PHYSICS AND DETECTORS AT THE LARGE HADRON COLLIDER
AND AT THE CERN LINEAR COLLIDER

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1. INTRODUCTION

The workshop held in La Thuile (Val d'Aosta, Italy) from 7 to 10 January 1987 was the end-point of the activity started many months ago by the Physics and Detector Advisory Panel chaired by John Mulvey. The Panel acts in the framework of the CERN Long Range Planning Committee (LRPC) set-up by the CERN Council under the chairmanship of Carlo Rubbia. Since the beginning, the Advisory Panel has subdivided the subject among eight working groups. They are listed in Table 1 together with their conveners.

On 12 and 13 January, in the CERN Auditorium, reports were presented by the conveners. At the end of the meeting the main points were combined in a summary talk, which was addressed to an audience of machine physicists, engineers, experimentalists and theorists.
Table 1
Working groups and conveners

<table>
<thead>
<tr>
<th>Group</th>
<th>Convener(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physics</strong></td>
<td></td>
</tr>
<tr>
<td>1. Standard Model</td>
<td>G. Altarelli and D. Froidevaux</td>
</tr>
<tr>
<td>2. Beyond the Standard Model</td>
<td>J. Ellis and F. Pauss</td>
</tr>
<tr>
<td>3. Large cross-sections</td>
<td>Z. Kunert and W. Scott</td>
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<tr>
<td><strong>Detectors</strong></td>
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<tr>
<td>Jet detector</td>
<td>T. Akeson</td>
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<tr>
<td>Vertex detector and tracking</td>
<td>D.H. Saxon</td>
</tr>
<tr>
<td>Particle identification</td>
<td>F. Palmonari</td>
</tr>
<tr>
<td>Triggering and data acquisition</td>
<td>J.R. Hansen</td>
</tr>
<tr>
<td><strong>Interaction regions</strong></td>
<td>J.E. Augustin, W. Kienzle and W. Bartel</td>
</tr>
</tbody>
</table>

Leaving aside the usual apologies for the unavoidable incompleteness, in the written version I closely follow the oral presentation. After giving the main parameters of the Large Hadron Collider (LHC) and the CERN Linear Collider (CLIC) considered by the other two Advisory Panels (chaired by G. Brianti and K. Johnsen), I review the status of our knowledge and the main physics questions which are in front of us. Then, following the approach chosen by the physics working groups, by using a relatively wide spectrum of possible 'physics scenarios', I summarize the limits which can be put on twelve different phenomena by performing experiments at the LHC and at CLIC. Finally, I comment on the main problems facing those who will have to build suitable detectors and I point out the highlights among the results obtained by the Detector Groups and the Interaction Regions Group. As usual, the summary is filtered by my perception of what is really important, and only the reading of the proceedings can give a balanced view of what has been achieved.

The workshop was particularly stimulating because, for once, instead of concentrating on the physics questions which one particular accelerator can help to answer, we were obliged to discuss the relative merits of two very different colliders: the $E_{cm} = 16$ TeV proton–proton LHC to be installed in the LEP tunnel (and its electron–proton option) and CLIC, the electron–positron machine with $E_{cm} = 2$ TeV, which could be built, given enough R&D investment and time, using technologies already partially developed at CERN. At the workshop the studies were devoted to physics and detector issues without any reference either to the cost or to the time-scale of the colliders; the results of the comparison I shall present are thus an essential, but far from unique, component in the decisional process which aims at choosing the European accelerator for the end of the century.

The physics possibilities offered by the LHC were already analysed at the Lausanne workshop [1], whilst the promises of a TeV electron–positron collider had never been systematically studied even if, before now, a few papers had discussed them [2, 3].

Going back to the summer of 1985, when the CERN LRPC was set up, certainly the most widespread opinion on the issue of an LHC–CLIC comparison was: 'We (almost) know how to build the LHC but not its detectors, whilst we (almost) know how to build detectors for CLIC but not the collider itself'. The work done by the Advisory Panels chaired by G. Brianti, K. Johnsen and J. Mulvey have certainly modified this simplistic vision. I shall come back to this point in the concluding remarks.
2. LHC AND CLIC PARAMETERS

2.1 The LHC design

Table 2 contains the essential parameters of the present design of the Large Hadron Collider [4]. It is probable that an even higher luminosity, up to \( L = 10^{34} \text{ cm}^{-2} \text{s}^{-1} \), can be reached.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy, ( E_{cm} )</td>
<td>16 TeV</td>
</tr>
<tr>
<td>Luminosity, ( L )</td>
<td>( 1.4 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} )</td>
</tr>
<tr>
<td>Number of interaction regions</td>
<td>( \leq 7 )</td>
</tr>
<tr>
<td>Filling time</td>
<td>2 h</td>
</tr>
<tr>
<td>Filling rate</td>
<td>( 2 \text{ d}^{-1} )</td>
</tr>
<tr>
<td>Time separation between two crossings</td>
<td>25 ns</td>
</tr>
<tr>
<td>Number of interactions per crossing</td>
<td>2.5</td>
</tr>
</tbody>
</table>

The centre-of-mass energy appearing in the table corresponds to a 10 T field in the bending magnets. The superconducting magnets built for HERA, when cooled to 1.7 K reach about 7 T. At present an intense R&D program is going on, in collaboration with various European industries, to design and construct models of the needed 10 T magnets.

LHC proton bunches can be made to collide with LEP electron (or positron) bunches at an energy \( E_{cm} = (1.3-1.7) \text{ TeV} \) and a luminosity which decreases with the energy and varies in the range \( L = 10^{22}-10^{31} \text{ cm}^{-2} \text{s}^{-1} \). Electron and proton bunches will cross at the frequency of 6 MHz, corresponding to a time separation between two crossings of 165 ns.

2.2 The CLIC concept

By now LHC, and its electron–proton option, are well studied and documented. Most accelerator problems have been tackled and solved, and there is no need here to go into more details. On the other hand electron–positron linear colliders are still at the level of 'concepts' requiring not only the understanding and solving of some essential issues, but also analytical and numerical calculations, model work, prototype development and testing. According to the CLIC Panel, three to five years of intensive work are needed to transform the CLIC concept to a design that could be used in a decision-making process [5]. Moreover, the successful running of the \( E_{cm} = 0.1 \text{ TeV} \) SLAC Linear Collider (SLC) is an essential condition for any further development. Given the novelty of the scheme, I devote a few paragraphs to describing it.

The upper part of Fig. 1 schematically shows the main components of a linear collider. A few comments are in order: (i) in most schemes the positrons are obtained by using the spent bunches; (ii) the damping rings, which are needed to reduce the invariant emittance \( \epsilon_{n} \) of the positron bunches, are not a small component of the system and may be a few kilometres long; (iii) high gradients in the main linac are certainly useful, but a viable collider requires much more than an idea on how to produce such high gradients; (iv) the value \( \beta^{*} \) of the \( \beta \)-function at the interaction point determines, together with \( \epsilon_{n} \), the luminosity \( [L \propto (\epsilon_{n}\beta^{*})^{-1}] \), and small values of \( \beta^{*} \) are preferred; however, the 'natural' scaling law is \( \beta^{*} \propto E_{cm}^{-2} \) and in all schemes the final focus poses difficult problems. I shall come back to this question in subsection 6.3.
Fig. 1 Schematic representation of a linear collider complex. In practice the positron source will make use of either the accelerated or the spent bunches. The electron damping ring system will probably not be needed, because low-emittance sources are now available and, for this reason, is dashed in the figure. The lower part of the figure represents the two-stage accelerator proposed by W. Schnell, which uses superconducting cavities at 350 MHz (LEP 200) to power the drive beam [7].

It is generally recognized that, to achieve high luminosities ($L = 10^{34}$ cm$^{-2}$ s$^{-1}$), the ideal solution would be a fully superconducting (SC) linear collider running almost d.c. with a field frequency in the range $1000 \leq f_{RF} \leq 1500$ GHz and a quality factor $Q > 3 \times 10^{10}$ [6]. Unfortunately quality factors are at present ten times smaller and the maximum gradients achieved in a single cell are $\leq 20$ MV/m, so that the total length of an $E_{em} = 2$ TeV collider based on possible extrapolation of the available technology would be about 100 km. Whilst struggling toward higher gradients in superconducting structures may be helped by the new type of 'warm' superconductors recently discovered, other solutions have to be pursued.

New ideas have been proposed and developed [7] during the studies of the CLIC Panel; they still make use of the technology of superconducting cavities, well known at CERN, but indirectly, and can thus provide much higher gradients for acceleration in a very high frequency copper structure. The CLIC Panel is at present concentrating on the proposal by W. Schnell, which is schematically drawn in the lower part of Fig. 1. The superconducting (SC) cavities developed for LEP 200 ($f_{RF} = 350$ MHz, $\lambda = 85$ cm) accelerate a low energy (3-5 GeV) drive beam. Trains of electron pulses follow each other at a repetition frequency $f_t = 6$ kHz. Each train is formed of four pulses separated by a distance $\lambda_{RF} = 85$ cm; each pulse is made of about ten very short electron bunchlets which are about 1 cm apart and contain about $4 \times 10^{13}$ electrons each (in the figure, for simplicity, only five bunchlets are shown.) These bunchlets give energy to coupling cavities resonating at the 30 GHz frequency corresponding to the spacing $\lambda = 1$ cm of the bunchlets in a pulse. The electromagnetic field produced by the 30 GHz cavities is then fed to a copper accelerating structure of the main linac, which is about 20 cm long and 1 cm across. The average accelerating field in this structure is of the order of 80 MV/m for a field in the SC cavities of 7 MV/m, which is achievable today. The gradient in the 30 GHz structure increases in proportion to the field in the superconducting low-frequency cavities, so that about 150 MV/m can be foreseen for the near future. In the two cases (80 and 150 MV/m) the length of each linac would be about 15 km and 8 km, respectively.
Table 3

Main parameters of the CLIC electron-positron collider

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
<th>With respect to SLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Centre-of-mass energy, $E_{cm}$</td>
<td>2 TeV</td>
<td>SLC $\times$ 20</td>
</tr>
<tr>
<td>Luminosity, $L$</td>
<td>$10^{33}$ cm$^{-2}$ s$^{-1}$</td>
<td>SLC $\times$ 150</td>
</tr>
<tr>
<td>Number of interaction regions(^a)</td>
<td>1</td>
<td>SLC $\times$ 1</td>
</tr>
<tr>
<td>Repetition frequency, $f_r$</td>
<td>5.8 kHz</td>
<td>SLC $\times$ 35</td>
</tr>
<tr>
<td>RF frequency, $f_{RF}$</td>
<td>30 GHz</td>
<td>SLC $\times$ 10</td>
</tr>
<tr>
<td>r.m.s. bunch length, $a_z$</td>
<td>0.5 mm</td>
<td>SLC $\times$ 2</td>
</tr>
<tr>
<td>Number of particles per bunch, $N$</td>
<td>$5.4 \times 10^9$</td>
<td>SLC $\times$ 10</td>
</tr>
<tr>
<td>$\beta^<em>$-value at the collision, $\beta^</em>$</td>
<td>3 mm</td>
<td>SLC $\times$ 2</td>
</tr>
<tr>
<td>Invariant emittance, $\epsilon_0$</td>
<td>$2 \times 10^{-6}$ m</td>
<td>SLC $\times$ 10</td>
</tr>
<tr>
<td>r.m.s. final spot radius, $\sigma$</td>
<td>$65 \times 10^{-9}$ m</td>
<td>SLC $\times$ 25</td>
</tr>
<tr>
<td>Power per beam, $P$</td>
<td>5 MW</td>
<td>SLC $\times$ 50</td>
</tr>
<tr>
<td>Disruption parameter, $D$</td>
<td>0.9</td>
<td>SLC $\times$ 1</td>
</tr>
<tr>
<td>Average energy of beamstrahlung $\gamma$'s</td>
<td>45 GeV</td>
<td></td>
</tr>
<tr>
<td>Beamstrahlung power per beam, $P_\gamma$</td>
<td>0.5 MW</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) More interaction regions can be served by sharing the luminosity.

The main parameters of the CLIC collider as foreseen at the time of the workshop are collected in Table 3.

The comparison with the SLC parameters is useful in order to focus on the main challenges. In particular, a repetition frequency larger by a factor of 35, which is possible because of the use of SC cavities which run continuously, implies a roughly proportionally larger number of damping rings such that the sum of the circumferences is a few kilometres. Either the ISR or the LEP tunnel could house the damping system [8]. The needed invariant emittance $\epsilon_0$ is similar to what can be obtained today at the best synchrotron light sources. Extrapolating from SLC values with the natural scaling law ($\beta^* \propto \sqrt{E_{cm}}$) gives, at 2 TeV, a $\beta^*$ eight times larger than what is needed, and the larger fractional momentum spread of CLIC complicates the design of the final focusing system. The two parameters $\epsilon_0$ and $\beta^*$ define the transverse dimensions of the colliding bunches ($\sigma = \sqrt{\epsilon_0 \beta^*}$). At CLIC it should be 25 times smaller than at the SLC, which implies extremely tight alignment tolerances and very sophisticated feedback systems.

### 2.3 Luminosity comparisons

The power radiated at the interaction point by an electron (positron) in the intense magnetic and electric fields of the opposite bunch (beamstrahlung) gives a widening of the distribution of the electron-positron effective centre-of-mass-energies $\tilde{E}_{cm}$ as indicated by the continuous curve of Fig. 2, computed for an energy spread at the end of each linear accelerator of $\Delta E / E = 0.5\%$. Note that in the figure the effective energy dependence of the luminosity is represented by the behaviour of the function $F(\tilde{E}_{cm})$, which is such that the number of interactions per second is:

$$\text{rate} = L \int_{\Delta \tilde{E}} \sigma(\tilde{E}_{cm}) F(\tilde{E}_{cm}) \, d\tilde{E}_{cm}$$

(1)
Fig. 2  Parton–parton normalized luminosities at the LHC and CLIC as a function of the effective centre-of-mass energy $\hat{E}_{\text{cm}}$ [10]. The exact definition of $F(\hat{E}_{\text{cm}})$ is given in Eq. (1). The CLIC curve assumes an energy spread at the end of the linacs equal to 0.5% and has a FWHM of 20 GeV. (The LHC and CLIC curves have been computed by A. Nandi and P.T. Cox, respectively.)

$F(\hat{E}_{\text{cm}})$ was computed at the workshop by P.T. Cox using a modified version of the Yokoya program [9]. The peak in Fig. 2 is about 20 GeV wide (FWHM) and there is a long tail at low energies. Clearly the collider is working in a 'narrow-band' regime, in spite of the relatively large average photon energy (Table 3). This is good news.

It is interesting to compare the CLIC normalized differential luminosity $F(\hat{E}_{\text{cm}})$ with the LHC one. The LHC curves of Fig. 2 show that, as is well known, at low energies the gluon–gluon luminosity is larger than the quark–quark luminosity. Moreover the figure points out that, for a centre-of-mass subenergy equal to that of CLIC, the LHC is rather a quark–quark than a gluon–gluon collider.

Photon–photon physics is already playing an important role at present electron–positron storage rings. The dotted curve of Fig. 2 shows the relevant luminosity at CLIC. As we shall better see in the following, at TeV colliders the focus will be in a similar process, in which the initial fermions (leptons or quarks) radiate intermediate vector bosons. The two lower curves of Fig. 2 give the energy dependence of the luminosity for the collision of two longitudinally polarized intermediate bosons W at the LHC and CLIC. It is seen that they differ by a factor of about 7, so that the rates are higher at the LHC. But the quark–quark and gluon–gluon luminosity is almost six orders of magnitude larger, already indicating that at the LHC, for the rare phenomena which can be produced in the $W_{t}W_{t}$ channel, the problem will be background rather than rate.
3. **Extrapolation of Known Physics to the LHC and CLIC**

To examine the potentialities of accelerators running in a new energy regime, it is necessary to extrapolate established knowledge to higher energies. Today we are in a situation where the Standard Model provides a reliable framework for such an extrapolation, so that one can confidently compute the backgrounds due to known processes and compare them with the expected rates of the 'new' physics. I devote the next subsections to a review of the energy extrapolation of the main quantities describing proton-proton, electron-proton and electron-positron collisions.

3.1 **The proton-proton channel**

The nucleon-nucleon total cross-section continues the rising trend seen at the ISR and confirmed at the p̅p Collider. At the LHC it is expected to be $\sigma_{\text{tot}} = 100 \text{ mb}$ (Fig. 3). The total cross-section is dominated by complicated 'soft' phenomena in which the final energetic particles form small angles with the beam direction [10]. The production of jets of hadrons is a more dangerous background for any new physics. Jets in hadron colliders are usually defined by the total transverse momentum $p_T$ with respect to the collision axis. As indicated by the lower curve of Fig. 3, the jet cross-section has a strong energy dependence, i.e. a behaviour similar to the point-like

![Graph showing cross-section vs. $E_{cm}$](image)

**Fig. 3** Proton-proton cross-section as a function of the centre-of-mass energy. The dotted lines represent the extrapolations of the total cross-section. The continuous line is the cross-section for producing a jet having transverse momentum $p_T = x_T E_{cm}/2 > 0.03 \times E_{cm}$ [10].
cross-section characterizing the electron-positron channel to be discussed in subsection 3.3. (The cross-section $\sigma_{\text{jet}}$ plotted in Fig. 3 refers to jets having a transverse momentum larger than a constant fraction of the energy: $x_T = 2p_T/E_{\text{cm}} > 0.06$.) At the LHC the jet cross-section for $p_T > 500$ GeV is $2 \times 10^{-33}$ cm$^2$ = 2 nb, which corresponds to a rate of 2 ev./s at the nominal luminosity of $L = 10^{33}$ cm$^{-2}$ s$^{-1}$. This is about the rate of events which can still be written on today's magnetic tapes. Note that such a rate, being eight orders of magnitude smaller than the total interaction rate, imposes a sophisticated trigger for the on-line selection.

Jet events contain a very large number of particles: the most probable value for the number of charged particles is about 100 (Fig. 4a). These secondary hadrons form many jets, as shown in Fig. 4b. [Here, as in Ref. 10, a jet is technically defined by the conditions: $\Delta R = (\Delta \eta^2 + \Delta \phi^2)^{1/2} \leq 0.2, \theta > 5^\circ$; $\eta$ and $\phi$ are the pseudorapidity and the azimuthal angle, respectively.] The most probable number is six, without counting the two beam jets which

![Diagram](image)

(a) Distribution of the number of charged particles $n_{\text{ch}}$

![Diagram](image)

(b) Distribution of the number of jets $N_j$ (see text for the definition of 'jet')

![Diagram](image)

(c) Angular distribution of the jets with respect to the beam axis

Fig. 4  Summary of some of the main properties of proton–proton collisions at $E_{\text{cm}} = 16$ TeV [10]. (Computed by B. Webber and W. Kittel.)
go forward. About 1% of the events are expected to have more than 18 jets, and the corresponding rate is about 50 per hour. The jet angular distribution, plotted in Fig. 4c, is peaked forward and backward.

3.2 The electron–proton channel

I consider the charged-current reaction $e^- + p \rightarrow \pi^- + X$ caused by the exchange of a virtual charged intermediate boson W. Figure 5 shows that at low energy the total cross-section increases proportionally to $Ecm^2$, a well-known property shared with the inverse reaction $\pi^- + p \rightarrow e^- + X$ whose cross-section increases linearly with $E_\pi = Ecm^2/2m_\pi$. At higher energy the cross-section flattens owing to the finite mass of the exchanged W. The dash-dotted curve of Fig. 5 represents the total cross-section for momentum transfers $Q^2$ larger than $10^2$ GeV$^2$, i.e. $Q > 0.32$ TeV; $Q$ is nothing else than the (time-like) mass of the exchanged particle and, according to the Heisenberg relation $d = 2 \times 10^{-17}$ cm$\cdot$TeV/Q, corresponds to a space domain having dimensions of the order of $5 \times 10^{-17}$ cm. At LHC energies the cross-section for $Q > 0.32$ TeV is such that, with $L = 10^{32}$ cm$^{-2}$ s$^{-1}$, one expects about one event per hour.

![Cross-section graph](image)

**Fig. 5** Electron–proton cross-sections as a function of the centre-of-mass energy. The continuous line refers to charged-current inclusive events. The dash-dotted line is for a cut at $Q^2 > 10^2$ GeV. (Computed by R. Rückl). The thick dashed and continuous line gives the energy dependence of the jet cross-section for $x_T > 0.06$. (Computed by Z. Kunstel.)
The angular distribution of the hadron jets having $x_T > 0.06$, i.e. $p_T > 45$ GeV at $E_{cm} = 1.5$ TeV, is shown in Fig. 6, which quantifies the well-known fact that the jets tend to keep the direction of the incoming protons: electron-proton detectors have to be asymmetric in order to accurately measure hadron jets produced within a few degrees with respect to the proton beam.

![Diagram showing angular distribution of jets](image)

Fig. 6 Angular distributions of the jets with respect to the proton direction at the electron-proton option of the LHC. Most of HERA physics is here confined at $\theta_j < 5^\circ$. (Computed by M. Holdler.)

3.3 The electron–positron channel

The continuous curve of Fig. 7 represents what is known today of the hadronic ‘annihilation’ cross-section, i.e. the sum of the cross-sections of all the processes in which the positron and the electron disappear having annihilated. The figure is taken from Ref. [8] and is based on experimental data up to $E_{cm} = 45$ GeV and on the predictions of the Standard Model above 45 GeV. Since the overall trend is roughly parallel to the dashed curve, which represents the ‘point-like’ cross-section applicable to $\mu^+\mu^-$ and $\tau^+\tau^-$ production, the figure proves that, in the explored energy range, quarks (and leptons) are point-like particles. The four sets of peaks appearing below about 10 GeV are due to the pair-creation of quark-antiquark pairs, which together have the same quantum numbers as the electron-positron pairs and, immediately after production, whirl thousands of times one around the other in a resonance state. The four sets are due to the production of unstable bound states of the quark pairs $u\bar{u}$ and $d\bar{d}$ ($q$ and $\omega$), $s\bar{s}$ ($\phi$), $c\bar{c}$ ($J/\psi$) and $b\bar{b}$ ($T$). We would like to complete the figure by plotting the set of resonances due to $t\bar{t}$ bound states, but at present we only know that they must lie above $E_{cm} = 45$ GeV and below $E_{cm} = 200$ GeV. There are also indications that the lower limit could be as high as $\sim 80$ GeV.

The $Z$ peak is not only taller than the others but, according to the Standard Model, it is also of a very different nature, because the $Z$ boson is a single elementary particle having the quantum numbers of the initial electron-positron pair and not a composite system. After climbing on the $Z^0$ peak, LEP 200 will open the possibility of exploring the much smaller shoulder due to the production of pairs of charged bosons: $\gamma^+\gamma^- \rightarrow W^+ + W^-.$

The point-like cross-section decreases as $E_{cm}^{-3}$ so that at CLIC $\sigma_{pp} = 2.2 \times 10^{-38} \text{ cm}^2$; by running one third of a calendar year ($T = 10^7$ s) at a luminosity $L = 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, only $220 \mu$ pairs would be collected. Figure 7 shows that at CLIC the rate of production of $W$ pairs in a $4\pi$ detector is 50 times larger than for $\mu$ pairs, whilst the production of single $W$'s is 500 times bigger. This cross-section increases with energy because the initial leptons (the electron and the positron), do not annihilate, but are still present in the final state as an electron (or positron) plus an antineutrino (or neutrino). It is difficult to say whether such a large production rate will be 'useful' for physics or should only be considered as a source of background.
The dotted line in the top right-hand corner of Fig. 7 gives the total cross-section for the 'two-photon' channel $e^+ + e^- \rightarrow e^+ + e^- + \mu^+ + \mu^-$. In this reaction the initial leptons survive and form very small angles with respect to the beam direction. The events can easily be distinguished from 'annihilation' events, and the fact that the cross-section is about seven orders of magnitude larger is not really a problem. By comparing Fig. 7 with Fig. 3 we notice that: (i) both in hadron-hadron and electron-positron collisions the 'interesting' cross-sections of the known point-like phenomena decrease as $E^2_{\text{cm}}$, whilst for the 'uninteresting' reactions, which send most of the particles in the direction of the beams, the cross-sections increase slightly with energy; (ii) for both the LHC and CLIC, these cross-sections are seven or eight orders of magnitude larger than the 'interesting' ones. The fact that the pp and $e^+e^-$ 'uninteresting' cross-sections differ by a factor of $\sim 10^6$ is a direct consequence of the fact that strong-interacting partons are contained in a bag having a radius of about $10^{-13}$ cm and that the electromagnetic interaction is much weaker than the strong interaction.

The distribution of the number of charged particles expected at CLIC is shown in Fig. 8a: the most probable value is about 60. These particles are grouped in jets and the most probable number of jets is 4.5 (Fig. 8b). Their angular distribution (Fig. 8c) is flatter than in the proton-proton case (Fig. 4c).
4. PHYSICS TARGETS AND ACHIEVABLE LIMITS

Comparing the physics potentialities of two accelerators is a formidable task for at least three obvious, though fundamental, reasons: (i) the unknown cannot be predicted; (ii) even after having agreed on a list of ‘expected’ new phenomena, the relative importance is subjective; (iii) tomorrow’s discovery may completely modify the ‘relevance’ weights given to the selected phenomena.

Looking for inspiration in the past, I want to underline that almost exactly 25 years separated the only three great discoveries which were ‘expected’ and eventually found to be there: nuclear reactions produced by artificially accelerated protons (1932), antiprotons and antineutrons (1955–1956), charged and neutral asthenons (1982–1983).
By linear extrapolation, I conclude that the next 'expected' discovery will take place around 2005–2007, too late to be relevant in the comparison of accelerators which should run before the end of the century. Probably history wants to tell us that it is wrong to try and compare LHC and CLIC potentialities on the basis of the 'new physics predicted' today. Still, for want of a better solution, this is what the physics groups have done; I shall here summarize the results, after having recalled the main theoretical ideas behind the choice of the expected 'new' physics.

4.1 The theoretical framework and its questions

The Standard Model gives a rationale to the existence of the weak, electromagnetic, and strong forces, but offers no explanation for the fact that we have observed only three families of fermions, the matter-particles which act as sources of the known force-particles: the photon (γ), the asthenons (W and Z), and the gluons (g). I shall use here, as I did in the oral report and in Ref. [3], the term 'asthemon' to indicate a weak intermediate vector boson with a single word, which sounds more or less as 'photon' and 'gluon'. I am convinced that, five years after the W and Z discovery, such a symmetry in nomenclature is needed; perhaps a better neologism could be found.

A first very natural series of questions is thus:

**Questions 1:** Do heavier (sequential) leptons and quarks exist?

What about heavier asthenons both charged (W⁺) and neutral (Z⁺)?

Whatever the answer to these questions is, there is a fundamental problem related to the force-sector. The Standard Model of the electroweak interaction is very successful in explaining a host of data and, at the same time, very unsatisfactory. This is true not only because it contains about twenty free parameters, but also because it needs an ad hoc mechanism, not yet confirmed experimentally, to justify the rest energies of the asthenons. At the fundamental level these bosons are very similar to photons. A photon has zero rest mass and thus, once emitted by a particle in a virtual process, can fly far away from its source, giving rise to a force of infinite range (Fig. 9a). Why is the range R of the weak force ~ 10⁻¹⁶ cm instead (Figs. 9b and 9c), i.e. why are the masses of the asthenons ~ 0.1 TeV? (In this case the Heisenberg relation reads: R = 2 × 10⁻¹⁷ cm·TeV/0.1 TeV = 2 × 10⁻¹⁶ cm.)

The answer theorists give is: Because of the Higgs mechanism. According to the prevailing point of view, all space is filled by a boson field which behaves as the collection of Cooper pairs in a superconductor. The macroscopic wave function of such a collection repels out of the metal the virtual photons of an external magnetic field, so that they do not penetrate in the conductor (Meissner effect). The Higgs field has a similar effect on the asthenons, but the other way around: since it fills all space, it pushes back the asthenons radiated by leptons and quarks, so that they can be felt only at less than 10⁻¹⁶ cm from their source (Figs. 9b and 9c). The Higgs field fills the physical vacuum because its self-interaction is so strong that the state of minimum energy is reached when the average field is non-zero.

As always in quantum theory, there are quanta associated to fields, thus also to the Higgs field. They are called 'Higgs particles' or simply 'Higgses'. As the Cooper pairs of normal superconductivity, they carry no

![Fig. 9: Leptons (and quarks) radiate virtual photons γ (a), and virtual asthenons W (b) and Z, (c) but according to the Standard Model, the Higgs field pushes back the asthenons and obliges them to remain close to the sources, so that the range of the weak force is R = 10⁻¹⁶ cm and not infinite, as for the photon.](image)
intrinsic angular momentum — in other words they are bosons of spin $J = 0$. In the simplest model there is only one neutral Higgs field, but it is well possible that charged Higgs fields are also present.

The above arguments do not fix the mass of the neutral Higgs quantum. One of the main arguments in this direction comes from considering $W_L W_L$ scattering at very high energies (Fig. 10a). If the neutral Higgs bosons did not exist, the cross-section computed in perturbation theory would increase as the square of the centre-of-mass energy ($\sigma \sim E_{cm}^2$) and would violate probability conservation (unitarity, in theoretical parlance) when $E_{cm} \gg 1800$ GeV. If a scalar ($J = 0$) Higgs particle exists, it will contribute to the virtual processes which take place in the dashed region at the centre of Fig. 10a: perturbative calculations show that in this case there is no unitarity violation provided the Higgs mass is smaller than about 1 TeV. There is also the possibility that perturbation theory does not apply and that new strong forces come into play at this mass scale. Anyway, the fact that both LHC and CLIC are sources of $W_L W_L$ collisions (Fig. 2) indicates that the new accelerators will give us the opportunity of studying directly this fundamental process.

The argument which gives an upper limit for the mass of the Higgs looks simple, but one may wonder if the reasoning is sound enough. We can find some confirmation going back to past experience and recalling that already once unitarity guided us to a correct mass scale. As mentioned in subsection 3.2, for the neutrino–quark scattering shown in Fig. 10b the old theory of weak interactions, now superseded by the Standard Model, gives a cross-section which is proportional to $E_{cm}^2$, so that unitarity would be violated when the energy is larger than about 300 GeV. This was a fundamental problem already thirty years ago, and, while experimentalists were collecting data around 1 GeV, theorists were bold enough to conclude that, to cure this disease, something had to happen at energies smaller than about 300 GeV. They were right and everybody now knows that probability is conserved in weak interactions, because the exchanged $W$ has a finite mass so that the cross-section flattens at high energy, as shown in Fig. 5. Experience is thus telling us that unitarity arguments are very powerful and the present indication of violation in $W_L W_L$ scattering around 2000 GeV, while we are experimenting around 100 GeV, should not be lightly dismissed. This long argument focuses on The Problem of today’s physics [11]:

Questions 2: Does the standard neutral Higgs exit?
And if yes, which is its mass?
Do charged Higgses exist?

Higgs particles could be bona fide Cooper pairs, so that they can be broken into two fermions at energies of the order of 1 TeV. For this, and other reasons, some theorists contemplate composite models, in which the known ‘elementary’ particles are made of more fundamental fermions. If a particle is made of two other particles, one expects to find their excited states, in the same way as the $c\bar{c}$ quarks form both the fundamental state $J/\psi$ and its excited states $\psi'$, $\psi''$, etc. Thus the questions arise:

Questions 3: Are quarks and leptons composite systems of other simpler fermions?
Are $W$, $Z$, and Higgs themselves composite?
Do excited leptons ($\ell'$) and quarks ($q'$) exist?
Fig. 11 A Higgs particle H gets mass by virtual emission and absorption of (a) athenons, (b) Higgs, and (c) fermion–antifermion pairs. The virtual boson contributions are positive, whilst the fermion ones are negative.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Spin</th>
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<th>Symbol</th>
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<tr>
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Unfortunately a consistent and unique theoretical framework for introducing compositeness does not exist. By necessity, composite models contain various parameters, whose definition has to be closely scrutinized before they are interpreted in terms of a spatial dimension by applying the Heisenberg uncertainty relation. To increase the confusion, usually all those parameters are indicated by the letter A, so that one meets symbols such as \(\Lambda_{\text{ee}}, \Lambda_{\text{e\nu}}, \Lambda_{\text{VH}}, \ldots\), which have different meanings in different contexts. In the following I shall use for simplicity a single symbol \(\Lambda\) which has the dimension of an energy and can be used to roughly define the linear dimensions \(d\) at which the composite nature of the particles would become apparent through the Heisenberg relation \(d = 2 \times 10^{-17}\) cm \(\cdot\)TeV/\(\Lambda\).

Not many theorists are today following the composite route. Many more pursue the idea of a fundamental Higgs, and here they meet with a difficulty: while propagating through space, a Higgs particle \(H\) emits and reabsorbs various other particles (Fig. 11) and, through their interaction, picks up weight very easily. This is a general property of spin-0 particles since there is nothing to protect them from becoming massive. Theorists are then faced with the problem of cancelling the many different contributions to the mass increase. As is shown in Fig. 11, the contributions due to virtual bosons (W, Z, H) are positive, whilst the contributions of virtual fermion pairs (f̄f) are negative. It can be shown that a miraculous cancellation occurs if each known boson has a related fermion (and vice versa) and their couplings are in a well-defined relation. Supersymmetry gives exactly the needed pattern: for each particle of integer (half-integer) spin there is a sparticle of half-integer (integer) spin (Table 4).

If the cancellation is to be effective, the masses of the sparticle should not be much larger than \(\approx 1\) TeV, the known limit on the Higgs mass. Other arguments also point to the existence of sparticles, but we cannot discuss them here. We can thus express the following questions:

**Questions 4:** Do sparticles exist?
If yes, what are their masses?
In the last few years, theorists have become very interested in superstring theories, in which fundamental particles are not point-like objects but strings about $10^{-35}$ cm long. Such theories give rise to a consistent treatment of quantum gravity, fulfilling a long-standing dream, and to supersymmetry; but they are not unique. Some theorists think that in the cold world in which we live it even reduces naturally to the Standard Model, but with some interesting additions. A particularly fashionable model foresees the existence of an additional neutral asthenon $Z'$, a set of other 'normal' particles (such as a neutrino, a neutral lepton and a quark of charge $-1/3$) and a new kind of particles which carry at the same time the 'flavour' of a lepton and a quark. These predictions are very definite but not all experts agree on their necessity and, anyway, the masses of these particles are unknown. The 'leptoquark' $D_0$ is a particularly interesting object: it is a boson (spin $J = 0$) which couples in a well-defined manner to a lepton and a quark. Thus:

Questions 5: Do leptoquarks of spin 1 and spin 0 exist?

In particular, does the spin-0 leptoquark $D_0$ exist?

In summary, theorists indicate to machine builders and experimentalists the following 'discovery targets':

i) Higgs particles, both neutral ($H^0$) (with mass less than $\sim 1$ TeV) and charged ($H^\pm$);

ii) sequential leptons and quarks;

iii) sparticles with masses less than about 1 TeV;

iv) various new particles, and among them a particularly puzzling leptoquark $D_0$;

v) a new neutral asthenon $Z'$ of unknown mass and, possibly, new charged asthenons $W'$;

vi) compositeness, which reflects either in various compositeness scales $\Lambda_{\text{ex}}, \Lambda_{\text{ew}}, \Lambda_{\text{qs}}$ or in

vii) the existence of excited states of quarks ($q'_1$) and of leptons (for instance $e'$).

4.2 The relevant cross-sections

Figures 12, 13, and 14 reproduce the main contents of Figs. 3, 5, and 7 with the addition of curves representing the energy dependence of the cross-sections of some of the most important 'new' phenomena. For the proton-proton channel I have chosen the production of an asthenon $Z'$ having a mass $m_{Z'} = 1$ TeV and a neutral Higgs with $m_{H^0} = 0.5$ TeV. Figure 12 shows that at the LHC these cross-sections are respectively four and five orders of magnitude smaller than the jet cross-section computed for a fixed value of the transverse momentum ($p_T = 0.25$ TeV). This is the relevant background cross-section, since one wants to cut the events having a $p_T$ smaller than a fixed fraction of the produced mass. The figure shows that the signal-to-background ratio does not improve when the c.m. energy increases. Higgs production is a relatively abundant process: for a luminosity $L = 10^{33}$ cm$^{-2}$ s$^{-1}$ and $m_{H} = 0.5$ TeV, the expected rate is a few events per hour [11]. The problem is that the $H^0$ decays in jets and, as discussed in the next subsection, the signal is easily hidden under the $10^5$ times larger background due to normal jet events [12].

Electron-proton collisions are ideal for producing leptoquarks. This is due to the large cross-section for $D_0$ production plotted in Fig. 13, which at LHC energies for $m_{D_0} = 1$ TeV is even larger than the charged-current cross-section for $Q > 0.32$ TeV. On the other hand, the exchange of a heavy charged asthenon $W'$ having $m_{W'} = 1$ TeV has a cross-section $\sigma = 0.1$ pb. If $W'$ is associated with a neutrino which can be distinguished from the usual electron-neutrino $\nu_e$, its production rate is very low, 1 event per day, but it may still be seen. If a $\nu_e$ is produced, then the major effect will come from the interference between $W$ and $W'$ exchanges, whose contribution to the cross-section is intermediate between the one represented in Fig. 13 by the dashed and continuous lines.

In electron-positron annihilations the superstring-inspired $Z'$ appears as an enormous peak, which I have drawn in Fig. 14 for $m_{Z'} = 1$ TeV. Clearly at CLIC it would be possible not only to see it but also to study it up to the available centre-of-mass energy, i.e. $m_{Z'} = 2$ TeV. The cross-section for a Higgs of mass $m_{H} = 0.5$ TeV is large, since it corresponds to $\geq 10^5$ events per year at $E_{\text{cm}} = 2$ TeV and $L = 10^{33}$ cm$^{-2}$ s$^{-1}$. Compositeness would
Fig. 12 Proton-proton cross-sections as a function of the centre-of-mass energy. The continuous and dash-dotted lines are the computed cross-sections for a neutral Higgs meson and a $Z'$ of masses $m_H = 0.5\text{ TeV}$ and $m_{Z'} = 1\text{ TeV}$. (Computed by the Large Cross-Section Group.) The dotted line represents the jet cross-section for a fixed $p_T$, relevant to the production of masses of the order of 1 TeV. (Computed by W. Scott and W.J. Stirling.)

Fig. 13 Electron-proton cross-sections as a function of the centre-of-mass energy. The continuous curves refer to the production of a leptoquark $D_0$ and of an asthenon $W'$ having masses of 1 TeV. (Computed by R. Rückl.) The other curves are taken from Fig. 5.
be signalled by a flattening electron-positron total cross-section, as indicated by the dash-dotted line of Fig. 14. For a value of the parameter $\Lambda$ of the order of 0.5 TeV (i.e. for distances $d = 4 \times 10^{-17}$ cm), the effect shown in Fig. 14 is striking, so much as to remind us of the surprise of the physicists working in 1969 at Adivon when, thanks to the pair-production of point-like quarks, they found a hadron production rate which greatly exceeded the expectations. (The parameter $\Lambda$ is the one appearing in the particle form-factors and it is about a factor of 10 smaller than the parameter appearing in the composite model used at the workshop and discussed in Ref. [13].)

In Fig. 14 the shaded areas indicate the cross-section ranges of three particle channels produced in the annihilation of an electron-positron pair. No unique value can be given because various parameters enter the calculations [13]. In general one can state that electron pairs are produced about 10 times more abundantly than wino pairs, whose cross-section is of the same order as the point-like one ($\sim 200$ events per year for $L = 10^{15}$ cm$^{-2}$ s$^{-1}$). Smoons are expected to be somewhat rarer, but are very interesting because it was shown at the workshop that, if found in the reachable mass range, their bosonic nature (spin $J = 0$) can be proven by measuring the angular distribution of the decay muons. This is a unique and most interesting possibility of really pinning down
supersymmetry, since in hadron colliders production of SUSY particles can only be seen through a missing-transverse-energy signal and no spin can be measured.

4.3 Overview of the discovery limits

In Fig. 15.1 have collected the detection limits of the LHC and CLIC. For each of the twelve phenomena the four vertical bars represent the limits achievable with (i) proton-proton collisions at the LHC, (ii) electron-proton collisions at the LHC; (iii) $e^+e^-$ collisions at CLIC with $L = 10^{37} \text{cm}^{-2}\text{s}^{-1}$; (iv) $e^+e^-$ collisions with $L = 4 \times 10^{39} \text{cm}^{-2}\text{s}^{-1}$. The phenomena follow the order presented at the end of subsection 4.1.

1. The first histogram refers to the discovery of the neutral Higgs $H^0$ expected in the simplest form of the Standard Model. For $m_H < 0.2 \text{ TeV}$ the two-quark decay $H^0 \rightarrow q + \bar{q}$ gives mainly two jets and the workshop has confirmed what was already known: at a hadron collider there is no general way to pin down such a signal. For $m_H > 0.2 \text{ TeV}$ the decay $H^0 \rightarrow W^+ \rightarrow W^- \rightarrow q + \bar{q}$ is dominant; the very detailed analysis performed at the workshop shows that at the LHC the signal is certainly visible only for $m_H \leq 0.6 \text{ TeV}$ [11, 12]. Kinematics may help to extend this range, because the main production mechanism is the fusion of two charged asthenons to form a heavy Higgs meson: $W^+ \rightarrow W^- \rightarrow H^0$. (The luminosity for such a process is shown in Fig. 2.) For this process the quarks radiating the virtual asthenons go forward and their jets may be tagged by calorimeters placed at angles $2^\circ \leq \theta \leq 15^\circ$. The Calorimeter Detector Group concluded that this is possible (see subsection 5.2). In this case, the usual jet background is greatly reduced and it may be possible to see (dashed line in Fig. 15.1) a mass as large as the theoretical upper limit above which perturbation theory cannot be trusted ($m_H = 1 \text{ TeV}$).

As for the LHC, the production of heavy neutral Higgs at CLIC is dominated by the asthenon fusion process, whose luminosity is plotted in Fig. 2. At CLIC the rate is relatively large and, at variance with the LHC, the background is negligible up to $m_H = 0.8 \text{ TeV}$. The Standard Model Working Group concluded that in electron-positron collisions masses up to $m_H = 0.85 \text{ TeV}$ (1.2 TeV) can indeed be reached if the luminosity is $L = 10^{33} \text{cm}^{-2}\text{s}^{-1}$ (4 $\times$ $10^{35} \text{cm}^{-2}\text{s}^{-1}$) [11, 12]. Most important here is the observation that the 'low' mass range $m_H = 0.2 \text{ TeV}$ is fully available because the decay $H^0 \rightarrow q + \bar{q}$ is not masked by the background as at all hadron colliders. I want to underline that LEP 200 will reach $m_H = 0.08 \text{ TeV}$.

In summary, as far as the upper limit of the Higgs mass is concerned, it seems that CLIC is slightly superior to the LHC. However, the great advantage of $e^+e^-$ collisions stems from the possibility of covering the theoretically very important window $m_H < 0.2 \text{ TeV}$, for which an energy $E_{cm} = 0.5 \text{ TeV}$ and a luminosity $L \geq 2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}$ should be sufficient. The main question is then: are we really sure that such a mass range cannot be covered at the LHC? The Standard Model Working Group concluded that the electron-electron mode of the LHC does not help solving the intermediate-Higgs problem [11, 12]. In the proton-proton mode a search for rare and characteristic decays (of the type $H^0 \rightarrow \gamma + \gamma$ and $H^0 \rightarrow Z^0 + \gamma$) may help in discriminating against background events, but the present understanding is that it is not possible to guarantee that the signal will be seen. However, this may be possible in some special cases, for instance if either (i) the top mass is so large ($m_t \geq 80-90 \text{GeV}$) that, for $m_H \leq 2m_t$, the main decay is $H^0 \rightarrow bb$, or (ii) a fourth generation and the heavy-lepton decay $H \rightarrow L^+L^-$ is searched for [11, 12, 14].

2. Charged Higgses are not foreseen in the simplest version of the Standard Model, but they are expected in any supersymmetric theory. Their search is a must. Charged Higgses are expected to decay into heavy quarks or lepton pairs, typically $H^+ \rightarrow t + \bar{b}$. Unfortunately, at the LHC, charged Higgses cannot be found because of the high jet-jet background, so that the discovery limit appearing in Fig. 15.2 is $m_H = 0$. But it is worth remarking that, if a quark Q heavier than $H^+$ exists, a search for the decays $Q \rightarrow H^+ + q$ and $Q \rightarrow W + q$ in the same event may open an interesting window [11, 12]. At CLIC, the cross-section is small but the signal is clear and the discovery limit, plotted in Fig. 15.2, is $m_H = 0.8 \text{ TeV}$. For a search at low masses it is convenient to reduce the collision energy $E_{cm}$ so that the rate increases. Still, below $m_H = 0.2 \text{ TeV}$ the background is not easy to handle and in Fig. 15.2 this range is indicated with a dashed line.
Fig. 15 Summary of the discovery limits expected for 12 different processes. The vertical scale is in TeV and changes by a factor of 4 (2.5) when passing from the first (second) to the second (third) line. The four dashed areas in each diagram refer to the following beam conditions, from left:
proton-proton at $E_{cm} = 16$ GeV with $L = 10^{33}$ cm$^{-2}$ s$^{-1}$;
electron-proton at 1.5 TeV with $L = 10^{32}$ cm$^{-2}$ s$^{-1}$;
electron-positron at 2 TeV with $L = 10^{32}$ cm$^{-2}$ s$^{-1}$ (indicated for simplicity as 'low' L);
electron-positron at 2 TeV with $L = 4 \times 10^{32}$ cm$^{-2}$ s$^{-1}$ ('high' L).

The detailed explanations of the 12 histograms are given in the text. Note that in working out the discovery limits and in compiling the figures all the quoted luminosities have been taken for granted, even if the CLIC electron-positron collider is still at the level of a 'conceptual design'.
3. At the LHC sequential heavy quarks $Q$ are best searched for through the decay $Q \to W + q$. The Working Group concluded that they can be seen also if $m_Q < m_W$ and that, as indicated in Fig. 15.3, $m_Q \leq 0.8$ TeV [12]. Owing to the limited centre-of-mass energy, the electron-proton mode gives only $m_Q \leq 0.1$ TeV [2]. At CLIC the electron–positron annihilation cross-section in pairs of heavy quarks is small; to cover the full range up to $m_Q \leq 0.8$ TeV it is useful to vary the energy of the collision.

4. Sequential leptons are better seen at CLIC than at the LHC, as shown in Fig. 15.4: $m_\ell \leq 0.8$ TeV and $m_\ell \leq 0.5$ TeV respectively [11]. At CLIC the higher luminosity will allow more stringent cuts and give a better signal-to-noise ratio, but a very detailed discussion of the detector properties is needed before concluding that the discovery range can be sizeably increased.

5. At the LHC the discovery limits of squarks and gluinos are both $m = 1$ TeV [13]; this value is plotted in Fig. 15.5, which refers to 'strong' sparticles. (Note that the vertical scale changes by a factor of 4 when passing from processes 1-4 to processes 5-8.) In electron–proton collisions the final states $(\tilde{\ell} + \tilde{q} + X)$ and $(\tilde{\ell} + \tilde{q} + X)$ have the largest cross-sections. The discovery limits depend on the masses of the squark $\tilde{q}$ and the slepton $\tilde{\ell} = \tilde{\ell}$ or $\tilde{\ell}$.

6. The Beyond the Standard Model Working Group concluded that $m_\ell + m_\ell \leq 0.7$ TeV. For this reason, by assuming $m_\ell = m_\ell$, I plotted $m_\ell = 0.7$ TeV in Fig. 15.5.

At CLIC the squark–antisquark cross-section is small, of the order of the cross-section for electron-pair production plotted in Fig. 14. Fortunately the events due to the decay $\tilde{q} \to q + \gamma$ have a very characteristic signature: missing energy, missing momentum, and two acoplanar and acoplanar jets. The discovery limit is close to the kinematic limit, $m_S = 0.85$ TeV [12], if the CLIC luminosity is 'large'. For $L = 10^{33}$ cm$^{-2}$ s$^{-1}$ the Working Group concluded that one cannot be sure that sparticles can be found at all. For this reason in Figs. 15.5 and 15.6 a dashed line has been used for CLIC with $L = 10^{33}$ cm$^{-2}$ s$^{-1}$.

6. Figure 15.6 shows that the discovery limits of electroweak sparticles are better at CLIC, if $L = 4 \times 10^{33}$ cm$^{-2}$ s$^{-1}$, than at the LHC. In proton–proton collisions two reactions were studied in detail [13]: $e^+ + e^- + X$ and $q + \bar{W} + X$. The best discovery limit, plotted in Fig. 15.6, is $m_A = 0.45$ GeV. In the electron–proton mode the already quoted limit $m_\ell + m_\ell \leq 0.7$ TeV, combined with the assumption $m_\ell \leq m_\ell$, gives $m_\ell \leq 0.35$ TeV. The electron pair cross-section, plotted in Fig. 14 is the largest one among the weak particle channels, and the discovery limit at CLIC is $m_\ell \leq 0.85$ TeV.

7. At the LHC, if the leptoquark $D_0$ decays in the channel $e^+ + q$, which has the most favourable signature, the discovery limit could be as large as 2 TeV [13]. I have already remarked that electron–proton collisions are ideal for a leptoquark search. It is no surprise that, in spite of the limited c.m. energy, the $e\mu$ mode of the LHC opens a window up to $m_0 \leq 1.6$ TeV (Fig. 15.7). CLIC is not as good because $D_0$ has spin $J = 0$ and the cross-section is minimal: high luminosity is needed to reach $m_0 = 0.85$ GeV.

8. Heavier asthenons of different sorts occur in many theoretical models. The Beyond the Standard Model Group has considered a superstring-inspired model and concluded with the discovery limits plotted in Fig. 15.8. At the LHC the most promising channels are $Z' \to e^+ + e^-$ and $Z' \to \mu^+ + \mu^-$, providing [13] a conservative limit as large as $m_{Z'} \leq 4$ TeV! Indirect effects of the $Z'$ on asymmetries measured in electron–proton collisions give a much lower limit. As evident from the prominence of the $Z'$ peak in Fig. 14, CLIC would discover and study neutral asthenons up to the available energy $m_{Z'} = E_{cm} = 2$ TeV even with 'low' luminosity. For $m_{Z'} > E_{cm}$ and 'high' luminosity, a mass up to = 4 TeV can be indirectly inferred by measuring the asymmetry in the channel $e^+ + e^- \to \mu^+ + \mu^-$, as indicated by the dotted line in Fig. 15.8.

9. At the workshop no particular attention was devoted to the discovery limits of heavy charged asthenons. The entries to Fig. 15.9 have been obtained from the review paper of Llewellyn Smith [2]. (Note that for processes 9–12, the vertical scale changes by another factor of 2.5.) The LHC discovery limit is impressive: almost 5 TeV. The electron–proton limit (1.25 TeV) applies for a second W boson which would couple as the standard W boson; the much more interesting right-handed charged asthenon has a similar discovery limit. CLIC is not at all competitive
in $W'$ searches, since the limit is at about 80% of the energy available to pair-produce them: 0.8 TeV. Single $W'$ production gives a comparable limit.

10. As anticipated, in Fig. 15.10 the vertical axis does not represent the mass of a particle but rather the discovery limit for a parameter ($\Lambda$) that has different meanings in different reactions and is roughly connected to the scale of particle compositeness through the Heisenberg relation. (The limits obtained by the Beyond the Standard Model Working Group on the parameter appearing in the four-fermion contact interaction [13] have been divided by 10 before plotting them in Fig. 15.10, so as to roughly transform them in the $\Lambda$ parameter appearing in particle form-factors.) The figure shows that in this field CLIC can put much better limits than the LHC. This is mainly due to the spectacular modification of the total electron-positron cross-section, shown as an example in Fig. 14 for $\Lambda = 0.5$ TeV. In the proton-proton case, instead, the best limit comes from a careful study of the angular distribution of two-jet events.

11. If particles are made of other subparticles, one expects to see excited states of the known quarks and leptons. Quite naturally in the discovery of excited quarks $q'$, hadron colliders are better than electron-positron colliders. By searching for the decay $q' \rightarrow q + g$ the LHC discovery limit may be as large as $m_{q'} \sim 5$ TeV (Fig. 15.11). At CLIC one can reach the kinematic limit on $m_{q'} \sim 2$ TeV.

12. The production of an excited electron $e'$ has not been studied in detail, but it may be that the LHC is better than CLIC. This is due to the fact that the decay mode $e' \rightarrow e + \gamma$ has a very clear signature, even in a hadronic environment. In the CLIC case the kinematic limit $m_{e'} = 2$ TeV can be extended up to about 3 TeV (dotted line of Fig. 15.12) by probing indirectly the contribution of virtual $e'$ states to the cross-section of the reaction $e^+ + e^- \rightarrow \gamma + \gamma$.

5. DETECTORS

The Working Groups have concentrated on the problems posed by the LHC environment, since in first approximation CLIC detectors can be considered costly, but relatively simple, scaled-up versions of LEP detectors.

5.1 Track detectors at the LHC

At the LHC proton-proton bunches will collide at the frequency of 40 MHz and produce about 2.5 interactions per crossing ($\sigma_{int} = 100$ mb, $L = 10^{33}$ cm$^{-2}$ s$^{-1}$). The inelastic interactions ($\sigma_{inel} = 60$ mb) will be 1.5 per crossing but, since the trigger system will not accept crossings without events, the average number of inelastic events per accepted trigger will be $\approx 2.2$ [15]. Detectors will have to cope with these extreme conditions, never encountered before in high-energy physics experiments. At HERA, for instance, the crossing spacing is 96 ns, but the expected rate of events with particles going outside of the beam pipe is much smaller: only $10^{-3}$ per crossing.

The Vertex Detector and Tracking Group has devoted a lot of attention to the problem of running a track chamber and measuring particle momenta in such a difficult environment. Previously the problem had been studied in the United States in connection with the Superconducting Super Collider (SSC) [16]; the status of these studies was summarized at the workshop by M. Gilehrize [17]. At present the favoured solution foresees the combination of a central track detector (CTD) and a vertex detector (VXD). The VXD will need to measure accurately enough the longitudinal position of the vertex of an event ($\Delta y < 1$ mm) to be able to assign tracks to each vertex and thus handle more than one event per trigger. The CTD, formed by many superlayers, will be a vector drift chamber, with enough on-line computer power to provide a vector for each superlayer from the registered hits in the 200 MHz flash analog-to-digital converter (FADC). Left-right ambiguities can be eliminated on-line and tracks from previous bunches will be sorted out with the scheme shown in Fig. 16 [18]. The Working Group is convinced that relatively simple on-line algorithms can combine the vectors from each superlayer in a track, whose information can also be used in the trigger. Formidable problems have to be solved for running such a detector at $L = 10^{33}$ cm$^{-2}$ s$^{-1}$, but both the Working Group on Vertex Detector and Tracking and the one on Particle Identification [19] concluded their work on a positive note.
Fig. 16 The Vertex Detector and Tracking Group studied, as an example for the LHC, the use of a chamber structure similar to the one of the ZEUS central detector. (Figures taken from Ref. [18].) (a) Sector of the ZEUS CTD layout. There are nine superlayers each with eight sense layers. Five layers are axial with a design resolution $\sigma_{z} = 100 \mu$m and four are at small stereo angles. The chamber is designed to run in a field of 1.8 T. (b) Electron drift lines and isochrones. Superimposed on this is an indication of a stiff track, together with its associated hits, and the apparent track sectors for a similar track from the previous (or three crossings later) LHC bunch. Left-right ambiguities omitted for clarity.

5.2 Calorimetry for hadron colliders

The LHC is the worst environment not only for track detectors but also for calorimeters. The Jet Detector Working Group concentrated on the study of a compact silicon calorimeter (COSICA) which uses silicon as the sensitive medium (as proposed a few years ago by G. Barbiellini and P.G. Rancoita) and uranium as the inert material. Careful Monte Carlo calculations indicate that the response of such a calorimeter to electrons and pions can be equalized by sandwiching the silicon detectors with 100 $\mu$m thick polyethylene layers [20]; of course the experimental proof is now needed. A silicon calorimeter shares with liquid-argon and warm-liquid ionization chambers the essential property that it can be absolutely calibrated with electronic pulses and/or radioactive sources. Moreover, its mechanical construction is simple and the segmentation relatively easy. The cost, however, is still high. Figure 17 reproduces the schematic layout of COSICA at the LHC [20].

Fig. 17 Structure of the Compact Silicon Calorimeter considered by the Jet Detector Working Group. At angles smaller than about 8° silicon detectors cannot survive and a different technique is needed. (Figure taken from Ref. [20].)
Silicon detectors and their electronics are sensitive to radiation. The working group has computed the integrated doses expected at the LHC and concluded that the limiting dose is reached at angles $\theta = 7^\circ$ with respect to the beam direction. For this reason a silicon calorimeter cannot operate safely around $\theta = 5^\circ$, the angular region in which the quarks, radiating virtual aethons, should be tagged to extend the discovery limit of neutral Higgses (subsection 4.3.1). Different, less performing calorimeters have to be used for this very important task; solutions have been proposed.

5.3 Triggering and data acquisition

This is a most challenging enterprise at the LHC, and the Working Group on Triggering and Data Acquisition discussed it in great detail. The trigger has to reduce the event rate by a factor of $10^3$, and this can be obtained with a three-stage trigger if each stage reaches a rejection factor of about $500$. The external superlayer of the CTD discussed in subsection 5.1 may be used to trigger on large-transverse-momentum tracks [18], but here I concentrate on calorimetric triggers.

For the first-level trigger, the Triggering Group worked on the hypothesis that the $\sim 5 \times 10^5$ ($\sim 5 \times 10^3$) electromagnetic (hadronic) calorimetric cells will be reduced to $\sim 5 \times 10^5$ ($\sim 10^3$) by adding the signals from $10 \times 10$ (2 $\times$ 2) cell matrices. A special output of each cell must be clipped to 25 ns, as shown in Fig. 18a [15]. In the 25 ns time interval following a bunch crossing, the analog signals from the electromagnetic (hadronic) calorimeter cells are added (with weights $\sin \theta$) to form the basic electron/photon and jet signals. As shown in Fig. 18a, the next 25 ns are used to sum the weighted signals from the hadron calorimeter matrix with the corresponding signals from the electromagnetic matrix and obtain the transverse energy ($E_T$) signal. Then 25 ns are needed to obtain a signal proportional to ($E_\gamma + E_T$), by summing the transverse energy $E_T$ from each matrix weighted with $(\cos \theta + \sin \theta)$. (This is used to form a rough missing-transverse-energy trigger.) The scheme of Fig. 18a allows to apply, within about 100 ns, thresholds to signals proportional to the electromagnetic and hadronic energies deposited in localized regions of the calorimeter, $\Sigma E_T$ and ($E_\gamma + E_T$), and to the muon trigger, which is built in parallel. To take

![Block representation of the three levels of the calorimetric trigger considered by the Triggering and Data Acquisition Group. (Figures taken from Ref. [15].)](image)

(a) Operations to be performed on the clipped signals of the calorimeter cells to obtain the first-level trigger. The shift register is used as digital pipeline to keep the data whilst the summing circuit forms the trigger. The time scale of the operations is indicated at the bottom. (b) Block diagram indicating the flow of FADC signals to the second- and the third-level trigger.
into account the length of the cables, the digital pipeline, represented by the shift register of Fig. 18a, has to be 200 ns deep.

For the higher trigger levels the signals from the single cells have to be used. Each cell has to be equipped with a 12-bit to 16-bit FADC, which samples continuously at twice the collision rate, i.e. at 80 MHz. Note that today’s 10-bit ADCs running at a sampling rate of 40 MHz cost about 10 kSF! Electronics develop very fast, but it is clear that a close collaboration with industry has to be started now, if one wants to reduce the cost of the single channel to an affordable level.

The flow of the calorimeter data to the second- and third-level triggers is shown in Fig. 18b [15]. The 12.5 ns shift registers are used here also as digital pipelines; they are necessary because the time needed for a decision is much longer than the bunch spacing. About 12 FADC samplings (for a total time of 150 ns) are enough to correctly integrate the charge of any modern calorimeter, subtract the pedestal, and spot events following each other within a few bunches.

The second-level processor has the full digitized calorimeter information available. Multiple buffering of events between the first-level and the second-level trigger will be necessary to make the dead-time small. A grid of transputers, or similar type of processors, could find clusters in few microseconds [15]. Afterwards, the data are moved to buffer memories from which the third-level processor can collect the relevant information, including data from the track chambers to compute the vertex position.

The above sketchy description of a possible trigger architecture indicates the complexity of the tasks and the many problems which have to be solved to fully use the LHC luminosity of the order of $10^{33}$ cm$^{-2}$ s$^{-1}$. However, the conclusions of the Working Group are not as pessimistic as one could have expected; the feeling of the experts involved was that, given enough time and investment, viable solutions to the major problems can be found.

6. THE INTERFACE BETWEEN ACCELERATORS AND DETECTORS

6.1 The proton–proton LHC Interaction regions

Figure 19 shows a general layout of the LEP ring. The Interaction Regions (IR) free and suitable for proton–proton physics are IR5 and IR7, together with the four even-numbered regions which are at present devoted to LEP experiments. As remarked by the Interaction Regions Working Group [21], each of these collaborations may have proposals of their own on how to re-use their equipment at the LHC. IR3 is not available, because it is used for the beam abort system. IR1 may also be used, but the interference with the injection system has to be clarified. However, IR1 could be used for a dedicated electron–proton detector.

At the Workshop two types of proton–proton IRs have been examined [21]: (i) a push-pull experimental area, consisting of a garage, in which the detector is mounted, and of a collision hall (Fig. 20a); (ii) a bypass solution, which allows the detector to be mounted from the beginning in its final position and avoids interferences with LEP (Fig. 20b). The working group favours the second solution because it does not interfere with LEP running, the excavated volume is about half, and the infrastructures are much simpler. Of course, one has to add the excavation of the bypass, which has not been studied in detail yet and will certainly increase the cost.
6.2 Electron–proton collisions at the LHC

Since most of the particles go in the direction of the proton beam (Fig. 6), an electron–proton interaction region has to be designed in such a way as to have ±10 m full space around the interaction point. In Ref. [22] the Working Group proposes a new solution, which leads to a luminosity reduction of only about 20% with respect to the previous design based on a free space of ±3.5 m. For electron–proton collisions at (60 GeV + 8.0 TeV), i.e. for $E_{cm} \approx 1.4$ TeV, the foreseen luminosity is now $L = 10^{32}$ cm$^{-2}$ s$^{-1}$. This is obtained with the beams colliding head-on, so that the electron beam has to be brought to the level of the proton beam, which runs $90 \text{ cm}$ higher in the LEP tunnel. A zero crossing angle is obtained by bending up the electron beam about $200 \text{ m}$ from the crossing point. The second bend is made in the interaction region itself with a weak horizontal field ($B = 0.1 \text{ T}$) which extends over $16-20 \text{ m}$. The scheme sketched in Fig. 21, taken from Ref. [22], has the advantage that synchrotron

![Diagram](image)

**Fig. 20** (a) Push-pull experimental area at the LHC. (b) Bypass solution for a detector dedicated to proton-proton collisions at the LHC. (Figures taken from Ref. [21].)

![Diagram](image)

**Fig. 21** Electron–proton dedicated interaction region with bypass for the electron–positron operation of LEP. (From Ref. [22].)
radiation has a low critical energy ($\approx 300$ keV). However, a fraction of the radiation hits the aperture of the magnets belonging to the proton ring. To avoid problems, these magnets either have to be normal conducting or must use a warm bore.

Since the detector disposition for electron–proton collisions is so special, the use of a single interaction region for both electron–proton and proton–proton collisions is complicated and will have to be studied further, in case experimenters have sufficient interest in such an option.

6.3 The CLIC final focus

Very high field gradients are required if the magnets of the final focus system have to focus a 1 TeV beam with $\beta^*=3$ mm, even smaller than the value foreseen for SLC ($\beta^*=5$ mm). Since, as discussed in subsection 2.2, the natural scaling law is $\beta \propto E_{\text{lab}}^{1/2}$, the focusing system designed for SLC would produce at CLIC $\beta^*=25$ mm. Stronger focusing is clearly needed, and this can be achieved by either using quadrupoles with a much smaller aperture or employing plasma lenses [23].

Whether permanent quadrupoles are a viable solution for the head-on collision of CLIC bunches is as yet uncertain. This is due to the interplay between two effects [24]: (i) for head-on collisions, the quadrupole aperture has to be large enough to contain the disrupted beam and the radiated photons; (ii) the focusing system has a chromaticity that causes a broadening of the spot proportional to the energy spread $\Delta E/E$, which at the end of the acceleration is of the order of a per cent. The traditional method of correction by means of dipoles and sextupoles may be excluded by prohibitive emittance growth due to the quantized radiation.

One expects that the angular distribution of the electrons (positrons) after the collision has a core which is of the order of $D^{1/2} \cdot a/a_{\text{r}} = 150$ μrad (for the values of the parameters see Table 3) and tails due to lower-energy particles which have suffered a large fractional energy loss in the first part of the opposite bunch and a correspondingly larger deflection in the second. The distribution of the scattered electron total energy has been computed at the workshop and is plotted in Fig. 22, together with the distribution of the total energy of the beamstrahlung photons. It is seen that the widths of the two distributions are similar, even if the detailed shapes are

![Fig. 22 Angular distribution of the energy of the electrons (positrons) and of the photons radiated by beamstrahlung in the CLIC interaction region [20]. (Calculations made using the program of Ref. [9] by P.T. Cox.)](image-url)
different. Waiting for more accurate and complete calculations, which take into account also secondary and tertiary effects, at present it can be concluded that for head-on collisions the quadrupoles must have an opening certainly larger than $-5 \times 10^{-4}$ rad, i.e. a diameter larger than $\approx 0.5$ mm at a distance of about 1 m from the crossing point. This is almost feasible with permanent magnets, but then the energy spread has to be very small ($\Delta E/E = 10^{-6}$), otherwise chromatic effects increase too much the transverse dimensions of the bunches. Since one expects $\Delta E/E = 10^{-2}$, the conclusion is that tip-fields definitely larger than 2 T are needed [24]. Plasma lenses, which focus in both planes simultaneously, may provide a solution. 'Flat' bunches crossing at an angle have also been considered [25], the advantage being that the disrupted beam could avoid the opposite quadrupole without loss in luminosity. For these reasons the CLIC final focus is still one of the main areas of study and concern.

7. CONCLUDING REMARKS

In the introduction I quoted the opinion widely spread in our community less than two years ago: 'We (almost) know how to build the LHC but not its detectors, whilst we (almost) know how to build detectors for CLIC but not the collider itself'. I believe that the present status of the CLIC concept and the work done by the Detector Groups (coupled with the results of similar studies made for the SSC [16, 17]), justify the statement that, given three to five years of intense R&D, it is highly probable that one will be able to design the detectors able to utilize hadron-hadron luminosities of the order of $10^{31}$ cm$^{-2}$ s$^{-1}$, as well as TeV electron–positron colliders. However, construction costs and time schedules cannot at present be realistically estimated.

The first conclusion is that Europe should give the highest priority to R&D projects in these two fields.

Before touching upon the issue of the LHC–CLIC physics comparison, I want to put forward three caveats. As far as the LHC is concerned, the workshop did not consider the very abundant forward production of heavy flavours, and in particular of b-quarks, which could be used to study rare decays and CP-violation effects, as proposed for the SSC [16]. In connection with CLIC, the present parameters list is such that the bunches are heavily disrupted after the collision and only one experiment can run at any given time. Since at the LHC more detectors could run simultaneously, a comparison, based on discovery limits, does not make full justice to the other physics issues which can be tackled simultaneously by different detectors at a hadron collider. As a third point, I want to underline the statement made at the beginning of Section 4: comparing LHC and CLIC potentialities on the basis of 'predicted new' physics is probably unjustified: this is the only approach we can adopt, but the 'unknown and unpredicted' have, in the past, always been much more rewarding.

The discovery limits of the LHC and CLIC for predicted new physical phenomena are summarized in Fig. 15, which displays at once the richness of the physics potentials of both accelerators and the complementarity between the two approaches. Whilst CLIC appears to be better in the search for Higgs particles and in the possibility of finding (or excluding) a compositeness scale, the LHC has its strong points in the searches for new astrophons, $Z'$ and $W'$ (the CERN $p\bar{p}$ Collider docet), and of leptoquarks decaying into charged leptons. The limits which can be reached by the LHC on excited quarks are definitely larger, whilst CLIC promises more in the search for heavy leptons. For sparticle searches the competition slightly favours the LHC for discovering strongly-interacting sparticles and CLIC for electroweakly-interacting sparticles. However, for checking SUSY theories CLIC is superior because one can measure better the masses and spins of sparticles. Moreover, all SUSY schemes imply the existence of charged Higgses, and these can be seen at CLIC but are very difficult to fish out of the hot environment of hadron–hadron collisions.

The second conclusion is that the two colliders are rich of potential physics and complementary, and thus a balanced world-wide program should foresee the construction of one accelerator of each sort. This conclusion is supported by well-known examples of the past, which point to another kind of complementarity that cannot be read from the histograms of Fig. 15: hadron–hadron colliders have been good in exploring really new territories, whilst electron–positron colliders have been necessary to map them in detail.
For some channels the discovery limits computed for CLIC at ‘low’ \( L = 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) and ‘high’ \( L = 4 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) luminosity differ appreciably. In particular, at the lower luminosity the leptoquark \( D_0 \) cannot be seen, whilst Fig. 15 shows that the discovery ranges of neutral Higgses, of a new heavy asthenon \( Z' \), and of compositeness are sizeably extended if \( L = 4 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \).

The third conclusion is that CLIC must aim at reaching at least \( L = 4 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1} \) per interaction region [13]. More generally, one can state that an electron-positron collider of c.m. energy \( E_{\text{cm}} \) must provide, at each interaction region, a luminosity

\[
L_{\text{IR}} \geq \left( \frac{E_{\text{cm}}}{\text{TeV}} \right)^2 \times 10^{33} \text{ cm}^{-2} \text{s}^{-1}
\]

in order to make good use of the physics potentials opened by the available energy [3]. Such a luminosity corresponds to the production of about 1000 \( \mu^+ \mu^- \) pairs per year. If an advanced, general-purpose detector which can well measure all types of particles cannot be built and two of them have to be foreseen, then the collider has to provide a luminosity twice as large to be shared between the two interaction regions, where two complementary detectors can be located.

The set of parameters that are considered at present for CLIC, and are summarized in Table 3, corresponds to \( L = 10^{33} \text{ cm}^{-2} \text{s}^{-1} \). It is clear that, by requiring a luminosity at least four times larger, a heavy burden is put on the shoulders of the machine physicists who are working on the CLIC concept. But the needs have now been analysed and spelled out; further machine studies have to take them into account. (I recall that multibunch schemes have been proposed [5] and their implementation could give the factor required, but they introduce new problems which have not yet found a convincing solution.)

Is it possible to go beyond the three conclusions listed above and integrate all the information produced at the workshop in a ‘choice’ between LHC and CLIC? No, because to do this, at least one prejudice and two further dimensions have to be added to the collection of histograms of Fig. 15. The prejudice has to do with an estimate of the ‘probability’ that one (or more) of the twelve processes we have considered is realized in nature; the added dimensions refer to the cost of each project and to its time-scale. I believe that most theorists would agree on the statement that the search for Higgs particles is a more relevant physics problem today than hunting for new asthenons. In fact, in ordering the twelve physics targets of Fig. 15 I tried, as much as this is possible, to follow present theoretical prejudices in order of decreasing ‘probability’. From this point of view, clearly limited to the consideration of expected ‘new’ physics, CLIC has to be preferred to the LHC because it promises to perform better on more important problems. (But the enthusiasts should not forget that a LEP 200 discovery of, for instance, a neutral Higgs with \( m_H = 80 \text{ GeV} \) would immediately influence the physics priorities.)

On the other hand, cost and time scale carry us out of the simple bidimensional space of the physics comparison considered at the workshop and summarized in Fig. 15. By looking only at these extra dimensions, the LHC has to be preferred to CLIC, which needs between three and five years of R&D to become a design [5], accompanied by a cost estimate, which I do not think will be lower than the LHC cost.

To make a definite choice many other arguments have to be considered, in particular the SSC project recently endorsed in the United States and the needs of a balanced and timely world-wide program. During the next months many committee meetings and coffee-table discussions will be exploring this multidimensional space and, I believe, will make frequent use of the careful mapping of the physics plane done at this workshop. The members and the Chairman of the Detector Physics and Advisory Panel and all the participants in this workshop have to be warmly thanked for providing this essential instrument. Moreover, I want to express my personal gratitude to the conveners of the working groups, for passing and explaining to me an enormous amount of information, and to all those who have been quoted in the figure captions, for their help in collecting the data needed for the plotting of the graphs.
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