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Summary and Look to the Future

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Summary and look to the future

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A brief review is given of (i) the initial performance and impact of LEP, and (ii) possible improvements in LEP's capabilities and research which may be carried out in the future. Following an overview of the experimental and theoretical shortcomings of the so-called Standard Model, the potential of future colliders that are under construction or consideration is summarized. Emphasis is placed on the potential of the Large Hadron Collider that may be built at CERN in the LEP tunnel, which would be a natural successor to LEP.

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1. Introduction

This paper is divided into three parts. I deal first, relatively briefly, with the performance and the impact of LEP up to now. Next, I consider the future of LEP. Finally, I review the outstanding problems of particle physics that are unlikely to be answered by LEP and the experimental means to address them that may be available in the future.

2. LEP up to now

As we have heard (Myers 1991), LEP has performed excellently in its first 18 months. The maximum luminosity has already reached half the design value: the missing 50% seems to be understood and, given that many of the parameters have exceeded their design values, it is likely that the design luminosity will be exceeded during the coming year. The machine has delivered an integrated luminosity of about 10 pb^{-1}, corresponding to about 200000 events (hadronic plus leptonic), to each of the four experiments, all of which are now essentially complete. In the last 24 hours of operation transverse polarization was observed, which has important implications for the future to which I will return in the next section.

It is convenient to summarize the impact of LEP by means of before/after snapshots of various topics.

Constituents

Before LEP, we knew that there were not more than four or five standard families of quarks and leptons. LEP has shown us that the number is three (Carter 1991; Stone 1991).

The strong force

Quantum chromodynamics was generally considered to be well-established pre-LEP, but its spectacular successes in describing LEP data has confirmed QCD beyond doubt and LEP, which has become the main testbed of our ability to understand QCD jets, has pinned down α_s (Venus 1991).

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The electroweak force

Pre-LEP we knew that the couplings of the W, Z and photon to fermions approximately satisfy the SU(2) × U(1) algebra: LEP has confirmed this to a new very high degree of precision (Carter 1991; Stone 1991). Pre-LEP we believed that the interactions of the vector bosons were described by a renormalizable gauge theory. The great consistency between this hypothesis and the LEP data, especially the fact that analyses (to which we return below) of different sets of data yield consistent allowed ranges for the mass (m_t) of the so far undiscovered top quark, provides the first quantitative test of the hypothesis of an underlying gauge theory.

The origin of mass/mechanism for hiding the gauge symmetry

The text book procedure for hiding the underlying gauge symmetry, and so giving mass to the W, Z, quarks and leptons, is to use the Higgs mechanism. Pre-LEP there were only very feeble limits on the mass of the associated Higgs boson, which excluded small mass ranges on the basis of questionable theoretical calculations. LEP has shown us (Green 1991) that $M_H > 50$ GeV, is beginning indirectly to put upper limits on M_H, and has produced severe problems for the alternative 'technicolour' scheme for hiding the symmetry (see below).

Non-standard particles

LEP has greatly extended the mass limits on many hypothetical particles (heavy leptons, supersymmetric quarks and leptons, etc.). All particles with couplings to the Z that are not very much less than electroweak in strength are now excluded for masses up to about 45 GeV (Green 1991). In particular, the data put strong constraints on particles that might form the dark matter which dominates the universe (Ellis 1991).

So far, LEP has not had a major impact on B physics but, as we have heard (Dornan 1991), the ALEPH measurement of the B lifetime is now competitive in accuracy with the world average of other experiments, and B^0–$\bar{B}^0$ mixing and the forward–backward asymmetry of b-quark jets have been measured. The asymmetry does not yet provide a really stringent test of the Standard Model but it will do so as the data accumulate. The polarization of τ leptons, which has now been observed by measuring the decay asymmetry, will also provide an additional stringent test in the future.

Returning to precision measurements, we recall that in Born approximation all 'electroweak observables' are determined by the fine-structure constant (α_{em}), the lifetime of the muon (τ_μ), and the mass of the Z boson (M_Z) (and also the Cabibbo–Kobayashi–Maskawa angles and phase in the case of flavour changing processes) according to the standard electroweak gauge theory, with higher-order corrections that depend on

$$\alpha_s,\ m_q,\ m \quad \text{and} \quad M_H.$$

There is a particularly strong dependence on m_t from the diagram in figure 1. The effect of the $t\bar{b}$ loop cannot simply be absorbed in a redefinition of the SU(2) coupling because it breaks weak isospin invariance, thereby generating a correction to the SU(2) coupling inferred from τ_μ which is proportional to $G_F(m_t^2 - m_b^2)$. The result is that predictions of the partial widths of the Z, and of all processes involving Z

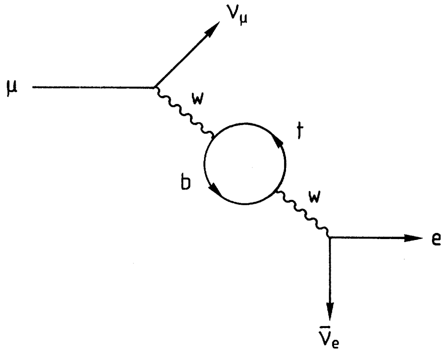

Figure 1. The diagram which introduces a dependence on m_t^2 in the value of the SU (2) coupling inferred from the muon lifetime.

exchange, involve higher-order corrections proportional to $G_F\, m_t^2$. There are additional contributions proportional to $\ln m_t$ and $\ln M_H$, the only other correction proportional to m_t^2 being in $\Gamma_{Z\to b\bar{b}}$ due to the $t\bar{t}$ intermediate state.

Data on the partial widths Γ_Z^i, M_W, deep inelastic neutrino scattering, ν–e scattering, and parity violation in inelastic electron and muon scattering (but not yet (?) in atoms) are now all accurate enough to be sensitive to second-order effects and each is consistent with the standard electroweak theory only for a limited range of values of m_t. The χ^2 for fitting certain combinations of these data for a range of assumed values of m_t is shown in figure 2, where VBM is the curve obtained by fitting M_W, HE (high energy) is given by a simultaneous fit to M_W and Γ_Z^i, ν–q is obtained from a fit to deep inelastic lepton scattering, LE is for a simultaneous fit to ν–q and all the other low-energy data, and ALL is a fit to all the data. In each case it was assumed that $M_H = M_Z$, but the fit is rather insensitive to M_H, the minimum for ALL moving from 122 GeV for $M_H = 40$ GeV, to 127 GeV for $M_H = M_z$, and 147 GeV for $M_H = 1$ TeV. Figure 1 is based on the data that were available in July 1990 but, although it would be interesting to see an update, the more accurate data now available cannot have changed the results very significantly (certainly the analyses presented at this meeting by Stone lead to very similar conclusions). The consistency between the results inferred from data for such different processes provides very strong support for the standard electroweak theory and also an increasingly sharp prediction for m_t.

For a given m_t the complete data-set is now only consistent with the Standard Model for a limited range of M_H at the 1σ level, as seen in figure 3 which shows the best fit and the 1σ contour in the m_t–M_H plane. It will be very interesting to see the effect on this figure of improved experimental accuracy, plus additional input, e.g. from measurements of τ-polarization.

In the framework of non-standard models it is necessary to re-do the analysis of the one loop corrections. In the case of the minimal supersymmetric model, for example, the radiative corrections mimic those of the Standard Model with a relatively light (less than 100 GeV) Higgs boson (Barbieri *et al.* 1990), and the value of m_t inferred from the data is shifted down by order 10 GeV (Ellis 1991). Likewise, in the case of a model with just one additional Z boson there is also consistency, but the upper limit on m_t is moved downwards (del Aguila *et al.* 1991). However, it would appear (Ellis 1991) that the data are *not* consistent with the technicolour mechanism for hiding the gauge symmetry. Actually there is no simple technicolour scheme

Figure 2

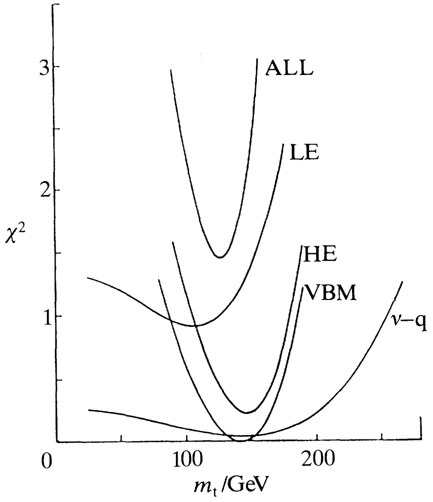

Figure 3

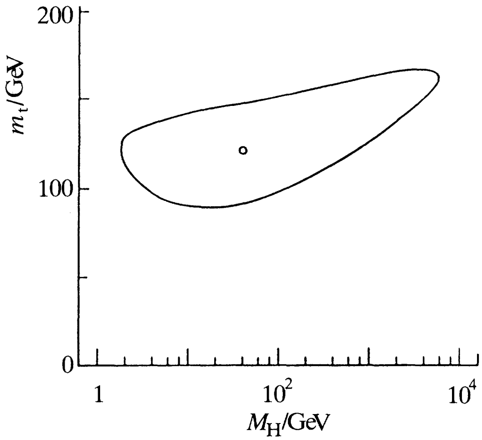

Figure 2. χ^2 as a function of m_t for fitting Standard Model predictions to the different data sets described in the text, assuming $M_H = M_Z$ (Ellis & Fogli 1990).

Figure 3. The 68% confidence level contour in the m_t–M_H plane for fitting the Standard Model predictions to all the data used in figure 2 (Ellis & Fogli 1990).

which successfully accounts for the fermion masses without running into phenomenological disasters, but nevertheless this result is an important one.

The very accurate LEP data also provide the last nail in the coffin of minimal non-supersymmetric grand unified theories, according to which (in a first approximation to the evolution equations) the SU(3), SU(2) and U(1) running gauge coupling constants are supposed to meet at a certain energy scale M_X, which they clearly do not (Ellis 1991). However, if the supersymmetric partners of the standard particles are included in the evolution equations, the couplings do appear to meet at $M_X \approx 10^{16}$ GeV (Ellis 1991).

3. LEP: the future

The capability of LEP will be extended in three ways (Myers 1991):

Energy. One hundred and ninety-two additional, superconducting, cavities have been ordered and are expected to be installed for the run in 1994. This will bring the energy up to (nominally) 2 × 90 GeV, the exact value depending on the performance of the cavities.

Luminosity. It is hoped that the integrated luminosity in 1991 will be three or four times that achieved in 1990 as a result of a planned change in the tune of the machine and other alterations which will build on the steady improvement during 1990. In 1992 the present four bunch per beam operation of the machine will be replaced by eight-bunch operation, using electrostatic separators from the $p\bar{p}$ collider to keep the beams apart at the extra interaction points: this should increase the luminosity by a factor of two. In principle additional separators would allow up to 36 bunches per beam, but this would require the installation of extra klystrons and in any case no more than eight bunches will be possible at 2 × 90 GeV.

Polarization. The transverse polarization that has been observed in single beam

Table 1. *Accuracy expected from each* LEP *experiment under various assumptions* (*Haissinski 1990*)

	now	4×10^6 Zs	25×10^6 Zs or 10^6 Zs + P = 0.5
$\delta \sin^2 \theta_W$	± 0.003	± 0.0007	± 0.0004
M_H fixed $\delta m_t\|_{m_t=150}$	± 90 GeV	± 20 GeV	± 12 GeV
m_t fixed $\delta M_H\|_{M_H=300}$	± 1400 GeV	± 320 GeV	± 180 GeV
$\delta m_t = \pm 10$ GeV $\delta M_H\|_{M_H=300}$	± 1400 GeV	± 350 GeV	± 240 GeV

operation will be used during the coming year to measure the beam energy, and hence M_Z, to ± 5 MeV. Furthermore, if polarization survives beam–beam interactions and the effects of the solenoids in the experiments, it will permit the study of the interactions of longitudinally polarized electrons and positrons, which provide especially sensitive tests of the electroweak theory, if/when money and time allow the installation of spin rotators.

There are therefore two new physics frontiers for LEP: high precision, through greatly increased integrated luminosity and/or longitudinal polarization, and increased energy. In September 1990 the LEP Committee made a detailed study of the possibilities (Haissinski 1990). They studied the physics that could be done with 4×10^6 Zs per experiment, which may be achieved before the energy upgrade in 1994, and either 25×10^6 Zs per experiment or 10^6 Zs per experiment with 50% longitudinal polarization, which might be achieved by the end of the century. The precision that could be achieved in measuring $\sin^2\theta_W$ or inferring m_t and M_H is shown in table 1.

The main topics that will be addressed when LEP is upgraded to 2×90 GeV are the following.

Accurate measurements of M_W. With an integrated luminosity of 500 pb^{-1} it should be possible to measure M_W to ± 100 MeV in each experiment, and ± 50 MeV for the four experiments taken together, by reconstructing the masses of the Ws produced in the reaction $e^+e^- \rightarrow W^+W^-$. For comparison, the present error from collider experiments is ± 350 MeV, and it may be that this will be reduced to ± 100 MeV by experiments at FNAL in the mid to late 1990s. A measurement of M_W to ± 50 MeV would constitute an indirect measurement of m_t to ± 10 GeV for m_t of order 150 GeV and given M_H, in the framework of the Standard Model.

Measurement of the three vector boson coupling. Study of W^+W^- production would be sensitive to deviations from the standard gauge theory couplings of order ± 10%.

Searches for the Higgs boson. By searching for the production of a Higgs boson in association with a Z it should be possible to search for this elusive particle up to $E_{cm} - M_Z - O(10 \text{ GeV})$. It has frequently been argued that this should be sufficient to substantiate or exclude the minimal supersymmetric Standard Model, which was thought to require at least one Higgs boson to be lighter than the Z but, as we have learned from Ellis at this meeting, this limit is not valid when higher-order corrections are taken into account. Nevertheless, an extension of the Higgs search up to 80 GeV or so will be very interesting.

New particle searches. Without the colossal amplification due to the Z resonance, particle searches will take much longer and will not be able so nearly to approach the kinematic limit as those reported at this meeting: nevertheless, experiments at the top energy of LEP will extend the mass limits on many particles up to somewhere around order 80 GeV.

4. Beyond LEP

Problems for the Standard Model

A good starting point for a discussion of physics beyond LEP is a summary of (i) open questions inside the framework of the Standard Model, (ii) experimental facts that cannot be explained by the model, and (iii) its theoretical shortcomings. The main challenges inside the Standard Model are the following.

1. To find the top quark, both because this will essentially fix the predictions of the standard model, and because we would like to check whether the top quark is 'standard'. It is sometimes argued that being so heavy, the top may be the odd quark out; however, while it could indeed be mixed with some heavier exotic quark, it is actually the top which appears to have a normal electroweak mass (of order M_W) while the others appear anomalous in having very small couplings to the Higgs field and hence small masses.
2. To find the Higgs boson, of which more anon.
3. To discover whether CP violation is entirely due to the phase in the Cabibbo–Kobayashi–Maskawa matrix, and understand why there is no strong CP violation although it is allowed in principle by QCD.

The following experimental observations cannot be explained by the Standard Model.

1. Evidence for a neutrino with a mass of 17 keV obtained by studying the Kurie plot for beta decay as first reported by Simpson. A recent high statistics study (Hime & Jelley 1991) of the decay of ^{35}S is consistent with a decay to a mixture of neutrino states

$$\nu_e = \nu_1 \cos\theta + \nu_2 \sin\theta$$

with $m_{\nu_1} < 9.6$ eV $\leqslant m_{\nu_2} = 17.2 \pm 0.5$ keV (Wilkerson 1991) and $\sin^2\theta = 0.0085 \pm 0.0006 \pm 0.0005$. If true, this is the first laboratory evidence for physics beyond the Standard Model. There are strong constraints on mixing of ν_μ with ν_e but all laboratory data are consistent with the hypothesis that the orthogonal state is

$$\nu_\tau = \nu_2 \cos\theta - \nu_1 \sin\theta.$$

However, Hime *et al.* (1991) have pointed out that a 17 keV neutrino would disastrously over-close the Universe unless it decays with a lifetime 10^{12} s or less, and they have constructed models in which this occurs (since the meeting Kolb & Turner (1991) have presented a wide range of cosmological and astrophysical constraints which are hard to reconcile with the existence of Simpson's neutrino and may require a much shorter lifetime). For example, in one model ν_2 decays to ν_1 plus a scalar (isoscalar) Majoron, but this model only works if there are also heavy neutral leptons N which would appear with a branching ratio 10^{-7} in $Z \rightarrow \nu N$, followed by $N \rightarrow \nu f\bar{f}$. It is premature in this review talk to dwell further on the models – the first thing is to establish (or discredit) the effect – but this discussion illustrates the rich physics which may lie beyond the Standard Model.

2. The unexpectedly low fluxes of neutrinos (for reviews see Bachall (1991) and

Table 2

spectrum of quarks and leptons?	unification? compositeness?	more? masses (m_ν), mixings? structure?
further unification of forces? gravity?	left × right theories? GUTS? strings?	new gauge bosons? new forces? rare decays?
how are symmetries hidden? origin of mass?	Higgs SUSY? technicolour?	Higgs boson(s)? SUSY particles? technicolour states?

Nakamura (1991)) that have been observed in the Homestake mine experiment, the Kamiokande experiment, and also, but not yet at a statistically significant level, in the SAGE experiment. The results are

$$\frac{\text{Homestake}}{\text{standard solar model}} = 0.027 \pm 0.04, \quad \frac{\text{Kamiokande}}{\text{standard solar model}} = 0.46 \pm 0.08,$$

which are not incompatible as the two experiments are sensitive to different parts of the spectrum. It should be realized, however, that in calculating these ratios it is assumed that the standard solar model is perfect, i.e. that all the errors come from the numerator. The solar model used here is that of Bachall *et al.* which gives a solar neutrino flux of 7.9 ± 0.9 SNUs. However, another model calculation (Turck-Chieze *et al.* 1990) gives 5.8 ± 1.3. The uncertainties in the calculation have recently been reviewed by Morrison (1991) who concludes that 5.3 with an error of at least ± 1.2 is a more reasonable value. If correct, this would reduce the deficit to a 2.5σ effect in the Homestake mine experiment and a 1σ effect in the Kamiokande experiment. I hope that the experts will soon reach agreement on the important question of the reliability of solar models.

3. The powerful evidence for dark matter in the Universe which cannot be accounted for by the Standard Model.

4. The fact that the baryon:photon ratio for the Universe as a whole is of order 10^{-10} compared with the value of order 10^{-20} which would be expected in the Standard Model unless very special boundary conditions are invoked.

Even if it were not for these possible failures to explain observations, it is generally agreed that the Standard Model is incomplete. It is simply too complex and arbitrary to be the whole story, which in any case must include a quantum theory of gravity. The way to a better model is through experiment guided by intelligent speculations about the issues that are not satisfactorily resolved by the Standard Model, which are the problem of the number of flavours, the question of complete unification of the forces, and the problem of the origin of mass. Some speculations about these issues and experiments that might address them are listed in table 2.

The problem of mass is likely to yield first to experimental attack because it is associated with a reasonably well-defined mass/energy scale which is almost within reach. If there is no Higgs boson, or if $M_H > 1$ TeV, the predictions of the Standard Model are probably theoretically inconsistent for energies greater than an energy (proportional to M_W/g where g is the SU(2) coupling) of about 1 TeV. Hence either M_H will be less than 1 TeV or new (non-standard) physics awaits discovery below 1 TeV. On the other hand, if the Higgs boson exists, there are strong arguments, reviewed below, for (hidden) supersymmetry with supersymmetric particles having masses below 1 TeV.

Exact electroweak gauge symmetry appears to require that $M_{\mathrm{W}} = M_{\mathrm{Z}} = M_{\gamma} = 0$, while experimentally M_{W} and M_{Z}, which are of order 100 GeV, are at least 26 orders of magnitude greater than M_{γ}, which is presumably zero. Given that their masses are non-zero, the W and Z must have three polarization states (standard quantum mechanics allows $J_{\mathrm{Z}} = \pm 1, 0$ in the rest frame) in contrast to the massless photon, which has only two polarization states. The question of how the W and Z got their masses can therefore be rephrased as – how did they get their third (longitudinal: L) polarization states?

These states must either be extra fundamental degrees of freedom, or composite (bound) states. In the textbook Standard Model they are supplied by introducing a Higgs doublet and the corresponding anti-doublet:

$$\begin{pmatrix} \mathrm{H}^{+} \\ \mathrm{H}^{0} \end{pmatrix}, \quad \begin{pmatrix} \bar{\mathrm{H}}^{0} \\ \mathrm{H}^{-} \end{pmatrix}.$$

$\mathrm{H}^{\pm}$ and a mixture of H^{0} and $\bar{\mathrm{H}}^{0}$ supply $\mathrm{W}_{\mathrm{L}}^{\pm}$ and Z_{L}, leaving a single neutral Higgs boson. While the Higgs mechanism supplies a working model, it is not necessarily correct and in fact leads to the difficulty that if the Standard Model is part of a grander scheme with a larger mass scale M_{X} (e.g. the grand unification scale, or, unavoidably if there is no smaller scale, the Planck mass), then M_{W} gets quantum corrections $\delta M_{\mathrm{W}}^{2}$ of order $g^{2} M_{\mathrm{X}}^{2}$. This destabilization of M_{W} can be avoided if the world is supersymmetric, in which case there must exist supersymmetric particles $\tilde{\mathrm{P}}$ (bosons or fermions) accompanying all particles P (fermions or bosons). Together X and $\tilde{\mathrm{X}}$ make a contribution of order $g^{2}(M_{\mathrm{X}}^{2} - M_{\tilde{\mathrm{X}}}^{2})$ to $\delta M_{\mathrm{W}}^{2}$ and M_{W} is stabilized in the sense that no 'fine tuning' of the bare mass will be needed to cancel $\delta M_{\mathrm{W}}^{2}$ provided $g^{2}(M_{\mathrm{X}}^{2} - M_{\tilde{\mathrm{X}}}^{2})$ is less than or of order M_{W}. The same argument suggests that the splitting between the known particles (leptons, quarks, vector bosons) and their supersymmetric partners must be less than or of order a few times M_{W}/g, say 1 TeV.

The alternative is that the longitudinal components of the W and Z are composites, presumably bound states $\mathrm{Q}\bar{\mathrm{Q}}$ of some heavy 'techniquarks' bound together by a superstrong 'technicolour' force. As noted above, the technicolour scheme is unable to account successfully for fermion masses (at least in an elegant manner) and seems to be ruled out by the high precision LEP data. Nevertheless, it is worth bearing in mind as the only known alternative to the Higgs scheme. There is a variant of the technicolour scheme (Nambu 1991 and references therein; Bardeen *et al.* 1990) in which $\mathrm{W}_{\mathrm{L}} \sim \mathrm{t}\bar{\mathrm{b}}$, $\mathrm{Z}_{\mathrm{L}} \sim \mathrm{t}\bar{\mathrm{t}}$ while there is a Higgs-like $\mathrm{t}\bar{\mathrm{t}}$ bound state. This model is certainly very economical (for this reason Nambu calls it the 'sub-standard model') but requires an unnatural fine tuning of parameters to keep M_{W} small compared to the scale of the superstrong binding force (which is of order 10^{15} GeV in this model). Interestingly the model predicts M_{H} to be approximately equal to $2M_{\mathrm{t}}$. A similar relation occurs in superconductors, where the phase of the order parameter produces a longitudinal degree of freedom for the photon (and hence the Meissner effect) and an excitation in the modulus, which is analogous to the Higgs boson, has actually been observed (Sooryakumar & Klein 1980; Littlewood & Carona 1982; Balseiro & Falicov 1980) at 2Δ where Δ is the gap energy.

Future colliders

Future colliders which will extend the experimental attack on the unknown physics beyond the Standard Model fall into two categories. The first comprises the so-called 'factories' that are designed to give the highest possible luminosity at relatively modest energy. The second comprises colliders designed to reach the highest achievable or affordable energy, at which the luminosity is then maximized, the goal being to explore constituent collisions above 1 TeV centre of mass energy where new phenomena seem almost guaranteed according to the arguments above.

In the first category, the so-called 'B factories' are most interesting. They are electron–positron colliders (with asymmetric energies so that Bs are produced with high velocity) that are designed to run on the $\Upsilon(4s)$ which decays to $B\bar{B}$. The aim is to produce enough Bs to observe CP violation and hence cast light on its origin. It should be possible to observe CP violation with a luminosity of order $10^{33}\ \text{cm}^{-2}\ \text{s}^{-1}$ but a definitive experiment would require a luminosity greater than or of order $10^{34}\ \text{cm}^{-2}\ \text{s}^{-1}$. Construction of such a machine is a difficult, and expensive, task but should be possible following some R&D and it appears likely that at least one B factory will be built sooner or later. This factory would also produce plenty of charmed particles and taus, which could also be studied (much less expensively and more cleanly) at a charm-tau factory, which may be proposed in Seville.

There are clearly three possibilities on the high-energy frontier, namely to collide (i) leptons with leptons; in practice electrons with positrons, (ii) leptons with quarks and gluons; in practice electrons with protons, (iii) quarks and gluons with quarks and gluons; in practice protons (or heavier nuclei) with (anti-) protons (or nuclei).

The first approach is temporarily stalled. Circular electron–positron colliders require straight accelerating sections with a length proportional to the energy loss per turn in the curved sections, which is proportional to E^4/ρ where ρ is the bending radius. The capital cost therefore involves a term proportional to E^4/ρ as well as a term proportional to ρ and the total, when minimized with respect to ρ, grows like E^2. The result is that linear colliders become more economical for centre of mass energies of order 300 GeV or more. The problem then is to produce a high enough repetition rate and small enough beams to give sufficient luminosity to do interesting physics. To produce 10000 events per year for a process with a 'point-like' cross section $4\pi\alpha^2/E^2_{\text{cm}}$ a luminosity of $10^{34}[E(\text{TeV})]^2$ is required (for comparison, LEP has a design luminosity of 2.5×10^{31} at $E\approx0.2$ TeV). To appreciate the difficulty note that the Stanford Linear Collider, which is the only linear collider built so far, has achieved $10^{28}\ \text{cm}^{-2}\ \text{s}^{-1}$ at $E\approx0.1$ TeV: while construction of a 1 TeV collider 'only' requires an order of magnitude increase in energy, an increase in luminosity of six orders of magnitude would be required to produce 10000 events per year (and three orders even to produce a miserly 100 per year).

Experts believe that it should be possible to make a serious proposal to build a linear collider with a centre of mass energy of order 500 GeV in a few years time and that this is probably a necessary preliminary step to building a collider that reaches the desired TeV region, which will be a formidable technological challenge (the parameters of a collider with an energy of order 10 TeV seem to be in the realm of science fiction at present). Discussions of a possible 'intermediate' (500 GeV) collider are under way in Japan, Europe and the U.S.A. It could reveal very exciting physics (Higgs, supersymmetry, etc.), but the energy is not high enough to be confident of this and I would therefore very much hope that any such machine would be built

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Table 3. *Some existing and proposed high energy colliders (from Kalmus 1990)*

	LHC	'other' machine parameters	SSC parameters
pp		TEVATRON	
$\sqrt{s}$/TeV	15.4	1.8	40
$\mathscr{L}/(\mathrm{cm}^2\ \mathrm{s}^{-1})$	$(1.7\text{–}5)^{a} \times 10^{34}$	5×10^{31}	$10^{33} \rightarrow 10^{34\,b}$
ep		HERA	
$\sqrt{s}$/TeV	1.7–1.3	0.3	—
$\mathscr{L}/(\mathrm{cm}^{-2}\ \mathrm{s}^{-1})$	up to 2×10^{32}	1.5×10^{31}	
PbPb		RHIC	
$\sqrt{s}$/(TeV/nucleon pair)	6.3	0.15	—
$\mathscr{L}/(\mathrm{cm}^{-2}\ \mathrm{s}^{-1})$	1.8×10^{27}	5×10^{26}	

[a] $1.7 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ is for each of three interaction regions while $5 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ is if collisions occur only in one intersection region.

[b] The initial design luminosity at SSC is $10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, but there are plans to upgrade this later to $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

with an eye to extending it and upgrading the energy at a later stage, which would make it a very exciting prospect.

The situation with respect to future ep and pp colliders is summarized in table 3. I now outline the potential of the ep collider HERA (Hadron Elektron Ringe Anlage), which will begin operation later this year, and the pp collider LHC (Large Hadron Collider), which is not yet approved but could in principle start operation before the end of the century.

Physics at HERA

HERA will generate collisions of (longitudinally polarized) electrons and positrons with protons in an unexplored kinematic region, as shown in the figure 4. The 45000[800] ep → eX events with $Q^2 > 10^3[10^4]\ \mathrm{GeV}^2$ and 11000 ep → νX events (900 with $Q^2 > 10^4\ \mathrm{GeV}^2$) that are expected to be obtained in two years' running will probe the structure of the proton at an unprecedentedly small scale allowing (see Peccei 1987) stringent tests of QCD, detailed exploration of the gluon structure function, measurements of structure functions at very low Bjorken x (down to 5×10^{-5} with $Q^2 > 5\ \mathrm{GeV}^2$), where there are very interesting open theoretical questions, a search for possible substructure of quarks and gluons, and for possible contact interactions between electrons and quarks or gluons up to a cut-off parameter Λ of order 7 TeV.

The cross sections for ep → eX and ep → νX will be sensitive to the exchange of new heavy vector bosons with masses up to about 500 GeV. As far as new particle production is concerned, HERA could produce supersymmetric electrons and quarks provided $m_{\tilde{e}} + m_{\tilde{q}}$ is not more than 180 GeV which unfortunately is not far above the existing limits. Excited electrons (a very long shot in my opinion) can be sought for masses up to 200 GeV. More likely, HERA could make the really sensational discovery of 'leptoquarks', which exist in supersymmetric models in which 'R parity' is not imposed: they could be produced directly by the fusion of the incoming electron with a quark in the proton for masses up to about 300 GeV.

Figure 4

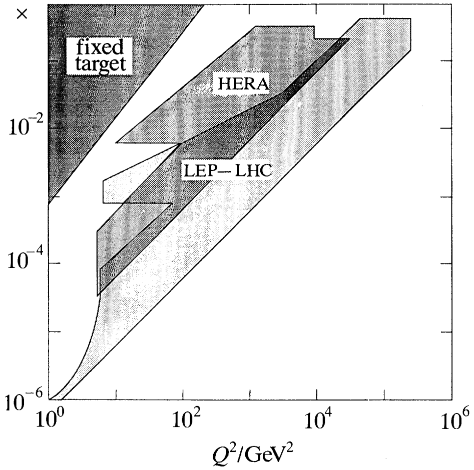


Figure 5

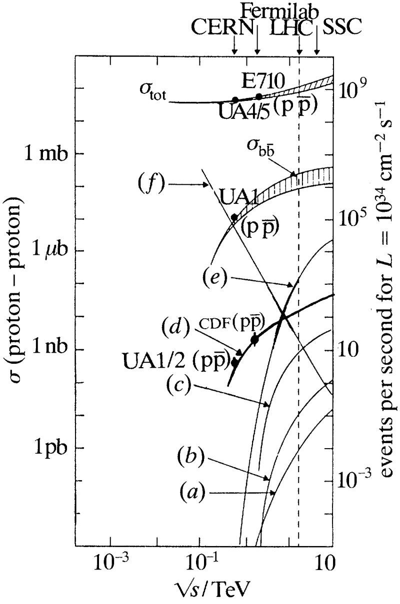


Figure 4. The domain accessible with statistical and systematic errors below 10% in measurements of neutral current events at HERA (30 GeV × 830 GeV with an integrated luminosity of 100 pb^{-1}) and LEP/LHC (50 GeV × 8 TeV with an integrated luminosity of 1000 pb^{-1}): the corresponding domain that has been explored in fixed-target experiments is also shown (Feltesse 1990).

Figure 5. Energy dependence of some characteristic cross sections, from present colliders to the LHC and SSC (Denegri 1990). (*a*) σ_{Higgs}, $m_{\text{H}} = 500$ GeV; (*b*) σ_{Z}, $m_{\text{Z}} = 1$ TeV; (*c*) $\sigma_{t\bar{t}}$, $m_{\text{top}} = 200$ GeV; (*d*) σ ($\text{W} \rightarrow \text{l}\nu$; (*e*) σ_{jet}, $E_{\text{T}}^{\text{jet}} > 0.25$ TeV; (*f*) σ_{jet}, $E_{\text{T}}^{\text{jet}} > 0.03 \sqrt{s}$.

Physics at LHC

Some pp cross sections in the region up to 100 TeV centre of mass energy are shown in figure 5. This figure shows the by now well-known fact that as far as rate is concerned, higher luminosity can compensate for the lower energy of the LHC relative to the SSC. This is of course by no means the whole story given the difficulty of doing experiments at very high luminosity, and the fact that backgrounds and signals do not vary with energy in the same way. However, the physics potentials of the SSC and LHC (in pp mode) are sufficiently similar that it makes no sense to discuss them separately in a talk such as this, and I have chosen for definiteness – and because this is a meeting on LEP, and the LHC is a natural successor to LEP – to give numbers for the LHC.

Topics which the LHC in pp collider mode might explore, starting with the standard and moving to the more exotic, include (see Jarlskog & Rein 1990) the following.

The top quark. If not already found, the LHC will be able to discover the top quark provided the mass is less than 600 GeV (anything this heavy or heavier would be a very severe embarrassment for the standard model) and measure the mass to ±5 GeV for m_{t} of order 150 GeV.

B *physics.* As shown in table 4, the LHC and SSC will produce enormous numbers of B quarks and *if* triggering and tagging proves possible, which has yet to be demonstrated, could turn out to be the desired B factories that may unravel the origin of CP violation.

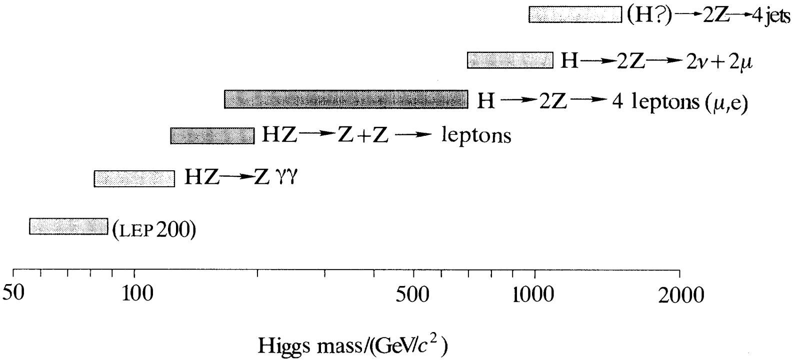


Figure 6. The primary Higgs signatures at the LHC (Rubbia 1990).

Table 4. *Statistics and backgrounds for* B *studies at several accelerators* (*Rubbia 1990*)

	mode	intensity / luminosity	$\langle n_c \rangle$	$s(b\bar{b})/s_T$	$N(b\bar{b})/(10^7\ s)$
LHC	jet gas target	10^8 p s^{-1}	~ 17	~ 1/25 K	$\sim 9.6 \times 10^9$
SSC			~ 20	~ 1/8000	$(1–5) \times 10^{10}$
LHC	pp collider	10^{32}	~ 80	~ 1/550	$\sim 2 \times 10^{11}$
SSC			~ 115	~ 1/200	$\sim 5 \times 10^{11}$
CESR	e^+e^- collider	10^{34}	~ 12	~ 1/4	1.2×10^8
SLAC		10^{33}	~ 12	~ 1/4	3.6×10^7

QCD jets. The LHC will produce large numbers of jets with transverse energies in the multi-TeV region and will be sensitive to contact interactions between quarks and gluons with cut-off parameters Λ up to about 13 TeV.

Higgs. The Higgs boson can be sought through the modes shown in figure 6. Discovery is considered 'easy' in the range 180–800 GeV, and hard but possible for 80–180 GeV and 800 GeV–1 TeV. Thus LEP and LHC will together cover the full range in which it is thought that the mass of a standard Higgs boson must lie, and the search (which looks for the Higgs boson as a resonance in the scattering of longitudinal Ws and Zs) will explore WW/ZZ scattering up to about 1 TeV, which some other new phenomena must reveal if there is no conventional Higgs boson.

The triple gauge vertex. The production of transverse W pairs will allow measurements of the triple gauge vertex with almost an order of magnitude greater precision than at LEP.

$W_L\ Z_L$ *scattering.* If there are resonances in the scattering of longitudinal gauge bosons, as must be the case for example in technicolour models or presumably any other model in which there is no conventional Higgs boson, and if these resonances have widths that are much smaller than their masses, they could be seen up to about 2.5 TeV.

Heavy vector bosons. Heavy Ws could be produced and discovered up to about 4 or 5 TeV and heavy Zs up to 3 or 4 TeV at the LHC.

Supersymmetry. Gluinos and squarks with masses up to about 1 TeV would be discovered at the LHC.

Electron–proton collisions can be studied at the LHC by colliding one of the beams with LEP, and as indicated in table 3 and figure 4, this would open up an enormous

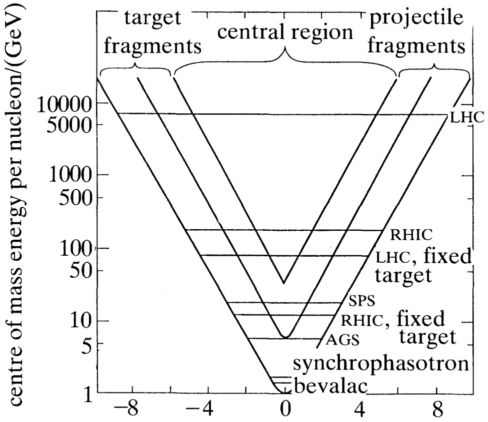


Figure 7. The rapidity domain covered by several heavy ion machines as a function of the centre of mass energy per nucleon in nucleus–nucleus collisions with $A \approx 200$ (Rubbia 1990).

kinematical range beyond that which will be explored at HERA. LHC will be able to store beams of lead ions and, as indicated in table 3 and figure 7, will open up an enormous range beyond that which will be explored at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven, the goal being to discover and explore the quark-gluon plasma phase of QCD. The existence of the ep and heavy ion options make LHC really excellent value for money.

5. Conclusions

LEP has been an outstanding success, the machine and experiments having come into operation more quickly and successfully than we had any right to expect. It has already provided severe tests of the Standard Model and put stringent constraints on alternatives. In my opinion the most important results are the very accurate measurement of the number of neutrino species and the very high consistency that is obtained when the different precision measurements are analysed in the framework of the Standard Model, which serves to establish the existence of an underlying gauge theory. The fact that so far nothing really new has been discovered is a disappointment but (i) higher statistics and energy may still lead to surprises, and (ii) it is not in itself a mystery. Personally, I expect new physics to show up at energies/mass scales of order M_W, so the failure to see anything new up to now is not a deep surprise, although I will be very surprised if something new does not show up in the range up to a few times M_W.

HERA and LEP when upgraded to full energy will provide further steps which may open up new horizons, but these steps will not go very far beyond the range that has already been explored at the Tevatron, the CERN Collider and LEP and I cannot imagine that they will fully resolve the problem of mass/symmetry breaking. This will require studying the collisions of constituents at centre of mass energies of order 1 TeV which will first be possible at the SSC and LHC. The LHC will be a natural successor to LEP both in terms of physics and because it uses much of the same infrastructure (and has therefore been foreseen since the infancy of LEP). Let us hope that the future to which I have looked in this paper will include the LHC and that a decade from now we can reassemble for a Discussion Meeting on results from LHC.

References

Bachall, J. N. 1991 *Proc. Neutrino 90, CERN.* (In the press.)

Balseiro, C. A. & Falicov, L. M. 1980 *Phys. Rev. Lett.* **45**, 662.

Barbieri, R., Figeni, M., Giuliani, F. & Haber, H. E. 1990 *Nucl. Phys.* B **341**, 309.

Bardeen, W., Hill, C. & Lindner, M. 1990 *Phys. Rev.* D **41**, 1647.

Carter, J. R. 1991 *Phil. Trans. R. Soc. Lond.* A **336**, 261. (This volume.)

del Aguila, F., Moreno, F. M. & Quiros, M. 1991 *Phys. Lett.* B **254**, 497.

Denegri, D. 1990 Large Hadron-Collider workshop, vol. I, p. 56, CERN 90-10, ECFA 90-133 (ed. G. Jarlskog & D. Rein).

Dornan, P. 1991 *Phil. Trans. R. Soc. Lond.* A **336**, 201. (This volume.)

Ellis, J. 1991 *Phil. Trans. R. Soc. Lond.* A **336**, 247. (This volume.)

Ellis, J. & Fogli, G. L. 1900 CERN-TH/5817/90.

Feltesse, J. 1990 Large Hadron Collider workshop, vol. I, p. 219, CERN 90-10, ECFA 90-133 (ed. G. Jarlskog & D. Rein).

Haissinski, J. 1990 Presentation to the CERN Scientific Policy Committee, October 1990.

Hime, A. & Jelley, N. A. 1991 *Phys. Lett.* B **257**, 441.

Hime, A., Phillips, R. J. N., Ross, G. G. & Sarkar, S. 1991 Phys. Lett. B **260**, 381.

Jarlskog, G. & Rein, D. 1990 Large Hadron Collider workshop, CERN 90-10, ECFA 90-133.

Kalmus, G. 1990 Large Hadron Collider workshop, vol. I, p. 581, CERN 90-10, ECFA 90-133 (ed. G. Jarlskog & D. Rein).

Kolb, E. W. & Turner, M. S. 1991 Fermilab-Pub-91/50A.

Littlewood, P. M. & Varma, C. M. 1981 *Phys. Rev. Lett.* **47**, 811.

Littlewood, P. M. & Varma, C. M. 1982 *Phys. Rev.* B **26**, 4883.

Morrison, D. R. O. 1991 *Proc. 25th Conf. on High Energy Physics.* (In the press.)

Myers, S. 1991 *Phil. Trans. R. Soc. Lond.* A **336**, 191. (This volume.)

Nakamura, N. 1990 *Proc. 25th Int. Conf. on High Energy Physics.* (In the press.)

Nambu, Y. 1991 *The Dalitz Conference* (ed. I. J. R. Aitchison, C. H. Llewellyn Smith & J. E. Paton). (In the press.)

Peccei, R. D. (ed.) 1987 *Proc. HERA Workshop*, DESY.

Rubbia, C. 1990 Large Hadron Collider workshop, vol. I, p. 9, CERN 90-10, ECFA 90-133 (ed. G. Jarlskog & D. Rein).

Simpson, J. J. 1985 *Phys. Rev. Lett.* **54**, 1891.

Sooryakumar, R. & Klein, V. 1980 *Phys. Rev. Lett.* **45**, 660.

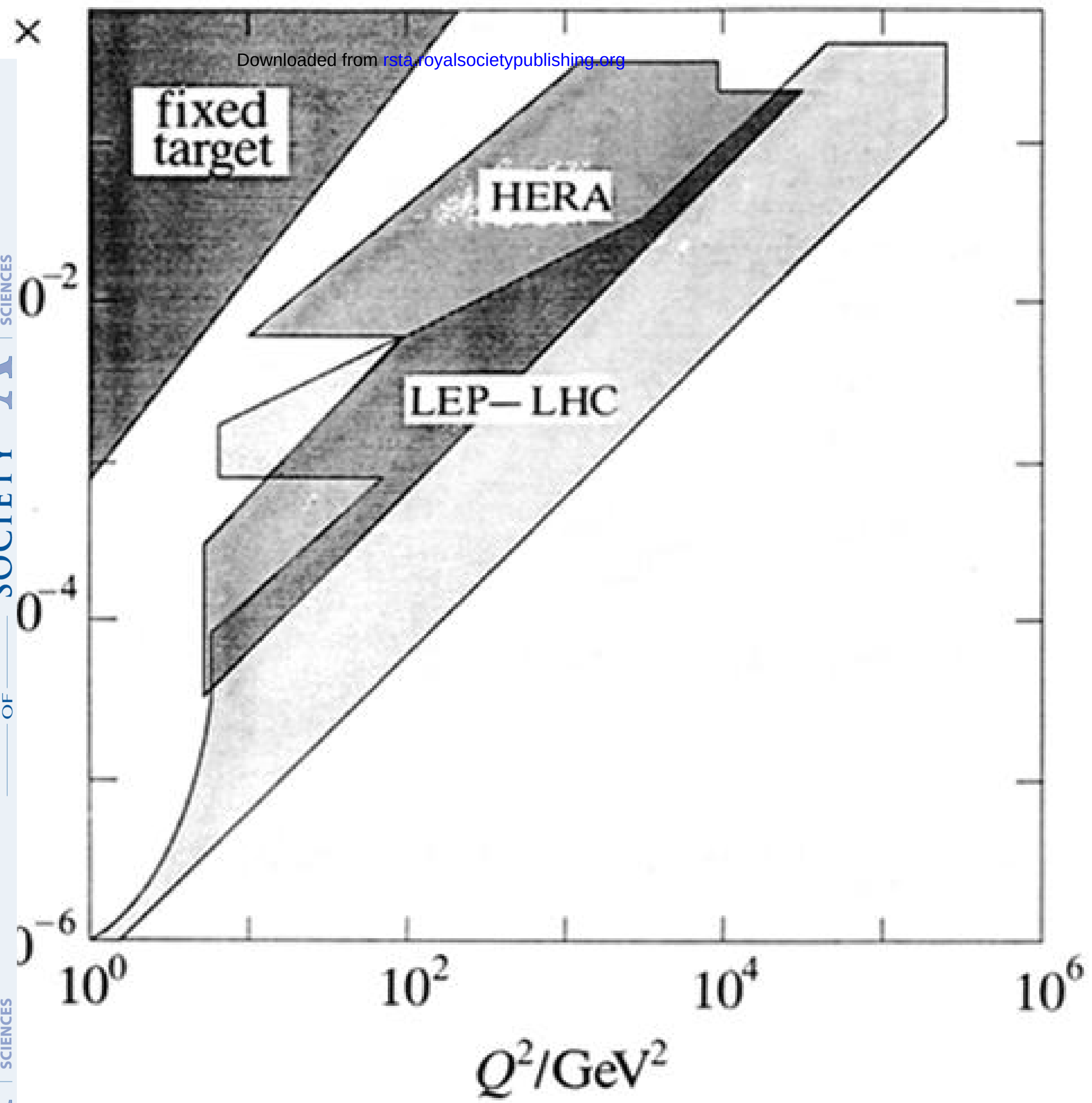
Stone, H. 1991 *Phil. Trans. R. Soc. Lond.* A **336**, 271. (This volume.)

Turck-Chieze, S., *et al.* 1988 *Astrophys. J.* **335**, 415.

Venus, W. 1991 *Phil. Trans. R. Soc. Lond.* A **336**, 295. (This volume.)

Wilkerson, J. F. 1991 *Proc. Neutrino* 90, *CERN.* (In the press.)

Figure 4



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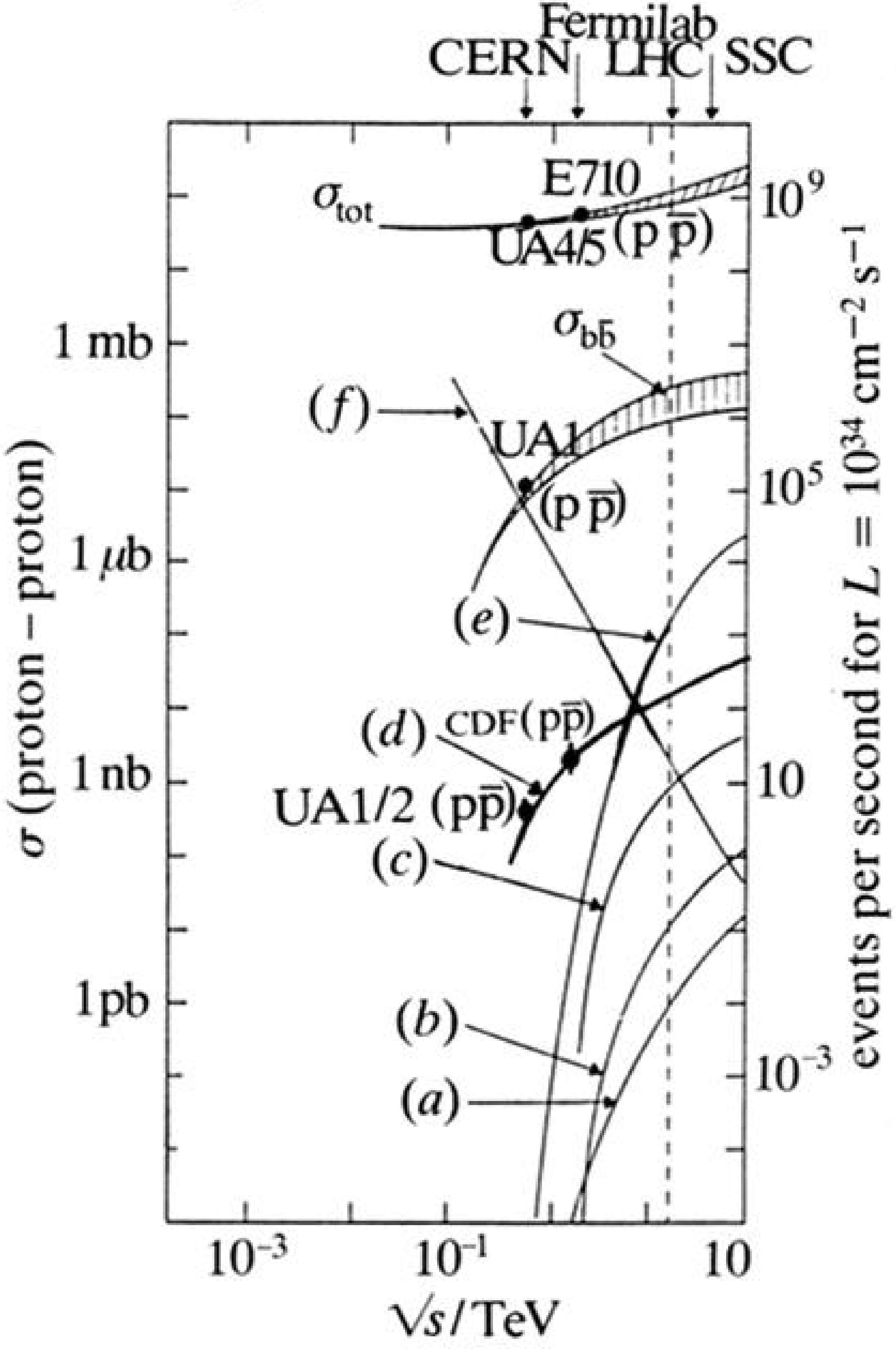

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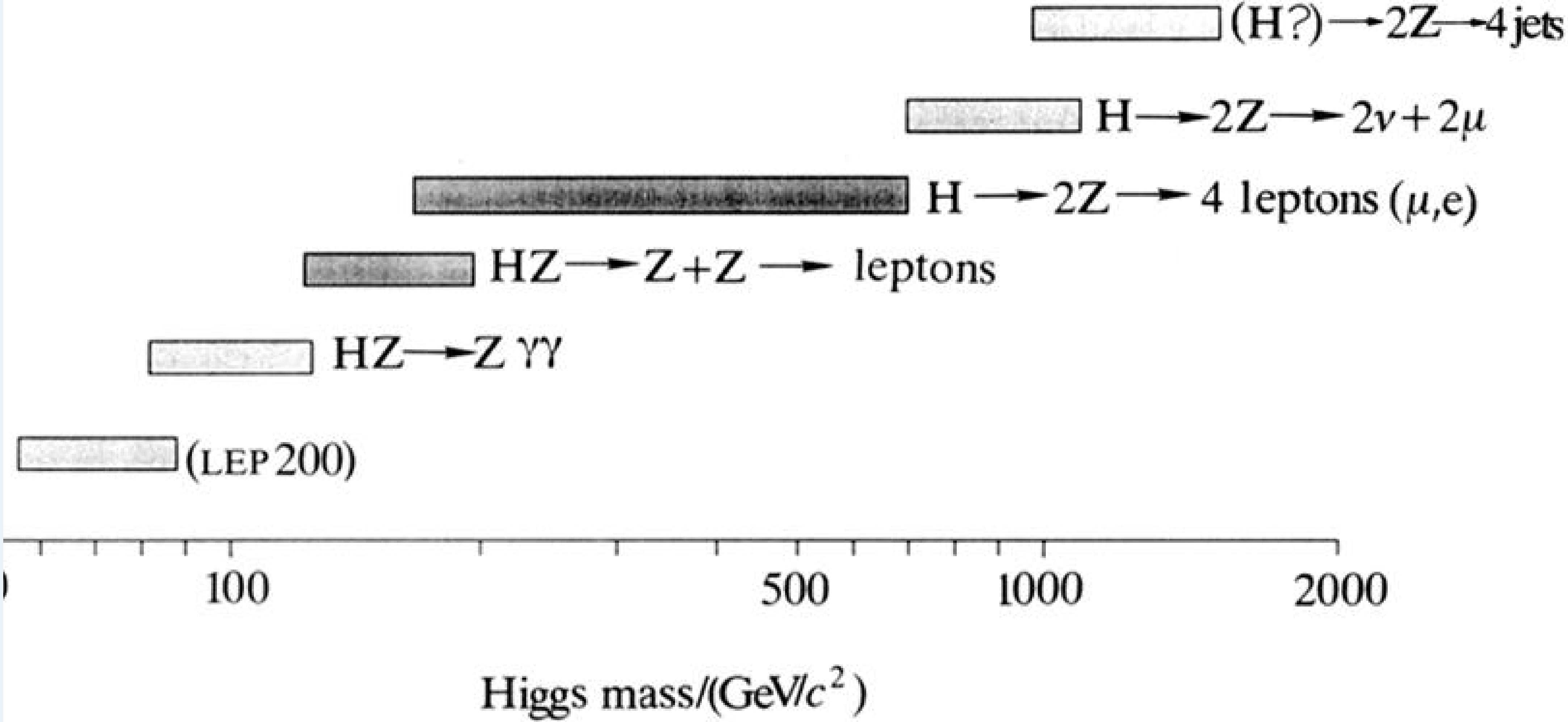

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