experimental
resolution in $p_T^Z$. The prerequisite is, however, that the other significant backgrounds can be suppressed.

Figure 40 also shows the (reducible) QCD background of $Z +$ jet production. It exceeds the signal by about three orders of magnitude before any cuts. It can be reduced below the $ZZ$ continuum by a missing transverse energy cut. The shape of the $E_T^{\text{miss}}$ distribution from the $Z \rightarrow \ell^+ \ell^-$ decay is the same as that of the $p_T^Z$ distribution for the visible $Z \rightarrow \ell^+ \ell^-$ decay. The decisive element is here the calorimetric coverage, which allows the transverse energy balance to be measured in the event [41]. The (integrated) $E_T^{\text{miss}}$ distribution is shown in Fig. 41 for calorimetric jet detection up to $|\eta|_{\text{max}} = 2, 3$, and 4 units in rapidity (Froidevaux). For the Higgs signal to emerge above the $Z +$ jets background, a calorimetric coverage up to at least $|\eta| = 4$ is required at the LHC. About 0.5 unit more is needed at the SSC. This is probably the minimal coverage needed, since this simulation is only at parton level and does not include fragmentation, hadron showers, and the $E_T^{\text{miss}}$ resolution degradation due to cracks, large-angle leakage, or non-containment, etc.

Thus, provided a large-geometrical-coverage calorimeter can be built to limit the background to the $ZZ$ continuum one, the Higgs signal for $m_H = 0.8$ TeV would appear as in Fig. 42 (signal of $= 190$ events) at $10^5$ pb$^{-1}$ (Froidevaux). A $p_T^Z$ cut has been applied to enhance the signal-to-background ratio, but clearly a very good knowledge of the continuum shape and absolute magnitude is mandatory in order to observe the signal.

**The $H \rightarrow WW$ channel**

This mode might be interesting for extending the mass reach, because of the much more favourable $W (Z) \rightarrow q \bar{q} \rightarrow$ jet jet branching ratios of $\sim 70\%$, as compared with the leptonic modes. Figure 43 shows the various backgrounds generating $WW$ or quasi-$WW'$ final states that have to be faced. For $H \rightarrow WW$, the dominant backgrounds are $t \bar{t} \rightarrow WWbb$ [42] and $W +$ jets (i.e. $WW'$) production [43]; for $H \rightarrow ZZ$ it is the $Z +$ jets production. Note that all backgrounds have continuum $WW$ or $ZZ$ mass distributions, as compared with a (very broad) resonant peak for the signal.

It is here that the Higgs production mechanism may help. For $m_H = 1$ TeV, the $WW(ZZ)$ fusion mechanism $qq \rightarrow Hqq$ of Fig. 31 becomes comparable to $gg \rightarrow H$, or even takes over (Fig. 32). Advantage can then be taken of the additional signature, provided by the two forward 'tagging' jets, to suppress the $W, Z +$ jets and $t \bar{t}$ backgrounds [35, 31]. The rapidity distribution of the tagging jets is shown in Fig. 44 (Seymour). These are TeV jets with $<p_T> \sim 1$ TeV at the LHC (and $\sim 2.5$ TeV at the SSC) and $<p_T> \sim m_W \sim 100$ GeV. These tagging jets are emitted at $\sim 1^\circ$ to $5^\circ$ from the beams. The detection of these jets thus requires a calorimetric coverage over the $2.5$ to $4.5$ rapidity range at the LHC ($\sim 2.5$ to $5$ at the SSC). It is a real experimental challenge to build such a calorimeter, able to sustain $L > 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$.

An important question is also how these forward tagging jets survive the hadronization
Fig. 40: Expected Higgs signals in the $H \rightarrow ZZ \rightarrow 4\ell$ channel, and the backgrounds.

Fig. 41: Integrated $E_T^{miss}$ distribution in $Z + J$ for various calorimetric coverages.

Fig. 42: Expected Higgs $H \rightarrow ZZ \rightarrow 4\ell$ signal for $m_H = 800$ GeV.
Fig. 43 Energy dependence of $H \rightarrow WW$, and WW or quasi-WW final states.

Fig. 44 Rapidity distribution of tagging jets at $\sqrt{s} = 16$ TeV.

Fig. 45 Energy flow within tagging jets, 16 m downstream the interaction point.
phase (previous studies were at the partonic level only), and whether they can be recognized close to the beams in the presence of the underlying event and the superposition of minimum-bias events in high-luminosity running. Progress has been made in the understanding of these problems. The spatial distribution of tagging-jet fragments (the jet 'width' in terms of the energy flow), 16 metres downstream from the interaction region, as obtained from the parton-shower Monte Carlo HERWIG, is shown in Fig. 45 (Seymour). Jets are well collimated, and at such a distance more than 95% of the jet energy flow is contained within 20 cm from the jet axis. The evaluation of the experimental feasibility of this detection is not yet finished, but, provided jet tagging is possible, the statistical significance for a 1 TeV Higgs signal at the LHC, for an experimental sensitivity of $10^5 \text{ pb}^{-1}$, is estimated to be: $\frac{\text{signal}}{\sqrt{\text{background(continuum)}}} = 6.0$, whilst $S/\sqrt{B} = 2.5$ at $10^4 \text{ pb}^{-1}$ (for details, see Seymour in Vol. II).

These tagging feasibility studies will be pursued, as tagging is the only way to reach the $m_H = 1 \text{ TeV}$ domain, and more generally to study both resonant and non-resonant electroweak WW, WZ, and ZZ interactions at high $M_{VV} \geq 1 \text{ TeV}$, which is an important issue in itself (Baur, and Refs. [44, 45]).

The $H \to \gamma\gamma$ mode

As previously mentioned, this mode has a slowly varying branching ratio at the $10^{-3}$ level for $m_H \leq 150 \text{ GeV}$. It may be useful for extending the Higgs detection below the $2m_Z$ mass range. The signature is the presence of two isolated photons with $E_T > 50 \text{ GeV}$. Figure 46 shows the $\sigma$-BR($H \to \gamma\gamma$) in the interesting mass range. The number of events expected for $10^5 \text{ pb}^{-1}$ is also shown, and amounts to $3 \times 10^3$ events produced. The $H \to \gamma\gamma$ signal must, however, be searched for in the presence of two formidable backgrounds. First, the irreducible continuum QCD diphoton production via $q\bar{q} \to \gamma\gamma$ (Bonesini, Camilleri, Werlen, and Refs. [37, 38]). Figure 47 shows a sketch (not a simulation) of a possible signal superimposed on this background. As in this mass range $\Gamma_H/m_H \sim 10^{-4}$, the calorimeter $M_{\gamma\gamma}$ resolution is very important: the better the resolution, the smaller the mass-bias required, and the more significant will be the signal. A detailed study shows that a mass resolution of better than 1% is required (Seez, Virdee, and Ref. [37]). This, combined with the necessity of working at $-10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, is very demanding on calorimetry.

The second - dangerous, but reducible - background comes from QCD jet-jet events faking $\gamma\gamma$ events. Figure 48 shows the inclusive jet, $\pi^0$, single-photon, and the irreducible $\gamma\gamma$ background in the relevant $E_T$ range. The ratio of jet-jet to $\gamma\gamma$ events is $\sim 10^7$. This is thus the minimal rejection factor needed against jet-jet events. The solutions here are detector (calorimeter) granularity and a good resolution position detector to separate isolated photons and suppress $\pi^0 \to \gamma\gamma$ decays. The study shows that, by requiring that there be no particle with $p_T > 2 \text{ GeV}$ within $\Delta\eta\Delta\phi = 0.2\times0.2$ around the $\gamma$ candidate, and with the ability to detect the presence of two photons with an angular separation of $\Delta\theta > 5 \text{ mrad}$, the probability for a
Fig. 46 $\sigma \cdot \text{BR}(H \to \gamma\gamma)$ versus $m_H$ at $\sqrt{s} = 16$ TeV.

Fig. 47 Continuum QCD $\gamma\gamma$ production, with a sketch of the $H \to \gamma\gamma$ signal.

Fig. 48 Inclusive jet, $\pi^0$, direct $\gamma$, $\gamma\gamma$, and 'fake $\gamma$ (jet $\to \gamma$) $E_T$ spectrum.
$E_T \sim 50\text{ GeV}$ jet to fake a $\gamma$ is $< 10^{-4}$, as is visible from the curve labelled $\gamma$ in Fig. 48. Thus the needed rejection can be attained, and we have to worry only about the irreducible $\gamma\gamma$ background. The isolation region is chosen to be small, in order not to reject too many genuine events at high luminosity owing to event pile-up. At a luminosity of $10^{34}\text{ cm}^{-2}\text{s}^{-1}$, 93% of the signal would still be kept (Seez, Virdee).

The statistical significance of the $H \rightarrow \gamma\gamma$ signal that would be observed with an integrated luminosity of $10^5\text{ pb}^{-1}$, in an excellent calorimeter with resolution $\Delta E/E = 2\%/\sqrt{E} + 0.5\%$, and assuming a longitudinal vertex position known to $\sigma_{\text{VTX}} = 1\text{ cm}$, would be the following: signal/\sqrt{background} = 4.5 at $m_H = 80\text{ GeV}$, $S/\sqrt{B} = 8.4$ for $m_H = 100\text{ GeV}$, and $S/\sqrt{B} = 10.7$ for $m_H = 150\text{ GeV}$. If, because of event pile-up, the event-vertex information were lost — that is, taking $\sigma_{\text{VTX}} = 5\text{ cm}$ — the significance of the signal for $m_H$ in the 100 to 150 GeV range would fall to $S/\sqrt{B} = 5.0$ (for details, see Seez in Vol. II). In conclusion, this would be a very demanding experiment and may require a dedicated detector.

**The $WH \rightarrow W\nu\gamma\gamma$ channel**

The associated WH (or ZH) production is the way to bridge the possible gap between the domains that could be explored at LEP 200 and at the LHC. The $\sigma\cdot\text{BR}(W \rightarrow \ell\nu)\cdot\text{BR}(H \rightarrow \gamma\gamma)$ channel cross-section is shown in Fig. 49 (Kleiss, Kunszt, Stirling). For an integrated luminosity of $10^5\text{ pb}^{-1}$, the yield is thus ~30 WH and ~4 ZH events — before any acceptance cuts. Clearly, statistics is an important limitation. At the SSC the production cross-sections are larger by a factor of ~3.

There are two types of backgrounds to contend with. An irreducible background of $W\gamma\gamma$ events, with a continuum $M_{\gamma\gamma}$ mass distribution shown in Fig. 50 together with the expected WH signal, assuming the detector has a $\gamma\gamma$ mass resolution of $\lesssim 5\text{ GeV}$. The acceptance cuts are also indicated. The signal-to-background ratio is of order 1, with ~20 events per signal bin and per $10^5\text{ pb}^{-1}$ of integrated luminosity. The other backgrounds investigated are the various QCD-induced backgrounds from $W$ +jets, $b\bar{b}$, $b\bar{b}\gamma$, etc. These can be either eliminated or reduced below the $W\gamma\gamma$ level, provided: i) the probability for a jet to fake a $\gamma$ can be kept lower than $10^{-4}$, and ii) a lepton isolation criterion can be implemented with a rejection factor $R_{\text{ISO}} > 5$ (Di Lella et al.; for details, see Vol. II). Under these conditions the only important background would be the irreducible one (Fig. 50), and the main limitation is the statistics, with ~20 observable signal events per year at $10^{34}\text{ cm}^{-2}\text{s}^{-1}$, and with, in addition, a few $ZH \rightarrow \ell\gamma\gamma$ events (Pancheri). None the less, this WH channel is very important since it is complementary to the $H \rightarrow \gamma\gamma$. It works best at lower Higgs masses and makes it possible to probe the $m_H \lesssim 100\text{ GeV}$ region best, thus providing a junction with the LEP 200 domain.

**Review of Higgs detection possibilities and limitations**

As the Higgs search is central to the LHC physics programme, it is worth reviewing
briefly the possibilities and limitations of the various modes investigated (Fig. 51):

i) $H \rightarrow ZZ \rightarrow 4 \ell^\pm$, with $\ell = e, \mu$; $m_H > 2m_Z$:
   - mass reach: up to $\sim 0.8$ TeV with $10^5$ pb$^{-1}$;
   - backgrounds: $ZZ$ continuum dominant, $t \bar{t}$ reducible with lepton isolation;
   - resolution: not crucial; $\Delta p/p \sim 10\%$ plus a $Z$ mass constraint would do it.

ii) $H \rightarrow ZZ^* \rightarrow 4 \ell^\pm$, $\ell = e, \mu$; for $m_H < 2m_Z$:
   - mass reach: $-130 < m_H < 2m_Z$ with $10^5$ pb$^{-1}$;
   - acceptance: needs $p_T^{\ell} \geq 10$ GeV/c with $|\eta_{\ell}| \leq 3$;
   - backgrounds: $qq \rightarrow ZZ^*$ small; $Zb \bar{b}$ is larger, reducible with lepton isolation;
   - $t \bar{t}$ is largest, reducible with $M_{\ell\ell} = m_Z$ mass cut and/or lepton isolation, a resolution-isolation trade-off possible.

iii) $H \rightarrow ZZ \rightarrow \ell^\pm \ell^\mp \nu \bar{\nu}$:
   - mass reach: possibly up to $\sim 0.9$ TeV for $10^5$ pb$^{-1}$;
   - backgrounds: $ZZ$ continuum, $Z +$ jets very dangerous, reducible with $E_T^{\text{miss}}$
   - cuts or veto on jets back-to-back to $Z$, to be studied further;
   - acceptance: calorimetric coverage must extend up to at least $|\eta| = 4$.

iv) $H \rightarrow WW, ZZ \rightarrow \ell^\pm \ell^\mp$ jet jet from WW(ZZ) fusion:
   - mass reach: $\sim 1$ TeV;
   - acceptance: tagging of forward jets in $|\eta| = 2$ to 4.5 is mandatory;
   - backgrounds: $W$, $Z +$ jets and $t \bar{t}$ reducible by jet tagging; the non-resonant
   - $WW, ZZ$ electroweak interactions are irreducible, but small.

v) $H \rightarrow \gamma\gamma$, for $m_H < 2m_Z$:
   - mass reach: $100 \leq m_H \leq 150$ GeV for $10^5$ pb$^{-1}$;
   - acceptance: $E_T^{\gamma} \geq 25$ GeV in $|\eta_\gamma| \leq 2$;
   - backgrounds: irreducible $q \bar{q}, gg \rightarrow \gamma\gamma$; reducible jet-jet and jet-$\gamma$, eliminated
   - provided $\text{Prob (jet} \rightarrow \gamma) < 10^{-4}$;
   - resolution: $M_{\gamma\gamma}$ resolution is crucial; $\delta M_{\gamma\gamma}/M_{\gamma\gamma} \leq 1\%$ needed, with vertex
   - known to $\lesssim 1$ cm; two-$\gamma$ separability at $\geq 5$ mrad needed;
   - requires a dedicated detector.

vi) $H \rightarrow \gamma\gamma$ from WH (ZH) $\rightarrow \ell^\pm \gamma\gamma$, $\ell = e, \mu$; for $m_H < 2m_Z$:
   - mass reach: $80 \leq m_H \leq 130$ GeV for $10^5$ pb$^{-1}$;
   - acceptance: $p_T^{\ell, \gamma} \geq 20$ GeV/c in $|\eta_{\ell, \gamma}| \leq 2.5$;
   - backgrounds: irreducible $W\gamma\gamma$ requires resolution $\delta M_{\gamma\gamma} \leq 5$ GeV; $W +$ jets ,
   - $b \bar{b}g, b \bar{b}\gamma$, etc., are reducible, eliminated provided $\text{Prob (jet} \rightarrow \gamma) < 10^{-4}$ and with lepton isolation;
   - a $H \rightarrow \gamma\gamma$ dedicated detector plus a muon/electron capability would do it.
Fig. 49  Cross-sections for associated WH and ZH production at √s = 16 and 40 TeV.

Fig. 50  M_γγ from the Wγγ background and the WH (H → γγ) signal at √s = 16 TeV.

Fig. 51  Higgs mass range covered by the various channels, and the luminosities required.
Conclusions on the SM Higgs search

The present limit from LEP searches is at $m_H \gtrsim 44$ GeV [46], and the expectations are that LEP 100 and LEP 200 will explore up to $m_H \sim 80$ to 90 GeV. The LHC and the SSC will explore the $\sim 80 < m_H \lesssim 1$ TeV domain.

The range $-2m_Z < m_H < 0.7$ to 0.8 TeV is relatively 'easy', with $H \to ZZ \to 4\ell^\pm$. The range $m_H \gtrsim 0.8$ TeV, with $H \to ZZ \to 4\ell^\pm$, $\ell^+\ell^-\nu\bar{\nu}$, is harder, as the Higgs peak broadens and dissolves into the background shape. The LHC, at a $10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity, is energy-limited to $m_H = 1$ TeV, and this mass range can be accessed using the $qqH \to qqWW \to qq\ell\nu\ell\nu$ or $qqZZ \to qq\ell\ell\nu\bar{\nu}$ final states, provided jet tagging works. The SSC at $10^{33}$ cm$^{-2}$ s$^{-1}$ has a comparable mass reach.

The range $-130 < m_H < 2m_Z$, with $H \to ZZ^* \to 4\ell^\pm$, is hard but feasible; the range $-80 < m_H \lesssim 140$ GeV, with $H \to \gamma\gamma$, is harder still, and requires an excellent calorimeter, but the WH process complements it at $m_H \lesssim 100$ GeV; the $WH \to \ell\nu\gamma\gamma$ (and $ZH \to \ell\ell\gamma\gamma$) final state is largely limited by statistics. For $H \to \gamma\gamma$, the S/\sqrt{B}$ is better at the LHC for $10^{34}$ cm$^{-2}$ s$^{-1}$ than at the SSC with $10^{33}$ cm$^{-2}$ s$^{-1}$, but it places more demands on the detectors.

It is clear that for $m_H < 2m_Z$, an $e^+e^-$ collider with $\sqrt{s} = 350$ to 400 GeV and $L > 10^{32}$ cm$^{-2}$ s$^{-1}$ would have a much easier time, as the signal-to-background ratio is much more favourable than at a hadron collider [31].

5. NEUTRINO PHYSICS AT THE LHC

Of the 12 fundamental fermions implied by the neutrino count of three generations, the only as yet unobserved members are the $t$-quark and the $\tau$-neutrino $\nu_\tau$. The evidence for the $\nu_\tau$ comes from several sources: the $Z$ total width, giving for the number of neutrino species $N_V = 2.89 \pm 0.10$ [47]; the measurement of the axial coupling of the $\tau$, indicating that its weak isospin is indeed $1/2$ ($I_3 = -1/2$) requiring an $I_3 = +1/2$ partner [48]; the ratios of $W \to \tau v/\nu/\mu \nu$ final states measured by UA1 [11], etc. The evidence is certainly convincing, yet indirect. It would be satisfactory to have direct evidence for the $\nu_\tau$ as a distinct particle species, from its specific interactions with matter. What is needed is the observation of the $\nu_\tau \to \tau$ transition in a reaction $\nu_\tau N \to \tau + X$. This has not yet been achieved, owing to the smallness of $\nu_\tau$ fluxes produced at present machines and to the space resolution required for the detector to reveal the short-lifetime signature of the produced $\tau$ [48].

Neutrino-$\tau$ production at the LHC

Neutrino beams at the LHC (and the SSC) are produced via $p p \to c\bar{c}, b\bar{b}$ heavy flavour production followed by the prompt (semi)leptonic decays $c, b \to \mu \nu_{\mu}/e\nu_{e}/\tau \nu_{\tau} + X$. The main source of $\nu_\tau$ is the leptonic mode $D_s \to \tau \nu_\tau$ (expected $BR \sim 3\%$) with $\tau \to \nu_\tau + X$, and the semileptonic $b \to c \nu_\tau \tau$ decay ($BR \sim 6\%$). The $c\bar{c}, b\bar{b}$ production cross-sections are large at a multi-TeV $\sqrt{s}$ collider, and the LHC/SSC can provide the fluxes
of $\nu_\tau$ that are needed for its observation, as well as larger and comparable fluxes of prompt $\nu_e$, $\nu_\mu$.

Three distinct ways of producing prompt $\nu_\tau$ (and $\nu_e$, $\nu_\mu$) can be envisaged. The beam-dump mode requires an extracted proton beam on a dump, shielding, and a $\nu_\tau$ target-detector. In this fixed-target mode the $\nu$'s result from decays of D's and B's produced in p-nucleus interactions at $\sqrt{s} = 120$ GeV for an 8 TeV incident beam. This is also the case for the beam internal-gas-jet target mode of operation, with the advantage that no external beam is needed. However, as discussed later on, the equivalent luminosity that can be achieved is substantially lower. The third possibility, first suggested by De Rújula and Rückl [18], is to exploit the collider mode of the machine, taking advantage of the substantialy larger c $\bar{c}$, b $\bar{b}$ production rates and the forward collimation of produced D's and B's. The prompt-decay neutrinos ($\nu_e$, $\nu_\mu$, $\nu_\tau$) are emitted preferentially at 0°, i.e. tangentially to the beams. At $\sqrt{s} = 16$ TeV, the c $\bar{c}$ production cross-section is of the order of a few millibarns, which is a factor of ~20 higher than in a fixed-target mode, whilst b $\bar{b}$ production is a factor of ~200 higher (section 2). To be competitive, however, this scheme requires a high luminosity ($\sim 10^{33}$ to $10^{34}$ cm$^{-2}$ s$^{-1}$) interaction region. The main advantage is that the neutrino fluxes are for free, the experiments running in parallel with a high-luminosity, hard-collision search. The sharp forward collimation of the $\nu_\tau$ beam also means that the detector located at 0° to the beam line, if it can be brought close to the interaction point, can be of smaller transverse dimensions.

In order to estimate the $\nu_\tau$ flux produced, realistic estimates of the c $\bar{c}$, b $\bar{b}$ production cross-sections are needed, in both absolute magnitude and shape, i.e. in the $x_F = 2p_L/\sqrt{s}$ longitudinal momentum distribution of produced D's and B's. Perturbative QCD calculations are less reliable when applied to c $\bar{c}$ than to b $\bar{b}$ production, and uncertainties are necessarily large [16]. The multiparticle production quark – gluon string model of Kaidalov et al. [17] has been used to compute D and B cross-sections. At lower energies this model describes successfully the production of light and heavy flavours in hadron–hadron collisions. The model's predictions have been compared with PYTHIA-QCD predictions for c $\bar{c}$, and with perturbative QCD predictions for b $\bar{b}$ production as illustrated by Figs. 15a and 24. The model predicts $\sigma_D$ $\bar{b}$ ~ 1 mb per D$^+$, D$d$, and D$s$, with $\sigma_{D^+} = \sigma_{Dd} = \sigma_{Ds}$, and $\sigma_B$ $\bar{b}$ ~ 75 $\mu$b. The scaling-law approach of De Rújula - Rückl gives $\sigma_c$ $\bar{c}$ ~ 5 mb, and $\sigma_b$ $\bar{b}$ ~ 1/10 $\sigma_c$ $\bar{c}$ at $\sqrt{s} = 16$ TeV [18].

Figure 52a shows the expected energy-weighted $\nu_\tau$ flux $E_{\nu} dN/dE_{\nu}$, and Fig. 52b the $\nu_\tau$ laboratory production angular distribution, from $D_S \rightarrow \tau \nu_\tau$ decays, the main source of $\nu_\tau$ (De Rújula, Fernandez, Gomez). The secondary $\nu_\tau$ from the $\tau$ decay has a much harder spectrum, $<E_{\nu}> \sim 300$ GeV, than the primary one with $<E_{\nu}> \sim 60$ GeV, thanks to the large Lorentz boost of the parent $\tau$. The beam is forward-collimated within few milliradians. The contribution to the $\nu_\tau$ flux from $b \rightarrow \tau \nu_\tau + X$ is intermediate in hardness to the two components from $D_S$ in Fig. 52a, and at an ~10% level in magnitude at $E_{\nu} = 750$
GeV. The stability of these predictions has been studied, varying the magnitude of the $D_\tau$ cross-section and the $x\tau$ shape within reasonable limits. Both $<E_\nu>$ and $<\theta_\nu>$ are sensitive to the assumed $(1 - x\tau)^n$ power-law exponent $n$ parametrizing the model predictions (De Rújula - Rückl and Kaidalov et al.), and the present estimates are probably conservative. The fluxes of prompt $\nu_e, \nu_\mu$ are discussed by Camilleri and Winter in Vol. II.

What would the event rates be? Of the three methods that can be used to produce (τ) neutrinos at the LHC, the beam on a gas-jet target is the most limited one in terms of rate. With a gas density of $\sim 4 \times 10^{14}$ nucl. per cm$^3$ and a circulating beam of $5 \times 10^{14}$ protons, the equivalent luminosity is $\sim 2 \times 10^{33}$ cm$^{-2}$ s$^{-1}$ (Camilleri). The beam-dump mode with a slow ejection of $10^{10}$ protons per second, is equivalent to $L = 2 \times 10^{35}$ cm$^{-2}$ s$^{-1}$, whilst in the collider mode $L \approx 1$ to $4 \times 10^{34}$ cm$^{-2}$ s$^{-1}$. For a year of running $(10^7$ s) in a detector at $0^\circ$ subtending $\pm 2.5$ mrad with a mass of 2 kg/cm$^2$ (i.e. 2 g/cm$^3$ density, 10 m long) and $\sim 5$ t of total mass if located 100 m downstream from the interaction point, the number of expected $\nu_\tau$ interaction is the following: $\sim 25$ $\nu_\tau$ events for the gas-jet target mode, $\sim 2500$ $\nu_\tau$ events for the beam-dump mode, and $\sim 3800$ events for the beam-beam mode at $L = 10^{34}$ cm$^{-2}$ s$^{-1}$.

$\nu_\tau$ detection

How to detect the $\tau$ signature the $\nu_\tau$ interaction? The best signature to exploit is the short $\tau$ lifetime (and flight path) followed by a $\tau \rightarrow \nu_\tau \mu \nu_\mu$ muonic decay (BR = 18%), Fig. 53 [48]. The $\tau$ transverse impact parameter (or transverse decay length) $|\tau| = c\tau \sim 100 \mu$m is almost Lorentz-invariant and provides a measurement that is independent of the wide $\nu_\tau$ (or $\tau$) energy spectrum. The idea is to look for tracks with kinks or significant impact parameters. Whilst in a longitudinal view of the interaction the $\tau \rightarrow \mu$ kink angle is small, in the transverse view the $\tau \rightarrow \mu$ decay angle is isotropic, i.e. large, and $E_\nu$-independent. Detection of this $\tau \rightarrow \mu$ decay requires a detector with a space resolution of the order of $\sim 20$ $\mu$m. A time resolution of $\sim 1$ $\mu$s is also needed, as the expected muon flux is $\sim 10^5$ to $10^6$ $\mu$/s. The high granularity and the large number of output channels limits the vertex detector size, which must therefore be located as close as possible to the interaction point.

A possible detector discussed in more detail is a scintillating-fibre detector (CHARM II/Zeuthen group, and Ref. [48]) with fibres of a few tens of microns in diameter, and fibre bundles along the ν beam direction, as sketched in Fig. 54a. It would have the desired spatial and time resolutions. The $\nu_\tau \rightarrow \tau \rightarrow \mu$ event in the transverse plane would appear as sketched in Fig. 54b. The possible detector locations could be at $\approx 85$ m and/or $\approx 130$ m from the interaction point, as indicated in Fig. 55 (Camilleri, De Rújula). In the beam-beam mode, the vertex detector would be located between (and surrounding) the two beam pipes (18 cm apart), and in the beam-gas mode, tangentially to the outgoing proton beam in the region of the LHC beam-crossing dipoles. The transverse size would be $\sim 20 \times 20$ cm$^2$ (for details, see Winter in Vol. II).
Fig. 52  a) Energy-weighted $\nu_\tau$ flux, and b) $\nu_\tau$ lab. angular distribution, for $D_s \to \nu_\tau \tau \to \bar{\nu}_\tau \nu_\tau \nu_\mu \mu$ at $\sqrt{s} = 16$ TeV.

Fig. 53  Method for the detection of the $\nu_\tau$.  

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Fig. 54  a) Scintillating-fibre $v_\tau$ vertex detector, and b) simulation of a $\tau \to \mu$ decay in such a detector.

Fig. 55  Possible locations for $v_\tau$ detectors at the LHC.
Other detection possibilities are also investigated: with silicon strips, with fibres transverse to the beam (CHARM II/Zeuthen group, and Ref. [48]), or with a liquid-argon drift chamber (Dumarchez, Nedelec, Vannucci). In the latter case, the space resolution achieved up to now is \(\approx 60\, \mu\text{m}\) in the drift direction [49]; the problem is the poor resolution on the other coordinate and the two-track resolution. An advantage of this technique is, however, the possibility of having a large detection volume. More work is needed before a choice can be made.

The backgrounds to this \(\tau \to \mu\) topological signature have been studied. They come from charm \(\to \mu\) decays in \(v_e, v_\mu\) interactions, and are reducible to \(\leq 5\%\) of the expected signal (Winter). The background from \(\pi, K \to \mu\) decays or from elastic hadron scattering near the production vertex can be reduced, by a transverse momentum \(p_T > 0.2\, \text{GeV/c}\) cut, to such a level that the sum of all investigated backgrounds does not exceed \(~10\%\) of the signal in the \(\tau \to \mu\nu\nu\) mode. (For more details about background, halo backgrounds, shielding problems, etc., see Camilleri and Winter in Vol. II).

In conclusion, the \(v_\tau\) flux seems to be sufficient for \(v_\tau\) detection in both the beam-dump and beam—beam modes, but rather marginal in the beam—gas-jet mode. For a beam-dump type of experiment, however, a slow ejection with \(10^{10}\) protons per second would be necessary, whilst in the beam-beam (and beam-gas) mode the neutrino beam is free. Schemes for detecting the \(v_\tau \to \tau \to \mu\) chain exist, but more work is needed before a practical detector can be developed. The \(v_\tau N \to \tau + X\) reaction should be detectable, with no excessive backgrounds expected, provided the \(~20\, \mu\text{m}\) resolution can be achieved.

\(v_e, v_\mu\) interactions

The observation of the \(v_\tau\) may be among the first motivations for neutrino experiments at the LHC, especially if the \(v_\tau\) has not been observed by then, for example at UNK [48]. The high spatial resolution needed will of necessity require a costly specialized detector of limited size, located close to the interaction region. However, as already mentioned, the large \(c \bar{c}\) and \(b \bar{b}\) production cross-sections provide also larger and comparable fluxes of \(v_e, v_\mu\). A coarser and much larger (\(~2\, \text{m radius}\)) conventional detector for energetic \(v_e, v_\mu\) interactions, which require a large calorimeter, could be located \(~500\, \text{m}\) downstream from interaction point 1, in a hall for which an access shaft already exists. At this location the interaction-point 0°-degree line is \(~8.5\, \text{m}\) from the beam (Camilleri, De Rújula). Clearly the classical programme of neutrino physics could be pursued with energetic neutrinos, \(15\%\) of \(v_e, v_\mu\) having \(E_\nu > 500\, \text{GeV}\). In a 15 m long Fe detector subtending \(\pm 2.5\, \text{mrad}\), there would be \(\approx 15000\, v_e\) interactions, and as many \(v_\mu\) ones, at \(E_\nu > 500\, \text{GeV}\), for a collider luminosity of \(10^{34}\, \text{cm}^{-2}\, \text{s}^{-1}\). The potential of such a high energy neutrino programme, never pursued before with electron-neutrinos, has not yet been analysed in full detail. It would be more appealing with dedicated full-intensity external beams. These are, however, unlikely, since the LHC lattice is not optimized for slow extractions (Scandale).
6. CONCLUSIONS

$\sigma_{\text{tot}}$ and $\sigma_{e\ell}$: Important to measure; no particular difficulty foreseen; the present high $\beta^*$ insertion gives $L \sim 10^{31}$ cm$^{-2}$ s$^{-1}$ and allows a $t_{\text{min}}$ of $\sim 5 \times 10^{-3}$. The differential cross-section can be measured up to $t_{\ell}=\text{a few GeV}$. If the value of $\rho = 0.24$ is confirmed by UA4/2, then it would be important to have both the pp and p $\bar{p}$ options (a luminosity of $\sim 10^{28}$ cm$^{-2}$ s$^{-1}$ would be possible with the present high-$\beta^*$ insertion, and is adequate); the p $\bar{p}$ option will not exist at the SSC. If a measurement of $\rho$ is considered important, then access to the Coulomb region is needed, and a $\beta^*$ in the few km range is required; a $\beta^*$ of $\sim 2$ km may be possible but difficult; here, the SSC has an advantage with its longer straight sections.

Hard Collisions: Jets and direct photons in the TeV transverse energy range are accessible; QCD can be tested over 10 to 11 orders of magnitude with jets, and 8 to 9 orders of magnitude with direct photons. Sensitivity to compositeness scale in a year of running at $10^{33}$ cm$^{-2}$ s$^{-1}$ is $\Lambda_c = 13$ TeV with jets and $\approx 8$ TeV with photons.

$W$, $Z$ production: the pride and glory of yester-year will be a big nuisance at the LHC, generating backgrounds to t-quark and Higgs searches; large $p_T$ $W,Z$ production will none the less provide an interesting test of QCD.

$WZ$ and $W\gamma$ pairs production is an important issue at hadron colliders (LHC or SSC) and is much more sensitive, at the few percent level, to anomalous gauge couplings, i.e. possible deviations from Standard Model couplings, than at LEP 200 (at the $\sim 10\%$ level), because of access to vector-boson-pair masses in the TeV range.

B Physics: pp collisions (LHC and SSC) are perhaps the desired 'b-factories', in the collider and/or the fixed-target modes. If experimentally feasible (b-triggering and tagging in particular) – which is not yet proven but may at least be partly illuminated by on-going collider and fixed-target experiments – such experiments would provide a unique potential for testing the Standard Model scenario of CP violation. For a fixed target option, an extracted beam of $>10^8$ protons per second is needed, which may be easier at the SSC. In the collider mode the two machines are rather comparable.

Top Physics: The LHC/SSC are 'top factories', with $\sim 10^7$ $t\bar{t}$ events produced per year at $10^{33}$ cm$^{-2}$ s$^{-1}$, and a few times $10^4$ observable $t\bar{t}$ events per year in channels with large signal-to-background ratios, the two-hard-and-isolated-leptons mode, and the single-lepton mode with b-tagging. The single-lepton mode may also allow first observation at low luminosity, i.e. at machine start-up, if not observed by then. The mass reach of the LHC for a heavy quark is in general $\sim 1$ TeV. The precision obtainable on the Standard Model t-quark mass is $\delta m_t = 5$ GeV; t-quark decays are a potential source of $H^\pm$, detectable through a breakdown of $e-\mu-\tau$ universality.
Higgs Physics: The Higgs, 'l'objet de tous nos désirs', if $2m_Z < m_H \ll 0.8$ TeV, is relatively 'easy' to detect in the $H \rightarrow ZZ \rightarrow 4\ell^\pm$ modes (with $\sim 10^{34}$ cm$^{-2}$ s$^{-1}$). It is perhaps detectable up to $m_H = 1$ TeV with jet tagging in the $qqH \rightarrow qqWW(ZZ) \rightarrow qq\ell\ell'\ell'\ell'$ final states.

For $m_H^{\text{LEP} 200} = m_Z < m_H \ll 2m_Z$, it is harder. The mode $H \rightarrow ZZ^* \rightarrow 4\ell^\pm$ is appropriate for $\sim 130$ GeV $< m_H \ll 2m_Z$; it requires good acceptance for $p_T \ell \geq 10$ GeV leptons and $\sim 10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity.

For $\sim 80$ GeV $< m_H \ll 150$ GeV, the $H \rightarrow \gamma\gamma$ mode requires an excellent calorimeter and high luminosity ($\sim 10^{34}$ cm$^{-2}$ s$^{-1}$) — a difficult experiment, but one that seems feasible.

For $\sim 80$ GeV $< m_H \ll 130$ GeV, the $WH \rightarrow A\gamma\gamma$ production channel would make it possible to bridge the gap with LEP 200; again, it requires an excellent calorimeter and the maximum luminosity available; it is mainly limited by statistics. The LHC at $10^{34}$ cm$^{-2}$ s$^{-1}$ and the SSC at $10^{33}$ cm$^{-2}$ s$^{-1}$ are comparable in terms of the Higgs mass reach.

Neutrino Physics: The $\nu_\tau$ flux seems to be sufficient for $\nu_\tau$ detection in both the beam-dump and beam — beam modes, but rather marginal in the beam — gas-jet mode. The $\nu_\tau N \rightarrow \tau + X$ reaction should be detectable, with no excessive backgrounds expected, provided the $\sim 20$ $\mu$m resolution can be achieved. For a beam-dump type of experiment, a slow ejection with $10^{10}$ protons per second would be necessary, whilst in the beam-beam (and beam-gas) mode the neutrino beam is for free, experiments running in parallel with a high-luminosity hard-collision search. Conventional high-energy $\nu_e$ and $\nu_\mu$ physics is also a possibility.

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REFERENCES AND FOOTNOTES

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Beyond the Standard Model in pp Collisions

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1 Introduction

Experimental data, collected up to now, strongly support the Standard Model (SM) as being the correct description of physics at currently available energies. In particular, the analysis of about 700,000 Z at LEP has resulted in a very good agreement with the SM, which is at present tested to the 1% level. In spite of this impressive success, the SM leaves many fundamental questions unanswered. There is a general consensus that the SM is not the ultimate theory, and that new phenomena should manifest themselves in the energy region of the order of 1 TeV. The next generation of high-energy hadron colliders, the LHC at $\sqrt{s} = 16$ TeV and the SSC at $\sqrt{s} = 40$ TeV, will be the first machines to probe parton-parton collisions directly at energies of the order of 1 TeV. Such energies may be essential for an understanding of the outstanding problems of the SM: the electroweak symmetry breaking (the Higgs sector), the origin of the particle mass scales, and the origin of the number of matter species.

In the ECFA LHC Workshop, we have addressed the question of Physics Beyond the Standard Model in three working groups:

- Supersymmetry [1],

- New Heavy Gauge Bosons [2],

- Alternative Symmetry Breaking [3].

Supersymmetric theories [4] are of interest because they provide an elegant solution to the problem of stabilizing the mass of the Higgs boson, as a consequence of which, supersymmetric particles should be found with masses below about 1 TeV—thus directly accessible to future hadron colliders. In Section 2 we present possible signatures of supersymmetry within the Minimal Supersymmetric Standard Model (MSSM) with an exact multiplicatively conserved R-parity. The R-parity could be broken [5], and as a consequence new signatures are expected, which will be discussed as well.

Extending the gauge group [SU(3)$_C \times SU(2)_L \times U(1)_Y$] of the SM (with or without supersymmetry), results in predictions of new vector bosons and possible other new particles beyond the SM [6]. The search for new heavy gauge bosons will be discussed in Section 3.

One of the main physics goals of the LHC is the understanding of the nature of electroweak symmetry breaking [7]. The symmetry-breaking sector can be either a weakly interacting system with a Higgs particle below 1 TeV or a strongly interacting system with just the longitudinal components of the weak bosons W and Z. The strongly interacting
Figure 1: Ratio of signal to total cross-section at the LHC as a function of mass, together with examples of background cross-sections ratios.

symmetry-breaking sector has been studied in two different approaches \cite{8, 9} and possible signatures at future hadron colliders have been established; these will be discussed in Section 4.

Before discussing the possibility of detecting the above-mentioned 'predicted' new physics at the LHC, let us recall the challenge for the experiments to observe a signal above the enormous background from SM processes. Figure 1 shows examples of the ratio of signal cross-sections to the total cross-section at the LHC (100 mb) as a function of mass for gluino pair production, for $Z'$ decaying into electron pairs, and for longitudinal WZ scattering $W^+_L Z_L \rightarrow \ell^+ \nu \ell^- \ell^-$ (BESS\textsuperscript{1} Model) together with some of the most important background cross-section ratios. For example, to observe a new vector resonance $Z'$ of 1 TeV mass decaying into electron pairs, the ratio of signal to total cross-section is about $10^{-12}$, i.e. three orders of magnitude smaller compared with the discovery of the $Z \rightarrow e^+e^-$ at the CERN pp Collider where 1 out of $10^9$ interactions produced one $Z$ into electron pairs.

2 Supersymmetry

2.1 The Minimal Supersymmetric Standard Model (MSSM)

Supersymmetry production in hadron colliders has been discussed extensively in the literature \cite{4, 10, 11}. We will recall a few important features of the MSSM that are relevant to our discussion on sparticle detection at the LHC \cite{12}. The conservation of a new multiplicative quantum number, known as R-parity, has the following phenomenological consequences: i) sparticles, defined as R-odd states and denoted by a tilde, must be pair-produced, e.g. $pp \rightarrow \tilde{g}\tilde{g} + X$; ii) each sparticle can decay only into a lighter sparticle, e.g. $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$; iii) the lightest sparticle (LSP) must be stable.

\textsuperscript{1}BESS stands for Breaking Electroweak Symmetry Strongly.
At least two Higgs doublets are needed to give masses to all particles. The characteristics of the MSSM is the existence of five Higgs bosons with the following tree level mass relations: charged Higgs $H^\pm$: $m_{H^\pm} > m_W$; lightest neutral scalar $h^0$: $m_{h^0} < m_{Z^0}$; heavy neutral scalar $H^0$: $m_{H^0} > m_{Z^0}$; and a pseudoscalar $A^0$: $m_{A^0} > m_{h^0}$. However, new calculations of radiative corrections indicate that the lightest neutral Higgs ($h^0$) could be significantly heavier than $m_{Z^0}$, if the top-quark mass is much larger than the W mass [13].

Electroweak symmetry breaking induces mixing between gauginos and Higgsinos of the same charge. Thus the photino, the Z-inos, and the neutral Higgsinos (the weak eigensates) mix to produce (in order of increasing mass) the mass eigenstates $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\chi}_3^0$, and $\tilde{\chi}_4^0$ (neutralinos). Similarly, the W-inos and charged Higgsinos mix to give mass eigenstates $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^\pm$ (charginos). It is generally assumed that the lightest neutralino, $\tilde{\chi}_1^0$, is the LSP. It has very small interaction cross-section and escapes detection, thus resulting in a missing transverse energy ($E_T^{\text{miss}}$) event signature. For gluino pair production, for example, the amount of $E_T^{\text{miss}}$ expected depends on the assumed decay modes. For direct decay into the LSP (e.g. $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$) one expects large $E_T^{\text{miss}}$. Alternatively, heavy sparticles can decay into heavier charginos and neutralinos, which in turn decay into lighter charginos and neutralinos until the LSP is reached. In such cascade decays, where the LSP appears at the end of the decay chain, a softer $E_T^{\text{miss}}$ spectrum is expected. Cascade decays via charginos and neutralinos will produce final states that often contain W and Z bosons. In general, transitions from heavier to lighter neutralinos proceed via a Z and/or $h^0$, and transitions from or to charginos occur via W's. The decay chain can be rather complicated [14]. However, these cascade decays can also introduce interesting new signatures, which will be discussed later. A complete survey of all possible gluino and squark decay modes has been performed, including the loop decays $\tilde{g} \rightarrow g + \tilde{\chi}_i^0$ and taking into account the t-quark Yukawa coupling as well as all t-quark mass terms [15].

If one takes into account the unification constraints within the MSSM, in first approximation the masses of sparticles are related via five basic parameters: $m_{\tilde{g}}$, $m_{\tilde{q}}$, $\tan \beta \equiv v_2/v_1$, $\mu$, and $m_{\phi}$, where $\mu$ is the Higgsino mass parameter, $v_1$ and $v_2$ are the vacuum expectation values of the two Higgs doublets, and $m_{\phi}$ is (any) Higgs mass. Therefore, for example, fixing $m_{\tilde{g}}$ and assuming that $m_{\tilde{g}} < m_{\tilde{q}}$ and $m_{H^\pm} = 500$ GeV leaves two free parameters: $\mu$ and $\tan \beta$. Thus for a given $\mu$ and $\tan \beta$, we can calculate all gluino branching ratios and all masses of $\tilde{\chi}_2^\pm$ and $\tilde{\chi}_3^0$. For example, for $m_{\tilde{g}} = 1000$ GeV (300 GeV), $\mu = -440$ GeV and $\tan \beta = 10$ one obtains for the neutralino masses 168.2 (51.1), 323.3 (101.4), 446.8 (449.3) and 464.1 (449.4) GeV and for the chargino masses 323.5 (101.5) and 466.0 (454.4) GeV. For these parameters the direct decay into the LSP amounts to 5.1% (16.6%).

The choice for $\mu$ and $\tan \beta$ is guided by the present limits from LEP and from future expectations, summarized in Fig. 2 [16]. The present limit on $\tan \beta$ is $> 1.6$, if one uses tree-level formulae. This limit is, however, weakened if radiative corrections are included [13]. With a foreseen sensitivity expected for 500 pb$^{-1}$ of integrated luminosity at $\sqrt{s} = 200$ GeV and using all the decay modes of the reaction $e^+e^- \rightarrow (H^0 \text{or } h^0)Z$, LEPT can exclude the minimal supersymmetric model. However, it is important to note that this exclusion of the MSSM is possible only if $\sqrt{s} \geq 190$ GeV [13]. If the radiative corrections push the mass of $h^0$ above the $Z^0$ mass, then $\sqrt{s}$ has to be raised accordingly.

### 2.2 Sparticle production at the LHC

A systematic survey of supersymmetric particle production mechanisms in high-energy hadron–hadron collisions has been carried out by EHLQ [17], and matrix elements for most
Figure 2: Present limits from LEP, and future expectations in the \((\tan \beta, m_{A^0})\) plane. The expected cross-section sensitivity corresponds to an integrated luminosity of 500 pb\(^{-1}\) at \(\sqrt{s} = 200\) GeV.

processes of interest can be found in Ref. [18]. An example of \(\tilde{g}\tilde{g}\), \(\tilde{g}\tilde{q}\), and \(\tilde{q}\tilde{q}\) production at the LHC is shown in Fig. 3. Gluino (squark) cross-sections depend on both gluino and squark masses. The cross-sections of Fig. 3 were computed [19] assuming that \(m_{\tilde{g}} = 2m_{\tilde{q}}\), using EHLQ1 structure functions [20] and \(\delta\) for the \(Q^2\)-scale, leading to a conservative estimate of the cross-sections. For example, for a total integrated luminosity of \(10^4\) pb\(^{-1}\) (corresponding to one year of running at \(L = 10^{33}\) cm\(^{-2}\) s\(^{-1}\)), we expect about \(0.5 \times 10^4\) gluino pairs to be produced at the LHC for \(m_{\tilde{g}} = 1\) TeV. Strongly interacting sparticles such as gluinos and squarks are copiously produced and are therefore clearly a domain for hadron colliders.

2.3 Gluino signatures

Because of the large production cross-section, searches for gluino signals at future hadron colliders have received a lot of attention. Detailed studies have been performed for direct decays into the LSP, leading to the ‘classical’ \(E_T^{miss} + n\) jet signature. As mentioned above, this signature should still remain valid if cascade decays are included. Details of gluino signatures depend on the chosen parameters: \(m_{\tilde{g}}, \mu\), and \(\tan \beta\) (the squark is assumed to be heavier than the gluino). The branching ratios as a function of \(\mu\) for \(m_{\tilde{g}} = 1000\) GeV and \(\tan \beta = 10\) are plotted in Fig. 4 for two representative cases: i) direct decay into LSP: \(\tilde{g}\tilde{g} \rightarrow q\bar{q}'\chi_1^0\bar{q}'\chi_1^0\), and ii) cascade decays into ZZ: \(\tilde{g}\tilde{g} \rightarrow ZZ + X\), together with the \(\mu\) range covered by LEP 200 [15]. A large variation of the branching ratios as a function of \(\mu\) is observed.

To establish a gluino signal in the \(E_T^{miss} + n\) jet channel, two different gluino masses have been chosen: \(m_{\tilde{g}} = 300\) GeV and \(m_{\tilde{g}} = 1000\) GeV, using \(\tan \beta = 2\) and \(\tan \beta = 10\) at \(\mu = -440\) GeV. This choice allows the sensitivity to the \(\tan \beta\) parameter to be studied.
Figure 3: Gluino–gluino, gluino–squark, and squark–squark production cross-section as a function of $m_\tilde{g}$ for $m_\tilde{q} = 2 m_\tilde{g}$ at the LHC.

Figure 4: Branching ratios as a function of $\mu$ for $m_\tilde{g} = 1000$ GeV and $\tan \beta = 10$ for $\tilde{g}\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0 q\bar{q}\tilde{\chi}_1^0$ (solid line) and $\tilde{g}\tilde{g} \rightarrow ZZ + X$ (dashed line). The $\mu$ range covered by LEP 200 is also shown.
Taking for $\mu$ an asymptotic value rather than a $\mu$ value which is more optimistic in terms of event rates, reflects the conservative assumption for the second parameter. The $m_{\tilde{g}} = 300$ GeV value was chosen in order to study the capability of an LHC experiment to cover a mass spectrum down to gluino masses not yet excluded by previous experiments.

We have also studied a gluino signal in the $(ZZ \to 4$ lepton) channel for $m_{\tilde{g}} = 750$ GeV, $\tan \beta = 2$, and $\mu = -300$ GeV. Even though the branching ratio into $ZZ$ increases with increasing gluino mass [15], the resulting event rate into four leptons is small owing to the $Z \to \ell^+\ell^-$ branching ratio and the smaller cross-section at higher gluino masses. For example, as shown in Fig. 4, for $m_{\tilde{g}} = 1000$ GeV and $BR(\tilde{g} \tilde{g} \to ZZ + X) = 10\%$, one expects only about 25 events in the four-lepton channel for $10^8$ pb$^{-1}$.

2.3.1 Gluino: ($E_T^{miss} + n$ jet) channel

To study the ($E_T^{miss} + n$ jet) signature, cascade decays have been included in the simulation [21]. For $m_{\tilde{g}} = 300$ GeV, only decays into $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, and $\tilde{\chi}_1^+\tilde{\chi}_1^-$ are possible, owing to the low gluino mass. Neglecting loop decays for $\tan \beta = 10$ in the simulation [BR $(\tilde{g} \to g\tilde{\chi}_1^0) \approx 2\%$], we obtained for the two different $\tan \beta$ values: $\sigma$-BR = 640 pb ($\tan \beta = 2$) and $\sigma$-BR = 617.9 pb ($\tan \beta = 10$). For $m_{\tilde{g}} = 1000$ GeV, decays into all $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^\pm$ are possible. For $\tan \beta = 2$, we have included the largest branching ratios but have ignored loop decays, resulting in $\sigma$-BR = 0.235 pb. For $\tan \beta = 10$, loop decays become more important [e.g. $BR(\tilde{g} \to g\tilde{\chi}_1^0) = 32\%$], therefore they have been included in the simulation resulting in $\sigma$-BR = 0.424 pb. For more details, see Refs. [15, 21].

We have used ISAJET [22] on the particle level for signal and background evaluation, and the UA2 SUSY [23] Monte Carlo to study the effect of smearing and pile-up. Figures 5a,b show the resulting $E_T^{miss}$ distributions for $m_{\tilde{g}} = 300$ GeV and 1000 GeV, together with the total background contribution from $t\bar{t}$ ($m_t = 150$ GeV), $W \to \ell\nu$ ($\ell = e,\mu,\tau$), and $Z \to \nu\bar{\nu}$. As expected, the $E_T^{miss}$ distribution is softer because of the addition of cascade decays, compared with the same distribution obtained for direct decays into LSP in Ref. [24]. The gluino signal always remains below the background.
Figure 6: Distribution of a) $N_{\text{jet}}$ for $E_T^{\text{jet}} > 200$ GeV, b) circularity $C$, and c) $\Delta \phi_{12}$ for gluino pair production of 1000 GeV mass and $\tan \beta = 2$ (solid histogram) and $\tan \beta = 10$ (dashed histogram), compared with Standard Model background (points with errors bars) for $E_T^{\text{miss}} > 100$ GeV. The distribution are normalized to 1.

The background contributions can be reduced by exploiting the difference in topology of signal and background events. Jet finding was carried out on the particle level, using a jet algorithm similar to that used by UA1. The highest track with $E_T > 10$ GeV was used to initiate a new jet, and all tracks within $\Delta R < 0.4$ of its initiator track were associated with the jet, where $(\Delta R)^2 = (\Delta \eta)^2 + (\Delta \phi)^2$. Only tracks with $E_T > 1$ GeV were considered. To study the topology of signal and background events, the following quantities were defined: i) jet multiplicity $N_{\text{jet}}$; ii) circularity $C$, computed from the transverse projection of the calorimeter jets ($E_T > 10$ GeV) and the $E_T^{\text{miss}}$ vector, defined as $C = \frac{1}{2} \min (\sum E_T \cdot \hat{n})^2 / (\sum E_T^2)$; and iii) $\Delta \phi_{12}$, the azimuthal angle between the two highest transverse-energy jets. A comparison of $N_{\text{jet}}$, circularity, and $\Delta \phi_{12}$ distributions for gluino production of $m_{\tilde{g}} = 1000$ GeV with the total background is shown in Figs. 6a,b,c, for events with $E_T^{\text{miss}} > 100$ GeV. The expected differences in event topology for signal and background are clearly seen in each case. The $E_T^{\text{miss}}$ distributions for gluino pair production and for background are shown in Figs. 7a,b for one possible selection requiring $N_{\text{jet}} \geq 3 (E_T^{\text{jet}} = 200$ GeV), $\Delta \phi_{12} < 130^\circ$ and $C > 0.2$. This selection is aimed at finding isotropic multijet events—a signature expected from gluino decays. Because of the addition of cascade decays, the isotropic multijet topology is even more pronounced than in the case of the direct decay into the LSP.

The number of signal events that are expected for an integrated luminosity of $10^4$ pb$^{-1}$ with the above-mentioned cuts and $E_T^{\text{miss}} > 300$ GeV are: for $m_{\tilde{g}} = 300$ GeV: $414 \pm 299$ ($419 \pm 289$) events for $\tan \beta = 2$ (10); for $m_{\tilde{g}} = 1000$ GeV: $114 \pm 7$ ($190 \pm 12$) events for $\tan \beta = 2$ (10). The total background contribution is $31 \pm 12$ events, where the dominant contribution comes from $t\bar{t}$ (27 events). The quoted errors are the statistical errors arising from the Monte Carlo generation. The size of the error on the number of signal events after selection cuts, expected for $m_{\tilde{g}} = 300$ GeV, demonstrates that very few of the generated events survive the cuts. This analysis is therefore clearly sensitive to the tails of distributions for $E_T^{\text{miss}} > 300$ GeV because of the softer $E_T^{\text{miss}}$ spectrum, and a lower $E_T^{\text{miss}}$ cut would be desirable. We have also checked that the removal of isolated leptons with $p_T > 25$ GeV (isolation: $\Sigma p_T < 5$ GeV in $\Delta R < 0.2$) does not improve the signal-to-background ratio. This was expected, because isolated leptons from W and Z decays are present in the cascade decays of gluinos.

The proposed event selection should allow extrapolation to high-luminosity running,
Figure 7: Missing transverse energy distribution after selection cuts for a) $m_{\tilde{g}} = 300$ and b) $m_{\tilde{g}} = 1000$ GeV. The solid (dashed) histogram corresponds to $\tan \beta = 2$ (10). The points with error bars show the total background contribution.

thus extending the expected gluino mass reach of about 1 TeV, for the assumed $10^4$ pb$^{-1}$ and a somewhat conservative choice of parameters. In order to make sure that in this case the conclusions are not altered, we have studied the effect of calorimeter smearing and pile-up. As expected, calorimeter smearing has little effect on the distributions employed in this analysis. Figure 8 shows the effect of pile-up on the highest-$E_T$ jet in the event, simulated by superimposing $n$ minimum-bias events (generated using the PYTHIA [25] Monte Carlo program) on the signal, with <$n$> = 2 or <$n$> = 15 Poisson-distributed. The difference between 15 and 2 superimposed minimum-bias events, displayed in Fig. 8, results in <$\Delta p_T$> = 1.6 GeV, reflecting the fact that the jet definition used is not very sensitive to pile-up. We have also verified that the other distributions used in the selection are unaffected by pile-up.

So far, only physical backgrounds to the $E_{T}^{\text{miss}}$ signature have been considered. However, for an $E_{T}^{\text{miss}}$ requirement as low as $E_{T}^{\text{miss}} > 200$ or 300 GeV, it is necessary to get an estimate of $E_{T}^{\text{miss}}$ due to jet mismeasurements. This estimate has been made using the PAPAGENO [26] Monte Carlo at the parton level, which includes matrix elements for three, four, and five jets. A simulation at the particle level is not possible owing to the prohibitively large CPU-time required. To obtain a more realistic simulation [27], the parton jets have been 'dressed up' using a jet profile parametrization. ISAJET has been used to parametrize the $E_T$ flow of a jet as a function of $\Delta R$ and $E_T$. The resulting jets have been simulated in a calorimeter with pointing geometry (CDF geometry and granularity). The parts of the jet that fall into the calorimeter cells have been smeared, i.e. fluctuation of overall jet energy and fluctuation of jet direction via cell-to-cell fluctuations; the parts of the jet that fall into a crack were considered as lost. The resulting $E_{T}^{\text{miss}}$ distributions for three-jet events assuming three different jet resolutions are shown in Fig. 9. The effect of a fourth jet being lost in $|\eta| > 4.5$ results in a similar distribution. The $E_{T}^{\text{miss}}$ distribution thus obtained has a much steeper slope compared with those of the gluino signal and background displayed in Fig. 5 before selection cuts. Therefore, we can expect that, after selection cuts, the background from jet mismeasurement will be substantially reduced (as is the case for physics backgrounds), provided the calorimeter has a coverage of at least
Figure 8: Effect of pile-up on the highest transverse energy jet in the event, simulated by superimposing an average of 15 or 2 minimum-bias events.

Figure 9: Missing transverse energy distribution for three jet events after calorimeter smearing, as explained in the text.
Figure 10: Mass distribution of the four hardest electrons from $\tilde{g}\tilde{g} \rightarrow ZZ + X \rightarrow 4e + X$ for $m_\tilde{g} = 750$ GeV and from ZZ and $t\bar{t}$ background. A t-quark of 150 GeV was assumed.

$|\eta| = 4.5$. Cracks clearly play an important role; however, their effect can only be studied in detail given a specific design for a detector at the LHC.

2.3.2 Gluino: (ZZ $\rightarrow$ 4 lepton) channel

If a gluino signal is detected at the LHC, the possibility of detecting many different gluino decay modes allows this signal to be confirmed in possibly several different channels. It has already been pointed out that at larger gluino masses the $\tilde{g}\tilde{g} \rightarrow ZZ + X$ channel offers a very striking signature, but with a low rate. This signature was studied [21] for $m_\tilde{g} = 750$ GeV, and the dominant decay modes $\tilde{g} \rightarrow q\bar{q}\tilde{\chi}_2^0$, $g\tilde{\chi}_2^0$, and $g\tilde{\chi}_4^0$, with the subsequent decay of $\tilde{\chi}_2^0 (\tilde{\chi}_4^0) \rightarrow Z\tilde{\chi}_1^0 \rightarrow \ell^+\ell^-\tilde{\chi}_1^0$, have been included in the simulation. Thus using a total branching ratio into Z of 20.1%, for $10^6$ pb$^{-1}$, results in a signal of 63 events with a signature of four leptons from the two Z's, two or more hard jets, and $E_T^{miss}$. The main background is expected from ZZ and $t\bar{t}$ production. Because of the low rate, $L \geq 10^{34}$ cm$^{-2}$ s$^{-1}$ is clearly desirable. For this reason, the four-electron channel was studied, including the effect of calorimeter smearing and pile-up. The electron resolution used was $\Delta E/E = 10\%/\sqrt{E} \oplus 1\%$, and the electron energy was deposited in one cell of a calorimeter of granularity $\Delta\eta \times \Delta\phi = 0.05 \times 0.05$. In contrast to the SM Higgs $\rightarrow \ell^+\ell^-\ell^+\ell^-$ signature, no mass peak is expected for the gluino signature, as shown in Fig. 10, where the mass of the four hardest leptons in the event is plotted for signal and background. No sign requirement has been imposed for electrons. The $E_T^{miss}$ distribution, after demanding $m_{4e} > 250$ GeV, two Z (each pair of leptons defines a Z, if $81 < m_{ee} < 101$ GeV), and two hard jets ($> 200$ GeV and $> 100$ GeV, respectively), is shown in Fig. 11. A clear difference between signal and background is observed. The number of four-electron events expected for $10^6$ pb$^{-1}$ after these selection cuts is: 7.5 events for the signal and 2 (7.2) from ZZ ($t\bar{t}$) background, using a t-quark mass of 150 GeV. There is a very large statistical
Figure 11: Missing transverse energy distribution after selection cuts from $\bar{g}g \rightarrow ZZ + X \rightarrow 4e + X$ for $m_{\tilde{g}} = 750$ GeV, and from ZZ and $t\bar{t}$ background.

uncertainty attached to the background numbers for ZZ and $t\bar{t}$ owing to the cut-efficiency for the background, of $10^{-3}$ and $10^{-4}$, respectively. The effect of pile-up of 15 minimum-bias events results in a small decrease in the number of events after cuts, which is due to the isolation requirement imposed for electron identification in the calorimeter simulation. Adding the $\mu$ channel will increase the statistics by about a factor of 4. Therefore, for a gluino mass of 750 GeV, one expects a signal of about 30 events with negligible background, which should, if necessary, allow a signal to be confirmed in the ($E_T^{miss} + n$ jet) channel.

Another possibility to search for a gluino signal makes use of the distinctive feature of gluinos being Majorana fermions, thus decaying with equal probability into fermions and antifermions. The $g\bar{g}$ production will result in like-sign dileptons in the final state [11]. We have not investigated this signature in detail, but clearly it should be included in a more complete survey of interesting gluino signatures.

2.4 Squark signatures

For any given quark flavour in the MSSM, there are two spin-0 superpartners ($\tilde{q}_L$, $\tilde{q}_R$) corresponding to the two chiralities of the associated fermions. Left–right mixing can be neglected for the first five squark flavours, which are expected to be degenerate in mass. The special case of a stop-quark will be discussed later. Since the couplings of $\tilde{q}_L$ and, $\tilde{q}_R$ are different, one expects different signatures for the two cases. This difference has been studied [21] for one particular example: $m_{\tilde{q}} = 1000$ GeV, $\tan \beta = 10$, and $\mu = -440$ GeV; we further assumed that $m_{\tilde{g}} = 1500$ GeV and $m_{\tilde{q}_L} = m_{\tilde{q}_R}$.

2.4.1 $\tilde{q}_R$ decays
Figure 12: Missing transverse energy distribution after selection cuts for $\tilde{u}_L$ and $\tilde{d}_L$ pair production of 1000 GeV mass (histogram). The points with error bars show the total background contribution.

For the parameters mentioned, the right squark decays into $\tilde{X}_1^0$, with $\text{BR}(\tilde{q}_R \to q\tilde{X}_1^0) \approx 99\%$, except for $\tilde{t}_R$, if the t-quark mass and t-quark Yukawa coupling are fully taken into account [15]. For the first five squark flavours, we can therefore use the result from the analysis performed for the La Thuile Workshop [24], for $m_{\tilde{q}} = 1000$ GeV, where 100% branching ratio into the LSP was assumed, to obtain the number of events expected after analysis cuts. The La Thuile results have been re-scaled to account for the change in the production cross-section and for the fact that we only consider $\tilde{q}_R$. A signal-to-background ratio of order $8/1$ is still obtained for the proposed selection cuts [$E_T^{\text{miss}} > 800$ GeV, $N_{\text{jet}} \geq 3$ ($E_T^{\text{jet}} > 250$ GeV), and $C > 0.25$] for $10^4$ pb$^{-1}$. Scaling the results of the high-luminosity studies, 214 events from $\tilde{q}_R$ decays over a total background of 25 events are expected for $5 \times 10^5$ pb$^{-1}$ [24].

2.4.2 $\tilde{q}_L$ decays

For the assumed parameters the dominant decay modes for $\tilde{u}_L$ and $\tilde{d}_L$ are into $\tilde{X}_1^\pm$: $\tilde{u}_L \to d\tilde{X}_1^\pm$ (45%) and $\tilde{d}_L \to u\tilde{X}_1^\pm$ (37%), with the subsequent decay $\tilde{X}_1^\pm \to W\tilde{X}_1^0$ ($m_{\tilde{X}_1^\pm} = 385.6$ GeV, $m_{\tilde{X}_1^0} = 209.8$ GeV). Again, $\tilde{b}_L$ and $\tilde{t}_L$ are different owing to the t-quark Yukawa coupling and the t-quark mass terms [15]. The $\tilde{u}_L$ and $\tilde{d}_L$ decays have been simulated using ISAJET for the above-quoted branching ratios, resulting in a total of $1.1 \times 10^3$ events in $10^4$ pb$^{-1}$ for a squark mass of 1 TeV. Figure 12 shows the $E_T^{\text{miss}}$ distribution, after possible selection cuts, for $m_{\tilde{q}_L} = 1000$ GeV [$N_{\text{jet}} \geq 3$ ($E_T^{\text{jet}} > 250$ GeV), $E_T^{\text{jet}} > 400$ GeV, and $C > 0.25$]. For $E_T^{\text{miss}} > 300$ GeV and an integrated luminosity of $10^5$ pb$^{-1}$, a signal of $348 \pm 198$ events and a total background of $185 \pm 41$ events (t$\bar{t}$ being again the dominant contribution) are expected. To obtain a mass-reach estimate for squarks ($\tilde{q}_L, \tilde{q}_R$), one can combine, as in the gluino case, all possible decay modes, which will allow us to set a discovery limit for squarks of about 1 TeV for $10^4$ pb$^{-1}$, i.e. one year of running at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$. The effect of pile-up and calorimeter resolution and rapidity coverage, as investigated for the gluino case, applies to the squark case as well [21].

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2.4.3 The possibility of a light stop

Squark signatures discussed in the previous sections were derived assuming five degenerate squark flavours. The scalar partner of the top quark is an exception, because the stop mass matrix contains a potentially large off-diagonal term, proportional to the top quark mass. It is therefore not excluded that the stop could be lighter than the top quark and $m_t \ll m_\tilde{t}$.

Among the variety of possible stop scenarios the following cases have been studied [28]:

a) $m_\tilde{t} = 110$ GeV and $m_\tilde{t} = 200, 110,$ or 50 GeV. For the first two cases, where $m_\tilde{t} \geq m_\tilde{t}$, stop can be produced only via stop pair production and $\sigma(t\tilde{t}) \approx 1/10 \sigma(t\tilde{t})$. In the third case, where the stop can also be produced in the t-quark decay ($t \rightarrow \tilde{t}_1^0$), large event rates are expected. The t-decay modes are different for all three $\tilde{t}$ masses assumed, thus leading to different event signatures. For the signal evaluation, the following t-decays have been used: $t \rightarrow t\tilde{t}_1^0$, $t \rightarrow \tilde{t}_1^0b$, and $t \rightarrow c\tilde{t}_1^0$, for $m_\tilde{t} = 200, 110,$ and 50 GeV, respectively.

b) $m_\tilde{t} = 190$ GeV and $m_\tilde{t} = 110$ GeV: in this case the stop can also be produced in the t-quark decay, and the expected signature is similar to that of the SM t-decay, except that one expects more $E_T^{miss}$ from the $t \rightarrow \tilde{t}_1^0 \rightarrow \tilde{t}_1^0b\tilde{t}_1^0$ decay chain.

Signal and SM backgrounds have been evaluated using the ISAJET Monte Carlo program. Selection criteria are based on at least one isolated lepton with $p_T > 50$ GeV and angular correlations between the lepton and $E_T^{miss}$. Details of the event selection cuts can be found in Ref. [28]. A stop signal can be detected for the case where the stop is lighter than the stop, allowing a $t \rightarrow \tilde{t}_1^0$ decay with BR $\geq 10\%$. In this case an increase of a factor of about 8 of the event rate for $E_T^{miss} > 300$ GeV is expected for $m_\tilde{t} = 50$ GeV, which decreases to a factor of about 2 for $m_\tilde{t} = 110$ GeV, assuming a top mass of 110 GeV (190 GeV) respectively. The 'standard top' selection criteria used in Ref. [29] are not adequate to establish the existence of a light stop.

2.5 Chargino and neutralino production

Production cross-sections for electroweak sparticles such as $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^0$ are small in relation to those for squarks and gluinos of the same mass. As already mentioned, charginos and neutralinos can decay via (real or virtual) W's and Z's, resulting in multilepton final states. One promising detection possibility for charginos and neutralinos involves three leptons in the final state [30]. The contour lines in Fig. 13 represent the cross-section in picobarns for $pp \rightarrow \tilde{\chi}_2 \rightarrow \ell\ell\ell + X$ for $p_T^\ell > 15$ GeV, $p_T^\ell > 10$ GeV, and $|\eta_\ell| < 3$, $|\eta_\mu| < 2.5$, and one more lepton with $p_T > 10$ GeV in $|\eta| < 3$. Also shown in the $M_{\tilde{\chi}_2-\mu}$ plane of Fig. 13 is the exclusion region from LEP 200 if no chargino with $m_{\tilde{\chi}_2} < 80$ GeV is found. The main background contributions are expected from WZ and $t\bar{t}$ production. The estimate of the background was done on the partonic level for the $t\bar{t}$ case, resulting in a background cross-section of 0.25 to 0.67 pb for $m_\tilde{t} = 150$ GeV and of 0.01 to 0.041 pb for $m_\tilde{t} = 200$ GeV, by cutting on the presence of a jet with $p_T$ less than 30 GeV (50 GeV), respectively. For more details see Ref. [30]. The WZ background is believed to be negligible provided one removes events with $m_{WZ} = m_Z$. It is difficult to establish a clear signal in the three-lepton channel, because the background is strongly t-mass dependent. A Monte Carlo simulation on the particle level is needed to confirm a three-lepton signal if $m_\tilde{t} \leq 150$ GeV.
Figure 13: Cross-section contours in picobarns for $p p \rightarrow \tilde{\chi} \tilde{\chi} \rightarrow lll + X$ after imposing lepton $p_T$ cuts (see text). Also shown is the exclusion region from LEP 200; $M_2 = 500$ GeV corresponds to a gluino mass of about 1500 GeV.

2.6 Slepton pair production

Sleptons are expected to be the lightest charged sparticles in the MSSM. Already a relatively low bound on their mass translates into a rather stringent bound on the supersymmetric particle spectrum [31]. The dominant production mechanism for slepton pair production is via Drell–Yan, as shown in Fig. 14. Taking into account the small production cross-section for $\tilde{e}_L \tilde{e}_L \rightarrow e e \tilde{\chi}_1^0 \tilde{\chi}_1^0$ and the large background from $WW \rightarrow e e e e$ (also shown in Fig. 14), and an additional background contribution from $t\bar{t}$ production does not leave us much hope of detecting a clear signal above background.

A more promising case for observing a signal could be $pp \rightarrow \tilde{\ell} \bar{\nu} \rightarrow \ell\ell \tilde{\chi}_1^+ \tilde{\chi}_1^- \nu \tilde{\chi}_1^0$. Again, the background from SM is very large, and very likely it will not permit the observation of a signal. Clearly, for both the chargino–neutralino and the slepton pair production, the knowledge of the $t$-quark mass would be very helpful for establishing a criterion with which to detect electroweak sparticles at the LHC.

2.7 Broken R-parity

In the MSSM, a matter parity (equivalent to R-parity) is introduced to forbid $\Delta B \neq 0$ and $\Delta L \neq 0$ terms and to avoid fast proton decay. However, it is sufficient for proton stability to forbid either $\Delta B \neq 0$ or $\Delta L \neq 0$ terms, so that new models (with broken $R$-parity) may be constructed with the same minimal particle content as the MSSM. One of the motivations for broken R-parity [5,32] comes from the hypothesis that squarks and leptons may transform differently under discrete symmetries as a possible consequence of ‘string’ compactification. If one allows R-parity to be broken, 45 additional terms coupling quarks and leptons are possible and $\Delta B \neq 0$ or $\Delta L \neq 0$ is allowed. To study the effect of these additional terms [32], we make the following (plausible) simplifying assumptions: i) one term dominates, and ii) the LSP is neutral and a $(\tilde{\gamma}, \tilde{Z}, \tilde{H})$ mixture.

The experimental consequences of broken R-parity are: i) single-sparticle production
Figure 14: Slepton pair production cross-section as a function of slepton mass at the LHC. Also shown is the SM background from $WW \rightarrow eee'\nu$.

and ii) decay of the LSP. The latter can occur in many different ways, e.g. LSP $\rightarrow \bar{d}d\nu$ or $e^+\mu^-\nu$ or three quarks, which again opens up a variety of different signatures, some of which look a priori very difficult to detect (e.g. $g \rightarrow q\bar{q}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow 3$ quarks), some that have a chance of being detected above background, and some that provide a rather spectacular signature (e.g. $g \rightarrow q\bar{q}\tilde{\chi}_1^0$, $\tilde{\chi}_1^0 \rightarrow e^+\mu^-\nu$). It should be noted that even in the case where the LSP decay does not offer a detectable event signature, cascade decays via $W$ and $Z$ may still provide a detection feasibility.

In the case of single-sparticle production the decay of the LSP is constrained by the particular mechanism chosen. Examples of single-sparticle production are: a) $q\bar{q} \rightarrow \nu\tilde{\chi}_1^0$ via squark exchange; for $m_{\tilde{q}} = 300$ GeV, the cross-section for this process is very small, making a detection unlikely; b) s-channel $\tilde{\nu}$ production: $\bar{d}d \rightarrow \tilde{\nu}$, with cross-section $O(\text{nb})$. For more details, see Ref. [32].

Conventional gluino pair production has been used to study one particular LSP decay signature, admittedly a very striking one. Taking $m_{\tilde{g}} = 300$ GeV and the same parameters and branching ratios as discussed in subsection 2.3 for the gluino decay modes, i.e. for $\tan\beta = 2$ and $\mu = -440$ GeV, BR($g \rightarrow q\bar{q}\tilde{\chi}_1^0$) = 17%, and allowing the LSP ($m_{\tilde{\chi}_1^0} = 53.2$ GeV) to decay with BR($\tilde{\chi}_1^0 \rightarrow e^+\mu^-\nu$) = 30%, leads to $1.6 \times 10^4$ events in one year of running at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$ with an event signature of 2$e^+$, 2$\mu^-$, $\geq 4$ hard jets, and softer $E_T^{\text{miss}}$. The main background is expected to come from $t\bar{t} \rightarrow e^+\mu^-e^+\mu^-+X$. The signal and background has been evaluated with ISAJET, using a t-quark mass of 200 GeV. In the signal case, one expects a correlation between the $e^+$ and $\mu^-$ coming from the LSP decay. This correlation is shown in Fig. 15a, where the difference in azimuthal angle between the highest transverse momentum $\mu^-$ and the nearest electron is plotted for the signal and for the $t\bar{t}$ background (no sign requirement was imposed for the electron). The angular distribution was plotted after requiring two electrons ($p_T > 20$ GeV), two $\mu^-$ ($p_T > 10$ GeV), and $N_{\text{jet}} \geq 3$ ($E_T^{\text{jet}} > 100$ GeV). A similar distribution is obtained for the second $\mu^-$ and the other electron in the event as shown in Fig. 15b. For $\Delta\phi(\mu^-_1-e) < 80^\circ$, a signal of $884 \pm 11$ events over a background of $23 \pm 11$ events was obtained for $10^4$ pb$^{-1}$. No further requirement is necessary to establish a clear signal [32].
Figure 15: Difference in azimuthal angle between a) the highest transverse momentum $\mu^-$ and the electron nearest to the $\mu^-$ after selection cuts and b) the second $\mu^-$ and the other electron. The histograms are for the signal from $gg \rightarrow q\bar{q}X_1^0q\bar{q}X_1^0, X_1^0 \rightarrow \mu^- e^+ \nu$, assuming $m_{X_1} = 300$ GeV; the points with error bars are for $t\bar{t}$ production, assuming $m_t = 200$ GeV.

3 New Heavy Gauge Bosons

New heavy Abelian gauge bosons occur in a number of different attempts to extend the gauge group of the SM, because extra U(1) symmetries arise when larger groups are broken down to SU(3) \times SU(2) \times U(1) [33]. In superstring theories based on Calabi-Yau compactifications, the low-energy group is a subgroup of $E_6$ [34]. Being of rank 6, an extra U(1) gauge boson may be left light after breaking. In superstring-inspired $E_6$ models the Higgs sector is constrained and the breaking of $E_6$ is specified. The angle $\theta_2$, which gives the direction of intermediate breaking, is fixed ($\theta_2 = 0$ or $\pm \arcsin \sqrt{\frac{5}{8}}$), whereas in $E_6$ grand unified theories this angle appears as a free parameter.

Among the possible $E_6$ subgroups obtained at low energy, left–right (LR) models [35] are motivated by the attempt to understand the origin of parity violation and small neutrino masses. These LR models predict also a new charged boson $W^\pm_R$, which mixes with the ordinary $W$s. In order to avoid a possible problem in the mixing sector, alternative left–right models (ALRM) [36] were introduced with the help of $E_6$ superstring-inspired theories. The production mechanism for these ALRM vector bosons involves quark–gluon scattering instead of the Drell–Yan mechanism.

A less model-dependent possibility of extending the gauge group of the SM is by retaining SM-like $Z'$ couplings as in the reference model (RM) and in the extended gauge model (EGM) [37]. These models differ only by the couplings of the $Z'$ to ordinary vector bosons. In both models the couplings to fermions are as in the SM. In the EGM, the $Z'$ coupling to ordinary $W$ and $Z$ are suppressed by a factor $\approx m_Z^2/m_{Z'}^2$. This leads to a linear increase of the total $Z'$ width with mass. For the RM, the $Z'$ width increases with $m_{Z'}^2$, resulting in a total width of about 10 TeV for a 1 TeV $Z'$, which is unrealistic and not detectable.

In the above models, owing to the existence of elementary Higgses, the problem of the Higgs mass—receiving quadratically divergent loop corrections—can be solved by intro-
ducing a supersymmetric scenario. An alternative approach is offered by the BESS [9] model, with the possibility of breaking electroweak symmetry strongly in a non-linear way. In this scheme no Higgs is present, and the only physical states belonging to the symmetry-breaking sector below the TeV scale are the longitudinal components of the vector bosons. Within this model, a triplet of new vector resonances, $V^±$ and $V^{0}$, are predicted, which are similar to the $\rho$ of QCD, or to the techni-$\rho$ of technicolour theories. The parameters of the model are the mass of the $V$ triplet $m_{V}$, the new gauge coupling constant $g''$, and the parameter $b$ that describes the possibility of having a direct coupling of $V$ to fermions. Even for $b = 0$ there will be always a coupling of $V$ to fermions via mixing with $(W, Z, \gamma)$, the mixing angles being of order of $g/g''$.

The possibility that vector bosons are composite objects has been studied as well. Within the framework of an effective Lagrangian that satisfies local U(1)$_{\text{em}}$ invariance and is invariant under global SU(2) weak isospin symmetry, two kinds of isoscalar vector bosons have been considered [38]: those that couple to the weak hypercharge current ($Y$), and those that couple to left-handed currents only ($Y_L$). The parameters of these models are the mass of the isoscalar and the mixing parameter $\lambda^2_Y$. For the first excited isotriplet ($W^*, Z^*$) there is only one parameter $m_{W^*}$. The masses of $W^*$ and $Z^*$ are degenerate, and the coupling to gauge boson pairs is dominant, thus limiting the discovery potential in the lepton channel [39].

We will summarize the potential discovery limits for new heavy vector bosons at the LHC, and will address the question of whether it is possible to distinguish between different models. The search for a signal in $Z' \rightarrow W^+W^- + X$ is expected to be impeded by the large background from $t\bar{t}$ production; therefore only the decay of $Z'$ in lepton pairs is considered. The difficulty in observing a signal in the jet–jet mass spectrum is discussed in Ref. [40].

Before data-taking will start at the LHC, either mixing of the $Z'$ with $Z'$ at LEP 1 will have been discovered, or a limit on a possible mixing of $< 1\%$ will have been set. With LEP 200, there will be a sensitivity to masses of new neutral vector bosons, and from precision measurements it will be possible to exclude certain models. For more details about present limits and future expectations from LEP, see Ref. [41].

3.1 Z' discovery in the lepton channel

The total width of the $Z'$ as a function of the $Z'$ mass is shown in Fig. 16 for the models discussed above [33], except for the reference model (where for $m_{Z'} = 1$ TeV, $\Gamma_{Z'} = 10$ TeV) and the excited $Z'$ (where for $m_{Z'} = 1$ TeV, $\Gamma_{Z'} = 260$ GeV). For $Y_L$ and $Y$, only two points are shown as examples owing to the strong dependence of the width on the parameter $\lambda^2_Y$. For the BESS model a direct coupling of $b = -0.02$ was assumed. The branching ratios of $Z' \rightarrow e^+e^-$ for $m_{Z'} = 1$ TeV are displayed in Fig. 17. As can be seen, most of the models have a branching ratio into electron pairs between $\sim 1\%$ and $10\%$, except for the reference model and the BESS model for which the branching ratios are less than $10^{-3}$ if there is no direct coupling to fermions (i.e., if $b = 0$), thus limiting the discovery potential for $V^0$ in the lepton channel.

All the above-mentioned models have been simulated using the PYTHIA Monte Carlo [25] program, version 5.4, where the $Z'$ couplings to fermions have been modified accordingly. The background contributions to new vector bosons have also been evaluated with PYTHIA.

In order to establish a discovery limit, a simple detector simulation was performed, assuming a rapidity coverage up to $|y_{\text{max}}| = 2$ and an electron resolution of $\Delta E/E =$
Figure 16: $\Gamma_{\text{tot}}(Z')$ as a function of $Z'$ mass for different models discussed in the text.

Figure 17: Branching ratios of $Z' \rightarrow e^+ e^-$ for a $Z'$ mass of 1 TeV.
Figure 18: Invariant $e^+e^-$ mass spectra after calorimeter smearing for a $Z'$ signal from the extended gauge model. Also shown are background contributions from Drell–Yan, $t\bar{t}$, and $b\bar{b}$.

$15\%/\sqrt{E}\oplus2\%$ [42]. Figure 18 shows the invariant $e^+e^-$ mass spectra for a $Z'$ signal from the extended gauge model, together with background contributions from Drell–Yan, $t\bar{t}$, and $b\bar{b}$. These distributions were obtained by including all electron pairs in a range of $\pm2\Gamma_{\text{tot}}(Z')$ around the $Z'$ mass peak. For this analysis, the two highest-$p_T$ electrons (with a conservative $p_T$ cut of 15 GeV) have been taken irrespective of their charge. No significant difference has been found between the mass spectra thus obtained and those taking the charge of the electron into account. For an integrated luminosity of $10^5$ pb$^{-1}$ and requiring at least 20 $Z' \rightarrow e^+e^-$ events, the following discovery limits [42] are obtained: EGM: 4 TeV; $E_\theta (\sin \theta = 0)$: 3.4 TeV; $E_\theta (\sin \theta = -\sqrt{\frac{5}{8}})$: 3.3 TeV; LRM: 3.7 TeV; ALRM: 4.2 TeV.

For the BESS model the discovery limit [43] is strongly dependent on the assumed direct coupling to fermions, as can be seen in Fig. 19. For $b = 0$, the production rate above 1 TeV is too small to observe a signal above SM background. The situation is, however, quite different if there is a small direct coupling to fermions. To evaluate the discovery limit, a detector simulation has been performed using a calorimeter coverage of $\pm3$ in rapidity and a segmentation of $\Delta \eta \times \Delta \phi = 0.06 \times 2\pi/100$. The energy of each particle entering the calorimeter is smeared according to $\Delta E/E = 15\%/\sqrt{E}\oplus2\%$ for electrons and photons, and $\Delta E/E = 50\%/\sqrt{E}\oplus4\%$ for hadrons. Figure 20a indicates that the discovery limit will reach 1.5 TeV only if $b = -0.02$. For a 1 TeV mass, no clear signal is visible after calorimeter simulation if $b = -0.01$ (see Fig. 20b). The electron-finding efficiency in this analysis was about 60%, as inferred from comparing the shaded area with the full one in Fig. 20. A value of $b = -0.02$ for $g'' = 13$ is allowed by present LEP and CDF/UA2 data, and also by future precision measurements at LEP, assuming that within the experimental errors no deviation from the SM is observed. The production and decay of $V^\pm$ in the WZ channel will be discussed in connection with alternative symmetry-breaking mechanisms.
Figure 19: $d\sigma/dm$ as a function of $(e^+e^-)$ mass for $m_{\nu\nu} = 0.5$, 1.0, and 1.5 TeV (BESS model), assuming $g'' = 13$ and $b = 0 (-0.02)$ shown by the dashed (solid) lines.

Figure 20: Invariant mass distribution of lepton pairs obtained with the BESS model for a) $m_{\nu\nu} = 1$ TeV, $b = -0.02$, and b) $m_{\nu\nu} = 1$ TeV, $b = -0.01$. The histogram is without detectors simulation, whereas the shaded area corresponds to the mass distributions obtained after detectors simulation.
(see Section 4). The discovery of $V^\pm$ in the leptonic channel looks hopeless because of the small branching ratio into a lepton + neutrino.

Two examples of $e^+e^-$ mass distributions for isoscalar vector bosons are shown in Fig. 21 [44]. The discovery limit for $Y_L$ ranges between 4.1 and 4.5 TeV, depending on $\lambda_Y^2$. In the case of the $Y$ vector bosons the discovery limit is strongly $\lambda_Y^2$-dependent. For example, for $0.1 < \lambda_Y^2 < 0.4$, the limit ranges between 4.2 and 4.7 TeV; for $\lambda_Y^2 = 0.68$ (the maximal value allowed) the limit is 3.2 TeV; and if $\lambda_Y^2 = 0.03$, it will be very difficult to find a resonance for $m_Y = 2$ TeV with $\Gamma_Y = 800$ GeV. Finally, for the excited $Z^*$ of 1 TeV mass with a branching ratio into electron pairs of 1% and a width of 260 GeV (for $m_{Z^*} = 1.3$ TeV, $\Gamma_{Z^*} = 750$ GeV), the discovery limit will not exceed 1 TeV, as can be seen in Fig. 22 [44].

### 3.2 Forward–backward asymmetry $A_{FB}$

The rapidity dependence of the forward–backward asymmetry (where $F$, $B$ of the leptons is defined with respect to the $Z'$ direction) is expected to show a characteristic distribution for the different models. Provided there is enough statistics at larger rapidities, distinction between the models, or at least classes of models, should therefore be possible. Figure 23 shows the theoretical asymmetry values together with the expected experimental errors for one year of running ($10^5$ pb$^{-1}$) for a $Z'$ mass of 1 TeV [45]. The $A_{FB}$ distribution for the excited $Z^*$ is very similar to the one obtained from the BESS model, plotted in Fig. 23. In some cases such as $B_3$ (a special $E_6$ model), one expects a clear difference in the $A_{FB}$ distribution compared with LR or BESS. However, making a distinction among $E_6$ models seems more difficult. In order to establish a certain model within $E_6$ it seems necessary to accumulate more than $10^5$ pb$^{-1}$ of integrated luminosity. The experimental requirements for $A_{FB}$ are evident: the sign of the leptons is necessary, and leptons should
Figure 22: Invariant mass distribution of lepton pairs for excited $Z^*$ of 1 TeV mass with (shaded area) and without (histogram) detector simulation.

Figure 23: Forward–backward asymmetries as a function of rapidity for different models. Theoretical predictions are shown together with the expected statistical errors for an integrated luminosity of $10^8 \text{pb}^{-1}$. 
be measured at least up to $|\eta| = 2.5$.

3.3 Discovery of $W'$ in the $W' \rightarrow e\nu$ and $W' \rightarrow WZ \rightarrow e\nu\nu$ channels

The $W'$ discovery potential has been studied within the framework of the extended gauge model [46]. Again, the PYTHIA Monte Carlo program was used for simulation of signal and backgrounds. In Fig. 24a, $\sigma \cdot \text{BR}(W' \rightarrow e\nu)$ is plotted as a function of $m_{W'}$. For $m_{W'} = 3$ TeV, one expects about 2000 events in the $e\nu$ channel for $10^5$ pb$^{-1}$. Figure 24b shows the corresponding $\sigma \cdot \text{BR}(W' \rightarrow WZ \rightarrow e\nu\nu)$ as a function of $m_{W'}$. For this channel the discovery potential is clearly limited by the low rate. The transverse mass is plotted in Fig. 25 for different $W'$ masses with a clearly visible Jacobian peak, expected from $W' \rightarrow e\nu$ decay, together with the background coming from $W \rightarrow e\nu$ and $t\bar{t}$ ($m_t = 120$ GeV). The $m_T$ distribution was obtained using the highest-$p_T$ electron in the event and assuming an electron resolution of $\Delta E/E = 15\%/\sqrt{E_T} \oplus 2\%$ and an $E_T^{\text{miss}}$ resolution of $\Delta E_T^{\text{miss}}/E_T^{\text{miss}} = 70\%/\sqrt{E_T}$. A cut on $p_T^e$ and $E_T^{\text{miss}}$ of 180 GeV improves the signal-to-background ratio at low $W'$ masses. However, at higher $W'$ masses a clear signal above background is visible without applying additional selection requirements. The discovery limit for the $W' \rightarrow e\nu$ channel is 4 to 5 TeV for an integrated luminosity of $10^5$ pb$^{-1}$.

The decay chain $W' \rightarrow WZ \rightarrow e\nu\nu$ has been investigated as well [46]. As mentioned earlier, because of the low rate the discovery limit will not exceed 1 TeV. The background from $WZ$ and $t\bar{t}$ can be kept small, provided that one requires $p_T^Z > 400$ GeV, $m_{\nu\nu} = m_Z \pm 3\sigma$, and all three leptons to be isolated. The latter cut is especially efficient in removing the $t\bar{t}$ background; this will be discussed in more detail in the next section.

For minimal left–right models, the discovery limit [47] depends on the mixing angle $\zeta$. For $\zeta = 10^{-3}$, the channel $W_R^\pm \rightarrow W\pm Z \rightarrow \ell^\pm \nu \ell'^\pm \ell'^- \ell^-$, which is well suited to obtaining discovery limits if $W_R^\pm \rightarrow \ell^\pm \nu_\tau$ is forbidden, allows us to reach a mass limit in the most favourable case of 2.8 TeV before detector simulation for $10^5$ pb$^{-1}$. The background
Figure 25: Transverse mass distributions for a $W' \rightarrow e\nu$ signal of different $W'$ masses from the extended gauge model, and for $W \rightarrow e\nu$ and $t\bar{t}$ background after detector smearing.

contribution from $WZ$, investigated on the parton level, is small. The $t\bar{t}$ background is expected to be small also (see discussion in Section 4), and will not prevent a possible discovery of $W_R^\pm \rightarrow W^\pm Z \rightarrow \ell^\pm \nu \ell^+ \ell^-.$

4 Alternative Symmetry Breaking

Gauge boson pair production in the presence of a strongly interacting electroweak symmetry-breaking sector has been studied [48] using two different approaches: the BESS model and the DHT model (DHT stands for Dobado, Herrero and Terron).

4.1 The BESS model

In the BESS model [9] the electroweak symmetry breaking is described in a non-linear way, and the most relevant elements of a possible strong electroweak breaking are expected to be contained. In this scheme no Higgs particle is present. A triplet of new vector resonances $V^\pm$ and $V^0$ are assumed, which are similar to the $\rho$ of QCD or to the techni-$\rho$ of technicolour theories. It is explicitly assumed that the bosons $V$ constitute effective dynamical degrees of freedom. Because of diagonalization of the boson mass matrix, the $V$ particles are expected to mix with $W$, $Z$, and $\gamma$, with a mixing angle of order $g/g''$ ($g''$ being a new gauge-coupling constant introduced in this model). In addition, a possible direct coupling to fermions can be present, specified by the parameter $b$. The detection of $V$ into lepton pairs has already been discussed (see Section 3). In this section the decay of $V$ into pairs of ordinary gauge bosons will be studied. The $ZZ$ mode has not been considered because it does not proceed via an $s$-channel contribution.
Figure 26: Invariant mass distribution of WZ pairs produced per year ($10^5$ pb$^{-1}$) for $m_V = 1500$ GeV, $g' = 13$, and $b = 0$, after selection cuts, for the BESS-model. The lower, intermediate and higher histograms refer to the background, background plus fusion signal and background plus fusion plus $qar{q}$ annihilation signal, respectively.

The $V$ bosons are produced through $qar{q}$ annihilation and IVB fusion. The process $qar{q} \rightarrow V$ depends on the assumed direct coupling of $V$ to fermions, but is still present even in the absence of this direct coupling. The decay of $V$ is dominated by $V \rightarrow WW$ or $WZ$ owing to the large couplings for $(V^0 W^+_L W^-_L)$ and $(V^\pm W^\pm_L Z_L)$. The fusion process, where ordinary bosons are emitted from a quark or antiquark, is expected to be weak in the SM of electroweak interactions. In the BESS model this rescattering of two longitudinally polarized $W/Z$'s proceeds through the exchange of a $V$ boson.

The two production mechanisms have been evaluated for the process $pp \rightarrow W^\pm Z + X$. The observation of a signal in the $W^+W^-$ channel is expected to be impeded by the large background coming from $t\bar{t}$ production. Figure 26 shows an example of the expected signal [9, 49] in the invariant mass distribution for WZ pairs, assuming that $m_V = 1500$ GeV, $g' = 13$, $b = 0$, and requiring $|\eta_{W,Z}| < 2.5$ and $p_T^Z > 480$ GeV. For the choice of the model parameters, present limits and future limitations from LEP data have been taken into account. Also shown in Fig. 26 are the SM background contributions from WZ production through $q\bar{q}$ annihilation and $\gamma W^\pm$ fusion. For $m_V = 1500$ GeV after optimized cuts ($|\eta_{W,Z}| < 2.5$, $p_T^Z > 480$ GeV, $m_{WZ} > 1250$ GeV) one expects a signal of about 36 events over a total background of about 16 events in the $W^+_L Z_L \rightarrow \ell^\pm \nu \ell^-\ell^-$ channel for $10^5$ pb$^{-1}$ of integrated luminosity. At the LHC, the $q\bar{q}$ annihilation contribution to the signal dominates for the mass range considered, and amounts to about 80% for the example shown in Fig. 26 [9, 49].

4.2 The DHT model

In the DHT model [8], the dynamics that governs the symmetry-breaking sector is studied through the scattering of the longitudinal components of the weak bosons based on chiral perturbation theory. This approach incorporates everything that is known about the symmetry-breaking sector. Three possible scenarios have been considered: i) a unita-
Figure 27: WZ invariant mass distribution of the signal and background processes after cuts for the DHT model with $m_\rho = 1.5$ TeV, $N_{TC} = 5$, and $\Gamma_\rho = 185$ GeV. The number of events correspond to $5 \times 10^6$ pb$^{-1}$. The lower solid (dotted) histogram represents the signal from WZ fusion (q$q$ annihilation); the total background is the dashed histogram. The upper solid histogram represents the signal plus the total background contributions.

rized SM with a heavy Higgs to one-loop (Higgs-like scenario, $m_{H^1} \gg s$); ii) a QCD-like scenario, where the longitudinal components of the weak bosons play the role of the pions in QCD; and iii) an underlying theory within the framework of technicolour [50]. The different scenarios can be simulated by choosing the parameters of the effective Lagrangian accordingly.

The most effective way to probe the Higgs-like dynamics is through the $pp \rightarrow ZZ$ channel; however, signal-to-background ratios never exceed 1 in this case. As discussed above, the WZ channel is the best mode for searching for a signal of a strongly interacting symmetry-breaking sector in the case of a QCD-like or technicolour scenario. The WZ channel has been evaluated in the DHT model under the assumption that the underlying dynamics contains a vector resonance (QCD-like or technicolour scenario). The physical parameters that define this vector resonance (e.g. mass and width) are dependent on the SU(N) dynamics chosen. A systematic study of the above-mentioned scenarios has been performed, considering the WZ fusion mechanism. However, in SU($N_{TC}$) scenarios it is important to incorporate also the process $pp \rightarrow W^\pm \rightarrow \rho_{TC} \rightarrow W_L^\pm Z_L$. This annihilation process via $\rho_{TC}$–W mixing is described in terms of Vector Meson Dominance. The expected signal in the WZ invariant mass distribution for the technicolour scenario is shown in Fig. 27 for $m_\rho = 1500$ GeV and $|y_{W,Z}| < 2.5$. The background processes, also shown in Fig. 27 include WZ production via q$q$ annihilation (65%), $\gamma W^\pm$ (15%), and $W^\pm Z$ (20%), this last background being predominantly $W_T^\pm Z_T$. For an integrated luminosity of $10^5$ pb$^{-1}$, one expects for $m_\rho = 1500$ GeV a signal in $W_L^\pm Z_L \rightarrow \ell^\pm \nu \ell^\mp$ of about 49 events over a background of about 11 events, requiring $|y_{W,Z}| < 2.5$, $p_T^Z > 300$ GeV, and $1400 < m_{WZ} < 1550$ GeV. The WZ fusion contributes about 24% to the signal for the example shown in Fig. 27 and the optimal cuts mentioned above. An increase in $m_\rho$ results in a larger contribution from WZ fusion. Thus for large enough values of $m_\rho$ this process will be the best mechanism for probing the strongly interacting symmetry-breaking sector in a technicolour scenario [50].
4.3 Monte Carlo simulation of signal and background for $p\bar{p} \rightarrow W_L^\pm Z_L \rightarrow \ell^+\nu\ell^+\ell^-$

We have discussed possible signals of $W_L Z_L$ pair production in the presence of a strongly interacting electroweak symmetry-breaking sector. In both approaches, the signal and backgrounds have been evaluated with a Monte Carlo simulation on the parton level. However, the potentially large background from $t\bar{t}$ production has not been evaluated for the two models discussed above.

In order to understand the experimental requirements for observing a possible signal in the $W_L Z_L$ channel, a Monte Carlo simulation on the particle level has been performed [51]. The signal has been evaluated using the PYTHIA program, where the $q\bar{q}$ annihilation (using BESS) and the WZ fusion process (using DHT) have been included. The WZ and $t\bar{t}$ backgrounds were simulated with ISAJET. A $t$-quark mass of 200 GeV was assumed. For the parameters of the models, the choice was such that for the same mass one obtains the same width for the BESS model and for the DHT model: $m_V = m_\tau = 1$ TeV, $\Gamma_V = 55$ GeV (corresponding to $N_{TC} = 12$, and $g'' = 5.9$) and $m_W = m_\tau = 2$ TeV, $\Gamma_V = 480$ GeV (corresponding to $N_{TC} = 3$, and $g'' = 11.7$). For the BESS model, no direct coupling to fermions has been assumed, i.e. $b = 0$, which leads to a more conservative rate estimate. Only the leptonic decays of W and Z have been considered. The dilepton mass spectrum for the signal and the background from WZ and $t\bar{t}$ is shown in Fig. 28, requiring that $p_T^\ell > 20$ GeV, $|\eta| < 3$, and a lepton resolution of $\Delta p/p = 5\%$. For an integrated luminosity of $4 \times 10^5$ pb$^{-1}$, we can expect about 277 events for the signal, assuming that $m_V = 2$ TeV, 4829 events for $m_V = 1$ TeV, $3.1 \times 10^4$ events from WZ, and $2.9 \times 10^6$ events from $t\bar{t}$ background. A clear mass peak at the Z mass is observed for the signals and for the WZ background in Fig. 28, where all mass combinations are plotted without imposing a sign requirement.

In order to reduce the background, the differences in the topology of signal and background events have been exploited. The signal is expected to have a much harder $p_T^\ell$ distribution compared with the background processes, as can be seen in Figs. 29a,b for $m_V = 1$ TeV and 2 TeV, respectively. These distributions were obtained by imposing a constraint on the lepton-pair mass, $m_{\ell\ell} = m_\tau \pm 3\sigma$, using a lepton resolution of $\Delta p/p = 5\%$ and requiring that $p_T^\ell > 20$ GeV for $|\eta| < 3$. For a 1 TeV mass, a clear signal is observed at high $p_T^\ell$, coming mostly from the $q\bar{q}$ annihilation process. For a 2 TeV mass, no clear signal is visible, and in this case the fusion process amounts to about half the signal. The main background contribution comes from $t\bar{t}$ production. Imposing a more stringent cut on the lepton-pair mass by requiring better lepton resolution, improves the signal-to-background ratio only slightly. A gain of a factor of about 4 in background reduction is expected if $\Delta p/p = 2\%$ is used instead of $\Delta p/p = 10\%$. However, the $t\bar{t}$ background can be further reduced by requiring $p_T^\tau > 400$ GeV and imposing an isolation cut on all three leptons. The signal is expected to have three isolated leptons, whereas in the $t\bar{t}$ case the third lepton has to come from $b$- or $c$-quark decay and is therefore not expected to be isolated. The efficiency of reducing the $t\bar{t}$ background via isolation requirements increases with increasing $p_T^\ell$ cuts. However, an isolation cut of $\Sigma p_T < 5$ GeV in $\Delta R < 0.2$ around the lepton does not leave enough Monte Carlo statistics to obtain a reliable estimate for the $t\bar{t}$ background contribution—a well-known problem when dealing with cut efficiencies $\ll 1\%$. Therefore a conservative $t\bar{t}$ background reduction of a factor of 50 was used after requiring $p_T^\tau > 400$ GeV. This reduction factor has been extrapolated from a study done in the Top Working Group [52].
Figure 28: Dilepton mass spectra for $p_T > 20$ GeV and $|\eta| < 3$. From top to bottom, the histograms show the backgrounds from $t\bar{t}$ and $WZ$, and the signals from the decay chain $pp \rightarrow V/\rho_T \rightarrow W_LZ_L \rightarrow \ell\nu\ell\ell$, for masses of 1 TeV and 2 TeV.

Figure 29: The $p_T (Z)$ distribution for a signal from $pp \rightarrow V/\rho_T \rightarrow \ell\nu\ell\ell$ for a) $m = 1$ TeV and b) $m = 2$ TeV. The solid histogram represents the total signal, the dashed histogram shows the contribution for $WZ$ fusion only. The stars show the total background from $t\bar{t}$ and $WZ$ production.
Figure 30: The same distribution as in Fig. 29, but after the final selection cuts have been applied.

The result, after imposing a cut of $p_T^Z > 400$ GeV and applying the reduction factor from lepton isolation for the $t\bar{t}$ background, is shown in Figs. 30a,b. For $4 \times 10^5$ pb$^{-1}$, one expects a signal of $2450 \pm 637$ ($107 \pm 27$) events for $m_W = 1$ TeV ($2$ TeV). The quoted errors are the statistical errors arising from the Monte Carlo generation. For the signal of 1 TeV mass, the fusion process contributes about 6%; for the signal of 2 TeV, 56% are contributed via the fusion mechanism after selection cuts. The total background amounts to $74 \pm 30$ events (64 events from WZ and 10 events from $t\bar{t}$). For $m_V = 2$ TeV, an improvement in signal-to-background ratio is obtained by applying a harder $p_T^Z$ cut. For $p_T^Z > 600$ GeV a signal of $67 \pm 17$ events is expected over a total background of $15 \pm 3$ events. Thus the background can be reduced sufficiently to observe a signal from vector resonances with masses up to 2 TeV, provided the integrated luminosity exceeds $10^5$ pb$^{-1}$ [51]. It should be noted that the stringent cuts on $p_T^Z$ are imposed to obtain the final signal-to-background ratios. However the full $p_T^Z$ range has to be measured experimentally, in order to see a clear Jacobian peak or an excess at high $p_T^Z$ over the SM background.

At the LHC, we can explore a possible strong electroweak symmetry-breaking sector if the underlying dynamics contains a vector resonance as predicted in the technicolour scenario or in the BESS model. A clear signal can be expected in the Jacobian peak of the $p_T^Z$ distribution for $m_V = m_e = 1$ TeV. To reach a 2 TeV mass scale for these new resonances, a luminosity $L > 10^{24}$ cm$^{-2}$ s$^{-1}$ is required, in order to observe the expected enhancement at high transverse momentum of the $p_T^Z$ spectrum.

5 Conclusions

Within the framework of the Minimal Supersymmetric Standard Model, gluino and squark signatures—clearly a domain for hadron colliders—have been studied including the complex decay chains via charginos and neutralinos. For the ($E_T^{miss}$ + n jet) signature, the SM background can be sufficiently reduced by using cuts on $E_T^{miss}$, on jet multiplicity, and on event topology. Given the uncertainties involved for signal and background, it is difficult to quote exact 'discovery limits'. With the selection cuts applied for the ($E_T^{miss}$ + n jet)
signature, acceptable event rates for gluino and squarks are obtained for masses up to about 1 TeV for one year of running at $L = 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$. In the gluino case, the study was extended down to $m_{\tilde{g}} = 300$ GeV, resulting in a signal-to-background ratio of 13:1. To establish a signal for low gluino masses, contributions from jet mismeasurements to the $E_T^{\text{miss}}$ signature have to be taken into account owing to the softer $E_T^{\text{miss}}$ spectra for the signal. Preliminary studies indicate that this additional background can be kept small, provided there is a calorimeter rapidity coverage of $|\eta| \geq 4.5$. Pile-up seems to have only a small effect on the selection efficiencies; therefore, extrapolation to high-luminosity running is feasible. Cascade decays offer the possibility of many different signatures. In the case of gluino pair production, the $ZZ \rightarrow \ell\ell\ell\ell$ final state has been studied for large gluino masses. Small event rates are expected, but with negligible background.

Searches for electroweak sparticles are more difficult at hadron colliders owing to the low cross-section and large background from SM, in particular from t-quark production. However, the effort to find ways of extracting signals for electroweak sparticles should continue, because relatively low bounds on their masses translate into rather stringent bounds on the supersymmetric particle spectra. It should be also mentioned that, in the time available, it was not possible to fully optimize the event selections, and further improvements in signal-to-background ratios for sparticle searches are certainly possible in all cases.

Broken R-parity could be a possible extension of the MSSM. New signatures are expected in this case, arising from the possibility of single-sparticle production and from decays of the LSP. A variety of new signals emerge: some seem to be \textit{a priori} very difficult to extract (e.g. LSP $\rightarrow$ 3 quarks); some have a fair detection possibility; some provide a rather spectacular signature (e.g. LSP $\rightarrow$ $e^+\mu^-\nu$), which makes it possible to establish a clear signal above background. This was demonstrated for the example of $\tilde{g}\tilde{g} \rightarrow q\bar{q}X^0_1 \rightarrow q\bar{q}q\ell^+\ell^-\nu$ or $q\bar{q}q\ell^+\ell^-\nu$, assuming a gluino mass of 300 GeV. These initial results are promising, and more detailed signal and background evaluations would be desirable.

The observation of new heavy vector bosons ($Z', W'$) will be the necessary input for establishing higher symmetries. The discovery potential for new vector resonances decaying into lepton pairs is very high at hadron colliders. The discovery limit depends on the assumed model parameters. Many different models have been studied, ranging from 'simple' extensions of the gauge group of the SM to the concept of a strongly interacting electroweak symmetry-breaking sector. For an integrated luminosity of $10^5 \text{ pb}^{-1}$ and requiring at least 20 $Z' \rightarrow e^+e^-$ events, one obtains a discovery limit of 4 TeV for the extended gauge model and 4.2 TeV for the alternative left-right model. These are examples of the 'maximal' mass reach for a $Z'$ expected in the electron channel. Similar limits are obtained for the $W' \rightarrow e\nu$ decay using the extended gauge model. The $W_R$ mass reach is, in the most favourable case, about 2.8 TeV, obtained in the $W_R^\pm \rightarrow W^\pm \nu \rightarrow \ell^\pm \nu$ channel and assuming that $W_R^{\pm} \rightarrow \ell^\pm \nu_R$ is forbidden.

The physics background to the new vector bosons is expected to be small for the lepton channel, even with the very conservative selection cuts used in establishing a signal. The rapidity dependence of the forward–backward asymmetry should allow us to distinguish between models, or at least classes of models, predicting a heavy neutral vector boson. For the $A_{FB}$ measurement, the sign of the leptons is necessary, and leptons should be detectable up to $|y| = 2.5$. To reduce the statistical errors for $A_{FB}$ at large $y$-values, high luminosity is desirable.

One of the main physics goals of the LHC is the understanding of the nature of electroweak symmetry breaking. The symmetry sector typically should be either a weakly
interacting system with a Higgs particle below 1 TeV or a strongly interacting system with mostly the longitudinal components of the weak bosons W and Z. Gauge boson pair production in the presence of a strongly interacting electroweak symmetry-breaking sector has been studied using two different approaches. In the BESS model, a triplet of new vector resonances is used, similar to the ρ of QCD or the techni-ρ. No Higgs particle is present in this scenario. The second approach is based on chiral perturbation theory. Scenarios with scalar resonances (Higgs-like) or vector resonances (QCD-like, or technicolour-like) can be simulated by choosing the parameters of the effective Lagrangian accordingly. A signal above background can be established in the \( W^+_L Z_L \rightarrow \ell^+ \nu \ell^- \ell^- \) channel for masses up to 2 TeV if the underlying dynamics contains a vector resonance and if \( L > 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \). Lepton isolation requirements are necessary in order to reduce the \( t \bar{t} \) background sufficiently in the case of a 2 TeV vector resonance.

With the high-luminosity option at the LHC we can therefore explore the symmetry-breaking sector: if it is a scalar resonance (Higgs particle of the SM) up to \( \leq 1 \) TeV; if it is a strongly interacting system with a vector resonance (as predicted in technicolour scenarios or in the BESS model) up to 2 TeV. Therefore, an analysis of the \( ZZ \) and \( WZ \) channel at the LHC should help us to understand the nature of the symmetry-breaking sector.

*Although the most exciting discoveries will be those of totally unexpected new particles, we can only prepare experiments for discovering anticipated new particles. However the experiments designed under these considerations should allow us to discover whatever nature will offer us.*

**Acknowledgements**

This paper is based on the work of the three pp physics working groups 'Beyond the Standard Model', and I would like to express my thanks to all members of these groups for their contributions. I am grateful to all conveners for numerous discussions and for providing a very enjoyable and stimulating working atmosphere. My special thanks go to T. Sjöstrand and R. Kleiss (conveners of the Event Generator Group); without their help, some of the signals presented would still await a realistic Monte Carlo simulation. The help of P. Chiappetta, F. Feruglio, S. Hellman, M. Herrero, M. Lindner, G. Polesello, G. Ross, F. Zwerger and D. Treille in the careful reading of this manuscript is also much appreciated.

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Proton–proton physics at the LHC: an overview

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1 Introduction

The present work is devoted to a concise overview of the results obtained by the Proton–Proton Working Group, organized by D. Denegri, F. Pauss, and myself. The workshop activities started in February 1990, so that only a relatively short time was available for much work to be done in order to update and further advance the studies started with the Lausanne Workshop [1] in 1984, continued at the La Thuile Workshop [2] in 1986, and extended to the high-luminosity option [3] in 1987. More than 200 people participated in the eight groups on pp physics that were created. These groups are listed below in Table 1, with their conveners. Table 1 List of the pp physics groups and conveners

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As indicated, the Standard Model and the New Physics subgroups were coordinated by D. Denegri and F. Pauss. The Standard Model Cross-Sections and the Event Generators

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Groups are in a sense in common, for their ubiquitous relevance for background evaluation and for event simulation.

The Standard Model Cross-Sections Group studied a collection of QCD and electroweak processes: single \( W^\pm \) and \( Z \) production (total cross-sections, rapidity and transverse-momentum distributions), double production (WW, WZ, ZZ, W\( \gamma \), etc.), heavy-quark production (total cross-sections and one-particle inclusive distributions), QCD jets, single hard-\( \gamma \) and double \( \gamma \gamma \) cross-sections. Tables of cross-sections at the LHC have been produced. Extensive comparisons of results from different structure functions sets were performed. These results are collected in Vol. II in the written versions of the reports by P. Nason, H. Plothow-Besch, M. Werlen and others. Two subgroups of the Standard Model Group finally emerged as units in their own right. The first, led by K. Winter, was devoted to neutrino physics at the LHC. They discussed the possible applications of c- and b-generated prompt neutrinos in the collider mode, as originally proposed by De Rújula and Rückl [4], and of the neutrinos produced by an extracted proton beam. The main physics item that was analysed is the possible direct observation of the \( \tau \)-neutrino, through its interactions with matter in \( \nu, N \rightarrow \tau N' \). The second, led by A. Martin and G. Matthiae, was the group on total and elastic cross-sections. Their results were reported by E. Leader and by G. Matthiae. The measurements of \( \sigma_{\text{tot}} \) and \( d\sigma/dt \) at the LHC are both feasible and important. The LHC point can discriminate between a \( \ln s \) versus \( \ln^2 s \) behaviour of \( \sigma_{\text{tot}} \), which are both at present compatible with the data. The structures measured in \( d\sigma/dt \) are crucial for distinguishing different models of diffraction. The total pp cross-section is a very simple observable, which at present is still not quantitatively understood by theory. The measurement of \( \rho = \text{Re} A/\text{Im} A \) would be very interesting also, but it is almost prohibitively hard and expensive at the LHC.

The Event Generators Group made a catalogue of the existing event generators and software. Comparisons among the programs in selected key areas were performed (structure functions, minimum-bias physics, b production properties, multijet production, etc.). Several bugs and shortcomings were evidenced. The analytic and numeric results gathered from other working groups (Higgs branching ratios, SUSY simulations, jet characteristics) were implemented in existing event generators. Most important, this group provided an unvaluable support to other working groups. For example, the process \( gg \rightarrow Zbb \), which is an important background for Higgs searches, was calculated [5] and many new processes were implemented in the event generators. The activities of the Event Generators Group were summarized by T. Sjöstrand.

In the following I will first discuss the physics motivations for the LHC and the SSC and then review the discovery potential of the LHC as it emerged from the Workshop. A more detailed and systematic description of the results from the pp Working Group can be found in the accompanying articles by Denegri [6] and Pauss [7] and in the summaries from the individual working groups, collected in Vol. II of these proceedings.

## 2 Why the LHC after LEP?

### A clear physics motivation for the LHC

The experimental verification of the Standard Model, which is made up of QCD [8] and the electroweak theory [9], is still to be completed in that the top quark and the Higgs boson [10] have not yet been found. Both are important. The large mass of the t quark as compared with the other known quarks might indicate that its couplings are
Figure 1: Combined limits (from Ref. [17]) on $m_H$ and $m_t$ from vacuum stability and avoiding the Landau pole up to a scale $\Lambda$.

Perhaps different from the Standard Model prediction (e.g. by mixing with some heavier exotic state [11]). Also the knowledge of the $t$ mass is essential to sharpen the Standard Model predictions, thus allowing more stringent precision tests of the theory at LEP and elsewhere. However, there is no doubt that the most essential problem facing experimental particle physics in the next decade is the question of the physical origin of the electroweak symmetry breaking.

If the Standard Model is a reliable guidance, the top quark should be found in the next few years at the Tevatron of Fermilab. In fact, assuming the Standard Model, from precision tests of the electroweak theory the limit [12] $m_t \leq 200$ GeV is derived and, actually, values around $m_t \approx 130-140$ GeV are favoured. The search for the Higgs is being pursued at LEP 1 and will continue at LEP 200. Indeed all previous limits on the Higgs mass $m_H$ have been dwarfed by only a few months of LEP operation. For the standard Higgs we now know [13] that $m_H > 44$ GeV while for the lightest Higgs of the minimal supersymmetric extension of the Standard Model we have $(m_H)_{SUSY} > 33$ GeV.

As is well known, the value of the Higgs mass is not predictable even in the minimal Standard Model with a single Higgs doublet. What is certainly true is that the Higgs boson cannot be too heavy or the perturbative theory becomes sick and breaks down [14]. If $m_H \geq O(1$ TeV) the perturbative rates for $VV \to VV$ scattering ($V \equiv W, Z$) violate the unitarity limit [15] for $\sqrt{s} \gg m_W$. More important than this, in non-asymptotically free gauge theories there are Landau poles where the coupling constant blows up according to the renormalization group improved perturbation theory (unless the renormalized coupling is vanishing so that the theory is a free theory, i.e. trivial). This phenomenon is also present in QED but it would only occur beyond the Planck scale of mass, so that the problem can be solved at such large energies by embedding the theory in a larger context (e.g. grand unification). The coupling of the quartic term $\lambda (\phi^+ \phi)^2$ in the Higgs potential increases with $m_H^2$ ($m_H^2 \sim \lambda / G_F$). In addition, for a given $m_H$, $\lambda$ increases logarithmically with energy because the theory is not asymptotically free in the Higgs sector. Thus the position of the Landau pole depends on $m_H$. Imposing that the Landau pole is far enough for the theory to make sense up to a scale $\Lambda$, gives a bound [16] on the standard Higgs mass which is plotted in Fig. 1, taken from Ref. [17]. We see that for a light Higgs, i.e. $m_H \leq$
180–200 GeV the perturbative regime is valid up to $M_{\text{GUT}}$ or $M_{\text{Pl}}$. For a heavier Higgs, the value of $\Lambda$ decreases until eventually $\Lambda \sim m_H$. For $m_H \sim 1$ TeV, the theory is valid up to $\Lambda \sim 1$ TeV. The precise value of the upper limit depends on the exact definition of $\Lambda$ and is not easy to evaluate, this one being a non-perturbative problem. Computer simulations of the electroweak theory on the lattice [18] confirm that the upper limit is in the range $m_H \simeq 500–800$ GeV. In Fig. 1 there is also a forbidden region at large $m_t$ and small $m_H$. This is derived from vacuum stability [19]. For large $m_t$, large values of $m_H$ are necessary in order to prevent that the coefficient of $(\phi^+ \phi)^2$ in the effective potential becomes negative after quantum corrections, thus making the Hamiltonian unbound from below. Note that in case that there are two or more Higgs doublets the limits refer to some average mass. Thus for the lightest Higgs the lower limit can be easily evaded but the upper limit is a fortiori valid. In conclusion either the Higgs is found below $\simeq 1$ TeV or new physics beyond the Standard Model should appear. At least one should see the onset of a new non-perturbative regime where the weak interactions become strong.

There is a widespread opinion among theorists that there must be some new physics beyond the Standard Model at a scale of energy of $O(1 \text{ TeV})$. It is considered implausible that the origin of the electroweak symmetry breaking can be explained by the standard Higgs mechanism without accompanying new physics. The argument is one of naturalness and runs along the following lines. In the $SU(2) \otimes U(1)$ symmetric limit there are no masses. Both the gauge bosons and the fermions are massless. After symmetry breaking, all masses are proportional to the Higgs vacuum expectation value $v$ or equivalently to $G_F^{-1/2} \simeq 293$ GeV ($v = 2^{-3/4} G_F^{-1/2}$) which is called the weak (or Fermi) scale. This is the characteristic scale of the electroweak theory. While the smallness of the Yukawa couplings that determine the light fermion masses and their ratios are not understood, it remains true that $G_F^{-1/2}$ is the scale of mass of the theory. As is well known, a direct extrapolation of the Standard Model leads to grand unified theories [20] at a scale $M_{\text{GUT}} \simeq 10^{14–10^{18}}$ GeV, close to the scale of quantum gravity $M_{\text{Pl}} \simeq 10^{19}$ GeV. One is perhaps led to imagine a unified theory of all interactions, including gravity (at present the best attempt of such a theory is provided by superstrings [21]). But certainly particle physics can no more ignore such large scales of mass as $M_{\text{GUT}}$ and $M_{\text{Pl}}$. Indeed, going from $G_F^{-1/2}$ up to $M_{\text{Pl}}$ is an enormous gap of about 17 orders of magnitude (the hierarchy problem). The obvious question is whether the Standard Model can extend its validity up to $M_{\text{Pl}}$. The answer is that this appears unlikely. A natural explanation of $M_{\text{Pl}}/G_F^{-1/2} \simeq 10^{17}$ demands the presence of new physics near $G_F^{-1/2}$. The reason is that, if the Standard Model is valid up to a large scale $\Lambda$, even if one sets a small value for $m_H$ at the tree (classical) level, $m_H \ll \Lambda$, the loop (quantum) corrections would make $m_H$ increase up to the order of $\Lambda$. The problem is especially acute for scalar fields because the corresponding mass divergences are quadratic, while they are only logarithmic for spin 1/2 fermions. Note that here the discussion is on the relation between bare and renormalized masses, where the cut-off dependence is hidden. In the renormalization procedure a physical value is simply assigned to $m_H$ and it is left to the bare mass and the cut-off to adjust to each other. The naturalness problem arises if the divergences are seen as a low-energy effect, to be eventually removed by some new physics at the scale $\Lambda$ (e.g. by gravity at $M_{\text{Pl}}$). Then the large momentum cut-off and the scale of new physics can be physically identified. The quadratic divergences associated with scalars are unacceptable in a 'natural' theory, while the logarithmic singularities of fermion masses can be tolerated. The fermion masses are also protected by chiral symmetry, which demands mass corrections to vanish in the massless limit, i.e. $\delta m \sim m \ln \Lambda/m$.

One possible solution is that the Higgs doublet really consists of fundamental scalar
fields but naturality is restored by broken supersymmetry [22]. In the supersymmetric limit there is complete boson–fermion symmetry. The quadratic mass divergences associated with scalars cancel away so that only logarithmic singularities for both scalars and fermions are present. When supersymmetry breaking is switched on the scale for $\delta m_0^2$ is naturally set by the splitting between partners in supersymmetric multiplets. The Fermi scale is natural if the masses of sparticles are around the Fermi scale. In the limit of exact supersymmetry and exact gauge $\text{SU}(2) \otimes \text{U}(1)$, all particles are massless. When supersymmetry is broken while $\text{SU}(2) \otimes \text{U}(1)$ is still preserved, ordinary particles remain massless while sparticles become massive. It is important to note that observed particles are precisely those whose mass terms are forbidden in the $\text{SU}(2) \otimes \text{U}(1)$ limit, while sparticle masses are allowed. For example, quark and lepton masses are forbidden while squark or slepton masses are allowed, the gauge boson masses are forbidden but the gaugino masses are allowed. Thus the fact that all ordinary particles were observed but no sparticles is not unnatural. When finally the $\text{SU}(2) \otimes \text{U}(1)$ symmetry breaking is switched on, the scalar mass naturally takes a value of the order of the scale of sparticle masses and all ordinary particles acquire a mass.

Many theorists working on quantum gravity and superstrings tend to consider SUSY as ‘established’ at $M_{\text{Pl}}$ and beyond. For economy one is then naturally led to try to use SUSY at low energy, in order to solve some of the problems of the Standard Model. It is thus very important that it was indeed shown [23] that models where SUSY is softly broken by gravity do offer a viable alternative. The minimal supersymmetric Standard Model [24] (MSSM), which will be often mentioned in the following, is a well-specified theory, completely consistent and, in some respects, better than the Standard Model, as we have seen. The supersymmetric option is very appealing to theorists. It would represent the ultimate step of a continuous line of progress obtained by constructing field theories with an increasing degree of exact and/or broken symmetry and applying them to fundamental interactions. The value of the ratio of knowledge versus ignorance would be remarkably large in the case of SUSY: the correct degrees of freedom for a description of physics up to gravity would have been identified, the Hamiltonian would be known—apart from the values of a number of parameters—and the theory would be, to a large extent, computable up to the Planck scale.

The alternative main avenue to solve the hierarchy problem is to avoid fundamental scalar fields at all. This necessarily implies the existence of new strong forces. For example, the electroweak symmetry could be broken by condensates of new fermions attracted by a new force with $\Lambda_{\text{new}} \sim G_F^{-1/2}$, $\Lambda_{\text{new}}$ being the analogue of $\Lambda_{\text{QCD}}$, as in technicolour theories [25]. The mechanism that gives mass to $W^\pm$ and $Z$ would be the analogue for a gauge theory of the breaking of chiral symmetry (a global symmetry) in QCD. A new anomaly-free multiplet of heavy technifermions, bound by a very strong gauge force called technicolour, must be introduced. The longitudinal modes of $W^\pm$, $Z$ would be analogous to the pions in QCD. This approach faces problems [26] related to the existence of additional light pseudo-Goldstone bosons that should have been detected. In addition the fermion masses remain an unsolved question (the so-called extended technicolour introduced [27] to solve this problem leads more to new difficulties than to advantages).

Recently it has been proposed [28] that a very heavy top mass ($m_t \geq 230$ GeV) could induce the electroweak symmetry breaking. The Higgs would be a sort of $t \bar{t}$ bound state with mass $m_H \simeq 1.1 m_t$. This model (of the Nambu–Jona Lasinio type [29]) is non-renormalizable and involves many ad hoc four-fermion interactions to fix the fermion masses. More generally, the Higgs could be a composite of new fermions bound by a new force [30]. Or the $\text{SU}(2) \otimes \text{U}(1)$ symmetry could be a low-energy fake [31]. At large
energies, $E \gg G_F^{-1/2}$, the $W^\pm$ and $Z$ would be resolved into their constituents.

However it is fair to say that the above ideas become increasingly generic (going down the list). No sound theoretical framework has been developed out of them. The compositeness alternative, in all its different forms, is not at all so neatly formulated as the supersymmetric option. On the contrary, in many respects the compositeness way is not well defined at all and leads to many unsolved problems. But, of course, this state of affairs could only be due to a lack of ingenuity on the part of theorists.

In conclusion there are solid arguments for new physics near the Fermi scale of mass $G_F^{-1/2}$. Either a fundamental scalar Higgs exists and naturalness is restored by supersymmetry, or new strong forces will manifest themselves, drastically changing the framework of the Standard Model beyond $O(1 \text{ TeV})$. A new non-perturbative regime will set up, with new resonances and the physics will become less predictable above that energy. An important point is that all conceivable possibilities are very complex. Each of them implies a rich new spectrum of states and phenomena: the whole spectrum of superpartners in SUSY; new hadrons, excited vector bosons, etc., in the composite alternative. The new physics is in all cases distributed over a large interval of energies. The low-lying fringes of the new spectroscopy, or at least their virtual effects, should already be accessible to LEP 1 and LEP 200. A lot of discoveries are expected at the LHC, to be followed by more at the SSC. In conclusion, the physics case for the LHC and SSC is well defined:

1. Search for the Higgs if not found at LEP.

2. Clarify the physical mechanism of the electroweak symmetry breaking.

3. Search for new physics near the Fermi scale of mass (extended gauge models, supersymmetry, technicolour, $tt$ bound systems, composite Higgs, composite $W^\pm$ and $Z$, weak interactions becoming strong).

In the following we will compare these goals with the actual physics potential of the LHC as it is derived from the results of the Workshop.

3 The standard Higgs

The search for the minimal Standard Model Higgs [32] at the LHC has been discussed in great detail at this workshop as well as at previous ones on LHC [1–3] and SSC [33] physics. This is a good reference problem, but not necessarily the central issue of physics at the LHC. After all the Higgs might be found at LEP. Such a discovery at LEP would not at all mean that the LHC is no longer necessary. In fact, we have seen that one expects some new physics at the weak scale to accompany the Higgs. The minimal Standard Model might well be wrong for the Higgs sector. For example, the Higgs sector of supersymmetric models involves at least two Higgs doublets [24, 32]. The couplings of the lightest SUSY Higgs are not as in the minimal Standard Model. However, it would in many cases be impossible to prove at LEP that the Higgs candidate is the particle predicted by the minimal Standard Model. The Higgs search is a good reference problem in the sense that experiments must be good enough to see the standard Higgs in order to prove adequate for the solution of the electroweak symmetry-breaking question. The discovery of the Higgs is in fact a very difficult experimental problem, because the Higgs is heavy and, its couplings being proportional to masses, it is essentially not coupled to light particles (the most common ones). Heavy real or virtual states must be excited in order to produce the
Figure 2: The total width (from Ref. [44]) of the standard Higgs as a function of $m_H$ (and $m_t$).

Higgs, so that the cross-sections are relatively small. In addition, below the WW or ZZ threshold, the dominant decay into the heaviest accessible pair of quarks is swamped by the QCD background.

The case of the Standard Model Higgs was studied by a dedicated group at the Workshop, convened by Z. Kunszt and J. Stirling. The results were summarized in the talks by Z. Kunszt, by D. Froidevaux and by C. Seez at the parallel sessions and by Denegri [6] in the plenary session. The problem was restarted from scratch. Calculations of the total width (Fig. 2) and of the branching ratios (Fig. 3) were updated by Z. Kunszt and J. Stirling. The inclusion of the effects from the running of the $b$-quark mass makes the $b\bar{b}$ partial width smaller, and the rare decay branching ratios below the $t\bar{t}$, WW, and ZZ thresholds larger. In particular the $H \to \gamma\gamma$ branching ratio was found to be larger by a welcome factor of 2 with respect to previous calculations. The production occurs mainly through gluon–gluon fusion ($gg \to H$) via a quark loop (dominated by virtual $t$ exchange) or through WW fusion plus a small ZZ contribution ($q\bar{q} \to Hq\bar{q}$). For $m_t \geq 90$ GeV the gluon-fusion process is dominant up to very heavy Higgs masses: $m_H \geq 600$ GeV for $m_t \simeq 90$ GeV, or $m_H \geq 1$ TeV for $m_t \simeq 180$ GeV (Fig. 4).

The intermediate-mass Higgs is the most difficult case. It is assumed that a light Higgs with mass $m_H \leq m_Z$ will be discovered at LEP 1 or LEP 200. The intermediate Higgs range is defined by $m_Z \leq m_H \leq 2m_Z$, i.e. below the threshold for $H \to ZZ$. This region would be hopeless if $H \to t\bar{t}$ were allowed. Now it is known from CDF results that indeed $m_t \geq m_Z$, so that the dominant decay of the intermediate Higgs is $H \to b\bar{b}$. This implies that the accessible decay modes $H \to ZZ^* \to 4\ell^\pm$ and $H \to \gamma\gamma$ have a much larger branching ratio. High luminosity, $L \simeq 10^{34}$ cm$^{-2}$ s$^{-1}$, is absolutely necessary for detecting the intermediate Higgs.

The first very important conclusion which was obtained is that with $\int L \, dt \simeq 10^5$ pb$^{-1}$ and both $e$ and $\mu$ detection, it is possible to observe the intermediate Higgs for $m_H \geq 130$ GeV through the chain $H \to ZZ^* \to 4\ell^\pm$ ($\ell = e, \mu$) [34]. The signal rate before cuts is 100–700 events per year as seen from Fig. 5 (the dip at $m_H \sim 160$ GeV corresponds to the opening of the threshold for WW decay, which is not practicable because of the $t\bar{t} \to WWbb$ background). A thorough study of backgrounds was done. Particular attention
Figure 3: The branching ratios (from Ref. [44]) of the standard Higgs. For $m_H > 200$ GeV, the WW and ZZ channels are dominant. There is little dependence on $m_A$.

Figure 4: Production cross-sections (from Ref. [44]) of the standard Higgs at the LHC.
Figure 5: The cross-section times branching ratio (from Ref. [44]) for $pp \rightarrow H (\rightarrow Z^*Z^* \rightarrow 4\ell\nu)X$ at the LHC and SSC.

was devoted to the $Zb\bar{b}$ channel (the leptons from $b\bar{b}$ can be hard and isolated enough to mimic the $Z^*$). The dominant process $gg \rightarrow Zb\bar{b}$ was studied by van Eijk and Kleiss [5]. Detailed simulations of the $t\bar{t}$, $Zb\bar{b}$, $Z^*Z^*$, and $Z^*\gamma^*$ backgrounds were performed [35]. The signal is already visible over the background without isolation cuts (Fig. 6a), but becomes much more prominent with isolation cuts (Fig. 6b).

Much work was devoted to the problem of closing the window $m_2 \leq m_H \leq 130$ GeV. This is a particularly hard task. The main line of attack is based on the process $pp \rightarrow H(\rightarrow \gamma\gamma)X$, first discussed in Ref. [34] and then widely studied [2, 3, 33, 36]. This process was further analysed at the present Workshop. I refer the reader to the talk by C. Seez for a detailed discussion. The conclusion was that this channel is extremely difficult but feasible with a very good detector. The signal rate is $0.5\sim 1 \times 10^3$ events per $\int L \ dt \simeq 10^8 \ pb^{-1}$ (Fig. 7). The intrinsic background from $q\bar{q} \rightarrow \gamma\gamma$ and $gg \rightarrow \gamma\gamma$ (which was also studied by the Standard Model Cross-Sections Group, as reported in the talk by M. Werlen) already poses a formidable problem. A superb electromagnetic calorimeter is required, and vertex localization is very important for the $\gamma\gamma$ invariant-mass reconstruction. In Table 2 we show the comparison of signal versus intrinsic background for $m_H = 80\sim 150$ GeV and $\int L \ dt \simeq 10^8 \ pb^{-1}$.

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$\Delta M$ (GeV)</th>
<th>Signal</th>
<th>Background</th>
<th>$S/\sqrt{B}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>1.0</td>
<td>570</td>
<td>11800</td>
<td>5.2</td>
</tr>
<tr>
<td>100</td>
<td>1.5</td>
<td>1180</td>
<td>13700</td>
<td>10.1</td>
</tr>
<tr>
<td>150</td>
<td>2.0</td>
<td>830</td>
<td>5600</td>
<td>11.1</td>
</tr>
</tbody>
</table>

The reducible background from jets misidentified as photons demands a large rejection factor $r_{2j} = r_{ij}^2 > 10^8$, where $r_{2j}$ and $r_{ij}$ correspond to double- and single-jet misidentification, respectively. The possibility of a position detector, located some 2 m away, in order to see the separation between the two $\gamma$'s from $\pi^0$ decays, was suggested [37] as a main device for the discrimination of the jet background.

An additional possibility, at small $m_H$, is provided by the associated production of $HW$ followed by $H \rightarrow \gamma\gamma$: $pp \rightarrow H(\rightarrow \gamma\gamma)W(\ell\nu)X$. This process was studied at the Workshop
Figure 6: The signal and background for the intermediate-mass Higgs ($H \rightarrow ZZ' \rightarrow 4 \ell^\pm$), while $\ell = e, \mu$, a) without and b) with isolation cuts (from Ref. [40]).

Figure 7: The signal for $H \rightarrow \gamma\gamma$ at the LHC and SSC (from Ref. [44]).
Figure 8: The signal rate for $pp \to (H \to \gamma\gamma)W(\ell\nu)X$ or $pp \to (H \to \gamma\gamma)Z(\ell\ell)X$ at the LHC and SSC (from Ref. [44]).

by Kleiss, Kunszt, and Stirling [38], and, from the experimental point of view, by Di Lella et al. [39]. The good thing about this process is that the sum of the irreducible background from $W\gamma\gamma$ and of the reducible one from $b\bar{b}g$, $b\bar{b}\gamma$, $b\bar{b}\gamma\gamma$, $Wjj$, ..., with misidentifications, is very small in comparison with the signal [39]. The bad thing is that the signal rate is also very small (Fig. 8) [38]. The resulting number of events for signal and background after cuts are collected in Table 3. It is concluded [39, 40] that this channel is very difficult but could provide a useful way of confirming the signal from $pp \to H(\to \gamma\gamma)X$.

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>Signal</th>
<th>Background</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Irreducible</td>
</tr>
<tr>
<td>75</td>
<td>17</td>
<td>6</td>
</tr>
<tr>
<td>100</td>
<td>22</td>
<td>3</td>
</tr>
<tr>
<td>130</td>
<td>18</td>
<td>2</td>
</tr>
</tbody>
</table>

The possibility of detecting the Higgs via $H \to \tau^+\tau^-$ as proposed in Ref. [41] was also considered in detail. The conclusion is negative: this channel turns out to be hopeless for the standard Higgs [42]. As we shall see in Section 8, for particular values of the parameters, it could be of use for the SUSY Higgs A [40].

Turning to the case of a heavy Higgs, $m_H > 2m_Z$, the golden channel is $H \to ZZ \to 4\ell^{\pm}$ [43], while $H \to WW \to \ell\nu\nu\nu$ is much more difficult, particularly because of the $t\bar{t}$ background. The rate for $H \to ZZ \to 4\ell^{\pm}$ is displayed in Fig. 9 as a function of $m_H$ and $m_t$ [44]. Detailed studies and simulations of the irreducible background from $q\bar{q}$, $gg \to ZZ$ (which is the dominant one in this case) and of the reducible background from $t\bar{t}$, $Zb\bar{b}$, and $Z + \text{jets}$ were performed [45]. The reducible background is in all cases small after cuts. With $\int L dt \approx 10^5 \text{ pb}^{-1}$ and $\ell = e, \mu$, the discovery range at the LHC extends up to $m_H = 800 \text{ GeV}$ (Fig. 10) (with $\int L dt \approx 10^4 \text{ pb}^{-1}$ the corresponding value would go down to 400 GeV). The ultimate discovery range at the LHC could be improved, perhaps, up to $m_H \approx 1 \text{ TeV}$ by using $H \to ZZ \to \ell\ell\nu\nu$, but the possibility of extracting the signal from the background from $b\bar{b}$, $Zb\bar{b}$, etc., is not demonstrated [40]. Alternatively one could
Figure 9: Signal for $H \rightarrow ZZ \rightarrow 4\ell^\pm$ at the LHC and SSC (from Ref. [44]).

Figure 10: Signal versus background for $H \rightarrow ZZ \rightarrow 4\ell^\pm$ for $m_H = 0.6$–0.8 TeV (from Ref. [40]).
try to use $H \rightarrow WW \rightarrow \ell\nu\jib$ or $H \rightarrow ZZ \rightarrow \ell\ell\jib$ with jet tagging [40]. Jet tagging was first studied in Ref. [46] and further considered at this Workshop by M. Seymour. At large $m_H$, a substantial fraction of the Higgs events is produced by $WW$ fusion. As is well known, the idea of tagging is to detect the near forward and backward quark jets, with $E_T \sim O(1$ TeV) and $p_T \sim O(m_W)$ left out after $W$ emission. Studies done at the Workshop [47] indicate that jet tagging may indeed be possible, perhaps even at $L > 10^{33}$ cm$^{-2}$ s$^{-1}$.

The conclusions of the Higgs Working Group have been summarized by D. Froidevaux [40]. At the LHC, with $10^5$ pb$^{-1}$, the process $H \rightarrow ZZ \rightarrow 4\ell\pm$ with real or virtual $Z$, allows the range $m_H = 130$–800 GeV to be covered. The same range is obtained at the SSC with $10^4$ pb$^{-1}$. For $m_H = 80$–130 GeV the channels $H \rightarrow \gamma\gamma$ and $HW \rightarrow \gamma\ell\nu$ are extremely difficult but feasible. The ratio $S/\sqrt{B}$ is actually better at the LHC with $10^5$ pb$^{-1}$ than at the SSC with $10^4$ pb$^{-1}$, but the operation at a luminosity 10 times larger is more demanding for the detector. The ultimate discovery range at the LHC could perhaps be extended up to 1 TeV by using $H \rightarrow ZZ \rightarrow \ell\ell\nu\nu$ or $H \rightarrow WW \rightarrow \ell\nu\jib$ with jet tagging, but this is not established.

4 Longitudinal $W^\pm$ and $Z$

The $V$ states ($V \equiv W^\pm, Z$) with helicity zero (longitudinal $V$, denoted by $V_L$) are absent in the symmetric limit where the $V$ are massless. It is thus clear that the longitudinal modes are directly related to the symmetry-breaking mechanism. If the Higgs is not found in the LHC discovery range, then the $VV$ interactions become strong and the perturbative cross-section violates unitarity [15] for $m_H, \sqrt{s} \geq O(1$ TeV). This is due to the growth of the $V_L V_L \rightarrow V_L V_L$ scattering amplitudes, which become dominant in that regime. If the Higgs is not found at the LHC, the study of the interactions among $V_L$ becomes the most direct way of attacking the symmetry-breaking problem [48]. In a theory with spontaneous symmetry breaking, no matter if the breaking is dynamical (e.g. due to condensates) or induced by either elementary or composite Higgses, the longitudinal $V$ arise from the Goldstone bosons with the corresponding quantum numbers. In fact, at large energies, when contributions of order $m_V/\sqrt{s}$, arising from mass terms, can be neglected, the amplitudes for $V_L V_L$ scattering approach those for the corresponding Goldstone bosons ($\sqrt{s}$ being the $V_L V_L$ centre-of-mass energy). For example

$$A(W_L^\pm Z_L \rightarrow W_L^\pm Z_L) = A(w^\pm z \rightarrow w^\pm z) + O\left(\frac{m_V}{\sqrt{s}}\right)$$

where $v_1$ is the Goldstone boson which corresponds to $V_{1L}$. This 'equivalence theorem' [49], valid to all orders of perturbation theory, is also used as a handy method for practical computations.

At low momenta, the Goldstone boson couplings are fixed by the symmetry. As a consequence, there are low-energy theorems [50] that specify the Goldstone boson amplitudes at threshold. An effective Lagrangian formalism can be based on the low-energy theorems. This provides a framework for an extrapolation near threshold of the amplitudes which satisfy the low-energy theorems. At $\sqrt{s} \gg m_V$ but not too large, one may think to combine the equivalence theorem and the low-energy limit and to apply the effective Lagrangian results directly to $V_L V_L$ scattering. Such smooth extrapolations can provide reasonable approximations only for $\sqrt{s} \ll 4\pi G_F^{-1/2}$, provided that no resonances are met on the way. For example, in the Standard Model the regime of low-energy theorems is no longer valid for $\sqrt{s} \simeq m_H$, because $m_H$ is a resonance in the $VV$ channel. At large $\sqrt{s}$ ($\sqrt{s} \gg m_H$), the
Higgs contribution cancels [15] the bad high-energy behaviour—obtained by extrapolating the trend derived from the low-energy theorems—which eventually would violate unitarity. For a light Higgs, the high-energy $V_L V_L$ scattering amplitudes remain small, of order $\mathcal{O}(m_H^3)$ [15]. In the absence of the Higgs, some other mechanism, which one would like to discover, should intervene to quench the singular high-energy behaviour.

An analogy with QCD can be established: $W_L^\pm$ and $Z_L$ are analogous to $\pi^\pm$ and $\pi^0$ in QCD because $V_L$ are eaten up Goldstone bosons of $SU(2) \otimes U(1)$, while the pions are the (pseudo)-Goldstone bosons of $SU(2) \otimes SU(2)$ chiral symmetry. The pions obey Weinberg’s low-energy theorems [51] which are embodied in the formalism of chiral Lagrangians [52]. The chiral Lagrangian regime would hold up to $\sqrt{s} \ll 4\pi F_\pi \approx 1.2 \text{ GeV}$ were it not for the presence of vector mesons $\rho, \omega$ that induce drastic differences already at $\sqrt{s} \sim m_\rho$. In the case of $W_L^\pm$ and $Z_L$, $F_\pi$ is replaced by $G_F^{1/2}$.

Two broad possibilities emerge and have been amply discussed in the literature and also at this Workshop. On the one hand, the situation of the Standard Model can be stretched up to large $m_H$, where a very broad enhancement is present in the scalar channel with $I = 0$ ($I$: weak isospin). On the other hand, the QCD picture can be mimicked with vector resonances with $I = 1$ ($\rho$) or $I = 0$ ($\omega$). This is for example the case of models based on $SU(N_{TC})$ technicolour [25–27] or scaled-up QCD (i.e. $N_{TC} = 3$) or the ‘BESS’ model of Casalbuoni, Gatto et al. [53], which is a non-renormalizable Lagrangian model with no Higgs (eliminated as in the non-linear $\sigma$ model [54]) extended to include an extra $SU(2)$, which leads to heavy vector $\rho$-like states (with $I = 1$).

A more general approach that can generate a QCD-like or a Higgs-like model, or other cases as well, was adopted by Dobado, Herrero and Terron [55] (for related work, see also Ref. [56]). Higher-order terms in the momenta are added to the lowest-order effective Lagrangian. While the lowest-order effective Lagrangian is fixed by the low-energy theorems in terms of a single-energy parameter, $G_F^{1/2}$, the next-order couplings depend on two arbitrary parameters. By varying those constants one can switch from one type of physics to another. Some procedure of unitarization is implemented in order to extend the model at large $\sqrt{s}$ (in a purely phenomenological way) so that the model formally makes sense also in the presence of resonances.

Extensive studies based on the various models listed above were performed at the Workshop, together with detailed experimental simulations, in order to evaluate the capabilities of the LHC in this domain of physics [57]. The general procedure is to compute the $VV$ scattering amplitudes in a given model, to compare the results with the Standard Model prediction for some large but still admissible Higgs mass, and to check whether the deviations would be measured at the LHC, and to disentangle the different models.

The processes that are best suited for an experimental investigation are those with no $t\bar{t} \rightarrow WWb\bar{b}$ background: ZZ, $W^\pm Z$, and $W^\pm W^\pm$ (equal charges!) final states. Different qualitative behaviours are expected in these channels, depending on the dynamics of $V_L V_L$ scattering: in the Higgs-like regime, sizeable effects are expected in the ZZ channel and not in the $W^\pm Z$ or $W^\pm W^\pm$ reactions. Conversely a $\rho$-like resonance would show up in the WZ channel and not elsewhere. In the following, we discuss some significant examples of the results obtained at the Workshop, presented in talks by R. Casalbuoni, M.J. Herrero, T. Rodrigo and summarized by Lindner [57] (see also the plenary talk by Paus [7]).

For equal-sign WW final states, the production rate of $W^+ W^-$, with $M_{WW} > 0.8$ TeV, is about one third of that of $W^+ W^+$ (because $u$ quarks are more abundant than $d$ quarks at large $x$ in the proton). The background from $W^\pm t\bar{t}$, from $q\bar{q} \rightarrow W^\pm W^\pm q\bar{q}$ via gluon exchange, and from QCD jets has been evaluated by Barger et al. [58]. In models with no $I = 2$ resonances, as those studied by Dobado et al. [55], there is little activity
Figure 11: Like-sign WW invariant-mass distribution for various strongly-interacting models and for the total background. Rates for $W^+W^+$ and $W^-W^-$ are added [55]. The short-dashed line is for the QCD-realized case and the lower solid line is for the Higgs-like model. The upper solid curve corresponds to the unitarized-LET results [58]. The Standard Model results for $M_H = 1$ TeV are also displayed for comparison [58] (dot-dashed line). The long-dashed lines are the predictions for the total background in the cases $m_t = 100$ GeV (upper line) and $m_t = 200$ GeV (lower line), respectively [58].

In the channel $pp \rightarrow W^{\pm}W^{\pm}X \rightarrow \ell^{\pm}\nu\ell^{\pm}\nu X$, and the signal is small with respect to the background (Fig. 11). For $\int L \, dt \simeq 10^5$ pb$^{-1}$ the rate is of the order of 10 events per year at $M_{WW} > 0.8$ TeV. The situation is not better at the SSC with $10^4$ pb$^{-1}$. This does not necessarily mean that this process is not interesting, because the actual dynamics could be different from that of the models studied at the Workshop. If a doubly-charged resonance exists, it would show up in this channel.

In the $ZZ \rightarrow 4\ell^{\pm}$, $\ell = e, \mu$, channel the signal from $W_LW_L \rightarrow Z_LZ_L$ plus $Z_LZ_L \rightarrow Z_LZ_L$ was computed in the model by Dobado at al. [55], compared with the irreducible background from the Standard Model processes $q\bar{q}, gg \rightarrow ZZ$. For $\int L \, dt \simeq 10^5$ pb$^{-1}$, $M_{ZZ} > 0.5$ TeV, $p_T^Z > 10$ GeV, $|y_Z| < 2.5$, the background amounts to about 220 events (for $m_t = 100$ GeV), while the signal is of about 15 events in a Higgs-like picture and half of that in a real-up QCD model. The corresponding numbers at the SSC, with $10^4$ pb$^{-1}$ and the same cuts, are 73 (background), 10 (Higgs-like) and 5 (QCD-like) events. Without jet tagging it is difficult to separate the $VV \rightarrow VV$ signal from the irreducible background, particularly because the latter is only computeable with limited accuracy and both the signal and the background have a structureless mass distribution. (Recently, the next-to-leading QCD corrections to $q\bar{q} \rightarrow ZZ$ have been computed [59].)

The prospects are much more promising for models with resonances, as for example a $\rho^{\pm}$-like particle observable in $W^{\pm}Z$ final states or an $\omega$-like object visible in $Z\gamma$. At the Workshop the WZ channel was studied in full detail in SU(NTC) models realized in the effective Lagrangian approach [55] and in the BESS model [53, 60]. In scaled-up QCD

$$m_{\rho^T} \simeq \frac{v}{F_\rho} m_{\rho} \sim 2 \text{ TeV}$$

$$\Gamma(\rho_T \rightarrow VV) \simeq \frac{m_{\rho_T}^3}{96\pi v^2} \simeq 450 \text{ GeV}.$$
Figure 12: WZ invariant-mass distribution for the signal and background processes with the optimal cuts (the 2.5 rapidity cut has been chosen) [55]. Rates are for $W^+Z + W^-Z$ and for $L = 4 \times 10^8$ pb$^{-1}$. The results of the signal are for three possible cases in $SU(N)$ theories corresponding to: $m_\rho = 1.0$ TeV, 1.5 TeV, and 2.0 TeV, respectively. The lower solid histogram represents the WZ fusion contribution to the signal. The dotted histogram is the $q\bar{q}^*$ annihilation contribution to the signal via $\rho - \omega$ mixing. The total background is the dashed histogram, and the total signal $+$ background is the upper solid histogram.

For $SU(N_{TC})$ with $N_{TC} \neq 3$ one takes [25]:

$$m_{\rho_T} \simeq 2 \text{ TeV} \sqrt{\frac{3}{N_{TC}}}, \quad \Gamma (\rho_T \to VV) \simeq 450 \text{ GeV} \left( \frac{3}{N_{TC}} \right)^{3/2}.$$ 

Thus for $N_{TC} \simeq 12$ one has $m_{\rho_T} \simeq 1$ TeV and $\Gamma_{\rho_T} \simeq 55$ GeV while for $N_{TC} = 5$, $m_{\rho_T} \simeq 1.5$ TeV and $\Gamma_{\rho_T} \simeq 185$ GeV. The results for these three representative cases ($m_{\rho_T} = 1, 1.5, 2$ TeV) are summarized in Fig. 12. The full process under consideration is $pp \to W^{\pm}ZX \to \ell^\pm \nu \ell^\mp X$, $\ell = e, \mu$. The $W^+Z$ rate is about twice the $W^-Z$ rate. The resonant signal in $W^+_LZ_L$ is produced either by WZ fusion or by $q\bar{q}$ annihilation with $\rho_T$ coupled via $W^-\rho_T$ mixing. The irreducible background is from the standard processes $q\bar{q} \to WZ, W\gamma \to WZ$, and $WZ \to WZ$ (with no $\rho_T$ exchange). With optimized cuts the following S/B ratios were obtained at the LHC [55] (in number of events per $10^8$ pb$^{-1}$): 660/53 for $m_{\rho_T} = 1$ TeV, 50/11 for $m_{\rho_T} = 1.5$ TeV, and 20/13 for $m_{\rho_T} = 2$ TeV. At the SSC with $10^4$ pb$^{-1}$ (with different cuts optimized to the SSC case) the corresponding numbers are: 263/24, 36/8, and 24/16, respectively. The resonance is visible in the mass and $p_T$ distributions. The invariant mass distributions in the LHC case are shown in Fig. 12. Detailed simulations presented by Rodrigo [57] show that the signal clearly emerges at large $p_T$ over the complete background, also including the reducible one with 3-lepton events from $t\bar{t}$ production (Fig. 13).

The production of a different type of $\rho$-like resonance in the WZ channel was studied in the context of the BESS model [53, 60]. The values of the free parameters $m_{\rho_T}, g''$ were
Figure 13: Signal and background for $\rho_{TC}$, with $m_{\rho_{TC}} \simeq 1$–2 TeV. The solid line is the total signal in $W^{\pm}_{R}Z_{L}$ final states (obtained by adding boson fusion and $q\bar{q}'$ annihilation). The dashed line is the fusion contribution alone. The stars indicate the total background. (From Ref. [57].)

\[
\begin{align*}
pp &\rightarrow WZ + X \text{ in BESS} \\
M_{W}(\text{GeV}) &= 2000 & \Gamma_{W}(\text{GeV}) &= 353 & \omega^{*} &= 13 & b &= 0.00
\end{align*}
\]

\[
\begin{align*}
# \text{ WZ Events/year} &\rightarrow WZ + X \text{ in BESS} \\
\text{pp} &\rightarrow WZ + X \text{ in BESS} \\
M_{W}(\text{GeV}) &= 2000 & \Gamma_{W}(\text{GeV}) &= 353 & \omega^{*} &= 13 & b &= 0.00
\end{align*}
\]

Figure 14: Transverse-momentum distribution of signal and background at the LHC (a) and the SSC (b), for $\rho_{TC}$ production in BESS (from Refs. [53] and [60]), with $m_{\rho_{TC}} = 2$ TeV and $b = 0$. The upper histogram is the signal from $q\bar{q}'$ annihilation, the centre one that from fusion, and the lower one from the total background.
chosen in such a way as to have $m_{\rho_T} = 1, 1.5, 2, 2.5$ TeV with widths $11-44, 84-355, 353, 455$ GeV, respectively. The $p_T^b$ is coupled to WZ and also to q\bar{q} via the $W^+ - p_T^b$ mixing (an additional direct coupling with quarks could be switched on by letting a parameter called $b$ be different from zero). The background is the same as in the previous discussion. In Fig. 14a,b, we report the $p_T$ distributions for the case $\rho_T = 2.0$ TeV, with $b = 0$. Here again the LHC with $\int L dt \simeq 10^5$ pb$^{-1}$ is compared with the SSC with $\int L dt \simeq 10^4$ pb$^{-1}$. Even if $m_{\rho_T} \simeq 2$ TeV is large enough to provide a special advantage to the SSC, we see that the S/B ratio is comparable in the two cases [684/310 (LHC) and 1010/462 (SSC)]. The discovery range at both LHC and SSC extends up to $\sim 2.5$ TeV.

Summarizing: $W^\pm W^\pm$ is small, below the background, in models with no $I = 2$ resonances. The ZZ channel is in principle good for the Higgs-like case, but it is very difficult to disentangle a non-resonant signal from the continuum. The $W^\pm Z$ (or $Z\gamma$) is good for $\rho$-like ($\omega$-like) resonances. A $\rho_T$ resonance with $m_{\rho_T} < 2.5$ TeV can be detected in the WZ channel at the LHC with $\int L dt \simeq 10^5$ pb$^{-1}$ or at the SSC with $\int L dt \simeq 10^4$ pb$^{-1}$. In conclusion if there are resonances with $\Gamma \ll M$, they can be detected. Otherwise a structure-less signal is difficult to be established both at the LHC and at the SSC.

5 Anomalous WWγ and WWZ couplings

At present the predictions of the Standard Model on the three-gauge couplings WWγ and WWZ [61] have not yet been tested with significant precision. At the Workshop this issue has been addressed in some detail. The conclusion is that the LHC is more sensitive than LEP 200 [62] to possible deviations of the three-gauge couplings from the Standard Model. For example, one can add to the Standard Model Lagrangian the extra term [61, 63]:

$$\Delta L = \frac{i}{m_W^2} \left( g_\gamma \lambda_\gamma F^\gamma_{\mu\nu} + g_Z \lambda_2 F^Z_{\mu\nu} \right) W^{\mu\nu} W^\nu_\sigma,$$

with $g_\gamma = g \sin \theta \equiv e, g_Z = g \cos \theta$ and

$$F^\gamma_{\mu\nu} = \partial_\mu A_\nu - ig_\gamma W^\mu_\nu - (\mu \leftrightarrow \nu),$$

$$W^\mu_\nu = (\partial_\mu - ig_\gamma A_\mu - ig_Z Z_\mu) W^\nu_\nu - (\mu \leftrightarrow \nu);$$

$\lambda_\gamma, Z$ vanish in the Standard Model. These are not the most general vertices, but the ones with the most singular behaviour at large momenta (where the non-renormalizable nature of the couplings is manifest). Low-energy precision tests of the electroweak theory, also including LEP 1 results, essentially put bounds on $|\lambda_\gamma - \lambda_2|$ but do not put constraints on $\lambda_\gamma$ and $\lambda_2$ separately [61]. At LEP 200, $\lambda_\gamma, Z$ can be observed provided $|\lambda_\gamma, Z| \geq 0.2-0.3$ [61, 62]. LEP 200 is not very sensitive because it is close to the WW threshold.

At hadron colliders the effects of the non-vanishing of $\lambda_\gamma, Z$ can be observed in pp $\rightarrow$ WZX and pp $\rightarrow$ WγX, at large invariant masses or large $p_T$ [64]. In Fig. 15 the transverse WZ mass distributions for pp $\rightarrow$ WZX $\rightarrow$ ℓνℓX presented by H. Plocho-Besch is shown as a function of $\lambda_2$. In principle, at the LHC with $\int L dt = 10^5$ pb$^{-1}$ one could detect values of $\lambda_2$ well below $|\lambda_2| \simeq 0.1$. Also in this case the difficulty is in the uncertainty on the continuum level for $\lambda_2 = 0$ as predicted by the Standard Model. The problem can perhaps be alleviated by calibration at small values of the transverse mass. Similarly the $p_T^b$ distribution for the process pp $\rightarrow$ WγX $\rightarrow$ ℓνX, studied by F. Pastore, M. Pepe, M. Werlen, is shown in Fig. 16. In this case also, with the same words of caution as before, one would be able to go below $|\lambda_\gamma| \simeq 0.1$. 

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Figure 15: Transverse WZ mass distributions for $pp \rightarrow WZX \rightarrow \ell\nu\ell\ell X$, for different values of $\lambda_Z$ (from H. Plothow-Besch).

Figure 16: Transverse-momentum distribution for $pp \rightarrow W\gamma X \rightarrow \ell\nu X$, for $\lambda_\gamma = 0$ (Standard Model) to 0.1 (from F. Pastore, M. Pepe, M. Werlen).
6 New Gauge Bosons

It is well known that large hadron colliders are ideal tools for discovering new heavy $W'$ or $Z'$. This conclusion is reaffirmed by the results obtained at the Workshop, summarized in the talks by P. Chiappetta and C. Wulz. The production cross-sections were computed [65] for the whole catalogue of heavy neutral $Z'$ that have been discussed in the recent literature. As can be seen from Fig. 17, the values of $\sigma$-B for $pp \rightarrow Z'X \rightarrow e^+e^-X$ are distributed in a rather narrow band. The discovery limits are quite extended even for relatively modest luminosities. At the LHC one can discover a heavy $Z'$ up to 2–2.5 TeV with $\int L \, dt = 10^5 \, pb^{-1}$, up to 3–3.5 TeV with $10^4 \, pb^{-1}$, and up to 4–5 TeV with $10^5 \, pb^{-1}$ [even if only the electron mode $Z \rightarrow e^+e^-$ is used (Fig. 17)]. For comparison, at the SSC with $10^4 \, pb^{-1}$, one obtains 5–6 TeV.

As the cross-sections are very similar, the different models can clearly be distinguished only on the basis of angular distributions and decay correlations. The forward-backward asymmetries have been studied in detail [65]. One considers the $e^-$ angle $\theta$ with respect to the $Z'$ direction of flight, boosted to the $Z'$ rest frame. The forward and backward definitions are according to the sign of $\cos \theta$. The asymmetry as a function of the $Z'$ rapidity shows marked differences from one model to the other. A full study of the experimental sensitivity to the different models was performed by V. Cavasinni, M.C. Cousinou and C. Wulz. Large luminosity and resolution are clearly needed for a good distinguishing power among the models. The conclusion is that, with $\int L \, dt \simeq 10^5 \, pb^{-1}$, one can go a long way in disentangling one model from the other (Fig. 18), but of course some of the models which lead to very similar distributions cannot be resolved. For charged $W$'s the discovery limits were found in the 4–5 TeV range in the $W' \rightarrow e\nu$ mode, with $\int L \, dt \simeq 10^5 \, pb^{-1}$. For $m_{W'} \leq 1$ TeV the mode $W' \rightarrow WZ$ is also detectable. For the right-handed $W$ of left-right models, a discovery range of 1–3 TeV was found, depending on the parameters of the model.

![Figure 17: Cross-section times branching ratio for $pp \rightarrow (Z' \rightarrow e^+e^-)X$ at the LHC, in various models (from Ref. [65]). A shows the Tevatron discovery limit for $\int L \, dt = 10^2 \, pb^{-1}$; B, C, and D those for the LHC.](image-url)
Figure 18: Forward–backward asymmetries, as a function of the rapidity, for the $Z'$ of different models. The dots are the theoretical predictions, the bands indicate the experimental errors (from V. Cavasinni et al).

7 Supersymmetry

Among supersymmetric particles, certainly gluinos and squarks are the most direct candidates for discovery at hadron colliders. The production cross-sections are large ($10^4$ gluinos with $m_{\tilde{g}} \approx 1$ TeV are produced at the LHC for $\int L \, dt \approx 10^4$ pb$^{-1}$). Earlier studies, including those done at the La Thuile Workshop [2, 3] assumed direct decays of gluinos and squarks into the stable neutralino $\chi_1$: $\tilde{q} \rightarrow q \chi_1$, $\tilde{g} \rightarrow q\bar{q}\chi_1$. However, for heavy masses cascades are possible [66], for example $\tilde{g} \rightarrow q\bar{q}\chi_2 \rightarrow q\bar{q}\chi_1 Z$. Cascade decays have been studied in detail at the present Workshop. Even if the MSSM [24] is adopted, the branching ratios of the interesting modes are complicated functions of the parameters. A systematic study of the branching ratios was done by Bartl et al. [67].

As discussed in detail by Pauss [7], the missing-energy analysis for gluinos becomes more difficult when cascade decays are included. However, by improving and refining the strategy of cuts and selection criteria one can compensate for the initial disadvantage of a softer missing-energy spectrum. The conclusion of the present study [7, 67] is that the discovery ranges given at La Thuile can indeed be confirmed: at the LHC with $\int L \, dt \approx 10^4$ pb$^{-1}$ one can find gluinos with $300 \text{ GeV} \leq m_{\tilde{g}} \leq 1 \text{ TeV}$. The inferior limit is low enough that no gap should remain after the Tevatron runs, with all improvements, are completed. If the luminosity is increased up to $10^5$ pb$^{-1}$, the upper limit of the discovery range is increased up to $m_{\tilde{g}} \leq 1.5 \text{ TeV}$. The signal to background comparison for $m_{\tilde{g}} \leq 1$ TeV is shown in Fig. 19a,b. We did not perform the same extensive simulations for the SSC case. However, the discovery range for the SSC with $\int L \, dt \approx 10^4$ pb$^{-1}$ should be in the interval $m_{\tilde{g}} \leq 1.5\text{--}2 \text{ TeV}$.

Alternative signatures for gluinos have also been studied at the Workshop. In particular it was shown [7, 67] that the $gg\rightarrow ZZX \rightarrow 4\ell^{\pm}X$ selection can provide an important confirmation of the gluino signal, at least for a wide range of favourable values of the parameters.
For squarks the cases of $\tilde{q}_L$ and $\tilde{q}_R$ were treated separately; $\tilde{q}_L$ is a doublet under weak isospin, while $\tilde{q}_R$ is a singlet. Thus, for $\tilde{q}_L$, charged-current decays are also allowed: $\tilde{u}_L \rightarrow d\chi^+$, $\tilde{d}_L \rightarrow u\chi^-$, where $\chi^\pm$ are charginos. Both $\tilde{q}_L$ and $\tilde{q}_R$ can undergo neutral-current decays (the case usually studied): $\tilde{q} \rightarrow q\chi$ where $\chi$ is a neutralino, not necessarily stable. The signal for $m_{\tilde{q}} = m_{\chi} \approx 1$ TeV from charged-current decays (followed by $\chi^\pm \rightarrow W^\pm\chi_1$) is compared with the background in Fig. 20 (for $\int L dt \approx 10^5$ pb$^{-1}$). The study of neutral-current decays was also updated. As for gluinos, the final result on the discovery range for squarks is up to 1.5 TeV at the LHC with $\int L dt \approx 10^5$ pb$^{-1}$.

Chargino and neutralino production was also studied at the Workshop [7, 67]. The production mechanism is dominantly via Drell–Yan type processes. The signature is $p p \rightarrow \chi\chi X \rightarrow \ell\ell\ell X$. The background from $t\bar{t}$ and WZ was only studied at the parton level. Although difficult, the experiment could lead to a substantial extension of the discovery potential with respect to LEP 200.

Other interesting studies at the Workshop were devoted to the possibility of a light scalar top. Non-minimal SUSY models were also considered, in particular models with
broken R invariance, presented by G. Ross. In the R-symmetric limit, vertices with an odd number of superparticles are forbidden. R non-invariance is accompanied by B or L breaking. It can occur in many different ways. Some interesting possibilities were analysed. For example the decay chain $\tilde{g} \rightarrow q\tilde{q}\chi_1 \rightarrow q\bar{q}e\mu $ was considered. In this case R invariance is broken in the $\chi_1$ decay, where the lepton number L is violated ($\chi_1$ is no more stable in the presence of R breaking).

8 Supersymmetric Higgses

As we discussed in the introduction, many theorists consider that a fundamental scalar Higgs is most likely to be accompanied by supersymmetry in order to make the theory natural when looked down from very high energy scales such as $M_{\text{GUT}}$ or $M_P$. However in all supersymmetric extensions of the Standard Model at least two Higgs doublets are necessary [24, 32], giving their masses one to the up fermions and the other to the down ones. Thus in supersymmetric models there are at least three neutral and one charged physical Higgses. In the MSSM the spectrum of physical Higgses is specified by two parameters: the mass of one of the neutral Higgses and $\tan\beta = v_u/v_d$, the ratio of the vacuum expectation values of the Higgses that give mass to up fermions, $v_u$, and to down fermions, $v_d$. In the MSSM, $\tan\beta$ is always larger than 1 [68] (while in a generic two-doublet model there is no such restriction). Also, values of $\tan\beta > m_t/m_h$ are not allowed [68]. The neutral Higgses are denoted by $h$, $A$, and $H$: $h$ is the lightest Higgs ($J^{CP} = 0^+$), $A$ is the Higgs with opposite CP ($0^-$), and $H$ is the heavy Higgs with quantum numbers $0^+$. At tree level, in terms of the parameters $\tan\beta$ and $m_A$, one has [24, 32, 68]

$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

$$m_{H,H}^2 = \frac{1}{2} \left[ (m_A^2 + m_Z^2) \pm \sqrt{(m_A^2 + m_Z^2)^2 - (2m_A m_Z \cos 2\beta)^2} \right],$$

so that $m_{H^\pm} \geq m_W; m_h \leq m_Z, m_A; m_H > m_Z, m_A$. From LEP we know that $\tan\beta \geq 1.6, m_A \geq 40 \text{ GeV}, m_h \geq 33 \text{ GeV}$. For large $m_t$ there is the possibility that radiative corrections could induce rather large shifts in the Higgs masses [69]. In particular $m_h$ could exceed $m_Z$. The results are still preliminary, but it seems that, for $m_t \sim 130 \text{ GeV}$, the shift of $m_h$ due to the radiative corrections is of a few GeV and becomes rapidly larger with increasing $m_t$.

The case of the MSSM is a particularly important and interesting one. The implications on the LHC of the possibility that the supersymmetric version of the Higgs sector is realized in nature have been discussed at the present Workshop by Kunstz and Zwirner [68]. The first observation is that if the MSSM is true, then most probably a Higgs will be found at LEP. We stress that the lucky event of the discovery of a Higgs particle at LEP does not in any sense diminish the physics case for the LHC. This is obviously true if the observed properties of the light Higgs depart from the behaviour of the standard Higgs and are consistent with the MSSM. But this is also true if the accessible information obtained at LEP on the light Higgs is compatible with the Standard Model. In fact for most of the parameter space the properties of the light Higgs are close enough to the Standard Model for LEP not to be able to clearly distinguish the two cases [68]. It is only the experimental investigation of the LHC energy domain that can possibly clarify the issue. In particular we addressed the question of the search for the SUSY Higgses at the LHC.

First we consider the difficult case for LEP where the light MSSM Higgs has a mass very close to $m_Z$ or is pushed even further up by radiative corrections. It turns out that the
Figure 21: Cross-section times branching ratio, for the neutral Higgses of the MSSM in the $\phi \to \gamma \gamma$ mode ($\phi = h, H, A$), expressed as a function of $\tan \beta$ and $m_A$ (from Ref. [68]). Note, for $h$ and $H$, that their mass is not $m_A$. The symbols show the kind of particle and the value of $\tan \beta$ (for instance H:30 means $\phi = H$ and $\tan \beta = 30$).

detection of the light Higgs $h$ with mass $m_h \sim m_Z$ is in some cases easier at the LHC than that of the standard Higgs of the same mass. This is because the conditions $m_A > 100$ GeV and $m_h \to m_Z$ (at tree level) imply a large value of $\tan \beta$. But in this case the production cross-section of $h$ is larger than in the Standard Model (because of the squark contribution in the loop for the $ggg$ vertex) [68] while, in a sizeable domain of the parameter space, the $\gamma \gamma$ branching ratio is not suppressed by an equally large amount (Fig. 21).

Then we consider the case where $h$ is found at LEP. Then the search for the heavy Higgses $A$ and $H$ belongs to the LHC. At the Workshop, the production cross-sections and the branching ratios were computed. For large $\tan \beta$, the $bb$ coupling is enhanced and the channel $gg \to bbA$ becomes an important production process (Fig. 22). The branching ratios for $A$ and $H$ are plotted in Fig. 23a,b,c as functions of the mass and $\tan \beta$. For $A$

Figure 22: The $A$ production cross-section at the LHC, compared with that of a standard Higgs of the same mass (from Ref. [68]).
Figure 23: Branching ratios, for $m_t = 150$ GeV, of $A$ (a) and $H$ (b, c), for two representative values of $\tan \beta$ (from Ref. [68]).
there is no AWW or AZZ coupling. The best opportunity for the detection of A is offered by the decay modes $A \rightarrow \gamma \gamma$ and $A \rightarrow \tau \tau$. For $\tan \beta$ large, the $A \rightarrow \gamma \gamma$ mode has a larger value of $\sigma \cdot B$ than the standard Higgs with the same mass (Fig. 21). For small values of $\tan \beta$ and $m_A \ll 2m_t$, the $A \rightarrow \tau \tau$ mode is the most promising possibility. After experimental simulations, it is confirmed that the mode $A \rightarrow \tau \tau$ is viable for favourable values of the parameters [40]. For H, the $\gamma \gamma$ mode is only accessible for $m_H \approx m_Z$, while the $H \rightarrow ZZ \rightarrow 4\ell^\pm$ channel is marginally interesting for small $\tan \beta$ and $2m_Z < m_H < 2m_t$.

In conclusion, for the neutral Higgses of the MSSM the detection is in general a hard problem. A separate analysis, as complicated as the one for the Standard Higgs, would be necessary for each set of values of $\tan \beta, m_{A,H}$, and $m_t$. While much more work is needed on this subject, there certainly are windows in the parameter space where detection is possible for at least A or H.

The case of the charged Higgs was also considered at the Workshop, especially by M. Falcini. The charged Higgs could be observed if it is present in t decays: $t \rightarrow H^+ b$. As the dominant $H^\pm$ decay would be $H^+ \rightarrow \tau^+ \nu$, the signature would be a measurable violation of $\tau-\mu$ universality in tt events. For $m_t \approx 200$ GeV, $m_{H^\pm}$ could be detected in the range $m_{H^\pm} = 100-150$ GeV, while for $m_t = 150$ GeV, $m_{H^\pm}$ would be visible up to $m_H \sim 100$ GeV (Fig. 24).

9 The top and other heavy quarks

We all expect that the top quark will be discovered at the Tevatron (the sooner the better). The present upper limit [12] on $m_t$ from electroweak radiative cross-sections, $m_t \leq 200$ GeV, is strictly valid only if the Standard Model is true. It one allows for departures from doublet Higgses [70] or new interactions are introduced [71], then the limit can be stretched to 250 GeV, 300 GeV, or more, depending on how much concocting and fine-tuning one is willing to accept. In brief, the upper limit on $m_t$ can be moved somewhat up but, barring completely ad hoc cancellations, not by much. In any case at the LHC one can identify the t quark and make extensive studies of its main properties. In particular
Figure 25: Top cross-sections as a function of its mass at different machines (from Ref. [6]).

the mass can be measured with the precision $\delta m_t \approx \pm 5$ GeV and the decay modes can be investigated. While a conventional fourth family (with a light neutrino, $m_{\nu 4} \lesssim 40$ GeV) is excluded by LEP, new non-sequential quarks or more general coloured states are certainly still possible. The discovery range for new heavy quarks extends up to $m_Q \lesssim 1$ TeV at the LHC with $\int L \, dt \approx 10^5$ pb$^{-1}$.

At the Workshop the LHC cross-sections and distributions (in the rapidity $y$ and the transverse momentum $p_T$) were re-evaluated, as summarized in the talk by Reya [72] (see for example, Fig. 25). The most recent progress on parton distributions and on QCD non-leading cross-sections was taken into account in contributions from R. Meng, P. Nason et al., not only for total cross-sections but also for single-t distributions. Analytic calculations were compared with event generators. The $t$-quark fragmentation was studied. Perturbative gluon bremsstrahlung is the dominant component. In practice a $\delta(1-z)$ description is a good approximation. But most of the work was devoted to detailed simulations of top signatures and backgrounds, with the special goal of the precise measurement of the top mass. Top searches in final states with one, two, or three charged leptons were studied by F. Cavanna, D. Denegri, and others. The calculation of the important background from the production of $W + 4$ jets was contributed by F. Berends and W. Giele. The best mass determination (discussed by L. Fayard, G. Unal et al.), $\delta m_t = \pm 5$ GeV, is obtained from the two-lepton signal. For this task a luminosity $L \simeq 10^{33}$ cm$^{-2}$ s$^{-1}$ is sufficient.

10 b-physics

There is a large potential for b-physics at the LHC and SSC. The production cross-section in the collider mode at $\sqrt{s} = 16$ TeV is $\sigma \simeq (0.1-0.7)$ mb, as estimated by P. Nason and the Standard Cross-Sections Group, using $O(\alpha_s^2)$ QCD calculations [73] (but $m_b/\sqrt{s}$ is too small for a really reliable determination of the cross-section), and by A.B. Kaidalov, using reasonable extrapolations of the measured heavy-quark cross-sections [74]. With a manageable luminosity of $10^{32}$ cm$^{-2}$ s$^{-1}$, this corresponds to $(1-7) \times 10^{11}$ b$\bar{b}$ pairs.
produced per year. The cross-section is a factor of 2.5–3 larger at the SSC. In the fixed-
target mode with $\sqrt{s} \simeq 123$ GeV, the cross-section is $\sigma \sim 0.3–2 \mu$b and one can produce
$(0.5–1) \times 10^9$ $b\bar{b}$ pairs per year (for $10^8$ protons per second). The smaller rate in this
case could be compensated by the smaller average multiplicity ($\langle n_{\tau} \rangle \sim 18$, while $\langle n_c \rangle \sim 80$
in the collider mode), the larger values of the $B$ particle and decay-lepton momenta and of the $B$-decay length due to the asymmetric geometry of the fixed-target configuration, all of this resulting in much better trigger and tagging efficiencies. For comparison, note
that an $e^+e^-$ $B$-factory at the $\Upsilon$ with $L \simeq 10^{34}$ cm$^{-2}$ s$^{-1}$ produces about $10^8$ $b\bar{b}$ per year. For CP-violation studies one would like to collect $\sim 10^3$ events of processes such as
$B^0_d \to \psi K \to \mu^+\mu^-\pi^+\pi^-$ with branching ratios $\sim 10^{-5}$, so that even with full efficiency at
least $10^8$ $b\bar{b}$ pairs are required.

The subject of CP-violation studies in $b$ decays in the context of the LHC was reviewed by Pich [75]. A. Fridman presented a comparison of $e^+e^-$, fixed-target, and collider hadron
machines. He also studied, by performing full simulations, the problem of the fake asymmetries which are induced in pp collisions by the fact that the pp initial state is not a CP
 eigenstate. The conclusion, also confirmed by an independent study by M. Lusignoli, A. Pugliese and H. Steger, is that these asymmetries are an order of magnitude below the expected CP-violation effects and moreover, to a reasonable precision, they can be corrected for. M. Lusignoli and M. Masetti contributed an analysis of $B_c \equiv b\bar{c}$ mesons that can be studied at the LHC but not at $e^+e^-$ $B$-factories.

On the experimental side the key issue is to which extent the large number of produced $b\bar{b}$ pairs can really be identified and studied. The results of UA1 and those recently
obtained by CDF on the identification of a number of clear $b$ events are a promise for the
future development of $b$ physics at hadron colliders. At CERN the group led by P. Schlein
is currently testing at the SPS collider a relatively simple silicon detector for $b$ physics at hadron colliders. At the Workshop this group contributed a study of a possible detector
for the LHC, based on the idea which is now being tested (presented in talks by P. Schlein
and S. Ehren).

The different options for $b$ physics in the fixed-target mode were discussed by G. Fide-
caro and by F. Grancagnolo.

11 Exotica

Clearly one can think of an almost unlimited collection of unexpected phenomena. Many types of exotic phenomena were considered at the Workshop. Some of these un-
orthodox possibilities have been already mentioned in the previous sections (new heavy
quarks, coloured states, broken R-parity). Others have been considered at the Workshop,
particularly (not surprisingly) by the Working Group on Alternative Symmetry Breaking
and Exotica [57]: compositeness effects, excited quarks and leptons, heavy stable particles,
etc. But the most interesting subject in the area of exotic phenomena is the issue of $B+L$
violation through instantons. It was originally observed by 't Hooft [76] that electroweak
instantons in general break fermion number. While, at zero temperature, the effect is
suppressed by a factor of $\exp (-4\pi/\alpha_W)$ it could become unsuppressed at sufficiently large
 temperatures or large energies [77]. Recently a number of authors have attempted to cal-
culate the electroweak-instanton amplitudes for the production of large numbers of gauge
and Higgs bosons. In the naive instanton approximation, the production cross-sections
increase with the number of produced particles and with energy. On the basis of these
calculations it has been suggested that such fantastic events, with tens of $W$, $Z$, and Higgs
bosons, could possibly be visible at LHC/SSC energies. Such types of events would certainly not go unnoticed in any detector, so that no particular experimental preparation is needed. However, it must be said that calculations that predict large enough cross-sections to be observable at the LHC or SSC are based on approximations that violate unitarity. Arbitrarily the cross-sections are fixed at the maximum allowed by unitarity. The treatment of phase space is also very crude [79]. As a result, at parton level one then obtains a threshold value at around 10 TeV. It is evident that all quantitative predictions are without foundation, without an understanding of the mechanism that restores unitarity. Recent works [80] show that the first corrections to the basic instanton result considerably suppress the production cross-sections. Most probably, the LHC and SSC are far too low in energy to have any realistic possibility of observing such phenomena, even assuming that the effect is genuine. Although most likely not of relevance to the LHC and SSC, the conceptual problem connected to this phenomenon is of the utmost importance. It could be a serious indication for the onset of a non-perturbative regime at multi-TeV energies. It is clear that this is a most interesting subject and a continuing theoretical effort for a deeper understanding of the whole question is under way.

12 Conclusion

The main goal of experiments on particle physics in the near future is the clarification of the electroweak symmetry-breaking problem. The solution must be within the TeV energy region: the origin of the weak scale cannot lie too far from $G_F^{1/2} \sim 293$ GeV. Probably a whole universe of new physics will open up. Examples are offered by the supersymmetric model, which provides a well-defined extension of the Standard Model, which is more natural than the Standard Model itself. Other possibilities are less well defined. Apart from possible completions of the Standard Model in the direction of extending the electroweak group (new W' and Z'), all alternatives to fundamental scalar Higgses and supersymmetry involve new strong forces and a breakdown of the perturbative regime in the TeV energy region.

A common feature of all conceivable ways beyond the Standard Model is the prediction of a rich spectroscopy of new states and new phenomena. This means that one expects discoveries over a wide range of energies. Actually it would be a great thing for the LHC and SSC if the low-lying fringes of the new spectroscopy were already found at LEP 1 and 200. Far from decreasing the physics motivations in favour of the LHC and SSC, the discovery at LEP of some new physics or at least of some departures from the Standard Model would make the argument for the LHC even stronger.

The results obtained at the present Workshop, summarized in this article and more in general in these volumes, clearly demonstrate that the discovery potential of the LHC with $L \approx 10^{34}$ cm$^{-2}$ s$^{-1}$ is perfectly adequate to the goal of solving the problem of the electroweak symmetry breaking and of the origin of the weak scale of mass. It is also evident, from the detailed comparison made in the previous sections, that the LHC with $L = 10^{34}$ cm$^{-2}$ s$^{-1}$ is very much comparable with the SSC with $L = 10^{33}$ cm$^{-2}$ s$^{-1}$. For standard Higgses, we have seen that the discovery range extends up to (0.8–1) TeV in both cases. In WW, WZ, ZZ scattering resonances, such as the $R$-like or $\omega$-like ones, vector bosons of technicolour are visible up to 2–2.5 TeV at the LHC and the SSC, while in both cases non-resonant amplitudes are very difficult to study. New W' and Z' can be
found up to 4.5–5 TeV at the LHC, and up to 5–6 TeV at the SSC. Gluinos and squarks can be observed up to 1.5 TeV at the LHC and up to 1.5–2 TeV at the SSC.

In conclusion, I think that it is a fair statement to say that the studies completed for this Workshop have substantially consolidated the case for the LHC.

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HEAVY ION PHYSICS AT VERY HIGH ENERGIES

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1 Introduction

The principal aim of high energy heavy ion experiments is the study of strong interaction thermodynamics. We want to understand the behaviour of bulk matter at densities so high that the interaction of its constituents is governed by QCD. Statistical QCD predicts that at sufficiently high density, there will be a transition from hadronic matter to a plasma of deconfined quarks and gluons—a transition which in the early universe took place in the inverse direction some $10^{-5}$ seconds after the big bang. Ultimately, we hope that heavy ion experiments will provide the tool to study in the laboratory both the transition to and the properties of the primordial quark-gluon plasma. We therefore have to determine the energies necessary to achieve this and find the observables that will give us the information needed to test the thermal nature and probe the primordial state of the system.

A further proposed aim for heavy ion physics at very high energies is the study of coherent $A - A$ collisions (photon-photon or pomeron-pomeron interactions) in a regime where these could lead to the production of Higgs bosons, supersymmetric particles, or $W$ pairs. In particular, coherent heavy ion collisions can provide a high luminosity $\gamma - \gamma$ source; this could allow the observation of specific final states without the strong hadronic contamination present in the corresponding gluon-gluon interaction in proton-proton collisions. We thus have to investigate for what ion beam luminosities such experiments become feasible.

In Table 1 we summarize the present status and the future plans for heavy ion experimentation; it shows three distinct stages. At present, existing sources and existing accelerators are used to provide rather light ion beams (up to $^{28}$Si and $^{32}$S). The main aims at this stage are to establish the feasibility of high energy ion-ion experiments with their very abundant secondary hadron production, to show that there is a chance to obtain high densities, and to look for the onset of new, collective phenomena. It is generally agreed that the experiments carried out so far have achieved these objectives to a considerable degree and provide sufficient justification to continue.

In a second phase, to begin in about three years, both the BNL-AGS and the CERN-SPS will have new injectors able to accommodate really heavy ions, all the way up to uranium. This should make it possible to determine to what extent we can actually get into
Table 1: Status and Planning of Heavy Ion Experimentation

<table>
<thead>
<tr>
<th>Time:</th>
<th>Machine</th>
<th>Beam</th>
<th>CMS Energy [GeV /n-n]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986-1993</td>
<td>BNL-AGS</td>
<td>up to $^{28}$Si</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>CERN-SPS</td>
<td>up to $^{32}$S</td>
<td>20</td>
</tr>
<tr>
<td>1993-1998</td>
<td>AGS+Booster</td>
<td>all A</td>
<td>4 (Pb)</td>
</tr>
<tr>
<td></td>
<td>SPS+Pb Injector</td>
<td>all A</td>
<td>17 (Pb)</td>
</tr>
<tr>
<td>1998-</td>
<td>RHIC</td>
<td>all A</td>
<td>200 (Pb)</td>
</tr>
<tr>
<td></td>
<td>LHC</td>
<td>all A</td>
<td>6300 (Pb)</td>
</tr>
</tbody>
</table>

a regime of thermodynamic behaviour. Moreover, if present estimates are correct, there should be a chance to obtain more conclusive evidence for the onset of quark deconfinement.

The third stage, expected to start around 1998, will bring us into the true high energy heavy ion regime. We should now get average energy densities well above the deconfinement threshold, so that a study of the properties of the quark-gluon plasma should become possible. Now we can also produce systems of nearly vanishing baryon number density (similar to the state of the early universe); it should thus become possible to study critical behaviour in a wide range of the temperature-density phase diagram of QCD matter. And it appears within reach to get even to energy densities for which the quark-gluon plasma is approaching its asymptotically free “ideal gas” form.

2 QCD Thermodynamics

2.1 Results from Statistical QCD

The advent of the quark structure of elementary particles led rather directly to the prediction of quark matter. Since then, both the new state and the transition between hadronic matter and quark-gluon plasma have been studied extensively. We expect deconfinement in dense matter, because the presence of many colour charges will screen the confining potential between the members of a given $q\bar{q}$ or $qqq$ system. The density of the system can be increased either by “compression” (an increase in baryon number density or baryonic chemical potential $\mu_B$), or by “heating” (an increase in the initial energy density $\epsilon$). This leads to a critical transition curve in the phase diagram of strongly interacting matter, as shown in Fig. 1.

The crucial features for our present considerations are the values of the transition parameters (temperature, density, energy density, screening length). These questions have been addressed in statistical QCD both in the lattice formulation and in various effective Lagrangian models.

In the computer simulation of statistical QCD on the lattice [1], one tries to calculate the relevant quantities from first principles, without any simplifying physical assumptions. The quantitative reliability of the results is at present, however, still somewhat limited by technical restrictions (memory size, operating speed of available supercomputers). Nevertheless, the results of lattice QCD today do give us a reasonably good general
understanding of the critical behaviour of strongly interacting matter at vanishing baryon number density, and this appears to be the first time that basic dynamics leads directly to predictions for equilibrium thermodynamics.

Figure 1: The phase diagram of strongly interacting matter.

Figure 2: Energy density $\varepsilon$ and pressure $P$ for QCD matter with quarks of two flavours, as function of the temperature $T$; from [2].

In Fig. 2, we show the behaviour of energy density and pressure for QCD matter with light quarks of two flavours ($u$ and $d$), as calculated on the lattice [2]. We note that at a critical temperature $T_c$, the energy density undergoes a rapid transition from low values, corresponding to a hadron gas, to much higher values, corresponding to a quark-gluon plasma. For ideal (i.e., non-interacting) systems, the ratio of the energy densities of pion gas to quark-gluon plasma is given simply by the corresponding degrees of freedom; for $N_f = 2$, this means $\varepsilon_\pi/\varepsilon_{QG} = 1/10$. The energy density of the ideal plasma, including finite lattice corrections [3], is also shown in Fig. 2, and at high temperatures, the calculations appear to approach this value. In an ideal gas, however, energy density and pressure
are related by $(\varepsilon - 3P)/T^4 = 0$, and we see that this condition is certainly not fulfilled for $T \leq 1.5 T_c$; below $1.5 T_c$, the energy density overshoots the Stefan-Boltzmann limit, the pressure falls much below it. For a pure $SU(3)$ gauge system (i.e., for $N_f = 0$), these deviations from ideal gas behaviour were recently studied in detail [4]; the result is shown in Fig. 3 and indicates that the system may not become ideal until even higher temperatures.

Figure 3: Energy density $\varepsilon$ and interaction measure $(\varepsilon - 3P)/T^4$ in pure $SU(3)$ gauge theory, as function of the temperature $T$; from [4].

The order of the transition is at present under intense investigation by lattice studies [1]. One finds a first order deconfinement transition for $N_f = 0$, and a first order transition corresponding to chiral symmetry restoration and deconfinement for $N_f \geq 3$, in the limit of massless quarks. For $N_f = 2$, the transition appears to be continuous for present lattice sizes and quark masses; however, for two light and one heavy quark species (corresponding to the actual $u, d, s$ quarks), it becomes first order when the strange quark mass reaches a certain values [5]. More detailed quantitative studies are needed here. All results at vanishing baryon number density agree, however, on the same transition point for deconfinement and chiral symmetry restoration.

The physical value of the transition temperature is for present, not yet asymptotic lattice sizes best determined by calculating both $T_c$ and the hadron masses in units of the lattice spacing; the ratio then gives us $T_c$ in terms of meson or baryon masses. In Fig. 4 we show the result for $T_c$ as determined from $m_{\rho}$, for different $N_f$. The most reasonable value for the actual physical case is $T_c \approx 150$ MeV; we must keep in mind, however, that in present calculations the ratio of $\pi$ to $\rho$ mass has not yet reached its physical value, and hence quantitative results are not yet final. To be on the safe side, we shall consider the critical temperatures to lie in the range $T_c = 150 - 200$ MeV; the corresponding critical values of the energy density necessary for deconfinement are $\varepsilon_c \approx 1 - 3$ GeV/fm$^3$.

Finally we want to note the result of lattice calculations of the screening length. Since bound states will "melt" in dense matter when the screening radius becomes significantly smaller than the binding radius, the temperature dependence of the screening radius $r_D(T)$ gives us some idea of when specific bound states will disappear. From Fig. 5 we see that above $T \approx 1.2 T_c$, even the tightly bound $c\bar{c}$ state $J/\psi$ will become deconfined.

An alternative approach to statistical QCD is offered by the study of effective La-
Figure 4: Deconfinement temperature $T_c$ for QCD matter with $N_f$ flavours of light quarks, as function of the lattice size $N_T$, from [1].

The basic idea here is to construct a model Lagrangian which incorporates as much as possible of the known low density hadron physics, and then check what it predicts at higher densities. Rather detailed studies in the framework of chiral perturbation theory [6] reproduce the known pion physics at zero temperature, and predict chiral symmetry restoration at $T_c \simeq 190$ MeV, in accord with lattice results. Another effective Lagrangian study [7] has also been extended to non-zero baryon number density; it leads to the interesting phase diagram shown in Fig. 6, with a continuous transition at zero baryonic chemical potential $\mu_B$, which then turns into a first order transition at some tricritical point for $\mu_B > 0$. This behaviour illustrates that new features can still be expected in the region of the phase diagram not yet accessible to lattice studies.

Figure 5: Colour screening radius $r_D$ as function of the temperature $T$, for QCD matter with $N_f$ light quarks; from [1].
Figure 6: Phase diagram for chiral symmetry restoration in QCD matter; from [7].

2.2 Conditions in Nuclear Collisions

In statistical QCD, we study the equilibrium thermodynamics of strongly interacting matter. We would like to test the results experimentally in high energy heavy ion collisions. This leads us immediately to the basic question which such studies have to face: do heavy ion collisions lead to systems dense enough, large enough, and long-lived enough to treat them by the equilibrium thermodynamics based on QCD? Let us first consider the density regime attainable.

The basic observable for an estimate of the initial energy density is multiplicity of the secondary hadrons emitted in the collision. The total multiplicity (1.5 times the observed charged multiplicity) per unit central rapidity interval can be parametrised in high energy proton-proton collisions by

\[(dN/dy)_p = 0.8 \ln \sqrt{s};\]  

(1)

this form describes well all data from SPS to Tevatron energies [8], with \((dN/dy)_p\) growing from 2.4 at 20 GeV to about 6 at 1.8 TeV. This is extrapolated to central \(A - A\) collisions by

\[(dN/dy)_A = A^\alpha (dN/dy)_p,\]  

(2)

with \(\alpha \geq 1\). For \(\alpha = 1\), we simply have a superposition of \(A\) independent \(p - p\) collisions; if there is rescattering between the different nucleons and/or the produced secondaries, we will have \(\alpha > 1\). Present data from nuclear collisions give \(\alpha \geq 1.1\) [9], and this leads for the multiplicity per unit central rapidity in \(Pb - Pb\) interactions \((A=208)\) to the range of values:

\[
\begin{array}{lcl}
\text{SPS} & (17 \text{ GeV}) & 500 - 800 \\
\text{RHIC} & (200 \text{ GeV}) & 900 - 1500 \\
\text{LHC} & (6300 \text{ GeV}) & 1500 - 2500
\end{array}
\]

(3)

The lower number always corresponds to \(\alpha = 1\), the higher to \(\alpha = 1.1\). Large as these numbers may seem, it should be noted that fixed target experiments at SPS and AGS, which cover several units of rapidity, have shown that multiplicities in the hundreds can indeed be handled.
If the observed secondaries have come from the initial interaction region in "free flow", then the initial energy density \( \varepsilon \) in a central \( A - A \) collision is given by [10] \[
\varepsilon = \left\{ (dN/dy)_A m_T \right\} / (\pi R_A^2 \tau),
\]
where \( m_T = (p_T^2 + m^2) \) denotes the transverse energy of the secondary, \( R_A \simeq 1.2 A^{1/3} \) the nuclear radius, and \( \tau \) the formation time or longitudinal extension of the equilibrium system. With the estimates \( m_T \simeq 0.5 \text{ GeV} \) and \( \tau \simeq 1 \text{ fm} \), we obtain from eqs.(1) and (2) \[
\varepsilon = 0.09 A^{-2/3} \ln \sqrt{s},
\]
and from this for central \( Pb - Pb \) collisions:

\[
\begin{array}{ccc}
\text{SPS} & 1.5 & 2.5 \text{ GeV/fm}^3 \\
\text{RHIC} & 2.8 & 4.7 \text{ GeV/fm}^3 \\
\text{LHC} & 4.6 & 7.8 \text{ GeV/fm}^3 \\
\end{array}
\]

The values we have used for \( m_T \) and \( \tau \) are "conservative" — the transverse mass increases somewhat with \( \sqrt{s} \), and enhanced nuclear stopping would reduce \( \tau \); there are models [11] which give \( \tau \sim A^{-1/6} \). On the other hand, a diffuse edge of the interaction region would result in a larger value for \( R_A \), which could offset these effects. We should further note that the values in eq.(6) give the expected average initial energy density; it should be possible to trigger on higher values. But even the average values give a gain by a factor of 4–7 in comparison to the average energy density in \( p - p \) collisions.

![Graph showing the expected range of the average initial energy density \( \bar{\varepsilon} \) versus incident CMS energy \( \sqrt{s} \); also shown is the predicted range of the critical energy density \( \varepsilon_c \) for deconfinement.]

In Fig. 7 we show the variation of the average energy density in central \( Pb - Pb \) collisions, together with the critical energy density \( \varepsilon_c \) determined in section 1.1. We note that at the LHC we are well above this value and are in fact getting into the range in which \( \varepsilon \) becomes high enough to produce an ideal quark-gluon plasma.

We now want to consider briefly the question of how the energy density \( \varepsilon \) can in practice be varied for a given collider. In \( A - B \) collisions, with \( A \ll B \), we have different values...
of $\epsilon$ for events at different impact parameter $b$, i.e., for events of different multiplicity or different transverse energy $E_T$. Going from peripheral to central collisions, we increase $\epsilon$: the effective transversal overlap area remains constant, as the smaller projectile after complete "immersion" hits the larger target at smaller and smaller $b$; the effective number of participants increases, however, since the target contains more nucleons in the center, at $b = 0$, than at the edges. In "symmetric" $A - A$ collisions, with large $A$, this is no longer the case, since over most of the impact parameter range, the number of participants and the overlap area are essentially proportional. The result [12] is illustrated in Fig. 8, where we show $\epsilon$ as function of $E_T(b)/E_T(0)$. For an infinite nucleus, $\epsilon$ becomes independent of $E_T(b)/E_T(0)$; deviations from constancy are thus of purely geometric origin. In particular, the drop of $\epsilon$ as $E_T(b)/E_T(0) \rightarrow 0$ is extremely dependent on the specific nuclear edge structure; it is more a surface than a volume effect and hence not useful to study the $\epsilon$ dependence of any observables. For $A - A$ collisions, we thus have to find some other way to change $\epsilon$.

![Figure 8: Energy density $\epsilon$ vs. transverse energy $E_T$ as function of the impact parameter $b$, for $O - Pb$ and $Pb - Pb$ collisions; the dashed line shows the behaviour for $A - A$ collisions in the limit of infinite nuclear size; from [12].](image)

In principle, the best way would be to vary the incident energy $\sqrt{s}$ for given $A$, since this would change $\epsilon$ at constant volume. In practice, this requires large variations of the beam energy, since $\epsilon \sim \ln \sqrt{s}$. Moreover, a reduction of $\sqrt{s}$ at a given collider is in general accompanied by a considerable luminosity drop [13][14] and hence for many experiments not very useful.

This leaves us with $A - A$ collisions at several $A$ and fixed $\sqrt{s}$ as the only viable road to different $\epsilon$, even though this changes the associated volume as well. Going from $U - U$ to $S - S$ collisions reduces $\epsilon$ by a factor two or more; to achieve such a change by varying $\sqrt{s}$ would require going from the peak LHC energy of 6.3 TeV down to one-hundredth of this value, which is expected to decrease the luminosity by almost two orders of magnitude. In contrast, reducing $A$ will generally increase the luminosity, so that most rates should not be too much affected. For these reasons, it is very important to include the capability to run at varying $A$ from the beginning among the essential requirements in planning the heavy ion mode of any collider.
Finally we should note that in view of these considerations, the study of QCD thermodynamics at different accelerators, but for the same or similar $A$, plays an important complementary role.

What temperatures do the values of $\epsilon$ in eq.(6) correspond to? For an ideal plasma with three flavours of massless quarks we have

$$\epsilon = (47.5\pi^2/30)8 T^4,$$

which leads to an initial temperature $T = \epsilon/(1553)^{1/4}$, with $\epsilon$ in GeV/fm$^3$ and $T$ in GeV. We can now use the energy density estimates of eq.(6) to get the corresponding temperatures. Before we list these, we want to note an alternative way to estimate $T$. If the initial bubble of matter undergoes longitudinal hydrodynamic expansion to attain the observed final state, rather than the free flow assumed in eq.(4), then the entropy is conserved, not the energy: part of the initial energy goes into work against the pressure of the vacuum on the system [16]. The initial entropy density $s$ in a central $A - A$ collision is obtained from

$$s = 3.6(dN/dy)A/(\pi R_A^2 \tau),$$

which for an ideal plasma leads to $T = (s/2605)^{1/3}$, with $T$ in GeV and $s$ in fm$^{-3}$. As already noted, this leads to somewhat higher initial temperatures, and hence also to higher initial energy densities. The temperature values for $Pb - Pb$ are (in MeV):

<table>
<thead>
<tr>
<th></th>
<th>$s$</th>
<th>$T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS</td>
<td>170 - 190</td>
<td>160 - 190</td>
</tr>
<tr>
<td>RHIC</td>
<td>200 - 220</td>
<td>200 - 240</td>
</tr>
<tr>
<td>LHC</td>
<td>220 - 250</td>
<td>230 - 280</td>
</tr>
</tbody>
</table>

The first column corresponds to free flow, the second to isentropic expansion. With increasing collision energy, the difference between the two temperature estimates (and hence between the corresponding energy densities) increases. For $Pb - Pb$, we obtain for free flow $\epsilon_{Bj} \approx 0.52 \ln \sqrt{s}$, for isentropic expansion $\epsilon_S \approx 0.32 (\ln \sqrt{s})^{4/3}$. The resulting behaviour of $\epsilon$ is illustrated in Fig. 9. We note that only at LHC energies the two have

![Figure 9: Initial energy density $\epsilon$ vs. incident CMS energy $\sqrt{s}$ for free flow [10] and hydrodynamic flow [16].](image)
become really distinct, so that then the effects of longitudinal hydrodynamic expansion should become evident even for average quantities.

In section 1.1, we had seen that so far the most reliable calculations are available for systems of vanishing baryon number density; this is also the situation which presumably existed at the end of the quark-gluon phase of the early universe. When can we expect similar conditions in nuclear collisions? From $p - A$ collisions at $A \simeq 200$, we know that in passing through the nuclear target, the projectile proton looses approximately two units in rapidity. The corresponding baryon number distribution is then centered at $Y - \delta y$, where $Y \simeq \ln(\sqrt{s}/m_p)$ denotes the maximum rapidity and $\delta y$ the rapidity shift of a nucleon passing a nuclear target; the distribution vanishes at $Y$ and $Y - 2\delta y$. The overall baryon-free region in rapidity thus becomes

\[ (\Delta y)_0 \simeq 2(Y - 2\delta y), \]  

(10)

target. If $\delta y$ is the same in $A - A$ collisions as for $p - A$, then we get:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$2Y$</th>
<th>$\delta y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS</td>
<td>0.8</td>
<td>5.8</td>
</tr>
<tr>
<td>RHIC</td>
<td>2.7</td>
<td>10.7</td>
</tr>
<tr>
<td>LHC</td>
<td>9.6</td>
<td>17.6</td>
</tr>
</tbody>
</table>

(11)

Eq.(11) is consistent with recent $p - \bar{p}$ data [17], which show at $\sqrt{s} = 1800$ GeV, where $2Y \simeq 15$, a baryon-free region of at least 6.5 units; even with $\delta y = 2$ we expect seven units. It is not clear, however, if $A - A$ collisions do not give enhanced stopping, i.e., $\delta y > 2$, and hence a smaller baryon-free region. This has to be studied by event generators for nuclear collisions, and we shall return to such studies shortly. In Fig. 10 we show the baryon-free regions at the different accelerator energies. Even if there is more stopping than expected from $p - A$ collisions, however, the LHC still provides an ample safety margin.

What can we say about the baryon-rich fragmentation region at very high energies? The kinematic compression experienced by target and projectile is essentially determined by the rapidity shift $\delta y$ for nucleons [18]; if this is not dependent on $\sqrt{s}$, then the kinematic compression will not increase by going to higher incident energies. The energy deposited in target or fragmentation regions is also expected to depend only very weakly on the incident

![Figure 10: Baryon number density distribution in rapidity $y$ vs. incident energy $\sqrt{s}$.](image)

197
energy [9]. This leads to the conclusion that a baryon-rich state of strongly interacting matter is better studied at a fixed target machine with high A beams; there appears to be no particular reason to consider this regime at high energy colliders, where it is not so easily accessible.

So far, we have addressed general aspects of nuclear collisions, extrapolating from known features of p−p and p−A interactions. This is done in more detail in specific event generators, which are obtained by assuming some particular form of interaction in the course of the collision [19]. In PYTHIA, the interaction is simply taken to be a superposition of individual nucleon-nucleon collisions, without any secondary interactions; particular attention is paid, however, to obtain the correct high energy behaviour of the p−p interaction, including minijet effects. In VENUS, on the other hand, the interaction is assumed to be string fragmentation, with strings formed also between nucleons and secondaries, as well as between different secondaries. This model has been used so far more at lower energies, and it probably has to be complemented for high energy features (minijets). It does give us some idea of rescattering effects already now. In addition, studies using FRITIOF and the dual parton model are under way. In all cases, the event generator should be tuned to account correctly for the general features of p−p data at all available energies. For A−A collisions, the different codes will then show us the role of different interaction schemes corresponding to different extrapolations.

![Graph](image)

Figure 11: Multiplicity for unit central pseudorapidity η as function of incident CMS energy square root of s in p−p and p−̄p collisions, compared to calculations by PYTHIA and VENUS; the dashed line is the fit from [8] used in the text.

Let us look at some first results. In Fig. 11, we see that both PYTHIA and VENUS describe correctly the energy dependence of the average multiplicity per unit central rapidity in p−p collisions, and that this dependence is in fact well reproduced by eq. (1). Going to Pb−Pb collisions at LHC energy, PYTHIA recovers the result listed in eq.(2), with (dN/dy)_{pB} = 1500. On the other hand VENUS, because it includes rescattering, gives a considerably larger value, (dN/dy)_{pB} = 2500. First estimates from the dual parton model give much larger values still. It is thus possible that our “conservative” estimates of energy densities and temperatures for RHIC and LHC are in fact too conservative.

In Fig. 12, we show the baryon number distributions from PYTHIA and VENUS. For Pb−Pb at the LHC, PYTHIA gives about 14 units of baryon-free rapidity region. This
Figure 12: Net baryon number distribution for $Pb - Pb$ collisions at LHC energy as predicted by PYTHIA (a) and VENUS (b).

is more than the 10 units we had found in eq. (11) by extrapolating $p - A$ data, since PYTHIA contains no nuclear stopping. VENUS, with more secondary interactions, gets only 8 units, which, however, is still only half of the total LHC rapidity region.

These results are just the beginning of event generator studies in this field. Much further work is in progress and should give us information also on particle ratios and momentum spectra.

2.3 Volumes and Life-Times

Before we can use heavy ion collisions to study equilibrium thermodynamics, we must make sure that the volume and the life-time of the systems experimentally produced are sufficiently large. This becomes all the more crucial for the study of critical behaviour, which becomes really "critical" only in the infinite volume limit. How can we check volumes and life-times?

The initial interaction volume has already been introduced in eq. (3); for a central $A - A$ collision, it is $V_0 \simeq \pi R_A^2 \tau$, where $R_A \simeq 1.2 A^{1/3}$ denotes the effective transverse nuclear radius and $\tau \simeq 1$ fm the initial longitudinal extension of the system which will later thermalize, or, equivalently, the formation time. This system now expands, and at the time of transition to hadronic matter, it has attained the size $V_c = V_0 (\varepsilon_0/\varepsilon_c)$, where we have used $\varepsilon_0$ to denote the initial energy density. This means that $V_c$ increases with $(dN/dy)$; at the LHC, the transition volume $V_c$ is about 5 - 8 times larger than the initial volume. For $Pb - Pb$, this gives at the transition point a volume of some 800 – 1200 fm$^3$. The system now continues to expand until freeze-out. The freeze-out radius can be estimated by supposing that interactions stop when the energy density has dropped to that of an ideal pion gas at $T \simeq T_c = 150$ MeV. For lead beams, this gives us a freeze-out radius

$$ R_F \simeq 1.24 (dN/dy)^{1/3}. $$  \hspace{1cm} (12)

Another possible estimate for $R_F$ is obtained if one supposes freeze-out to take place when the mean free path $\lambda$ of pions has reached the size of the system [20],[21]. With
\( \lambda = V_F/(dN/dy)\sigma_* \) and \( \sigma_* \approx 20 \text{ mb} \), this leads to
\[
R_F^\lambda \approx 0.69 \left(\frac{dN}{dy}\right)^{1/2}.
\] (13)
for the freeze-out radius. Introducing an energy dependence of \( \sigma_* \) [9,22] leads to yet another form, which grows as \( (dN/dy)^{8/12} \) and thus falls between the two cases we had discussed.

Figure 13: Freeze-out radii \( R_F \) vs. central charged multiplicity, determined from mean free path (\( \lambda \)) and ideal gas (\( \varepsilon \)), for hadron-hadron and nucleus-nucleus collisions; from [21].

Experimentally, the freeze-out size can be determined by particle interferometry, based on the Hanbury-Brown–Twiss method to measure star sizes. In Fig. 13 we see that at present multiplicities, both forms (12) and (13) accommodate the data. It should be emphasized that these data lead to freeze-out radii which are almost a factor two larger than the radii of the projectiles. This supports the idea that nuclear collisions indeed produce bubbles of expanding strongly interacting matter and thus gives us a first hint that we are on the right track. From Fig. 14 we conclude that already a lead beam in the SPS should allow us to distinguish the two forms (12) and (13), and that at the LHC lead-lead collisions should produce volumes of some \( 10^4 \) to \( 10^5 \text{ fm}^3 \). Thus nuclear collisions can indeed be expected to lead to volumes which are very much larger than the few \( \text{fm}^3 \) typical of nucleon-nucleon interactions.

The use of like-particle interferometry to determine the freeze-out radii will, however, encounter some difficulties at very high energies. The linear size of the system is inversely proportional to the momentum resolution needed to study the interference between partners, and this may at LHC energy surpass the feasible. Moreover, at a radius of some 20 fm the Coulomb interaction between like-sign charged particles becomes very strong and may mask the Bose-Einstein interference. Hence the proposal [23],[24] to study correlations in the longitudinal instead of the transverse dimension is very interesting. It would replace the transverse scale of nuclear size by the longitudinal scale of only one fermi, so that after expansion even by a factor five, the corresponding radii would still be less than 5–10 fermi.

The life-time of the produced bubble in a possible plasma phase can be estimated if we assume longitudinal hydrodynamic expansion; from entropy conservation we then get
\[
\tau_c = \tau_0 \left(\frac{T_c}{T_0}\right)^3,
\] (14)
with $\tau_0 \approx 1$ fm for the initial state formation time. This gives

$$SPS \quad RHIC \quad LHC$$

$$\tau_c[\text{fm}] \quad 1.2 - 2.0 \quad 2.4 - 3.2 \quad 3.6 - 6.5$$

for the plasma life-time at the various energies. A higher initial temperature, and even more so a first order transition, would prolong considerably the time until the system is completely hadronized.

### 2.4 The Onset of Thermalisation

How can we test whether the system produced in a heavy ion collision has reached thermal equilibrium? The starting point of the collision is evidently the interaction of individual nucleons in the projectile with those in the target. The extreme opposite to thermalisation is thus a superposition of nucleon-nucleon collisions, with each projectile nucleon interacting with just one target nucleon. On the way to thermalisation, we have "rescattering": a given nucleon will interact with more than one other nucleon, it will interact with secondaries produced in previous collisions, and these secondaries will interact with each other. Particle ratios provide us with an effective tool to check whether rescattering has occurred and brought us closer to thermal equilibrium. Consider as example the production ratio $K^+/\pi^+$. In $p - p$ interactions at $\sqrt{s} = 20$ GeV, it is found to be $0.07 \pm 0.02$ [25]. Recattering will increase this ratio, and after "enough" rescattering, there will be equilibrium. The $K^+/\pi^+$ ratio attains a value of about 0.20 in an equilibrium hadron gas at $T = 150$ MeV and vanishing baryon number density [26]. We therefore want to check how far nuclear collisions bring us on the road to equilibrium, and the observation of $K^+/\pi^+ \simeq 0.19 \pm 0.03$ in $Si - Au$ collisions at the AGS [27] certainly points towards an onset of thermal behaviour. Data from the SPS are in agreement with this. At $\sqrt{s} = 20$ GeV, central $S - S$ collisions [28] give $0.15 \pm 0.03$ at midrapidity for the $K/\pi$ ratio, to be compared to the quoted $p - p$ value; central $S - W$ collisions give about 0.2 at this energy [29]. In general, we expect to move towards thermalisation by increasing the effective $A$ at fixed $\sqrt{s}$ and by increasing $\sqrt{s}$ at fixed $A$: in both cases, the number of secondaries and hence the chance for rescattering increases. It still has to be checked, however, how far
particle ratios such as the considered $K/\pi$ ratio increase in event generator codes which include only one or two rescatterings and thus are probably not yet thermal. Furthermore,

![Graph](image)

Figure 15: The $K/\pi$ ratio in $p-p$ and $p-\bar{p}$ collisions as function of the incident energy square root of $s$, from [25]; also shown are the hadron gas limits for two temperatures [26].

it should be noted that in $p-p$ and $p-\bar{p}$ interactions, the $K/\pi$ ratio increases with increasing $\sqrt{s}$ (Fig. 15) [25] as well as with increasing multiplicity (Fig. 16) [17]. This could be

![Graph](image)

Figure 16: The $K/\pi$ ratio vs. central multiplicity, from [17].

due to rescattering among the produced secondaries, but as well to enhanced strangeness production in minijets. Both can again be checked by event generator studies.

The onset of thermalisation can thus be tested by studying the evolution of strangeness away from the $p-p$ level, for kaons as well as hyperons. We have here implied that a gas of non-interacting hadrons is the equilibrated end-phase; as well, one could consider the ratios obtained from an equilibrium quark-gluon plasma, which expands and subsequently hadronises. It is found, however, that for most ratios the two scenarios agree [30], even though it may take longer to attain equilibrium by hadron interactions alone [31]. There
may be cases, however, for which hadron gas and quark gluon plasma do lead to very different ratios, and hence the study of strangeness evolution has also been proposed as a way to obtain information about the primordial state [31],[32]; we shall return to this point later on.

2.5 Primordial Features

There are two ways to test whether the system produced in a high energy heavy ion collision was in its early “primordial” history in a deconfined state.

We can look for signals which are produced at such early times and are not affected by the subsequent hadronisation. Possible signals of this type are thermal dileptons or direct photons, which are emitted by the plasma and then escape [33][34][35]. In this spirit, one may also study the effect of the produced medium on the observed production rates of heavy quark bound states [36],[37] or hard jets [38]; their initial production is non-thermal, presumably occurs very early in the collision, and can be understood reasonably well in terms of perturbative QCD.

Another approach is to look for primordial remnants in the observed hadronic features. Possible candidates considered in this vein are discontinuities in the momentum distribution of the secondaries, reflecting a first order phase transition [39]; particle ratios which are significantly different for a hadron gas and a hadronising quark-gluon plasma [31],[32]; and droplets of strange matter, baryonic states of very low charge to mass ratio [40].

2.5.1 Thermal Dileptons and Direct Photons

There are several sources for dilepton production in nuclear collisions. They are produced in the decay of the low mass vector mesons $\rho$, $\omega$ and $\phi$. Thermal dileptons are emitted when $\pi^+\pi^-$ or $q\bar{q}$ pairs annihilate in a pion or quark gas. Finally, there are comparatively rare “hard” interactions between incident partons at a very early stage of the collision, leading to Drell-Yan production or to the production of heavy ($c\bar{c}$ or $b\bar{b}$) vector mesons which subsequently decay into lepton pairs. The distinction between dileptons from low mass and high mass vector mesons, as well as that between thermal dileptons from $q\bar{q}$ annihilation and Drell-Yan pairs is somewhat arbitrary; it is mainly motivated by the fact that the production mechanism of high mass dileptons seems to be comparatively well understood in terms of perturbative QCD. In the typical “soft” hadronic regime around the $\rho$, $\omega$ and $\phi$ this is not the case. However, it may well be that below the $\rho$ region, for very soft dileptons, finite temperature perturbation theory may become applicable; this region has been the subject of much recent theoretical work [41],[42],[43].

Thermal dileptons and Drell-Yan pairs moreover lead to different functional behaviour in the dilepton mass $M$. We have

$$ (d^2\sigma/dM^2dy)_{y=0} \sim \exp - (M/T) $$  \hspace{1cm} (16)

for thermal pairs emitted from a system at temperature $T$, and

$$ (d^2\sigma/dM^2dy)_{y=0} \sim M^{-4}f(\tau) $$  \hspace{1cm} (17)

for Drell-Yan pairs, with $\tau \equiv M^2/s$. Eq. (17) does not include contributions from scaling violation terms; these are, however, expected to contribute more at large $P_T$ and not affect greatly the integrated cross-section. Since the mass distribution of thermal dileptons contains directly the temperature of the emitting system, it has been proposed as a “thermometer” for strongly interacting matter [34]. Note here that if used in this way, it does
not tell us whether the system is deconfined or not, since a pion gas as well as a quark-gluon plasma would emit thermal dileptons. In addition, however, we have to ask under what conditions thermal dileptons are at all observable: is there some window between the "hadronic" region around the low mass vector mesons and the high mass Drell-Yan regime, in which thermal pairs should dominate? Theoretical studies [44] based on what we consider today extreme temperatures \( T = 500 - 800 \text{ MeV} \) led to significant thermal production in the mass region above 2.5 GeV, dominating the Drell-Yan distribution. To check this more quantitatively, we need calculations of the thermal spectrum, based on LHC conditions as upper limit, as well as the corresponding Drell-Yan calculations for \( P - P \) collisions, with \( 3 \leq M \leq 10 \text{ GeV} \), including higher order QCD contributions. For the latter task, we encounter some further problems: since at the LHC even \( M = 10 \text{ GeV} \) leads to \( \tau \approx 10^{-8} \), we need quark and gluon structure functions at very small \( x \), where they are not yet known. Moreover, it is known that at small \( x \) there is "shadowing" in nuclear collisions, i.e., the structure function in a nucleus is at small \( x \) reduced in comparison to that in a nucleon. Detailed studies lead us to expect for Drell-Yan production at the LHC a reduction of up to 50% [45].

![Figure 17: Production rates for thermal [46] and Drell-Yan dileptons [47], as function of the dilepton mass \( M \).](image)

Both thermal [46] and Drell-Yan [47] production have now been calculated for LHC conditions; for the latter, the DFLM [48] structure functions were used, without any nuclear shadowing. The result is shown in Fig. 17 for two different initial temperature values, corresponding to our conservative density estimate for the lower and to about twice that density for the higher value. We conclude that for the lower density, there does not seem to be a clear-cut window for the observation of thermal dileptons; this, incidentally, is in accord with the observation that the mass distribution for \( 1.7 \leq M \leq 3.5 \text{ GeV} \) in present dilepton data from nuclear collisions [49] is in accord with the functional form found in \( p - p \) Drell-Yan production. At the higher density, the situation improves somewhat. All in all, the usefulness of thermal dileptons as thermometer for strongly interacting matter is not a priori clear; if we can get to densities at or above the upper end of our estimated average, it appears possible.

For direct photons, the main competition at low momenta comes from the decay of hadrons, mainly \( \pi^0 \) and \( \eta \) [50]. At high momenta, there are in addition direct photons from
Compton scattering. The rates for thermal photons were compared [46] to those from the other two mechanisms; the result is shown in Fig. 18, again for two possible densities. At low density, the thermal photon rate is a factor 20 lower than that from hadron decays; at higher density, this improves, particularly at higher momenta. The feasibility thus depends very much on how well the hadron decays can be identified and eliminated. At low density, signal and background moreover have almost the same functional form; for higher densities (higher $T$ and hence flatter thermal distributions) this again improves.

2.5.2 The Spectral Analysis of $c\bar{c}$ and $b\bar{b}$ States.

In view of the problems encountered for thermal dileptons and photons as tools to probe the primordial features of strongly interacting matter, another means of analysis would certainly be very helpful. This may be provided by studying the spectra of heavy quark bound states ($c\bar{c}$ and $b\bar{b}$) produced in heavy ion collisions. A suppression of the $J/\psi$ signal relative to the Drell-Yan continuum had in fact been predicted as a signature for deconfinement [36] and was subsequently observed by the NA38 collaboration at the CERN-SPS [51]. The observed features have in the meantime also been accounted for by absorption in dense hadronic matter, coupled with initial state parton scattering [52][53]. The effect thus does seem to establish the production of dense, strongly interacting matter; to check whether this matter is already deconfined or still in a hadronic state, further experimental study is required. But we can use it as a starting point for a spectral analysis of QCD matter [12], very similar to the spectral analysis of stellar matter used in astrophysics. Stellar matter emits radiation containing spectral lines from the excitation and ionisation of various elements. The hotter the matter is, the lower is the intensity of the spectral lines from low-lying atomic excitation/ionisation states: with increasing temperature, these states become "suppressed" by thermal excitation. In much the same way, we expect "cold" QCD matter to show charmonium and bottomium signals at the same rate, relative to the Drell-Yan continuum, as in $p - p$ collisions; an increase in temperature should then lead to $J/\psi$ and $\psi'$ suppression, and still further increase to stronger suppression and to that of higher mass bound states (Fig. 19). Different suppression mechanisms (deconfinement, absorption) will also lead to different suppression patterns in energy density and in the
Figure 19: Schematic illustration of the spectral analysis of strongly interacting matter, using $c\bar{c}$ and $b\bar{b}$ bound states; from [12].

$P_T$ of the bound states. In Fig. 20, we show the predicted $P_T$ distributions for $J/\psi$ production in $S-U$ and $Pb-Pb$ collisions at the SPS, based on deconfinement, absorption, and absorption with initial state parton scattering as suppression mechanisms. We note that the present $S-U$ data are in accord with all three schemes; considerable differences in the predictions arise, however, already for the large $P_T$ behaviour in $Pb-Pb$ at the SPS. In Fig. 21, the suppression patterns of the $\psi$ at SPS, RHIC, and LHC energies are shown, as predicted by deconfinement. The difference between the suppression patterns by deconfinement and absorption is in Fig. 22 illustrated for $\psi$ and the $\Upsilon$ production at the LHC. The basis for the proposed analysis is certainly not yet complete, however: at TeV energies and large $P_T$, there is abundant $J/\psi$ production from $B$ decay [54], and much of the observable $\Upsilon$ production will come from $\chi_b$ decay [55]. Both these effects have to be taken into account in a realistic analysis of charmonium and bottomonium production in high energy heavy ion collisions.

Finally, let us consider for what energies and luminosities such a spectral analysis is at all possible. We measure the suppression of the different bound states relative to the Drell-Yan continuum, whose overall production rates are unaffected by the nuclear environment. Therefore we want to know under what conditions the Drell-Yan production of lepton pairs in the $J/\psi$ and the $\Upsilon$ range is feasible. To obtain an estimate of the Drell-Yan rates, we use a scaling cross-section form [56] for $p-p$ collisions

$$
(d^2\sigma/dM^2dy)_{p=0} = 3.75 \times 10^{-5} \ M^{-4} \ exp(-15\sqrt{\tau}).
$$

It fits all existing $p-p$ data; to obtain the rates for central $A-A$ collisions, we simply multiply it by $A^2$. Scaling violations are expected to increase the results somewhat [47], and shadowing will reduce it by up to 50% at high energies [45]. Neglecting these effects, we get the cross-sections and rates shown in Table 2. In general, there is a danger that the increase in cross-section with energy is compensated by the lower luminosity of high energy colliders; the need for high luminosities can thus not be emphasized enough. To get a rough estimate of the production rates for heavy quark resonances, assuming a mass resolution of about 100 MeV, we can multiply the Drell-Yan rates by a factor $10^2$ for $J/\psi$ and $\Upsilon$, by a factor 10 for $\psi'$ and $\Upsilon'$. On the other hand, the restriction to central collisions
Figure 20: $J/\psi$ suppression as function of transverse momentum, in central $S-U$ (a) and $Pb-Pb$ (b) collisions at the SPS. The behaviour for by deconfinement (QGP), absorption (HG), and absorption after initial state scattering (IPS) is calculated with parameters tuned for $S-U$ collisions [12]. Data in (a) is from [51].

Figure 21: $\psi$ suppression by deconfinement, as function of transverse momentum, for central collisions at SPS, RHIC, and LHC energies; from [12].

Figure 22: $\psi$ and $\Upsilon$ suppression for central collisions at LHC energy, by deconfinement (QGP) and absorption (HG); from [12].
Table 2: Drell-Yan Cross-Sections and Rates

<table>
<thead>
<tr>
<th>Energy</th>
<th>SPS(17 GeV)</th>
<th>RHIC (200 GeV)</th>
<th>LHC (6300 GeV)</th>
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<td>$L[cm^{-2} s^{-1}]$</td>
<td>$10^{28}$</td>
<td>$10^{26}$</td>
<td>$10^{27}$</td>
</tr>
<tr>
<td>$(d\sigma/dM^2 dy)_{y=0}^{M=4}$</td>
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<td>$4.8 \times 10^{-3}$</td>
<td>$6.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$(d\sigma/dM^2 dy)_{y=0}^{M=9}$</td>
<td>$8.7 \times 10^{-8}$</td>
<td>$1.3 \times 10^{-4}$</td>
<td>$2.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>(events/month)$_{y=0}^{M=4}$</td>
<td>$4.9 \times 10^{3}$</td>
<td>$1.2 \times 10^{3}$</td>
<td>$1.7 \times 10^{4}$</td>
</tr>
<tr>
<td>(events/month)$_{y=0}^{M=9}$</td>
<td>2.3</td>
<td>3.4</td>
<td>$6.2 \times 10^{2}$</td>
</tr>
</tbody>
</table>

and the experimental acceptance will reduce the rates by at least a factor 10, perhaps by as much as $10^2$. Thus a study of the $b\bar{b}$ regime may well be possible only at the LHC.

In terms of the rates just discussed, we can illustrate particularly well the effect of dense strongly interacting matter on charmonium and bottomonium production. Without suppression, we should expect $20 \,000 - 100 \,000 \ J/\psi$'s per month at the LHC, produced predominantly at small $P_T$; with suppression by deconfinement or absorption, there should be essentially none in the range $P_T \leq 3 - 4$ GeV.

### 2.5.3 Jet Quenching and Jet Structure

The production of “hard” jets at large transverse momenta is, just as Drell-Yan or $c\bar{c}/b\bar{b}$ production, a process which in its early stage should be describable by perturbative QCD and hence be understood. We can therefore hope to learn something about dense strongly interacting systems by studying the effect they have on this process. In a $p-p$ collision, a hard parton will be emitted and subsequently hadronize by forming $q\bar{q}$ pairs as it passes through the vacuum. This process leads for the parton to a certain energy loss per unit rapidity. In dense matter, this loss will presumably increase (“jet quenching”), but it should be quite sensitive to the state of matter [38]. Recently, the energy loss for jet production in hadronic matter was compared to that in a quark-gluon plasma [57],[58]; the latter is found to give very little damping (“jet unquenching”), so that a change in the jet production could signal a change of state of the medium through which it has passed. More detailed studies comparing jet production in $p-p$ collisions to that in hadronic matter and in a plasma are certainly needed.

Another possible tool to probe the early history of heavy ion collisions may be the study of the fractal structure of multiparticle production. Jet cascades, again presumably describable by perturbative QCD in their early stages, would lead to intermittent hadron distributions, if these cascades were self-similar [59]. For most types of cascade, this results in a multifractal pattern, whereas it was shown that continuous phase transitions in spin systems lead to fractal behaviour [60]. It has therefore been proposed recently [61],[62] that the fractal dimension of the production process provides information about the thermal or non-thermal nature of the primordial state.

### 2.5.4 Primordial Remnants in Hadronic Observables.

Finally we want to consider the possibility that the observed hadronic final state in some specific features still reflects its early history.

If we produce a thermalised system which subsequently undergoes hydrodynamic expansion, then this should be reflected also in the momentum spectrum of the observed
particles: they should gain in momentum from the collective flow of the medium, and the gain should be greater for heavier particles [63]. As already indicated, it is not so clear, however, whether such flow can be detected at energies below the LHC. The effect of a first order phase transition on such flow has been proposed [39] as a way to check if the system has passed from a quark-gluon plasma to a hadron gas. If we increase the initial energy density of the collision, collective flow will increase the average transverse momentum of the emitted secondaries. In case of a first order transition, there will be a coexistence regime in energy density, for which the pressure (and hence flow) remains unchanged. This predicts a flattening of the $p_T$ distribution of the secondaries when the multiplicity of the reaction is increased. A further increase of multiplicity (and hence initial energy density) should eventually bring us into the plasma regime, with an increasing pressure and hence increasing $< p_T >$. Before we can judge whether a transverse momentum pattern showing such behaviour indeed provides a indication for a phase transition, we must understand more clearly the role of minijets in $p - p$ or $p - \bar{p}$ collisions. At the Tevatron [17], an increase and subsequent flattening of $< p_T >$ of the type just discussed is observed for pions (Fig. 23). An increase is also obtained in event generator studies (Fig. 24), using PYTHIA (with minijets and no rescattering) as well as VENUS (with rescattering but no minijets). Before any interpretation of the energy density variation of $< p_T >$ in nuclear collisions becomes possible, we clearly have to understand better the behaviour in hadron-hadron interactions, in particular the role of jet and mini-jet production [64].

Specific features of strangeness production in heavy ion collisions may constitute another hadronic observable capable of reflecting primordial properties, in particular whether the different quark species were present according to their ideal gas ratios, i.e., were in "chemical" equilibrium [32]. An overall increase of strangeness production in comparison to the average value for $p - p$ collisions is, as already discussed, simply a consequence of multiple rescattering and arises as well for a hadron gas as for a quark-gluon plasma [9][26]. Moreover, it is also observed for high multiplicities in $p - \bar{p}$ collisions at the Tevatron [17]. Nevertheless, for certain channels, hadron gas and quark-gluon plasma may lead to very different predictions. Thus the $\phi$ remains on the hadronic level just a slightly more massive

![Figure 23: The average $P_T$ of $K^\pm$ and $\pi^\pm$ in $p - \bar{p}$ collisions, as function of the charged particle multiplicity; from [17].](image)

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Figure 24: The average $P_T$ of charged particles produced in $p - \bar{p}$ collisions, compared to calculations using PYTHIA and VENUS [19].

$\omega$; on the quark level, it is a $s\bar{s}$ bound state and thus could reflect an enhanced presence of strangeness in the early stages of the system. Similarly, the production of multistrange antibaryons should be enhanced, if the primordial state was a quark-gluon plasma $[32]$, in both cases, a comparison of the ratios for a hadron gas and for a quark-gluon plasma would be very interesting.

Finally we note the possibility of producing and observing hitherto unknown forms of hadronic matter. If up, down and strange quarks are present in equal amounts in an initial state of chemical equilibrium, then bubbles of strange matter may arise as stable end products in the subsequent hadronisation $[40]$. These "strangelets" would be systems of non-vanishing baryon number, containing all three quark species in equal amounts and thus electrically neutral. The observation of baryonic states with $A \gg 1$ and $Z/A \approx 0$ would certainly constitute a very striking signal for the production of quark-gluon matter.

3 Coherent Heavy Ion Collisions

High energy heavy ion collisions in general lead to abundant production of hadronic secondaries; because of just this feature we hope to use such collisions for the study of statistical QCD. However, at large impact parameters $b > 2R_A$, where $R_A$ denotes the nuclear radius, the ion-ion interaction is predominantly electromagnetic. In coherent collisions, in which the ion acts as a whole, this interaction becomes very strong, since it is proportional to the nuclear charge: compared to $p - p$ collisions, we gain a factor $Z^4$, i.e., for $Pb - Pb$ a factor $5 \times 10^7$, in the photon-photon interaction cross-section. Clearly this factor will be reduced by coherence requirements; nevertheless, it stimulated considerable interest in the possibility to use coherent heavy ion collisions for the production of Higgs bosons and supersymmetric particles $[65],[66]$. In the mass range above about 80 GeV (the upper limit for LEP II) and below about 160 GeV (the threshold for $ZZ$ production), any Higgs production in $p - p$ colliders would be severely contaminated by hadronic background. Hence a possible alternative, using coherent heavy ion collisions without any such hadronic background, became particularly enticing $[67]$. Today, after a number of rather detailed studies
[68],[69],[70],[71] this possibility does not seem so promising any more. Let us rather briefly look at what difficulties arise.

The Higgs produced in a $\gamma\gamma$ interaction would subsequently decay into a $b\bar{b}$ pair; hence the signal would be two high $P_T$ $b\bar{b}$ jets, without any associated "debris" from hadronic $A - A$ interactions, to assure coherence. For a Higgs of 100 GeV mass, this leads for $Pb - Pb$ collisions at the LHC to a cross-section of about 100 pb [67]. The upper bound for the ion luminosity at the LHC is [14] $\mathcal{L} \simeq 10^{28}$ cm$^{-2}$s$^{-1}$; this would give about 10 events per year. It was then pointed out, however, that even after coherent Higgs production, the ions could still interact, leading to hadron production; hence this part of the cross-section must be experimentally vetoed [68]. As a result, the accepted cross-section is reduced by a factor 2−5 [68] - [71], as shown in Fig. 25.

![Graph](image)

Figure 25: Higgs production cross-section as functions of Higgs mass $M_H$, without corrections for final state ion-ion interactions (DEZ) and with such corrections (BF, CJ).

Furthermore, the Higgs decay into a $b\bar{b}$ pair has a strong irreducible background of direct $b\bar{b}$ production through $\gamma\gamma$ interactions. Since the direct production is peaked along the $\gamma\gamma$ collision axis, a restriction to large $P_T b\bar{b}$ jets increases the signal-to-background ratio. At best, however, it becomes about 1/5 (see Fig. 26). For the 100 events necessary to provide a 4 standard deviation signal in this case, a luminosity of $10^{30}$ cm$^{-2}$s$^{-1}$ would be needed—well above the possible LHC limit [14].

In addition, there is a strong $c\bar{c}$ background from $\gamma\gamma \to c\bar{c}$; the 2/3 charge of the c makes the $c\bar{c}$ cross-section a factor 16 larger than that for the $b\bar{b}$. Hence an excellent b identification is necessary.

Finally, we have cross-sections for hadronic $b\bar{b}$ production, such as $gg \to b\bar{b}$ or $\gamma\gamma \to b\bar{b}$, which are by orders of magnitude larger than the photon induced production [72]. Hence an excellent veto against beam jets is absolutely essential.

After taking all these factors into account, we conclude [70] [71] that a Higgs search in $Pb - Pb$ collisions at the LHC, with a luminosity of $\mathcal{L} = 10^{28}$ cm$^{-2}$s$^{-1}$ or less, is not feasible.

A possible search for supersymmetric particles or a production of $W$ pairs turned out to be of as little promise [71]. For new charged particles, the mass range accessible to the LHC falls below that for LEP II. As far as $W^+W^−$ production is concerned, the top LHC ion luminosity leads to some 50 – 100 pairs per year. The produced $W$'s decay
Figure 26: Higgs production cross-section with transverse momentum cut $P_T/M_{bb} > 0.4$, compared to hadronic $b$-quark background with same cut [70].

Predominantly into jets however, which would make it difficult to reach sufficient statistics for a systematic study of the process $\gamma\gamma \rightarrow W^+W^-$. Finally we want to comment on the possibility to use diffractive heavy ion interactions for a Higgs search at the LHC [71]. Although the cross-section for Pomeron-Pomeron induced Higgs production is a factor $10^3$ higher for $Pb - Pb$ than for $p - p$ collisions, the attainable luminosity in the ion-ion mode is a factor $10^{-6}$ lower, making a Higgs search with $A - A$ collisions uninteresting.

The detailed considerations of coherent $A - A$ collisions at the LHC, carried out over the past year, thus only reinforce our earlier statement: the raison d'être of high energy heavy ion physics is the study of strong interaction thermodynamics.

Conclusions

We have seen that high energy heavy ion colliders can provide us with the best possible tool for the experimental study of statistical QCD. The LHC is moreover unique in several aspects:

- the expected energy density is well above the critical value for deconfinement and may be high enough to produce an asymptotically free quark-gluon plasma;
- the expected energy density should be high enough to observe any collective flow of the expanding dense matter produced in the collision;
- over half of the available rapidity range will have essentially zero baryon number density, even if there is enhanced stopping in $A - A$ collisions;
- the design luminosity should allow a full spectral analysis of both $c$ and $b$ bound states.

In closing, let us emphasise once more the two requirements which at present appear crucial for an optimal use of the LHC in the study of QCD thermodynamics: the integrated,
as well as the design luminosity must be sufficiently large, and it should be possible to accelerate ions of different $A$, in order to be able to vary the initial energy density.

Acknowledgements

This report is a physics assessment carried out for the ECFA Working Group HEAVY ION PHYSICS AT THE LHC. As such, it is to a large extent based on the work done in the various subgroups of this Working Group; in the APPENDIX, a list is shown of all those who have contributed at various stages to the work of the project, and who have have worked very hard to obtain the results which I have presented here. To all of them, I want to express my sincere appreciation for their help in preparing this assessment. Many results will be given in more detail in Volume III of these Proceedings, and a discussion of the experimental aspects will be given by H. Specht in this volume. – In addition, I want to express particular thanks to U. Heinz, E. Papageorgiu, V. Ruuskanen and D. Zeppenfeld for helpful comments and a critical reading of parts of the manuscript.

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APPENDIX

ECFA Working Group
HEAVY ION PHYSICS AT THE LHC
Conveners: H. Satz and H. Specht

QCD Thermodynamics


Coherent Heavy Ion Collisions

Experimentation at LEP/LHC

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Contributions to this section come from the ep Experimental Area and Detector subgroup and from a part of the Deep Inelastic subgroup.

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1 Introduction

The LHC/LEP complex offers a unique possibility to study collisions between electrons and protons with an energy in the center of mass about 5 times larger than at HERA. In this section we summarise the most relevant aspects of experimentation at this very asymmetric collider.

2 Beam Energies

The choice of the beam energies is a compromise between running at the highest available energies and at the highest luminosities.

2.1 Luminosity

A detailed study of the beam optics and currents [1] has shown that at the highest energy of the proton beam the luminosity is optimum when the electron energy is around 50 GeV and is about 8 times smaller when the electron energy is at 100 GeV, the highest energy of the electrons at LEP (fig. 1). The design peak luminosities are respectively $3 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ and $5 \times 10^{31}$ cm$^{-2}$ s$^{-1}$. In a normal year of data taking, where the colliders would be dedicated to the ep mode, this corresponds to accumulated luminosities of about 1000 pb$^{-1}$ and 100 pb$^{-1}$ at electron energies of 50 and 100 GeV respectively.

2.2 Rates

To quantify the differences between these two extreme modes of operation we have calculated the corresponding rates of events per bin of $(Q^2, x)$. The results are displayed in figures 2 and 3 for neutral and charged current respectively. It is clear that the extension of the phase space does not compensate the loss of luminosity at high energy. The increase of the accessible domain in the $(Q^2, x)$ plane is larger in charged current than in neutral current because it extends the range both to the highest and the lowest $Q^2$. The highest $Q^2$ is a few
times $10^5$ GeV$^2$ and can only be reached at the lower electron energy. It is about 10 times higher than at HERA. The only interest to run at high energy would be to reach the smallest possible $x$ (the Bjorken variable) at a given $Q^2$ where the higher electron energy allows to go two times lower in $x$. This extreme limit in $x$ is 30 times lower than at HERA. We should also mention that it is possible to run the proton energy at 2 TeV without loosing luminosity. This is of special interest to measure the longitudinal structure function. In addition, the luminosity of collisions of electrons with deuterons has been evaluated. Using the present performances of the deuteron bunches at CERN, the anticipated luminosity should be only twice smaller than with the proton beam [1].

3 Background and pile up

In the ep mode, the time between two bunch crossings is 164 ns which is larger than at HERA (96 ns). Moreover, the rate of collisions is at most 100 Hz for $Q^2$ above 5 GeV$^2$ and reaches $10^3$ to $10^4$ Hz when the photo-production events are included. This shows that, in contrast to normal LHC operations, the probability of pile up of two genuine ep interactions is almost zero. There is however a copious source of background which is generated by the electron beam in the LEP/LHC operation: the synchrotron radiations.

3.1 Synchrotron Radiation

To get head on collisions, the electron beam from the LEP ring has to be bent vertically to reach the level of the proton beam which is 1.2 m above in the LHC ring. The bending magnets have to be placed close to the interaction point to minimise dispersion and losses of luminosity. These magnets generate synchrotron radiations from which the detector has to be shielded. The work to optimise the synchrotron radiation in the interaction area was still going on at the time of writing. The first version presented at the Aachen meeting yields 237 kWatt of radiation with a critical energy of 1.3 MeV. This looked prohibitive. Since then, a solution has been found with bending magnets much more segmented. This will lead to a drastic reduction of the synchrotron radiation in the detector [1][2].
Figure 2: Contour of \((\log x, \log Q^2)\) bins (4 bins per decade in \(x\) and \(Q^2\)) which contain more than 100 neutral current events for integrated luminosities of 1000 \(\text{pb}^{-1}\) and 100 \(\text{pb}^{-1}\) at beam energies of 50 GeV \(\otimes\) 8 TeV and 100 GeV \(\otimes\) 8 TeV respectively. The dark shaded area is only accessible with 100 GeV beam electrons. The pale shaded area displays the bins which contain more than 100 events at the higher luminosity and less than 100 events at the lower luminosity.

Figure 3: The same as fig.2 but with charged current events
Figure 4: Basic diagram for deep inelastic scattering

3.2 Proton Induced Background

The usual beam gas and halo background events induced by the proton beam should not present a particular problem. There is however a potential source of background due to the interaction of the tails of the proton beam with the synchroton masks. This effect is the anticipated dominant source of background events at HERA and should be taken into account in the optimisation of the synchrotron radiation.

4 Measurement of Deep Inelastic events

A major topic of physics in ep collisions rests on the measurement of inclusive deep inelastic scattering events. In this section we discuss which part of the \((Q^2, x)\) plane is accessible to measurements with small systematic errors and what are accordingly the detector requirements.

Deep inelastic scattering is an inclusive process which depends only on two variables which are usually two of the three following variables: the square of the four-momentum transfer \(Q^2\), the Bjorken variable \(x\) and the relative energy transfer \(y\). These variables are related by: \(Q^2 = s x y\), where \(s\) is the square of the energy in the center of mass.

In charged current events the scattered lepton is a neutrino (fig. 4). The kinematics can then be only reconstructed from the hadrons. For neutral current events the kinematics can be reconstructed by using either the scattered electron or the hadron flow or both. Let us consider first the case of the electron measurement.

a. Electron measurement

The lines of constant scattered angle in the laboratory frame are drawn in the \((Q^2, x)\) plot of figure 5. It can be seen that even at \(Q^2\) as low as 5 GeV\(^2\), it is possible to cover the complete \(x\) range (from \(x = Q^2/s\) to \(x = 1\)) provided the scattered electron can be measured down to an angle of 3 degrees in the electron direction. From the energy and the angle of the scattered electron, \(Q^2\) can be reconstructed with a very good precision with any modest calorimeter but, as at HERA, the main difficulty is the \(x\) determination, due to the \(1/y\) enhancement factor in the \(x\) resolution:
$\delta x / x = 1 / y \times \delta E_e / E_e$

(where $E_e$ is the energy of the scattered electron)

The $1 / y$ factor implies first that the smearing induced by a sampling calorimeter of resolution $\delta E_e / E_e = 0.10 / \sqrt{E_e}$ can only be kept under control for $y$ above 0.1, second that an error of 1% in the energy scale of the calorimeter generates on the differential cross section an unknown systematic shift which rises as the inverse power of $y$ and reaches already 10% at $y$ around 0.1. It is still possible to improve the energy resolution by using a homogeneous calorimeter but it is very hard to control the energy scale of a calorimeter at a level better than 1%. However, in the LEP/LHC complex there is a very precious tool to calibrate the detector: the $Z_0$ events. By sending positrons and electrons in the LEP ring while keeping the optics of the e-p mode, the estimated luminosity is $10^{30}$ cm$^{-2}$ s$^{-1}$ [1], which is sufficient to produce 3000 $Z_0$ per day.

At the present level of the study it seems therefore possible that from the electron measurement, the systematic errors on the structure functions can be kept below 10% for $y$ above 0.05.

b. Hadron measurement

A deep inelastic event can be described as a three-particle final state with a scattered electron, a current jet, and a target jet in the direction of the proton beam (fig. 4). In detailed Monte-Carlo studies for the HERA collider, it has been shown that $Q^2$ and $x$ can be reconstructed from the total visible hadron flow without identifying the current jet [3] and that when the polar angle of the current jet is larger than 10 degrees, the loss of particles in the beam pipe does not affect the reconstruction of $Q^2$ and $y$ provided the hadrons are measured down to 20 mrad in the proton direction [4]. These detailed Monte-Carlo studies have also shown that the salient features of the detector performances can be inferred by considering only the kinematics of the current jet in the laboratory frame. On figure 6 are drawn lines of constant current jet energies and constant current jet angles in the $(Q^2, x)$ plane at LEP/LHC energies. We can see that the low current jet energies are at low $x$ and that, when $x$ rises, the current jet is emitted more and more in the forward direction. To be more quantitative,
Figure 6: Lines of constant current jet energy $E_j$, lines (dashed), lines of constant current jet polar angle $\theta_j$ with the proton direction (full) and the line of $P_T = 10$ GeV (dot-dashed) at beam energies of 50 GeV $\otimes$ 8 TeV.

Let us consider the following partial derivatives, where the angle $\theta$ is the average polar angle of the current jet:

$$\delta x/x = (-2\cot(\theta) + (1 - 2y)/(1 - y) \times \cot(\theta/2)) \times \delta \theta$$

$$\delta Q^2/Q^2 = (2\cot(\theta) + y/(1 - y) \times \cot(\theta/2)) \times \delta \theta$$

The resolution in the forward direction is clearly dominated by the $\cot(\theta/2)$ and $\cot(\theta)$ terms. For example, assuming that the direction of the current jet is measured with a precision of $\pm 20$ mrad, the uncertainty on $Q^2$ is larger than 25% when the jet angle is below 10 degrees. In addition, the loss in the beam pipe would deteriorate the resolution even more and should thus be kept as small as possible. The measurement of charged current events will therefore be restricted to events with a current jet angle above roughly 10 degrees.

The sensitivity to the energy resolution can be seen in the expressions of the other partial derivatives, where $E_j$ is the energy of the current jet:

$$\delta x/x = 1/(1 - y) \times \delta E_j/E_j$$

$$\delta Q^2/Q^2 = (2 - y)/(1 - y) \times \delta E_j/E_j$$

The resolution on $Q^2$ and $x$ is clearly poor at large $y$ or at low jet energy. So, requiring the resolution on $Q^2$ and $x$ to be better than 20%, it has been shown that, even with an excellent hadronic calorimeter with an energy resolution of $\delta E_h/E_h = 0.4/\sqrt{E_h} \otimes 0.02$, it will be very hard to do a clean measurement at $y > 0.7$ or at $x < 10^{-3}$ [5].

c. Accessible domain for charged current events

To clearly identify the missing scattered neutrino, the missing transverse momentum has also to be above 10 GeV. By combining the limits due to the statistics, the resolution and the identification, we can now assess in which part of the $(Q^2, x)$ plane the systematic errors on the charged current events can be kept below roughly 10%. The resulting contour is drawn in figure 7 and show a sizeable reduction of the accessible domain, especially at large $x$. 
Figure 7: Accessible domain to charge current events. The bold line surrounds the bins where systematic and statistical error can be kept below 10% (4 bins per decade in $x$ and $Q^2$) for an integrated luminosity of 1000 pb$^{-1}$ at 50 GeV $\otimes$ 8 TeV beam energies.

Figure 8: Accessible domain to neutral current events by using electron and hadron measurements. In the surrounded domains, systematic and statistical errors can be kept below 10% for an integrated luminosity of 1000 pb$^{-1}$ at 50 GeV $\otimes$ 8 TeV beam energies.
Figure 9: Accessible domain to neutral current events with statistical and systematic errors below 10% at LEP/LHC (50 GeV $\otimes$ 8 TeV, $L = 1000$ pb$^{-1}$) and HERA (30 GeV $\otimes$ 820 GeV, $L = 100$ pb$^{-1}$). Also shown is the domain measured in fixed target lepton scattering experiments at SLAC, FNAL and CERN.

d. Accessible domain for neutral current events

To reconstruct neutral current events, the scattered electron and the visible hadron flow will be used. The relative weight of the two contributions to the determination of the kinematical variables depends on $Q^2$ and $x$. The overall resulting contour is shown on figure 8 where the accessible domain has been divided for illustration in four parts: the domains where most of the precision comes from the electron or from the hadron flow alone, the domain where the two measurements are available and finally the domain where both measurements will be combined and where $Q^2$ is determined from an electron measurement and $x$ from the hadrons. This overall domain accessible at LEP/LHC at maximum luminosity is also compared in figure 9 with the domain accessible to fixed target experiments at CERN, FNAL and SLAC, and to the domain estimated for HERA with similar assumptions [4]. Compared to HERA there is a gain of about a factor 10 in the highest $Q^2$ and 15 in the lowest $x$. As discussed in section 2.2, by running for a short time with an electron beam of 100 GeV, it is possible to gain another factor of two down to the lowest $x$. The overlap of LEP/LHC with HERA is only significant in the range $10^{-3} < x < 10^{-2}$ but could be easily improved by lowering the energy of the proton beam.

5 Detector Requirements

From the above discussion we can deduce what should be the main criteria that a detector for deep inelastic scattering at LEP/LHC should satisfy:

- detection of hadrons in the proton direction down to 10 mrad,
- good hadronic calorimetry, especially in the forward hemishere,
Figure 10: Sketch of a detector for e-p collisions

- detection of electrons in the electron direction down to 30 mrad,
- absolute energy scale of the electromagnetic calorimeter better than 1% (the energy resolution is worth to be better than 0.10 / \sqrt{E} only if the absolute calibration can be better than 1%).

Physics of the inclusive deep inelastic scattering is only a part of the physics which can be done in e-p collisions. The detector requirements for the measurement of the other final states are common to all large collider detectors: identification and measurement of multi leptons (electron and muon), measurement of multi jets, excellent hermiticity. As there are no real problems of rates and pile up, these requirements can be fulfilled by current techniques. The specific aspect of an e-p collider comes of course from the strong asymmetry between the two beams. By pure kinematics we know that the maximum energy in the backward direction is equal to the electron beam energy (50 to 100 GeV), it reaches at most twice the electron energy (100 to 200 GeV) at 90 degrees and due to the unavoidable loss in the beam pipe it is about half the proton energy (4 TeV) in the proton direction. The detectors have to be designed accordingly. A detector which satisfies the above requirements is sketched in figure 10 [2]. It is a simple extrapolation of the two large detectors H1 and ZEUS which are being installed at HERA. A conventional tracker of resolution \( \sigma(p_t)/p_t = 0.2 \% \) is surrounded by an hermetic calorimeter to measure electrons and hadrons, followed by a backing calorimeter made of instrumented iron which acts in addition as a muon detector. The magnetic field of 1.5 Tesla is produced by a solenoid. The detector is complemented in the forward direction by an iron muon toroid and at low angles in both directions by plug calorimeters.

6 Conclusion

Experimentation at LEP/LHC does not present special difficulties. A detector can be built tomorrow with the present techniques. A special effort has to be done in the design of the interaction region to allow measurements down to 10 mrad in the proton direction and down
to 30 mrad in the electron direction, while keeping the synchrotron radiation at a tolerable level. Due to the importance of the calibration of the electromagnetic calorimeter, to have some dedicated runs in the $e^+ e^-$ mode at the $Z_0$ energy will be an unrivalled tool.

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ep PHYSICS AT LEP ⊗ LHC

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ABSTRACT

This is a summary of results reported and discussed in the parallel sessions of the Working Group on ep Physics. Conclusions are presented on the physics potential of the ep option at LHC emphasizing the unique physics domains. The following topics are considered:

1. ep - Option at LHC
2. Deep Inelastic Processes
3. Heavy Flavours
4. W, Z Bosons, Higgs Boson
5. New Weak Bosons, Contact Interactions
6. Excited Leptons, Leptoquarks
7. Supersymmetric Processes
8. Conclusions

*Convener of the ep - Physics Group
1. ep - Option at LHC

The general goal of ep physics is the same as the goals of pp and $e^+e^-$ physics, that is the completion and test of the Standard Model, and the search for physics beyond the Standard Model*. On the other hand, the fundamental processes that can be explored through ep collisions are to a large extent complementary to the basic processes in pp and $e^+e^-$ collisions. This reflects the different nature of the projectiles and forces involved – the electron being a pointlike electroweak particle, the proton being a complicated QCD boundstate, and the forces between them being mediated by virtual photons, Z and W bosons, and possibly other, yet unknown quanta. The ep option investigated at the present Workshop can be realized by intersecting an electron or positron beam from LEP(50–100 GeV) with a proton beam from the LHC(8 TeV) [2,3]. In this mode, the center-of-mass energy at the constituent level is about one fifth of the constituent energy in pp collisions, the luminosity is roughly one hundred times smaller than the luminosity foreseen for the pp mode of LHC, and on top of that, one has to deal with an extreme Lorentz boost in the proton direction up to $\gamma \approx 6$. As a consequence, the physics potential of the LEP $\&$ LHC collider is generally not comparable with the potential of the pp mode of LHC. Nevertheless, the complementarity of the fundamental ep and pp processes, the relative simplicity of the final states produced in ep collisions, and the uniqueness of ep physics in certain domains make the ep option to an exciting opportunity within the LHC project. Not only can one expect valuable additions to the pp physics program, but also important independent research possibilities. This is the general conclusion of the evaluation by the ep Physics Group which I shall now briefly summarize.

The work has been carried out by seven subgroups. The physicists collaborating in this groups and the assigned physics topics are listed in Table 1. Needless to say, the present summary can only indicate the actual amount of work accomplished in this joint endeavor. For details and further results I must refer the reader to the individual contributions in Volume 2 of these Proceedings. There, one can also find more appropriate references to original works. Explicitly, I want to acknowledge the great benefit we have had from previous ep studies in connection with the 1987 HERA Workshop [4], the 1984 LHC Workshop [5], and the Workshop on Future Accelerators in 1987 [6].

*Theoretical perspectives are explained, for example, in the summary talk on pp physics by Altarelli [1]. I will, therefore, not repeat the motivations for the various physics topics studied at this Workshop.
Table 1. ep Working groups, Conveners: R. Rückl (Munich), J. Feltesse (Saclay), Subconvenors.*

<table>
<thead>
<tr>
<th>1. Interaction Region, Detector, Experimentation</th>
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<tbody>
<tr>
<td>W. Bartel (DESY)*</td>
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<td>G. Ingelman (Uppsala)</td>
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<td>K. Potter (CERN)</td>
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<th>2. Deep Inelastic Processes</th>
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<tr>
<td>J. Bartels (Hamburg)*</td>
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<tr>
<td>G. Ingelman (Uppsala)*</td>
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<td>N. Magnussen (Wuppertal)</td>
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<td>H. Spiesberger (Hamburg)*</td>
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<th>3. Heavy Flavours</th>
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<tr>
<td>J. Abraham (NIKHEF)</td>
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<td>J. v. der Bij (NIKHEF)*</td>
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<tr>
<td>G.J. v. Oldenborgh (NIKHEF)</td>
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<td>J.F. de Trocóniz (Madrid)</td>
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<th>4. W, Z, Higgs Bosons</th>
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<tr>
<td>U. Baur (Madison)</td>
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<tr>
<td>G. Grindhammer (MPI Munich)*</td>
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<tr>
<td>J. Ohnemus (Florida State)</td>
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<th>5. New Vector Bosons, Contact Interactions</th>
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<tbody>
<tr>
<td>J. Blümlein (Zeuthen)</td>
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<td>F. Feruglio (Geneve)</td>
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<td>T. Riemann (Zeuthen)</td>
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<th>6. Excited Leptons, Leptoquarks</th>
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<tr>
<td>Ch. Berger (Aachen)*</td>
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<td>F. Raupach (Aachen)</td>
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<th>7. SUSY Processes</th>
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<tr>
<td>A. Bartl (Vienna)*</td>
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<td>M. Janssen (NIKHEF)</td>
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<td>N. Oshimo (Vienna)</td>
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For convenience, I have compiled below the experimental conditions [7,8] which have been generally assumed for our studies:

(i) beam energies $E_p = 8 \, \text{TeV}$ and $E_e = 50, 60, 100 \, \text{GeV}$ leading to the c.m. energies $\sqrt{s} = 1.26, 1.38, 1.79 \, \text{TeV}$*

(ii) integrated luminosities of 1 $\text{fb}^{-1}$ per year for the lower range of electron beam energies at $E_e = 50 - 60 \, \text{GeV}$, and 100 $\text{pb}^{-1}$ per year for the high energy option with $E_e = 100 \, \text{GeV}$, corresponding to the expected maximum

---

* At this Workshop, the proton beam energy at LHC has been downgraded to $E_p = 7.7 \, \text{TeV}$ [2,3]. Clearly, this small change has no impact on our conclusions.
luminosities \( L = (3 - 2) \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1} \) and \( 2 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1} \), respectively.

(iii) \( e^- p \) and \( e^+ p \) collisions under similar conditions

(iv) 80% longitudinal polarization of the \( e^\mp \) beams at \( E_e = 50 \text{ GeV} \)

(v) energy resolutions and absolute calibration errors \( \frac{\delta E}{E} \approx 0.4/\sqrt{E} \oplus 0.02 \) for hadronic calorimeters and \( \frac{\delta E}{E} \approx 0.1/\sqrt{E} \oplus 0.01 \) for electromagnetic calorimeters

(vi) angular resolutions \( \delta \theta \approx 10 \text{ mrad} \) for jets and \( \delta \theta \approx 1 \text{ mrad} \) for electrons

(vii) beam hole cuts \( \theta \geq 5^\circ - 10^\circ \) for jets and \( \theta \geq 1^\circ - 4^\circ \) for electrons.

The above resolutions are typical for the HERA detectors H1 and ZEUS, and thus represent present-day detector technology. In fact, for some studies we have directly made use of existing simulation programs for the HERA detectors. However, a few special physics cases demand excellent vertex detection. Whether this is feasible is a question for dedicated detector studies. At the present Workshop, a first rough design for an \( ep \) detector in a LEP-LHC interaction region has been presented [7].

2. Deep Inelastic Processes

The most prominent class of Standard Model processes occurring in \( ep \) collisions is certainly deep inelastic neutral (NC) and charged (CC) current scattering. Fig. 1 depicts the parton model description to lowest order perturbation theory. Deep inelastic scattering (DIS) is known as the most direct way to probe the nucleon structure. With LEP \( \otimes \) LHC one can reach values of the momentum transfer \( Q \) far beyond the weak boson masses \( m_{W,Z} \), corresponding to a resolving power better than \( 10^{-16} \text{ cm} \). Moreover, DIS is famous for providing some of the most rigorous QCD tests through the study of scaling violations. At the large values of \( Q \) typical for LEP \( \otimes \) LHC measurements, the genuine logarithmic QCD effects should clearly emerge from the hadronic background which is expected to drop as a power of \( Q^2 \).

On the other hand, also the logarithmic scaling violations shrink somewhat as \( Q^2 \) increases because of asymptotic freedom so that experimental observation may not always be easy. This problem should, however, not exist at sufficiently small values of the Bjorken-variable \( x \) which represents the fraction of the nucleon momentum carried by the struck parton. On the contrary, LEP \( \otimes \) LHC can be used as an excellent low-\( x \) microscope to explore the whole range from \( x \approx 10^{-2} \) to almost \( x \approx 10^{-6} \). The dynamics at such extremely small values of \( x \) is essentially unknown. Therefore, an understanding of low-\( x \) physics is not only of great theoretical interest, but also very important for the phenomenology at supercolliders. Last but not least, in \( ep \) collisions at high \( Q^2 \) electromagnetic and weak interactions appear with equal strength. This fact offers interesting electroweak tests, in particular, if longitudinally
polarized $e^-$ and $e^+$ beams are available since left- and right-handed fermions have different weak interactions and can thus be used as independent probes. Since electroweak physics in the energy range of LEP $\otimes$ LHC is being tested in precision experiments at LEP, and in the near future also in $ep$ experiments at HERA, we have decided to concentrate on the QCD issues.

More definitely, the following topics have been investigated for the present Workshop:

- Deep inelastic measurements, resolution and beam hole effects, etc. [9]
- Extraction of structure functions and quark distributions [10]
- QCD analysis of structure functions [11]
- Determinations of the gluon density [11, 12]
- Prospects for low-$x$ physics [13]
- Electroweak radiative corrections [14, 15].

The results obtained are exemplified in the subsequent sections.*

2.1. Extraction of Structure Functions and Quark Momentum Distributions

The prospects for measuring NC structure functions at LEP $\otimes$ LHC are illustrated in Fig. 2 and compared with the expectation for HERA. As direct observables we have examined the differential cross sections for $e^+p \rightarrow e^+X$ divided by a suitable overall factor to get

$$\bar{\sigma}_{NC}(e^+p) = F_2(x, Q^2) \pm \frac{1 - (1 - y)^2}{1 + (1 + y)^2} x F_3(x, Q^2)$$

where $y = Q^2/xs$. The structure function $F_2$ receives contributions from $\gamma$-exchange, $Z$-exchange, and $\gamma - Z$ interference, and approaches the familiar electromagnetic structure function $F_2^{em}(x, Q^2) = \sum_f e_f^2 \frac{x q_f(x, Q^2) + \bar{q}_f(x, Q^2)}{x}$ when $Q^2$ becomes much smaller than $m_Z^2$. In contrast, $x F_3$ has no purely photonic part, and hence

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*The possibilities of extracting the gluon density will be summarized in the section on heavy flavours, while the purely experimental aspects of DIS measurements are included in the summary by Feltess [8].
vanishes as $Q^2 \to 0$. Concentrating first on the range $x \geq 0.01$, one can see from Fig. 2:

(i) The LEP ∩ LHC measurement is expected to deviate significantly from $F_2^{em}$ due to contributions from the $Z$ boson*. In contrast, a similar measurement at HERA energies is practically indistinguishable from $F_2^{em}$. This reflects the larger values of $Q^2$ probed at LEP ∩ LHC as compared to HERA.

(ii) The change in shape of the $x$-distributions expected from QCD when comparing HERA and LEP ∩ LHC results is minute and barely visible. On the other hand, the effects of the $Z$-propagator on the structure functions $F_2$ and $xF_3$ can be sizeable and may obscure the QCD scaling violations as shown in more detail later.

(iii) The statistical precision at LEP ∩ LHC is inferior to the precision expected at HERA, despite of the five times larger integrated luminosity assumed for LEP ∩ LHC in the present simulation. This again is a consequence of the shift of the accessible kinematical region at LEP ∩ LHC to higher values of $Q^2$, that is to lower cross sections, relative to the situation at HERA.

At smaller values of $x$ in the range $10^{-6} \leq x \leq 10^{-2}$, NC measurements are

*Interestingly, the $Z$-boson effects are smaller in $e^+p$ scattering than in $e^-p$ scattering, and even smaller than in the sum $\frac{1}{2}(\delta_{NC}(e^-) + \delta_{NC}(e^+)) = F_2$. The reason is a partial cancellation of the $\gamma - Z$ interference contributions to $F_2$ and $xF_3$ in the case of $e^+p$ scattering [16].
expected to become considerably more precise. Since low-\(z\) experiments play a very special role, they will be discussed separately later.

Further information on the quark structure of the proton can be obtained from the CC cross sections

\[
\sigma_{CC}(e^-) = x[\sum_i u_i(x, Q^2) + (1-y)^2 \sum_i d_i(x, Q^2)]
\]

\[
\sigma_{CC}(e^+) = x[\sum_i \bar{u}_i(x, Q^2) + (1-y)^2 \sum_i d_i(x, Q^2)]
\]

where a simple factor containing the \(W^+\) propagator has been divided out, and \(u_i\) (\(d_i\)) denote the up (down) - type quark densities. Whereas in the NC case the variables \(x\), \(y\), and \(Q^2\) can be reconstructed from measurements of the scattered electron and/or from the hadron flow, in the CC case only the latter possibility exists. Unfortunately, at large \(x\) and moderate \(y\) the forward boost due to the asymmetric beam energies pushes the current-jet below \(10^6\) where measurements become difficult. As a result, one cannot hope for a good determination of the CC structure functions in the valence quark region at \(x \geq 0.2\), while measurements at \(10^{-3} \leq x \leq 0.2\) should be rather accurate. Comparable results are not expected from HERA in the region below \(x \approx 0.01\).

Finally, maximum flexibility is gained if both \(e^-p\) and \(e^+p\) collisions are provided [17]. One can then in principle combine measurements of the four independent cross sections \(\sigma_{NC}(e^-)\) and \(\sigma_{CC}(e^+)\). This would allow to extract particularly interesting distributions such as the total singlet structure function \(F_s(x, Q^2) = \sum_f x[q_f(x, q^2) + \bar{q}_f(x, Q^2)]\), and to separate quark flavours as well as valence and sea quark components. The potential of such combined measurements is exemplified in Fig. 3. This figure shows the momentum distributions of the valence up-quark \(u_v\) and the total sea \(U_{sea}\) of charge \(\pm \frac{2}{3}\) quarks and antiquarks as extracted from combinations of all four DIS cross sections. Other interesting examples are given in [10]. Although possible uncertainties in the relative normalization of different data sets are not yet taken into account, the results are quite encouraging and show that exploring the proton structure is undoubtedly a unique domain for LEP \(\otimes\) LHC experiments.

So far, the focus has been on the determination of the shape in \(x\) of structure functions and quark densities. In order to make best use of the available statistics the distributions have been averaged over \(y\) (i.e. \(Q^2\)). This procedure excludes detailed QCD tests. Nevertheless, a comparison of \(x\)-distributions from LEP \(\otimes\) LHC with low energy measurements should allow global consistency checks between theory and experiment as indicated in Figs. 2 and 3. More stringent tests of the
QCD renormalization group predictions require precise measurements of DIS cross sections in sufficiently small bins in $x$ and $Q^2$. This is a much more difficult task as discussed next.

2.2. QCD Analysis of Structure Functions

Through a QCD analysis of DIS structure functions one can in principle measure the running coupling

$$
\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln(Q^2/\Lambda^2)},
$$
determine the scale parameter $\Lambda$, and extract the gluon density. In a detailed study for HERA [16] only NC measurements have been found suitable for that purpose, whereas the accuracy of CC measurements turned out to be insufficient for sensitive QCD tests. This conclusion is expected to be also true for LEP $\otimes$ LHC. The general prospects can be read off from Fig. 4 where the statistical precision and other important features of a complete measurement of the differential NC $e^+p$ cross section are exposed [10].

At first sight, one may expect QCD tests to be quite straightforward. However, finite resolutions, calibration errors, and losses in the beam pipe lead to smearing effects in $x$ and $Q^2$ and systematic shifts [9] which spoil the ideal cross section measurements shown in Fig. 4. For example, a HERA-type detector would allow measurements with acceptable systematic uncertainties only in the restricted kinematical region distinguished in Fig. 4 from the ideal measurement by full data.
symbols. This limitation has two crucial implications. Firstly, nonsinglet QCD fits in the valence quark region, \( x \geq 0.2 \), do not look feasible because of the short lever arm in \( Q^2 \) and marginal statistics. Secondly, the presence of the \( Z \) boson leads to apparent scaling violations which constitute a large, in certain regions even dominant background to the QCD effects. Therefore, for \( x \geq 0.01 \) one has to modify the usual QCD analysis as explained in [11].

In contrast, in the low-\( x \) domain exhibited in Fig. 4a one expects much less problems with systematic uncertainties and, at the same time, very good statistical accuracy. It should be noted that the integrated luminosity taken for illustrative purposes in Fig. 4a is only 10\% of our reference luminosity, 1 \( fb^{-1} \), assumed in Fig. 4b. Moreover, the \( Z \)-boson effects die away as \( x \) decreases leaving \( F_2^{em} \) as the only relevant structure function. Here, the crucial question is a theoretical one, namely whether or not the Altarelli-Parisi evolution is still valid at such small values of \( x \). I shall return to this question in the next section and assume for the moment that this is indeed the case.
Under this assumption, we have performed QCD fits to $F_2 = \tfrac{1}{2}(\hat{\sigma}_{NC}(e^{-}) + \hat{\sigma}_{NC}(e^{+}))$ in different regions in $x$, including the contributions from the $Z$ boson [11]. The results of this simulation are summarized below and compared in Fig. 5 to the expectations at HERA:

(i) The most precise values of $\alpha_s$ can be obtained from measurements below $x \approx 0.01$. Quantitatively, a QCD analysis in the range $10^{-4} \leq x \leq 10^{-2}$ ($x \leq 10^{-4}$) should allow to determine $\Lambda$ with a statistical error of 50 (10) MeV.

(ii) Measurements at $x \geq 0.01$ alone yield at most a very rough result for $\alpha_s$.

(iii) The range in $Q^2$ over which the running coupling can be tested at LEP $\otimes$ LHC lies roughly one order of magnitude above the range of similar measurements at HERA. The expected precision is comparable for the two colliders.

(iv) Since luminosity is more important for QCD tests than energy, preference is given to the low energy $ep$ option at LHC.

![Figure 5. Measurements of the running coupling of QCD as expected for HERA and LEP $\otimes$ LHC (from Ref. 11).](image)

Finally, I should at least mention the possibility to obtain useful constraints on the input gluon density from the analysis of scaling violations at small $x$. In addition, QCD predicts the longitudinal structure function $F_L$ or, equivalently, the ratio $R$ of the longitudinal to transverse $\gamma^*p$ cross sections to become big below $x \approx 0.01$. This is interesting, since in principle $F_L(x, Q^2)$ provides a more direct probe of the gluon density than the $Q^2$-variation of $F_2$. However, in order to separate out $F_L$ or $R$ at fixed $x$ and $Q^2$ one needs measurements of the cross sections at different $y$, i.e. different c.m. energies. One possibility consists in varying the electron beam energy at the cost of luminosity. Technically, it is also possible to run with a reduced proton beam energy $E_p = 2$ TeV and almost maximum luminosity [3]. Results which can be expected for LEP $\otimes$ LHC conditions are described in [11, 12].
2.3. LOW-\(x\) PHYSICS

From the above discussion it should be clear that precision tests of QCD at LEP \(\otimes\) LHC require a good understanding of the behaviour of structure functions at very low \(x\). At \(x \geq 10^{-2}\), the behaviour in QCD is well known. Here, the nucleon appears as a state of quasi-free partons which contribute incoherently to the DIS structure functions. Quarks and gluons evolve independently as described by the familiar single-ladder diagrams. Technically, one uses the Altarelli-Parisi equations [18] to sum up these contributions. As \(x\) decreases, the parton densities grow. Simple extrapolation of the Altarelli-Parisi prescription leads to an increase which is stronger than any power of \(ln \frac{1}{x}\), and would eventually violate unitarity. Hence, there must be additional physical effects which slow down the evolution. Such screening effects are indeed expected since at sufficiently high density the partons can no longer be considered free [19]. For instance, parton annihilation and splitting give rise to so-called fan diagrams. These multi-ladder contributions are supposed to be responsible for a depletion of the structure functions at low \(x\). Generalized evolution equations including screening effects are however not yet fully developed [20]. Finally, as one approaches the Regge limit \(x \rightarrow 0\), QCD perturbation theory is no more applicable. New, still unclear nonperturbative dynamics should become important which may lead to a complete saturation of the structure functions. Although the boundaries in \(x\) and \(Q^2\) between the different regions are not yet absolutely clear, recent estimates sketched in Fig. 6 suggest that HERA may already allow a first glimpse into the new regime. However, as one can see from this graph, LEP \(\otimes\) LHC provides a far better chance to study the transition from perturbative to nonperturbative behaviour in detail in a wide range in \(x\) and \(Q^2\). How striking the deviations from standard behaviour might be is discussed in [13].

![Figure 6. Boundaries in the \((x,Q^2)\)-plane indicating regions of different behaviour of structure functions. Curve 1 denotes the estimate of [21], while curves 2 and 3 are obtained in [20] (from Ref. 13).](image-url)
Figure 7. Electroweak radiative corrections to the differential NC cross section with $x$ and $y$ determined from the scattered electron (from Ref. 14).

2.4. ELECTROWEAK RADIATIVE CORRECTIONS

Before leaving the subject of DIS, I should point out an essential prerequisite for any of the above measurements and tests, and also for numerous other experiments at LEP $\otimes$ LHC. This is the control over the electroweak radiative corrections, a problem which has been studied for HERA in great detail over the past years. Meanwhile, independent calculations by several groups [22] are in complete agreement. For the present Workshop, the calculations have been extended to LEP $\otimes$ LHC energies. The magnitude of the corrections can be inferred from Fig. 7 as a function of $x$ and $y$. It turns out that in NC scattering the dominant corrections are due to photon emission from the incoming and scattered electron. One can distinguish the following two procedures.

If $x$, $y$ and $Q^2$ are determined from measurements of the scattered electron, the corrections which have to be applied to the differential cross sections tend to be rather large, in particular at large $y$ and small $x$. However, the necessary corrections can be greatly reduced if the hard bremsstrahlung events are separated out [14]. This is demonstrated in Fig. 7 by applying suitable cuts in the photon energy and angle, and by putting additional constraints on the difference between the measured
and expected jet-angle. The expected angle is defined as the angle calculated for
the quark-jet from the measured electron momentum under the assumption that
no photon was radiated. The remaining corrections are typically of the order of
(10−30)% and almost independent of y or Q². The latter feature also facilitates
tests of QCD scaling violations.

Alternatively, one can also determine x, y, and Q² from a hadron flow measure-
ment, at least for x ≥ 10⁻³. In this case, the migration of events in x and y due
to radiative effects is found to be considerably smaller than in the case of electron
measurements. Therefore, also the necessary corrections of the differential cross sec-
tions are smaller [15]. Quantitatively, they are comparable to the corrections shown
in Fig. 7 after application of the cuts quoted.

Other interesting questions have been raised, but need more study, for example,
the sensitivity of radiative corrections to the parton distributions and the complex
correlations of QCD evolution, QED radiation and weak boson effects. Clearly,
radiative corrections are a very important nontrivial aspect of the data analysis.
However, they do not pose an unsolvable problem. Moreover, HERA will provide
plenty of opportunities to learn and to optimize strategies.

3. Heavy Flavours

In ep collisions, heavy quark flavours are mainly produced via vector boson-
gluon fusion processes. The lowest order diagrams are displayed in Fig. 8. In the
case of charm and bottom quarks, γ − g fusion is by far dominant, Z − g and W − g
fusion being suppressed by the heavy boson propagators*. However, for a heavy
top quark with mass mt ≥ 100 GeV single top production via W − g fusion wins
over the pair-production mechanisms because of the more favourable phase space.
The production rates expected at LEP ⊗ LHC are very large for c- and b-quarks,
and still substantial for t-quarks in the (100−200) GeV range. For example [23],
for √s = 1.3 TeV and 1 fb⁻¹ one predicts O(10⁹) c ¯c and O(10⁷) b ¯b events, and
assuming a top quark mass of 150 GeV, roughly 2000 t ¯b and 150 t ¯t events. The
charm and bottom rates expected at HERA are considerably smaller, while t-quarks
heavier than 100 GeV are out of reach.

The most obvious and urgent task in heavy flavour physics is the discovery and
study of the t-quark. Other main issues are rare decays, flavour mixing and CP-
violation. Moreover, interest in heavy flavour production focusses also on QCD

*In addition, the CC processes involve small quark mixing angles, with the exception of the c ¯c
and t ¯b channel.
perturbation theory and the gluon distribution in the nucleon. In order to examine the potential of LEP ⊗ LHC in this domain we have selected the following topics for a detailed study:

- Extractions of the gluon density [24]
- Observability of $B\bar{B}$ oscillation [23]
- Top search and mass reconstruction [23].

It is quite clear that LEP ⊗ LHC cannot add much to top physics. Not only will top be discovered at LHC if it has not yet been seen at the Tevatron Collider [1, 25], but also the production rates at LEP ⊗ LHC are too small for detailed studies of the properties of the top quark. Nevertheless, top does play an essential role as one of the main backgrounds in searches for the Higgs boson and for physics beyond the Standard Model. Just the opposite is true for charm and bottom physics where LEP ⊗ LHC is well suited for experimental tests in a wide area ranging from strong interactions to flavour dynamics. Some possibilities are described in the following.

3.1. Extractions of the Gluon Density

$ep$ collisions provide several handles on the gluon density. The most important probes are enumerated in Table 2 together with the accessible regions in $x$ and the associated values of $Q^2$ [13]. It is interesting to note that at LEP ⊗ LHC one can reach typically one order of magnitude lower in $x$ than in similar experiments at HERA. Particularly promising is the extraction of the gluon from inclusive charm and bottom production [24]. Firstly, the underlying hard subprocesses can be reliably calculated in perturbative QCD. Secondly, the rates are sufficiently big so that one can afford to use clean samples of isolated dilepton events for extraction. Thirdly, the gluon momentum fraction $x_g$, although being not directly observable, can be reconstructed rather well from observables such as the rapidity $y_{ll}$ of the lepton pair and the DIS variable $y$ obtained from the hadron flow. The relevant relation to be used is given by $x_g \approx \frac{E_p}{E_p} y e^{-2y_{ll}} + \frac{Q^2}{s}$ with $Q^2/s$ being negligible. The power of this method is illustrated in Fig. 9.

Another possibility is to make use of $J/\psi$ production followed by the leptonic decays $J/\psi \rightarrow e^+e^-, \mu^+\mu^-$ [24]. Also these channels are found to yield a very nice
Table 2. Methods for extracting the gluon density.

<table>
<thead>
<tr>
<th>measurement</th>
<th>$x$-range</th>
<th>$Q^2$-range (GeV$^2$)</th>
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<tbody>
<tr>
<td>$Q^2$-variation of $F_2$</td>
<td>$5 \cdot 10^{-4}$ - $3 \cdot 10^{-2}$</td>
<td>$\leq 10$</td>
</tr>
<tr>
<td>long. struc. func.</td>
<td>$7 \cdot 10^{-4}$ - $2 \cdot 10^{-3}$</td>
<td>$25$ - $150$</td>
</tr>
<tr>
<td>$\gamma g \rightarrow J/\psi g$</td>
<td>$5 \cdot 10^{-5}$ - $2 \cdot 10^{-2}$</td>
<td>$\sim 10$</td>
</tr>
<tr>
<td>$\gamma g \rightarrow c\bar{c}, b\bar{b}$</td>
<td>$6 \cdot 10^{-5}$ - $1 \cdot 10^{-2}$</td>
<td>$100$ - $2500$</td>
</tr>
</tbody>
</table>

Figure 9. Gluon momentum distribution inside the proton as extracted from $c\bar{c}$ and $b\bar{b}$ production in comparison to the input distribution (from Ref. 24).

measurement of the gluon density. However, one must carefully select the event sample in order to discriminate the relevant direct production process $\gamma g \rightarrow J/\psi g$ and contributions to the $J/\psi$ yield from higher charmonium resonances and from bottom production and decay. Moreover, it is necessary for a reliable calculation to restrict the analysis to the class of events where the gluon recoiling against the $J/\psi$ is sufficiently hard. Together with the results from DIS structure functions [11, 12], one can thus expect a variety of independent determinations the gluon distribution which should cover the range $10^{-4} \leq x \leq 10^{-2}$ and permit reassuring cross-checks.

3.2. $B\bar{B}$ Oscillations

As an interesting example for rare $B$ processes we have studied the observability of $B\bar{B}$ oscillations [23]. Again, the analysis makes use of dilepton final states originating from semileptonic decays $B \rightarrow \ell^+X$ and $\bar{B} \rightarrow \ell^-X$ ($\ell = e, \mu$) of the two $B$ mesons produced in the process $ep \rightarrow (e)B\bar{B}X$. Obviously, $B \leftrightarrow \bar{B}$ transitions give rise to like-sign dilepton events accompanied by a corresponding lack of unlike-sign dilepton events. The relative transition probability $r = P(B \rightarrow \bar{B})/P(B \rightarrow B)$ is related to the ratio $x = \Delta m/\Gamma$ by $r = \frac{x^2}{2 + x^2}$, where $\Delta m$ is the mass difference of the two mass eigenstates and $\Gamma$ is the total decay width. For the $B_d$ system, the parameter $x$ is measured to be $x_d = 0.70 \pm 0.13$ [26], while for the heavier $B_s$
system the Standard Model predicts a considerably larger value $x_s = O(10)$. For the oscillation length of a $B$ meson with energy $E$ one finds $\lambda \approx 2mm(\frac{\beta^2}{x})$ where $\gamma = 1/\sqrt{1 - \beta^2} = E/m_B$. Thus, fast $B$ mesons have oscillation lengths in the $mm$ range. Although the most energetic $B$ mesons are lost in the beam pipe, the oscillations should still be visible in the remaining sample provided one has a detector with good lepton identification and vertex detection. The first requirement is necessary in order obtain a well defined sample of inclusive dilepton events. In addition, the events have to be separated into sufficiently narrow bins in the $B$ meson energy. Otherwise the effect would be washed out due to superposition of different oscillation lengths. Furthermore, vertex detection is the only way to determine the decay length in $z$-direction as well as in the $(x, y)$-plane. Since the proton remnants fly very forward in or close to the beam pipe, while the two $b$-jets are back-to-back in the transverse plane, the transverse view of the events is reminiscent of $b\bar{b}$ production in $e^+e^-$ annihilation. Here, we have a physics case where the strong Lorentz-boost is actually advantageous. Fig. 10 shows the oscillation pattern which may be observed in decay length distributions if the above experimental requirements can be met.

![Decay length distributions](image)

**Figure 10.** Decay length distributions from an unlike-sign dilepton sample assuming $x_d = 0.5$, $x_s = 10$, $\sigma = 100 \mu m$, $\int L dt = 1 fb^{-1}$ (from Ref. 23).

### 3.3. Top Quark Production

Our third example of heavy flavour physics at LEP @ LHC deals with the awaited top quark. As top is presumably heavier than 100 $GeV$ we have assumed $m_t = 150 GeV$ as a representative case for signal and background studies [23]. The signal events predominantly result from single top production and decay, $e^-p \rightarrow$
\( \nu_e b \bar{b} + X \rightarrow \nu_e b \bar{b} W^- + X \) and similarly for \( e^+p \) collisions, while \( t \bar{t} \) pair-production is down by one order of magnitude in cross section as already mentioned. A relatively clean signature is provided by the leptonic decays \( W \rightarrow e \nu_e \) and \( W \rightarrow \mu \nu_\mu \), leading to final states with isolated, high-\( p_t \) leptons. However, there are also numerous background processes: (i) NC scattering including photoproduction of light quark and gluon jets, (ii) charm and bottom production, (iii) CC scattering, and (iv) single \( W \) and \( Z \) production. The irreducible background should mainly come from the processes (iii) and (iv).

The analysis could proceed as follows. In order to trigger on interesting events a minimum transverse energy \( \sum E_t \geq 20 \text{ GeV} \) is required. The events are then divided up into two complementary samples, events containing at least one isolated, high-\( p_t \) lepton and events with no such leptons. As selection criteria one may use the transverse momentum of the hardest lepton and the energy in a cone \( \Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.4 \) around the lepton axis. In [23] an isolated, high-\( p_t \) lepton is defined by the cuts \( p_t \geq 8 \text{ GeV} \) and \( E_{acc} \leq 1 \text{ GeV} \).

In the leptonic event sample, the only remaining background is due to \( b \bar{b} \) production. The \( b \bar{b} \) background can be eliminated quite easily by a cut on the missing transverse momentum in the event, e.g. \( p_t^{miss} \geq 15 \text{ GeV} \). The \( W \) background is more difficult. However, by requiring at least one jet in the central rapidity range \( |\eta| \leq 2 \) one can reduce also this background to an acceptable level. As checked by MC simulation of complete events, it is possible in this way to obtain a rather clean sample of top events without the need for \( b \)-tagging. In numbers, from the 2000 top events expected for \( m_t = 150 \text{ GeV} \) and a luminosity of \( 1 \text{ fb}^{-1} \) roughly 300 signal events are recovered in a background of about 50 events from \( W \) bremsstrahlung. The procedure should work for top masses up to 250 \text{ GeV}.

Unfortunately, from the leptonic event sample it is not possible to reconstruct the top mass in a satisfactory manner. The main obstacles are the presence of two neutrinos, one from the leptonic vertex \( e \rightarrow \nu W^* \) and one from the decay \( W \rightarrow l \nu \), and the loss of particles in the beam pipe.

For this reason, we have also investigated the possibility to reconstruct the top mass from the complementary sample of hadronic events which contain no isolated, high-\( p_t \) leptons. The signal events in this sample come almost completely from hadronic decays of the \( W \) in \( t \rightarrow bW \). Without \( b \)-tagging, but assuming a very good three-jet-mass resolution of 15 \text{ GeV} \), one can obtain mass distributions of the kind illustrated in Fig. 11 for 3- and 4-jet events. In both cases, the distributions peak at a mass slightly below the input mass \( m_t = 150 \text{ GeV} \). Although one has a reasonably large number of signal events in the peak region, the irreducible background,
dominantly consisting of CC events, is rather sizeable. For heavier top masses the
signal to background ratio becomes worse and for $m_t \approx 200$ GeV the procedure fails.
However, with some minimal $b$-tagging using, for example, the non-isolated leptons
from $b$-decays, it is possible to suppress the background further without loosing too
much of the signal. This is one way to improve the mass reconstruction and to reach
somewhat higher masses as demonstrated in [23]. We have not studied top search
assuming more sophisticated means of $b$-tagging.

4. Weak Vector Bosons, Higgs Boson

An evaluation of the physics potential of LEP $\otimes$ LHC would not be comprehen-
sive without consideration of open questions in the electroweak sector of the Stan-
dard Model. I have already mentioned the role of NC and CC scattering through
the exchange of virtual $Z$ and $W$ bosons as the basic electroweak processes in $ep$
collisions. More interestingly, virtual weak vector bosons can be used as a source
for the standard Higgs boson, the only missing particle in the minimal Standard
Model besides the top quark. The search for the Higgs boson, or for the physics
which replaces the Higgs boson in case it does not exist, is one of the main mo-
tivations for the construction of supercolliders. While a light Higgs boson with a
mass $m_H \leq m_W$ will most likely be found or excluded at LEP, the mass range
from $m_H \approx 130$ GeV up to about 1 TeV can be completely covered at the LHC.
However, the intermediate region from $m_H \approx 80$ GeV to 130 GeV is a very difficult
one for searches in $pp$ collisions [1]. Hence, it is of great interest to find out whether
or not the $ep$ option of the LHC could help to close this window. This question has
been studied very carefully and extensively in our working group [27]. The results
are reported in a separate paper by Zeppenfeld [28]. For completeness of the present
general summary, I shall review the main conclusions.

Not quite as important, but certainly interesting is the production of real $W$ and $Z$ bosons. Similarly as for the top quark, the production rates in $ep$ collisions are less comfortable than the rates in $pp$ collisions (not to speak about the number of $Z$ bosons produced in $e^+e^-$ annihilation on resonance). Consequently, properties such as masses and couplings to fermions are better measured at LEP and hadron colliders. However, the number of $W$ and $Z$ bosons which can be produced at LEP $\otimes$ LHC is sufficiently big to allow sensitive tests of other essential properties, for instance, the $WW\gamma$ and $WWZ$ couplings. Hence, we have selected this topic as a second example of electroweak physics [29]. One specific test and its sensitivity are described in the next section.

4.1. THREE-BOSON COUPLINGS

The production mechanisms for single real $W$ and $Z$ bosons are indicated in Fig. 12. While the diagrams (a) and (b) have the structure of bremsstrahlung processes, the diagram (c) involves the $WW\gamma$ and $WWZ$ three-boson vertices which we want to put to test. One of the most promising reactions is $ep \rightarrow eWj + X$ [29]. Since the dominant contributions come from the exchange of almost real photons, it is mainly the anomalous $WW\gamma$ couplings which are probed in this channel. For the total cross section at LEP $\otimes$ LHC with no cuts one finds about 20 $pb$. However, hadronic $W$ decays are difficult to detect in the large multi-jet background and, therefore, only the leptonic modes $W \rightarrow e\nu, \mu\nu$ are useful. Including the corresponding branching ratios of the $W$ and imposing a series of cuts, one predicts 1.6 $pb$ for the observable cross section corresponding to 1600 events per 1 $fb^{-1}$. The most important cuts are $p_{tj} > 10$ $GeV$ and $|\eta_{ij}| < 3.5$. Furthermore, the background from charm and bottom production can be eliminated by requiring an isolated, high-$p_t$ lepton ($p_{tl} > 10$ $GeV$, $\Delta R_{lj} > 0.5$). Also top production is not expected to be a serious background, the effective cross section for the channel $t\bar{b} \rightarrow Wb\bar{b} \rightarrow l\nu b\bar{b}$ being only about 0.8 $pb$ for $m_t = 100$ $GeV$ and 0.2 $pb$ for $m_t = 200$ $GeV$.

![Diagram](https://example.com/diagram.png)

Figure 12. Typical diagrams contributing to single $w$ and $Z$ production.
As compared to HERA, LEP ⊕ LHC offers two clear advantages: (a) a 20 times bigger cross section leading together with the higher luminosity to substantially larger event rates, and (b) a harder distribution in the invariant energy $\hat{s}$ of the subprocess giving a greater sensitivity to contributions from anomalous couplings. The reason is that the anomalous effects grow with a power of $\sqrt{\hat{s}}/m_W$.

Fig. 13 shows the jet $p_T$-spectrum for the process $ep \rightarrow eWj + X; W \rightarrow l\nu$ in the Standard Model as well as the influence of anomalous $WW\gamma$ couplings. The sensitivity to the parameter $\lambda^\gamma$ is particularly good. If no effect is seen, one should be able to exclude $|\lambda^\gamma| \leq 0.1$ at 90% c.l.. Extracting information on the parameter $\kappa^\gamma$ from this measurement is more difficult. Here, the sensitivity is strongly correlated with the uncertainty in the normalization of the Standard Model prediction, as can be seen from the figure. For a normalization error of 10% to 30%, the estimated 90% c.l. limit is roughly $|\kappa - 1| \leq 0.2$ to 0.4. These expectations are comparable to the sensitivity of corresponding test at LEP using $e^+e^- \rightarrow W^+W^-$. It is also interesting to note that polarized $ep$ collisions would provide additional tests through the angular distribution of the decay lepton from $W \rightarrow l\nu$ [29].

Other channels which have been investigated include $ep \rightarrow \nu Wj + X$, $\nu Wp$, and $ep \rightarrow \nu Zj + X$. Without quoting numerical results, I just point out that the $\nu Wj$-channel is useful for testing the $WWZ$ vertex. For example, the sensitivity to $\kappa^Z$ is found to be similar to what is expected from $pp \rightarrow WZ + X$ at the LHC [29].

![Figure 13. Transverse momentum distributions of jets accompanying single $W$ production in the Standard Model (SM) and in the presence of non-standard $WW\gamma$ couplings. The parameters $\kappa$ and $\lambda$ appearing in the $W$ magnetic dipol moment $\mu_W = e(1 + \kappa + \lambda)/2m_W$ and the electric quadrupol moment $Q_W = -e^2(\kappa - \lambda)/m_W^2$ have the Standard Model values $\kappa = 1$ and $\lambda = 0$ (from Ref. 29).]
4.2. Higgs Search

Since the couplings of the standard Higgs scalar to light fermions are strongly suppressed by the light fermion masses, it is necessary to first produce real or virtual heavy particles such as the weak vector bosons or the top quark which can then act as sources for the Higgs boson. In ep collisions, the most efficient production mechanism are the WW and ZZ fusion processes shown in Fig. 14. As a side-remark, in pp collisions the analogous mechanisms become important only for very heavy Higgs masses. Here, one has another example for the complementary role of fundamental processes in pp and ep collisions. The production rates for the Higgs boson in the interesting mass range between 80 and 130 GeV are exemplified in Table 3 [27, 28]. Also given are the branching ratios for $H \rightarrow b\bar{b}$ which is the dominant decay mode in this mass range. As expected, Higgs bosons are not produced very frequently in ep collisions, at least in comparison to the corresponding rates in pp collisions. As a consequence, one cannot afford to search in rare decay channels such as $H \rightarrow \gamma\gamma$, one of the modes considered at hadron colliders [1, 25], but one must try to detect the Higgs signal in the main decay channel $H \rightarrow b\bar{b}$, or for somewhat heavier masses up to $m_H \approx 150$ GeV, through $H \rightarrow WW^*$ where one of the W bosons is off-shell. So far, only the channel $ep \rightarrow \nu H q + X \rightarrow \nu b\bar{b}q + X$ has been investigated [27].

![Figure 14. Main production mechanisms for the standard Higgs boson.](image)

<table>
<thead>
<tr>
<th>$m_H$ (GeV)</th>
<th>$WW$-fusion</th>
<th>ZZ-fusion</th>
<th>$B(H \rightarrow b\bar{b})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>180</td>
<td>40</td>
<td>.86</td>
</tr>
<tr>
<td>100</td>
<td>150</td>
<td>30</td>
<td>.84</td>
</tr>
<tr>
<td>130</td>
<td>110</td>
<td>20</td>
<td>.60</td>
</tr>
</tbody>
</table>

In the above channel, the Higgs signal is characterized by
- missing transverse momentum due to the escaping neutrino
- two central b-quark jets at large $p_T$ peaking at a mass $m(b\bar{b}) \approx m_H$
- a more forward spectator jet with smaller but still sizeable $p_T$
• very large transverse energy.

These features suggest to focus on 3-jet events selected, for example, by the cuts $p_T^{jj} > 20 \text{ GeV}$, $|\eta_j| < 4.5$ and $\Delta R_{jj} > 1$, and to require $E_T > 100 \text{ GeV}$ and $p_T^{\text{miss}} > 20 \text{ GeV}$. Furthermore, it is useful to order the jets in rapidity such that $\eta_1 \leq \eta_2 \leq \eta_3$. While the probability for jet 1 and 2 to be the b-jets coming from Higgs decay is about 90%, the total acceptance for the signal varies from 30% at $m_H \approx 80 \text{ GeV}$ to 50% at $m_H \approx 140 \text{ GeV}$.

The main background is expected to come from NC (including photo-) production of jets, multi-jet CC scattering, and single $W$, $Z$ and $t$-quark production with subsequent hadronic decays. $W$ and $Z$ production is only dangerous if $m_H \approx m_{W,Z}$. On the other hand, the top background is important in the whole mass range considered. Moreover, we know from section 3.3 that practically all top events contain two b-quarks as do the signal events. The dominant background, however, is due to the NC and CC processes. Particular care is required in the case of photoproduction of jets where the scattered electron escapes undetected through the beam pipe, while detector effects and losses of hadrons in the beam pipe fake the missing $p_T$ signature. Taking $m_H \approx 100 \text{ GeV}$ and employing the cuts specified above, one is left with about 60 signal in 380 background events. Here, the signal is assumed to be contained in a mass bin of 10 GeV around the value $m_H$.

![Graph showing dijet mass distribution](image)

**Figure 15.** Cross section for Higgs production and dijet mass distribution for the irreducible background, assuming cuts and flavour identification as described in the text (from Ref. 28).

This result implies that excellent flavour identification is needed in order to establish a clear Higgs signal. For illustrative purposes, we have assumed a 10% and 25% probability for misidentifying a light jet or c-quark jet as a b-jet, respectively.
and 80% efficiency in identifying a b-jet. In addition, we require a very good resolution for measurements of the $b\bar{b}$-dijet masses. Definitely, the mass resolution must not be much worse than 10 GeV. If these requests can be fulfilled, it is possible to detect the Higgs boson in the mass range from 80 to 140 GeV as demonstrated in Fig. 15. Therefore, the $ep$ option could play a very important role in the Higgs search at the LHC as an additional tool for hunting in the intermediate mass range. This conclusion calls for dedicated studies whether it would be feasible to meet the above detector requirements in the LEP ⊗ LHC environment.

5. New Vector Bosons, Contact Interactions

The remainder of this summary is devoted to physics beyond the Standard Model. Among the many speculations on what the new physics might be, we have selected only a few cases according to the following criteria: good physics motivation, characteristic experimental signature, evident subject of research at $ep$ colliders.

New physics may begin to reveal itself in small and vague deviations from Standard Model expectations. Typical examples in $ep$ collisions are additional $W'$ and $Z'$ bosons or residual contact interactions. The latter could be remnants of a new confining force associated with a further level of substructure, and occur in violent electron-quark collisions due to interchange of common subconstituents as indicated in Fig. 16a. However, also the exchange of new heavy bosons can lead to similar four-fermion interactions. Thereby, one may either be dealing with new fundamental gauge bosons as assumed in Fig. 16b or with $\rho$ meson-like resonances as depicted in Fig. 16c. In any case, consistency with present-day experiment [30] requires new weak bosons to be so heavy that direct production is very unlikely at LEP ⊗ LHC. This mainly leaves the possibility to search for indirect effects in deep-inelastic NC and CC processes similarly as in the case of contact interactions originating from compositeness. Thus, hypotheses of the kind represented in Fig. 16 can be tested experimentally by one and the same data analysis.

![Figure 16. Effective four-fermion interactions generated by (a) interchange of subconstituents, (b) exchange of new heavy gauge bosons, and (c) exchange of a heavy vector meson resonance.](image)

We have estimated the sensitivity achievable at LEP ⊗ LHC as described below [31,32]. The quantities to be used for the tests are the inclusive, differential cross sections $d\sigma/dQ^2 \, dx$, integrated over $x$ in bins of $Q^2$, both for unpolarized and polarized $e^+\pi^-p$-scattering. In addition, we have looked at asymmetries derived from these
cross sections such as the charge asymmetry $A^{-+}$ or the polarization asymmetry $A_{LR}^{-+}$. Here, the notation is $A_{ab}^{rs} = \frac{d\sigma(e_a^r e_b^s) - d\sigma(e_a^r e_b^s)}{d\sigma(e_a^r e_b^s) + d\sigma(e_a^r e_b^s)}$. Furthermore, we have made the following experimental assumptions:

(i) runs at 50 GeV e-beam energy with the option of 80% longitudinal polarization

(ii) 500 $pb^{-1}$ integrated luminosity for each independent data set, i.e. $e^- p$, $e^+ p$, $e^- L p$ data, etc.

(iii) accurate NC and CC measurements in the kinematical regions $0.01 \leq z \leq 0.5$, $0.075 \leq y \leq 0.8$, $1.2 \cdot 10^3 \leq Q^2 \leq 6.4 \cdot 10^5$ (in GeV$^2$) and $0.01 \leq x \leq 0.25$, $0.05 \leq y \leq 0.8$, $1.0 \cdot 10^3 \leq Q^2 \leq 3.2 \cdot 10^5$ (in GeV$^2$), respectively [9]

(iv) systematical uncertainty of 5% in the normalization of the DIS cross sections.

Roughly speaking, we imagine that the Standard Model predictions are adjusted to the data in the lower $Q^2$ range where no observable effects from new interaction of the above kind are expected. The calculations are then extrapolated using again standard theory to the highest accessible values of $Q^2$ and compared to the data. The absence of deviations would allow to put the following bounds on the existence of contact interactions and additional vector bosons.

5.1. CONTACT INTERACTIONS

For the contact interactions we have adopted the usual effective four-fermion Lagrangian [30]

$$L_{\text{eff}} = \pm \frac{g^2}{\Lambda^2} \bar{e} \gamma^\mu e a(q \gamma_\mu q)_b$$

where $a, b \in \{ L \text{ (left), } R \text{ (right), } V \text{ (vector), } A \text{ (axial vector)} \}$ denote the chiral structure of the currents, and $g^2/4\pi$ is set equal to 1. The sensitivity of LEP $\otimes$ LHC experiments can then be expressed in terms of the only remaining parameter $\Lambda = \Lambda_{ab}$. In Table 4, I have summarized the results of a systematic study [31] for a variety of contact terms and for both signs relative to the Standard Model Lagrangian. From the table and further results reported in [31] one can conclude:

(i) Values of $\Lambda_{ab}^\pm$ up to (and, if different tests are combined, a few $TeV$ beyond) $20 \, TeV$ are within reach.

(ii) Lepton polarization increases the sensitivity by 1 to 5 $TeV$ depending on the chiral structure and the sign of the contact terms.

(iii) Although asymmetries provide less stringent bounds than cross sections, they are very helpful in differentiating models if an effect is observed.

(iv) The higher energy/lower luminosity $ep$ option is inferior to the lower energy/higher luminosity option.
Table 4. Most sensitive tests of contact interactions through NC cross section and asymmetry measurements using unpolarized and polarized $e^\mp$ beams. Quoted are the achievable bounds (95% c.l.) on $A_{as}$ in TeV.

<table>
<thead>
<tr>
<th>couplings</th>
<th>unpol. cross sections</th>
<th>pol. cross sections</th>
<th>asymmetries</th>
</tr>
</thead>
<tbody>
<tr>
<td>$+(-)LL$</td>
<td>$\epsilon_-$ 13.1 (11.1)</td>
<td>$\epsilon_L^-$ 16.1 (14.6)</td>
<td>$A_{LR}^{-+}$ 10.4 (9.4)</td>
</tr>
<tr>
<td>$+(-)LR$</td>
<td>$\epsilon_+^+$ 11.9 (7.4)</td>
<td>$\epsilon_R^+$ 14.2 (8.6)</td>
<td>$A_{LR}^++$ 11.8 (7.2)</td>
</tr>
<tr>
<td>$+(-)RL$</td>
<td>$\epsilon_+^+$ 11.8 (7.9)</td>
<td>$\epsilon_L^+$ 16.0 (12.6)</td>
<td>$A_{LR}^+-$ 13.4 (9.8)</td>
</tr>
<tr>
<td>$+(-)RR$</td>
<td>$\epsilon_-$ 12.6 (10.3)</td>
<td>$\epsilon_R^+$ 17.8 (16.4)</td>
<td>$A_{LR}^{++}$ 14.7 (13.7)</td>
</tr>
<tr>
<td>$+(-)VV$</td>
<td>$\epsilon_\pm^-$ 19.3 (17.8)</td>
<td>$\epsilon_L^-$ 20.8 (19.3)</td>
<td>$A_{LR}^{--}$ 13.1 (11.3)</td>
</tr>
<tr>
<td>$+(-)AA$</td>
<td>$\epsilon_-$ 16.4 (13.4)</td>
<td>$\epsilon_R^+$ 17.2 (14.2)</td>
<td>$A_{LR}^{+-}$ 13.8 (15.5)</td>
</tr>
</tbody>
</table>

(v) LEP \& LHC is able to extend the existing bounds [30,31] by almost one order of magnitude and also exceeds HERA in sensitivity by a factor 3 to 4.

5.2. $Z'$ AND $W'$ GAUGE BOSONS

For our analysis we have assumed three different $E_6$-type models predicting one additional neutral vector boson $Z'$ associated with an extra $U'(1)$ factor in the low energy gauge group:

$$E_6 \rightarrow SU(3)_c \otimes SU(2)_L \otimes U(1) \otimes U'(1).$$

In addition, we have investigated the case of a left-right symmetric model based on the minimal group

$$SU(2)_L \otimes SU(2)_R \otimes U(1)$$

where one has a new triplet of two charged and one neutral gauge bosons. The precise description of the above scenarios can be found, for example, in [6,31]. We have tried to choose models which are favourable as well as unfavourable with regard to experimental test.

In the presence of several weak bosons, the mass eigenstates $Z_i$ and $W_i$ ($i = 1,2,...$) are in general mixtures of the respective weak eigenstates $Z$, $Z'$,... and $W$, $W'$,... Obviously, the lightest mass eigenstates $Z_1$ and $W_1$ are to be identified with the observed $Z$ and $W$ bosons. Furthermore, symmetry arguments suggest to take for the new gauge couplings the values $g' = \sqrt{3} g_L$ in the $E_6$-models, and $g_R = g_L$ in the left-right symmetric model, where $g_L = \frac{\epsilon}{\cos \theta_W}$. The masses $m_{Z_2}$ and $m_{W_2}$ of the heavier mass eigenstates and the $Z - Z'$ and $W - W'$ mixing angles are treated as independent free parameters. Finally, the right-handed neutrino appearing in the
left-right symmetric model is assumed to be light.

Upper boundaries of the mass ranges which can be explored at LEP \( \otimes \) LHC assuming no mixing [31] are summarized in Table 5. In most models, mixing effects tend to enhance the deviations from the Standard Model. The main features manifest in Table 5 are similar to what has been found for contact interactions. However, the discovery range is surprisingly limited, although the reach beyond the present mass bounds [30] and beyond the masses accessible at HERA is still significant, in particular, in the case of the \( Z_{LR} \). The apparent model dependence of the sensitivity can be traced back to differences in the strength of the new gauge couplings, and to the fact that one is mainly probing \( \gamma-Z' \) and \( Z-Z' \) interference effects.

Table 5. Most sensitive tests of new gauge bosons appearing in \( E_6 \) models (\( Z_q, Z_X, Z_C \)) and a minimal left-right symmetric model (\( Z_{LR}, W_R \)). Quoted are the achievable bounds (95\% c.l.) on the vector boson masses in TeV in the absence of \( Z-Z' \) and \( W-W' \) mixing.

<table>
<thead>
<tr>
<th>models</th>
<th>unpol. cross sections</th>
<th>pol. cross sections</th>
<th>asymmetries</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Z_q )</td>
<td>( e^- ) 210</td>
<td>( e_R^- ) 500</td>
<td>( A_{LR}^- ) 400</td>
</tr>
<tr>
<td>( Z_X )</td>
<td>( e^+ ) 390</td>
<td>( e_R^+ ) 450</td>
<td>( A_{LR}^+ ) 340</td>
</tr>
<tr>
<td>( Z_C )</td>
<td>( e^- ) 130</td>
<td>( e_L^- ) 180</td>
<td>( A_{LL}^- ) 140</td>
</tr>
<tr>
<td>( Z_{LR} )</td>
<td>( e^- ) 730</td>
<td>( e_R^- ) 1190</td>
<td>( A_{RR}^- ) 1120</td>
</tr>
<tr>
<td>( W_R )</td>
<td>( e^- ) 490</td>
<td>( e_R^- ) 770</td>
<td>( e_R^-/e_L^- ) 780</td>
</tr>
</tbody>
</table>

A remark is also due concerning the electroweak radiative corrections. For the present analysis we have used relations between the electroweak parameters which include radiative corrections as obtained in the Standard Model. Additional corrections due to the presence of a \( Z' \) are neglected. The latter have been estimated in [33] so that one could now refine the analysis. We do, however, not expect significant changes in the conclusions presented in this section.

5.3. BESS Model

As a final example, we have investigated the value of LEP \( \otimes \) LHC in testing the possibility of electroweak symmetry breaking by a strongly interacting sector. For that purpose, we have employed the BESS model [32] which predicts an isotriplet of vector meson resonances, \( V^0 \) and \( V^\pm \). The observable effects in \( ep \) scattering are rather small. Although there is a window beyond the existing experimental bounds which could be probed at LEP \( \otimes \) LHC, this window will probably be covered by LEP. Details are described in [32].

*The interesting case of a heavy (Majorana) neutrino is discussed in [5].
In summary, t-channel physics can generally not compete in sensitivity with resonance production. Therefore, it is not so surprising that hadron colliders are much more powerful in \( W' \) and \( Z' \) searches \([1, 34]\) than ep colliders. Nevertheless, if a positive signal is observed elsewhere LEP \( \otimes \) LHC may be quite useful in discriminating different models and determining some of the couplings to light fermions, provided longitudinally polarized lepton beams are available. This also applies to contact interactions of composite leptons and quarks. In this case, however, the explorable ranges of the relevant compositeness scales \( \Lambda \) are comparable for \( pp \) and ep collisions at the LHC.

6. Excited Leptons, Leptoquarks

Having an electron in the initial state ep colliders are excellent tools to search for new particles carrying the e-quantum number. Well-known species of this kind are excited leptons, leptoquarks and leptogluons. The existence of such degrees of freedom is a basic prediction in composite and unified models. On the other hand, the probable mass range of these objects is a much more speculative matter. For the time being, only experiment can give a reliable answer. In order to clarify the discovery potential of LEP \( \otimes \) LHC we have worked out two characteristic cases assuming the experimental capabilities of the HERA detectors \([35, 36]\). I want to focus on these two examples.

6.1. EXCITED ELECTRON

Let us first consider a heavy replica \( e^* \) of the ordinary electron. In ep collisions, the \( e^* \) can be singly produced at the leptonic vertex. The relevant subprocess \( eq \rightarrow e^*q \) is dominated by the photon pole\(^*\). Furthermore, the transition \( e\gamma \rightarrow e^* \) can be described by the effective Lagrangian \([35, 37]\)

\[
\mathcal{L}_{ee^*\gamma} = \frac{\epsilon}{\Lambda} \bar{e}_R \sigma^{\mu\nu} e_L \partial_\mu A_\nu
\]

where \( A_\nu \) denotes the photon field. The parameter \( \Lambda \) is a new kind of compositeness scale which is not to be confused with the scales \( \Lambda_{q^0}^\pm \) used in the previous section to parameterize contact interaction. In the absence of a complete theory, these scales should rather be treated independently. In addition to the photon coupling, one expects a similar coupling between \( e, e^* \) and the Z boson. SU(2) symmetry then implies \( \nu e^* W, e^* W, \) and \( \nu\nu^* Z \) transitions where the excited neutrino \( \nu^* \) is the weak isospin partner of the \( e^* \).

\(^*\)It is conceivable that excited leptons (and quarks) are produced via contact interactions of the form \( \mathcal{L}_{ee^*q} = \frac{g}{\Lambda} (\bar{e}^*\gamma^\mu e)(\bar{q}\gamma_\mu q) \). This case is also briefly considered in \([35]\).
The existing bounds on $\Lambda$ and on the masses $m^*$ of the excited states still permit abundant production rates at LEP $\otimes$ LHC. For example, for $\Lambda \approx 1 \text{ TeV}$ and $200 \leq m^* \leq 600 \text{ GeV}$ one predicts a few thousand to a few hundred excited leptons per $1 \text{ fb}^{-1}$. Moreover, using the known nucleon form factors one finds that the elastic process $ep \rightarrow e^*p$ sketched in Fig. 17 is almost as strong as inelastic production, $ep \rightarrow e^*q + X$. For the above specifications, the expected yield is about 1000 to 100 $e^*p$ events. These events provide an extremely clean signature and are thus most favourable for detection [35]. Firstly, the decay $e^* \rightarrow e\gamma$ allows to reconstruct the mass of the $e^*$ from completely known kinematics. In the mass range considered, the branching ratio for the above channel is roughly 30%, while the remaining 70% of the decays lead to $eZ$ and $\nu W$ final states. Obviously, the $e^*$ is a very narrow resonance with a total width $\Gamma_{e^*} \leq 2 \text{ GeV}$ for $m^* \leq 1 \text{ TeV} \leq \Lambda$. Secondly, the elastic events are very quiet since even the proton leaves undetected through the beam pipe. Thirdly, in the channel $e^* \rightarrow e\gamma$ there is essentially only one source of background, namely wide angle bremsstrahlung from the electron or proton leg. While for the electron-bremsstrahlung one has to calculate the Compton process $e\gamma \rightarrow e\gamma$, it is less straightforward to estimate the bremsstrahlung on the hadron side. A reasonable approach is to consider quark-bremsstrahlung processes $eq \rightarrow eq\gamma$ where the scattered quark stays inside the beam pipe, together with the spectator system, so that only the scattered electron and the bremsstrahlung photon is observable. Both signal and background events have been analysed with the help of a simulation program for the H1 detector. The visible cross sections integrated over realistic mass bins are shown in Fig. 18. This result proves that the $e\gamma$ channel is practically background-free.

Thus, a few elastic $e\gamma$ events clustering at a large invariant mass would be sufficient to verify the existence of an excited electron. Alternatively, the absence of a signal at LEP $\otimes$ LHC would exclude a large region in the $(\Lambda, m^*)$-plane as indicated in Fig. 19. For comparison, at HERA one will be able to probe the range $m^* \leq 200 \text{ GeV}$ and $\Lambda \approx 1 \text{ TeV}$. So far, we have only exploited the elastic $e\gamma$ channel. Corresponding signals are expected in $eZ$ and $\nu W$ final states, and in appropriate inelastic event samples, if the $e^*$ exists. Some of these additional signals should be observable and provide further evidence. Finally, one can and certainly should also search for heavy neutrino species such as the $\nu^*$ mentioned above. To
conclude, LEP ⊗ LHC has the potential to extend the discovery window for excited leptons far beyond the detection limits at HERA, and to reach the $TeV$ range.

Figure 18. Effective cross sections at $\sqrt{s} = 1.26$ TeV for the signal process $e p \rightarrow e^+ p \rightarrow e \gamma p$ and the bremsstrahlung backgrounds (from Ref. 35).

Figure 10. 95% confidence limits on $e^+$ parameters from the non-observation of a signal in the elastic $e \gamma$ channel (from Ref. 35).

6.2. LEPTOQUARKS

Another domain where $ep$ collisions are hard to beat is the search for leptoquarks with appreciable couplings to electrons and light quarks. Such particles appear, for example, in the fundamental scalar multiplets of $E_6$ models which have become popular in connection with superstring phenomenology [6], but also in many other theoretical scenarios [38]. For our study, we have assumed a rather typical species, namely a scalar, colour triplet, weak isospin singlet leptoquark with Yukawa-type couplings to the first family of ordinary fermions. The effective $SU(2) \otimes U(1)$ symmetric Lagrangian is given by [38]

$$\mathcal{L}_S = [\lambda_L (\bar{u}_L e_L - \bar{d}_L \nu_L) + \lambda_R \bar{u}_R e_R]S^c$$

where $S$ is the leptoquark field and the upper index $c$ denotes charge conjugation. Furthermore, we set the right-handed coupling $\lambda_R$ to 0 in order to avoid problems with present experimental knowledge* (see e.g. Ref. 38), and write $\frac{\lambda_L^2}{4\pi} = F_L\alpha$ using

---

*The experimental constraints could also be satisfied with $\lambda_L \approx 0$ and $\lambda_R = O(\alpha)$. However, the main conclusions we have reached are independent of the choice made, except that for $\lambda_L = 0$ the $\nu d$ channel is not existent.
$F_L$ as a measure of the leptoquark coupling strength relative to the electromagnetic coupling.

In electron-quark collisions, leptoquarks can be resonance-produced as indicated in Fig. 20. For this reason, ep colliders are potential leptoquark factories. To give a numerical example, at LEP $\otimes$ LHC one could produce more than 10000 S-leptoquarks per year if the mass is 500 GeV and the coupling is comparable to $\alpha$, i.e $F_L \approx 1$. Moreover, the decays $S \rightarrow eu$ and $S \rightarrow ud$ give rise to striking signatures. Although the resulting final states are indistinguishable from ordinary NC and CC scattering processes, $ep \rightarrow eqX$ and $\nu q X$, as far as the particle content is concerned, there are dramatic differences in various distributions. For instance, while the NC background is steeply falling in $y$, the signal events are characterized by a flat $y$-distribution. Even more remarkable is the peaking of the signal events at $x = m_S^2/s$, $x$ being the Bjorken-scaling variable. In contrast, ordinary NC and CC events have smooth, structureless $x$-distributions. Therefore, a suitable cut in $y$ will suppress the background and possibly lead to the appearance of a narrow resonance line* in inclusive $x$-distributions. This is demonstrated in Fig. 21 for the NC channel which contains the $S \rightarrow eu$ signal. The Monte Carlo study has been performed using

*In the accessible mass range the total decay width $\Gamma_S = O(1 \text{ GeV})$. 

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a simulation program for the ZEUS detector [36]. Note that even before cutting in $y$, a 500 GeV leptoquark with a coupling which is ten times weaker than the electromagnetic coupling would show up as a visible peak in $z$. The signal in the CC channel from the decay $S \rightarrow \nu d$ is a little bit less pronounced. This reflects the different experimental resolutions resulting from the necessity in CC events to reconstruct $x$ alone from hadron measurements, whereas in NC events one can also use the scattered electron. Nevertheless, also in CC distributions one can expect a clear resonance peak after applying a cut in $y$ as illustrated in Fig. 21.

The discovery limits at LEP $\otimes$ LHC and HERA are summarized graphically in Fig. 22. We see that with LEP $\otimes$ LHC one could make a big step beyond HERA, similarly as in excited lepton searches. In fact, for couplings of order $\alpha$ it is feasible to reach masses up to $m_S \approx 0.8\sqrt{s} \approx O(1\ TeV)$. Alternatively, in the few hundred GeV range one is sensitive to very weak couplings, $\lambda^2/4\pi \approx 10^{-3}\alpha$. Fig. 22 shows further that the higher energy $ep$ option is only favourable over the lower energy option when one approaches the kinematical limit.

![Figure 22. Discovery limits for S-leptoquarks requiring a 5$\sigma$ signal (from Ref. 36).](image)

7. Supersymmetric Processes

Supersymmetry is commonly considered to be one of the theoretically most attractive, powerful and precise suggestions for new physics [1]. Therefore, SUSY searches deserve high priority at future accelerators. In supersymmetric extensions of the Standard Model, the ordinary particles and their supersymmetric partners are usually distinguished by a conserved parity-like quantum number, called R-parity*.

*We have not considered scenarios with broken R-parity.
As a consequence, supersymmetric partners can only be produced in pairs and the lightest of them (LSP) is stable. This again has far-reaching phenomenological implications. In the minimal supersymmetric Standard Model [39] which we assume for definiteness, the following SUSY processes can occur in ep collisions:

- slepton-squark pair production, $eq \rightarrow \tilde{t}q'$, involving neutralino and chargino exchange [40, 41]
- squark-gluino pair production $\gamma q \rightarrow q\tilde{q}$ [42]
- squark pair production $\gamma g \rightarrow q\tilde{q}$ [42]
- slepton (squark)-gaugino production $eq \rightarrow \tilde{t}q\tilde{\chi}$ and $eq \rightarrow l\tilde{q}\tilde{\chi}$ [5].

This list is by no means exhaustive, but it contains the main reactions. Among them slepton-squark production plays the most important role for at least two reasons: complementarity to the dominant SUSY processes in pp and $e^+e^-$ collisions, and maximum search window for SUSY in ep collisions. We have, therefore, focussed our attention on this particular class of processes.

![Diagram](image)

**Figure 23.** (a) Neutralino and (b) chargino exchange diagrams contributing to slepton-squark pair production.

The relevant diagrams are exemplified in Fig. 23. Although the Lagrangian of the theory is completely specified, one has many new parameters which are not fixed within the supersymmetric Standard Model. This makes definite predictions somewhat ambiguous, or at least model-dependent. In the case at hand, one has to choose values for the slepton and squark masses, $m_l$ and $m_{\tilde{q}}$, as well as for the parameters appearing in the neutralino and chargino mass matrices. The gaugino mass eigenstates are mixtures of the $SU(2)_L \otimes U(1)$ gaugino ($\tilde{\omega}$, $\tilde{\chi}$, and $\tilde{\gamma}$) and higgsino states. Employing unification relations one is left with a minimum of three unknown parameters: the gaugino and higgsino mass parameters $M$ and $\mu$, respectively, and the ratio $\tan\beta = \frac{v_2}{v_1}$ of the vacuum expectation values of the two Higgs doublets required in the minimal model. Diagonalization of the mass matrices yields the physical masses and composition of the mass eigenstates denoted by $\tilde{\chi}_{1,2,3,4}^0$ (neutralinos) and $\tilde{\chi}_{1,2}^\pm$ (charginos) in Fig. 23. The composition plays an important role since only the $\tilde{w}$, $\tilde{z}$, and $\tilde{\gamma}$ components enter in the processes $eq \rightarrow \tilde{t}q$, whereas the couplings of the higgsino components are strongly suppressed by the light electron and quark masses. The magnitude of the production cross sections is mainly deter-
mined by the sum $m_\ell + m_{\tilde{q}}$ of the slepton and squark masses, and only moderately influenced by the parameters $M$, $\mu$ and $\tan\beta$. However, the decay properties of the sparticles depend strongly on the whole set of parameters.

The theoretical background recapitulated above has been worked out for our specific needs in [40]. Paying attention to the unavoidable model-dependence, we have considered two quite different scenarios:

(A) Sleptons and squarks decay directly into the lightest neutralino (LSP), $\tilde{t} \rightarrow l \tilde{\chi}_1^0$ and $\tilde{q} \rightarrow q \tilde{\chi}_1^0$, with a branching ratio of 100%. The $\tilde{e}\tilde{q}$ events have a familiar and relatively clean signature, namely an isolated high-$p_T$ electron, jets, and large missing momentum. In $\tilde{\nu}\tilde{q}$ events, the lepton signature is absent.

(B) Sleptons and squarks decay directly, but also in cascades, $\tilde{f} \rightarrow f' \tilde{\chi}_i \rightarrow \tilde{\chi}_j + \ldots \rightarrow \tilde{\chi}_1^0 + X$, into the LSP. Correspondingly, one expects events with higher lepton and jet multiplicities, smaller transverse momenta, and a less pronounced $p_T^{miss}$-signature. On the other hand, a fraction of the $\tilde{e}\tilde{q}$ and $\tilde{\nu}\tilde{q}$ events lead to very similar visible final states.

![Diagram](image.png)

Figure 24. Gaugino-higgsino parameter space. The crosses $\otimes$ in region II and III and the corresponding diagrams characterize the scenarios (B) and (A), respectively (from Ref. 40).

These possibilities are characterized pictorially in Fig. 24. Also indicated is the corresponding choice of parameters and the location of models (A) and (B) in the $(M,\mu)$-plane. While region I is already partly excluded by recent LEP data [43], region IV is kinematically forbidden for the assumed slepton and squark masses because $m_{\tilde{\chi}_1^0} > m_{\tilde{l},\tilde{q}}$. Using the cross sections and branching fractions provided in [40], the MC group [41] has investigated the observability of SUSY events in both
scenarios.

Obviously, the most favourable signal with regard to detection comes from $\tilde{e}q$ production in (A), while $\tilde{\nu}q$ events are very difficult to detect in scenario (A) since the decay $\tilde{\nu} \to \nu\tilde{\chi}_1^0$ produces no visible particles which could be used to separate the signal from ordinary CC events, $ep \to \nu + jets$. In scenario (B), on the other hand, a large fraction of the $\tilde{\nu}q$ events have an observable charged lepton in the final state coming, for example, from the decay $\tilde{\nu} \to e\tilde{\chi}_1$. However, it is now virtually impossible to distinguish $\tilde{\nu}q$ from $\tilde{e}q$ final states so that both types of events are treated in one sample.

The background arises mainly from ordinary, deep-inelastic NC and CC scattering, from single $W$ and $Z$ production, and from the awaited production of the $t$-quark and the decay in the channel $t \to bW \to be\nu$. The NC, CC, and top background processes are included in the MC simulation, while the $W$ and $Z$ backgrounds are only argued to be eliminated by the cuts which will be specified below [41]. This needs some further work. The analysis is performed for the beam energies $E_e = 50 \text{ GeV}$ and $E_p = 8 \text{ TeV}$, and under the usual assumptions on the detector capabilities. In a careful study of the event sample which contain an isolated high $p_t$ electron and which are therefore most promising, one has first tested the efficiency of various isolation and transverse momentum cuts. An optimal choice for $m_\tilde{e} + m_q \leq 700 \text{ GeV}$ and $100 \leq m_t \leq 200 \text{ GeV}$ is given by $p_{te} > 80 \text{ GeV}$ and $p^\text{miss}_t > 50 \text{ GeV}$. The effect of the $p_{te}$-cut on the signal and the top background can be inferred from Fig. 25. For $m_\tilde{e} = m_q = 250 \text{ GeV}$ and scenario (A) one finds that one should be able to collect about 60 $\tilde{e}q$ events above an irreducible background of 10 top events in one year of running.

![Figure 25. Transverse momentum spectra of the electrons from selectron decay, $\tilde{e} \to e\tilde{\chi}_1^0$, assuming $m_\tilde{e} = 250 \text{ GeV}$ and $m_{\tilde{\chi}_1^0} \approx 125 \text{ GeV}$, and from top decay, $t \to bW \to be\nu$, taking $m_t = 150 \text{ GeV}$ (from Ref. 41).](image-url)
We have also derived detection limits for the $\tilde{e}q$ channel by varying the selectron and squark masses and requiring more than 20 signal events, i.e. a signal to background ratio greater than 2. The result is shown in Fig. 26. If $m_{\tilde{e}} \leq m_{\tilde{q}}$ as theoretically preferred [39] and if the LSP is light, one can probe selectron and squark masses up to values slightly above 300 GeV and 400 GeV, respectively. Furthermore, even if the LSP is heavy, e.g. $m_{\tilde{e}_1^\pm} = 100$ GeV, one can still search for the selectron in the mass range $160 \leq m_{\tilde{e}} \leq 320$ GeV, provided $m_{\tilde{q}} \leq 350$ GeV.

The expectations for scenario (B) are actually quite similar. This has a simple, but extremely model-dependent reason. Despite of the existence of a huge number of different decay channels with more or less appreciable branching fractions, the experimentally preferred two-body decay $\tilde{e} \rightarrow e\tilde{\chi}^0$ still has a branching ratio of about 50%. This is sufficient for detection although the $p_T^{miss}$ signature on the hadron side is degraded because squarks decay dominantly via $\tilde{q} \rightarrow q'\tilde{\chi}^\pm_{1,2}$ and subsequent chargino decays in this scenario. It should be noticed that the analysis described here only makes use of the lepton-missing momentum signature. Differences of signal and background events in the jet-structure of the final states and in the electron-jet correlations [44] are not exploited. Finally, we have studied the observability of cascade events in the channels $2e+\text{jets}+p_T^{miss}$ and $1e+1\mu+\text{jets}+p_T^{miss}$. According to [41], one can obtain a small, but very clean sample of signal events following the above procedure and relaxing the lepton-$p_T$ cut.

![Diagram](image)

**Figure 26.** Detection limits for selectron-squark production at LEP $\otimes$ LHC assuming dominance of the direct decays $\tilde{f} \rightarrow f\tilde{\chi}^0$ into the LSP (from Ref. 41).

In summary, LEP $\otimes$ LHC allows to search for sleptons and squarks in an interesting mass window. While squark searches are also possible at hadron colliders with a much greater lever arm, searches for sleptons are considerably less promising, if not hopeless [1, 34]. In this situation, the $ep$ mode would save the day, unless the results from $pp$ collisions exclude the existence of squarks with $m_{\tilde{q}} \leq 400$ GeV.
8. Conclusions

The task assigned to the ep Working Groups was twofold: evaluation of the physics potential of the ep option at the LHC, and rough, but specific design studies for an ep detector in a LEP-LHC interaction region. In the present paper, I have summarized the work of the physics subgroups. The detector studies and basic considerations about experimentation at LEP ⊗ LHC are described in separate, short contributions [7,8]. From the results obtained at this Workshop, one can draw the following conclusions.

The LHC ep mode provides the unique possibility

- to explore the proton structure and study QCD in extreme regions in $x$ and $Q^2$ extending to $x < 10^{-5}$ and $Q^2 > 10^5 \text{ GeV}^2$
- to determine the gluon density in the range $5 \cdot 10^{-5} \leq x \leq 10^{-2}$ from several complementary processes
- to search for the standard Higgs boson in the intermediate mass range from 80 GeV to 140 GeV using the dominant decay mode $H \rightarrow b\bar{b}$ (This puts strong demands on b-flavour identification and dijet-mass resolution.)
- to probe physics beyond the Standard Model by searching for new particles which carry the e-quantum number such as SUSY selectrons, excited leptons and leptoquarks in the mass ranges $m \leq 300, 800, \text{ and } 1200 \text{ GeV}$, respectively
- to test the hypothesis of composite of leptons and quarks up to energy scales $\Lambda \approx 20 \text{ TeV}$.

In other domains, for instance, heavy flavour and electroweak physics, ep experiments would be a valuable supplement to the pp physics program.

Furthermore, with LEP ⊗ LHC one can make a big step beyond HERA. More definitely, the region in $x$ and $Q^2$ accessible at HERA can be extended to lower values of $x$ by a factor 15 and to higher values of $Q^2$ by a similar factor. Moreover, one gains a factor 4 in the mass and energy scales which can be reached. This opens up new search windows for theoretically expected or unknown physics.

However, there are also some requirements which must be fulfilled in order to achieve the physics goals put forward by our evaluation. On the machine side, the main requests are

- luminosity $L \geq 10^{32} \text{ cm}^{-2} \text{ sr}^{-1}$
- $e^-p$ and $e^+p$ intersections
- longitudinal polarization of e-beams.

High luminosity has absolute priority. In comparison, the gain in c.m. energy by
increasing the electron beam energy from 50 \textit{GeV} to 100 \textit{GeV} is less important. To exploit the flexibility of \textit{ep} physics it is essential to have electron and positron beams, while longitudinal polarization is very desirable, in particular, for electroweak physics, but not really indispensable. Finally, the possibility to run at a proton beam energy of 2\textit{ TeV} is mainly interesting for structure function measurements and direct comparison with HERA results.

With some modifications, the HERA detectors H1 and ZEUS have been used in our study as models for a suitable \textit{ep} detector at LEP \otimes LHC. Clearly, the strong synchrotron radiation produced by the necessary bending of the electron beam in order to collide with the proton beam, and the very large asymmetry of the electron and proton beam energies requires special design at small angles. Perfect hermeticity and particle detection at smallest angles is very important for excellent measurements. In addition, for some physics one needs the capability to identify flavours. It has not yet been studied whether flavour identification is feasible in the LEP \otimes LHC envirement.

To finish, the \textit{ep} option considered here is not only a unique feature of the LEP-LHC complex, it would also provide unique physics opportunities. With the operation of HERA in the near future one will gain more experience with physics at \textit{ep} colliders, and thus learn more about the actual value of LEP \otimes LHC.

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Higgs Search at LEP/LHC


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Abstract

Production of an intermediate mass Higgs boson in ep collisions at LEP/LHC (80 GeV < m_H < 140 GeV) leads to a dijet invariant mass peak due to the decay H → b̅b. The visibility of this Higgs signal above backgrounds has been investigated. A detector with good forward coverage, good b-identification capability, and good b̅b invariant mass resolution will be able to suppress backgrounds below the signal level.

Present search strategies for the Higgs boson leave an important gap for Higgs masses between about 80 GeV and 140 GeV, the mass range of the so-called intermediate mass Higgs boson. If m_H ≤ 80 GeV, the Higgs will presumably be discovered at LEP. For Higgs masses above 140 GeV Higgs production via gluon fusion at the LHC and/or the SSC will allow the detection of the decay mode H → ZZ (with one of the Z's possibly being virtual)[1]. This leaves the intermediate mass range where Higgs searches at hadron colliders face serious background problems.

We have studied whether the SM Higgs boson with a mass in this intermediate range would be observable in ep collisions at LEP/LHC. More specifically we have concentrated on the observability of the dominant H → b̅b decay. All calculations are done for 60 GeV on 8 TeV ep scattering assuming an integrated luminosity of 1 fb⁻¹, which corresponds to one year (10⁷ sec) running at L = 10^{32} cm⁻² sec⁻¹.

At an ep collider the important Higgs production mechanisms are WW and ZZ fusion[2–4]. The relevant Feynman graphs are shown in Fig. 1. Because of the W's strong coupling to fermions the WW fusion cross-section turns out to be about 5 times larger than the ZZ fusion contribution.

![Feynman graphs for Higgs production in ep collisions via WW and ZZ fusion.](image-url)
Fig. 2: Total Higgs production cross-section from a) $WW + ZZ$ fusion (dash-dotted line), b) $WW$ fusion only (dashed line), c) $WW$ fusion including the branching ratio for $H \rightarrow bb$ (upper solid line), and d) including the cuts described in the text.

The sum of both contributions as well as the $WW$ fusion cross-section alone is shown in Fig. 2 as a function of the Higgs mass $m_H$. Because of the more severe neutral current (NC) backgrounds to ZZ fusion as compared to the charged current (CC) backgrounds to $WW$ fusion we have only studied the latter production process.

The main features of the $H \rightarrow bb$ signal can be read off Fig. 1, detailed distributions for the complete production and decay process were generated with a parton level Monte Carlo and are shown in Fig. 3 for a 100 GeV Higgs. The signal consists of two high $p_T$ $b$-jets which reconstruct the Higgs mass and which appear in the central part of the detector (Fig. 3b). They are accompanied by a relatively forward spectator jet with intermediate $p_T$. In the following partons are accepted as jets provided they pass the following transverse momentum, pseudo-rapidity and separation cuts

$$
\begin{align*}
    p_T & \geq 20 \text{ GeV} \\
    |\eta_j| & \leq 4.5 \\
    \Delta R_{jj} & = \sqrt{\Delta \eta_{jj}^2 + \Delta \phi_{jj}^2} > 1
\end{align*}
$$

Because of the isotropic decay of the scalar Higgs the $b$ jets will in general deposit a large amount of transverse energy in the detector. We hence require a total $E_T > 100$ GeV in order to define the phase space region in which the Higgs search is performed. Finally we observe from Fig. 3b that the spectator jet has the largest average rapidity. We hence search for a peak in the invariant mass distribution of the two lowest rapidity jets only. This procedure correctly identifies the two $b$ jets in about 90% of the Higgs events.

Apart from the three jets discussed so far Higgs events contain a neutrino arising from the production of the virtual $W^-$ in Fig. 1. The resulting $p_T$ spectrum is shown in Fig. 3a; requiring $p_T > 20$ GeV retains most of the signal but greatly reduces the NC induced backgrounds.

Combining all the cuts one is left with an acceptance of 30% to 50% of the $H \rightarrow bb$ events in the intermediate mass range. The resulting usable cross-section
Fig. 3: Characteristics of the signal arising from a 100 GeV Higgs boson. Shown are a) the $p_T$ spectra of the spectator jet and the missing neutrino (solid line) and of the 2 $b$ jets. In b) the rapidity distributions of the $b$ jets and of the spectator jet are shown. $b_1$ denotes the $b$ jet with the lowest rapidity and $b_2$ the one with the highest rapidity.

is shown in Fig. 2: for Higgs masses around 100 GeV one is left with about 50 events/year.

Whether or not this relatively small number of events suffices to establish a Higgs signal is purely a function of the background rejection which is achievable. We have studied a variety of backgrounds:

- Photoproduction of multijet events. More generally, NC production of multijet events where the $e^-$ is lost in the beam pipe can give rise to a missing $p_T$ signature due to mismeasurement/cracks in the calorimeter or very energetic particles which are lost in the beam pipe. Because of the huge photoproduction cross-section of dijet events, $\sigma_{NC}(dijet) = 1.5 \text{ nb}$ within the acceptance cuts of Eq. (1), this is a potentially devastating background[4].

- CC multijet production. Although having a smaller rate, $\sigma_{CC}(dijet) = 56 \text{ pb}$, these events exhibit a generic $p_T$ signature and are hence more difficult to suppress.

- Single $W$ or $Z$ production with subsequent hadronic decay. Production cross-sections are in the pb range:

\[
\begin{align*}
\sigma(ep \rightarrow eWj) \text{ Br}(W \rightarrow jj) &\approx 10 \text{ pb} \\
\sigma(ep \rightarrow eZj) \text{ Br}(Z \rightarrow jj) &\approx 2 \text{ pb} \\
\sigma(ep \rightarrow \nu Wj) \text{ Br}(W \rightarrow jj) &\approx 1 \text{ pb} \\
\sigma(ep \rightarrow \nu Zj) \text{ Br}(Z \rightarrow jj) &\approx 0.4 \text{ pb}
\end{align*}
\]

(2)

These backgrounds will be important if the Higgs is degenerate with the $W$ or the $Z$. Most troublesome are $\nu W$ and $\nu Z$ production with their generic $p_T$ signature.
• Top production: $ep \rightarrow \nu \bar{b}X, i \rightarrow \bar{b}jj$. The level of this background depends critically on the as yet unknown top mass. For $m_t = 160$ GeV on finds $\sigma(ep \rightarrow \nu \bar{b}X) \approx 2$ pb[5]. Because these events almost always contain a $b\bar{b}$ pair, top production is a dangerous background even if good $b$-identification is available.

All these backgrounds have been studied in detail using parton level Monte Carlo programs based on the full tree level QCD matrix elements. Cross checks were made with the parton shower Monte Carlo programs LEPTO[6] and AROMA[7] and reasonable agreement was obtained. As an example for the background reduction which is obtained by applying the acceptance cuts described for the signal, let us consider the background with the largest rate, photoproduction of multijet events.

In order to find the Higgs signal we are searching for a peak in the invariant mass distribution of the two jets with the lowest rapidity. Photoproduction will lead to a large number of high invariant mass dijet events, either via photon-gluon fusion or via the mixed QED-QCD Compton process. For the jet acceptance cuts of Eq. (1) the resulting dijet invariant mass distribution is given by curve a) in Fig. 4. Even in a relatively narrow mass bin of 10 GeV only, this dijet rate is $10^3$ times larger than the Higgs signal plotted in Fig. 1. However we have not used the additional characteristics of the Higgs signal yet. Requiring the presence of a spectator jet ($p_T > 20$ GeV, $|\eta| < 4.5$) and imposing a transverse energy requirement on the 3-jet system of $E_T > 100$ GeV reduces the background rate by an order of magnitude, to curve b) in Fig. 4.

![Graph](image)

**Fig. 4:** Invariant mass distribution of the 2 jets with the smallest rapidity for multijet events from photoproduction. a) All dijet events, b) 3 jet events with $E_T > 100$ GeV, c) requiring $p_T > 20$ GeV, and d) events satisfying all of the above which contain a $b\bar{b}$ pair.

A further strong reduction is achieved by requiring $p_T > 20$ GeV. Energy mismeasurement in the detector has been simulated by Gaussian smearing of the parton momenta with an optimistic resolution of $\delta E/E = 0.35/\sqrt{E} \oplus 1\%$ and with a conservative one of $\delta E_T = 0.5\sqrt{E_T}$. The resulting $p_T$ distributions for 3 parton events satisfying the criteria of Eq. (1) are shown in Fig. 5. A more effective way to generate missing transverse momentum is from very energetic particles lost in the beam...
Fig. 5: $p_T$ distribution of photoproduction events with 3 jets inside the detector. The curves labeled $jjj$ allow for energy mismeasurement only, while for the $jjj(j)$ curves a fourth jet of finite $p_T$ is lost inside the proton beam pipe.

pipe[8]. For this purpose 4 jet events were generated at tree level with 3 jets inside the detector (satisfying Eq. (1)) and one jet with $\eta_j > 4.5$ and finite $p_T$. The $p_T$ distributions arising from this lost jet are shown in Fig. 5 for both energy resolutions. They probably overestimate losses in the beam pipe because in the simulation one single parton carries away the transverse momentum while in reality it will be shared by several hadrons with ensuing cancellations of $p_T$.

Requiring $p_T > 20$ GeV leads to a further reduction of the photoproduced 3 jet events by a factor $\sim 40$. This reduction factor was confirmed by studying fully hadronized NC events generated with the AROMA Monte Carlo: even the presence of neutrinos from semileptonic $b$ decays in a pure $b\bar{b}$ sample still gave a reduction factor of 20. The resulting dijet invariant mass distributions for all photoproduction processes and for true $b\bar{b}$ events are given as curves c) and d) in Fig. 4.

While the background level after the $p_T$ cut is still critical, flavor identification promises to reduce the NC background well below the signal level. At this point it should be noted that we have not yet optimized the acceptance cuts for maximal $S/\sqrt{B}$. An increase of the $p_T$ or $p_T$ cuts will affect the NC background much more strongly than the Higgs signal. Hence a NC background level as shown in Fig. 4 will be achievable in practice after a slight tune of the cuts.

Requiring the presence of a spectator jet and $E_T > 100$ GeV reduces the CC background to about the same level as the NC one, before flavor identification. Because CC events rarely contain high mass $b\bar{b}$ pairs, a good flavor identification capability will be more effective to reduce this CC background. The same is true for the single $W$ production background. An irreducible physics background arises from $ep \rightarrow \nu Z j$, $Z \rightarrow b\bar{b}$ when searching for a Higgs with $m_H \approx m_Z$. About 90 $Z \rightarrow b\bar{b}$ events are expected in a sample of 1 fb$^{-1}$.

For possible $b$ identification capabilities we may extrapolate studies performed for the DELPHI detector at LEP[9]. The $b$ jets from Higgs decay appear in the central part of the detector (see Fig. 3b), with dijet invariant masses as at LEP, and hence such an extrapolation appears permissible. Exploiting event shape variables
and information from the microvertex detector a Monte Carlo study[9] arrived at
the probabilities to identify light, charm, or b quark pairs as b b events which are
given in the table:

<table>
<thead>
<tr>
<th>pair generated</th>
<th>seen as light</th>
<th>seen as charm</th>
<th>seen as bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>light</td>
<td>0.87</td>
<td>0.11</td>
<td>0.009</td>
</tr>
<tr>
<td>c</td>
<td>0.30</td>
<td>0.62</td>
<td>0.07</td>
</tr>
<tr>
<td>b</td>
<td>0.02</td>
<td>0.09</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Since at LEP quarks are always produced in pairs we have taken the square roots
of these numbers as the probabilities that a jet originating from a light or charm
quark is seen as a b-jet. More precisely we assume a 10% chance to identify a gluon
or a u, d, or s quark as a b, a 25% chance for seeing a c as a b, and an 80% efficiency
to identify a single b jet correctly.

Using these assumptions for b-identification we have added the dijet invariant
mass distributions of all the backgrounds, including the b b three-jet events arising
from a 160 GeV top quark[10]. The result is shown in Fig. 6 together with the total
Higgs signal cross section after flavor identification.

![Graph](image)

Fig. 6: Signal (dashed line) and background rates (solid line) after flavor identifica-
tion as discussed in the text. The signal curve gives the total visible H → b b cross
section as a function of the Higgs mass.

Notice that in Fig. 6 the background differential cross section is compared to the
total signal rate. Hence we need to know the b b invariant mass resolution in order to
obtain the significance of the Higgs signal. For this purpose the dijet system arising
from the H → b b signal has been studied with the PYTHIA Monte Carlo[10]. When
effects from final state gluon radiation are taken into account the results indicate
that a resolution of order

\[ \delta m_{bb} / m_{bb} \approx \pm 0.05 \]

should be achievable in principle. From Fig. 6 it is clear that an excellent mass
resolution of this order will lead to a highly significant Higgs signal over the entire
intermediate Higgs mass range, except perhaps around m_H = 90 GeV.
This conclusion rests on the assumption that an excellent detector will be available for doing ep experiments at LEP/LHC. Vital features are

- good forward coverage, down to at least 1° in the proton beam direction in order to identify the spectator jet.

- good energy resolution and "no cracks" in order to allow for the use of $p_T$ as a signal requirement.

- excellent $b$ identification capability with high $b$ acceptance in the central detector.

In particular for the last point, $b$ identification, dedicated studies are needed for the LEP/LHC environment.

Finally it should be noted that we have not yet optimized our analysis for maximal significance of the Higgs signal. Improved cuts on jet transverse momenta, $p_T$ or angular correlations will clearly reduce the dominant photoproduction and top quark backgrounds further and studies along these lines will be continued.

This research was supported by the University of Wisconsin Research Committee with funds granted by the Wisconsin Alumni Research Foundation and by the U.S. Department of Energy under contract DE-AC02-76ER00881.

References

[1] See e.g. D. Denegri, these proceedings.


[10] For details see G. Grindhammer et al., Searching for the Higgs in ep Collisions at LEP/LHC, these proceedings.
D9 - DETECTOR INTEGRATION

Lars Leistam, CERN


* * * * *

1. Introduction

The activities of the ECFA-LHC working group on Detector Integration have concentrated on problems where experimentation and machine design are closely interconnected. The principal aim has been to collect a sufficient amount of basic information about future LHC experiments in order to propose realistic designs for the new LHC experimental areas. The discussions in the Detector Integration group have been a complement to the presentations made in the detector instrumentation groups and concentrated on the various aspects of constructing, installing and operating an experiment at LHC.

This report tries to summarize the overall concepts and boundary conditions concerning new experimental areas for LHC. More detailed description of specific subjects can be found in Volume 3 of the proceedings.

2. Site considerations

The lattice of LHC foresees crossings of the two proton beams in all eight straight sections of the accelerator. Consequently, experiments could in principle be conducted in each of these eight areas.

The working group has assumed that the four large LEP experiments are still collecting data with LEP at the even numbered points of the accelerator during the initial round of LHC experiments. LHC experiments could, therefore, be housed in newly excavated caverns at the three interaction regions 1, 5, and 7. No considerations have been made concerning the installation of an experiment in Point 3, because of the very difficult geological conditions.

Point 1 The beam line is at 79 m below ground level. The geological conditions are good and large caverns and access shafts could be constructed. However, many structures exist already above and below ground which have to be taken into account. There are transfer and machine tunnels (LEP and SPS) and a service cavern for LEP (US15). To avoid disturbance to LEP, these existing structures should not be
modified. A cavern in Point 1 has therefore about LEP-like dimensions in a longitudinal orientation, while for a perpendicular cavern larger diameters up to 35 m are possible.

**Point 5** The beam line is located at 86 m below the surface. A number of water layers have to be traversed in order to reach the underground area, making the construction of access shafts more complicated and more expensive. The molasse rock starts at a relatively large depth below ground and is of inferior quality. The construction of a large diameter cavern (> 24 m) is therefore excluded.

**Point 7** The beam line is located at 94 m below ground level and the geological conditions are similar to those of Point 1. The construction of a large diameter cavern can be envisaged. The interaction region at Point 7 is, however, close to the border between France and Switzerland. The access shafts and surface buildings will fall to a large extent on Swiss territory and new land will have to be acquired.

The working group concluded that in case only two new experimental areas would be needed, Points 1 and 7 should be used in preference to Point 5.

3. **Interaction region layout**

The proton beams will normally collide in only three areas as the total beam-beam tune shift will be limited. The standard insertion for an LHC interaction region when operating with pp or ion-ion consists of a quadrupole triplet giving a $\beta^*$ between 0.5 and 15 m, corresponding to a pp luminosity range of $1.65 \times 10^{34}$ to $5.5 \times 10^{32}$ cm$^{-2}$ s$^{-1}$.

To obtain the maximum luminosity ($5 \times 10^{34}$ cm$^{-2}$ s$^{-1}$) at one interaction point (i.e. no interactions anywhere else), the bunch spacing must be increased to 45 ns and the number of particles per bunch be increased to $3 \times 10^{11}$, but the beam line layout will remain the same.

At these very high luminosities it is important to consider the resulting induced radioactivity in elements close to the beam pipe.

The closest magnet is 20 m from the interaction point but, as it is a high gradient superconducting quadrupole, the physical end of the cryostat of approximately 1 m diameter will be about 30 cm closer. In addition, the coils of this magnet must be protected from the flux of small angle particles from the interaction region by a suitable absorber of about 3 m length. With a minimum of space for vacuum pumps and valves, and maybe a correction magnet, the completely clear region for physics experiments will not exceed ± 16 m. An example layout of a standard pp interaction region is shown in Fig. 1.

The room temperature vacuum chamber through the experiment will have a nominal diameter of 5 cm. Some arguments were presented in favour of a smaller diameter vacuum chamber, a 2.5 cm central chamber was suggested. The working group could not conclude on this subject, since the minimum aperture required by the machine is not known. If required, the vacuum chamber can be equipped with a thin-walled central section. Space will have to be found for supports and vacuum getter pumps about every 2 m throughout the ± 16 m. An in-situ bakeout will also be needed to ensure the lowest possible residual gas pressure and avoid pressure bumps in the presence of the beams.
Fig. 1 Layout of a standard LHC interaction region beam line in a longitudinally-orientated cavern. The LEP beam elements at a non-collision point are also indicated.

It was generally agreed that the proposed standard interaction region is suitable for LHC experiments, but the absence of a mechanical design of the interaction quadrupoles and its support structure (its movability !) prevents a more detailed appreciation.

4. ep interaction region

In the ep mode of the LHC the two beams will collide in only one interaction region. The layout of such an interaction region was discussed in detail. The electron beam of LEP must be deflected vertically through an angle of about 6 mrad, in order to raise it to the LHC beam 1.2 m higher. A further bend is needed at the entry to the experiment to provide head-on collisions. This bend results in a synchrotron radiation fan, which will traverse the experiment.

A careful optimization of this bend will be necessary to keep the critical energy of the radiation as low as possible, taking into account the acceptance requirements of the experiment. To reduce backscattering, the synchrotron radiation will have to be absorbed on a dump some 50 m downstream.

5. LEP/LHC alternate operations

The long-term physics program of LEP and the construction schedule for the LHC lead to the assumption that both machines will operate alternately for a number of years after the
installation of the LHC has been completed. This alternate running has consequences for both of the accelerators and for the experiments associated with them.

During operation of one of the machines, the experiments associated with the other machine must allow the corresponding beams to pass. The problem is compounded by the space requirements for shielding [1], if safe access to the experimental cavern has to be guaranteed during beam operations.

The difference of 1.20 m in elevation between the two accelerators leads to three possible scenarios:

1) Experiments are rolled out of the interaction region into a garage position.

2) A sufficiently large passage is cleared through the detector, in order to let the beam pass and to install shielding where necessary.

3) The detector is lowered or raised to the beam line of the other machine, so that the beam can pass through the beam pipe at the centre of the experiment.

The working group recognizes that the question of alternate LHC/LEP operation must be regarded as particularly difficult. Alternate LHC/LEP operation will indeed introduce some constraints to the design of LHC experiments and necessitate some adaptation of the LEP experiments:

-shielding/access: shielding the LEP experiments in their garage position is non trivial, a possible shielding arrangement for an LHC experiment is shown in Fig. 2

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*Fig. 2* Shielding arrangement for a LHC experiment during LEP operation.
-design: additional constraints due to difference between LEP and LHC intersections

-schedule: the change-over time will set a limit on the change-over frequency

6. Dimensions of experiments

The design of LHC experiments is still in a very early phase, however, several conceptual detector designs were presented during the workshop. The working group made a preliminary survey of possible large detectors, designed to include a muon detection system, see Table 1.

Table 1

Detector Dimensions

<table>
<thead>
<tr>
<th>Type</th>
<th>length [m]</th>
<th>diameter [m]</th>
<th>weight [ton]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron toroid</td>
<td>24</td>
<td>17</td>
<td>25'000</td>
</tr>
<tr>
<td>Compact solenoid</td>
<td>33</td>
<td>14</td>
<td>21'000</td>
</tr>
<tr>
<td>Shaped solenoid</td>
<td>28</td>
<td>24</td>
<td>23'000</td>
</tr>
<tr>
<td>Muon toroid (coil)</td>
<td>22</td>
<td>18</td>
<td>4'100</td>
</tr>
<tr>
<td>L3 + 1</td>
<td>32</td>
<td>16</td>
<td>11'000</td>
</tr>
</tbody>
</table>

The main difference with respect to the LEP experiments is the overall size. The length is about 2 to 3 times that of LEP experiments and the weight is expected to range from 10,000 to 30,000 tons. The diameters transverse to the beam range from 15 to 25 m.

The dimensions of these conceptual detectors suggest that one needs either a cavern of little or no more than LEP dimensions with the axis parallel to the beam or a cavern of substantially bigger diameter perpendicular to the beam direction. Common to both orientations is the difficulty of providing a good crane coverage over the experiments.

Presentations of ep and ion-ion experiments show that they do not differ significantly in size and weight compared to the large "muon" experiments.

The working group took note of several presentations suggesting experiments using gas-jets, fixed targets or detecting the neutrinos/muons from the collision point. Table 2 gives a tentative listing of their installation regions.
The LHC lattice leaves two larger equipment-free regions in the standard straight section layout: a 29 m gap starting 60 m away from collision point and a 99 m gap starting 118 m away from collision point. There are no such corresponding free regions in the LEP straight section layout and it is therefore possible that some equipment must be removed during the operation of LEP.

Table 2

<table>
<thead>
<tr>
<th>Type</th>
<th>Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas-jet</td>
<td>in straight section, enlargement of present tunnel</td>
</tr>
<tr>
<td>Fixed target</td>
<td>in straight section, enlargement of present tunnel</td>
</tr>
<tr>
<td>Beauty detector</td>
<td>intersection, forward regions up to about 20 m</td>
</tr>
<tr>
<td>Neutrino-tau (from collision point)</td>
<td>in straight section, limited size detector; would fit in present tunnel</td>
</tr>
<tr>
<td>Neutrino-e, µ (from collision point)</td>
<td>special cavern at ~ 500 m</td>
</tr>
<tr>
<td>µ-beams (deflected)</td>
<td>“side” cavern</td>
</tr>
</tbody>
</table>

Here the influence on the design of the experimental areas is very different to the large “muon” detectors. Special caverns will have to be constructed far from the intersection regions or enlarged sections of the straight section tunnels will have to be arranged to accommodate a forward-region detector. In particular, the possible conflicts with machine installations must be studied in detail.

7. New experimental caverns

The possible sites for the construction of the experimental caverns allow them to be situated in the molasse rock, which is covered by a layer of moraine deposits of variable thickness. The depth and existing surface structures preclude a cut-and-fill construction of the underground areas.

The foreseen construction method will be identical to the one used for excavating the LEP experimental caverns, which have a diameter of 21 m. This method allows the rock mass surrounding the excavation to be employed as active support, which will minimize the cost and time for the excavation in comparison with other techniques. However, the cavern dimensions depend on the properties of the molasse rock and the thickness of the covering moraine deposits. Preliminary studies indicate that caverns with diameters up to 35 m can be excavated under good rock conditions.

Following the general civil-engineering considerations and the overall dimensions indicated in Table 1, the working group has designed two experimental areas: a perpendicular cavern and a longitudinal cavern.

Fig. 3 shows the layout of a 35 m diameter hall in a perpendicular orientation with respect to the beam line. A 20 m diameter shaft, offset to the side of the cavern, serves as the
Fig. 3  A 35 m diameter, 100 m long, perpendicular cavern (possible at point 1 and 7).
main equipment access shaft. Small tunnels for personnel access and safety run along both sides of the cavern at floor level. Personnel reach the cavern through a 9.10 m diameter shaft situated in the shielded extension of the experimental hall. This shielded hall will also house the counting rooms and service installations for the experiment. A second independent access shaft will be provided in order to fulfill the basic safety requirements concerning access to underground halls. The overall length of the hall, shown as an example, is 100 m. This length is justified by the space needed for a 20 m diameter experiment: space in the beam position, access space, garage position, free loading space in front of the access shaft and storage space during installation.

A longitudinal orientation as shown in Fig. 4 makes better use of the hall diameter limited by civil engineering constraints. The 24 m diameter hall shown allows a convenient axial (along the beam) opening of the experiment. The arrangement of a "garage" is, however, difficult. A parallel garage hall can be built, but the transfer of detector parts from garage to beam position is more difficult than in the perpendicular layout. The cavern shown has two large 18 m diameter access shafts placed directly over the beamline to facilitate the assembly of a very large or heavy experiment. The garage position is here replaced by the possibility of moving large detector parts to the surface. Counting rooms and service installations would be installed in a second cavern placed at a radiation safe distance (8 m of rock) from the experimental hall.

As mentioned in Section 2, the construction of a large diameter cavern is not possible in Point 5. Consequently, only a LEP size cavern, as shown in Fig. 5, can be constructed in this area.

It is also conceivable to construct a cavern with a different geometry in order to accommodate very particular detector arrangements, such as small angle spectrometers, gas-jet and fixed target experiments, for which modest enlargements of the machine tunnel can be envisaged.

Independent of the orientation of the cavern, it will be essentially impossible to arrange adequate shielding around LHC experiments, such as to allow permanent access to the experimental hall during the operation of the accelerator. In addition, the induced radioactivity along the beam line will require careful access control and monitoring during shutdowns.

Because of the inclined construction of the LEP/LHC tunnel, the beam line traverses the experimental hall at an angle compared to the horizontal floor. In Points 1 and 5, the inclination is 1.23% and in Point 7 it is 0.72%.

In general the next generation of large experiments will require sophisticated and bulky service and support installations: electrical power, cables, cooling and ventilation, cryogenics, gas-distribution, communications, etc. Some of these installations constitute an integral part of the experiment and space in underground areas and surface buildings must be allocated during the initial design phase. Furthermore the size of the experiments will not allow the installation of conventional bridge cranes in the caverns. Crane installations over the experiments will be limited to monorails or possibly arc-shaped cranes with maximum capacities of 35 to 40 tons.
Fig. 4  A 24 m diameter longitudinal cavern with two 18 m access shafts, of which one could be equipped with a 2500-ton lift (shown at Point 1 but adaptable for 5 and 7).
Fig. 5  A 24 m diameter, 82 m long, LEP type cavern.
8. Installation of experiments

The installation procedure of an LHC experiment will be determined by the construction of the detector, the civil engineering schedule for the underground cavern and the availability of the surface buildings. The tentative planning is shown in Fig. 6.

**Fig. 6** Tentative installation planning for a LHC detector.

Two scenarios can be envisaged:

i) **Perpendicular cavern with garage position.**

If the underground area incorporates a garage position for the experiment this area can be made available nearly two years in advance of the first beam. In this case the experiment can be assembled with similar techniques to those used for the LEP experiments. In the garage position the experiments are assembled from relatively small parts which can be transported on public roads to the experimental site. The detector is then rolled to the beam line position in a few large sections or as a complete assembly. A possible installation scenario is shown in Fig. 7.
ii) **Longitudinal cavern without garage position**

A longitudinal cavern will be available for the installation of its experiment somewhat later than in case i), because of the presence of the LEP shielding. The detector design and installation procedure has to take this into account. The experiment should therefore be preassembled into a few large components at the surface of the experimental site. These heavy units are subsequently lowered into the experimental cavern and assembled on the beam line. The surface area has therefore to provide sufficiently large halls for the preassembly of the large detector components and the access shafts have to be equipped with heavy lifting gear, capable of lowering several thousand tons at a time [2]. An example of an installed detector is shown in Fig. 8.

The size of the LHC experiments is such that indivisible components, eg a large superconducting coil, may exceed the dimensions and weight which can be transported on public roads. Therefore sufficient surface hall and lab space must be provided, in order to allow large experiments to meet the overall schedule.

The working group recognized the effort to accommodate a sufficient installation period for the experiments. However, with the present knowledge of future LHC experiments, it is not possible to judge whether this installation time is adequate.
9. Conclusions

We have examined the various conceptual detectors proposed for the LHC and find that the basic features of the proposed experimental areas and interaction regions are suitable for experimentation. However, more work remains to be done on the installation of large experiments.

We also note that the overall installation schedule for the LHC project, including the scheduling of LEP/LHC alternate operation, plays an important role in the considerations regarding new experimental areas for LHC.

Finally, it must be stressed that the absence of more definite LHC detector designs has set "natural" limits to the work performed by the Detector Integration Working Group and the presented designs should be regarded as a starting point for future work on experimental areas.

REFERENCES


RADIATION HARDNESS STUDIES FOR LHC DETECTOR MATERIALS

STATUS REPORT

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F. Wulf, Hahn Meitner Institute, Berlin, Germany

Abstract

This report gives a summary of the continued ECFA activities on detector R&D working group "Radiation Hardness". This includes the present status on doses and dosimetry, available sources for irradiations, and radiation test results on scintillators, crystals, semiconductor detectors, electronics, optical fibre cables, warm liquids, insulating materials and structural materials. It also gives recommendations on irradiation and test procedures, and finally a summary and outlook for the future.

Contribution to Plenary Session of LHC Workshop Physics and Instrumentation, Aachen, 4-9 October 1990
1. **INTRODUCTION**

Radiation hardness studies have now become an integral part of any R&D Project for LHC where detector materials will be exposed to ionizing radiation. These studies originally started 3 years ago within the LAA Project (1), have been complemented by studies in other collaborations and were regularly reported within the activities of ECFA (2).

For the continued ECFA activities on detector R&D a working group was created to keep contact to the various groups which were involved in radiation hardness studies for LHC especially on vertex detection and tracking, calorimetry and electron identification.

This report gives the present status on doses and dosimetry, available sources for irradiations, and radiation test results on scintillators, crystals, semiconductor detectors, electronics, optical fibre cables, warm liquids, insulating materials and structural materials. It also gives recommendations on irradiation and test procedures, and finally a summary and outlook for the future.

2. **DOSES AND DOSIMETRY**

Radiation dose calculations have been carried out during the last three years in close collaboration between LBL and CERN (3). New dose calculations have been presented at the Workshop (4). They include doses and neutron fluences in a lead calorimeter of 2 m radius for a luminosity of \(10^{34}\) cm\(^{-2}\) s\(^{-1}\), an effective running time of \(10^7\) seconds per year and an inelastic cross section of 60 mbarns. As can be seen from Fig. 1 the yearly doses at low angles are between \(10^5\) and \(10^6\) Gy. Also the doses in the inner cavity are extremely high close to the beam line (~10\(^6\) Gy, see Fig. 2). The lead albedo yearly neutron fluence in a spherical shell is also shown in Fig. 2; further details can be found in Ref. 4.

Apart from the total dose also the induced radioactivity will be of major concern in the forward direction at high luminosities where values in the range of mSv/h are expected; even after 24 hours of cooling time the access will be very restricted (4).

High-dose dosimetry at the present stage is mainly needed to survey radiation tests. The criteria for selection of suitable dosimetry systems are:

- Stability
- Ease of calibration
- Traceability of calibration to International Standards
- Simplicity of use
- Availability
- Reasonable dosimeter and operation cost
- Response in required:
  - Dose range
  - Energy range
  - Radiation type
- Dose rate independent.

The dosimetry methods listed below have been successfully tested and used in high energy particle accelerator environments (5):

- Radioluminescence
- Activation detectors
- Electron-spin-resonance (Alanine)
- Gas evolution (Hydrogen pressure).

Investigations will be carried out for LHC application of ethanol chlorobenzene for total dose (6) and silicon diodes for neutron measurements (7).

3. IRRADIATION SOURCES

3.1. Sources in industry and specialized institutes

There are many radiation sources in Europe for irradiation testing on materials and electronic components. Appendix 1 gives addresses, contact persons and a summary of the different cobalt, electron and neutron sources which can be used by external experimenters. A corresponding list is shown in reference 8. The presentation in Appendix 1 and in reference 8 is not complete and will be regularly updated. It is important to notice, that for the characterization of many materials and electronic devices, the measurement equipment should be available at the radiation facility. Especially for the annealing studies of electronic components -including detectors- the time between the irradiation and the measurement must be well defined during the whole test procedure.

X-ray sources can be used for radiation testing, but the dosimetry for a large energy spectrum as well as the dose response enhancement for low energy x-rays makes the interpretation of the test results sometimes very difficult. Therefore, an accurate dosimetry for each radiation source is necessary, otherwise a comparison of the irradiation test data from different experiments is impossible.

There are some institutes which are already specialized to perform radiation tests on different materials and components.
The Hahn-Meitner-Institut Berlin carries out irradiation tests on electronic components and circuits for more than 15 years, mainly for space applications. They have a well equipped laboratory to perform in-situ characterization of nearly all electronic components (11). Harwell Laboratory has a special low dose rate radiation test facility (LORAD) with a measurement system for electronic devices. The Fraunhofer-Institut Euskirchen has an excellent laboratory to characterize optical fibres (34).

3.2. Sources near HEP accelerators

Several neutron irradiation facilities are available near HEP accelerators.

At Rutherford Appleton Laboratory a graphite copper collector is used as a target of the ISIS beam. A light weight frame has been designed and built to be placed on top of the collector box. This frame and the measured neutron spectrum at three different distances is shown in Fig. 3 (9). Note that the peak at 1 MeV is exactly the same as expected in the cavity of future detectors (4).

At LAL Orsay, a 1 GeV electron beam incident on a tungsten converter produces $1.5 \times 10^{13}$ n/cm$^2$ h and a dose of 5 Gy/h; again the neutron energy peak is between 1 and 2 MeV (Fig. 4, Ref. 10).

At CERN small items (18 cm dia, 20 cm height) can be lowered down from outside into the dump and the target area of PS-ACOL (Fig. 5, Ref. 8); a shuttle to irradiate small electronic devices to neutrons is available at the University of Uppsala (32). For the latter two, the measurement of the neutron spectrum still needs to be carried out.

Recommendations on radiation sources and dosimetry are given in Appendix 3.1. Note to be very careful when making conversion from fluence to dose which depends on the radiation type, energy, and material and should therefore be avoided, unless these parameters are precisely known. It is also recommended to investigate a built in dosimetry for future detectors to measure the integrated radiation dose during operation, as is done in many accelerators (5).

4. RADIATION EFFECTS ON DETECTOR MATERIALS

In this chapter we give a summary of ongoing activities of radiation tests for LHC detectors by main subjects, eg. scintillators and crystals, semiconductor detectors, electronics and other materials
including optical fibres, insulators and structural materials. For each topic we also give recommendations for standardization of radiation tests as far as applicable.

4.1. Scintillators and crystals

The identified institutes active in this field are listed in Appendix 2.1.

For Tracking, an extensive radiation test programme is in progress for plastic scintillators and scintillating fibres (12). This comprises of base materials such as polystyrene, PMMA and PVT and the commercial scintillators SCSN 38, SCSN 81, NE 110, and the new scintillator found by the CERN-LAA Group, which is PMP in a polystyrene and PVT matrix. Irradiations are carried out in air and nitrogen and at various sources: gamma, neutron, and near the CERN accelerators. Irradiations have been carried out exceeding 10 kGy (1 Mrad) (Fig. 6). The results have shown that PMMA is less suitable as a matrix material than polystyrene and PVT. For the scintillating material good results have been obtained for SCSN 38, SCSN 81 and NE 110, whereas the PMP doped samples show some absorption, which can however be mostly recovered in an oxygen atmosphere after one month.

The results obtained so far can be summarized as follows (12):

- Irradiation in N$_2$-atmosphere causes less damage than in air (samples were outgased several days in vacuum).
- Recovery depends on the dose-rate. The samples were irradiated at a rate of ~ 40 Gy/h. This rate is ~ 50 times higher than at 15 cm distance from the collider beams ($10^{33}$ cm$^{-2}$ s$^{-1}$).
- At 40 Gy/h the samples recover to a stable plateau of damage (corresponding to an average dose-rate of 8 Gy/h), therefore there should be a continuous recovery during beam-exposure.
- PMP - doped samples and fibres are more vulnerable to radiation than other samples. Therefore new dopants with large stokes-shifts were synthesized. They show improved radiation hardness by preserving all other advantages such as light yield.

Also at LIP in Lisbon (13) an extensive radiation test programme for the compact electro-magnetic and hadronic calorimetry is going on. This is concentrated on the spaghetti calorimeter (SPACAL) consisting of 1 mm diameter scintillating fibres embedded in a lead module.
The irradiation of scintillating fibres was made using $^{60}$Co $\gamma$-rays and reactor neutrons under controlled atmospheres (air, $N_2$, $O_2$, argon, vacuum), with the aim of understanding the mechanisms of radiation damage.

S-101 fibres produced by Optectron (France) were exposed to a mixed neutron-gamma radiation field at three different dose rates of 0.65, 6.5 and 65 kGy/h, and doses ranging up to 0.1 MGy (10 Mrad). For comparison, fibres of the same type were exposed to $^{60}$Co photons at a single dose rate of 0.3 kGy/h. Before and after irradiation, the fibres were connected to a phototube and excited by a beta source at various distances from the phototube window. The radiation damage resulted in a reduction of the phototube signal. Fig. 7 summarizes these results for a distance source-phototube of 15 cm and shows that:

(i) the damage from neutrons is not larger than the damage from photons at any given dose,

(ii) the damage produced by neutrons does not depend on the dose rate (as shown by the three similar points at 10 kGy (1 Mrad) which were obtained at three different dose rates over a factor of 100).

Different types of fibres were enclosed in sealed tubes containing different gases and vacuum, and irradiated in an inhomogeneous field of $^{60}$Co-photons for a maximal dose of 30 kGy (3 Mrad) and a dose rate of 0.22 kGy/h at a distance of 30 cm from fibre end. The results are shown in Fig. 8. The significance of the striking pattern is not yet understood: the absence of $N_2$ (irradiation in oxygen) seems to decrease strongly the light emission after irradiation, while the absence of $O_2$ (irradiation in nitrogen) seems to decrease strongly the light transmission. Air is, fortunately, the atmosphere which is the best from the point of view of radiation hardness. Measurements not shown here indicate that the effects are dose-rate dependent; the fibres recover, within a few days after the end of the irradiation, from most of the additional damage produced under $O_2$ or $N_2$ atmospheres.

Further studies included the use of filters to cut off the wave-lengths of high radiation damage (see Fig. 9) and the influence of the glue which drastically reduced radiation resistance (13).

The future programme for SPACAL, will include 15 kinds of fibres from Kyowa, Optectron, Bicon and Cunz with different compositions and dopants. Irradiations will be carried out in a cobalt source on 2.3 metre long fibres at dose rates of 0.14, 1.4 and
60 Gy/h up to totally 100 kGy (10 Mrad); both scintillation yield and transmission will be measured to study damage effects on transmission and emission separately.

High and low dose rate irradiations of scintillators and wave-length shifters were carried out at the University of Hamburg for the ZEUS detector (14). For SCSN38 scintillators a strong dependence on atmosphere, dose rate and sample thickness were found (see Fig. 10). The higher radiation damage in air and with thin samples suggest a strong effect of oxygen diffusion; however no dose rate effect was found below 100 Gy/h. An average loss in light yield of \( \sim 7 \times 10^{-4} \% \) per Gy was found.

PMMA based wave-length shifters Y-7 and K-27 were found to be more radiation sensitive than the scintillators, for the latter also the recovery was much faster. Further studies will be carried out on the radiation sensitivity of the fluor and at very low dose rates (depleted uranium).

An interesting alternative to plastic scintillators are crystals where at present most radiation test data are available from BGO (15) and BaF\(_2\) (16); they both have the quality of high purity and high radiation resistance; also recovery is very pronounced. Figure 11 shows the radiation damage of BGO which saturates with dose and Fig. 12 the transmission of BaF\(_2\) crystals after irradiations up to 1.7 MGy (170 Mrad). Purification techniques for new materials are continuously progressing, therefore even higher radiation resistance could be expected. Further promising studies are conducted with Ce F\(_3\) crystals. Recommendations on radiation tests with scintillators and crystals are given in Appendix 3.2.

4.2. Semiconductor detectors

4.2.1. Silicon detectors

The degradation of silicon detectors is caused by ionization and displacement effects. For pixel-, stripes-, single or double sided detectors, the ionization effect at the surface, p-n junction and in the SiO\(_2\) insulator has a strong impact on the radiation hardness of these types of detectors.

The displacement damage in the bulk silicon reduces the charge efficiency and increases the leakage current and noise. High neutron doses invert the type of silicon. The basic physical mechanisms has been studied in great detail for many years, but in most cases on medium or highly doped material for semiconductor devices. The degradation can be described by the reduction of the minority-carrier-lifetime, carrier removal and
reduction of the bulk mobility (17). The damage coefficients caused by $^{60}$Co gamma and neutrons are well explained in ref. (18). Taking into account the different displacement cross sections of the individual particles (electron, proton, neutron) and their energy, a comparison of the non ionizing energy loss (NIEL) can be achieved (see Fig. 13).

This allows the calculation of the minority-carrier-lifetime damage constant $K$ for different types of particles and their energies (Fig. 14). It should be noted, that electrons generate normally only point defects and protons and neutrons additional cluster defects. The interaction of electrons and protons with the silicon is also combined with the generation of electron-hole pairs. Therefore, the individual defects in the silicon depend on the particle type. The damage constant $K$ gives no information about the individual trap types, energy level in the forbidden band gap of silicon or their cross sections. The deep level transient spectroscopy (DLTS) measurements and calculated trap types shown by G. Lindström (20) and C. Furetta (21) are in agreement with the early results on standard n- and p-type material (22) and the results of proton damage on high-resistivity neutron transmutation doped silicon (23).

The large variation of the leakage current damage coefficient as shown by G. Hall (24) based on different materials and radiation sources can be understood if the corrections of NIEL is used. Therefore, for the radiation test of silicon detectors, neutrons with different energies can be used and the test results should be normalized to 1 MeV neutrons (Fig. 15).

Another important parameter is the carrier removal, which is related to the clusters of displaced atoms (> 1000 atoms). These clusters are near the end of the range of the recoil atoms. The clusters trap majority carriers and provide also recombination centres for minority carriers. Because majority carriers are trapped at these clustered damage sites and recombination of majority and minority carriers occurs at these sites, there is also a reduction in the density of majority carriers. This process reduces the density of free carriers available for transport through the lattice and make the semiconductor more intrinsic. This can invert the semiconductor material as shown by G. Linström. After the inversion of the semiconductor the detector is still working (20).

Because the majority carriers trapped at defect clusters have an electric field that can scatter majority or minority carriers through Coulomb interactions or Rutherford scattering, the carrier mobility is reduced.
On the basis of understanding the generated defect centres in the bulk silicon, an improved radiation hardness material can be achieved. Pixel- and stripe detectors can be optimized by using the same techniques for the radiation hardening as already demonstrated for MOS devices. Therefore, it should be possible to use silicon detectors for many applications, but an intensive study on different materials and processing conditions in cooperation between the individual groups is needed.

4.2.2. GaAs detector

Radiation damage results of a GaAs detector were presented for the first time (25). Figure 16 shows the noise of different diodes irradiated up to 160 kGy (16 Mrad) with $^{60}$Co gamma rays and $7 \times 10^{14}$ n/cm$^2$ at RAL. The results are very promising and show a realistic opportunity for fast and radiation hard GaAs detectors. However, many more investigations and improvements are necessary.

4.3. Electronics

4.3.1. Industry

Since the last workshop (2) contact with the European semiconductor industry of radiation hard devices has been intensified and the industry showed great interest in supporting the LHC activities. In the case of optimized radiation hard CMOS-SOI technology it has been demonstrated by J.L. Lery (26), that the $\mu$P 29101 did not fail after a total dose of 1MGy(Si). A ring oscillator works up to 6.5 MGy(Si). These results from a research laboratory demonstrate for the first time the possibility to achieve radiation levels for CMOS devices up to 1MGy(Si) or above. This represents great progress in the hardening techniques of CMOS-devices in recent years.

The CMOS-SOI or CMOS-SOS technology is designed for digital circuits. This allows no applications for low noise preamplifiers needed for LHC. Leti has demonstrated the possibility to integrate P-JFET in the SIMOX-process. The P-JFET has lower noise than the standard CMOS devices (27). The noise of the P-JFET is found to be close to the expected value correlated to the drain-source equivalent resistance. The only shift of about 20% of the saturation current occurs at 0.30 kGy(Si). Up to 10 kGy (1 Mrad) (Si) there is no more change in the static electrical parameters (threshold voltage, conductance and saturation current). The P-JFET have also been irradiated with 1MeV neutrons up to a maximum fluence of $10^{15}$ n/cm$^2$. The degradation of the static electrical characteristics under worst bias
conditions is below 10% at $10^{14}$ n/cm$^2$. These are first results and this activity needs support by the R&D groups at CERN/LHC, otherwise this R&D programme can not be continued.

Marconi Electronic Devices (England) (28) have produced radiation hard microelectronic circuits in SOS-technology since 1982. They will continue this work in the next years and a 0.7 μm SOS-process is under development and will go into production in 1992. The wide range of different devices/circuits (gate arrays, standard cells,mixed analog and digital, ADC, SRAM,ROM, μP, data bus driver) makes this manufacturer attractive for the LHC R&D groups.

Texas Intruments has given an impressive review of the large number of radiation hard devices for space application which can also be used for the new colliders (29). There is a lack for analog / linear applications; these devices are very sensitive to ionizing radiation as well as to neutron radiation.

The companies which are interested in LHC R&D activities are listed in Appendix A2.3.

The high price for radiation hard devices can be reduced by a factor of ~ 10 or more if the quantity of the required devices is high enough. Therefore, a concerted procurement programme is recommended. On the other hand the manufacturers of radiation hard devices are at present not able to deliver large quantities of qualified devices. This also needs a long term agreement between the R&D groups and the semiconductor industry.

The test results of irradiated materials, detectors and electronic devices should be collected and summarized in a computer data base to establish an approved part list (APL) for all users. For space application the ESA has started a data base for qualified radiation hard devices using the data base structure of ORACLE. This data base will be open for the R&D groups at CERN (30) and therefore the use of the same data base is recommended. HMI-Berlin intends in the next year to publish test reports directly into this data base.

4.3.2. Detector collaborations

For leading particle detection the components need to be placed at small angles and very close to the beam. The expected doses are therefore extremely high ($>10^6$ Gy per year). A research collaboration has been established between LAA at CERN and the University of California, Santa Cruz, to develop radiation-hard compact VLSI electronics.
The project includes analog and digital devices. The analog part consists of the development of a fast amplifier-discriminator system with a dielectric isolated bipolar technology. The digital part consists of a pipeline, buffer and read-out system, matched in speed to the analog part and designed in CMOS.

A series of radiation tests on service electronics for a leading proton spectrometer were carried out in a cobalt source, behind T6 of the SPS and in an electron beam at Hahn Meitner Institut, Berlin. Octal buffers, and balanced RS485 line drivers and receivers from different manufacturers and technologies were tested. The LS-technology failed at a total dose level of 0.7-0.8 MGy, (70-80 Mrad Si) (see Fig. 17)

The degradation of the ALS-technology is strongly bias dependent. The input currents $I_{H}, I_{L}$ are the most sensitive parameters. They degrade most when the inputs are connected to VCC during irradiation. The F-technology is very radiation sensitive. Parameter specifications were out of tolerance below 0.1 kGy (10 krad Si) and the functional test failed between 0.05-1kGy (5-100 krad Si). The details of these results including the cobalt and HEP irradiations will be published shortly (31).

A further project of LAA is based on a collaboration with Uppsala University and the Swedish Institute of Microelectronics. The goal is to design read-out electronics circuits in a silicon on sapphire CMOS process with a radiation resistance exceeding $10^4$ Gy (1 Mrad). Irradiations are carried out with gamma rays and neutrons. A first test chip showed some mask errors and high noise levels. Nevertheless some positive radiation tests could be carried out. A new version is now under development in collaboration with ABB Hafo (32).

Recommendations for radiation tests on silicon detectors and detector electronics are given in Appendix A.3.3 and A.3.4. For the coordination of the large amount of different activities in the field, a radiation hardness assurance programme (RHAP) is recommended. This programme should include:

- definition of test procedures according to the high dose environment
- coordinating of the procurement of electronic devices,
- installation of an approved parts list.

4.4. Other materials

First results have been presented of radiation tests with room temperature liquids. Tetramethylpentane (TMP) was
irradiated in a CERN target area up to 20 kGy (2Mrad) where the electron lifetime decreased from 11.7 to below 1 μs (33). During 5 weeks of irradiation and several days of cooling time the induced radioactivity of the test chamber was 500 μSv/h, an effect which for future detector design has also to be accounted for (see also chapter 2). Irradiation tests on warm liquids for calorimetry will be continued.

Important progress has been reported on radiation resistant optical fibres for data transmission. There exist a variety of single mode and graded index fibres with radiation induced losses of less than 20 dB/km at 10 kGy (1 Mrad, see Fig.18). With a multimode step index fibre losse of only 0.7 dB/km were reported (34). A number of parameters which influence radiation resistance are being investigated; these are dose rate, light power, wave-length, launching conditions and temperature (34, 35).

Large experience has been gained especially at CERN on radiation effects on accelerator structural and insulating materials during the tender and construction period of the main CERN accelerators and storage rings e.g. ISK, SPS and LEP. With this a large amount of radiation damage test data became available, which are compiled and documented (36). This documentation is also of interest for future detectors, where in some places the doses will be higher than in present accelerators (37).

5. SUMMARY

The main points of the last years work of the ECFA detector R&D working group "Radiation Hardness" can be summarized as follows:

1. New dose calculations confirm earlier data.
2. Dosimetry methods for the LHC machine and detectors are available or under study.
3. A variety of irradiation sources are available in Europe for radiation testing.
4. Scintillators for tracking can cope with radiation levels at 15 cm and $10^{33}$ cm$^{-2}$ sec$^{-1}$ luminosity. It is possible to go to higher luminosities by improvement of the radiation resistance of fibre and dye.
5. Plastic scintillators for calorimetry are available up to $10^4$ to $10^5$ Gy (1 to 10 Mrad).
6. Inorganic crystals are available with radiation resistance exceeding $10^5$ Gy (10 Mrad).
7. In semiconductor detectors the limiting part is rather the silicon detector and not the electronics.
Electronics may stand doses $> 10^4$ Gy (1 Mrad) and neutron fluence up to $10^{15}$ n/cm$^2$ (Radiation hard technologies). First promising results were presented for GaAs as a complementary technology to silicon.

8. European and US semiconductor industry (space, military) has become interested in detector projects and offer radiation hard devices.
Improved radiation hard SOI technologies are available up to $> 10^6$ Gy (100 Mrad) for low noise applications.
High price for rad. hard devices can be reduced by factor $> 10$ if large quantities are involved. This requires however well defined procurement procedures.

9. Optical fibres with radiation resistance exceeding $10^4$ Gy (1 Mrad) are available in Europe.

10. Structural and insulating materials are available with radiation resistance exceeding $10^6$ Gy (100 Mrad).

6. **FUTURE WORK**

1. Any R&D proposal with materials in the radiation area of a future detector must include radiation damage studies and require manpower and funds.
2. Further work is required for:
   - Dose and dosimetry
   - Sources for irradiations
   - Standardisation of radiation tests
   - Data compilations
3. Define limits and use of semiconductor detectors for various applications (vertex, tracking, calorimetry) in high luminosity detectors.
4. Continue research to improve Silicon and GaAs detectors.
5. Intensify contacts and collaboration with industry and specialised research institutes to use radiation hard electronics in future detectors.
6. Carry out studies to understand radiation effects in plastic scintillators.

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## APPENDIX 1: Irradiation facilities in Europe and their main characteristics

### A1.1 Irradiation facilities

<table>
<thead>
<tr>
<th>No.</th>
<th>address</th>
<th>contact person</th>
<th>phone</th>
<th>Fax</th>
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<td>Österreichisches Forschungszentrum Seibersdorf GmbH A-2444 Seibersdorf</td>
<td>P. Gehringer</td>
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<td></td>
<td>J. Casta</td>
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<td>J.M. Baugnet</td>
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<td>0032/14/315021</td>
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### A1.2: Main characteristics of irradiation sources

#### A1.2.1 $^{60}$Co Sources:

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<td>2.847 (27.8.90) water</td>
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<td>~3500</td>
<td>max. 15%</td>
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<td>Fricke</td>
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<td>9×10$^{-2}$ (10.90)</td>
<td>1075 max.</td>
<td>75 000 max</td>
<td>depending on area</td>
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<td>0.2 - 1</td>
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<td>no</td>
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<td>0.03 - 3</td>
<td>several 10$^4$</td>
<td>several 10$^6$</td>
<td>according to sample size</td>
<td>no</td>
<td>blue nylon (Far West)</td>
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<tr>
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<td>$^{106}$ Ci</td>
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<td>125 m$^3$</td>
<td>15% industr. 10% study</td>
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<td>$2.5×10^{-2} - 2.5$ (10.90)</td>
<td>10×10$^2$</td>
<td>$5×10^6$</td>
<td>yes</td>
<td>blue nylon (Far West)</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>3.5 (10.90)</td>
<td></td>
<td></td>
<td>no</td>
<td>yes</td>
<td>TLD</td>
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#### A1.2.2 Electron Accelerators:

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<tbody>
<tr>
<td>1</td>
<td>0.5</td>
<td>2.5 kGy(H2O)/s max. variation factor 25</td>
<td></td>
<td>100×4</td>
<td>± 10%</td>
<td>yes</td>
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<tr>
<td>3</td>
<td>0.4</td>
<td>$10^2$ - $10^3$ Gy/s</td>
<td>80×60 max.</td>
<td>80×60 max.</td>
<td>± 5%</td>
<td>no</td>
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<tr>
<td>5</td>
<td>0.3 - 0.6</td>
<td>$2×10^15$</td>
<td>variable</td>
<td>± 5%</td>
<td>no</td>
<td>blue nylon (Far West)</td>
</tr>
<tr>
<td>6</td>
<td>2.5 - 4.5</td>
<td>$2×10^15$</td>
<td>variable</td>
<td>± 5%</td>
<td>no</td>
<td>blue nylon (Far West)</td>
</tr>
<tr>
<td>7</td>
<td>0.3 and 3</td>
<td>3 and 30 kW</td>
<td>150-3000</td>
<td>yes</td>
<td>Faraday cups, toroidal current, pin diodes calorimeter</td>
<td></td>
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<tr>
<td>8</td>
<td>50</td>
<td>$4×10^{13}$</td>
<td>20×20</td>
<td>± 10%</td>
<td>yes</td>
<td>Faraday cup, TLD</td>
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#### A1.2.3 Neutrons:

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<tbody>
<tr>
<td>2</td>
<td>thermal</td>
<td>10$^{12}$ - 10$^{15}$</td>
<td>700</td>
<td>depending on area and vol.</td>
<td>yes</td>
<td>Co, Ni, Ag, Fe detectors</td>
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<tr>
<td>3</td>
<td>&gt;1 BR2 reactor</td>
<td>10$^{11}$ - 4×10$^{14}$</td>
<td>700</td>
<td></td>
<td>yes</td>
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<tr>
<td>5</td>
<td>2×10$^{14}$</td>
<td>$2×10^9$</td>
<td>5</td>
<td>500</td>
<td>± 10%</td>
<td>no</td>
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<tr>
<td>6</td>
<td>2×10$^{13}$</td>
<td>$2×10^8$</td>
<td>230 cm$^3$</td>
<td>± 5%</td>
<td>no</td>
<td>activation detector</td>
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<tr>
<td>7</td>
<td>1.5×10$^{10}$</td>
<td>$7×10^6$ - 1×10$^{10}$</td>
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<td>8</td>
<td>72 MeV proton on Cu target</td>
<td>$7×10^8$</td>
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<td></td>
<td>no</td>
<td>activation detector</td>
</tr>
<tr>
<td>9</td>
<td>1 GeV electrons 3×10$^9$ on W target</td>
<td>$7×10^6$</td>
<td></td>
<td></td>
<td>no</td>
<td>activation detector</td>
</tr>
<tr>
<td>10</td>
<td>PS-ACOL Beam dump</td>
<td>3×10$^9$</td>
<td></td>
<td>250</td>
<td>yes</td>
<td>activation detector alanine</td>
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</table>
## APPENDIX 2: ACTIVITIES RADIATION TESTING (OCT. 1990)

### A2.1 SCINTILLATORS AND CRYSTALS

<table>
<thead>
<tr>
<th>Institutes</th>
<th>Contact Persons</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN and LAA</td>
<td>H. Leutz</td>
</tr>
<tr>
<td>CERN and LAA</td>
<td>C. D'Ambrosio, S. Tailhardat</td>
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<tr>
<td>LIP LISBON</td>
<td>P. Sonderegger</td>
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<tr>
<td>UNIV. Hamburg</td>
<td>A. Maio, A. Henriques</td>
</tr>
<tr>
<td>ECOLE POLYTECHNIQUE</td>
<td>U. Holm, K. Wick</td>
</tr>
<tr>
<td>Palaiseau</td>
<td>J. Badier</td>
</tr>
<tr>
<td>DPh PE SACLAY</td>
<td>M. Neveu, P. Rebourgeard,</td>
</tr>
<tr>
<td></td>
<td>A. Savoy Navarro</td>
</tr>
<tr>
<td>CERN</td>
<td>P. Lecoq</td>
</tr>
<tr>
<td>FLORIDA STATE UNIVERSITY</td>
<td>K. Johnson</td>
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<tr>
<td>SANDIA Nat. Lab.</td>
<td>R. Clough</td>
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</table>

### A2.2 SEMICONDUCTOR DETECTORS

#### A2.2.1 SILICON

<table>
<thead>
<tr>
<th>Institutes</th>
<th>Contact Persons</th>
</tr>
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<tbody>
<tr>
<td>CERN</td>
<td>E. Heijne, P. Jarron</td>
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<tr>
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<td>H. Kraner</td>
</tr>
<tr>
<td>BROOKHAVEN NAT. LAB.</td>
<td>D. Nygren and H. Spieler</td>
</tr>
<tr>
<td>LBL, Berkeley</td>
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<tr>
<td>UNIV. CALIFORNIA</td>
<td>H. Sadrozinski</td>
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<tr>
<td>SANTA CRUZ</td>
<td>G. Lindström</td>
</tr>
<tr>
<td>UNIV. Hamburg I.</td>
<td>G. Lutz</td>
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<tr>
<td>MPI Munich</td>
<td>P. Cattaneo</td>
</tr>
<tr>
<td>UNIV. FLORENCE</td>
<td>M. Bruzzi</td>
</tr>
<tr>
<td>INFN Milano, SICAPO Group</td>
<td>C. Furetta, L. Vismara</td>
</tr>
<tr>
<td>IMPERIAL COLLEGE</td>
<td>G. Hall</td>
</tr>
<tr>
<td>Inst. Nucl. Physics, Cracow</td>
<td>M. Turala</td>
</tr>
<tr>
<td>SANDIA Nat. Lab.</td>
<td>W.R. Dawes</td>
</tr>
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</table>

#### A2.2.2 GALLIUM ARSENIDE

<table>
<thead>
<tr>
<th>Institutes</th>
<th>Contact Persons</th>
</tr>
</thead>
<tbody>
<tr>
<td>CERN, LAA and RAL/Glasgow</td>
<td>C. Del Papa, K. Smith, M. Edwards</td>
</tr>
</tbody>
</table>
A.2.3 DETECTOR ELECTRONICS

CERN/LAA
UNIV. CALIFORNIA SANTA CRUZ
UTMC

CERN and LAA
Thomson TMS, Mietec, Faselec, ESZ,
UNIV. UPPSALA, CERN-LAA
ABB-Hafo
Hahn Meitner Institut, Berlin

T. Massam, H. Larsen
H. Sadrozinski
P. Giubellino
K. O'Shaugnessy
E. Heijne, P. Jarron
T. Ekelöf, N. Bingefor
F. Wulf, D. Bräunig

The following companies are active or interested in collaboration with LHC R&D Groups:

ABB HAFO (Sweden)
SOI-ASIC analog /digital

CEA LETI (France)
SOI-ASIC analog/digital total dose >1 M Gy(Si)

Thomson TMS (France) [R&D done by Leti Grenoble]
SOI-ASIC analog/digital up to 1 MGy(Si)

INVOMEC/MIETEC (Belgium)
CMOS ASIC/ custom design 3- and 1.5 μm-technology

Marconi Electronic Devices Ltd. (England)
ASIC (SOS-CMOS) and HCMOS-types / bulk CMOS

Matra Harris Semiconductor (France/ Germany)
ASIC Bulk CMOS digital 2-.8μm / analog 3- 2μm technology
Gate Arrays / static RAM/ μP

Texas Instruments (USA/France/Germany)
HCMOS / bipolar / LS- ALS-F-technology
A3.1 RECOMMENDATIONS RADIATION SOURCES AND DOSIMETRY

RESTRICT TO A FEW REPRESENTATIVE SOURCES
   e.g. $^{60}$Co gamma rays
        Neutrons in MeV range (252Cf, Neutron Generator, Reactor)
        HEP accelerator environment
        (X-rays) (Electrons)

RELATE RADIATION DAMAGE TO DOSE OR FLUENCE
   whatever was measured, conversions can be a considerable source of errors

CONSIDER FOR FUTURE DETECTORS:
   - Induced radioactivity
   - Built in dosimetry

A3.2 RADIATION TESTS ON SCINTILLATORS

RADIATION SOURCE:  $^{60}$Co
                   HEP
                   Test beams

TEST ENVIRONMENT:  Air
                   Ambient Temperature (25°C)
                   Dose rate: 10 Gy/h - $10^4$ Gy/h

CRITICAL PROPERTY: Scintillation Efficiency
                    Transmission Loss
                   Size of bulk samples:
                    2.5 cm dia. 10 cm length for transmission
                    2.5 cm dia. 2 mm thick for scintillation efficiency

DAMAGE CRITERION:  Operational at 10 K Gy (1 Mrad)
                   (300 K Gy in forward dir. < 5°)
### A3.3 Radiation Tests on Silicon Detectors

**Radiation Sources:** Neutrons (\( ^{252} \text{Cf}, 14 \text{ MeV Neutron Generator} \))
HEP accelerators environment
Gamma rays (\(^{60}\text{Co}\))
(X-rays)
(electrons)

**Test Environment:** Air
Ambient temperature (20°C)
Power during irradiation

**Critical Properties:** Leakage current (tracking)
Noise (calorimetry)

**Damage Criterion:** 1-5 \( \mu \text{A} \) leakage current
(needs to be specified for each application)

### A3.4 Radiation Tests on Detector Electronics

**Radiation Sources:** Neutrons (\( ^{252} \text{Cf}, 14 \text{ MeV Neutron Generator} \))
HEP accelerators environment
Gamma rays (\(^{60}\text{Co}\))
Electrons (2 - 2.5 MeV)

**Test Environment:** Air
Ambient temperature (20°C)*
Power during irradiation
Dose rate: \(< 5 \text{ K Gy/h} \)
\((0.5 \text{ Mrad/h})\)

*Argon Calorimetry: Low temperature

**Critical Property:** See Mil and ESA SCC Standards

**Damage Criterion:** Worst case analysis (general studies)
Depending on application

### A3.5 Radiation Tests on Insulators and Structural Materials

**Radiation Source:** \(^{60}\text{Co} \gamma\)

**Test Environment:** Air
Temperature: \(\leq 50°C\) maximum
Dose rate: low: 100 Gy/h
high: up to \( \times 10^4 \) (10\(^5\)) Gy/h

**Critical Properties:** Rigid materials: flexural strength
Flexible materials: elongation at break

**Damage Criterion:** 50 % of initial value at \( 10^5 \text{ Gy} \)

**Exclude Halogen Containing Materials** (e.g. no PVC)
Fig. 1  Total dose in a lead calorimeter (Ref. 4)
Dose in inner cavity

Annual dose in Gy

SSC-SR-1033
GRS guessed dE/dx
FLUKA, 3 mm Al at 1 m for η<8: Histogram

Radial distance from beam in m

Fig. 2 Annual dose and neutron fluence in inner cavity (Ref. 4)
Fig. 3  Neutron irradiation facility and neutron energy spectrum at RAL (Ref. 5)
Fig. 4 Irradiation facility and neutron spectrum at LAL Orsay (Ref. 10)
Fig. 5  Irradiation facility at CERN PS-ACOL Target (Ref. 8)
Fig. 6  Reduction in light transmission for SCSN 81 and polystyrene doped with PMP (Ref. 12)

Fig. 7  Comparison of light output before and after gamma and neutron irradiation for Optlectron S-101 fibres (Ref. 13)
Fig. 8  Radiation effects in different atmospheres, measured 2 hours after the end of irradiation. Gamma dose was 30 kGy, (Ref. 13).
Fig. 9  Effect of filter on SCSN 38 fibre at different doses (Ref. 13).
Fig. 10 Absorption coefficient induced by radiation measured at 430 nm, immediately after irradiation to 24 kGy of SCSN 38 fibres for different atmospheres, dose-rates and sample thickness (Ref. 14).
Fig. 11 Saturation of radiation damage to BGO crystals with dose (Ref. 15).

Fig. 12 Transmission of a BaF2 crystal as a function of wavelengths: 1) Before irradiation; 2) after 0.5 MGy; 3) after 1.7 MGy; 4) after three weeks recovery (Ref. 16).
Fig. 13 Calculation of nonionizing energy deposition in silicon by electrons, protons and neutrons (Ref. 19).

Fig. 14 Damage factor ratios versus calculated NIEL for electrons, protons and neutrons (Ref. 19).
Fig. 15 Displacement cross section for neutrons and leakage current as function for particle fluence for silicon detectors (Ref. 20).
Fig. 16 Noise for 160 kGy $^{60}$Co (above) and $7 \times 10^{14}$ neutrons/cm$^2$ (below) irradiated GaAs diodes (Ref. 25).
### Failure Dose [ krad (Si) ]

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<thead>
<tr>
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<th>101</th>
<th>102</th>
<th>103</th>
<th>104</th>
<th>105</th>
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<td><img src="image4" alt="Graph" /></td>
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<tr>
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<td><img src="image7" alt="Graph" /></td>
<td><img src="image8" alt="Graph" /></td>
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<td>74 ALS 244 TI 8848</td>
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<td>54 ALS 151 J TI 8848</td>
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<td>74 F 241 F 8832</td>
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<td><img src="image34" alt="Graph" /></td>
<td><img src="image35" alt="Graph" /></td>
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</tbody>
</table>

Fig. 17 Relative radiation resistance of different technologies for leading proton spectrometer service electronics (Ref. 31).
Fig. 18 Induced radiation loss in various optical fibres:
1. Fibre M10, Graded index, Ge + P doped, $\lambda = 1308$ nm;
2. Philips FL 1048C, Single mode, Ge doped, $\lambda = 1309$ nm;
3. Heraeus SS 1.2 152/90, Multimode step index, SiO$_2$ core with $\geq 800$ ppm OH, $\lambda = 865$ nm. Dose rate $= 20$ rad/s, $T = 22$ °C
Detector Simulation and Software Tools

R. Brun, F. Carminati
CERN-CN, Geneva, Switzerland

December 1, 1990

Abstract

The rapid evolution of the computing environment and the increased computational needs of the high energy physics community call for major developments both at the software and system level. The advent on the market of high-performance workstations and advanced user interfaces at affordable prices is driving the evolution of the computing environment in the direction of the distribution of services and resources over local and wide-area connections. The successful exploitation of such complexes depends on the development of adequate software and communication tools. New languages and software technologies will help physicists to make use of the new possibilities offered by technology.

Detector simulation is becoming the most demanding activity in terms of computational resources, and a major effort will be devoted to the development of present detector simulation tools to respond to the needs of the new experiments which are in preparation. Simulation is now heavily used in the detector design phase, where a better communication is necessary between engineers and physicists, allowing detector structural information to be exchanged among them.

The present paper describes the activities undergoing at CERN to address these problems.

1 Present status and future plans for the CERN Computer Centre

In the following we will be mainly concerned with the situation of CERN central computing facilities, which provide one third of the total capacity required by experiments, the other two thirds coming from the collaborating institutes. At the moment of writing the CERN Computer Centre offers to its users an IBM 3090 600E, a CRAY X-MP 48, a Siemens 7890 and a VAX Cluster. The main features of the machines are presented in table 1. Sixteen 3480 model cartridge drives shared among the CRAY, the IBM and the VAX are connected to an automatic mounting machine accessing a library of more than 16000 cartridges, which can retrieve and mount a cartridge in a minute. The Computer Centre has today a total of more than 7000 users. Presently all machines are running at full capacity and the computer time needed (requested) in 1991 for physics production for LEP and machine and detector design studies for LHC largely exceeds the available capacity. The limitations come not only from the CPU time available. The response time on mainframes makes interactive work very difficult for anything beyond trivial file handling and job submission. Memory is also becoming a limitation, either imposed by the system (CRAY, Siemens) or by performance considerations (IBM, VAX), causing a heavier utilization of other resources like I/O and CPU. Another problem is the nonuniformity of the software environments and
data formats. Four different operating systems and three data representations are present, more or less incompatible. The option to standardize on UNIX as a unique operating system is, at the moment, not viable due to the lack of maturity of the IBM and VAX implementations (CRAY features an excellent UNIX environment for mainframes), but is under active study for the future.

Various upgrade plans are under consideration for the Centre. The acquisition of a DEC VAX 9000 to replace the physics VAX Cluster has already been agreed. Even if the most optimistic plans (upgrade of the IBM system with a six processor 9000 machine and of the CRAY with a Y- MP 832 machine) are implemented, still the CERN Computer Centre will provide only limited resources for LHC R&D, given likely large increased requests from the experimental programs, notably the LEP experiments. The requests for LHC will increase mainly for the design cycle of the detectors, which will involve massive use of time-consuming simulations. Apart from the CPU time, the memory problem may prove to be a real bottleneck even on the new machines, and the interactive response time may not see any substantial improvement.

Additional computing resource are the more than 250 Apollos (including more than 50 DN10000 CPUs) and the more than 500 workstations (mainly DEC) present on site. This adds up to more than 5 times the capacity of the mainframes in the Centre, but the utilization of this complex is very nonuniform and generally minimal. Recently a pilot service has been opened for the Opal collaboration in the framework of a joint project with HP Apollo on a DN10000 (HOPE project) with the aim of providing a general high quality batch service including integrated 3480 compatible support. This has proven a reliable and successful experiment.

Communications are a growing concern as well. At the moment mainframes and workstations are connected via ETHERNET running various protocols. The speed and capacity of these connections need to be upgraded, and the replacement of the ETHERNET wire with an FDDI connection may turn out not to be a solution to the problem. Already now a fraction exceeding one tenth of the CPU of the IBM mainframe is devoted to communication handling at peak times. With FDDI the rather limited increase in capacity (not exceeding one order of magnitude) corresponds only to a limited reduction of the load per Megabyte of the CPUs which have to run the protocol. Tables 2 and 3 present some data on the CPU utilization of the various protocols. In the time scale of one or two years one hopes that outloading of protocol handling (done in slave processors rather than in the mainframe) will significantly change this situation.

In summary, given the present budget situation and the foreseeable increase in the demand, both qualitatively and quantitatively, of services, new solutions need to be found

---

1The figures reported in these tables come from measurements done at RUS, Stuttgart on May 21-22, 1990. The source for the tables is the SHIFT proposal.
<table>
<thead>
<tr>
<th>Medium</th>
<th>Direction</th>
<th>Kbytes/sec</th>
<th>Sun sec/Mbyte</th>
<th>CRAY sec/Mbyte</th>
</tr>
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<tbody>
<tr>
<td>Ethernet</td>
<td>CRAY → Sun</td>
<td>220</td>
<td>0.95</td>
<td>0.05</td>
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<tr>
<td>Sun → CRAY</td>
<td>250</td>
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<td>0.39</td>
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<tr>
<td>Ultra</td>
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<tr>
<td>Sun → CRAY</td>
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Table 2: Sun 3/110 and Cray 2

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<th>Kbytes/sec</th>
<th>Sun sec/Mbyte</th>
<th>CRAY sec/Mbyte</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethernet</td>
<td>CRAY → Sun</td>
<td>305</td>
<td>0.85</td>
<td>0.07</td>
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<tr>
<td>Sun → CRAY</td>
<td>290</td>
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<td>FDDI</td>
<td>CRAY → Sun</td>
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<td>0.95</td>
<td>0.12</td>
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</table>

Table 3: Sun 3/260 and Cray 2

to satisfy the needs of the physics production for LEP and of R&D for LHC.

## 2 Shift and beyond

Workstations seem to be the natural solution to the problems mentioned in the previous section. Large memories and advanced user interfaces are packaged into systems with a very attractive price compared to mainframes, both for CPU and disk storage. The operating system of all new generation workstations is UNIX, and the IEEE data formats and ASCII character set seem to be accepted standards. The unit performance of high-end machines approaches that of conventional mainframes. It seems therefore natural to use these machines to complement and possibly eventually replace conventional mainframes to meet the demand of HEP users, connecting several of them in a loosely coupled system. It should be noted, however, that the question of providing a general batch service, and also the interaction requirements for a general community, may take significant time to resolve. This will shift the emphasis of the computer centre from mainframes managing their own resources with respect to user requests, to a network (compunet) connecting different resources to end users. This scheme not only allows the exploitation of market offers of inexpensive CPUs and disks packaged inside workstations, but it also offers the advantages of being open, replicable on larger or smaller scale, evolutive and exportable. If enough attention is devoted to using industry standards for communication, different elements can be connected to the network, encouraging competitive pricing and allowing the rapid evaluation and exploitation of new market offerings. Such a system is scalable in the sense that new elements can be added, increasing the total power without the need for global upgrades. Scalability in this sense also means the possibility for the system to be cloned on a smaller scale at other sites, without the need for them to acquire expensive mainframes to be compatible with CERN.

The idea of such a system is to evolve from the present situation of distributed computers to one of centrally allocated and physically distributed heterogeneous resources. The main elements to be developed in this scenario are networking and software. Communications and resource allocation/sharing are the key areas where effort will be devoted. A group working in the CERN Computing and Networks Division has proposed the implementation of a prototype system for data analysis (SHIFT) along these lines [1]. An extension of this proposal is under consideration to include interactive data analysis and
MonteCarlo simulation, with the aim of providing the full capabilities of conventional mainframes. The main idea of SHIFT (fig 1) is to have CPU servers and disk servers connected to a high-speed backplane of the kind protocol-on-card (with dedicated interfaces handling network protocol conversion) to avoid loading the CPU of the servers with the handling of the communication protocol. ULTRA seems to be the best candidate for this at the moment. Data are stored on cartridges, and conventional mainframes connected to the backplane will serve as staging machines (as well as CPU and disk servers). Data are distributed, in the sense that any CPU can access any file on the network. Existing software (FATMEN [11]) will be used and enhanced to support a seamless user access to the distributed environment. The foreseen mode of operation is mainly batch, with user requests being submitted by NQS\(^2\) via a router connecting the backplane to the local network (ETHERNET or possibly FDDI) of end-users sitting on workstations. Users will be able also to submit requests to the system via normal terminals connected to conventional mainframes.

![Diagram of the SHIFT plus proposal](image)

Figure 1: The SHIFT plus proposal

The amount of CPU time required to design the new era (LHC) detectors and to simulate the behavior of existing ones (LEP) is leading to an extension of the SHIFT project to include a new resource on the network, especially dedicated to low I/O, CPU intensive, parallel work. A MonteCarlo sub-unit is to be included in the system, where the MonteCarlo simulation work should be performed. This complex can be a farm of CPUs connected to the backplane where the MonteCarlo requests should be routed automatically (by NQS). Again this sub-unit should be scalable and open to accept the lowest price/performance ratio offering available on the market. A high-speed connection to the backplane is not necessary, at least in the detector design phase, while probably necessary for physics pro-

\(^2\)Networking Queuing System, a distributed batch facility developed at NASA and running today on the CERN CRAY XMP-48
duction work. The full exploitation of a parallel complex presumably composed by VLIW\textsuperscript{3} superscalar units will require major optimization work on the MonteCarlo codes to achieve a high degree of macro and micro-parallelism. As it will be explained later in greater detail, this work is already under way for the GEANT MonteCarlo program.

High energy physicists are increasingly realizing the potentialities of interactive data analysis. To be effective, this requires access to very large data sets, availability of large CPU bursts and advanced graphics facilities. Currently only lucky users of high-end workstations or semi-dedicated mainframes can hope to have these resources. The typical computing environment which will exist in the coming years is one of users of medium or low end workstations (the meaning of this term evolves with time) with bitmap screens sitting at an ETHERNET (possibly FDDI) connection with the central computing facilities. To offer to these users the possibility of a real interactive service with adequate response time, cooperative processing between these workstations and the resources available on the network should be exploited. Users should be able to perform interactive data analysis from their workstations accessing disk and CPU resources in a transparent way according to their needs. So if a user requires to display on the screen of his machine the result of a numerical intensive analysis on a large data set, the software must be able to locate the data set, staging it if necessary, find the appropriate CPU resources, which can even be a vector machine or a parallel complex, perform the data movement and the computation and use the workstation resources for the data presentation. Of fundamental importance is the development in the cooperative sense of existing analysis tools (i.e. PAW [12]) and the definition of a network broker which is able to find and activate the appropriate resource to perform short but intensive computational tasks, taking care of the data transfer. One of the key factors for the success of the whole project will be the careful optimization of the usage of the connections, particularly on the software side, where care must be taken to minimize the amount of data transferred.

3 Code Management Systems

Code management systems are of fundamental importance in High Energy Physics. The size of the code and multiple authorship, as well as the necessity to maintain multi-machine versions and to manage the updates are among the principal reasons. With the spread of the interactive use of computers, particularly graphic workstations, the role of a code management system has evolved so that we can now talk of code development and code maintenance systems. The needs during the code development phase of a software product start just now to be addressed by code managers, which were usually designed with the batch-oriented code maintenance phase in mind. Several code management systems are now used in high energy physics, all but one (PATCHY [13]) commercial products, some of which can be acquired at a special discount by the physics community. In the following we will try to enumerate the principal features which should be considered in the choice of a code management system, referring to the paper in the proceedings of the parallel sessions for more details.

In the code development phase the code management system should aim as much as possible at providing a complete environment -- a code management shell -- where the code could be modified and tested without change of environment. This requires transparent access to operating system services like the editor, the compilers, the linker and the command shell in general. During the development of a software product it is

\textsuperscript{3}Very Long Instruction Word
important to have the possibility to structure the code elements into a database. A code development system should have integrated tools to modify the formal aspect of the code according to a set of rules and to check the compliance with these rules. This is very important in large collaborations to ensure the consistency of the different parts of the code. Diagnostic tools which can detect static programming errors or provide information on the code are particularly relevant for FORTRAN programmers. Efficient version control should include the possibility to store and retrieve several versions of the same object. In connection with this, the size of the database during program development, when typically two or three versions of every element are stored in average, should also be considered, as well as the speed to access a particular version.

In the code maintenance phase the robustness of the system and the ability to maintain different versions are the main requirements. Other important issues are the compatibility with other existing systems and the confidence clients have in vendors. A code management system for high energy physics should run on all systems used by physicists and should also be reasonably easy to port on new platforms. The ability of the product to be integrated in a distributed environment where the database can be non-local and physically subdivided must also be considered.

CERN has officially acquired a license for the CMZ [9] [8] system covering all high energy physics laboratories and academic physics departments in member states and their collaborators. This system is compatible with PATCHY and it is intended to be a replacement of both PATCHY and HISTORIAN as recommended code management system used by CERN for software maintenance and distribution.

4 CASE and Data Structures

In spite of the fact that high energy physics programmers are facing considerable software management issues, CASE (Computer Aided Software Engineering) techniques are not commonplace amongst programming physicists. Similarly, while high energy physics programmers have pioneered the usage of data structures with sophisticated data management programs, very little use has been made to now of the facilities offered by many programming languages in this area. These are two aspects of the relative slowness with which modern software technologies are penetrating the high energy physics programming scenario.

One of the reasons of this situation is cultural. A substantial fraction of the physicists have no formal training in software techniques, their knowledge being limited to the FORTRAN or C programming languages. In this sense the shift in emphasis from FORTRAN to C which we are witnessing in the new generation of physicists is more the reflection of the large availability of UNIX workstations in the academic environments than the sign of a real evolution.

As far as data structures are concerned, the requirements of high energy physics in terms of dynamism and complexity of the structure, I/O and data format exchange are such that no programming language can provide a complete solution without a substantial software effort. This is unfortunately still true, even if many of the elements which are contained in the data managers used in high energy physics are now also part of modern programming languages like FORTRAN 90 or C++.

The programming language of high energy physics for the last twenty years has been FORTRAN. The need to reuse modules and procedures of general utility in high energy physics has lead on one side to the creation of the CERN Program Library and on the other to the consolidation of FORTRAN in its different versions (II, IV, 77) as the main
programming language in the field. There are now some millions of lines of FORTRAN code in high energy physics which constitute a huge software investment which should not be underestimated.

As a result of the above situation, data management is done mainly in FORTRAN and data structures are stored in FORTRAN common blocks and addressed by array indexes used as pointers, obviously leading to unsafe and obscure code. Probably independent of the underlying programming language, high energy physics programmers need a higher level of abstraction in the data structures at their disposal. A substantial effort should be devoted to provide tools to access data structure at a higher level giving precedence to the data to be handled rather than to the structure itself. Of fundamental importance would be the introduction of a data dictionary to correlate a name to a structure in a way more transparent than what is done now. Special attention should be devoted to understanding how the facilities offered by modern languages and software techniques could be integrated in the existing environment.

A workshop dedicated to data structures in high energy physics will be help in the Ettore Majorana Centre in Erice on November 11-18, and the proceedings will be published.

5 Languages

FORTRAN has been the programming language for high energy physics for the last 20 years and today roughly 95% of the code used is in FORTRAN. FORTRAN had (and arguably still has) a large lead over other languages in terms of portability, reliability and efficiency of the compilers, robustness in large applications, I/O capabilities and ability to express mathematical algorithms. During these years both the computing environment and the software technologies have evolved substantially and there is now an animated debate among the programming physicists on how to take advantage of the facilities offered by modern (and future) programming languages. This debate express the difficulty to manage (and even to imagine) the transition between different programming languages for a large and demanding community which, up to now has used a single language.

In a sense programming languages are a link between the needs and the resources available to satisfy these needs. When both these elements evolve, it is natural that the programming language has to evolve as well. Failure to do so would hinder the utilization of the computer and, ultimately, the progress of science. In other word the choice (usually technology driven) of a computer environment and consequently of a programming style leads to the selection of the programming languages which are best suited to satisfy the needs of the community of users. This has implications on many elements such as program libraries and packages, user interfaces, code management systems and programming models.

One boundary condition is the computing model adopted. As we have said before, this will be based on the client-server model. The language should offer natural ways to access and express network-wide naming services, resources allocation and scheduling, remote procedure calls and data and process dependence. Unfortunately existing (and even future) programming languages are very far from that, and while the introduction of FORTRAN 90 is a very welcome step in the right direction, one cannot avoid noting that array processing has been introduced in a standard language more than ten years after the hardware was invented. No provision is made in FORTRAN 90 for remote procedures or parallelism.

On the operating system side there seems to be no question about the advent of UNIX. This has many implications on the programming language and its integration in the UNIX
world, particularly in the area of I/O, system services and asynchronous processing.

The huge investment in FORTRAN 77 programs is also a boundary condition which should not be forgotten. The size of the programs and the multiple authorship are strong arguments to introduce better and safer programming techniques. On the other hand the fact that the authors are usually non-professional may discourage the introduction of too much sophistication.

One of the best candidates to complement and, in the long run, replace FORTRAN is FORTRAN 90 [10]. The standard has been recently sent out for a last round of comments, and, apart from technicalities, it can be considered as definitive. FORTRAN 77 will survive as an independent standard even if it is formally contained within FORTRAN 90. Among the main features of the new language are the introduction of derived data types, internal procedures and operator overloading. The notation for arrays is very rich (133 array functions) and dynamic arrays and pointers (intended as dynamic equivalences) are present. The possibilities of data abstraction and the concept of module are potentially very interesting for high energy physics [18]. The complication of the language has cast some doubts on the level of optimization possible for the object code, particularly for RISC/VIW architectures which were not particularly important when the language was designed. The principal weaknesses of FORTRAN 90 are the lack of provision for asynchronous processing, minimal error handling and no inheritance. The lack of pointer arithmetic is sometimes pointed at as another of the weaknesses of the language, but this is a rather controversial point. Besides, FORTRAN 90 does not blend well with UNIX, even if a UNIX binding is being standardized. Even when this is implemented, probably there will still be the need for an additional language closer to the operating system, like C for UNIX. Strong points of FORTRAN 90 are the power of expressing mathematical algorithms, the protection of the existing software investment and, last but not least, the tradition of using FORTRAN. Resistance to the adoption of this language can be based on the grounds that C is becoming more and more common in the online environment and uniformity between online and offline is very important. Moreover FORTRAN 90 does not fully support the objective programming paradigm which seems very popular these days, even if its real usefulness for high energy physics has still to be demonstrated. The FORTRAN 90 compilers should be available around 1992-1993.

C++ [14] is the other main candidate to be the programming language of the LHC era. It is an object-oriented extension to C where the concept of class is added. This permits the introduction of overloading of operators and function names and inheritance via implicit type conversion, some of which is not possible in FORTRAN 90. C++ (as well as C) is really compatible only with one operating system, UNIX, but this is a real strength rather than a weakness. Inherited properties of classes are powerful tools for object oriented programming which are included in the language. C is the natural choice for all the applications dealing with graphics and communications, where the FORTRAN binding is usually very poor if it exists at all, while the C binding is the native one. The language has not yet been formally standardized and the portability of applications among different machines is not yet as good as the one of FORTRAN code. Parametrized derived types (not present in FORTRAN 90) and exception handling will probably come with the standardization process which is due to start in 1991. C++ is certainly a fashionable language even if its ability to express mathematical algorithms is inferior to FORTRAN. It is certainly a logical choice for online programming, graphics and networking applications.

In conclusion, although FORTRAN 90 is a modern and complete language it will not be enough, and more and more C will be used. Whatever the final choice of the high energy physics community will be, a number of problems will remain. The I/O problem is still
unsolved in its full generality by any language and something like ZEBRA [15] will still be necessary. Complete dynamism of the data structure may not be present in any language, here again ZEBRA-like systems must be used if this is really needed. Parallelism in general is not addressed by any language, only the array syntax being included in FORTRAN 90, although X3H5 is preparing standardized parallel extensions to FORTRAN for 1991-2. Error handling facilities offered by programming languages are still very primitive. There are potential problems of inter-language communication which may become worse with the new languages. The new compilers are likely to be unstable and buggy, which may cause a lot of problems.

The most probable scenario will be a bi-lingual software environment toward which we should try to evolve in the smoothest way to protect the existing software investment and to avoid split and duplicated efforts in the physic community.

6 Detector simulation software

The program GEANT, designed in 1982, in view of the LEP experiments, is now being used by a large fraction of the HEP experiments in the world. The current version 3.14 is the result of a fruitful collaboration between the implementation team and physicists modelling detectors for the LHC.

A major upgrade of GEANT (discussed in the parallel sessions) is currently in progress for the detector-description part and also for tracking speed-up and parameterization techniques. The status of the physics algorithms can be summarized as follows:

6.1 Electromagnetic processes

The GEANT routines initially developed from the EGS code ([2]) have been continuously upgraded in the past years, in particular in the areas of delta-rays production, Landau fluctuations, energy-loss and multiple scattering. We think that the version 3.14 is a major step in the understanding of some low-energy processes and in the automatic computation of the parameters controlling the precision of the tracking. These improvements have shown to be essential for the correct simulation of fine grain calorimeters. The simulation of electron beams is now in excellent agreement with experimental results (linearity and resolution). Additional developments are still required in case of tracking at very low energies (below 1 KeV), very thin materials or gaseous detectors.

6.2 Hadronic processes

The GHEISHA package ([3]), developed by H.Fesefeldt in the context of the PETRA experiments, has been for a long time the only hadronic package accessible from GEANT. Version 3.14 provides an interface with the packages HADRIN and NUCRIN (see [4]) for secondary products generated by particles below 5 GeV/c. It is our intention to provide in the next version of GEANT an interface with the hadronic part of the FLUKA package (see [5]). Comparisons with experimental results have been reported in the references above. Additional comparisons have been done in the context of the LHC simulations (See Proceedings of Parallel sessions). Discrepancies between simulation and experimental results are reported for the detector resolution. Experimental resolutions are in general better than the ones obtained with GEANT/GHEISHA or GEANT/GHEISHA/NUCRIN/HADRIN. The fact that the results seem to be model independent suggests that the problem might be in the treatment of the energy loss and multiple-scattering of very low energy hadrons.
6.3 Muon physics

Muon physics is becoming very important at high energies. The model built in GEANT is based on the initial work by Lohmann, Kopp and Voss (see [6]). Further developments have been necessary to parametrize differential cross-sections and substantially reduce the tracking time. While very good agreements with experimental data have been reported in the 100 GeV energy range or below, we think that some additional work is required for energies above 1 TeV. Note that a very interesting article has been recently published on punch-through simulations (see [7]).

7 Detector model and data base

The GEANT geometry package has proven successful for detector design, and the complicated LEP experimental set-ups have been simulated within the original program structure. The detectors of the new generation appear more complex and costly than their predecessors. At the same time, the computing environment has dramatically changed to a much richer scenario. This calls for a major improvement of the GEANT program, to be able to meet the new needs of the High Energy Physics community and provide a tool which can be used for the next decade or more. The CERN GEANT team, together with the Serpukhov Institute of High Energy Physics (USSR), has launched a project aimed at rewriting completely the geometrical detector description of GEANT in order to meet the new requirements.

The cost of a detector and the time taken to build and operate it call for a closer collaboration among engineers designing its mechanical structure and physicists designing its functional part. Simulation MonteCarlo are used to predict the detector behavior before it is built to optimise its design in a loop that involves several iterations during which the detector parameters must be exchanged between the CAD and detector simulation programs in an efficient and reliable way. The new geometrical description of the detector will be constructive, in the sense that complex shapes are formed by basic elements which are a subset of the ones used in CAD systems to describe objects. This will allow writing interface programs to communicate with CAD systems.

The physicist optimising the detector functional design needs new tools to improve the efficiency of his work. An integrated interactive environment will be developed to design, modify, test and optimize a detector structure, and subsequently output a set of specifications which could be passed directly to the engineers’ CAD system for the next iteration. The detector description can be stored into a database. Several front-ends will allow the user to access the information stored in the database, either directly or over a network in a distributed environment, for tracking, event reconstruction, communication with CAD systems, graphics and interactive detector design. High level 3D graphic interaction will be used where possible, while the program will be accessible also from low level, eventually even non-graphic terminals. To guarantee the possibility of simulating events interactively in the design phase and analysing interactively the result of a modification, performance will be substantially improved and the level of detail of the simulation will be tunable to the answer requested.

In the analysis phase the quality of the results depends also on the statistics available. With the foreseen luminosity of the new detectors, the rule of thumb of two simulated events for every measured one sets formidable CPU time requirements. More than half of the CPU time to simulate an event is spent in the geometrical calculations, which must therefore be optimized. In the new scheme the tracking is done using an optimum binary
tree which is built from the constructive description of the detector either read from the
data base or given at run-time via a set of routine calls. Information on the symmetry of
the detector provided by the user in one or more dimensions will be used to optimise the
tree structure. This will be a substantial improvement with respect to the present situation
with the volume search time increasing with the logarithm of the number of volumes in
the worst case. In addition, the basic shapes which constitute the detector are all bounded
by second order surfaces, so that the algorithms used are independent of the particular
shape. This replaces the algorithms which are used today for the geometry with a limited
set of basic routines, making the program easier to optimise on advanced architectures,
like parallel or vector computers. This also allows boolean operations to be performed on
the basic shapes, giving to the user the possibility to describe new and complex objects.
In view of the perspective of simulating larger and more complicated detectors, this more
flexible and general way to describe new shapes is extremely important. At the moment
new shapes can be introduced in GEANT, but at the price of a substantial programming
effort prone to coding and logic errors.

The obvious advantages of an integrated and uniform environment should be extended
also to the event viewing and reconstruction phase. The new structure will also serve as
base for a general event reconstruction and event viewing scheme.

8 Parametrization

The necessity to improve the performance of the detector simulation by some orders of
magnitude has lead to the consideration of a general parametrization scheme which could
be part of the GEANT program to be applied to any detector. After a careful analysis
of the parametrization techniques used in the past, it has been decided to introduce in
GEANT such a tool to perform very fast simulations with limited precision. The basic
idea is to reduce the complexity of the processes and of the detector and the number of
particles handled.

A set of routines has been introduced in GEANT to scan the detector and describe
it via a set of $f(\theta)$-$\phi$-$r$ sectors which are stored in a very compact data structure. This
idealized detector description can coexist with the detailed geometrical description. The
granularity in $f(\theta)$-$\phi$ is defined directly by the user, while the dimension of the $r$ sectors
are determined by the programs as the crossing of the boundaries of a set of user-specified
volumes in a given $f(\theta)$-$\phi$ sector. This is equivalent to reduce the detector to a limited
set of volumes and to describe them in a spherically symmetric approximation. Average
tracking quantities are automatically computed for these volumes based on the material
encountered along each $f(\theta)$-$\phi$ sector.

At tracking time a threshold can be defined for every type of particle. When a particle
falls below the threshold normal tracking stops and the particle is replaced by a set of
energy rays which are then tracked in the scan geometry. The spectrum of these energy
rays can be determined by the well known parametrization formulas to be found in the
literature. These energy rays are only sensitive to the energy deposition mechanism. The
gain in CPU time depends on the setting of the thresholds, but it can reach some order of
magnitudes over conventional full shower development.

The energy deposited in the cells of the scan geometry is then correlated to the real
detector via an extension of the existing GEANT HITS and DIGI data structures.

An advantage of this parametrization scheme is that the primary tracks are still tracked
in the complete geometry, so that the loss of particles through detector cracks is still
present. Also in the parametrization phase the energy is carried by rays, and here again
the effect of cracks is still somewhat present.

The algorithmic uniformity reached in this scheme, where all particles produce the same kind of energy rays, makes it possible to write a code with a large degree of micro-parallelism. This is very important to obtain high performances not only on conventional vector machines, but also on the latest generation of superscalar machines now on the market.

9 Standard communication interface

An essential tool for the analysis of experimental data in high energy physics experiments is the possibility to simulate fully candidate physics processes and their background processes in conjunction with full detector simulation. Especially very rare physics processes need detailed and often time consuming (Monte Carlo) computer calculations. Generally, the amount of computer time spent in the simulation exceeds the computer time needed to obtain and reconstruct the experimental data.

The design of new detectors also heavily relies on the quality of the simulation programs. Size, thickness, type, speed etc. of parts of the detector are defined using detailed simulation techniques. Both the interaction process and the interaction of particles with materials need to be accurately simulated before a prototype can be manufactured.

Increasing beam energies and rapidly falling cross-sections as a function of the collision centre-of-mass energy introduce serious complications in the potential for discovery and study of new physics processes. Over the last years, only little fundamental progress has been made to improve Monte Carlo methods and techniques. Lack of coordination among authors of different programs and lack of standardisation of data formats etc. are some of the reasons for this.

The COSMOS [16] [17] project proposes a fundamental approach to the organisation and interfacing of different simulation packages. It is not an event or detector simulator in itself! Standardised data formats, standard initialisation procedures, particle coding and naming conventions etc. provide the framework for flexibility and modularity in the building of a software simulation chain. Potential users may define a chain of different building blocks according to their needs with the help of a self guiding human interface. Analysis directives and utilities (like for instance PAW) may give direct (real time) feedback to the user so he can decide whether the models he is using are appropriate for his goal. The usual event generator may be split in four well-defined physics modules. In principle, each event generator presently on the market contains one or more of these building blocks. Analysis may be performed at each stage. An intelligent data base provides the user with all the tools he needs to set up the system and to have access to generated data. The system is able to set up batch jobs as well. Analysis may than be performed by reading generated data from an external medium. The shaded areas in the picture indicate where the project has well left the stage of R&D and prototyping is well on its way.

10 Optimization on advanced architectures

Typically, an high energy physics program performs the same set of operations on a large number of events one after the other, each one of them being independent from the others. The physical problem analyzed presents an high degree of data independence, and from this one may conclude that high energy physics codes are ideal for parallel processing of any sort, be it on conventional vector, superscalar or massively parallel machines. In spite
of this, high energy physics programs not lend themselves easily to such optimization and one could even affirm that in many aspects high energy physics code is a worst possible case for advanced parallel architectures. Even if independence is indeed present, algorithmic uniformity is lacking. The variety of the physics processes and the complication of the detectors make a sequential code with frequent logical switchyards much more easy to write and to maintain than a program structure which allows easy optimization on parallel or vector machines. As a result of this the entire program and the service libraries are usually thought in terms of scalar sequential processing of one particle of one event through one detector element at a time. Past storage limitations and the portability issue have contributed to consolidate this coding practice. The situation is well summarized saying that application of automatic vectorizing compilers to high energy physics code generally introduces only a 10% variation in performance.

To obtain a substantial improvement in performance on advanced architectures, the programs must be radically modified. But modification of existing programs has to be carefully planned in order not to disrupt the scientific work in progress. Stability and continuous development have to be balanced to keep programs and publicly available libraries up-to-date with the needs of the physics community but fully operational. Backward compatibility is another issue, given the fact that a new version may take months if not years to reach all active remote users.

The optimization of existing code must be thought in terms of programs which are hundred of thousands lines long, updated every few months and which are anyway modified by non-professional programmers sometimes at every run. The need for a deep understanding of the details of the programs by the end users and the portability issue, both in terms of functionality and of efficiency, tend to discourage the introduction of extreme coding practices to take advantage from a specific architecture. The evaluation of the optimization effort of such programs must take into account their life time as well. While every experiment tends to reuse and join together code coming from previous experiments, so that selected fragments of code may stay around for tens of years, the life time of bigger codes may not exceed a few years, with updates every few months.

As a result of this, parallel processing at the event level has been successfully implemented whereas finer grain parallelization of high energy physics code has frequently been described as impossible or not worth the effort. On the other hand the event level parallelism, even if it requires only minimal modifications in the code, may prove not to be enough for massively parallel systems. In this case synchronization and data movement may become unsolvable problems, as well as that of the scarce availability of large local memories. Again the minimal parallel approach, avoiding to deal with the problem of the local optimization of the code, which is crucial in the exploitation of the new machines, does not provide for the efficient implementation of high energy physics code on vector or VLIW based architectures.

The performance improvements in the coming years will come principally from compiler technology and concurrent execution at all levels. If the code hides the data and process independence inherent in the phenomena described, as it is the case today, even the best compiler technology will not improve substantially the performance above what is given by the clock rate.

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Track and Vertex Detection

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Abstract

A wide range of possible physics discoveries is made accessible by the use of good track and vertex detectors. The demands of fermion (t) and boson (H^0) studies are contrasted. We discuss the options in terms of luminosity and magnetic field choices. Progress is reported on a range of detector techniques – gaseous, scintillating fibres and semiconductor – in performance and lifetime. First results are presented on GaAs detectors. The use of tracking information in triggering is sketched and ideas in forward tracking and magnet construction are indicated. Two approaches to high-luminosity electron tracking in non-magnetic detectors are described and multiple-event background strategies are outlined. Finally we address vertex-finding in the channel H^0 → γγ.

1. Physics Objectives and Strategy

A good detector design starts from consideration of the physics objectives to be pursued, and develops the techniques from there. We have been asked by the organisers of this workshop to explore the full range of physics potential of the LHC machine. To make our task tractable we have focused on a few major topics within the realm of 'expected' discoveries, where LHC has the opportunity to do this before anyone else. A new factor in the discussion is that we now know that the t-quark (if it exists, for which there is ample circumstantial evidence - most rigorously from the measurement of the weak isospin of the b-quark [1]) is sufficiently massive to decay to real W-bosons, t → Wb [2]. Further, if its mass is above 200 GeV, it will be undiscovered before LHC comes into operation.

A suitable set of physics targets seems to be:

a) Search for H^0, via H^0 → γγ and H^0 → b ¯b in the range m(H^0) < 2M_w, and
H^0 → ZZ (or ZZ*) → ℓ^+ℓ^- ℓ'^+ℓ'^- at higher masses.

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Contributors to the work of this group include:

b) Search for the t-quark and/or detailed study of its decays - searches for
t \rightarrow H^+b, \tau \gamma, W\nu, W^+s, Z^0c ......

c) Search for a new Z' giving asymmetries in charged lepton angular distributions.

d) Study of the (WWZ) vertex, via W^* \rightarrow W^\pm Z around 1 TeV, and of W_LW_L
scattering via W^\pmW^\pm.

We find below that the demands of the (s)femion and boson sectors are rather different. t-
production up to say 500 GeV mass is relatively copious, but event signatures need detailed
reconstruction. As a result one prefers clean events, and to run modest luminosity. In the
boson sector the cross-sections are all small but have simple and outstanding signatures not
too vulnerable to faking by overlapped events. High luminosity is therefore preferred.

Figure 1 shows the angular range over which good lepton detection is required  a) four-
lepton acceptance for Higgs detection for M_H = 300 and 800 GeV. Note that extending the
range from -1.5 < \eta < 1.5 to -2.5 < \eta < 2.5 is worth a factor 2.4 in luminosity as regards
numbers of H^0 events and is much better in terms of backgrounds and acceptance effects.
b) Lepton charge asymmetry for production of various Z'. Rates at 1 TeV are low. Signs of
both e^\pm and \mu^\pm are needed both to acquire statistics and to check the validity of an
observation over two channels.

In both the (s)femion and boson sectors the discovery potential is high. In both cases
substantial technical and financial investment is needed. In order to achieve the physics
potential of LHC it is necessary therefore that both are emphasised from the start, and that
those who dedicate their lives over a long period can foresee continuing activity and
developing potential for new work.

2. Event Characteristics

This Aachen study is one of a series. Thankfully, knowledge progresses over the years, but
the reader may find it useful to refer to previous studies [3,4]. A small amount of material is
repeated to make this readable on its own. We shall confine ourselves to particle detection
between production vertex and calorimeter entry. External muon tracking is covered
elsewhere [5].

The pp total cross section is of order 100mb. For a crossing internal of 15ns and a
luminosity of 10^{34} cm^{-2} s^{-1} fifteen minimum-bias events occur per crossing. The charged
particle p_T distribution is shown in figure 2(a). It is conveniently represented as a Gaussian
in \eta p_T, peaking around p_T = 0.4 GeV/c. The pseudorapidity spectrum (\eta = -\ln \tan \theta/2) is
flat over the whole angular range of the detector (|\eta| = 4.5 at \theta = 1.3^\circ), with \partial^2 N/\partial \eta \partial \phi \sim
1.0, ie dN/d\eta = 2\pi. Thus a central detector covering -2 < \eta < 2 will on average see 25
particles from each such event. If a solenoidal magnetic field is used, low momentum tracks
from complete circles ("loops") and make repeated hits in the detector, causing event
1a). Four lepton acceptance for Higgs Particles decaying via $H \rightarrow ZZ, Z \rightarrow l^+l^-$ as a function of minimum angle for two different Higgs masses.

b). Forward-backward charged lepton asymmetries plotted against pseudorapidity for a specific model with $Z'$ at 1 TeV.

2a). $p_T$ distribution of charged tracks in minimum-bias events

b). minimum angle between neighbouring tracks in 1 TeV $p_T$ jets

3. A complete high-$p_T$ event seen in a large magnetic detector.
confusion and shortening detector lifetime. The looping transverse momentum is given by
\[ p_T^m = 0.15 \ Br_{max} (p_T^m \text{ in GeV/c, B in T, r in m}). \]
For \( B = 2T \) and \( r_{max} = 1.8m, p_T^m = 0.54 \text{ GeV/c}. \) Depending on the dimensions, the total number of hits, and rate of chamber aging, may be doubled by loopers.

High \( p_T \) events show more activity. Jet charged multiplicities are 30-70; jet opening angles are of order 20 mrad at 0.5 TeV/c. Figure 2(b) shows the distribution of angles to nearest neighbour tracks in TeV jets. One needs to resolve particles with separations of 0.5 to 1 mrad. At a distance of 10 cm radius this implies a detector pixel size of 50 x 50 or 100 x 100 \( \mu m^2 \). Figure 3 shows a complete high \( p_T \) event seen in a large magnetic detector. The event has \( \sim 1 \) TeV visible energy, over 200 charged particles and a track density of \( 10^3/\text{sterad} \).

We can imagine two classes of experiment. A medium luminosity detector would have the capacity to reconstruct successfully 300 tracks, and to resolve, say, five production vertices, spread along the beam interaction envelope (\( \sigma (z_v) \sim 55 \) mm). It can perform b-tagging by decay vertex identification, and is allowed to reject some events as too overlapped to analyse. It can therefore handle a 1 TeV event plus four minimum-bias events (300 = 200 + 4 x 25) and runs at a luminosity up to \( 2.5.10^{33} \text{ cm}^{-2}\text{s}^{-1} \).

A high luminosity detector accepts the maximum the machine can deliver \( \sim 2 \) to \( 4.10^{34} \text{ cm}^{-2}\text{s}^{-1} \). There are 30 to 60 events per crossing with 800 to 1500 tracks. We do not attempt to resolve different vertices but can check, (looking at the implied \( z_v \) of tracks), whether two tracks could have originated from the same event. Tracking is confined to lepton candidates. Jets are reconstructed in the calorimeter.

The range of momenta to be covered is illustrated in figure 4 showing \( p_T \) distributions for electrons from Higgs decay, and for hadrons from b-decay following top production. The high \( p_T \) lepton signal from Higgs implies a need for a momentum resolution of order 30% at 1 TeV (for charge determination of electrons, whose energy is measured in the calorimeter) or better (say 5-10%) if \( Z^0 \rightarrow \mu^+ \mu^- \) is to be reconstructed accurately.

### 3. Magnetic field choices

For tracking before the calorimeter, we have to make a choice. Shall we have a magnetic field, or not? With \( B = 0 \) we can:
- sort out overlapped events (\( z_v \))
- identify electrons well (cf UA2)
- have simple tracks to reconstruct, untroubled by loopers
- have minimal interference with the calorimeter.

With \( B \neq 0 \) we gain
- \( e^\pm \) sign. This allows us to extend and to check the physics we do with \( \mu^\pm \). For checking the \( W^\pm W^\pm \) rate or \( Z \) asymmetries we shall be short of events. So both the increased rate and the increased credibility of an independent check are needed. Because the pp initial state contains more valence u-quarks than d-quarks, we expect
4. \( p_T \) distributions
   a) Electrons in Higgs events for \( m_H = 400 \text{ GeV} \). The hatched bins indicate the contribution from non-Z sources in Higgs events (from [6]).
   b) Particles from b-decay following t-production at LHC (\( m_t = 150 \text{ GeV} \)) [7].

5. Cross-sections for \( pp \to t\bar{t}X \), followed by \( W^+W^-b\bar{b} \) decay with one \( W \) decaying leptonically. Cross-sections for the signatures lepton + 3 jets and lepton + 4 jets (\( > 40 \text{ GeV} \)). We demand \( l \eta (\ell, j) l < 2, \Delta R(\ell, j), j \) > 0.4. Also shown \( W + 3 \text{ jets and } W + 4 \text{ jets backgrounds (after Cavanna).} \)

6. \( M(jj) \) and \( M(jjb) \), (selecting \( 52 < M(jj) < 92 \)) for one year's running at \( \mathcal{L} = 10^{33} \), for events with an isolated lepton and two tagged b-jets [7]. For \( M_t = 250 \text{ GeV} a \pm 5 \text{ GeV measurement of } M_t \) is possible.
more \( W^+Z \) than \( W^-Z \) at 1 TeV. If a heavy first-generation neutrino is found (decaying to \( e^\pm \nu_e \)), only \( e^\pm \) charge measurement will establish whether it is a Dirac or a Majorana particle.

- \( \mu^\pm \) momentum without recourse to large external detectors
- \( \tau^\pm \) tagging by isolated 1 and 3 prongs giving low-mass jets (including neutrals).
  Impact parameter signatures can further help \( \tau \)-identification [3,46].
- \( b \)-tagging by impact parameter absolutely requires knowledge of multiple scattering, and hence of momentum. This opens up the area of \( t \)-quark studies.
- high \( p_T \) track triggers (see section 7.2 below)
- additional detector calibration possibilities
- additional cross-checks which add credibility to physics analysis.

However, there is a price to pay. It is more vulnerable to pile-up at low \( r \) (from loopers). Photon conversions to electrons in the beam pipe provide a nuisance background in heavy flavour studies. The detector grows in complexity. More, and more accurate, points are required for reconstructing curved tracks. The ever-present conflict between the coil and the calorimeter forces compromises on technique and adds to costs.

We have considered the choice between dipole and solenoidal detectors previously [3]. Dipoles have a number of advantages - easy access to the vertex region, ease of construction of a modular tracking system, excellent performance at high rapidity, only limited conflict between the coil and the calorimeter. However, we prefer a solenoid, even for forward tracking for the following reasons: azimuthal symmetry, good forward tracking is possible, and most importantly the severe limitation on material close to the beam pipe in a dipole, because low-momentum secondaries are swept into the tracking volume. By contrast in a solenoid they are piped harmlessly away along the magnetic flux tubes.

Looking at our physics objectives we conclude that a well-equipped laboratory, such as CERN, needs both magnetic and non-magnetic facilities from the start. An individual detector collaboration could decide on a policy of evolution.

4. \( t \)-quark physics and vertex tagging

CDF may achieve 1 fb\(^{-1}\) of data in the 1990s, which could enable them to discover top up to about 200 GeV/c. If they do not find it, the prize passes on to LHC. Whether it has been found earlier or not, LHC has important work to do on studying \( t \)-decays, which are a window on new physics.

For \( m_t < 350 \) GeV, production is dominantly via \( gg \rightarrow t\bar{t} \) with decay to \( W^+W^-b\bar{b} \) [8]. Detection proceeds via one \( W \) decaying to \( 4\nu \) and the other to \( 4\nu \) or jets. The signatures are \( \ell b\bar{b}jjp_T \) for the jet mode or \( \ell bb\bar{b}jjp_T \) where both decay leptonically. If we want to reconstruct the top mass the \( \ell bbjjp_T \) mode is preferred, using \( m(bjj) \). The main background is \( WW + \) jets. \( \sigma(pp \rightarrow WWX) = 70pb \). The \( t\bar{t} \) production rates are as follows:
\[
\begin{array}{|c|c|c|}
\hline
m_t & \sigma(t\bar{t}) & \mathcal{L} \text{ needed for } 10^5 \text{ events/year} \\
\hline
100 & 12 \text{ nb} & 8.10^{29} \\
200 & 870 \text{ pb} & 1.10^{31} \\
300 & 163 \text{ pb} & 6.10^{31} \\
350 & 84 \text{ pb} & 1.10^{32} \\
\hline
\end{array}
\]

Production is prolific. There is thus the opportunity to lower the luminosity to get rid of multiple-event backgrounds.

Figure 5 shows some cross-section calculations (by Cavanna). The experimental demand to isolate three or four jets of high energy cuts the signal to a level scarcely above the W+ jets background. We conclude that additional signatures are highly desirable to isolate the t-quark signal, and concentrate on b-identification. Two methods are possible. One uses the semileptonic decay of the b’s. However, charm is a prolific source of leptons, and the increased Q-value of b-decay does not affect the lepton isolation significantly at these energies. A stronger separation occurs if one takes advantage of the longer b-lifetime, and higher decay multiplicity.

Based on techniques developed for the CDF silicon vertex detector (1991 running) Bedeschi et al. [7] have presented a study of t mass reconstruction via gg → t\bar{t} → W^+W^-b\bar{b} → b\bar{b}4vjj. A W → jj mass peak is found (see figure 6). Selecting 52 < M(jj) < 92 one reconstructs M(jjb). For m_t = 250 GeV a 10 GeV determination of m_t is possible with one year’s data at \mathcal{L} = 10^{33}. The first opportunity to do this will be at LHC. Measurement of the b-fusion function will reduce the error on M(jjb).

For m_t > 350 GeV the dominant production mechanism is gW → t\bar{b} followed by t → Wb, W → \ellν as signature [9]. With perfect mass resolution a strong signal is obtained in a plot of m(4ev) without b-tagging, but a 20 GeV measurement error causes this to be lost in the background. Again b-tagging can dramatically improve the situation.

The CDF Silicon vertex detector is illustrated in figure 7. There are four layers of 60-100 µm pitch with 1D readout. It is 51 cm long and offers three layer coverage for |η| < 2.2 and four layers for |η| < 1.9. The closest layer is a 2mm radius. The impact parameter resolution, \sigma_\delta, as a function of p_T is shown in figure 8(a). For higher p_T tracks it is 12µm, and 40µm for p_T = 1. A small-diameter beam pipe, for the lever arm, and thin walls are vital for this resolution. As can be seen from figure 4(b), we need to use particles down to p_T = 1 GeV/c.*. The scale of the problem is set by the b-lifetime, which gives an average impact parameter <δ > ~ 0.8 ct ~ 240 µm for b-quarks, (almost) independent of their Lorentz boost. Figure 8(b) gives the impact parameter distribution expected for tracks from b-decay. For successful event tagging it is absolutely vital that \sigma_\delta << < δ >. Once \sigma_\delta ~ < δ >, only statistically weighted event studies are possible, but individual events cannot be labelled.
7. End view schematic of the CDF silicon vertex detector.

8a). Impact parameter error as a function of $p_T$ - CDF.
     b). Impact parameter distribution of b-decay prongs, ($m_t = 150$ GeV, $\sqrt{s} = 16$ TeV) (cm).

9a). Plot of impact parameter against track azimuth. Two linear clusters due to b-decay are visible. b) Overall tagging efficiency as a function of top quark mass (SDC study).
However, precision alone is not enough. One must also be accurate in avoiding track-finding errors which can put massive non-Gaussian tails on distributions and completely infect the population of high impact parameter candidates. (For a discussion of error handling strategies see [10], see also [11]). Therefore a sparse, precise vertex detector must be embedded in an outer detector with strong track finding ability, principally obtained through track continuity such as one obtains in jet or "vector" drift chambers [12,13]. A second problem arises from γ-conversions in the beam pipe. Conversion to a 1GeV electron at a radius of 2cm in a 2T field produces an apparent impact parameter of 125μm and a spurious b-candidate. For both these reasons one should not rely on single-track (eg leptonic) tagging, but take advantage of the high (~5.5) b-decay charged multiplicity.

A method has been shown by Bedeschi [7], for b-tagging by impact parameter. Consider a track passing at distance of closest approach, \(d_0\), to the origin of coordinates in the \((r,\phi)\) plane. Let its direction at this point be \(\phi_0\) and its radius of curvature be \(R_0\). Then the equation of the track in a constant magnetic field is

\[
\phi = \phi_0 + \sin^{-1} \left( \frac{r_2 R_0 + (1 + d_2 / 2R_0) d_2 / r_2}{1 + d_2 / R_0} \right)
\]

For \(r \ll R_0\), \(d_0 \ll R_0\) this becomes

\[
r \sin (\phi - \phi_0) = d_0.
\]

Then a set of tracks \(\{\phi_{oi}, d_{oi}\}\) coming from a common vertex at \((r_v, \phi_v)\) satisfy

\[
d_{oi} = r_v \sin (\phi_v - \phi_{oi})
\]

\[
d_{oi} = r_v (\phi_v - \phi_{oi})
\]

Thus they lie on a straight line in the \((d_0, \phi_0)\) plane. Figure 9(a) illustrates this. Two linear clusters are visible (Secondary \(b \rightarrow c \rightarrow u\) decays can spoil the perfect straight line).

One develops this into a b-tagging algorithm [14]. Find the primary vertex in the \((r,\phi)\) plane and move the origin of coordinates here. Remove all tracks consistent within 3σ with this vertex and look for clusters in those which remain in the \((d_0, \phi_0)\) plane. Projected efficiencies

\[\text{Projected efficiencies}\]

\footnote{For two layers with resolution \(\sigma_x\) at radii \(r_1\) and \(r_2\), with material of thickness \(t\) radiation lengths at \(r = r_1\), for a 90° particle of momentum \(p\) and velocity \(\beta\), the error on the impact parameter, \(\delta\), is given by}

\[
\sigma^2 = \sigma^2 \left( \frac{r_1 + \delta}{r_1 - \delta} \right)^2 + r^2 \left( \frac{0.015}{\beta^2} \right)^2 t
\]
are shown in figure 9(b) (Study for SDC collaboration). The solid lines show the efficiencies that can be reached using the strip detector of figure 7. Adding a closer-in pixel detector achieves the results in the dashed lines.

We see that ~ 50% efficiency can be achieved for b\bar{b}. Background suppression estimates are probably not yet reliable but are surmised, for 30 GeV jet-jet pairs as about 0.3% (gg) plus 1.1% for charm plus the contribution from g \rightarrow b\bar{b}. Gottschalk [15] has studied this question. For 50 GeV g-jets he estimates a 3% probability of producing a b\bar{b} pair by fragmentation. At face value this gives a 6% probability of a single tag of gg as b\bar{b}, and 0.1% for a double tag. He speculates on substantial further improvements based on jet containment in \Delta R = 0.4. (Since quarks have weaker colour-couplings than gluons, b-jets are narrower than g-jets. Another obvious difference is that since b-fragmentation is hard, the b-momentum/jet energy ratio is much higher for b-jets than for g \rightarrow b\bar{b} jets.

LHC will be the first place to see top if 200 < M_t \leq 500. LHC will be the best early t-factory if 100 \leq M_t \leq 500. Since gg \rightarrow t\bar{t} produces pairs of t-quarks one can tag one t-quark via the Wb decay and look for the properties of the other. Just to list a few ideas:

K-M check : t \rightarrow Wb, t \rightarrow Ws
K-M test : t \rightarrow H^0c, Z^0c, c\gamma, cg
SUSY factory : t \rightarrow \tilde{t}\gamma, \tilde{W}b,
H^+ search : t \rightarrow H^+b, followed by H^+ \rightarrow c\bar{s} or \gamma \nu (see figure 10).

LHC as a t\bar{t} factory may be the best source of SUSY particles. There is a potential mine of discoveries here. t-physics has particular demands - clean events and vertex reconstruction. The LHC programme must have room for this.

5. **Higgs detection via H^0 \rightarrow b\bar{b}**

If b-tagging can open t-quark studies, can it access also the intermediate mass Higgs through its dominant b\bar{b} decay? The answers are not so encouraging. We give some numbers here, based on calculations by Poggioli [16].

gg \rightarrow b\bar{b} presents huge backgrounds, we look therefore for associated production of ZH or WH, the intermediate vector bosons being tagged by leptonic decays. One looks for a peak in the jet-jet mass spectrum. For M_H = 100 GeV we expect a signal of width of 10 GeV at the base. Consider first the ZH mode. Without b-tagging one year at \sqrt{s} = 2.10^{34} gives 1086 signal events and 408K Z\bar{z} background in the same bin. The significance S/\sqrt{B} is 1.7 - not good enough. With b-tagging for one year at \sqrt{s} = 3.3.10^{33} we find, for single b-tagging (\epsilon = 0.6, background rejection factor R = 15), a signal of 97 events. The background is 634 (from Zb\bar{b}) plus 4533 (from Z\bar{z}) : S/\sqrt{B} = 1.4. For double tag (\epsilon(0,675),(32,700)(0,675),(32,700)(0,675),(32,700)(0,675),(32,700)(0,675),(32,700)(0,675),(32,700)(0,675),(32,700)(0,675),(32,700) = 0.12, R = 900), S = 19. B = 126 + 75 : S/\sqrt{B} = 1.3.
10. $H^+$ couplings v. mixing angle (from Bellettini).

11. Microstrip gas avalanche chamber a) layout schematic, b) electron and positive ion drift paths.

12. a) End face of 1 x 1 mm$^2$ multibundle containing 900 scintillating fibres of 30mm diameter. b) Schematic of a single shell of 1 cm thickness.
In the WH mode the signal is 873 (single tag 1 or 114 (double) and the backgrounds 634(Wb\overline{b}) + 45330 (Wjj) : S/\sqrt{B} = 4 (single tag) or 126 + 750 : S/\sqrt{B} = 3.9 (double tag). Lest one becomes momentarily excited however we must add that production of a t-quark of virtually any mass produces an overwhelming Wb\overline{b} signal, (via gg → t\overline{t} → W^+W^- b\overline{b}), two or three orders of magnitude above WH. Unless nature takes an unexpectedly subtle turn, this avenue is closed to us.

6. Detection Media for Charged Particles

There has been much progress in detection of charged particles in the areas of gaseous, fibrous and semiconductor detectors. Some typical state-of-the-art numbers are given below.

<table>
<thead>
<tr>
<th></th>
<th>Gas</th>
<th>Scint. fibre</th>
<th>Semicond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hits/0.1 X₀</td>
<td>&gt;100</td>
<td>~60</td>
<td>~20</td>
</tr>
<tr>
<td>response time (ns)</td>
<td>~50</td>
<td>2.5 to 5</td>
<td>5 to 10</td>
</tr>
<tr>
<td>precision (μm)</td>
<td>30</td>
<td>35</td>
<td>5 to 10</td>
</tr>
<tr>
<td>2-μm res (μm)</td>
<td>250</td>
<td>80</td>
<td>25</td>
</tr>
</tbody>
</table>

With these figures, occupancy and loss of hits due to close tracks are rapidly diminishing problems. However, none of these techniques is yet ready to deliver detectors on the scale required by LHC - there are R & D needs everywhere. There has been substantial progress on radiation hardness - this is dealt with elsewhere in these proceedings [17], so we make just a few remarks, as we discuss each technique. Hardness of on-detector electronics has progressed greatly. The emphasis is now on the detectors themselves.

6.1 Gaseous Detectors

Meyer has compared the advantages of different techniques [18]. A particularly exciting innovation is the microstrip gas-avalanche chamber (MISGAC) [19]. Thin anode (5-10μm) and cathode (30-60μm) parallel strips are placed by lithography on a 500 μm thick glass substrate to form cells of 125-200μm pitch. Currently detectors of 10 x 10cm² are available. The detector layout and electron and positive ion drift paths are shown in figure 11. The chambers are operated with gas gains of up to 10⁴ and have negligible ion feedback into the drift volume. In principle various geometries are possible. Anode hit readout gives σ = 0.3 x pitch. Cathode pulse height readout has achieved 30μm position resolution from centroid measurements, of 200μm strips with two-track resolution of 250μm - both for tracks incident normally. One can imagine stereo (?) orthogonal) readout on the glass back-plane.

Because of the high detector element density and the positive ion removal rate tolerance is two orders of magnitude better than in MWPCs. No loss of signal is observed up to 10⁷ counts/cm²/s, equivalent to 15cm from the vertex at ζ = 4.10¹⁴. Gas amplification provides a high S/N ratio and radiation tolerance is better than with silicon. With any gas chamber,
provided the gas is kept clean, no damage occurs when the high voltage is turned off. 50ns pulse shaping is used. Favoured gases for high ionisation density (and therefore rapid efficient readout), are Ar-DME or Xe-DME mixes.

The "occupancy" of a single-hit device is the chance that you find a cell occupied. It is equal to the rate x busy time. The occupancy of a 10cm long MISGAC strip is 1% at 15cm (\( \tau = 2.10^{33} \), factor 2 for loopers) and 0.5% at 70cm radius at \( \tau = 4.10^{34} \), far better than any rival technique, except for the induction drift chamber, which can perhaps be regarded as a step in the evolution to this detector [20,4]. The survival time, setting a conservative lifetime limit of 0.1 Ccm\(^{-1}\) is 40 years at \( \tau = 4.10^{34} \). Note that neutron backgrounds do not directly affect gaseous detector lifetimes.

Udo has suggested layouts for a MISGAC-based detector [21]. Orienting the strips radially outwards on planes tilted at 70° with respect to the particle direction in a solenoidal field, he gains a factor 3 in number of electrons (and therefore speed) and in \( E \times B \) effects, and a massive suppression of looping tracks. The detector is fully efficient (\( B = 4T, r = 0.9m \)) for tracks of 1.8 GeV/c \( p_T \), but becomes insensitive to looping tracks.

All of this is very interesting. We point out that current devices are quite small, and that there is little evidence on longevity problems as regards high-voltage phenomena - for example track or substrate erosion by corona discharge. The material thicknesses can build up. We also need to study the hit background due to neutrons knocking highly ionisation protons out of the hydrogen atoms in DME, for example.

### 6.2 Scintillating fibres

D'Ambrusio and Gys have presented progress on scintillating fibre detectors and readout [22]. There has been considerable progress in the development of scintillating materials that allow 30μm diameter fibres to be used. Tests have shown a spatial resolution of 35μm. Two-track resolutions of 80μm are found. The response is intrinsically fast (\( \leq 5ns \)) and Kuroda has suggested ways of using this in a high-\( p_T \) level-1 track trigger [23]. (The only way I have heard in which this could be achieved). A two hit resolution of 0.7mm is used in the proposed trigger system. One thinks of an isolated stiff-track trigger \( \sigma_p \approx 100\mu m \) per superlayer). This is implemented using position-sensitive photomultipliers, which must be located at the end of optical fibres outside the magnetic field.

For position readout the 30μm fibres are formed into multi-bundles of 900 fibres, occupying 1mm x 1mm. (see figure 12). A detector shell is made of eight layers (2.4% \( X_0 \), 1.8% int. length) - a full detector therefore builds up material). The shell has 240 fibre layers, arranged in four groups z-u-v-z, where the u and v layers are at small stereo angles. Such a shell then forms an element of a vector drift chamber. The spaced z-layers allow both a track position and direction to be established in the (rφ) plane before any external linking - a great and in tracking finding. The (zuv) triplet allows a z-position to be assigned also.

We have learned from UA2 members of the detector robustness needed for track finding in scintillating fibre detectors. They made several recommendations:
a) The elimination of optical cross-talk between axial and stereo layers, and of
smearing within the CCD readout.
b) More fibres per layer - to produce vectors at the first level of track finding.
c) Strong track finding in projection.
d) More than three stereo projections and or pad detectors.

All of these improvements occur in the present work. Note that the fibre diameter has been
reduced by a factor of 30. A large stereo angle leads to more precise \( z \)-measurement after
track finding, but a greater number of ghost tracks. The stereo angles should be kept small,
consistent with the required \( z \) accuracy, \( \sigma_z = \sigma_{\xi} / \sin \alpha \), where \( \alpha \) is the stereo angle of the
fibres), and should be varied from shell to shell so that ghosts fail to propagate.

Gensch has studied track-finding in a five-shell detector running between 15 and 100cm
radius in magnetic fields of 1T and 3T [24]. For a \( \pi \) event superimposed on 10 minimum
bias events the occupancy is between 0.3 and 1%. Preliminary studies of three-dimensional
pattern recognition for tracks of \( p_T > 1 \text{ GeV/c} \) indicate that over 80% are fully found with
less than 2% ghosts. Five shells are not necessary for the pattern recognition and the
efficiency can readily be raised to over 95% with, however, some price in additional ghosts.
For this reason we conclude that:

All LHC tracking detectors should include some pixel/pad/short strip elements to solve
combinatorics, avoid ghosts, and to save a great deal of computer time.

The group has made great progress in developing scintillators with large Stokes shifts
[22,25]. The importance of this is two-fold. First the emitted light is more red, but still well
within the phosphor acceptance, so that longer attenuation lengths are obtained (\( \sim 1 \text{ m} \)).
Secondly, the energy transfer to the PMP dopant is non-radiative and therefore local. For
POPOP, for example, a radiative transfer is needed which has a 300\( \mu \text{m} \) absorption length.
This would be a massive source of cross-talk between fibres and is strongly to be avoided.
Figure 13(a) illustrates the progress and in 13(b) we show a picture with 2.4 hits/mm from a
test beam run [26]. A position resolution of 35\( \mu \text{m} \) is found with some tail. Further
developments look to improve the cladding (and hence the light capture and reflection).

A crucial part of the detector is the electron drift tube that serves as a 1\( \mu \text{s} \) memory [22].
Electrons of 4-6eV energy are drifted over 20cm and reflected from a potential gradient
adjusted to keep individual crossings in synchronisation. Following a first-level trigger the
pulse is accelerated amplified (40ns deadtime) - A 10cm prototype tube introduces only
25\( \mu \text{m} \) of smearing when used in a magnetic field of 0.7T.

6.3 Semiconductor Detectors

Double-sided orthogonal Si strip detectors have been installed and run in the ALEPH
experiment [27]. Tuuva has shown developments for Delphi with \( S/N = 16 \) on the p-side
and 10 on the n-side, giving efficiencies > 98% on both sides and position resolutions of 8.8
13. Absorption and emission bands of polystyrene doped with a) PMP, b) p-terphenyl and POPOP as a wave-shifter. c) Test beam event. 24 hits in 10mm.

14. a,b) Calculated pulse shapes in Si microstrip double-sided detectors p-side and n-side, the particle passing through a strip centre ($x = 0$), edge ($x = \frac{1}{2}$), and centre of the neighbouring strip ($x = 1$). c) GaAs pulse shapes measured using a 1.5ps laser (U Florence).

15. a) Principle of bump-bonded pixel detector and readout.

b) Monolithic silicon on insulator detector.
and 11.6 μm [28]. A numerical calculation of detector operation by Gadomski and Turala shows that fast pulses can be obtained from such devices [29] (see figure 14(a)(b)). The radiation hardness of Si-strip double sided readout to the level required for SSC operation has yet to be established.

As we see from figure 2(b), the closer one approaches the production vertex, the smaller must be the total detector element area, if neighbouring tracks are to be resolved. At the same time this leads naturally to improve three-dimensional position measurement and, as we discuss below, radiation hardness. At a radius of 10 cm, hit efficiency alone indicates a pixel size of 100 x 100 μm². Anghinolfi has reported on the development of a hybrid pixel detector, currently 200 x 200 μm² but aiming for perhaps 30 x 100 μm² eventually [30]. 150 μm Si layer has 12000 e-h pairs when a particle passes through. This signal passes directly through a bump bond on each pixel to an electronics chip below (see figure 15(a)). The active signal processing conducted within the 200 x 200 μm² area is an amplifier, latched comparator, digital memory and switch. Running at 10 MHz it uses 30 μW per channel and tolerates 10 Mrad radiation dose. To date a 9 x 12 pixel array is in use and an active development program is foreseen. In parallel a monolithic Silicon-on-Insulator detector is proposed to be developed.

Figure 16 gives a sketch of radiation doses from one year at Σ = 1.10^{34} from minimum ionising particles and the equivalent damage to silicon from neutrons inside a Pb calorimeter void. (The comparison is based on induced leakage currents in Si of 1.10^{-17} A cm^{-1} m.i.p^{-1} and 8.10^{-17} A cm^{-1} n^{-1} - numbers which have been the subject of some discussion [17,31]). The charged particle flux falls rapidly with radius, whereas the neutron dosage is much more constant. Since the leakage current due to radiation damage is proportional to detector area, whereas the particle signal is not, it follows that S/N ~ 1/A, and small pixels are a remedy against radiation backgrounds. It follows logically that the pixel size should be smaller at r = 5 cm than at r = 10 cm, but that it should not thereafter get much larger. One strategy being pursued to ameliorate the neutron flux problem for larger pixels is to shield the calorimeter by interleaved layers of hydrogenous material. Up to an order of magnitude improvement may occur.

We conclude that pixel detectors are of great importance because of their great precision, including z-information, and lack of ambiguities. They support more leakage current than long strip detectors. They can be put closer to the interaction point because of occupancy and damage advantages, and they offer a better speed/power ratio. This is surely an important area for development.

Recently, a diamond-based detector has been proposed for development for the SSC [32], using microstrip detectors of 200 μm thick diamond, double sided, with 50-100 μm pitch. Compared to Si it is reported to survive 10^7 rad, and 10^{14} n/cm². The charge can, under very high electric fields, be collected within 1 ns. The capacitance is lower and the radiation length longer. Chemical vapour deposition (CVD) polycrystalline diamond is preferred. Owing to the larger band-gap the primary signal is only one-third that of Si. First tests indicated 2% charge collection, which makes double-sided detectors some distance away.
16. Sketch of radiation damage to silicon against radius from minimum ionisation particles and neutrons (no calorimeter shielding).

17. Minimum ionising particle pulse height spectrum from GaAs Schottky diode detector before and after irradiation by $7 \times 10^{14}$ neutrons/cm$^2$.

18. a) The silicon inner tracker of the SDC EOI ($^{14}$n view). b) Efficiency for passing $H^0 \rightarrow ZZ$ cuts as more minimum bias events are added ($m_H = 800$ GeV). In the right hand plot the upper points at zero added events correspond to muons (no bremsstrahlung losses), and to electrons at $m_H = 300$ GeV.
We watch for developments with interest.

Test results which are most encouraging have been reported at this conference on GaAs [33]. The main attractions of GaAs, as compared to Si, are radiation hardness, potential high speed and the possibility of coupling with devices providing optical output signals. A main disadvantage is poorer semiconductor material, leading to charge trapping.

LEC Czochralski GaAs has been used, surface passivated by SiO$_2$. Schottky diodes are made using multilayer evaporated contacts on 500μm thick wafers of 10$^8$Ωcm resistivity. It is fully depleted at zero bias, and charge collection efficiencies of 10-40% are obtained depending on bias conditions. Pulse lengths of less than 5ns have been measured - see figure 14(c). Neutron irradiation tests have been most encouraging. Figure 17 shows the pulse height spectrum for m.i.p.s before and after irradiation by 7.10^{14}_n\text{cm}^{-2}. We conclude that semi-insulating GaAs detectors for minimum ionising particles work. They are very hard against radiation, and potentially very fast. The (incomplete) charge collection and (high) noise are still not completely understood. Matching readout electronics is also under study. Given the hostile radiation environment at LHC, these devices look well worth further development.

7. Magnetic Tracking Detector

7.1 Detector Layouts

We consider here the performance of two radically different magnetic detector layouts discussed at this conference. The compact Si-microstrip magnetic tracker concept was first presented by the Santa Cruz group [34] and has evolved into the SDC inner tracker presented here by O'Shaughnessy [35]. It is illustrated in figure 18(a). The detectors are double-sided, AC-coupled 50μm pitch, 300μm thick with double-sided readout at 5mrad stereo. Each tile is 3 x 6cm$^2$. The barrel section has ten layers at 18 ≤ r ≤ 45cm, usually two detectors bonded together. High rapidity tracking is provided by forward telescopes. In all there are 38m$^2$ of Si and 11.7 million readout channels in the detector described in the Expression of Interest [36]. The Si material amounts to 3-4% $X_0$. Together with an outer tracker (assumed to be 64 measurements of $\sigma = 150\mu m$) in a 2T field it achieves ≤ 10% momentum resolution of a 1 TeV track over ± 1.9 units of rapidity. Sharp Z$^*$ mass peaks are obtained in $H^* \rightarrow ZZ^*$, $Z^* \rightarrow e^+e^-$ even for 800 GeV Higgs, though electron bremsstrahlung adds a tail to the mass peak. Figure 18(b) shows the $H^*$ reconstruction efficiency ($M_H = 300, 800$ GeV) as the number of accompanying minimum bias events is added. Clearly this does better than our medium-luminosity target in this channel. Fifteen minimum bias events in addition correspond to a luminosity exceeding $\mathcal{L} = 1.10^{34}\text{cm}^{-2}\text{s}^{-1}$, and the performance is only slightly degraded.

A large magnetic field is to some extent an enemy at small radii from the beam. Loopers crowd the detector causing loss of wanted hits and pattern recognition problems and shortening detector life. Track-finding becomes non-trivial and lots of precise hits are needed to find a way through a thicket of tracks. However, a large magnetic field is a friend at large
radii. Jets are opened up for track finding and low $p_T$ tracks are curled up at smaller radii. Thus a high $p_T$ track shines out clearly away from a pile of soft tracks, whether in the same jet or in superposed events. The compact muon detector (CMD) concept takes advantage of this. (See figure 19(a)). We discuss here the use of the tracking chambers at 70-80 and 140-150cm radius within this volume. In a field of 4T the outer layer alone gives a muon momentum measurement accuracy of $\Delta p_T/p_T = 0.05$ at 1 TeV. If the 70cm layer, which is more crowded, can be used, further improvements result. Based on the techniques developing as described in Section 6, and the jet spreading already achieved at 70cm, it seems sensible to pursue this with some vigour. The looper momentum $p_T^m$ is 420 MeV/c at 70cm and 840 MeV/c at 140cm. Thus the vast majority of minimum bias tracks never reach the outer tracker.

Buttar and ten Have [37] have studied the effect of the high magnetic field on muon isolation. Figure 19(b) shows, for a luminosity $\mathcal{L} = 4.10^{34}$cm$^{-2}$s$^{-1}$, the number of hits within a 10cm radius of a decay muon as a function of radius. The curve has been calculated for top decay ($m_t = 100$ GeV) and the point, for b-decay. The agreement between the two shows, even at 70cm, that the magnetic field has opened up jets. We conclude that the CMD inner tracking concept is sound and gives a clean muon (or electron) signal at calorimeter entry.

7.2 Track finding and triggering

How do we find tracks in such a tracking superlayer, and can we use them in a trigger? One needs to make a vector chamber superlayer, with a number of closely packed hits over the 10cm length. Track finding then amounts to searching for a straight line of say six to twelve hits in a MISGAC or similar array. Neural networks provide an attractive technique [38,4]. These present a highly parallel computing structure, capable of processing an event in $\sim 1\mu$s. With say 64 presently available 64-input chips one could cover the complete azimuth. The input is the hit pattern from the detectors, which can be in very precise steps. The network assembles links between hits and builds these into trees, assigning weights so that the straightest tracks have the lowest sum of weights. Weights are assigned to link patterns based on network training on Monte-Carlo data. The search methods become rapidly efficient, beating all sequential methods and the output is accurate track vectors. The raw data, an immense volume, can then be thrown away. This step is vital to reduce the tracking data volumes which could otherwise dominate the experiment.

If real-time track reconstruction is available so fast, we can use it in a high-$p_T$ track trigger. Once an outer superlayer vector is found, linking it to the origin implies a $p_T$. High $p_T$ triggers can then be set, with thresholds as high at 100 or 200 GeV, and trigger rates well below 1 Hz [4]. Supposing that isolated electronic muon triggers were already available, why do it? For three reasons, even if one does not wish to make a tau trigger (high $p_T$ lone track not $e$ or $\mu$), or an isolated $\gamma$ trigger. First, having more than one trigger available for the same process allows thresholds to be lowered, thus increasing the physics acceptance. Secondly it allows control of the trigger rate whilst maintaining substantially the acceptance, and thirdly it provides a check of systematics. Following the logic that you can never study the events you do not record, matching different trigger signatures together provides invaluable checks.
19. a) Compact muon detector schematic. b) Muon isolation study at $\mathcal{L} = 4 \times 10^{34}$ cm$^{-2}$s$^{-1}$, showing number of hits within 10cm of a muon as a function of radius in a 4T magnetic field. Line- $t$-decay ($m_t = 100$ GeV) point ($b \rightarrow \mu$ decay) [37].

20. Possible forward tracking layout and momentum resolution as a function of polar angle.

21. Schematic of possible layout of solenoid with fibre support [40].
7.3 Forward Magnetic Tracking

A glance at figure 1 reminds us of the need to have good magnetic tracking down to 9.5° polar angle ($\eta = 2.5$). We remind ourselves here of work done for La Thuile [3] and Barcelona [39]. The CMD solenoidal detector could usefully be extended forward with a different detector geometry. Figure 20 illustrates this with a notional detector and its performance and shows its performance. The natural geometry for such a detector (in $r, \phi, z$ cylindrical polars) is to measure $\phi$ well and $r$ (perhaps less well) at fixed $z$. This has two benefits. The number of accurate channels required for a given momentum resolution is only half that needed for a Cartesian detector. More important, track finding is easy in the ($\phi z$) plane. The helix of a track coming from the origin in a uniform magnetic field is given exactly by

$$\phi = \phi_0 + (eB/2p_z)z$$
$$r = (2p_\gamma/eB) \sin (eBz/2p_z) \sim p_T z/p_z.$$

The exact ($\phi z$) straight line and the (high $p_T$) approximate ($rz$) straight line facilitate fast online track finding. An incidental bonus is that $\gamma$ conversions in the detector do not make good ($\phi-z$) tracks - a positive feature of forward magnetic tracking.

A detector concept which is viable up to $\mathcal{L} = 3.10^{33}$ is to follow the H1 forward tracker design [39] with a 300-cell radial-wire drift chamber with azimuthal drift [36]. Armed with a fast MWPC (or MISGAC) crossing-tagger, it provides adequate track finding in modest backgrounds. For higher luminosities one should keep the radial geometry but seek a faster detector medium, as described in section 6 above. We note in passing that LHC $ep$ collisions (125ns crossing internal) provide an environment actually more benign than in the present HERA experiments. Whilst some additional magnetic analysing power would be welcome, it is not total nonsense just to move an existing HERA experiment in due course [3].

7.4 Superconducting Solenoid Construction

High field superconducting coils are thick (in radiation lengths). This is a severe nuisance. It forces one to place coils outside calorimeters to avoid compromising their performance, which vastly increases the technical problems, cost and complexity of the whole experiment. It seems sensible to see if there is a way out. Daum has made a challenging proposal that could cause a dramatic re-assessment of many detector concepts [40]. We have seen the viability of accurate muon tracking at small (1.5m) radii. If a 4T coil could be placed in front of an electromagnetic calorimeter just outside this the whole detector could perhaps be simplified. Equally one could reassess the dimensions and philosophy of large external muon trackers.

The bug-bear is the hoop stress in the coil. The magnetic pressure causes a surface-tension-like stress $\sigma_2 = B^2R/\mu_0 t$ in the support cylinder, of thickness $t$. One must not exceed (or approach) the yield point of the support cylinder, whose thickness therefore grows as $B^2R$. 
Aluminium support cylinders become rapidly thicker beyond $B = 1.8T$, $R \sim m$, dimensions typical of current detector solenoids. Stainless steel dramatically increases the thickness, measured in radiation lengths. There are alternatives. The Tensile strength divided by the radiation length is as follows:

<table>
<thead>
<tr>
<th>Material</th>
<th>$T/X_o$ (MPa/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>5341</td>
</tr>
<tr>
<td>HT graphite</td>
<td>10108</td>
</tr>
<tr>
<td>Boron fibre</td>
<td>16247</td>
</tr>
</tbody>
</table>

If Boron fibre could be used, an otherwise conventional coil can be considered with $B = 7.8T$, $R = 1m$, and $1X_o$ thickness (see figure 21).

There are, of course, technical problems, not least the contraction of Al-stabilised conductor relative to the support cylinder as it cools. The traditional remedy is to pre-stress the Al during winding on to the inside of the support, without, of course, increasing its low-temperature electrical resistance by work-hardening of this very soft material. However, an idea of such challenge and potential application deserves at least a moment's serious thought.

8. Non-magnetic tracking

For tracking with $B = 0$ one sets a different set of objectives. One wants to identify electrons, either by matching an electromagnetic shower to a track coming from the production vertex, or by building a track in a detector sensitive to electrons. One wants in the same device to find $\gamma$-directions for accuracy in $\gamma\gamma$-invariant mass plots in the search for $H^+ \rightarrow \gamma\gamma$. For muons one wants to show that an interesting muon candidate found in an outer detector links successfully back to the production point. At high luminosity running one has also the opportunity to test whether two candidate lepton tracks could come from the same event, taking advantage of the spread of production points along the beam direction. One does not set out to track every individual hadron, as the lack of any momentum information makes this exercise unrewarding. We describe here two techniques developed for electron tracking. The discussion is somewhat brief as these are dealt with more fully by Akesson [41].

Figure 22(a) illustrates the problem. The "interesting" electron signal (from b, W and more exciting objects) lies four orders of magnitude below the jet rate, and still ten times below the rate of isolated $\pi^0$ and $\gamma$. One tactic adopted for electron verification is to use a localised pre-shower detector. Up to six layers of Si detector are used in the sequence $x$-$y$-pad/converter 1.5 RL/$x$-$y$-pad. The strip widths are 375mm giving 1.1m two particle resolution and the pads $3 \times 3\text{mm}^2$, a size chosen for matching accurately to the centre of electromagnetic showers. Silicon is chosen as a tracking medium because of the excellent pulse height information in separating 1 mip from 2 mips. The signatures of $e^\pm, \pi^\pm, \gamma(\pi^0)$ are then different (see figure 22(b)). $e^\pm$ and $\pi^\pm$ show as 1 mip before the converter, $\gamma$ as no track.
22a). Rates of jets, $\pi^0$, $\gamma$ and electrons from various sources [42].

b). $\pi^\pm$, $\gamma$ signatures in a pre-shower detector.

23. TRD tracker schematic and possible layout (end view).
e$^\pm$ and $\gamma$ have an e-m shower pulse height after the converter and strong e-m calorimeter pulses, unlike $\pi^\pm$. Note that $e^+e^-$ pairs from $\gamma$-conversion are distinguished from single electrons. Without a magnetic field they stay close together at all energies and give a 2 mip signal before the converter. The baseline between the strips also allows one to extrapolate e$^\pm$ accurately back to the vertex. As we shall mention in section 10, it would be nice also to do this for $\gamma$s by accurate tracking immediately after the converter and sampling the shower profile at maximum a few $X_0$ further back.

A different approach is the so-called TRD tracker [43]. The detector is an array of 4mm straw tubes filled with a Xe : CO$_2$ 50 : 50 mixture run at a gas gain of $10^4$, giving 34ns maximum drift time. See Hanson [44] for a discussion of tracking with straw tubes. The added features that the straw tubes are embedded in a matrix of expanded CH$_2$ foam, with 200$\mu$m cells separated by 15$\mu$m walls. See figure 23 for the concept and an end view of a possible detector schematic. The essential point is the following. Electrons give rise to TRD X-rays in the foam. These are absorbed in the Xe gas and cause pulse heights on electron tracks to be higher than on pion tracks. Straw tubes are selected as the detection medium because apart from their virtues of cheapness for filling the detector volume their simplicity means that they have a very uniform gain distribution (all within $\pm 4\%$) and with Xe-CO$_2$ virtually no ageing is seen up to 1C cm$^{-1}$ of wire.

Passing through 100 layers one makes repeated pulse-height samples. Three discriminator levels are used, and electrons have the signature of many high and few middle-range pulses (see Akesson for details [42]). Figure 24 illustrates the result in a sector of the detector at $\mathcal{L} = 2.10^{34}$. Once electrons are selected, the event again looks clean - the device can also track muons above 100-200 GeV/c. One's first reaction after admitting the cleverness of the technique is to wonder whether the 4mm granularity is sufficient for performance at high luminosity. Figure 25 illustrates the capabilities, showing the occupancy as a function of distance from the jet axis and the pion and $\gamma$ rejection at different luminosities.

The detector appears to perform well on isolated electrons and up to $2.10^{34}$ luminosity. However, the margins on occupancy are not great and there is potential vulnerability to backgrounds. Based on experience operating near to Uranium calorimeters, neutrons (knocking protons out of CH$_2$) and photoelectrons from $\gamma$s rays are expected to add only a little to the detector occupancy.

9. Pile-up of Backgrounds

Barger et al. have considered four-parton processes as a background to two-parton processes, for example in the accumulation of multi-jet signature [45]. Considering the proton as a bag of partons one sees that these four-parton events could come from collisions of the same protons, or from independent collisions. The four-parton rate for overlap of processes 1 and 2 is given by

$$\sigma_{1,2} = \sigma_1 \sigma_2 \left(1/\pi R^2 + \mathcal{L} t\right)$$
24. TRD tracker sector at $\Sigma = 2.10^{34}$ a) all hits, b) high only, c) tracks identified as electrons.

25. a) Occupancy (all tracks) as a function of distance from the jet axis in a background of 40 minimum bias events, b) pion rejection at various luminosities.
The first term corresponds to same-proton collisions, with $\pi R^2 = 40\text{mb}$. The second is the different-protons background, $\mathcal{L} = \text{luminosity}$, $\tau = \text{crossing internal} = 15\text{ns}$. The two terms are equal at about one event per crossing. Thus the parton pile-up background is independent of $\mathcal{L}$ for all luminosities below $1.10^{33}$ and therefore worsens linearly with luminosity.

We can gain further discrimination against overlapped events by looking at the distribution of production points along the beam direction. Figure 26(a) from the CDF vertex TPC illustrates pile-up in a medium luminosity situation. With an adequate pixel detector one can follow this strategy and separate out charged particles and jets into different events to obtain powerful clean-up of the event signal. The interaction point envelope has $\sigma = 53\text{mm}$.

Figure 26(b) however reminds us that this strategy fails at high luminosity. It plots the probability that a given production point lies within 1mm of another, and is a step function in log $\mathcal{L}$. We cannot therefore attempt to resolve all production vertices, but we still can check event integrity, as sketched in figure 27. To see if two candidate tracks (e$^+e^-$ say) come from the same event we extrapolate them in the rz-plane to the beam line to positions $z_1$ and $z_2$. It is relatively undemanding to obtain a 1mm error. There is no point aiming for $100\mu\text{m}$ accuracy as heavy flavour decays randomise the apparent vertex point at this level. We then plot $\Delta z = z_1 - z_2$. For single events $\Delta z = 0$ within error ($\pm 2\text{mm}$ say). For false combinations the distribution is a Gaussian of width $53\sqrt{2} = 75\text{mm}$. Thus a true discovery seen in the calorimeter should also show as a clear peak in a $\Delta z$ plot. This test of event integrity provides a gain of order 25 in pile-up rejection.

We are thus encouraged to persist in high-luminosity running for low cross-section processes. However, events are always cleaner if rates are lower. For example consider $gg \rightarrow \bar{t}t \rightarrow l^+l^-jjjj$. For $m_t = 200$, $\sigma(2 \text{ leptons}) \sim 1\text{pb}$.

<table>
<thead>
<tr>
<th>$\mathcal{L}$</th>
<th>$4.10^{34}$</th>
<th>$3.10^{34}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>events/year</td>
<td>$4.10^5$</td>
<td>$3.10^4$</td>
</tr>
<tr>
<td>$\sqrt{\sigma_1 \sigma_2}$ to fake</td>
<td>41nb</td>
<td>145nb</td>
</tr>
<tr>
<td>(the higher the better) Confused events</td>
<td>Accept</td>
<td>Discard</td>
</tr>
</tbody>
</table>

If we have the choice, where complex topological signatures are needed, go for fewer, cleaner events, and use every reconstruction weapon available.

10. **Mass Resolution in $H^0 \rightarrow \gamma\gamma$**

Reconstructing $H^0$ candidates as a mass peak in the $\gamma\gamma$ spectrum we recall that $m(\gamma\gamma) = \sqrt{E_1E_2} \sin \theta/2$, where $E_1, E_2$ are the $\gamma$-ray energies and $\theta$ is the opening angle. For $\Delta m/m < 1\%$ we require $\Delta \theta/\theta < 1\%$, (for small $\theta$). Let the $\gamma$ calorimetry points be at radius $r$ from the beam line and at $z_1, z_2$ along it. Let the supposed production point be at
26. a) Tracks seen in the CDF vertex TPC. Beams enter left and right. Several production vertices can be identified. b) Probability that a random event has another production vertex within 1 mm, as a function of luminosity.

\[ r = 100 \text{ cm} \]
\[ r = 90 \text{ cm} \]

\[ \sigma = 108 \mu \text{m} \]

27. \( \Delta z \) test for two candidate tracks for a new discovery.
position $z_\nu$ with error $\Delta z$. Then $\Delta \theta \sim (z_1 + z_2 - z_\nu) \Delta z/\nu^2 + \ldots$. Setting $z_\nu = 0$ note that the coefficient of $\Delta z$ vanishes if $z_1 = -z_2$, i.e. the two $\gamma$s are at $\pm$ the same rapidity. (Note this includes 180° separations). High-school geometry tells us we should have known this. In the case where both $\gamma$s are at positive or negative rapidity, good knowledge of $z_\nu$ is vital. On average we require $\Delta z_\nu \sim 8\text{mm} \ll \text{beam spot length}$.

At one event per crossing it is easy - use the charged tracks to find $z_\nu$. At high luminosity one has some options. Those events with $|z_1 + z_2| \ll \nu$ may be selected as "golden geometry" candidates. For the rest one can attempt to tag the Higgs vertex by looking for jet activity recoiling against it. Seez has made a study of this.

Looking in a cone $\pm 0.75\,\text{rad}$, $\eta = \pm 3$ opposite the Higgs candidate one selects $p_T \ (\gamma \gamma) > 15$ (65% efficiency for $m_H = 100\,\text{GeV}$). Counting tracks of $p_T > 1$, histogram $z$ (production) for each in 2mm bins and pick the highest bin. The result (not very sensitive to these cuts over a wide range) is that 75% of the time one is correct, and $\Delta z \sim 1\,\text{mm}$. 25% of the time one is wrong and $\Delta z$ grows to 75mm, worse than the starting point. Overall for these events $\Delta z$ is reduced from 53mm to 38mm, which falls short of our target. One therefore prefers to find the $\gamma$-directions from the $\gamma$'s themselves using a pre-shower detector. However, watch for two problems. A 1.5 $X_0$ converter is only 48% efficient for 2 $\gamma$s. Secondly if one reconstructs the directions by drifting in air to the next measuring plane, vital shower energy is lost to neighbouring towers. If these are added in the calorimeter noise is increased and a 2%/\sqrt{E} calorimeter degrades to 3%/\sqrt{E}. It seems better, if one can, to map the profile instead at the shower maximum.

If $H^0$ rate is the prime objective, a mix of all these strategies may be the best method, as each one involves some class of compromise.

11. Summary and Conclusions

We have identified a strategy with targets in the fermionic and bosonic sector: $t$, leading to $H^+, \ SUSY, \ K$-M tests and $H^0, \ W^\pm, W^+, W^+$. The detector demands are rather different. $t$-quark studies demand good vertex reconstruction. The TeV Higgs sector demands isolated leptons.

The physics reach of magnetic and non-magnetic detectors is different and for this reason both strategies should be foreseen from the start. An individual detector may choose to evolve with time, but this should be planned from the beginning.

Medium luminosity event reconstructions and high luminosity lepton trackers have complementary virtues. We need to develop a policy for the cohabitation of these, either in different intersections, or more likely since resources are limited and we do not wish to fall short of both objectives, by time-sharing the same apparatus. We note that gaseous detectors, when turned off, are not damaged by radiation. On the other hand their inert mass if permanently present may enrage the owners of pristine external detectors.
This is a time of great activity on detectors. There are initiatives to tackle the challenge of congested events and high radiation levels in gaseous, scintillating fibre and semiconductor detectors. We have seen the first results on GaAs detectors. The issue of occupancy is yielding to the inventiveness of scientists. Issues which persist as a focus for attention are detector thickness and in particular data volumes and processing and the use of tracking information in triggers. For the next round of discussions tracking data volumes are a crucial topic. Without rapid compression, they can distort the entire experimental data flow and analysis.

Sound concepts have been presented for magnetic tracking detectors for medium and maximum luminosity. The detail provided by the medium luminosity detector is needed for t-quark studies. The maximum luminosity detector is viable to the highest rates for isolated leptons.

For non-magnetic trackers two electron-tracking strategies have been proposed that seem worthy of pursuit for running at $10^{34}$ luminosity.

Event pile-up strategies have been suggested for medium and high luminosity.

For the immediate future one sees a need to enter an intense development phase of the techniques currently on offer. Physicists are inventive and determined. Given that the strategy outlined above is accepted as a basis for progress, they will pursue vigorously the techniques needed to extract the full breadth of physics from the LHC.

May I thank the organisers of this workshop for the opportunity to take part, and the participants for taking such patience to educate me on the issues involved.
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CALORIMETRY AT THE LHC

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Calorimetry plays an important role in the present high energy hadron collider experiments in identifying and measuring the energies of electrons, reconstructing and measuring the energies of jets and detecting non-interacting particles via missing transverse energy. This will become even more so at the LHC and the SSC. Only calorimeters have resolutions that improve with increasing energy with only a moderate increase in the detector depth. They can also cope with the high particle densities expected at the future colliders. As at the present colliders, leptons at high transverse momenta are expected to sign new particles and new physics. Electromagnetic calorimeters with a large dynamic range will play an especially important role.

The new challenges that the calorimeters at the LHC will have to face are:

- luminosities in excess of $10^{34}$ cm$^{-2}$s$^{-1}$ with inter-bunch crossing times of $\sim$15 ns, requiring radiation hardness and speed of response far beyond what has so far been achieved,
- performance at high energies will be dominated more by instrumental deficiencies such as non-uniformity of response, finite containment, inter-cell calibration etc. than by intrinsic calorimeter resolution thus requiring much better control of the systematic effects,
- the calorimeters will have to provide, at different levels of triggers, rejection factors that are several orders of magnitude in the presence of very large interaction rate ($\geq 10^9$ s$^{-1}$),
- large calorimeter volumes and the large number of readout channels will require new designs for the mechanics and the electronics.

It is the first point that at present appears to be the most difficult, important and urgent to address. Thus a significant part of this report is devoted to it.

Calorimetry at the future hadron colliders has been the subject of several workshops [1]. Last year ECFA organized a study week on Instrumentation Technology for High Luminosity Hadron Colliders in Barcelona [2]. Since then the study of the required detector performance and the experimental R&D has intensified.
The Calorimeter Working Group of this workshop was formed in April 1990. In order to define the performance criteria necessary for the extraction of the physics signals, usually in the presence of large backgrounds, the subgroup "Physics versus Calorimeter Performance" convened by J. P. Repellin, worked closely with the Physics Working Group. This work is summarized in section 1.

The Calorimeter Working Group devoted much time to the evaluation of the different calorimeter techniques with a view of their use at luminosities of $10^{34}$ cm$^{-2}$s$^{-1}$ and higher. We present here a summary of the contributions made by a large number of people during the last six months. The questions asked of each technique were:

- What is the radiation sensitivity?
- What is the signal shape and the effect of pileup?
- What are the measurement resolutions (energy, position) for electrons, hadrons and hadron jets, what is the linearity of response?
- What calibration accuracy can be achieved?
- What is the achievable segmentation?
- What hermeticity can be attained?
- What level of particle (electron) identification can be achieved?
- Is the technique affected by a magnetic field?
- What is the level of the maturity of the technique?
- What is the estimated R&D effort required and the time required in order to be able to reach a decision on suitability at the LHC?

At the first working group meeting in April, subgroups for the following techniques were formed (persons in parentheses took over the work in the cases where the convenor could not attend the Aachen meeting):

<table>
<thead>
<tr>
<th>Sampling Calorimeters (em/had)</th>
<th>Subgroup Convenors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scintillator Tiles-Wavelength Shifter</td>
<td>H. Tiecke, (R. Klanner)</td>
</tr>
<tr>
<td>Scintillating Fibers</td>
<td>L. Poggioi</td>
</tr>
<tr>
<td>Liquid Argon</td>
<td>D. Fournier</td>
</tr>
<tr>
<td>Room Temperature Liquids</td>
<td>E. Rademacher</td>
</tr>
<tr>
<td>Silicon</td>
<td>G. Lindstroem</td>
</tr>
</tbody>
</table>

Homogeneous EM Calorimeters:

| Crystals | H. Newman, (P. Lecoq) |
| Noble Liquids | T. Virdee |

The subgroups met independently and reported regularly at the working group meetings and finally during the first three days of the Aachen Workshop. Section 2 summarizes this work and short conclusions are given at the end of each of the sub-sections dealing with the individual calorimeter techniques. More details can be found in the sub-convenor reports in
Vol. 3 of these proceedings. Section 2 also briefly summarizes the performance parameters relevant for the front-end electronics chain and recalls the radiation levels that the calorimeters will have to stand.

1. PHYSICS REQUIREMENTS

1.1 Cross-sections

Most of the physics reactions of interest at the LHC have low cross-sections. For example, the production cross-section for a Higgs boson, a new Z or a new W are in the picobarn range whereas the total cross section is of the order of 100 mb. Furthermore the inclusive jet cross-section for a jet with a transverse momentum larger than 20 GeV/c is about 300 μb. This QCD background is many orders of magnitude larger than most of the signals of interest. This leads to an emphasis on the leptonic signatures. They provide a large rejection factor against the QCD backgrounds but at the price of a loss in rate due to the smallness of the leptonic or semileptonic branching ratios eg. BR( W -> eν ) or B( t -> eνb ) are both \( \sim 10\% \) and BR( Z -> ee ) \( \sim 3\% \). As an example, Fig. 1 shows the \( \sigma \cdot BR( H -> ZZ -> 4 l ) \) where \( l = e \) or \( μ \). It is about 10 fb for a Higgs with a mass of 400 GeV [3,4]. The \( \sigma \cdot BR( H -> γγ ) \) is shown in Fig. 2 and has a similar value [3,5].

![Graph showing cross-section times branching ratio for the 4 lepton decay of the Higgs](image)

**Figure 1:** Cross-section times branching ratio for the 4 lepton decay of the Higgs : H -> ZZ -> 4 l where \( l = e \) or \( μ \). The number of events shown are for an integrated luminosity of \( 10^5 \) pb\(^{-1}\).

The observation of signals with such low cross-sections requires a high luminosity, perhaps in excess of \( 10^{34} \) cm\(^{-2}\)s\(^{-1}\). Consequently we have set the benchmark at a luminosity of \( 2 \cdot 10^{34} \) cm\(^{-2}\)s\(^{-1}\) and 15 ns between crossings. This necessarily introduces a bias to the conclusions as they may be different for a lower luminosity running and should thus be borne in mind throughout the rest of the report.
Figure 2: Cross-section times branching ratio for the $H \rightarrow 2\gamma$ decay as function of the Higgs mass.

1.2 Acceptance: Rapidity Coverage and Transverse Momentum Thresholds.

Heavy objects in high energy pp collisions are preferentially produced at central rapidities. This usually applies also to their decay products. In this section, a few processes are used to investigate the extent of rapidity coverage that is required.

1.2.1 $H \rightarrow ZZ \rightarrow eeee$

This process, with a striking signature, requires a large rapidity coverage and the measurement of electrons with low transverse momenta [4]. A large acceptance is needed as both the production cross-section and the Z branching ratio into electron pairs is small. The acceptance as a function of the transverse momentum of the electron having the smallest $p_t$ is shown in Fig.3 for three different Higgs masses and for a rapidity coverage of $\pm 3$ units. These curves indicate that the observation of a low mass Higgs requires the detection of electrons with transverse momenta as low as 10 GeV/c. This is also true of the search for SUSY particles which have cascade decay chains leading to electrons. The same figure shows the acceptance of the leptons from the decays of Z's produced in the process $\bar{g}g \rightarrow \tilde{\chi}\tilde{\chi} + X \rightarrow ZZ + X \rightarrow 4l + X$ with a gluino of a mass of 1 TeV/c$^2$ and for the full rapidity coverage [6].
Figure 3: Acceptance as function of the transverse momentum of the electron having the smallest $p_t$ for two physics processes: $H \rightarrow 4\,e$ and $g \rightarrow Z + X \rightarrow 2\,e + X$.

Table 1 summarizes the acceptance, for the process $H \rightarrow ZZ \rightarrow 4\,l$, of a calorimeter for 3 values of the Higgs mass (140, 200 and 500 GeV/$c^2$). The first column gives the acceptance of an electron pair trigger with a $p_t$ cut of 20 GeV/$c$. This shows that such a trigger maintains a reasonable acceptance for a low mass Higgs boson even if the acceptance is limited to ±2 units of rapidity. As can be seen from the last two columns, a low $p_t$ threshold for the lepton with the smallest $p_t$ is crucial for detecting a low mass Higgs. The geometrics acceptance grows almost linearly with the rapidity coverage. An electromagnetic calorimeter with a rapidity coverage between ±2 and ±3 units is clearly desirable.

| $|\eta|$ | $p_t^{1/2} > 20$ GeV | $p_t^{1/4} > 10$ GeV | $p_t^{1/4} > 20$ GeV |
|-------|------------------|------------------|------------------|
| $M_H =$ 140 GeV |  |  |  |
| $<3$ | .91  | .54  | .11  |
| $<2$ | .67  | .33  | .07  |
| $M_H =$ 200 GeV |  |  |  |
| $<3$ | .94  | .76  | .56  |
| $<2$ | .73  | .48  | .38  |
| $M_H =$ 500 GeV |  |  |  |
| $<3$ | .98  | .88  | .80  |
| $<2$ | .82  | .62  | .57  |

Table 1: Acceptance for the $H \rightarrow ZZ^{(*)} \rightarrow 4\,l$ decay channel as function of the angular coverage and transverse momentum cut on the electrons (see text below).
1.2.2 $H \rightarrow \gamma \gamma$

Studies of this mode [5] show that a calorimeter coverage of ±2 units of rapidity provides an adequate acceptance for Higgs masses around 100 GeV/c$^2$. Fig. 4 shows the $p_t$ distribution of the photon with the higher and the lower $p_t$. An asymmetric cut on the $p_t$ of the two photons is used to reject the background. Cuts set at 40 GeV/c and 25 GeV/c for the two photons within a rapidity range of ±2 units lead to an acceptance of 41% for $M_H = 100$ GeV/c$^2$ and 51% for $M_H = 150$ GeV/c$^2$. Extending the coverage to ±3 units increases the signal acceptance, after $p_t$ cuts, by 45%. The background, however, is increased by more than 50% resulting in a gain in the significance of 18%.

![Graphs showing p_t distributions for H -> gamma gamma](image)

Figure 4: $H \rightarrow \gamma \gamma$: Transverse momentum distribution of the photon with the higher and lower $p_t$ for a Higgs with a mass of 100 GeV/c$^2$.

1.2.3 Tagging of IVB fusion process

For Higgs masses larger than ~700 GeV and depending on the mass of the top quark the IVB fusion production mechanism competes with the gluon fusion process. Consequently identification of the two very forward quark jets can be used to identify events from the IVB fusion process and thus extend the detectability of the Higgs boson to higher masses.

The rapidity distribution of the "tagging" jets and the energy distribution of the jet with the lower energy are shown in Fig 5 [7]. In order to be sensitive to this process the coverage of a hadronic calorimeter has to extend to rapidities up to at least ±4 units. This calorimeter will have to survive a very high level of radiation. However the calorimeter performance does not have to be very good as the jets have very high energies and are well collimated.
Figure 5: Rapidity distribution of the "tagging" jets and energy distribution of the lower energy jet for the \( p\bar{p} \rightarrow q\bar{q}H \) process. Dashed line is the signal and the full line is the QCD background.

1.3 Missing Transverse Energy.

The observation of an imbalance in the transverse momentum is an important signature for the presence of non-interacting particles, e.g., a neutrino or the lightest supersymmetric particle. The usefulness of such a signature, based on a cut on the missing transverse momentum, depends on the process under study, the particular backgrounds that fake the signal and the coverage and the performance of the calorimeter. We examine these points by considering a few examples.

1.3.1 \( H \rightarrow ZZ \quad (Z \rightarrow ee, Z \rightarrow \nu\nu) \)

This reaction is of interest for large Higgs masses (\( \geq 500 \text{ GeV/c}^2 \)) where the larger branching fraction of the \( Z \rightarrow 2\nu \) can be used to extend the range of sensitivity. The identification relies on the observation of one \( Z \) decaying into electrons (with for example \( p_T^Z > 100 \text{ GeV/c} \)) accompanied by a large missing \( p_T \). The signal appears as a Jacobian peak in the \( p_T^Z \) distribution above an irreducible background from \( Z \) pair production. However, this assumes that the huge background from \( Z + \text{jets} \) events, where the jets are mismeasured or are outside the calorimeter
acceptance, can be rejected. The level of this background is shown in Fig. 6 as a function of the missing $p_t$ for different rapidity coverages ($\pm 2, \pm 3, \pm 4$ units) [4]. A rapidity coverage of $\pm 4$ units is essential for the observation of this process.

![Graph showing missing transverse momentum distribution for different scenarios](image)

Figure 6: Missing transverse momentum distribution for the $H \rightarrow ZZ \rightarrow 4\nu$ signal and for backgrounds from the $ZZ$ continuum and from $Z$+jets events, as a function of the calorimeter coverage.

1.3.2 $pp \rightarrow t\bar{t} \rightarrow ev + jets$

The observation of $t\bar{t}$ pair production with a top quark decaying semi-leptonically requires a rejection factor of $\sim 10^5$ against jets faking electrons. The effectiveness of a cut on the missing transverse momentum has been studied to see whether the level of rejection required can be relaxed [8]. Fig. 7 shows, for $M_{top} = 130$ GeV/c$^2$, the rejection obtained by the cuts $p_t^{miss} \geq 50$ GeV/c (upper set of curves) and $p_t^{miss} \geq 100$ GeV/c (lower set of curves). For $p_t^{miss} \geq 50$ GeV/c the rejection factor that can be obtained is $\sim 10 \cdot 100$ depending on the rapidity coverage. A large rapidity coverage $|\eta| \geq 4$ units seems necessary though the rejection power comes at the price of a loss of acceptance (crosses) and is considerably affected by the pile-up from 20 minimum bias events. But a higher $p_t^{miss}$ cut leads to a substantial loss in acceptance.

The pile-up from minimum bias events at high luminosity widens the missing $p_t$ distribution. To reduce the apparent missing $p_t$ from the fluctuation in the minimum bias pileup only jets exceeding some $p_t$ threshold could be used in the computation of $p_t^{miss}$. The effect is then limited to the smearing of the energy in the cells used for the jet energy reconstruction and to the
fluctuation in the number of jets which pass the $p_t$ threshold. Quantitative estimates thus require specific simulation for each process.

![Diagram showing acceptance for the process $t\bar{t} \rightarrow ev + \text{jets}$ and the QCD background rejection factor for two cuts on the missing transverse momentum, as a function of the calorimeter coverage.]

Figure 7: Acceptance for the process $t\bar{t} \rightarrow ev + \text{jets}$ and the QCD background rejection factor for two cuts on the missing transverse momentum, as a function of the calorimeter coverage.

1.3.3 $p_t^{\text{miss}}$ for events with $\geq 3$ jets.

A study of the $p_t^{\text{miss}}$ distribution of 3 jet events has been made in the context of the search for supersymmetric particles [9,10]. A procedure has been developed to simulate the energy smearing and the lateral development of jets. Fig. 8 shows that a deterioration of the energy resolution of the calorimeter from 40% $\sqrt{E}$ to 80% $\sqrt{E}$ would correspond to a shift of a $p_t^{\text{miss}}$ cut from 120 GeV/c to 160 GeV/c [9]. The pile-up from minimum bias events was not included in this simulation.

The interplay between the effects of limited calorimeter coverage, energy resolution, energy losses in cracks and event pileup has still to be studied in depth.
1.4 Pileup, Detector Speed and Calorimeter Granularity

At a luminosity of $2.10^{34} \text{ cm}^{-2}\text{s}^{-1}$ there are ~20 inelastic pp interactions in each bunch crossing. Hence even an ideally fast calorimeter will suffer pileup. Moreover, hadronic shower development is not instantaneous but requires at least $\approx 45$ ns, as measured by the SPACAL collaboration in the scintillating fiber calorimeter [11]. Low energy neutrons in the hadronic shower are moderated by collisions with essentially free protons in the plastic fibers with a time constant of the order of $\approx 10$ ns (Fig. 9).

The vast majority of hadronic collisions which constitute the pileup produce particles with low transverse momenta with the spectrum being parametrized by:

$$\frac{dN}{dp_t} = p_t e^{-p_t} \text{ with } \langle p_t \rangle = 0.65 \text{ GeV/c}$$

with an average number of 10 charged and neutral particles per unit of rapidity.

The particles from the overlapping events will contribute to the energy measured in the calorimeter. The calorimeter energy resolution is thus degraded although their average contribution can be subtracted.
1.4.1 Pile-up and Jets

Present collider experiments usually measure the energy of a jet by summing the energy contained in cells in a rather large cone, of half-angle $\Delta R = \sqrt{(\Delta \eta^2 + \Delta \phi^2)} \sim 0.7 - 1.0$. For the LHC, the studies at high luminosities (2.10$^{34}$ cm$^{-2}$s$^{-1}$) show that $\Delta R$ has to be reduced to $\leq 0.4$. Small cone sizes cut hard into the jet core but larger ones sum over too much pile-up. Fig. 10 shows the distribution of the transverse energy piling into a cone of half-angle $\Delta R=0.4$ as estimated from equation (1). This is computed for two types of detectors, an ideally fast calorimeter which is sensitive to only one crossing and a "slow" one which integrates over 60ns i.e. four crossings. The two distributions are nearly Gaussian as expected from the fact that $\approx 20$ particles per crossing deposit their energy into the cone. The pileup can be considered as an additional source of noise once the average value of this contribution is subtracted. Assuming no short range correlations e.g. from jets, the dependence of the average and the r.m.s. values of these distributions with luminosity, cell size and detector sensitive time ($\tau$) are given by:

$$<\text{pileup}> \propto <p_t> \cdot \text{Luminosity} \cdot \text{area} \cdot \tau$$

$$<\sigma_{\text{pileup}}> \propto <p_t> \cdot \sqrt{\text{Luminosity} \cdot \text{area} \cdot \tau}$$

For a hadronic calorimeter with 45ns integration time using a cone of a half-angle of $\Delta R=0.4$, the r.m.s. of the pile-up energy ($\sigma_E \geq 6.2$ GeV) sets a lower limit on the jet energy resolution that corresponds to $\sim 60\% / \sqrt{E_T}$ for a 100 GeV jet. This however is a small effect for very high energy jets ($E \geq 1$ TeV) as the constant term will probably dominate the hadronic energy resolution.

More work is needed to fully understand the effect of pile-up on missing transverse momentum although some work has already been done for the detection of the top quark [8] and for the search for SUSY particles [6]. It should also be noted that calorimeter triggers will preferentially pick up events with large pile-up and thus worsen the situation. This also has to be studied more carefully.
Figure 10: Distribution of the transverse energy from minimum bias events piling up in a cone of half opening angle $\Delta R = 0.4$ for a luminosity of $2.10^{34}\text{ cm}^{-2}\text{s}^{-1}$. Two types of detector are considered: a "fast" one which can resolve two crossings and a "slow" one which integrates over 4 crossings.

### 1.4.2 Pile-up and Photons, Electrons

Electromagnetic showers have a much smaller transverse size: $\approx 90\%$ of their energy is contained in a cylinder with a diameter of $\sim 5 X_0$ (i.e. 4 - 15 cm depending on the calorimeter characteristics). The average number of particles from minimum bias events in such a small region is smaller than unity and pileup is not Gaussian anymore. Consider a typical calorimeter having a $\sigma_E = 400$ MeV for 20 GeV electrons (i.e. $\sim 9\% /\sqrt{E}$). Assume a lateral segmentation into square cells which are large enough to contain the electromagnetic shower. Then the probability to have less than 400 MeV from event pile-up can be computed using equation (1). Fig. 11 shows that, at $L = 2.10^{34}\text{ cm}^{-2}\text{s}^{-1}$, 30% of the events will have more than the 400 MeV of pileup energy in a cell of $\Delta \eta \Delta \phi = .12^2$ in the case of a fast calorimeter. A size of $\Delta \eta \Delta \phi = 0.06^2$ is required for a "slow" detector in order to get the same result. Good granularity is thus very important for an LHC calorimeter which aims to measure electron or photon energies precisely. Note that the true granularity has to be $\geq 3$ times better in order to take into account particles falling near cell boundaries and for the calorimetric measurement of the electron/photon impact point.

The lateral size of the shower determines the containment radius for a given electromagnetic calorimeter. This can be used to put a lower limit on the inner radius needed for that calorimeter so that the energy resolution not be degraded by pileup. For example: if at a luminosity of $2.10^{34}\text{ cm}^{-2}\text{s}^{-1}$ only 10% of the events are allowed to have pileup energy $\geq 400$ MeV in an area of a size of $\sim 10 \times 10 \text{ cm}^2$, then the inner radius should be $\geq 1.4$ m.

Pile-up sets a limit on the effectiveness of the electron/photon isolation criteria and also spoils the reconstruction of shower position (which is useful to identify electrons using the spatial matching with a charged track). Again this sets constraints on the calorimeter granularity and will be discussed below in section 1.6.1.
1.5 Trigger on Electrons and Photons

The importance of the detection of charged leptons and photons in the search for new heavy particles was stressed in section 1.1. Calorimeters thus need to be able to trigger on events containing electrons and photons with high transverse momenta. This provides the first level of suppression of the large background resulting from QCD interactions. Some of the implications of such a requirement are considered below.

Consider a trigger based on an electron from the semi-leptonic decay of one of the top quarks in the reaction $pp \rightarrow t \bar{t}$ where $t \rightarrow Wb \rightarrow evb$ [8]. The acceptance for such an electron with $p_t > 40$ GeV/c, in a rapidity range $|\eta| \leq 2$, is 33% (52%) if the mass of the top quark is 100 (200) GeV/c$^2$. Although both the acceptance and the production cross-sections (10nb for $M_t=100$ GeV/c$^2$ and 0.7nb for $M_t=200$ GeV/c$^2$) for the top quark are large, the inclusive jet cross-section for the same kinematic cuts is $\sim 50\mu$b which would give a trigger rate of 50 kHz at a luminosity of $10^{33}$ cm$^{-2}$ s$^{-1}$. A reduction of this rate by 2 orders of magnitude is needed from the first two levels of trigger [12]. At a luminosity of $2.10^{34}$ cm$^{-2}$ s$^{-1}$ either the rejection factor has to be $\sim 1000$ or the $p_t$ threshold has to be raised to 100 GeV/c for the same rate of inclusive electron triggers. This can be compared with a reduction of 5-6 orders of magnitude required offline to take the background below the level of the signal.
1.5.1 Single Electromagnetic Cluster Trigger

From the discussion above it can be seen that the calorimeter has to provide, at the trigger level, a rejection of a factor of $\sim 100$ or more against jets.

A first rejection factor comes from the requirement of a threshold on the transverse energy deposited in the electromagnetic part of the calorimeter. A thickness of 25-30 radiation lengths is required to collect the energy of high energy electron or photon showers. The jets also deposit a sizeable fraction of their energy in such a thickness but it is considerably less localized as compared with single electron or photon energy deposits. This characteristic has already been used in the present generation of collider experiments. GEANT simulations show that a rejection factor of $\sim 50$-100 against jets [13] can be expected for a threshold of $p_T \geq 20$ GeV/c for a "cell" with dimensions $\Delta \eta, \Delta \phi = 0.1^2$. This rejection has a weak dependence on the cell size and can be roughly parametrized as $1/\sqrt{\Delta \eta \Delta \phi}$. This rejection is still smaller than the jet/$\pi^0$ ratio which is $\sim 200$ at $p_T \sim 20$ GeV/c (Fig. 13).

A further rejection can be obtained by requiring that the e.m. energy deposit be isolated. This is effected by allowing only a limited amount of energy in the electromagnetic cells surrounding and in the hadronic cells behind the trigger cells. The above mentioned GEANT simulations show that an overall rejection factor of $\sim 1000$ can be attained for an electron inefficiency of less than 5% in a fast calorimeter and about 10% in the "slow" calorimeter defined in 1.4.1.

1.5.2 Electromagnetic Pairs Trigger

As explained in section 1.2, the calorimeter has to provide the trigger for $H \rightarrow 2\gamma$ or $H \rightarrow ZZ$ ($Z \rightarrow ee$) channels. A $p_T$ threshold no higher than $\sim 20$ GeV/c is required to have a sizeable acceptance for a low mass Higgs boson.

The cross-section for 2 jet production, with both jets having a $p_T \geq 20$ GeV/c and within a rapidity range $|\eta| \leq 2$, is $\sim 330 \mu$b. Including the effect of pileup, which becomes significant at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$, leads to a 2 jet rate of $\sim 10$ MHz. However the electromagnetic trigger is less affected by pileup, as compared to a jet trigger, and an online rejection of a factor of $\sim 100$ per leg brings the trigger rate down to $\sim 300$ Hz which can then be handled by the 2nd level trigger. It should be noted that the $\sigma.BR(Z \rightarrow ee) \sim 1$ nb for a rapidity coverage of $|\eta| \leq 2$ leading to a di-electron rate of $\sim 10$ Hz at $L = 10^{34}$ cm$^{-2}$ s$^{-1}$. A large number of events can thus be accumulated in a relatively short time and may enable the precise calibration of an electromagnetic calorimeter. Various other processes eg. SUSY particle decays having $Z$'s in their decay cascades, $ZZ$ and $ZW$ production also require such a di-e.m. shower trigger.

1.6 Calorimetric Identification of Electrons and Photons

Except for a limited number of processes involving more than 2 leptons, the rejection factor of $\sim 1000$ against jets is not sufficient to reduce the QCD background to the levels of irreducible
backgrounds. For example, in the channel \( pp \rightarrow t \bar{t} \rightarrow e^+ + jets \), a jet rejection of the order of \( 10^5 - 10^6 \) is required. In this section we consider what rejection factors can be attained by calorimeters.

1.6.1 Electron Identification

A charged track pointing to an electromagnetic shower is obviously the minimum that is required for the shower to be identified with an electron. This signature can however be faked by eg. a charged track overlapping with a \( \pi^0 \), a hadron showering like an electron.

The difference between the development of electromagnetic and hadronic showers, both laterally and longitudinally can be used to distinguish electrons from charged hadrons. The UA1 collaboration has shown that given a sufficient longitudinal and lateral segmentation a charged hadron rejection factor of \( \sim 10^4 \) for single high energy showers can be attained for an electron efficiency of 90% [14]. The effect of pileup and the rejection in jets has not been studied during this workshop.

![Diagram showing shower and pileup](image)

**Figure 12:** Percentage loss of 20 GeV electron due to charged track - calorimeter impact mismatch as a function of mismatch distance. Pileup effect becomes substantial for coarse calorimeter granularity. This is computed for the "slow" calorimeter defined in 1.4.1, with an effective radiation length of 1.1 cm.

The lateral development of an electron shower can be used to determine the position of the impact which can then be compared with the position given by the extrapolation of a track found by a tracking device. The calorimeter-track matching has been used by experiments at present hadron colliders to reject charge track-\( \pi^0 \) overlaps. In a high luminosity environment the effectiveness of this method is compromised by pileup. GEANT simulation has been done to study this problem [13]. The results are summarized in Fig. 12 which shows the loss of showers with \( p_t = 20 \) GeV/c as a function of the maximum distance allowed between the extrapolated track and the shower position. It can be seen that the maximum distance is \( \sim 3 \) mm.
for a 5% loss in efficiency and is not too dependent on pileup as long as the calorimeter cell size is kept smaller than $\Delta \eta \cdot \Delta \phi = 0.02^2$. For larger cell sizes eg $\Delta \eta \cdot \Delta \phi = 0.04^2$ this distance has to be substantially increased (to 14 mm) in order to maintain the same efficiency and the pileup substantially degrades the matching precision. These simulations were done with a simple model for a calorimeter with an inner radius of 1m and a radiation length of 1.1 cm.

The rejection factor against jets obtained by track-shower match depends on the type of background. It is effective against accidental overlap of a high energy $\pi^0$ and a charged track from either a jet or a minimum bias event. This background can be reduced below the genuine electron background provided that the transverse segmentation of the electromagnetic calorimeter is of the order of $\Delta \eta \cdot \Delta \phi = 0.02^2$. These rejection factors should be compared and contrasted with those obtained by other identification techniques discussed by the Electron Identification Working Group [15].

Figure 13: Inclusive cross-sections for jets, $\pi^0$ and direct photons in a rapidity range of $|\eta|<2$. The effect of isolation criteria (isolated $\pi^0$) [5] is shown together with the additional rejection one could obtain from the observation of the 2 $\gamma$s from the $\pi^0$ which are separated in angle by $\geq 5$ mrad ("$\gamma_1\gamma_2$ ").

1.6.2 Photon Identification

The process $pp \rightarrow H \rightarrow \gamma\gamma$ is a crucial one for the detection of an intermediate mass Higgs boson at the hadron colliders. The irreducible background, from QCD di-photon production, is large and hence very good mass resolution is required for the $H \rightarrow \gamma\gamma$ peak to stand out in the slowly varying background. However the reducible background, from $\pi^0$'s in jets, would be
dominant unless reduced substantially. Fig 13 shows the inclusive cross-sections for jets and $\pi^0$s as a function of $p_t$ in a rapidity range of $|y| \leq 2$ [5]. The jet background, surviving the cuts described in 1.5.1, is below the inclusive $\pi^0$ spectrum and is dominated by the isolated $\pi^0$s. A further rejection factor of $\sim 10$ is required, especially for $\pi^0$s at low $p_t$, to take the background from two jets, both faking photons, substantially below the direct di-photon background. For such a reduction a calorimeter capable of detecting the presence of two photons having an angular separation of $\geq 5$ mrad is needed as shown in Fig. 14.

1.7 Calorimeter Resolution

1.7.1 Electron Energy Resolution

Good energy resolution for leptons is essential for the measurement of masses and widths of new, narrow and heavy objects eg. a $Z$ decaying into a pair of energetic electrons [16]. In such an energy range ($\geq 500$ GeV) the ability of a calorimeter to measure the energy is limited by the control of the systematics and the knowledge of the energy inter-calibration. With some care 1-2% energy resolution can be achieved (see section 2 below). Such a resolution seems well matched to the natural widths predicted for these new particles by most models. On the other hand, this process defines the large dynamic range required as particles with a mass of up to 4 TeV could be detectable using the high luminosity available at the LHC.

Electromagnetic calorimeter energy resolution is also important in the search for new particles with a $Z$ among the decay products like in the mode $H \rightarrow ZZ^*$ where both the production cross-section and the Higgs width is small. A powerful tool to extract a signal from a large background is to compare the reconstructed mass of an electron pair to the $Z$ mass. Here a better resolution allows a tighter mass cut resulting in a smaller non-resonant background. However in this particular channel, resolution may not be critical as the background, coming mainly from $t\bar{t} \rightarrow 4e$ and $Zb\bar{b} \rightarrow 4e$ [17], is not very large and can be further reduced by lepton isolation cuts. Note here that the isolation requirement is also necessary for muons. Indeed, the muon momentum resolution usually is not as good as that for an electron.

1.7.2 Photon Energy Resolution

Photon energy resolution appears to be much more important. The $H \rightarrow \gamma\gamma$ channel seems to be the best candidate for the detection of a Higgs if its mass is in the range 80-130 GeV/c$^2$. As mentioned earlier there is a large irreducible background from QCD prompt photon production. However as the Higgs has a very small natural width in this mass range the signal can be extracted if the $\gamma\gamma$ mass resolution is good enough [5]. Fig 14 shows the statistical significance of a Higgs signal as function of the calorimeter resolution for an integrated luminosity of $10^5$ pb$^{-1}$ ($\Theta$ denotes the squareroot of the sum of the squares). A very low sampling fluctuation term typical of homogeneous calorimetry is useful only if the systematics can be kept below $\sim 0.5\%$.
In addition, all the benefit of very good photon energy resolution is lost if the vertex position is not known to within a certain precision. This leads to a deterioration of the $\gamma\gamma$ mass resolution due to the resulting uncertainty in the angle between the two photons. The calorimeter must thus have some pointing capability with a precision of $\approx 5$ mrad. Moreover in Fig.14 it is assumed that all isolated $\pi^0$ from hard jet fragmentation, with a $\gamma\gamma$ angular separation of $\geq 5$ mrad, have been removed (see 1.6.2). Combining all these properties will certainly be a challenge for the calorimeter builders.

![Graph showing significance as a function of a vs b]  

Figure 14: Significance of a peak in the $2\gamma$ mass distribution as function of the calorimeter resolution parametrized as $a/\sqrt{E} \otimes b$. The effect of pileup and the dependence on the precision of the vertex position is also shown. Only the $2\gamma$ irreducible background is considered. The QCD jets hadronizing into isolated $\pi^0$ and faking a $\gamma$ are assumed to have been removed.

1.7.3 Hadron Energy Resolution

Several reactions have been studied at this workshop to investigate the requirement on jet energy resolution.

It would be advantageous to try detect an intermediate mass Higgs via its abundant $H \rightarrow b\bar{b}$ decay mode. The reaction $pp \rightarrow ZH \rightarrow ee + b\bar{b}$ has been studied [18]. Fig.16 shows that the $b\bar{b}$ mass distribution has an r.m.s. width of $\approx 11$ GeV due to $b$ fragmentation effects alone and would only marginally be further widened by a poor calorimeter resolution of $100\%/\sqrt{E} \otimes 4\%$. It seems to be very difficult to extract this signal from the much more abundant $Z+2$ jets background. One way out could have been to increase the luminosity in order to improve the statistical significance of the signal. However the multiple event pile-up starts to dominate as discussed in section 1.4. Fig. 17 compares the reconstructed mass distribution, at the particle level, of a $Z \rightarrow jj$ decay without pileup and in the presence of 40 minimum bias events. Even when a very small cone half-angle of $\Delta R = 0.3$ is used to measure the jet energy, in order to minimize the pile-up contribution, the r.m.s. of the $Z$ peak is still $\approx 12$ GeV before any smearing due to calorimeter resolution is taken into account.
An area where one would benefit from the large branching ratio of $Z \rightarrow jj$ is the search for the Higgs in the high mass region. Although in this region the Higgs particle has a large width and does not require good mass resolution, one would like to extract the signal by reconstructing the decay $Z \rightarrow jj$. This has been studied for a Higgs boson of a mass of 800 GeV/c$^2$. The $Z$'s are produced at large transverse momenta and hence the decay jets start to merge. Hence the jet jet mass resolution turns out to be poor ( $\sigma \sim 12$ GeV $)$ even before account is taken of the smearing due to the finite calorimeter energy resolution. The $\sigma$ increases to only 13.1 GeV if a calorimeter with an energy resolution given by 100% / $\sqrt{E} \oplus 4\%$ is used.

Figure 16: Two jet mass distribution in the $pp \rightarrow ZH \rightarrow ee + b\bar{b}$ reaction. Smearing due to finite calorimeter energy resolution is not included.

Figure 17: The effect of pileup on the 2 jet mass resolution from a $Z \rightarrow jj$ decay. a) jj mass without pileup; b) in the presence of 40 minimum bias events. Smearing due to finite calorimeter energy resolution is not included.
The reconstruction of the mass of the top quark has been studied [8] using the jets in the reaction \( pp \rightarrow t \bar{t} \) where one of the two top quarks decays semi-leptonically and provides the trigger. The other one decays into 3 jets which are then used to reconstruct the mass. As the cross section for this channel is large it can be studied at a relatively low luminosity. Pile-up is then not a problem. The 3 jet mass distribution is wide and sits on a large combinatorial background. Thus here again the calorimeter resolution does not seem to be critical. It is also interesting to note that the multilepton channel \( t \bar{t} \rightarrow 3 \ell + X \) provides a more accurate determination of the top mass [8].

The top working group has also studied the production of the charged Higgs in the decay \( t \rightarrow bH^+, H^+ \rightarrow c\bar{s} \). For some values of the parameters in the minimal SUSY model, the width of \( H^+ \) can be small. The \( bH^+ \) decay mode competes with the \( t \rightarrow bW^+ \) one. Fig. 18 shows the mass distribution of two of the three jets. A \( H^+ \) signal can be seen close to the \( W \) peak. This simulation was carried out using a calorimeter with an energy resolution given by \( 50\% \sqrt{\Delta E} \pm 2\% \). The separation of the \( H^+ \) peak from the \( W \) one becomes marginal in a calorimeter with a worse resolution eg. \( 100\% \sqrt{\Delta E} \pm 4\% \).

![Graph](image)

Figure 18: The mass distribution of two out of the three jets from the decay \( t \rightarrow bH^+, H^+ \rightarrow c\bar{s} \) and \( t \rightarrow bW^+ \)

1.8 Summary: Physics Requirements

This ends the brief survey of physics requirements on calorimetry. The main ones are:

- an ability to stand luminosities in excess of \( 10^{34} \text{ cm}^{-2} \text{ s}^{-1} \) which implies the need for a radiation hard calorimeter that can provide fast signals.
Detection and energy measurement of leptons is crucial requiring a calorimeter that can provide the trigger, the identification and a good energy measurement of the electrons. This requires fine lateral segmentation of the electromagnetic part of the calorimeter.

A geometric acceptance for electrons and photons of at least ±2, and possibly ±3, units of rapidity. A useful measurement of the missing transverse momentum and the search for a heavy Higgs via jet tagging requires an even larger rapidity coverage for jets (at least ±4 units). This is summarized in Fig. 19.

The requirements on energy resolution are process dependent. The most demanding one is $H \rightarrow \gamma\gamma$ for the electromagnetic calorimeter. For jet energy measurement at high luminosity, event pile-up will limit the performance of a good hadron energy resolution calorimeter.

Figure 19: Angular acceptance requirements from various physics processes.
2. CALORIMETER TECHNIQUES

The most serious problem that all calorimeter techniques will have to solve is the one of radiation damage. To underline the importance of this problem, we discuss it first. Then we report on the various techniques that were reviewed during this Workshop.

2.1 Radiation Levels

The high luminosity needed to study low cross-section phenomena will induce high radiation levels in the calorimeters. This has already been discussed at Barcelona in the previous ECFA meeting by D. Groom and G. Stevenson [2]. Since then, a more detailed computation, using hadronic cascade simulations, has been performed and has confirmed the previous results apart from a change in the value of the hadron and photon dose [19].

The basic assumption is that beam-beam collisions dominate over other sources of irradiation. This is not true at the present proton-antiproton collider but is expected to be so at the LHC in view of the much higher interaction rate. The computation by Stevenson assumes an inelastic interaction cross-section of 60 mb, a 3 m thick spherical lead calorimeter starting at an inner radius of 2 m. The computation should be correct to within a factor of 2. Simulation of the eventually chosen geometry will obviously have to be done. However, for this study we have simply scaled the dose and the neutron fluence, at a given angle, by the inverse of the square of the distance from the interaction vertex. This may introduce some additional uncertainties.

Consider a detector running for $10^7$ seconds/year at a luminosity of $2.10^{34}$ cm$^{-2}$s$^{-1}$ and for 5 years. The doses which the calorimeters will have to stand, under these conditions, is illustrated in Fig. 20 for two typical calorimeter configurations. The dose reaches a maximum in the electromagnetic part of the calorimeter and comes from the myriad of low energy $\pi^0$ produced in the pp collisions. The typical dose in the large central barrel is $\sim 10^4$ Gy and is four times higher in the compact design. As was already stressed in Barcelona, the situation worsens rapidly when one gets closer to the beam line where a level of $\sim 4.10^5$ Gy is expected at a rapidity of 3 at a distance of 4 m (and $\sim 1.6 \times 10^6$ Gy for the compact calorimeter). In this angular region, the radiation level increases by $\approx 20$ per unit of rapidity and the forward calorimeter, even if it is retracted as far back as 15 m from the interaction region, will have to stand more than a MGy.

Damage may depend on the type of irradiation e.g. silicon detectors are much more sensitive to low energy protons and neutrons (see 2.6 below). The neutron flux is also large ranging from $10^{14}$ n/cm$^2$ in the barrel region to more than $10^{16}$ n/cm$^2$ in the forward region (Fig. 20). The energy spectrum of these neutrons peaks around 1 MeV. The exact neutron flux depends on the precise calorimeter composition. If uranium is used as absorber, instead of lead, the neutron flux increases by $\approx 2$. If iron is used, the neutron flux decreases by $\approx 2.5$. The presence of hydrogenous materials like scintillators decreases the flux by $\approx 3$.

Under this large irradiation, the calorimeter itself will become radioactive. This is especially true for calorimeters in the forward region where the induced radioactivity will be in the range of
milli Sievert per hour. The materials will have to be carefully chosen to minimize activation, and from this point of view, uranium does not seem to be the best choice. For more details the reader is referred to the report by G. Stevenson at this workshop [19].

![Diagram](image)

Figure 20: Typical doses and neutron fluences in a calorimeter exposed to an integrated luminosity of $10^{42}$ cm$^{-2}$.

2.2 Scintillator Tiles-Wavelength Shifter

The technique of scintillator (SCI) tiles read-out via wavelength shifter (WLS) plates, rods or fibers has been used in numerous sampling calorimeters. After the pioneering work of the AFS Collaboration [20], the ZEUS collaboration [21], through a systematic programme of tests, have optimized this technique as far as energy resolution for hadrons and jets, compensation, calibration and uniformity are concerned. The main achievements are (Fig. 21):

- hadronic energy resolution : $35\% / \sqrt{E}$ with a constant term $<1\%$ and a noise of 180 MeV for a calorimeter volume of $1 \text{ m}^2 \times 7$ interaction lengths,
- an electron energy resolution: $18\% / \sqrt{E}$ with a constant term $<1\%$ and a noise of 8 MeV for towers containing electromagnetic showers,
- $e/h=1$ to within $2\%$ for energies above 2 GeV,
- tower to tower calibration of $\sim 1\%$ using the uranium signal (thus avoiding the need to calibrate in particle beams); a similar number is expected for the absolute energy calibration,
- transverse uniformity for electrons within a tower of $\sim 2\%$, 
- spatial (lateral) uniformity for electrons between modules of \( \approx 5\% \) (for angles between the incident particle and the module boundary above 40 mrad),
- spatial (lateral) uniformity for hadrons \( \approx 2\% \),
- timing accuracy of \( \approx 1 \) ns for signals above a few GeV.

It was mainly through the experimental and theoretical work on U/SCI and Pb/SCI calorimeters, that the present understanding of compensating hadron calorimetry has been reached. As a result detailed experimental data and simulation programs are readily available both of which are very useful for any calorimeter design and optimization.

![Energy Resolution: \( (\sigma/\sqrt{\langle E \rangle}) \cdot \sqrt{E_{\text{beam}}} \)](image)

![e/h ratio](image)

Figure 21 ZEUS prototype calorimeter: a) energy resolution for electrons and hadrons, and b) the e/h ratio.

The strength of this technique lies in the excellent energy resolution for hadrons, in particular at high energies, that can be achieved if the correct material thicknesses are chosen, the low energy equivalent of the noise and the vast amount of experience. If uranium is used, its radioactivity provides an excellent calibration signal. The problem of the uniformity of response between the modules has been solved by placing lead absorbers between the modules. These absorb some of the shower energy to counterbalance the Cerenkov light produced in the WLS’s. The use of plastic SCI and photomultipliers results in fast signals with a typical decay time constant of \( \approx 10 \) ns. There is an additional tail arising from the time taken for the neutrons to be moderated in the SCI. These are the neutrons that provide the necessary "nuclear signal" to achieve compensation. This signal is also fast and has essentially died out after 40ns. Such integration times however are required for perfect compensation. For a discussion of the time dependence of the signal we refer to [22]. Given the fast pulses and the low noise, timing resolution below 1 ns can be achieved. Thus an assignment of a signal to the proper bunch crossing is relatively easy, as is the detection of off-bunch pileup.

The drawbacks of compensating calorimeters readout via SCI tiles and WLS are:
- the limited electromagnetic energy resolution,
- the limited segmentation, both longitudinally and transversely and

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- the difficulty in achieving projective geometry.

Experience in ZEUS suggests that a transverse segmentation better than 5cm x 20cm (with readout on two sides over the 20cm) will be difficult to achieve. This can be partially compensated for by the installation of finely segmented position detectors in the front part of the electromagnetic section (e.g. ZEUS use silicon pads [23]). By placing these detector planes, having a segmentation of 10 square centimeters, at a depth of 3 and 6 radiation lengths, they achieve a hadron rejection of ≥200 for an electron efficiency of 90% for particle energies ≥ 10 GeV. Their segmentation is too coarse to achieve a position resolution beyond the pad size. A finer segmentation can clearly result in an improved hadron rejection, a more precise determination of the shower position and the angle of photons and a better separation of nearby showers.

To improve the segmentation, SCI both liquid and solid, can be readout using WLS-fibers. This has been done by several groups in the past (e.g. MPI-Munich, UA1-tests, ZEUS-tests [24 a,b,c] respectively), and was again presented at this workshop [25]. It is also one of the options for calorimetry in the SSC detectors. Progress has been made at Serpukhov by embedding the WLS-fibers into plastic SCI at the SCI production step via injection molding and by developing a technique of efficient and reproducible coupling of WLS-fibres to clear fibres. However no new experimental results on the uniformity, which has been one of the reasons why this technique has not been used in large experiments, have been shown. Another difficulty of this design is the enormous number of fragile fibers which have to be handled.

For an LHC calorimeter the radiation damage of SCI and WLS is the major concern. ZEUS have made a detailed investigation of the radiation sensitivity of their SCI (SCSN-38) and WLS (Y7 dissolved in PMMA) [26]. Both materials show a very strong reduction in attenuation length immediately after irradiation at a high dose rate (above 100 Gy/h). In the presence of oxygen (e.g. air), the material recovers within days for SCSN-38 and ~ 1 year for Y7-PMMA with some sign of permanent damage. In an experiment an equilibrium of damage and recovery close to the level of the permanent damage will be reached. Radiation damage also causes a decrease of the local light yield of about 4% / kGy in both air and nitrogen. Taking as a criterion that an acceptable dose only results in:

i) a deterioration of ≤±2% in the uniformity (lateral) of response over a cell size of 20 cm read out from two opposite sides,

ii) a longitudinal uniformity for the WLS's of ≤±5% in the electromagnetic section of a depth of 25cm and

iii) a longitudinal uniformity of ≤±10% in the hadronic section of a depth of 60cm

A calorimeter like the one of ZEUS could work up to integrated doses of ~10-20 kGy. From the recent progress in radiation resistance of SCI-fibers [27] one can expect an improvement of a factor ten in radiation resistance over the next few years. Thus it may be possible to use this technique up to a rapidity of about 2.5 at the LHC.

Compensation requires a SCI/U volume ratio of about 0.82. This volume ratio is ~ 0.25 for SCI/Pb. This requires thin SCI plates, especially for Pb, in order to achieve an electromagnetic resolution of 15% / √E or below. This results in a light yield which is marginal if
photomultipliers are used as these typically have quantum efficiencies of ~15%. An improvement in the light yield (e.g., optical cladding of SCI or WLS to improve the light transport, more efficient SCI or more efficient photodetectors etc) would be very desirable.

Photomultipliers (PMs) are normally used to read out compensating SCI/WLS calorimeters as solid state photodiodes are too noisy given the small light yield (~200-500 photoelectrons/GeV for PMs). It appears that the gain and resolution of PM's with synthetic quartz windows is not affected by doses up to $4 \times 10^5$ Gy and $4 \times 10^{14}$ n/cm² [28]. PMs with linear dynode chains have a typical lifespan of 500 to 1000 C of charge seen by the anode, and thus will have to work at low gain at the LHC. Another reason to work at low gain is the dependence of the gain on the anode current (typically 0.5% / μA). PM's may have the required dynamic range for experimentation at the LHC as ZEUS already use signals from 1 to 80,000 photoelectrons. The gain of PM's, even of the mesh type, is affected by magnetic fields, and different photodetectors would have to be developed if the calorimeter is required to work in a strong magnetic field. The light yield of plastic scintillators also depends on the magnetic field.

G. Stevenson [19] has pointed out that the use of uranium as the absorber in a LHC calorimeter is very undesirable because of the increased neutron production and the secondary activation - this has to be checked quantitatively. However without uranium radioactivity it may be difficult to achieve the ≤ 1% calibration accuracy for an optical detector in the LHC environment. Secondary activation in the high radiation field at LHC also rules out the use of the uranium radioactivity as a long term calibration method. Thus lead may be a more suitable absorber material.

Large calorimeters based on SCI tiles have already been built and an extension to the dimensions required at the LHC appears reasonable, but no work towards this goal has yet been done. The difficulty in realizing a projective geometry should be kept in mind. Because of the coarse segmentation and energy resolution, this type of calorimeter does not fulfill the requirements of electromagnetic calorimetry at the LHC. It may offer an attractive and economic solution for a compensating hadron calorimeter following a high resolution electromagnetic calorimeter. However there are a number of problems that have to be resolved before an LHC calorimeter can be built. At present the necessary R&D is not being pursued.

### 2.3 Scintillating Fibers

To overcome the drawbacks of the SCI-WLS technique while retaining its advantages, calorimeters using scintillating fibers are being developed. The most impressive results so far have been shown by the SPACAL collaboration [29]. They use 1 mm diameter SCSN-38 plastic fibres, embedded in a Pb-matrix, which run at a small angle with respect to the direction of the incident particles. The SCI/Pb volume ratio is chosen to be 0.25 to achieve compensation. This results in a very dense calorimeter having a short radiation (0.75cm) and interaction (21cm) lengths. A fine lateral granularity and an excellent uniformity of response can be achieved without the introduction of dead spaces. Given the small intrinsic fluctuations
of about 12% $\sqrt{E}$ for a compensating SCI-Pb calorimeter [30], a hadronic energy resolution of $-30%/\sqrt{E} + \leq 1\%$ is expected and an electromagnetic energy resolution of $\sim 13% / \sqrt{E} + 1\%$ has been measured. The SPACAL group has addressed most of the problems e.g. fiber to fiber uniformity, uniformity along the fiber, optical readout, embedding of the fibers into the lead matrix, radiation damage etc. and have built a series of prototype calorimeters, the largest one with a diameter of 1 m and a depth of 10 interaction lengths. The progress and the results obtained in a recent beam test are impressive (Fig. 22):

- energy resolution for electrons of $13% /\sqrt{E} + 1\%$ for incidence angles greater than 50 mrad (at lower incidence angles a non-Gaussian tail towards higher pulse heights develops due to the channeling of particles in the fibers),
- position resolution for electrons of 1.8 mm at 80 GeV for a readout segmentation of 48.7 cm$^2$,
- uniformity of response to electrons of 1% even over tower boundaries,
- $e/\pi$ measured to be $\sim 1.05$,
- hadronic energy resolution of $30% /\sqrt{E} + 2.6\%$, with a small non-Gaussian tail towards higher pulse heights,
- hadron jet resolution better than the hadronic energy resolution, measured by using interactions in a CH target placed in front of the calorimeter,
- position resolution for hadrons of 5.0 mm at 150 GeV for a readout segmentation of 48.7 cm$^2$,
- a fast pulse shape. After unfolding the effect of the cable a FWHM of 4 ns for electrons and 6.4 ns for hadrons, with a tail of 10 ns time constant from the moderation of the neutrons is observed [11].
- hadron (isolated) rejection of 800 at 99% electron efficiency from the analysis of pulse shape.

In addition the group has presented results on the time dependence of $e/\pi$ and on the influence of the transverse containment on the hadronic energy resolution.

Work is in progress to understand and improve the hadronic energy resolution, where the optimum value has not yet been achieved. The main difficulty is due to the remaining longitudinal non-uniformity of the fibers. The response increases by about 30% in the last 30 cm near the readout device. This results in the non-Gaussian tail in the hadronic energy resolution for the showers that develop late (Fig. 22 a). If these showers can be identified, a correction can be applied and the hadronic energy resolution at 150 GeV improves from 4.8% to 3.7%. This effect is significantly reduced for jets, which are typically one interaction length shorter than single hadron showers of the same energy and also exhibit smaller longitudinal fluctuations.

The longitudinal non-uniformity of the readout also reduces the measured $e/\pi$ ratio. It is estimated that the corrected $e/\pi$ should be about 1.1 for the present prototype. The hadron response is about 10% smaller than expected, presumably due to the proton recoil energy lost in the cladding of the fibers.
Figure 22: SPACAL test: Energy response for 150 GeV/c pions and uniformity scan for 80 GeV/c electrons at modules boundaries.

Again it is the radiation damage of the SCI fibres which is the major worry for an LHC detector. This is particularly difficult because of the length of the fibers and the sensitivity of the response to longitudinal non-uniformities. The non-uniform distribution of the radiation dose (maximum in the electromagnetic section) eases the problem somewhat as has been shown by a Monte Carlo study by the SPACAL group [27]. A major R&D effort on the evaluation and improvement of radiation resistance of plastic scintillation fibers by several groups has already shown encouraging results. For details we refer to the working group on radiation damage. Results on new fiber compositions (e.g. 3HF doped with PTP) have been shown. 38cm long fibres have been irradiated up to 220kGy and the maximum light losses have not exceeded 50%. It is hoped that eventually radiation hardness up to 100 kGy can be achieved, so that the coverage up to rapidities of 2.5 could be reached at the LHC.

Calibration at the 1% level is very difficult particularly for techniques using optical readout. No new ideas on how this can be achieved have been presented at this meeting. It is felt that a systematic R&D on this question is required before building an LHC calorimeter.

Present prototypes are read out with PM’s and the comments made in section 2.2 apply. To fully exploit the high transverse granularity a more segmented photodetector is desirable. The quite old idea of the hybrid vacuum photomultiplier (photocathode, a high drift field with about 10kV potential difference and a silicon detector to detect the accelerated electrons) has been revived and prototype samples have been produced by industry though no quantitative results have yet been shown. As this readout technique (assuming it will stand the radiation dose at the back of the calorimeter) is very promising for other applications as well, its R&D should be pursued.
There was a lot of discussion about the need for longitudinal segmentation. In the design of a projective calorimeter of the SPACAL type some longitudinal segmentation is achievable as only a fraction of the fibers will start at the front face. Thus grouping of the readout will give some longitudinal information. The extent to which electrons can be identified and measured in the midst of jet fragments at high luminosities with the SPACAL segmentation is under study.

First sketches of a projective SPACAL calorimeter for the LHC have been shown. A possible layout can also be found in the expression of interest of the Texas SSC detector. So far no practical solution for the construction of a self supporting Pb/fiber structure has been presented and R&D work should focus on this issue. The manufacture of the enormous number of fibers within strict quality criteria needs a major breakthrough in the production and the quality control techniques to make such a calorimeter affordable.

To summarize, compensating fiber calorimeters are good candidates for high resolution hadronic calorimeters at the LHC, in particular in a limited central rapidity range. There is however a number of difficult questions to be solved before a LHC calorimeter can be built.

2.4 Liquid Argon

Major progress has recently been made in the field of liquid argon sampling calorimetry in spite of it being a mature technique and in use for many years.

- The H1 collaboration has built a hermetic electron/hadron calorimeter with a large solid angle coverage for HERA and have shown that given a fine longitudinal granularity weighting methods can achieve a hadronic energy resolution of $44\% / \sqrt{E} \oplus 1\%$. Even better energy resolution and a linearity within 0.5% are achieved for jets [31] (Fig.23),
- the Helios collaboration at CERN has operated a liquid argon uranium calorimeter with a peaking time of $\sim150$ ns, with preamplifiers immersed in the liquid,
- a new readout geometry, named the "accordion" (Fig 24), has been designed and recently tested at CERN leading to a realistic hope of achieving peaking times around 40 ns with an electronic noise level equivalent to $\sim200$ MeV for electromagnetic showers [32].

In addition, the known strengths of liquid argon sampling calorimeters are:
- temporal stability and calibration,
- (probable) radiation resistance up to doses of more than 100kGy (limited by the readout electronics),
- readout uniformity,
- flexible granularity, making possible the construction of calorimeters with good spatial resolution, electron/hadron separation etc...,
- possibility of achieving an electromagnetic energy resolution of $8\% / \sqrt{E}$ with a constant term below 1%,
- insensitivity to magnetic field.
The main difficulties of this technique are:

- the speed of the charge collection and the charge transfer to the electronics,
- moderate hadronic resolution of $50\% / \sqrt{E} + 3\%$, unless a weighting technique is used,
- the need for a cryostat, which makes a hermetic design difficult, and which introduces about $0.5 - 1.0$ radiation length of material in front of the active part of the calorimeter.

For a description of the accordion layout we refer to [32]. To avoid channeling absorber plates and readout gaps are shaped as in an accordion (Fig.24). The readout boards are made from multilayer Kapton foils with resistive coating, thus already including the blocking capacitors. The preamplifiers are directly connected to the Kapton boards, thus minimizing the capacitance and the inductance. This results in about a factor of five reduction in the capacitance per unit volume compared to the already optimized Helios layout. The preamplifiers are immersed directly into liquid argon. A prototype that can contain high energy electromagnetic showers has been built with a total of $16 \times 15$ cells of dimensions of $2.5 \text{ cm} \times 2.7 \text{ cm}$ each. There are two longitudinal readout segments, with the amplifiers placed at the front (for the first sampling) and at the rear (second sampling) of the calorimeter. Si J-FET's and GaAs MESFET's were used, together with the Helios shapers having a peaking time of 140ns. The main results (preliminary) obtained so far are:

- a noise equivalent to $\sim 25 \text{ MeV}$ for towers containing a high energy electromagnetic shower, with negligible coherent pickup,
- an electromagnetic energy resolution of $10\% / \sqrt{E} + (0.03\pm0.05)\%$,
- lateral uniformity of response within $1\%$. 
- linearity of response within 1%,
- position resolution of ~ 0.5mm in both the directions for 125 GeV electron showers,
- measurement of the shower direction with a precision of ~ 7 mrad at 100 GeV.

Figure 24: A 40 GeV electron showering in a lead liquid argon accordion structure. The lead absorber plates run at ± 45° to the particle direction thus avoiding channelling. Preamplifiers are located at the front and at the back of the calorimeter, minimizing the connection capacitances.

Further beam tests are planned for spring 1991 using electronics with a peaking time of 40 ns. As a next step towards an LHC calorimeter the following R&D has started:

- design to be followed by the construction of the electromagnetic and the hadronic calorimeter modules with a pointing geometry,
- optimization of the performance by detailed simulation,
- development of appropriate front end electronics,
- development of radiation hard components,
- radiation hardness tests.

For the hadronic sections, where the segmentation will be much coarser (e.g. 20 cm x 20 cm) than in the electromagnetic ones, readout pads will be connected in series to improve the impedance matching to the front end electronics. This will result in approximately the same capacitance (400pF) per readout channel as in the electromagnetic part. A detailed simulation study (cross checked with an electrostatic model) indicates that no significant degradation of the energy and position resolution of jets is induced by the effect of de-localisation of charge inherent in such a scheme [33].

Low electron drift velocity and limited hadron energy resolution are drawbacks of this technique. The impact of the low drift velocity on pileup can be minimized by bipolar shaping. So far excellent hadronic energy resolution, at high energies, has only been achieved via software compensation. One idea to improve the e/h is to reduce the electromagnetic response by cladding a high Z (e.g. Pb) absorber material with a low Z material (e.g. Fe) to stop the low energy electrons penetrating into the active part of the calorimeter. This is presently under study, but from the experience of the ZEUS group, who have a foil of 0.4 mm of Fe separating the U absorber and the plastic scintillator, the maximum reduction of e/mip is only about 4% and thus not sufficient to achieve compensation.

Dopants may be used to increase the signal from heavily ionizing particles and possibly increase the electron drift velocity at the same time. One of the difficulties of doping will be to achieve both a stable calibration and radiation hardness.
Several groups have studied the addition of methane which, in a concentration of about 0.5%,
doubles the electron drift velocity in liquid argon. At the same time the recoil protons, from
neutron interactions, may boost the hadron signal. Experimental studies by Helios and others
observe the increase in speed, but also observe a worsening of the e/h ratio from 1.1 to 1.15 at
100 GeV, due to the increased charge saturation for highly ionizing particles.

The e/h ratio may be improved by using a photoionizing additive to transform the UV
scintillation light from LAr, which shows no ionization saturation, into charge. As LAr emits
two components with time constants of 6 ns and 1000 ns, the slow component has first to be
quenched. This can be done with 125 ppm LXe, resulting in a decay constant of 65 ns, or by
LN$_2$ leading to a decay constant of 5.6 ns. There are many candidates for photosensitive
dopants, e.g. allene (C$_3$H$_4$) with a concentration of a few tens of pps. There are several
encouraging lab results and a systematic R&D to investigate the above questions has been
started at CERN [34]. It should give first results on performance and also radiation sensitivity
during the next year.

To summarize, LAr appears to be one of the prime candidates for use at the LHC with a
possibility of providing a large rapidity coverage. A vigorous and systematic R&D program is
under way in Europe and elsewhere.

2.5 Room Temperature Liquids

Calorimeters using room temperature liquids [35] attempt to improve on the following
drawbacks of liquid Argon:

- slow drift speed,
- limited hadronic energy resolution,
- need of a cryostat.

So far the use of room temperature liquid calorimeters is limited. The two liquids used so far
are TMSi and TMP. The UA1 collaboration has built and tested a U-TMP calorimeter with a
depth of 2.35 interaction lengths followed by a Fe-SCI backing calorimeter [14]. The uranium
calorimeter consists of an electromagnetic part made out of 2 mm U-plates, split into 4
longitudinal samplings, and a hadronic one made out of 5 mm U plates and split into two
sections. A position detector (filled with TMP) is placed at 3.5 radiation lengths. The TMP is
contained in stainless steel boxes of a thickness of 3.3 mm. At a field of 12 kV/cm the charge
collection time is ~ 300 ns. A 1μs shaping time is used and the equivalent noise is ~ 100 MeV
for a high energy electromagnetic shower and ~ 1 GeV for hadron showers. The measured
resolution for electrons is 12% / √E Θ ≤1%. For hadrons it is 58% / √E Θ 6.8% (Fig.25).
The method used to extract the e/π ratio, quoted to be about 1.05, introduces some effective
weighting. The tower to tower uniformity is better than 1%. The frames of the ionization
chambers are made from stainless steel bars of a width of 3 mm resulting in a drop of ~60% in
the electron response where the two ionization chambers meet. No change in the free electron
lifetime in a prototype electromagnetic calorimeter, initially measured to be \( \sim 15\mu s \), has been observed over the last 4 years. Lifetimes of several hundred \( \mu s \) are routinely achieved in the purification but only a lower limit of \( \sim 30\mu s \) can be obtained for the liquid in the ionization chambers. The position detector (PD), which consists of strips with a pitch of 9.1 mm, achieves a position resolution of \( \leq 1 \) mm for electrons with an energy \( \geq 30 \) GeV. A hadron rejection factor of \( \sim 10,000 \) is achieved using the full lateral and longitudinal segmentation of the calorimeter and the position detector for an electron efficiency of 90%.

![Energy resolution for electrons and hadrons](image)

Figure 25: UA1 uranium-TMP test: energy resolution for electrons and hadrons.

The WALIC Collaboration is also conducting tests using TMP [36]. They are building a modular calorimeter consisting of 70 planes (60 x 60 cm²) of TMP filled ionization chambers of a construction similar to the ones used by UA1. These can be interleaved with absorber plates made out of different materials. First tests were done at FNAL this summer using 34 TMP chambers. An energy resolution for electrons of \( 18\% / \sqrt{E} \) with a constant term of 2.7%, attributed to the beam momentum uncertainty, has been measured using absorber plates of a thickness of 6.35 mm of Pb. The electronics noise was \( \sim 150 \) MeV. For the hadronic setup, only shower profiles have been shown.

An ITEP/Karlsruhe collaboration [37] is preparing a modular test calorimeter with 100 TMSi chambers and U, Pb, Cu and Fe as absorbers. Presently 40 planes are available and measurements done at ITEP using a single plane placed at different positions in the calorimeter for various absorber combinations have been presented.

As a result of the above systematic test program the calorimetric properties like \( e/h \), hadronic energy resolution, intrinsic fluctuations etc of TMSi and TMP in conjunction with different absorbers should be known soon.

An issue for discussion is whether it is preferable to use room temperature liquids in chambers or to immerse the absorber in the liquid. So far the sealed chamber solutions presented have significant wall thicknesses, resulting in non-uniformities for electrons which are unacceptable for precision calorimetry. An interesting concept [38] uses a welded structure made from the
plastic VECTRA, with metallized electrodes deposited onto the plastic, with thin detection gaps through which the liquid can flow. The absorber pieces are introduced into the VECTRA drawers. The entire structure can probably be baked out before filling. No results have yet been presented.

A study of the compatibility of different materials (W, Ti, Pb, Cu, glue, Kapton) and TMSi, as far as the electron lifetime is concerned has been presented [38]. It concludes that the materials that do not contain electronegative substances are usually compatible with the room temperature liquids if properly cleaned.

The performance of room temperature liquids under irradiation is one of the major concerns for use at the LHC. Under irradiation radicals are formed, which then interact with the liquid or themselves to produce new compounds. At a dose of 100 kGy typically 1% of the liquid will be destroyed. This can lead to a very large pressure increase and to a reduction in the electron lifetime. In addition positively charged heavy compounds may form insulating layers. Very little is known and a systematic R&D on pressure buildup, life time and analysis of the radiolysis products is planned at CERN. Equally important is the study of the radiation hardness and possible influence under irradiation of the materials in contact with the liquids.

In order to reach collection times comparable to the 15 ns bunch crossing time, much higher field strengths or the use of liquids like TMSi, which is about three times faster than TMP, have to be used provided the safety aspects can be handled. Substantial R&D work on this topic has been proposed [39]. Work is also going on to reduce the time required to transfer the charge to the electronics. As in the case of liquid argon the electrostatic transformer concept (serial connection of the readout gaps) and front end transistors directly mounted onto the electrodes are under study.

To summarize, room temperature liquids are an interesting option for LHC calorimeters. So far it is not yet a mature technology, and a large R&D effort is required to answer all the questions needed before a decision can be made on its suitability at the LHC.

2.6 Silicon Calorimeters

So far the use of silicon diode ionization detectors as a sampling medium in calorimeters has been limited to very specific tasks, like measurement of the luminosity at LEP, the forward plug calorimeter of the H1 experiment or as sampling planes to discriminate hadrons from electrons in the ZEUS calorimeter. There are however several R&D programs underway for electromagnetic and hadronic calorimetry, which have already produced significant results [40].

Potentially silicon as the detecting medium in a sampling calorimeter has the following advantages:
- high speed with charge collection times below 20 ns,
- ease of calibration,
- linearity over a very wide energy range,
- high longitudinal and transverse segmentation,
- compactness, with a typical sampling layer of 0.4 mm,
- insensitivity to magnetic fields,
- room temperature and modest operating voltage (100V).

This should be contrasted to the (present) difficulties:
- lack of radiation hardness,
- high cost of the detectors,
- large number of costly readout channels, if the speed and segmentation offered by silicon is to be properly exploited,
- no large scale experience in experiments,
- no detailed knowledge of the performance for hadron calorimeters,
- uncertainty in simulation due to the small sampling fraction.

The energy resolution for electromagnetic calorimeters using silicon is similar to other sampling calorimeters: 18% / √E for one radiation length sampling with a negligible constant term. The work by the SICAPO collaboration and by a Hamburg/ITEP collaboration shows that the e/mip (mip = minimum ionizing particle) sampling fraction ratio can be tuned by putting low Z materials like G10 or Fe between the high Z absorber (Pb,U) and the Si detectors. Thus low energy electrons, abundantly produced in the high Z absorber due to the strong Z dependence of photo- and Compton-effect, do not reach the detectors. In this way e/mip can be tuned to lie between 0.9 and 0.6. Highly ionizing particles show no pulse height saturation. It thus appears possible to achieve e/h=1. This has been shown by the SICAPO collaboration using 25mm U plates separated by 2mm of G10 from the silicon detectors. Even if compensation is achieved, the expected intrinsic resolution is however worse than the one measured for Pb or U-scintillator calorimeters. This is under study by the SICAPO collaboration, but no data have yet been presented.

Detailed information on the transverse and longitudinal shape of hadron showers has been measured by SICAPO and also by ITEP/Hamburg group. This is used to tune the simulation programs.

The radiation damage of the silicon detectors is under study by several groups. Three effects are important [41]:
- increase in leakage current,
- loss of collected charge,
- change of bulk resistivity.

The damage constants, taking into account the benefits of self-annealing, for the increase in the leakage currents for neutron, hadron and electron irradiation are now well known. Typical values for a thickness of 300 µm are:
- 10 µA/cm² per 10¹³ n/cm² for neutrons of 1.2 MeV,
- 10 µA/cm² per 10 kGy for protons of 21 MeV,
- 10 µA/cm² per 5 MGy for electrons of 2 MeV.
The neutron damage is the most serious. Higher neutron energies cause a damage that is larger by about a factor of two. As the leakage current decreases by about a factor of two for every 8-10°C drop in temperature, cooling the detector may solve this problem.

The charge collection for detectors irradiated with neutrons has been measured separately for electrons and holes. For a flux of $2.4 \times 10^{12}$ n/cm$^2$ of 5 MeV typical losses are 1.1% for a 50ns shaping. Self annealing reduces this loss by a factor two in 152 days. Further work on this question, in particular the extension to higher fluxes and the effects of temperature has to be done before firm conclusions can be drawn.

Irradiation with neutrons leads to an increase in bulk resistivity and finally to an inversion from n- to p-type at fluxes around $10^{13}$ n/cm$^2$. This has been clearly demonstrated by the Hamburg group. Nevertheless the detectors continued to work without any additional current contribution from the rectifying junction. Apparently the metallisation of the back contact acts as new barrier. More work, including the temperature behaviour is needed.

Significant progress has been achieved on the characterisation of the defects using the DLTS-method. This work leads to a detailed understanding of the damage problems and may give clues how, eg. via specific impurities diffused into the crystals, radiation hard detectors could be built. This interesting possibility will certainly require a lot of development effort and time, and may come too late for the LHC but given its importance, also for other silicon devices like photodiodes, a very strong R&D effort should be supported.

To summarize, silicon detectors for LHC calorimetry, in spite of the many attractive features, have many open questions, and it appears improbable that they will be solved in time for a first generation LHC detector.

### 2.7 Homogeneous Electromagnetic Calorimeters

The often quoted reason for requiring very high electromagnetic energy resolution is the detection of the Higgs boson in the mass range $80 \leq M_H \leq 150$ GeV/c$^2$ through its two photon decay mode. As mentioned earlier (sections 1.4.2, 1.6.2), in order to be confident of detecting the Higgs boson at the LHC, in the mass range $80 \leq M_H \leq 130$ GeV/c$^2$, some further severe constraints are put on high energy resolution calorimeters. These are:

- minimum constant term in the energy resolution. For the above mentioned process a constant term of 0.5% is equivalent to a term $\sim 3-4% / \sqrt{E}$.
- separation of two photons with an angular separation $\geq 5$ mrad.
- measurement of the direction of the photons to within $\sim 5$ mrad.

Homogeneous calorimeters are good candidates to achieve high energy resolution. Such calorimeters cannot be placed very close to the interaction point as explained in 1.4.2. Media with smaller Molière radii can be brought closer but the two photon separation will become correspondingly more difficult. A realistic simulation must be carried out to fix the optimal radius for a given material.
With these conditions in mind we proceed to consider some candidates for very high energy resolution electromagnetic calorimetry.

2.8 Crystals

Several large scale crystal calorimeters have been built in the past eg. Crystal Ball using NaI(Tl), CLEO and Crystal Barrel using CsI(Tl) and L3 using BGO. These have provided valuable working experience of the problems of light collection non-uniformity, monitoring and inter-calibration of crystals together with those related to the mechanical structures. A very high energy resolution of $\sigma/E \sim 2\% / \sqrt{E} \oplus 0.5\%$ has been achieved for a large number of BGO crystals in a test beam. This has yet to be achieved in the running experiment where the resolution for electrons from Bhabha events is presently $\sim 1.3\%$. This is thought to be due to an uncertainty in the knowledge of the temperature of the crystals indicating the difficulty of achieving small constant terms in large scale structures.

Several crystals fulfill many of the requirements for use at LHC (Table. 2):
- high speed with very short decay constants for the scintillation light,
- very good energy resolution,
- large light yield,
- high transverse segmentation,
- short radiation length and Molière radius,
- room temperature operation.

This should be contrasted with difficulties:
- possible lack of radiation hardness of large crystals,
- non-uniformity of light collection,
- high cost of crystals and their readout,
- existence of long decay constants for a major fraction of the light in some cases,
- temperature dependence of the light output in some cases,
- difficulty in obtaining longitudinal segmentation and good two gamma separation,
- possible mechanical brittleness and hygroscopicity,
- problem of readout in a magnetic field if amplification is required in the photo-device.

Radiation hardness tests of crystals are usually made on small samples (~ few cm$^3$) and with $\gamma$ or $\beta$ sources. The intrinsic scintillation process does not appear to be affected even up to doses of $10^7$ Gy. However reduced transmission is observed due to the formation of colour centres. This is thought to be due to impurity atoms which are embedded in the crystal lattice. Long crystals are required for good energy resolution but the impurity levels in long crystals increase with increasing depth due to the manufacturing process. Hence long crystals tend to have less uniform light output, attenuation length and are more prone to radiation damage. Use of pure meltstocks seems to improve the radiation hardness. It appears that the impurities have to be controlled at a level of ppb instead of ppm levels presently used. Clearly it is desirable to
<table>
<thead>
<tr>
<th></th>
<th>NaI</th>
<th>BGO</th>
<th>BaF₂</th>
<th>CsI</th>
<th>CeF₃</th>
<th>PbF₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>3.67</td>
<td>7.1</td>
<td>4.89</td>
<td>4.51</td>
<td>6.16</td>
<td>7.77</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>2.59</td>
<td>1.12</td>
<td>2.05</td>
<td>1.86</td>
<td>1.7</td>
<td>0.93</td>
</tr>
<tr>
<td>Molière Radius (cm)</td>
<td>4.4</td>
<td>2.7</td>
<td>4.3</td>
<td>3.8</td>
<td>2.6</td>
<td>1.8*</td>
</tr>
<tr>
<td>Photons/Mev (k)</td>
<td>40</td>
<td>8</td>
<td>10</td>
<td>18</td>
<td>4</td>
<td>CV</td>
</tr>
<tr>
<td>% light in fast component</td>
<td>-</td>
<td>-</td>
<td>23</td>
<td>30</td>
<td>100</td>
<td>CV</td>
</tr>
<tr>
<td>Decay Const. Fast (ns)</td>
<td>-</td>
<td>-</td>
<td>0.6</td>
<td>10.36</td>
<td>5.30</td>
<td>CV</td>
</tr>
<tr>
<td>Slow (ns)</td>
<td>230</td>
<td>300</td>
<td>620</td>
<td>1000</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>λ peak (nm) Fast</td>
<td>-</td>
<td>-</td>
<td>220</td>
<td>305</td>
<td>310,340</td>
<td>CV</td>
</tr>
<tr>
<td>Slow</td>
<td>410</td>
<td>480</td>
<td>310</td>
<td>same</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ΔL/ΔT at 20°C (%/°C)</td>
<td>-</td>
<td>-1.55</td>
<td>**</td>
<td>-1.5</td>
<td>+0.08</td>
<td></td>
</tr>
<tr>
<td>Radiation Damage* (kGy)</td>
<td>1</td>
<td>1</td>
<td>100</td>
<td>10</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>Cost : SFr / (RM² x X₀)</td>
<td>120</td>
<td>60</td>
<td>120</td>
<td>50</td>
<td>-</td>
<td>10</td>
</tr>
</tbody>
</table>

CV* - Cerenkov radiator
* "apparent" Molière radius
** the slow component shows a variation of ΔL/ΔT = -2.4 % /°C.
* see discussion below

Table 2: Properties of crystals.

identify and eliminate the impurities that lead to damage eg. Pb in BaF₂. Another possibility to improve the radiation hardness is to dope the crystals with elements that allow de-excitation of the trapping centres eg. Eu in BGO. Generally recovery takes place in most crystals with improvements seen over times ranging from hours to days. This may be undesirable as the calibration would then depend on the running conditions. More work on the radiation damage of full size crystals is clearly required.

For use at the LHC, in addition to other undesirable properties, NaI and BGO are sensitive to radiation damage at relatively low doses (~ 1000 Gy). Small samples of BaF₂ have been shown to be radiation resistant up to photon doses of 10⁵ Gy. Recent measurements [42] on the radiation resistance of CeF₃ show a loss of only ~ 5 (33) % in transmission for doses of ~ 10⁴ (5 10⁵) Gy. Samples of a size of ~ 1 cm² x 8 cm were used. Undoped CsI crystals of a diameter and length of 2.54 cm have recently been irradiated using γ's from ⁶⁰Co [43]. The absorption coefficient increased by 0.05 / cm for a dose of 1.5·10⁴ Gy. The levels of radiation damage given here are those at the wavelength of emission of the fast component. It is believed that with further work the radiation resistance of most crystals can be improved. Both BaF₂ and CeF₃ appear to be able to operate at 10⁴ Gy/year.

The slow component of BaF₂, accounting for ~80% of the total emission, has not only a decay constant of 600 ns but also a strong temperature dependence. Hence it has to be strongly suppressed. It can be filtered out by using a "solar blind" CsTe photocathode as the peak emission wavelengths of the fast and slow components are different. A fast / slow intensity ratio of ~ 1 can be achieved as can be seen from Table 3 [44]. These have been measured using 20 ns and 1 μs gates with the corrections applied for the additional slow component outside the 1 μs gate. The slow component can also be suppressed by doping BaF₂ with a small amount of
lanthanum (Table 3). Hamamatsu have recently developed a K-Cs-Te photocathode which has a sharper cutoff against the slow component [45]. The relative quantum efficiency curves of the two photocathodes as a function of wavelength indicate that a fast to slow ratio of 1:0.1 can be achieved with K-Cs-Te. Doping may then become unnecessary. Most of the light in the fast component is sacrificed in the suppression of the slow component. A photoelectron yield from the fast component of ≥ 50 p.e./MeV is expected using the K-Cs-Te photocathode. Vacuum photodiodes with quartz windows are proposed for the readout though some gain may be necessary. Even further suppression of the slow component is required and is obtained by pulse shaping. The readout of BaF₂ with such a technique is non-trivial and will be expensive.

<table>
<thead>
<tr>
<th>Photocathode Sample</th>
<th>Bialkali</th>
<th>CsTe</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fast</td>
<td>Slow</td>
</tr>
<tr>
<td>BaF₂</td>
<td>1.00</td>
<td>6.20</td>
</tr>
<tr>
<td>BaF₂ : La (1%)</td>
<td>0.76</td>
<td>1.52</td>
</tr>
<tr>
<td>BaF₂ : La (20%)</td>
<td>0.48</td>
<td>0.48</td>
</tr>
<tr>
<td>BaF₂ : Tm (1%)</td>
<td>0.77</td>
<td>1.40</td>
</tr>
</tbody>
</table>

Table 3: Slow component suppression in doped BaF₂

Recently a promising readout device for the scintillation light of BaF₂ has been developed. This is based on the parallel plate avalanche chamber, PPAC [46], where a thin film of CsI is deposited, under vacuum, on a metal substrate (Fig. 26). The quantum efficiency can be increased, e.g. from 20% to ~ 30% at 190 nm, by forming an adsorbed layer of TMAE. This also renders the photocathode less sensitive to contact with air. There is practically no sensitivity to the slow component of BaF₂ and hence drastic suppression of the slow component is not required. These chambers can be operated with or without gas gain. Without gain the yield of photo-electrons is small (~10000 p.e.'s/GeV) and the energy equivalent of the electronic noise could be large. Use of high gain leads to a reduced response with irradiation as the ion bombardment gradually destroys the photo-cathode. These aspects are currently being investigated.

---

Figure 26: Schematic of a parallel plate avalanche chamber used to read-out a preshower counter.
The emission wavelengths of the slow and the fast components in undoped CsI overlap significantly [43]. Hence the slow component cannot be reduced by filtering but short decay constants (2 and 20 ns) have recently been measured for light emission from CsI(Br) [47]. The sizeable temperature dependence of the light yield of CsI will require precise temperature monitoring. This is potentially a serious drawback in a large system.

CeF₃, a newly found scintillator [48], has short radiation and Molière lengths, does not have a slow component and shows a very small temperature dependence of the light yield. The absence of the slow component may allow the use of Si photodiodes with the radiation damage of Si kept in mind. CeF₃ is not yet available in large enough quantities and more work, especially on the part of industry, is required before it can be considered for large scale calorimetry.

All the crystals mentioned so far are expensive and the demand for them is driven by HEP. Large volume production will require considerable initial investment. The necessary size of the inner radius may thus may not allow their use in a first generation LHC experiment.

Recently there has been renewed interest in Čerenkov radiators like PbF₂ [49] and KRS-6 [45]. Their very short radiation and Molière lengths coupled with low cost makes them attractive. Recent tests on the radiation damage of PbF₂ showed disappointing results but complete recovery from the effects of a dose of 4.10³ Gy was observed after exposure to UV light for 10 minutes. However permanent damage was observed for a dose of 4.10⁴ Gy. The light yield is usually low and photodevices with gain are necessary. Measurements in PbF₂ yield ~ 1300 photoelectrons / GeV leading to a resolution of ~ 3% / √E. Like CeF₃, PbF₂ is a material still under development by industry. Further investigation is clearly required.

From recent studies of scintillation properties and radiation damage mechanisms in several scintillators [45], it may be possible to "design" a scintillating glass, probably in the fluoride family, with the desirable properties of a short radiation length and a short decay constant but most significantly of all low cost. Tests on small samples of several heavy fluoride glasses have already started and preliminary radiation tests are encouraging. The R&D on these glasses should be vigorously pursued.

In summary, BaF₂ and CeF₃ appear to be able to meet the required performance. CeF₃ due to its shorter radiation and Molière lengths, absence of any slow component and better mechanical properties appears to be more promising but large scale production has still to be established. If a large volume is required then cost and availability may become the dominant selection criterion. New heavy scintillating or Čerenkov emitting glasses may resolve this but much more R&D work is required.

### 2.9 Noble Liquids

Recently the use of noble liquids like xenon (LXe) and krypton (LKr) has evoked a great deal of interest. The energy measurement can be carried out by collecting the ionisation
electrons and/or collecting the scintillation light. The best results for energy resolution with these liquids have been obtained with LKr [50] using charge read-out. An active volume given by a cylinder of diameter of 42 cm and a length of 76 cm led to an r.m.s. energy resolution of 1.7 % for positrons of an energy of 1.2 GeV.

The main advantages of this technique are:
- radiation hardness (probably limited by the hardness of the read-out elements),
- fast signals if scintillation light is used,
- ease of lateral and longitudinal segmentation,
- insensitivity to magnetic fields,
- modest purity is necessary if only the scintillation light is detected,
- yet to be demonstrated possibility of tuning e/π to 1 by exploiting the different decay constants for lightly and heavily ionizing particles.

The drawbacks are:
- cost and availability (for xenon),
- not much experience even at the level of a prototype of a size that can contain high energy electromagnetic showers,
- need for a cryostat leading to material in front of the calorimeter,
- for light readout the non-uniformity of light collection may lead to a sizeable constant term,
- difficulty in obtaining longitudinal segmentation and good two gamma separation if using the light readout only,
- complexity if a combined light and charge readout is used.

The relevant properties of the liquids are listed in Table 3.

<table>
<thead>
<tr>
<th>Property</th>
<th>LAr</th>
<th>LKr</th>
<th>LXe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>1.39</td>
<td>2.45</td>
<td>3.06</td>
</tr>
<tr>
<td>Radiation Length (cm)</td>
<td>14.3</td>
<td>4.76</td>
<td>2.77</td>
</tr>
<tr>
<td>Molière Radius* (cm)</td>
<td>7.3</td>
<td>4.7</td>
<td>4.1</td>
</tr>
<tr>
<td>Photons/MeV (k)</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>% light in fast component</td>
<td>8</td>
<td>1</td>
<td>77</td>
</tr>
<tr>
<td>Decay Const. Fast (ns)</td>
<td>6.5</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Slow (ns)</td>
<td>1100</td>
<td>85</td>
<td>30</td>
</tr>
<tr>
<td>λ peak Fast (nm)</td>
<td>130</td>
<td>150</td>
<td>170</td>
</tr>
<tr>
<td>V_drift (10kV/cm) cm/μs</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>Temperature °K</td>
<td>94</td>
<td>124</td>
<td>160</td>
</tr>
<tr>
<td>Cost : SFr / (R_M² X_0)</td>
<td>-</td>
<td>55</td>
<td>150</td>
</tr>
</tbody>
</table>

* PDG definition

Table 3: Properties of some noble liquids.

Of the noble liquids, LXe has the shortest radiation length, the shortest scintillation decay constant, the highest emission wavelength and the highest temperature. LXe is a scintillator
with a light output which is ~20 times larger than found in the fast component of BaF₂. Although the electron drift velocity in LXe saturates at a relatively low electric fields it is too small for use at the LHC. A factor ~ 6 increase in the drift velocity has been achieved by doping liquid Xe with a small quantity (7.10¹⁹ mols/cm⁻³) of butane [51]. Small drift gaps and short bipolar shaping time may allow a reasonably fast response. The effect of radiation damage to the molecular solutes has still to be investigated.

The light collection method allows, in principle, a fast total energy measurement. The major difficulty here is the point to point uniformity of light collection. The individual calorimeter cells may have to be long, since the radiation length of LXe is fairly large, and narrow as fine granularity is important. Most of the light will thus have to suffer several reflections. Surfaces of high reflectivity to 170nm light are needed. Non-uniformity of light collection has to be minimized as it can lead to a sizeable constant term. Another problem may be the availability of LXe in a sufficiently large quantity. The lower cost and easier availability of LKr makes it an interesting candidate. It may be possible to add a small amount of LXe as a wavelength shifter to shift the light to a higher wavelength but more importantly to shorten the decay time constant.

Though the Molière radius is not much larger than that for LXe, the radiation length is much larger thus aggravating the problem of the uniformity of light collection. A depth of ≥ 120 cm for an electromagnetic calorimeter at the LHC would probably only be acceptable for a dedicated experiment. An energy resolution of ~ 4%/NE is attainable in a sampling mode if ≥ 50% of the shower energy can be deposited in LKr. Increasing this fraction would lead to even better energy resolution.

Two readout schemes are currently being pursued. The first one [52] uses self supporting trapezoidal cells with walls made out of thin (~ few hundreds of μm) UV reflecting Al foils (Fig. 27). The light readout elements are large area UV sensitive Si photodiodes immersed in the liquid. The results obtained so far come from tests using small volumes of LXe. These are:
- a quantum efficiency ~1 for light of a wavelength of 170 nm [53],
- development of fast amplifiers with a peaking time of 10 ns and a dynamic range of ~ 10⁵ [52],
- an energy resolution below 1% for an energy deposit of ~2.65 GeV by 80 MeV/c ⁴⁰Ar ions [52],
- an attenuation length larger than 20cm [53].

![Diagram](image)

Figure 27: A single cell of the scintillating liquid xenon detector, showing 3 photodiodes, UV reflector and cables.
The second scheme [53] combines light and charge read-out and should be able to achieve a better energy resolution and, perhaps more importantly, a smaller constant term as the two measurements are essentially independent. An illustration of a single cell is shown in Fig. 28. Deposited on the side walls is the (CsI+TMAE) photocathode described in the previous section. The photo-electrons, ejected by the scintillation light incident on these walls, are injected into the liquid. A fast signal is induced the moment the electrons leave the surface. The charge from the shower and the photocathode drifts across the gap and is digitized to determine the position of the shower in two dimensions. Excellent two gamma separation and determination of the direction (≤ 1 mrad) is potentially possible. However the low drift velocity means that information from many events and crossings has to be unravelled. It is not yet clear whether such a scheme can work satisfactorily at high luminosities, even with a factor ~ 6 increase in drift velocity from doping. A full simulation has to be carried out. The main experimental results obtained [53] so far are:

- observation of the anti-correlation of light and charge signals previously seen by Doke et al. [54],
- measurement of the photon yield of (30.9 ± 3.0) × 10^3 MeV^{-1},
- a free electron lifetime in excess of ~ 150 µs [55],
- an energy resolution using a charge readout of LAr of Σ ~ 1.2% at 1 GeV.

Photo-electron injection into the liquid from a CsI+TMAE photocathode has still to be demonstrated.

![Schematic of a cell for light and charge readout in liquid xenon [52].](image)

In summary, an energy resolution of ≤ 1% / √E appears to be possible but the smallness of the constant term, with implementation of directional and two shower separation capability, is
probably the real test for such techniques. Large prototypes of both schemes are planned and the results should be available within one to two years. A significant problem may be the availability of LXe in a sufficiently large quantity (LKr is a factor of \( \sim 10 \) more abundant). A quantity of 15 m\(^3\) of LXe can be procured by 1999 at a price of 2.5 M$/m^3 if a sufficient guarantee is given for the production to start in 1991 [52]. It is believed that a quantity of \( \sim 20-40 \) m\(^3\) is required to have confidence of achieving the intended physics goals.

2.10 Front-end Electronics.

A fine granularity (\( \sim 0.02 \times 0.02 \)) over a large geometric acceptance (\( |m| < 3 \)) requires a large number of independent cells (\( \sim 10^5 \)) and an even larger number of electronics channels if the calorimeter is subdivided in depth. The electronics must have a large bandwidth to cope with the 15 ns bunch crossing interval.

Each channel has to span a large dynamic range. The maximum is set by the possible observation of a new heavy vector boson decaying into an electron pair (1.7.1 above). Depending on the exact calorimeter granularity, the maximum energy in a cell will be \( \sim 1-2 \) TeV. The low end is determined by the muon peak (\( \sim 300 \) MeV depending on the calorimeter longitudinal segmentation) and by the calorimeter noise (\( \sim 30 \) MeV depending on the calorimeter technology). The consequent 16 bit dynamic range is large but the same precision is not needed over the whole range. It is sufficient to demand that the readout electronics not deteriorate the intrinsic calorimeter resolution and then a non-linear transfer function can be used [56]. Fig 29 shows, for two typical electromagnetic calorimeter resolutions, that an effective 10 bit dynamic range is adequate. In this example the electronics noise term was assumed to be a factor two lower than the intrinsic resolution term.

![Graph showing two transfer functions for two typical electromagnetic calorimeter resolutions.](image)

**Figure 29:** Optimum transfer function for two typical electromagnetic calorimeter resolutions. An effective 10 bit dynamic covers the whole energy range. In this example, the electronics noise is only half the calorimeter noise.
The temporal shape of the calorimeter pulses has already been discussed. Shaping will make the pulses from various calorimeters, using different techniques, similar and probably bipolar in shape (to minimize the base line shift) though the peaking times may vary from $= 10$ to $50 \text{ ns}$. Some carry additional information eg. the pulse shape from the SPACAL fiber calorimeter allows discrimination of electrons from hadrons. A very fast sampling rate ($= 7 \text{ ns}$) would be needed to exploit this characteristic [11].

The large amount of information from the calorimeter will have to be stored either in an analog [57] or a digital [56] form in a long ($= 1 \mu \text{s}$) pipe-line to wait for the trigger decision [12]. This pipeline device must have the same length for all detector components. It must run synchronously with the machine clock at the same or a multiple of the bunch crossing frequency. It may be worth noting that the experiments at HERA have already the problem of a trigger decision time greater than the bunch crossing time and all the information has to be stored in pipelines. Hence concepts working at 10MHz already exist.

Calorimeters will also have to provide data for the trigger. As the granularity required at the trigger level is much coarser, a summation over several calorimeter cells has to be carried out either in an analog or in a digital form. A fully digital architecture, consisting of non-linear transfer function at the digitization level, trigger summation and pipelining..., spurred stimulating discussions [56]. It was argued that most of the readout problems are similar to the ones that are being addressed by the high definition television industry [12].

To summarize, reading out such a large number of channels at high speed will be a formidable task. The practical consequences eg. the number of cables, power dissipation, electronics layout were not sufficiently studied at this workshop. A lot of the problems eg. length of pipelines, synchronisation etc. are probably common to all detectors and a close coordination will be required. The difficult problem of radiation hardness of the electronics is addressed by the Radiation Hardness Working Group.

3. CONCLUSIONS

The discussion in this paper has been guided by the physics potential of the LHC at luminosities in excess of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. This has resulted in very stringent requirements for the detection of electrons and photons in order to be able to detect the Standard Model Higgs particle if its mass lies in the range $80 \leq M_H \leq 1000 \text{ GeV/c}^2$. In such a scenario the need for a very good hadronic energy resolution was less obvious and will in any case be compromised by pileup energy from minimum bias events. The calorimeter requirements at luminosities an order of magnitude lower than used above, eg. for higher cross-section precision experiments, will certainly lead to different conclusions. This should be studied. The effect of pileup has only been studied roughly. Triggers will select rare combinations of peculiar events and this effect should be studied further.
As far as the individual calorimeter techniques are concerned, none of them is presently at a point where one can state, with reasonable confidence, that it could work at the LHC at luminosities of $10^{34}$ cm$^{-2}$s$^{-1}$ or more. Radiation damage of the calorimeter and its electronics must not be underestimated. The same is true for the implications of the large number of cells required, using electronics with a high bandwidth dissipating power etc. These practicalities have not been studied and may in the end decide the feasibility of a given calorimeter. Techniques suitable for forward calorimetry were not discussed at this workshop. Radiation hardness is the main criteria there. If it is confirmed that coarse calorimetry is good enough, a solution can probably be found.

Given the schedule for the construction of LHC, many participants felt that the time available is probably too short to develop completely new ideas for a first generation LHC detector. Major R&D effort on present, already proven, technologies by well organized and well supported groups is required. Such groups have been and are being formed and some of the questions that have been raised should have answers in the next two years.

Significant progress has been made since the ECFA Workshop at Barcelona last year. There is a much better understanding of the calorimeter performances required to answer the fundamental physics questions that can be tackled by the LHC. On the detector side, whereas at Barcelona many, frequently speculative ideas were presented, Aachen has seen positive results from new, medium to large scale, test experiments and, last but not least, the completion of the calorimeters for the HERA detectors.

A development which appears necessary is the availability of the proper computer aided engineering design tools which can predict, accurately and speedily, the performance change for a given design change. More effort in this direction is required in the near future so that the tools and trained experts are available in time for the optimization of LHC detectors. As substantial part of any LHC detector will probably be built by industry close collaboration is required both in the design and the construction phases.

Within the calorimeter working group, emphasis was put onto the detectors themselves, and very little on electronics, triggering and DAQ aspects. This has to change in the near future. These may be at least as difficult as the problems of the detector proper and may well in the end be the determining factors. How much of such an effort can be done generically and how much within a detector and even within a specific sub-detector has to be understood.

Given the short time available, the working group concentrated on the calorimeter techniques with little contact with other subgroups. It was frequently felt that it is not really possible to think of a calorimeter in the absence of the rest of the experiment. In order to progress further, it will soon be necessary to consider a complete detector in order to optimize the calorimeter performance.
Acknowledgements.

We would like to thank all the people, especially the sub-conveners, who contributed to the work of the Calorimetry Working Group.

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IDENTIFICATION OF ELECTRONS AT THE LHC

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INTRODUCTION

Three main subjects were discussed in the working group on electron identification:

i) **Physics requirements on electron identification.**

Requirements from the detection of the neutral Higgs boson. Daniel Froidevaux.
Requirements from t quark physics. Guillaume Unal.
Requirements from physics concerning the intermediate vector boson. Hartmund Plathow-Besch
Requirements from physics topics beyond the standard model. Felicitas Pauss.

ii) **The calorimeter contribution to electron identification.**

A Monte Carlo study on the contribution from the calorimeter to electron identification was presented by Jean-Paul Repellin. This is a general study using the GERAT Monte Carlo but also with the specific effects from a fast liquid-argon calorimeter included.
A second study dealt with a BaF₂ detector and was presented by Renyuan Zhu from Caltec.

iii) **The R&D projects that have started during the ECFA workshop.**

Three such projects were discussed during the parallel session:
The silicon track-stub finder and preshower detector, by Anthony Weidberg, Oxford University.
The straw-TRD tracker, by Boris Dolgoshein, Moscow Physical Engineering Institute.

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The fibre tracker R&D project, by Vincenzo Cavasinni, Pisa.

Before entering these topics we will give some general comments on electron identification. We assume that we will have a calorimeter combined with some other device. Electron identification requires:

a) The energy deposition in the calorimeter should be consistent with one and only one electromagnetic shower. This leaves a background of jets that have fragmented into hard $\pi^0$:s.

b) There should be no hadronic energy behind, and only a small energy around, the electromagnetic shower, indicating that it was not part of a jet. This is what usually is called the isolation requirement. These criteria give a rejection against the QCD jets which is of the order of $10^3$, at an electron efficiency of 90%.

c) There should be one and only one charged track that spatially matches the electromagnetic shower.

The background that survives a), b) and c) is dominated by jets fragmenting into a hard $\pi^0$ and spatially overlapped with a charged particle.

To go further we need to extract more information from the charged track that points to the shower: 1) The momentum of the track should be consistent with the energy deposition in the calorimeter. For this, a magnetic field and tracking is needed. 2) The gamma factor of the track should be consistent with the expectations for an electron. For this, one needs transition radiation.

**Physics Requirements**

*The neutral Higgs boson (D. Froideveaux) [1]*

We have two different decay channels to study:

$H^0 \rightarrow Z^0 Z^0 \rightarrow 4e \text{ or } 2e + 2\nu$

$H^0 \rightarrow W^+ W^- \rightarrow e + \nu + \text{jets}$

Fig. 1 shows the acceptance for Higgs decaying into four
charged leptons, as a function of the electron $p_T$-threshold. This is shown for three different Higgs masses: 140 GeV, 200 GeV and 500 GeV, and for each of these, for a rapidity coverage of ±2 or ±3 units. The larger rapidity acceptance of ±3 is clearly desirable. The required jet rejection, needed to measure this decay, is 3000. The second decay channel, i.e. the $W^+W^-$ decay, requires a rejection against jets of the order of $10^5$ to $10^6$ to reduce the fake electron level by an order of magnitude below the production of real electrons. These will come predominately from $b$ quark, $t\bar{t}$ and $W$ decay. Additional requirements on the event structure are needed to extract a Higgs signal from this channel.

To summarize: A $p_T$-threshold of 20 GeV is needed on each electron when two electrons are required and of (50-100) GeV when only one electron, is required. The rejection against QCD jets should be $3\times10^3$, in the rapidity region $2<\mid\eta\mid<3$, and $- (10^5-10^6)$ for $0<\mid\eta\mid<2$. Isolation cuts are needed to reduce the physics background, e.g. electrons produced by $b$ decays.

Measurement and discovery of the $t$-quark (G. Unal) [1]

It is not unlikely that the $t$ quark will be discovered at the LHC. However, if it is found already at the Tevatron, the LHC would certainly be the first place where a detailed study of its production and decay can take place. The $t$ quark can be studied in two different channels:

a) $t\bar{t} \rightarrow e + \mu + 2\nu + 2b$

b) $t\bar{t} \rightarrow e + \nu + $ jets.

(a) is the most reliable channel to find the $t$ quark. (b) is the channel needed to measure the mass of the $t$ quark by reconstructing the invariant mass of the three-jet system while tagging on the electron and possibly on missing-$p_T$. A good energy resolution is not needed since the mass measurement is determined by the jet-resolution. The electron identification requires a rapidity coverage of ±1.5 and a $p_T$-threshold of the order of (40-50) GeV. The needed jet rejection in case (b) is $10^5$. However if missing-$p_T$ is available this can be reduced to $10^4$. For (a) one would need
a rejection of $10^3$ to $10^4$. In addition, isolation is needed to reject b jets. For events with one electron and one muon in $|\eta| < 1.5$, each with $p_T > 50 \text{ GeV}$, and with the angle between the electron and the muon between $20^\circ$ and $160^\circ$, the cross section for $t\bar{t}$ ($m_t = 200 \text{ GeV}$) is 2 pb, while the corresponding cross section from b, is 3 pb. This b contribution can be reduced by a factor of $10 \rightarrow 20$ at an electron efficiency of 80% by making an isolation cut. All quoted numbers apply to a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

Physics of the Intermediate Vector Boson, IUB, (H. Plothow-Besch) [1]

Some test of the standard model with the study of IUB vertices are close to those that will be done at LEP-200. However, at the LHC, the $\W\W$-production is not accessible since this channel is swamped by $t\bar{t}$. One should concentrate on the $\W^\pm Z^0$- and the $\W^\pm \gamma$-channels. The study of these channels will test the structure of the $\W^\pm Z^0$-vertex and one could look for deviations from the standard model. In addition, from the $\W^\pm \gamma$-channel one could measure the magnetic moment of the $\W^\pm$.

The $\W^\pm Z^0$-channel was studied with the following selection: Electrons within $|\eta| < 2.5$, electron-$p_T$ more than 25 GeV, and a jet-rejection of $10^4$.

An integrated luminosity of $10^5 \text{ pb}^{-1}$ (one year) gives 11,000 signal and 2850 background events. This is shown in fig. 2 as the cross section versus the transverse mass of the $\W^\pm Z^0$ system. Two different cases are displayed: Pure standard model, and the case with an anomalous vector boson self interaction of strength 0.1. There is a clear and measurable excess after one year of data taking. Such a measurement could, at the LHC, probe the $\W^\pm Z^0$-vertex one order of magnitude higher in mass than the corresponding measurement at LEP-200. To extract the origin of an enhancement one has to look at the angular distribution of the produced electron. Knowing the charge of the electron would give a higher sensitivity for such a measurement.
Beyond the Standard Model (F. Pauss) [1]

Of the many examples discussed we will mention two: The detection of a $Z'$ and of supersymmetry.

a) A $Z'$, with a mass of 4 TeV, would produce 20 events in $|\eta| < 2$ and $\pm 2 \Gamma$ after one year of data taking, i.e. $10^5$ pb$^{-1}$. The charge asymmetry with respect to the $Z'$ motion has to be measured to establish the signal. For this, the charge of the electron is needed in $|\eta| < 2.5$. This is a very strong requirement on magnetic tracking.

b) The most relevant signature for supersymmetry is when a gluino pair produces two $Z^0$, each one decaying into two charged leptons. The signature of this would be four leptons, at least two hard jets, and missing-$p_T$. The background is $t\bar{t}$, and $Z^0Z^0$. For $10^5$ pb$^{-1}$, $m_{\tilde{g}} = 750$ GeV, $m_{\tilde{q}} = 1.5$ TeV, selection criteria: $(81 < m_{e^+e^-} < 110)$ GeV, $m_{4e} > 250$ GeV, $E_{jet1} > 200$ GeV, $E_{jet2} > 100$ GeV, and taking 15 pile-up events into account, one would obtain four events from gluino pair production, 1.6 events from $Z^0Z^0$ production and 3.2 events from $t\bar{t}$. The missing-$p_T$ distribution from these sources is shown in Fig. 3. The distribution from $Z^0Z^0$ and $t\bar{t}$ is very different from that of the gluino pair. As it can be seen, this signature is very close to that of the decay of the neutral Higgs. However, from the experimental point of view there is an important difference. In the neutral Higgs decay, one can constrain the two electron mass to be equal to the $Z^0$ mass, which would give a good mass resolution even with a bad calorimeter. In the case of supersymmetry one needs a good resolution of the calorimeter, in order to cut out background from $t\bar{t}$ by demanding that the electron pair mass should be equal to the $Z^0$ mass.

Summary of requirements from physics issues.

Jet rejection of ~3000 is needed in $|\eta| < 3$. In the two central units of rapidity one would need a jet rejection of the order of $10^5$ to $10^6$. With the large rejection in the central region, it may be that the calorimeter rejection of $10^3$ is sufficient in $2 < |\eta| < 3$.

The $p_T$-threshold needed is as low as 20 GeV in the case of 2 electron selection, and > (50-100) GeV for inclusive
selection.
The sign of the electron is needed but, for the $Z'$ case, difficult to get.

CONTRIBUTION TO E-ID FROM THE CALORIMETER

Having obtained some indications on the performance needed, we will now discuss what an apparatus can provide.

The first step, the calorimeter, has been simulated by Jean-Paul Repellin [1]. As the study was made with 20 GeV electrons, the results will have to be modified when looking at electron energies of other values. A cylindrical calorimeter, with a one meter inner radius and covering three units of rapidity, was simulated with the GEANT program [2]. Homogeneous lead was used as material, but with the density set to half of the lead value. The transverse calorimeter segmentation was 0.02 radians in $\phi$, and 0.02 units in $\eta$. It had also two longitudinal segmentations: One electromagnetic section of 25 $X_0$ and one hadronic section of 10 $\lambda$.

The assumed electromagnetic (hadronic) resolution was 10%/$/E + 1\%$ (50%/$/E + 2\%$), $e/\pi$ was set to 1.1. A noise of 70 MeV (140 MeV) was added to the electromagnetic (hadronic) section when the performance of a liquid argon calorimeter was examined. The calorimeter response in this case was a 400 ns long asymmetric bipolar pulse giving an effective luminosity of 3.8 times the instantaneous one (15 ns bunch spacing).

Three topics were studied: Energy resolution, jet-rejection, and position resolution. Of these, the two latter ones will be covered here.

Figure 4a shows the effect of isolation on the rejection of QCD jets and on the efficiency of 20 GeV electrons. The x-axis of the figure has two sets of values. The upper one shows the size, from 0.06$^2$ to 0.018$^2$, in which the electromagnetic energy is measured. The smallest value, 0.06$^2$, corresponds to a nonet in a calorimeter with a segmentation of 0.02. The lower numbers show the corresponding size in which the isolation requirement is made. When asking for an electromagnetic energy above 20 GeV we see a rejection against QCD jets that varies from $1.5 \times 10^{-2}$ to about $5 \times 10^{-2}$. Restricting the energy, in the
hadronic section behind the electromagnetic energy, improves the rejection to $6 \times 10^{-3}$. The numbers on the curve show (in GeV) the values of the restrictions made. The isolation requirement strengthens the rejection down to a level of $10^{-3}$. The full curve shows the case where one has only used the GEANT simulation whereas the dashed curve shows the case when the noise and time response typical of the liquid argon calorimeter has been incorporated into the simulation.

The corresponding effect on the electron inefficiency is shown in fig. 4b. The restriction of the hadronic energy behind the electromagnetic deposition introduces an inefficiency of the order of 2%. The isolation requirement increases this to about 4% in the case of pure GEANT simulation. This worsens to something like 5% to 9% in the case of the liquid argon calorimeter.

The calorimeter can reject QCD jets with a factor of about $10^{-3}$ at the expense of an electron inefficiency of the order of 6-9%. When matching this electron candidate to a charged track, without any dedicated preshower detector, the position resolution on the electromagnetic shower from the calorimeter clearly matters. This was simulated and the results are shown in fig. 5. Fig. 5a (5b) shows the case of the 0.02 (0.04) segmentation. The y-axis gives the percentage of electrons lost and the x-axis displays where the cut is made. This is quoted in radians which corresponds to millimeters at the one meter radius of this calorimeter. Results from GEANT only (dash-dotted curve), with liquid argon noise (dashed curve) or pile-up at $L = 2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ (dotted curve) incorporated, and, as the full curve, the case when both the noise and the pile-up is included in the simulation. Fig. 5a shows that, for a 0.02 segmentation, the electron inefficiency is slightly below 5% with a position cut of the order of 4 mm. However, with the slightly larger segmentation of 0.04 this cut has to be increased to almost 18 mm to retain the same electron inefficiency.

To summarize the expected performance from the calorimeter: A jet rejection of $-10^{-3}$ seems achievable at the expense of an electron inefficiency of $-10\%$. This was obtained with 20 GeV electrons. Different energy would modify the result. The jet rejection was simulated in the central rapidity region and it cannot be excluded that it is
more difficult to reject the more focused jets in the forward region.

An examination of the jet-rejection given by a BaF₂ detector was reported by R. Zhu [1].

DETECTOR R&D PROJECTS

The three R&D projects that have been discussed during the session dealt with pushing the electron identification beyond what is achieved by the calorimeter alone. In the introductory remarks on the principles of electron identification we see that each of these R&D-projects corresponds to one of the points made. The first project, the silicon track-stub finder, aims at doing an optimal spatial match and at rejecting conversions. The TRD tracker intends to check the gamma factor of the track and also to reject the conversions. The fibre tracker goal is to measure the momentum of the track and to compare it with the energy deposited in the calorimeter.

Silicon track-stub finder and preshower detector (A. Heidberg) [3]

Fig. 6 shows the principle of this detector. Indicated on the upper image is the signature of a true electron in such a device. Before the converter we see a single charged track and after it, the start of an electromagnetic shower, roughly giving 20 charged tracks. What would then the background look like? A single charged pion would both before and after the converter look like a single minimum ionizing particle. An overlap between a charged and a neutral pion would be rejected due to lack of perfect spatial matching between the shower started by the photon and the minimum ionizing track produced by the charged pion. A converted photon would be rejected in the case of a nonmagnetic detector as it gives twice the ionization in front of the converter.

Consequently such a device would require a good precision on track/shower match and a good measurement of dE/dx.
This R&D project proposes to make a prototype consisting of two types of silicon detector elements: a pad detector, where the detector consists of 64 pads of 3×3 mm², and a strip detector, also having 64 channels. They would be arranged as shown in fig. 6: Three detector nonets in front of the converter and three behind it. The aim is to have such a device in a test beam at SPS in 1991. One will study the performance of the new counters and compare the detector response and resolution with what has been calculated using the Geant Monte Carlo.

A simulation of the full device is shown in fig. 8. It has an inner radius of one meter and a length along the beam line of four meters. With a pad area of 9 mm² and a luminosity of 2×10^{34} cm^{-2} s^{-1} one would get a occupancy of about 1.5×10^{-4}. This is a low occupancy which therefore will give unambiguous space points, hence excellent pattern recognition at high luminosity. Fig. 9 shows the position resolution in the match between the track and the preshower. This simulation gives a resolution in both φ and z of 250 µm for isolated electrons, corresponding to a rejection of 10³ against overlap background.

Substantial amount of work is needed: Fast, radiation resistant, low power readout electronics will have to be developed. One should have in mind that there are a lot of independent electronic channels in a full scale device and that one would easily get a total power production of the order of (10-100) kW if one does not keep the single channel power dissipation at a minimum level. Also the neutron flux has to be reduced since otherwise the leakage current in a 9 mm² pad after one year of running at the LHC would be ~ 14 µA. This would give 870,000 electrons in a 10 ns gate, which is clearly unacceptable. However there is the hope that a moderator just before the calorimeter could be able to reduce the neutron flux by one order of magnitude. In addition, the effect of annealing may help with a factor of 2.5.

The TRD/tracker (B. Dolgoshein) [4]

Fig. 10a shows the cross section of such a detector. It consists of 4 mm diameter straw chambers which are made of
kapton foils and having a 50 μm anode wire in the center. The chambers are embedded in a polypropylene foam. This foam, constituting the radiator, also gives mechanical stability. Fig. 10b shows the cross section of one possible layout with about 100 layers. This layout is usually called the pinwheel design. It has the advantage of no cracks and that all the electronics can be mounted on the outside. The straws are perpendicular to be beam, which means that even in the case of a small magnetic field, the conversions will produce a double signal since they will open up along the straw chambers and not be split between different ones.

Fig. 11a illustrates the occupancy of charged particles in a straw chamber. This is shown as a function of the angle from a jet axis. Indicated by the full line is the occupancy, at 70 cm radius, produced by a 100 GeV jet, and by the dashed line by 40 minimum bias events. The occupancy of X-rays, i.e. energy depositions above 4.5 KeV, is significantly lower and is shown in fig. 11b. The occupancy produced by strongly ionizing protons kicked into the chambers by the neutrons is also indicated in fig. 11b. It lies one order of magnitude below the level of the charged particle from the minimum bias events.

The first 200 channel prototype of this detector has already been made and put into the X5 test beam at CERN this summer. The measured performance is shown in fig. 12 as the probability to get energy depositions of more than 4.5 keV as a function of the particles' Lorentz factor. The measurement spans a gamma factor from slightly below $10^2$ up to $10^5$. As indicated, almost all particles and QCD jets are in the low γ region, i.e. between 10 and $10^2$, while the electrons have a γ between $10^4$ and $10^5$.

Fig. 13 shows the simulation of how a full scale detector would behave in an LHC environment. It simulates the appearance of an event in one sector at a luminosity of $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$ which corresponds to 40 overlapped minimum bias events. Fig. 13a shows the event display of all hits with energy deposition of more than 0.2 KeV. Clearly large occupancy. However, when raising the discriminator level to 4.5 KeV we see a cleaned up picture as indicated in fig. 13b. In fig. 13c is shown what the information looks like after a pattern recognition program has been applied to fig. 13b, and all relevant points have been added to the found tracks. These tracks should be matched with electron
candidates from the calorimeter. There is clearly a reduction of track candidates, compared with fig. 13a.

The identification algorithm of the straw-TRD compares the number of straws along a track that have energy depositions that correspond to 4.5 keV or more, with the number of straws on the track having energy depositions corresponding to a minimum ionizing particle. A scatter plot with the number of minimum ionizing hits on the y-axis and the number of E > 4.5 keV - hits on the x-axis, fig. 14, illustrates how this works. Fig. 14a shows this distribution for the electrons and fig. 14b for all the particles in the event at the luminosity of $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$. The line drawn in the scatter plot marks the selection cut of 90% electron efficiency. The result of such a cut is quantified in fig. 15 as a function of the number of crossed straws. About 70 straws will be crossed in the proposed device, giving a rejection power of $10^2$. This rejection is in addition of what a pre-shower detector will give. The rejection power of a conversion is almost an order of magnitude better.

The fibre-tracker (U.Cavasinni)

Scintillating fibres are attractive because of their high speed, good two track resolution, light material, low power dissipation, radiation hardness and inexpensiveness. Their disadvantages are that of a projective device and that the front-end read out solution is not yet clear.

A possible configuration for the tracking detector at the LHC is given in fig 16. Fig. 16a shows one quadrant of the layout. It has two superlayers: At half a meter and at one meter radius respectively. Each superlayer, made out of two fibre layers that are separated by 5 cm, is four fibres in depth (fig. 16b). Such a device would have an occupancy, at $4 \times 10^{34}$ cm$^{-2}$s$^{-1}$, which is about 3% for the superlayer closest to the beam axis and about 1.6% for the superlayer at one meter radius. This is just the charged particle occupancy.

The spatial resolution in a superlayer is estimated to be 36 $\mu$m and the pointing accuracy for a superlayer track segment is 1.2 mrad. Pointing a track segment from the middle super layer, using the known vertex position, one can hit the outer superlayer with a precision of a few fibres.
This, together with the occupancy of 1.6% in the outer superlayer, indicates that pattern recognition is possible in the transverse plane. However, the authors of this project are careful to point out that the purpose of this device is mainly to enhance the precision on tracks having already been found by pad detectors.

The readout is non-trivial: Signal pipelining requires a fast, compact, and cheap readout system. The possibility of avalanche photodiodes, silicon intensified tubes, direct read out pixel arrays, the vacuum image delay line, position sensitive photomultipliers with fast memories, and maybe the most interesting one: the solid state photomultiplier with fast memories are examined.

The performance of such a tracking device has been studied for two different options: One with a weak and one with a strong magnetic field. With a weak magnetic field of 0.3 T, the $p_T$-resolution, $\frac{dp_T}{p_T^2}$, is equal to $3.5 \times 10^{-3}$ [GeV]. Therefore all particles with a $p_T < 10$ GeV, overlapping an electromagnetic shower, could be rejected. With a strong magnetic field of 5 T, one gets a resolution, $\frac{dp_T}{p_T^2}$, of $20 \times 10^{-2}$ [TeV]. A 20% $p_T$-resolution for a one TeV particle! In addition, all the particles with a $p_T$ less than 500 MeV will be trapped inside the outer tracking device, and quickly disappear along the beam line.

**CONCLUSION**

The electron identification at the LHC seems feasible at a level that will be quantified through the R&D projects that have started during this workshop. Preliminary studies show that one can reach, at $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$, a jet-rejection of $10^{-4}$ to $10^{-5}$ while retaining an electron efficiency of the order of 90%. This seems adequate for some of the main physics aims of the LHC.
FIGURE CAPTIONS

Figure 1. Acceptance for $H^0 \rightarrow Z^0Z^0 \rightarrow 4e$ as a function of $p_T$-threshold, Higgs mass, and rapidity coverage. $|\eta|<3$ is shown as a full line, and $|\eta|<2$ as a dashed line.

Figure 2. Cross section branching ratio for electrons from $W^\pm Z^0$-events as a function of the $W^\pm Z^0$ transverse mass.

Figure 3. Distribution of missing-$p_T$ for events with gluino pairs that has decayed to $Z^0Z^0$ (full line) and for the corresponding background events from $t\bar{t}$ and $Z^0Z^0$ (dashed line).

Figure 4. a) Jet-rejection for different calorimeter requirements versus cell size and isolation size in the calorimeter. The numbers, on the curves, indicate in GeV the magnitude of the cuts. The full lines are from GEANT simulation only, while the dashed lines include effects from liq.Ar pile-up and electronic noise. b) The corresponding curves for electron inefficiency.

Figure 5. Electron inefficiency as a function of electromagnetic shower position cut in the calorimeter. Dash-dotted curve: GEANT only Dashed curve: GEANT + liq. Ar. noise Dotted curve: GEANT + pile-up Full line: GEANT + noise + pile-up a) For a calorimeter with segmentation 0.02x0.02. b) For a calorimeter with segmentation 0.04x0.04.

Figure 6. Schematic representation of the signatures, for an electron and some electron background sources, as seen in a preshower detector.
Figure 7. Proposed prototype of a silicon preshower detector.

Figure 8. A possible layout of a preshower detector at LHC as simulated by GEANT.

Figure 9. Distribution of residues from track-preshower match, as simulated in GEANT, for the set-up shown in fig. 8.

Figure 10. The straw-TRD.
   a) Schematic drawing showing the structure of the detector.
   b) A possible layout of a full detector.

Figure 11. Occupancy in the straws at 70 cm radius.
   a) For hits with $E > 0.2$ keV.
   b) For hits with $E > 4.5$ keV. The dashed line shows the contribution from neutrons.

Figure 12. Probability for a crossed straw to get an energy deposition exceeding 4.5 keV as a function of the Lorentz factor. From the 1990 test-beam measurement.

Figure 13. Simulation of an event in a 45° TRD-sector at the nominal luminosity of $2 \times 10^{34}$ cm$^{-2}$s$^{-1}$.
   a) All hits with $E > 0.2$ keV.
   b) All hits with $E > 4.5$ keV.
   c) All hits associated with a found track.

Figure 14. Number of minimum ionizing straws versus number of high ionization straws for tracks traversing a 70 cm deep straw-TRD. The line indicates the selection cut for 90% electron efficiency.
   a) For electrons only.
   b) For all tracks.

Figure 15. The TRD rejection power of tracks as a function of number of crossed straws for different luminosities. The rejection of conversions is also indicated.
Figure 16. Possible layout of a scintillating fibre tracker.
a) One quadrant of the tracker.
b) Detail of a fibre superlayer.
REFERENCES

[ 1 ] Individual contribution to this workshop.
$H^0 \rightarrow 4l$

$\varepsilon_e = 90\%$

- $|\eta| < 3$
- $|\eta| < 2$

$m_{H^0} = 200$

$m_{H^0} = 500$

$m_{H^0} = 140$

Events $/ 10^5 \text{ pb}^{-1}$

Threshold $p_T^e$ [GeV]

Fig. 1
Fig. 2
Fig. 5
64 pads of 3x3 mm²

64 strips of 0.375x24 mm²

TYPE

A

B

90 degree rotation

Converter

B

B

90 degree rotation

A

Fig. 7
Fig. 9
Fig. 10

-100 layers of straws

100 cm

240 cm

Electronics
Fig. 11
Fig. 12
The figure illustrates the TRD rejection power ($e_e = 90\%$) as a function of the average number of crossed straws and rapidity $\eta$. The graph is labeled with $\sqrt{s} = 16$ TeV. The data points represent different particle types:

- Upsilon ($\Upsilon$) particles
- Charged particles ($\pi^\pm, k^\pm, p$)

The axes are as follows:

- Y-axis: TRD rejection power
- X-axis: Average number of crossed straws
- Radial axis: Rapidity $\eta$

The graph includes several curves with markers indicating different particle types. The markers are denoted by different symbols and colors, with error bars indicating the uncertainty in the measurements.
Fibre superlayers

2.6 m

0 ≤ η ≤ 1.7

100 cm

50 cm

beam axis

70°

Carbon Fibre (0.5 mm) layer

4 layers of Fibres (0.5 mm) staggered 1/4 diameter

Total: ~300,000 Fibres

Fig. 16
Muon Detection at the LHC

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and

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Presented by Karsten Eggert at the Large Hadron Collider Workshop,
Aachen, 4–9 October 1990.
1. Introduction

This contribution is concerned with all aspects of muon identification at the proposed Large Hadron Collider LHC. Several groups in Europe with physicists from all the member states of CERN and beyond have contributed to this study. At the end of 1989 several sub-working groups were organized, resulting in meetings in March and June of 1990 at CERN where intermediate results were presented. The physicists involved in the actual work came predominantly from the UA1, UA2 and L3 Collaborations and the LAA project.

We have subdivided from the beginning the problems into several areas. We tried to be as general as possible where rates, acceptances, punch-through, energy loss, requirements on momentum resolution and magnet concepts are concerned. It is however unavoidable to assume specific features of a detector when one studies possible level-1 trigger concepts or the details of the mass resolution of Higgs particles decaying into four muons or other new phenomena. The results of these studies and the individual contributions to the Aachen workshop can be found in Volume III of the proceedings. This contribution is organised in such a way that we report on the general problems of muon identification first and we become less general towards the middle and final sections. These sections can be summarized as follows:

- Physics simulations of muon distributions from the decays of Higgs, Z and W particles and heavy quarks in order to be able to calculate geometrical acceptances and the requirements on muon momentum resolutions are presented in section 2 and [1].
- Muon rates are presented in section 3 and [1].
- Background from known decays [1] and punch-through [2] to the interesting muon signals; the energy loss of highly energetic muons [3] and some ideas about a simulation of an LHC muon detector at the SPS test beam [4] can be found in section 4.
- A level-1 trigger concept for a solenoidal detector is described in section 5 and a detailed write-up can be found in reference [4].
- New muon chamber developments and test results are presented in section 6 and in references [5–8].
- The various magnet and detector designs are described in section 7 and in references [9–15].
- A comparison between the different proposed detector designs in terms of momentum resolution and the conclusions can be found in section 8.
2. Momentum Precision and Acceptance [1]

In this section we discuss the requirements from the expected important physics processes at the LHC concerning; 1) the precision on the muon momentum measurement and 2) the muon acceptance in rapidity and transverse momentum. These requirements will determine the size and for a large part the cost of an experiment and were therefore hotly debated and the question of the required momentum precision remains controversial.

With a pragmatic approach one could argue that the physics in this new energy domain may differ from expectations, and that narrow particles such as non-standard Higgs particles, new vector bosons or leptoquarks may exist. Consequently, an experiment with the best possible momentum resolution will have the best discovery potential. Here we want to study, as a test case, the search for the standard Higgs decay into four muons. We have to discuss two cases: $m_H > 2m_Z$, the high-mass Higgs with its decay into two real $Z$'s and $m_Z < m_H < 2m_Z$, the low-mass Higgs decaying into one real and one virtual $Z$.

First we discuss the case $m_H > 2m_Z$. The requirements on the muon momentum are determined by:

- the natural width of the Higgs which increases with $m_H^3$
- the background from known processes to the Higgs decay $H \rightarrow \mu^+\mu^-\mu^+\mu^-$

The main backgrounds consist of the $Z$ pair continuum:

$$pp \rightarrow ZZ + X \rightarrow \mu^+\mu^-\mu^+\mu^- + X$$

and a non-resonant part for which at least one muon pair does not arise from a $Z$. In this case the dominant contributions are pair-produced top quarks and $Z$ b\bar{b}:

$$pp \rightarrow tt + X \rightarrow \mu^+\mu^-\mu^+\mu^- + X$$

$$pp \rightarrow Z b\bar{b} + X \rightarrow \mu^+\mu^- - \mu^+\mu^- + X.$$

Other background sources, such as $b\bar{b}$ and $c\bar{c}$ or $Z t\bar{t}$ production seem to be small. The non-resonant background can be strongly suppressed by requiring that the invariant mass of the two $\mu^+\mu^-$ pairs be equal to the $Z$ mass within a small window. However, the background from $Z$ pair production is, of course, not reduced since the muons come from genuine $Z$ decays.
Fig. 1 The four muon invariant mass distribution for a Higgs with a mass of 200, 400, and 700 GeV/c² and the background from resonant Z production and non-resonant t̅t̅ and Z b̅b̅ production. Also included is the Z pile-up. A muon-momentum resolution of 15% was assumed.

The μ⁺μ⁻μ⁺μ⁻ invariant mass cross-section is shown in Fig. 1 for the background processes to be compared with the Higgs signal for three different masses (m_H = 200, 400 and 700 GeV/c²). The requirements of p_T > 20 GeV/c and |η| < 2.5 for each muon and a loose cut of |m(μ⁺μ⁻) - m(Z)| < 16 GeV/c² reduces the non resonant background well below the resonant ZZ background. Hence a muon momentum resolution of some 15% as achievable with 3 m of iron, magnetized to 1.8 T, would be adequate. This momentum resolution only affects the low mass Higgs (m_H = 200), where the experimental mass resolution of ~ 10 GeV/c² is considerably larger than the natural width of 1.4 GeV/c². In order to improve the Higgs mass resolution, the Z mass constraint can be used for the two diMuon systems. The momenta of the two muons are rescaled such that the dimuon mass is forced to be the same as the Z mass. The Higgs mass peak at 200 GeV/c² is now clearly visible above the background continuum and its width is close to the natural Higgs width (Fig. 2). At large Higgs masses the Z mass constraint becomes less effective, but also the natural width of the Higgs increases.
Fig. 2 The four muon invariant mass distribution for a Higgs mass of 200 GeV/c^2, but with Z mass constraint. Background contributions are as indicated.

Fig. 3 The four lepton invariant mass distribution for the low mass Higgs together with the background. The cuts are explained in the text.
The search for the Higgs is more involved in the mass range:

\[ 130 \text{ GeV/}c^2 < m_H < 2 \text{ m}_Z, \]

where the Higgs decays into one real and one virtual Z and the Z mass constraint can be used only once. Furthermore, in order to maintain a good detection efficiency the transverse-momentum cut on the two muons from the virtual Z has to be lowered, thus increasing the background. In fact, the invariant mass distribution of the four muons (Fig. 3) is dominated by the background, mainly from pair-produced top quarks, and less from \( Z b \bar{b} \). A possible Higgs signal (indicated for three different masses) would barely be visible. The cuts on the transverse momenta were 20 GeV/c for the two fastest muons (\( \mu_1 \) and \( \mu_2 \)) and 10 GeV/c for the others (\( \mu_3 \) and \( \mu_4 \)). A mass cut of \( m(\mu_3, \mu_4) > 12 \text{ GeV/}c^2 \) was applied to remove background from virtual photons. The \( \mu^+\mu^- \) system with the largest mass had to be within a window of \( \pm 10 \text{ GeV/}c^2 \) around the Z mass. This cut is appropriate for a detector with a moderate momentum resolution of \( \Delta p/p = 0.15 \). With such a resolution the Z represents only a broad enhancement in the mass distribution of the two leading muons (Fig. 4a). On the contrary, an excellent mass resolution of 2% at 100 GeV/c allows a much narrower cut of \( \pm 2.5 \text{ GeV/}c^2 \) around the Z peak (Fig. 4b) and reduces the \( t\bar{t} \) background in Fig. 3 by a factor of 4 to the level of the other backgrounds. Furthermore, the experimental width \( \sigma \) of the Higgs, i.e. the invariant mass of the four muons, can be as small as 1 GeV/c² for a momentum resolution of \( \Delta p/p = 0.2 \rho_T(\text{TeV}) \).

![Figure 4](image-url)  

Fig. 4 The mass distribution of the highest mass \( \mu^+\mu^- \) pair. A muon momentum resolution of \( \Delta p/p = 15\% \) (a) and \( \Delta p/p = 0.2 \rho_T(\text{TeV}) \) (b) was assumed.
An excellent muon momentum resolution is thus helpful to extend the search for the Higgs decay into four muons to the lowest experimentally attainable masses, which are around 130 GeV/c². Other possibilities to reduce the background, for example by the requirement of isolated muons, are under study but become more difficult at high luminosities.

The acceptances of muons in rapidity and transverse momentum are important design parameters for an LHC experiment. The muon trigger becomes exceedingly difficult in the forward directions owing to the steeply increasing particle densities. Figure 5 shows the acceptance for a Higgs decaying into four muons as a function of the lowest muon transverse momentum. For the high-mass Higgs particles that are centrally produced, the chosen rapidity interval for the muons of $|\eta| < 3$ and a transverse momentum cut of 10 GeV/c present no significant detection loss. In the case of a low mass Higgs a larger rapidity coverage would be advantageous, but even more important muons have to be identified and measured at transverse momenta as low as 5 GeV/c. This requirement may be demanding for some of the muon-detector designs. The trigger is not so much affected since the two muons from the Z decay will usually have transverse momenta above 15 GeV/c.

Fig. 5 The acceptance for a Higgs decay $H \rightarrow \mu^+\mu^-\mu^+\mu^-$ as a function of the transverse momentum of the lowest $p_T$ muon in a rapidity interval of $|\eta| < 3$ and for different Higgs masses.
3. Muon Rates [1]

The inclusive rates of prompt muons and multimuenos at the LHC have been extensively calculated with different Monte Carlo programs and are reported in these proceedings. The standard sources for prompt muons are the decays of heavy flavours (charm, bottom, and top), W- and Z-decays and Drell-Yan processes. Large uncertainties in the calculation of these cross-sections are due to substantial higher order corrections and an incomplete knowledge of the structure functions. Nevertheless, the calculations show that the inclusive muon rate is huge and is dominated at all transverse momenta by charm and bottom decays. The fact that these muons are generally contained in jets is of primary importance for their identification and for the trigger.

The integral inclusive muon spectrum ($|\eta| < 3$), calculated with ISAJET, is given in Fig. 6. At the assumed LHC luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ the prompt muon rate exceeds 10$^5$ Hz in the central region for $p_T > 5$ GeV/c, which will be in most of the experiments the natural cut-off due to the thickness of the absorber. Whereas at such small transverse momenta the muon rate from charm and bottom decays is dominating by three orders of magnitude, the individual rates become similar within one order of magnitude for large $p_T$ muons. To obtain single-muon trigger rates below 100 Hz the $p_T$ threshold has to be chosen above 50 GeV/c, a difficult task for a muon-trigger system.

The integral dimuon rate is shown in Fig. 7. In the transverse-momentum range of 20 to 40 GeV/c the dimuon rate is dominated by the inclusive Z production. At large $p_T$ the contributions from Z decays and Drell-Yan processes are comparable and are an order of magnitude larger than the ones from heavy-flavour decays. A dimuon trigger with a $p_T$ cut-off at 20 GeV/c is an efficient Z trigger with a typical rate of 30 Hz. It is worth noting that about $10^8$ Z decays into muons will be observed during one year of LHC operation at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. This large number of Z decays may also serve for the calibration of the detector.
Fig. 6 The contributions to the inclusive muon cross-sections from dominant physics sources as indicated at $\sqrt{s} = 16$ TeV as a function of the $p_T$ threshold. The rates for an assumed LHC luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$ are also given (right vertical scale).

Fig. 7 As in Fig. 6 but for dimuons.
4. Identification

In this section we discuss the background to the prompt muons, the energy loss of muons, and some ideas about a simulation of an LHC muon detector at the SPS test beam.

4.1 Background from decay and punch-through [2,3]

Background associated with beam-beam collisions results from π or K decays before the absorber (primary decays) and from leakage of hadron-initiated cascades through the absorber (secondary decays and punch-through).

The rate due to primary decays in the inner region follows from the charged hadron rate at the LHC. The probability $P_{PD}$ for a decay in a free path $L$ can be written as:

$$P_{PD}(p, x < L) \sim mL/cTp$$

where $p$ is the momentum of the primary particle. The momentum distribution of the decay muons is uniform within fixed limits.

The rate due to secondary decays and hadron punch-through requires either Monte Carlo simulations or parametrizations of existing punch-through data. Fesefeldt has shown [16] that a fast version of GEISHA [17] implemented in GEANT [18] can reproduce a variety of punch-through measurements. As an example, the total punch-through probabilities, calculated with GEANT and with GEANT/GEISHA, are compared in Fig. 8 with measurements performed with an iron-scintillator calorimeter [19]. The simulations seem to be precise for absorber thicknesses below 20 $\lambda$ and punch-through probabilities above $10^{-2}$. For larger absorbers an uncertainty of a factor of 2 cannot be excluded. Figure 9 shows the integral punch-through probability for single pions after an absorber of 16.3 $\lambda$ as a function of the pion momentum, predicted by the Monte Carlo calculation. In this example the decay path before the absorber is 80 cm. The three components from primary, secondary and punch-through hadrons are shown separately. The primary decay dominates at low $p_T$. The other two components are of roughly equal importance, but they have a different dependence on the absorber thickness, as observed experimentally in agreement with full-shower calculations. After 20 $\lambda$ the hadronic part becomes negligible and only muons can escape from the absorber.
Fig. 8 Total punch-through probabilities as a function of the longitudinal depth for an iron-scintillator calorimeter, compared with GEISHA and GEANT calculations.

Fig. 9 Integral punch-through probabilities for pions as a function of incident momentum for an absorber of 16.3 λ without (a) and with a magnetic field of 4–6 T (b).
The effect of a strong magnetic field can be evaluated by comparing integral punch-through probabilities without (Fig. 9a) and with a magnetic field of 4–6 T (Fig. 9b). The magnetic field reduces the contributions from secondary decays and leaking hadrons by an order of magnitude for incident pions below 20 GeV/c. This can be understood from the calculated energy spectrum of muons escaping from the absorber (Fig. 10). Two components are clearly visible. The flat hard component, \(8<E<16\ \text{GeV}\), mainly from primary decays is not much affected by a magnetic field. The soft component (\(E<8\ \text{GeV}\)) of the spectrum from secondary decays is removed by a strong magnetic field.

![Energy spectrum of the decay muons produced by 20 GeV pions after 16.3 \(\lambda_0\) with magnetic field on (dashed histogram) and off (full histogram).](image)

In order to calculate the transverse momentum spectrum of misidentified muons one has to convolute the charged hadron spectrum with the momentum distribution of primary and secondary decay muons. As mentioned above, hadronic punch-through can be neglected after 20 \(\lambda_0\). Figure 11 shows, for the central region \(|\eta|<3\), the \(p_T\) spectrum of jets and charged hadrons. Since the jet yield is large at the LHC most of the high-\(p_T\) hadrons are embedded in jets, a topology very similar to the prompt muons from beauty decays. The background-muon rate from pion and kaon decays before the absorber is compared in Fig. 11 with the prompt muon rate. The background is large at low \(p_T\), but already at \(p_T \sim 10\ \text{GeV}/c\) it is small compared with the prompt muon rate. The background from the secondary decays of the shower particles in the absorber is difficult to estimate reliably and is therefore only indicated by arrows for magnetic field on and off. The \(p_T\) spectrum of muons from secondary decays is expected to be softer than the one from primary decays. For \(p_T > 5\ \text{GeV}/c\) and at a luminosity of \(10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}\), the contributions from prompt muons, primary decays and secondary decays are of similar size and result in a total rate of \(10^5-10^6\ \text{Hz}\).
In many detector concepts the muon detection starts immediately after the calorimeter which has a typical thickness of some $10 \lambda$. As an example we calculate the muon rate for a model LHC detector, which consists of free space cylindrically shaped of 1.3 m radius and 4.4 m length for tracking. It is followed by a barrel calorimeter of $10 \lambda$ and an end-cap calorimeter of $16 \lambda$. In Fig. 12 the rate of charged hadrons (full line), of primary decays (dashed line), and of secondary decays and hadron leakage (dotted line) is given as a function of the production angle. A luminosity of $4 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ was assumed. The rate is of the order of $10^{6}$ Hz in the barrel region and exceeds $10^{7}$ Hz in the forward region ($|\eta| < 3$). Even a much larger absorber thickness would not significantly reduce this rate, since these are predominantly decay muons. The only possible way is to increase the $p_T$ threshold in the trigger.

**Fig. 11** Expected cross-sections and rates at $10^{34}$ cm$^{-2}$ s$^{-1}$ for jets, charged hadrons, prompt muons from charm and bottom decays, and muons from primary hadron decays as a function of the $p_T$ threshold. The two arrows indicate the level of the punch-through background for $B=0$ and $B=4$ T for the configuration explained in the text.

**Fig. 12** Expected rates at $4 \times 10^{34}$ cm$^{-2}$ s$^{-1}$ luminosity from charged hadrons (full line), primary decays (dashed line), and secondary decays and punch-through (dotted line) as a function of the polar angle for the configuration described in the text.
4.2 Energy losses [3]

At low energies the mean energy loss is by ionization and this loss ($\Delta E_{\mu}$) is suppressed with respect to that of an electron by a factor $(m_e/m_\mu)^2 \sim 2.3 \times 10^{-5}$. At sufficiently high energies, direct electron-pair production, bremsstrahlung, and nuclear interactions will start to dominate. The energy loss of the muons can be expressed as follows:

$$-\frac{dE}{dx} = a + b \ln \left( \frac{E'_{\text{max}}}{m_\mu} \right) + \left( \sum_{i=1}^{3} k_i \cdot E_\mu \right),$$

where the last three terms of the expression describe the processes other than ionization loss ($a$, $b$, and $k_i$ are constants depending on the material of the absorber and $E'_{\text{max}}$ is the maximum energy transfer to a knock-on electron). In Fig. 13 the muon energy loss in iron as function of its energy is shown according to a calculation done by Lohmann et al. [20]. However, it should be noted that different calculations can lead to 20% differences in the result, owing to uncertainties in the screening effects of atomic electrons, the nuclear form factors, and the cut-off values applied.

![Graph showing energy loss vs. muon energy for iron](image.jpg)

**Fig. 13** Total energy loss of muons as a function of their energy. The total curve is the sum of the contributions due to nuclear interactions, ionization, bremsstrahlung, and direct electron-pair production.
Fig. 14  Muon tracks from the decay of a 500 GeV Higgs particle traversing an iron toroid. One of the muons undergoes a so-called catastrophic energy loss.

A detailed study of the effects of energy losses was performed by using the simulation program GEANT [18]. The decay of a 500 GeV Higg's particle into four muons was simulated for a iron-toroid detector. Figure 14 shows an event with considerable energy loss as indicated by the blacker areas along the trajectories of the tracks. This event also shows the importance of measuring muons at small production angles because in this particular example three of the four muon tracks have angles smaller than 20° with respect to the beam axis.

Muon tracks with energies ($E_{\mu}$) of 10, 25, 50, 100, 500, and 1000 GeV were traced through 2 m of iron. The results of these simulations can be summarized as follows:

- The values of the width of the energy-loss distributions normalized to the muon energy $\sigma(\Delta E_{\mu})/E_{\mu}$ are 3%, 1.5%, and 1% for muon energies of 10, 50, and $\geq$100 GeV respectively (see Fig. 15).
- The $\Delta E_{\mu}$ distributions show substantial tails at large $\Delta E_{\mu}$. The fraction of events in the tails with $\Delta E_{\mu}$ larger than 25% of $E_{\mu}$ is independent of $E_{\mu}$, and the probability of such occurrences is ~ 0.6% in 2 m of iron.
- Part of the electromagnetic showers initiated by the muons can leak into the muon-tracking detectors positioned inside the absorber and may limit chamber resolutions.
- The additional clusters in the chambers add to the confusion in the muon trigger and the momentum reconstruction.
Fig. 15 Relative fluctuation of the muon energy loss after 2 m of iron as a function of the muon energy.

The GEANT predictions were checked with available data in the literature. The high-energy (100 GeV < $E_\mu$ < 13 TeV) cosmic ray experiment MUTRON [21], measured both $E_\mu$ and $\Delta E_\mu$ and the GEANT expectations agree well with the measured $\Delta E_\mu$ spectra up to the highest measured energies.

The influence of additional clusters of soft particles inside the tracking chambers on the resolution was studied by the NA4 Collaboration [22]. The measured chamber resolutions for muons of 60–80 GeV could only be described by assuming a worsening of the intrinsic chamber resolution ($\sigma_i = 1.15$ mm) due to $\delta$ rays with a component $\sigma_\delta = 1.0$ mm.

The GEANT predictions of the number of additional clusters of soft particles accompanying a muon track inside the iron and appearing in the muon detectors were compared with the measurements of the NA4 experiment [22]. The generated muon tracks of an energy of $E_\mu = 100$ GeV after 2 m of iron have 0, 1, 2 and $\geq$ 3 additional clusters in 83%, 10%, 4%, and 3% of the cases respectively, in excellent agreement with the NA4 measurements of 87.5%, 10%, 2%, and 0.5% respectively for muon energies between 20 and 160 GeV. The simulation also indicates that the average distance between the cluster of soft particles and the muon track is ~ 3 cm, also in good agreement with the NA4 measurements. This fact could be a severe drawback for the triggering concepts using the measurements of muon chambers inside iron toroids or absorber materials.
4.3 R & D Proposals

To investigate the problems of muon trigger and identification two R&D proposals [23, 24] have been submitted to the new Detector R & D Committee (DRDC) at CERN. The proposal P7 [23] has been accepted by the DRDC. The main objective of this proposal is to demonstrate the advantage of a strong magnetic field in rejecting efficiently hadron punch-throughs and decays at the trigger level. For this purpose it is proposed to construct a small fraction of a muon detector in a strong magnetic field and to expose it to a beam containing hadrons and muons.

The P7 set-up is shown in Fig. 16. The superconducting EHS magnet with coils in a Helmholtz-like arrangement provides a maximal field of 3 T over a free space of about $1.5 \times 1.5 \times 0.8$ m$^3$. A calorimeter of about $10 \lambda$ with tracking chambers every $0.5 \lambda$ is located in the magnet and acts as an active hadron absorber. It identifies hadron showers and rejects genuine muons in the beam which would affect the punch-through measurements. Leaking particles are momentum analyzed in a second iron magnet. Three trigger and measurement stations are located along the beam line: the first behind the EHS magnet, the others inside and behind the iron magnet. The stations are composed of muon chambers arranged in the same way as in the UA1 experiment and of multiplanes of Resistive Plate Chambers (RPC) which could serve for triggering due to their fast response and their excellent timing resolution. The first two stations mimic approximately a typical muon detector at LHC: the first station behind the calorimeter ($\sim 10 \lambda$) and the second one behind the absorber.

![Image of the experimental set-up of proposal P7.](image-url)
With pion, kaon and proton beams punch-through data will be recorded under various conditions, including the effect of a strong magnetic field. The angular momentum and timing distributions of the leaking particles will be measured. With these data the efficiency of different trigger algorithms and their rejection power against punch-through and low momentum muons can be studied. With incident muon beams the reconstruction and momentum measurement of muons in a magnetized absorber will be investigated, with particular emphasis on the effects of ionization and catastrophic energy losses on momentum precision and chamber resolution [3]. Furthermore, the performance of different muon chambers, e.g. the Resistive Plate Chambers [5] or the Honeycomb Chambers [8], as fast muon triggers and precise space detectors is of vital interest for the design of an LHC muon detector.

5. Trigger Considerations [4]

The prompt muon rate at the LHC is huge and exceeds $10^6$ Hz in the central region ($|\eta| < 2$) and $10^7$ in the forward regions (see Fig. 11) for $p_T > 3$ GeV/c, the natural cut due to ranging out in the absorber. The only possible way to reduce this large rate is a significant increase of the $p_T$ threshold in the trigger. The problems for an electron trigger and a muon trigger are complementary. Whereas it is easy to raise the threshold in an electron calorimeter trigger, it is very demanding to determine muon transverse momenta around 50 GeV/c with sufficient precision at the trigger level. On the other hand, the background to the prompt muons is negligible at these transverse momenta, in contrast to the electron background which is several orders of magnitude larger than the prompt electron signal.

An important argument in favour of a strong magnetic field for a muon detector at the LHC is to achieve a good momentum resolution with moderate chamber precision, while keeping the detector dimensions reasonably small. It also allows a transverse momentum cut of around 50 GeV/c in the first-level trigger with modest spatial resolution of about 1 cm for the trigger hodoscopes. If chambers with cathode readout were used, the digital information from the strips (typical strip width 1 cm) can serve for the trigger and the analog-pulse height information yields a precise space resolution.

In principle two possible orientations of the magnetic field can be considered: a toroidal field or a solenoidal field parallel to the beams. The solenoidal field is better for triggering in the central region, since the bending is in the plane perpendicular to the beams, and the small size of the beam spot (~ 10 \( \mu \)m) provides a precise point for the momentum determination. Hence simple trigger algorithms based on track-pointing to the vertex in the R–\( \phi \) plane can provide a fast and efficient cut on the muon $p_T$ needed to reduce the muon rate to an acceptable level.
Figure 17 shows the transverse view of a possible detector based on a strong solenoidal field of 4 T. This detector concept was chosen to illustrate the general trigger problem. A calorimeter of ~ 10λ is installed inside the coil. The return yoke of the magnet, about 2 m of magnetized iron at 2.3 T, completes the absorber with a total of ~ 22λ. Fast trigger hodoscopes of granularity of σ_{RΦ} = 1 cm are placed in front and behind the coil (station 1) and outside the return yoke (station 2). Pointing of the muon track to the vertex is a measure of the muon p_T and can be checked in the two trigger stations by measuring the angle α defined in Fig. 17. Clearly station 1 profits from the full bending power of the magnet and therefore provides a sharper p_T cut than station 2, where the net bending is reduced by the reversal of the field in the return yoke. However, station 2 is cleaner since it will see less punch-through background than station 1. Muons are often embedded in jets which may leak to station 1 and may cause a confusion due to combinatorial background in the momentum reconstruction of the muon, in particular at the trigger level.
Figure 18 shows the efficiency of a trigger based on an angular cut $\alpha$ in the R–$\phi$ plane at stations 1 and 2 and with an improved resolution of 1 mm as achievable in a second-level trigger. Going from station 2 to station 1 and then to the second-level trigger improves the steepness of the efficiency curves considerably. Being able to choose the $p_T$ cut between 10 and 100 GeV/c enables one to adapt the trigger rate to the luminosity. The tightest cut on $\alpha$ in station 2 with full efficiency for large momentum muons is 80 mrad. It results in a $\geq 90\%$ efficiency for $p_T > 17$ GeV/c but still accepts 10% of $p_T = 8$ GeV/c muons. The efficiency functions are used together with the muon $p_T$ spectra to calculate the trigger rate for a given angular cut in each of the discussed trigger options. The corresponding single and dimuon rates for $|\eta| < 3$ are given in Figs. 19 and 20 for a luminosity of $2 \times 10^{34}$ cm$^{-2}$ s$^{-1}$. The different production mechanisms are shown separately.

Single-muon triggers are needed for the observation of large $p_T$ W’s and in combination with other triggers, e.g. from the calorimeter. The single muon rate for the above cut of 80 mrad in station 2 is as large as $2 \times 10^4$ Hz. The same cut applied to station 1 reduces the single muon rate to about $10^3$ Hz, still maintaining a high efficiency for muons with $p_T > 60$ GeV/c. This rate can then be further reduced by the second-level trigger ($\alpha < 40$ mrad) to an acceptable data-taking rate of $10^2$ Hz without significant losses in the efficiency. Muons from background are already negligible after the trigger in station 2.

The dimuon trigger has to pick-up all the Z's decaying into muons and hence has to be efficient for a muon $p_T > 25$ GeV/c. This can be achieved with an angular cut of 150 mrad in station 1 and of 100 mrad in the second-level trigger. The main contribution to the rate of $\sim 50$ Hz is then from Z decays.

With this example we wanted to demonstrate that with an optimized muon detector the trigger problem can be solved, even for the single-muon trigger, up to the highest expected LHC luminosities.
Fig. 18 Muon trigger efficiency as a function of the muon transverse momentum for different pointing angle cuts and three trigger options.
Fig. 19 Single muon trigger rate as a function of the cut angle for three different trigger options.
Fig. 20 Dimuon trigger rate as a function of the cut angle for three different trigger options.
6. Muon Chambers

Because of the high luminosities anticipated at the LHC, the extremely short time of 15 ns between bunch crossings and the resulting high muon rates of 1 MHz to 10 MHz, the demands on the muon chambers for LHC experiments are different from the requirements at previous colliders. The chambers have to provide fast signals in order to trigger the events of interest. In addition, their resolution has to be as good as possible in order to keep the detectors within reasonable limits of size and costs. The ideal solution would be the combination in one detector of a good timing resolution, a fast signal propagation (comparable with scintillation counters) and a high precision. The requirements are the following:

- The timing should be better than 5 ns.
- The readout should be fast. Simple algorithms should give a spatial resolution of about ~ 1 cm per layer in order to have the possibility of fast first-level triggering.
- The chambers should cover large areas and, as a consequence their design should be simple with adaptable geometry. They should have mechanical stability, and features should be built in to align different chamber layers up to 50 μm.
- The chambers should be able to operate in large magnetic fields.
- They should be able to tolerate rates of up to 100 Hz/cm² for production angles θ > 30° and up to 10⁴ Hz/cm² in the forward direction.

In order to achieve the above goals, one has to compare and optimise conflicting design considerations with their advantages and disadvantages, such as drift time versus induced charge, or high versus low gain. Experience exists with chambers based on drift-time measurement. They have a good signal-to-noise ratio and a good two-track resolution. But the time resolution may not be appropriate and distortions in magnetic fields limit the space resolution. The measurements based on the induced charge, and which are intrinsically more accurate are complementary. The chambers can be fast, with an excellent time definition, and the pattern of the readout electrodes can be adapted to geometrical requirements. The operation modes of the chambers with high or low gain are also complementary. Low gain offers the advantage of safer operation and allows higher rates, but it needs amplifiers and suffers from noise and grounding problems. With high gain, the electronics can be simplified, but the operation becomes more critical, space charges and ageing may become problematic, and the maximum tolerable rate of the chambers is definitely much lower.
Several new developments have been presented at this workshop and they will be discussed in the following sections.

6.1 Resistive Plate Chambers [5]

Plastic Resistive Plate Chambers, RPCs, developed in Rome [25], are gaseous parallel-plate detectors which work in the limited streamer mode. They combine over a large surface the space resolution typical of wire chambers with the time resolution typical of scintillators. A schematic drawing of the chamber is shown in Fig. 21. These RPCs are made of two parallel plates of phenolic polymer, bakelite, with a bulk resistivity $\rho \sim 10^{11} \Omega \cdot \text{cm}$ enclosing a thin gap filled with a mixture of argon and organic gas. The two plates are kept parallel with spacers of polyvinyl chloride (PVC), and gas tightness is ensured by a frame of the same material. The outer surfaces of the resistive plates, painted with graphite, are the electrodes that generate the electric field. The inner surfaces of the resistive plates are painted with an oil-based varnish. The readout electrodes where the charge is collected are separated from the field-generating electrodes by a thin insulating layer of PVC. The whole structure is about 2 cm thick and can be built in large arrays.

![Sketch of a Resistive Plate Chamber](image)

**Fig. 21** Sketch of a Resistive Plate Chamber.
Chambers filled with a gas mixture of 60% argon and 40% n-butane reach a plateau at a voltage of about 8 kV with an efficiency for minimum-ionizing particles of typically 97%, limited by the dead zones around the PVC spacers. The rise-time and the length of the pulses are typically 3 ns and 10 ns, respectively, and the charge collected is 100–200 pC, producing a pulse of about 300 mV over a 50 Ω resistance: there is thus no need for further amplification of the signal. The intrinsic time resolution is about 1 ns. The readout electrodes can be shaped in various configurations: in case of strips the propagation time along the transmission line is about 5 ns/m with no appreciable attenuation over a few metres.

Whenever a limited streamer discharge occurs in the gas, it extends over an area of typically 10 mm² and the recovery time needed to recharge locally the capacitance is \( \tau = \rho \varepsilon \approx 10 \text{ ms} \) (where \( \varepsilon \) is the dielectric constant of the resistive plate). This limits the efficiency of the chamber at large particle fluxes. Measurements of the efficiency as a function of the particle flux have shown that there is no substantial degradation of the chamber performances for fluxes up to 100 Hz/cm² [26].

RPCs look very attractive for a fast muon tracker at the LHC, since they have a time resolution much smaller than the time interval between bunch crossings, and can provide a fast first-level trigger. A trigger with a momentum cut-off of 20–50 GeV/c can be realized with RPCs with a strip width of about 1 cm in different magnetic configurations. Such a trigger system would require more than 2000 m² of active surface. Large-area RPC arrays have been used in the experiments NADIR [27], FENICE [28] and E771 (Fermilab), showing reliability and little need for maintenance.

The main areas for further study in order to support an RPC solution for LHC experiments are:

- The space resolution with analog readout of the charge, in order to obtain the ultimate resolution of these chambers.
- Their operation in high magnetic fields, which in principle should not present any problems.
- The reduction of the discharge as a function of gas mixtures and plate resistivity in order to obtain high efficiencies under large particle fluxes.

### 6.2 The Coated Cathode Conductive Layer Chamber [6]

The COCA COLA chamber [29] is shown schematically in Fig. 22. The basic idea is derived from the microstrip gas avalanche chamber [30], but instead of having the electrodes on the same side of the insulating material, they are put on opposite sides. Consequently, when high voltages are applied, the electric field lines show the same pattern as the microstrip chamber. However, this arrangement solves the problem of
strips being destroyed by sparking. In the case of the COCA COLA chamber, the insulator is a plastic foil (Tedlar) of 100 μm thickness, with a bulk resistivity of $\rho = 10^{10}$ Ω cm and a dielectric strength of $\sim 10$ kV/100 μm. A small test chamber was irradiated with a $^{106}$Ru β-source and pulses of 0.1 pC were obtained from the anode, corresponding to a gain of $10^4$. An efficiency of 75% was reached for a voltage difference of 2 kV between anode and cathode, with at least $-3$ kV at the cathodes. The time constant observed for the recovery of the efficiency when going down in voltage could be due to space-charge effects from the ions settling on the Tedlar foil. If a larger chamber could be built and its problems understood, the main advantage of such chambers could be the possibility of easily varying their shape and size. In principle large areas could be covered at a low cost.

![Diagram](image)

**Fig. 22** Schematics of the Coca Cola Chamber

### 6.3 The Blade Chamber [7]

A chamber operated in the limited streamer mode, in which a blade, instead of a wire, is used as the amplification electrode, has been built as part of the LAA project at CERN [31]. As the blade can be bent to follow a circular shape, chambers can be built with cells ideally matched to the geometry of an experiment, in particular in the forward directions at rapidity values larger than 2.5. A cross-section of this chamber is shown in Fig. 23. The roof of the chamber is made of an insulating Kapton foil with pick-up strips to measure the position in the direction perpendicular to the blades and is located 6 mm above the 30 μm thick blades. The walls are at ground potential and the blades at 10 kV.
Figure 24 shows the field and equifield lines in the chamber. The electrons liberated along the particle trajectory drift towards one of the blades where a streamer then develops towards the roof. As only field lines in the upper part of the chamber reach the tip of the blade, where the multiplication takes place, only part of the gas volume can be considered sensitive for traversing ionizing particles. Large signals with an average of 60 pC and 20 pC were observed from the blades and pick-up strips, respectively. Efficiencies of 95% were obtained in a CERN-PS pion test beam, where the loss of efficiency could be completely understood as a loss due to geometrical effects such as wall thickness etc. Using the signal differences between the charges collected on the walls surrounding a blade (see Fig. 25) the left–right ambiguity could be solved in 93.5% of the cases. The resolution obtained with the measurements of the drift times to the
blades is $\sigma = 250 \mu m$. The pickup strips yield a resolution in the perpendicular direction of $\sigma = 380 \mu m$.

The main areas for further study for these chambers are:

- Their operation in magnetic fields.
- The effect of particle rate on chamber efficiencies and resolution.
- The construction of a large-scale prototype to understand the problems connected with mass production.

6.4 The Honeycomb Strip Chamber [8]

The honeycomb strip chamber [32] is a segmented-cathode-readout chamber. It is made from foil with conductive strips. The foil is folded perpendicularly to the strips into a 'ribbon' foil. Two of these foils glued together give a layer of honeycomb cells. A wire is positioned in the centre of each cell. A schematic overview of the successive steps needed to construct such a chamber is given in Fig. 26. End covers, acting as honeycomb facings, provide a mechanical support for the wires and, together with a stack of layers, form a stiff, self supporting and light honeycomb structure. In Fig. 27 the basic element of the chamber is shown: each wire is coaxially surrounded by conducting hexagonal rings. A minimum-ionizing particle passing the volume inside the rings causes an avalanche on the wire.

Fig. 26 Schematic view of the steps to construct a Honeycomb Chamber

Fig. 27 Basic element of the Honeycomb Chamber
A prototype chamber was constructed at NIKHEF, consisting of 8 layers of 24 cells and 54 strips each, with a surface area of $30 \times 30$ cm$^2$. The strip width was 4.0 mm, with a strip pitch of 5.0 mm, and a cell radius was 5.77 mm. The chamber was placed inside the magnet of the L3 test beam area and exposed to the X3 SPS test beam consisting of 10 GeV/c momentum pions. Runs were taken with different gas mixtures (Ar/ethane 62/38, Ar/CO$_2$ 80/20 and Ar/CO$_2$ 50/50) and magnetic fields ranging up to 0.93 T. A positive HV was applied on the wires; the value was adjusted between 1500 kV and 2000 kV. The corresponding gas gain was $10^5$. In Fig. 28 the resolutions are shown for different gas mixtures and magnetic fields as a function of $\phi$. Shifts of the minima of the curves are seen in agreement with the Lorentz angle induced on the drifting electrons in the gas of the cell. At $\phi = 0$ a best resolution is reached of $\sigma_0 = 90$ $\mu$m. The angular dependance corresponds reasonably well with the one found with a Monte Carlo calculation.

The main areas for further study of these chambers are:

- The construction of a large-scale prototype to understand the problems connected with mass production.
- The development of the readout electronics so that virtually all these components can be located on the chambers, substantially reducing the cabling problem for a large LHC experiment. The chambers could in principle be made to be self-triggering within 200 ns. These features would require a substantial amount of special purpose electronics.

Fig. 28 Measured resolutions of the Honeycomb Chamber as function of the incident particle angle for various conditions

As discussed earlier the muon detection should extend over a rapidity range $|\eta| < 4$ and the momentum resolution should be of the order of a few per cent. There are two basic magnetic field configurations which are almost complementary:

- the toroid, with the field lines circular around the beams
- the solenoid, with the field lines parallel to the beams

A large and uniform rapidity acceptance can be achieved more easily with toroids. The bending power of the magnetic field increases as $\int B \, dl \sim \sin^{-1} \theta$ ($\theta$ is the production angle) and is almost independent of geometry. This is due either to the increase of the path length with decreasing $\theta$ for the central toroids or to the $1/R$ dependence of the field of the forward toroids. Thus the bending power compensates the increase of the momentum of the forward particles and yields a constant momentum resolution at fixed $p_T$ over a large rapidity range. A schematic view of two possible toroidal field configurations is given in Fig. 29 (from Ref. [9]). The field lines in a toroid are completely surrounded by the coils, which makes the stray field small, but complicates the instrumentation. Even modest demands on the field uniformity require a large number of coils. The net forces towards the centre have to be compensated by a rigid structure between the individual coils, making the access and the alignment of the chambers problematic. Coil dimensions are large and it is difficult to stabilize the rectangular shape of an individual coil [10]. In summary, one can conclude that toroids are an attractive solution, but they are difficult to build if the magnetic fields are large.

Fig. 29 Schematic view of two toroidal field configurations.
Another feature of the toroid, the absence of a central magnetic field around the intersection point, can be discussed controversially. Central tracking will be easier since the trajectories are straight lines and curling tracks are not confusing the pattern recognition. Electron pairs from gamma conversions or Dalitz decays are not opening up and can be rejected by pulse-height measurements. The jet resolution of the calorimeter is not affected by the deflection of low-momentum particles. Electronics sensitive to the magnetic field can be chosen for the inner detectors. On the other hand, the sign and the momentum of the particles entering the calorimeter cannot be determined, which is a major disadvantage for the electron identification. The muon momentum will be only measured behind the absorber thus limiting the resolution of low-momentum muons.

In contrast to the configuration of the toroidal field, the solenoidal one offers the advantage that the bending takes place in the transverse plane; the precise beam position can therefore be used in the trigger and for the momentum determination. The mechanically more favourable geometry of a solenoid with circular coils makes a magnet with 4–6 T possible, facilitating the first-level trigger. The iron return yoke acts as a muon filter and enables a second momentum measurement. For a given $\int B \, dl$, a solenoid is much more compact and the stored energy is smaller compared with a toroid. But a strong magnetic field, as used in a compact detector, may impose severe constraints on the muon chambers. The major disadvantage of a solenoid is the degradation of the resolution in the forward directions. A central solenoid has therefore to be complemented, for instance by forward toroids, with some possibly complicated transition regions between the two magnets.

For the muon-momentum measurements, different alternatives can be presented as far as the positions of the muon chambers are concerned. They can be placed inside or outside the magnetic volume, which can be filled with iron or not. In the following the resulting momentum resolutions are given (field $B$ in teslas, length $L$ in metres, momentum $p$ in TeV/c and chamber resolution $\sigma$ in mm).

An elegant and compact solution is the simultaneous use of magnetized iron for bending the muons and absorbing the hadrons. In the case where multiple scattering is dominating, the resolution is independent of the momentum and is given by:

$$\Delta p \over p = 0.4 \sqrt{L \cdot B}.$$  

For a 3 m iron absorber, saturated at 1.8 T, the resolution is limited to ~13%. Increasing the thickness would only marginally improve the momentum resolution but would drastically increase the total weight. Of course, above a certain momentum the chamber resolution starts to dominate and the importance of precise tracking becomes obvious. According to Ref. [33] it is important to measure the incident and the exit angles of the
track precisely. Figure 30, taken from Ref. [9], demonstrates at which momenta the momentum resolution deteriorates if tracking (200 μm) is only done inside the iron (1), if one outside direction with a precision of 0.1 mrad is used (2), and if both outside directions are determined (3). The outer measurements are the most important ones and do not suffer so much from the degradation of the chamber resolution due to muon-induced showers. Magnetizing the iron to 5 T with a superconducting coil improves the resolution significantly (Fig. 30).

![Graph showing momentum resolution of an iron toroid for different chamber scenarios. Dashed curve is for a 5 T superconducting toroid.](image)

**Fig. 30** Momentum resolution of an iron toroid for different chamber scenarios. Dashed curve is for a 5 T superconducting toroid.

Another concept is the measurement of the muon track inside an almost material-free magnetized volume. It has been demonstrated that the best momentum measurement can be achieved if the particle is measured at three positions along its trajectory, at the entry of the field region (N1 independent measurements), the middle (N2 independent measurements) and at its exit (N1 independent measurements). The resolution is then given by:

\[
\frac{\Delta p}{p} = 26.7 \sigma \left( \frac{1}{2N_1} + \frac{1}{N_2} \right)^{\frac{1}{2}} \frac{p}{BL^2}.
\]

In this case, relatively low fields of less than 1 T are preferred, so that precise, conventional drift chambers can be used over large distances L. This concept is successfully used in the L3 detector at LEP [34]. In general, the resolution is limited by the precision of the chamber alignment (better than 50 μm) and the chamber resolution.
In some detector concepts, difficulties may arise with the accessibility of the chambers in the magnet. If only the incident and exit trajectory outside the magnet can be measured, then the momentum resolution is limited by the multiple scattering in the coils and the support structure between the measurement and the field:

\[ \frac{\Delta p}{p} = \sqrt{\frac{D}{BL}}. \]

The material thickness \( D \) (in units of radiation lengths) should obviously be reduced to a minimum for a precise momentum determination.

7.1 Iron Toroid [9, 10]

In this section we will present the muon spectrometer of Ref. [10] and briefly discuss an alternative high-field iron toroid.

An overview of the detector is shown in Fig. 31. An inner region, cylindrical in shape with a size of 8 m in diameter and 13 m in length for inner tracking and calorimetry (for certain calculations a 12\( \lambda \) Pb calorimeter inside this volume is assumed), is surrounded by segmented iron toroids in the central and forward regions. The total weight of the iron is 30,000 tons and the anticipated Al coils weight \( \sim 100 \) tons. The power consumption of such a magnet would be 3 to 5 MW [10]. The toroids are subdivided in 4 layers of iron of 0.75 m and 1 m thickness in the central and forward regions respectively. The iron layers are interleaved with muon detectors giving a total of 5 measuring stations.

The essentials of the muon momentum resolution for this detector concept are already given in Fig. 30 (curves 1, 2 and 3). If the incident and exit track angles are measured precisely (curve 3), the charge of the muon can be measured up to at least 2.5 TeV/c [9]. The requirements on the muon chamber precision and their alignment to this accuracy is however a difficult problem.

A first estimate has been made of the total number of measuring wires in the muon system. Assuming five stations of chambers with 8 planes each, a total of 200,000 wires are needed. If conventional electronics would be used the price for the electronics can be estimated to be \( \sim 40 \) MSfr. Price estimates for the iron and coils range between 95 and 125 MSfr. The iron and aluminimum alone are estimated to constitute between 70 and 90 MSfr. Further studies for this design are underway, in particular a triggering scheme has to be evaluated.

To improve upon the moderate muon momentum resolutions obtainable with the example given above a high field iron toroid has been studied. Very high currents are
required above the saturation point of iron at 2.16 T, which leads automatically to superconducting coils. In Fig. 32 the layout of a possible detector is shown [9]. The 5 T field over the 1.5 m thick iron core improves the multiple scattering limit of the momentum resolution to 6.5% (see also the dashed curve of Fig. 30). The iron in this example serves as absorber and as a rigid support structure for the coils. The total amount of iron is a factor 3 smaller than in the example of the warm toroid. The disadvantage is that the 10000 t of iron has to be cold. Further problems are the large size of the coils themselves, the required vacuum vessel, and the large stored energy of 3.6 GJ in the barrel.

Fig. 31 An iron toroid spectrometer inside a possible experimental area.

Fig. 32 A detector with superconducting iron toroids.
7.2 Air Core Toroid [12]

The Large-Area Devices group of LAA investigated a muon spectrometer with toroidal magnetic field [35]. The field configuration was studied using the finite-element program TOSCA. In Fig. 33 a side view of one quadrant of the proposed detector is shown. An inner region, cylindrical in shape, with a diameter of 6 m and a length of 8 m, is surrounded by 16 large superconducting coils, complemented by two sets of 16 smaller coils in the forward regions. Figure 34 gives a perspective view of the central superconducting coils with their support system. The magnetic field is 2 T in the centre and reaches a maximum of 2.7 T in some other regions. Detailed field maps can be found in references [12] and [36]. The total stored energy is estimated to be 3.14 GJ, of which 2.9 GJ is in the central coil.

![Diagram of Air Core Toroid]

Fig. 33 Side view of one quadrant of the air core toroid.

Muons are tracked by three staggered chamber layers (to avoid dead angles) positioned in front, inside, and outside the coils. No iron return yoke is necessary, giving in principle a light, compact detector. The momentum resolution was studied for 500 GeV/c muon tracks originating from the central interaction region and tracing them through the magnetic field. No multiple scattering was assumed in the various detector layers. In Fig. 35 the $\Delta p/p$ as a function of $\theta$ is shown for the 500 GeV/c muon tracks. The resolution is better than 4% over the full $\theta$ range, except below 7° and around 25°, at the change-over from central to forward magnet. The authors stress the fact that this
Fig. 34 Perspective view of the central superconducting coils with their support system.

resolution is obtained using the muon spectrometer only: no additional information was used from inner detection elements. They also remark that one of the muon detector elements has to be inside a magnetic field of up to 3 T. If drift chambers are used, this is not a trivial requirement.

In their conclusions, the members of the LAA group state the following [35]: "The main difficulties in this design come from the large amount of stored magnetic energy and the high forces on the superconductors. To prevent the detector from damage during a magnetic quench, a sophisticated protective circuit will be necessary. It is clear that many contact points between the superconductor and the support are necessary to absorb the high forces, which makes the thermal insulation difficult".

Fig. 35 Momentum resolution versus production angle. Line A and B are for two different $\phi$ angles.
7.3 Compact Muon Solenoid [13]

As discussed earlier, a strong central magnetic field offers the possibility to achieve a good momentum resolution, while keeping the size of the detector reasonably small. Figure 36 from Ref. [13] shows a design study for a Compact Muon Solenoid (CMS). A 15 m long solenoidal coil with an inner diameter of 7 m produces a magnetic field of 4–6 T. The field map in Fig. 37 has been calculated for a current density varying from 8 MA/m² at the centre to 13 MA/m² at the edges. The material-free region (R < 1.5 m) for inner tracking is followed by an electromagnetic calorimeter (1.5 < R < 2 m) and a hadron calorimeter (2 < R < 3.5 m) made out of iron. The use of iron as a muon filter has a twofold advantage for the momentum measurement: the magnetic field is increased from 4 to 6 T and the number of radiation lengths (85X₀) for a 9λ hadron calorimeter is small compared with the 275X₀ in the case of uranium. Since the coil is behind the calorimeter there are no limitations on the thickness of the coil. The return yoke of the magnet with about 2 m iron at 2 T completes the absorber, which has a total of 22λ.

Valuable experience already exists for the construction of a very large superconducting coil. The BEBC magnet [36] was a solenoid producing a central field of 3.5 T, with a thick superconducting coil of 5.5 m diameter. A similar 'pancake' design of the coil has been found feasible for this solenoid [37].

**Compact Muon Solenoid (CMS)**

<table>
<thead>
<tr>
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<th>muon chambers</th>
</tr>
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<tbody>
<tr>
<td>2 very forward toroids</td>
<td>750 tons</td>
</tr>
<tr>
<td>4 forward toroids</td>
<td>5000 tons</td>
</tr>
<tr>
<td>solenoid</td>
<td>11500 tons</td>
</tr>
<tr>
<td>calorimetry</td>
<td>4000 tons</td>
</tr>
<tr>
<td>Total</td>
<td>20750 tons</td>
</tr>
</tbody>
</table>

![Diagram of CMS](image)

**Fig. 36** Side view of the Compact Muon Solenoidal Detector.
Fig. 37 Magnetic field lines and the z-component \( B_z \) in the transverse plane at \( z = 3 \) m.

In order to extend the limited rapidity coverage of the solenoid, three superconducting toroids are placed on each side of it, behind the end-caps. The toroidal field in the saturated iron varies from 4 T near the inner edge to about 2–3 T at the outer edge. The forward calorimeters are inside the end-caps and the first toroids.

Muon chamber arrays are placed before and after the coil (assumed resolution of the array in the transverse plane \( \sigma = 100 \mu m \)) and outside the return yoke (\( \sigma = 200 \mu m \)). In the inner volume the vertex is known with 20 \( \mu m \) precision and the two inner tracking stations, at 0.75 m and 1.5 m, are supposed to reach a precision of 50 \( \mu m \). Under these assumptions the momentum resolution has been calculated with full reconstruction of simulated tracks. The resolution is shown in Fig. 38 for different rapidities as a function of the momentum. The three plots correspond to different inner tracking configurations: no inner tracking, one point at \( R = 1.5 \) m and an additional point at \( R = 0.75 \) m. The inner measurements are difficult, because of the large particle flux. But the strong magnetic field introduces an effective \( p_T \) cut of 0.9 GeV/c for tracks reaching the chambers at \( R = 1.5 \) m, thus reducing the particle flux by a factor of 4. The muons can be tracked from outside, so that the positions in the two inner tracking stations are known with a precision of about 1 mm. With fine-grain detectors the occupancy will therefore be acceptable, even at large particle fluxes.
Fig. 38 Momentum resolution versus momentum for three different tracking options.
RESOLUTION vs RAPIDITY
Central solenoid + Forward toroids, Iron calorimeter

Fig. 39 Momentum resolution versus rapidity for three different tracking options.
The momentum resolution improves considerably if the two inner tracking chambers can be used. The momentum is then also measured before the absorber, where the random effects of energy losses and multiple scattering are negligible. The second and third measurements after the absorber basically improve the resolution at large momenta. But even if the most difficult chamber station at \( R = 0.75 \) m can only be realized with new technologies at a later stage, the momentum resolution still ranges between 4 and 6%. With the complete reconstruction an exceptional momentum resolution at low \( p_T \) can be achieved

\[
\Delta p/p = 0.2p_T \quad (p_T \text{ in TeV/c}) .
\]

In Fig. 39 the resolution is plotted versus the muon rapidity for different momenta. Up to \(|\eta| \sim 2\) the resolution is dominated by the measurements in the central solenoid. At larger rapidities the superconducting toroids take over and the resolution decreases to 6-8% independently of momentum up to 1 TeV/c.

A possible trigger scheme for this detector has already been discussed in section 5.

The concept of the CMS is very demanding and it has to be proved that a superconducting solenoid of this size, with a stored energy of about 4 MJ and such big superconducting toroids, can be realized. The muon chambers around the coil are essential for the momentum measurement. Leakage from jets after 10\( \lambda \) may cause confusion in the track reconstruction. This problem will be investigated with the DRDC proposal of Ref. [23].

7.4 Shaped Solenoid for Muon Spectroscopy [14]

Two principal ingredients of air-field spectroscopy are presented in Ref. [14]: the magnet and the tracking possibilities for muons. The concept is that of the L3 [34] detector, even though the detailed approach is different and is claimed to offer possible experimental advantages. As the magnetic coverage down to small polar angles is difficult for unshaped solenoids, a shaped solenoid has been proposed for supercolliders [38]. A variation of this concept with the field shaping accomplished by six discrete superconducting coils is shown in Fig. 40. By increasing the current density at the ends and by extending the yoke into cones for improved flux bending at small polar angles, a considerable bending power is possible down to rapidity values smaller than 2.3. Figure 41 shows the integral \( BL^2 \) of the magnet as a function of rapidity. The anticipated current densities of 20 A/mm\(^2\) in the two forward coils and 5 A/mm\(^2\) in the large central coils allow for known conductor technology. The overall diameter of the
Fig. 40 Cross-section through the solenoidal magnet with shaped iron poles.

Fig. 41 Integral $BL^2$ of the shaped solenoid (left ordinate and solid line) and the sagitta for a 1 TeV particle (right ordinate and dashed line).

magnet, including the return yoke, is approximately 20 m. The cylindrical yoke contains about 25,000 t of iron; the two forward portions each weigh about 4500 t.

A conceptual detector layout is shown in Fig. 42. The cylindrical yoke supports the central (3000 t) detector by means of support rods, possibly arranged as the spokes of a bicycle wheel. The support system for the muon trackers, a so-called 'space frame', is foreseen to be constructed from composite materials combining high strength, stiffness, and relatively low atomic number, with almost zero thermal expansion. For muon tracking, three recent developments are under consideration: microstrip avalanche chambers [30], pad chambers [39], and straw chambers [40].

The next steps to evaluate the feasibility of the ideas sketched above are:
- The engineering aspects of the magnet should be studied in more detail,
- The technique for supporting the muon trackers should be investigated and a detailed engineering program should be started.
- A R&D program is needed to study the tracking performance of the several possible muon trackers mentioned.
Fig. 42  Conceptual layout of a muon spectrometer inside the shaped solenoid.

7.5  The L3 + 1 Detector [15]

The L3 Collaboration has investigated the possibility of using, with a limited amount of additions and modifications, the existing L3 [34] detector at the LHC. As the beam height of the LHC will be 1.20 m above the LEP beams, the first question to be addressed is the raising of the L3 magnet by that amount. An engineering firm, together with some of the engineers of the CERN-EF division, has made a detailed feasibility study. By making access paths inside the concrete bed on which the L3 magnet rests and by placing hydraulic jacks at various positions, the iron structure could be raised in a relatively short time (see Fig. 43).

The existing central drift chamber TEC and the electromagnetic BGO calorimeter of L3 could be replaced by a new central-barrel uranium calorimeter. The existing uranium calorimeters in the central and forward regions could be adapted by replacing each second layer of the proportional chambers with new uranium plates, and interchanging the existing muon filter with absorber material. The remaining proportional chambers could be replaced by containers filled with liquid scintillator and optical fibres. The total number of absorption lengths is increased to $\geq 13\lambda$ and $\geq 17\lambda$ in the central and forward regions, respectively (see Fig. 44). The advantage of this solution
is the utilization of the existing mechanical structures; the disadvantage is that the calorimeter starts already at 20 to 40 cm from the interaction point.

The possibility of replacing the existing L3 detector inside the support tube with a silicon calorimeter as an alternative to the uranium-liquid scintillator option is also being investigated by the group [15].

Fig. 43 Side view of the L3 + 1 detector.

Fig. 44 Perspective view of the L3 + 1 central calorimeter.
Fig. 45 Perspective view of the central and forward magnets.

Fig. 46 Momentum resolution versus the polar angle a 50 GeV/c muon.

In order to increase the solid angle for muon detection, two additional solenoids in the forward and backward regions, with their magnetic field lines perpendicular to the beam axis, would be necessary (see Fig. 45). One of the advantages of this configuration is the homogeneous magnetic fields inside these iron boxes, giving the opportunity to use the same type of drift chambers as in the central and existing part of the L3 detector. Another advantage is the fact that the existing underground cave at I2 of LEP can be fully utilized, no alterations would be necessary, and a possible installation scenario has been investigated.
At the moment the resolution obtained with the L3 central muon system is $\Delta p/p = 2.4\%$ at 50 GeV/c for $BL^2 = 4.5$ Tm² [34]. The magnets in the forward regions are currently designed in such a manner that the same resolution can be reached for muons measured by three forward-chamber layers. The magnetic field strength is kept relatively low (0.2 T) in order to minimize the costs. Given the size of these magnets, the analysing power of the proposed set-up is $BL^2 = 5$ Tm².

The resolution $\Delta p/p$ of the L3+1 detector for muons with a momentum of 50 GeV/c is shown in Fig. 46 as a function of $\theta$. In the angular regions covered by two layers of chambers, the resolution jumps from $\sim 2\%$ to $\sim 5\%$ and $\sim 7\%$ in the central and forward regions, respectively. The geometrical acceptance for four muons originating from the decay of a Higgs particle was calculated to be 70% for the mass range of $130$ GeV/c² $\leq m_H \leq 600$ GeV/c². A gap in the acceptance appears for regions covered either by one muon chamber only or by two muon chambers, belonging to two different systems (central and forward, for instance). The L3 Collaboration is working towards solutions to fill the acceptance gap and to improve the resolution in $p_T$ in the forward–backward regions.

8. Conclusions

The discussions about the optimization of a muon detector at the LHC clearly show that these detectors must be large if the muon momentum resolution and acceptance are to be appropriate for the Higgs search. A strong central magnetic field may allow the size to be reduced, at the expense of operating the muon chambers in this strong field. With the enormous particle densities and the short time interval between bunch-crossings, we are entering with the LHC a virgin territory in instrumentation. The requirements on high spatial resolution and excellent timing information, together with a fast response time, make the development of new chamber technologies mandatory. Special emphasis has to be given to problems of chamber alignment and operation in such a hostile environment. One should be aware that the magnetic field configuration and the chamber design are intimately linked.

It has been demonstrated - at least on paper - that muon triggers and identification are possible up to the highest LHC luminosities. In contrast to the situation at LEP and the p+p Colliders, the rate of prompt muons is huge, typically $10^7$ Hz, and can only be reduced to an acceptable data-taking level by applying a rather large $p_T$ cut. In this case the background from pion and kaon decays in an inner detector is negligible.

When comparing different detector designs one recognizes that good momentum resolution is only achievable with either precise tracking in an open air-core magnet or
with an iron absorber magnetized far above saturation. The best solution may be a combination of both.

<table>
<thead>
<tr>
<th></th>
<th>B (T)</th>
<th>L (m)</th>
<th>B.L**2</th>
<th>s (mm)</th>
<th>Δs (μm)</th>
<th>Δp/p (1 TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>L3 + 1</td>
<td>0.5</td>
<td>3.0</td>
<td>4.5</td>
<td>0.17</td>
<td>68</td>
<td>40%</td>
</tr>
<tr>
<td>Air Toroid (LAA)</td>
<td>1.6</td>
<td>4.6</td>
<td>33.8</td>
<td>1.27</td>
<td>90</td>
<td>7%</td>
</tr>
<tr>
<td>Shaped Cold Solenoid</td>
<td>0.7</td>
<td>5.0</td>
<td>18.0</td>
<td>0.70</td>
<td>90</td>
<td>13%</td>
</tr>
<tr>
<td>CMS (inner tracking)</td>
<td>4.0</td>
<td>1.5</td>
<td>9.0</td>
<td>0.34</td>
<td>50</td>
<td>14%</td>
</tr>
<tr>
<td>CMS (all)</td>
<td>6.0</td>
<td>3.5</td>
<td></td>
<td></td>
<td></td>
<td>5.6%</td>
</tr>
</tbody>
</table>

The parameters of the discussed detector concepts are compared in the table above and the resulting momentum resolutions are given in Fig. 47 as a function of the momentum. At low momenta, all muon measurements behind the absorber are limited by multiple scattering and energy loss fluctuations. In Fig. 48 the momentum resolutions are given as a function of the rapidity for a fixed transverse momentum of 100 GeV/c, which corresponds to a momentum of 1 TeV/c at |η| = 3. Resolutions of the order of a few percent can be reached by most of the designs over a large rapidity range. That such a resolution is of importance for the search of the low-mass Higgs can be deduced from Fig. 49, where the mass distribution for a 140 GeV Higgs is shown for different resolutions. In this case an excellent resolution at momenta as low as 10 GeV/c is essential.

![Graph showing comparison of momentum resolution](image)

**Fig. 47** Comparison of the momentum resolution of discussed detector concepts at |η| = 0.
Fig. 48 Momentum resolution versus rapidity at $p_T = 100 \text{ GeV}/c$.

Fig. 49 The mass distributions of a 140 GeV Higgs for different resolutions.
At the end of this report we want to stress the importance of a vigorous R&D programme which should concentrate on the following topics:

- Feasibility studies of large magnet designs;
- Detailed engineering studies of possible detectors in order to understand the necessary modularity, their installation, and the resulting consequences for the experimental underground halls;
- Construction of prototype muon detectors for tests of their behaviour in magnetic fields and at high rates;
- Alignment studies for large muon detectors;
- Investigation of trigger concepts and construction of prototypes to test their behaviour under conditions as close as possible to those of the LHC environment.

Acknowledgements

We would like to thank all members of the Muon Working Group for their contributions to this Workshop, and for the many fruitful discussions we have had with them. We have also greatly appreciated the help given by the CERN Scientific Reports Editing Section.

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Signal Processing, Triggering and Data Acquisition

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Abstract

We address issues of triggering and data acquisition for the LHC. The parameters of the accelerator together with predictions for cross sections and a detector model are used to evaluate the system requirements. We then review the available technology and discuss how a trigger and data acquisition system might be constructed. We comment on areas in which the design of detectors, and of trigger and data acquisition systems affect each other. We also indicate areas of rapid technological advance which are relevant to triggering and data acquisition. Finally, we highlight areas in which further R&D is required.
1. Introduction

Some of the general issues of signal processing, triggering and data acquisition for the LHC were addressed at previous workshops [1]. Here we attempt to outline in more detail how a trigger and data acquisition system might be built. Obviously much needs to be done before such a system could be realized. However, our studies suggest that it is possible in principle to construct a system with the required performance using technology which is either available now or which is in an advanced state of development.

In chapter 2 we try to set out the assumptions we have made regarding the performance which is required for the trigger and data acquisition system. Starting from a beam crossing interval of 15 ns, we estimate trigger rates and data volumes at various points in the system. The trigger rates are affected by the parameters of the machine, the predicted cross-sections and the physics signatures which are deemed to be of interest; data volumes are in addition affected by the number of channels and occupancy of the detectors. We use estimates for a typical general purpose detector operating at a luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$.

In chapter 3 we outline a possible architecture for the trigger and data acquisition system. This is based on a multilevel trigger in which the crude trigger decisions made quickly at the first level are progressively refined at higher trigger levels. Data are buffered in digital or analogue memories during each stage of trigger processing. We pay attention to the interaction between different trigger levels and the data acquisition system. We also emphasize areas in which the design of detectors affects the trigger and data acquisition systems and vice versa.

The design of trigger systems is discussed in more detail in chapter 4. We discuss triggers based on calorimeter information for high transverse momentum ($p_T$) electrons and jets, and for large missing transverse energy ($p_{T \text{miss}}$). Next, we discuss triggers for high $p_T$ muons, based on information from external muon detectors. Finally, we discuss more specialized triggers based on electron identification detectors which are unlikely to contribute at the first trigger level, but could be important at the second trigger level.

Chapter 5 describes in more detail developments for some of the key components of the front end of the data acquisition system. These include very fast analogue-to-digital converters (ADCs), analogue and digital pipeline memories, and digital signal processors (DSPs). We also discuss developments in microelectronics – it is worth noting that custom chips are now accessible to the electronics designer. Developments being made by industry for high definition television (HDTV) are also mentioned.

In chapter 6 we review some components which will be important at higher levels in the data acquisition and trigger system. These include buses and data
links, and mass storage media. We also discuss possible scenarios for event building.

The complexity of trigger and data acquisition systems for the LHC will require much more use of software tools than was previously the case. A brief discussion of software aspects can be found in chapter 7.

In our conclusions (chapter 8) we summarize and try to identify areas in which the design of the trigger and data acquisition systems affect the overall design of experiments. We also indicate areas where we feel more R&D work is required in order to build trigger and data acquisition systems to be ready for the LHC.

2. Parameter Overview

In order to establish the framework that signal processing, triggering and data acquisition will have to face at LHC, an analysis of the expected trigger and event rates, and of data volumes must be performed. Event rates are calculated in section 2.1 from the estimated total inelastic cross section at centre-of-mass energy $\sqrt{s} = 16$ TeV. The average event size is extracted in section 2.2 from a model of a general purpose detector. Results of Monte Carlo physics studies performed in this and in other working groups are used in section 2.3 to estimate trigger rates. Finally, in section 2.4 we combine these parameters to predict the overall data volumes and estimate the required bandwidths.

At this stage any evaluation is necessarily very rough leading to enormous uncertainties in the conclusions. This parameter overview should be considered only as an exercise to establish a working hypothesis.

2.1. Event rate

The cross section, $\sigma_{\text{inel}}$, visible to experiments for high-$p_T$ physics is estimated by subtracting the contribution of elastic and single diffractive interactions from the total cross section, $\sigma_{\text{tot}}$. Extrapolations of existing $p\bar{p}$ collider data [2] suggest the value $\sigma_{\text{tot}} = 110 \pm 20$ mb for the total cross section at $\sqrt{s} = 16$ TeV, which corresponds to a visible cross section in the experiment of $\sigma_{\text{inel}} \sim 60$ mb. For luminosities in the range $10^{33} - 4\times10^{34}$ cm$^{-2}$s$^{-1}$, the rate of visible interactions will be in the range $6\times10^7 - 2\times10^9$ interactions/second. However, given the bunch structure of the beam with bunch crossings every 15 ns, the relevant rate will be $6.7\times10^7$ bunch crossings/second with between one and forty overlapping events per bunch crossing.

In reality, the bunch structure of the machine contains eleven holes of $\sim 1$ $\mu$s and one of $\sim 3$ $\mu$s [3] due to beam injection and dump, giving an average bunch crossing rate of 54 MHz. Independently of any effect that such beam structure might have on the performance of the various detectors, it could be used for the synchronization (local clocks, reset, etc).
2.2. Event size

In order to stress the extent of the triggering and data acquisition problem at LHC, we will consider the case of a general purpose detector, i.e. a detector capable of electron, muon and jet identification and of missing transverse energy measurement. Such a detector would consist of inner tracking detectors with electron identification power, electromagnetic and hadronic calorimetry and muon chambers. The pseudorapidity coverage required for most of the physics signals studied in the physics working groups of this workshop is $|\eta| < 3$. The measurement of the missing transverse energy requires a bigger coverage, possibly to $|\eta| < 5$. Detectors with good resistance to the high level of radiation will have to be used at such small angles to the beams. The granularity of these forward detectors will be coarse, providing a negligible contribution to the overall event size. A general purpose detector of this kind will presumably be located in a 'medium' luminosity area, where peak luminosities up to about $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ are expected [3]. The following estimates are therefore based on a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$.

From a parametrization of the energy dependence of the charged particle multiplicity, $n_{ch}$, using CDF results at 0.63 and 1.8 TeV [4], the expected number of charged particles per unit of rapidity at $\sqrt{s} = 16$ TeV is $d n_{ch} / d\eta = 6$ for $\eta = 1$. Consequently the expected total number of particles in the calorimeter is 12 per unit of rapidity. Studies of the rate of particles reaching the muon chambers [5] indicate that for an absorber thickness of 12 absorption lengths, only one track will be seen in the muon chambers for $\sim 10^4$ incident charged hadrons. Hence, at a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and for a detector coverage of $|\eta| < 3$ one expects:

- $\sim 350$ tracks / 15 ns in the inner tracking detectors
- $\sim 700$ particles / 15 ns in the calorimeters
- $< 1$ tracks / 15 ns in the muon detectors.

2.3. Trigger rate

Prompt triggers will be based on signatures of electrons, muons, jets and missing transverse energy, based on the rough particle identification achievable in the shortest possible time with information from calorimetry and fast muon detectors. The basic selection parameter at the first trigger level will be a threshold on the transverse energy or momentum. Table 1 summarizes the expected inclusive rates [6] for a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a coverage of $|\eta| < 3$. 

# TABLE 1. Inclusive rates

<table>
<thead>
<tr>
<th>Muons</th>
<th></th>
<th>10^5 – 10^6 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full single-muon rate after 12 λ of lead</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single-muon rate for p_T &gt; 20 GeV</td>
<td>2x10^3 Hz</td>
<td></td>
</tr>
<tr>
<td>Two-muon rate for p_T &gt; 20 GeV (both muons)</td>
<td>25 Hz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electrons (1)</th>
<th></th>
<th>10^5 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-electron rate for p_T &gt; 20 GeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-electron rate for p_T &gt; 20 GeV (both electrons)</td>
<td>10^3 Hz</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jets (2)</th>
<th></th>
<th>10^4 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-jet rate for p_T &gt; 180 GeV (both jets)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two-jet rate for p_T &gt; 300 GeV (both jets)</td>
<td>10^3 Hz</td>
<td></td>
</tr>
</tbody>
</table>

(1) Note the lowest possible rate for a first level trigger based on calorimeter cuts only is the one of the single π, which for p_T > 20 GeV is 2x10^4 Hz.

(2) There is an uncertainty of almost an order of magnitude in the Monte Carlo prediction of jet production at p_T = 20 GeV due to choice of structure functions, fragmentation parametrization and other factors.

The inclusive rates of table 1 give an indication of the thresholds necessary for a first level trigger rate not exceeding 10^5 Hz. These have to be confronted with the thresholds required by the physics signals that are sought. In table 2, three important physics channels expected at LHC are used as examples to demonstrate the feasibility of first level triggers. The thresholds listed correspond to acceptable efficiencies for the detection of the physics signals indicated, and are the result of studies performed in other working groups of this workshop.

# TABLE 2. First level trigger rates with thresholds required by physics signatures

<table>
<thead>
<tr>
<th>Top [7]</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>t\bar{t} \rightarrow (e or \mu) + 3 jets:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single muon with p_T &gt; 40 GeV</td>
<td>2x10^2 Hz</td>
<td></td>
</tr>
<tr>
<td>Single electron with p_T &gt; 40 GeV</td>
<td>5x10^3 Hz</td>
<td></td>
</tr>
<tr>
<td>t\bar{t} \rightarrow e + \mu + X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Single muon with p_T &gt; 50 GeV</td>
<td>10^2 Hz</td>
<td></td>
</tr>
<tr>
<td>Single electron with p_T &gt; 50 GeV</td>
<td>4x10^2 Hz</td>
<td></td>
</tr>
</tbody>
</table>
Higgs [8]

\[ H \rightarrow ZZ \rightarrow 4 \text{ leptons:} \]

- Two muons with \[ p_T > 20 \text{ GeV} \] \(25 \text{ Hz}\)
- Two electrons with \[ p_T > 20 \text{ GeV} \] \(10^3 \text{ Hz}\)

SUSY [9]

\[ \bar{g}g \rightarrow p_T^{\text{miss}} + \text{multi-jets:} \]

- Three jets with \[ p_T > 200 \text{ GeV} \] \(5 \times 10^2 \text{ Hz}\)
- \[ \bar{g}g \rightarrow ZZ + 2 \text{ jets} + \gamma\gamma \rightarrow 4 \text{ leptons + jets + } p_T^{\text{miss}} \]
- Two muons with \[ p_T > 30 \text{ GeV} \] \(10 \text{ Hz}\)
- Two electrons with \[ p_T > 30 \text{ GeV} \] \(10^2 \text{ Hz}\)

From table 2, it appears that the prompt trigger rate will be dominated by triggers requiring electrons. Assuming that thresholds can be kept reasonably sharp it seems possible to provide prompt triggers with sufficient acceptance for physics at rates of the order of 10 kHz. Rates might be reduced further by demanding more complicated signatures. It should be noted that an inclusive missing transverse energy trigger, if implemented, might also give a high rate. We assume a total first level trigger rate of \(10^4 - 10^5 \text{ Hz}\). As described in more detail in chapter 3, after the fast (\(-1 \mu s\)) first level trigger, higher levels of trigger are needed with increasing background rejection power. Tracking information combined with more refined calorimeter cuts for electron identification, precise \(p_T\) cuts on muon candidates, and kinematic and topological selections can be applied by second level trigger processors. A rejection compared to the first level trigger of at least \(10^2\) should be possible, leaving an overall rate after the second level trigger of \(10^2 - 10^3 \text{ Hz}\).

Further reduction has to be gained to meet data storage and offline analysis capabilities. No detailed evaluation of third level trigger algorithms has been done by our working group. However, full event reconstruction and online filtering probably performed by general purpose processor farms must reduce the data rate to acceptable levels.

2.4. Data volumes and Bandwidths

An accurate estimate of the data volumes that an LHC data acquisition system will have to face could only be done if the detector configuration were known. At this stage we can only make an educated guess based on the number of electronic channels of typical subsystem examples. The expected granularity
of detectors under study in other working groups, which are also the object of
detector R&D projects, are summarized in table 3.

TABLE 3. Number of electronics channels.

<table>
<thead>
<tr>
<th>Inner Tracking:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon tracking and preshower [10]</td>
<td>$2 \times 10^7$ channels</td>
</tr>
<tr>
<td>TRD straw tube [11]</td>
<td>$4 \times 10^5$ channels</td>
</tr>
<tr>
<td>Scintillating fibres</td>
<td>$10^6$ channels</td>
</tr>
<tr>
<td>Expected occupancy: $10^{-2} - 10^{-3}$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calorimetry [12,13] (dominated by electromagnetic compartment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>for a granularity of $\Delta \eta \times \Delta \phi = 0.02 \times 0.02$ with</td>
</tr>
<tr>
<td>at least two readout samplings and for $</td>
</tr>
<tr>
<td>Expected occupancy: $10^{-1} - 10^{-2}$</td>
</tr>
<tr>
<td>$2 \times 10^5$ channels</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Muon Tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistive plate chambers [33] or drift chambers $10^5 - 10^6$ channels</td>
</tr>
<tr>
<td>Expected occupancy: $10^{-5} - 10^{-6}$</td>
</tr>
</tbody>
</table>

Combining the numbers of channels and the expected occupancies from
table 3, we obtain estimated data volumes, assuming the use of zero suppression,
which are shown in table 4.

TABLE 4. Data volumes

| Inner Tracking: | $10^4 - 10^5$ hits/15 ns or $\sim 10^6$ bytes/15 ns |
| Calorimetry:    | $10^3 - 10^4$ cells/15 ns or $\sim 10^5$ bytes/15 ns |

| Muon detector: | negligible. |

Data rates after the different trigger levels are obtained by combining the data
volumes from table 4 with the trigger rates evaluated in section 2.3. The
required bandwidths are summarized in table 5, where we assume zero
suppression but no further data compression.
As described in more detailed later, the enormous amount of data corresponding to the first level trigger accepts might not need to be moved out of local memories. A possible scheme, in which the first level trigger is used to drive the second level algorithms, would require that only sections of detector which are flagged by the first level trigger are read out by the second level processors, leaving the bulk of the data in local storage until the second level trigger decision is made.

The rate of second level triggers is such that bandwidths of the order of Gbytes/s are needed in order to empty the buffer memories, build the events and transfer the data to processor farms for higher level filtering and data storage. Buses, networks and data links capable of such throughput are discussed in section 6.2.

The 10 – 100 Mbytes/s rate for data storage has been estimated by arbitrarily assuming a further reduction of a factor of 10 at the highest trigger level. No systematic study has so far been done on how to achieve such a rejection. However, it is common prejudice to believe that enough processing power will be available in a processor farm to perform quite advanced physics analysis in order to reach a manageable level of data storage.

3. An Architecture Based on Multi-level Triggers

Irrespective of the detailed form that a trigger and data acquisition system might have in an LHC experiment, the boundary conditions described in chapter 2 impose a few basic features that must be satisfied to cope with LHC requirements:

- The system must be designed for the highest possible performance.
- The first level trigger processors, whether based on analogue or digital electronics, must be pipelined to handle a new event every 15 ns.
- Pipelined buffering and hierarchical data collection are essential.
- Where possible, the system should be characterized by a high degree of parallelism for easy scaling and adaptation to evolution of required performance.

In the following, we explain in more detail how these requirements come about.
Following experience from experiments at the SPS [14,15] and Tevatron [16,17] proton-antiproton colliders, and from the preparation of the future e-p collider HERA [18,19], we envisage a trigger system for experiments at the LHC based on several levels. The same conclusion has been reached in studies for the SSC [20]. Relatively crude decisions made quickly at the first level can be refined at the second and third levels using more detailed information from the detectors and more complicated algorithms. The role of each trigger level is to reduce the trigger rate to the point where it can be accepted by the next higher level. In Fig. 1 we illustrate the structure of such a trigger system, based on three levels, where we have indicated order-of-magnitude rates which might be achieved after each level of triggering.

![Diagram](image_url)

**Fig. 1a:** Model of a multi-level trigger system. (Conceptual model)

![Diagram](image_url)

**Fig. 1b:** Model of a multi-level trigger system. (Showing more details)
Here we discuss the feasibility of such a model system, but it must be stressed that this architecture only reflects our current ideas for a powerful trigger and data acquisition system. We feel that it is not appropriate to try to define a final solution for trigger and data acquisition now, since we do not yet have at our disposal the technology needed, especially in the front end. Instead we review the state-of-the-art of the technologies involved in order to define a plan of work and provide recommendations to the high energy physics community. The first level of trigger processing must be very fast because information from all channels of the whole detector (perhaps $10^7$ to $10^8$ channels for a detector with central tracking) must be stored until the decision is available. It is likely that the first level storage will be done in electronics on or near the detector.

The size of a typical LHC detector is about 30 m long by 20 m across. For such a large detector, the time to form a first level trigger decision is at least 400 ns, allowing only for cable delays to bring information from the whole detector to one central place and then to send the trigger decision back to the electronics mounted on the detector. From this it should be clear that the routing of cables carrying first level trigger information will be critical in determining the decision time. This must be taken into account at a sufficiently early stage in detector design.

Given that the first level decision time must be at least several hundred nanoseconds and since a bunch crossing occurs every 15 ns, information for many events must be stored for each channel during first level processing; each event may contain several interactions. Storage devices known as pipelines are expected to fulfil this role. The pipeline memories, which may be analogue or digital storage devices, accept new information every 15 ns. The data are stored until the first level decision is available, after which they are either discarded (first level reject) or transferred to the second level (first level accept). The number of storage elements in the pipeline for each detector channel is determined by the first level decision time. For a first level decision time of 1 μs, 67 storage elements are required. Design studies for such devices are discussed below in section 5.1.2.

The first level trigger may take up to ~2 μs to deliver its verdict to the detector electronics, this latency being made up of a combination of the response times of detectors and their associated electronics, cable delays and propagation delays through trigger electronics. However, the trigger must be able to start analyzing a new event every 15 ns. We must therefore think of a trigger system concurrently processing many events each separated in time from the next one by 15 ns. The idea of pipelined processing, commonly employed in high-performance computers, can be adopted. Possible architectures for first level processors are discussed separately for calorimeter-based triggers and for muon triggers in sections 4.1 and 4.2 respectively.
We consider it important to combine information from different detectors in the first level trigger. An obvious example is the need for a trigger based on electron–muon coincidences. To facilitate this, careful consideration must be given to the layout of the whole first level trigger system. Thought must also be given to problems of synchronizing triggers from different sources. The need for a single first level central trigger processor must be foreseen in the overall detector design.

The trigger rate after the first level trigger will still be very large. Rates studies, discussed in section 2.3 above, suggest that with thresholds for electron and muon triggers chosen to have good efficiency for interesting physics channels, the rate after the first level trigger will still be in the range $10^4 - 10^5$ Hz. To achieve this we require a reduction of at least $10^3$ compared to the beam crossing rate, and more than a factor of $10^4$ compared to the interaction rate for luminosities in excess of $10^{34}$ cm$^{-2}$ s$^{-1}$.

When an event is accepted by the first level trigger, the data from the whole detector are moved into a buffer memory where they are stored during the second level trigger processing. In our model, we envisage using digital second level buffers, so for detectors with analogue first level pipelines an ADC must be included in the scheme as shown in Fig. 2a. The alternative of prompt digitization and a digital first level pipeline is shown in Fig. 2b. These two alternatives can coexist, some subdetectors using analogue and others using digital pipelines. However, independently of whether or not the storage elements are analogue or digital, all first level pipelines from all subdetectors must be synchronized. This essential consideration, which is already important in HERA detectors, means that a detector-wide view must be taken before detailed design of the readout electronics for individual subdetectors.

![Diagram](image_url)

**Fig. 2a:** Second level buffer memory with analogue first level pipeline.

**Fig. 2b:** Second level buffer memory with digital first level pipeline.
A particularly delicate area is the interface between the first level pipeline and the second level buffer. While some proposed systems involve deadtime following a first level trigger (during which time data are converted and moved into a second level buffer), other systems avoid this. Although deadtime is in general unwelcome, it may be at an acceptably low level. This is another issue which needs to be addressed detector-wide.

The second level trigger system must access information from the detector. There is therefore an intimate relationship between second level trigger processing and second level data storage. One extreme view is to consider the second level buffer as an integral part of the second level trigger and to move all the data from the detector (or subdetector) into the trigger processor system. At the other extreme, one could buffer the data on the detector, only moving those data which are needed by the second level trigger processors.

For some subdetectors very large volumes of data are involved – perhaps $10^5$ bytes per event for a calorimeter and even more for a central tracking detector, even after some data compression (or zero suppression) has been performed. Moving such large amounts of data after each first level trigger will not be easy given trigger rates up to $10^5$ Hz. Where possible, it may be preferable to buffer the data locally until after the second level trigger has accepted an event. We note that external muon detectors are a special case because the data are expected to be very sparse.

We discuss the benefits of storing data locally during second level processing in the context of a second level electron trigger in section 4.1.2 below. Note that for triggers in which the processing is localized to a small part of the detector, such as electron or muon triggers, the first level trigger can be used to flag regions of the detector containing candidates. This information can then be used by the second level trigger, avoiding the need to access data from the whole detector.

While we think of second level trigger systems loosely associated with specific detectors, it may be important to combine information from different detectors in the second level trigger. This is particularly true in the case of electron identification where the second level trigger may only be able to reduce the background rate to an acceptable level by combining information from calorimetry and another detector such as a preshower/tracker or a transition radiation detector. We discuss this further in section 4.3 below.

Detailed rate calculations for second level triggers are still at an early stage. However, we believe that the second level trigger should be able to gain a factor of more than $10^2$ in rejection by refining the first level trigger decision using more precise information from the detectors, and by combining information from different detectors. Thus the rate from the second level trigger will be in the region $10^2 - 10^3$ Hz. Note that the information available at this stage need
not be crude – if up-to-date calibration is available, electrons, muons and jets could be measured using the full precision of the detector.

In our model shown in Fig. 1, events selected by the second level trigger are fully read out before third level processing is performed. The second level trigger will already have made sophisticated decisions based on information from several (maybe all) subdetectors. Third level processing may have to do full event reconstruction and make physics analysis cuts – at a luminosity of $4 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, the rate for $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ decays is predicted to be hundreds per second!

We have not considered in detail the structure of a third level trigger system. However, we note that very powerful (and relatively inexpensive) commercial processor systems are already available, with yet more powerful products promised in the near future. Such processor systems, connected to make a processing farm, could form the basis of a third level trigger. Each incoming event is allocated to a processor which performs the third level processing for that event (i.e. the events are farmed out). Concurrently, other processors are working on different events. With such a system, the limiting factor is not so much computational power (one can always add more processors to the farm), but the problem of moving data from the readout electronics to the processors. We discuss data transmission and networking in section 6.2.

4. Trigger Techniques

In this chapter we discuss how first and second level triggers based on calorimeter or muon detector information could be implemented. Triggers based on other detectors, probably used to refine the electron signature at the second trigger level, are also discussed.

4.1. Calorimeter Triggers

As discussed in chapter 3 above, calorimeter triggers should allow one to select events on the basis of high $p_T$ electrons and photons, jets, and also missing transverse energy. The isolation of electrons and photons can provide an additional handle for separating interesting physics from the dominant background of jets.

4.1.1. First Level Calorimeter Trigger

One can envisage implementing a first level calorimeter trigger using either analogue [21] or digital electronics [22]. A trigger for high-$p_T$ electrons (or photons) could be implemented by a system of discriminators attached to the front end electronics of the electromagnetic calorimeter. One would have to make an analogue sum over samplings in depth (if more than one), and might in addition perform lateral summation. Even if one wishes to retain the full
The granularity of the calorimeter, it is desirable to form overlapping windows so that showers which share their energy between calorimeter cells trigger with good efficiency. Such a system was implemented for the UA2 experiment [23]. Summing over larger areas of the calorimeter has the advantage of reducing the number of channels to be handled by the first level trigger. It should be noted that even for this "analogue" trigger, a considerable amount of digital electronics will be required - for example to count the number of clusters in the calorimeter - and that this will have to be pipelined to handle the 15 ns bunch crossing period.

The identification of isolated electrons in the first level trigger is potentially very useful, giving a substantial rejection against the background from jets. This is not easy to implement using analogue electronics, although resistive networks [24] could provide a solution.

A trigger for high-$p_T$ jets might also be possible by making analogue sums over jet-sized areas of the calorimeter, and discriminating on the sum. For this, analogue information from the electromagnetic and hadronic calorimeters would have to be combined. In such a scheme it is important to control carefully the relative calibration of the different calorimeters which enter the analogue summing logic, otherwise the resolution will be degraded and the trigger threshold smeared out.

The problem of implementing a missing transverse energy trigger using analogue electronics looks very hard. Whereas electron and jet triggers can be implemented with the electronics mounted locally, on or near to the detector, missing transverse energy requires a global sum. With such a large number of calorimeter cells involved, it is hard to see how such a system could be built.

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**Fig. 3a:** ADC and look up table for a pipelined digital calorimeter trigger.

**Fig. 3b:** Illustration of pipelined trigger processing for a first level calorimeter trigger.

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An alternative approach to first level calorimeter triggering is to use a digital trigger processor. This technique, which is illustrated in Fig. 3, has already been used in a number of experiments. One generally makes an analogue sum of a small number of calorimeter channels before digitizing using a fast ADC. This sum combines the different depth samplings of the electromagnetic calorimeter and generally involves some lateral summation as well, typically over an area of $\Delta \eta \times \Delta \phi = 0.2 \times 0.2$. This reduces the number of channels to be digitized for the first level trigger. It is desirable to make independent digitization of the hadronic calorimeter so that calibration differences between the different calorimeters can be corrected. This also makes possible the implementation, in the first level trigger, of electron identification based on the longitudinal profile of the shower, as well as lateral isolation.

Having digitized information from the detector, a look-up table is used to convert to energy units – probably transverse energy. Note that flash ADCs operating at 100 MHz (for 8-bit resolution) and RAMs with 15 ns access times are standard items. In Fig. 3a, latches are included after the ADC and after the RAM. These are memory registers which synchronize the pipelining of data – every 15 ns the data from a given beam crossing move downwards from one latch to the next. Thus, the digital transverse energy value is available 30 ns after the signal was presented to the ADC.

It is worth noting that a more ambitious approach [25] is to digitize fully all channels from the calorimeter before the first level pipeline. If this were done, separate digitization for the first level trigger would be unnecessary. This would allow the trigger to use information from the detector calibrated channel by channel.

The principle of operation of a pipelined digital processor is illustrated in Fig. 3b. This logic, which would be repeated for every electromagnetic trigger channel in the calorimeter, sums over two-by-two (overlapping) windows and compares the sum with a threshold. The latches again control the flow of data through the processor; three pipeline steps are included between the input to the first adder and the output of the logic, corresponding to 45 ns. Much more elaborate logic would be used in a practical processor.

A major advantage of the digital compared to the analogue scheme is that it is possible to make more complicated decisions at the first level. A digital processor can offer electron triggers with overlapping sliding windows, several thresholds with different multiplicity requirements, and (optional) isolation requirements. For jet triggers, the relative calibration of the electromagnetic and hadronic calorimeters can be adjusted. Most important of all, a full missing transverse energy calculation can be implemented. In addition, a digital implementation gives easy control of the calibration, good monitoring and lots of flexibility.
Preliminary studies for a trigger processor offering all the features described above look encouraging. Simple calculations give a calculation time (excluding cable delays) of less than 400 ns. Recent technological advances make custom chip design much more accessible to us than a few years ago. Even very complicated processors could be made using only a few custom chip designs, each containing a large amount of logic. A single custom chip could in the future perform functions which in previous digital processors occupied almost a whole circuit board. This gives higher speed and better reliability; it can also be very cost effective. As in existing systems, the number of interconnections will be a serious problem. Thankfully, custom chip packaging now allows very large numbers of external connections.

Of course, there are many considerations which have to be taken into account when comparing analogue and digital solutions for first level triggering [21]. The amount of power dissipated by digital electronics may be larger than that for an analogue system; for some calorimeters this may be an important consideration which is related to the question of where one should locate the electronics and also to problems of cabling. Also relevant is the issue of radiation hardness of any electronics which is installed inside the detector; it is worth noting that radiation hard digital and analogue electronics are now available to us from industry as discussed in section 5.3. While a digital solution may require larger numbers of connections (several bits in parallel instead of a single analogue signal), there are not the same problems with noise.

Both for digital and for analogue first level calorimeter triggers, the implementation of synchronized pipelined processing distributed over the area of the detector is not going to be easy. However it is encouraging that both solutions look possible in principle, at least for electron triggers. Further work is required in order to master the techniques required to build a real system. It is important to develop both analogue and digital trigger designs further so that a detailed comparison can be made between them. The best choice may depend on the calorimeter technique selected; equally, the choice of calorimeter technique should be influenced by how well the calorimeter can be used in the trigger.

4.1.2. Second Level Calorimeter Trigger

The longer time available for the second level trigger allows one to use programmable devices instead of hard-wired processors. There is a large variety of commercial processors from which to choose. High performance general purpose processors, including RISC (reduced instruction set computers) are the most flexible and easiest to program. Digital signal processors (DSPs) offer more computing power for certain applications [26]. Parallel computers (e.g. transputers [27], distributed array processors or associative string processors [28]) are an even more powerful alternative for problems which can be solved by a parallel algorithm. Image processors, used in the television industry, may also
have a role to play; new developments for high definition television (HDTV) may be particularly relevant here, as discussed in section 5.2. One should also mention that neural networks [29] could offer an alternative to traditional computing techniques.

The second level trigger system is more than just processing power. Equally important are the data links, buses or networks which allow the processors to access the data. The overall architecture of the second level system – buffer memories, data transmission systems and processors – must be considered as a whole. Different problems require different architectures, particularly depending on whether the problem is a local one (such as finding clusters in a calorimeter) or a global one (such as calculating the missing transverse energy).

The interaction between the first and second level triggers is also relevant. If, for example, the first level trigger has already identified the location of all candidate high $p_T$ electrons, this information can be used by the second level trigger [30]. This is illustrated in Fig. 4 which shows a system in which local processors, distributed over the detector, validate electron candidates identified by the first level electron trigger. In this case, the need for extraordinary processing power and data transfer rates is avoided, as described below.

![Diagram](image)

*Fig. 4: Example of a second level architecture for an electron trigger. The ovals represent trigger processors.*

Following a first level trigger, the data are stored in the second level buffer memory which may be located on the detector. The first level trigger informs local processors if there is an electron candidate in the part of the calorimeter for which they are responsible. Assume 1000 local processors each responsible for $1/1000$ of the detector; then if the global first level trigger rate is $10^5$ Hz, each processor only has to respond to $10^2$ Hz! There must in addition be global
processors which gather together information from the local processors before making an overall decision. These could be implemented as a processor farm, with \( \sim 100 \) processors taking turns to process events; each global processor must then respond to \( \sim 1\% \) of the first level triggers, giving a rate per processor of \( 1000 \text{ Hz} \). Thus, the timescale for processing an event is \( \sim 1 \text{ ms} \) instead of \( \sim 10 \mu\text{s} \) required if different events are not processed in parallel. Given the processing power of today's microprocessors, very sophisticated algorithms can be executed given a \( \sim 1 \text{ ms} \) timescale.

The data rates in such a second level architecture must also be considered. Suppose each local processor in the above example has to access an area of the detector corresponding to \( \sim 2000 \) calorimeter cells (\( \sim 1\% \) of the calorimeter) in order to validate the electron candidate. Then the data rate into each local processor is only \( \sim 0.4 \text{ Mbyte/s} \). Very little data need be sent from the local processors to the global processors – just a few words per candidate electron (\( E_T, \eta, \phi, \chi^2 \)) – with a first level trigger rate of \( 10^5 \text{ Hz} \) and \( \sim 100 \) bytes per event, this corresponds to a total of only \( 10 \text{ Mbyte/s} \) into the farm of global processors.

Thus, by making use of information from the first level trigger about the location of candidate electrons and by moving only those data which are required, one can envisage an architecture in which each processor has a long decision time and in which data transfer rates are modest. The full data from the events must, of course, be stored somewhere during the second level trigger processing – this can be done locally. The requirement that the second level processors should selectively access the data must be included in the design of the buffer memories; a system which includes this possibility is under study [25]. The communication between the buffer memories, the local processors and the global processors is also not trivial despite the low data transfer rates.

The electron trigger architecture described above demonstrates how the different elements of a second level trigger system – buffer memory, local and global processors, and data communications – need to be considered together. It is useful to model such architectures using simulation programs such as SIMSCRIPT or Verilog [31]. We believe that detailed simulation is essential in order to evaluate and compare a variety of second level architectures. Simulation allows the performance of a system to be studied as a function of parameters such as buffer depth or algorithm execution time. It also allows one to study the response under more realistic conditions by simulating error conditions – in some existing experiments error recovery is a dominant source of deadtime.

It must be made clear that the architecture described above for an electron trigger is only one possibility. Alternative schemes using massively parallel processors and image processors have also been studied [28]. These studies have concentrated on the comparison of different computer architectures for cluster analysis.
The problem of making a second level missing transverse energy trigger is very different from that of finding or validating electron candidates. One needs to access data from the whole detector, but the algorithm is very simple and well defined - essentially a weighted sum over calorimeter cells. This could already be done by a digital first level trigger.

It must be remembered that the second level trigger must be powerful enough to gain a factor of $10^2$ in rate compared to the first level trigger. Simulation studies for second level algorithms should take account of the fact that the first level trigger may already have used many of the easy signatures. Ideally, the first and second level simulation should be integrated.

4.2. Muon Triggers

The physics requirements described in section 2.3 demand triggers on high-$p_T$ muons. Such triggers can be implemented using information from external muon detectors which are shielded from the interaction region by many interaction lengths of material [32]. These detectors provide several position measurements along each track, with good precision in at least one coordinate. High-$p_T$ muons are identified by their ability to penetrate the hadron absorber and by their small angular deflection by bending in a strong magnetic field and by multiple scattering. The detector must provide fast signals for first level triggering; this requirement must be considered in the detector design. At the second level it will be necessary to measure accurately the momentum of very high-$p_T$ muons, possibly requiring a detailed analysis of the track trajectory in the magnetic field.

4.2.1. First Level Muon Trigger

We envisage a first level trigger which uses as input a pattern of hit elements from the muon detector. The logic compares the pattern on hits in the muon chambers with patterns which are valid for high-$p_T$ muons that originate from the interaction region. Several techniques are possible [33] such as look up tables stored in RAMs or programmable logic; both of these are very fast ($\sim 15$ ns). The result is a flag indicating the presence of a muon candidate - the first level trigger provides the position of candidates but no information on their transverse momenta.

Thresholds can be controlled by changing the list of valid hit patterns. Essentially, one defines roads from the interaction region through the muon chambers in which one requires hits. Narrow roads correspond to high-$p_T$ muons, wider roads to lower-$p_T$ muons. While the implementation of such a trigger system appears to be relatively straightforward, the details depend on the geometry chosen for the muon detector.
4.2.2. Second Level Muon Trigger

As for calorimeter triggers, there is a large choice of commercial processors which might form the basis of a second level muon trigger system. Alternative solutions include neural networks, associative memories and data-driven processors. The possibility of using information from the first level trigger about the location of muon candidates should be considered. However, the external muon chambers are expected to have very low occupancy, so there is much less to be gained from selective movement of data than in the case of calorimetry. Various architectures are possible for second level muon triggering such as processor farms with each processor handling a different event, or architectures using a massively parallel computer system. The latter possibility has been studied [34]; using a system of associative string processors execution times of ~10 µs should be possible without making any reference to information from the first level trigger.

4.3. Triggers Based on Other Detectors

Triggers based on the calorimeters and external muon chambers alone should give sufficient rejection against background at the first level. A number of other detectors, particularly those associated with electron identification, can help to provide additional rejection at the second level. We illustrate this with two examples – a preshower/tracker detector [35] and a transition radiation detector [36].

4.3.1. Preshower/Tracker

A preshower/tracker detector described in Ref. [35] can be used at the trigger level to select electrons. The detector consists of several layers of silicon tracking, then a converter followed by several more layers of silicon tracking. Electrons are signalled by a single ionising track before the converter which starts to shower before the second tracking stage. Charged hadrons are unlikely to interact in the converter, while electron pairs from converted photons (in a non-magnetic detector) will give a twice-ionising signal in the tracking before the converter. Good rejection against background is obtained by exploiting the excellent granularity of the detector when forming a coincidence between the silicon layers before and after the converter, and with a high energy cluster in the calorimeter.

It is apparent that the preshower tracker trigger only makes sense when combined with information from the calorimeter. This would probably be done in the second rather than the first level trigger, although the fast response of the silicon detectors is compatible with the first level timescale. Combining information from different detectors will require a common effort on trigger design. It is worth noting that there are several similarities between

4.3.2. Transition Radiation Detector

A TRD has the capability to separate electron and hadron tracks on the basis of pulse height. The detector and trigger which were described at this workshop [36] produce transition radiation X-rays in a foam radiator and detects them using straw tubes. Digitization is performed using only three thresholds, yielding 2-bit values for each channel. Roughly speaking, the first threshold is set to be sensitive to a single pion track, the second one to be sensitive to two overlapping pion tracks, and the third one to be sensitive to an electron track. Good separation of electrons is obtained by comparing the number of straws above the third threshold with the number between the first two thresholds. A possible second level trigger architecture was presented which makes use of a massively parallel computer system to find the tracks.

5. Front End Electronics

Undoubtedly, one of the most difficult technological challenges for LHC experimentation is in the area of front end electronics. Although good progress is being made in many areas, the state-of-the-art of electronics is still inadequate and it is widely recognised that a big R&D effort is necessary in order to meet the LHC timescale. In particular, industrial developments must be watched closely in order to take full advantage of the fast progress in this domain.

In this chapter, we briefly mention a few examples of the features required of some basic components (section 5.1) and we discuss how technological developments might influence our preparations for the LHC (section 5.2). A few comments on micro-electronics are given in section 5.3.

5.1. Examples of components

A number of basic components will be essential elements of any trigger and data acquisition system for the LHC. Analogue-to-Digital Converters (ADCs), analogue and digital memories for pipelined readout structures, first level trigger processors, data flow processor systems and Digital Signal Processors (DSPs) will all have to be developed. The demands of the LHC include:

- very high speed with clocks at multiples of 67 MHz for front end applications
- low power dissipation, and compact packaging and cabling where required
- excellent reliability for detector electronics in closed areas
- radiation hardness for electronics mounted on the detectors (up to hundreds of MRad in some cases).
Prototypes exist which satisfy one or the other of the above requirements, but no one satisfies all of them.

5.1.1. Analogue-to-Digital Conversion

Critical requirements come from calorimetry, for which a dynamic range equivalent to 15–16 bits and a precision equivalent to 9–10 bits are needed. Low power consumption and radiation hardness will be critical issues for inner detectors, including an electromagnetic calorimeter, if digitization is done locally. Speed is critical for every detector in which digitization is done before the first level trigger.

Many techniques of conversion are available today. Alternatives to the standard Flash ADC are the multistage flash ADC [37], ADCs based on the Σ-Δ technique [38] and pipelined ADCs [39]. These have some advantages and disadvantages, either in reality or in the promises of their development trends. Table 6 shows a comparative analysis of ADCs presently under development [40]. In any case, progress in this field is very fast based on new technology. The solution adopted will depend on the detector type and the front end electronics (e.g. at which stage in the trigger hierarchy the digitisation takes place).

<table>
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<th>No. bits</th>
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5.1.2. Pipeline Memories

As discussed in chapter 3, the first level trigger decision time will be much longer than the bunch crossing period of 15 ns. The information from all the
detector channels must therefore be buffered until the first level decision is available, probably for ~2 $\mu$s.

Given the high data flow, the simplest organisation of the buffering at this level is by means of pipelines with steps of (submultiples of) 15 ns and a fixed length equivalent to the decision time of the first level trigger.

Several architectures could be envisaged depending on the pulse characteristics and on the occupancy of the detector channel. Fig. 6 shows schemes of three different pipelines with somewhat complementary fields of application. Analogue pipelines may be preferred where high packaging and low power dissipation are critical issues, but they might be restricted to limited dynamic range and their timing and calibration are likely to be complex. Digital pipelines are simpler to control and offer large dynamic range, but their use might be limited to areas where high power dissipation is acceptable, allowing fast digitization. A third type consist of a mixture of analogue and digital electronics, namely a one stage analogue memory to store the pulse, coupled to a one bit shift register to identify the bunch crossing to which the content of the analogue memory belongs. The latter scheme is applicable to detectors for which the occupancy is such that the probability of having two hits in the same cell during the trigger decision time is negligible. A prototype of an analogue pipeline [41] has already been operated at 66 MHz and details were presented at this workshop [42]. A scheme for a chip for calorimetry readout, containing fast digitizers and digital pipelines was also presented at this workshop [25].

- Long pulse (> 15ns)
- Large dynamic range
- High (9-11 bits) precision

- Short pulse (= 15ns)
- Low occupancy

![Diagram of pipeline architectures](image)

Fig. 6: Pipeline architectures.
5.1.3. Digital Signal Processing

The signals generated by an LHC calorimeter (or other detector) may extend over more than one bunch crossing. In such cases, a digital channel with programmable filter capability can be used to extract the physical information and to associate events to a given bunch crossing. For detectors where particle identification can be done by signal shape analysis in single channels, this can be a part of the trigger process.

Ignoring considerations of power consumption, density of packaging and radiation hardness, it is very attractive to go digital at an early stage, complementing the analogue shaping with a pipelined digital signal processor; this is included in the design of Ref. [25].

If prompt digitization is not possible, digital signal processing can still be done after the first level trigger, probably forming part of the second level trigger, and fulfilling a data compression role. A review of the state-of-the-art in DSPs was given at this workshop [26].

5.2. Technology trends

The technology of CMOS and BiCMOS is quickly moving towards its physical limit. Compared with what was available ten years ago there is an increase of at least two orders of magnitude in memory density (Fig. 5a) and in microprocessor performance (Fig. 5b).

![Graph 5a. Trends in density of logic in microelectronics](image1)

![Graph 5b. Trends in processing power per chip](image2)

Provided such trends continue, the projected compactness seems to match the requirements for the readout of highly granular detectors, and the projected speed matches the needs of fast front end electronics and trigger systems. These projections might even be overtaken by technology changes, such as the use of GaAs components or the introduction of new processor architectures (e.g.
massive parallelism). Obviously, in order to take full advantage of the technology the high energy physics community must develop the capability of exploiting this progress.

5.2.1. High Definition Television

One of the main driving forces for the rapid innovation and the fast appearance on the market of technological developments is the programme for the production of a new television standard. In the last 20 years the needs related to telecommunications and, particularly, to television have strongly contributed to the large scale industrial exploitation and development of standard technologies (CMOS, BiCMOS). The popular video market provides the justification for the enormous financial investment needed. Together with people in other fields, researchers in fundamental physics have made extensive use of this 'spin-off'. Flash ADCs, analogue memories, personal computers, helical scan recording, data compression techniques and image processing systems are all examples of television industry spin-off from which we can profit.

In the last few years the extensive intellectual and technological resources of the European studio and consumer television industry, broadcasters, PTTs and universities have been brought together in the EUREKA project, EU95, to meet a new challenge: the development of a High Definition Television (HDTV) [43]. Designed to progress in an evolutionary way, the HDTV project represents a tremendous effort of R&D in the field of the standard technology.

The HDTV specifications are in a similar range of the ones needed for LHC experiments. Transmission encoding of 144 MHz will require fast ADCs and high speed, high density mass storage devices; high performance imaging will need powerful image processors, digital filters, etc.; data communications of 1.3 Gbits/s are also planned. Independently of the signal transmission technique, the signal treatment at reception is fully performed digitally. Therefore, a TV channel might be seen as an LHC detector channel both from the performance and from the functionality points of view: fast digitization; enormous throughputs; inherent pipelining (one pixel after another instead of one bunch crossing after the other).

In addition, the need to adapt multi-standard formats in a digital framework imposes the development of powerful programmable video signal processors [44]. Their announced performance figures are very promising and the modular and programmable structure makes them ideal candidates for application in the first levels of LHC triggers. In conclusion, given the timescale defined for the EU95 project, analogue bandwidths of ~100 MHz and digital throughputs of ~1 Gbit/s can be expected in the middle of the 1990's as a spin-off from the European HDTV development. This does not mean that HDTV components could be used directly in LHC experiments. Other requirements do not match
our needs: power consumption, density of packaging and radiation hardness are additional problems for the LHC. However, it is important to be aware that an extensive R&D program is under way in Europe addressing problems similar to ours. The use of HDTV prototypes to exercise architectures in realistic conditions and the combination of our expertise and competence with their methods and means would be beneficial for the solution of LHC problems.

5.3. Micro-Electronics

An evaluation performed in the context of the SSC has concluded that the investment necessary for the electronics in a typical experiment would amount to as much as 40% of the total cost. A good fraction of the electronics will need to be micro-electronics: in the front end where it will have to be mounted directly on detectors, in the trigger and data acquisition systems in order to meet the requirements of complexity and power consumption, and at the interconnection level to provide high density, reliability and low unit cost. Micro-electronics is, therefore, a crucial issue for LHC experiments. Digital microelectronics developments will be increasingly more re-usable and easily adapted to the changes of technology. In the near future increasingly big libraries of macrocells will be available, development systems will become more standard, and they should be used more easily by the designer. In order to avoid duplication of effort, a coordination of European activities is desirable. European initiatives, such as EUROCHIP [45], will help this by providing universities and laboratories with the proper tools for the training of a new generation of engineers. By taking advantage of such programmes, high energy physics laboratories and institutions should coordinate their efforts in order to pursue the development of this cost effective, advanced technology necessary for LHC experiments. Discussions in this direction have been initiated in this working group and will be continued in the immediate future with the aim of establishing a suitable European micro-electronics environment.

A very important issue for electronics developments is the need of radiation hardness, at least in some areas of the detectors. Although no detailed investigation has been performed in our working group we do not underestimate the importance of this problem for the LHC. A few contacts with representatives of some major industries [46] have shown us encouraging signs of industrial interest. Processes for the production of radiation hard components seem to be available today. The task of the high energy physics community is to develop test systems to ascertain their usefulness.

6. Data Filtering and Acquisition

The last stage of the architecture introduced in chapter 3 has to deal with the events accepted by the second level trigger. The data from individual detector sub-systems have to be merged into full events at an estimated rate of 100 to 1000
events/s and, after an extra level of data reduction, have to be stored on suitable recording media for final offline data analysis. In this chapter we present the results of studies of event building techniques (section 6.1) and of a detailed compilation of all the buses which are used today in high energy physics experiments or are likely to become available in a near future (section 6.2). Section 6.3 deals with mass storage of the finally accepted data.

6.1. Event Building

Event building is the process of connecting the data sources (i.e. the front end electronics and local memories) to the data destinations (i.e. higher trigger level processor farms and data storage media). Various approaches are considered at present. Among the more traditional ones are shared bus architectures and tree structures. Less traditional alternatives have a greater degree of parallelism based on dual port memory interconnection networks, processor networks, or switching networks (e.g. cross-bar or barrel switches). A review of these techniques was presented at this workshop [47], including examples of existing systems and giving relevant references.

The more traditional techniques mentioned above imply the movement of the totality of the data accepted by the first and second level trigger from local memories to full event buffers. Consequently, the data communication system requires very high performance. The cache memory techniques available in many recent micro-processor architectures and extended to data link protocols such as SCI (Scalable Coherent Interconnect) (see section 6.2) may allow a logically simpler interface between the front and the back ends. Often the highest trigger level needs to process only a small fraction of the data. In a virtual and cache memory environment the trigger processing unit can see the full event data as a logical structure in its local virtual memory. An SCI link between the processing unit and the front end local buffers would provide, in a transparent way, the physical access to the data; only those data needed by the selection algorithm would actually be moved. Consequently, the readout of the full event data would be done only for the finally selected events, giving a big saving in required bandwidth (e.g. 10 to 100 Mbytes/s on several parallel paths).

A cache memory scheme of this kind would be advantageous only if the fraction of data required by the final trigger algorithms did not exceed a few percent of the total. In any case, the choice of the optimal event building technique is also closely coupled to the overall data acquisition architecture, and will depend on the type of buses and data links used, the data control paths, and the location and amount of processing power. It is, therefore, too early to concentrate on any event building architecture. Instead, as in many other areas, the activity should concentrate on simulating different ideas and initiating demonstrator projects in order to be able to make a choice suitable for a given
architecture, and to build prototypes and study integration into the full data acquisition architecture.

6.2. Buses and Links

The basic advantage of using standard buses is the homogeneous environment with guaranteed, well defined properties. Industry provides standard components for use in complex systems. Standards provide a safe environment for the chip and board level designer as well as for the system architect. Standard buses fulfil the following requirements:

- uniform transmission properties of data paths
- no cross-talk, error detection and recovery
- unique addressing schemes for single and multiple access
- minimal, well defined read–write protocols and access protocols (arbitration)
- live insertion and removal of modules
- modular mechanical framework for replacement, renewal and maintenance
- a reliable power supply and cooling environment.

A fundamental question for LHC is whether buses are adequate for the requirements of a data acquisition system and whether they are needed at all. In this section we summarise a detailed study, prepared in the context of this workshop [48], of existing standard buses, such as Fastbus, VMEbus, VXI and VME64, and other buses under development in industry, such as Futurebus+ and SCI.

Good performance is a question of implementation. Even conventional buses can be pushed to 40 – 100 Mbytes/s. New, powerful bus generations are evolving, driven by interest from the high end computing industry, to provide performance and interconnectivity far beyond the limits of conventional buses. For example:

- VME64 practically doubles the performance of VMEbus
- Futurebus+ may achieve 3.2 Gbytes/s on 256-bit backplanes
- SCI, a point-to-point cable bus, will have a performance of 1 Gbyte/s/node.

Note that Fastbus could also increase significantly its real performance if necessary investments were made.

A loss of performance can be due to several factors:

- embedded 'de-luxe' software
- lack of parallelism for the sake of economy
- failure to make use of data driven concepts where applicable
- curing of 'flakey' implementations by slow speed operation
- general purpose designs which have inferior performance compared to purpose built ones
- module design with functionality specifications instead of performance.

Although careful implementations taking into account the above aspects might make use of existing buses (e.g. Fastbus and VMEbus) in areas where
independent units with local buses do not require high bandwidths, it is clear that for the main data streams new bus standards will have to be used. The global second level trigger system, the third level processing farm and the data logger all require bandwidths in the order of $10^8 - 10^9$ bytes/s. New bus standards give bandwidths which extend well into the 1 Gbyte/s range. Futurebus+ could be used in the area of bandwidth beyond 100 Mbytes/s. The event builder stage and the interconnection between local and global second level triggers may use this choice if a link-type interconnection between Futurebus+ backplanes becomes available. This might possibly be the Scalable Coherent Interconnect (SCI); both standards are being developed in parallel and have common parts of specification concerning crates and control registers. Point-to-point buses like SCI provide a novel way of interconnecting processor and memory nodes at very high speed, largely independent of the number of nodes. Any node may send or receive data or commands to or from other nodes in the network. Topologies of interconnected ringlets can be easily changed and optimized by changing the cabling. Interconnections between high end (commercial) processors with backplane bus units are expected to become available in addition to a node chip for memory interface design. The availability of new features like caching, split transaction and virtual memory access will allow for better performance, more throughput and new data acquisition concepts (see, for example, event building in section 6.1). Further studies in connection with test setups and system simulation are, however, required. The SCI seems to be the most promising candidate for the global second and third level triggers and for event building. The link-type nature of SCI presents a considerable advantage since all three areas can be covered by a three layer topology of 50 to 100 SCI ringlets, interconnecting (commercial) high end processor farms with uniform backplane-bus units. Features like caching, virtual address and very high bandwidth are available to simplify architectures both in hardware and software.

Buses will also be suitable backbones for slow control systems. A VME based system with VXIbus for interconnection seems to be a good choice for this role.

High speed links will certainly complement buses in data acquisition systems for massive data transfers. Gigabit optical links are starting to appear on the market. Major computer manufacturers including IBM, DEC and HP all have working prototypes. Components to build such links are also now available from companies like Gigabit Logic, Vitesse and BT&D.

Examples of applications of optical links in high energy physics are:

- a 160 Mbits/s VMEbus inter-crane module (VMExi) using the ADM TAXI chipset
- a 16.6 Mbits/s system used on UA1, based on the PArallel TTransmission Optical Link (PATROL)
- a prototype of a 100 Mbits/s version of PATROL
- a project for a 10 km, 1 Gbit/s optical link between the L3 online and offline
computers, which should be completed within two years. A detailed compilation of several projects currently under way has been prepared in the framework of this workshop and can be found in Ref. [49].

Finally, one should not exclude the possibility of the development of specialized systems designed to achieve maximum speed. An example of a readout controller capable of data transfers of 80 Mbytes/s has been presented at this workshop [50].

6.3. Mass Storage

According to the evaluation described in section 2.4, data bandwidth for mass storage at LHC could be of the order of 100 Mbytes/s (i.e. the equivalent of one 3480 cartridge every 2 seconds). No device commercially available today is capable of such rates, but developments are under way, pushed by the commercial broadcast industry.

Although the best performance are expected from optical devices, mass storage for LHC will probably be based on the products derived from studio high definition Video Tape Recording systems which are being developed with the helical scan technique.

Helical-scan is the most cost effective technique today, providing higher recording capacity in smaller physical package than any other computer storage technique at unbeatable prices. Sony has recently announced a Digital Instrumentation Recorder (DIR-1000) with a recording/playing rate of 1 to 30 Mbytes/s based on a 19 mm videocassette tape with total capacity of up to 96 Gbytes. Moreover, one should not forget that the HDTV program requires tape recording at 200 Mbytes/s.

7. Software

Although it is too early to start the development of data acquisition systems for LHC experiments, one cannot overemphasize the important role of a well designed online system. The control and the monitoring of the experiment, the management of thousands of CPU's distributed at the various levels of the trigger and data acquisition system and the organisation of the multiplicity of tasks in the several-thousand processor environment will require a software system of such a complexity that modern software engineering must be used to handle it.

The high energy physics community is not used to modern programming techniques, but it should become acquainted with them now in order to develop the necessary expertise in time. At this stage, software activities should proceed in two directions.
• Develop tools for program design and code generation with the use of new techniques such as:
  - specification and description languages (graphical and textual description)
  - object oriented programming
  - platform independent operating systems (UNIX)
  - CASE techniques.
• Exercise architecture modelling by means of simulation techniques, animation, timing and statistics analysis. Modelling tools such as Verilog, normally used for electronics chip layouts, have been or are being used for full architecture simulations, but languages like SIMSCRIPT and MODSIM are considered more suited for full trigger and data acquisition system modelling [31].

8. Conclusions

Our investigations show that although building front end electronics, triggers and data acquisition systems for the LHC will be very difficult, it is not impossible provided the necessary R&D commences immediately with sufficient investment of manpower and funding. The areas which we feel are most in need of further study are those closest to the detectors where high speed is needed, in some cases in conjunction with low power dissipation and radiation hardness. In particular, front end analogue electronics, pipeline memories, fast ADCs, and first level trigger processors need to be developed. In some of these areas, we may be able to benefit from developments in industry which must be followed closely.

Further away from the detector (beyond the first level trigger) we feel that more of the components of the trigger and data acquisition system can come from industry. High performance processors, data links, networks and buses are already available and the technology is moving fast. Here we see a need to follow developments from industry by testing and evaluating the latest products. The challenge will be to combine the available technology to build the trigger and data acquisition system. The complexity of such systems will require the use of modern software methods and software tools for design and modelling.

We would also like to emphasize the need to consider requirements of the trigger and data acquisition system in the overall detector design. Clearly, all detectors used in the first level trigger must provide fast signals. In addition, physically large detectors will necessarily have a long first level trigger decision time due to cable delays; it is important to make provision for short cable runs from the outset. The choice of detectors may also affect the location of the front end and first level trigger electronics; problems of cabling must be weighed against problems of power dissipation and radiation hardness. Synchronization
is a major issue that must not be neglected given the short bunch crossing period. For every detector channel there will be pipeline and buffer memories, distributed over the detector, which must be synchronized to much better than 15 ns. (The synchronization of movement of data from first level pipelines to second level buffers is particularly delicate.) The message here is that the first level readout electronics of all detectors and all the first level trigger systems must be designed in a coherent way.

Considering the large event size and high first level trigger rate, one is faced with very large data transfer rates. It is not desirable to move these data over large distances before second level trigger processing unless there are constraints from the overall detector design. A related issue is that each trigger level can benefit from calculations performed at lower levels. For example, the first level electron and muon trigger processors could be used to flag areas of the detector containing candidates to be validated by the second level. There is a general need for a coherent design of the trigger system both between different detectors and between trigger levels.

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TRANSMISSION AND SWITCHING OF ANALOG AND DIGITAL SIGNALS

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1. INTRODUCTION

This paper aims to propose a general survey of the various principles, studied at TCSF/LER, that could be involved to solve point to point links or networks problems, optical or coaxial, in the analog or digital transmission domain.

The activity and vocation of TCSF/LER is in fact extended to the overall imagery chain starting with the video signal origination (different types of cameras) to the visualization (displays), through image analysis and understanding real time video processing, switching, transmission, modulation...

The studies are carried out through :

- Software simulation
- Realization of equipments

Chapter 2 gives in a few words a general description of TCSF/LER activity.

Following chapters are focused on studies in transmission and switching areas carried out in the transport-switching laboratory. They are based on three main axis :

a) Analog transmission : one or multi TV channels, AM or FM
b) Digital transmission : specific bit rates or STM levels
c) Switching facilities : analog and digital, low and high bit rates.

2. TCSF/LER IN A FEW WORDS

THOMSON-CSF Laboratoires Electroniques de Rennes (TCSF-LER) is a corporate research unit of THOMSON S.A. It was created in 1973 and specialises in electronic imaging. Applied research is carried out mainly in the fields of electronic systems for defense applications, telecommunications, professional and consumer television.

TCSF-LER deals with all the "image chain", whatever the nature of the image may be : video or TV-like, computer designed, infrared, radar... More generally, TCSF-LER addresses all applications involving image representation and processing as a solution to a specific problem.
Theoretical studies provide the basis of the research activity and are assessed using powerful simulation tools. The studies usually result in prototypes and small series of advanced equipment designed with the latest technologies.

TCSF-LER is largely involved in international cooperation programs: Commission of the European Communities projects (ESPRIT, RACE...), industry driven EUREKA projects: EU 95 HDTV (high definition television), EU 45 PROMETHEUS (automotive electronics).

3. GENERAL STRUCTURE OF AN OPTICAL LINK

The main parts of an analog or digital optical link are given fig. 1, which provides a general description of an optical link including the transmitter, the receiver, and the transmission media, optical fibre in the circumstance.

The baseband signal must be adapted and transformed into a suitable format in order to be compatible with the optical transmitter; that is realized by the coding function.

The coding function could be a frequency multiplexer or time multiplexer, followed by a transcoder or a scrambler, if the source signal is respectively analog or digital.

Sometimes the coding function also includes an analog to digital conversion.

It could be more or less elaborated, depending on the application. For instance, bits can be added to provide exploitation facilities at the receiving end.

Then the electrical signal (high frequency, high bit rate, or mixture of analog and digital signals) drive the optical component (LED or laser) with the suitable or required level.

Before driving the laser a frequency or linearity compensation network can be introduced.

The choice of the optical transmitter depends on the type of fibre, the bandwidth requirement for the overall link, but also the linearity and the required performances particularly the Signal/Noise ratio.

An important point, impacting the link budget, that need be taken in account, is the organization of the optical line, the number and type of connections or splices, the use of optical couplers or multiplexers.

On the other side of the optical link, at the receiving end, the first operation consists in converting the received optical signal into an electrical signal.

The main features of this function is to have a low sensitivity threshold, high bandwidth, high optical power range, and also good linearity in case of analog applications.

In digital transmission the clock recovery function is also included in the optical receiver.
The decoding function is symmetrical to the coding function. It delivers the original signal with less errors or degradations as possible. Very often in digital transmission, the decoding function also performs exploitation facilities: synchronization, errors rate estimation, error correction... that generates alarm signals.

4. ANALOG TRANSMISSION

4.1. SQUARE PULSE FREQUENCY MODULATION (SPFM)

This modulation concept establishes a biunivocal correspondance between a baseband analog video signal, which information is beared by the amplitude axis, and an analog signal frequency modulated, which information is this time beared by the time axis (fig. 2).

The main feature of this type of modulation is to oppose a strong resistance to non linear degradations, particularly advantageous in case of optical transmission.

The modulation is parametrable in mean frequency (about 30 MHz) and in frequency excursion, that offers a flexibility of ajustment to a large variety of video signals or any other signal with similar features or less exacting.

In other respects the SPFM modulator delivers a Square signal. The unity duty cycle gives a constant mean power to the optical signal, no depending on the signal source, and optimizes the amplitude of the fundamental (4Ef') which is the only part of the transmitted signal exploited at the receiving end for demodulation.

The outgoing signal has only two levels, and can, therefore be treated by highspeed digital integrated circuits, and particularly switching circuits (see chapter 5.1.).

By the mere fact of the modulator parametrability (mean frequency and frequency excursion) and the unity duty cycle the control and selection of the fundamental part in the frequency spectrum is very easy by simple band-pass filtering.

It offers attractive facilities for the elaboration of frequency multiplexed signal, only by transposing the fundamental part, with a local oscillator, of each SPFM signal corresponding to the base-band video.

As a last point the demodulation of a SPFM signal extremely simple and performing.

This type of modulation is exploited in point to point optical links over long distances (10 km), or very long distances (100 km) when using repeaters. The degradations due to those repeaters have a low incidence on the overall transmission performances. With a DFB Laser it is possible to cover 100 km without repeater.

This principle of video transmission is today largely exploited by FRANCE-TELECOM. (Leased video links, video communication networks...).
4.2. ELECTRICAL FREQUENCY AND OPTICAL WAVELENGTH MULTIPLEXING

The main features of optical components never ceased to improve since the first optical link was set up for exploitation (fig. 3):

- Now the availability (in labs or industrially) of optical components at 1,3 m or 1,55 m allows to take advantage from the low optical loss of the fibre at these wavelengths.

- The use of monomode fibre allows to escape the bandwidth limitation due to the modal dispersion

- The lower chromatic effects owing to a close to zero chromatic dispersion parameter at 1,3 m (and 1,55 m) bring also considerable benefits on the overall optical bandwidth. This point could yet be improved using DFB lasers.

- The best theoretical (and real) sensitivity ratio in microamperes per optical microwatts of the photodetectors at high wavelength

- The improvement in optical coupling on monomode fibre

- The availability of performing optical multiplexers and demultiplexers.

For the same distance, all these improvements release the constraint on the optical budget and allow to share the same optical power for transmission of several sources, instead of one, by the way of electrical multiplexing and the use of passive components for coupling and wavelength filtering.

The number and the frequency carriers in the electrical multiplex need to be carefully choosen in order to reduce the second and third order intermodulation products.

After a non-linear operation (typically an optical transmission using a laser), in addition to the original source, the signal contains parasitic terms which are the harmonics of each carrier, but also terms resulting from linear combination of different frequency carriers. Though the frequency carriers are choosen in order to avoid that these last parasitic terms fall very close to the useful carriers (fig. 4).

In addition to this non-linear aspect, another main obstacle consist in realizing an optical receiver (optical to electrical conversion), having a very low sensitivity threshold and a very wide bandwidth (B  1 GHz) at the same time. The know-how in designing high sensitivity optical receivers is well controlled at LER and the realizations that have been done successfully do not systematically involve heavy technology like hybrid circuits.

In other respects the important growing need in video (and generally widebandwidth) links bring us to take seriously in account the economical aspect. Considering an optical link, over a few km the cost of the fibre and its installation become predominant. In order to keep reasonable the costs, and due to the availability of components at 1,3 m and 1,55 m, it is possible to double the number of transmitted channels by multiplexing the wavelengths.

Such analog transmission equipment, using the basic SPFM modulation, and combining electrical and wavelength multiplexing have been realised.
It is able to transmit up to 8 video sources, each of them accompanied with two sounds (fig. 5), or D2MAC signals (fig. 6), or 16 sources if we are slightly less exacting on performances.

With such an equipment it is possible to considerably reduce the cost of a point to point multichannels link, still guaranteeing a broadcast quality for distances up to 20 km (Weighted S/N 63 dB).

4.3. **BASE BAND OPTICAL TRANSMISSION**

This type of optical links are particularly vulnerable to non-linearity due to the generally required high bandwidth.

- A Base-band optical link have been studied for HDTV applications. It transmits 4 Baseband signals (Red, Green, Blue and Synchro), each having up to 60 MHz bandwidth, on 4 optical fibres, involving a predistortion network in the laser driver. The performances of this equipment can be extended up to 120 MHz.

Many link equipments have been realized and are exploited on HDTV exhibition sites or in european labs.

This link could be used with any other type of signal than video, or applications (High Definition graphical Display, measurement signals...).

- Multichannels AM/VSB optical link :

This link is in current study at LER.

It is expected to transmit over 30 AM/VSB channels on one fibre, with rather stringent Carrier to Noise and linearity performances (C/N 50 dB, C/Im3 64 dB).

With such a link it is possible to transmit any channel or analog multiplex up to 1 GHz.

5. **DIGITAL TRANSMISSION**

This is the second axis of the transmission and switching laboratory's activity.

The main required features for a digital link are recalled hereafter.
5.1. OPTICAL RECEIVERS FOR DIGITAL TRANSMISSIONS (FIG. 7)

In order to appraise the quality of a digital optical link, we observe a diagram called "Eye Pattern" at the receiving end. This diagram represents in one time slot (a clock period) the superposition of successive binary elements in the received bit stream. It is obtained, using a Pseudo-Random Binary Sequence (PRBS), the received signal connected to the oscilloscope, time triggered by the transmission clock (transmitted or received).

This diagram informs on two main features:

- the noise level at the receiver
- the frequency performances (Attenuation and Phase) of the transmission media.

A good transmission is achieved when the "eye pattern" is widely open on the two axis: Amplitude and Time.

In order to reach this objective two fundamental operations are required at the receiving point after optical to electrical conversion by the way of a low noise and wide bandwidth optical receiver:

- Equalization and Amplification to open the "Eye pattern" on the amplitude axis.
- Clock restitution to retiming the signal on the horizontal axis (horizontal opening).

The sensitivity threshold of a digital optical receiver is generally defined at a bit error rate of $10^{-9}$.

5.2. TRANSMISSION CODING

In order to effectively operate these two functions the line signal must have a few properties (fig. 8):

- Constant mean power:

  The optical receivers do not transmit the direct current component, so the mean power of the optical signal must be free of any information.

- Limitation in successive 0 or 1 sequence:

  A long sequence of the same binary element would be derivated by the link time constant and may cause errors increase at the amplitude decision node.

- High transition density

  It will be easier, and better will be the bit error rate, to generate energy at the clock frequency and therefore regenerate the clock, if the spectrum line at half the clock frequency is high.

It is the role of the transmission coding function to give the signal these properties.
A very large variety of transmission codes can be involved, depending on the source format and bit rate.

The three main ways of coding are (fig. 9):

- **Self retiming signal code**:

  The clock is contained in some part of the transmitted signal. This coding family need a very wide bandwidth and, therefore not easy to realise for high bit rate applications. Biphase, Alternate Mark Inversion (AMI), Complementary Mark Inversion (CMI) belong to this family.

- **Scrambling code**:

  Rather easy to involve, all the more they do not change the nominal bit rate.

  However, they require to be causiously used particularly due to blocking phenomenas.

- **Transcoding code**:

  Some codes establish a biunivocal correspondance between a source "n bits word" and a transmitted "m bits word" in which only the best combinations of binary elements are retained regarding the required properties.

  Other codes consist in adding binary elements to the source bit stream which elaborating rule is known a priori.

  These codes lead to a slight increase (m/n) in the transmitted bit rate which is generally acceptable regarding the transmission media.

  However, the electrical circuitry at the transmitting and receiving ends is a bit more complicated due to the change from local clock to transmission clock.

  The codes are very convenient for parallel to parallel transmission.

  These codes are able to provide exploitation information, as statistical quality of the transmission, owing to redonduncy voluntarily introduced in the line signal.

5.3. **INTER STUDIO 1.3 GB/S HIGH DEFINITION TELEVISION OPTICAL LINK**

TCSF/LER is deeply involved in the European project EUREKA 95 dealing with Compatible High Definition Television.
"Compatible" means that High Definition Television (HDTV) will be smoothly and progressively introduced to the subscriber with less discontinuity as possible in three main steps:

- TV Set with D2-MAC receivers
- HDTV signals distributed under HDMAC format, that could be received by D2-MAC receivers
- Advent of fully HDMAC receivers.

Within the studio, due to considerable progress in cameras analog to digital conversion, and integration in digital techniques it is now possible to produce High Definition Video signals.

In parallel, in the framework of this EUREKA project, the distribution and reception of HDTV signals are also investigated.

The rough bit rate for a production studio interlaced HDTV signal under 4/2/2 format recommended by CCIR is 1,15 Gb/s. This high bit rate brought us to fundamentally reconsider the transmission structure inside the studio. The existing solution based on standard coaxial cable is no further exploitable in this new environment.

The transmission department of LER have studied and developed an optical high bit rate link to solve these production needs (links between production studios and post-production centres) where the rough bit rate is handled (fig. 10).

The main problems in such a transmission system are:

- The choice of a transmission code easy to implement and able to perform synchronisation and exploitation functions in spite of the high bit rate.

- To realize a very wide bandwidth optical receiver with a very low sensitivity threshold and high optical dynamic range.

- To solve clock recovering at a very high frequency.

Typically the digital TV signal does not meet at all the required properties described in chapter 4.2. The input and output of the transmission interfaces are 8 bits parallel signals at a 144 MHz word rate (fig. 11).

A transmission coding consisting in adding a bit per word have been retained and two ways of coding have been investigated and compared. A first solution was based on a 8 to 9 bits word transcoding using a High speed ECL RAM, and the second associated synchronized scrambling on the 8 bits before adding a complementary bit. In both cases the resulting bit rate is 1,3 Gb/s and the line signal meet the required properties.

That is an important point, because the video signal is one of the more exacting signal regarding this transmission coding aspect and that means that the same procedure could by applied to treat any other signal less stringent, as data for example.

At this bit rate the conception rules are very close to those of the microwave domain. Propagation delay needs to be taken in account at the designing level (the bit durations is 0,7 ns) and all the interconnection lines need to be causiously matched.
The optical transmitter is a 1.3 m laser diode (BH) and the peak to peak output optical power is about -2 dBm (600 W). The sensitivity threshold of the optical receiver for a $10^{-9}$ bit error rate is about -30 dBm; that allows optical links up to 20 km.

Current works on optical receivers will lead to a sensitivity threshold of -33 dBm and the link range will be brought up to 35 km.

A wavelength transfer to 1.55 m would allow links over 50 km (with DFB laser).

The deserializer make a symmetric operation to the serializer and delivers the initial parallel words accompanied with the word rate.

It also performs synchronization facilities and alarm.

Several 1.3 Gb/s equipments have been realized and one of them is under demonstration in a network called OPTOGIGANET. Other equipments are under development for FRANCE-TELECOM and devoted for the 92 Olympic Games in Albertville.

Based on this previous development, a second optical link have been realized for the transmission of a Progressive HDTV signal (1250/50/1). It is operating at 2.6 Gb/s (twice the first bit rate).

5.4. NEW TRANSMISSION CONCEPTS (DIGITAL DOMAIN)

In parallel with the existing transmission levels recommended by CCITT, for future developments two new transmission modes have to be considered, depending on the application:

- Synchronous Digital Hierarchy (SDH)
- Asynchronous Transport Module (ATM)

The deployment of those new transmission modes is beginning and particularly investigated in RACE projects.

The aim of SDH is to facilitate:

- Interconnection of transmission equipments from different manufacturers by specifying logical and physical parameters of the optical interface (not specified in the existing hierarchy due to the fact it was devoted for coaxial cable mainly).

- Elaboration of higher transmission level from different tributaries

- Operation, Administration and Maintenance of networks due to preaffected fields in the overhead in the bit stream resulting from coding operation.

SDH is mainly guided by a transmission and meshed network approach.
The basic level for this new hierarchy is STM1 (Synchronous Transport Module - level 1) which bit rate is 155 Mb/s.

The aim of ATM is to facilitate:
- The coexistence of a great variety of services
- Flexibility in handled bit rates.

It is mainly a high flexibility service approach.

In the framework of another European project (RACE 1036), TCSF/LER is developing an hybrid optical receiver and a clock recovery function respectively intended to work at 2.5 Gb/s and 2.5 GHz (STM.16). Circuits have already been tested.

A brief description of this RACE project is given in chapter 6.

Other department of LER are involved in RACE projects dealing with ATM concept.

LER is aware of those two new techniques.

These new techniques have not the ambition of solving all the transmission problems; a lot applications will remain too specific, will reveal too expensive or will not need, to fit with the constraints of such transmission recommendations.

Nevertheless, it will be possible to take advantage of technology development led and required for these new techniques.

6. NETWORKING TOOLS

In order to complete and structure the different types of point to point optical link previously discussed, in the same department, LER is also having a switching activity. This third axis allows the realization of complete networks from end to end, reducing interfacing problems.

This activity is illustrated by describing in a few words two complementary networks, one based on a meshed concept and the other on a star approach.

6.1. BROADBAND SWITCHED NETWORK (FIG. 12)

As previously said, the need in professional video links is considerably increasing, and accordingly the installation costs are becoming unreasonable and dissuading for the exploiters and subscribers.
To avoid overcosts due to frequent links reconfiguration the idea consists in realizing a meshed network, able to interconnect any subscriber with another. At each node of such a network there is a wide bandwidth switching equipment, controlled by a central computer which received the subscriber link reservation and automatically establishes the transmission at the predetermined time.

TCSF/LER have studied and developed (under FRANCE-TELECOM Contract) such a switching equipment, compatible with the SPFM and multichannel video optical links discussed above and with digital links at 34 Mb/s or 140 Mb/s (CCITT recommendation G703).

The main features of the transmission network are:

- Meshed network based on Primary Nodes (heart of the network) and Secondary Nodes (on which the subscribers are connected).

- The node dimensions are 32 inputs x 32 outputs, extendable to 64 inputs x 64 outputs.

- At the same moment the switching equipment can handle different types of signals:

  SPFM, Intermediate Frequency in terrestrial radiolinks (70 MHz), 34 Mb/s HDB3, 140 Mb/s CMI...

  The equipment is easily adaptable to other signals, particularly digital signals up to 350 Mb/s NRZ.

- The switching equipment at a node have also a diffusion facility. The same input can be sent at the same time to several subscribers.

- The node equipment can also be locally controlled by a Terminal Handset.

In order to achieve the required performances, a lot of new and high technology are involved, particularly:

- High bit rate 16 inputs x 16 outputs switching matrix in ECL 100K technology.

- Transcoding component for HDB3 signal

- Surface Acoustic Wave (SAW) filters for clock restitution resonator

- Realization of hybrid circuits for clock restitution functions (as previously discussed)

- New concept for high efficiency power converters

- In the equipment all the boards are multilayers boards with matched stripline interconnections.

A view of the equipment is given on fig. 13.

At the present time an experimental network is exploited by FRANCE TELECOM in PARIS.
6.2. OPTICAL WAVELENGTH MULTIPLEXING IN A STAR NETWORK

6.2.1. Basic Demonstrator (fig. 14)

A demonstrator have been set up in order to show that it was possible to mix a large number of optical wavelength, each of them bearing any kind of signal (analog or digital, low frequency or high bit rate), in a star network built around a passive optical coupler.

The demonstrator is routing 5 optical wavelengths; the optical budget allows up to 8 wavelengths.

In order to unliven this network, one of the HDTV high bit rate optical link at 1.3 Gb/s and an analog SPFM optical link previously described are connected to the network. The three other wavelengths are loaded with Pseudo-Random Binary Sequence (PRBS) delivered by a lab equipment.

The main difficulty to overcome in such network is to insure compatibility between wavelength stability with temperature and driving current, and optical demultiplexer.

Such a network could be exploited to route a set of signals, whatever they are (video, measurement or control data,...) from a distant room to a control centre using only one fibre.

6.2.2. Wavelength and Time Division Multiplex (WTDM)

An european project have been set up two years ago in the framework of RACE (project RACE 1036), based on the same principle of mixing numerous wavelengths in a star coupler (fig. 15).

This RACE project is a complete system, bidirectionnal on two fibres and including a lot of electronic functions, particularly high bit rate switching, down to the subscriber interface, gathered in a Local Routing Centre (LRC), whereas the basic system (fig. 14) intend to demonstrate the optical feasability.

Concerning the technique aspect this system mainly involves the new SDH hierarchy presented above, at the STM 16 level (2.5 Gb/s) and concerning the technological point of view it is exploiting 16 wavelengths, with a channel spacing of 4 nm, in the 1.5 m window of a monomode fibre.

It is intended to produce a lot of circuits to handle STM-16 level and protocole, and high bit rate optical components (DFB laser at 1.5 m, hybrid optical receivers...).

As it is a RACE project several europeans partners are involved. TCSF/LER is in charge of the high bit rate optical receiver, the clock recovery function and the high bit rate switching matrix implementation at 2.5 Gb/s.

Samples of optical receivers (fig. 16) and clock recovering functions have been realized and tested.
Fig. 17 shows a very satisfying data "Eye pattern" before retiming. The sensitivity threshold of the optical receiver is about -28 dBm (mean power) at 2.5 Gb/s.

The bit duration is 0.4 ns at 2.5 Gb/s. Fig. 18 shows a rise and fall time of about 0.1 ns. It is noticeable that the time jitter at the crossing point is considerably lower and the crosspoint itself is at mid-height; the "Eye pattern" is widely open on the horizontal axis. This signal is strong enough to be sent on treated on another board.

7. NEW WAYS OF IMPROVEMENT IN PROSPECT

The following points belong to the research domain in basic components.

However, as soon as those developments will be mature and enough reliable, TCSF/LER will not hesitate to introduce them in systems if it is a consistent way of improving the performances.

TCSF/LER, with the support of other TCSF departments also realizes some systems, particularly close to physical phenomenas. Typically very wide bandwidth analog optical link (up to 20 GHz), very low propagation delay measurement or compensation, wide bandwidth delay lines...

The new prospects are:

- Optical amplification:

  At the present time optical amplifier begin to be commercially available in US at a rather reasonable cost.

  Noise and linearity performances need to be improved or checked to envisage the use of such equipment in the transmission area we have been considering.

  Nevertheless the advantages are considerable compared to a standard repeater in a trunk. Owing to the transparency regarding the application and the aperiodicity of this device it will be easy to involve in future systems.

- Optical switching:

  Even if today the large square optical matrix is still being a dream, considerable progress have been made in this area.

  Mechanical optical switch are available. Some integrated optics components on Lythium Niobate or Indium Phosphure are available in labs but the size is only 2 inputs x 2 outputs. The controlling level is about a few volts and the switching speed of the order of the nanosecond.
- Coherent optics
  Particularly investigated in RACE projects

- Distributed FeedBack Lasers (DFB laser)
  Devoted to analog applications up to 20 GHz

- Quantic Well Laser (QW Laser)
  The performances of these components are at midway between Buried Heterostructure Laser (BH) and DFB laser for a very lower cost.

8. CONCLUSIONS

In this paper, various aspects of the activity on the video transmission and switching areas covered by TCSF/LER, within their transport/switching laboratory have been presented. From the point to point analog optical link to high bit rate optical network, from the elementary function to the complete system ready to work, each of the mentionned applications has its own main difficulty or technological problem to be solved.

The multiplexing and coding techniques involved in video transmission and switching equipments were also covered.

It must be pointed out that the above mentionned systems or techniques, analog or digital, could apply to any other signal (High bit rate data exchange between computers, periodic or not measurement signal, radar or astronomical antenna, graphical display...). Examples of such applications have already been treated by LER as a consequence of their expertise.
GENERAL STRUCTURE OF AN OPTICAL LINK

FIG. 1
**SQUARE PULSE FREQUENCY MODULATION (SPFM)**

![Diagram of SPFM Modulator]

**Main Features**

1) **The Analog Information is Supported by the Temporal Axis:**
   So it is much more resistant to any channel linearity degradation; particularly when optical components are involved.

2) **It is a Two Levels Signal:**
   It can be handled by high speed digital integrated circuits (ECL 100K Family); and particularly by digital switching matrix for networking applications.

3) **It is Easy to Elaborate a Frequency Multiplex for Multichannels Applications** by Filtering the fundamental part of the spectrum and using frequency transposition. There is no second order terms in the Fourier serie.

4) **The SPFM Signal is Very Easy to Demodulate**
MAC SIGNAL COMPARE TO STANDARD VIDEO SIGNAL

Existing (FDM)

MAC (TDM)

FIG. 6
REQUIRED PROPERTIES OF DIGITAL SIGNAL CARRIED BY A SINGLE SUPPORT

- Average value : constant

\[ A_0 = \frac{A}{2} \quad (A: \text{peak to peak received data amplitude}) \]

- High transition density.

- Number of binary digits consecutively set to 0 or 1 as low as possible.

1) Biphase type code.

2) Scrambling.

3) Type code : 8 bits \(\rightarrow\) 9 bits:

- 8 bits scrambled - 1 C bit

<table>
<thead>
<tr>
<th>Serial signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 1 2 3 4 5 6 7 8</td>
</tr>
</tbody>
</table>

- 8 bits \(\rightarrow\) 9 bits transcoding:

8 bit words \(\rightarrow\) 9 bit words

256 possible words \(\rightarrow\) 512 possible words

choice of words with most of transitions
FIG. 10

POST-PRODUCTION CENTRE

DATA PROCESSING CENTRE

BROADCASTING CENTRE

L some 10Kms

10m to 100m

HDTV SIGNAL NORMALISATION AND STUDIO PROCESSING

PRODUCTION STUDIO

POST-PRODUCTION CENTRE
DIGITAL HDTV TRANSMISSION SYSTEM

FIG. 11
TER 5100

Widebandwidth Switching Array

FIG. 13
OPTICAL WAVELENGTH MULTIPLEXING IN A STAR NETWORK

CODEUR TVHD

CODEUR SPFM

COUPLEUR ETOILE 8X8

BOBINE FO 1 Km

DMUX

DECODEUR TVHD

DECODEUR SPFM

E: EMETTEUR OPTIQUE
D: PHOTODETECTEUR

FIG. 14
RACE Project 1036
WTDM Broadband Customer Premises Network

16 SIGNAL SOURCES

Local Routing Centre (LRC) No.1

LRC 2

LRC 3

16x16 optical star coupler

LRC 16
LRC 15

LOCAL ROUTING CENTRES 4-14

A WTDM routing system

FIG. 15
PHOTOGRAPH OF THE STM 16 (2.48832Gb/s)
OPTICAL RECEIVER

TOPOLOGY OF THE OPTICAL RECEIVER HYBRID CIRCUIT
Eye pattern at the input of the D type Flip Flop

Waveform of the recovered clock

Ch. 1 = 200.0 mVolts/div
Ch. 2 = 200.0 mVolts/div
Timebase = 200 ps/div
Delta V = 643.75 mVolts
Vmarker1 = -287.50 mVolts
Delta T = 1.4000 ns
Start = 18.0880 ns

Offset = -408.7 mVolts
Delay = 17.7880 ns

Vmarker2 = 356.25 mVolts
Stop = 19.4880 ns

FIG. 17
Trigger on External at Pos. Edge at -2.000 mVolts

Eye pattern of the retimed data at the STM 16 bit rate

Function = 200.0 mVolts/div
Horizontal = 200.0 mVolts/div
Ch. 2 = 200.0 mVolts/div
Timebase = 100 ps/div
Delta V = 643.75 mVolts
Vmarker1 = -287.50 mVolts
Delta T = 1.4000 ns
Start = 18.0880 ns
Offset = -488.7 mVolts
Offset = -11.25 mVolts
Delay = 17.7880 ns
Vmarker2 = 356.25 mVolts
Stop = 19.4080 ns

FIG. 18

RACE 1036
WTDM - BCPN
SUPERCONDUCTING ACCELERATOR AND DETECTOR MAGNETS

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A short review on the status of superconducting dipole and quadrupole magnets for existing (HERA/DESY) and planned (LHC/CERN and SSC/Texas) accelerator rings is given. Concerning the state of the art of mid-size and large detector magnet systems it is reported on the solenoidal magnet system for CERES/CERN and on the CLAS Torus Magnet System planned at CEBAF/USA. Examples of complex internally cooled superconductor cables for nuclear fusion applications are shown which may be utilized for the realization of large detector magnet systems with high magnetic field.

Introduction

With the HERA collider ring at DESY a first accelerator ring (protons) built of industrially fabricated superconducting magnets has recently been completed. For subsequent collider rings, e. g. the Large Hadron Collider (LHC) at CERN and the Superconducting Super Collider (SSC) at Texas higher magnetic fields are needed. For cost optimization reasons these colliders have to be planned with superconducting magnets.

Concerning the design of detector magnets there is a general trend to use superconducting magnets because stronger magnetic fields are needed.

This paper gives a short review on the status of the capabilities for fabricating superconducting (s.c.) accelerator and detector magnets: As an example the industrial fabrication of the s.c. quadrupole coils for HERA is described in chapter 1. In chapter 2 an overview on the status of the development of s.c. dipole magnets for the LHC and for the SSC is given. The detector magnet
system for the CERES project at CERN is described in chapter 3 and the CLAS Torus Magnet System planned for the Continuous Electron Beam Facility (CEBAF)/USA is introduced in chapter 4. Examples of complex internally cooled superconducting cables are shown.

1. Industrial Fabrication of Superconducting Quadrupole Coils for HERA

For the HERA ring 246 quadrupole magnets were fabricated by industry, 122 were manufactured by Interatom/Siemens UB KWU at Mülheim. About 90 magnets out of these have the standard length of 1.86 m. The development was performed under contract of DESY by CEN-Saclay, where four prototypes were fabricated. The know-how transfer from CEN to industry was established by a preseries of five magnets built by each manufacturer.

The procedure and the details of the manufacturing process of the quadrupole coils as shown in Figure 1 and Figure 2 are described in more detail in Reference [1].

Quality control is of outstanding importance for the manufacturing procedure. Dimensions, winding tension, Young's modulus and resistance were routinely measured, high voltage tests with 5 kV to mass and warm field measurements were performed for each of the collared coils. For all coils the field harmonics were within the specified tolerances. Nevertheless, there were some material problems which demanded for a lot of changes in planning of personnel and logistics during the contract period, see Table 1.

After the assembly of each coil into its cryostat by another contractor all quadrupole magnets were successfully cold tested at DESY.
Table 1: Material Problems and Corrective Measures

- Conductor Tolerances at upper limit
  → Insulation Tayloring (Kapton thickness, resin content in prepreg tape)
  → Temperature (instead of time) controlled curing profile

- Permeability of Collar Laminations too high (≥ 1.02)
  → New melt of DIN 1.4429 stainless steel (AISI 316 LN)

- Fine Blanking of Collar Laminations:
  → 15% sorted out because of severe mechanical defects

2. Superconducting Dipole Magnets for LHC and SSC

In Table 2 the main parameters of the dipole magnets planned for LHC and SSC are shown in comparison with those for the HERA dipole magnets.

Table 2: Superconducting Dipole Magnets for LHC and SSC

<table>
<thead>
<tr>
<th></th>
<th>HERA (single aperture)</th>
<th>LHC (double aperture)</th>
<th>SSC (single aperture)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Induction</td>
<td>4.7 T (4.5 K)</td>
<td>10 T (1.8 K)</td>
<td>6.6 T (4.3 K)</td>
</tr>
<tr>
<td>Length</td>
<td>8.8 m/3.3 m</td>
<td>~10 m</td>
<td>15.8 m/13.3 m</td>
</tr>
<tr>
<td>Aperture</td>
<td>75 mm</td>
<td>50 mm</td>
<td>50 mm</td>
</tr>
<tr>
<td>Superconductor</td>
<td>NbTi</td>
<td>NbTi</td>
<td>NbTi</td>
</tr>
<tr>
<td>Operating Current</td>
<td>5000 A</td>
<td>15000 A</td>
<td>6500 A</td>
</tr>
<tr>
<td>Number of dipole magnets</td>
<td>453</td>
<td>~2000</td>
<td>~8500</td>
</tr>
<tr>
<td>production rate per contractor</td>
<td>1 magnet/day</td>
<td>10 magnets/day</td>
<td></td>
</tr>
</tbody>
</table>
The dipole magnets for LHC and SSC have an aperture of 50 mm which is much smaller compared to the HERA dipoles with 75 mm. The highest field is planned for the LHC dipoles with 10 T which is only achievable with He-II cooling at 1.8 K using a NbTi superconductor. A correspondingly high current of 15 kA is needed.

The dipole magnets within their cryostats can be seen in Figure 3 (LHC) and in Figure 4 (SSC). A very special feature of the LHC dipole magnets is the combination of the two separate beam channels into one cryostat, i.e. both dipole coils are embedded into a common collar. The extremely high electromagnetic forces demand for a prestress on the coils which will also be maintained by a shrinking cylinder of Aluminium around the common iron yoke.

Table 3 gives a brief summary on the status of the present steps for the development of the LHC and the SSC dipole magnets.

<table>
<thead>
<tr>
<th>Table 3: Status of the Development for the LHC and the SSC Superconducting Dipole Magnets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>LHC, dipole magnets</strong></td>
</tr>
<tr>
<td>• 2 model coils, single aperture, NbTi, 1 m long fabricated; 9.3 T and 9.45 T reached</td>
</tr>
<tr>
<td>• 1 model coil, single aperture, Nb3Sn (wind &amp; react), 1 m long fabricated; 9.4 T reached</td>
</tr>
<tr>
<td>• Contracts with 4 companies for delivery of 4 double aperture, NbTi, dipole coils, first dipole coil at CERN in October '90</td>
</tr>
<tr>
<td>• Decision for ordering of 8 full scale dipole magnets, double aperture, NbTi, from European industry → complete cell (~ 100 m)</td>
</tr>
</tbody>
</table>

| **SSC, dipole magnets**                   |
| • Several versions of magnets successfully tested at Fermilab |
| • "Industrialization Phase" for magnet procurement: 16 industrial participants |
| • Schedule: begin of magnet production by industry planned in 1993 |
3. Detector Magnet System for CERES/CERN

The experiment CERES at the SPS of CERN has a mid-size solenoidal magnet system. It is about 4 m long and 3 m high and consists of a set of 6 large normal conducting (n.c.) water cooled coils with an inner diameter of about 2.2 m and superconducting Helmholtz (twin) coil with an inner diameter of about 0.8 m nearly in the center of the n.c. coils, see Figure 5 and Figure 6. Being charged equally the s.c. coils generate a magnetic induction of 1 Tesla on the magnet axis. (For the CERES experiment the two s.c. coils are operated with opposite current.)

The s.c. coils were electrically and cryogenically supplied through one of the four support bars which connect the vacuum vessel of the s.c. magnet and the support vessel for the n.c. coils. Thus, only a minimum in absorption of the Cherenkov radiation to be detected was achieved. This was a challenging task because only a cross section of 25 mm x 100 mm was usable within the supply bar for three current leads, the instrumentation wires (temperature sensors, potential taps), the liquid Helium inlet tube, inlet and outlet tubes for gaseous Helium (radiation shield, Helium vessel), and for the superinsulated radiation shield of the supply bar itself. On top of the outer vessel a Helium dewar with a supply turret for all connections and a relief valve is positioned. The whole magnet system was designed, fabricated, assembled, and tested within a period of 14 months by Interatom GmbH, Bergisch Gladbach.

4. CEBAF Large Acceptance Spectrometer (CLAS)

The CLAS Magnet System planned for the Continuous Electron Beam Accelerator Facility (CEBAF) at Newport News/USA consists of a toroidal arrangement of six large superconducting coils, see Figure 7. The axis of the torus is equal to the beam axis. The shape of the coils was chosen in such a way that their magnetic field covers a large area
behind the target and close to the beam axis. The maximum field at the coils is 3.5 Tesla. This complex structure is especially demanding with respect to cryostat technology and to a safe cryogenic operation.

In contrast to the superconducting cables used for the bath cooled dipole and quadrupole magnets for the collider rings the CLAS coils are to be wound from a so called Cable-In-Conduit Conductor (CICC) which is a bundle of superconducting wires surrounded by a stainless steel tube. The CLAS conductor is very similar to the CICC which was recently proposed for the s. c. coils of the German fusion experiment Wendelstein VII-X planned at IPP/Garching [2], see Figure 8a). Between the s. c. wires liquid Helium is flowing. Such internally cooled superconducting cables are usually used and planned for large superconducting magnets because of their high mechanical strength and high cryogenic stability. They have already been developed for different nuclear fusion applications, e. g., the Large Coil Task (LCT). This experiment was built of six large (4.6 m x 3.6 m) superconducting D-shaped magnets at Oak Ridge. Three coils are wound from internally cooled superconducting cables of different design. These six magnets were successfully tested three years ago. One of the coils, the EURATOM LCT coil built by Siemens, was wound from the superconductor shown in Figure 8b. It carries a current of up to 16 kA at 4.2K. The maximum magnetic induction at the coil is 8 Tesla.

The examples mentioned so far are mainly based on the NbTi superconducting material. But with Nb$_3$Sn higher fields can be obtained although the technology is less advanced than that for NbTi superconductors. The forefront of the technology of complex s.c. cables is in the field of nuclear fusion where toroidal magnet systems for the next generation of fusion experiments are conceptually designed which are more than a factor of two larger than the coils for the LCT project.
Conclusion

The capabilities of industry for the series production of superconducting dipole and quadrupole magnets were proven by the completion of the HERA collider. This well established technology has to be extended to the series production of forthcoming colliders. The superconducting magnets for the collider rings like LHC and SSC are technologically more challenging because of the higher fields or gradients, a smaller aperture, and a larger axial dimension. Moreover, they are needed in much larger quantities, which demands for a production rate of about 10 magnets per day and contractor for the SSC, e. g. This requires a well defined quality assurance program and a high standard of quality control during series production. The conceptual design and the development of large detector magnets can take profit from the development of complex superconductor cables for the large magnet systems being developed for nuclear fusion.

References


Figure 1: Cross Sectional View of Collared Quadrupole Magnet for HERA

Figure 2: Quadrupole Magnet for HERA Completed with Collar Laminations, End Caps and Current Leads
Figure 3: Cross Section of a LHC Superconducting Dipole Magnet

Figure 4: Superconducting Dipole Magnet for SSC
Figure 5: Magnet System for the Elementary Particle Detector CERES/CERN

Figure 6: Superconducting Magnet for Elementary Particle Detector CERES/CERN
CLAS Torus Magnet System/CEBAF

- 6 superconducting coils (4.5 m/2.5 m)
- Conductor: "cable in conduit" (CICC)
- Rated current 10 kA
- Coil (cold mass) coupling via two cold rings
- Magnetic field at coil: 3.5 T

Figure 7: Superconducting Coil System for the CEBAF Large Acceptance Spectrometer (CLAS)

Figure 8: a) Cross Section of a Superconducting Cable-in-Conduit-Conductor (CICC) (Proposed for the Fusion Experiment Wendelstein VII-X)
b) Superconductor for the EURATOM LCT Coil
1. INTRODUCTION

This workshop, consisting of two and a half days of parallel sessions followed by two and a half days of plenary talks which reported on the conclusions reached by each of the working groups, was both intense and very fruitful. It has marked a watershed, the time, when the LHC project, in the eyes of the European particle physics community, graduated from being still speculative to being the way forward for European particle physics. This is not to say that all problems have been solved, but rather that the physics goals are exciting and the technologies of both the accelerator and the detectors though daunting do not appear to be unattainable.

In order that this summary be concise and the conclusions emerge clearly I will not try to justify most of the statements I make in a quantitative manner, I leave that to the authors of the relevant papers in these proceedings.

Should the reader feel that on the basis of the individual working group reports in these proceedings my conclusions are not justified then this is either due to my using additional information not contained in the written reports, or due to my having misunderstood some important point, in which case I apologise.

My personal involvement in LHC or SSC studies has up to now been minimal and therefore I had the advantage of looking at the scene without too much prejudice or prejudice but the disadvantage of having to work extremely hard to understand the myriad of problems from the point of view of physics and the technology posed by the LHC. It was both an exhausting but rewarding experience.

2. THE MACHINE

Table 1 gives a comparison of the two of the most important design parameters of LHC and of other machines likely to be operating at LHC start up as well as the SSC parameters.
TABLE 1

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>&quot;Other&quot; Machine parameters</th>
<th>SSC parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>pp</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\sqrt{s}$ (TeV)</td>
<td>15.4</td>
<td>TEVATRON</td>
<td>40</td>
</tr>
<tr>
<td>$L$ (cm$^2$s$^{-1}$)</td>
<td>(1.7 - 5)$ \times 10^{34}$</td>
<td>1.8 $\times 10^{31}$</td>
<td>$10^{33} \rightarrow 10^{34}$**</td>
</tr>
<tr>
<td></td>
<td>Up to $2 \times 10^{32}$</td>
<td>$0.3$</td>
<td></td>
</tr>
<tr>
<td><strong>ep</strong></td>
<td></td>
<td>HERA</td>
<td></td>
</tr>
<tr>
<td>$\sqrt{s}$ (TeV)</td>
<td>1.7 - 1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$L$ (cm$^2$s$^{-1}$)</td>
<td>Up to $2 \times 10^{32}$</td>
<td>$0.3$</td>
<td></td>
</tr>
<tr>
<td><strong>PbPb</strong></td>
<td></td>
<td>RHIC</td>
<td></td>
</tr>
<tr>
<td>$\sqrt{s}$/Nucleon pair</td>
<td>6.3</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>$L$ (cm$^2$s$^{-1}$)</td>
<td>$1.8 \times 10^{27}$</td>
<td>$5 \times 10^{26}$</td>
<td></td>
</tr>
</tbody>
</table>

* $1.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$ is for each of 3 interaction regions while $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ is if collisions occur only in one interaction region.

**The initial design luminosity at SSC is $10^{33}$cm$^{-2}$s$^{-1}$, but there are plans to upgrade this later to $10^{34}$cm$^{-2}$s$^{-1}$.

From this table it can be seen that the LHC represents very large energy and luminosity jumps from the 3 most advanced facilities that will be in operation and even in pp it will have a large luminosity advantage over SSC when this comes on stream even though at a lower energy. The flexibility of the machine, is as we shall see, a great strength.
3. EXPERIMENTAL AREAS

Of the 8 LEP experimental areas, one (probably Pit 3) is needed as a beam dump leaving 7 for all other purposes.

When running LHC in either pp or ion-ion mode one additional experimental area is required for beam cleaning. Therefore for LHC running 6 experimental areas are in principle available. These 6 can be divided up as 2 LHC and 4 LEP or 3 LHC and 3(+ 1) LEP with one LEP experiment in its garage position while LHC is operating, that intersection region being temporarily used for beam clean up. This process can be quickly restored for LEP operations. Presumably later as LEP experiments die, the number of LHC experimental regions can increase.

When running in the ep mode only one experimental region will be available (either pit 5 or 7).

Another important feature of LHC is the possibility of decreasing by up to a factor of 30 the luminosity at any one intersection region without affecting the luminosity at any other.

4. PHYSICS TOPICS

4.1 Proton-Proton Interactions

The working groups have addressed the following topics:

<table>
<thead>
<tr>
<th>Standard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Higgs sector</td>
</tr>
<tr>
<td>(b) b-physics</td>
</tr>
<tr>
<td>(c) t-physics</td>
</tr>
<tr>
<td>(d) Standard processes - cross-sections, structure functions, neutrino physics etc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Beyond the Standard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>(e) Super symmetry</td>
</tr>
<tr>
<td>(f) Compositeness</td>
</tr>
<tr>
<td>(g) New vector bosons</td>
</tr>
<tr>
<td>(h) New Quarks</td>
</tr>
<tr>
<td>(i) Exotica</td>
</tr>
</tbody>
</table>

These topics cover two aspects of a machine like LHC.
Firstly, the exploration of a new energy frontier due to the very large increase in centre of mass energy and luminosity compared to the Tevatron (about factors of 10 and 10³ respectively) and secondly the systematic study of partially explored phenomena taking advantage again of the high energy and luminosity to obtain large data sets.

For this summary, I have chosen two examples from the many explored to illustrate the power of the LHC in these two areas:

4.1.1 The Standard Model Higgs, $H^0$

If we assume that the $H^0$ has not been discovered at LEP 200 i.e. $M_{H^0} \sim 80$ GeV/c², then ideally the mass range explored by LHC should cover the region from 80 GeV/c² to $\sim 1000$ GeV/c² where the width of the Higgs is roughly equal to its mass! Figure 1 shows the cross-section for Higgs production as a function of $\sqrt{s}$ while Figure 2 shows the width of the $H^0$ as function of its mass. Two features should be emphasised because they are of importance experimentally in the search. Firstly, the cross section is such that below a mass of $\sim 400$ GeV/c² about $10^6$ Higgs are produced in a standard $\mathcal{L} = 10^{34}$ cm⁻²s⁻¹ year, i.e. $\mathcal{L}dt = 10^{41}$ cm⁻², and even at 1 TeV/c² about $10^4$ Higgs are produced. Secondly, at masses below about 300 GeV/c² the width of the $H^0$ is very small and in this mass range the width will be dominated by the experimental resolution.

Nine channels have been explored in some detail some of which still need further work. The conclusions are summarised in Table 2.
<table>
<thead>
<tr>
<th>Channel</th>
<th>$\mathcal{L}dt$ (cm$^{-2}$)</th>
<th>Mass Range covered (GeV/c$^2$)</th>
<th>Special Comments (see relevant reports in these proceedings for more details)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pp→H→ZZ→llll</td>
<td>(10^{40}) (10^{41}) (10^{44})</td>
<td>180-400 (130-800)</td>
<td>Needs moderate to good electromagnetic energy and/or muon momentum resolution over</td>
</tr>
<tr>
<td>pp→H→Z*Z→llll</td>
<td>(10^{41})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pp→H→γγ</td>
<td>(10^{41})</td>
<td>80-150</td>
<td>*see below</td>
</tr>
<tr>
<td>pp→WH→llγγ</td>
<td>(10^{41})</td>
<td>70-140</td>
<td>Very low rate ~20 events, but background low. Confirmatory channel to γγ channel</td>
</tr>
<tr>
<td>pp→H→ZZ→llvv</td>
<td>(10^{41})</td>
<td>180-700</td>
<td>Maybe possible but needs more work</td>
</tr>
<tr>
<td>pp→H→WW→lljj</td>
<td>(10^{41})</td>
<td>600-1000</td>
<td>Quark jet tagging necessary. Need large $\eta$ coverage ($</td>
</tr>
<tr>
<td>pp→H→ZZ→lljj</td>
<td>(10^{41})</td>
<td>-</td>
<td>Not possible</td>
</tr>
<tr>
<td>pp→H→ττ</td>
<td>(10^{41})</td>
<td>-</td>
<td>Not possible</td>
</tr>
<tr>
<td>pp→H→b̅b̅</td>
<td>(10^{41})</td>
<td>-</td>
<td>Not possible</td>
</tr>
</tbody>
</table>

*The Branching fraction of H→γγ is shown in Figure 3. This channel, in spite of the low branching fraction together with the channel pp→WH→llγγ, provides the window for discovering the intermediate mass H^0. However, this requires very high quality electromagnetic calorimetry, in segmentation, in energy resolution, in shower direction determination and in two-shower resolution. The requirements are $|\eta|<2.3$ coverage, $\Delta\eta \times \Delta\phi$ segmentation ~ 0.03 x
0.03, \( \Delta E/E \leq \frac{6\%}{\sqrt{E}} + 1\% \), \( 2\gamma \) separation \( \sim 1\)cm, and \( \gamma \) shower direction to \( \sim 5 \) mrad. These extremely stringent requirements have to be met in a very high radiation environment.

The conclusion from this work is that the range \( 180 < M_H < 400 \) GeV/c\(^2\) can be covered by \( \mathcal{L} \sim 10^{33}\) cm\(^2\)s\(^{-1}\) operation and the entire range \( 80-1000 \) GeV/c\(^2\) can in principle be covered at \( \mathcal{L} \sim 10^{34}\) cm\(^2\)s\(^{-1}\) however, extremely sophisticated instrumentation will be needed for some of this range in a hostile environment. So far at least this has not been shown to be impossible.

4.1.2 Investigation of Top

The present experimental lower limit for the mass of the top is about 90 GeV/c\(^2\) and there are arguments which indicate that the mass of the top should not be greater than about 200 GeV/c\(^2\). If it is in this mass range, then there is a good chance that it will be discovered at the Tevatron. If this is the case the role of the LHC will be to investigate systematically its properties and in particular its mass. If either the mass is above \( \sim 200 \) GeV/c\(^2\) or for some other reason it has not been found at the Tevatron, then it should either be discovered at the LHC or its mass has to be so high (>500-600 GeV/c\(^2\)) as to severely embarrass our current theoretical understanding.

A figure of merit for the LHC in top studies can be obtained by noting that at \( M_t = 150 \) GeV/c\(^2\) the ratio of the cross sections for top production at the LHC and the Tevatron is \( \frac{\sigma_{\text{LHC}}}{\sigma_{\text{TEV}}} \sim 200 \) (whereas \( \frac{\sigma_{\text{LHC}}}{\sigma_{\text{SSC}}} \sim \frac{1}{5} \)) and added to this the luminosity is a factor of \( \sim 10^3 \) higher at LHC than at the Tevatron.

Figure 4 shows the cross section for pp\( \rightarrow \)t\(\bar{t}\) as a function of \( M_t \) together with the cross section times branching ratio for the t\(\bar{t}\) to decay to e\(\mu\)X -a channel which has been studied and after suitable cuts have been made appears to offer the possibility of low background.

From this figure it can be seen that at \( M_t \sim 150 \) GeV/c\(^2\) more than \( 10^7 \) t\(\bar{t}\) pairs are produced in an \( \mathcal{L} = 10^{33} \) cm\(^2\)sec\(^{-1}\)year (\( \mathcal{L} dt = 10^{40} \) cm\(^{-2}\)). In the channel t\(\bar{t}\)\( \rightarrow \)e\(\mu\)X, after cuts have been made to reduce background to a low level more than \( 10^4 \) events remain. This should enable the mass of the top to be determined to about 5 GeV/c\(^2\).

The demands on the detector for these studies are, in general, not as great as those required for the H\(^0\) search.
Conclusions on pp physics

Apart from the above two topics, the two working groups (Standard Model Physics and Beyond the Standard Model Physics) studied in detail many other possibilities and I have extracted summaries from the two rapporteurs.

4.1.3 Standard Model Physics

(a) Total and elastic pp cross sections surprisingly are not well predicted at √s=16TeV, they are important to measure and should not prove difficult.

(b) In hard collisions, jets and direct photons in the TeV range are accessible. QCD is testable over 10-11 orders of magnitude. WZ and Wγ pair production can be studied. Gauge couplings can be measured to a few percent.

(c) Very large numbers of b-mesons will be produced (see figure 5). This opens the possibility, among many others, of using LHC as a b-factory to study CP violation. However, this topic requires much more study before any firm conclusions on this matter can be reached.

(d) For the standard model Higgs, the range 70<M_H<1000 GeV/c^2 can in principle be explored but at the low and high end of the range this is by no means straightforward.

(e) Top should be accessible for detailed study up to masses of at least 500 GeV/c^2. The mass should be determinable to -5 GeV/c^2.

(f) The pp collisions in LHC can be used as an intense source of ν_{τ} and the design of a special experiment is being studied which would directly observe the interaction of the ν_{τ}. Thereby establishing by direct rather than indirect means the existence of the tau neutrino.

4.1.4 Beyond the SM Physics

In this area of physics a very large number of possibilities has been examined. Since no physics beyond the standard model has so far been experimentally confirmed it is difficult to judge the relative importance of the various possibilities. Nevertheless, in
going to a new energy regime, a thorough exploration of possibilities is clearly needed. This is perhaps particularly so for supersymmetric particles which are the consequences of an elegant and persuasive theory.

In the summary of the work of this working group I have not only indicated some of the discovery limits but also some particular features that the detector needs for the work. I feel this is of interest since it will indicate to a potential detector designer which channels are accessible.

(a) **New Heavy Vector Bosons Z', W'**

The discovery limits for the $Z'$ are model dependent. For the Extended Gauge Model they vary from 3.3 to 4.2 TeV/c$^2$ at $\mathcal{L}\cdot dt = 10^{41}\text{cm}^2$. The signs of the electrons in the decay $Z'\rightarrow e^+e^-$ are necessary for the asymmetry measurement. For $W'\rightarrow \nu e$, the discovery limit from the EGM is 4.5 TeV/c$^2$.

(b) **SUSY**

In the supersymmetry sector, there is a window of discovery even for $\mathcal{L}\cdot dt = 10^{40}\text{cm}^2$ for the gluino, $\tilde{g}$ in the range 0.3 - 1.0 TeV and the squark $\tilde{q}$ up to 1 TeV. In the case that R-parity is spontaneously broken then again there are windows of discovery for the gluino however these are very dependent on the detailed assumptions made. Electron sign is not needed for these, however calorimeter coverage is needed in the range $|\eta|=4.5$.

(c) **WLZL**

In the strongly interacting Higgs sector, new vector resonances ($V^+,\rho_T$) responsible for the symmetry breaking, are accessible up to 2 TeV but only for very high $\mathcal{L}\cdot dt = (5 \times 10^{41} \text{ cm}^{-2})$. Lepton identification at high $\mathcal{L}$ needed.

From these it can be seen that at LHC there are many possibilities for discovering effects due to physics beyond the standard model.

4.2 **Electron-Proton Interactions**

The electron-proton collisions will take place at one intersection region, and will require a
considerable amount of additional installation. The reach of LEP ∩ LHC goes far beyond the reach of HERA, a factor 10 lower in x a factor 10 higher in $Q^2$ and a factor 4 in mass scales.

The working group’s conclusions were that the following physics topics can be addressed:

(a) Proton structure over the range $5 \times 10^{-6} < x < 0.1$ with particular emphasis at the low x end.

(b) Gluon probes in the range $5 \times 10^{-5} < x < 10^{-2}$

(c) Excited/exotic electron species with mass up to $\sim 1$ TeV/c²

(d) SUSY electron (if $M_{\tilde{e}} \sim M_{\tilde{q}}$) with mass $\lesssim 300$ GeV/c²

(e) Higgs search in the range $80 \lesssim M_H \lesssim 140$ GeV/c²

The working group emphasised that in order to exploit the full potential of this machine, the high luminosity option i.e. 60 GeV ∩ 8 TeV was desirable and that both $e^-$ and $e^+$ be available for collision. Finally, polarisation of the electron beam would also be advantageous.

Although little work has been done on detector design, it is clear that an optimum detector will have different features to either a LEP or an LHC detector (or even a HERA detector); however, whether any of these can be modified to meet the requirements remains to be seen.

4.3 Heavy Ion Collisions

The working group in this area of physics addressed three main topics:

(a) QCD thermodynamics, encompassing quark deconfinement, chiral symmetry restoration and the quark-gluon plasma,

(b) Features of multiparticle production, encompassing jet structure and fractal structure (intermittency).
(c) Photon photon physics, in particular searches for the Higgs', $W^+W^-$ pair production and supersymmetric particles.

Of these three topics it appeared that the prospects for (c) were not good and that the main interest at present is in (a), QCD thermodynamics. In this latter area, it is important to know whether heavy ion collisions at these energies produce systems sufficiently large and long lived to equilibrate so as to be able to study thermodynamics, and if they do will deconfinement occur and will a quark-gluon plasma form?

LHC operating as a heavy ion collider should be ideally placed to address these questions and is a big step up from RHIC.

The design of experiments is only at the ideas stage at present and serious work on this is just starting.

5. DETECTOR TOPICS

Detectors have so far almost entirely been studied for the LHC operating as a pp collider and therefore the following remarks strictly apply only to this mode of operation.

5.1 Central Solenoidal Magnetic Field - To $B$ or not to $B$?

A short summary of the arguments for and against having a central magnetic field is given in Table 3.
### TABLE 3

<table>
<thead>
<tr>
<th>$\mathcal{B}^3 \neq 0$</th>
<th>$\mathcal{B}^3 = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>For</strong></td>
<td><strong>Against</strong></td>
</tr>
<tr>
<td>• Sign of charge determined.</td>
<td>• Tracking at small-medium radii complicated by low $P_T$ tracks (loopers).</td>
</tr>
<tr>
<td>• Muon momentum measured.</td>
<td>• Separation of high $P_T$ electrons from asymmetric $\gamma$ conversion difficult.</td>
</tr>
<tr>
<td>• No overlap background to electron signal.</td>
<td>• High detector cost. (Solenoid and high precision tracker).</td>
</tr>
<tr>
<td>• $\tau^\pm$ detection (1 or 3 highly collimated tracks).</td>
<td>• In situ calibration of electromagnetic calorimeters.</td>
</tr>
<tr>
<td>• Reconstruction of secondary vertices (e.g. $b$ decays).</td>
<td></td>
</tr>
</tbody>
</table>

These pro's and con's have also to be taken in conjunction with the effect of the extremely high radiation level environment close to the beam pipe, especially at the highest luminosities. At present it would appear that a magnetic detector with full tracking capability may be feasible at $\mathcal{L} = 10^{33}$ cm$^{-2}$s$^{-1}$ (although expensive) but probably not at $\mathcal{L} \leq 10^{34}$ cm$^{-2}$s$^{-1}$, whereas a non-solenoidal detector or a solenoidal...
detector, without full tracking near the interaction point, could go to the higher luminosities. The decision as to what to build will clearly depend on the physics one wishes to do. Some physics will be locked out by the absence of a central field, however a non solenoidal detector still has the potential for exciting discovery physics and has the probable advantage of being better able to cope with the highest luminosity.

It is worth at this point injecting a word of caution - my impression from the meeting was that the whole question of the effect on detectors of the high radiation environment has only just started to be studied in a quantitative way. What is clear is that the environment close to the intersection point is "hot" and particularly so in the forward direction. This has implications on the active detector materials, on the passive material and support structures and on the readout electronics. It also has implications on people because of the induced radioactivity acquired by components close to the beam pipe, making maintenance and installation very difficult.

Clearly this whole question of radiation damage and induced radioactivity in the detectors being planned needs to be better understood. My impression at the end of the workshop was that there was some optimism among the experts that these problems were not intractable, but they clearly have not yet been solved.

5.2 Tracking

The working group associated with tracking has been very active and a large number of interesting techniques and scenarios for detectors has been investigated and discussed. Clearly, tracking is essential in some form or other for all detectors. The number of readout channels and therefore the electronics costs of most (all?) detector designs will be dominated by the tracking requirements.

In this summary I confine myself to listing some of the relatively new techniques in which progress has been made and which show promise.

These are:
(a) Gas detectors - Microstrip gas avalanche
    - Straw
    - Induction drift
(b) Scintillating fibre detector
(c) Semiconductor - Silicon strip/pad
    - Gallium arsenide
    - Diamond
In table (4) I give a list of the properties of one (representative?) detector in each of these three categories:

**TABLE 4**

<table>
<thead>
<tr>
<th>Detector</th>
<th>Response time ns</th>
<th>Precision $\mu$m</th>
<th>2-hit resolution $\mu$m</th>
<th>Comments (Problems)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(i) Microstrip Gas Avalanche</td>
<td>$\sim50$</td>
<td>30</td>
<td>250</td>
<td>(a) Large Number of channels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(b) Longevity not established</td>
</tr>
<tr>
<td>(ii) Scintillating Fibre</td>
<td>2.5-5</td>
<td>35</td>
<td>80</td>
<td>(a) Thick Material</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(b) Readout not clear</td>
</tr>
<tr>
<td>(iii) Silicon</td>
<td>5-10</td>
<td>5-10</td>
<td>25</td>
<td>(a) Radiation damage at &quot;high&quot; $\mathcal{L}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(b) Large numbers of channels</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(c) High cost</td>
</tr>
</tbody>
</table>

At present the only technique with sufficient precision for secondary vertex detection (e.g. b-tagging) is the silicon strip (pad) detector. At what luminosity levels this will survive a few centimetres from the collision point is not well known and may well limit vertex detectors of this type to lower luminosity operation.

The other techniques are all relevant for high precision tracking.

The microstrip gas avalanche detector has made great progress in the past year. There has been an increased understanding of the technique and new geometries have been studied.
which might be advantageously employed in a solenoidal field. These somewhat alleviate the problems caused by "loopers".

Although continuing R & D is required in all areas of tracking detectors, it is clear that there is a need to concentrate efforts. However, where to concentrate these efforts will depend on the detector strategy to be adopted at LHC. Will there be a magnetic and/or a non-magnetic detector, will one or both be designed to operate at full luminosity .......?

My belief is that within the financial constraints imposed on us, a broad programme should be planned - we will be opening up a new energy regime and the place where the treasure is buried is not well marked.

5.3 Calorimetry

Like tracking, calorimetry is going to be necessary, indeed crucial, for all detectors at LHC except those solely designed to detect muons. The calorimeter working group set itself an ambitious set of targets which are needed for one or other aspect of the physics being explored. If not all the aims are achieved then some areas can still be very adequately covered. The question of separate e.m. and hadronic or combined calorimetry was addressed and some attention was also focussed on the barrel (small |η|) and end cap (large |η|) regions. The following targets were set:

(a) Ability to utilise $\mathcal{L} \sim 2 \times 10^{34}$cm$^{-2}$s$^{-1}$

(b) Ability to measure $P_T$ down to $\sim 10$ GeV/c

(c) Coverage of $|\eta|<3$ for electrons and $\gamma$s and $|\eta|<4-5$ for missing $P_T$

(d) $E_{em}/E_{had} = 1$

(e) Electromagnetic energy resolution $\frac{\sigma_{em}}{E} \sim \frac{2-6\%}{\sqrt{E}} + 0.5-1\%$

(f) Hadronic energy resolution $\frac{\sigma_{had}}{E} \sim \frac{35\%}{\sqrt{E}} + \text{"small" const term}$

The calorimeter should also be radiation resistant, have no cracks, have good time resolution and have high segmentation with depth resolution.
In order to achieve these aims the working group has studied a large number of possibilities, which included:

(g) Scintillator tiles with wavelength shifter  
(h) Scintillating fibres  
(i) Liquid argon  
(j) Room temperature liquids  
(k) Silicon  
(l) Other crystals, BaF$_2$, CsI, CeF$_3$ .....  
(m) Scintillating glasses  
(n) Liquid Xenon and Krypton

This present phase of R & D has spread a broad net with a great deal of interesting work being reported, however soon the resources need to be concentrated on the most promising and cost effective techniques. Time is pressing if a detector with good calorimetry is to be available at LHC start up.

The conclusion I came to was that high quality calorimetry at $\mathcal{L} \sim 2 \times 10^{34}$cm$^{-2}$s$^{-1}$ was difficult and will require a large and coordinated effort to achieve the needed resolution. However the majority of the participants felt that such calorimeters can be built to fulfill LHC requirements.

5.4 Electron/pion Separation

Although this was not the subject of any particular working group it clearly is an important issue and was addressed by several speakers. The ability to identify electrons with great certainty, when isolated, is necessary for many of the physics topics. It is also highly desirable to be able to identify electrons in or close to jets, as is the ability to distinguish electrons from converted $\gamma$s or from an overlap of a charged hadron and a $\pi^0$.

This requires good spacial resolution in tracking, fine granularity electromagnetic calorimetry with spatial matching and longitudinal shower development. On top of this it is probable that some other independent information is required, for example, from a presampler, a transition radiation detector or by matching energy and momentum. All these areas are being actively pursued.
5.5 Muon Detection

The working group in this area has been very active. I will concentrate, as did the plenary speaker, on the channel pp → H^0 → ZZ^(*) → μ^+μ^-μ^+μ^- in order to explore the feasibility of detecting the Higgs.

Studies of the following have been carried out;
(a) Detector geometries - including high and low field solenoids and air and iron cored toroids.
(b) Muon rates and triggering scenarios.
(c) Required momentum resolution.
(d) Large area muon chambers.

In summary the following conclusions were reached:

(e) The rate from prompt muons, mainly from b-decay will be high (∼10^6 muons/sec at ∏ - 4 x 10^{34} cm^-2 s^-1).
(f) A cut at P_T ~ 50 GeV/c is needed to reduce the trigger rate to a manageable level.
(g) A muon trigger should be possible up to the highest ∏. But leakage of jets can cause confusion at trigger level and further study is needed.
(h) Different magnets (solenoids and toroids) have been studied and their properties evaluated. The cost of some of these is likely to be high.
(i) New techniques for building large area muon chambers "cheaply" are under investigation.
(j) Adequate muon momentum resolution of a few percent up to P_μ ~ 1 TeV/c can be achieved.
(k) R & D is still needed in many aspects of such a detector. As are tests of trigger algorithms, punch through calculations etc.
(l) The present feeling is that a detector operating at ∏ ~ 4 x 10^{34} cm^-2 s^-1 is however likely to be feasible for the 4μ channel.

5.6 Data Acquisition

I believe this to be a very challenging and crucial area for the following reasons:
(a) Bunch crossings occur every 15 ns with ∏ = 1.7 x 10^{34} cm^-2 s^-1.
(b) This represents an average of 17 inelastic interactions per crossing.
(c) Inelastic events have high multiplicities.
(d) The number of channels in a tracking detector is likely to be in the 10^6-10^7 range.
(e) The front end electronics has to be on the detector and therefore needs to be radiation hard.

The working group believes that in principle the techniques needed are available now but only in the research laboratory, they will in ~5 years be needed on a very large scale and cheaply. They must therefore go into general use within this time period for the unit price to fall. The whole area of data acquisition requires R & D, money, manpower and coordination.

5.7 Triggering

This topic is also vital. At $\mathcal{L} \sim 1.7 \times 10^{34} \text{cm}^{-2}\text{sec}^{-1}$ there are $10^9$ inelastic interactions/sec and this rate has to be reduced to a few tens of hertz at the most for writing on some output medium. The working group came to the following conclusions:

(a) It looks possible in principle to build level 1 trigger systems able to reduce the rate to $10^4$ - $10^5$ Hz for calorimeter and muon triggers.
(b) Level 2 trigger systems are under investigation and several alternatives using, for example, general purpose processors or image processors or associative memories or neural networks have been studied.
(c) Synchronisation is a major issue. Pipelines, buffers, trigger systems must be kept in phase over tens of metres to within a few nanoseconds.
(d) Chips will probably have to be custom designed.
(e) Solutions to the triggering problems look possible at LHC but are not easy and still require much R & D.

6. CONCLUSIONS

Before coming to the conclusions I would like to comment on a matter which occupied a great deal of time and thought at the workshop and which I have scarcely mentioned. That is the question of the effect of multiple interactions in a single bunch crossing on the detectors, trigger and most importantly, on the physics. The reason I have not discussed this even though I think it is important is because the simulations used to reach the conclusions of the working groups have at least in principle taken this into account. There is however always a nagging concern as to the effect of non gaussian tails of distributions on some of the background processes.
(a) The next step in the investigation of the real vacuum requires machines like the LHC/SSC. The mass generation mechanism can be studied in principle over the range $80 \rightarrow 1000 \text{ GeV}/c^2$

(b) Linear $e^+e^-$ colliders in the TeV range which might compete in some areas of physics are not at present realisable.

(c) The energy and high luminosity of the LHC gives it an excellent physics reach for new discoveries in $pp$, $ep$ and heavy ion interactions.

(d) There is a wealth of "standard" physics of the highest quality to be done at the LHC. Discoveries are also made by precision measurements.

(e) The technology of the LHC is challenging in the 2 in 1 magnet design operating at 10T and 1.8oK. The feasibility of this needs to be demonstrated before construction begins.

(f) The greatest challenge however is in the design of detectors. Much R & D has been done, but much still remains. Complete detector systems able to endure the environment have not yet emerged

(g) Radiation damage and high induced radioactivity present new challenges to our community.

(h) Solutions are being sought to many other challenging problems such as hermiticity, high spatial and energy resolution, high data rates, $e/\pi$ separation and compensating calorimetry.

(i) So far cost has not really been a parameter in the deliberations on detector design. However, it clearly is going to be an important, indeed possibly limiting parameter, and should now be considered in making choices.

(j) Feasibility studies of realistic complete detector systems operating at various luminosities together with their physics potential need to be carried out. Cost must be a parameter in these studies. Time is already short. (These studies are also needed for the design of the experimental pits).

(k) Such studies should lead to a strategy as to how best to exploit the LHC.

(l) The most important resource we have is people, followed by money. Both have to be carefully nurtured in order to bring an ambitious programme like the LHC to fruition.

(m) The cost of the detectors is likely to be an appreciable fraction of the cost of the machine. This information must be clearly understood by member state funding agencies if the LHC is to be properly exploited.

(n) LEP (and HERA) must continue to be developed in order to reach their full potential and their physics programmes should be pursued with vigour. We have a duty as physicists (and tax payers) to ensure that the investment in these machines is fully exploited.
(o) The SSC with its lower initial luminosity but higher energy and its fixed target possibilities has somewhat different strengths and offers a highly desirable competitive and complementary programme.

(p) The versatility of the LEP/LHC complex, with its $e^+e^-$, pp, ep and heavy ion possibilities will make CERN a unique centre. The ability to test theories and models as well as to make and confirm new discoveries by a wide variety of means is crucial in the progress of science.

(q) The LHC is clearly the way forward for Europe.
Figure Captions

Fig 1 Cross-section for standard model Higgs production as a function of its mass. The right hand scale gives the number of events per $10^7$ sec year at a luminosity of $10^{33}$cm$^{-2}$s$^{-1}$. The three curves are for different top masses.

Fig 2 Width of the S.M. Higgs as a function of its mass for two different top masses.

Fig 3 Branching fractions of S.M. Higgs to $\gamma\gamma$, $\mu^+\mu^-$ and 4 $\mu$'s as a function of its mass.

Fig 4 Cross-section for $t\bar{t}$ production as a function of the mass of the top. (Top curve). Lower two curves, cross-section times branching ratio of $t\bar{t}\rightarrow b\bar{b}w^+w^-\rightarrow b\bar{b}e\mu\nu\bar{\nu}$ before and after cuts to reduce backgrounds. The arrows indicate background levels before and after cuts.

Fig 5 Cross-section for $b\bar{b}$ production as a function of the centre of mass energy.
Fig. 1

$p + p \rightarrow H + X$

$\sqrt{s} = 16$ TeV

$m_t = 100, 150, 200$ GeV

$\sigma$ (pb) vs. $M_H$ (GeV)

Events/Year at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$
Fig. 2
Fig. 3
Fig. 4
Fig 5

The graph shows the relationship between the cross-section $\sigma$ (in nb) and the square root of the energy $\sqrt{s}$ (in TeV). The shaded region represents the uncertainty due to poor knowledge of the gluon structure function. The number of events per year at $\mathcal{L} = 10^{33} \text{cm}^{-2} \text{s}^{-1}$ is also indicated on the right vertical axis.
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