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SEARCHING FOR HEAVY LEPTONS *†

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This talk was presented at the University of Wisconsin Topical Workshop on the Production of New Particles in Super High Energy Collisions. The spirit of the Workshop was speculative and this talk is in that spirit. The known leptons were discovered in very different ways and we can only speculate about the ways in which other and heavier leptons can be found. Indeed we do not even know if there are leptons beyond the tau.

1. BEYOND THE τ

1.A. Status of the τ:

The status of the τ has been recently reviewed in detail[1]; therefore I will give a brief and qualitative discussion. All measurements are consistent with the τ having the following properties:

a) spin 1/2, charged, Dirac, point particle;

b) obeys conventional quantum electrodynamics;

c) obeys conventional weak interaction theory;

d) has no strong interactions; and

e) has a unique, conserved lepton number.

Hence the τ is a sequential[2] charged lepton to the best of our knowledge.

There are three interesting new pieces of data on the τ.

a) The Mark J collaboration[3] at PETRA has measured the τ pair production cross section $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ up to $E_{cm} = 31$ GeV. Within the statistics, which are still small, the cross section is consistent with the τ being a spin 1/2, Dirac, point particle obeying conventional quantum electrodynamics. For example in an E_{cm} region near 30 GeV they find about 20 events and their measured $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ in that region agrees with the τ being a point particle. We assume a form factor[2]

$F_\tau(E_{cm})$ which modifies the theoretical cross section as follows:

$$\sigma(e^+e^- \to \tau^+\tau^-) = \frac{4\pi\alpha^2}{3E_{cm}^2} \frac{\beta(3-\beta^2)}{2} \left| F_\tau(E_{cm}) \right|^2$$

Then the 2 s.d. limits on the deviation of F_τ from 1 are roughly ± 20%.

b) The SLAC-LBL Magnetic Detector Group has found[4] the Cabibbo suppressed decay mode $\tau \to K^*(890) + \nu_\tau$. The measured branching ratio of roughly 1% is in agreement with theory.

c) The PLUTO Group[5] has done a spin-parity analysis of the decay $\tau \to \rho^0 + \pi + \nu$. The $\rho^0\pi$ Dalitz plot distribution is consistent with $J^P\ell = 1^+0$ or 2^-1. The $\rho^0\pi$ mass distribution excludes 2^-1 but is consistent with 1^+0 if an A_1 resonance is assumed.

There is still a great deal of research to be done on the τ:

a) The $e^+e^- \to \tau^+\tau^-$ cross section should be measured with good statistics at PETRA and PEP energies to test the point particle nature of the τ.

b) The τ lifetime should be determined to measure the $\tau - \nu_\tau$ coupling and see if the coupling constant equals the Fermi constant.

c) Experiments should be done with the ν_τ. The most promising method for producing ν_τ's is to allow a high intensity, multi-hundred GeV, proton beam to "dump" in a high density target. In this "beam dump" experiment we expect the following reaction sequence to occur[6]

$$\begin{aligned} p + \text{nucleus} &\to F + \text{anything} \\ F &\to \tau + \nu_\tau \qquad (1) \\ \tau &\to \nu_\tau + \text{other particles} \end{aligned}$$

Here F is the charm meson. The ν_τ's along with ν_e's and ν_μ's would escape the beam dump, and a neutrino detector downstream of the dump would detect the ν_τ's and exhibit their interactions. The problem of separating ν_τ interactions from ν_e or ν_μ interactions may be difficult.[6]

d) To show that the τ is definitely a sequential heavy lepton it is still necessary to show that ν_τ is different from ν_e. This can be done by the ν_τ experiment described in c) or by an experiment using a ν_e beam.

e) The present upper limit on the ν_τ mass is 250 MeV/c^2; either a smaller upper limit or a non-zero mass should be established.

1.B. Sequential Charged Leptons Beyond the τ:

Searches for sequential charged leptons with masses greater than the τ have been carried out at SPEAR and DORIS and are now being conducted at PETRA. Three search methods are used:

a) e or μ + hadron events from the production and decay sequence

$$e^+ + e^- \rightarrow \underset{\substack{\downarrow \\ e \text{ or } \mu + \nu\text{'s}}}{L^+} + \underset{\substack{\downarrow \\ \text{hadrons} + \nu\text{'s}}}{L^-} \qquad (1)$$

b) $e^\pm \mu^\mp$ events from

$$e^+ + e^- \rightarrow \underset{\substack{\downarrow \\ e + \nu\text{'s}}}{L^+} + \underset{\substack{\downarrow \\ \mu + \nu\text{'s}}}{L^-} \qquad (2)$$

c) an increase in R from

$$e^+ + e^- \rightarrow \underset{\substack{\downarrow \\ \text{anything}}}{L^+} + \underset{\substack{\downarrow \\ \text{anything}}}{L^-} \qquad (3)$$

Events of type a) or b) must, or course, be distinguished from $\tau^+\tau^-$ events.

In c)

$$R = \frac{\sigma(e^+e^- \to \text{anything except } e^+e^-,\ \mu^+\mu^-)}{\sigma(e^+e^- \to \mu^+\mu^-)} \qquad (4)$$

where σ is the indicated cross section.

We have comprehensive data from SPEAR up to an E_{cm} of 7.4 GeV. Allowing for threshold inefficiencies for a lepton with a mass near 3.5 GeV/c^2, this data shows that there are no additional sequential cahrged leptons beyond the τ with masses less than 3 GeV/c.

Searches for sequential charged leptons are being conducted at PETRA up to an E_{cm} of about 31 GeV; and in early 1980 those searches will be extended to an E_{cm} about 38 GeV. No evidence for the existence of sequential charged leptons has been published; and some evidence has been presented against the existence of a new sequential charged lepton in the lower and middle energy range of PETRA.[8] Additional evidence against the existence of a new sequential charged lepton in the lower energy range of PETRA comes from the Mark J measurement[3] of the $e^+e^- \to \tau^+\tau^-$ cross section near 30 GeV (See 1.A). For example: a sequential lepton of 5 GeV/c^2 mass would produce tau-like events and be counted in the τ pairs cross section. On the other hand a sequential lepton of say 12 GeV/c^2 mass would not give tau-like events at 30 GeV. However, all these searches are based on low statistics and are somewhat insensitive because the detector triggers used to acquire the early PETRA data tend to ignore events with low multiplicity and/or low total visable energy. Therefore there is still hope that a new charged sequential lepton might appear in the PEP and PETRA energy range.

1.C. Other Heavy Charged Leptons at PEP, PETRA, CESR:

Since the discovery of the τ, search methods for heavy charged leptons tend to emphasize sequential lepton properties. However, one can devise other types of charged leptons, aome of which might have properties less sensitive to the search methods outlined in Section 1.B. Some possibilities are:

a) leptons which decay via $L^{\pm} \rightarrow \ell^{\mp} + \gamma$, where ℓ is an e, μ or τ;

b) leptons which decay primarily with only one charged prong or with very little visable energy;

c) leptons which decay only to neutrinos and hadrons, not to other leptons;

d) spin 0 lepton-like particles such as the scalar, supersymmetry theory, leptons described by Farrar and Fayet;[9,10]

e) stable or long lived leptons..

We note that possibility e) is severely limited by PETRA measurements[3] on the $e^+e^- \rightarrow \mu^+\mu^-$ production cross section which show that only one mu-like lepton with mass less than 15 GeV/c^2 exists. For example, the production of a pair of 10 GeV/c^2 stable leptons would lead to a pair of collinear, highly penetrating tracks; hence the event would look like a μ pair. Such events would be easily observed, and then their low momentum would immediately call attention to their anomalous nature.

Therefore in searching for new charged leptons at PEP, PETRA and CESR, it is important to use general and sensitive search methods. For example, the leptons in b) would have an inefficient trigger, and in c) would appear to be Hadrons. Indeed this brings up the question of what is a lepton. I define it[2] as a particle with weak and electromagnetic but not strong interactions, which acts as a point particle in

$e^+e^- \to L^+L^-$. Of course higher order weak and electromagnetic interaction diagrams must be taken into account, if required, as is done in g-2 comparisons of theory with experiment.

1.D. Charged Leptons with Mass $\gtrsim$ 20 GeV/c^2:

In the next few years, searches for charged leptons with masses greater than 20 GeV/c^2 must be done at proton accelerators. Three production methods are possible:

a) Hadron-Hadron Collisions: New leptons can be produced in p + nucleus collisions in fixed target experiments or in p + p and $p + \bar{p}$ collisions in colliding beam machines. Unfortunately there are no clear signatures for new lepton production in these completed collisions, and the new leptons will be submerged[11,12] in an ocean of e's, μ's and hadrons. Hadron-hadron collisions are not a practical search method for new charged leptons.

b) Photon-Hadron Collisions: The Bethe-Heitler process

$$\gamma + \text{nucleus} \to L^+ + L^- + \text{anything} \qquad (2)$$

seems to be a somewhat more fruitful way to search[13,14] for new charged leptons. However there are still enormous backgrounds; and the only feasible search method[14] is to select events in which the "anything" in Eq. 2 has very low multiplicity and $L^+ \to e^+ + \nu$'s, $L^- \to \mu^- + \nu$'s or visa versa. that is, $\mu^\pm e^\mp$ is the L pair production signature. However even this is very difficult as is demonstrated by the fact that the τ has not yet been detected by this method because charmed particles produce a $\mu^\pm e^\mp$ signal that is several orders of magnitude larger.

c) ν - Hadron Collisions: If a new charged lepton couples to a ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$, ν_τ or $\bar{\nu}_\tau$ then the production reaction

$$\nu + \text{nucleon} \rightarrow L^{\pm} + \text{anything} \qquad (3)$$

can occur. The cross section depends upon the mass of the L, the ν energy, and the strength of the coupling of the ν to the L lepton. Since in general we expect no coupling between a ν and an arbitrary lepton, this is a very restrictive search method. But if there is a new L which couples to a ν this is a powerful search method. Thus charged lepton search methods at proton accelerators are either very difficult or very restrictive. Definitive searches for new charged leptons with masses above 20 GeV/c^2 require new higher energy e^+e^- colliding beam machines.

1.E. Unstable Neutral Heavy Leptons:

We can conceive of various kinds of neutral heavy leptons:[2,16]

a) Unique, Conserved Lepton Number: If the L^0 has a unique, conserved, lepton number it can only decay if there is a lighter ℓ^0 or $\ell^{\pm}$ with the same lepton number. In that case, examples of decay modes are

$$\begin{aligned} L^0 &\rightarrow \ell^0 + e^+ + e^- \\ L^0 &\rightarrow \ell^0 + \text{hadrons} \\ L^0 &\rightarrow \ell^- + e^+ + \nu_e \\ L^0 &\rightarrow \ell^- + \text{hadrons} \end{aligned} \qquad (4)$$

If there are no lighter particles with the same lepton number the L^0 will be stable as discussed in Section 1.F.

b) Non-Unique Lepton Number: If the L^0 shares a lepton number with a lighter known lepton, such as the e, then decays such as the following can occur:

$$\begin{aligned} L^0 &\to \nu_e + e^+ + e^- \\ L^0 &\to \nu_e + \text{hadrons} \\ L^0 &\to e^- + \text{hadrons} \end{aligned} \quad (5)$$

In Section 1.D. we pointed out that it is very difficult to search for heavy charged leptons at proton accelerators; it is equally difficult to search for heavy neutral leptons at such machines. Indeed, it is probably more difficult because photoproduction cannot be used. Again the exception to these statements is the case where the L^0 couples to ν_μ, $\bar{\nu}_\mu$, ν_e or $\bar{\nu}_e$. The only general and powerful search method for neutral heavy leptons is the e^+e^- reaction

$$e^+ + e^- \to \text{neutral current} \to L^0 + \bar{L}^0 \quad (6)$$

shown in Figure 1.

We will use Weinberg-Salam theory[18] to estimate this cross section:

$$\sigma\left(e^+e^- \to L^0\bar{L}^0\right) = \frac{G_F^2 E_{cm}^2}{96\pi} \; \frac{M_Z^4}{\left(E_{cm}^2 - M_Z^2\right)^2 + M_Z^2 \Gamma_Z^2} \times \left[v_e^2 + a_e^2\right]\left[v_L^2 + a_L^2\right][T] \quad (7)$$

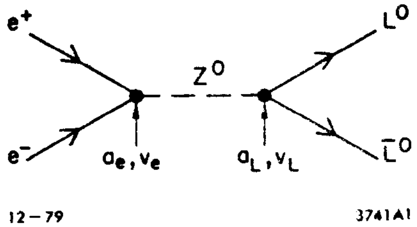

Figure 1.

Here G_F is the Fermi weak interaction coupling constant $\left(1.02 \times 10^{-5}/M_{proton}^2\right)$, M_Z is the Z^0 mass which we take as 90 GeV/c^2, and Γ_Z is the Z^0 width. a and v are the coupling constants as defined by Ellis;[18]

for example $a_e = -1$ and $v_e = -1 + 4\sin^2\theta_W$. [T] is a threshold factor which takes account of the non-zero mass of the lepton.

Applying Eq. (7) at PETRA and PEP energies ($E_{cm} \lesssim 40$ GeV) we simplify as follows:

$$\begin{aligned} M_Z &\gg E_{cm} \\ \left[v_e^2 + a_e^2\right] &\approx 1 \\ \left[v_L^2 + a_L^2\right] &\approx 1 \end{aligned} \qquad (8)$$

Of course the last approximation in Eq. (8) is just speculation. Then

$$\sigma(e^+e^- \to L^0\bar{L}^0) = \frac{G_F^2\,E_{cm}^2}{96\pi} \qquad (9a)$$

$$R(e^+e^- \to L^0\bar{L}^0) = \frac{G_F^2\,E_{cm}^4}{128\pi^2\alpha^2} \approx 2\times10^{-9}\,E_{cm}^4 \qquad (9b)$$

where E_{cm} is in GeV.

At the maximum PETRA or PEP energy of 40 GeV

$$R(e^+e^- \to L^0\bar{L}^0, \text{max at PEP,PETRA}) \approx .005 \qquad (10)$$

which is much too small a signal to detect. For example, a year long run (200 days) at a luminosity of 10^{31} cm^{-2} sec^{-1} yields 50 $L^0\bar{L}^0$ pairs. One might observe a few strange events from decays such as

$$\begin{array}{l} L^0 \to L^- + e^+ + \nu_e \\ \qquad\;\; \hookrightarrow \mu^- + \nu_\mu + \nu_L \end{array} \qquad (11)$$

But it will not be possible to establish the existence of this L^0 at PEP or PETRA. The only way an L^0 can be found at PEP or PETRA is if its production is enhanced through the sequence

$$\begin{array}{l} e^+ + e^- \rightarrow L^+ + L^- \\ \qquad\qquad\quad \llcorner\!\!\rightarrow L^0 + \text{anything} \end{array} \tag{12}$$

where the L^+L^- pair production has $R = 1$ and the branching ratio for $L^\pm \rightarrow L^0$ might be 10%.

Thus the only way to make a general L^0 search is to go to e^+e^- collisions at energies above the PETRA-PEP range.

I.F. Stable Neutral Heavy Leptons:

The most difficult leptons to detect are stable neutral heavy leptons. Even the general search method

$$e^+ + e^- \rightarrow \text{neutral current} \rightarrow L^0 + \bar{L}^0$$

is not useful because there is no way to detect this reaction directly (see however, Section 2.B.). Indirect production of the L^0 via Eq. (12) can be detected but this is a special case.

A search method for stable or almost stable neutral leptons at proton accelerators has been proposed by Shrock.[19] This method uses a beam dump for L^0 production, a neutrino-type detector and precise timing. The sensitivity of such a search method is not calculable since the L^0 production process is in general not known.

2. THE Z^0 AND BEYOND

The obvious solution to most of the problems of searching for large mass charged leptons and any mass neutral leptons is an e^+e^-

colliding beam storage ring[20,21] with

$$
\begin{aligned}
E_{cm} &\gtrsim \text{several hundred GeV} \\
\mathcal{L}(\text{luminosity}) &\approx 10^{32}\ \text{cm}^{-2}\ \text{sec}^{-1}
\end{aligned}
\qquad (13)
$$

An example of such a machine is the LEP design[22] which has an ultimate E_{cm} of 260 GeV if superconducting cavities are used for the radio-frequency (RF) power. Otherwise the ultimate E_{cm} is 186 GeV. The construction of such a machine is a very major undertaking for several reasons.

a) Cost: The recent LEP proposal[22] has a construction cost of 1.3×10^9 Swiss francs and a yearly operating cost of 10^8 Swiss francs. Half of the operating cost is electric power; hence this part of the operating cost could increase rapidly in the future.

b) Construction Time: The estimated construction time is seven years;[22] hence we cannot expect such a machine to be working before the late 1980's.

c) Size and Complexity: One measure of the size of the machine is its diameter of 10 km. Another measure is that it will use 128 MW of RF power at $E_{cm} = 186$ GeV (with room temperature RF cavities).

A tremendous amount of very basic elementary particle physics[23] can be done with this type of e^+e^- machine. Therefore it is crucial that such a machine be built and that it be started as soon as possible.

However, even if construction of this machine is started soon, we will still have to wait a decade before effective heavy lepton searches can be made with this machine. Is there a way to accomplish sooner at least part of our heavy lepton search goals? There is a way, *if* the Z^0 with a mass M_Z of about 90 GeV exists! Then we can search for all leptons with mass M_L where $M_L < M_Z/2$ using the reaction

$$e^+ + e^- \rightarrow Z^0 \rightarrow L + \bar{L} \qquad (14)$$

As we show in the next sections the Z^0 has two valuable properties with respect to heavy lepton searches:

a) A luminosity enhancement of about 100 is obtained. This allows a simpler and cheaper e^+e^- colliding beams machine to be built faster if its maximum E_{cm} is just above the Z^0 mass.

b) A definitive search for neutral leptons can be made.

Of course such a machine does not have the heavy lepton search capabilities of a LEP type machine because the latter has twice the energy range.

2.A. $Z^0 \rightarrow L^+ + L^-$:

If $M_L < M_{Z^0}/2$ the reaction (Figure 2)

$$e^+ + e^- \rightarrow Z^0 \rightarrow L^+ + L^- \qquad (15)$$

has the cross section

$$\sigma(e^+e^- \quad L^+L^-) = \frac{G_F^2}{96\pi} \frac{M_Z^4}{\Gamma_Z^2} \left[v_e^2 + a_e^2\right] \times \left[v_L^2 + a_L^2\right] [T] \qquad (16)$$

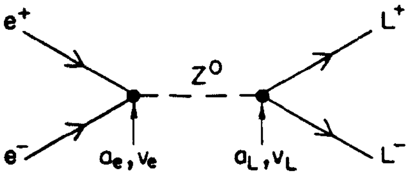

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Figure 2.

This equation comes from Eq. (7) with $E_{cm} = M_Z$. We have ignored the L^+L^- production via a virtual photon. Using

$$\left[v_e^2 + a_e^2\right] \approx 1$$
$$\left[v_L^2 + a_L^2\right] \approx 1 \qquad (17)$$

$$\sigma(e^+e^- \to L^+L^-) \approx \frac{G_F^2\, M_Z^4}{96\pi\Gamma_Z^2} \quad [T] \tag{18a}$$

$$R(e^+e^- \to L^+L^-) \approx \frac{G_F^2\, M_Z^6}{128\pi^2\alpha^2\Gamma_Z^2} \quad [T] \tag{18b}$$

Finally using

$$\begin{aligned} [T] &\approx 1 \\ M_Z &= 90 \text{ GeV}/c^2 \\ \Gamma_Z &= 2.5 \text{ GeV (see Section 2.B)} \end{aligned} \tag{19}$$

we obtain

$$R(e^+e^- \to L^+L^-) \approx 130 \tag{20}$$

This is the luminosity enhancement factor mentioned at the end of the last section. Also

$$\sigma(e^+e^- \to L^+L^-) \approx 1.4 \times 10^{-33} \text{ cm}^2 \tag{21}$$

Next we calculate the luminosity required for a heavy lepton search. We need 100 identified events to establish a new lepton. Assuming that 5% of the produced new lepton pairs can be so identified, we need 2000 produced lepton pairs. If the search is to be done in one year we require

$$2000 \,\frac{L\bar{L}\text{ pairs}}{\text{year}} \cdot \frac{1\text{ year}}{200\text{ days}} \cdot \frac{1\text{ day}}{10^5\text{ sec}} = 10^{-4}\,\frac{L\bar{L}\text{ pairs produced}}{\text{sec}}$$

Thus we need a luminosity of

$$\begin{aligned} \mathcal{L} &\approx (10^{-4}/\text{sec})/(1.4 \times 10^{-33}\text{ cm}^2) \\ &\approx 10^{29}\text{ cm}^{-2}\text{ sec}^{-1} \end{aligned} \tag{22}$$

This is much smaller than the usual design luminosity of 10^{32} cm^{-2} sec^{-1} or the expected average luminosity of 10^{31} cm^{-2} sec^{-1} of a LEP type machine. Hence the use of the Z^0 substantually eases the luminosity requirements on such a machine.

2.B. Use of R_{Z^0} and Γ_{Z^0}:

At the Z^0 we expect pair production of all the fundamental leptons and quark. For example we expect

$$\begin{aligned} e^+ + e^- &\to Z^0 \to e^+ + e^- \\ e^+ + e^- &\to Z^0 \to \nu_e + \bar{\nu}_e \\ e^+ + e^- &\to Z^0 \to \mu^+ + \mu^- \\ e^+ + e^- &\to Z^0 \to \nu_\mu + \nu_\mu \\ e^+ + e^- &\to Z^0 \to \tau^+ + \tau^- \\ &\vdots \qquad \vdots \qquad \vdots \end{aligned} \tag{23a}$$

and

$$\begin{aligned} e^+ + e^- &\to Z^0 \to u + \bar{u} \\ e^+ + e^- &\to Z^0 \to d + \bar{d} \\ e^+ + e^- &\to Z^0 \to s + \bar{s} \\ &\vdots \qquad \vdots \qquad \vdots \end{aligned} \tag{23a}$$

Each cross section is proportional to $\left[v_f^2 + a_f^2\right]$ where v_f and a_f are the coupling constants[18] for the $Z^0 - f - \bar{f}$ vertex. Here f represents any of the fundamental fermions such as e, ν_e, μ, ... u, d, s, ... In Weinberg-Salaam theory $\left[v_f^2 + a_f^2\right]$ is or order one so that all the cross sections in Eq. (23) are roughly the same size.

Ignoring QCD corrections and threshold effects, the total cross section at the Z^0 is[18]

$$\sigma(e^+e^- \rightarrow Z^0 \rightarrow \mathrm{all}) = \frac{G_F^2 M_Z^4}{96\pi\Gamma_Z^2}\left[v_e^2 + a_e^2\right] \sum_f \left[v_f^2 + a_f^2\right] \tag{24}$$

where the sum is over all the fundamental fermions. The total Z^0 width is

$$\Gamma(Z^0 \rightarrow \mathrm{all}) = \frac{G_F^2 M_Z^3}{24\pi\sqrt{2}} \sum_f \left[v_f^2 + a_f^2\right] \tag{25}$$

Inserting Γ from Eq. (25) into Eq. (24) yields

$$\sigma(e^+e^- \rightarrow Z^0 \rightarrow \mathrm{all}) = \frac{12\pi}{M_Z^2} \frac{\left[v_e^2 + a_e^2\right]}{\sum_f \left[v_f^2 + a_f^2\right]} \tag{26}$$

Equation (25) provides a method in principle of searching for <u>all</u> leptons with conventional weak interaction couplings and masses less than $M_{Z^0}/2$. Measuring (Z^0 → all) and knowing M_Z and G_F allows us to calculate $\sum_f \left[v_f^2 + a_f^2\right]$. If the known leptons and quarks do not explain the total value of $\sum_f \left[v_f^2 + a_f^2\right]$ then there are missing leptons or quarks; and deliberate searches can be made for these missing particles. Let's estimate the magnitude of this effect. The average value of $\left[v_f^2 + a_f^2\right]$ is

$$\left\langle\left[v_f^2 + a_f^2\right]\right\rangle \approx 24 \times 1.4 \approx 36 \tag{28}$$

<u>or larger</u> if there are more fundamental fermions. The effect of one additional lepton would be an increase of 1/24 ≈ 4% in $\Gamma(Z^0 \rightarrow \mathrm{all})$. Unfortunately this 4% effect is not easy to measure; there are statistical errors, systematic errors, radiative corrections, and perhaps QCD corrections.

Equation (26) cannot be used to precisely calculate $\sum_f \left[v_f^2 + a_f^2\right]$ because we cannot completely measure $\sigma(e^+e^- \to Z^0 \to \text{all})$. Reactions such as $e^+e^- \to \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau$ contribute substantially to this cross section; yet they cannot be detected. We can only measure a lower limit on $(e^+e^- \to Z^0 \to \text{all})$ and hence an upper limit on $\sum_f \left[v_f^2 + a_f^2\right]$

2.C. If Heavier Z^0's Exist?

It is obvious that the existence of heavier Z^0's allows us to extend the heavy lepton search to higher masses. Since finding Z^0's is much more feasible than finding leptons at proton accelerators, one can visualize the following grand strategy for lepton, or indeed quark, searches:

a) Use $p + p$ or $\bar{p} + p$ colliding beams machines to find heavier Z^0's. These machines are the cheapest way to get to higher E_{cm}.

Build the cheapest and simplest e^+e^- colliding beams machine to get to that new Z^0!

c) The required e^+e^- luminosity can be estimated as follows, from Eqs. (18a) and (25),

$$\sigma(e^+e^- \to Z^0 \to L\bar{L}) = \frac{\text{constant}}{M_{Z'}^2 \left(\sum_f \left[v_f^2 + a_f^2\right]\right)^2} \tag{29}$$

also $\sum_f \left[v_f^2 + a_f^2\right]$ is proportional to the number of fundamental fermions N_f. Hence

$$\sigma(e^+e^- \to Z^0 \to L\bar{L}) = \frac{\text{constant}}{M_{Z'}^2\, N_f^2} \tag{30}$$

Using the 2000 produced $L\bar{L}$ pair criterion that led to Eq. (22)

$$\mathscr{L}(\text{required to find non-}L\bar{L}\text{ pair}) = \left(\frac{M_Z'}{90}\right)^2 \left(\frac{N_f}{24}\right)^2 10^{29}\text{cm}^{-2}\text{sec}^{-1} \qquad (31)$$

Thus the required $\mathscr{L}$ increases as $M_{Z'}$ or N_f increases, so that the technology for building the required cheap and simple e^+e^- colliding beams machine must be improved.

3. CLASHING e^+e^- LINACS AND THE SLAC LINAC-COLLIDER PROPOSAL

We return to the question of how to build a relatively simple and cheap e^+e^- colliding beams machine whose E_{cm} reaches the Z^0 mass (90 GeV) and whose luminosity at the Z^0 is at least 10^{29} cm^{-2} sec^{-1}. There are two directions being investigated these days:

a) Moderate luminosity ($10^{30} - 10^{31}$ cm^{-2} sec^{-1}), $E_{cm} = 100$ GeV e^+e^-, storage rings are being discussed at DESY and Cornell. The saving of money and construction time compared to the LEP type e^+e^- storage ring is obtained by the lower maximum E_{cm} (100 GeV compared to roughly 200 GeV) and by economies of scale and facilities.

b) The SLAC linac-collider proposal, in which the e^+ and e^- bunches are not stored and collide just once.

This audience is well acquainted with the general design of e^+e^- storage rings; but the linac-collider proposal involves ideas new to many of you; therefore I will devote the remainder of this talk to a general description of clashing e^+e^- linear accelerators and the linac-collider proposal.

3.A. Comparison of Storage Rings with Clashing Linacs:

A general review of clashing linear accelerator ideas and theory has recently been given by Amaldi.[24] He also gives a full set of references to the contributors to the field and its history. A brief review has been given by Richter.[21] Here I will present a qualitative comparison of the two types of e^+e^- colliding beam machines.

a) e^+e^- Storage Rings: In a storage ring, Figure 3, the luminosity of all interaction regions combined is

$$\mathscr{L}_{\text{ring}} = \frac{n\, N_{\text{ring}}^2\, f_{\text{ring}}}{A_{\text{ring}}} \qquad (32)$$

Here n is the number of interaction regions; N_{ring} is the number of e^+ or e^- in a bunch; A_{ring} is the cross sectional area of a bunch; and $f_{\text{ring}} = c/(2\pi R)$ where c is the velocity of the light and R is the ring's radius. For a fixed radius the RF voltage required to make up for the beam energy lost through synchotron radiation is proportional to the fourth power of the beam energy. This means that in an optimum design[20,21,23]

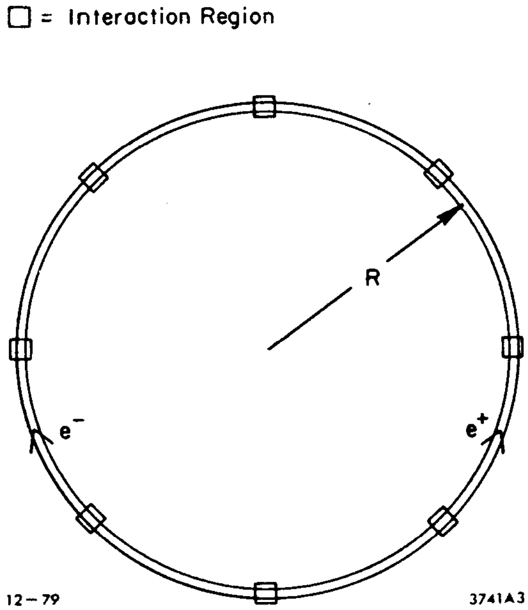

Figure 3.

$$R \propto E_{\text{cm}}^2 \qquad (33)$$

and

$$\text{cost} \propto R \propto E_{\text{cm}}^2 \qquad (34)$$

<u>b) e^+e^- Clashing Linear Accelerator</u>: In an e^+e^- clashing linear accelerator machine, Figure 4, the luminosity is given by

$$\mathscr{L}_{linac} = \frac{N^2_{linac}\, f_{linac}}{A_{linac}} \tag{35}$$

where f_{linac} is the linear accelerator pulse rate. Note that the bunches collide just once. The length of one of the linear accelerators is L; and the cost is proportional to E_{cm}

$$\text{cost} \propto L \propto E_{cm} \tag{36}$$

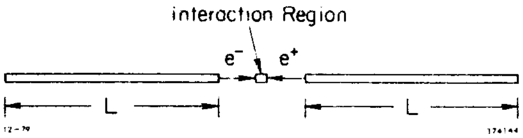

Figure 4.

<u>c) Cost Comparison</u>: Figure 5 shows a qualitative comparison of the cost of a storage ring and a clashing linac. At present we do not know where the cross over occurs; knowing enough to calculate that cross over point is one of the major objects in developing clashing linac technology. (See Section 3.B.). However, if we look at the roughly 2×10^9 Swiss franc cost of an $E_{cm} \approx 200$ GeV type storage ring, using Eq. (34) (cost $\propto E^2_{cm}$), we know that we must either develop a new technology such as clashing linacs or soon reach an energy ceiling in e^+e^- physics.

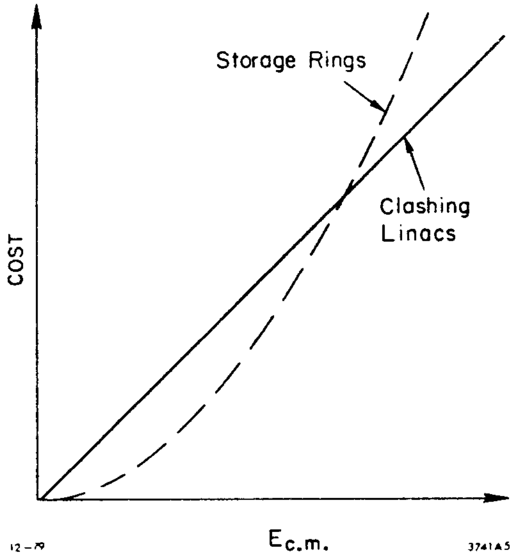

Figure 5.

d) Luminosity Comparison: To give a general idea of the requirements on a clashing linac we will make a crude comparison with an $E_{cn} = 200$ GeV LEP type storage ring. For such a storage ring N_{ring} is 5×10^{11} to 10^{12} particles per bunch; we will use

$$N_{ring} \sim 10^{12} \text{ particles/bunch} \tag{37a}$$

also

$$A_{ring} \sim 4\pi \times 100\mu \times 30\mu \sim 10^{4}\pi\mu^{2}; \; (\mu = \text{micron}) \tag{37b}$$

$$f_{ring} \sim \frac{3 \times 10^{8} \text{ m/sec}}{30 \times 10^{3} \text{ m}} = 10^{4} \text{ Hz} \tag{37c}$$

$$n \sim 10 \text{ interaction regions} \quad . \tag{37d}$$

In a linear accelerator purposely build for a chashing linac we expect

$$N_{linac} \sim 10^{22} \text{ particles/bunch} \tag{38a}$$

$$f_{linac} \sim 10^{3} \text{ Hz} \quad . \tag{38b}$$

Then from Eqs. (32) and (35)

$$\frac{\mathscr{L}_{linac}}{\mathscr{L}_{ring}} \approx \left(\frac{10^{11}}{10^{12}}\right)^{2} \left(\frac{10^{3}}{10 \quad 10^{4}}\right) \left(\frac{A_{ring}}{A_{linac}}\right) \approx 10^{-4} \left(\frac{A_{ring}}{A_{linac}}\right)$$

For the same $\mathscr{L}$, using Eq. (37b)

$$A_{linac} \approx 10^{-4} A_{ring} \approx \pi\mu^{2} \quad .$$

If the linac beam has a circular cross section of radius r

$$A_{linac} \sim \pi r^{2} \sim \pi\mu^{2}$$

and (39)

$$r \sim 1\mu$$

Equations (38a) and (39) state the crucial requirement on e^+e^- clashing linac technology to obtain a luminosity equal to the total luminosity of an e^+e^- storage ring. We must learn to make, accelerate, steer, focus and collide e^- and e^+ bunches with 10^{11} particles per bunch and with one micron transverse dimensions at the collision point. Studies now in progress indicate that this can be done.

3.B. The SLAC Linac-Collider: General Description:

B. Richter has proposed a very ingenious application of the clashing linacs principle to the existing SLAC linear accelerator. This proposal, shown schematically in Figure 6, contains the following elements:

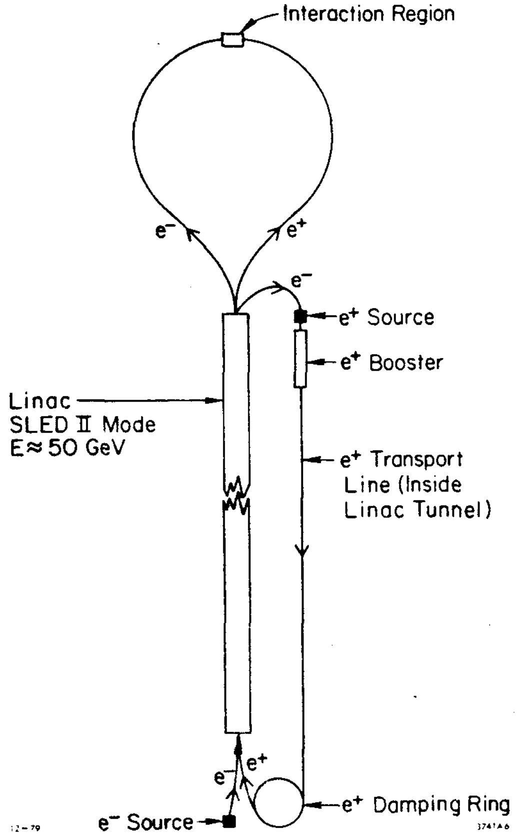

Figure 6.

a) Using the SLED mode[25] of operation of the accelerator the accelerator energy is raised to about 50 GeV.

b) The e^- bunch and the e^+ bunch are accelerated in the same accelerator pulse, one bunch following the other one down the accelerator separated by a distance of the order of tens of meters.

c) The e^- and e^+ bunches are transported in opposite directions by the roughly circular transport system to the interaction point.

d) At the interaction point the bunches, which were of the order of 100 μ in transverse dimensions as they left the linac, are focussed by the transport system and interaction regions quadrupoles to transverse dimensions of the order of one μ.

e) The e^- bunch with $\approx 5 \times 10^{10}$ particles is produced by an improved e^- source.

f) The e^+ bunch with $\approx 5 \times 10^{10}$ particles is produced in a more complicated way. Several e^- bunches follow the primary e^- and e^+ bunches through the accelerator. These secondary e^- bunches are steered into a positron source. The e^+ so produced are accelerated to an energy of ~1 GeV and transported to a damping ring. This ring reforms the phase space of the positrons so that an e^+ bunch with wuitable phase space and intensity can be injected into the linear accelerator.

The design of this proposed linac-collider is in its early stages. A number of physicists and engineers at SLAC are working on the overall theory, on detailed engineering designs of the transport system, on experiments with the quality of the linac beam, on an improved electron source, on the design of the damping ring, and on other aspects of the proposal. Therefore I can only give here very rough and preliminary parameters for the linac-collider.

$$\begin{aligned} E_{cm} &\approx 2 \times 50 \text{ GeV} \approx 100 \text{ GeV} \\ N &\approx 5 \times 10^{10} \text{ particles/bunch} \\ f &= 180 \text{ Hz} \\ \sigma_r &\approx 2\mu \\ \mathscr{L} &= \frac{N^2 f}{4\pi\, \sigma_r^2} \approx 10^{30} \text{ cm}^{-2} \text{ sec}^{-1} \end{aligned} \tag{40}$$

Here σ_r is the root mean square transverse radius of the bunches. The length of the bunches will be several mm. By further SLED type improvements, the addition of more klystrons to the linear accelerator, and other improvements, it is possible in principle to increase the E_{cm} to about 130 or 140 GeV. The luminosity might also increase through the focusing effect that one beam has on the other and through the increase of N, the particles per bunch. The numbers given in Eq. (40) are for one collision point; additional collision points are being considered.

3.C. SLAC Linac-Collider: General Physics:

I have discussed the Z^0 with reference to the finding of new leptons and the study of their properties because leptons were my assigned topic at this workshop. However, it is obvious that there is a tremendous amount of physics[23] that can be done with the general process

$$e^+ + e^- \rightarrow Z^0 \rightarrow \text{everything} \qquad (41)$$

One can study quark and hadron physics, look for new quarks, do QCD tests, study weak interactions, test QED, etc. One measure of the richness of the physics is the event rate. Using

$$\begin{aligned} &R(e^+e^- \rightarrow Z^0 \rightarrow \text{all, radiatively corrected}) \approx 3000 \\ &\mathscr{L} = 10^{30}\ \text{cm}^{-2}\ \text{sec}^{-1} \end{aligned} \qquad (42)$$

we obtain

$$\text{Events/hour} \approx 100 \qquad (43)$$

This is about the same event rate that occurred at SPEAR and DORIS. It is obvious that a great deal of physics can be done with such a rate.

There is a question that is faced by those who propose this linac-collider or by those who propose moderate luminosity, $E_{cm} \approx 100$ GeV e^+e^- storange rings. What if the Z^0 does not exist or what if its mass is far beyond 100 GeV? My answer is twofold:

a) If the Z^0 does not exist or if its mass is far beyond 100 GeV then some very strange things are going on in the $E_{cm} = 50 - 100$ GeV range. It will be crucial for physicists to study this region via e^+e^- interactions as soon as possible.

b) If there is no Z^0, R at 100 GeV will be about 7 for

$$e^+ + e^- \rightarrow \gamma \rightarrow \text{hadrons or } \tau^+\tau^- \qquad (44)$$

This yields about 5 events/day for $\mathscr{L} = 10^{30}$ cm^{-2} sec^{-1} at $E_{cm} = 100$ GeV. One can still do very interesting physics at this rate. For example: 1000 events will be acquired in a year; R can be measured to 3%; and one can definitely determine if new <u>charged</u> leptons or new charge 2/3 quarks have been produced.

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