e^+e^- PHYSICS BEYOND LEP

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1. INTRODUCTION

It is manifestly absurd to speculate about possibly interesting physics issues at an e^+e^- collider of 350 × 350 GeV (SLEP), separated from the present one by perhaps $2\frac{1}{2}$ generations of intermediate energy machines (PEP/PETRA, HERA, LEP). However, that is my commission, and I can only hope that these myopic gropings may accidentally touch on some general principles or stimulate someone else to greater clairvoyance. After this ritualistic expression of humility and awe, we should get down to business.

This discussion is based on the following assumptions about the physics issues to be settled before the conjectured e^+e^- collider is switched on.

- The (first) Z^0 has been discovered, its decays studied exhaustively, and its couplings to all light fermions determined$^{1)}$.
- The (first) $W^\pm$ have been discovered, the $e^+e^- \to W^+W^-$ reaction has been probed close to threshold, and the gauge nature of vector boson couplings has been ascertained$^{2)}$.
- Any Higgs bosons with masses $\lesssim$ 100 GeV have been discovered$^{3)}$.
- The spectroscopy of fundamental fermions with masses $\lesssim$ 100 GeV has been determined.
- QCD has been shown to be the correct theory of the strong interactions$^{4)}$.

What else is there left to live for? The following is a preliminary list of the new questions which one can anticipate will be raised by the above answers.

- Are there any more Z^0's or $W^\pm$'s indicating that the Nobel-Prizewinning $SU(2)_L \times U(1)$ weak group$^{5)}$ is not the whole story?
- Are there any Higgs bosons with masses above 100 GeV? (A reasonable question, regardless of whether there are any lighter Higgs bosons or not.)
- Are there any superheavy fermions? (The other side of this coin is: Do we still care about the lighter fermions?)
- What qualitatively new phenomena or principles emerge in the mass range of a few hundred GeV? One obvious candidate is technicolour$^{6)}$ -- a whole new range of strong interactions with scales $\sim 10^3$ larger than those associated with QCD, whose dynamical symmetry breakdown may generate the $W^\pm$ and Z^0 masses. A more speculative candidate is supersymmetry$^{7)}$, which introduces a completely new principle of fermion-boson interrelation whose aesthetic attraction is generally conceded, but whose possible scale of relevance is totally obscure.

As usual, we hope that none of the above questions will be the most interesting ones when the conjectured e^+e^- collider SLEP starts operation, and that what it finds will in turn be more interesting than even the answers to those questions. In particular, it is arrogant to assume that our present gauge theories are even partially correct, and some remarks will be made later about possible alternatives. Nevertheless, it may be appropriate at this point to regard the questions listed above as a suitable Monte Carlo input for imagining what experiments might look like. Estimates of the cross-sections for some processes of interest are presented in Table 1 below. They are expressed in units R of the purely electromagnetic contribution to $e^+e^- \to \mu^+\mu^-$:

$$R_{\text{process}} \equiv \frac{\sigma(\text{process})}{\sigma_{\text{pt}}} , \qquad \sigma_{\text{pt}} \equiv \sigma(e^+e^- \to \gamma^o \to \mu^+\mu^-) = \frac{4\pi}{3}\frac{\alpha^2}{E^2_{\text{cm}}} \tag{1}$$

It is worth recalling that

$$\sigma_{\text{pt}} \approx \frac{87}{E^2_{\text{cm}}(\text{GeV}^2)}\ \text{nb} \approx 2 \times 10^{-37}\ \text{cm}^2 \quad \text{at} \quad 350\ \text{GeV} \times 350\ \text{GeV} \tag{2}$$

corresponding to about 1½ events/theoretical day8) for R = 1 if the collider has a luminosity $\mathcal{L} \sim 10^{32}\ \text{cm}^{-2}\ \text{s}^{-1}$. (A theoretical day has 24 hours, each of 60 minutes with 60 seconds:

Table 1

Compilation of cross-sections

$e^+e^- \to$		Cross-section in units of σ_{pt}	Remarks
Weak vector bosons	W^+W^-	∿ 20	Background reactions.
	Z^0Z^0	∿ 20	
	$Z^0\gamma$	∿ 20	
Higgs bosons	Z^0H^0	0.16	Best ways to look for heavy Higgs?
	$W^\pm H^\mp$	0.10	
	H^+H^-	$0.26\ \beta^3$	Useful for $H^\pm$ which are not superheavy.
Fermions	$\mu^+\mu^-$	1.19	Includes Z^0 contribution as well as γ.
	$Q(2/3)\bar{Q}(-2/3)$	2.04	
	$Q(-1/3)\bar{Q}(+1/3)$	1.17	
	3 generations of $q\bar{q}$	9.6	
Resonances	New Z^0	∿ 5000?	Assuming couplings similar to first Z^0.
	New onium	1 or 2	Broadened by weak decays.
	Technicolour ρ	∿ 7?	Assuming couplings similar to ordinary ρ^0.
Super-symmetric continuum	$\tilde{W}^+\tilde{W}^-$	1.99	Partners of $W^\pm$.
	$\tilde{W}^0\tilde{W}^0$	0	Partners of I = 1 part of Z^0.
	$\tilde{Q}(2/3)\bar{\tilde{Q}}(-2/3)$	0.37	Partners of charge -2/3 quarks.
	$\tilde{Q}(-1/3)\bar{\tilde{Q}}(1/3)$	0.11	Partners of charge -1/3 quarks.
	$\tilde{\ell}^0\bar{\tilde{\ell}}^0$	0.60	Partners of neutral leptons.

a real day is probably a factor of ∿ 4 shorter for various obscure reasons.) This rate and the cross-sections in Table 1 immediately lead one to the first conclusion that *a luminosity of* 10^{32} *cm*$^{-2}$ *s*$^{-1}$ *is insufficient.* This should not be surprising: one of the main reasons why e^+e^- collisions are so interesting is that they utilize point-like particles, and point-like cross-sections necessarily fall as $1/E_{cm}^2$. Since this machine has E_{cm} ∿ 3 times larger than LEP, it seems reasonable to aim for a luminosity 10 times higher, *namely* $\mathcal{L} \simeq 10^{33}$ *cm*$^{-2}$ *s*$^{-1}$ *per interaction region.* If this theoretical argument conflicts with the machine possibilities, then the experimentalists will have a lot of time for twiddling their thumbs.

Details of Table 1 will be justified (?) in subsequent sections of this report. Section 2 discusses possible future aspects of weak boson physics, while Section 3 discusses fermion physics. Section 4 introduces a couple of speculative new areas of physics, and Section 5 makes brief remarks about some old favourite questions about e^+e^- collisions: How important are polarization and $\gamma\gamma$ physics? Section 6 contains a brief summary.

2. WEAK INTERACTIONS

It will be assumed in most of this section that the basic gauge-theoretical framework[5)] for describing weak interactions is correct, despite the continued absence of any evidence for this hypothesis that is not merely circumstantial. If weak intermediate vector bosons do *not* in fact exist, then at the centre-of-mass energies contemplated for the e^+e^- collider a linear extrapolation of the presently observed low-energy cross-sections yields values at the unitarity limit:

$$\frac{\sigma(e^+e^- \xrightarrow[\nu]{} X)}{\sigma_{pt}} = \frac{q}{\alpha^2} = 1.7 \times 10^5 \ . \tag{3}$$

The cross-section *must* turn over at the unitarity limit, which corresponds to a useful event rate of a few events per second even at a luminosity of 10^{32} cm^{-2} s^{-1}. If this wholesale collapse of theoretical ideas occurs, there will be no shortage of events to probe the *débâcle*. Assuming this does not occur, then we fall back on "higher-order" questions within the conventional gauge theory framework. As stated in the Introduction, we assume that the Z^0 and $W^\pm$ have been discovered. A logical possibility is that their self-interactions do not have the conventional gauge-theoretic form. In this case, the reaction $e^+e^- \to W^+W^-$ is of special interest[2)], its cross-section becoming much larger than expected in gauge theories.

If this does not occur, then the reaction $e^+e^- \to W^+W^-$ would seem to be of marginal interest. Already at LEP the basic gauge vertices will have been seen to produce their predicted cancellations[1,2)]. There will be increasing forward-backward peaking in $e^+e^- \to W^+W^-$ because of the growing role of neutrino exchange, but it seems that the main interest may lie in the domain of radiative corrections. It has been computed[9)] that massive Higgs bosons may manifest themselves indirectly through radiative corrections to $e^+e^- \to W^+W^-$ at the level of a few percent (see Fig. 1 for an example of a relevant diagram). If these are to be seen, a luminosity in excess of 10^{32} cm^{-2} s^{-1} seems essential.

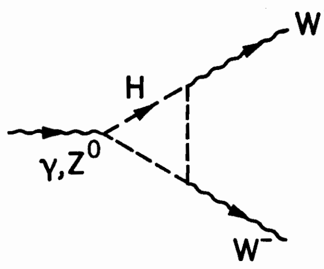

Fig. 1 Important radiative corrections to $e^+e^- \to W^+W^-$ come from Higgs boson diagrams like these

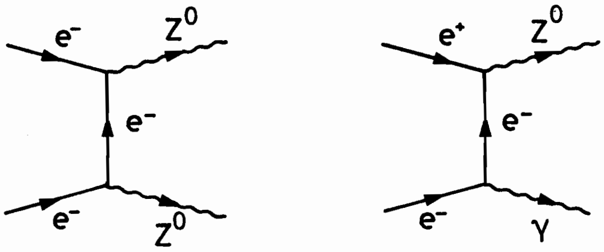

Fig. 2 Dominant diagrams for $e^+e^- \to Z^0Z^0$ and $e^+e^- \to Z^0\gamma$

However, it seems likely that SLEP will have sufficient energy to produce massive Higgs bosons directly through the interactions $e^+e^- \to Z^0H^0$ [10] or $W^\pm H^\mp$ [11]. In view of these remarks, it seems likely that the reaction $e^+e^- \to W^+W^-$ may be rather boring in the SLEP energy range, and will be regarded here as a background to be suppressed in the search for more novel phenomena.

Similar remarks apply with more force to the reactions $e^+e^- \to Z^0Z^0$ [12] and $Z^0\gamma$, which are dominated by electron exchange in the t-channel as in Fig. 2. At low energies these will perhaps have proved interesting for neutrino counting [by looking at events where a γ or Z^0 tag determines a missing mass $\simeq m_{Z^0}$, but there are no observable decay products]. However, we assume here that the neutrinos have been counted -- either by these or by other (toponium decays, Z^0 total width, ...) measurements at lower energies[13]. In this case, the reactions $e^+e^- \to Z^0Z^0$ and $Z^0\gamma$ will probably also be regarded as "background". Background to what?

2.1 A new Z^0?

The Glashow-Weinberg-Salam (GWS) $SU(2)_L \times U(1)$ model[5] is unique in having only one Z^0. Even though there is much circumstantial evidence for this model's neutral currents at low energies, it is consistent with all present measurements to believe that the GWS model is only part of the story, and that there are one or more other Z^0's with masses $\gtrsim O(200)$ GeV [13]. What would such a new Z^0 look like? We assume that its couplings $g_{Z^{0\prime}f\bar{f}}$ to fermions are of the same order as those $g_{Z^0f\bar{f}}$ of the GWS Z^0. Then, because of the relatively large number of fermion flavours, we expect that $Z^{0\prime} \to \bar{f}f$ decays dominate decays into other vector bosons such as $Z^{0\prime} \to W^+W^-$. We therefore have

$$\frac{\Gamma_{\mathrm{total}}(Z^{0\prime})}{\Gamma_{\mathrm{total}}(Z^0)} \approx \frac{m_{Z^{0\prime}}}{m_{Z^0}} \tag{4}$$

and if the number of fermion generations is $N_g \geq 3$:

$$\frac{\Gamma_{\mathrm{total}}(Z^{0\prime})}{m_{Z^{0\prime}}} \approx N_g\ \% \ . \tag{5}$$

The resultant cross-sections at the peak of the $Z^{0\prime}$ are¹⁾

$$\frac{\sigma(e^+e^- \to Z^{0\prime} \to X)}{\sigma_{pt}} = \frac{q}{\alpha^2} B(Z^{0\prime} \to e^+e^-)B(Z^{0\prime} \to X) \ . \tag{6}$$

If we consider the sum of all decays X so that $\sum_X B(Z^{0\prime} \to X) = 1$ and assume that as for the Z^0 ¹⁾

$$B(Z^{0\prime} \to e^+e^-) \approx \frac{1}{10\ N_g} \tag{7}$$

then Eq. (6) gives a peak total cross-section of order

$$\frac{\sigma(e^+e^- \to Z^{0\prime} \to \text{all})}{\sigma_{pt}} \approx 5600 \quad \text{if} \quad N_g = 3 \tag{8}$$

as given in Table 1. Comparing this with the expected value of R in the absence of a $Z^{0\prime}$, we conclude it should be possible to find a $Z^{0\prime}$ if it exists! We then find for the total event rate on the peak

$$N(Z^{0\prime}) = \frac{4.9 \times 10^4}{m^2_{Z^{0\prime}}(\text{GeV}^2)} \ \text{per second} \tag{9}$$

for a luminosity of 10^{32} cm^{-2} s^{-1}. If the mass of the $Z^{0\prime}$ is close to the nominal maximum energy of SLEP:

$$m_{Z^{0\prime}} \approx 700 \ \text{GeV} \Rightarrow N(Z^{0\prime}) \approx 0.1 \ \text{per second} \ . \tag{10}$$

This is a liveable event rate comparable with that of the proposed Single Pass Collider¹⁴⁾ at SLAC ($\mathcal{L} \approx 10^{30}$ cm^{-2} s^{-1} at the Z^0 peak).

We reach the obvious conclusion that $Z^{0\prime}$ physics would be possible and interesting. It may well be that in the design of SLEP a compromise has to be made between the luminosity and the beam energy resolution. For this reason it is important to bear in mind the likely widths of possible "narrow" structures in the e^+e^- centre-of-mass energy. We see from Eq. (5) that a beam energy resolution better than about 3% should be adequate for precise measurements of any possible $Z^{0\prime}$.

2.2 Heavy Higgs bosons

Previous studies have indicated that LEP could produce directly and detect a neutral Higgs boson H^0 with mass up to O(100) GeV ¹,³,¹⁵⁾. The most powerful production mechanism seems to be $e^+e^- \to Z^0H^0$ ¹⁰⁾, for which the cross-section in the GWS model is¹⁶⁾

$$R_{Z^0H^0} = \frac{\sigma(e^+e^- \to Z^0 + H^0)}{\sigma_{pt}} \longrightarrow \frac{1 - 4\sin^2\theta_W + 8\sin^4\theta_W}{128\sin^4\theta_W\cos^4\theta_W} \tag{11}$$

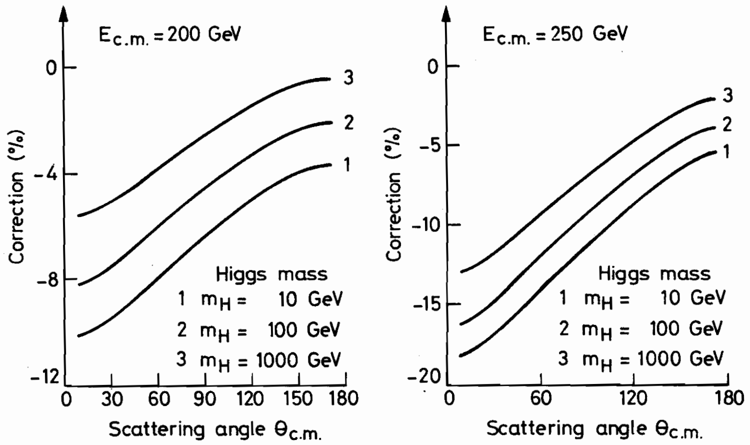

Fig. 3 Some calculations (Ref. 9) of radiative corrections to $e^+e^- \to W^+W^-$ which are sensitive to the Higgs boson mass m_H.

when $E_{cm} \gg m_{Z^0} + m_{H^0}$. Formula (11) gives $R_{Z^0H^0} = 0.16$ if $\sin^2 \theta_W = 0.20$. If the neutral Higgs H^0 is beyond the direct kinematic reach of LEP, indirect effects of its existence may have been seen through the radiative corrections to $e^+e^- \to W^+W^-$ mentioned earlier. Shown in Fig. 3 are some of the results of calculations$^{9)}$ of these radiative corrections at LEP centre-of-mass energies due to diagrams like those in Fig. 1. We see that the differences between the uncorrected cross-section, the radiatively corrected cross-section with a small Higgs boson mass, and that with a large Higgs boson mass, are all of a few percent. Therefore detecting the Higgs boson indirectly with LEP if it has a large mass will be a *tour-de-force*. In this case the reaction $e^+e^- \to Z^0H^0$ is probably the best prospect for producing heavy H^0 directly at SLEP. If we put in the finite-mass and phase-space corrections to Eq. (11), we find at E_{cm} = 700 GeV the cross-sections $R_{Z^0H^0}$ shown in Fig. 4. If we had a luminosity of 10^{33} cm^{-2} s^{-1}, we could see neutral Higgs bosons with masses almost up to the kinematic limit of $E_{cm} - m_{Z^0}$.

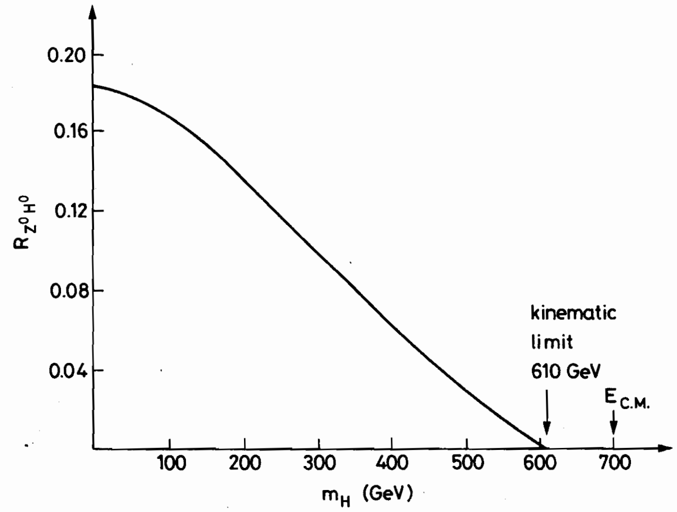

Fig. 4 The cross-section ratios $R_{Z^0H^0} \equiv \sigma(e^+e^- \to Z^0H^0)/\sigma(e^+e^- \to \gamma^+ \to \mu^+\mu^-)$ at E_{cm} = 700 GeV for different Higgs boson masses m_H, neglecting effects due to the large decay width of a heavy Higgs boson.

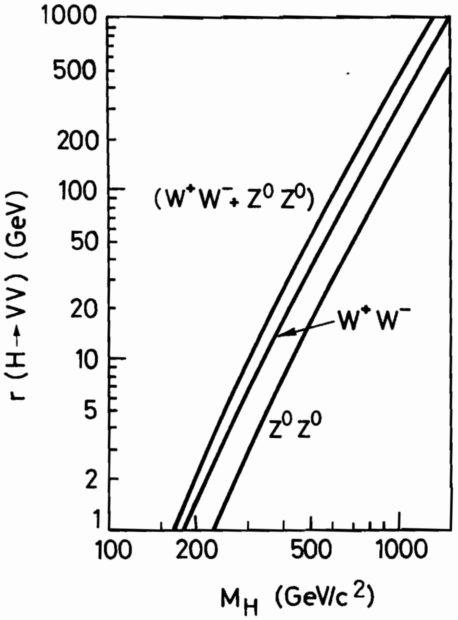

Fig. 5 The decay width of a heavy Higgs boson (Ref. 16)

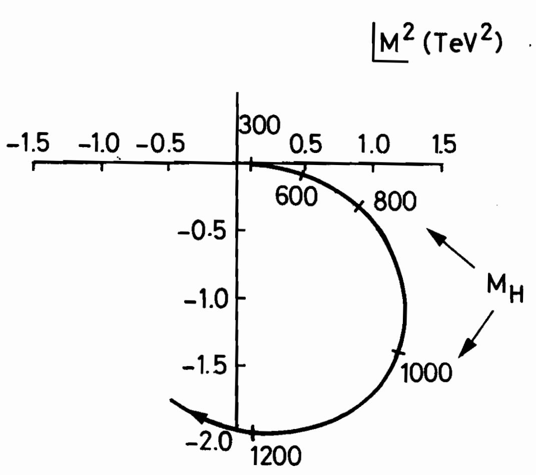

Fig. 6 The position of the pole corresponding to the unitarized Higgs boson (Ref. 16) in the complex m^2 plane

When the H^0 is heavier than 200 GeV its dominant decay modes are into Z^0Z^0 and W^+W^-, with a decay width Γ_{H^0} shown in Fig. 5 $^{16)}$. We see that Γ_{H^0} becomes comparable with m_{H^0} when the mass approaches 1 TeV, as is also indicated in Fig. 6 $^{16)}$, which shows the motion of the unitarized Higgs boson pole in the complex m^2-plane as a function of its nominal "mass". We see clearly the approach to a strong coupling régime where many other interesting phenomena may occur [technicolour? $^{6)}$]. A signal for H^0 production via $e^+e^- \to Z^0H^0$ would be six-jet events where the jets combine pair-wise to give the masses of intermediate vector bosons (cf. Fig. 7). The finite decay width for large m_{H^0} will enhance $R_{Z^0H^0}$ above the values shown in Fig. 4, which were calculated neglecting its decay width. In fact, one could in principle even detect H^0's with masses $> E_{cm} - m_{Z^0}$ if some substantial part of their Breit-Wigner tails came down into the kinematically accessible régime. The signatures for such events would be six-jet events of the type of Fig. 7, but with an indeterminate mass for each of the vector boson pair combinations.

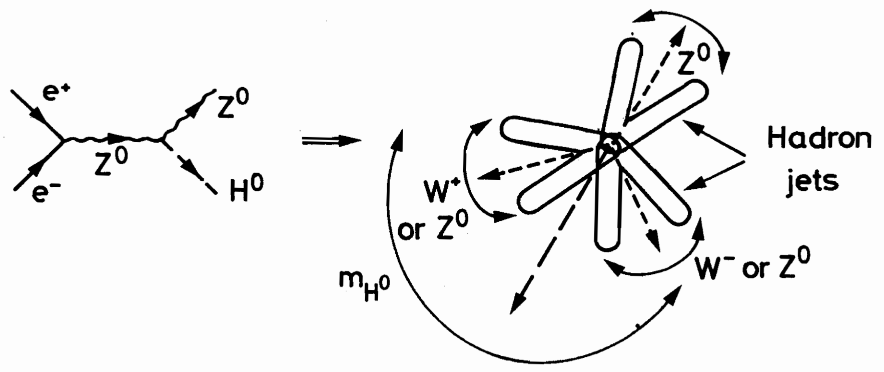

Fig. 7 A six-jet signature for $e^+e^- \to Z^0H^0$

Similar remarks to the above apply also to the production and detection of charged Higgs bosons $H^\pm$, if they exist as anticipated in all gauge theories except the simplest version of the GWS model[5]. LEP should have detected $H^\pm$ with masses up to O(100) GeV, probably through the reaction $e^+e^- \to W^\pm H^\mp$ [3,11], for which the cross-section (apart from kinematic factors and a model-dependent factor of order 1) is expected to be

$$\sigma(e^+e^- \to W^\pm + H^\mp) \approx O\left(\frac{m_W}{m_Z}\right)^4 \sigma(e^+e^- \to Z^0 + H^0) \ . \tag{12}$$

This gives $R_{W^+H^-} = R_{W^-H^+} \approx 0.1$ at $E_{cm} >> m_{W^\pm} + m_{H^\mp}$. Another possible production mechanism is $e^+e^- \to H^+H^-$, which has a cross-section

$$\frac{\sigma(e^+e^- \to H^+H^-)}{\sigma_{pt}} \approx 0.26\beta^3 \tag{13}$$

at high energies. Events of this type would have a characteristic $\sin^2\theta$ angular distribution.

The dominant decays for heavy $H^\pm$ may be anticipated to be into $Z^0W^\pm$, giving signatures analogous to those mentioned earlier for H^0. One difference is a mechanism for getting eight-jet events from

$$e^+e^- \to H^+H^- \begin{array}{l} \to Z^0 W^- \begin{array}{l} \longrightarrow 2 \text{ jets} \\ \longrightarrow 2 \text{ jets} \end{array} \\ \to Z^0 W^+ \begin{array}{l} \longrightarrow 2 \text{ jets} \\ \longrightarrow 2 \text{ jets} \end{array} \end{array} \tag{14}$$

as indicated in Fig. 8.

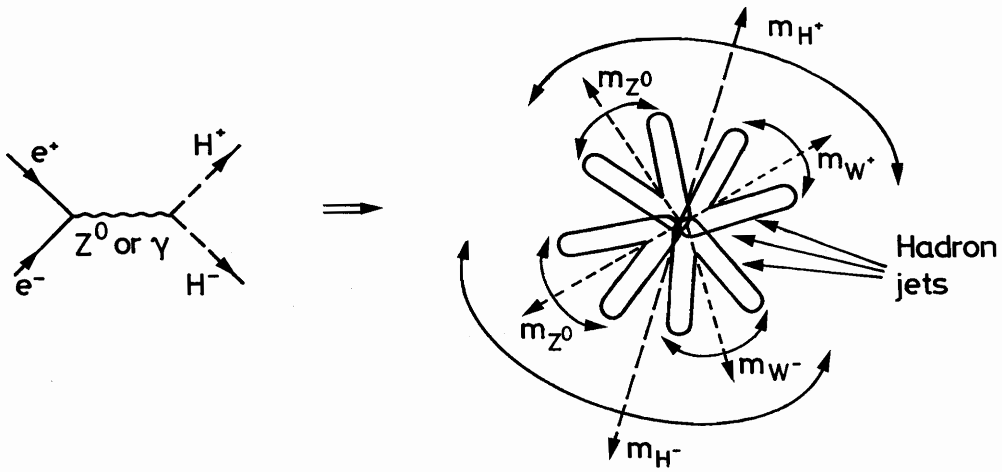

Fig. 8 An eight-jet signature for $e^+e^- \to H^+H^-$

We conclude that heavy Higgs bosons with masses up to O(700) GeV could be produced and detected with SLEP -- as long as the luminosity is high enough to cope with the low event rates implied by Table 1. R = 0.16 corresponds to about 1 event/4 theoretical days at a luminosity of 10^{32} cm^{-2} s^{-1}.

3. FERMION PHYSICS

Most gauge physics up to now has concerned the interactions of fermions, and this may conceivably still be interesting at SLEP energies. However, this is not obvious, since we are assuming that all fermions with masses up to 100 GeV will have been produced and studied at LEP. These "light " fermions may therefore be boring after the year 2000, and it is not clear that there will be any previously inaccessible fermions with masses > 100 GeV. However, we will see that their physics would reveal some interesting features.

3.1 Bounds on masses

There are three arguments against the existence of very heavy fermions, all of which have loopholes and should not be taken too seriously, but they may have some cultural value.

A) The neutral to charged current ratio is sensitive to the ratio of $W^\pm$ and Z^0 masses:

$$\frac{\sigma(NC)}{\sigma(CC)} \propto \left(\frac{m_W}{m_Z}\right)^4 . \tag{15}$$

The ratio m_W/m_Z is in turn sensitive to the masses of heavy fermions through radiative corrections due to the fermion loops of Fig. 9 [17]:

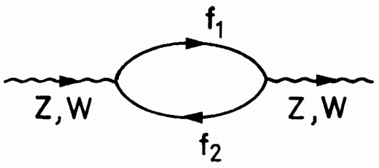

Fig. 9 Fermion loops which renormalize (Ref. 17) the ratio m_W/m_Z cos θ_W

In the simplest GWS model with just I = ½ Higgs:

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 + \begin{bmatrix} 1 \text{ (leptons)} \\ \text{or} \\ 3 \text{ (quarks)} \end{bmatrix} \frac{G_F}{8\sqrt{2}\pi^2} \left[\frac{2m_1^2 m_2^2}{m_1^2 - m_2^2} \ln\left(\frac{m_2^2}{m_1^2}\right) + (m_1^2 + m_2^2) \right] \tag{16}$$

where the sum is over all pairs f_1, f_2 of fermions in weak doublets. If we accept uncritically the complete GWS model with only I = ½ Higgs multiplets and neglect the masses of all except the heaviest fermion f in the most massive doublet (assumed to be a quark), then present data on neutral currents which imply[18]

$$\rho = 1.002 \pm 0.015 \tag{17}$$

would mean that

$$m_f \lesssim 400 \text{ GeV} . \tag{18}$$

Presumably this argument will have been tightened by the time of SLEP, and either one will have a much better limit on m_f ($\lesssim$ 100 GeV?), or there will be some positive indication that ρ deviates from 1.

Should we abandon hope for heavy fermions if ρ does seem to be 1 to a good approximation? No, because

- a doublet of approximately degenerate heavy fermions would not cause ρ to differ significantly from 1;
- maybe the Higgs are not all $I = \frac{1}{2}$;
- maybe there are no explicit Higgs at all[6)], and the whole basis for calculating m_W/m_Z has to be reconsidered.

B) The Higgs potential $V(\phi)$ gets radiative corrections from the fermion loops of Fig. 10b which come in with a minus sign[19)]:

$$\Delta V(\phi) \propto -\sum_f \left(\frac{m_f}{m_W}\right)^4 |\phi|^4 \ln |\phi|^2 \ . \tag{19}$$

If there are fermions that are sufficiently heavy, this negative contribution to the Higgs potential could cause it to go haywire at large $|\phi|$, and invalidate the usual structure of spontaneous symmetry breaking. To avoid this, we need[20)]

$$\sum_f m_f^4 \lesssim O\left[(130 \text{ GeV})^4\right] \tag{20}$$

if we neglect all other effects. Should we take this argument very seriously? No, because

- heavy Higgs bosons (Fig. 10c) would make a contribution to $V(\phi)$ analogous to (19) but with a plus sign[19)]

$$\Delta V(\phi) \propto +\sum_H \left(\frac{m_H}{m_W}\right)^4 |\phi|^4 \ln |\phi|^2 \tag{21}$$

  which could easily counterbalance the fermions;
- maybe there are no explicit Higgs fields[6)], and the whole framework of the argument is invalidated.

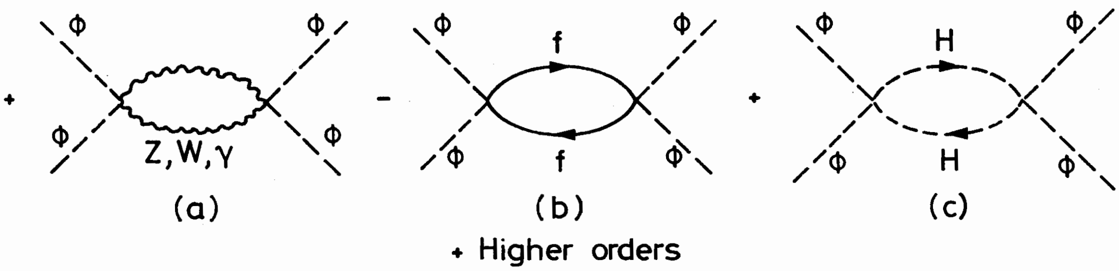

Fig. 10 Radiative corrections (Ref. 19) to the Higgs potential $V(\phi)$ which come from a) vector boson loops, b) fermion loops, and c) Higgs boson loops.

C) When we compute the evolution of coupling constants in certain grand unified theories[21], we find[22] that to avoid their going haywire, the Higgs and fermion masses cannot be too large:

$$m_{H,f} \lesssim O(200)\ \text{MeV}\ . \qquad (22)$$

But

- Who believes in grand unified theories[21] anyway?

In addition to the above arguments against massive fermions, there are a couple of arguments against a proliferation of fermion generations beyond 3. If we assume that the top quark has been found at or before LEP, then there may be no scope for very heavy fermions.

According to standard cosmology, primordial nucleosynthesis gives the correct abundances of helium and deuterium only if there are at most 3 or 4 essentially massless [$\lesssim O(1)$ MeV] neutrinos[23]. But perhaps the neutrinos are not massless, and Who believes standard cosmology anyway?

In some grand unified theories[21], we can predict the bottom quark mass and get about the right value of ∿ 5 GeV if there are three or at the most four generations[24]. But even if we do believe in grand unified theories, we do not necessarily have to accept the extra assumptions leading to this quark mass estimate.

None of the above arguments is sufficiently convincing to make us disbelieve in very massive fermions accessible only to SLEP. So *la lutte continue*.

3.2 A new quark threshold

We now have a standard picture of a new quark threshold[1,4,25], illustrated in Fig. 11. It is presaged by a collection of onium states whose hadronic decays are strongly suppressed by some variant of the Zweig rule. According to QCD they should decay predominantly into planar final states as in Fig. 11b. Just above threshold one expects final states to look very different -- approximately spherical, because the heavy quarks are expected to cascade weakly down to light quarks. These give jets because of their relatively high energies, e.g.

$$\begin{tikzcd}
e^+e^- \arrow[r] & h\bar{h} \arrow[rrrr] \arrow[dr] & & & & \text{similar cascade} \\
& & tq\bar{q} \arrow[dr] & & & \\
& & & bq'\bar{q}' \arrow[dr] & & \\
& & & & c\,q''\bar{q}'' \arrow[dr] & \\
& & & & & s\,q'''\bar{q}'''
\end{tikzcd} \qquad (23)$$

which implies a total of 18 quark jets in the final state: probably rather spherical, as indicated in Fig. 11c!

How should this picture look for very massive quarks Q with $m_Q > 100$ GeV? It is probably reasonable to expect on the basis of QCD that the spectroscopy of at least the

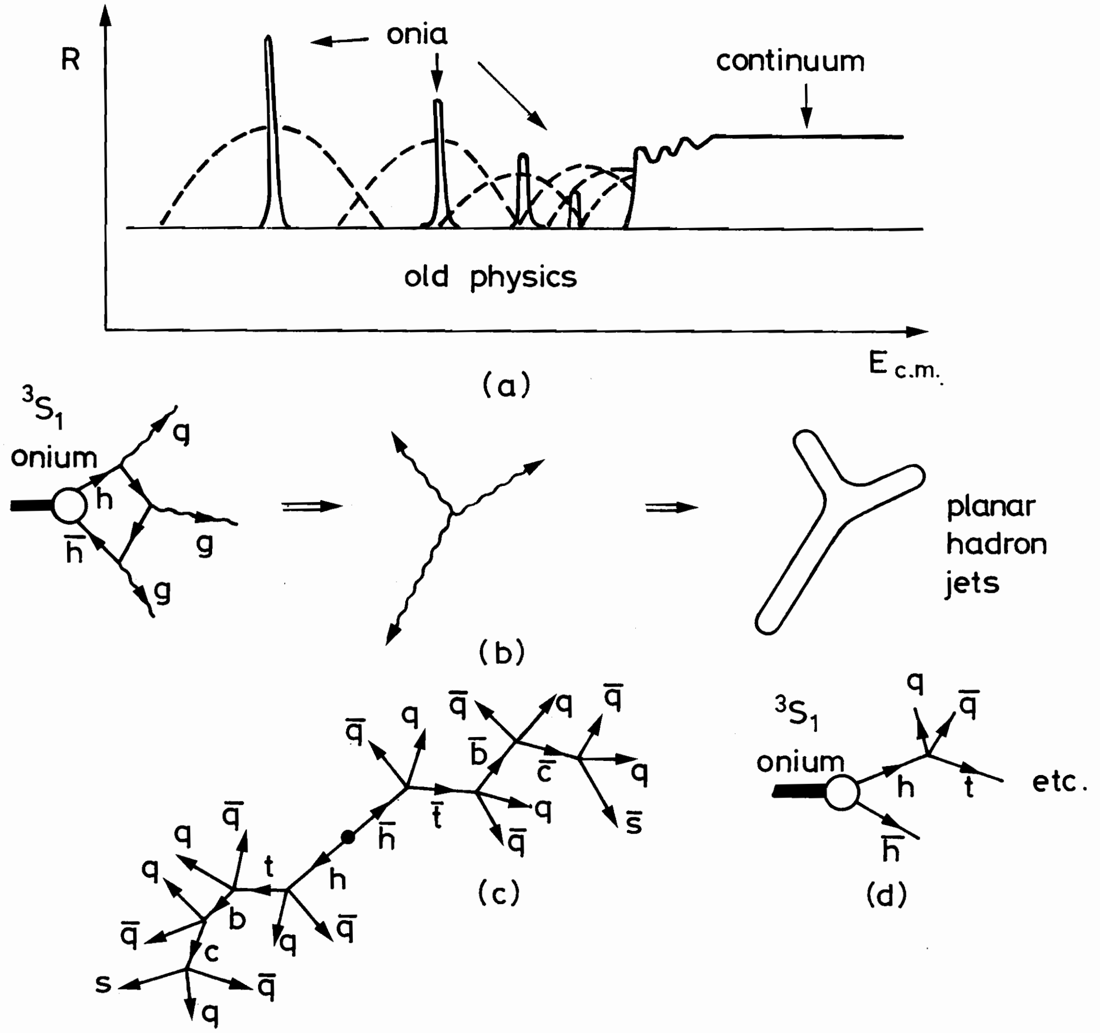

Fig. 11 A new heavy quark threshold: a) narrow onia preceding the continuum may be broadened (dashed lines) by weak decays $Q \to W^+ + q$, so that while b) normal Zweig-suppressed decays give planar final states, c) weak decay chains of heavy quarks probably give essentially spherical final states, and d) these probably dominate the final states of heavy onia because the heavy quarks decay before they can annihilate as in (b).

lower-lying states will be approximately Coulombic. Hence the binding energy of the first N^3S_1 onia is expected to be

$$\text{B.E.} = \frac{1}{4N^2}\left(\frac{4}{3}\alpha_s\right)^2 m_Q \qquad (24)$$

If we use the asymptotic freedom formula

$$\alpha_s \approx \frac{12\pi}{(33-2f)\ \ln Q^2/\Lambda^2} \qquad (25)$$

and take the number of flavours $f = 6$, $\Lambda^2 = \frac{1}{2}$ GeV^2 and a typical value of $Q = 2m_Q = 600$ GeV, then we get

$$\alpha_s \simeq 0.13 \quad . \qquad (26)$$

which when substituted into the formula (24) for the binding energy gives for the lowest state

$$\text{B.E.} \approx (7.5 \times 10^{-3})\ m_Q \tag{27}$$

and a separation from the second state of

$$(7.5 \times 10^{-3})\ m_Q \times \left(1 - \frac{1}{4}\right) \approx 5 \times 10^{-3}\ m_Q \tag{28}$$

The most dramatic modification of the conventional image of onium decays is that the weak decay width of an individual quark -- where the onium just falls apart as in Fig. 11d -- is no longer negligible: in fact it dominates Zweig-forbidden hadronic decays (Fig. 11b) of the $Q\bar{Q}$ bound state. Neglecting generalized Cabibbo angle suppression factors, one may estimate

$$\begin{aligned} \Gamma(Q \to W^{\pm} + q) &\approx \frac{G_F}{\pi}\frac{m_Q m_W^2}{10} \\ &\approx 3 \times 10^{-3}\ m_Q \end{aligned} \tag{29}$$

Remembering that an onium state contains both a quark and an antiquark, we find

$$\Gamma(\text{Onium}) \approx (6 \times 10^{-3})\ m_Q \tag{30}$$

which is comparable with the separation [formula (28)] between different onium states, as indicated by the dashed lines in Fig. 11a.

It can therefore be anticipated that the onium region may closely resemble the region above "threshold", which should follow the "standard" expectations and contain spherical events of the type of Fig. 11c. A signal for reaching this region would be a jump in $e^+e^- \to W^+W^-$ + hadrons events. Because of the large decay width [formula (30)] and not especially unique final state, it is not obvious that one should fight hard to get very good beam energy resolution, much better than 1%: a good match with the capabilities of colliders?

3.3 Jets

There are two important aspects of jet physics at SLEP energies. One is the expected broadening and possible splitting due to QCD effects[4,26]. Another is the difficulty and possible optionality of discriminating between the different flavours of quark jets.

3.3.1 QCD jets

It is now a commonplace that we expect the average p_T in $e^+e^- \to$ QCD jets to grow almost linearly with the jet energy:

$$\langle p_T \rangle = O\left(E_{jet} \times \frac{\alpha_s}{\pi}\right) \propto E_{jet}/\ln E_{jet} \tag{31}$$

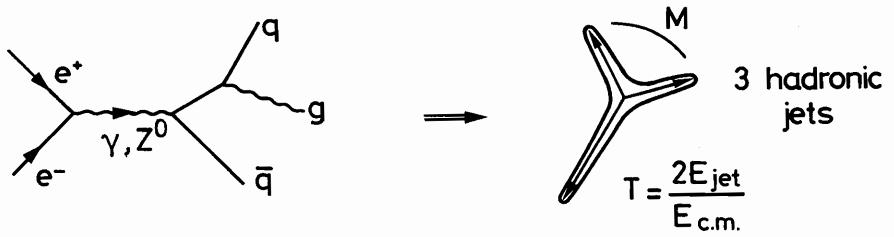

Fig. 12 The dominant process giving p_T spread in e^+e^- annihilation is hard-gluon bremsstrahlung which gives three-jet events

We also expect events with a particularly large p_T spread to have a relative probability of $O(\alpha_s/\pi)$ and to show up mainly as three-jet final states[26] as in Fig. 12. Both of these phenomena seem to be seen at PETRA[27], and will probably be very old hat at SLEP. These phenomena are part of a generally expected jet perturbation theory:

$$\sigma(2\,\text{jet}) : \sigma(3\,\text{jet}) : \sigma(n\,\text{jet}) = 1 : O\left(\frac{\alpha_s}{\pi}\right) : O\left(\frac{\alpha_s}{\pi}\right)^{n-2} \tag{32}$$

for conventional $e^+e^- \to$ hadrons events. It is not clear whether the multi-jet events are of great intrinsic interest within the framework of QCD: for example, they do not seem to be very sensitive measures of the three-gluon vertex[28]. On the other hand, they are an important discriminator between QCD and theories which are not asymptotically free, for which one might expect

$$\sigma(2\,\text{jet}) : \sigma(3\,\text{jet}) : \sigma(n\,\text{jet}) = 1 : O(1) : O(1) \tag{33}$$

However, as mentioned earlier, we assume that the choice between (32) and (33) has been decided[4] prior to SLEP, with QCD and (32) emerging victorious.

One will perhaps be more interested in the structure within an individual QCD jet: both for its intrinsic interest and for its implications for reconstructing complicated final states from their multi-jet signatures: e.g.

$$\begin{tikzcd}[row sep=small] & & W^+W^- \arrow[r] \arrow[dr] & 2\,\text{jets} & \\ e^+e^- \arrow[r] & Z^0 + H^0 \arrow[ur] \arrow[drr] & & 2\,\text{jets} & \left.\right\} \Rightarrow 6\ \text{jets} \\ & & & 2\,\text{jets} & \end{tikzcd} \tag{34}$$

The expectations (32) mean that such processes should be relatively background-free, but the finite width of QCD jets might in principle give problems when we try to reconstruct di-jet invariant mass combinations. To assess this, we recall that in e^+e^- annihilation into two or three jets[25,26],

$$M = E_{cm}\sqrt{1-T} \tag{35}$$

is the invariant mass of the two less energetic jets (see Fig. 12) recoiling against the most energetic jet with

$$E_{jet} = \frac{T}{2} E_{cm} \tag{36}$$

where T is the conventional thrust[29] variable. From (35) we see that the average

$$\langle M \rangle = E_{cm} \left\langle \sqrt{1-T} \right\rangle = O\left(\frac{\alpha_s}{\pi}\right) E_{cm} \tag{37}$$

When M is > O(10) GeV, we expect to be able to resolve the di-jet combination into two distinct jets. When $E_{jet} \approx 1$ TeV and $\langle M \rangle$ is O(100) GeV we can expect that quite often one of the sub-jets will itself have mass > O(10) GeV, and itself be resolvable into two jets. And so it may continue for ever more energetic (and massive) jets. This process of "fractalization" of jets is illustrated in Fig. 13.

The spectrum of invariant masses of jets is expected to fall sharply with increasing mass, reflecting the classic bremsstrahlung spectrum. This means that when seeking out di-jet combinations at SLEP with masses $\sim m_Z$ or m_W = O(100) GeV, we do not expect to have significant background problems (see Fig. 14). However, if we go to much higher energies than SLEP, so that the typical jet energy is in excess of 1 TeV, the problems may be more serious. This is a question which requires much more thought, calculation, and computation.

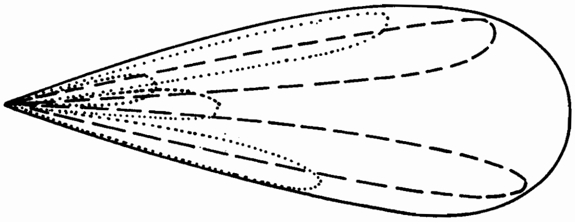

Fig. 13 Two stages of fractalization where an energetic and massive jet (solid line) is resolved into two subjects (dashed lines), each of which can, if observed carefully, be resolved into two mini-jets.

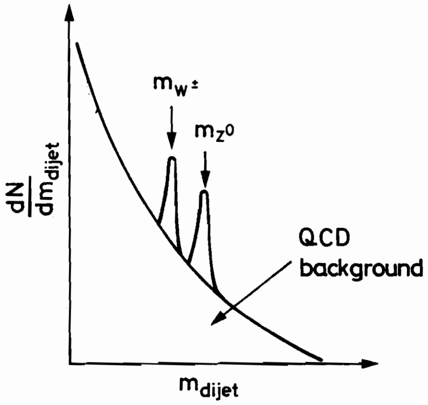

Fig. 14 Given good enough resolution, it should be possible at SUEP to pick out di-jet combinations from $W^\pm$ and Z^0 decays, despite the QCD background.

3.3.2 Jet flavouring

It would clearly be nice to be able to discriminate between jets of different flavours -- for example, to pick out different decay modes of the $W^\pm$ and Z^0, or to test whether Higgs bosons really do like to couple to fermions proportional to their masses[10]. However, it is not clear that jet flavouring is essential, and it presents certain difficulties. Let us consider, in turn, u, d, gluon, s, c, b, and t jets. It is difficult to see how we can ever discriminate reliably between u and d jets, as the primordial charge of a jet is presumably not observable[30]. At high enough energies, gluon jets may be distinguishable on the basis of their greater perturbative width[31], but we must await quantitative data on gluon jets before judging the reliability of this method of flavouring (or unflavouring) a jet. Even in the presence of QCD effects, the information that a jet comes from an s-quark is probably carried by the four or five fastest particles. These particles are probably those with z ($\equiv E_{\mathrm{hadron}}/E_{\mathrm{jet}}$) $\gtrsim 0.1$: it is difficult to see how the valence quark could fall much further down in the z variable. Probably the slower 95% of the particles carry little or no flavour information and are not interesting from this point of view, and experimental efforts should be focused on the faster particles.

Charm jets should mainly contain strange particles, but at lower z than is characteristic of s jets. The mass of the c-quark is not high enough for it to give a signature in the form of an abnormally high value of $\sum_{\mathrm{hadrons}} |p^T_{\mathrm{hadron}}|$. One may be able to exploit the finite lifetime of charmed particles $\tau \approx 3 \times 10^{-13}$ s. This implies a typical decay length

$$d \approx \gamma c\tau \approx 10^{-2}\ \gamma\ \mathrm{cm} \tag{38}$$

which becomes O(1) cm for $\gamma = 100$, corresponding to an energy of about 200 GeV. It is possible that we may be able to detect events of the types shown in Fig. 15, either by getting a detector within 1 cm of the interaction point -- which is perhaps possible at large angles to the beam directions -- or by very accurate tracking at larger distances.

The medium-heavy b quark is expected[32)] to have the decay chain $b \to c + \bar{u} + d$ predominating: this suggests a trigger based on a c signature in the jet. Unfortunately, the b probably decays too rapidly $[O(10^{-13}$ to $10^{-14})$ s$]$ for it to be practicable to look for its finite track length at SLEP. In principle, one might expect from the three-quark decay mode to find three mini-jets, each with transverse momentum $\sim 1\frac{1}{2}$ GeV (cf. Fig. 16a). Unfortunately, the transverse energies are probably not sufficient to reveal this structure,

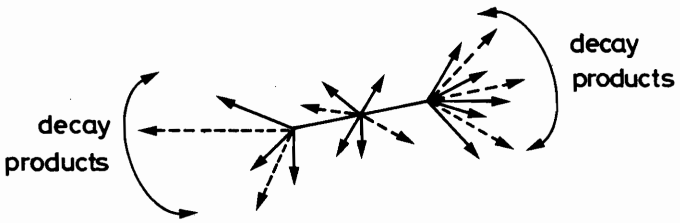

Fig. 15 Charmed particles travel an observable finite distance before decaying. In general, other particles will also be produced at the e^+e^- annihilation point.

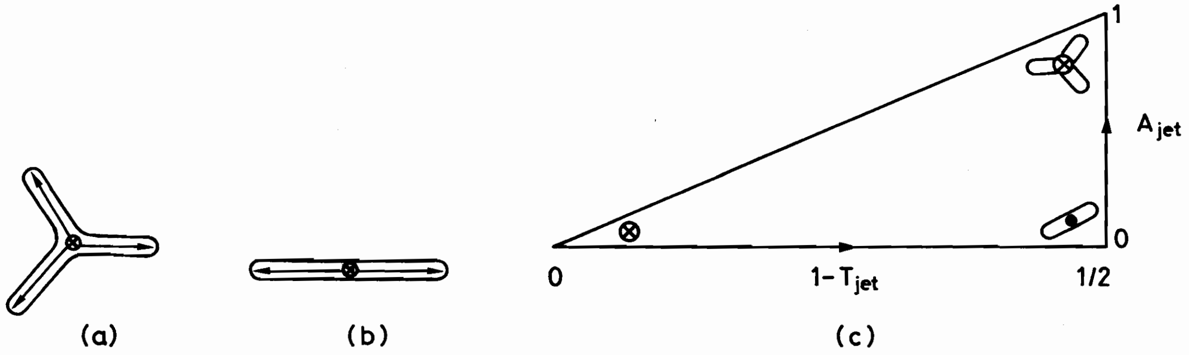

Fig. 16 a) The transverse section of a heavy quark jet decaying as $Q \to q q \bar{q}$. b) The transverse section of a QCD jet broadened by $q \to q + g$, or $g \to g + g$, $g \to q + \bar{q}$. c) Jet "Dalitz plot" analogous to those used in e^+e^- annihilation, with the familiar thrust and acoplanarity variables defined for an individual jet (Refs. 25 and 27).

and the transverse sections of b jets will probably just look circular. They might tend to have anomalously high values of $\sum_{\text{hadrons}} |p^T_{\text{hadron}}|$, but in the absence of data it is not clear that this quantity will be very different from a c, u, d, s or gluon jet. Because of the possible cascade

$$\begin{array}{l} b \to c + \ell^- + \nu \\ \quad \llcorner\!\!\to \ell^+ + \nu + s \end{array}$$

a few b jets will have a dilepton signature, but because of the two low branching ratios of O(10)%, this would be a very inefficient way of triggering. It may be difficult to find b jets reliably.

The situation is likely to be better in the case of t-quark jets. One expects the $t \to b + u + \bar{d}$ decay chain to produce the 3 sub-jet structure of Fig. 16a in the plane transverse to the jet axis. Each sub-jet should have $p_T \gtrsim 5$ GeV on the average, and so the triple structure should show up if one looks for events with high spherocity $(\sum_{\text{hadrons}} |p^T_{\text{hadron}}| / \sum_{\text{hadrons}} E_{\text{hadron}})$, low thrust $(\sum_{\text{hadrons}} |p^L_{\text{hadron}}| / \sum_{\text{hadrons}} E_{\text{hadron}})$, or high acoplanarity. This latter might be the best way to distinguish a t-quark jet from a QCD jet effect. In QCD we expect the predominant jet-broadening effect to be a splitting $(q \to q + g,\ g \to q + \bar{q}$ or $g + g)$ which produces jets which are oblate or planar as in Fig. 16b. To discriminate between different types of jet, we could make jet "Dalitz plots" analogous to those popular in e^+e^- collisions today[25,27)], but now on a jet-by-jet basis, rather than treating the event as a whole. Narrow jets would show up at the apex of the triangle in Fig. 16c, QCD jets would appear along the bottom side, and top-quark jets would populate the upper part of the triangle. The effectiveness of this procedure should increase with the (as yet unknown) mass of the t-quark and of even heavier quarks.

In summary, the above analysis suggests that it may well be possible to find c and t flavour jets reasonably easily, that s and b quark jets present more problems, that distinguishing a gluon jet on the basis of its perturbative width may be possible, but that we should give up on u- and d-quark jets.

4. NEW PHYSICS

If the physics described above is all that we find to do with SLEP, we (or our descendants) will all be very disappointed. We will also be disappointed if all that is discovered is what follows in the rest of *this* section, but the things described here may serve as mind-expanders that help to generate the sort of questions we may be asking of our experiments with SLEP.

4.1 Technicolour

As mentioned briefly in the Introduction, the technicolour idea[6)] is that there may be a new set of strong interactions on a scale ∿ (1 to 3) × 10^3 the scale of the conventional strong interactions generated by QCD. One postulates a new exact non-Abelian symmetry analogous to SU(3) of colour. Just as asymptotic freedom,

$$\alpha_s \approx \frac{12\pi}{(33-2f)\ \ln Q^2/\Lambda^2} \tag{39}$$

run backwards from high energies gives strong interactions at momenta $Q = O(\Lambda)$, so a technicolour interaction

$$\alpha_T \approx \frac{12\pi}{\ln (Q^2/\Lambda_T^2)} : \Lambda_T \approx (1 \text{ to } 3) \times 10^3 \Lambda \tag{40}$$

becomes strong on a scale of momenta $Q = O(\Lambda_T)$. If one chooses a technicolour group with a coefficient

$$A < \frac{12\pi}{(33-2f)} \tag{41}$$

[e.g. SU(4) with f flavours of techniquarks] then at some superhigh energy $\alpha_s \simeq \alpha_T$, and we can imagine unifying colour and technicolour in some grander theory.

Just as ordinary hadrons have a complicated spectrum starting at masses $O(\Lambda)$, e.g. ρ, p, Δ, σ, ..., so we also expect a complicated new spectrum of technihadrons[33] with masses

$$m_{T\rho}, m_{Tp}, m_{T\Delta}, m_{T\sigma}, \ldots \approx (0.5 \text{ to } 3) \text{ TeV} \tag{42}$$

The original motivation for technicolour was to replace explicit Higgs fields by composites of techniquarks and antiquarks. In the most economical version of the conventional Higgs mechanism, one introduces a single complex doublet of Higgs fields

$$\begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \begin{pmatrix} \bar{\phi}^0 \\ \phi^- \end{pmatrix} \tag{43}$$

of which the $\phi^\pm$ and $1/\sqrt{2}i\ (\phi^0 - \bar{\phi}^0)$ combinations are eaten by the $W^\pm$ and Z^0 to become their longitudinal polarization states, allowing them to acquire a mass. The fourth combination $1/\sqrt{2}\ (\phi^0 + \bar{\phi}^0)$ acquires a vacuum expectation value which generates the masses, and the shifted field H^0 is a physical neutral Higgs boson. In the most economical technicolour model there are two techniquarks U and D (each coming in several technicolours) which bind to form technipions π_T^+, π_T^0, π_T^- and a techniscalar field σ_T. Just as in the old σ model of chiral symmetry breaking, the σ_T field is postulated to acquire a vacuum expectation value of $O(\Lambda_T)$ dynamically. The $\pi_T^\pm$ and π_T^0 are then eaten by the $W^\pm$ and Z^0 as before, and there is a physical shifted scalar field σ_T^0. This field is strongly interacting and may (like the conventional σ field) not really correspond to a recognizable physical particle. If it does, it will probably have a mass of order 1 TeV and be like our old friend, the strongly interacting Higgs boson of Section 2.2, with a decay width of order 1 TeV. Like a heavy Higgs boson, the dominant couplings of the σ_T^0 might be to longitudinal polarization states of $W^\pm$ and Z^0 bosons. If its mass were sufficiently low, the σ_T^0 might be produced directly at SLEP via the reaction $e^+e^- \to Z^0\sigma_T^0$. Because the physical σ_T^0 would be so broad, this reaction would have the signature of giving continuum $e^+e^- \to Z^0Z^0Z^0$ or $Z^0W^+W^-$ events. If it was too heavy to be produced in this way, effects of the σ_T^0 would only be seen indirectly in the reaction $e^+e^- \to W^+W^-$.

However, in addition to providing a dynamical basis for the strong interactions of heavy Higgs bosons, technicolour also leads us to expect[33] that there would be other technihadrons, at least one of which, the technirho ρ_T, should show up as a direct channel resonance in e^+e^- annihilation. If its mass were between (1 and 3) × 10^3 times the ρ mass, then

$$m_{\rho_T} \simeq (700 \text{ to } 2000) \text{ GeV} \tag{44}$$

and we should be able to see at least its tail, if not its peak at SLEP. At low energies it would appear as a deviation from point-like behaviour of the longitudinal polarization components of the $W^\pm$ and Z^0, which would be expected to be the dominant decay products of the ρ_T. At the peak of the ρ_T, the cross-section would be

$$R_{\rho_T} \equiv \frac{\sigma(e^+e^- \to \rho_T \to X)}{\sigma_{pt}} = \frac{q}{\alpha^2} B(\rho_T \to e^+e^-)B(\rho_T \to X) \tag{45}$$

If we guess that

$$B(\rho_T \to e^+e^-) \approx B(\rho \to e^+e^-) \approx 4 \times 10^{-5} \tag{46}$$

then we estimate from (45) that

$$R_{\rho_T} \approx 7 \tag{47}$$

which is not an impressively large bump, and indicates that the low-energy tail of the ρ_T may be difficult to see. Perhaps the energy of SLEP is too low?

There are other types of technihadrons which might show up. In QCD there are some particles -- the pseudoscalars π, K, and η, which have masses rather less than the typical hadronic scale. In the conventional ideology, this is because their masses are given by

$$m^2_{PS} = O(\lambda) \times m_q \tag{48}$$

rather than being of order Λ^2 like ordinary hadronic $(\text{mass})^2$, and some quarks have masses much less than Λ. A similar situation might occur with technicolour. In the simplest version of the theory, there are just two massless techniquarks, giving $\pi_T^{\pm,0}$, which are all eaten by the $W^\pm$ and Z^0. But if there are three or more techniquarks there would be some uneaten technipseudoscalars. If the techniquarks have masses, these states would have masses given by the techni-analogues of Eq. (48) and might be expected to have masses $\lesssim$ O(100) GeV. If the techniquarks have zero mass, then these pseudoscalars would also have zero mass in lowest order, but some mechanism may be found to give them a mass in higher order:

$$m^2_{PS_T} = O(\alpha \text{ or } \alpha^2) \times \Lambda_T^2 \tag{49}$$

in which case their masses would be O(10 to 100) GeV. Also, in most models[33] there are technicoloured partners of leptons as well as of quarks, and so more light pseudoscalars than in the single two-fermion flavour model we used above.

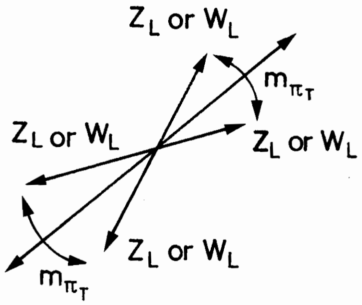

Fig. 17 Four-jet signature for $e^+e^- \to \rho_T$ followed by $\rho_T \to \pi_T^+\pi_T^-$, and subsequent decay of the $\pi_T^\pm$ into longitudinally polarized Z or W bosons.

These PS_T particles are generically called Pseudo-Goldstone Bosons (PGBs) [33,34]. They would be produced at LEP, but at those low energies they would look point-like and probably be mistaken for conventional Higgs particles. However, SLEP should be able to see their structure and strong interactions begin to emerge. If PGBs exist, pairs of them would be important decay modes of the heavier σ_T and ρ_T technicolour particles discussed earlier, along with longitudinally polarized vector bosons. Each PGB would presumably decay into pairs of ordinary quark jets, so a signature for ρ_T or σ_T production would be four-jet events as indicated in Fig. 17. Therefore jet detection, measurement, and combination in search of invariant mass bumps seems to be an inescapable aspect of technicolour physics.

There is one other class of amusingly exotic PGBs that should be mentioned, which may provide the most distinctive signature for technicolour. Recall that flavour is invariant under the conventional QCD strong interactions, so that we have flavoured PGBs of the colour interactions such as $\pi^\pm$, $K^\pm$, etc. In a similar way, in simple models technicolour commutes with ordinary colour, and we can imagine[33] *coloured* PGBs of technicolour such as

$$\pi_T^c \propto \bar{U} \frac{\lambda^c}{2} D \tag{50}$$

where λ^c is a matrix in ordinary colour space. It has been guessed that these coloured PGBs may have masses O(150 to 300) GeV. Their decay modes would include[33] coloured particles such as gluons, and one anticipates decays such as that in Fig. 18:

$$\pi_T^c \to g + (W^\pm \text{ or } Z^0 \text{ or } \gamma) \tag{51}$$

Looking for invariant mass bumps in combinations such as formula (51) would certainly be a distinctive signature for technicolour.

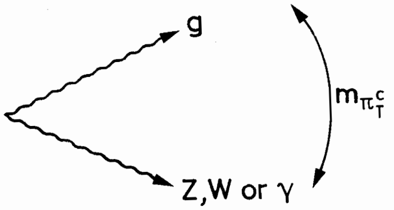

Fig. 18 Signature for a coloured technipion: $\pi_T^c \to g^c + (Z \text{ or } W \text{ or } \gamma)$.

If it exists, there should be plenty of technicolour to see -- if SLEP has a high enough energy. Presumably before it is constructed we will have a better idea whether technicolour really exists, and if so on what scale -- in the range 0.5 to 3 TeV?

4.2 Supersymmetry

Supersymmetry is a conjectured symmetry between fermions and bosons which groups them into common supermultiplets7). It is a very beautiful idea which may help to reduce some of the infinities in conventional field theory and also gravity. Unfortunately, no sign has yet been seen of its relevance to high-energy physics -- no candidates for supermultiplets have been seen, and any superpartners of the known elementary particles must have considerably higher mass. How high, we do not know, though there have been some suggestions that the scale of supersymmetry may be related to that of the conventional weak interactions -- about 100 GeV 35). If so, we would expect supersymmetric partners of many familiar particles to be kinematically accessible to SLEP. Table 2 shows a compilation7,35) of possible supersymmetric particles, together with the cross-sections expected for them at SLEP as well as some remarks about signatures. Let us discuss each of them in turn.

Table 2

Catalogue of supersymmetric particles

Type of supersymmetric particle	Production at SLEP	Signature
Scalar quarks $\tilde{q}$	$R = \left\{\begin{array}{l} 0.37 \text{ for } \tilde{u}\tilde{u} \\ 0.11 \text{ for } \tilde{d}\tilde{d} \end{array}\right\}$ (Fig. 19) Visible for $m_{\tilde{q}} < \frac{1}{2} E_{cm}$?	Almost back-to-back jets with large missing energy from $\tilde{q} \to \tilde{\nu} + q$.
Scalar leptons $\tilde{\ell}$	$\left.\begin{array}{l} R_{\tilde{\ell}^+\tilde{\ell}^-} = 0.26 \\ R_{\tilde{\ell}^0\bar{\tilde{\ell}}^0} = 0.60 \end{array}\right\}$ Visible for $m_{\tilde{q}} < \frac{1}{2} E_{cm}$? $\left.\begin{array}{l} R_{Z^0\tilde{\ell}^0} = 0.1? \\ R_{W^\pm\tilde{\ell}^\mp} \approx 0.1? \end{array}\right\}$ Visible for $m_{\tilde{\ell}} < E_{cm} - 100$ GeV?	As above, but with jet → lepton from $\tilde{\ell} \to \tilde{\nu} + \ell$. Similar cross-sections to those for Higgs bosons?
$\left.\begin{array}{l} \text{Wino } \tilde{W}^\pm \\ \text{Zino } \tilde{Z}^0 \end{array}\right\}$	$R_{\tilde{W}^+\tilde{W}^-} = 1.99$ Visible for $m_{\tilde{W}} < \frac{1}{2} E_{cm}$	Different forward-backward asymmetry from $e^+e^- \to \ell^+\ell^-$.
Gluino $\tilde{g}$	Gluino bremsstrahlung $e^+e^- \to q\bar{\tilde{q}}\tilde{g} + \bar{q}\tilde{q}\tilde{g}$ (Fig. 20) Onium decays	Different angular distribution from $e^+e^- \to q\bar{q}g$. Missing neutral energy.

Scalar quarks $\tilde{q}$ are partners of ordinary quarks. Their vector onia are expected to have negligible couplings to e^+e^- 7,36). Their continua have observable cross-sections, with a β^3 threshold behaviour and a $\sin^2\theta$ angular distribution. In simple models, scalar

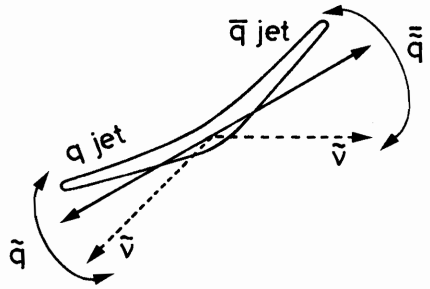

Fig. 19 Signature for production of scalar quarks by $e^+e^- \to \tilde{q}\bar{\tilde{q}}$.

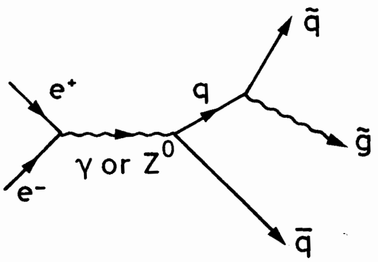

Fig. 20 A typical gluino bremsstrahlung diagram for $e^+e^- \to \bar{q}\tilde{q}\tilde{g}$.

quarks decay to ordinary quarks and another neutral spin ½ supersymmetric particle, a nuino $\tilde{\nu}$ akin to the neutrino. This suggests the event signature shown in Fig. 19 where about half the centre-of-mass energy is invisible in the form of $\tilde{\nu}$'s.

Scalar leptons $\tilde{\ell}$ are charged or neutral partners of conventional leptons[37]. The cross-sections for their pair production are appreciable and have a $\beta^3 \sin^2 \theta$ dependence in common with scalar quarks. Decays of the type $\tilde{\ell} \to \ell + \tilde{\nu}$ would give distinctive signatures. They might be produced analogously to Higgs bosons in the reactions $e^+e^- \to Z^0\tilde{\ell}^0$ or $W^\pm\tilde{\ell}^\mp$ with analogous cross-sections of R = O(0.1).

Winos $\tilde{W}^\pm$ *and Zinos* $\tilde{Z}^0$ are spin ½ leptons which are partners of the $W^\pm$ and Z^0. In the simplest supersymmetry models they have weak isospin I = 1, and so $e^+e^- \to \tilde{W}^+\tilde{W}^-$ has a larger cross-section and forward-backward asymmetry than conventional I = ½ heavy leptons[7]. This should enable them to be distinguished from conventional heavy leptons, which they would resemble in their decay modes ($\tilde{W}^\pm \to \tilde{\nu}\ell^\pm\nu$ or $\tilde{\nu}q\bar{q}$, for example).

Gluinos $\tilde{g}$ are the spin ½ partners of the conventional QCD gluons. They might be detectable[7] via "gluino bremsstrahlung" $e^+e^- \to q\bar{\tilde{q}}\tilde{g}$ or $\bar{q}\tilde{q}\tilde{g}$ three-jet events, which should have angular distributions different from those of conventional $e^+e^- \to q\bar{q}g$ events (cf. Fig. 12), as well as having distinctive decay signatures. They may also be detectable in certain heavy quark onium decays[7].

The above discussion suggests that if supersymmetric particles exist in the kinematic range accessible to SLEP, then they can be produced and detected. Of importance in their detection seem to be calorimetry and "jetometry" to pin down the existence and momenta of missing energy carried off by nuinos $\tilde{\nu}$.

5. OLD FAVOURITES

In discussions of new high-energy e^+e^- machines, there are two questions which recur perennially. They are:

- Are polarized beams interesting?
- Are γγ collisions either an unacceptably large background, or perhaps intrinsically interesting?

This section makes some brief and unperspicacious remarks about these questions.

5.1 Polarization

In conventional weak interaction models, e^+e^- collisions, with the exception of Bhabha scattering, are dominated by vector exchanges in the direct channel or by fermion exchanges in the crossed channel. These exchanges have very definite and distinct helicity properties, e.g. direct channel vectors only couple to e^+e^- with parallel longitudinal helicities ($\rightarrow\rightarrow$, not $\rightarrow\leftarrow$), and neutrinos only couple to left-handed fermions. Thus cross-sections may be strongly modulated by cunning choices of the e^+e^- polarization states. This may be a very useful tool for analysing details of the weak interaction couplings, but it has been emphasized that the same information is in principle obtainable in other ways[38]. Thus total cross-section and forward-backward asymmetry measurements in $e^+e^- \to f\bar{f}$ determine the relative magnitudes of the vector and axial couplings of fermions f, while the relative signs can in principle be determined from measurements of final-state helicities. However, the only case where such helicity measurements are clearly practical is that of $e^+e^- \to$ heavy lepton pairs, where the ($\ell^\pm \to \pi^\pm\nu$ and $(e,\mu)^\pm\nu\bar{\nu}$ decays are suitable helicity analysers. No reliable way of measuring the helicity of a quark has yet been devised. For this reason, within the standard framework, polarization would be a very nice tool to have, but it cannot really be regarded as truly essential.

However, if as we surely hope there are deviations from the standard framework, then polarization may be essential in attempts to disentangle what is happening. One example would be if there were no Z^0, and e^+e^- cross-sections approached the unitarity limit. There would then be no reason to expect exchanges in vector channels to dominate the cross-sections, and the observations of different helicity states would be necessary to build up a complete picture of the deviations from naive gauge theories. A second example would be if there were indeed a strongly interacting Higgs sector (technicolour) in which direct channel exchanges in other partial waves (scalar, pseudoscalar, ...) might no longer be negligible by comparison with vector exchanges.

It therefore seems that polarization is not essential at the beginning of SLEP, but might well become so if present theoretical ideas are drastically wrong. It would in any case be a useful thing to have[38], and if it can be introduced with little extra cost and complication into an e^+e^- linear collider system as seems to be the case, by contrast with a colliding ring machine, then this should clearly be done at some stage.

5.2 $\gamma\gamma$ physics

Since the total two-photon cross-section $\sigma(e^+e^- \to e^+e^- + X)$ increases like $(\ln s/m_e^2)^2$, it will be of order 300 nb at SLEP energies, or about 10^6 larger than an e^+e^- annihilation cross-section with R = 1. This contrasts with a ratio of about 10^3 at PETRA/PEP energies. The first question that arises is whether one can reliably separate the $\gamma\gamma$ event background from annihilation events, and do the annihilation physics which is the primary objective of a high-energy e^+e^- collider. LEP studies[39] have indicated that this problem can be solved in an energy region where the background/annihilation ratio is 10^4 to 10^5, and there seems no reason to think the situation will become catastrophic at LEP. Also experiments at PETRA have experienced no unexpected problems in separating $\gamma\gamma$ events. The PLUTO experiment[40] has started a careful study of $\gamma\gamma$ events, and has a useful event rate about equal to its total $e^+e^- \to$ hadrons rate, corresponding to R = O(4). Since leptonic and point-like cross-sections essentially scale with the centre-of-mass energy to within logarithmic factors, it is to be expected that a higher energy experiment with similar geometric criteria (solid angles of tagging detectors, cut on transverse momentum fraction p_T/E_{cm}, cut on fractional longitudinal momentum imbalance $\Delta p_L/E_{cm}$, etc.) would have similar success at separating and measuring $\gamma\gamma$ events.

The question then arises whether $\gamma\gamma$ events are intrinsically very interesting, in view of the potentially very large event rates. In principle $\gamma\gamma$ collisions can copiously produce pairs of fermions ($\gamma\gamma \to q\bar{q}$ or $\ell^+\ell^-$) but the only ones produced in really large numbers will probably be those already discovered at or before LEP, with masses $\lesssim$ 100 GeV. However, heavy "light" fermions with masses between 50 and 100 GeV will probably be produced with higher rates at SLEP than at LEP, and the relative cleanliness of tagged $\gamma\gamma$ events by comparison with hadronic collisions may mean that SLEP would be the best place to study fermions in this mass range. The process $e^+e^- \to e^+e^-W^+W^-$ may also be interesting at SLEP as a probe of higher-order gauge couplings, but this has not yet been investigated in detail. It has been realized that $\gamma\gamma$ collisions offer useful tests of QCD in events with two, three, or four jets at large p_T [41]. However, it seems likely that this physics will first be done with LEP, which should have sufficient kinematic range for all these jets to be distinguished.

Certainly $\gamma\gamma$ physics will have a place at SLEP, but it is unlikely to avoid being overshadowed by the fundamental interest of e^+e^- annihilation physics.

6. SUMMARY

A brief, preliminary and myopic summary of e^+e^- physics beyond LEP is the following.

A) In contrast to weak vector bosons at LEP, there is not yet any clear advance suggestion of a new energy threshold in the SLEP energy range of (200 to 700) GeV in the centre of mass. (Unless LEP shows that the Z^0 and $W^\pm$ do not exist, in which case SLEP will sit on top of the saturation of unitarity by the weak interactions.) However,

B) if it turns out that there are no "light" $m \lesssim 100$ GeV Higgs bosons, then SLEP may come into its own as a tool for studying heavy, strongly interacting "Higgs" systems, such as technicolour. However, it is possible that technicolour may have an energy scale $>$ 700 GeV and hence be beyond even the reach of SLEP, though perhaps not beyond the reach of a next-generation (20 TeV × 20 TeV) hadron-hadron collider. Of course

C) e^+e^- collisions continue to offer the advantages of easily distinguishable and clean hard-scattering events. However

D) the point-like cross-sections' falling as $1/E_{cm}^2$ means that the rates for "interesting" events at SLEP will be even smaller than those at LEP, suggesting that a luminosity of *10^{33} cm^{-2} s^{-1} per interaction region* will be necessary for SLEP to realize its physics potential.

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