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THE INTEREST IN e^+e^- EXPERIMENTS AT LEP ENERGIES

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ABSTRACT

A review is presented of various open theoretical questions and how LEP experiments may help answer them. Besides the conventional gauge theories of the strong, weak and electromagnetic interactions, LEP should also provide us with useful information relevant to grand unified theories, supersymmetry and dynamical symmetry breaking. New emphasis is laid on toponium as a laboratory for studying the weak interactions as well as the strong, and on the possibilities for testing technicolour at LEP.

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1. General Theoretical Overview

In this talk I hope to keep you convinced that the theoretical interest in LEP experiments is still, as always [1,2], enormous. This is true whether one follows conventional theoretical ideas or espouses more unconventional possibilities. LEP physics is remarkably resilient, with all new theoretical notions that come along apparently amenable to experimental test at LEP. This reflects the fundamental advantages of e^+e^- annihilation: it is an unbiased, 100% energy-efficient and background-free factory for new particles and hard interactions. In this first Section I will present a brief overview of current theoretical ideas and the evidence for their validity, pointing out some important outstanding problems which may be illuminated by LEP. Subsequent sections will take up in more detail some specific questions of interest and how LEP experiments may explore them.

It is now generally believed that all the fundamental interactions are due to gauge theories. Gravitation is described by General Relativity which can be regarded as a local gauge theory of $SO(3,1)$ Lorentz symmetry. Electromagnetism is described by QED, an Abelian $U(1)$ gauge theory. There is good experimental evidence for both these gauge theories, on a large scale at the classical level, and also on the quantum level at small scales in the case of QED. It is generally believed that the charged weak interactions also form part of a gauge theory based on a non-Abelian $SU(2)$ group, which is thought to be combined with QED into a "unified" $SU(2) \times U(1)$ gauge theory of weak and electromagnetic interactions [3]. In parallel to this framework, it is thought that the strong interactions are an (indirect) manifestation of QCD, a non-Abelian gauge symmetry based in this case on the $SU(3)$ group associated with the concealed colour symmetry. The experimental evidence for the $SU(2) \times U(1)$ weak-electromagnetic and the QCD strong interaction gauge theories is only indirect so far, and we will see that a primary capability of LEP will be to establish or disprove these candidate gauge theories. In recent years it has become fashionable to speculate [4,5] that the strong, weak and electromagnetic gauge theories may all be combined together into a "Grand Unified Theory" based on a larger group such [5] as $SU(5)$. The experimental evidence for this idea is very weak, and must presumably always

remain somewhat indirect because of the enormous energy-scale at which the grand unified gauge symmetry would become exact. We will see that LEP is among the devices capable of providing indirect evidence for grand unification. Still more speculative are attempts to combine particle interactions and gravitation, possibly in a supersymmetric framework. (For reviews of the phenomenology of supersymmetric theories, see Refs 6 and 7.) There is no evidence at all for such "super-unification", but we will see that LEP should be capable [7] of detecting any supersymmetric particles with masses $\lesssim$ the 100 GeV or so typically associated with the weak interactions.

Swept somewhat under the rug of our enthusiasm for gauge theories are two fundamental problems which have not yet been solved. One is how the various gauge symmetries are broken to give the different mass-scales we see about us. It is generally thought that this symmetry breaking is spontaneous, brought about either [8] via explicit scalar Higgs fields in the theory, or else [9] by some sort of dynamical effect such as "technicolour". Our experimental ignorance about this problem is well-nigh total, and it is an aspect of our theoretical structure about which there is no consensus. The nature of symmetry breaking is a truly fundamental problem to whose resolution LEP can make a unique and possibly conclusive contribution [10,11,12]. Another fundamental problem - though one about which a consensus has developed - is the problem of confinement. Motivated by experiment, the prejudice has built up that quarks and gluons never escape from their hadronic prisons. However, confinement has not yet been demonstrated theoretically and the existence of free quarks has not yet been totally excluded by experiment [13,14,15]. The high momentum transfers and event rates on the Z peak will provide us with a unique opportunity to tear apart many hadronic bags extremely violently, and see [16] whether any quarks or gluons come out.

After this brief overview, let us now turn to the closer inspection of experiments at LEP which may probe these different theoretical ideas.

2. QCD

The theory of QCD is compatible with all strong interaction experiments to date [17], but no dramatic, detailed and unambiguous confirmation has been found analogous to the success of QED in predicting the

anomalous magnetic moments of the leptons to many decimal places (no "smoking gluon"). QCD contains many elements which have qualitative support from present experimental results, but which could be pinned down conclusively by LEP. These include the following.

Vector Gluons There are many hints in favour of vector gluons from low-energy hadron physics, especially spectroscopy [18]. Examples are chiral symmetry and the success of naïve one-gluon exchange models for the spin-spin and spin-orbit splitting of hadrons made out of light quarks. It is not clear why one gluon exchange should be a good approximation for these low-mass systems. However, QCD expects it to become increasingly valid as one progresses to heavier quarks, whose lowest lying states should sink into an (asymptotically free) Coulombic well with precisely predictable spin-spin and spin-orbit splittings:

Coulomb potential:
$$V(r) = -\frac{4}{3} \frac{\alpha_s(r)}{r} + \dots \quad (1a)$$

Chromomagnetic forces:
$$\frac{4\alpha_s(r)}{3 m_q^2} \left[-\frac{8\pi}{3} \underline{\mu}_1 \cdot \underline{\mu}_2 \delta(\underline{r}) + \frac{1}{r^3} \left(\underline{\mu}_1 \cdot \underline{\mu}_2 - 3 \frac{(\underline{r} \cdot \underline{\mu}_1)(\underline{r} \cdot \underline{\mu}_2)}{r^2} \right) \right] \quad (1b)$$

The toponium system has yet to be discovered, and there is an increasing chance that LEP will be the place to discover and explore toponium, and/or still heavier quarkonium systems if they exist. They could indeed prove to be the long-heralded "hydrogen atom" (or more accurately, positronium) of the strong interactions. Hints for the vector nature of gluons also come [20] from the scaling violations observed in deep inelastic lepton-nucleon scattering. However, these data are prey to ambiguities of interpretation [21], and some people persist in finding them controversial. Another nice hint [22] for vector gluons comes from T decays, where the thrust and angular distributions disfavour scalar gluons. However, it is not yet clear that lowest order perturbation theory is directly applicable to T decays. These tests would be made much more precise in the analysis of toponium decays. Perturbation theory should then be reliable and one would have direct visual evidence for the expected decays

$$^3S_1 \rightarrow 3g, 2g+\gamma; \quad ^1S_0 \rightarrow 2g; \quad ^3P_{0,2} \rightarrow 2g; \quad ^3P_1 \rightarrow q\bar{q}+g \quad (2)$$

and their angular distributions [23,24], as well as their basic topologies, provide sensitive tests of the vector nature of gluons. The vector nature of gluons can also be tested in $e^+e^- \rightarrow q\bar{q}g$ three jet events [24,25] though high statistics and the large kinematic range afforded by high energies both seem necessary. As an example of a proposed test, the angular distribution of the two least energetic jets, measured in their centre-of-mass relative to the direction of the most energetic jet, should [26] be

$$\frac{dN}{d(\cos\theta^*)} \propto \begin{cases} (1+2\cos^2\theta^*) & \text{for vector gluons} \\ (1+0.2\cos^2\theta^*) & \text{for scalar gluons} \end{cases} \quad (3)$$

The discrimination between these possibilities requires looking at small θ^* , which in turn entails a relatively low energy for the softest jet. These tests may be possible with improved statistics at PETRA or PEP, but would clearly be much easier in $Z^0 \rightarrow q\bar{q}g$ decays.

Three gluon vertex The vector gluons of QCD should also possess trilinear and quadrilinear couplings. There are weak hints from analyses of scaling violations in deep inelastic structure functions and fragmentation functions [27] that the three-gluon vertex is indeed present, and also a suggestion [28] from large p_T physics, but these can only be regarded as very tentative. There are in principle clear signatures [29] of the three-gluon vertex in the broadening and softening of gluon jets at high energies. The energies of gluon jets accessible to PETRA and PEP are presumably too low for these effects to become apparent, but LEP gluons would surely be suitable from this point of view.

Asymptotic freedom The most distinctive feature of QCD by comparison with any other theory, such as QED, is that of asymptotic freedom [30]

$$\alpha_s(Q^2) \approx \frac{12\pi}{(33-2N_q) \ln(Q^2/\Lambda^2)} + \dots \quad (4)$$

We now have indications [31] from the rate of $e^+e^- \rightarrow q\bar{q}g$ events observed at PETRA that α_s is indeed small in that Q^2 range, but the kinematic range is too small for the expected decrease (4) to be observable at present. Ultimately one would like to see that for fixed angle jets

$$\frac{\sigma(3\text{ jets})}{\sigma(2\text{ jets})} \approx O\left(\frac{1}{\ln Q^2}\right) \quad (5)$$

but this probably has to wait for LEP. A hint for the decrease of α_s with Q^2 comes from comparisons of the J/ψ and τ hadronic decay rates, which seem [32] to indicate that

$$1 \gg \alpha_s(J/\psi) > \alpha_s(\tau) \quad (6)$$

This conclusion is difficult to make quantitative because the magnitude of radiative corrections to orthoquarkonium decay rates is not yet known. Clearly the analysis of toponium decays could make this type of result much more reliable. Furthermore, the negative results of PETRA searches [19], for toponium have now pushed the mass of the top quark so high that one may really feel the asymptotic freedom of the Coulomb potential (1a) directly in the toponium spectrum [33]. Clearly toponium will be a very interesting strong interaction laboratory, especially if it is so massive that LEP is the machine that discovers and exploits it.

3. Weak-Electromagnetic Unification

There is much indirect information favouring the unification of weak and electromagnetic interactions into a gauge theory [3], but direct confirmation is still lacking. We are left with the following open questions to be answered before the conventional weak interaction theory is completed.

Fermion spectroscopy Does the top quark in fact exist [34] ? Are there more than six quarks and six leptons ? LEP can answer these questions by looking for new thresholds and quarkonia [1,2], and by looking in Z^0 decays, e.g., for $Z^0 \rightarrow \text{nothing} = \sum \nu \bar{\nu}$.

Charged currents What are the various weak mixing angles ? We know one such parameter - the Cabibbo angle θ_c - but there are at least three more such parameters [35] even in the minimal 6 quark model. Furthermore, to a theorist the values of these angles are as important and fundamental as the masses of the quarks and leptons themselves. To measure these angles it is necessary to observe t and b quark decays, and LEP has great potential in this respect. The peak rate for $Z^0 \rightarrow b\bar{b}$ is higher than for $e^+e^- \rightarrow \gamma^* \rightarrow b\bar{b}$ close to threshold, and weakly decaying t quarks can be produced copiously by toponium decays [36] as well as in the continuum above threshold.

Neutral currents We now know that low energy neutral current interactions among the first generation of fermions (u,d,e) are well described by an effective interaction agreeing quantitatively [37] with that expected from the Glashow-Weinberg-Salam model [3]. But we do not know whether the neutral current interactions of heavier fermions such as the $\mu, s, c \dots$ can also be described by the same theory. Still less do we know whether the neutral weak interactions are mediated by vector bosons. Should all these tests agree with the Glashow-Weinberg-Salam model, theorists will be interested in having the most accurate determination of $\sin^2 \theta_W$. Since it is closely related to the ratio of SU(2) and U(1) gauge coupling constants, it is as fundamental a constant of nature as α or Newton's constant. Furthermore, as we will see later on, Grand Unified Theories [5] may make a precise prediction [38] for the value of $\sin^2 \theta_W$. LEP can measure [1,2] it via the masses of the $W^\pm$ and Z^0 and in detailed measurements of Z^0 decays.

Vector bosons Assuming that the vector bosons exist and are detected before the advent of LEP, what questions about them remain for LEP to solve? Gauge theories make very specific predictions for the $\gamma W^+ W^-$ and $Z^0 W^+ W^-$ couplings which can be seen directly [39] only in the reaction $e^+ e^- \rightarrow W^+ W^-$. If the vector bosons do have gauge interactions and the symmetry is broken spontaneously, then the theory is renormalizable and this can be tested [40] by checking the magnitudes of weak-electromagnetic radiative corrections. Among their effects should be increases in m_W and m_Z and modifications to the angular distributions and cross-sections for $e^+ e^- \rightarrow f \bar{f}$ and $W^+ W^-$. Verifying them gets to the core of the motivations for gauge theories.

Symmetry breaking At present no-one knows how this is achieved in the Glashow-Weinberg-Salam model, whether by explicit Higgs fields or by composite ones. LEP can look for Higgs bosons or their replacements (technicolour?) in many different ways [10,11,12]: $\text{toponium} \rightarrow H^0 + \gamma$, $Z \rightarrow H^0 + \gamma$, $Z^0 \rightarrow H^0 + e^+ e^-$, $e^+ e^- \rightarrow Z^0 + H^0$, $e^+ e^- \rightarrow H^+ H^-$, $e^+ e^- \rightarrow W^+ H^\pm$.

After this general analysis of the weak interaction issues to be addressed by LEP, let us now focus in turn on the capabilities of different features of high energy $e^+ e^-$ annihilation as laboratories for weak interaction studies.

3.1 Toponium as a weak interaction laboratory

Since PETRA has not found [19] toponium with a mass less than about 36 GeV, and only the narrow range between 36 and 46 GeV is likely to be scanned before the advent of LEP, there is a real possibility that LEP will be the first machine to produce and explore toponium, assuming that exists. Recently the realization has grown [1,2,36,41] that a "heavy" quarkonium state - even one with a mass between 40 GeV and the mass of the Z^0 - has fascinating possibilities as a weak interaction Laboratory. For example, forward-backward asymmetries and measurements on resonance with polarized beams provide unique possibilities for probing the neutral current couplings of the top quark.

Other interesting features of weak interaction studies with toponium concern its decays, as shown in Fig. 1. When the mass of toponium is larger than about 60 GeV the top quark or antiquark may well

decay [1,2,36,41] before it can annihilate in the usual way into gluons and/or photons:

$$\Gamma(V(t\bar{t}) \rightarrow \begin{matrix} t+\bar{b}+X \\ \bar{t}+b+X \end{matrix}) \approx \Gamma(V(t\bar{t}) \rightarrow 3g) \approx \Gamma(V(t\bar{t}) \rightarrow \frac{8}{3} \gamma \rightarrow q\bar{q}) \quad (7)$$

This charged weak decay mode is of course proportional to the square of the $t \rightarrow b$ charged weak coupling, one of the fundamental parameters we would like to measure, and probably has a significant branching ratio even for $m(V(t\bar{t}))$ down to 40 GeV. In this region about 10% of the $t + \bar{b} + X$ final states may [41] actually contain a $t\bar{b}$ meson: $V(t\bar{t}) \rightarrow V(t\bar{b})$ or $P(t\bar{b}) + X$. Whereas the predominant decays of the vector mesons, ρ, K^* and D^* are cascades down to the corresponding pseudoscalar π, K or D , the vector $V(t\bar{b})$ state's dominant decays are likely [41] to be direct weak annihilations:

$$V(t\bar{b}) \rightarrow c\bar{s}, u\bar{d}, \bar{e}\nu, \bar{\mu}\nu, \bar{\tau}\nu \quad (8)$$

This type of weak annihilation decay may [41] also be important or dominant for other vector mesons containing t quarks: $V(t\bar{u}, t\bar{d}, t\bar{s}, t\bar{c})$ and might give us ways of measuring the other weak mixing parameters in $e^+e^- \rightarrow t\bar{t}$ continuum final states. [In fact the weak annihilation $V(t\bar{t}) \rightarrow b\bar{b}$ can also be a significant decay mode of toponium itself.] The basic reasons for the importance of weak decay modes of all these vector mesons is that while the rates for $V(q\bar{q})$ charged weak decays increase with the masses of the quarks, we expect the mass difference

$$m(V(t\bar{q}) - P(t\bar{q})) \propto \frac{1}{m_t}$$

so that the strong decay $V \rightarrow P + \pi$ is not kinematically allowed, while the electromagnetic decay $V \rightarrow P + \gamma$ becomes smaller in rate for heavier m_t .

A particularly exciting weak decay of toponium is $V(t\bar{t}) \rightarrow \nu\bar{\nu}$. This decay mode has [42] a significant branching ratio:

$$\frac{\Gamma(V(t\bar{t}) \xrightarrow{Z} \Sigma \nu \bar{\nu})}{\Gamma(V(t\bar{t}) \xrightarrow{Z} e^+ e^-)} = \frac{G_F^2 m_V^4}{64\pi^2 \alpha^2 e_t^2} (1 - 4|e_t| \sin^2 \theta_w)^2 N_\nu \quad (9)$$

$$\approx 0.2 \times 10^{-8} \times m_V^4 \times N_\nu \quad \text{for } e_t = \frac{2}{3}$$

which yields a promising way of counting the number of neutrinos. One may look for decays $V(t\bar{t}) \rightarrow$ nothing visible, tagging the events by looking for the $V'(t\bar{t}) \rightarrow V(t\bar{t}) + \pi^+ \pi^-$ cascade so as to tell that a $V(t\bar{t})$ was made. This type of search has already been made for J/ψ decays, and the limit [43] of 1/10 on the ratio $\Gamma(J/\psi \rightarrow \text{nothing visible})/\Gamma(J/\psi \rightarrow e^+ e^-)$ gives an upper limit of order 5×10^5 on the total number of neutrinos. In view of the strong dependence of the expected ratio (9) on the mass of the top quark, future searches using toponium should be much more sensitive.

Other amusing decays of toponium may involve Higgs bosons, if they exist. The $V(t\bar{t}) \rightarrow H^0 + \gamma$ decay rate is given [44] by

$$\frac{\Gamma(V \rightarrow H + \gamma)}{\Gamma(V \rightarrow \mu^+ \mu^-)} \approx \frac{G_F m_t^2}{\sqrt{2} \pi \alpha} \left(1 - \frac{m_H^2}{m_V^2}\right) \quad (10)$$

which increases with increasing m_t , and is $\geq 1\%$ for toponium in the LEP energy range ≥ 40 GeV. If charged Higgs bosons exist then the dominant weak decay of the top quark may be [10] $t \rightarrow b + H^+$ if $m_{H^+} < m_t - m_b$. In fact this rate may be so large as to make $V(t\bar{t}) \rightarrow t + \bar{b} + H^- + X$, $\bar{t} + b + H^+ + X$ the dominant decay modes of toponium even for $m(V(t\bar{t})) < 60$ GeV as shown in Fig. 2. Then the spectator $\bar{t}$ (or t) quark will also decay, giving a final state

$$V(t\bar{t}) \rightarrow H^+ + H^- + X \quad (11)$$

What if Higgs bosons do not exist? The most popular alternative to them is "Technicolour" [9] which predicts [45] the existence of several pseudoscalar bosons with masses $O(10 \text{ to } 20)$ GeV which might be produced even more readily in toponium decay, as we will see in Section 5.

3.2 Z^0 as a weak interaction laboratory

This possibility has been much discussed in previous LEP studies [1,2]: here I will just briefly remind you of a few interesting things to look for in Z^0 decays, see Fig. 3. One important recent observation [46] has been that the mass of the Z^0 is very sensitive to weak radiative corrections (see Fig. 4) and hence to the renormalizability of the supposedly underlying gauge theory. One has approximately

$$m_{Z^0} \approx \frac{37.3 \text{ GeV}}{\sin \theta_w \cos \theta_w} + (3.3 \pm 0.3) \text{ GeV} \quad (12)$$

where the uncertainty is related to our poor knowledge of low energy e^+e^- annihilation data, ignorance of m_t , heavier quarks, etc. On the basis of Eq. (12) we see that measuring m_{Z^0} to an accuracy of 0.3 GeV or better would give an estimate of $\sin^2 \theta_w$ with a precision of about 0.001. This is of interest to grand unified theories [5] as we will see in Section 4. It is well known [1,2] that a precision measurement of the Z^0 width Γ_Z is also interesting, as it measures the total number of neutrinos and of quarks lighter than $m_Z/2$:

$$\frac{\Delta \Gamma_Z}{\Gamma_Z} \approx 6\% \quad \text{per extra neutrino} \quad (13)$$

This will enable us to "count" the number of neutrinos much as we discussed in connection with toponium, and it is difficult to imagine a more fundamental experiment that one could do with LEP, as this will tell us the number of different basic types of fermionic "stuff" in the world. Counting the number of neutrinos at LEP could also be done with measurements of $e^+e^- \rightarrow Z^0 + X$, $Z^0 \rightarrow \text{nothing}$, such as the electromagnetic radiative correction $e^+e^- \rightarrow Z^0 + \gamma$, or even [47] $e^+e^- \rightarrow Z^0 + H^0$. For comparison, the best direct limit on the number of neutrinos now available from a particle physics experiment is from an upper limit [42] on $K \rightarrow \pi + \text{nothing}$:

$$N_\nu \leq 6000 \quad (14)$$

whereas there is an indirect limit of about 1000 coming [2] from the fact that PETRA requires all undetected heavy leptons to have masses ≥ 15 GeV. This arises because in the Glashow-Weinberg-Salam model [3] the ratio of neutral current to charged current cross-sections restricts the ratio [48]

$$\frac{m_w^2}{m_z^2 \cos^2 \theta_w} = 1 + \sum_l O(\zeta_F) m_l^2 \quad (15)$$

to such an extent that

$$\sum_l m_l^2 \leq (400 \text{ GeV})^2 \quad (16)$$

which means there cannot be too many heavy leptons yet to be discovered. A much better limit of 3 or 4 on the number of the neutrinos comes from cosmology [49], but particle physicists may be forgiven some scepticism as to its reliability. In any case, this cosmological limit applies to neutrinos with masses < 1 MeV, whereas we are no longer shocked by the possibility of massive neutrinos, and Z^0 decays could produce any neutrinos with masses up to 45 GeV.

There are of course important measurements to be made in individual Z^0 decay modes. From forward-backward asymmetry measurements [32] or experiments with polarized beams one could determine $\sin^2 \theta_w$ in another very precise manner, and search for deviations from the neutral current couplings predicted by the Glashow-Weinberg-Salam model [3]. Also, one could hope for the first measurements of the neutral current couplings of heavy fermions such as s, c, b quarks and τ leptons. Finally, there are decays of the Z^0 which involve Higgs bosons. One expects branching ratios B:

$$\begin{aligned} B(Z^0 \rightarrow H^0 e^+ e^-) &\sim 10^{-4} && \text{for } m_H \sim 10 \text{ GeV [50]} \\ B(Z^0 \rightarrow H^+ H^-) &\sim 10^{-2} && \text{for } m_H \leq 45 \text{ GeV [10]} \\ B(Z^0 \rightarrow H^0 + \gamma) &\sim 10^{-6} && \text{for } m_H \sim 45 \text{ GeV [51]} \end{aligned} \quad (17)$$

Furthermore the reaction $e^+e^- \rightarrow Z^0 + H^0$ has a substantial cross-section [8,52] $\geq 1/10$ of $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ for $m_{H^0} \leq 100$ GeV once one gets above the threshold $E_{c.m.} = m_{Z^0} + m_{H^0}$. The Z^0 , like toponium, should be a useful Higgs spectrometer.

3.3 The reaction $e^+e^- \rightarrow W^+W^-$

This reaction has often been emphasized [29,1,2] as an essential test of gauge theories, being the first example of a process where the trilinear gauge boson vertex can be measured directly. Here I just pick out a few aspects of the process. One is that, as was the case for m_Z , m_W is affected by radiative corrections [46] (see Fig. 4) and hence sensitive to the renormalizability of the theory. In this case

$$m_W \approx \frac{37.3 \text{ GeV}}{\sin \theta_w} + (3.1 \pm 0.3) \text{ GeV} \quad (18)$$

which means that

$$\begin{aligned} \sin^2 \theta_w = 0.25 & \Rightarrow 77.7 \text{ GeV} \\ \sin^2 \theta_w = 0.23 & \Rightarrow 80.9 \text{ GeV} \\ \sin^2 \theta_w = 0.21 & \Rightarrow 84.5 \text{ GeV} \end{aligned} \quad (19)$$

Clearly it is desirable that an early stage of LEP be able to reach beam energies higher than (19). One may hope to measure m_W precisely via the exact location of the threshold. We recall the result (15) and the ensuing limit (16). It would be desirable to improve the determination of this ratio so as to be sensitive to $m_f \approx 100$ GeV if possible. A pair of fermions with this mass would be produced directly at LEP, and one would thereby have a good prospect of finally completing all of fermion spectroscopy in the Glashow-Weinberg-Salam model [3].

Once above threshold, the total cross-section for $e^+e^- \rightarrow W^+W^-$ and the various angular distributions for different e^+ , e^- , W^+ and W^- helicity states are very sensitive [53] to the expected gauge nature of the γW^+W^- and $Z^0 W^+W^-$ couplings. Shown in Fig. 5 are some typical angular

distributions for canonical gauge couplings and some non-canonical couplings. They can clearly be distinguished. The cross-section for $e^+e^- \rightarrow W^+W^-$ is also subject to radiative corrections [40] in gauge theories, some of which are sensitive to the Higgs boson mass. Figure 6 shows some typical results of the calculated [40] effects: clearly measuring the Higgs mass in this way requires a very precise measurement of $\sigma(e^+e^- \rightarrow W^+W^-)$.

4. Grand Unification

This topic [4,5] has become very fashionable in the last couple of years, and one may well ask how LEP could say anything about its validity, as no-one can observe baryon-number non-conservation or neutrino oscillations with LEP. However, it should be borne in mind that one will only ever be able to make indirect tests of the grand unification idea, since the symmetry only becomes exact on a scale of 10^{15} GeV if ever, and that there are also some significant indirect tests which can be made with LEP. If the proton lifetime is a little longer than the experimentally accessible range of 10^{33} years, and if the neutrino mass or the mixing angles too small for neutrino oscillations to be detectable, we may be forced to rely on less dramatic indirect tests of grand unification.

One such test is to measure $\sin^2\theta_W$. In the simplest grand unified theory based on SU(5), one can calculate [38] $\sin^2\theta_W = 0.209 \pm 0.006$ (?). This is somewhat below the central value of present experiments [37] which suggest $\sin^2\theta_W = 0.230 \pm 0.015$. Clearly one would like to measure $\sin^2\theta_W$ more precisely, and LEP is the best machine to do it. If it can measure $\sin^2\theta_W$ with a precision of ± 0.001 as discussed earlier, it should be able to tell us whether SU(5) or perhaps some other grand unified theory can be correct.

Another suggestion from grand unified theories is that there may only be three generations of quarks and leptons (six quarks, three charged leptons and three neutrinos). This limitation is required in the simplest models if one is to retain the successful use [54] of $m_T = 1.78$ GeV to predict $m_b \sim 5$ to $5\frac{1}{2}$ GeV. LEP has the unique capability among proposed high energy machines to determine the number of fermions, by a combination

of finding all fermions with masses ≤ 100 GeV, getting upper limits on fermion masses from radiative corrections (15) to m_W/m_Z , and by counting neutrinos.

Another way to test grand unified theories is the suggestion [55] that in such models with explicit Higgs fields the mass of the neutral Higgs boson may be due to radiative corrections [56] and calculable:

$$m_H^2 \approx \frac{3\alpha^2}{8\sqrt{2}G_F} \left\{ \frac{2 + \sec^4 \theta_W}{\sin^4 \theta_W} - O\left(\frac{m_f}{m_W}\right)^4 \right\} \quad (20)$$

Incorporating higher order radiative corrections which are [57] about 500 MeV, the SU(5) value of $\sin^2 \theta_W$ substituted into (20) gives

$$m_H = 10.9 \pm 0.3 \text{ GeV} \quad (21)$$

Other high energy accelerators have difficulty in producing Higgs bosons because of their small coupling to light quarks and gluons, and their decay signatures are unlikely to be easy to pick out at such unclean machines. By contrast, there are several ways of producing H^0 reasonably copiously at LEP, e.g., $V(t\bar{t}) \rightarrow H^0 + \gamma$, $Z^0 \rightarrow H^0 + e^+e^-$, $e^+e^- \rightarrow Z^0 + H^0$, and the final states seem sufficiently simple that one should be able to detect a light Higgs if it is produced [10]. Therefore LEP has a unique capability to investigate the mass (21) suggested by grand unified theories: its decay modes shown in Fig. 7 would be quite revealing.

We therefore see that LEP is able to make several indirect tests of grand unified theories which are difficult or impossible with other types of high energy accelerators.

5. Unconventional Ideas

So far we have concentrated on relatively conventional theoretical ideas and the interest that LEP physics has for testing them. In this section we will see that LEP experiments are also interesting in the context of less conventional theoretical ideas, such as supersymmetry [6,7], quark liberation [16] and technicolour [12].

5.1 Supersymmetry ?

In this framework, to every particle of spin J is associated a "supersymmetric" partner of spin $J \pm \frac{1}{2}$. The motivation for this idea is to increase the symmetry of the fundamental particles by introducing for the first time a direct correspondence between fermions and bosons. A practical pay-off from supersymmetry is improved convergence for higher order calculations. Indeed when supersymmetry is made local and becomes supergravity one has for the first time a theory of matter coupled to gravity which avoids all divergences in diagrams with just one or two quantum loops. It is therefore attractive to postulate a supersymmetric world, but no phenomenological trace of supersymmetry has ever been found [6,7]. The "known" "fundamental" particles do not occur in supersymmetric pairs, and their partners must have masses larger than a few GeV. No-one knows the scale at which supersymmetry may become apparent, if ever, but a sensible possibility [6] is that the breaking of supersymmetry may have a scale of ≤ 100 GeV typical of the weak interactions.

The table gives a list of conventional particles, their possible supersymmetric partners, and some possible reactions at LEP in which they may be sought. In some supersymmetry models, all the supersymmetric particles carry a conserved quantum number R , so that two particles with $R = \pm 1$ must be present in all final states where pairs of supersymmetric particles were made, such as $e^+e^- \rightarrow S_\ell^+ S_\ell^-$. In these models the decay products of a supersymmetric particle generally include a "nuino" - a neutral, neutrino-like object of low mass. These give useful signatures [6,7]: e.g., the reactions $e^+e^- \rightarrow S_\ell^+ S_\ell^-$ or $e^+e^- \rightarrow S_q^+ \bar{S}_q^-$ could be expected to be marked by 50% missing centre-of-mass energy as in Fig. 8:

$$e^+e^- \rightarrow S_\ell^+ S_\ell^- \begin{matrix} \searrow \rightarrow \ell \tilde{\nu} \\ \searrow \rightarrow \bar{\ell} \tilde{\nu} \end{matrix} ; e^+e^- \rightarrow S_q^+ \bar{S}_q^- \begin{matrix} \searrow \rightarrow \bar{q} \tilde{\nu} \\ \searrow \rightarrow q \tilde{\nu} \end{matrix} \quad (22)$$

The gluinos could [7] be searched for in toponium decays (see Fig. 9): in particular the decay of $^3P_1(t\bar{t}) \rightarrow \tilde{g}\tilde{g}g$, analogous to the more familiar $^3P_1(t\bar{t}) \rightarrow q\bar{q}g$, should be an important decay mode of $^3P_1(t\bar{t})$ if $m_{\tilde{g}} < m_t$. The Winos and Zinos have different cross-sections from conventional

heavy leptons because they have weak isospin 1, not $\frac{1}{2}$. In particular, their cross-sections have rather different forward-backward asymmetries. The total number of nuinos could be measured in the conventional neutrino counting reactions such as $V(t\bar{t})$ or $Z^0 \rightarrow \tilde{\nu}\tilde{\nu}^*$. It seems likely that LEP could tell us whether or not Nature is supersymmetric on the mass scale of the weak interactions.

5.2 Free quarks and gluons ?

Although a consensus has built up that quarks are confined, it is worthwhile to remind ourselves that confinement has not been proved theoretically in QCD, and that it has not even been confirmed beyond any reasonable doubt that QCD is the correct theory of the strong interactions. Confinement is and will always remain a fundamental experimental question. Naïvely, one might imagine that LEP is particularly appropriate for searching for free quarks, as it may "rip open" hadronic "bags" very vigorously with its large momentum transfers. If quarks (and gluons) do indeed get out, there are several ideas about their possible experimental signatures.

Most searches [16] have been for "conventional" free quarks which are weakly ionizing ($Q^2 = 1/9$ or $4/9$ instead of 1) and have a low dE/dX signature. Their interactions are often supposed to be weak because of the additive quark model for total hadronic cross-sections:

$$\sigma(h_1 h_2) = \sum_{q \in h_1} \sum_{q \in h_2} \sigma(q, q^*) \quad (23)$$

Measuring ionization or dE/dX can be done easily in most modern e^+e^- detectors, and limits on quark production obtained. For example the JADE group [15] at PETRA have already established

$$R_q \equiv \frac{\sigma(e^+e^- \rightarrow q\bar{q}X)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} \lesssim 0.1 \quad (24)$$

A search at the Z^0 peak in e^+e^- annihilation could in principle reach a sensitivity of $R_q = 10^{-6}$ at a much larger Q^2 , where there is perhaps a better chance of breaking open the hadronic "bag".

It has also been proposed [58] that free quarks may actually have exceptionally strong interactions with ordinary hadrons, because free quarks have uncompensated naked colour. The suggestion then is that

$$\frac{\sigma(qN)}{\sigma(NN)} \approx \frac{1}{4} \left(1 + \left(\frac{2m_q}{m_N} \right)^{\frac{1}{3}} \right)^2 \quad (25)$$

where the quark mass m_q is unknown. At least at low energies, much of this cross-section may involve the eating [58] of one or more nucleons from the nucleon target in each collision (see Fig. 10). Furthermore, final state interactions at the interaction point may cause the free quark (or gluon) to eat [16] one or more of the other particles produced in the same interaction. These strongly interacting quarks with appetite may therefore have apparent electromagnetic charge $\neq -1/3$ or $+2/3$, and their charge and mass may change within the detector if they interact with one of its elements.

An unorthodox proposal [59] is that quarks may have indeterminate mass. In this case they would tend to expand physically as they move away from a production point. Within the volume they occupy they may either have a homogeneous "jelly" or inhomogeneous granular or "dust-cloud" structure (see Fig. 11). As they expand, one would expect their internal electric fields and hence their capacity to ionize (or polarize molecules so as to trigger Cerenkov radiation) to decrease. Thus an indeterminate mass particle (IMP) may be expected to seem to "fizzle out" as it moves away from the production point (see Fig. 12). However, as long as they have not expanded too far to pass entirely between the pole pieces of a magnet, they will be bent by a magnetic field although apparently electrically neutral [16] (see Fig. 13). After bending they could perhaps be observed in a directional hadronic calorimeter by looking for "neutral" showers not pointing back to the production vertex.

It seems that each variety of free quark proposed has some distinctive features which would enable its detection, should LEP in fact liberate quarks.

5.3 Technicolour ?

Many people have recently proposed [9] replacing the conventional (ugly?) explicit Higgs fields by bound states of new types of quarks and leptons with superstrong interactions, sometimes called "technicolour". The dynamics of the techniquarks Q and technileptons L is supposed to parallel that of ordinary quarks in QCD. They are supposed to be confined, and condense in the vacuum:

$$\left. \begin{aligned} \langle 0 | \bar{Q} Q | 0 \rangle &\neq 0 \\ \langle 0 | \bar{L} L | 0 \rangle &\neq 0 \end{aligned} \right\} \text{c.f. } \langle 0 | \bar{q} q | 0 \rangle \neq 0 \quad (26)$$

and thereby replace the ordinary vacuum expectation value of the Higgs field $\langle 0 | \phi | 0 \rangle \neq 0$. One then finds typically that the scale parameter Λ_{TC} analogous to the conventional QCD Λ_{colour} parameter determines

$$m_W^2 = O(\alpha) \Lambda_{TC}^2 \quad (27)$$

In order to get $m_W \sim 100$ GeV, Λ_{TC} must be of order 10^3 GeV and hence

$$\Lambda_{TC} \approx O(10^3) \Lambda_{\text{colour}} \quad (28)$$

The natural scale of technicolour interactions should therefore be $O(1 \text{ TeV})$, and one expects to find many technihadrons (technirho, technidelta, techni- ...) with masses $O(1 \text{ TeV})$ which would be invisible at LEP. However, technicolour theories also [9,45] have pseudoscalar particles analogous to the pion which have masses $\leq 1 \text{ TeV}$. The most basic of these technipions is in fact eaten by the $W^\pm$ and Z^0 in technicolour theories in order to furnish masses for these particles. In order to also give masses to the "fundamental" fermions, quarks and leptons, it is necessary to extend [9] the basic technicolour interactions. When this is done, many of these extended technipions P finish up as relatively light, observable particles. Shown in Fig. 14a is the minimal technipion spectrum [45], while Fig. 14b shows the spectrum in a plausible non-minimal model.

We see there are several candidates for detection at LEP, particularly if the masses estimated for the colour non-singlet states are somewhat too high:

$$e^+e^- \rightarrow P^3 \bar{P}^3, P^6 \bar{P}^6, P^8 + \text{gluons} \quad (29)$$

where we use P^3 , P^6 and P^8 to denote the leptoquark, diquark and colour octet bosons of Fig. 14, respectively. The bosons of class 1 P^0 , $P^{0'}$ and $P^\pm$ should have masses $O(10 \text{ to } 20) \text{ GeV}$ and can be produced in many of the interactions normally considered for the production of conventional light Higgs bosons [10]:

$$\begin{aligned} e^+e^- &\rightarrow P^0 + Z^0; \quad V(t\bar{t}) \rightarrow P^0 + \gamma; \quad Z^0 \rightarrow P^0 + \gamma; \\ e^+e^- &\rightarrow P^+ P^- \end{aligned} \quad (30)$$

In some cases the production rates are [11] very favourable, e.g.,

$$\frac{\Gamma(V(t\bar{t}) \rightarrow P^0 + \gamma)}{\Gamma(V(t\bar{t}) \rightarrow H^0 + \gamma)} = \frac{1}{3} \text{ or } 3 \quad (31)$$

in the two simplest technicolour models, while in other cases the production rates are [11] less favourable, e.g.,

$$\frac{\sigma(e^+e^- \rightarrow Z^0 + P^0)}{\sigma(e^+e^- \rightarrow Z^0 + H^0)} = O(10^{-4})! \quad (32)$$

In either case, the P^0 has a distinctive production rate. The P^0 and $P^\pm$ also have distinctive decay signatures, in that the relative branching ratios into quarks and leptons are expected [11] to be different from those of the corresponding Higgs bosons. In the simplest models

$$\frac{\Gamma(P \rightarrow q \bar{q})}{\Gamma(P \rightarrow l \bar{l})} \approx \left(\frac{1}{3} \text{ or } 27\right) \left(\frac{m_q^2}{m_l^2}\right) \quad (33a)$$

while for Higgs bosons [8]

$$\frac{\Gamma(H \rightarrow q \bar{q})}{\Gamma(H \rightarrow l \bar{l})} \approx 3 \left(\frac{m_q^2}{m_l^2}\right) \quad (33b)$$

Furthermore it seems possible that the weak mixing angles in $P^\pm$ decay may be closely related to the conventional Cabibbo angles, whereas the same is not necessarily true for $H^\pm$ decays. The decay modes (33) should provide a useful signature for $e^+e^- \rightarrow P^+P^-$: final states containing heavy quarks and/or heavy leptons.

It seems likely [12] that LEP could detect these light technipions if they exist, and discriminate between them and conventional Higgs particles. This would be of profound physical importance, as it would tell us whether the mass scales of gauge theories are generated dynamically or by explicit Higgs fields. It seems unlikely that any other proposed high energy accelerator could provide us with the same knowledge. Hadron-hadron and lepton-hadron collisions have relatively low production cross-sections for Higgs bosons or technipions, and detecting them among all the copious hadron background would be a non-trivial problem [60].

6. Conclusions

It seems fair to say that the theoretical interest in e^+e^- experiments at LEP energies is as high as it has ever been. LEP experiments can

- prove or disprove gauge theories such as QCD or Glashow-Weinberg-Salam (perhaps the number of Z^0 's is $\neq 1$?),
- complete our knowledge of the fundamental fermion spectrum,
- tell us how gauge symmetry is broken, whether by explicit Higgs fields or by a dynamical mechanism such as technicolour,

- perform significant indirect tests of grand unified theories,
- make powerful probes of many unconventional theoretical ideas.

In many cases, LEP seems to be the only high energy accelerator which can answer such physical problems - so

LEP'S DO IT !

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Table

Possible supersymmetric particles

Type of conventional particle	Spin,		
	1	1/2	0
Matter		quarks q	scalar quarks S_q
		leptons ℓ	scalar leptons S_ℓ
Massive gauge bosons	$W^\pm, Z^0$	supersymmetric heavy leptons Wino $\tilde{W}^\pm$, Zino $\tilde{Z}^0, \tilde{H}$	Higgs scalar H
Massless gauge bosons	photon γ gluon g	photino $\tilde{\gamma}$ + other $\tilde{\nu}$ nuinos gluinos $\tilde{g}$	

References

1. L. Camilleri et al., CERN Yellow Report 76-18 (1976).
2. Proceedings of the ECFA/CERN Les Houches Summer Study on LEP, CERN Yellow Report 79-01 (1979).
3. S.L. Glashow, Nucl. Phys. 22, 579 (1961);
S. Weinberg, Phys. Rev. Letters 19, 1264 (1967);
A. Salam, Proc. of 8th Nobel Symposium, ed. N. Svartholm (Almqvist and Wiksells, Stockholm, 1968) p. 367.
4. J.C. Pati and A. Salam, Phys. Rev. Letters 31, 661 (1973); Phys. Rev. D8, 1240 (1973); Phys. Rev. D10, 275 (1974).
5. H. Georgi and S.L. Glashow, Phys. Rev. Letters 32, 438 (1974).
6. P. Fayet, "New frontiers in High Energy Physics", proceedings of Orbis Scientiae, Coral Gables, 1978, (Plenum Press, N.Y., 1978) p.413;
G. Farrar, Proc. Int. School of Subnuclear Physics, Erice 1978 (to be published by Plenum Press, N.Y.);
P. Fayet, CERN preprint TH-2864 (1980).
7. G. Barbiellini, G. Bonneaud, G. Coignet, J. Ellis, M.K. Gaillard, C. Matteuzzi and B.H. Wiik, DESY preprint 79/67 (1979).
8. J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Nucl. Phys. B106, 292 (1976).
9. L. Susskind, Phys. Rev. D20, 2619 (1979);
S. Weinberg, Phys. Rev. D19, 1277 (1979);
E. Eichten and K. Lane, Phys. Letters 90B, 125 (1980);
S. Dimopoulos, Nucl. Phys. B168, 69 (1980).
10. G. Barbiellini, G. Bonneaud, G. Coignet, J. Ellis, M.K. Gaillard, J.F. Grivaz, C. Matteuzzi and B.H. Wiik, DESY preprint 79/27 (1979).
11. J. Ellis, M.K. Gaillard, D.V. Nanopoulos and P. Sikivie, CERN preprint in preparation (1980).
12. G. Barbiellini, G. Coignet, J. Ellis, M.K. Gaillard, G. Girardi, C. Matteuzzi, D.V. Nanopoulos, A. Savoy-Navarro, P. Sikivie, P. Sorba and B.H. Wiik, DESY preprint in preparation (1980).
13. G.S. La Rue, W.M. Fairbank and A.F. Hebard, Phys. Rev. Letters 38, 1011 (1977);
G.S. La Rue, W.M. Fairbank and J.D. Phillips, Phys. Rev. Letters 42, 142 (1979).

14. M. Marinelli and G. Morpugo, I.N.F.N. Genova preprints (1980).
15. JADE Collaboration, D. Haidt (private communication, 1980).
16. G. Barbiellini, G. Bonneaud, R.J. Cashmore, G. Coignet, J. Ellis, M.K. Gaillard, J.F. Grivaz, C. Matteuzzi, R.D. Peccei and B.H. Wiik, DESY preprint 80/42 (1980).
17. For a review and references, see
J. Ellis, Proceedings of the 1979 Int. Symp. on Lepton and Photon Interactions at High Energies, Fermilab, ed. H.D.I. Abarbanel and T.B.W. Kirk (Fermilab, Batavia, 1980), p. 412.
18. For a review, see
C.H. Llewellyn Smith, Oxford University preprint 54/79 (1979).
19. For the latest unsuccessful searches at PETRA, see
R. Cashmore, contribution to this meeting.
20. P.C. Bosetti et al., Nucl. Phys. B142, 1 (1978);
J.G.H. de Groot et al., Zeit. Phys. C1, 143 (1979); Phys. Letters 82B, 292, 456 (1979).
21. L.F. Abbott and R.M. Barnett, Ann. Phys. (N.Y.) 125, 276 (1980)
22. K. Koller and H. Krasemann, Phys. Letters 88B, 119 (1979).
23. M. Krammer and H. Krasemann, Phys. Letters 73B, 58 (1978).
24. A. De Rújula, J. Ellis, E.G. Floratos and M.K. Gaillard, Nucl. Phys. B138, 387 (1978).
25. J. Ellis, M.K. Gaillard and G.G. Ross, Nucl. Phys. B111, 253 (1976);
TASSO Collaboration, R. Brandelik et al., Phys. Letters 86B, 243 (1979);
MARK J Collaboration, D.P. Barber et al., Phys. Rev. Letters 43, 830 (1979);
PLUTO Collaboration, C. Berger et al., Phys. Letters 86B, 418 (1979);
JADE Collaboration, W. Bartel et al., Phys. Letters 91B, 142 (1980).
26. J. Ellis and I. Karliner, Nucl. Phys. B148, 141 (1979).
27. D.H. Perkins, Oxford University preprint 2/79 (1979);
K. Koller, T.F. Walsh and P.M. Zerwas, Phys. Letters 82B, 263 (1979);
H. Meyer, Proceedings of the 1979 Int. Symp. on Lepton and Photon Interactions at High Energies, Fermilab, ed. H.D.I. Abarbanel and T.B.W. Kirk (Fermilab, Batavia, 1980), p. 214.
28. M. Glück and E. Reya, Dortmund University preprint (1980).

29. M.B. Einhorn and B.G. Weeks, Nucl. Phys. B146, 445 (1978);
R.K. Ellis and R. Petronzio, Phys. Letters 80B, 249 (1979);
K. Konishi, A. Ukawa and G. Veneziano, Phys. Letters 80B, 259 (1979);
K. Shizuya and S.-H.H. Tye, Phys. Rev. Letters 41, 787 (1978).
30. H.D. Politzer, Phys. Rev. Letters 30, 1346 (1973);
D.J. Gross and F.A. Wilczek, Phys. Rev. Letters 30, 1343 (1973).
31. MARK J Collaboration, D.P. Barber et al., Phys. Letters 89B, 139 (1979);
JADE Collaboration, Ref. 25;
A. Ali, E. Pietarinen, G. Kramer and J. Willrodt, Phys. Letters 93B,
155 (1980);
TASSO Collaboration, R. Brandelik et al., DESY preprint 80/40 (1980).
32. J.K. Bienlein, private communication; see also R. Cashmore, Ref. 19.
33. M. Krammer and H. Krasemann, Phys. Letters 73B, 58 (1978).
34. For counter-propaganda, see, e.g.
H. Georgi and S.L. Glashow, Nucl. Phys. B167, 173 (1980).
35. M. Kobayashi and K. Maskawa, Prog. Theor. Phys. 49, 652 (1973).
36. G. Goggi and G. Penso, Nucl. Phys. B165, 429 (1980).
37. U. Amaldi, Proc. Neutrino 79, Bergen, ed. A. Haatuft and C. Jarlskog
(University of Bergen, 1979), p. 367;
F. Dydak, Proc. E.P.S. Conf. on High Energy Physics, Geneva 1979
(CERN, 1979), p.26;
K. Winter, Proc. 1979 Int. Symp. on Lepton and Photon Interactions
at High Energies, Fermilab, ed. H.D.I. Abarbanel and T.B.W. Kirk
(Fermilab, Batavia, 1980), p.258.
38. W.J. Marciano, private communication (1980).
39. W. Alles, C. Boyer and A.J. Buras, Nucl. Phys. B119, 125 (1977).
40. M. Lemoine and M. Veltman, Nucl. Phys. B164, 445 (1980).
41. I.I.Y. Bigi and H. Krasemann, CERN preprint TH-2854 (1980).
42. J. Ellis, Proc. 1978 SLAC Summer Institute on Particle Physics
(SLAC-215, 1978) p.69.
43. SLAC-LBL Collaboration, M. Breidenbach, private communication quoted
in Ref. 6.
44. F.A. Wilczek, Phys. Rev. Letters 39, 1304 (1977).
45. M.E. Peskin, C.E.N. Saclay preprint "The alignment of the vacuum in
theories of technicolour" (1980).

46. M. Veltman, LAPP preprint TH-12 (1980);
A. Sirlin, Princeton Institute for Advanced Study preprint (1980);
W.J. Marciano, Phys. Rev. D20, 274 (1979).
47. A. Van Proeyen, Phys. Rev. D20, 813 (1979).
48. M. Veltman, Nucl. Phys. B123, 89 (1977);
M.S. Chanowitz, M.A. Furman and I. Hinchliffe, Phys. Letters 78B,
285 (1978).
49. J. Yang, D.N. Schramm, G. Steigman and R.T. Rood, Ap. J. 227, 697
(1979).
50. J.D. Bjorken, Proceedings of the 1976 SLAC Summer Institute on
Particle Physics, (SLAC-198, 1977).
51. R.N. Cahn, M.S. Chanowitz and N. Fleishon, Phys. Letters 82B, 113 (1979).
52. B.W. Lee, C. Quigg and H. Thacker, Phys. Rev. D16, 1519 (1977).
53. K.J.F. Gaemers and G.J. Gounaris, Z. Phys. C1, 259 (1979).
54. A.J. Buras, J. Ellis, M.K. Gaillard and D.V. Nanopoulos, Nucl. Phys.
B135, 66 (1978);
D.V. Nanopoulos and D.A. Ross, Nucl. Phys. B157, 273 (1979).
55. J. Ellis, M.K. Gaillard, D.V. Nanopoulos and C.T. Sachrajda, Phys.
Letters 83B, 339 (1979).
56. S. Coleman and E. Weinberg, Phys. Rev. D7, 1888 (1973);
E. Gildener and S. Weinberg, Phys. Rev. D13, 3333 (1976).
57. K.T. Mahanthappa and M.A. Sher, University of Colorado preprint
COLO-HEP 18 (1980).
58. A. De Rújula, R.C. Giles and R.L. Jaffe, Phys. Rev. D17, 285 (1978).
59. B.M. Mc Coy and T.T. Wu, Phys. Letters 72B, 219 (1977) and Phys.
Rep. 49C, 193 (1979).
60. G. Girardi, S. Narison, A. Savoy-Navarro and P. Sorba, private com-
munication (1980);
R.R. Horgan and M. Jacob, private communication (1980);
F. Hayot and O. Napoly, C.E.N. Saclay preprint Dph-T/86 (1980).

Figure captions

- Fig. 1 : Some decay branching ratios of toponium $V(t\bar{t})$, taken from Ref. 41.
- Fig. 2 : Diagrams for the decay modes $V(t\bar{t}) \rightarrow t + \bar{b} + H^- + X$, $\bar{t} + b + H^+ + X$.
- Fig. 3 : The event rate for $e^+e^- \rightarrow Z^0 \rightarrow$ all expected at LEP, taken from M. Davier, Ref. 2.
- Fig. 4 : Some examples of weak radiative corrections to the vector boson V masses m_Z and m_W calculated in Ref. 46.
- Fig. 5 : Differential angular cross-sections for different polarizations (1,2,3) of W in the reaction $e^+e^- \rightarrow W^+W^-$, with various gauge and non-gauge three-boson couplings, taken from Ref. 53. (λ is the dipole moment and κ the quadrupole moment of the W boson.)
- Fig. 6 : The effects of radiative corrections on the angular distributions for $e^+e^- \rightarrow W^+W^-$, taken from Ref. 40
- Fig. 7 : Possible decay modes of a Glashow-Weinberg-Salam Higgs boson with a mass ≈ 10 GeV, taken from Ref. 55.
- Fig. 8 : Missing energy signature for the reactions $e^+e^- \rightarrow S_\ell^+ S_\ell^-$ or $S_q^+ S_q^-$ from decays into nuinos [6,7].
- Fig. 9 : Possible decay modes of toponium into gluinos [6,7].
- Fig. 10 : Possible ways in which a quark with appetite [58] may "eat" a hadron and change its apparent charge and mass, either (a) during an interaction after production, or (b) during production itself.

- Fig. 11 : Possible interpretations [16] of the internal structure of Indeterminate Mass Particles (IMPs) (a) as a jelly, or (b) as a dust-cloud.
- Fig. 12 : The ionization due to an IMP [59] may "fizzle out" as it moves away from the production point.
- Fig. 13 : IMPs may [16] be bent by a magnetic field even if they do not ionize.
- Fig. 14 : Possible spectra of technipions to be expected [45] in extended technicolour [9] theories: (a) the minimal version, and (b) a plausible non-minimal version.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

245 GeV — color octets

~ 0 — class 1

Fig. 14a

~ 0 — class 1

Fig. 14b

28