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FUTURE HADRON COLLIDER : THE LHC

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Abstract

The present strategy for the future of European high energy physics should allow Europe to retain its leading role well into next century by making optimal use of present facilities and within the present level of funding. It concentrates available resources on those areas in which Europe has both experience and an international reputation, and which we believe are most likely to address some of the key open questions on the subject. Within such a strategy, the LHC project is the most natural and cost effective way to address the several fundamental issues which are being formulated with increasing clarity by the exceptional quality of data collected at LEP. LHC is now being actively prepared by an intensive R&D phase, which is expected to lead to the final proposal by end 1993.

STRATEGY FOR THE FUTURE OF PARTICLE PHYSICS IN EUROPE

The international exploitation of LEP, HERA and Gran Sasso are the foundations of the European programme for the 1990's. Our investment of the previous decade will pay off in a series of detailed experimental investigations of the Standard Model and beyond.

However, it is unrealistic to expect all the open questions to be answered by the present programme : indeed some of them cannot even be addressed at LEP or HERA, where collision energies can only reach the 100 to 200 GeV region. These machines will have exhausted their potential for discovery around the end of the 1990's, and, since time scales to design, build and commission new accelerators and detectors are of the order of a decade, we must plan now for their successors.

In order to ensure that Europe can continue to make important contributions in particle physics in the late 1990's and beyond, we must aim at establishing a programme that makes the

most out of "pooled" financial resources which at best will remain constant in real value. This implies focussing upon a limited number of central issues. Our immediate priority is to ensure that we exploit fully our experiments at LEP, HERA and Gran Sasso. However, we need to prepare initiatives which will at first complement LEP and HERA and later on take over from them.

To achieve these goals will require flexibility. The nature of particle physics is such that we must be able to change direction in the light of new discoveries or new opportunities that may emerge, despite a heavy infrastructure. We also need to support a few smaller scale activities that impinge strongly on these main objectives : fixed target experiments and a number of "factories" which are now under construction or under consideration, for instance a Φ factory at Frascati¹, a charm- τ factory in Spain² and beauty factories in countries such as the United States³, Japan⁴ and Russia⁵.

In addition, we must encourage the development of new techniques if we are to stay

at the forefront of research in particle physics and continue to provide the new instruments and facilities that are so valuable to other areas of science.

Finally these goals are to be achieved within a collaborative effort on the full European scale. Today about 80% of the European physicists make use of CERN as their primary laboratory and both HERA and Gran Sasso are widely internationalized. Opening to the Central and Eastern European Countries has necessitated some additional temporary sacrifices but has also brought enormous new potentialities. Germany is unified, Poland, Czechoslovakia and Hungary are now CERN Member States and Russia and Israel are CERN-Observers. We are seeking to extend and to strengthen the involvement of the non-European partners through cooperation agreements etc.

I shall now outline, for the late 1990's, a programme which evolves naturally from our present programme, with new activities replacing current activities once machines have been fully exploited or when the research itself forces a change of emphasis.

Our main physics strategy is to target on at least four of the unresolved issues :

- to complete the precision tests of the Standard Model and understand the origin of symmetry breaking. Either the Higgs mechanism is confirmed or some entirely new phenomenology is revealed;

- to understand the three (by now firmly established) generations of quarks and leptons. The third generation (τ , ν_τ , top, b) is still poorly known. The asymmetries of weak interactions, and especially CP violation need to be clarified possibly within the CKM matrix texture;

- to discover the nature of the dark matter in the Universe : either massive neutrinos (hot dark matter) or SUSY particles (cold dark matter) are strong candidates. It is likely that both are needed to explain recent developments in Cosmology;

- to search for quark-gluon plasma and possible phase transitions in hot and highly compressed nuclear matter as predicted by QCD.

The programme we are concentrating upon is modest when compared to all the a priori conceivable possibilities. It concentrates available resources on those areas in which Europe has both experience and an international reputation, and which we believe are most likely to address some of the key open questions on the subject.

STATUS OF THE STANDARD MODEL

The Standard Model of electroweak interactions has so far been tested at LEP to a precision of 1% or better : no deviations have been observed as yet. With over 3 million Z^0 s collected by ALEPH, DELPHI, L3 and OPAL, LEP has entered the high precision era and the Z^0 mass determination is now dominated by small systematic uncertainties ($m_Z = 91.187 \pm 0.007$ GeV)⁶. The LEP absolute energy scale is calibrated using resonant depolarization which allows a current precision of $\sim 7 \times 10^{-5}$. This extreme precision can be illustrated by the

Figure 1. Difference between the energy obtained from resonant depolarization (E) and from magnetic field measurement (E_{FD}) versus the expected moon tidal force at LEP normalized to the range -1 to +1 for a complete moon cycle.

sensitivity to the moon tidal movements which only deform the LEP ring diameter by about 300 μm but produce detectable systematic energy shifts (Figure 1). Once these tidal movements have been taken into account and with a better control of temperature effects one should improve the present precision by a factor of 2-3.

Figure 2. Determination of the axial-vector (g_A) and vector (g_V) weak couplings for the three families of charged leptons produced in Z^0 decays at LEP using the production cross-section, the forward-backward charge asymmetry, the τ polarization and the forward-backward asymmetry of τ polarization.

One can judge the impressive progress from LEP in Standard Model tests by considering for example the determination of the neutral current weak couplings (Figure 2) where lepton universality has been verified down to 1% precision for the axial-vector coupling⁶. The direct determination of the effective mixing parameter, $\sin^2 \theta_W^{\text{eff}}$ from the measurements of forward-backward asymmetries of lepton and b-quark pairs and of τ polarization has now reached a high precision of 5×10^{-3} (Figure 3).

With forthcoming data from LEP and LEP200 we are aiming at tests of the Standard Model with an accuracy of 0.1% or better to provide crucial clues of what may lie ahead and

Figure 3. Determination of the effective weak mixing parameter $\sin^2 \theta_W^{\text{eff}}$ at LEP from lepton pair and $b\bar{b}$ forward-backward asymmetries, τ polarization and forward asymmetry of τ polarization. A comparison is made with the prediction of the Standard Model as a function of the top quark mass and for extreme values of the Higgs mass.

obtain important guide-lines to plan for the "next step". For instance many observables⁷ at LEP show sensitivity to the top quark mass (Figure 4) and to the Higgs boson mass and thus provide predictions for these masses within the Standard Model. Using the relation between the Weinberg mixing parameter and the top quark mass in the Standard Model⁸ (Figure 5) a W mass accuracy of 50 MeV expected with the next LEP energy upgrade, scheduled to start by 1994 (LEP200) will determine $\sin^2 \theta_W$ with an error of only 10^{-3} and therefore constrain the top mass to $10 \div 20$ GeV which is comparable to the expected experimental accuracy for the direct top observation by hadronic colliders and set

rather stringent limits to the possible Higgs mass.

Figure 4. Effect of varying the top quark mass from 100 GeV to 150 GeV on a selected sample of variables. r_a is a measure of the sensitivity of a given variable. It is defined as the ratio of the predicted change to the expected experimental error (see ref. 7).

Figure 5. $\sin^2\theta_w = 1 - m_W^2/m_Z^2$ versus the top quark mass. The gray area shows the range of predictions from the Standard Model for extreme values of the Higgs mass. The measurements shown are from the CDF/UA2 determination of m_W/m_Z and from neutrino-nucleus scattering data (ref. 8).

Figure 6. Top quark mass values corresponding to various measurements of Standard Model parameters and for two different Higgs mass ranges : (a) $M_{\text{Higgs}} \in [50, 100]$ GeV. The corresponding average top quark mass is 135 ± 17 GeV, (b) $M_{\text{Higgs}} \in [0.5 - 1]$ TeV, the corresponding average top quark mass is 177 ± 15 GeV. The combined value is : $m_{\text{top}} = 155 \pm 30$ GeV.

Figure 7. Top quark production cross-sections at hadron colliders (Tevatron, LHC, SSC) as a function of the top quark mass.

So far we have found that :

- the top quark mass is large, $m_{\text{top}} = 155 \pm 30 \text{ GeV}$ ⁸ (Figure 6). Searches at Fermilab become difficult because of the small production cross-section (Figure 7) and clearly LHC will be needed to provide a definite exploration of top quark phenomenology because of the factor 1000 increase in cross-section and because of the much higher luminosity (factor 100);
- the Higgs may well be in the range explorable by LEP200 whose mass reach extends to about 100 GeV. Present data indicate

Figure 8. The $\Delta\chi^2 = 1$ and 2.7 contours in the M_{Higgs} , M_{top} plane for (a) the full electroweak dataset, (b) LEP and collider data alone (see ref. 9).

Figure 9. Limits on the Higgs mass from direct searches at LEP. Individual experiment limits and combined limit are shown as function of the Higgs mass.

a very low preferred Higgs mass⁹ (Figure 8). The direct searches at LEP set a lower mass limit of 60 GeV (95% C.L.)⁶ (Figure 9) for the Standard Model Higgs;

- if the Higgs exists and is not found at LEP it will in any case be within the range explorable by LHC since the present upper limit on its mass at 90% C.L. is 1 TeV;

- the SUSY particle mass threshold¹⁰ (Figure 10) is also likely to lie within the explorable range of LHC and at the same time the Minimal SUSY's Higgses could be within the range of LEP200;

- many Technicolor models have been already excluded by LEP⁸, but the idea is still alive;

- proton decay and GUT are still "on" but at larger unification masses (10^{16} GeV)¹⁰ which will require new generation experiments (Gran Sasso).

Figure 10. Extrapolation of strong, weak and electromagnetic couplings to the unification scale (a) within the Standard Model, (b) within the minimal supersymmetric model.

In conclusion, LEP physics is a necessary pre-requisite for further studies at the TeV constituent energy range and it must be vigorously pursued as a fundamental preparatory step. With the LEP machine performing better than ever we can only be confident that in the future we shall be able to target with sufficient accuracy where the LHC should find such a new physics. In turn this leads to what one could call a “no-lose” condition for the LHC : either these new particles are found or there is even a bigger surprise signalling a breakdown of the Minimal Standard Model. In this sense LEP and LHC are two closely connected programmes within a common strategy aiming at elucidating a phenomenology which CERN has initiated with the discovery of the Z and W bosons about ten years ago.

THE LHC PROJECT

In order to experimentally investigate the fundamental questions discussed above, whatever mechanism is involved, we need to perform experiments at constituent energies in the 1–2 TeV region. At present, such high energies are accessible only at machines that collide protons, where experiments observe the

interactions of their quark and gluon constituents. To reach such an energy domain, a proton beam with energy in excess of 6 TeV is needed. Since we know from dimensional arguments that cross-sections decrease as E^{-2} , we must at the same time master luminosities which are largely in excess of what is customary today.

We will be able to achieve proton beam energies of more than 6 TeV, at unprecedented luminosities well in excess of $10^{33} \text{ cm}^{-2} \text{ s}^{-1}$, with the proposed Large Hadron Collider (LHC)¹¹ (Table 1).

Figure 11. Schematic layout of the LHC injection complex.

Table 1. LHC Main Parameters

		pp	e-p	Pb-ions
Max c.m. energy	(TeV for B=9.5T)	15.4	1.36	1262
Luminosity	($\text{cm}^{-2}\text{s}^{-1}$)	$1.6 \cdot 10^{34}$	$2.8 \cdot 10^{32}$	$1.8 \cdot 10^{27}$
Number of bunches		4725	508	800
Bunch spacing	(m/ns)	4.5 / 15	49.4 / 164.7	31.5 / 105
Particles/bunch		10^{11}	$9.2 \cdot 10^{10}$ $3.0 \cdot 10^{11}$	$6.2 \cdot 10^7$
Particles/beam		$4.7 \cdot 10^{14}$	$4.7 \cdot 10^{13}$ $1.5 \cdot 10^{14}$	$5.0 \cdot 10^{10}$
Number of experiments		3	1	2
β at interaction point	(m (β_x, β_y))	0.5	0.85, 0.26 32.7, 3.05	0.5
r.m.s. radius at int. pnt.	(μm (x, y))	15	120, 37	12.4
r.m.s. collision length	(cm)	5.3	3.8	5.3
Crossing angle	(μrad)	200	0	200

As is now traditional at CERN, this new machine would exploit existing facilities. The LHC be built inside the LEP tunnel, and would use the older Proton Synchrotron and Super Proton Synchrotron as injectors (Figure 11), just as LEP does. Successful tests of the Linac/Booster complex (nominal intensity and emittance) have already been carried out, and tests are under way in the SPS to form tightly spaced bunches (10ns) (Figure 12). A 25 ns-spaced-bunch scheme is considered to possibly further increase the luminosity while maintaining the same total circulating current.

Figure 12. LHC beam in the SPS. The oscilloscope shows 10 ns spaced bunches which have been accelerated to 300 GeV.

To achieve high energies, it is proposed that LHC uses long, high-field superconducting magnets (Figure 13) based on an innovative "two-in-one" design.

This results in substantial savings in cost and construction time. The radius of the LEP tunnel and the maximum field that is likely obtainable in the superconducting magnets, make it possible to reach a maximum proton beam energy in the LHC of around 8 TeV, which is well into the region of interest. The radius of the LEP tunnel was indeed optimized with the LHC in mind. An intensive R&D programme is being carried out. A test of a 10 metre long twin dipole magnet with two sets of HERA coils (Figure 14) has been very successful and has demonstrated the inherent soundness of the "2 in 1" design. The innovating magnet cooling technique uses superfluid helium at 1.9K and is based on that already being installed for the superconducting accelerating cavities of the LEP-200 project.

Figure 13. Comparison of the sizes of superconducting dipole magnets for the Fermilab Tevatron, HERA, SSC and LHC.

Figure 14. Photograph of a 10 metre long twin aperture magnet prototype with HERA coils.

The cryogenic scheme was successfully tested in a realistic model showing that it

performs with a large safety margin. A full magnet string test is in preparation for 1993.

In a possible plan, the LHC would be ready for experiments in 1999, and from that date on would become a central part of CERN's programme. To obtain a reasonable rate for the interesting 1 TeV collisions at the LHC, the number of protons that collide together will have to be very large, resulting in challenging problems for detector technology.

Development work on detectors and electronics has already begun to face these challenges, and physicists are prominent in study groups set up to examine the design of experiments at the LHC. However, to be ready in 1999, this programme of research and development will have to be substantially increased in the coming years.

THE LHC EXPERIMENTAL PROGRAMME

The experimental programme is the object of a careful strategy in close cooperation with the SPC and ECFA. In October 1990, the Aachen workshop had confirmed the physics objectives and the experimental feasibility¹².

A strong detector R&D programme, coordinated by the Detector Research and Development Committee (DRDC) was designed to stimulate the necessary R&D, harnessing instrumentation activities for LHC and building the strength of the LHC experimental community. More than 1000 people are involved. In March 1992 the Evian Workshop¹³ set the stage for detector collaborations when four proton-proton and several heavy ion, B physics and other fixed target expressions of interest were presented.

Following the suggestion of an "adiabatic" approach to the approval of at most two detectors, the four proto-collaborations have started a merging process. ASCOT and EAGLE have merged [at this stage they are considering two options (Figure 15 a&b)]; CMS (Figure 16) and L3P (Figure 17) are in the discussion process.

Figure 15. Schematics of the ASCOT-EAGLE detector for LHC : (a) Warm iron toroids option, (b) Superconducting air core toroids option.

Figure 16. Schematics of the CMS detector for LHC.

Figure 17. Schematics of the L3P detector for LHC.

Figure 18. Simulation of the Higgs signal in the two photon channel in the crystal calorimeter of L3P.

Figure 19. Simulation of the Higgs signal in the four muon channels in the CMS detector.

Figure 20. Simulation of the Higgs signal in the four-charged lepton channels ($eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$) in the EAGLE detector.

It is particularly instructive to observe some of the important physics processes through the “eyes” of the detectors being planned. Detailed detector simulations have confirmed that the experimental environment at LHC would allow a search for the Standard Model Higgs in the whole relevant mass range, illustrated here by

the signal in the two-photon channel (Figure 18) for masses from 80 to 150 GeV, in the 4-lepton channel (Figure 19 and Figure 20) for masses up to 800 GeV. Other channels (W pairs) can be used to cover safely the 1 TeV mass region beyond which the Higgs would cease to appear as a clear resonance.

Figure 21. Simulation in the EAGLE detector of $W_L Z_L$ resonances.

The study of many other possible physics processes, for instance $W_L Z_L$ (Figure 21) and $Z\gamma$ resonances, heavy Z 's (Figure 22) have confirmed that foreseen detectors can cope with the highest luminosity at LHC.

Letters of intent are to be submitted by 1st of October 1992. The LHC Committee is set up with the idea of an "adiabatic" approach to approved programmes with LHCC using the expertise of the DRDC. A conclusion¹⁴ from the Evian Workshop was that, given the limited financial resources, there was a need to optimize detector cost versus detector performance and to consider an evolutionary rather than "all the way" approach for detector construction. In addition, before embarking in the mass production of the detector elements, the equivalent of the so-called "full string test" for the machine is necessary, with the corresponding need of a large amount of test beam and R&D.

B physics at the LHC

Both collider and fixed target modes are considered. Recently a first test using a bent Silicon crystal to extract 120 GeV protons from the SPS was successful (Figure 23) opening the possibility of using the technique at LHC. The

Figure 22. Simulation in the CMS detector of $Z' \rightarrow \mu^+ \mu^-$ for $m_{Z'} = 4 \text{ TeV}$ in ALR model and 10^5 pb^{-1} .

Figure 23. Layout of the test of crystal extraction of beams at the SPS.

$b\bar{b}$ rate at LHC will be very large both in the collider mode where the cross-section is of the order of 1 to $5 \times 10^5 \text{ nb}$ (Figure 24) and in the fixed target mode where it is about 500 nb. With a $b\bar{b}$ sample of 10^{13} events in collider mode and 10^{10} to 10^{11} events in the fixed target mode B physics at LHC promises to be exciting. Critical tests of the Standard Model¹⁵ will be performed in the study of $B^0 \bar{B}^0$ oscillations, in the search

for rare decay modes and in CP violation. The B sector constitutes a whole field by itself with a very broad physics potential.

Figure 24. Production cross-section for Beauty at hadron colliders as a function of the centre-of-mass energy.

OTHER PHYSICS POSSIBILITIES AT LHC

The facilities available on the CERN site will allow for other exciting possibilities for the LHC beyond its role as a proton-proton collider. This makes the LHC an even more attractive option for European particle physics beyond the year 2000.

Heavy ion collisions

One possibility actively explored is to collide beams of lead ions at the enormous energies of 800 TeV in the LHC (Table 1). Heavy ion beams are already accelerated in the SPS and it would be only natural to store them in the LHC. Such collisions can produce unprecedented energy densities and volumes, and could therefore reveal fundamental insights into the structure of QCD and perhaps the quark-gluon plasma, a new phase of matter¹⁷ predicted by QCD. Such a collider would be a natural development from the present heavy-ion

programme at CERN, in which sulphur ion beams are already produced with an energy of 6.4 TeV per sulphur nucleus, and lead beams are under preparation.

Electron-proton collisions

A further possibility is electron-proton physics at roughly four times the energy available at HERA. This could be done by colliding electron or positron beams of 70 GeV energy from LEP with a 7 TeV proton beam from the LHC (Table 1). Such a possibility is unique to the LHC complex since CERN will have both accelerators on its site. It would allow for instance studies of quark structure down to sizes of around 10^{-19} m¹⁶, a resolution significantly better than that of HERA. The discovery of quark substructure could explain the existence of the three generations of quarks and leptons that are known to exist.

CONCLUSION

Final approval of the Collider and the Detectors requires a decision of the CERN Council, which will start its deliberation procedure at the end of 1993, namely when the R&D phase and the definition of the experimental programme will be completed.

The combination of the various existing and planned accelerators will then give Europe an ensemble of facilities unrivalled anywhere in the world, thus continuing the strong European tradition in high energy physics.

In summary, the most important new initiative for European particle physics over the next decade will lie in the field of proton-proton collisions, some heavy ion collisions being also studied (lead in the CERN SPS). The LHC offers a relatively cheap way to access this crucial area of physics in Europe and has unique capabilities for further development into an electron-proton or heavy-ion collider. It thus has strong support of the European community of physicists and of the Member State Governments.

The SSC, on the other hand, will allow somewhat easier experimental conditions with its exploration of proton-proton collisions at higher energies, but at somewhat smaller luminosities. In broad terms however, the discovery potentials of the two machines appear quite comparable¹².

For both machines we emphasize the vital importance of timely and innovative detector development programmes, a domain where Europe and the United States could develop a strong collaboration, in order to exploit fully the exceptional physics potential of these new accelerators.

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