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PHYSICS POSSIBILITIES OF LEPTON AND HADRON COLLIDERS

by

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Physics Possibilities of Lepton and Hadron Colliders

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ABSTRACT

After a brief introduction to lepton and hadron colliders presently being planned, I give some examples of the nice standard physics which is expected to be seen in them. The bulk of the discussion, however, is centered on signals for new physics. Higgs searches at the new colliders are discussed, as well as signatures and prospects for detecting effects of supersymmetry, compositeness and dynamical symmetry breakdown.

Invited talk at the 5th Topical Workshop on Proton-Antiproton Collider Physics, Saint Vincent, Italy 25 February - 1 March 1985, to appear in the Workshop Proceedings

1. LEPTON AND HADRON COLLIDERS (planned and dreamed)

Within the next five years five colliders, presently under construction, will be producing new physics. In addition, the Sp$\bar{p}$S collider will be upgraded by the construction of the ACOL collector. These six colliders include three e^+e^- machines (TRISTAN, SLC, LEP), two proton-antiproton machines (Sp$\bar{p}$S, Tevatron) and an ep collider (HERA). Some of their principal characteristics are summarized in Table I

Table I: New Colliders and their properties

Collider	Location	Type	Expected operation date	Maximum CM Energy (GeV)	Maximum Luminosity ($cm^{-2}sec^{-1}$)
TRISTAN	KEK	e^+e^-	1986	60	2×10^{31}
SLC	SLAC	e^+e^-	1987	100	6×10^{30}
LEP(phase I)	CERN	e^+e^-	1989	120	1.6×10^{31}
Sp$\bar{p}$S + ACOL	CERN	$p\bar{p}$	1987	630	$2\text{-}3\times10^{30}$
Tevatron	FNAL	$p\bar{p}$	1986	2000	$\gtrsim 10^{30}$
HERA	DESY	ep	1990	314	3×10^{31}

Beside these accelerators, a number of future projects are under active study around the world. At CERN there will be a decision in the coming year on funding for the planned second phase of LEP. By installing superconducting cavities in the LEP tunnel, in phase II it will be possible to reach e^+e^- CM energies of around 200 GeV, at a luminosity in excess of 5×10^{31} $cm^{-2}sec^{-1}$. There is also continuing discussion about the possibility in the future of using the LEP tunnel to install a large hadron collider (LHC). Both a proton-proton and a proton-antiproton option for the LHC have been studied [2], with CM energy in the range of 10-20 TeV and luminosities of 10^{33} $cm^{-2}sec^{-1}$ and 10^{32} $cm^{-2}sec^{-1}$, respectively. The physics possibilities of a possible ep option for the LHC, with $E_{CM} \sim$ 1-2 TeV and a luminosity of 10^{32} cm^{-2}sec^{-1}, have also been examined [3].

In the United States an ambitious effort is underway to construct a multi TeV hadron collider, the Superconducting Super Collider (SSC) [4]. Although a proton-antiproton option for the SSC has been studied [5], the present effort is directed at a proton-proton machine with E_{CM} = 40 TeV, at a luminosity of 10^{33} cm^{-2}sec^{-1}. Such a machine could have a "second generation" ep option with $E_{CM} \sim$ 1.5 - 3.3 TeV [7]. Studies have also been made of the fixed target possibilities for the SSC [8]. The physics that can be explored by the SSC has been reviewed in impressive detail by Eichten, Hinchliffe, Lane and Quigg [9], referred in what follows as EHLQ.

In the Soviet Union at the moment plans seem to center on trying to construct high energy e^+e^- linear colliders ($E_{CM} \sim$ 100-500 GeV) at Novosibirsk [10], which will require developing accelerating cavities capable of accelerating electrons 100 MeV/m . Using accelerating fields of this order of magnitude, B. Richter [11] discussed some years ago the possibility of building large e^+e^- linear colliders with $E_{CM} \sim$ 1-2 TeV, at luminosities of the order of 10^{33} cm^{-2}sec^{-1}. The physics case for such colliders was examined by J. Ellis [12] two years ago, but since then there has not been much activity on these ideas in the West.

In what follows I want to discuss the physics possibilities of the machines soon to exist, as well as those proposed for a more distant future. I want to distinguish between expected physics - physics predicted by the standard SU(3) x SU(2) x U(1) Model - and speculative physics - which is physics beyond the standard model. It is important to remark that "expected" physics can be very interesting. I shall illustrate this contention by discussing

five different examples of nice "expected" physics which should emerge from future machines.

2. FIVE EXAMPLES OF NICE EXPECTED PHYSICS

As a first example, I will consider "standard" physics which will be done at HERA. The HERA ep collider will explore neutral current processes ($ep \to eX$) and charged current processes ($ep \to \nu_e X$) in a new momentum transfer regime. The presently explored q^2-range goes up to 150-250 GeV^2. At HERA q^2 of the order of $(2\text{-}4)\times10^4$ GeV^2 can be reached. This, two order of magnitude, increase in the q^2-range will allow tests of QCD in regions where non leading (higher twist) effects are truly negligible. QCD scaling violations have a typical $(\ln q^2)^{d_n}$ behaviour. Higher twist effects fall off with inverse powers of q^2. Since for $q^2 \sim 100$ GeV^2 these higher twist effects are, in the worst case, of the same order as the leading QCD terms, it is clear that at HERA these, presently uncontrolled, corrections can be totally ignored.

The worry that the scaling violations predicted by QCD cannot be measured at HERA, since these effects become smaller as $\alpha_s(q^2)$ becomes smaller, is actually unfounded. It turns out that the large q^2 range at HERA will in fact give a very useful lever arm. This is illustrated in Fig. 1, taken from Ref. 13, which gives the expected statistical errors on $F_2(x,q^2)$ for a run of 100 days at a luminosity of 3×10^{31} cm^{-2}sec^{-1}. It is apparent from the Figure that the q^2 dependence expected from QCD is clearly visible experimentally. Thus, there is no doubt that at HERA one should be able to check whether structure functions really run as predicted by QCD. Furthermore, HERA will also provide direct measurements of structure functions at q^2 values relevant for W/Z production at hadronic colliders, allowing a cross check of the evolution equations.

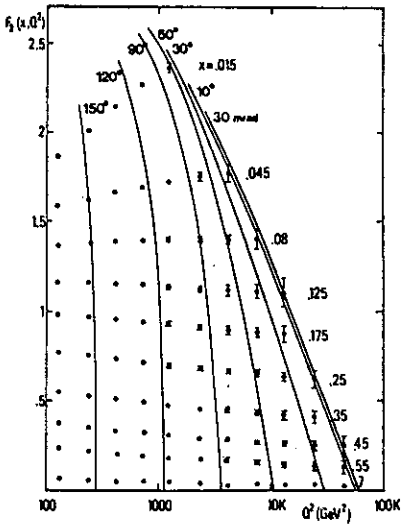

Fig. 1: Statistical errors on $F_2(x,q^2)$ for neutral currents in a run of 100 days at HERA, from Ref. 13

My second "standard" physics example concerns physics to be done at SLC and LEP (phase I). There a direct measurement of the Z^0 width, to within 100 MeV, should be feasible. Since each additional neutrino species in the standard model adds 170 MeV to the Z^0 width, such a measurement can provide a direct check on the number of generations. This test assumes that the mass of the t-quark is known. If only $m_t \gtrsim 30$ GeV were to be known *, then this uncertainty provides an additional theoretical error of 200 MeV.

The number of neutrino species can, however, be determined in an alternative way by studying the process $e^+e^- \to \gamma Z^0$ followed by $Z^0 \to \nu\bar{\nu}$, above the Z^0 peak in LEP. The background, to the

* unlikely to be the case in 1989, since $Z^0 \to t\bar{t}$ has a clean signal.

process $e^+e^- \to \gamma$ nothing, comes from radiative Bhabha scattering, in which the two leptons escape detection. This background can be tamed by requiring that the detected photon emerges at large angles. In Fig. 2, I show the expectation at E_{CM} = 105 GeV for the process $e^+e^- \to \gamma$ nothing, for the case of 3 neutrino generations, for photons in the energy interval $11.5 < E_\gamma < 16.5$ GeV, produced at an angle $\theta_\gamma > 20^o$. Also plotted in the figure is the cross section for radiative Bhabha scattering, as a function of a minimum angle cut on the charged leptons. The background appears manageable, and a 10 day run at LEP should be able to establish at the 3σ level that there are only three, and not more, generations of neutrinos [14].

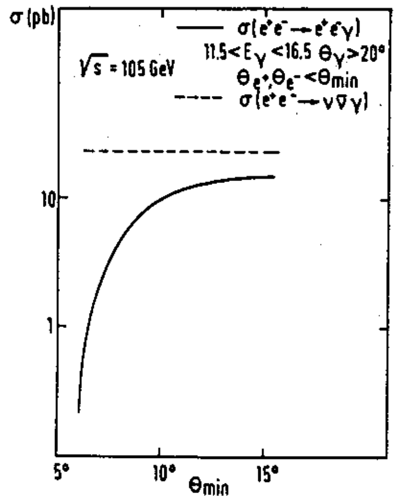

Fig. 2: Cross section and background for the process $e^+e^- \to \gamma$ nothing for three neutrino generations (Courtesy of the ALEPH collaboration)

My third example concerns physics which can be done at the $p\bar{p}$ colliders (Sp$\bar{p}$S, Tevatron). Heavy flavor production at these hadronic colliders is large. For instance, it has been estimated that over 10^5 $b\bar{b}$ pairs were produced already in the Sp$\bar{p}$S collider at $\sqrt{s} \approx 540$ GeV [15]. By looking at final states with dileptons one can hope to extract a signal for B-$\bar{B}$ mixing. The ratio

$$R = \frac{N(e^+e^+) + N(e^-e^-)}{2N(e^+e^-)} \tag{2.1}$$

arising from b-decays, vanishes in the absence of mixing. In the standard model one expects that mixing in the B_d^0-$\bar{B}_d^0$ system is suppressed by mixing angles. However, B_s^0-$\bar{B}_s^0$ mixing can be large since $\Delta M/\Gamma$ contains no small mixing angles. Hence the ratio R can be sizable, of the order of 20 % as estimated by Ali and Jarlskog [15].

A study of dilepton production in the $p\bar{p}$ colliders can then provide information on B-$\bar{B}$ mixing. As A. Ali has emphasized at this meeting [16], the same sign dilepton signal reported by the UA1 collaboration [17] can already be taken as an indication of mixing. The only counter indication is that the events appear to lack enough hadronic background. More data probably should resolve this issue. Although the Tevatron's higher energy will give many more dileptons, it is not totally clear that this will help for this issue, since there is also an increase in background. At any rate, hadronic colliders will be excellent tools for studying heavy quark physics. This remark applies also for SLC and LEP operating on the Z^0 where 14 % of the events are into $b\bar{b}$ states.

My fourth "standard physics" example deals also with heavy flavour production, but now at the SSC. The higher energy and higher luminosity of the SSC make it an unbelievably powerful source of $b\bar{b}$ pairs, estimated to be in the range of 10^{10}-10^{11}/year [9]. Kane [18] has remarked that with these many events it may become

feasible to look for CP violating effects in the B-system. This is of course very exciting, since apart from the kaon system there appears to be no other source available in nature to study CP violation *. The asymmetry

$$R' = \frac{N(e^+e^+) - N(e^-e^-)}{N(e^+e^+) + N(e^-e^-)} \tag{2.2}$$

in the number of produced dileptons, in principle, is a measure of CP violation in the B-system. This asymmetry is expected to be small ($\sim 10^{-3}$) in the standard model [19]. However, dilepton differences are not a particular good signal, especially since proton-proton collisions are not charge symmetric and because there exist many different backgrounds.

A more feasible proposal for observing CP violation at the SSC has been studied by Cronin et al. [20], following a suggestion of Bigi and Sanda [21]. The idea is to study final states which are common to both B^0 and $\bar{B}^0$ decays. Mixing then causes the two amplitudes to interfere, making the CP violation in the final state interaction observable. Cronin et al. [20] have studied particularly the case in which the $B\bar{B}$ produced pair decays into a ψK_s state and semileptonically. If there is CP violation then the ratio

$$R'' = \frac{N(\psi K_s, \ell^+) - N(\psi K_s, \ell^-)}{N(\psi K_s, \ell^+) + N(\psi K_s, \ell^-)} \tag{2.3}$$

is a measure of CP violation. In the standard model this ratio is calculated to be in the range of a few percent [20]. Cronin et al. [20] estimate that the number of events of the type

* The baryon asymmetry of the Universe, although ultimately reflecting some primordial CP violation, is rather recondite!

ψK_S + lepton which can be seen at the SSC, with an integrated luminosity of 10^{39} cm^{-2} and applying reasonable cuts, is of the order of 10^3. This would make a measurement of R" barely feasible. However, tagging is rather crucial and the issue whether one can really hope to detect a CP violating effect at the SSC remains open. Nevertheless, such an experiment will certainly be attempted, since the issue - although "standard" physics - is so important.

The last example of standard physics which I want to discuss concerns phase II of LEP. With E_{CM} of the order of 200 GeV one is above the threshold for W^+W^- production. The process $e^+e^- \to W^+W^-$ is totally predicted by the standard model and is a sensitive measure of the three gauge couplings: γW^+W^- and $Z^0W^+W^-$. The cross-section for this process rises very rapidly above $E_{CM} = 2\ M_W$ and is of the order of 20 pb at its maximum, as shown in Fig. 3.

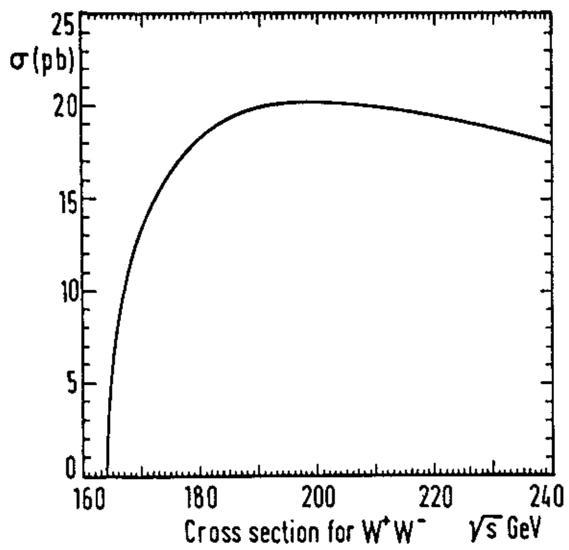

Fig. III: Cross section for the process $e^+e^- \to W^+W^-$, for M_W = 82 GeV

I should note that the flattening of the cross section above threshold is due to cancellations between the neutrino exchange graph and the graphs containing the three gauge vertices. If these vertices were ignored, the cross section at E_{CM} = 200 GeV would be twice as big as that shown in Fig. 3 and would keep rising linearly with s, eventually violating unitarity. With an integrated luminosity of 5×10^{38} cm^{-2} per year at LEP (phase II) one expects around 10^4 W^+W^- pairs at $E_{CM} \sim 200$ GeV. This number of events is comparable to that expected from normal hadronic and leptonic processes ($e^+e^- \to$ hadrons, $e^+e^- \to l^+l^-$) at these energies, and so represents a substantial fraction of the standard physics expected from LEP II.

The W^+W^- signal at LEP (phase II) can be rather easily seen by studying the 4-jet cross section. At E_{CM} = 200 GeV one can estimate that this cross section from pure QCD processes is at most 0.5 pb. In comparison, the 4-jet cross section arising from $e^+e^- \to W^+W^-$, with both W's decaying hadronically, should be about 10 pb. So the background here is truly negligible. This situation should be contrasted with what is expected in colliders, where the hope of studying the three gauge coupling via $\bar{q}q \to W^+W^-$ seems rather remote. This is certainly true for the Tevatron. Here the cross section $\sigma(p\bar{p} \to W^+W^-x) \simeq 10$ pb, is comparable to LEP (phase II) but the lower integrated luminosity will probably only provide about 10^3 events/year. Furthermore, the backgrounds arising from W production accompanied by a jet ($\sigma_{W\ jet} \sim 10^3$pb) and from 4 jet production ($\sigma_{4\ jet} \sim 10^5$pb) are hopeless. At the SSC, as shown in Fig. 4, the W^+W^- production cross section, even with stringent cuts is larger. This coupled with the higher luminosity could provide 10^6 W^+W^- events per year. Whether this signal can be extracted from the QCD background is, however, also here not terribly clear. In fact at these high energies there is the further problem that often the 2 jets from W decay tend to coalesce [9]. In view of these difficulties, it appears to me that LEP (phase II) remains uniquely suited to test the 3 gauge couplings of the standard model.

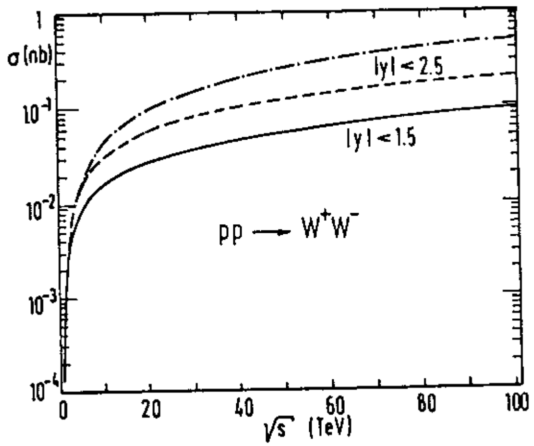

Fig. 4: The process $p\,p \to W^+W^-x$ at high energy, for various rapidity cuts, from Ref. 9

Because the W signal is so clean in LEP (phase II) one can hope to obtain a good measurement on the W mass this way. This matter has been investigated recently in connection with the LEP Jamboree (22) and the consensus is that a measurement of M_W to 100 MeV is probably possible. Four different methods have been considered, which are in principle independent measurements so that their results can be combined. They include: i) measuring M_W by following the $e^+e^- \to W^+W^-$ threshold curve; ii) obtaining a value for the W-mass from the end point of the electron spectrum from W-decay [23]; iii) reconstructing M_W from the 2-jet invariant mass; iv) reconstructing M_W from the $e\nu$ invariant mass recoiling from 2 jets produced by the other W.

It may appear surprising that the last two, calorimetric, methods can give M_W so precisely. The crucial point which allows this is the constraint, which one can impose in e^+e^- collisions, that the 2 jet (or $e\nu_e$) energies must add up to E_{beam}. The possibility for such a precise determination of M_W has also been claimed for the Tevatron [24], by looking at the transverse mass distribution of $e\nu_e$. The transverse mass distribution peaks at the real mass and is rather insensitive to the details of the precise W transverse momentum distribution [25]. Hence at the Tevatron, where one expects over 10^4 $W \to e\nu_e$ events/year, it may be possible theoretically to reach this precision. However, I worry about possible systematic effects connected with other sources of missing energy - like hadrons going down the pipe. So LEP (phase II) still appears to me to have an advantage for a precise determination of M_W *.

3. HIGGS SEARCHES

I would like now to move from "expected" physics to what might be called "half-expected" physics. Namely, the physics of Higgs bosons. In the standard model, as is well known, the breakdown of $SU(2) \times U(1) \to U(1)_{em}$ is accomplished by introducing a complex Higgs doublet $\Phi = \begin{pmatrix} \phi^0 \\ \phi^- \end{pmatrix}$, whose potential has an asymmetric minimum at $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \Lambda_F \\ 0 \end{pmatrix}$. Here

$$\Lambda_F = (\sqrt{2}\, G_F)^{-1/2} \simeq 250 \text{ GeV} \tag{3.1}$$

is the scale (the Fermi scale) which characterizes the breakdown. As the result of the breakdown, 3 out of the 4 real fields in Φ are eaten to give mass to the $W^\pm$ and Z bosons. The remaining neutral scalar field is the Higgs boson, H. Although the mass of the Higgs

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* To test the "interesting" part of the standard model radiative corrections, one really wants to know M_W (and M_Z) to one part per mil.

boson is unknown, its couplings to quarks, leptons and gauge bosons are fixed. Basically, the coupling of H to particle pairs is proportional to the mass of these states. Hence Higgs bosons will decay to the heaviest mass objects which are kinematically allowed.

Perhaps a little rashly, one may classify high energy physicists these days into three categories - depending on their attitudes towards Higgs bosons and the Higgs potential V, which causes the SU(2) x U(1) breakdown [26]. Either:

i) they are happy with V and try to devise ways to find H; or
ii) they are unhappy with V because it is unnatural *, but are happy to have elementary Higgs bosons; or
iii) they are unhappy with V and with the whole notion of elementary Higgs bosons.

Physicists of type ii) are vigorous proponents of supersymmetry (SUSY), since SUSY can restore naturalness to the Higgs sector. Physicists of type iii), on the other hand, presume that the breakdown of $SU(2) \times U(1) \rightarrow U(1)_{em}$ occurs via dynamical symmetry breaking. Thus they do not worry about a Higgs potential, or Higgs bosons, at all. I shall explore, in the next section, some of the physics expected at hadron and lepton colliders if some of these two latter speculations hold. In this section, however, I discuss ways to try to detect the standard Higgs.

One of the difficulties about trying to find the standard Higgs boson is that one does not know its mass. Consequently, it is not clear a priori where it will be best to look for it, since the answer to this question is certainly mass dependent. There are some theoretical arguments for M_H, but really no firm predictions. By asking that tree graph unitarity, in WW scattering not be violated, one obtains the bound [27] $M_H \lesssim 4\sqrt{\frac{\pi}{3}}\,\Lambda_F \simeq 1\ \mathrm{TeV}$

* Why, they ask, is $\Lambda_F \neq M_{Planck} \simeq 10^{19}$ GeV?

A much stronger bound follows if one requires that the perturbative renormalization group equations for the Higgs coupling be stable [(28)]. Then one finds $M_H \lesssim 2\sqrt{2}\,\cot\theta_W M_W \simeq 130$ GeV. On the other hand, lattice gauge theory calculations - in strong coupling - seem to indicate that [29] $M_H \gtrsim (1 \pm 0.3)\, M_W$, and one expects that this inequality becomes stronger for physical weak coupling. From an experimental point of view, the crucial point is more whether $M_H > 2M_W$ or not. If the Higgs mass is greater than the 2W threshold, then these decay modes will dominate. The hardest experimental region for M_H to lie in is $2m_t \lesssim M_H \lesssim 2M_W$, where it will be very difficult to detect Higgs bosons at all.

If the Higgs boson are light, e^+e^- colliders offer the best chance for their detection. For very heavy Higgs bosons ($M_H > 400$ GeV), hadronic supercolliders offer the only hope. HERA has not much bearing on this whole question, since Higgs production there is very tiny. At LEP (phase I) and SLC one can look for Higgs bosons in Z^0 decay. The most promising channel is $Z^0 \rightarrow H\mu^+\mu^-$, which is very clean. Unfortunately the branching fraction $B(Z^0 \rightarrow H\mu^+\mu^-)$ is small [30], ranging from 10^{-4} to 10^{-6} for $8\ \mathrm{GeV} < M_H < 50$ GeV, so that the limit of observability is probably around $M_H = 50$ GeV. In fact, toponium may be a much better place to observe Higgs in e^+e^- colliders than at the Z^0 [31]. The branching ratio for the decay $(t\bar{t}) \rightarrow H\gamma$ relative to $(t\bar{t}) \rightarrow \mu^+\mu^-$ is [32]

$$\frac{\Gamma(t\bar{t} \rightarrow H\gamma)}{\Gamma(t\bar{t} \rightarrow \mu^+\mu^-)} = \frac{1}{8\sin^2\theta_W}\left(\frac{M^2_{t\bar{t}}}{M^2_W}\right)\left[1 - \frac{M^2_H}{M^2_{t\bar{t}}}\right] \qquad (3.2)$$

Hence this decay, for the suspected t mass range $30\ \mathrm{GeV} \lesssim m_t \lesssim 50$ GeV, is a few percent of all toponium decays up to Higgs masses $m_H \lesssim M_{t\bar{t}}$, where it is kinematically cut off.

To reach higher Higgs masses one needs the higher energies of LEP (phase II). The cross section for the process $e^+e^- \rightarrow Z^0H$ as shown in Fig. 5 is above 0.1 pb for $M_H = 2M_W$. Unfortunately, to reach this mass range one needs E_{beam} = 130 - 140 GeV, which is beyond LEP (phase II). Higgs masses of O(100 GeV) can, however,

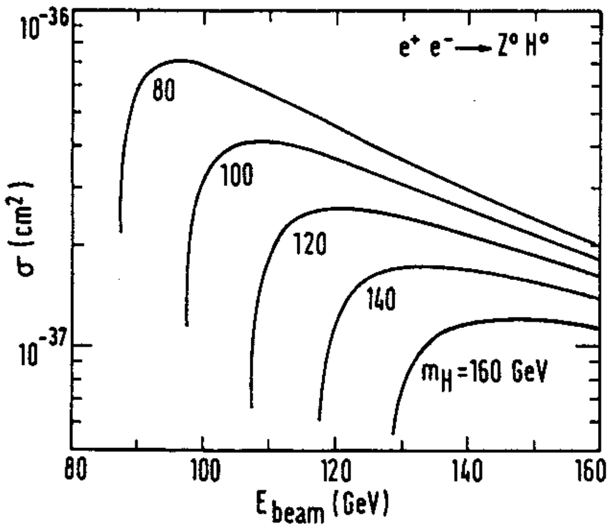


Fig. 5: The cross section for $e^+e^- \rightarrow HZ^0$ computed in Ref. 27, for various Higgs masses (courtesy of S. Ritz)

be detected at LEP II, where with an integrated yearly luminosity of 500 pb^{-1} one expects about 350 Higgs bosons of M_H = 80 GeV. A very clean signal would appear in $\ell^+\ell^-$ + 2 jets ($\sim$20 events). A much larger signal can probably be detected by looking at decays of the Z^0 into neutrinos. One expects approximately 70 events of the type: missing energy + 2 jets, which should be able to be picked out of the background [33]. Note, however, that the hadronic energy resolution must be good enough to be able to

distinguish an 80 GeV Higgs going into hadrons from a Z^0 going into hadrons, since at E_{CM}(200 GeV), $\sigma(e^+e^- \rightarrow Z^0Z^0) \simeq 1$ pb.

For very high energies in both e^+e^- and hadronic interactions the most efficient way to produce heavy Higgs bosons is via WW or ZZ fusion [34], as illustrated in Fig. 6. Dawson and Rosner [35] have studied Higgs boson production at a $\sqrt{s}$ = 1 TeV e^+e^- super linear collider, assuming an integrated yearly luminosity of 10^{39} cm^{-2}. Requiring a minimum of 10 events to be produced in the process $e^+e^- \rightarrow \nu_e \bar{\nu}_e H$, requires that the Higgs mass be less than 600 GeV (see Fig. 7). However, if one worries about possible backgrounds, like $e^+e^- \rightarrow W^+W^-$ which decay into jets which coalesce, the limit of observability deduced by Dawson and Rosner is $M_H \lesssim 400$ GeV.

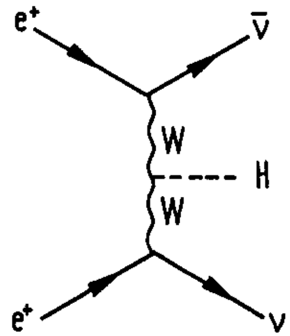


Fig. 6: Higgs production by WW fusion

For heavy Higgs production, hadronic supercolliders appear to fare better. For m_t = 40 GeV the dominant process for producing Higgs mesons is gluon-gluon fusion [36] if $m_H < 350$ GeV, but WW and ZZ fusion if $m_H > 350$ GeV [9]. At SSC energies ($\sqrt{s}$ = 40 TeV) the cross sections for producing massive Higgs bosons, which subsequently decay into W^+W^- and ZZ pairs, is substantial. Even requiring that the vector boson rapidity be less than 2.5, one has cross sections of the order of 1 pb all the way up to M_H = 1 TeV, as can be seen from Figs. 8, taken from EHLQ. The background to this process comes from direct W^+W^- and ZZ production, with the

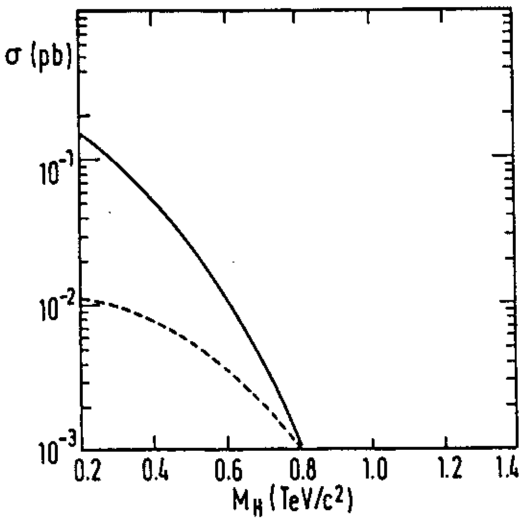
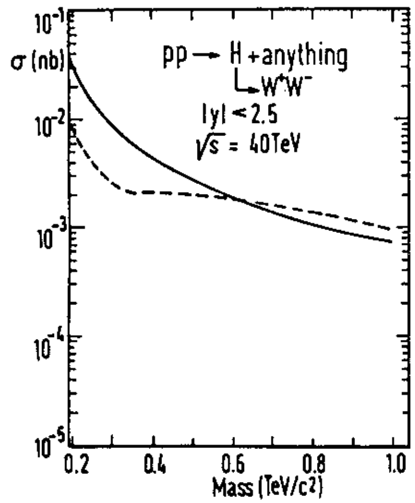


Fig. 7: Cross section for the processes $e^+e^- \to \nu_e \bar{\nu}_e H$ (solid line) and $e^+e^- \to Z^0 H$ (dashed line) at $\sqrt{s}$ = 1 TeV

vector boson pairs at an invariant mass equal to M_H. This background, $\Gamma_H \, d\sigma(pp \to VVX) / dM$, is shown as dotted lines in Figs. 8. Although the cross section for Higgs production and subsequent decay into ZZ pairs is about a factor of 2 smaller, the background from the process $pp \to ZZX$ is much better than that for the process $pp \to WWX$. Furthermore, as it is unlikely that the W's and Z can be reconstructed from their hadronic modes, the cleanest signal will be provided by the Z^0Z^0 channel decaying purely leptonically. The branching fraction $B(Z^0Z^0 \to l^+l^-l^+l^-) \simeq 0.0036$ is very small. Nevertheless, with an integrated yearly luminosity of 10^{40} cm^{-2} the number of events expected at the SSC is probably sufficient to observe Higgs bosons up to masses of the order of 1 TeV. In Table II, I give the expected number of $l^+l^-l^+l^-$ events/year for different Higgs boson masses, along with the number of background events.



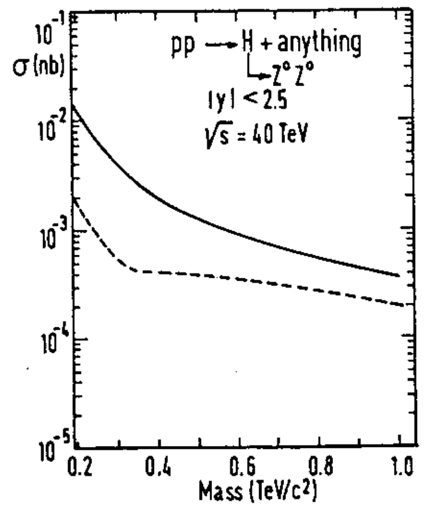


Fig. 8a: Cross section for the process $pp \to H \to W^+W^-$ and its background at the SSC, from EHLQ

Fig. 8b: Cross section for the process $pp \to H \to ZZ$ and its background at the SSC, from EHLQ

If the Higgs boson mass is lighter than 2 M_W but above $t\bar{t}$ threshold, their detection in hadronic colliders will be very tough. The most promising method to look for them at the super-colliders (LHC, SSC) is to study their production in association with a W boson ($pp \to HWX$) [37,38]. The cross section for this

Table II: Higgs boson events into $l^+l^-l^+l^-$ at the SSC per year, for an integrated luminosity of 10^{40} cm^{-2}

M_H (GeV)	Number of events	Number of background events
250	250	36
600	32	14
1000	13	7

process is also in the picobarn range, but the background from $Wt\bar{t}$ associated production is fierce (Background/Signal $\sim$10-15). Only by requiring very strict mass cuts on the dijet system ($\Delta M^2 = 0.1\ M_H^2$) one can reduce the background to be of the order of the signal. However, this may be very hard to do in practice, due to detector resolution and lost particles [39]. It may be that if the Higgs boson is in the mass range 100 GeV $< m_H < 2\ M_W$ the best hope for its eventual detection lies in linear e^+e^- supercolliders, operating in the energy range $\sqrt{s}$ = 200-350 GeV.

4. PHYSICS BEYOND THE STANDARD MODEL

As I have mentioned earlier, unhappiness with the unnaturality of the Higgs sector has led to two distinct sets of theoretical speculations. In one scenario, one tries to stabilize the Higgs sector and make it natural by assuming a supersymmetric extension of the standard model. In the other, one abandons the elementary scalar fields altogether and assumes that the SU(2) x U(1) breakdown

occurs dynamically, through the presence of condensates of some underlying theory. This is clearly not the place to discuss the theoretical nuances for or against these speculations. Nevertheless, I want to make some remarks which reflect my personal prejudices:

(i) Supersymmetry (if it exists) has a deeper raison d'être than just to stabilize the Higgs sector. However, to be effective for the naturalness problem, it is necessary that it be a good symmetry at scales of the order of the Fermi scale. Whence it follows that the superpartner masses $\tilde{m} \lesssim \Lambda_F$.

(ii) Underlying theories invented to provide condensates just to give the possibility of $SU(2) \times U(1) \to U(1)_{em}$ are not terribly sensible.
Much more reasonable is to suppose that the underlying theory (if it exists) is a preon theory which:

a) Binds quarks and leptons, as states which are light compared to the compositeness scale Λ ($m_f \ll \Lambda$)
b) Has condensates $\langle pp \rangle$, which allow for a breakdown of $SU(2) \times U(1) \to U(1)_{em}$ at a scale $\Lambda_F < \Lambda$.

(iii) The presence of supersymmetry and dynamical symmetry breaking together, although certainly not necessary, is not inconceivable.

I begin by discussing how some of the planned and proposed colliders can give us information about a supersymmetric extension of the standard model. In such a theory all particle have partners of different spin, so that the overall number of fermionic and bosonic degrees of freedom match. Hence, quarks (q) have as superpartners squarks ($\tilde{q}$), gluons (g) have gluinos ($\tilde{g}$), etc. The only slight complication is that the Higgs sector of the minimal standard supersymmetric model must have two doublets [40]. Thus the physical spin zero Higgs include a charged pair $H^{\pm}$ and three neutral Higgses H^o, $H^{o'}$ $H^{o''}$.

The good news about these extended models is that all interactions are known, since they follow by supersymmetry. The bad news, however, is that the masses of all the spartners are unknown , since they reflect the way in which supersymmetry is broken in nature. Although it is not a mathematical theorem, in most - if not all - the models discussed in the literature, it is difficult to have all three Higgs fields H^{0}, $H^{0'}$, and $H^{0''}$ heavy [40]. Supersymmetry (SUSY) searches can be profitably done at all the colliders in discussion. The sensitivity of different colliders depends really mainly on the mass range of the sparticles, the energy range of the collider and the total integrated luminosity.

I shall be quite brief about SUSY signals at the Sp$\bar{p}$S collider, since this topic has been extensively discussed by J. Ellis [41], G. Kane [42] and A. de Rujula [43] in this meeting. One remark, however, is in order. SUSY at $\sqrt{s}$ = 630 GeV is "visible" as missing energy events, due to $\tilde{g}$ or $\tilde{q}$ production and subsequent decay into quarks and a photino, which is the source of the missing energy. Present experiments are sensitive to cross sections of the order of 100 pb which, as can be seen from the contour plots of Fig. 9a, for $\not{p}_{\perp}$ > 40 GeV, correspond typically to $m_{\tilde{q}} \simeq$ 40 GeV, $m_{\tilde{g}} \gtrsim$ 100 GeV or $m_{\tilde{q}}$ = 60 GeV, $m_{\tilde{g}}$ = 80 GeV. Depending on the various choices the ratio of 2 jet to 1 jet events, with missing energy varies. This is shown in Fig. 9b.

At Tevatron energies, $\sqrt{s}$ = 2 TeV, and at a luminosity of 10^{30} cm^{-2} sec^{-1}, the production yield of SUSY partners is much increased over that at the Sp$\bar{p}$S collider at $\sqrt{s}$ = 630 GeV and $\mathcal{L} \sim$ 2-3 x 10^{29} cm^{-2} sec^{-1}. For instance, if indeed $m_{\tilde{q}}$ = 60 GeV $m_{\tilde{g}}$ = 80 GeV, so that the present missing energy events are really signals of supersymmetry, then at the Tevatron (depending a bit on cuts) one should see 40-60 times the present number of missing energy events. Alternatively, seeing no clear missing energy signals at the Tevatron will allow setting a bound $m_{\tilde{q}} \gtrsim$ 120 GeV on the masses of squarks, and a similar bound on gluino masses [45].

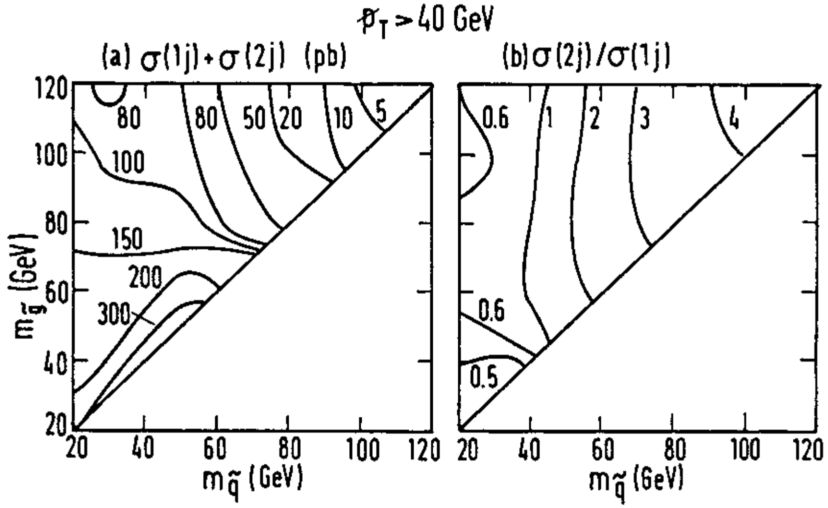


Fig. 9a: Contour plots of cross sections (in pb) for $p\bar{p} \to$ jet(s) + $\not{p}_{\perp}$ from Ref. 44, for various $\tilde{q}$ and $\tilde{g}$ masses

Fig. 9b: Ratio of 2 jets to 1 jet cross sections from Ref. 44, for various $\tilde{q}$ and $\tilde{g}$ masses

At the SSC and the LHC bounds on the scale of the superpartners near the TeV range will be possible, as illustrated in Fig. 10, taken from EHLQ.

HERA will be sensitive to selectrons, which are otherwise difficult to produce in hadronic colliders. The biggest cross sections for $\tilde{e}$ production, provided squarks are not too heavy, is via associated production, as shown in Fig. 11. This process has been calculated

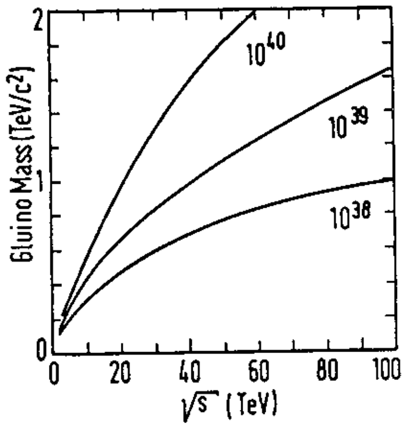


Fig. 10: Discovery limits for SUSY at the SSC and LHC, as a function of yearly integrated luminosity. (Discovery here is 10^4 events with rapidity less than 1.5)

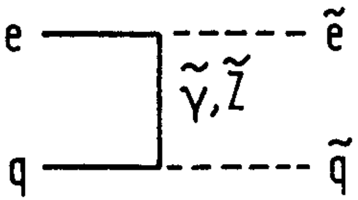


Fig. 11: Associated production of $\tilde{e}$ and $\tilde{q}$

by Jones and Llewellyn Smith [46)] neglecting in Fig. 11 possible Shiggs mixing. If this mixing is included [47)], the cross sections are somewhat reduced. At any rate, observable cross sections ($\sim$1 event/10 days) are obtained if $m_{\tilde{q}} + m_{\tilde{e}} \lesssim 160$ GeV. These events have a clean signature $\tilde{e} \to e\,\tilde{\gamma}$ and useful bounds on

selectrons can be obtained for $\tilde{q}$ near the maximum Tevatron range. I should note, however, that if selectrons are light enough they will be produced copiously at the Z^0, giving rise to wrong e^+e^- invariant mass distributions through the sequential decay $Z^0 \to \tilde{e}^-\tilde{e}^+ \to e^-e^+\tilde{\gamma}\tilde{\gamma}$. Thus LEP and SLC should easily establish if $m_{\tilde{e}} \lesssim M_{Z/2}$.

Higher energy e^+e^- machines (LEP (phase II) and super linear colliders) can provide pairs of SUSY sparticles at calculable rates, via their coupling to photons and to the Z^0. The cross sections for these processes have been neatly catalogued in Ref. 48 and are typically of the order of the point cross section: $\sigma_{pt} = 87/s$ nb, with s in GeV^2. The signature for these events are clean, consisting of jets plus missing energy for squarks, and leptons plus missing energy for sleptons. In essentially all cases one should be able to search up to near $\tilde{m} \lesssim \frac{1}{2}\sqrt{s}$. Specifically for LEP (phase II) one can expect to observe squarks if $m_{\tilde{q}} < 80$ GeV, (which is not as good as the Tevatron), selectrons if $m_{\tilde{e}} < 80$ GeV (better than HERA if $m_{\tilde{q}} > 80$ GeV) and smuons if $m_{\tilde{\mu}} < 80$ GeV (best limit on these objects).

I shall end my discussion by considering possible tests of the ideas of quark and lepton compositeness and dynamically symmetry breaking - which to my mind are deeply interconnected. Two nice tests of the idea that there is substructure involve:

(1) the discovery of the strong contact interactions among fermions (quarks and leptons), arising from their composite nature. These interactions are shown schematically in Fig. 12. The scale Λ, which may vary from process to process, is the compositeness scale; the coupling g^2 is presumed to be such that $g^2/4\pi \sim O(1)$, reflecting the underlying strong coupling theory.

(2) The discovery of excited leptons and quarks.

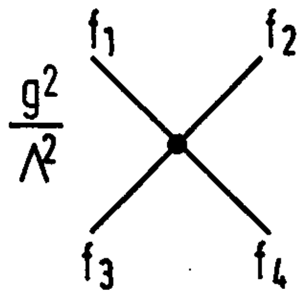


Fig. 12: Contact interactions caused by compositeness

The compositeness scale Λ is bounded by the precise (g-2) measurement of electrons and muons. For chiral theories, the muon (g-2) suggests $\Lambda \gtrsim$ 1 TeV [49]. PETRA and PEP put bounds on Λ, which range from 1-3 TeV [50] depending on the helicity structure assumed for the 4-fermion interactions [51]. It is sensible to suppose that if excited quarks and leptons exist, their masses should also be of order Λ ($m_f^* \sim \Lambda$). From this point of view, it may appear hopeless to search for these excited states. Nevertheless, at LEP (phase II) and HERA, it will be interesting to look anyway for excited electrons, since one can test for m_e^* up to 200 GeV, which is a sizable fraction of $\Lambda \simeq$ 1 TeV.

Excited electrons, which can couple to electrons and gauge bosons (γ, Z^0) by magnetic coupling, can have a sizable production cross section at e^+e^- and ep colliders because the one photon exchange graph provides a $\frac{1}{t}$ contribution which can become singular for quasi-elastic scattering ($e^+e^- \rightarrow e^* e$; $ep \rightarrow e^* p$). These processes have been analyzed recently by Hagiwara, Komamiya and Zeppenfeld [52] for a model [53] where the excited electrons are in a weak SU(2) doublet. The results for LEP (phase II) energies, taking a scale

parameter for the magnetic coupling of Λ = 1 TeV, are shown in Fig. 13. It is clear from the figure that excited electrons are visible up to the kinematic limit. Similar results apply for HERA where, with the same parameters, a 200 GeV e^* has a cross section of 0.1 pb. Note that even though the excited electrons are produced

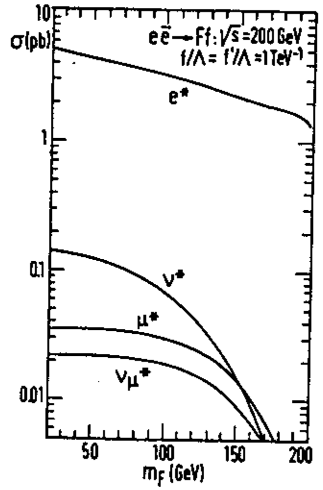


Fig. 13: Production of excited leptons in e^+e^- collisions in the model of ref. 53. From Ref. 52

along the beam direction, their decay byproducts (e, γ) are detectable, since they mostly come out at finite angles [52].

The contact interactions of Fig. 12 are detectable at much smaller CM energies in lepton colliders than in hadron colliders. This point is easily understood. Schematically, the quark or lepton cross section, including the contact interactions reads:

$$\sigma \sim s \left| \frac{\alpha_{eff}}{s} + \frac{1}{\Lambda^2} \right|^2 \qquad (4.1)$$

For processes involving leptons $\alpha_{eff} \to \alpha$, while for hadronic interactions $\alpha_{eff} \to \alpha_s$. Clearly, the contact interactions become important at $s \sim \alpha \Lambda^2$ for leptonic processes but only at $s \sim \alpha_s \Lambda^2$ for hadronic interactions. For $s \sim \Lambda^2$, Eq. (4.1) no longer applies, since at these energies one is really probing the substructure. Apart from logs, the cross section should in fact asymptote to $\sigma_{as} \sim \frac{1}{\Lambda^2}$ The expected behaviour of the cross section for leptonic processes is shown in Fig. 14. Here $\sigma_{pt} \sim \alpha^2/s$ is the usual electroweak cross section. Notice that

$$\sigma_{as} \sim \frac{1}{\Lambda^2} \gg \sigma_{dev} \sim \frac{\alpha}{\Lambda^2} \gg \sigma_{pt}(s \sim \Lambda^2) \to \frac{\alpha^2}{\Lambda^2} \qquad (4.2)$$

Hence, if there is compositeness the cross sections to be measured at high energies will be above those estimated from the standard model. Once deviations are seen at $s \sim \alpha \Lambda^2$ (for leptonic processes) or $s \sim \alpha_s \Lambda^2$ (for hadronic processes), the deviations will become bigger with energy.

The limits on Λ one can set in the various colliders differ depending on the detailed structure of the contact interactions and on the total CM energy available for the subprocesses. Typically, however, one expects limits $\Lambda_{ep} \gtrsim$ 5 TeV from HERA [54], $\Lambda_{ee} \gtrsim$ 10 TeV from LEP (phase II)[22] and $\Lambda_{qq} \gtrsim$ 20 TeV from the SSC [9]. Notice that the much higher CM energy of the SSC does not give substantially higher limits on Λ , since here $\alpha_{eff} \to \alpha_s \gg \alpha$.

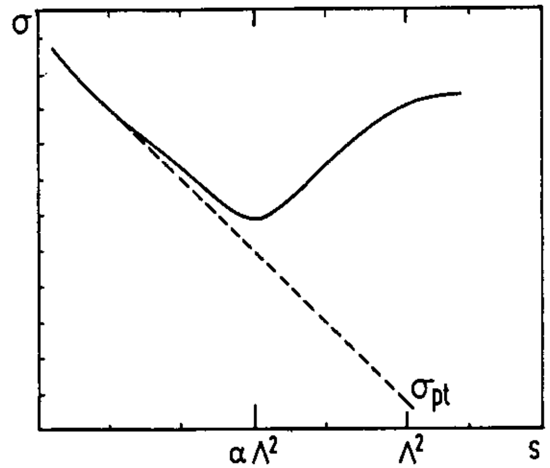


Fig. 14: Schematic behaviour of the leptonic cross section in the case that leptons have a substructure

If the underlying theory that binds preons into quarks and leptons is also responsible for the breakdown of SU(2) x U(1) - something I think is very sensible [26] - then the most sensitive test of compositeness may well be seeing the effects of this dynamical breakdown of the electroweak theory. There are two aspects of dynamical symmetry breaking which bear studying. One concerns the appearance at high energies of strong W-W interactions and the other is the whole issue of pseudogoldstone bosons. I discuss both issues in turn.

In theories of dynamical symmetry breakdown the longitudinal W-bosons get their masses by absorbing composite massless excitations, arising from the spontaneous breakdown of the underlying theory. In the specific case of the Technicolor scenario [55] these excitations are the Technipions, and I shall adopt this name generically in what follows. For energies $\sqrt{s} \gg M_W$ one can show that [56] the scattering amplitude for longitudinal W scattering is identical to that of Technipion scattering. As these excitations emerge from a strong coupling underlying theory, one expects that they should scatter strongly. It follows thus that also the longitudinal W's should scatter strongly. In fact, by comparing the expected behaviour of Technipions with that of ordinary QCD pions [26], one is led to expect that this strong scattering should manifest itself at energies of the order of

$$\sqrt{s} \simeq \sqrt{16\pi}\ \Lambda_F \simeq 1.7 \text{ TeV} \qquad (4.3)$$

A very interesting question is if such effects can be seen with a multi TeV hadronic collider. Eichten et al. [9] have investigated this point for the SSC, by specifically assuming that the W-W cross section gets a factor of 2 enhancement at $\sqrt{\hat{s}}$ = 1.7 TeV (Technirho enhancement) as shown in Fig. 15. The cross section for this signal, is of 5.4 x 10^{-2} pb on a background of 3 x 10^{-2} pb. For an integrated yearly luminosity of 10^{40} cm^{-2} one has thus only 540 events on a background of 300. To detect this will require extremely good W identification (i.e. reconstructing W's by their hadronic decay modes only). This looks unfeasible to me. However, it may well be that one has a W-W enhancement at a lower effective invariant mass. For instance, if the enhancement were $\sqrt{\hat{s}} \gtrsim$ 1 TeV, one would get a factor of 100 more events. Then the detection of this signal by letting one of the W's decay leptonically looks much more promising. I should add that although considereable work has already been done looking at the whole issue of W-detection at the SSC [57],

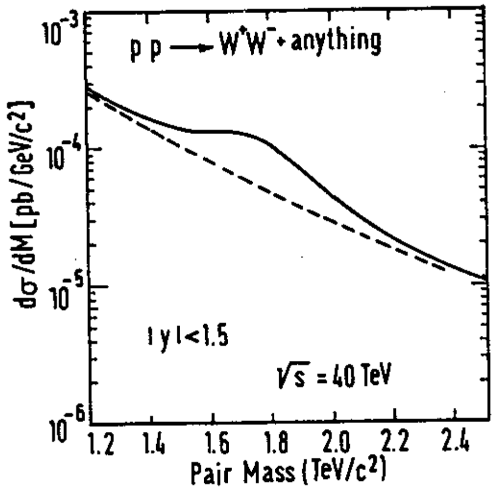


Fig. 15: Cross section for pp → WW at $\sqrt{s}$ = 40 TeV with a factor of 2 enhancement at M = 1.7 TeV, from EHLQ

Hinchliffe [58] in his overview of the Snowmass summer study on the SSC still feels that much remains to be done on this crucial point. I fully condivide his opinion.

If e^+e^- colliders in the TeV range really could be built, possible strong enhancements in the W-W channel would be simpler to study, because of the lack of background. I should note that at $\sqrt{s}$ = 1 TeV the standard model cross section for $e^+e^- \rightarrow W^+W^-$ is a, very respectable, 1 pb. Hence at an integrated yearly luminosity of 10^{39} cm^{-2}, one could collect around 10^3 events/year. These events, being essentially free of background, could allow one to envisage looking for W-W rescattering variations at the 10 % level.

A second expected byproduct of the dynamical breakdown of

SU(2) x U(1) is that there should be a certain number of pseudo-goldstone bosons in the theory. In general the underlying theory, in the limit in which all the standard model couplings are switched off, has global symmetries which are spontaneously broken by the condensates which break SU(2) x U(1), thereby causing the appearance of a certain number of massless states. These states acquire mass of order $\alpha_s \Lambda$ (or $\alpha \Lambda$) when the standard model couplings are restored. Typically some of these pseudogoldstone bosons have both quark and leptonic number, so they are leptoquarks: $\phi_{\ell q}$. Because the ϕ_{eq} are essentially Goldstone excitations, they couple with derivatives to the leptons and quarks:

$$\mathcal{L}_{int} \sim \frac{1}{\Lambda} \bar{q} \gamma^{\mu} \ell \, \partial_{\mu} \phi_{eq} \sim \frac{(m_q - m_e)}{\Lambda} \bar{q} \, \ell \, \phi_{eq} \qquad (4.4)$$

Thus effectively the couplings of these objects to light quarks and leptons is small, since they couple proportionally to the masses of the fermions. Hence they should not be strongly produced directly in quark and lepton collisions. However, since they have ordinary couplings to gluons and photons one expects that they mostly be produced by photon and/or gluon interactions. Fig. 16, for example, shows the expected yield from γ-g fusion of pairs of charge 2/3 leptoquarks at HERA. For an integrated luminosity of 1 pb^{-1}/day, HERA is sensitive (1 event/10 days) to pair production of leptoquarks with $m_{\phi_{\ell q}} < 60$ GeV. Note that this production cross section is identical to what one would expect for squarks of the same mass (and charge) [60]. However, squarks presumably always decay into quarks plus a photino, giving a jet plus missing energy. Leptoquarks have two decay modes (q + ν and q + e). Only the first of these resembles the squark decay.

I should note that at the Tevatron, provided one can dig out a jet + jet +l^+ +l^- signal, with an integrated luminosity of 10^{37} cm^{-2}

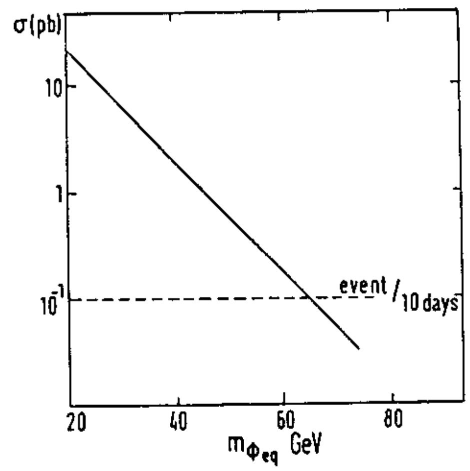


Fig. 16: Pair production of leptoquarks/or squarks from γ-g fusion at HERA. Adapted from Ref. 60

one can push the limit on $\phi_{\ell q}$ to 120 GeV, which is much above what HERA and LEP (phase II) can do. On the other hand, if there is not much mixing angle suppression, at HERA one can look for e-t-quark leptoquarks with masses in the 150 GeV range [61]. The potential background from heavy flavor production can be substantially reduced so that event rates below 1pb are observable [62].

5. CONCLUDING REMARKS

It is pretty clear that plenty of good physics can be reasonably expected to emerge from the planned hadronic, leptonic and lepto-hadronic colliders. Of course, the fondest hope is always that these new machines will produce different physics than what they are supposed to do. This may indeed be the case with the multi

TeV hadronic colliders since their energy region, which is presumed to hold the key to the SU(2) x U(1) symmetry breaking, is really terra incognita.

In thinking about the broad subject of this report, three points struck me as deserving to be emphasized in conclusion:

1) Reconstruction of W/Z from jets will be of crucial importance for physics studies at higher energy hadronic machines. Understanding the limitations of why this cannot be done with present data at the $Sp\bar{p}S$ may be of much use for the future.

2) Not enough thought on linear e^+e^- colliders with $\sqrt{s}$ = 1 TeV and a luminosity of 10^{33} cm^{-2} sec^{-1}, is being given. This is probably a mistake since much of the physics here is extremely clean.[63)]

3) Theorists as a whole should spend more time (or at least <u>some</u> time!) thinking about machine physics issues. Scaling up will not work anymore, and it is everybody's business to think on how to reach new energy frontiers.

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