THE 'FUTURE' IN HIGH-ENERGY PHYSICS

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Introduction

When the title of this talk was suggested to me by the organizers, I was not sure I should have accepted it. Talking about the future in elementary particle physics is a bit like looking into a crystal ball. This kind of exercise is usually quite frustrating: reviewed a few years later, it usually seems to have been rather dull, since by definition it cannot include 'surprises', very often the prime movers of progress. We should not forget that most of the advances have so far been completely unpredicted and unpredictable. We have also learnt that the largest energy and the fattest budgets are not necessarily ingredients for guaranteed major progress, and that the next step may spring from anywhere. It is, for instance, hard to predict whether colliding-beam accelerators will maintain the absolute leadership in the major discoveries in our field in the years to come, and which one amongst the various accelerators — under construction or planned — will do best.

We are all aware, however, of the fact that there would be little or no future for high-energy physics without new developments in particle accelerators. Together with developments in experimental techniques and in instrumentation, accelerator advances today remain one of the main vehicles of progress. In spite of the profound theoretical progress of the last decades, elementary particle physics remains primarily a field driven by experimental discoveries. The 'theory of everything' is not yet for tomorrow!

There is no doubt, for instance, that the new accelerators, either planned or being constructed, will be the main tool at least for the very essential and quantitative consolidation of the present Standard Model, with perhaps the exception of neutrino physics, where non-accelerator devices — either β decay or underground detectors — may turn out to be more effective.

Since this conference is the first of a series of European Accelerator Conferences, I shall add implicitly the adjective 'European' to the title, but without forgetting completely what is going on elsewhere.

The Immediate Future: LEP 1

The most relevant event in European high-energy physics in 1989 will almost certainly be the first turn-on of the Large Electron–Positron storage ring (LEP). So far remarkably within schedule and budgets, this unique facility, which was started about eight years ago, should commence operation at the Z^0 mass in the middle of next summer. The luminosity should then gradually increase toward its design value at this energy, namely $1.6 \times 10^{31}\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The sample of Z^0 that will be produced is extremely large. So far, the CERN $p\bar{p}$ Collider has observed only the leptonic decay channels of the few thousand Z^0 that have been produced in hadronic collisions.

At the peak of the $e^+e^- \rightarrow Z^0$ resonance, the cross-section with 'visible' final states (namely, subtracting neutrino-associated channels) is predicted to be about 25 nb. It is assumed that we shall operate LEP for at least 3000 hours per year, or about 10^7 seconds per year. At design luminosity and 50% overall efficiency, the four experiments around the ring will then presumably collect a total of

$$(0.5)\,(10^7)\,(1.6 \times 10^{31})\,(25 \times 10^{-33})\,(4) = 8.0 \times 10^6\ Z^0 \text{ per year.}$$

Over three fruitful years of running, a sample of 10–20 million Z^0 can eventually be collected. It is not the purpose of this talk to review systematically what LEP is going to deliver in the next few years. There are, however, a number of points which deserve to be mentioned.

One of the most important questions that LEP should settle with a *definitive* answer soon after turn-on, is how many replicas of the basic quark and fermion doublets exist in nature. We have at the moment no real key to the fact that both quarks and leptons come in at least three families. How many are they in total? Rabi used to make a joke about this, asking in a loud voice, 'Who ordered the muon?'.

The CERN $p\bar{p}$ Collider has set a limit of no more than five families coming from the effect that events of the type $Z^0 \rightarrow \nu_x + \nu_x$ (where $x \neq e, \mu, \tau$) would have on the Z^0 width. Each (additional) neutrino species will contribute with 160 MeV to the total width, since whilst new charged fermions and quarks, if they exist, are very massive, it is extremely likely that the associated neutrinos have masses much smaller than half the Z^0 mass.

LEP can do this job much better and settle the issue in a definitive manner, since the Z^0 width Γ can be measured to $\pm 20\ \mathrm{MeV}/c^2$. In addition, the 'invisible' decay modes of the type $Z^0 \rightarrow \nu_x + \nu_x$ (which are 6% for each neutrino species) can be tagged by operating slightly above the resonance and looking at the radiative emission of photons, the so-called Barbiellini–Richter reaction:

$$e^+ + e^- \rightarrow Z^0 + \gamma \rightarrow \nu_x + \nu_x + \gamma\,.$$

Therefore, one will soon be able to pin down the number of leptonic species to its final number. Since leptons and quarks are presumably related in families, this would give the *final* word on how far the hunting of elementary fermions — at least in the sense we give to this word today — must extend.

The energy of LEP 1 will be about twice that of other e^+e^- storage rings. Therefore it is possible that new production thresholds will appear, in which either new leptons, new quarks, or perhaps even completely new kinds of particles, are produced in pairs. Unfortunately, the results of the CERN Collider have set limits that make it extremely unlikely that the Z^0 resonance would decay into a possible fourth generation of leptons and quarks. Likewise, supersymmetric particles already have limits which exceed the energy available from the Z^0 decay. However, the limits are at present extremely near the kinematic limit of LEP 1, and it is still possible that the top-quark exists with a mass within the range of the LEP 1 energies, which has a maximum of about $\sqrt{s} = 110$ GeV.

There is still a significant chance that a definite conclusion on where the mass of the top lies will soon be reached, presumably before the actual start of LEP. The CERN Collider limits on the mass of the top will be improved shortly, when the data coming from Fermilab and from the luminosity-enhanced CERN Collider will be analysed. There are two possible production channels, namely

$$p + \bar{p} \rightarrow W \rightarrow t\bar{b}\,, \tag{1}$$

$$p + \bar{p} \rightarrow t\bar{t}\,. \tag{2}$$

Reaction (1) is dominant at the CERN Collider, where the energy is relatively low, and for relatively low masses, $m_t < 65\ \mathrm{GeV}/c^2$. At Fermilab, where the energy is higher, and for higher top masses, reaction (2) — i.e. associated strong production — is expected to dominate. The advantage of reaction (1) is that it is well predictable since the production rate for the W's and the decay branching ratios are known. Also the event topology is cleaner, consisting essentially of two jets [one from the decay of the b from the W, the other from the decay $t \rightarrow b + e(\mu) + \nu$], of an isolated lepton, and of some missing energy due to the neutrino. In reaction (2), rates can only be considered reliable within a factor of 2 because of QCD corrections, and the final state involves many more particles and jets.

Nevertheless, even if the top-quark does not show up at LEP 1, there will be a large number of other decay channels of extreme interest, and it will be possible to study with high precision and in extremely clean conditions a variety of processes involving quarks and leptons.

One should not forget that the primary *raison d'être* of the LEP programme in its initial phase and subsequent energy upgrades has been, from its conception, the systematic verification of the

Table 1
Sensitivity of various experiments to electroweak constants

Collider	Measurement	Integrated luminosity (pb^{-1})	Corresponding precision on	
			A_{LR}	$\sin^2\theta_w$
Fixed target	νN scattering	-	0.048	0.0060
Fixed target	νe scattering CHARM II	-	0.040	0.0060
LEP 1 (Z^0)	Z^0 mass	200 (no polariz.)	0.003	0.0004
LEP 1 (Z^0)	$A_{FB}(\mu^+\mu^-)$	200 (no polariz.)	0.012	0.0015
LEP 1 (Z^0)	$A_{FB}(s\bar{s})$	200 (no polariz.)	0.010	0.0012
LEP 1 (Z^0)	$A_{FB}(c\bar{c})$	200 (no polariz.)	0.016	0.0020
LEP 1 (Z^0)	$A_{FB}(b\bar{b})$	200 (no polariz.)	0.007	0.0009
LEP 1 (Z^0)	τ polarization	200 (no polariz.)	0.015	0.0019
$p\bar{p}$ Collider + ACOL	W, Z mass ratios (UA1/2)	10	0.010	0.0021
LEP 200	W mass	500 (no polariz.)	0.005	0.0006
SLC	A_{LR}	1-40 ($P_L = \langle 0.5 \rangle$)	0.014-0.003	0.0018-0.0003
LEP 1 (Z^0)	A_{LR}	40 ($P_L = \langle 0.5 \rangle$)	0.003	0.0003
LEP 200	F-B asym. with P	40 ($P_L = \langle 0.5 \rangle$)	0.005	0.0006

Theoretical deviations → [Higgs mass $10^{2\pm1}$ GeV/c^2 → ; Top mass 110 ± 20 GeV/c^2 →]

electroweak theory. It is believed that the electroweak theory is now, similarly to quantum electrodynamics (QED), an 'exact' theory, valid to all orders. In analogy to what has happened with QED, higher-order corrections (the Lamb shift, the g − 2 of the electron and of the muon, etc.) are necessary in order to consolidate our belief in the theory and to test the presence of a number of fundamental virtual diagrams. The electroweak graphs involve primarily virtual fermions, intermediate vector bosons, and Higgs bosons. Small but experimentally significant deviations are expected in the observables, depending on the assumptions regarding the top mass and the Higgs mass. The accuracy of the parameters already available from the UA1 and UA2 experiments at CERN has, for instance, already set an upper limit of 180 GeV/c^2 for the mass of the top.

These tests are primarily based on the high-precision comparison between the Z^0 mass m_Z, the $W^\pm$ mass m_W, and the parameter A_{LR}. For a number of years to come, however, the precision determination of m_W or rather of m_W/m_Z will have to rely on the precision measurements at the CERN Collider, where the UA1 and UA2 detectors have been specially modified to improve systematic errors. A few years later, LEP 200 would eventually reach the WW threshold and provide additional evidence.

The impact of these future experiments is shown in Table 1, where one can see the importance of longitudinally polarized beams. Will LEP 1 eventually be able to produce a sizeable polarization? Going from an early stage of optimism, there has more recently arisen concern about the possibility of there being a sufficiently large polarization, at least at the relatively low energy of LEP 1, where the synchrotron light effects are, relatively speaking, rather weak. But now it appears that the addition of wigglers may be very beneficial, and that one will be able to have some polarization after all. However, the question is still wide open, and probably we shall know for sure only when LEP becomes operational. Every effort will then be deployed in order to add such an important asset to the machine.

In this respect the SLAC Linear Collider (SLC) has an intrinsic advantage because at least the electron polarization may be injected at the source and accelerated without losses to top energy. Even a lower luminosity, if coupled with a good polarization, can indeed be effective in pinning down the basic electroweak parameters (see Table 1). For instance, one can measure A_{LR} to ±0.003 and $\sin^2\theta_w$ with a factor of ≈ 5 better uncertainty than the best measurement without polarization in five times less integrated luminosity (i.e. 200 pb^{-1} compared with 40 pb^{-1}) even if the polarization is not complete, as for instance $\langle P \rangle \approx 50\%$.

LEP as a Z^0 Factory

At lower energies, and more specifically at the mass of the -oniums (J/ψ, Υ), several proposals have been put forward that aim at the realization of e^+e^- colliders, either circular or colliding linacs, with a luminosity of $L \approx 10^{33}$ cm^{-2} s^{-1}. These machines are called 'xxx factories', where xxx stands for charm, beauty, τ-lepton, etc. Why not a Z^0 factory?

There are several scientific reasons which indicate that further increases of the luminosity of LEP 1 could be extremely beneficial, and some of them will be mentioned later on. The nominal LEP 1 luminosity is based on four bunches, each with a current of 0.75 mA.

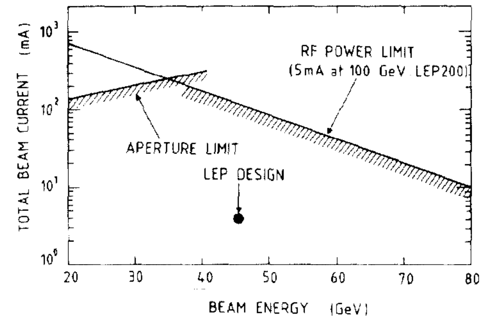

Fig. 1 Maximum beam current in LEP as a function of energy. The limits at low energies come from the aperture and at high energies from the RF power.

The design luminosity at the Z^0 resonance is $L = 1.6 \times 10^{31}\,cm^{-2}\,s^{-1}$ for each of the four useful interaction points. The possibility of increasing L substantially has obviously to be studied in more detail than is done here. However, the situation looks to me rather promising and it should be pursued very seriously.

One limit is the current of the beams, which in turn is related to the power required to compensate for the synchrotron radiation losses. Fortunately, the extraordinarily large bending radius of LEP, optimized to run for LEP 200 up to about 100 GeV per beam, comes in very handy, keeping the energy loss per turn at a relatively modest value compared, for instance, with that of a machine optimized for the Z^0. The maximum single-beam current allowed in LEP as a function of the beam energy is shown in Fig. 1, where one can see that, whilst at relatively low energies the aperture limit is effective, at the energies of interest, the design synchrotron power load corresponding to 5 mA at 100 GeV per beam could permit currents in excess of 100 mA at the Z^0 resonance. Such an amount of RF power will have to be generated in order to achieve the energy of LEP 200. The same installation could supply enough power to permit, instead, higher beam current at low energies. The vacuum chamber etc., where such power is eventually dissipated, has a corresponding cooling power. It should be noted that the penetrating power of the synchrotron radiation emitted at the Z^0 resonance is considerably softer, since the critical energy varies as γ^3.

An increase in the number of bunches from four to, say, eighty seems therefore possible, with a corresponding factor of increase in the luminosity, namely:

$$\text{from } L = 1.6 \times 10^{31}\,cm^{-2}\,s^{-1} \text{ to } L = 3.6 \times 10^{32}\,cm^{-2}\,s^{-1}.$$

Of course, before being sure that this factor can actually be achieved, a number of problems need to be investigated, e.g. the feasibility of a suitable electrostatic separation scheme of the bunches elsewhere than in the interaction point, probably in the horizontal plane, following, for instance, the 'pretzel' scheme pioneered at Cornell. Furthermore, I believe that a number of other additions, for instance mini-β etc., could give us another factor of 3 of multiplicative gain. We could then hope to reach a Z^0-factory level of luminosity with LEP 1.

Let us then assume, for a moment, that we could improve LEP to the point of reaching $L \approx 10^{33}\,cm^{-2}\,s^{-1}$. What will then be its impact on the achievable physics, assuming, of course, that the four experiments could handle a Z^0 rate of 25 per second? A triggering scheme selecting specific physics topics is probably needed, since it is unlikely that the community around LEP has the capacity to fully process a total of about one billion Z^0 per year!

It is interesting to compare the impact of this machine with that of the beauty factories, designed primarily to study B–$\bar{B}$ mixing using either the $\Upsilon(4S)$ or the $\Upsilon(5S)$ resonances. There is today a considerable amount of evidence that, in analogy with neutral kaons, B^0 and $\bar{B}^0$ mesons mix under the effect of the weak interactions. The first evidence was presented as early as 1986 by UA1. At that time, although both $B^0_s \equiv (b\bar{s})$ and $B^0_d \equiv (b\bar{d})$ were produced at the Collider, the result was interpreted as being mostly due to mixing B_s mesons, since the theoretical predictions for B_d mixing were typically small. Subsequently, the ARGUS Collaboration reported some beautiful events giving evidence for a substantial effect in the channel of B_d mixing, which in 1988 has been confirmed by the CLEO Collaboration. The present status of experimental information provides clear evidence that precise measurements are needed in *both* the $B^0_s \equiv (b\bar{s})$ and the $B^0_d \equiv (b\bar{d})$ mixings in order to constrain the Kobayashi-Maskawa (KM) matrix elements and give a quantitative interpretation of the phenomenon. Particularly important is the determination of a phase contained in the KM matrix, which is related to the amount of CP violation in the process. It is therefore clear that

i) one needs to study both B_d and B_s mixings, and
ii) since CP violation is intrinsically a delicate effect, specific channels must be reconstructed with high statistics. For instance, charmed and non-charmed final states must be identified (such as the channel $B_s \to \psi K$, which has a branching ratio of 10^{-4}, the decay chain $B \to D + f$, etc.). In general, for CP violation one expects small branching ratios on the interesting channels, and asymmetries of a few per cent. It is then clear that samples of initial beauty mesons, of $\gg 10^7$ events, should be studied with an efficient and very sophisticated 'see it all' detector.

It should be recalled that although more than twenty years have passed since the discovery of CP violation in the $K^0 \equiv (\bar{s}d) \leftrightarrow \bar{K}^0 \equiv (s\bar{d})$ channel its origin still remains a mystery, and this in spite of tremendous efforts and improvements in the detection techniques—which, for instance, have passed from the $\approx 30K_L \to 2\pi$ events of the discovery paper to statistics of 10^6–10^7 events. Only recently, a very beautiful experiment performed at the CERN Super Proton Synchrotron (SPS) has given the first indication that perhaps the effect is not only confined to mass matrix oscillations. The discovery of a similar phenomenon of oscillations with a mass matrix in the beauty system and rich with new experimental possibilities, appears today as a major breakthrough and the most promising way of making definitive progress. If we were to find CP violation in the beauty channel and a non-zero phase in the KM matrix, it could explain why and how both violations occur. To my mind, the fundamental nature of this problem fully justifies developing new facilities to study beauty physics.

Beauty factories make use of the resonances in the reaction

$$e^+ + e^- \to \Upsilon(S = n) \to B + \bar{B},$$

where $n \geq 4$ in order to be above threshold for B^0_d associated production and $n \geq 5$ for B^0_s. The cross-section for the $\Upsilon(4S)$ is about 1 nb, whilst the $\Upsilon(5S)$ has a peak cross-section as low as 0.1 nb above a hadronic continuum of about 3 nb. As a comparison, the reaction at LEP 1,

$$e^+ + e^- \to Z^0 \to B + \bar{B},$$

has a cross-section of 5 nb with roughly equal branching ratios into B^0_d and B^0_s. Therefore in the cross-section there are factors of 5 and 50 respectively in favour of the Z^0 factory. In addition to cross-sections, there are other points in favour of the Z^0 factory with LEP 1:

i) There are already four interaction points fully equipped with highly sophisticated experiments, whilst a new, dedicated facility, especially in the case of colliding linacs, would most likely operate with a single detector.
ii) The observation of the time evolution (lifetime) of the mixing of the B states requires the use of a microvertex. Because of the higher energy of the mesons produced, the spatial resolution requirements are a factor of 4 less demanding at the Z^0 than at the $\Upsilon(4S)$ ($\sigma \approx 20\,\mu m$ compared with $\sigma \approx 5\,\mu m$).
iii) Since the machine and the detectors already exist and a good deal of the added RF power is part of the LEP 200 programme, its implementation is most probably cheaper and faster than constructing a brand-new, dedicated machine.

The Z^0 factory appears therefore as highly competitive in the study of beauty oscillations; however, there may be differences in the physics of the two production approaches, which indicates that perhaps *both* the Z^0 and the Υ channels are worth pursuing in parallel by the scientific community.

In addition to its contribution to the study of the properties of the beauty channel, a substantial increase in the luminosity of LEP 1 could give access to a great deal of other physics. Indeed, a Z^0 factory is at the same time also a τ factory and a charm factory. Also, a large statistics study of Z^0 decays is in itself very important. Let me mention the search for rare decay modes: for instance $Z^0 \rightarrow 3\gamma$, which has an undetectable branching ratio of 7.7×10^{-10} in the Standard Model and a significant rate in composite models, where structure can radiate, which predict $\approx 5 \times 10^{-5} Q_c^4$, dependent on the charge of the constituents. In this reaction there is a difficult background problem, associated with the process $Z^0 \rightarrow 2\gamma$ + hard bremsstrahlung γ, which has to be mastered.

It should finally be stressed that a high-luminosity LEP 1 is by no means a substitute for the energy increase foreseen by LEP 200. As an example, and as shown later on, in the extraordinarily important search for a massive Higgs, the particle energy is more effective than the luminosity.

The Road Towards LEP 200

The ultimate scope of LEP will be to reach the centre-of-mass energy $\sqrt{s}$ = 190 GeV at the design luminosity of 2.7×10^{31} cm^{-2} s^{-1}. As already pointed out, the extension of LEP to its maximum energy is crucial for the completion of its many scientific goals. However, at higher energies, beyond the Z^0 resonance, cross-sections have dropped so much that luminosity in some instances starts to become the limiting factor. This is a general trend that will become dominant for all high-energy experiments, and it is associated with the fact that for dimensional reasons cross-sections must have an E^{-2} overall factor. The main cross-sections are shown in Fig. 2. The expected integrated luminosity can be evaluated, as before, over 10^7 s and an overall efficiency of 1/2:

$$(0.5)(10^7)(2.7 \times 10^{31})(4) = 540 \text{ pb}^{-1}/\text{year}$$

integrated over the four experiments. Taking into account detection efficiencies, minimal statistics, etc., one could say that cross-sections at the detectability horizon are of $\approx$ 1 pb. As one can see in Fig 2, most basic cross-sections, with the exception of that $2Z^0$ production, lie well above such a line. I have tried to divide the physics of LEP 200 into three broad classes:

1) *'Guaranteed' physics*. This is mostly related to the new threshold for WW production, which will open up at $\sqrt{s}$ = 165 GeV. The excitation curve expected and the possible errors due to statistics are shown in Fig. 3, with each point accumulating about 10 pb^{-1}. It is clear that besides a very accurate determination of the mass through

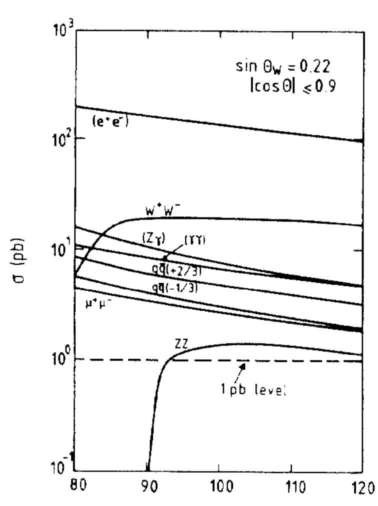

Fig. 2 Cross-sections for several relevant final states as a function of the centre-of-mass energy in e^+e^- collisions. The limit of detectability for LEP 200 is typically 1 pb.

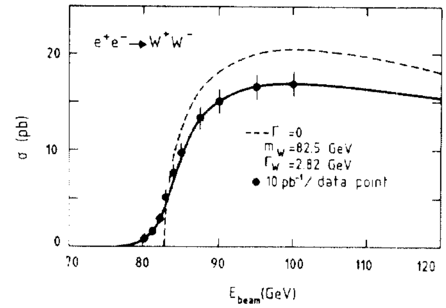

Fig. 3 Excitation curve at LEP for producing W-pairs. The errors indicate the statistical impact of the data for an integrated luminosity of 10 pb^{-1}.

the shape of the excitation curve, one can test a number of fundamental predictions of the electroweak theory, namely

i) the WW, γWW, ZWW couplings;
ii) the W-angular distribution at production and the measurement of its quadrupole moment;
iii) the ratio between longitudinally and transversely polarized W productions, namely $\sigma(W_L)/\sigma(W_T)$;
iv) although the sample of W's produced at LEP 200 will probably be smaller than that accumulated in the meantime at the CERN and Fermilab $p\bar{p}$ Colliders, events are highly constrained kinematically and are extremely clean. Therefore one could perform measurements of all the decay channels and a precise determination of the KM matrix elements.

2) *'Probable' physics*. Into this class one has to put the top-quark, provided it has not been found beforehand, and the Higgs particle, provided it exists and has a sufficiently small mass.

i) We firmly believe that the top-quark must exist. Attempts to invent 'topless' theories have, so far, not lasted very long. Its mass is now 'bracketed' between the upper bound of 180 GeV/c^2 coming from the good agreement between the UA1/UA2 data and the minimal electroweak model, and the lower experimental bound of 45 GeV/c^2 of UA1. As already pointed out, such a limit will soon be raised significantly, and eventually some positive evidence may even come out of the present experiments. Likewise, the upper bound may be improved with more accurate data. At present, one can only say that finding the top threshold within the range of LEP 200 is purely a matter of luck, and that nature may have decided otherwise—as has happened for the expectations at PETRA and TRISTAN. However, with centre-of-mass energy a few times that of LEP 200, one would have a 'no-fail' insurance from the upper bound of 180 GeV/c^2: namely, either the top is found or some new physics is in action.

ii) The Higgs particle can be produced with a calculable cross-section (Fig. 4) because of its known couplings to the Z^0. As can be seen, there are two bounds—one coming from the energy, the other

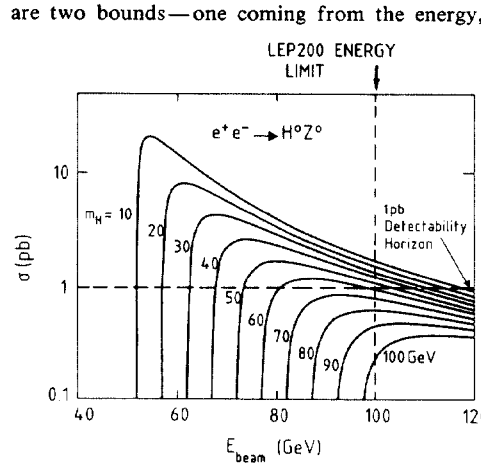

Fig. 4 Higgs production cross-section at LEP 200. Two boundaries—energy and luminosity—limit the mass range that can be explored.

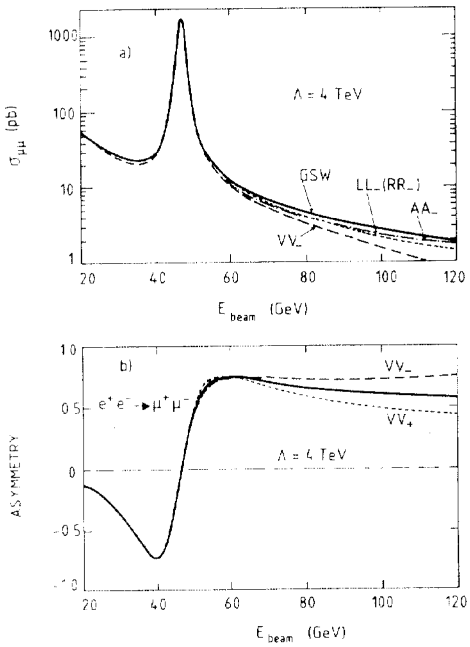

Fig. 5 Sensitivity of LEP to the compositeness scale in the muon-pair channel: a) cross-section, b) asymmetry. Curves are shown for a non-locality with a 4 TeV cut-off.

from the achievable integrated luminosity—that limit the sensitivity of LEP 200 to a standard Higgs with a mass of about 50 GeV/c^2.

3) *'Possible' physics.* Into this class one can put all 'exotica', such as excited leptons, bosons, supersymmetric particles, and so on. The old 'ansatz' of Panofsky can now be modified in the electroweak framework as follows: *All that which is either electrically charged or coupled to weak interactions is produced by e^+e^- collisions with a* calculable *cross-section,* which implies that once an e^+e^- collider of adequate luminosity has explored its energy domain, *definitive* limits can be set. In the case of LEP 200, this applies to almost everything as long as its mass is less than ≈ 90 GeV/c^2. Finally, amongst the possible physics, one has to recall the possibility of compositeness that LEP 200 can test up to a mass scale of about the order of 10 TeV (Fig. 5).

From the accelerator point of view, the road towards LEP 200 requires the realization of an 'industrial' amount of superconducting cavities, for which successful operation has already been achieved at the prototype level and with the installation of a large amount of additional RF power to compensate for the rapidly rising synchrotron-light losses. These topics have been amply covered by Emilio Picasso in his presentation in these Proceedings. Therefore I would simply like to show his planned time-scale for the deployment of the superconducting cavities (Fig. 6).

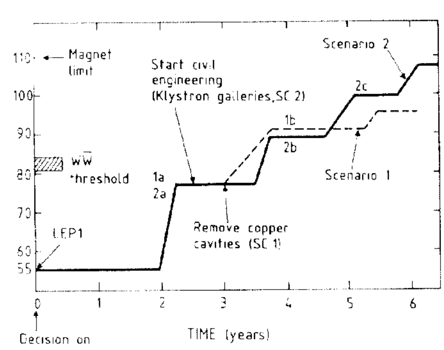

Fig. 6 Timetable of the deployment of superconducting cavities at LEP. The time-scale starts from 1988.

The Importance of ep Collisions

The first collider for electrons and protons, the Hadron-Electron Ring Accelerator (HERA), will start operation soon after the turn-on of LEP. Although the idea of realizing such a machine has been around for quite some time, this will be the first colliding-beam machine to study semileptonic interactions, so far limited to fixed-target neutrino or charged-lepton experiments.

In the fifties, semileptonic collisions have given us the form factors and the geometrical structure, first of nuclei and then of the proton and of the neutron. Deep-inelastic scattering experiments in the late sixties and in the seventies have brought into existence the parton model and have provided the input that is crucial to the invention of quantum chromodynamics (QCD). To my mind, the study of the form factor of the quarks and leptons with much higher energy ($\sqrt{s}$ = 314 GeV, equivalent to a ≈ 50 TeV electron or neutrino beam on a fixed target) pertains to the same level of fundamentality as the above-mentioned experiments.

At high energies the ep scattering process traditionally mediated by the photon propagator has also large contributions due to weak interactions through Z^0 and $W^\pm$ exchanges. Therefore, both the charged and the neutral currents can be studied, and the longitudinal polarization of the electrons (helicity), which in HERA is expected to reach ≈ 80%, is of considerable importance. Estimates of representative event rates are given in Table 2.

Table 2
Events rates at HERA for $\sqrt{s}$ = 314 GeV and an integrated luminosity of 200 pb^{-1}

Process	Underlying reaction	Experimental selection	Number of events (200 pb^{-1})
$e^-p \to \nu_e + h$	$e^-q \to \nu_e q'$	All Q^2	11250
		$Q^2 > 10^4$ GeV^2	880
$e^-p \to e^- + h$	$e^-q \to e^-q$	$Q^2 > 10^3$ GeV^2	44660
		$Q^2 > 10^4$ GeV^2	790
$e^-p \to e^-t\bar{t} + h$	$\gamma g \to t\bar{t}$	m_t = 50 GeV	120
$e^-p \to e^-Z^0 + h$	$\gamma e^- \to Z^0e^-$		7
	$\gamma q \to Z^0 q$	m_Z = 93.8 GeV	36
$e^-p \to e^-W^\pm + h$	$\gamma q \to W^\pm q'$	$\sin^2\theta_w$ = 0.217	154
$e^-p \to \nu_e W^\pm + h$	$\gamma e^- \to W^-\nu_e$	m_W = 83 GeV	3
$e^-p \to e^- + H + h$	$WW \to H$		2

Some of the 'detractors' of the HERA programme have claimed that it does not bear any new discovery potentials, since everything is already well predictable using, at the present level, QCD and the parton model. On the contrary, to my mind this is indeed an asset, since any deviation from predictions becomes *proof* of new phenomenology. For instance, a good example of this is given in the eventuality of structure at the quark or lepton level (Fig. 7).

HERA is also the prototype for a new kind of important machine. In order to increase the energy for this type of experiments further, it is expected that in the more distant future the study of ep collisions could be extended with the realization, at CERN, of the Large Hadron Collider (LHC), the proton storage ring in the LEP tunnel. It would then be only natural to collide the electrons of LEP with the protons of the LHC. The main parameters of the ep option at CERN are summarized in Table 3. These parameters are somewhat tentative, since a detailed project is being worked out at present.

The impact of a higher centre-of-mass energy ($\sqrt{s}$ = 1300 GeV compared with the $\sqrt{s}$ = 314 GeV of HERA) on the discovery potentials of ep collisions is illustrated in Fig. 8 for the specific case of two types of leptoquarks, the hypothetical particles with 'hybrid' properties.

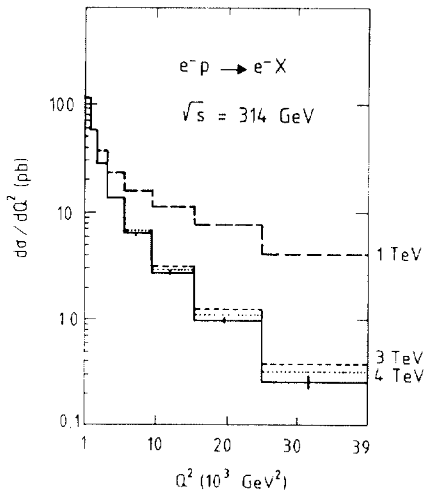

Fig. 7 Effect of the structure of quarks and leptons on the main HERA cross-sections.

Table 3
Expected performance of the ep option in the LEP/LHC tunnel

Parameters	Protons	Electrons
Beam energy (GeV)	8000	50
No. of bunches	540	540
Bunch spacings (ns)	165	165
Vert. emittance, inv. (rad·m)	$20\pi \times 10^{-6}$	$28\pi \times 10^{-9}$
Horiz. emittance, inv. (rad·m)	$20\pi \times 10^{-6}$	$3.4\pi \times 10^{-9}$
Beam–beam tune shift	3.3×10^{-3}	0.04
β_v at crossing (m)	2.8	0.24
β_h at crossing (m)	45.3	0.97
Centre-of-mass energy (GeV)	1265	
Luminosity ($cm^{-2} s^{-1}$)	2.0×10^{32}	

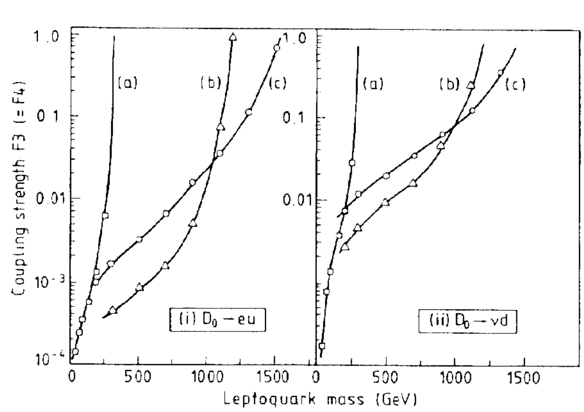

Fig. 8 Comparison between the HERA and LEP–LHC ep Colliders in the search for leptoquarks. It can be seen that with LEP–LHC the kinematical limit in the production of these hypothetical particles is attained. Curve (a) is for HERA and curves (b) and (c) cover the energy range available at CERN for different LEP energies. The two graphs correspond to two different types of leptoquarks, namely the 'neutrino-like' and the 'electron-like'.

Hunting for the Higgs: a Test Case for Future Colliders

The Higgs mechanism is an essential ingredient of the Standard Model and probably one of the 'hottest' topics in particle physics. It is essential in order to explain why gauge theories, which lead to massless vector boson fields, also describe weak interactions, where the carriers of the field are, on the contrary, the heaviest particles known today. In its simplest form, one starts from an initial doublet of scalar objects, leading at the end to a physical neutral scalar H^0 of known couplings but unknown mass. An argument due to Coleman and Weinberg has provided a plausible lower limit to the Higgs mass in the vicinity of 10 GeV/c^2. However, such a limit depends on the value of the top mass, now widely unconstrained and probably very high, and at present one should be prepared to find the H^0 anywhere. Other qualitative considerations seem to suggest masses ranging from those of the W and Z to a few times such a value.

However, it seems unlikely that the Higgs sector consists of a solitary, single neutral scalar H^0. Strong arguments dictate a minimum enrichment of two doublets and one invisible axion. A consequence of these more sophisticated schemes is the existence of an additional charged scalar, which could easily be observed by LEP provided it falls within its kinematical range.

Experimentally, mass limits for the H^0 are essentially non-existent, and very little or no improvement is expected from the hadron colliders at CERN and Fermilab. It should be noted that if the Higgs mass is light, almost 1% of the W and Z events are expected to contain an H^0. For masses larger than a few GeV/c^2, the H^0 decay is expected to manifest itself as one or more jets containing the heaviest kinematically accessible family of quarks (beauty). Unfortunately, in the *hadronic* production of the W and Z there is a large gluon radiative activity due to the incoming quark legs, and the signal is completely buried inside this background. One could try to overcome such background by selecting *leptonic* decays of H^0, for instance $H^0 \rightarrow \mu^+\mu^-$. Unfortunately, the branching ratio for these events is extremely small for any sizeable mass value, since the coupling of Higgs to fermions is proportional to their mass.

These hadrons are completely absent at LEP, where the first attempts to pin down the H^0 will soon be made. The production diagrams in Fig. 9 show the radiative emission of H^0 in Z^0 production.

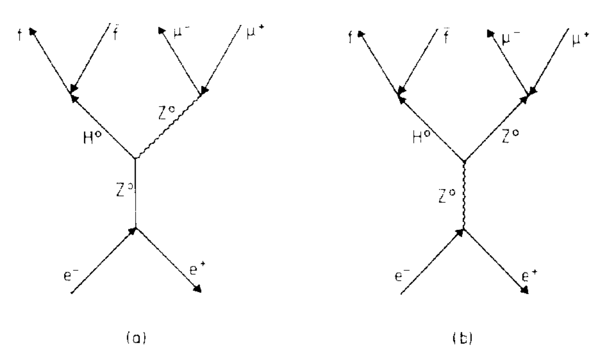

Fig. 9 Feynman diagrams for Higgs production for electron–positron collisions.

These are two important diagrams, the first (Fig. 9a) involving a real Z^0 decaying into a virtual Z^0 and the H^0, and the other (Fig. 9b) in which a virtual Z^0 mediates the decay into a Z^0 and the H^0. The cleanest signatures are the ones in which $Z^0 \rightarrow \mu^+\mu^-$ or $Z^0 \rightarrow e^+e^-$. One should then observe a peak in the missing mass recoiling against the lepton pair at the value of the H^0 mass, and some additional signatures from the decay of the H^0, such as heavy-quark production. Since a low-mass H^0 is very narrow, a very good momentum resolution for the lepton pair is important in order to let the H^0 mass

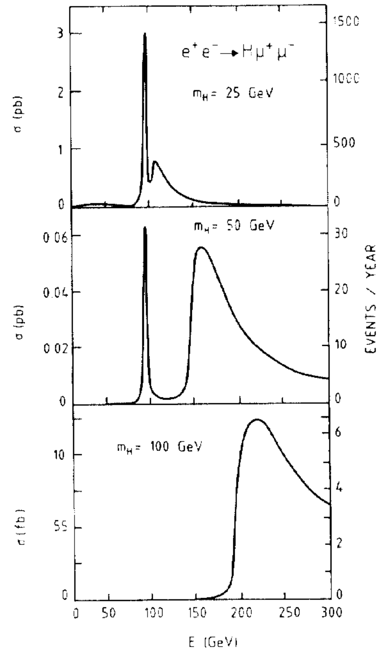

Fig. 10 Production cross-section for Higgs, as a function of the centre-of-mass energy for the reaction $e^+e^- \to H^0\mu^+\mu^-$ and m_H = 25 GeV/c^2, 50 GeV/c^2, and 100 GeV/c^2.

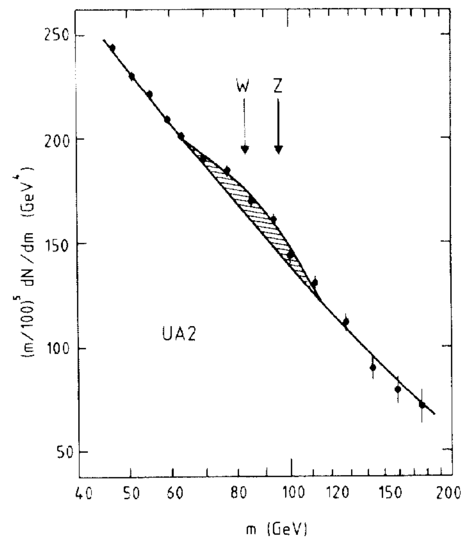

Fig. 11 Evidence for W and Z decays into hadrons observed by the UA2 Collaboration at CERN. Note the large background due to jet pairs, and that the mass resolution is not enough to separate the W from the Z.

peak stand out cleanly above the background. In Fig. 10 the cross-section is plotted as a function of the centre-of-mass energy for the reaction $e^+e^- \to H^0\mu^+\mu^-$ for three masses of H^0. One can clearly see that the direct Z^0 decay contribution (Fig. 9a), dominant at low masses, is dropping very quickly, and that the continuum due to Fig. 9b is gradually taking over. The number of events given in Fig. 10 is for a hypothetical integrated luminosity of 500 pb^{-1}. As already pointed out, LEP 200 becomes luminosity-limited for an H^0 mass around 50 GeV/c^2.

One of the most important justifications for constructing new, higher-energy hadron colliders is to extend the exploration of the Higgs sector beyond the limits of LEP 200. As is well known, there are today two main proposals, one for a $\sqrt{s}$ = 40 TeV collider in the US, the Superconducting Super Collider (SSC), and a smaller ($\sqrt{s}$ = 16 TeV), cheaper, but more luminous European project, the Large Hadron Collider (LHC), a pair of proton storage rings sharing the tunnel and the injectors with LEP.

For very large H^0 masses the dominant signature is the H^0 decay into intermediate vector bosons:

$$p + p \to H^0 + \text{anything}, \quad H^0 \to Z^0 + Z^0, \quad \text{or} \quad H^0 \to W_L^+ + W_L^- .$$

The backgrounds due to QCD jets, which have heavily plagued the searches for H^0 at the existing hadron colliders, are substantially reduced by the spectacular nature of the decay signature, although the experiment remains by no means trivial. There are two distinct schools of thought:

1) The first is what I would like to call the 'SSC approach', namely to look for signatures where one of the two Z^0 decays into leptons and, for rate reasons, the other is allowed to decay into two hadronic jets. Detecting the decay of intermediate vector bosons into jets at a hadron collider is not easy, and the best result has so far been obtained by UA2 (see Fig. 11). Furthermore, at very high energies the events are rather complex, and many additional jets may appear to be due to QCD radiative effects. Since the collider luminosity must be very high, it is possible that several independent interactions occur in one bunch crossing. The complex topology of Higgs-containing events at the SSC is shown in Fig. 12, taken from the Proceedings of Snowmass '87. The conclusion of these studies is that the collider energy must be as high as possible in order to improve the signal-to-noise ratio, and that at $\sqrt{s}$ = 40 TeV and L = 10^{33} cm^{-2} s^{-1} the

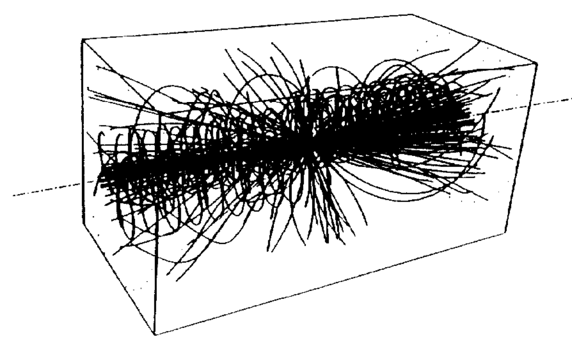

Fig. 12 Simulation of track topologies of Higgs events at the SSC. There are as many as 16 jets recognized by the program with energy > 25 GeV, due to spectator partons.

search becomes luminosity-limited already for $m_H \geq 0.8$ TeV/c^2. It is not completely clear at this stage how a detector that is capable of providing all the elements of information necessary to study the process, could be made to operate at such a high interaction rate ($\approx 10^8$/s, corresponding to L = 1.0 × 10^{33} cm^{-2} s^{-1}) with a full efficiency.

2) Because of differences in energy and radius, the LHC has built in the possibility of a much larger luminosity than that of the SSC. As shown in the Appendix, it is expected that the LHC could reach L = 0.5-1.0 × 10^{35} cm^{-2} s^{-1}, although at the price of a significantly lower energy. This difference in luminosities between the LHC and the SSC is of a fundamental nature, and it cannot be overcome trivially since it relates to the onset of synchrotron radiation losses for the protons and to the practical limits in the total energy that can be stored in the beams. The essential point of what I should like to call the 'LHC approach' is, then, that of concentrating on the cleanest signature, namely the one in which *both* Z^0's decay into muons, the only particles traversing a thick absorber surrounding the collision point completely. Outside the shield, a 4π detector with an excellent momentum resolution for the surviving four high-energy muons can be built relatively easily with today's technical know-how. However, because of the small branching ratio (3%) of $Z^0 \to \mu^+\mu^-$, the toll we have to pay is that of luminosity, of which the LHC has a sufficient

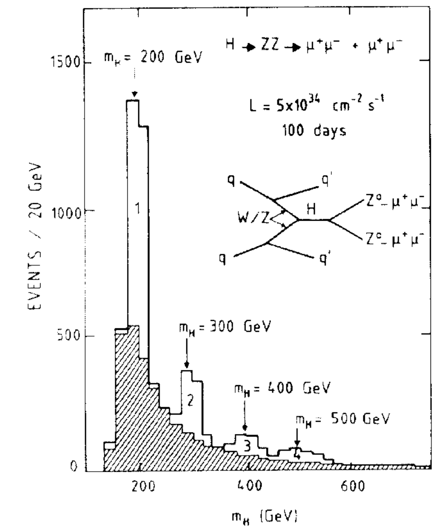

Fig. 13 Four-muon invariant mass at the LHC for production and decay of a heavy Higgs: $H^0 \rightarrow 2Z^0 \rightarrow 2\mu^+ + 2\mu^-$. The signal is shown for different values of m_H together with the expected background from other sources of muons. The statistics are for 100 days of running at $L = 5.0 \times 10^{34}\ cm^{-2}\ s^{-1}$.

reserve to make the experiment feasible. Figure 13 shows the expected signal and backgrounds after 100 days of running at $L = 5.0 \times 10^{34}\ cm^{-2}\ s^{-1}$. The detectability limit is $m_H \leq 1.0\ TeV/c^2$. It should be pointed out that at much larger masses, the natural width of H^0 becomes comparable with its mass, and the simple picture of a particle/resonance fades away. Also, several theoretical complications would arise.

It should be stressed that what I have called here the 'LHC approach', is nothing else than the natural extension of the Drell–Yan signature, already exploited many times at comparable 'luminosities' in the external proton beams on fixed targets, and which has led to the discoveries of the J/ψ and of the Υ. The necessity of relying on the cleanest, *fully leptonic* signature when dealing with hadron colliders and a small number of events has been amply proved also in the discovery of the W and the Z.

In conclusion, I believe that the very high luminosity — even if at the expense of a somewhat lower centre-of-mass energy — and a corresponding cleaner signature that can be handled confidently with today's technology by a dedicated experiment, is the most appropriate line of attack in the search for a heavy-mass H^0.

Higher-Energy e^+e^- Collisions?

There are a number of fundamental reasons that indicate the interest of an e^+e^- collider with an energy substantially larger than that of LEP 200. As is well known, this has prompted a big effort, on the part of the accelerator community, to invent new ways of achieving such a goal. In addition to the strain on energy, there is another — in some way even tougher — strain on luminosity, which has to grow as E^2. For instance, a machine with 10 times the energy of LEP 200 should have a luminosity 100 times larger, namely in the range 10^{33}-$10^{34}\ cm^{-2}\ s^{-1}$.

Some arguments suggest that a step of about a factor of 3 above LEP is adequate for a thorough exploration of the environment of the Fermi mass scale $M_F \approx 250\ GeV/c^2$, which is of considerable physical interest. Amongst these arguments let me mention just a few:

i) The exploration of the Higgs sector is limited at LEP 200 to about 50 GeV/c^2, and hadron colliders can only provide a credible signature if $m_H \geq 250\ GeV/c^2$. As already pointed out, an 'undetectability gap' exists between LEP 200 and the LHC/SSC, namely $50 \leq m_H \leq 250\ GeV/c^2$. This blind mass range is, unfortunately, the one preferred by several (although relatively qualitative) theoretical speculations and therefore it cannot be left unexplored.

ii) The top-quark mass is expected to be $\leq$ 180 GeV/c^2. This limit may soon be revised on the basis of the new data from the hadron colliders and LEP 1, and the top may even be found by one of the machines of the present generation. Still, many other particles may exist, such as a fourth generation of quarks, leptons, leptoquarks, excited leptons, supersymmetric particles, technicolour, etc.

iii) A further exploration of the cancellations in the W_LW_L channel is needed, and it becomes significant only well above threshold.

iv) Supersymmetric particles and similar objects should have masses much larger than those of the W and Z if they are to perform some of the functions for which they have been invented.

For instance, an e^+e^- collider with $\sqrt{s} \approx 0.7$ TeV and adequate luminosity could permit pair-produced particle spectroscopy (fermions, charged Higgs, supersymmetry, etc.) up to about 300 GeV, H^0 up to 450 GeV/c^2, and compositeness up to 40 TeV.

A second, more ambitious, class of machines would involve competing with e^+e^- collisions up to the LHC/SSC kinematical limits for the constituents. Even if the cross-sections and the types of processes initiated with quarks and leptons are most often comparable, the cleanliness and the kinematical constraints ensure that e^+e^- collisions are a very attractive and powerful additional research tool. This kinematical range of O($\approx$ 1 TeV) corresponds to the next, highly significant, energy domain beyond the Fermi energy. It may also be rich in unsuspected structures since, at O($\approx$ 1 TeV), perturbative approaches are no longer valid. The relative potentials of the different types of colliders can be compared, taking as a test case the cross-section for producing W_LW_L pairs — the amplitude in which, for instance, a Higgs will appear as a sharp resonance (Fig. 14). One can make the following remarks:

i) Comparing the LHC and the SSC, the lines for $\sqrt{s}$ = 15 TeV and $\sqrt{s}$ = 40 TeV run almost parallel all the way to 1 TeV. A factor of about 7 in luminosity can bring the two machines to comparable signal rates and hence to comparable discovery potentials. We remark, incidentally, that the luminosity comparison between the LHC and the SSC given in the Appendix suggests the possibility of much larger gains in favour of the LHC.

ii) An e^+e^- collider with comparable slope must have an energy of at least $\sqrt{s} \approx 2.0$ TeV. In this respect, $\sqrt{s} \approx 1.0$ TeV, for instance, will definitely be too low. The smaller cross-section of e^+e^- when compared with hadron colliders can be more than compensated by the cleaner nature of the events. The luminosity must definitely exceed $10^{33}\ cm^{-2}\ s^{-1}$.

Although an enormous conceptual effort is now being made to develop these new types of colliders, it is very likely that the full-energy $\sqrt{s} \approx 2.0$ TeV collider is not yet foreseen for tomorrow. Despite the tremendous competence and experience of the SLAC Laboratory, the serious difficulties encountered with the SLC show that the way to the highest-energy, high-luminosity, linear collider is very long and full of obstacles. A two-stage approach — first with a machine about a few times the energy of LEP 200, followed by the highest-energy $\sqrt{s} \approx 2.0$ TeV collider — seems to me the more sensible proposition.

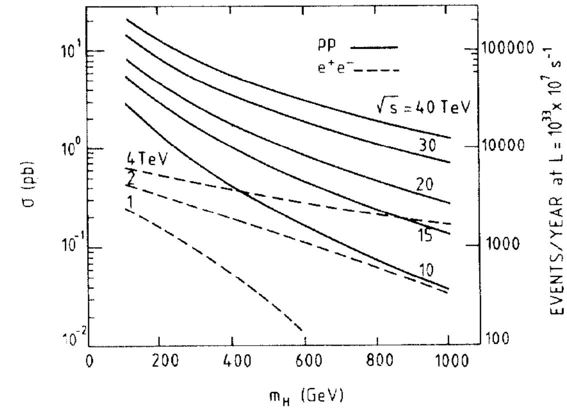

Fig. 14 Effective luminosity of the W_LW_L amplitude for hadron–hadron and e^+e^- initiated collisions.

'Intermediate-Energy' e^+e^- Collider

This machine should have an energy of the order of $\sqrt{s} \approx$ 0.6 TeV. Based on experience with LEP 200 and scaling according to E^2, a minimum luminosity of $L \approx 2.0 \times 10^{32}\ cm^{-2}\ s^{-1}$ is required. There are several ways in which such a collider may be realized. We shall list them in their increasing degree of novel design:

1) A circular machine of very large radius. Simple scaling arguments show that for an optimized machine, the physical radius should grow as E^2. Therefore a machine at three times the energy of LEP 200 would have a circumference in the region of 300 km (4 × the SSC = ELOISATRON), and an energy loss per turn about 10 times larger than in LEP. However, since the guide field is proportional to E^{-1}, it would perhaps be possible to invent some unconventional, ultracheap, magnetic structure, and to make use of the buried pipeline approach (at 300 GeV per beam the guide field is only 250 G!) instead of a fully fledged tunnel in order to keep the price within manageable limits, if built in some desertic land. Note that the period of rotation in a 300 km ring is 1 ms, and RF acceleration techniques conceived for linear colliders may apply, concentrating several bunches in a short segment of the circumference. In this sense, the linear collider mode is approached when the full energy is lost at each turn (zero recovery by recirculation). Since in a circular machine the beam-beam interactions have to be kept to a smaller level, the luminosity-to-power ratio becomes competitive with that of the linear collider only if the energy lost at each turn is not more than several per cent of the beam energy. The circumference of the machine is now so long that the synchrotron damping occurs in a few tens of turns. There could be plenty of interaction points and many experiments running simultaneously. The realization of such a huge but primitive ring structure offers no new fundamental problem — except, of course, the size and cost.

2) It would be possible to increase the centre-of-mass energy of e^+e^- collisions by colliding a high-energy linac against LEP [the Linac-LEP Collider (LLC)]. Obviously, only one experiment at a time can be accommodated. In Fig. 15 the energy of the linac is plotted as a function of the centre-of-mass energy for 65 GeV and 90 GeV stored beams in LEP. For instance, in order to reach $\sqrt{s}$ = 500 GeV in the 90 GeV LEP, we need a linac beam of 694 GeV — a gradient only 36% more than would be necessary to realize two 250 GeV colliding linacs with the same accelerating length (see point 3). The merit of this solution lies primarily in the reduced requirements on the emittance of the linac beam (compared with colliding linacs), since it has to match in size the relatively large LEP beam. As there is no longer any symmetry between the two bunches, one might exploit this in order to optimize the machine parameters:

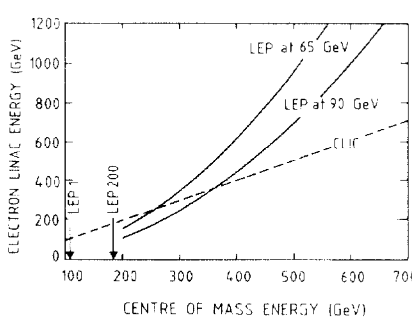

Fig. 15 Kinematics of a linac colliding against LEP (LLC). The centre-of-mass energy is plotted against the Linac energy for two different energies of the LEP beam.

i) Positrons are stored permanently in LEP and electrons are accelerated by the linac.
ii) Since the energy of the linac beam can hardly be recovered after collision, it is worth operating in the conditions in which a strong positron bunch is traversed by a weak electron beam disrupted by the crossing, after which the linac beam is dumped.
iii) In order to reach a high disruption parameter for the electrons, the emittance of the positron beam must be smaller than it normally is in LEP, where the beam-beam interactions are limited. This can be achieved with the help of synchrotron damping using a special lattice, as for the new dedicated synchrotron-light sources (achromatic bend), or with the standard FODO lattice increasing the tune, since the emittance goes as Q^{-3}. It is not obvious that the higher tune can be achieved with reasonable modifications of the existing LEP hardware, in which case the LLC and LEP operations will clearly be incompatible. An additional small-aperture, full-energy ring in the LEP tunnel may have to be considered so as to increase the flexibility of the scheme and to permit simultaneous operation of both facilities.

A possible, highly tentative, list of parameters is given in Table 4, in which the amount of beamstrahlung equals to 0.1 has been set as the input parameter. The linac must provide a high gradient, but at a conventional beam emittance with a modest bunch current. The bunch-crossing rate needed to reach the required luminosity is about 10 kHz. The linac repetition rate, however, should probably be smaller to ensure a better utilization of the RF power by the beam. A closely spaced bunch train can be accelerated at each pulse, with a matching bunch geometry in LEP. It is evident that all this is highly qualitative and that a serious optimization is required before reaching a conclusion on the feasibility of the scheme — which, however, looks quite promising to me.

Table 4
Tentative parameters of collisions of a beam in LEP and a high-energy Linac

Global parameters		
LEP ring energy (GeV)	65	90
Centre-of-mass energy (GeV)	400	500
Centre-of-mass energy (GeV)	615	694.4
Beamstrahlung	0.1	0.1
Luminosity ($cm^{-2}\ s^{-1}$)	1.21×10^{32}	1.48×10^{32}
LEP ring parameters		
Tune	170	220
Vertical β^* (cm)	2	2
Vertical beam size (μm)	1	0.94
Horizontal beam size (μm)	5	4.7
Bunch length (cm)	2	2
Synchrotron power (MW)	2.09	6.76
Linac parameters		
β^* at crossing (cm)	2	2
Electrons per bunch	5×10^9	6.2×10^9
Invariant emittance (μrad · m)	160	195
Collision rate (kHz)	11.7	11.7
Beam power (MW)	5.88	8.13

3) Two colliding linacs (mini-CLIC). Even if such an approach would most certainly be much more aleatory than the two other previously envisaged solutions, it would be of considerable importance as a Research and Development tool, and it would be the most natural follow-up of the pioneering work being performed at SLAC. Since a significant fraction of the device is energy-independent (for instance, the damping rings, the two-beam acceleration facility, etc.), it should be looked at, as far as possible, as an upgradable programme leading eventually to the full CLIC energy.

The 'Ultimate' e^+e^- Collider

Much of this Conference has been dedicated to the discussion of the CERN Linear Collider (CLIC), of the TeV Linear Collider (TLC), and of similar projects that are under consideration in various laboratories. It is therefore unnecessary to repeat these considerations here, except to stress the importance of continuing such studies for the future of high-energy physics. The highest-energy e^+e^- collider is an extremely important step following the exploratory role of the LHC and the SSC, and it is absolutely necessary for the accurate 'spectroscopy' of any new physics that may be discovered.

Conversely, some energy-scale indication from the LHC and the SSC is probably necessary before embarking on the full-scale realization of the multi-TeV e^+e^- linear collider.

Besides the very many machine-associated issues, we must not lose sight of the new conditions under which the experiment (probably only one at a time!) will have be carried out. The use of multi-megawatt beams, the very bad duty cycle associated with a relatively low crossing-rate, and the strong beam–beam interactions, may heavily pollute the environment around the crossing point and make the operation of sophisticated detectors very difficult. In other words, will the events recorded from the e^+e^- collisions of a linear collider be as clean as they have been 'advertised' to be? Is the halo from the 'spectator' electrons inside the very tiny bunch-crossings better or worse than the interactions of the 'spectator' partons in the LHC and the SSC?

Concluding Remarks

The spectroscopy of the ultimate constituents of matter is far from being complete, and new and more powerful colliders are needed. We believe that we have probably found most of the basic fermions (quarks and leptons) and the mediators of the three fundamental interactions (gluons, photons, W and Z). Although they are badly needed, fundamental scalars are still missing. In order to make further progress, we need to solve a multitude of formidable problems that go far beyond simply increasing the energy of the collisions. We have begun to realize that there are other parameters to master and that these have become at least as relevant as energy, namely:
- an adequate luminosity,
- a good detectability of events,
- financial constraints,
- world-wide planning of resources, politics, etc.

Despite all these difficulties, I believe that real progress lies ahead of us, as long as the many and remarkably ingenious new accelerator devices and ideas discussed at this conference are actively pursued.

APPENDIX

Luminosity Limitations for High-Energy Hadron Colliders

With the simplifying assumption of complete symmetry in the two transverse planes for the beams and lattice parameters of the crossing point, one can write the well-known formulae for the luminosity L and for the tune shift ΔQ_{bb}:

$$L = \frac{kN^2 f_0 \gamma}{\pi \epsilon^* \beta^*}, \qquad \Delta Q_{bb} = \frac{r_p N}{\pi \epsilon^*},$$

where N is the number of particles per bunch, k is the number of bunches, f_0 is the revolution frequency, ϵ^* is the invariant emittance, and β^* is the value of the betatron function at the crossing point. Usually the two formulae are combined, giving the relations:

$$L = \frac{\gamma}{r_p \beta^*} f_0(kN)\Delta Q_{bb}, \qquad \epsilon^* = \frac{r_p}{\pi}\frac{N}{\Delta Q_{bb}},$$

where the luminosity is universally related to the circulating current $I = ef_0(kN)$, and to the tune-shift ΔQ_{bb}, which in turns requires an emittance proportional to the number of particles per bunch.

For very high energy colliders, one has also to take into account the radiated synchrotron power P_{sync}:

$$P_{sync} = c_s \frac{\gamma^4}{\varrho} Nkf_0 .$$

Combining this and the luminosity formula, we find

$$L = \frac{1}{r_p c_s \beta^*} \Delta Q_{bb} \frac{\varrho P_{sync}}{\gamma^3},$$

i.e. the luminosity is proportional to the synchrotron power and the cube of the inverse of the energy (when comparing different machines there is another factor proportional to γ coming from ϱ, and therefore the effective dependence is rather proportional to the inverse of the square of the energy). Another relevant parameter is E_{beam}, the energy stored in the beam,

$$E_{beam} = e(kN)m_p \gamma ,$$

which, combined with the luminosity formula, gives

$$L = \frac{1}{r_p e m_p \beta^*} \Delta Q_{bb} f_0 E_{beam} .$$

This means that all other things being equal, the beam energy for a given luminosity grows with the circumference of the accelerator. These considerations have been applied by J. Gareyte (CERN) to the LHC and SSC cases and they are listed in Table A.1, calculated for $\beta^* = 0.3$ m.

One can see that the high-luminosity option for the LHC, with similar bunch spacings and low beta parameters, has a luminosity which is as much as 30-40 times larger for comparable amounts of stored energy and of radiated synchrotron power. It should be noted that both parameters are of critical importance. For instance, 600 MJ corresponds to the energy release of 150 kg of TNT that the designated *or accidental* point of the beam dump must withstand, and the synchrotron radiation is the thermal load at 4 K. Therefore the effective power load on the grid is several hundred times larger.

Table A.1
Comparison between several LHC options and the SSC design report

	LHC	LHC high luminosity			SSC
Beam energy (TeV)	8.0	8.0	8.0	8.0	20.0
Protons per bunch (10^{11})	0.26	0.30	0.64	1.00	0.073
Bunch spacing (ns)	25.0	15.0	15.0	15.0	16.0
Invariant transverse emittance (πmrad · mm)	5.0	7.0	11.0	15.0	4.0
Beam–beam tune shift (10^{-3})	2.5	2.2	2.9	3.4	0.8
Synchrotron power (kW)	4.0	7.0	14.0	21.0	18.2
Stored beam energy (MJ)	117.0	208.0	416.0	624.0	405.0
Luminosity ($cm^{-2} s^{-1}$)	1.4×10^{33}	8.2×10^{33}	2.4×10^{34}	4.0×10^{34}	1.0×10^{33}