SLAC-PUB-3449
September 1984
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EXPERIMENTS BEYOND THE STANDARD MODEL*

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1. INTRODUCTION

1A. The Standard Model

This paper is based on four lectures on techniques and directions in elementary particle physics which look beyond the so-called standard model[1.1–1.3] of particle physics. This model is actually a collection of experimental facts, established theory, and some attractive but not established models and theories; all set in a framework of relativistic quantum mechanics and conventional notions of space and time.

*Work supported by the Department of Energy, contract DE-AC03-76SF00515.

Four lectures presented at the 27th Scottish Universities Summer School in Physics, St. Andrews, Scotland, August 12-September 1, 1984

The main experimental facts are as follows.

- There are three kinds of elementary particles: the leptons, the quarks, and the force-carrying particles $\gamma, W^{\pm}, Z^0$ and gluon.
- Six leptons are known: the e, μ, τ and their associated neutrinos.
- Five quarks are known: the u, d, s, c, and b. There is preliminary evidence for a sixth quark, the t.
- Four fundamental forces are known: electromagnetic, weak, strong and gravitational.
- The phenomenon of CP violation occurs in the K meson system.
- There are vast numbers of experiments which rule out the existence of all sorts of hypothesized elementary particles and other types of fundamental forces.

The established theory is the beautiful unified theory of weak and electromagnetic interactions.[1.4] With the addition of some experimentally determined parameters, this theory classifies the leptons and quarks into three generations and explains all known properties of the weak and electromagnetic forces. The experimentally determined parameters include the mixing angles for the weak interactions of the quarks and the finding that to the best of our knowledge there is lepton conservation in each generation.

The standard model contains some attractive but not established models and theories.

- It assumes the existence of the t quark.
- The strong interactions are taken to be fully described by the theory of quantum chromodynamics (QCD).[1.2] Yet this theory is not established the way physicists need to have a theory established.[1.4,1.5] When we compare QCD to Newton's laws, Maxwell's equations, special relativity, non-relativistic quantum mechanics, or electro-weak theory, we see that quantum chromodynamics lacks many things. It does not have a clear area where it can be applied; many calculations are uncertain; it has few definitive, quantitative, experimental tests; and in many applications one does just as well with naive quark-gluon models of hadrons and hadronic interactions.
- An important part of the standard model of the electroweak interaction is the use of the Higgs mechanism to generate the W and Z masses. This mechanism, especially when used to generate fermion masses, raises more problems than it solves as presently understood.

All of these parts of the standard model are set into a theoretical framework based on the validity of quantum field theory when applied to elementary particles. We also assume that space and time are continuous, even at very small distances. And we assume a number of familiar symmetries: the conservation of electric charge, the conservation of four-momentum, and the laws of nature being independent of place or time.

1B. Beyond The Standard Model

The standard model has been achieved through three decades of major innovations in accelerator and particle detector technology, through a broad range of experiments, and through tremendous insights and progress in theoretical particle physics. It has been a revolutionary three decades. Yet the very success of this revolution has shown us that our work as particle physicists has just begun. We are now faced with fundamental questions which we can no longer avoid.

- What is the mechanism which sets the masses of the different elementary particles?
- What is the origin of the repetitive generation phenomenon? Are there more generations?
- Are there elementary particles which do not fit into the lepton and quark generation pattern?
- Will quantum chromodynamics be the final theory of the strong force?
- Is there a unified theory for the strong force and the electroweak force? What about the gravitational force?
- How can experimental progress be made in connecting the gravitational force to the world of elementary particles?
- Are there undiscovered fundamental forces?
- What is the origin of CP violation?
- Is quantum field theory the right framework for understanding very-small distance or very high-energy phenomena?

1C. The Scope of this Paper

This paper is based upon lectures in which I have described and explored the ways in which experimenters can try to find answers, or at least clues toward answers, to some of these questions. All of these experimental techniques and directions have been discussed fully in other papers, for example: searches for heavy charged leptons, tests of quantum chromodynamics, searches for Higgs particles, searches for particles predicted by supersymmetric theories, searches for particles predicted by technicolor theories, searches for proton decay, searches for neutrino oscillations, monopole searches, studies of low transfer momentum hadron physics at very high energies, and elementary particle studies using cosmic rays. Each of these subjects requires several lectures by itself to do justice to the large amount of experimental work and theoretical thought which has been devoted to these subjects.

My approach in these tutorial lectures is to describe general ways to experiment beyond the standard model. I will use some of the topics listed in the last paragraph to illustrate these general ways, but I do not have the time to begin to do justice to those topics. Also, in these lectures I present some dreams and challenges about new techniques in experimental particle physics and accelerator technology, I call these Experimental Needs.

Of course, our hopes of answering some of the fundamental questions depends upon progress in experimental techniques, particularly upon progress in building higher energy accelerators. So I begin with summaries of the physics capabilities of the very high energy particle colliders now being built as well as those which could be built with existing or near-term accelerator technology.

In the interest of giving a useable reference list I limit references to review papers and to papers of particular experimental interest. Hence in many cases credit will not be given explicitly to those who did the original work; I apologize for this.

Some of the material in these lectures is taken from a paper[1.3] entitled "Beyond the Standard Model" written by Gordon Kane of the University of Michigan and myself in 1982. I am greatly indebted to Gordon Kane for that very valuable collaboration.

2. ELECTRON-POSITRON INTERACTIONS AND COLLIDERS

I begin with electron-positron colliders and e^+e^- interactions because the basic calculations are more certain and simpler than in pp, $\bar{p}p$ or ep interactions.

2A. Basic Processes

The standard model predicts the following processes depending upon the energy[1.3,2.1,2.2]

Bhabha scattering:

$$e^+ + e^- \rightarrow e^+ + e^- \tag{2.1}$$

Elementary fermion production:

$$e^+ + e^- \rightarrow \ell^+ + \ell^-;\ \ell = \mu, \tau \tag{2.2a}$$

$$e^+ + e^- \rightarrow \nu_\ell + \bar{\nu}_\ell;\ \ell = e, \mu, \tau \tag{2.2b}$$

$$e^+ + e^- \rightarrow q + \bar{q};\ q = quark = u, d, s, c, b, t \tag{2.2c}$$

Elementary vector boson production:

$$\begin{aligned}
e^+ + e^- &\to \gamma + \gamma \\
e^+ + e^- &\to \gamma + Z^0 \\
e^+ + e^- &\to Z^0 + Z^0 \\
e^+ + e^- &\to W^+ + W^-
\end{aligned} \tag{2.3}$$

When $\sqrt{s} \lesssim 40$ GeV, the processes in Eq. 2.2 are mainly electromagnetic

$$e^+e^- \to \gamma_{virtual} \to f^+f^- \tag{2.4}$$

Assuming the fermion is a spin 1/2, unit charge, point particle, the differential cross section is:

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s}\,(2 - \beta^2 \sin^2\theta) \tag{2.5}$$

Here s is the square of the center-of-mass energy, α is the fine structure constant, and β is the fermion velocity in units of the velocity of light. The total cross section is

$$\sigma = \frac{2\pi\alpha^2\beta(3-\beta^2)}{3s} \tag{2.6}$$

When the $\sqrt{s}$ is much larger than the fermion mass we have the basic, point fermion, electromagnetic cross section,

$$\sigma_0 = \frac{4\pi\alpha^2}{3s} = \frac{86.7}{s}\ nb,\ \ s\,\mathrm{in}\,GeV^2 \tag{2.7}$$

A convenient mnemonic in the very high energy range is

$$\sigma_0 \sim \frac{10^{-37}}{s}\ cm^2,\ \ s\,\mathrm{in}\,TeV^2 \tag{2.8}$$

Finally, it is convenient to define a relative cross section

$$R = \sigma/\sigma_0$$

Equations 2.5 – 2.8 apply directly to $e^+e^- \to \mu^+\mu^-$, $\tau^+\tau^-$.

Hadron production away from the ψ and Υ resonances proceeds through Eq. 2.4 where the f is a quark q. Eq. 2.6 is modified to

$$e^+e^- \to q\,\bar{q}:\ \sigma = \frac{2\pi\alpha^2 Q_q^2 \beta(3-\beta^2)}{3s};\ \sqrt{s} \lesssim 40\ GeV \tag{2.9}$$

Here Q_q is the quark charge. This leads to the famous prediction that above the threshold for b quark production, but with $\sqrt{s} \lesssim 40$ GeV

$$R_{hadronic} = 3\,[Q_u^2 + Q_d^2 + Q_s^2 + Q_c^2 + Q_b^2] = 11/3 \tag{2.10}$$

a prediction which is confirmed by experiment.

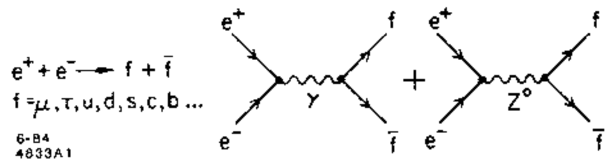

Fig. 2.1.

As $\sqrt{s}$ increases above 40 GeV and moves through the Z^0 resonance, the production of lepton or quark pairs now proceeds through both the electromagnetic and weak interaction, Fig. 2.1. In the vicinity of the Z^0, for our survey purpose, we can ignore the electromagnetic process and use[2.3]

$$\begin{aligned} e^+e^- \rightarrow f\bar{f} : \sigma &= \frac{G^2 s}{96\pi}\left[\frac{m_z^4}{(s-m_z^2)^2 + \Gamma_z^2 m_z^2}\right] C_{ef} \\ C_{ef} &= \left[v_e^2 + a_e^2\right]\left[v_f^2 + a_f^2\right] \end{aligned} \tag{2.11}$$

Here G is the Fermi weak coupling constant, m_z is the Z^0 mass, and Γ_z is the Z^0 width. The parameters v and a are from the v-aγ5 expression in the weak current. Table 2.1 gives their value in the standard model.

Table 2.1. Standard model expressions for ν_f, a_f, and $(\nu_f^2 + a_f^2)$; numerical values for $\sin^2\theta_W = 0.22$.

		ν_f	a_f	$\nu_f^2 + a_f^2$
lepton type	neutrino	$+1$	$+1$	2.00
	ℓ^-	$-1 + 4\sin^2\theta_W$	-1	1.01
quark type	up class (u,c,t)	$+1 - \frac{8}{3}\sin^2\theta_W$	$+1$	1.17
	down class (d,s,b)	$-1 + \frac{4}{3}\sin^2\theta_W$	-1	1.50

At the Z^0 for $e^+e^- \rightarrow f\bar{f}$

$$R = 160\ C_{ef};\ \textit{without radiative correction} \tag{2.12}$$
$$R = 110\ C_{ef};\ \textit{with radiative correction} \tag{2.13}$$

As the energy, $\sqrt{s}$, moves above Z^0, the contribution of the weak interaction begins to decrease relative to the electromagnetic interaction. Eventually the latter interaction dominates for charged fermion production. All this assumes the standard model of one Z^0. The cross sections all behave as 1/s and we have the simple rule [2.3] for $\sqrt{s} >> m_z$, and neglecting t-channel contributions to $e^+e^- \to e^+e^-, e^+e^- \to \nu_e \bar{\nu}_e$,

$$\begin{aligned} &R(e^+e^- \to \ell^+\ell^-) = 1.17 \\ &R(e^+e^- \to \nu^+\nu^-) = 0.31 \\ &R(e^+e^- \to q\,\bar{q}) = 1.95, q\ charge = 2/3 \\ &R(e^+e^- \to q\,\bar{q}) = 1.09, q\ charge = 1/3 \end{aligned} \tag{2.14}$$

Fig. 2.2 sketches this behavior for a charged lepton pair; the Z^0 peak has not been corrected for radiation.

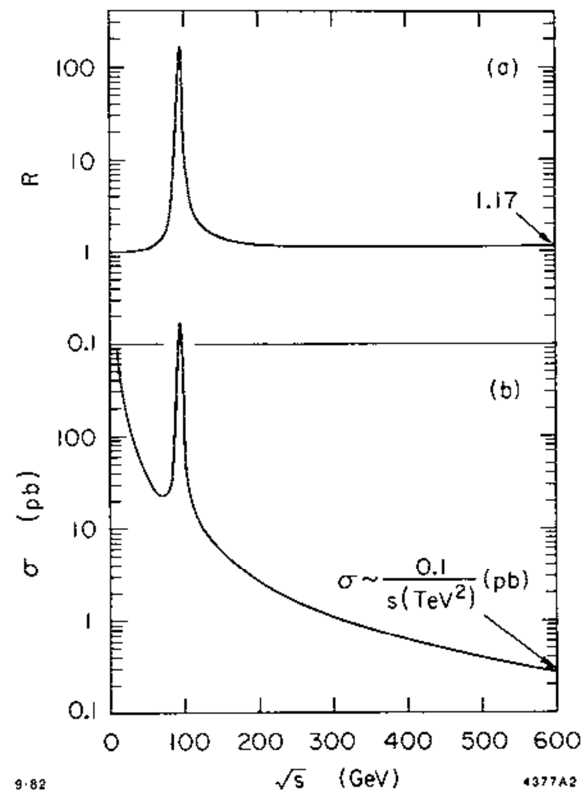

Fig. 2.2. For $e^+e^- \to \ell^+\ell^-$: (a) R and (b) cross section versus energy

Finally we consider vector boson production, Eq. 2.3, which occur through the

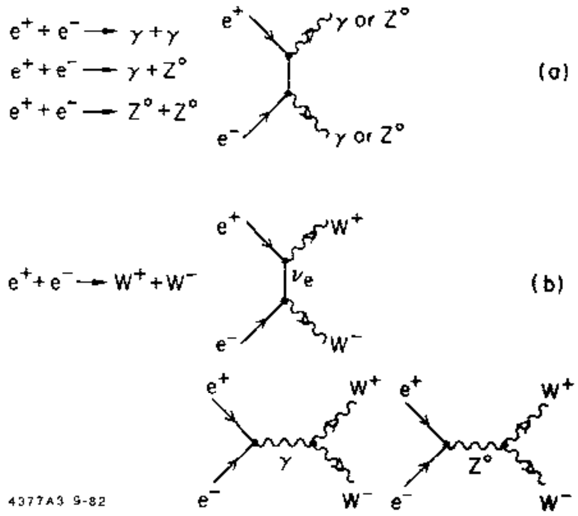

Fig. 2.3.

diagrams in Fig. 2.3. Figure 2.4a shows the behavior of R for $\sin^2\theta_W = 0.22$. Thus contrary to fermion pair production, R increases with $\sqrt{s}$.

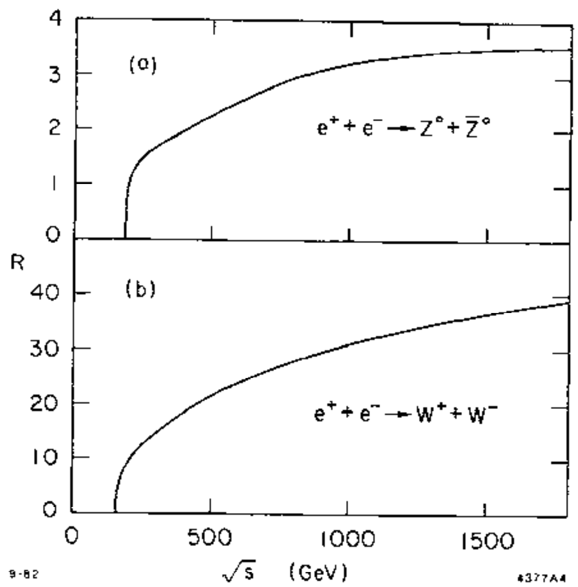

Fig. 2.4

The reaction

$$e^+e^- \rightarrow W^+W^- \tag{2.15}$$

occurs[2.2] through a complicated cancellation of the three diagrams in Fig. 2.3b. For large s

$$e^+e^- \rightarrow W^+W^- : \sigma = \frac{\pi\alpha^2}{2\sin^4\theta_W}\frac{1}{s}\left(\ell n\frac{s}{m_w^2} - 5/4\right) \tag{2.16}$$

Figure 2.4b gives the behavior of R versus energy. Table 2.2 summarizes the behavior of R as a function of energy.

Table 2.2. R for e^+e^- goes to the indicated final states assuming the standard model and $\sin^2\theta_W = 0.22$. The values at the Z^0 are corrected for radiation. From Ref. 1.3.

$\sqrt{s}$	$\ell^+\ell^-$	$\nu\bar{\nu}$	$q\bar{q}$ charge$=\frac{2}{3}$	$q\bar{q}$ charge$=\frac{1}{3}$	Z^0Z^0	W^+W^-
40	1.00	.02	1.33	.33	.0	.0
93(Z^0)	110	225	395	505	.0	.0
200	1.27	.50	2.37	1.54	1.1	9.5
700	1.18	.32	1.97	1.11	2.8	26.0
2000	1.17	.31	1.956	1.09	3.4	42.0

The physics of e^+e^- annihilation has also been discussed by Dowell[2.12] and Cashmore[2.13] at this school.

2B. Circular Electron – Positron Colliders : Energy and Luminosity

Figure 2.5 illustrates the basic concepts of a single ring collider, either e^+e^- or $\bar{p}\,p$.

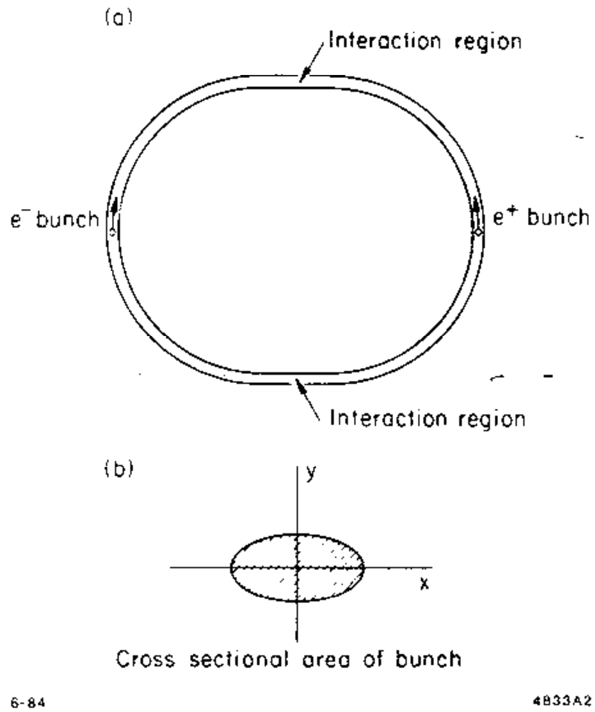

Fig. 2.5. (a) Schematic diagram of an e^+e^- circular collider. (b) Transverse cross sectional area of a bunch

The collision is head-on, usually each beam has the same energy E_b, and the total energy is

$$E_{tot} = 2E_b \tag{2.17}$$

while the total momentum is zero. The other crucial quantity, the luminosity per interaction region is

$$\mathcal{L} = n_b N^2 f/A \tag{2.18a}$$

where n_b is the number of bunches of e^+ or e^-, N is the number of e^+ or e^- in a bunch, f is the bunch rotation frequency, and A is the effective cross sectional area of a bunch. The number of events per second for a cross section σ is

$$events/second = \sigma\mathcal{L} \tag{2.18b}$$

Note that the transverse particle distribution in a bunch is usually taken to be Gaussian

$$A = 4\pi\sigma_x\sigma_y \tag{2.18c}$$

and where σ_x and σ_y are the horizontal and vertical Gaussian sigmas of the bunch cross section, Fig. 2.5b.

Two very high-energy circular electron-positron colliders are now being constructed: TRISTAN[2.5] in Japan will have a maximum total energy of 70 GeV, a maximum design luminosity of $8 \times 10^{31} cm^{-2}s^{-1}$ at 54 GeV, and 4 interaction regions. LEP at CERN[2.6] is the highest energy e^+e^- collider under construction, Fig. 2.6. In its first phase it will have a total energy of 120 GeV, a luminosity of about $10^{31} cm^{-2}s^{-1}$, and 4 interaction regions. Ultimately the total energy could be raised to between 200 and 250 GeV.

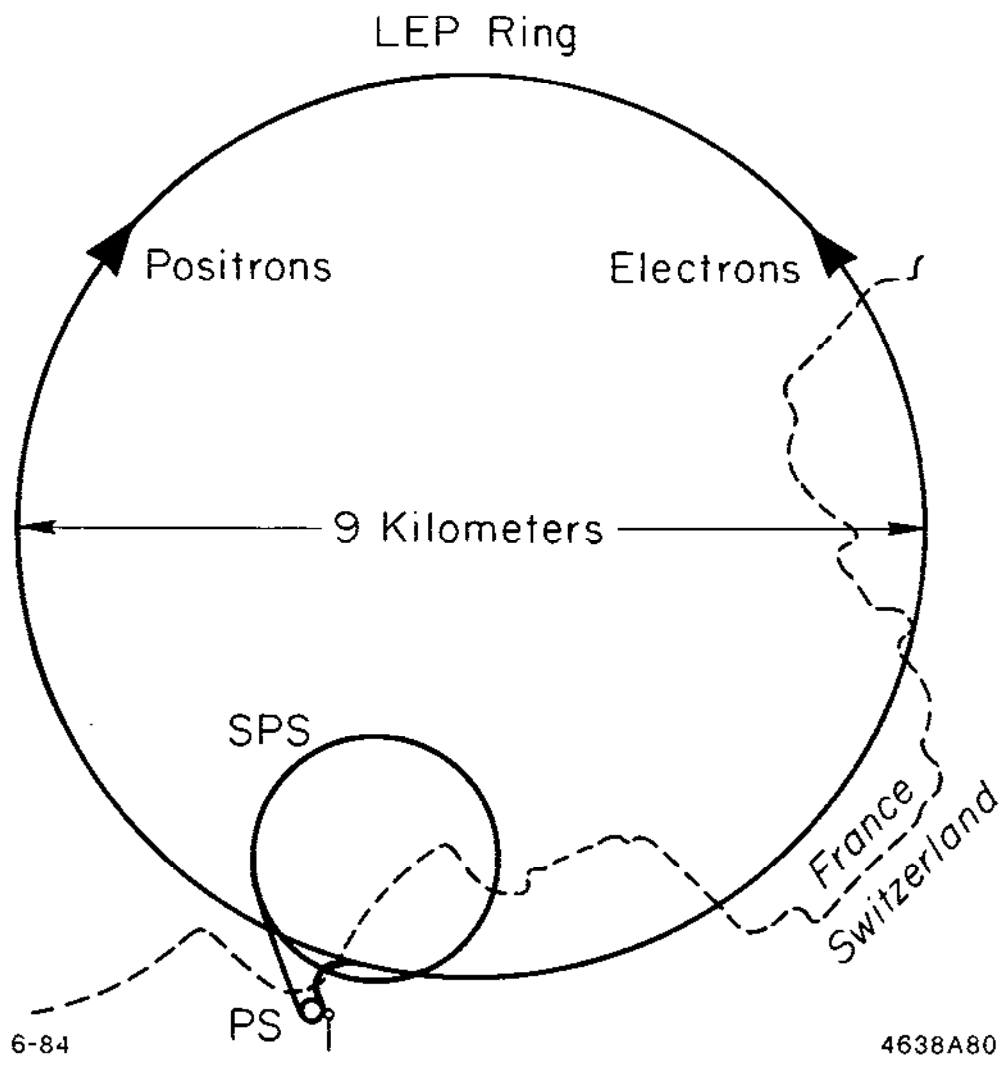

Fig. 2.6

Applying Eq.2.18 to LEP: the beam cross section, Fig.2.5b, is an ellipse with $\sigma_x \approx 300\mu m$ and $\sigma_y \approx 10\mu m$ giving $A \approx 4 \times 10^4 (\mu m)^2$, the 30 km circumference gives $f \approx 10^4 Hz$; and $n_b = 4$. Thus for a luminosity of $10^{31} cm^{-2} s^{-1}$

$$N \sim 4 \times 10^{11} \tag{2.19}$$

At the Z^0 energy a luminosity of 10^{31} is very satisfactory. For example the channel $e^+e^- \to \ell^+\ell^-$, where ℓ is a new charged lepton, would have R $\sim$ 100. Using Eq. 2.8 and using 10^7 s/yr this channel would yield 10^5 new lepton pairs per year. However, far above the Z^0 peak, larger luminosity is required. For example at 1 TeV the same channel has a cross section, Eq. 2.14, of $10^{-37} cm^2$.

Unfortunately in circular electron colliders, the synchrotron radiation power loss increases rapidly with the energy. Specifically

$$\Delta E = CE^4/\rho \tag{2.20}$$

where ΔE is the energy loss per turn per electron, E is the electron energy, ρ is the bending radius and C is a constant. One might try to reduce the total power by decreasing N, the particles per bunch, in Eqs.2.18 and 2.19. But to maintain $\mathcal{L}$ the bunch cross section A has to vary as N^2 and no one knows how to reduce A substantially in a circular collider. The combination of increasing construction costs for larger ρ and increasing power costs means that accelerator designers do not know how to get beyond the LEP parameters in energy and luminosity. To quote Skrinsky[2.7], "It is likely that the LEP, which is being constructed at CERN, is the terminal point on this path."

2C. Linear Electron – Positron Colliders

The only known alternative e^+e^- collider technology is the linear electron-positron collider[2.7,2.8] in which beams from two linear accelerators collide, Fig.2.7. In a simple linear collider the bunches traverse the accelerator just once and collide just once. The luminosity equation is

$$\mathcal{L} = \frac{aN^2 f}{A} \tag{2.21}$$

where f is the frequency at which the linear accelerators are pushed, a is a luminosity enhancement factor due to self-focusing of the two bunches at collision and is predicted[2.9,2.10] to be about 3, and N and A are as in Eq.2.18. The crucial innovation in a linear e^+e^-

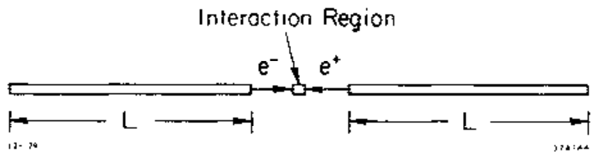

Fig. 2.7

collider is that the bunch cross section can be made much smaller than that for a circular e^+e^- collider. I'll give an example soon. The total energy of a linear collider is again

$$\begin{aligned} E_{tot} &= 2E_b \\ E_b &= GL \end{aligned} \tag{2.22}$$

Here G is the accelerating gradient in MeV/m.

The Stanford Linear Collider (SLC), Fig. 2.8, now being constructed at the Stanford Linear Accelerator Center uses the principle of the linear collider but only one linear accelerator[2.8]. Its initial energy wil be about 100 GeV, its maximum design luminosity is $6 \times 10^{30} cm^{-2} s^{-1}$ and it has one interaction region. The SLC is designed to have a circular bunch cross section with $\sigma_r = 1.4\mu$ radius. Hence $A \sim 25(\mu m)^2$, which is 10^{-4} of the bunch cross sectional area at LEP, for example. This factor of 10^4 in the relative luminosity equations, Eqs.2.18 and 2.21, allows one to use smaller values of N and f, which is necessary in present linear collider technology. The SLC uses $f = 180$ Hz and has a maximum design luminosity of $6 \times 10^{30} cm^{-2} s^{-1}$, hence from Eq.2.21 with $a \sim 3$

$$N \sim 5 \times 10^{10} \text{ particles per bunch.}$$

We are just at the beginning of the development of the technology of linear e^+e^- colliders, let's look ahead at three parameters: accelerator length, total power consumption, and beam size. The construction cost will be roughly proportional to the length L, hence from Eq.2.22 it is desirable to increase the accelerating gradient G. When the SLAC linear accelerator is refurbished for the SLC it is expected to have

$$G_{SLC} = 17 \; MeV/m \tag{2.23a}$$

in its accelerating tube which is a copper wave-guide with power coming from klystrons. That technology can probably be pushed to

$$G_{waveguide,max} \sim 100 \; MeV/m = 0.1 \; TeV/km \tag{2.23b}$$

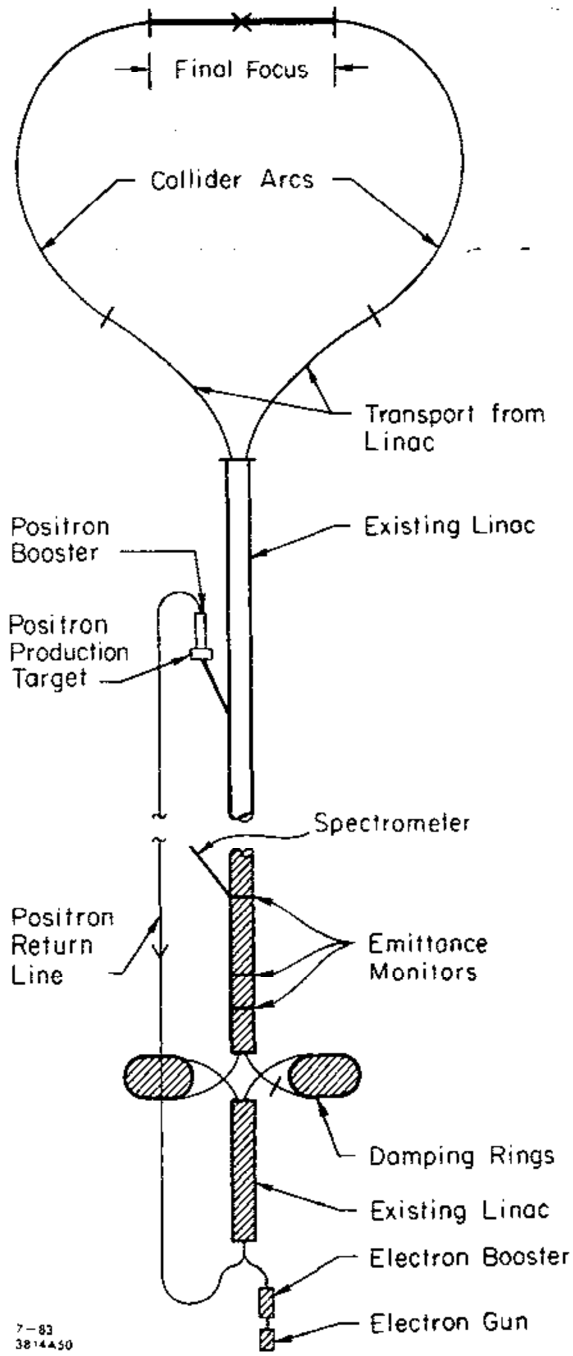
Final Focus
Collider Arcs
Transport from
Linac
Existing Linac
Positron
Booster
Positron
Production
Target
Spectrometer
Positron
Return
Line
Emittance
Monitors
Damping Rings
Existing Linac
Electron Booster
Electron Gun
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Fig. 2.8

This brings me to list a crucial experimental need.

Experimental Need: To build a linear e^+e^- collider with E_{tot} about 2 TeV and $\mathcal{L}$ about $10^{33} cm^{-2}s^{-1}$. The development of a technology with $G \sim 0.1 TeV/km$ and an efficient microwave power source will make this feasible.[2.8–2.10]

Now let's go further and talk about a 10 or 20 TeV linear e^+e^- collider. To keep L in Eq.2.22 reasonable we need

$$G \geq 1000\ MeV/m = 1 TeV/km \tag{2.23c}$$

But now consider the power. If we extrapolate with some improvements from the SLC designs we might set $a \sim 6, \sigma_r = 0.5\mu$, and $f = 2000\ Hz$. For $\mathcal{L} = 10^{33} m^{-2}s^{-1}, N = 5 \times 10^{10}$ particles per bunch. The total power in both beams per TeV is

$$P \approx 30\ MW/TeV$$

Assuming a 20% energy efficiency, the total power required by the collider for acceleration is 150 M W/TeV. Thus it is not feasible to go beyond $E_b \approx 1\ TeV$ with N as large as 5×10^{10}.

In fact the power problem in the 10 TeV range is even more serious; an $\mathcal{L}$ of $10^{34} - 10^{35}$ is needed. The only way to reduce P is to reduce N, but that will reduce $\mathcal{L}$, Eq.2.21. The way out is to drastically reduce the bunch area A by reducing the bunch radius to less than 0.1 μ! No one knows if this can be done. Hence we have a pair of experimental needs.

Experimental Needs: To explore the technology of ultra-high energy linear e^+e^- colliders, 10 TeV or more, we need to develop acceleration methods[2.11] with

$$G \geq 1000\ MeV/m = 1\ TeV/km$$

and to explore the possibility of a bunch size

$$r < 0.1\mu$$

3. PROTON-PROTON AND ANTIPROTON-PROTON INTERACTIONS AND COLLIDERS

3A. Basic Processes for $\sqrt{s} > 100$ GeV

When $\sqrt{s} > 100$ GeV we can take for the total cross section

$$\sigma_{tot}, pp \approx \sigma_{tot,\bar{p}p} \sim 23\ log_{10} \sqrt{s}\, mb\ ,\ \sqrt{s}\ in\ GeV \tag{3.1}$$

Almost all of this cross section comes from small momentum transfer elastic scattering and inelastic production of hadrons. This enormous cross section can constitute a difficult and sometimes deadly background for new particle searches and tests of new theoretical proposals. For most of these searches and tests the relevant cross sections are 10^{-8} to 10^{-12} times smaller because very large momentum transfers are required.

Consider a p-p or p̄-p collision in which a large momentum transfer collision, Fig. 3.1, produces a final state F of total energy $\sqrt{s_F}$. The overall reaction is

$$p + p \ or \ \bar{p} + p \rightarrow F + hadrons \tag{3.2}$$

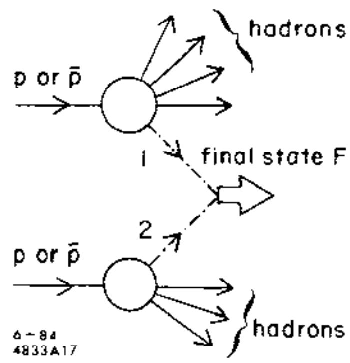

Fig. 3.1.

where restricting our considerations to collider reactions, p or p̄ have energy $\sqrt{s}/2$. The basic process is the interaction of constituent 1 with constituent 2

$$1 + 2 \rightarrow F \tag{3.3}$$

with a total cross section $\sigma(1 + 2 \rightarrow F, s_F)$ which is a function of s_F. Figure 3.2 gives some examples for this basic process. The constituent is a quark q, an antiquark $\bar{q}$, or a gluon g. The total cross section for Eq.3.2 is

$$\sigma = \int ds_F dx_1 dx_2 g(x_1, x_2)\, \sigma(1 + 2 \rightarrow F, s_F) \delta(x_1 x_2 - \tau) \delta(\tau - s_F/s) \tag{3.4}$$

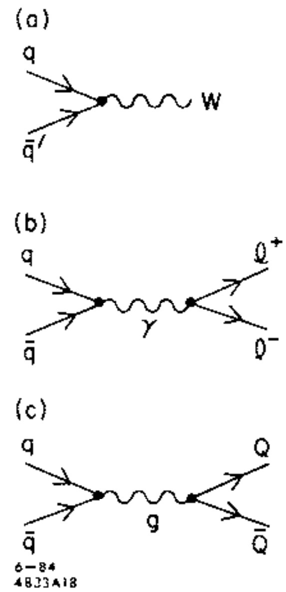

Fig. 3.2.

Here

$$x_1 = 2p_1/\sqrt{s}\ ,\ x_2 = 2p_2/\sqrt{s} \tag{3.5}$$

are the Feynman scaling variables for the constituents; and

$$\tau = s_F/s \tag{3.6}$$

The function $g(x_1, x_2)$ is a sum of products $f(x_1), f(x_2)$ where $f(x)$ is the distribution function for the x of the constituent in p or $\bar{p}$, Fig. 3.3. Finally

$$\sigma = \int_{s_T}^{s} ds_F \left(\sigma(1+2 \to F, s_F) \delta(\tau - s_F/s) \int_{\tau}^{1} dx_1 g(x_1, \tau/x_1)/x_1 \right) \tag{3.7}$$

where s_T is the threshold for $1 + 2 \to F$.

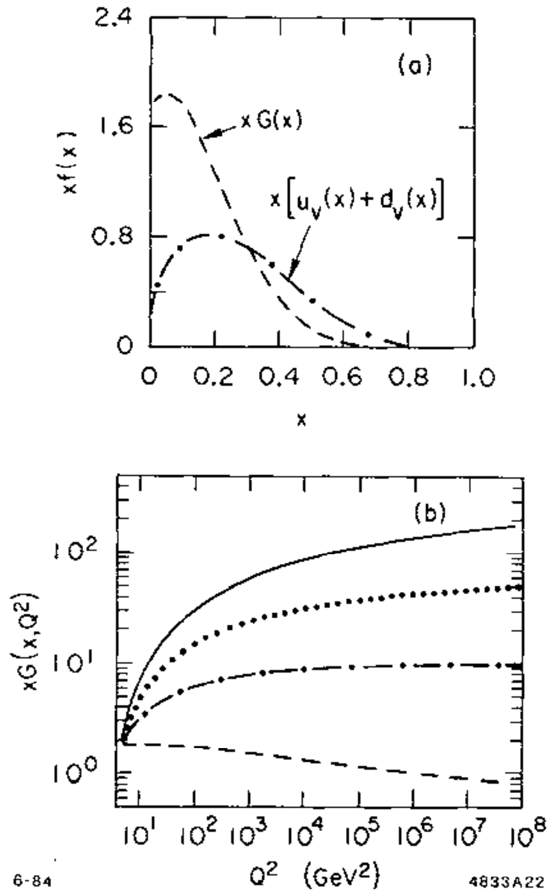

Fig. 3.3. (a) Example of the proton structure functions for the gluon, G(x), and for the valence quarks, $u_v(x)$ and $d_v(x)$, for small values of Q^2. (b) Example of the extrapolated behavior of G(x) versus Q^2. The x values for the four curves starting from the top are 0.0001, 0.001, 0.01, 0.1.

The evaluation of Eq. 3.7 has two parts. The calculation of $\sigma(1+2 \to F)$ uses electroweak theory or quantum chromodynamics. I'll give three examples. The calculation of the integral depends first upon experimentally determined structure functions. But the calculation is actually more complicated[3.1] than indicated above, because $f(x_1)$ and $f(x_2)$ have scaling violations and are actually $f(x_1, Q_1^2)$ and $f(x_2, Q_2)$.

The first example is the already observed production of a W boson, a tremendous scientific and technical achievement.[3.2] The physical process

$$p + \bar{p} \rightarrow W + hadrons \tag{3.8}$$

proceeds via the basic process in Fig. 3.2a. Ignoring factors of π and powers of 2

$$\sigma(u + \bar{d} \rightarrow W) \sim G_F(\hbar c)^2 \sim 10^{-33}$$

The integral in Eq. 3.7 has factors such as .1 and 1. Within a factor of 10 the integral is unity, hence

$$\sigma(p + \bar{p} \rightarrow W + \ hadrons) = 10^{-32} to\ 10^{-34}\ cm^2 \tag{3.9}$$

The observed cross section times the $W \rightarrow e\nu$ branching ratio is[3.2]

$$\sigma.B(W \rightarrow e\nu) \sim 5 \times 10^{-34}$$

Since $B(W \rightarrow e\nu) \sim 0.1$, this agrees with our rough calculation. The reader is cautioned that the integral in Eq. 3.7 is energy dependent. The crude calculations I do here ignore that dependence, hence they do not give the energy behavior of detail calculations such as those yielding Figs. 3.4 and 3.5.

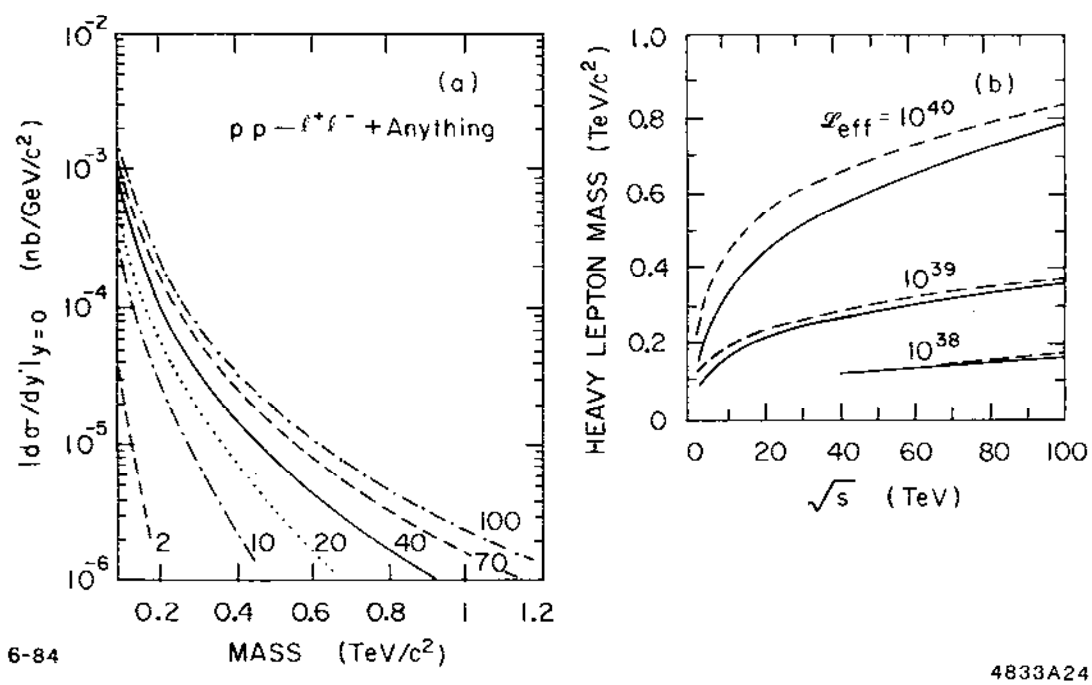

Fig. 3.4. (a) Differential cross section at rapidity=0 for pair production of heavy charged leptons in pp (solid lines) and $\bar{p}p$ (dashed lines). The numbers are the total energy in TeV. (b) Maximum lepton mass accessible in pp (solid lines) and $\bar{p}p$ (dashed lines) for various effective luminosities and the cross sections in (a). From Ref. 3.1.

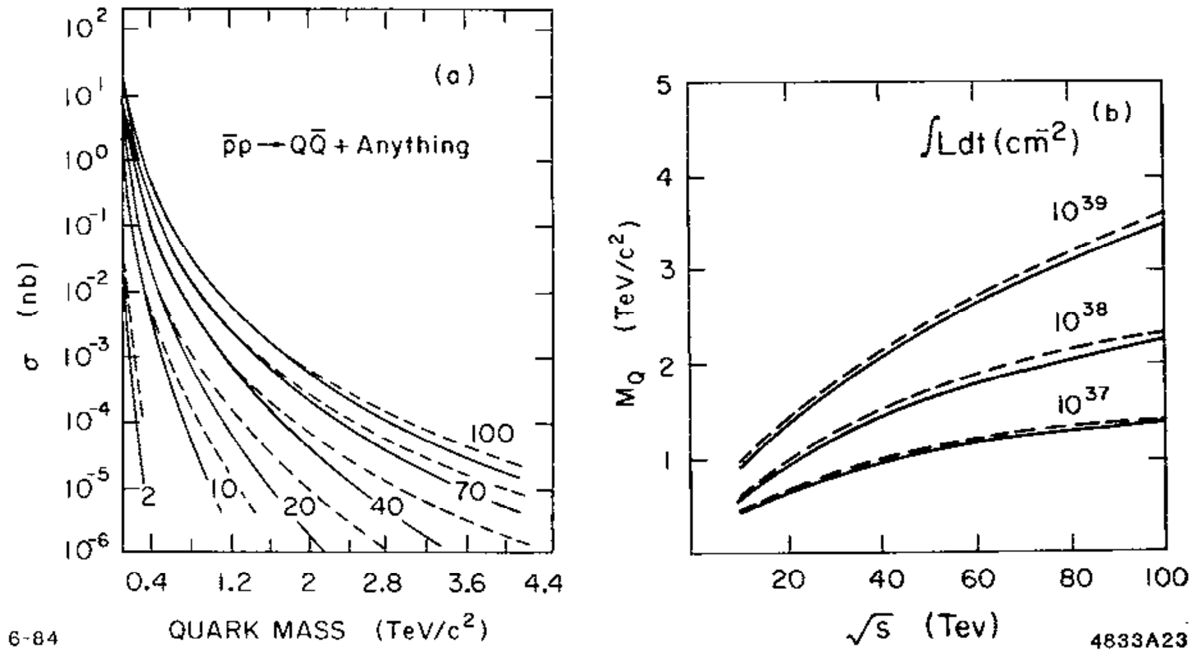

Fig. 3.5 (a) Integrated cross sections for pair productin of heavy quarks with rapidity less than 1.5 in pp (solid lines) and $\bar{p}p$ (dashed lines). The numbers are the total energy in TeV. (b) Maximum quark mass, M_Q, accessible in pp (solid lines) and $\bar{p}p$ (dashed lines) for various effective luminosities for the cross sections in (a). From Ref. 3.1.

The next example is the production of a pair of very heavy charged leptons, $2m_\ell >> m_Z$, via the basic process in Fig. 3.2b. As discussed in connection with Eq. 2.14, the electromagnetic process dominates and for any energy of the $q\bar{q}$ pair $\sqrt{s_F} > 2m_\ell$

$$\sigma(1+2 \to \ell^+ + \ell^-) = \frac{4\pi\alpha^2 e_q^2}{3s_F} \tag{3.10}$$

Here e_q is the quark charge. We should be integrating Eq.3.7 over s_F, but for order of magnitude estimates we simply replace $\sqrt{s_F}$ by $2m_\ell$ in Eq.3.10. Thus

$$\sigma(p+p \to \ell^+ + \ell^- + \ hadrons) \sim \frac{\pi\alpha^2(\hbar c)^2}{3m_\ell^2} \int_\tau^1 dx_1 \ g(x_1, \tau/x_2)/x_1 \tag{3.11}$$

comparing to

$$\sigma(e^+ + e^- \to \ell^+ + \ell^-) \sim \frac{\pi\alpha^2(\hbar c)^2}{3m_\ell^2} \quad 2m_\ell >> m_Z \tag{3.12}$$

we can make two observations. First the hadronic production cross section of an $\ell^+\ell^-$ pions is smaller than that for e^+e^- production because the integral in Eq. 3.11 is less than 1, perhaps of order 10^{-1} or 10^{-2}. Second the hadronic cross section also decreases as $1/m_\ell^2$. Figure 3.4 gives the results of a careful calculation.[3.1]

The final example, Fig. 3.2c, the production of a pair of heavy quarks illustrates the power of hadron colliders. There the basic process is a strong interaction, the exchange of a gluon. To lowest order we have

$$\sigma(p + p \to Q + \bar{Q} + hadrons) \sim \frac{\alpha_{strong}^2 (\hbar c)^2}{m_Q^2} \int_\tau^1 dx_1 \; g(x_1 \; g(x_1, \tau/x_1)/x_1 \qquad (3.13)$$

by analogy to Eq. 3.11 or dimensional arguments. As an example, consider $m_Q = 1$ TeV and a pp collider of sufficient energy so that the integral is 0.1 to 0.01. Using $\alpha_{strong} \sim 1$, we obtain

$$\sigma(p + p \to Q + \bar{Q} + hadrons) \sim 10^{-34} \; to \; 10^{-37} \; , \; m_Q = 1 \; TeV \qquad (3.14)$$

Figure 3.5 presents the results of a careful calculation. The kinds of arguments used here can be extended to other types of particle production in pp or p̄p colliders. This physics has also been discussed by Dowell[2.12], Darriulat[3.10] and Lederman[3.11] at this school.

3B. Antiproton – Proton Colliders

The CERN p̄p collider[3.4] has a maximum total energy at present of about 600 GeV, and it has obtained a luminosity of $5 \times 10^{28} cm^{-2} s^{-1}$ which can be raised to 2.5×10^{29}.

Fermilab is constructing an antiproton source[3.5] to allow the newly commissioned, superconducting magnet, Tevatron to operate as a 2 TeV p̄p collider. The design luminosity exceeds $10^{30} cm^{-2} s^{-1}$.

A great deal of physics has been done and will be done with these colliders, but they do not have sufficient luminosity to explore physics with cross sections less than $10^{-35} cm^2$. And the calculations done above indicate that such cross sections will occur for physics of great interest. Another problem is the available energy of existing p̄p colliders. The technology of p̄p and pp colliders has been discussed by Lederman[3.11] at ths school.

3C. Effective Energy in p p and p̄ p Colliders

The 3 valence quarks in a nucleon carry half of the nucleon momentum, the other half is carried by gluons and $q\bar{q}$ pairs. Thus each valence quark carries about 1/6 of the nucleon's momentum, this leads to the rough rule

$$E_{effective} \sim 1/6 \; E_{total} \qquad (3.15)$$

Hence to make a pair of 1 TeV heavy quarks, the pp or $\bar{p}\,p$ collider should have at least 12 TeV total energy. Ellis[3.6] has looked at the conversion factor in more detail, Table 3.1, and finds it usually smaller than 1/6, particularly at higher E_{total}.

Table 3.1. $E_{effective}/E_{total}$ for pp or $\bar{p}\,p$ collisions. From Ref. 3.6.

	$E_{c.m.}$	
	10 TeV	40 TeV
Jet Pairs	0.36	0.20
$\mu^+\mu^-$ or L^+L^-	0.03	0.01
Z^0	0.12	0.04
$W^{\pm}$	0.24	0.08
η_T	0.2	0.08
$\tilde{g}$	0.24	0.12
$\bar{Q}Q$	0.18	0.12
Geometric Mean	0.16	0.07

3D. Very High Energy pp and p̄ p Colliders

Experimental Need: Thus pp or p̄p colliders are needed with (a) luminosities 100 or 1000 times the present $10^{29} - 10^{30} cm^{-2} s^{-1}$ luminosities, and (b) with E_{total} 6 to 20 times the desired $E_{effective}$.

This need, the great accomplishment of finding the W and Z^0 using the CERN p̄p collider, and the success of the superconducting magnet Tevatron have led to proposals for colliders in the 5 to 40 GeV total energy region.[3.7,3.8,3.9,3.11]

The limitation on pp or p̄p collider energy comes from the bending radius

$$r_{bend}(km) = \frac{3.3 E_{beam}(TeV)}{B(T)}$$

Here B is the magnetic bending field in Tesla. Straight sections and other magnet elements increase the average radius to

$$r_{ave}(km) \approx \frac{4.5 E_{beam}(TeV)}{B(T)} \qquad (3.16)$$

The Tevatron uses 5T superconducting magnets, a technology which can be conservatively extended to 6 or 7 T, and with a great deal of development work to perhaps 8 or 10 T.

One can also consider smaller B fields to reduce magnet costs. But to give a feeling of the size of a collider with tens of TeV total energy, use B $\sim$ 5 T, thus

$$r_{ave}(km) \sim E_{beam}(TeV) \tag{3.17}$$

In the United States studies are being done[3.9] for a 40 TeV total energy pp collider with a maximum luminosity of $10^{33} cm^{-2} s^{-1}$. Table 3.2 gives some design parameters.

Table 3.2. Some design parameters being considered for the Superconducting Super Collider. The term 2-in-1 cryostat means that the adjacent bending magnets of the two rings are in the same superconducting cryostat.

	Design A	Design B	Design C
Bending Magnet (T)	6.5	5.0	3.0
2-in-1 cryostat	yes	no	yes
Cold iron yoke	yes	no	yes
Conductor dominated	yes	yes	no
Field shaped by iron	no	no	yes
Saturated iron	yes	no	yes
Length of bending magnet [m]	17.5	14	140
Ring circumference [km]	90	113	164

The luminosity situation in a *pp* collider such as this one is somewhat different than in e^+e^- colliders. The equation

$$\mathcal{L} = n_b N^2 f / A \tag{3.18}$$

still applies, but it is necessary to use many more bunches for the following reasons. In the single collision of a pair of bunches there will be

$$n_I = \sigma_{tot} N^2 / A \tag{3.19}$$

pp interactions. Inserting this in Eq.3.18

$$\mathcal{L} = n_b n_I f / \sigma_{tot} \quad ,$$

using a circumference of 100 km, and $\sigma_{tot} = 100 n_b$,

$$n_b n_I \approx 3 \times 10^4 \tag{3.20}$$

If n_I is to be kept to say 3 to prevent confusion from multiple events in a detector from a single collision of two bunches then $n_b \approx 10^4$ bunches. The design effective area of each bunch is about $10^3 \mu m^2$, hence there are about 10^{10} protons per bunch, and 10^{14} protons rotating in each direction.

Two adjacent rings must be used for pp colliders as shown in Fig.3.6 for the case of

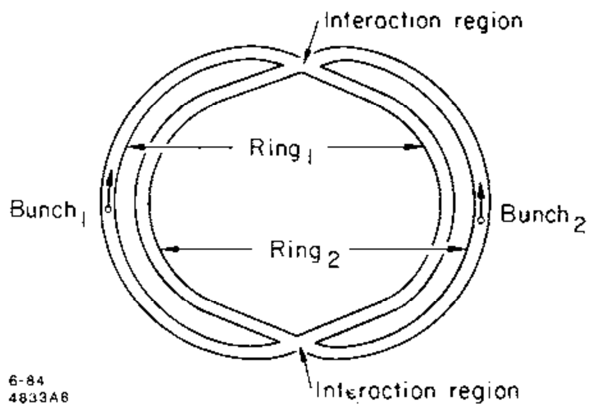

Fig. 3.6. Schematic diagram of the intersecting rings of a pp collider with two interaction regions. The bunches and rings are denoted by 1 and 2.

two interaction regions. One of the major design questions is how to arrange the adjacent bending magnets to minimize the cost of two rings. This is one of the parameters in Table 3.2.

In Europe the issue of putting a pp or $\bar{p}p$ collider in the LEP tunnel is being discussed.[2.6] Magnets with 5 T would yield $E_{total} \approx 10$ TeV, 10 T would yield $E_{total} = 18$ TeV.

4. ELECTRON-PROTON INTERACTIONS AND COLLIDERS

No electron-proton colliders have been built, but such a collider is the next step in the distinguished history of the physics of deep inelastic lepton-nucleon scattering. This subject was discussed in detail by Cashmore[4.5] at this school, therefore my discussion is brief.

4A. ep Kinematics

The basic ep kinematics are illustrated in Fig. 4.1. The four-momentum carried by the exchanged vector boson is q, and P is the four-momentum of the incident proton. The

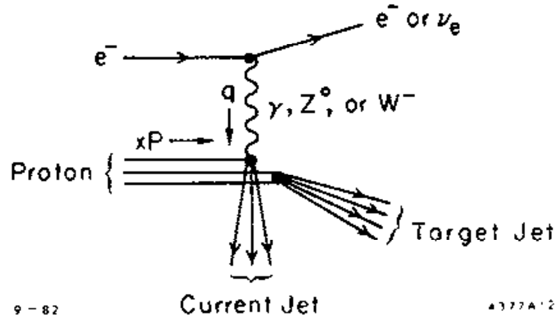

Fig. 4.1.

invariant mass at the hadronic vertex, $\sqrt{s_{had}}$, is given by

$$s_{had} = (q + P)^2 \approx q^2 + 2q.P$$

In our metric q^2 is negative and $|q^2| = 2q.P - s_{had}$. Hence $2q.P$ is the maximum value of $|q^2|$, and the Bjorken scaling variable is

$$x = \frac{|q^2|}{2q.P} \ ; \ 0 < x < 1 \tag{4.1}$$

It is conventional to define

$$\nu = q.P/m_{proton} \tag{4.2}$$

As shown in Fig. 4.1, if we think of the virtual boson as interacting with one of the quarks in the proton we may partition the reaction into two processes. The boson-quark interaction is said to lead to a current jet. The spectator quarks are said to lead to a target jet.

4B. ep Interactions

In the standard model there are three processes which occur in ep interactions

$$e^- + p \rightarrow e^- + anything\ via\ photon\ (\gamma)\ exchange \tag{4.3a}$$

$$e^- + p \rightarrow e^- + anything\ via\ Z^0\ exchange \tag{4.3b}$$

$$e^- + p \rightarrow \nu_e + anything\ via\ W^-\ exchange \tag{4.3c}$$

The cross section for the γ exchange process has the form[4.1,4.2]

$$\frac{d\sigma}{dq^2 d\nu} = \frac{\alpha^2}{q^4} f(s, q^2, \nu) \tag{4.4}$$

where f is a slowly varying function of q^2. Hence this cross section is dominated by very small q^2 events. When $|q^2| < m_\pi^2$ the photon is almost real and one can use concepts associated with the interactions of real photons with protons. The traditional rule is to think of each electron as passing through a radiator of 0.02 radiation lengths.

Then

$$q^2 \approx 0 \quad \sigma_{tot}, ep \sim 0.02\, \sigma_{tot}, \gamma p \sim 2 \times 10^{-30}\, cm \tag{4.5}$$

Here we have used $\sigma_{tot}, \gamma p \sim 0.1$ mb. Most ep events will be in this domain. Figure 4.2 gives the cross section $\sigma(|q^2| > Q^2)$ for events with $|q^2| > Q^2$. This is for an ep collider with 10 GeV e^- on 1 TeV protons.

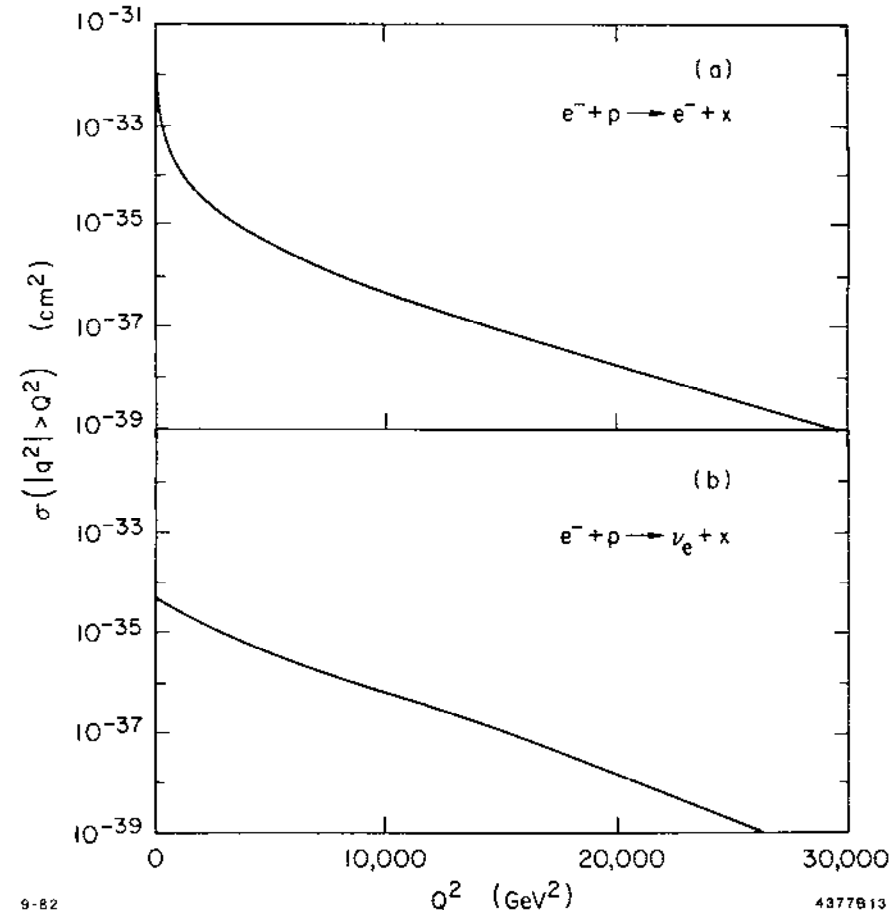

Fig. 4.2. Integrated total inelastic cross section for ep scattering with $|q^2| > |Q^2|$, for 10 GeV electrons and 1 TeV protons.

The cross sections for interesting processes such as the production of new particles can be calculated[4.2,4.3] using methods similar to those discussed in Sec. 3A. In general the effective energy for new particle production is smaller in ep colliders than it is in pp or $\bar{p}p$ colliders with the same c.m.s. energy.

ep colliders are particularly valuable for testing the electroweak theory, measuring the proton structure functions, probing the electron, and looking for excited states of the electron.

4C. ep Colliders

The first electron-proton collider, called HERA[4.4,4.5], is being constructed at DESY in Germany. The proton energy is 820 GeV, the electron energy is about 30 GeV, the luminosity is $6 \times 10^{31} cm^{-2} s^{-1}$, and there will be 4 interaction regions. The proton ring uses 4.5 T superconducting magnets.

The TRISTAN e^+e^- collider project[2.5] has the capability of being expanded into an ep collider, but its energy would be less than that of HERA.

In HERA and in all proposed very high energy ep colliders the e ring and the p ring are in the same tunnel, hence they have about the same radius. In the electron ring it is still necessary to make up for the energy loss per turn, Eq. 2.20, caused by synchrotron radiation. Therefore the electron energy is always much less than the proton energy, as in HERA.

5. EXPERIMENTAL SIGNATURES

5A. Changing Techniques in Studying Large Multiplicity Events

As collider experiments, and fixed target experiments as well, move to higher energies, it becomes increasingly difficult to use some of the traditional methods of studying final states: detection and identification of all particles in the event, measurement of the three-momentum of each particle, exact reconstruction of the masses of particles which have decayed. There are two connected reasons for this. First, the total multiplicity of particles in an event becomes unmanageable as the energy increases. Second, as we seek to study the heavier unstable particles, the multitude of their decay modes and the particle multiplicity of many of those decay modes makes it very difficult to do exact reconstruction of the unstable particle.

Experiments at PETRA, PEP, and the CERN $\bar{p}p$ collider have led the way into more general ways of studying very high energy events, of understanding their physics, and of searching for new particles and processes. These ways depend upon general experimental signatures for the known leptons, quarks, gluons and intermediate bosons. Jet physics was discussed by Darriulat[3.10] at this school, I will not discuss it.

5B. The e, μ, and τ

The e and u are still identified in the traditional ways, the e through its electromagnetic shower in dense matter, the μ through its ability to penetrate through dense matter.

The decay modes of the τ are

$$\tau^- \to \nu_\tau + e^- + \bar{\nu}_e\,,\ \nu_\tau + \mu^- + \bar{\nu}_\mu \tag{5.1}$$

and

$$\tau^- \to \nu_\tau + (hadrons)^- \tag{5.2}$$

In the hadronic decay mode all observed decays have 1 or 3 charged prongs. The 1 prong decay modes and the distinctive (at high energy) 3 prong decay modes, provide signatures for the τ.

5C. The Known Quarks

At sufficiently high energies, the signature for the highest energy quarks is the presence of jets of hadrons.[5.1,5.2] Figures 5.1 and 5.2 show some examples. The conversion of a

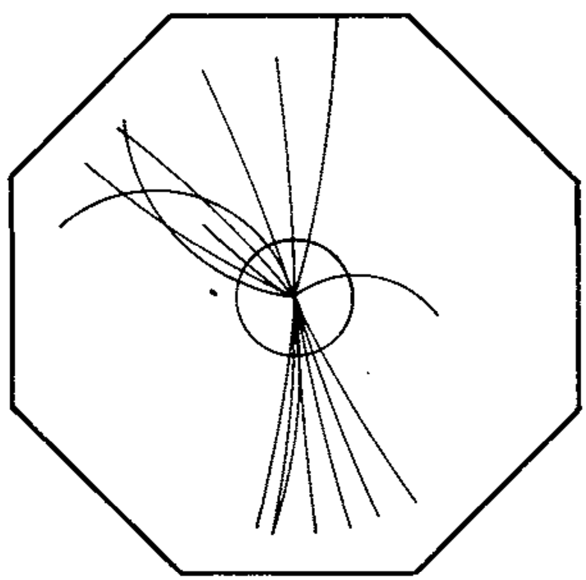

Fig. 5.1. Example of a two-jet event from the PEP electron-positron collider. See Ref. 5.1.

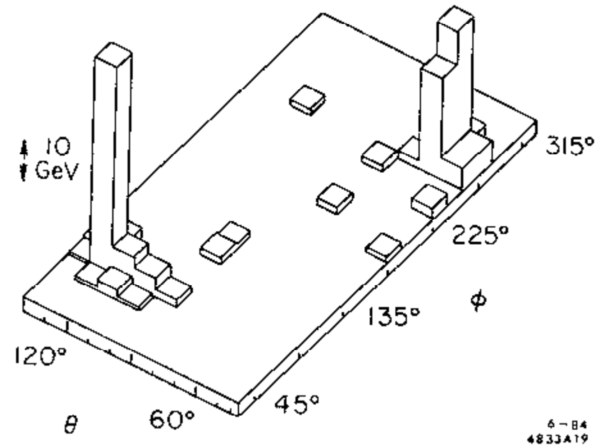

Fig. 5.2. Example of a two-jet event from the CERN proton-antiproton collider. From Ref. 5.2.

quark to a hadron jet has the conventional but inappropriate name of quark fragmentation. The quark fragmentation process is the subject of a large set of sometimes contradictory models and Monte Carlo computer programs based on those models.[3.10,5.1] At present there is no established reliable way to use the kinematic of a jet to decide if it came from a u, d, s, c, or b quark.

However, one can make statistically useful separations of some jets from c or b quarks by looking for an e or μ from the processes

$$\begin{aligned} &b\ quark \rightarrow B\ meson \rightarrow \ell + \nu_\ell + hadrons \\ &c\ quark \rightarrow D\ meson \rightarrow \ell + \nu_\ell + hadrons \end{aligned} \tag{5.3}$$

The last process in each line is the semileptonic decay mode, $\ell =$ e or μ. The transverse momentum of the ℓ relative to the jet axis will be about $m_B/3$ or $m_D/3$.

5C. Gluons

Like the quarks, sufficiently high energy gluons also have the hadron jet signature. This is seen in the three jet events in e^+e^- annihilation[5.1,5.3] and it is believed that most jets in p̄p events at the CERN collider are gluon jets.[5.2] We know of no way to distinguish a gluon jet from a quark jet using the kinematics of the jet.

5D. Secondary Vertex Signature for τ Leptons, c Quarks, and b Quarks

The 10^{-12} to $10^{-13}s$ lifetimes of the τ, D mesons and B mesons offer the possibility of using their decay vertex as signatures for the τ, c quark, and b quark respectively. The decay vertex, called the secondary vertex, would be represented by a distance measured by

$$\ell_{decay} = c\ \gamma\ T \tag{5.4}$$

Taking $T = 10^{-13}s$ and γ in the range of 10 to 100 gives $\ell_{decay} = 0.3$ to 3. mm. In colliders this must be measured indirectly because the decay occurs inside the beam pipe. As described by Jaros[5.4], it is at present possible to statistically measure ℓ_{decay} for the τ, D, and B at PEP and PETRA, thus measuring the lifetimes of these particles.

I want to look ahead to see what must be done to actually determine the existence of a secondary vertex. Figure 5.3a shows a secondary two-prong vertex and Fig.5.3b idealizes the measurement situation. Let the two-prong come from the symmetric decay of a neutral particle into two charged particles of negligible mass. In the very relativistic case and calculating within factors of 2

$$\ell \sim b/\theta \quad , \quad \theta = 1/\gamma \tag{5.5}$$

The uncertainty in ℓ, σ_ℓ, within a factor of 2 is

$$\sigma_\ell^2 = (\sigma_b/\theta)^2 + (\ell/\theta)^2 \sigma_\theta^2 \tag{5.6}$$

where σ_b is the measurement error in b and σ_θ that in θ. Definitive selection of a secondary vertex requires

$$\sigma_\ell \leq \ell_{decay}/10 \tag{5.7}$$

Putting all this together

$$(\sigma_b^2 + \ell^2 \sigma_\theta^2)^{1/2} \leq 0.1\, cT \tag{5.8}$$

Taking $T = 10^{-13}$s, and replacing ℓ by the beam pipe radius r

$$\sigma_b \lesssim 3\mu m \tag{5.9a}$$

and

$$\sigma_\theta \lesssim 3 \times 10^{-4}/r \; rad \quad , \quad r \; in \; cm \tag{5.9b}$$

For a linear collider such as the SLC r $\approx$ 1 - 2 cm, but in circular colliders r $\approx$ 5 - 10 cm.

Experimental Need: To develop secondary vertex measuring techniques at colliders which meet the requirements of Eq.5.9.

5E. The Photon

It is well known that the signature for a photon is a neutral particle producing an electromagnetic shower.

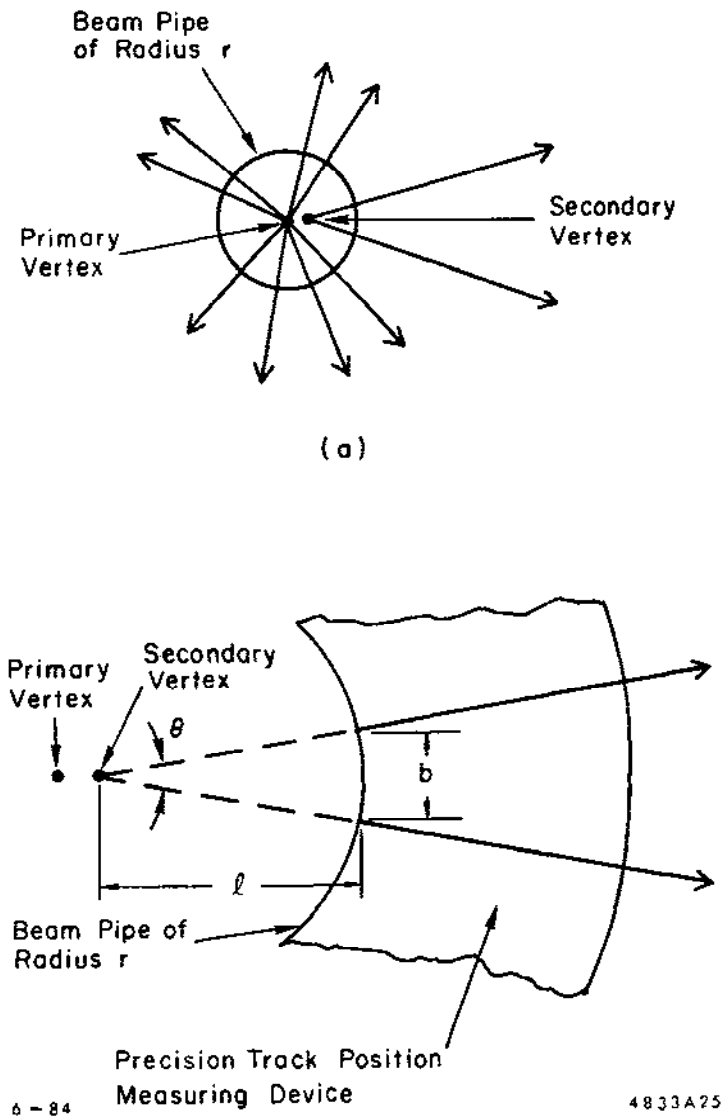
Beam Pipe
of Radius r
Secondary
Vertex
Primary
Vertex
(a)
Primary
Vertex
Secondary
Vertex
θ
b
ℓ
Beam Pipe of
Radius r
Precision Track Position
Measuring Device
6-84
4833A25

Fig. 5.3.

5F. The $W^{\pm}$ and Z^0

The signatures for the W and Z follow from their charged particle decay modes:

$$W^- \rightarrow e^- + \bar{\nu}_e \ , \ \mu^- + \bar{\nu}_\mu \qquad (5.5a)$$
$$W^- \rightarrow \tau^- + \bar{\nu}_\tau \qquad (5.5b)$$
$$W^- \rightarrow q + \bar{q}' \rightarrow 2 \ hadron \ jets \qquad (5.5c)$$
$$Z^0 \rightarrow e^+ + e^- \ , \ \mu^+ + \mu^- \qquad (5.6a)$$
$$Z^0 \rightarrow \tau^+ + \tau^- \qquad (5.6b)$$
$$Z^0 \rightarrow q + \bar{q} \rightarrow 2 \ hadron \ jets \qquad (5.6c)$$

The decay modes in Eqs. 5.5a and 5.6a were, of course, used to find the W and Z. In very high energy reactions where several very heavy particles are produced, it is not clear how useful Eq. 5.5a will be, but Eq. 5.6a will always be a very, very powerful signature.

The 2 hadron jets, Fig.5.4, in Eq. 5.5c and 5.6c will probably be very useful in very high energy events. But it will not be possible to separate the W from the Z using the signature.

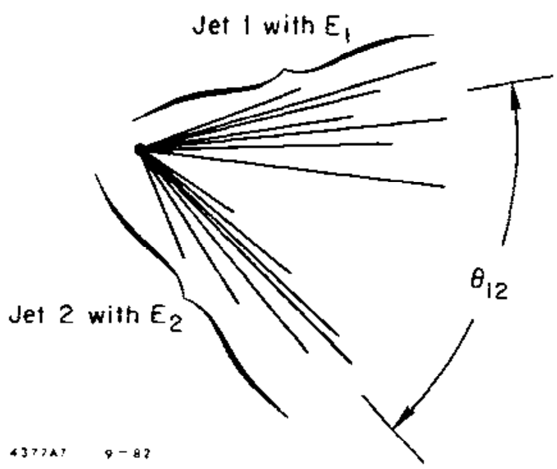

Fig. 5.4. Sketch of a W decaying into two quark jets.

6. LEPTONS AND THE CONCEPT OF ELEMENTARY PARTICLES

We begin with the leptons: they are the simplest elementary particles, they provide us with simple examples for thinking about elementariness, and they give us simple ways to think about the more complicated (because confined) quarks. The subjects of elementariness and composite particles have been discussed thoroughly by Lyons[6.1] and by Harari[6.2] and at this summer school[6.3]. Therefore I shall discuss just a few aspects of this subject from the experimental viewpoint.

Table 6.1. Properties of the known leptons.

Charged lepton	e	μ	τ
Charged lepton mass (MeV/c^2)	0.51	106.	1784.$\pm$3.
lifetime (s)	stable ($> 2 \times 10^{22} y$)	2.2×10^{-6}	$2.8 \pm 0.4 \times 10^{-13}$
associated neutrino	ν_e	ν_μ	ν_τ
neutrino mass	$<$46 eV/c^2 (may be $>$ 20 eV/c^2)	$<$0.52 MeV/c^2	$\lesssim$ 160 MeV/c^2

6A. The Known Leptons

The properties of the known leptons are given in Table 6.1. To the best of our knowledge they are spin 1/2 point particles which have just two unique parameters each, their mass and lepton number. Once these properties are fixed all other properties and interactions follow from the electroweak theory. This is our current picture.

6B. The Concept of Elementary Particles

We have a number of methods of defining an elementary particle, or more precisely determining when a particle is not elementary. All these methods or definitions have been developed by analogy with other physical phenomena, so it may be that we are being misled, that at the lepton and quark level there is some different and revolutionary meaning to elementariness.

If a particle can be broken up, the atom and the nucleus are examples, then it is not elementary. The term broken up has a special meaning. The hydrogen atom, H, is broken up by photodissociation, $\gamma + H \rightarrow p + e^-$; but the tau, τ, is not broken up by the decay $\tau^- \rightarrow \nu_\tau + \pi^-$. The distinction is based upon the concept of compositeness. The H atom is a composite of its constituents, the p and the e^-, because all the properties of the H can be explained by the properties of the p, the e^-, and the electromagnetic force. Conversely the properties of the τ cannot be explained by assuming it is composed of a π^- and a ν_τ. The compositeness concept pervades most of our thinking about the meaning of elementariness.

A related concept is that a particle is not elementary if it has internal structure, even if the particle cannot be physically broken up into the constituents which compose the internal structure. The hadrons with their constituent quarks are the only example. At present we do not know how to break up, or even if we can break up, a pion into its separate quark and antiquark. Hence in present thinking the concept of compositeness has been extended to include the hadron case.

Another test of elementariness is that an elementary particle should have zero size, excluding its apparent size due to the range of its interactions. This test is tied to the ideas of compositeness and internal structure.

Yet another test of elementariness is based on the observation that all known systems with excited states - molecules, atoms, nuclei, hadrons - are not elementary. Let us apply this test to the charged leptons. Excited states of the e, μ, or τ could be heavier charged leptons with the same lepton number which decay electromagnetically, for example

$$\begin{aligned} e^{*\pm} &\rightarrow e^{\pm} + \gamma \\ \mu^{*\pm} &\rightarrow \mu^{\pm} + \gamma \\ \tau^{*\pm} &\rightarrow \tau^{\pm} + \gamma \end{aligned} \tag{6.1}$$

No such particle has been found, an observation which is consistent with the e, μ, and τ being elementary.

6C. Tests of Elementariness of Leptons

Tests of the elementariness of leptons are fully reviewed in Ref. 6.1. All these tests consist of measuring a property or a reaction involving the particle and comparing the measurement with the theoretical prediction based on the particle being elementary. These include:

- measurement of the magnetic moment of the e and μ. (The interpretation of this method is dependent on the composite model and has been fully discussed in Refs.6.1, 6.4, 6.5.),
- measurement of the elastic scattering of the lepton, $\ell^{\pm}$ or ν, on a nucleon (This method[6.6] is no longer useful because the elastic cross section is too small at the large q^2 values now of interest.),
- measurement of the inelastic scattering of the lepton, $\ell^{\pm}$ or ν, on a nucleon

$$\begin{aligned} \ell^- + \mathrm{N} &\rightarrow \ell^- + hadrons \\ \nu + \mathrm{N} &\rightarrow \ell^- + hadrons \\ \nu + \mathrm{N} &\rightarrow \nu + hadrons\ ; \end{aligned} \tag{6.2}$$

- measurement of purely electromagnetic processes

$$\begin{aligned} e^+ + e^- &\rightarrow e^+ + e^- \\ e^+ + e^- &\rightarrow \mu^+ + \mu^- \\ e^+ + e^- &\rightarrow \tau^+ + \tau^- \\ e^+ + e^- &\rightarrow \gamma + \gamma \end{aligned} \tag{6.3}$$

I'll comment on the last two methods because there have been many discussions of major improvements in their sensitivity as accelerators increase in energy. Both methods are interpreted through ideas derived from the form factor concept of non-relativistic scattering.

Lepton – Nucleon Inelastic Scattering and Form Factors

The differential cross section for the Coulomb, elastic scattering of a particle of mass m and charge e by a fixed point charge e is

$$\begin{aligned} d\sigma/d\Omega &= |f(\vec{q})|^2 \\ f_{pt}(\vec{q}) &= 2me^2/\,|\vec{q}|^2 \end{aligned} \tag{6.4}$$

Here $\vec{q}$ is the three-momentum transferred:

$$\vec{q} = \vec{p} - \vec{p}'$$

If the fixed scattering center is not a point, but is a spherically symmetric charge distribution ρ(r); then

$$f(\vec{q}) = f_{pt}(\vec{q})\; F(q) \tag{6.5}$$

where

$$F(q) = \int \rho(r)\, e^{i\vec{q}\cdot\vec{r}/\hbar}\, d^3r \tag{6.6}$$

is the elastic form factor. Thus if

$$f(\vec{q})/f_{pt}(\vec{q}) \;\neq 1 \tag{6.7}$$

for any q, the fixed scattering center is not a point.

As an example, suppose ρ(r) has the exponential distribution

$$\rho(r) = \left(\frac{e}{8\pi b^3}\right) e^{-r/b} \tag{6.8}$$

then

$$F(q) = \frac{1}{(1 + b^2|\,\vec{q}^2\,|/\hbar^2)^2} \tag{6.9}$$

As $|\,\vec{q}^2\,|$ increases F(q) decreases. This is a general property of form factors which come from the spreading out of a point charge; they reduce the size of the cross section

$$d\sigma/d\Omega = (d\sigma/d\Omega)_{pt}\; F^2(q) \tag{6.10}$$

This concept is extended to relativistic elastic and inelastic scattering: if the cross section is smaller than the predicted point particle cross section, this indicates a non-zero size and external structure for at least one of the particles. This is where it all begins.

In high energy, inelastic, charged lepton scattering, Eq. 6.2 and Fig.4.1, the differential cross section for the scattered, point particle, lepton is[4.1,4.2]

$$\left(\frac{d\sigma}{dq^2 d\nu}\right)_{pt} = \frac{\pi\alpha^2}{q^4 E^2}\ [2|q^2|W_1 + (4EE' - |q^2|)W_2] \tag{6.11}$$

Here q^2 is the square of the four-momentum transfer q and $\nu = q^0 = E - E'$. W_1 and W_2, the electromagnetic structure functions, are in general functions of q^2 and ν. In ν inelastic scattering there are three structure functions. If Bjorken scaling were exactly true, W_1 and W_2 would be functions of just $x = |q^2|/2M\nu$. If the lepton is not a point particle, then we can describe the deviation by a form factor F(q) and

$$\frac{d\sigma}{dq^2 d\nu} = \left(\frac{d\sigma}{dq^2 d\nu}\right)_{pt}\ F^2(q) \tag{6.12}$$

Finally, by measuring the differential cross section over a range of q^2 and ν values, and assuming Bjorken scaling, one could determine F(q).

But nature is not so simple, there are deviations from Bjorken scaling and there are measurement errors. Some analysts[6.1] have used QCD to account for the scaling violations.

The functional form of F(q) has been a matter of taste. One can use Eq.6.9

$$F(q) = \frac{1}{(1 + |q^2|/\Lambda^2)^2} \quad , \quad \hbar = 1,\ c = 1 \tag{6.13}$$

This is the dipole form used in the description of the nuclear form factors. Here Λ replaces $b/\hbar$. Another choice is

$$F(q) = \frac{1}{1 + |q^2|/\Lambda^2} \tag{6.14}$$

However, since no deviation from point particle behavior has been found for the leptons, it is sufficient to use a linear approximation to Eq.6.14

$$\begin{gathered} F(q) = 1 - |q^2|/\Lambda^2 \\ \sigma(inelastic) = \sigma(inelastic,\ pt\ lepton) \times (1 - 2|q^2|/\Lambda^2) \end{gathered} \tag{6.15}$$

Lyons[6.1a] quotes two results: for μ N inelastic scattering $\Lambda > 85$ GeV and for ν_μ N scattering $\Lambda > 100$ GeV. Mann[6.7] compared ν_μ N and and μ N inelastic scattering to obtain $\Lambda > 30$ GeV.

The interpretation of Λ derives from the expansion of Eq.6.6

$$F(q) = 1 - |\vec{q}^2| < r^2 > /6\hbar + \ldots , \tag{6.16}$$

and one writes

$$r_{max} \sim \hbar/|q|_{max} \sim \hbar/\Lambda \tag{6.17}$$

Using $\hbar c = 2 \times 10^{-14}\ GeV\ cm$,

$$\Lambda = 100\ GeV\ gives\ r_{max} = 2 \times 10^{-16} cm \tag{6.18}$$

I don't know how satisfied one should be with this interpretation.

Finally, looking to the future, let's see how well one can do with the very large q^2 which will be available at HERA, Sec. 4C. In this collider there will be substantial data at $|q^2|$ values of 10^4 GeV. Assuming the e-p inelastic cross section can be measured and scaling violation effects understood to 5% accuracy, Eq.6.15 says that Λ's up to $\sqrt{40|q^2|}$ can be examined. (Here $40 = 1/2.5\%$). For HERA

$$\Lambda \sim 700\ GeV \quad or \quad \sim 3 \times 10^{-17}\ cm \tag{6.19}$$

Incidentally, the existence of F(q) $\neq$1 can have other interpretations. For example, it could mean that a new, unknown interaction is destructively interfering with the expected γ and Z^0 exchange diagrams.

Even larger values of q^2 can be reached in ep scattering if an ep collider is added to the proposed SSC, Sec.3D, by building an electron storage ring. The collision of 15 GeV, 30 GeV, or 200 GeV e's with 20 TeV p's has been considered.[6.8] Such an ep collider has many uses, one which is to test the elementariness of the e at very large $|q^2|$ values.

Experimental Need: To develop methods for distinguishing e form factor effects from scaling violations or other effects in tests of the e's elementariness at very large $|q^2|$ values.

6D. Elementariness Tests Using $e^+e^- \to e^+e^-, \mu^+\mu^-, \tau^+\tau^-$

The reactions

$$\begin{aligned} e^+e^- &\to e^+e^- \\ e^+e^- &\to \mu^+\mu^- \\ e^+e^- &\to \tau^+\tau^- \end{aligned} \tag{6.20}$$

provide direct tests of the elementariness of the charged leptons because they occur through the processes in Fig.2.1 which can be directly calculated[2.2,2.4] using electroweak theory and assuming the leptons are point particles.

An allowance for the leptons not being elementary is generally made by extending the form factor concept to the timelike four-momentum transfer region. Consider $e^+e^- \rightarrow \mu^+\mu^-$ for simplicity, then one puts a form factor

$$F(s) = 1 \pm s/\Lambda_\mu^2 \tag{6.21}$$

at the μ vertex, and measures the total cross section $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$. Comparing it to the point muon production

$$\sigma(e^+e^- \rightarrow \mu^+\mu^-) = 4\pi\alpha^2/3s \tag{6.22}$$

one looks for deviations from that simple s behavior. No deviations have been found for the μ or the τ. The $e^+e^- \rightarrow e^+e^-$ is more complicated[2.2] but again no deviations have been found. Results from the PETRA and PEP electron-positron colliders give roughly[6.1]

$$\Lambda_{e\ or\ \mu\ or\ \tau} > 200\ GeV \quad ; \tag{6.23}$$

and using Eq.6.17

$$r_{max} \sim 10^{-16} cm\ for\ e,\ \mu,\ \tau \tag{6.24}$$

How much better can we do at future e^+e^- colliders? The Λ in Eq.6.23 comes about because the tests were made at $s \sim (30\ \text{GeV})^2$; and we can set limits on the deviation of 1 $\pm 2s/\Lambda^2$ from 1 to about 5%. Hence $\Lambda \sim \sqrt{40}\ .\ 30\ GeV \sim 200\ GeV$. LEP is designed to reach $\sqrt{s} = 200$ GeV, hence such tests can be extended down to r_{max} of 10^{-17} And, as discussed in Sec.2, if an e^+e^- linear collider with $\sqrt{s} \sim 2$ TeV is built, then r_{max} down to 10^{-18} cm can be explored.

6E. Remarks on Composite Models

Once specific composite models[6.1–6.3] are used,the tests of elementariness become both more sensitive and more specialized. For example, suppose the e and the μ are composites of two simpler particles a spin 0 particle b and a fermion f, with the μ an excited state. Then the discovery of the decay mode.

$$\mu^- \rightarrow e^- + \gamma \tag{6.24a}$$

which violates lepton number conservation (Sec.7A) could be regarded as evidence for the composite structure of the μ and e, the decay occuring through the process in Fig.6.1. Similar remarks would apply to the discovery of the decay

$$K^0 \rightarrow e^- + \mu^+ \tag{6.24b}$$

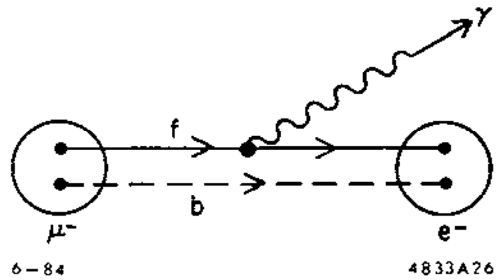

Fig. 6.1.

Thus searches for violation of lepton number conservation are sometimes regarded as searches for the composite nature of leptons.

As another example, consider a composite model in which the e and μ share the same b but different f's.

$$\begin{aligned} e^- &= (f_e, b) \quad e^+ = (\bar{f}_e, \bar{b}) \\ u^- &= (f_\mu, b) \quad \mu^+ = (\bar{f}_\mu, \bar{b}) \end{aligned} \tag{6.25}$$

Then

$$e^+ e^- \rightarrow \mu^+ + \mu^- \tag{6.26}$$

can occur through a contact interaction[6.9] among the f_e's and f_μ's as shown in Fig.6.2.

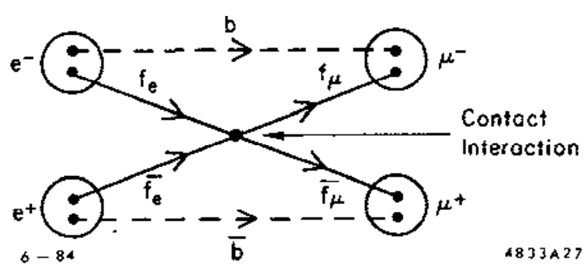

Fig. 6.2.

Figure 6.3 shows an example of possible effects.[6.10]

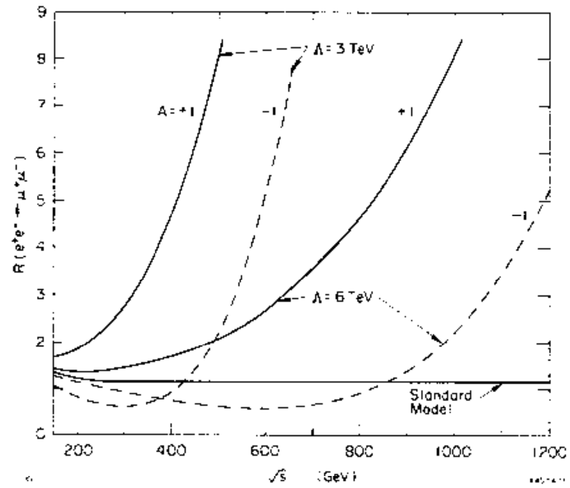

Fig. 6.3 Examples of the possible effects of the e and μ being composite on the R for the reaction $e^+e^- \to \mu^+\mu^-$. From Ref. 6.10.

Experimental Need: To find a new experimental method to test the elementariness of leptons which does not depend on the older analog ideas of Sec.6C or on specific composite models.

7. LEPTON TYPES AND LEPTON CONSERVATION

In this section I discuss the various types of leptons,[7.1,7.2], the known sequential leptons and the various of kinds which have been proposed but not found. I also consider lepton conservation because the discussion of lepton types is intertwined with the concepts of lepton conservation and lepton mixing. At the end of the section I consider the elusive neutrino.

7A. Sequential Leptons and Lepton Conservation

The e, μ, τ and their associated neutrinos form three generations of what we call sequential leptons. The properties are:

- the charged lepton has a unique conserved lepton number which is only shared by its associated neutrino. One generation does not decay to another.
- the neutrino has less mass than its charged partner and may have zero mass.

The immediate question is how perfect is lepton conservation? At present no violations have been found.[7.2,7.4] Table 7.1 gives the present limits and also gives estimates as to

Table 7.1. Some present upper limits of tests of lepton number conservation, and sensitivity which can be reached with present techniques. From Refs. 7.2, 7.4, 7.7.

Reaction	Present 90% CL upper limit on branching ratios	Expected sensitivity
$\mu^+ \to e^+\gamma$	$< 1.7 \times 10^{-10}$	10^{-12}
$\mu^+ \to e^+e^+e^-$	$< 1.9 \times 10^{-9}$	10^{-12}
$\mu^- Z \to e^- Z$	$< 7 \times 10^{-11}$	10^{-12}
$K_L^0 \to \mu^\pm e^\pm$	$< 2 \times 10^{-9}$	$10^{-11} - 10^{-12}$
$K^+ \to \pi^+\mu^\pm e^\pm$	$< 7 \times 10^{-9}$	$10^{-11} - 10^{-12}$
$\tau^- \to e^-\gamma$	$< 7 \times 10^{-4}$	10^{-5}
$\tau^- \to \mu^-\gamma$	$< 6 \times 10^{-4}$	10^{-5}

how much more precision can be obtained. In some processes we can hope to probe down to levels of 10^{-12} or smaller; but in others, such as τ conservation[7.7], we don't see how to get below 10^{-5}. This is unfortunate because one might hope that the relatively large mass of the τ and the possible relatively large mass of the ν_τ (the upper limit on the ν_τ mass is about 160 MeV) would lead to violations of lepton conservation and hence some clue to the connection, if there is one, between lepton generations.

Experimental Need: To press the tests of lepton number conservation.

Experimental Need: To find a new way to test lepton number conservation.

7B. Decay Modes of Sequential Leptons

The decay modes of sequential leptons illustrate how undiscovered heavy charged leptons would decay if they obey conventional weak interaction theory. Consider a hypothetical L-ν sequential lepton pair with

$$m_L > m_\nu \tag{7.1}$$

where m is mass. There are two cases

$$m_L - m_\nu < m_W \tag{7.2a}$$
$$m_L - m_\nu > m_W \tag{7.2b}$$

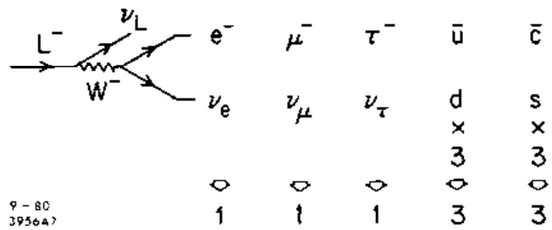

Fig. 7.1.

For the first case, decay proceeds through a virtual W, Fig.7.1. Ignoring the Cabbibo suppressed decay modes and assuming $m_L - m_\nu >> m_c + m_s$ the decay branching fractions are

$$\begin{aligned} B(L \to \nu e \nu_e) \approx & B(L \to \nu \mu \nu_\mu) \approx B(L \to \nu \tau \nu_\tau) \approx 1/9 \\ & B(L \to \nu \ hadron) \ \approx 2/3 \end{aligned} \tag{7.3}$$

The lifetime, T_L, is given by the famous m_L^5 formula

$$T_L = \frac{192\pi^3\hbar}{G^2 m_L^5}\left(\frac{1}{9}\right) \tag{7.4a}$$

or

$$T_L \sim 10^{-12}/(m_L \ GeV)^5 \tag{7.4b}$$

7C. Variations on Sequential Leptons

We can extend the sequential lepton concept in various ways. There is no need for the neutral lepton to have very small or zero mass. So we replace the ν by an L^0. Indeed we might have

$$mass_{L^0} > mass_L \tag{7.5}$$

Then

$$\begin{aligned} & L^0 \to L^- + \ell^+ + \nu_\ell; \quad \ell = e, \ \mu \ \tau \\ & L^0 \to L^- + (hadrons)^+; \end{aligned} \tag{7.6}$$

and the L^- may be stable. The branching fractions and the lifetime of the L^0 are given by Eqs.7.3 and 7.4. We can also consider pairs of neutral leptons L^0-$L^{0\prime}$ with the same lepton number. If L^0 is more massive, possible decay modes are

$$\begin{aligned} & L^0 \to L^{0\prime} + \ell^+ + \ell^-, \quad \ell = e, \ \mu \ \tau \\ & L^0 \to L^{0\prime} + \nu_\ell + \bar{\nu}_\ell \\ & L^0 \to L^{0\prime} + (hadrons)^0 \end{aligned} \tag{7.7}$$

These decays could not proceed through conventional weak interaction theory, because in that theory the weak current does not couple to two neutral fermions.

Pairs of charged leptons $L^- - L'^-$ may have electromagnetic decays and were discussed in Sec.6B.

We need not restrict our speculations to pairs of leptons. We may consider families of leptons with the same unique, conserved lepton number. An example would be a triplet $L^{0\prime} - L^- - L^0$ with

$$mass_{L^{0\prime}} > mass_{L^-} > mass_{L^0} \tag{7.8}$$

7D. Very Heavy Leptons with Partners

Now we consider the case in Eq.7.2b. Then the decay mode is (Fig.7.2)

$$L^- \rightarrow L^0 + W^- \tag{7.9a}$$

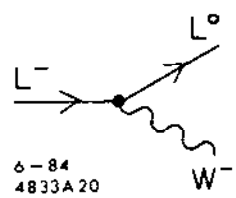

Fig. 7.2.

Of course the W will then decay

$$W^- \rightarrow e^- \bar{\nu}_e \,,\; \mu^- \bar{\nu}_\mu \;\; \tau^- \bar{\nu}_\tau \,,\; hadrons \tag{7.9b}$$

Therefore if the L^0 is stable the signature is

$$L^- \rightarrow e^- \quad or\; \mu^- \quad or\; hadrons + missing\; energy \tag{7.9c}$$

which is the same, of course, as the signatures in Eq.7.3. The decay width is

$$\Gamma(L^- \rightarrow L^0 + W^-) = \frac{Gm_L^3}{8\pi\sqrt{2}}\left(1 - \frac{m_W^2}{m_{L^2}}\right)^2 \left(1 + \frac{2m_W^2}{m_{L^2}}\right) \tag{7.10a}$$

where the L^0 mass has been ignored and a standard gauge coupling assumed. For $m_L >> m_W$,

$$\Gamma \approx G_F m_L^3/8\pi\sqrt{2} \approx 3 \times 10^{-7} m_L^3 \; GeV \tag{7.10b}$$

where m_L is in GeV. Thus for very heavy leptons the decay width can be the same magnitude as the mass. Similar considerations apply to L^0–L^- pairs with $m_{L^0} - m_L > m_W$. Incidentally, weak radiative corrections[7.12] to the W and Z masses in conventional theory put upper limits on $|m_{L^-} - m_{L^0}|$. If a pair of neutral leptons can couple to the weak current, we could have

$$L^{0\prime} \rightarrow L^0 + Z^0 \qquad (7.11)$$

7E. Leptons with Mixing Much of the above discussion applies to models for leptons in which there is some sort of mixing between leptons of different masses. Best known and most studied are the proposals that there can be oscillation between the known neutrinos. Many experiments have sought this effect but at present there is no established evidence[7.9] for the existence of neutrino oscillation. Other proposals call for mixing between neutrinos of very different mass[7.11]. I have nothing general to add to the many discussions of this subject. Rather I will give one example.

Suppose that the τ couples to a massless ν_τ and a massive neutral lepton N with mass $m_N > m_\tau$, and with mixing

$$\cos\phi\,\bar{\nu}_\tau + \sin\phi\,\bar{N} \quad ; \qquad (7.12)$$

so that the τ has the full weak coupling, g, to the ν_τ plus the N. The τ lifetime would be

$$T_\tau(measured)/T_\tau(predicted\ if\ no\ N) = 1/\cos^2\phi \qquad (7.13)$$

since the τ cannot decay to the N. Recent meaasurements[7.10] give the ratio in Eq.7.13 at the 95% confidence limit as

$$\cos^2\phi \geq 0.86 \quad , \quad \sin\phi \leq 0.4$$

If a non-zero value were established for $\sin\phi$, then one explanation would be that a heavy neutral lepton couples to the τ with strength $g\sin\phi$.

General possibilities as to the mixing of known neutrinos with heavy neutral leptons has been considered.[7.11] These possibilities when compared with experiment[7.11] place limits on the existence of some special types of neutral leptons.

It is clear that lepton mixing is a possibility that experimenters should keep in mind when studying the properties of the known leptons and when searching for new leptons. No one knows if it is a phenomena we shall ever see.

7F. Other Kinds of Leptons

There are other kinds of leptons that one can think about and then search for[7.1], the usual list is:

- stable heavy charged leptons;
- stable heavy neutral leptons;
- spin zero leptons. (One can use supersymmetry theory or just use the idea of why not.);
- fractionally charged leptons. (Many quark searches are also searches for fractionally charged leptons.);
- multiply charged leptons.

7G. Neutrinos

I don't know what to hope for with respect to the neutrinos. Perhaps in spite of all our future measurements they will remain, to the best of our knowledge, elementary, spin 1/2, particles with zero mass, no mixing, and obeying conventional weak interactions. Perhaps their tremendous simplicity will be a clue equivalent to the clue that gave Einstein special relativity –the velocity of light is a constant in vacuum. Or perhaps they have non-zero masses, then their simplicity is gone. They will then provide us with more data to test ideas about the origin of mass (Sec.11). And if they have a mass they might have a magnetic moment, something very small but something else to try to measure. No matter which way one's hopes go, there are three well known experimental needs.

Experimental Need: To determine if ν_e has a non-zero mass as indicated by one experiment.[7.12]

Experimental Need: To find a method to probe for the ν_μ mass below 0.5 MeV.

Experimental Need: To find a method to probe for the ν_τ mass below 100 MeV.

7H. Detecting Neutrinos

Many types of experiments are frustrated by our present methods of detecting neutrinos. Neutrinos in the MeV energy range are detected by the inverse beta decay method invented in the 1950's by Cowan and Reines. Higher energy neutrinos are detected by elastic scattering or inelastic scattering, a method used by Danby *et al* and also proposed by Pontecorvo in the 1960's. We have no other techniques.

If we had much more efficient methods of neutrino detection we might

- detect the black-body neutrino background left over from the big bang;
- settle the solar neutrino problem;

- do efficient neutrino astronomy;
- improve searches for new particles tremendously; and
- use neutrinos to explore the earth's interior.

But I know of no proposal for much more efficient neutrino detection, indeed the problem looks so intractable that I won't enter it as an experimental need. Instead I list it in Sec.13 as an experimental brick wall; I hope I am wrong.

8. SEARCHING FOR NEW LEPTONS

8A. Past and Present Searches for Charged Leptons

No charged leptons have been found[7.1,7.2,8.1] beyond the e, μ, and τ. The most definitive searches have used e^+e^- annihilation and the lower limits on the masses are

$$m_{charged\ lepton} \lesssim 15 \ to \ 20 \ GeV \tag{8.1}$$

If an e^{*-} coupled to the e^- is assumed, larger lower limits can be placed on m_{e^*}, but this requires the use of rather restrictive assumptions about the strength of the e-e* coupling. There are also lower limits of the order of 10 GeV/c^2 on charged leptons associated with muons or muon neutrinos.

8B. Past and Present Searches for Neutral Leptons

The experimental limits on the masses of undiscovered neutral leptons are very weak. Neutral leptons less than a GeV in mass could exist and we would not know that. The reason for our ignorance is that the definite search method

$$e^+e^- \rightarrow Z^0 \rightarrow L^0 + \overline{L^0} \tag{8.2}$$

has a very small cross section at the energies of existing e^+e^- colliders. Assuming conventional weak interactions the expected yield of $L^0\overline{L^0}$ pairs via Eq.8.2 at present energies is about 20 pairs per year of data taking at a luminosity of $10^{31} cm^{-2} s^{-1}$. Since there are various decay modes and the efficiency for deleting any single mode may be 1/2 or less, present searches may not be sensitive enough. Nevertheless as data is collected at PEP and PETRA the search for an L^0 continues.

Fixed target experiments have looked[7.1,7.2] for various special kinds of neutral leptons such as

(i) an L^0 associated with a μ;

(ii) an L^0 associated with an e;

(iii) a stable L^0 produced in pp collisions;

(iv) an L^0 produced in a K or D meson decay.

But these are not general searches and an L^0 with a mass as low as several hundred MeV/c^2 could exist and not have been detected in these searches. Reference 7.11 discusses various searches and search methods.

8C. Future Heavy Lepton Searches at e^+e^- Colliders

We have a great deal of experience in searching for charged leptons via

$$e^+e^- \rightarrow \gamma_{virtual} \rightarrow L^+ + L^- \tag{8.3a}$$

It is easy to extend that experience to

$$e^+e^- \rightarrow Z^0 \rightarrow L^+ + L^- \; ; \tag{8.3b}$$

and to neutral lepton production

$$e^+ + e^- \rightarrow Z^0 \rightarrow L^0 + \overline{L^0} \tag{8.3c}$$

These processes have very distinctive signatures. We first restrict our discussion to leptons with $m_L < m_W$ or m_Z. For brevity we consider only leptons with partners, the lighter partner being stable. Clearly more complicated decay schemes can be devised. Examples of signatures are

$$m_{L^-} > m_{L^0} \quad \begin{array}{ll} L^- \rightarrow L^0 + \ell^- + \bar{\nu}_\ell : & 1\ prong \\ L^- \rightarrow L^0 + hadrons : & hadron\ jet \end{array} \tag{8.4a}$$

$$m_{L^0} > m_{L^-} \quad \begin{array}{ll} L^0 \rightarrow L^- + \ell^+ + \bar{\nu}_\ell : & 2\ prong \\ L^0 \rightarrow L^- + hadrons : & L^- + hadron\ jet \end{array} \tag{8.4b}$$

$$m_{L^-} > m_{L'^-} \quad \begin{array}{ll} L^- \rightarrow +L'^- + \ell + \ell^- : & 3\ prong \\ L^- \rightarrow L'^- + \nu_\ell + \bar{\nu}_\ell : & 1\ prong \\ L^- \rightarrow L'^- + hadrons : & L'^- + hadron\ jet \end{array} \tag{8.4c}$$

Table 8.1 gives R values, and event rates for lepton pair production at $\sqrt{s} < 2M_W$. The event rates at the Z^0 are of course magnificent, but even below and above the Z^0 they are adequate.

Table 8.1. R values and produced lepton pair rates for $e^+e^- \to L\bar{L}$ with $\sqrt{s} < 2m_w$. $\mathcal{L} = 10^{31}\ cm^{-2}\ s^{-1}$ and 10^7 s/year is assumed. The Standard Model is used with the conventional coupling constants. The radiation correction is applied at the Z^0 peak. Threshold effects are ignored.

$\sqrt{s}$ (GeV)	L^+L^-		$L^0\overline{L^0}$	
	R	Events/yr	R	Events/yr
40	1.00	5,400	0.016	90
93 (Z^0)	110	110,000	225	225,000
150	1.43	550	0.81	310
200	1.27	280	0.50	110

As an example of how a new lepton is found consider the decay modes in Eq.8.4a and assume the branching fraction is 0.1 for each leptonic decay mode. Then the fraction of all pairs giving e+μ events, e+hadron jet events, or μ+hadron jet events is 0.3. The only important background to this signature is from τ pairs, and if hadron clusters are required to have more than 3 particles even this background is negligible. Hence it is quite easy to detect the presence of a new lepton even when the total production rate is only a few hundred pairs per year. The L^0 events are even more distinctive.

The mass of the new lepton can be roughly calculated from the kinematics of the events, as was done with the τ. Ultimately a threshold measurement is necessary to obtain a precise mass value.

Experimental Need: To construct the higher energy e^+e^- colliders, TRISTAN, SLC, and LEP, so that definitive heavy lepton searches can be made.

Now consider

$$m_L > m_W \text{ or } m_Z \tag{8.5}$$

Then some of the decay modes are

$$\begin{aligned}
L^- &\rightarrow W^- + L^0: && W\ jets + missing\ momentum \\
L^- &\rightarrow Z^0 + L'^-: && Z\ jets + L'^- \\
\overline{L^0} &\rightarrow W^- + L^+: && W\ jets + L^+ \\
L^0 &\rightarrow Z^0 + L'^0: && Z\ jets + missing\ momentum
\end{aligned} \tag{8.6}$$

These are distinctive signatures, for example

$$e^+ + e^- \rightarrow L^+ + L^- \rightarrow L^0 + \overline{L^0} + W^+ + W^- \tag{8.7a}$$

gives events with a pair of W's and missing momentum. And

$$e^+ + e^- \rightarrow L^0 + \overline{L^0} \rightarrow L^+ + L^- + W^+ + W^- \tag{8.7b}$$

is very distinctive. Backgrounds are discussed in References 1.3 and 2.9. Table 8.2 gives R values and event rates.

Table 8.2. R values and produced lepton pair rates for $e^+e^- \rightarrow LL$ with $\sqrt{s} > .2\ TeV$. $\pounds = 10^{33}\ cm^{-2}\ s^{-1}$ and 10^7 s/year is assumed. The Standard Model is used with the conventional coupling constants. Threshold effects are ignored.

$\sqrt{s}$	L^+L^-		$L^0\overline{L^0}$	
(TeV)	R	Events/yr	R	Events/yr
0.2	1.27	28,000	0.50	11,000
0.7	1.18	2,100	0.32	570
2.0	1.17	250	0.31	70

Thus e^+e^- colliders provide the most definitive way to search for heavy leptons, neutral as well as charged.

8D. Future Heavy Lepton Searches at ep Colliders

The ep collider offers a powerful way[4.3,7.1] to search for charged or neutral leptons which have the lepton number of the e. The reaction

$$e^- + p \rightarrow E^- + anything \tag{8.8a}$$

can occur through γ or neutral weak current exchange, while

$$e^- + p \to E^0 + anything \tag{8.8b}$$

can occur through charged weak current exchange. Figure 8.1 gives an example of the event rate.

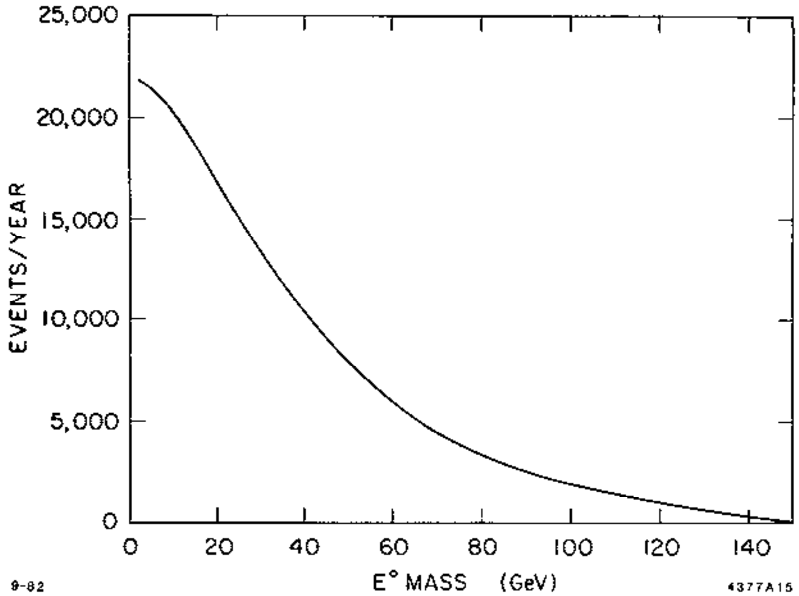

Fig. 8.1. Events per year for the production of a hypothetical E^0 heavy lepton for 10 GeV electrons colliding with 1 TeV protons, assuming an integrated luminosity of 10^{39} cm^{-2} per year.

The principle mechanism for the production of more general types of leptons is virtual photoproduction

$$\begin{aligned} e^- + p \to e^- + \gamma_{virtual} &+ anything \\ \gamma_{virtual} &\to L^+ + L^- \end{aligned} \tag{8.9}$$

Unfortunately this cross section becomes very small[7.1] for m_L greater than tens of GeV/c^2. Furthermore, we do not know how to find the L^+L^- pair under the large hadronic production. For example the photoproduction of τ pairs has yet to be detected.

8E. Future Heavy Lepton Searches at pp and $\bar{p}$p Colliders

There are two general methods for producing heavy leptons in hadron-hadron collisions. One general production mechanism is quark-antiquark annihilation:

$$\begin{aligned} &q + \bar{q} \to \gamma_{virtual} \to L^+ + L^- \\ &q + \bar{q} \to Z^0_{virtual} \to L^+ + L^- \quad or\ L^0 + \overline{L^0} \\ &q + \bar{q}' \to W^-_{virtual} \to L^- + \overline{L^0} \end{aligned} \tag{8.10}$$

The cross section for this process was discussed in Sec.3A and shown in Fig.3.4. For very heavy leptons, it is given by Eq.3.11. Consider $m_L = 100GeV$ and estimate the integral as 0.1. Then

$$\sigma(pp \ or \ \bar{p}p \rightarrow L + \bar{L} + hadrons) \sim 10^{-36} \ cm^2 \tag{8.11}$$

Therefore

$$\sigma_{L\bar{L}}/\sigma_{tot} \lesssim 10^{-11} \tag{8.12}$$

The signatures of the $L\bar{L}$ pair are those discussed in Sec.7, but they may be obscured by the hadronic background in the same event. This difficulty combined with the very small signal-to-noise ratio of Eq.8.12 has discouraged planning for heavy lepton searches at hadron-hadron colliders.

Experimental Need: To develop general signatures for heavy lepton searches at pp and $\bar{p}p$ colliders.

The second general mechanism for heavy lepton production at pp or $\bar{p}p$ colliders is the decay of a heavy particle

$$W^- \rightarrow L^- + \overline{L^0} \tag{8.13a}$$
$$Z^0 \rightarrow L^+ + L^- \tag{8.13b}$$
$$Z^0 \rightarrow L^0 + \overline{L^0} \tag{8.13c}$$
$$h \rightarrow L^- + \overline{L^0} + hadrons \tag{8.13d}$$

There have been interesting discussions of some of these search methods[8.2–8.4] using the W or Z. They are important because the W and Z are already being produced at the CERN $\bar{p}p$ collider. The signatures are not straightforward because there is usually missing momentum carried off by neutral leptons, and none of the masses can be reconstructed. (Of course if the $L^\pm$ is stable, $Z^0 \rightarrow L^+ + L^-$ is a superb signature.) The final process, Eq.8.13d, has the added difficulty of being speculative, no heavy h is known at present.

Heavy Lepton Searches in Fixed Target Experiments

There are many types of fixed target searches. The simplest type of search is to study the nature of the charged particle beam produced by a primary proton or electron beam hitting a fixed target. Such searches are always done when a new, higher energy, accelerator begins operation. A 20 TeV proton accelerator allows a mass range up to 190 GeV/c^2 for stable or long lived charged lepton searches.

The interaction of electron, muon or neutrino beams with a fixed target offers the possibility of the production of heavy leptons[7.1] associated with those leptons. For example, one can look for an $L^{\pm}$ lepton with the lepton number of the ν_μ using

$$\begin{aligned} &\nu_\mu + N \rightarrow L^{\pm} + hadrons \\ &L^{\pm} \rightarrow \nu_\mu + e^{\pm} + \nu_e\,(\bar{\nu}_e) \end{aligned} \tag{8.14}$$

This is a quite clean signature. The upper limit to the mass range of such secondary beam searches is

$$m \lesssim \sqrt{E_p/2}\ GeV \tag{8.15}$$

A very high intensity, primary, proton or electron beam provides opportunities for searching for stable or long-lived neutral leptons in a beam dump experiment. In such an experiment, Fig.8.2, the primary beam interacts completely in a dense target called the dump. A long shield absorbs all photons, charged particles and hadrons. Neutral penetrating particles, such as an L^0, are detected in a massive detector through their weak interaction. Or, if the L^0 is unstable its decay products might be detected[8.14].

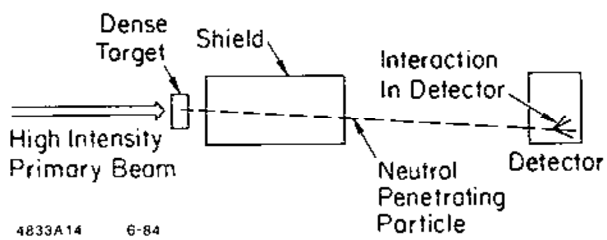

Fig. 8.2. Schematic diagram of a beam dump experiment searching for long-lived or stable neutral leptons.

8G. Total Number of Massless and Small Mass Neutral Leptons

The decays of the Z^0 to massless or small mass neutral lepton pairs (L^0 includes the known neutrinos here)

$$Z^0 \rightarrow L^0 + \overline{L^0} \tag{8.16a}$$

provides a general way to search for neutral leptons with

$$m_{L^0} < m_Z/2 \tag{8.16b}$$

which obey conventional weak interaction theory. Unfortunately our present methods of ν or L^0 detection are incapable of providing direct measurement of the decay modes in Eq.8.16.

Indirect methods must be used, Table 8.3, such as measurement of the decay width Γ_Z of the Z^0. Ignoring threshold effects

$$\Gamma_Z = \frac{G m_Z^3 \sum_f (v_f^2 + a_f^2)}{24\sqrt{2}\,\pi} \tag{8.17a}$$

Table 8.3. Limits from experiments on total number, N_{L^0}, of massless and small mass neutral leptons, including neutrinos.

Method	Present upper limit on N_{L^0}	Reference
Γ_Z from $e^+ + e^- \to Z^0$	Not possible yet	8.5
$e^+ + e^- \to Z^0_{virtual} \to \gamma + L^0\overline{L^0}$ above Z^0 peak	Not possible yet	8.6,8.7,8.8
$e^+e^- \to Z^0_{virtual} \to \gamma + L^0\overline{L^0}$ below Z^0 peak	43 (90% CL)	8.13
$\Gamma_Z \lesssim 10\ GeV$ from CERN $\bar{p}\,p$ collider experiments	~ 30	
$\sigma(\bar{p}\,p \to ZX)/\sigma(\bar{p}\,p \to WX)$	18 (90% CL)	8.11
$\sigma(\bar{p}\,p \to ZX)/\sigma(\bar{p}\,p \to WX)$	3 (90% CL)	8.12

where the symbols are defined in Sec.2.A, and the sum is over all fermions f such that

$$Z^0 \to f + \bar{f} \tag{8.17b}$$

In Eq.8.17a, $G m_Z^3/24\sqrt{2}\,\pi \approx 90 MeV$, and Table 2.1 gives $(v_f^2 + f_f^2)$. Excluding the t quark and using Table 2.1

$$\sum_f (v_f^2 + a_f^2) \approx 3 \times 2.0 + 3 \times 1.0 + 6 \times 1.2 + 9 \times 1.5 = 30$$

Hence we expect

$$\Gamma_Z \lesssim 2700\ MeV \tag{8.17c}$$

Each additional massless or small mass neutral lepton pair adds about 180 MeV or above 7% to the width. Such a measurement precision[8.5] can ultimately be obtained in

$$e^+ + e^- \to Z^0 \tag{8.18}$$

but it is not easy. An alternate method[8.6–8.8] is to measure the cross section for

$$e^+ + e^- \rightarrow Z^0_{virtual} \rightarrow \gamma + all\ L^0\overline{L^0}\ pairs \tag{8.19}$$

just above the Z^0 peak. This cross section directly measures the number of $L^0\overline{L^0}$ pairs, N_{L^0}.

Present experimental limits on N_{L^0} are listed in Table 8.3. The reaction[8.9]

$$K^\pm \rightarrow \pi^\pm + L_0 + \bar{L}_0 \quad , \tag{8.20a}$$

has been discussed[8.6] as a way to determine an upper limit on N_{L^0}, but according to Shrock[8.10] this cannot be done because the cross section calculation is so uncertain.

Experimental Need: To measure the total number of different kinds of small mass and zero mass neutrinos. This number plus 3 (for the charged leptons) tells us the minimum number of different kinds of leptons. It is also an important check on present cosmological theories which predict no more the 4 different kinds of massless neutrinos.

9. THE KNOWN QUARKS

9A. Quarks as Elementary Particles

In the standard model, the quarks have the same status as the leptons as elementary particles. In thinking of experiments beyond the standard model, we should for a moment go far beyond the standard model, and consider if the quarks are indeed physical entities at all. Will quarks, forever constrained to be hidden inside hadrons, go the way of the electromagnetic ether of the nineteenth century?

If we persist in thinking of the known quarks, Table 9.1, as physical particles, then we should apply the same elementariness tests we used for the leptons, Sec.6. These tests are, of course, less direct because the quarks being tested are always inside hadrons.

Table 9.1. The known quarks.

Quark	Charge	Mass (MeV)
u	+2/3	a few to 300 depending on definition
d	-1/3	a few to 300 depending on definition
s	-1/3	about 200 to 500 depending on definition
c	+2/3	about 1500
b	-1/3	about 5000

Of course, the modern language for considering corrections to the naive quark model is quantum chromodynamics. The question of the elementariness of the quarks is then: is the quark a point particle once the mechanism of quantum chromodynamics – gluons and the strong interaction – is taken into account? The major experimental area for such considerations is the inelastic lepton scattering discussed in Sec.6C. These experiments and Bjorken scaling led the way in the development of the concept of the quark as a point particle.

However the cleanest modern tests of the elementariness of quarks is hadron production in e^+e^- annihilation.

$$e^+ + e^- \rightarrow \gamma \rightarrow q + \bar{q} \rightarrow hadrons \quad ;$$

and the prediction that the total cross sections R value (see Eq.2.10) is

$$R_{hadronic} = 11/3 \tag{9.4}$$

above the b quark production threshold. Lyons[6.1a] parameterized deviations from this prediction by the factor $(1 + s/\Lambda^2)^{-2}$ and finds

$$\Lambda_{quark} > 240\ GeV \tag{9.5}$$

9B. Can Quarks be Isolated

There are three ways to look for free, that is isolated, quarks: search in cosmic rays, try to produce free quarks at an accelerator, or look in macroscopic pieces of matter.

The accelerator searches[9.1–9.3] have used fixed target experiments including heavy ions as projectiles[9.4], and e^+e^-, pp, and $\bar{p}p$ colliders. None of these experiments have found free quarks. There is also no accepted evidence for free quarks in cosmic ray searches.[9.1–9.3] The significance of upper limits on the production of free quarks in the accelerator and cosmic ray searches depends upon a bewildering variety of models and assumptions; I know of no useful way to summarize the limits. Although all these searches have been fruitless and although quantum chromodynamics prohibits the existence of free quarks, it is certain that as each higher energy collider turns on, the first experiment will include searches for free quarks.

Searches for isolated quarks in macroscopic pieces of matter[9.1–9.3,9.5–9.7] have the advantage that the interpretation of their significance requires just two assumptions. The assumptions are (a) that due to charge conservation there is at least one stable fractionally charged quark, and (b) that some free quarks could survive the big bang. Furthermore, if the search methods do not involve a quark concentration step, then the ratio of quarks found or not found to nuclei can be stated directly. I therefore turn to this class of searches as summarized in Table 9.2.

Table 9.2. Recent free quark searches as tabulated in Ref. 9.7.

Method	Ref.	Sample material	Mass mg	Quarks per nucleon
Superconducting levitometer	9.5	niobium	1.1	$\sim 10^{-20}$
Ferromagnetic levitometer	9.6	steel	3.7	$< 1.3 \times 10^{-21}$
Ferromagnetic levitometer	9.8	steel	0.7	$< 6.9 \times 10^{-21}$
Automated Millikan liquid drop	9.9	mercury	0.2	$< 2.8 \times 10^{-20}$
Automated Millikan liquid drop	9.7	water	0.05	$< 9.8 \times 10^{-20}$

As you know the situation is unresolved. W. Fairbank and his colleagues have reported several times[9.5] the existence of $\pm e/3$ fractional charge in niobium using a superconducting magnetic levitometer. No other experimenters have studied niobium directly or use this technique. On the other hand no evidence for such fractional charge has been found using the ferromagnetic levitometer technique[9.6,9.8] or an automated Millikan liquid drop technique.[9.7,9.9]

I think that these searches for free quarks, or at least fractional charge, in macroscopic pieces of matter must be pushed much further in sensitivity to probe beyond the standard model. It appears to be difficult to push the levitometer or liquid drop technique more than a factor of 10 in sensitivity. However two new electrometer techniques, one being developed by my colleagues and myself[9.10] and one being developed by Williams and Gillies,[9.11] may be capable of more sensitivity.

Experimental Need: To press on with the search for free quarks. QCD does not require that quarks be bound[1.4], but even if it did, physics in the end is an experimental science.

9C. Quark Mixing

The mixing of quarks in the weak interaction is properly part of the standard model. I will however summarize the facts, following the review by Jarlskog[9.13], because the known quark mixing is one of the stimuli for thinking about lepton mixing, Sec.8, and for thinking about new types of quarks, Sec.10. Here we assume the existence of the t quark.

The mass eigenstates of the quarks are

$$\begin{aligned} charge &= +2/3 : \; u, c, t \\ charge &= -1/3 : \; d, s, b \end{aligned} \tag{9.6}$$

But the weak interaction doublets are

$$\begin{pmatrix} \mu \\ d' \end{pmatrix} \quad , \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad , \quad \begin{pmatrix} t \\ b' \end{pmatrix} \tag{9.7}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \tag{9.8}$$

It is useful to use the approximate values

$$V = \begin{pmatrix} .97 & 0.23 & 0 \\ -0.23 & 1 & \pm 0.05 \\ 0 & \pm 0.05 & 1 \end{pmatrix}$$

Of course 0.23 is the sin of the Cabibbo angle. As noted by Jarlskog[9.13] it is surprising that the mixing between the first and third generation is so small, and that even the mixing between the second and third is small. Is this a portent for the behavior of higher generations?

10. SEARCHING FOR HEAVY QUARKS

10A. Conventional Heavy Quarks with Mass < W Mass

I consider for most of this section conventional heavy quarks, meaning quarks similar in properties to the known quarks: the u, d, s, c, b.

I define conventional heavy quarks to have the following properties:

a. their strong interaction obeys quantum chromodynamics;
b. their decay occurs only through the weak interaction;
c. their charge is $\pm 1/3$ or $\pm 2/3$;
d. they have spin 1/2.

Definitive lower limits on the masses of such quarks come from searches at PETRA. For example, M. Althoff *et al*[10.1] find

$$\begin{aligned} m(charge = 2/3) &> 22\ GeV \\ m(charge = 1/3) &> 21\ GeV \end{aligned} \tag{10.1}$$

Preliminary evidence has been presented[1.12] for the existence of the t quark in the mass range of 30 to 50 GeV/c^2.

As with the leptons, I consider first

$$m_Q < m_W \tag{10.2}$$

and note that the decays would proceed in analogy to the decay patterns of the b and c quarks:

$$\begin{aligned} &b \rightarrow c + d + \bar{u} \\ &b \rightarrow c + e^- + \bar{\nu}_e \\ &b \rightarrow c + \mu^- + \bar{\nu}_\mu \\ &b \rightarrow c + \tau^- + \bar{\nu}_\tau \end{aligned} \tag{10.3}$$

$$\begin{aligned} &c \rightarrow s + u + \bar{d} \\ &c \rightarrow s + e^+ + \nu_e \\ &c \rightarrow s + \mu^+ + \nu_\mu \end{aligned} \tag{10.4}$$

The Q decays are

$$Q \rightarrow q + f + \bar{f}' \tag{10.5}$$

where q is a quark with $m_q < m_Q$. The conventional requirement is that the flavor changing current be charged:

$$|\, charge_Q - charge_q \,| = 1 = |\, charge_f + charge_{\bar{f}'} \,| \tag{10.6}$$

and the $f\,\bar{f}$ are quark-antiquark or lepton pairs which satisfy Eq.10.6. If charged Higgs bosons or other light charged bosons exist, the decay mode

$$Q \rightarrow q + H \tag{10.7}$$

would also occur.

The known heavier quarks prefer to decay to the quark nearest in mass. If we apply this model to the Q quark we would get a cascade

$$\begin{aligned} Q \rightarrow\ & q_1 + f_1 + \bar{f}'_1 \\ & \hookrightarrow q_2 + f_2 + \bar{f}'_2 \\ & \qquad \hookrightarrow \ldots \end{aligned} \tag{10.8}$$

Thus the Q jet would be complicated: it might consist of several subsidiary jets; it would contain charm and strange mesons; and it would contain several leptons.

As long as we are considering new heavier quarks we might consider a type with a single decay to a very light quark

$$Q \rightarrow q_{light} + f + \bar{f}' \tag{10.9}$$

The jet from this quark would look quite different from that described above: it would have a simpler jet structure and less leptons.

The experimental determination that a jet or set of jets comes from a new heavy quark is a complicated procedure. Some considerations are:

- The mass of the Q quark may be indicated by a measurement of the jet mass or at least by a measurement of the jet angular width.
- Leptons with large p_t relative to the jet axis may also be used to indicate the large mass of the Q.
- If no jet is observed the presence of $Q + \bar{Q}$ production might be indicated by special multilepton events such as events containing an $e\mu$ pair.

10B. Heavy Quarks with Mass > W or Z Mass

As with leptons, Sec.7B, when

$$m_Q > m_W \tag{10.10}$$

the decay process is

$$Q \rightarrow W^{\pm} + q \tag{10.11}$$

These decay modes have useful signature when the jet configuration allows the q quark jet to be distinguished from the W jets. The considerations of Ref. 7.12 on $|m_Q - -m_q|$ may limit the mass range of a search for Q.

10C. Quarkonium

The c and b quarks were discovered through their vector meson bound states $V(q\,\bar{q})$, namely the ψ and Υ. There are two methods for finding and studying the $V(q\,\bar{q})$:

In e^+e^- annihilation one looks for

$$\begin{aligned} &e^+ + e^- \rightarrow V(q\,\bar{q}) \rightarrow hadrons \\ &e^+ + e^- \rightarrow V(q\,\bar{q}) \rightarrow \ell^+ + \ell^-;\ \ell = e, \mu \end{aligned} \tag{10.12}$$

A narrow peak in the cross section versus $\sqrt{s}$ indicates the presence of the V.

In hadron-hadron collisions one looks for

$$\begin{aligned} h + h \rightarrow &V(Q\,\bar{Q}) + anything \\ &\hookrightarrow \ell^+ + \ell^-,\ \ell = e, \mu \end{aligned} \tag{10.11}$$

The $\ell^+\ell^-$ pair is used to reconstruct the mass of the V.

Both methods of looking for heavy quarks through the detection of quarkonium get difficult when m_V is large.[1.3] The upper limits[1.3] seem to be $m_V \lesssim 80\ GeV$ for e^+e^- colliders and $m_V \lesssim 50\ GeV$ for pp or $\bar{p}\,p$ colliders.

10D. An Example of Heavy Quark Production and Detection

We have now developed enough background material that we need not give a complete discussion of heavy quark production and detection at colliders, an example will be sufficient. Suppose the t quark is found and the next heavier quark, Q, is the charge 1/3 member of a fourth generation quark doublet, and suppose

$$m_Q = 500\ GeV \tag{10.12}$$

Then the decay mode is

$$Q \rightarrow W^- + q \tag{10.13}$$

Consider first a 2 TeV total energy e^+e^- collider with $10^{33}\ cm^{-2}\ s^{-1}$ luminosity. The signature is

$$\begin{array}{l} e^+ + e^- \rightarrow Q + \bar{Q} \\ \qquad\quad \bar{Q} \rightarrow W^+ + q \\ \qquad\quad Q \rightarrow W^- + q \quad ; \end{array} \tag{10.14}$$

namely 2W jets plus 2 quark jets. The major background is the process

$$e^+ + e^- \rightarrow W^+ + W^- \tag{10.15}$$

From Sec.2A, Eqs.2.8 and 2.14, $R \sim 1$ and the total cross section above threshold is about $10^{-37}\ cm^2$. In a year of $10^7\ s$ this leads to 1000 produced $Q\bar{Q}$ pairs. The signature in Eq.10.14 is quite different from the major background of Eq.10.15. Therefore the events from $Q\bar{Q}$ production should be relatively easy to identify.

Consider next a 40 TeV total energy pp collider with $10^{33}\ cm^{-2}\ s^{-1}$ luminosity. There are three basic processes, Fig.10.1, which can produce $Q\bar{Q}$ pairs. The initial gluons or

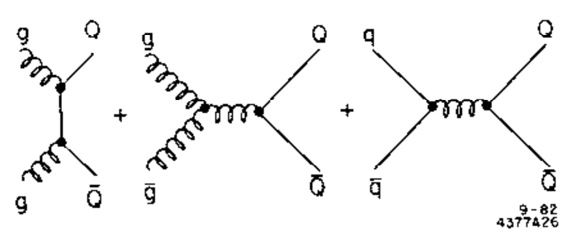

Fig. 10.1.

quarks come from the incident protons as described in Sec.3A. We could use the crude ideas of Sec.3A to estimate the cross sections of the processes in Fig.10.1, but it is better and easier to use the careful calculations of Ref.3.1, as reproduced in Fig. 3.5. The cross section is about $10^{-34}\ cm^2$ for 40 TeV pp collisions, yielding 10^6 produced $Q\bar{Q}$ pairs per year. Using the decay mode of Eq.10.13, the event is

$$p + p \rightarrow W^+ + W^- + q - jet + \bar{q} - jet + beam\ hadrons \tag{10.16}$$

The separation of this signal from the various backgrounds of multijet production might be difficult here, but there are other possibilities. For example, the large production rate might allow the use of a signature in which one of the W's decayed into an $\ell\nu_\ell$ mode instead of into a jet mode.

Incidentally, Fig.3.5 shows the importance of having high total energy to get a large production rate. For example, the cross section for production of a 500 GeV quark in 10 TeV pp collisions is about $10^{-36}\ cm^2$, a factor of 100 smaller than the 40 TeV cross section.

We conclude this subsection with a note on heavy quark production at ep colliders. The major production process is, Fig.10.2,

$$\gamma + g \rightarrow Q + \bar{Q} \tag{10.17}$$

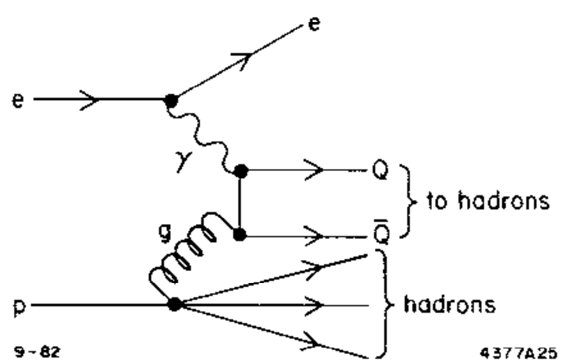

Fig. 10.2.

It is comparatively difficult for the gluon-photon system to attain a large invariant mass. Compare the heavy quark production in a 0.2 TeV e and 20 TeV p collider, Fig. 10.3, with a pp collider with 20 TeV p beams. In the ep collider the 1 pb cross section occurs at about 0.2 TeV quark mass; in the pp collider, Fig. 3.5, it occurs at about 1.3 TeV quark mass. Furthermore the ep collider will have smaller maximum luminosity by a factor of 10–100.

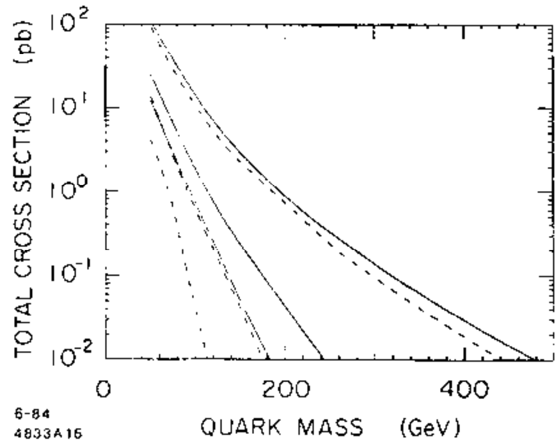

Fig. 10.3. Total cross section for the production of a charge 2/3 quark in ep collisions using the process in Fig. 10.2. The three sets of curves are for electrons of energy 15 GeV, 30 GeV, and 200 GeV colliding with 20 TeV protons. The solid and dashed curves are for angle cuts θ greater than 2° and 10° respectively on the produced fermions. From Ref. 10.2.

10E. Remarks on Unconventional Quarks

Just as we expanded our concept of leptons in Secs.7 and 8 so we can analogously expand our concept of possible new types of quarks. I'll just give one example, the reader can develop other analogies.

Suppose there is a heavy quark doublet

$$\begin{pmatrix} Q' \\ Q \end{pmatrix} \quad , \quad m_{Q'} >> m_Q \tag{10.18}$$

Let the $Q' - Q$ weak coupling be $g\cos\phi$ and the coupling of Q to all lighter quarks be $g\sin\phi$ with the mixing angle ϕ close to 0, for example even smaller then $V_{cb} \sim 0.05$ in Sec.9C. Then the meson composed of $Q + \bar{u}$ or $Q + \bar{d}$ quarks could have a very long lifetime, and the signature for the Q quark would be a massive meson with a very long lifetime.

11. THE ORIGIN OF MASS

11A. The Mass Question

One of the most important results of the last three decades of particle physics research is that we are no longer able to avoid the question of the origin of particle masses. If we accept the leptons, the quarks, and the force-carrying bosons as basic particles, then we must explain two things:

- What is the mechanism which produces mass?
- Why is the mass range so large, Fig.11.1, from possibly 0 for the photon and neutrinos to 100 GeV for the W and Z? Why is $m_\tau/m_e \approx 3500$? And if we assign a mass of a few MeV to the u and d quarks, why is the mass of the b quark 1000 times larger.

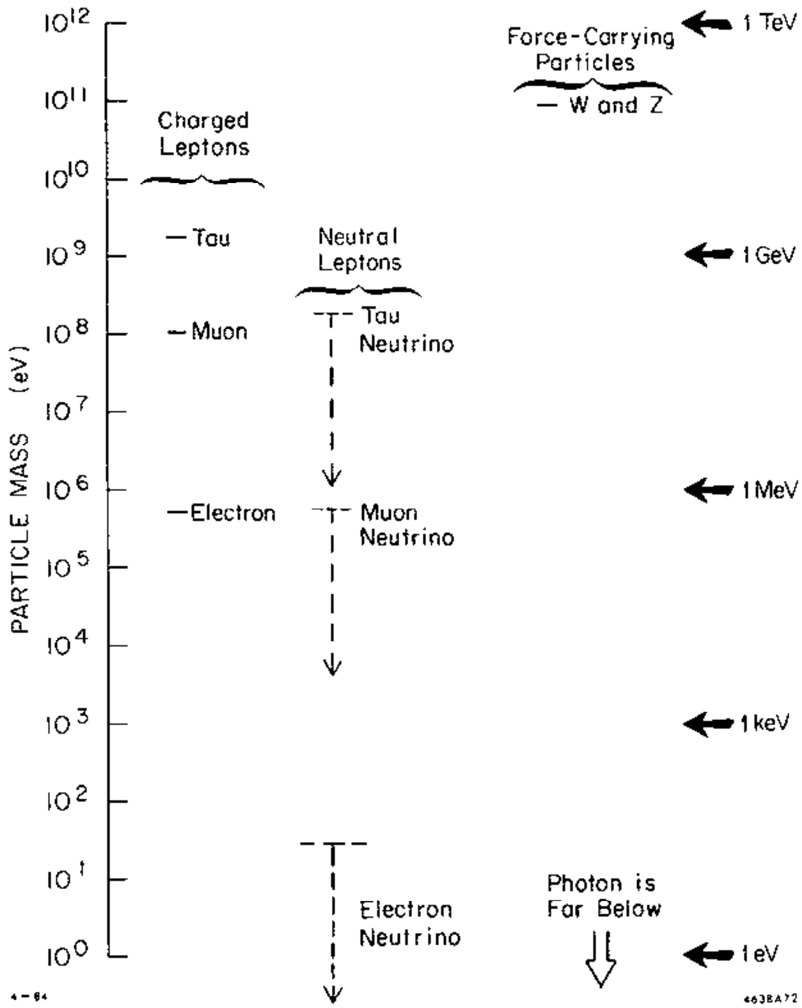

Fig. 11.1.

The problem of the origin of mass has plagued physicists since the era of Lorentz. The mass of the electron could be explained by assuming the electron was a uniformly charged ball of radius

$$r_e = e^2/mc^2 \; ; \tag{11.1}$$

but then where was the mass equivalent of the other force which held the electron together. And in the modern era, starting with quantum electrodynamics, we have had to deal with mass associated infinities by renormalization.

Present theories about the origin of mass mostly revolve around the Higgs mechanism, so I'll say a few words about the present status of that concept. Then I'll summarize some current ideas about the masses of fermions in composite models. Finally I'll turn to what can be done experimentally. We will see that except for searches for Higgs particles, all other experimental ideas are vague, an unfortunate situation.

11B. The Higgs Mechanism and Its Extensions

At present the Higgs mechanism[1,4] is the most accepted theory of the origin of mass. One begins with massless vector boson and fermion fields. They couple with each other according to the electroweak or strong interaction. But they also couple to a pair of special scalar fields called Higgs fields. These couplings give masses to the fermions and vector bosons, and they lead to some of the Higgs fields becoming physical particles.

A bit of symbolism for the fermion case. Consider a fermion of mass m_f. The Dirac equation

$$i\gamma^{\mu}\partial_{\mu}\psi - m_f\psi = 0 \tag{11.2}$$

comes from the Lagrangian

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}\partial_{\mu}\psi - m_f\bar{\psi}\psi \tag{11.3}$$

but where does the m_f come from? The only generally accepted alternative to just writing m_f in, is to replace

$$\mathcal{L}_{mass} = -m_f\bar{\psi}\bar{\psi} \tag{11.4}$$

by

$$\mathcal{L}_{mass} = -g_f\phi\bar{\psi}\psi \tag{11.5}$$

where g_f is coupling constant for the particular fermion f and ϕ is the scalar Higgs field. Then ϕ is given a non-zero expectation value $<\phi>_0$ and

$$\mathcal{L}_{mass} = -g_f <\phi>_0 \bar{\psi}\psi \tag{11.6}$$

gives Eq.11.4 with $m_f = g_f <\phi>_0$.

The strong support for this mechanism comes from several sources. In its simplest form it is incorporated in the standard model electroweak theory and it explains how the W and Z become massive while the photon remains massless. It also yields the correct quantitative mass relations of the W and Z. Finally, the physical Higgs particle plays a role in preventing divergencies in weak interactions at high energy.[1.4]

Why then is the Higgs mechanism still provisional? First, a physical Higgs particle has not yet been found. Second, quoting Weisskopf,

> "The Higgs coupling contains as many arbitrary coupling constants as there are masses. This is a rather awkward way to 'explain' the existence of masses and their magnitudes. It is possible, of course, that those Higgs particles really exist. Then the Higgs coupling *is* nature's way of making masses. I believe that nature should be more inventive, but experiments may prove me wrong."

The arbitrary coupling constants are the g_f's in Eq.11.5. Third, the Higgs mechanism raises some fundamental questions which may be harder to solve than the problems solved by the Higgs mechanism. For example: the mass of the physical Higgs particles are not given by the theory; the representation used for the Higgs field is arbitrary and even ugly, and quoting Ellis[3.6] "elementary scalar particle masses such as m_H are very unstable."

The Higgs mechanism as described above is carried out by elementary scalars. The theories of technicolor and extended technicolor provide composite scalars to carry out the Higgs mechanism. In technicolor a set of new elementary fermions,technifermions, are confined by a new strong force to produce composite particles analogous to hadrons. The technique is the technicolor scalar boson which replaces the elementary Higgs scalar and gives masses to the W and Z. The range of the technicolor force is taken to be $(1\text{ TeV})^{-1}$, the analogous range for the usual strong force is $(1\text{ GeV})^{-1}$. Quoting Kane and myself[1.3],

> "The Technicolor approach is a nice idea, with many attractive features. So far it has not been implemented in a simple model with good explanatory power and easily testable predictions, though interesting approaches do exist. Earlier comprehensive models have met contradictions when trying to get fermion masses, CKM angles, and small flavor changing neutral currents all correct, but it is not known whether such problems are intrinsic to the theory or due to insufficiently clever theorists."
>
> "From our viewpoint, Technicolor provides a useful guide to particles and interactions which might be the clues to new physics. It provides new and detectable particles both on the mass scales of 1 TeV and m $<$ 300 GeV, in accord with many prejudices."

11C. Mass in Composite Models

The old view of a composite elementary particle usually consisted of thinking about two or more very massive constituents, with masses M_i, bound together in a very strong potential. Then the particle mass m would be given by

$$m = \sum_i M_i - E_b \qquad (11.7)$$

when E_b is the binding energy. This view has fallen into disfavor because one needs to take

$$E_b >> m \qquad (11.8)$$

to explain the difficulty of breaking up the particle and then one needs to explain why $\sum_i M_i$ almost exactly cancels E_b.

The modern view[11.2,6.1] is that the constituents of the particle are massless or have masses on the order of the particle mass itself. Making the constituent massless makes it easy to explain the chiral symmetry properties of the leptons and quarks. There is still a large mass scale M_s, in the model. This is a measure of the compositeness energy scale and could be larger than the values of Λ discussed in Sec.6, for example. If the constituents are massless, then a non-zero fermion mass must come from a Higgs-like mechanism or from a dynamical effect. But most dynamical effects which generate mass require the existence of a massive gauge particle to interact with the constituents. And then the question of the origin of the masses of these gauge particles must be answered.

Summarizing, the modern concept of composite particles does not provide an alternative mechanism for the origin of mass, although it may explain the relatively small masses of the known leptons and quarks.

11D. Experiments on the Origin of Mass

Almost all experimental work and proposed experiments concerned with the origin of mass are searches for physical Higgs particles. The work and the proposals have been extensively reviewed; and I shall not discuss specific Higgs particle searches in these pre-lecture notes.

However the experimenter may generalize the concept of a Higgs particle search as follows. The interactions of all known particles depend upon the particle mass in a kinematic but not a dynamic way. The masses enter in phase space calculations and threshold considerations, but not into the strength of the interaction. For example the weak interaction decay rate of the Z^0 to an $f\bar{f}$ pair, Sec.8G, depends upon the coupling constants $(a_f^2 + v_f^2)$ which are independent of m_Z or m_f. The magnitudes of m_Z and m_f enters the calculation only because there is a threshold effect as m_f approaches $m_Z/2$.

General experiments on the origin of mass would search for dynamic effects of mass. The Higgs mechanism provides an example. The decay of a neutral physical Higgs particle to a lepton pair

$$H^0 \rightarrow L^+ + L^- \tag{11.7}$$

would be strongest for the largest mass L because the coupling of the Higgs particle to the L pair, Eq.11.5, is proportional to the L mass. Another example, I had once hoped that the τ lifetime would be shorter than that predicted by conventional weak interaction theory, Sec.7B. My hope was that the large mass would intrinsically lead to a less stable lepton, thus giving a clue to the origin of mass. Unfortunately the τ lifetime is as expected. Summarizing, searches for dynamic effects of mass involve:

- measurement of strong and electroweak cross sections, particularly of heavy particles;
- measurement of decay rates and branching ratios, particularly of heavy particles.

Beyond this, all we can do is the obvious:

- keep looking for heavier particles to give us clues to empirical rules for mass spectra;
- keep studying the masses or mass limits of the neutrinos and keep looking for other light particles to give us clues to the mass range of the known particles.

Experimental Need: There is a tremendous need to find new experimental methods to investigate the origin of mass.

12. EXPERIMENTAL CLUES TO BEYOND THE STANDARD MODEL

At present there are eight kinds of possible experimental clues to the physics that might lie beyond the standard model. In all cases the data is preliminary, or not yet verified by other experiments, or contradicted by other experiments. I list these possible clues in Table 12.1. Some of these clues were discussed by other speakers at this school, a few were discussed by me. I shall not reproduce any of that discussion here, but simply present the list along with recent references, and let the reader carry out their own evaluation. The clues are ordered according to energy range in the table.

Table 12:1. Possible experimental clues to the physics that might be beyond the standard model. The references given are quite incomplete, they are merely intended to introduce the subject.

Possible Clue	Energy Range (Center-of-mass)	Reference
Unexplained effects and events at CERN $\bar{p}p$ collider	30–150 GeV	P.Bagnaia *et al.*, Phys. Lett. 139B, 105 (1984) G.Arnison *et al.*, Phys. Lett 139B,115 (1984)
CELLO 2 μ + 2 jet event	40–45 GeV	H.J.Behrend *et al.*, Phys. Lett. 141B, 145 (1984)
Zeta (8.3)	8 GeV	C.Peck *et al.*, SLAC-PUB-3380 DESY 84-04 (1984)
Same sign dileptons in neutrino interactions	1–10 GeV	W.Smith, Proc.1984 SLAC Summer Inst. on Particle Phys.
Anomalies in neutrino production in beam dumps	1–10 GeV	M.E.Duffy *et al.*, Phys.Rev. Lett.52, 1865 (1984) K.Winter, Proc. 1983 Int. Symp. Lepton and Photon Interactions
Xi (2.2)	2 GeV	K.Einsweiler, Ph.D Thesis SLAC-272 (1984)
Anomalon effect in nuclear interactions	1–2 GeV per nucleon (not center of mass)	E.M.Friedlander *et al.*, Phys. Rev. 27C, 1489 (1983) J.D.Stevenson *et al.*, Phys. Rev. 52, 515 (1984)
Electron neutrino mass > 0	10–50 eV	S. Boris *et al.*, Proc. HEP83

13. EXPERIMENTAL BRICK WALLS

Throughout these lectures I have listed Experimental Needs, these were needed improvements or inventions in experimental and accelerator technology. I confined this list to those needs where I thought we had a hope or at least a prayer of making the improvement or invention. Looking beyond this list there are further needs which I don't see any way of meeting, I call these Experimental Brick Walls. I conclude these lectures with these Brick Walls. Are these walls impenetrable? Looking back on this list fifty years from now, one might find that some walls have been pushed down, some walls have been surmounted, and others may have turned out to be irrelevant. Here is the list.

13A. Laboratory Experiments on Gravitational Effects in Elementary Particle Interactions

Present day experiments on gravitation and relativity are directed towards the following major areas.

- Direct detection of gravitational radiation. The first object of such experiments is to test our current theory of gravity, but the major use of gravitational radiation detectors will be to do a new kind of astronomy.
- Tests of general relativity theory, such as the Stanford gyroscope experiment.
- Tests of the constancy of G, the inverse square law, and the equality of inertial and gravitational mass.

All these experiments are concerned with the classical behavior of the gravitational force, special relativity or general relativity. They are not concerned with quantum mechanical effects, nor with elementary particle effects. Yet they are already extremely difficult experiments. It appears to be impossible to do an experiment involving the interaction of individual elementary particles and the gravitational force.

13B. Efficient Neutrino Detection

Present methods for detection of neutrinos use the weak interaction and are extremely inefficient. We have no idea how to build a neutrino detector which will be small in size and have a high detection efficiency, of the order of 10%. Nor do we know how to measure the neutrino's energy in an efficient way.

13C. Very Small Hadron Calorimeter

The present technology of hadron calorimeters requires that the calorimeter's size be set by the strong interaction mean free path, λ_{strong}. This leads to very large general purpose particle detectors. We don't know how to build a hadron calorimeter with a size much smaller than λ_{strong}.

13D. Limits on Accelerator Energies

As discussed in Sec.2, even our boldest dreams about new accelerator technology seem to limit e^+e^- colliders to a maximum energy of 10 to 20 TeV. And it is very difficult to believe we can use known accelerator ideas, Sec.3, to extend pp or $\bar{p}p$ colliders beyond 100 TeV. Note from Sec.3C that these are equal effective energies. Will we be able to build accelerators which exceed effective energies of 10 to 20 TeV?

13E. Experimental Studies of the Continuous Nature of Space and Time

All our conventional physics assumes that space and time are continuous. Is there an experiment which will test these assumptions for very small distances or very small times? And what does small mean here?

13F. Do Elementary Particle Phenomena Ever Violate the Relativistic Quantum Mechanics?

There have been discussions of this, but is there a fruitful experimental program for probing deeply into the validity of relativistic quantum mechanics in elementary particle physics?

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