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ELECTRON-POSITRON COLLISION PHYSICS: 1 MeV TO 2 TeV[*]

Martin L. Perl
Stanford Linear Accelerator Center
Stanford University, Stanford, California 94309

ABSTRACT

An overview of electron-positron collision physics is presented. It begins at 1 MeV, the energy region of positronium formation, and extends to 2 TeV, the energy region which requires an electron-positron linear collider. In addition, the concept of searching for a lepton-specific force is discussed.

TABLE OF CONTENTS

A. Introduction

The initial purpose of this talk was to tell an audience of nuclear physicists and particle physicists about electron-positron collision physics: what we have learned and what we are doing. As I wrote the talk, I found that it provided me with the opportunity to give a broader view of electron-positron collision physics, to point out the areas where future research might be most fruitful. Some of these areas are well-known: electron-positron annihilation physics at the Z° and studying the properties of hadrons containing the b–quark. Less recognized fruitful areas are: understanding the decay modes of the tau lepton and studying hadrons containing the c–quark. There are two areas which I have never seen discussed: electron–positron collision physics below 500 MeV in the barycentric system and the search for what I call a lepton-specific force. In the written version, I have shifted the emphasis to pointing out these less recognized and unrecognized areas of electron-positron collision physics.

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Figure 1 is the route map for this talk. I start at 1 MeV and go up in energy, dividing the discussion into energy regions according to the physics, the experimental method and the accelerator technology.

I have restricted the references to a few special areas because I am covering a broad subject.

Unless otherwise noted, all energies are total energies in the barycentric system denoted by $\sqrt{s}$ or $E_{c.m.}$.

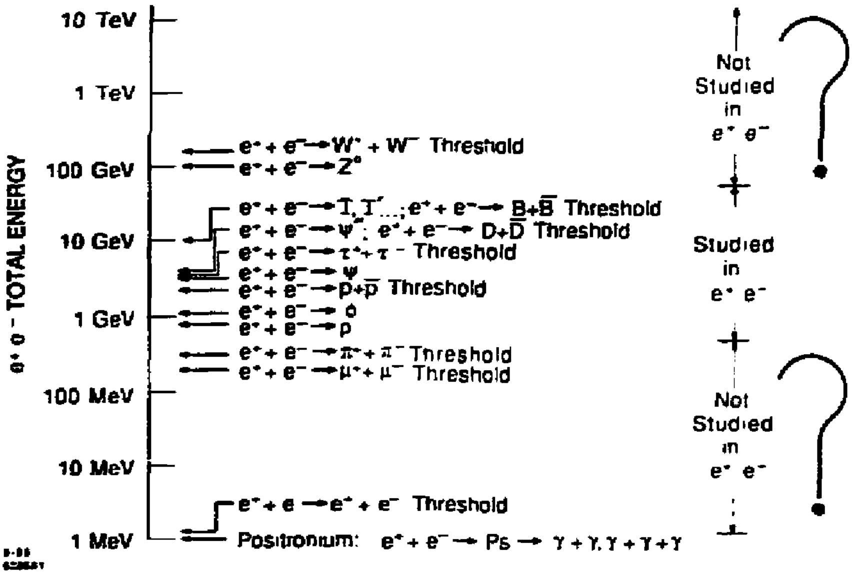

Figure 1

B. 1 MeV to 500 MeV and Positronium

I begin with the regions of 1 MeV to 500 MeV total energy. At the 1 MeV boundary of this region lies a vast area of e^+e^- physics: the formation of positronium

$$e^+ + e^- \to Ps\,, \tag{1a}$$

and its decay

$$Ps \to \gamma + \gamma\,, \quad \gamma + \gamma + \gamma\,. \tag{1b}$$

A minor subject in the region is the study of Bhabha scattering

$$e^+ + e^- \to e^+ + e^-\,. \tag{2}$$

Three decades ago, Bhabha scattering was studied using a positron beam on a fixed target, then work stopped in most of th[illegible] energy [illegible]. Research

90

continued only at the low-energy end, the area of atomic physics. In the last few years, a special interest in Bhabha scattering at an $E_{c.m.}$ of 1.6 to 1.8 MeV has developed, as I discuss later.

There are two reasons for there being no interest in general studies of Bhabha scattering or photon pair production,

$$e^+ + e^- \rightarrow \gamma + \gamma \, , \tag{3}$$

in the 1 MeV to 500 MeV region. First, the consensus is, or at least was, that quantum electrodynamics explains all e^+e^- physics in this region. Second, an e^+e^- circular collider of traditional design has low luminosity in this energy region, and no e^+e^- collider has been built in this energy region. The two reasons reinforce each other. If there is no physics interest, there is no incentive to build a collider. If a collider is very hard to build, why get interested in the physics. One set of perhaps anomalous measurements has revived interest in studying Bhabha scattering in the 1 MeV to several MeV region. Some experiments[1] show e^+e^- pairs produced in collisions of high Z ions, these pairs having masses of 1.6 to 1.8 MeV/c^2. The data on these pairs is confusing; the production mechanism is unknown. Electron beam dump experiments[2] have excluded a production mechanism involving a conventional, unstable elementary particle: $\phi \rightarrow e^+ + e^-$. Bhabha scattering at an $E_{c.m.}$ of 1.6 to 1.8 MeV might show a peak in the cross section if the unknown production mechanism can occur in a pure e^+e^- system; that is, if the presence of high Z ions is not required. Numerous measurements of Bhabha scattering in the energy region have been made in the past few years. An e^+ beam and a fixed target, usually of low Z, are used. At present, the measurements are contradictory and there is no confirmed observation of a peak.[3]

Interest in the several MeV region has also been stimulated by possible problems in precisely understanding the properties of positronium itself; the lifetime of orthopositronium, for example.[4]

I have been thinking about the best strategy for exploring the 1 MeV to 500 MeV region; measuring with precision the cross sections for

$$e^+ + e^- \rightarrow e^+ + e^- \, , \tag{4a}$$

$$e^+ + e^- \rightarrow \mu^+ + \mu^- \, , \tag{4b}$$

$$e^+ + e^- \rightarrow n\gamma \, , \quad n \geq 2 \, ; \tag{4c}$$

looking for anomalous differential cross sections and resonances in the total cross section. We do not know how to design an e^+e^- circular collider which can operate from several MeV to 500 MeV, because known design principles limit the dynamic range to three or four. Therefore, I am considering fixed target experiments. The SLAC linear accelerator can produce e^+ beams with a maximum energy of 50 GeV, corresponding to $E_{c.m.}$ = 220 MeV. Above about 500 MeV, the VEPP–2M e^+e^- circular (Sec. C) can take up studies of the reactions in Eq. 4; but there would still be a gap in energy coverage.

In Sec. L on lepton-specific forces, I will again take up the 1 MeV to 500 MeV region. There are indirect ways to explore this region, using processes such as

$$e^+ + e^- \rightarrow e^+ + e^- + e^+ + e^- \ ,$$

but these indirect methods have less sensitivity.

C. 500 MeV to 9 GeV and Hadron Production

The history of high-energy, e^+e^- collision physics began in this energy region: ADONE in Italy, the CEA collider in the United States, the DCI in France and the VEPP colliders in the Soviet Union. Today, there is only one e^+e^- collider in this region, VEPP-2M.

In this energy region, the production of hadrons becomes important

$$e^+ + e^- \rightarrow \text{hadrons} \ ,$$

and it was in this region that two main processes for hadron production were elucidated. Resonances such as the ρ, ω, ϕ, and at higher energies, the ψ and Υ, are produced through the process in Fig. 2a. The continuum production of hadrons,

$$e^+ + e^- \rightarrow \text{many hadrons} \ ,$$

occurs through the process in Fig. 2b, with the cross section per quark type and color,

$$\sigma(e^+e^- \rightarrow q\bar{q} \rightarrow \text{hadrons}) = \frac{4\pi\alpha^2 Q_q^2}{3s} \ . \qquad (5)$$

The recognized research to be done in this region concerns more precise studies of hadron production. I also see valuable research to be done on the reactions in Eq. 4, searching for anomalous behavior. Looking ahead, a high luminosity collider producing

$$e^+ + e^- \rightarrow \phi \rightarrow K^\circ + \bar{K}^\circ$$

can extend our knowledge of the CP violating mechanism in the $K^\circ\bar{K}^\circ$ system.

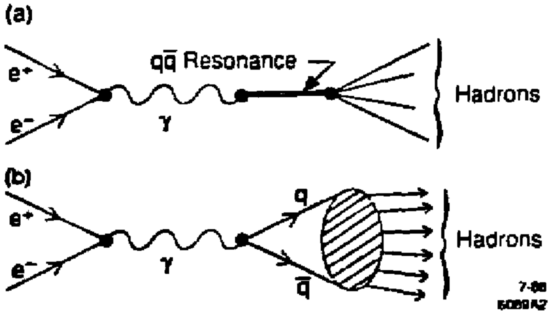

Figure 2

D. 3 GeV to 10 GeV: the ψ, the τ, the c-Quark and Hadron Jets

This is the energy region where four great discoveries were made in the 1970's:

(*i*) The ψ, ψ', ψ'' family of $c\bar{c}$-hadrons was discovered.

(*ii*) The τ heavy lepton was found through

$$e^+ + e^- \rightarrow \tau^+ + \tau^- \ . \tag{6}$$

(*iii*) The D-hadrons containing a single c-quark were found.

(*iv*) Hadron jets produced by the process

$$e^+ + e^- \rightarrow q + \bar{q} \ , \quad q \rightarrow \text{hadron jet} \ , \quad \bar{q} \rightarrow \text{hadron jet} \ ,$$

were identified.

One e^+e^- collider is now operating in this region, SPEAR in the United States. A new, higher luminosity e^+e^- collider, BEPC, is now being built in the Peoples Republic of China to operate in this region.

There are a number of recognized research areas in this region. There is much more to be done in studies of the ψ, D and F particle families. The complicated energy dependence of $\sigma(e^+e^- \rightarrow \text{hadrons})$ from $E_{c.m.} = 3.5$ *GeV* to about 5 GeV, Fig. 3, is not understood. The τ decay mode puzzle[5,6] needs to be unraveled. Some properties[7] of the τ, such as the mass of ν_τ, can be measured precisely using data from this region. I add to this list more precise studies of the lepton-photon vertices in Eqs. (4) and (6) and the search for a lepton-specific force.

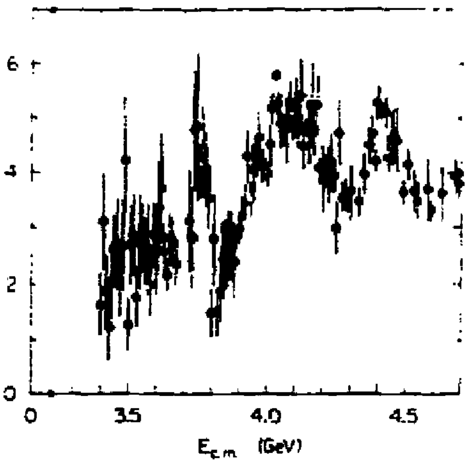

Figure 3

The need for large amounts of data to further the research listed in the previous paragraph has stimulated a proposal for a very high luminosity e^+e^- circular collider in this energy region.[8,9]

E. 10 GeV to 56 GeV: b-Quark Physics and Other Successes

At the lower end of the energy region lies the threshold for the production of the upsilon family of particles, Υ, Υ', Υ'', ..., made up of a $b\bar{b}$–quark pair, and the threshold for the production of hadrons containing a single b–quark. Three e^+e^- circular colliders operate in the 10 GeV region: CESR in the United States, DORIS in Germany and VEPP–4 in the Soviet Union.

At higher energies, there is the PEP collider in the United States, 20 to 30 GeV, and the new TRISTAN collider in Japan. The TRISTAN collider sets the upper end of this region, 56 GeV, the highest e^+e^- collision energy at which there is data. In the next few years, TRISTAN's energy will move into the 60–70 GeV range.

There have been four successes in the 10–56 GeV range. One triumphant success is the comprehensive research on the properties of hadrons containing the b–quark. The most recent research indicates the possible existence of substantial mixing of B^o and $\overline{B}^o$ mesons. This in turn allows the possibility of searching for CP violation in the B^o–$\overline{B}^o$ system and, if it exists, studying CP violation in this new system.

Future detailed studies of b–quark physics and searching for CP violation requires e^+e^- collider luminosities in the range of 5×10^{32} to 10^{34} cm^{-2} s^{-1}. Existing e^+e^- colliders have luminosities in the range of 10^{31} to 10^{32} cm^{-2} s^{-1}. Therefore, a great amount of discussion and design work is being devoted to higher luminosities. Plans and proposals[10] include: increasing the luminosities of the existing single-ring, circular colliders; building new double-ring, circular colliders; building a linear collider; and building a mixed linear-circular collider. These e^+e^-–collider proposals have to be compared with proposals to use the large number of B mesons produced in hadron-hadron collisions, in fixed target or collider experiments.

The second great success is the elucidation of the theory of quantum chromodynamics through the study of hadron production in the continuum. An important part of this elucidation came from the discovery and study of events with three hadron jets from the process

$$\begin{aligned} &e^+ + e^- \to q + \bar{q} + g \ , \\ &q \to \text{quark} - \text{hadron jet} \ , \\ &\bar{q} \to \text{quark} - \text{hadron jet} \ , \\ &g \to \text{gluon} - \text{hadron jet} \ . \end{aligned}$$

The third success is the study of hadron production and related physics in the two-virtual photon process,

$$\begin{aligned} &e^+ + e^- \to e^+ + e^- + \gamma_v + \gamma_v \\ &\gamma_v + \gamma_v \to \text{hadrons} \end{aligned}$$

in Fig. 4. Here γ_v is a virtual photon which in some kinematic conditions is almost a real photon.

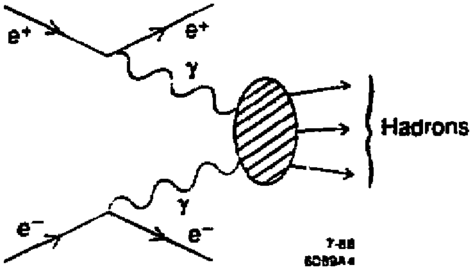

Figure 4

The fourth success is the measurement of the interference of the electromagnetic and weak amplitudes, Fig. 5, as the energy advances up the lower tail of the Z°. A taste of greater things to come.

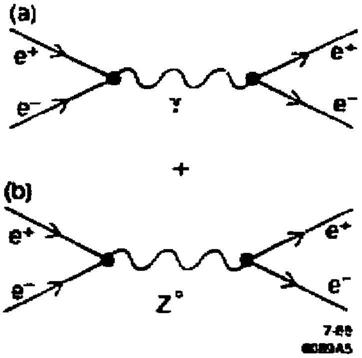

Figure 5

The PETRA e^+e^- collider in Germany contributed data to all of the mass, along with the other colliders listed in this section. PETRA which reached a maximum energy of about 46 GeV is not operated at present.

Out of the large amount of data collected in this 10 to 56 GeV region has also come a strange result. The many measurements of the decay modes of the τ lepton have resulted in a problem in understanding the decay modes with one-charged particle, Table I. There is a discrepancy[5,6] between the inclusive

Rows	Symbol	Decay Mode of τ^-	Branching Fraction (%)
1	B_1	1-charged particle inclusive	86.6 ± 0.3
2	B_e	$\nu_\tau + e^- + \bar{\nu}_e$	17.6 ± 0.4
	B_μ	$\nu_\tau + \mu^- + \bar{\nu}_\mu$	17.7 ± 0.4
	B_π	$\nu_\tau + \pi^-$	10.8 ± 0.6
	B_ρ	$\nu_\tau + \rho^-$	22.5 ± 0.9
		Sum for modes in Rows 2	68.6 ± 1.2
3	$B_{\pi 2\pi^0}$	$\nu_\tau + \pi^- + 2\pi^0$	7.6 ± 0.8
		$\nu_\tau + mK + n\pi^0$ $\longrightarrow$ 1-charged particle $m \geq 1,\ n \geq 0,\ K = K^0$ or K^-	1.8 ± 0.3
		Sum for modes in Rows 3	9.4 ± 0.9
4		$\nu_\tau + \pi^- + n\pi^0$ $n \geq 3$ $\nu_\tau + \pi^- + m\eta + n\pi^0$ $\longrightarrow$ 1-charged particle $m \geq 1,\ n \geq 0,$	
		Sum for modes in Rows 4	$\leq$ 2.7
5		Sum for modes in Rows 2, 3 and 4	80.7 ± 1.5

Table 1. Summary of present knowledge of 1-charged particle branching fraction in percent from Refs. 5 and 6. The numbers in Rows 1, 2, and 3 are the average of measured values and the associated standard deviation. The sum in Row 4 is the 95% upper limit obtained from other data and accepted theory. Note that Refs. 5 and 6 used Gaussian error distributions.

one-charged particle branching fraction and the sum of the known exclusive one-charged particle branching fractions.

The 10 to 56 GeV region has brought great disappointment, as well as great success. The top quark has not been found; a fourth generation quark has not been found; a fourth generation charged lepton has not been found; nor have additional neutral leptons been found—but the neutral leptons searches are not definitive.[12] Further e^+e^- searches for these particles requires higher energy: TRISTAN above 56 GeV, the SLAC Linear Collider (SLC) and LEP in the Z° region of 70 to 110 GeV, LEP above the Z° to about 200 GeV and, ultimately, e^+e^- linear colliders into the TeV region.

Before moving on from what we have measured below 56 GeV to what we hope to measure above 56 GeV, I will summarize our knowledge and expectations about the total cross sections for

$$e^+ + e^- \rightarrow \ell^+ + \ell^- \; ; \quad \ell = e, \mu, \tau \, ,$$

and

$$e^+ + e^- \rightarrow \text{hadrons} \, .$$

These reactions make up the explored land of known e^+e^- collision physics. We have to look beyond that land for new particles or new phenomena.

F. Overview of Cross Section for $e^+e^- \rightarrow \ell^+\ell^-$

The total cross section for

$$e^+ + e^- \rightarrow \ell^+ + \ell^- \; ; \quad \ell = e, \mu, \text{ or } \tau \, , \tag{7}$$

follows from electroweak interaction theory. In writing down these formulas, I keep in mind that the formulas have only been confirmed directly in the e^+e^- collisions below 56 GeV, and indirectly in the decays of Z°'s produced in $p\bar{p}$ collisions. There may be surprises. Consider three energy regions, Fig. 6: the region centered on the Z° mass of about 93 GeV; the region below the Z°; and the region far above the Z°, above 200 GeV. In these formulas I ignore threshold effects and radiative corrections. The latter may be substantive, changing cross sections by tens of percent.

Below the Z°, the electromagnetic process, Fig. 5a, dominates with

$$\sigma(e^+e^- \rightarrow \gamma \rightarrow \ell^+\ell^-) = \frac{4\pi\alpha^2}{3s} \approx \frac{87}{s} \text{ nb} \, , \tag{8a}$$

where s is in GeV^2. The weak process itself gives, Fig. 5b,

$$\sigma(e^+e^- \rightarrow Z^\circ \rightarrow \ell^+\ell^-) = \frac{G^2 s}{96\pi} = 1.8 \times 10^{-7} s \text{ nb} \, , \tag{8b}$$

where s is again in GeV^2. Thus, when $\sqrt{s} \lesssim 50$ GeV, the weak process is detected through its interference with the electromagnetic.

In the vicinity of the Z°, the weak process dominates as a real $Z^\circ$is produced. Here

$$\sigma(e^+e^- \rightarrow Z^\circ \rightarrow \ell^+\ell^-) = \frac{G^2 s}{96\pi} \left[\frac{m_Z^4}{(s - m_Z^2)^2 + \Gamma_Z^2 m_Z^2} \right] \, , \tag{9}$$

This is about 1.6 nb at $E_{c.m.} = m_Z$. Radiative corrections reduce this to about 1.2 nb.

Above 200 GeV, if there are no surprises, the electromagnetic process contributes according to Eq. (8a), but it is convenient to put s in TeV^2 and use picobarns instead of nanobarns. Then,

$$\sigma(e^+e^- \rightarrow \gamma \rightarrow \ell^+\ell^-) \approx \frac{0.087}{s} \text{ pb} \approx \frac{0.1}{s} \text{ pb} \, , \tag{10a}$$

a very small cross section. The weak process, ignoring interference, gives an even smaller cross section:

$$\sigma(e^+e^- \rightarrow Z^\circ \rightarrow \ell^+\ell^-) \approx \frac{G^2 m_Z^4}{96\pi s} = \frac{0.013}{s}\ \text{pb}\,, \tag{10b}$$

with s in TeV^2.

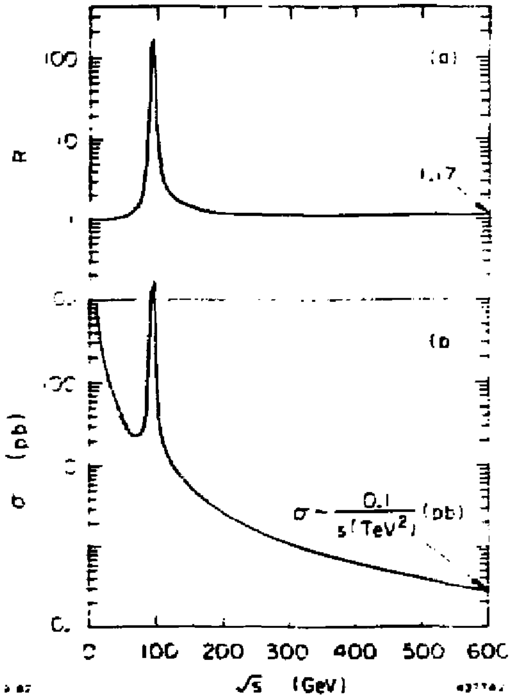

Figure 6

Figure 6 also gives the cross section in terms of R, where

$$R = \frac{\sigma}{\sigma_0}\,, \qquad \sigma_0 = \frac{4\pi\alpha^2}{3s}\,. \tag{11}$$

Thus far above this Z° region, $R(e^+e^- \rightarrow \ell^+\ell^-)$ is again about one.

G. *Overview of Cross Section for $e^+e^- \rightarrow$ hadrons*

Again, I consider three energy regions: below the Z°, in the vicinity of the $Z^\circ$and far above the Z°.

Below the Z°, hadron production is dominated by the electromagnetic process

$$e^+ + e^- \rightarrow \gamma \rightarrow \text{hadrons}\,, \tag{12}$$

operating through the two mechanisms described in Fig. 2: resonance production and continuum production. The cross section for continuum production is obtained from Eq. (5) by summing over the number of quarks multiplied by three, for the three colors. Ignoring quantum chromodynamic corrections

$$\sigma(e^+e^- \to \gamma \to \text{hadrons continuum}) \approx \frac{4\pi\alpha^2}{s} \sum_q Q_q^2 \,. \tag{13a}$$

Usually, as in Fig. 7,[13] R is displayed. Measurements confirm the expectation

$$R(e^+e^- \to \gamma \to \text{hadrons, continuum}) \approx 3 \sum_q Q_q^2 \,. \tag{13b}$$

Once quantum chromodynamics is taken into account, as $E_{c.m.}$ rises to the lower tail of the Z°, the weak process contribution

$$e^+ + e^- \to Z^\circ \to \text{hadrons} \,, \tag{14}$$

becomes obvious, Fig. 7b.

In the vicinity of the Z°, we expect an enormous increase in $\sigma(e^+ + e^- \to Z^\circ \to \text{hadrons})$, Fig. 8. At the Z°, $\sigma(e^+ + e^- \to Z^\circ \to \text{hadrons}) \approx 40$ nb, including the radiative corrections.

Far above the Z°(above, say, 200 GeV), the production of hadrons occurs through the combined amplitudes for the reactions in Eqs. (12) and (14). In analogy to Eq. (10)

$$\sigma(e^+e^- \to q\bar{q} \to \text{hadrons}) = \frac{0.087\, r_q\, T_q\,(m_q,\, s)}{s}\ \text{pb} \,. \tag{15}$$

Here s is in TeV^2, T_q is a threshold factor with $T_q = 1$ for $s \gg m_q^2$, m_q is the mass of the q–quark and

$$r_q = 1.9 \,, \quad \text{charge } \frac{2}{3} \text{ quarks}: \ u, c \,,$$

$$r_q = 1.1 \,, \ \text{charge } \frac{1}{3} \text{ quarks}: \ d, s, b \,,$$

These five known quarks will give

$$\sigma\,(e^+e^- \to \text{hadrons}) = \frac{0.6}{s}\ \text{pb} \,. \tag{16}$$

With these completed overviews of charged lepton and hadron production, I move above the 56 GeV boundary to energies yet to be explored in e^+e^- collision physics.

B. 56 GeV to 70 GeV

The new TRISTAN collider will soon explore this region. The great interest is to search for new particles, particularly the top quark, and to search for new phenomena. Other interests are the study of the interference between electromagnetic and weak amplitudes and the study of two-virtual photon physics.

I have though of a speculative possibility in this region where the cross sections for lepton and quark production are at a minimum before the rise of

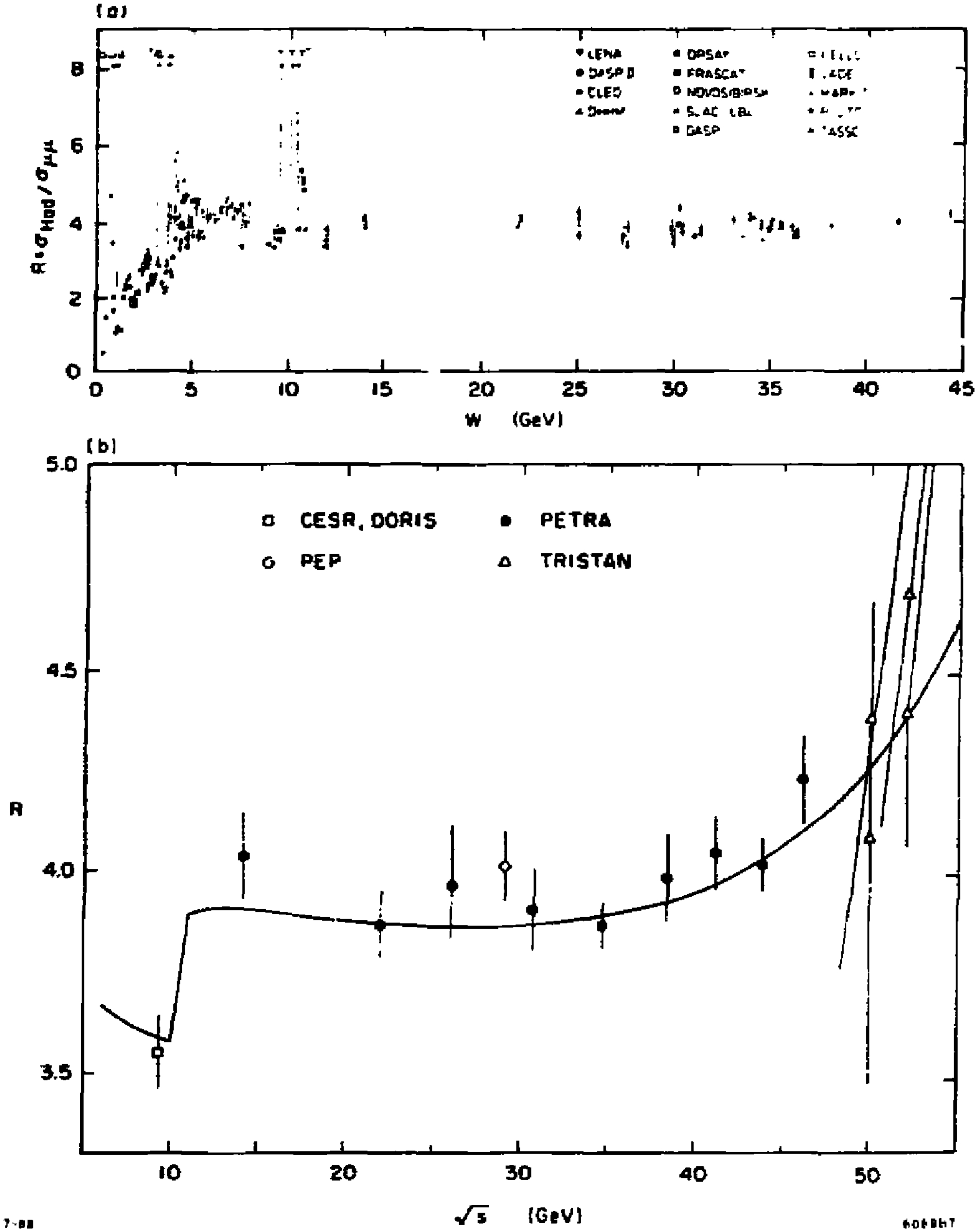
(a)
R = σHad / σμμ
0
2
4
6
8
0
5
10
15
20
25
30
35
40
45
W (GeV)
LENA
DASP II
CLEO
ORSAY
FRASCATI
NOVOSIBIRSK
SLAC LBL
DASP
CELLO
JADE
MARK J
PLUTO
TASSO
(b)
R
3.5
4.0
4.5
5.0
10
20
30
40
50
√s (GeV)
CESR, DORIS
PEP
PETRA
TRISTAN
7-88
606867

Figure 7

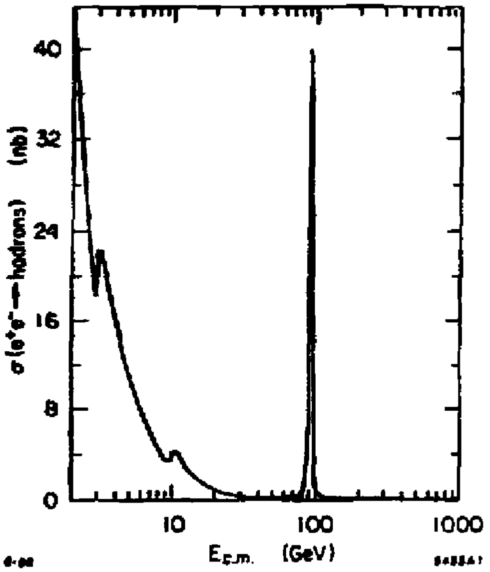

Figure 8

the Z°. Suppose there is a new phenomenon in e^+e^- collision physics which occurs at much higher energy. At lower energies, the cross section for effects due to this phenomenon might be proportional to s in analogy to Eq. (8b). The minimum in the cross section for lepton and quark production is an ideal place to look for such effects.

I. The Z° Region: SLC and LEP

We are entering this energy region with two new e^+e^- colliders. The SLAC Linear Collider (SLC) in the United States, Fig. 9, is starting operation at the Z°. Its energy range is 70 to 110 GeV. It is the first collider to use the linear collider principle,[13] pointing the way for this new collider technology.

In about a year, the LEP e^+e^- circular collider, Fig. 10, in Switzerland will begin operation; the largest diameter accelerator or collider in the world. It will begin in the Z° energy region. As the supply of radio frequency power to the circulating beams is increased, the energy range will be extended to about 180 GeV.

So much has been dreamed and written about e^+e^- collision physics at the Z°; too much to summarize. I will mention a few main points.[14]

The Z° resonance, Figs. 6 and 8, provides an enormous cross section for lepton and quark production at high energy. Neutral elementary fermions, such as neutrinos, are produce as copiously as charged fermions. At $E_{c.m.} = m_z$,

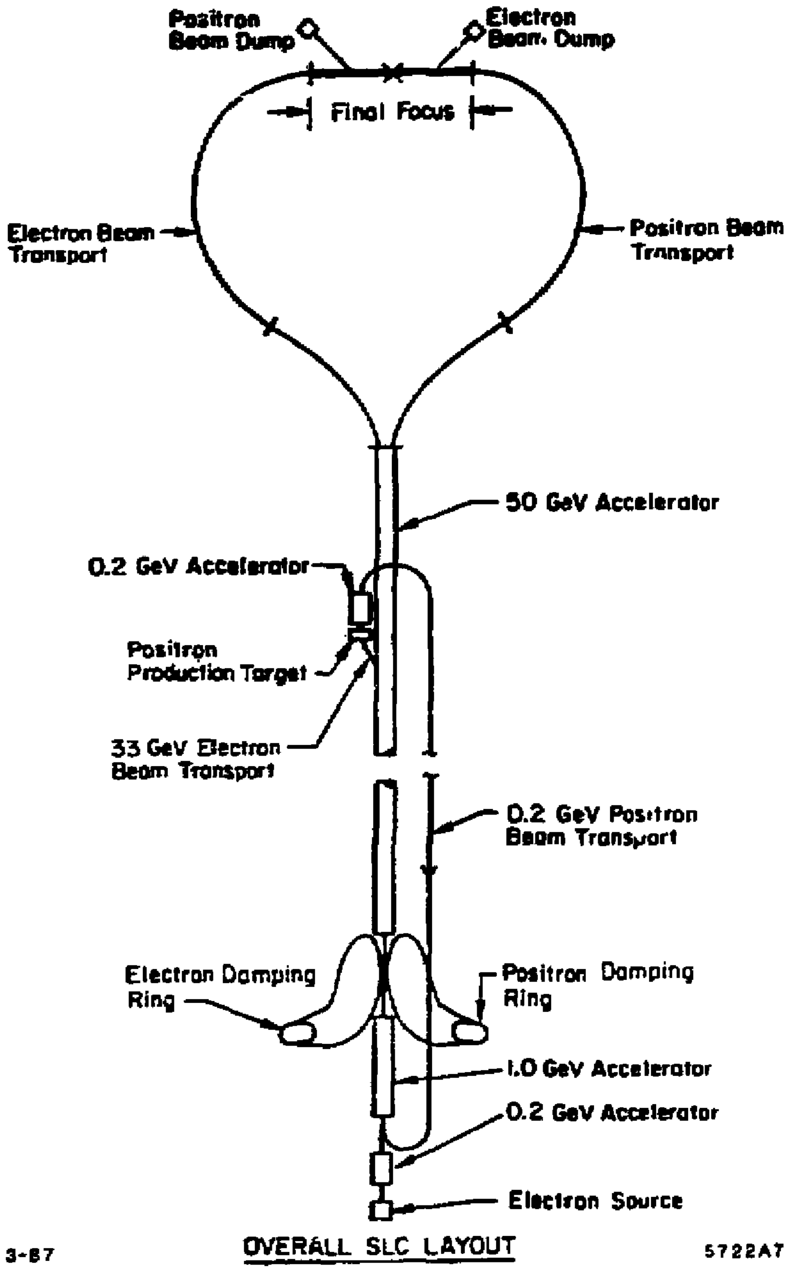
Positron Beam Dump
Electron Beam Dump
Final Focus
Electron Beam Transport
Positron Beam Transport
50 GeV Accelerator
0.2 GeV Accelerator
Positron Production Target
33 GeV Electron Beam Transport
0.2 GeV Positron Beam Transport
Electron Damping Ring
Positron Damping Ring
1.0 GeV Accelerator
0.2 GeV Accelerator
Electron Source
3-87
OVERALL SLC LAYOUT
5722A7

Figure 9

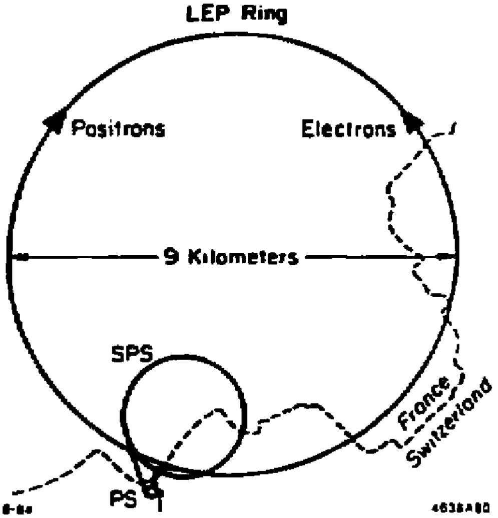

Figure 10

ignoring radiative corrections:

$$\sigma(e^+e^- \to Z^\circ \to f\bar{f}) = \frac{G^2 m_z^4 r_f T_f(m_f, m_z)}{96\pi\Gamma_Z^2} . \tag{17}$$

Here T_f is a threshold factor and

$$\begin{aligned} r_f &= 1.0 , & f &= \ell^- = e^-, \mu^- \text{ or } \tau^- \\ r_f &= 2.0 , & f &= \nu_\ell , \\ r_f &= 1.2 , & f &= u \text{ or } c \text{ quark} , \\ r_f &= 1.5 , & f &= d, s, \text{or } b \text{ quark} , \end{aligned}$$

Searches for new particles can be direct or indirect. If a new particle is charged, stable or unstable, or if a new particle is neutral and unstable, the search can be direct—unexplained events from the Z° decay.

The production of new stable neutral particles—massive neutrinos, for example—can be detected indirectly through additions to the predicted width of the Z°:

$$\begin{aligned} \Gamma_Z &= \sum_f \Gamma_{Zf} , \\ \Gamma_{Zf} &= \frac{G m_Z^3 r_f T_f}{24\sqrt{2}\pi} \end{aligned} \tag{18}$$

This, again, ignores radiative corrections which must be precisely calculated. If the mass of the new, neutral particle is of the order of a GeV/c^2 or less, the cross section for the reaction

$$e^+ + e^- \rightarrow Z^\circ \rightarrow \gamma + \text{missing energy} \,, \qquad (19a)$$

will be augmented above that contributed by

$$e^+ + e^- \rightarrow Z^\circ \rightarrow \gamma + \nu_\ell + \bar{\nu}_\ell \,, \qquad \ell = e, \mu, \tau \,. \qquad (19b)$$

If you believe in the existence of a physical Higgs particle, the elusive H° can be sought through

$$e^+ + e^- \rightarrow Z^\circ \rightarrow Z^\circ + H^\circ \,.$$

Returning to known physics, production and decay of the Z° at LEP and the SLC is a source of c–quarks, b–quarks and τ leptons, allowing extension of the knowledge gained in the 3 GeV to 56 GeV regions. In addition, electroweak theory and quantum chromodynamics can be tested in more detail.

J. 100 GeV to 200 GeV: LEP

Moving above the Z°, the energy region up to about 200 GeV will be explored by the LEP collider.[15] New searches will be made for more massive quarks and leptons, for the Higgs particle (if not yet found), and for speculative particles of all sorts.

The reaction

$$e^+ + e^- \rightarrow W^+ + W^- \,, \qquad (20)$$

is of great interest because one of its amplitudes, Fig. 11, has a W–Z°–W vertex. Electroweak theory predicts the cross section in Fig. 12. At 200 GeV, $\sigma(e^+e^- \rightarrow W^+W^-) = 20$ pb compared to $\sigma(e^+e^- \rightarrow \mu^+\mu^-) = 2.5$ pb from Eq. (10). Thus, the cross section for $e^+e^- \rightarrow W^+W^-$ is relatively substantial at the upper end of this energy range. Once W's are directly produced, their properties and their decay products can be studied in detail.

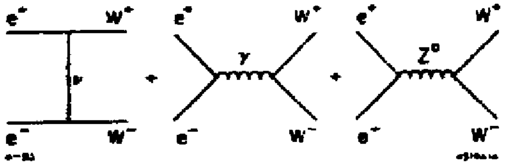

Figure 11

For most of us, the 100 to 200 GeV region is both fascinating and frightening. We expect to understand e^+e^- collision physics thorough the Z° region, although this may be hubris; but the 100 to 200 GeV region is the entrance to *terra incognita.* What if no new particles are found below 200 GeV, not even the top quark? What if $\sigma(e^+e^- \rightarrow f\bar{f})$ continues to decrease as $1/s$, beautifully simple, but *ever smaller*?

It will be eight to ten years before experimenters at LEP have concluded a through exploration of this region. We are too impatient to wait those years

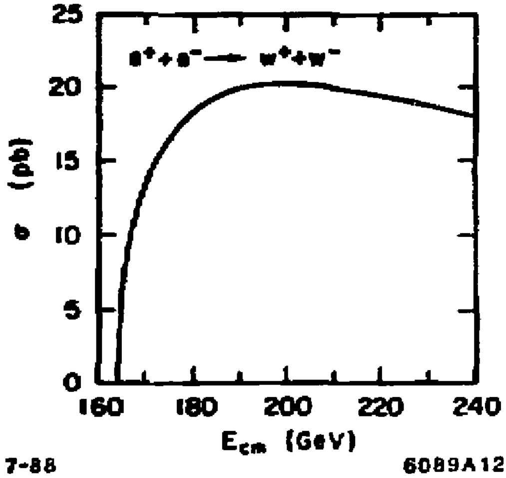

Figure 12

before deciding to push above 200 GeV in e^+e^- collision physics. Hence, our great interest in e^+e^- linear colliders[13] and e^+e^- collision physics from 200 GeV to 2 TeV.

K. *200 GeV to 2 TeV: e^+e^- Linear Colliders*

We are excited about with e^+e^- linear colliders, Fig. 13, because the traditional e^+e^- circular collider costs too much to build and operate above 200 or 300 GeV. We don't know yet how to design a 500 GeV or 2 TeV linear collider, but we know the general principles; we know what we have to do. Cross sections of the order of

$$\sigma \sim \frac{.1}{s}\ \mathrm{pb}\ ,$$

with s in TeV^2, require luminosities in the range of 10^{33} to 10^{34} cm^{-2} s^{-1}. This requires the transverse dimensions of the colliding e^+ and e^- bunches to be 10^{-3} to 10^{-1} μm, putting large demands on controlling the size and position of the bunches as they move through the linear accelerator. Large amounts of microwave power must be produced efficiently. Bunch halos and backgrounds from passage of the bunches through the magnets and collimators must be eliminated so as not to overwhelm the detector.

Linear collider research and development work[13] is going on in Europe, Japan, the Soviet Union and the United States. There is a great deal to learn and invent. It may not be wise to try to jump from the 100 GeV, pioneering SLAC Linear Collider to a 1 or 2 TeV linear collider. The best course may be to build an intermediate energy facility of, say, 500 GeV and then use that experience to go on.

As I have already said, the 200 GeV to 2 TeV region is *terra incognita*. Even conventional processes become strange and wonderful.[16,17] Suppose there

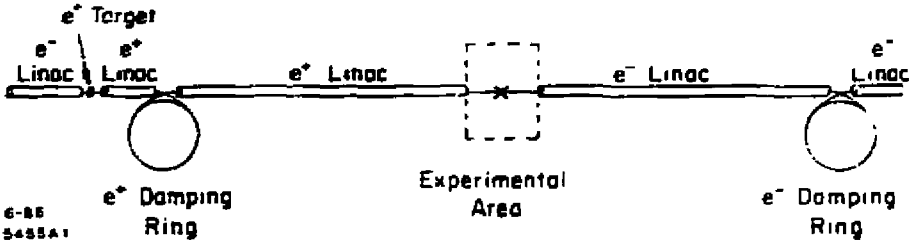

Figure 13

is a massive lepton pair L^-, L^o with

$$m_- - m_0 > m_W \ ,$$

where m_-, m_0 and m_W are the masses of the L^-, L^o and W. Then the major decay mode is

$$L^- \rightarrow L^o + W^- \ ,$$

where the W^- is real and itself decays. The W^- here is like the π^- or ρ^- in

$$\tau^- \rightarrow \nu_\tau + \pi^- \ , \quad \nu_\tau + \rho^- \ .$$

Similarly, the major decay mode of a massive quark pair q, q' with

$$m_q - m_{q'} \ > \ m_W \ ,$$

is

$$q \rightarrow q' + W^- \ .$$

Another wonderful effect of very high energy on conventional processes is that the "two virtual-photon" process of Fig. 14a is joined by the "two virtual-W" process of Fig. 14b. A variation of the process in Fig. 14b provides a neat way to produce a physical Higgs particle,

$$e^+ + e^- \rightarrow \bar{\nu}_e + \nu_e + H^o \ ,$$

via the process in Fig. 14c.

By now we are far in the future; it is almost time to conclude this journey from 1 MeV to 2 TeV. Before concluding, I want to speculate on something we can search for now—a lepton-specific force.

L. Speculations on a Lepton-Specific Force

It is strange to me that it is conventional to hope or expect that (a) lepton generations mix just as quark generations mix, and (b) neutrinos have nonzero mass. It is strange because experiment leads to opposite conclusions. There is no evidence for $e-\mu$, $e-\tau$ or $\mu-\tau$ generation mixing. Indeed, one of the most precise measurements in particle physics is the upper limit

$$\frac{\Gamma(\mu^- \rightarrow e^-\gamma)}{\Gamma(\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu)} \ < \ 10^{-10} \ .$$

There is no confirmed evidence for neutrino masses being other than zero.

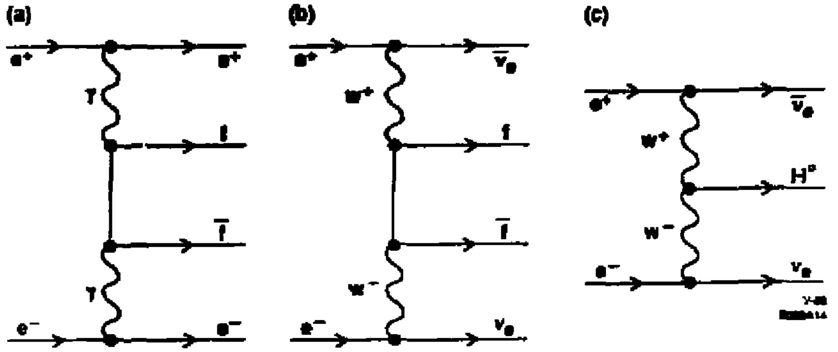

Figure 14

I see the leptons as very different from the quarks, and this has led me to speculate as to the existence of a force only exerted by and on leptons—a lepton-specific force.

I think of the force as being carried by a neutral particle λ, with mass m_λ and an L–λ–L coupling of strength $\sim \sqrt{\alpha_\lambda}$. Here L is a charged lepton or neutrino. This speculation overlaps axion and Higgs particle ideas, but the λ doesn't couple to nonleptons. The precise strength of the coupling may depend on the type of lepton or generation, but I don't think of $\sim \sqrt{\alpha_\lambda}$ as depending, like the Higgs particle, on the lepton mass.

Christopher Hawkins and I[18] have considered what ranges of m_λ and α_λ are ruled out by: atomic measurements such as $g_e - 2$, by previous particle physics measurements and searches, such as axion searches, and by deductions from astrophysics. We find that when

$$m_\lambda \gtrsim 10 \text{ to } 100 \text{ MeV}/c^2 .$$

There are few experimental limits on the existence of a particle λ carrying a lepton-specific force.

Three hypothetical processes in e^+e^- collision physics, Fig. 15, allow searches for the λ. The process in Fig. 15a, with a λ in the t–channel, would affect small angle Bhabha scattering—a reaction which has never been tested to better than several percent in e^+e^- collisions physics.

The process in Fig. 15b, annihilation through the λ, would show up as an energy resonance at $E_{c.m.} = m_\lambda$ in

$$e^+ + e^- \rightarrow \ell^+ + \ell^- , \quad \ell = e, \mu, \tau . \tag{21}$$

In Sec. B, I noted that there are precise experiments searching for a resonance in $e^+e^- \rightarrow e^+e^-$ at $E_{c.m.} \sim 1.8$ MeV; but many energy regions in $E_{c.m.}$ collision physics have not been explored for an energy resonance in the reactions in Eq. 21.

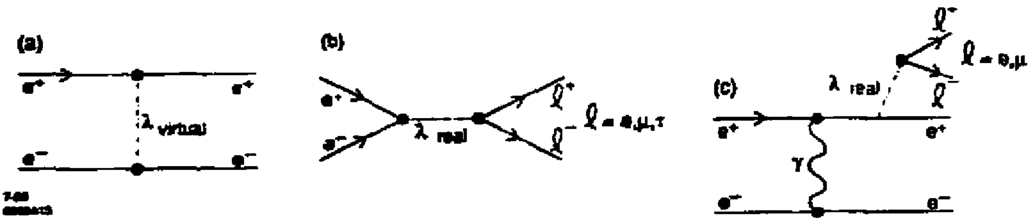

Figure 15

Hawkins and I are looking for the process in Fig. 15c, using 29 GeV data acquired with the Mark II detector at PEP:

$$e^+ + e^- \rightarrow e^+ + e^- + \lambda \,, \tag{22a}$$

$$\lambda \rightarrow e^+ + e^- \quad \text{or} \quad \lambda \rightarrow \mu^+ + \mu^- \,. \tag{22b}$$

One final e^+ or e^- in Eq. (22a) will usually have an angle close to the beam line; then the detected event is

$$e^+ + e^- \rightarrow e^\pm + \ell^\pm + \ell^\mp + \text{missing energy} \,,$$

the missing energy being carried off approximately along the beam line. The background is "two virtual-photon" processes.

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