BEYOND THE STANDARD MODEL

G.L. Kane
Randall Laboratory of Physics, University of Michigan, Ann Arbor, MI 48109

M.L. Perl
SLAC, Stanford, CA 94305

I. Introduction

A. Plan of the Paper

In studying physics "Beyond the Standard Model" we have made a number of assumptions. The most fundamental of these assumptions are that it is worthwhile to try to study Beyond the Standard Model even though no one knows what direction will be fruitful, and that such a study will be useful in making decisions about future facilities if choices must be made.

At the summer study we proceeded by breaking up our large group into smaller working groups to concentrate on various topics [deviations from the Standard Model, supersymmetry, Higgs physics and technicolor, grand unification, constituent ideas, rare interactions] with 5-10 participants in each. These groups discussed their findings with the larger group, and several of them have written contributions to the proceedings. In this report we are trying to summarize the main results and conclusions in one place. It would be nice if we could give a well interpreted and unified presentation, but that is probably impossible because by their very nature the topics we are discussing are fragmented and incomplete, and are often orthogonal approaches to physics.

Our plan for this report is then

1. Introduction
2. General Behavior of Particle Interactions At High Energy
3. New Leptons of Conventional Types
4. New Quarks of Conventional Types
5. Deviations from Standard Model Predictions
6. Grand Unified Theories
7. Higgs Physics Beyond the Standard Model, charged Higgs
8. Technicolor
9. Supersymmetry
10. The Flavor Problem
11. Constituent Ideas
12. Anomalous Currents and Interactions
13. Non-standard Objects
14. What if there is no Standard Model Z°?
15. Remark on Luminosity vs Energy

Wherever appropriate (e.g. for Technicolor, specific grand unification models, supersymmetry) we treat the various approaches as ways to get interesting indications of phenomena to study rather than as believable models of the right answer.

We have taken the standard model to be the following:

- 3 families of quarks and of leptons with massless ν
- $SU(3)_c \otimes SU(2)_L \otimes U(1)$ gauge theories of strong, weak, and electromagnetic interactions
- 1 neutral Higgs boson
- CP violation via the quark mass matrices

This is a remarkable accomplishment of particle physics in the past two decades.

The Standard Model may be correct and it may be fundamental, but it is incomplete. It does what it is meant to do, and it does not address many questions at all. It does not consider or explain

- the possible (grand) unification of quarks and leptons, and of the various forces in nature;
- why the Standard Model works i.e. why 3 colors, explicit parity violation, etc.
- the origin of mass, and the need for scalar bosons;
- the origin of flavors, and how many flavors.

It is these topics which all of the approaches to Beyond the Standard Model attempt to resolve. In a sense, the main question is how to find experimental clues to these problems.

Although the Standard Model is not yet fully established [at a minimum it is necessary to find $Z^\circ, W^\pm$, find or understand a Higgs boson, measure radiative corrections, and test QCD scaling violations and multijet behavior], our working hypothesis is that the Standard Model can be used to study how to go Beyond the Standard Model. In particular, any hypothetical new particle which carries electric charge will couple to a photon and can be produced in e^+e^-collisions, any particle which carries weak isospin couples to the Z° and will appear in Z° decay if energetically allowed, and any particle which carries color will couple to gluons and can be produced in hadron collisions. All of these production rates are calculable (with appropriate uncertainties -- see below). Similarly, many decay signatures can be discussed in terms of Standard Model properties.

"We assume the standard model is valid" can be interpreted several ways. (1) We certainly assume that the Standard Model is valid to calculate production cross sections, decays, renormalization group behavior, etc. Then whenever new objects have $SU(3)_c$, $SU(2)_L$, or $U(1)$ quantum numbers we can plan for their properties. (2) Further, we assume that $W^\pm, Z^\circ$ will be found as fundamental bosons at the predicted masses (apart from small corrections that might be a clue to physics Beyond the Standard Model --see section 5). (3) We also assume that QCD perturbative analysis and jet physics is reliable. These parts of the Standard Model could be valid and fundamental whatever the final outcome for the rest. For the purposes of our article, we do assume (1), (2), and (3). On the other hand, our results do not depend on the parts of the Standard Model involving Higgs physics, CP violation, or ν masses; rather, these are poorly understood subjects which need experimental and theoretical illumination.

B. When Can Calculations at Hadron Colliders be Trusted?

At e^+e^- colliders the production rates for new particles depend on their coupling to the photon (their electric charge) or to the Z° (their weak charge) and are clean to calculate. At hadron colliders the production depends mainly on the coupling to color. In principle that is as well-founded a part of the Standard Model as the electric or weak charges, but our practical knowledge of how to do calculations is limited by inexperience and the increased complexity of QCD.

All calculations at hadron colliders depend on coupling to quarks or gluons in the hadrons, and thus depend on our knowledge of the quark and gluon structure functions and how to convolute them. That certainly implies that no calculation of the absolute normalization of a cross section is reliable to better than a factor of two or so, and perhaps that is optimistic. This situation could be improved; the present knowledge of structure functions is based on analyses of older data with older techniques and should be updated. However, because of the intrinisic complexity and consequent need for approximations, plus doubts about factorization, the uncertainty will never totally disappear.

One can make two useful quantitative statements.

(a) Up to what mass can one believe the estimates for production of a heavy particle? A good guide here is that the FNAL lepton pair experiments have observed that the Drell-Yan scaling curve[1.1] is followed at least up to $m(\ell\bar{\ell}) \approx 17$ GeV for $\sqrt{s}=27$ GeV. The extrapolation of that result to higher energies can be expected to give reliable results. Thus it might be reasonable to accept estimates for $m/\sqrt{s} \lesssim 0.6$.

(b) Even if quark or gluon structure functions are well measured at present machines, scaling violations will cause them to vary at larger Q^2. The area under the curve of F(x) vs. x for a structure function F(x) will stay constant, but it will rise at small x and fall at large x. The cross over point is around x=0.1 and moves slowly toward x=0 with increasing Q^2. Consequently, estimates of production rates for $0.05<x<0.15$ should be rather reliable. For $x<0.05$ one should avoid too rapid a rise to be conservative, and for $x<0.01$ our present understanding of the theory probably does not permit reliable estimates. For $x>0.15$ the scaling violations decrease the rate and reasonable scaling violations must be included to avoid an overestimate. For $x>0.5$ present techniques may not allow a reliable estimate, although if data is present to guide us as in Drell-Yan production, it may be possible to do better.

There is some model dependence in relating x to the mass scales of interest, but it should be satisfactory to take $x=m/\sqrt{s}$ for production of a single object of mass m, $x = 2m/\sqrt{s}$ for pair production of a particle of mass m, and $x=2p_T/\sqrt{s}$ for production of a jet of transverse momentum p_T.

With these qualifications in mind, we give here on the following pages Tables 1.1 and 1.2 of cross sections in $e^+e^-$and hadron-hadron reactions for various kinds of hypothetical physics, so the reader can get a feeling for the numbers involved. Details, assumptions, and unfamiliar objects are explained in the appropriate section below. Objects with a ~ are supersymmetric partners, and $H^\pm$ are charged Higgs bosons; ρ_T is a Technicolor vector boson.

Table 1.1: Approximate values of R for various e^+e^- reactions at $\sqrt{s}$=1 TeV. We use $\sin^2\theta_W=0.22$. Note that at 1 TeV 1 unit of R corresponds to a cross section of 0.87×10^{-37} cm^2. β is the produced particle velocity.

Reaction $e^+e^- \to$	Approximate values of R at $\sqrt{s}$ = 1 TeV
L^+L^-	1.2 β
$L^\circ\bar{L}^\circ$	0.3 β
New $Q\bar{Q}$ (charge = 2/3)	2.0 β
New $Q\bar{Q}$ (charge = 1/3)	1.1 β
New Quarkonium resonance	~ 1 at peak, peak may be wide
H^+H^-	0.3 β^3
ρ_T	15-20 at peak peak may be wide
$\tilde{Q}\bar{\tilde{Q}}$ (charge = 2/3)	0.4 β^3 per flavor
$\tilde{L}\bar{\tilde{L}}$	0.9 β^3 per flavor
W^+W^-	30 before any cuts
$Z^\circ\bar{Z}^\circ$	4 before any cuts
$Z^\circ\gamma$ ($\|\cos\theta\|<0.9$)	2.3
$Z^{\circ\prime}$ (total σ)	~ 3000 assuming standard model with radiative corections
$\tilde{W}^+\tilde{W}^-$	2.0 β
$Z^\circ H^\circ$ with $Z^\circ \to \ell^+\ell^-$	0.2 β

C. Mass Scales for New Physics?

Let us briefly mention the questions of mass scales for new physics, and the generality of many of the phenomena we discuss. This is discussed in some detail by Peskin in a separate contribution. There appears to be no general agreement on where to expect a new fundamental mass scale. Technicolor ideas usually put it around 1 TeV, but in supersymmetric models it has ranged from around m_Z to 10^{12} GeV. Veltman[1.2], Bjorken[1.3] and others have argued that if the present Standard Model is not a fundamental gauge theory we will see new phenomena and strong interactions by 1 TeV; unfortunately, however, such interactions may be mainly in the gauge boson sector and might give numerically small effects[1.4] in experiments initiated with light fermion ($e^\pm$, u,d,s, quarks) beams as the coupling is effectively through the masses or suppressed by higher powers of g^2. Some people have even argued for the total absence of any fundamental scale below the Grand Unification scale.

There may be one useful consideration, however. Most current approaches to going beyond the Standard Model and explaining mass generation, flavor, etc, do predict new low energy phenomena. Typically there are a number of observable particles or interactions on a mass scale below 300 GeV. Particles are found below 300 GeV for one of two rather general reasons. (1) In some models the fundamental theory has a great deal of symmetry. Some global symmetries are broken for dynamical reasons, and produce massless (pseudo)

Table 1.2: Estimated cross sections for some hypothetical new particles or jets. Events for a possible machine in a given time can be obtained by multiplying by an appropriate luminosity and length of time. Numbers are not given where the masses are too heavy or too light for the calculations to be meaningful. The last two entries are jets from a point cross section normalized to $\sigma = G_F^2 s$.

	σ(pb) for $\sqrt{s}$ (TeV)			
Hypothetical Produced State	0.8 (pp)	2.0 ($\bar{p}p$)	10.0 (pp)	40.0
Z° (m=300 GeV)	1	50	500	--
Z° (m=1 TeV)	--	--	10	50
Z° (m=2 TeV)	--	--	0.5	10
η_T (m=240 GeV)	4	170	7,000	--
gluino pairs (m=150 GeV)	0.7	200	25,000	--
gluino pairs (m=1TeV)	--	--	2.5	200
Technirho (m=1 TeV)	--	--	4	8
$Q\bar{Q}$ pair (m=100 GeV)	5	160	10,000	--
$Q\bar{Q}$ pair (m=500 GeV)	--	--	3	80
light quark jets (p_T=100 GeV)	10	100	1,000	--
light quark jets (p_T=800 GeV)	--	--	0.03	0.7
jets from point σ (p_T=100 GeV)	0.04	0.4	4	--
jets from point σ (p_T=800 GeV)	--	--	1	10

Goldstone bosons. These bosons then get mass from Standard Model interactions. Such masses can be estimated with some confidence because they depend on Standard Model effects, and they will come out in the 10 GeV range for color singlet states, the 100-300 GeV range for colored states. This kind of result occurs in technicolor models. (2) If the Standard Model, with $m_{W,Z} \approx 100$ GeV is to be explained by some some new fundamental approach, there must be mechanisms to produce such a mass scale. Then many other particles which get mass by the same mechanism, e.g. radiatively, will occur on the same mass scale. This happens in some supersymmetry models. Thus there is good reason to hope for new particle phenomena on the mass scale below 300 GeV, as low energy manifestations of a higher unknown scale.

Other general phenomena may occur. If the apparent broken flavor symmetry we see is a spontaneously broken symmetry there should be either Goldstone bosons or gauge bosons which mediate flavor changing neutral transitions and violate universality between families. If the flavor symmetry is due to a constituent structure there should be rearrangement effects. Either way, flavor changing neutral interactions should be observed.

Additional neutral gauge bosons, perhaps with interactions much different from the usual Z°, are suggested by horizontal gauge theories, by constituent ideas, and by some Grand Unification ideas where additional U(1) symmetries occur. Anomalous (non-V-A) currents arise for charged and neutral interactions from many approaches. As far as is understood there is no reason for ν masses to be zero; non-zero masses occur naturally in horizontal gauge theories and some Grand Unified approaches. All of the above phenomena may occur for good general reasons in a gauge theory framework. Their absence would considerably constrain ideas, and finding them would help even more.

To conclude the introduction we want to emphasize some additional assumptions that have -- often rather implicitly -- guided the deliberations of this group.

- Once one is Beyond the Standard Model there are no theorems, except that the Standard Model should hold. Probably all results are model dependent at the level where they confront experiment.
- It is not known how to go Beyond the Standard Model. Clues might come from new particles, new interactions, rare decays, small deviations from Standard Model predictions. We examine predictions of today's interesting ideas, not because they are right, but as examples of probes of unknown phenomena.

- By their nature, some ways (perhaps the right ones) to go Beyond the Standard Model cannot be thought of or discussed along the lines we approach the problem. In spite of this it is wise to make physics comparisons and judgements using the ideas available, but a careful effort should be made to look for facilities and regions of variables where new effects might be found even though they are not automatic places to look.
- It appears to be likely that important discoveries that help answer the open questions will be a small part of the total cross section, because that is the case in all models and ideas anyone has imagined so far. In hadron-hadron interactions they will generally correspond to cross sections or branching ratios below 10^{-6} of the total rate.
- The available funding per year will not grow a lot beyond the present level, and the facilities we could fruitfully use cannot all be constructed within the available budget, so comparisons and choices must be made.
- We have purposely not tried to study how to distinguish between models, how to decide what an effect is once it is found, etc. Those questions will be left as interesting topics for a future study.

Finally we remark that we have not tried to do a thorough job of providing references and credit to the original literature, because many hundreds of references would be involved. Apart from places where a specific point or number is referenced to explain its origin we have mainly referred to reviews and summaries, where the original literature can be traced. We apologize for any imbalance or neglect in credit that might arise.

2. The General Behavior of Particle Interactions at High Energy

A. Introduction

In this section we outline the expected general behavior of particle interactions at high energy. We do this for two reasons. First, these interactions produce the background in which we must search for new phenomena and new particles. Hence questions of how difficult it will be to find new physics can only be answered by having a broad picture of these background interactions. Second, if we are looking for the unexpected without a specific hypothesis, then the recognition of the unexpected depends again upon a broad knowledge of the expected.

We begin with e^+e^- interactions in the range $0.1<\sqrt{s}<2.0$ TeV; it is here that the standard model of particle interactions provide the most definitive picture of what to expect. Next we consider pp and $\bar{p}p$ interactions in the energy range of $0.5<\sqrt{s}<40$ TeV. The recent $\bar{p}p$ interaction studies at the CERN SPS provide one starting point for this survey of pp and $\bar{p}p$ interactions. We also use experience with e^+e^- interactions to provide some hints of how jet phenomena might behave in hadron-hadron interactions. Finally we look at ep colliders in the range $0.2<\sqrt{s}<3.3$ TeV. The lower limit is for 10 GeV e's colliding with 1 TeV p's; the upper limit is for 140 GeV e's colliding with 20 TeV p's.

B. General Behavior of e^+e^- Interactions for $0.1\lesssim\sqrt{s}\lesssim2.0$ TeV

a. e^+e^- Cross Sections: In the energy range from the vicinity of the Z° to about 2 TeV, the standard model predicts the following processes in e^+e^- interactions, depending upon the energy

Bhabha scattering:

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

Elementary fermion production:

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

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

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

Elementary vector boson production:

$$e^+ + e^- \rightarrow \gamma + \gamma \tag{2.3a}$$

$$e^+ + e^- \rightarrow \gamma + Z^\circ \tag{2.3b}$$

$$e^+ + e^- \rightarrow Z^\circ + Z^\circ \tag{2.3c}$$

$$e^+ + e^- \rightarrow W^+ + W^- \tag{2.3d}$$

Two-virtual-photon processes:

$$e^+ + e^- \rightarrow e^+ + e^- + \gamma_{\text{virtual}} + \gamma_{\text{virtual}} \tag{2.4}$$

$$\gamma_{\text{virtual}} + \gamma_{\text{virtual}} \rightarrow \text{leptons, quarks, or bosons}$$

We shall now make some remarks on the size of these cross sections. All formula are for unpolarized beams.

We begin with the expression for the purely electromagnetic production of a fermion pair

$$e^+ + e^- \rightarrow \gamma_{\text{virtual}} \rightarrow f^+ + f^- \tag{2.5}$$

in the center-of-mass system. Assuming the fermion is a spin 1/2, unit charge, point particle

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2\beta}{4s}\,(2-\beta^2 \sin^2\theta) \tag{2.6}$$

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

$$\sigma = \frac{2\pi\alpha^2\beta(3-\beta^2)}{3s} \tag{2.7}$$

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

$$\sigma_0 = \frac{4\pi\alpha^2}{3s} = \frac{86.7}{s}\ \text{nb, s in GeV}^2 \tag{2.8}$$

A convenient mnemonic in the energy range of interest here is

$$\sigma_0 \sim \frac{10^{-37}}{s}\ \text{cm}^2, \quad \text{s in TeV}^2 \tag{2.9}$$

Finally, as we all know, it is convenient to define a relative cross section

$$R = \sigma/\sigma_0$$

Before proceeding to the energy range of interest in this study, we briefly review the cross sections for $\sqrt{s}<40$ GeV where the dominant processes are electromagnetic; and the weak processes can be treated as a correction[2.1].

The purely electromagneic differential cross section for Bhabha scattering (Fig. 2.1a)

$$e^+ + e^- \rightarrow e^+ + e^- \tag{2.10a}$$

is[2.1]

$$e^+ + e^- \rightarrow e^+ + e^-: \quad \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4s}\left(\frac{3+\cos^2\theta}{1-\cos\theta}\right)^2; \quad \sqrt{s} \lesssim 40\ \text{GeV} \tag{2.10b}$$

Hence the total cross section is infinite. Of course, Bhabha scattering events are valuable for measuring luminosity. However it is useful to note the total cross section for $|\cos\theta|<.9$

$$e^+ + e^- \rightarrow e^+ + e^-: \quad \sigma(|\cos\theta| < .9) \approx 30\alpha^2/s; \qquad \sqrt{s}\lesssim40\ \text{GeV} \tag{2.10c}$$

The purely electromagnetic differential and total cross section for

$$e^+ + e^- \rightarrow \mu^+ + \mu^-$$

$$e^+ + e^- \rightarrow \tau^+ + \tau^-$$

have already been given in Eqs. 2.5-2.8. We note that sufficiently far above threshold each process has R=1. Hadron production away from the ψ and Υ resonances proceeds through Eq. 2.5 where the f is a quark q. Eq. 2.7 is simply modified to

$$e^+ + e^- \rightarrow q+\bar{q}: \quad \sigma = \frac{2\pi\alpha^2 Q_q^2\beta\ (3-\beta^2)}{3s}; \quad \sqrt{s} \lesssim 40\ \text{GeV} \tag{2.11a}$$

where Q_q is the quark charge. Then for each quark color

$$R_{q\bar{q}} \underset{\beta\to 1}{=} Q_q^2 \tag{2.11b}$$

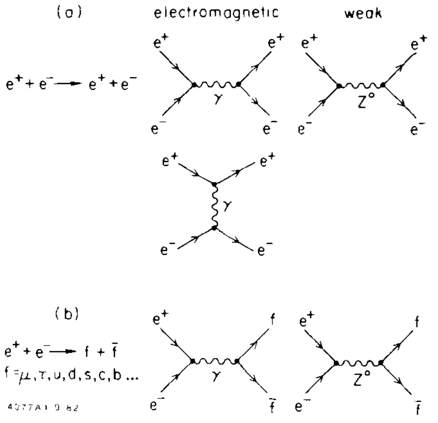
This leads to the famous prediction that above the threshold for b quark production, but with $\sqrt{s} \lesssim 40$ GeV

$$R_{\text{hadronic}} = 3\,[Q_u^2+Q_d^2+Q_s^2+Q_c^2+Q_b^2] = 11/3 \tag{2.11c}$$

a prediction which is confirmed by experiment.

Starting from this brief review we will now consider how these cross sections are modified as we proceed into higher energies, through Z° peak, and up to 2 TeV. This means we must consider weak interaction processes.

The weak interaction has little effect on the small angle Bhabha cross section because the t-channel photon exchange diagram, Fig. 2.1a, dominates; for large angles the concepts discussed next can be applied. The production of lepton or quark pairs now proceeds through both the electromagnetic and weak interaction, Fig. 2.1b



2.1. Diagrams for $e^+ + e^- \to f + \bar{f}$.

$$e^+ + e^- \to \gamma \to f + \bar{f}; \qquad f = \ell \text{ or } q \tag{2.12a}$$

$$e^+ + e^- \to Z^\circ \to f + \bar{f}; \qquad f = \ell,\ \nu, \text{ or } q$$

In the vicinity of the Z°, for our survey purpose, we can ignore the electromagnetic process and use[2.2]

$$e^+e^- \to f\bar{f}\!: \quad \sigma = \frac{G^2 s}{96\pi}\left[\frac{m_Z^4}{(s-m_Z^2)^2+\Gamma_Z^2 m_Z^2}\right] C_{ef} \tag{2.13a}$$

$$C_{ef} = [v_e^2+a_e^2][v_f^2+a_f^2]$$

Here G is the Fermi weak coupling const, m_Z is the Z° mass, and Γ_Z is the Z° width. The parameters v and a are from the v-$a\gamma_5$ expression in the weak current. Table 2.1 gives their value in the Standard Model.

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

		v_f	a_f	$v_f^2+a_f^2$
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

Equation 2.13 ignores the radiative correction to the peak and threshold effects of the f mass.

$$\begin{aligned} &\text{At the } Z^\circ \text{ for } e^+e^- \to f\bar{f} \\ &R \approx 160\, C_{ef}; \quad \text{without radiative correction} \\ &R \approx 110\, C_{ef}; \quad \text{with radiative correction} \end{aligned} \tag{2.13b}$$

which are enormous values for R.

As the energy, $\sqrt{s}$, moves above Z°, 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°. The cross sections all behave as 1/s and we have the simple rule[2.3] for $\sqrt{s} \gg m_Z$, and neglecting t-channel contributions to $e^+e^- \to e^+e^-$, $e^+e^- \to \nu_e\bar{\nu}_e$,

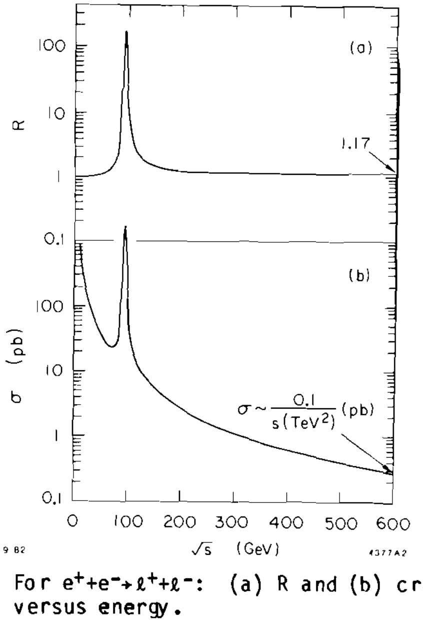
$$R(e^+e^- \to \ell^+\ell^-) = 1.17 \tag{2.14a}$$

$$R(e^+e^- \to \nu_\ell\bar{\nu}_\ell) = 0.31 \tag{2.14b}$$

$$R(e^+e^- \to q\bar{q}) = 1.95,\ q \text{ charge} = 2/3 \tag{2.14c}$$

$$R(e^+e^- \to q\bar{q}) = 1.09,\ q \text{ charge} = 1/3 \tag{2.14d}$$

Fig. 2.2 sketches this behavior for a charged lepton pair; the Z° peak has not been corrected for radiation. In Fig. 2.2a we indicate that for $\sqrt{s} \gg m_Z$



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

$$\sigma(e^+e^- \rightarrow \ell^+\ell^-) \sim 0.1/s \text{ pb} \qquad (2.14e)$$

with s in TeV^2. This expression can be applied to any of the fermion pairs using the ratio of the numbers in Eqs. 2.14a-d. Furthermore, this rule can be applied in a rough way to hadron-hadron collisions in which fermion pairs are produced through quark-antiquark annihilation via the Drell-Yan process

$$q+\bar{q} \rightarrow \gamma, \quad Z^\circ \rightarrow f+\bar{f}$$

Hence, in hadron-hadron collisions as well as e^+e^- collisions, the cross sections which produce $f\bar{f}$ pairs with invariant masses above several hundred GeV are less than a picobarn.

To conclude this section we turn to vector boson production; Eqs. 2.3. The processes

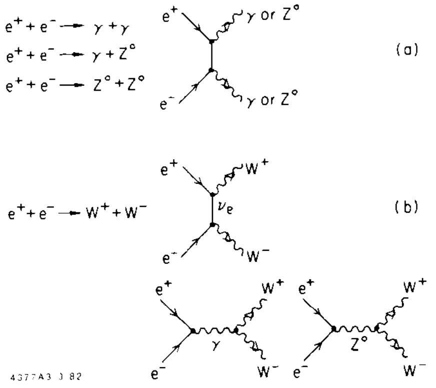
$$e^++e^- \rightarrow \gamma+\gamma \qquad (2.15a)$$

$$e^+e^- \rightarrow \gamma+Z^\circ \qquad (2.15b)$$

$$e^++e^- \rightarrow Z^\circ+Z^\circ \qquad (2.15c)$$

all occur thrugh the t-channel, e-exchange diagram in Fig. 2.3a. The $\gamma\gamma$ differential cross section is[2.4]

$$e^+e^-\rightarrow\gamma\gamma: \ \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s}\left(\frac{1+\cos^2\theta}{\sin^2\theta}\right) \qquad (2.16)$$



2.3. Diagrams for vector boson production

and has peaks at 0° and 180°. The γZ° differential cross section[2.4] also has forward and backward peaks. Indeed when $\sqrt{s} \gg m_Z$

$$e^+e^-\rightarrow\gamma Z^\circ: \ \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s}\left(\frac{1+\cos^2\theta}{\sin^2\theta}\right)\left(\frac{v_e^2 + a_e^2}{16\sin^2\theta_W\cos^2\theta_W}\right) \qquad (2.17)$$

For these two reactions

$$e^+e^- \rightarrow \gamma\gamma \ \sigma(|\cos\theta| < .9) \approx 8\pi\alpha^2/s \qquad (2.18a)$$

$$e^+e^- \rightarrow \gamma Z^\circ \ \sigma(|\cos\theta| < .9) \approx 3\pi\alpha^2/s \qquad (2.18b)$$

The $Z^\circ\bar{Z}^\circ$ differential cross section is[2.4]

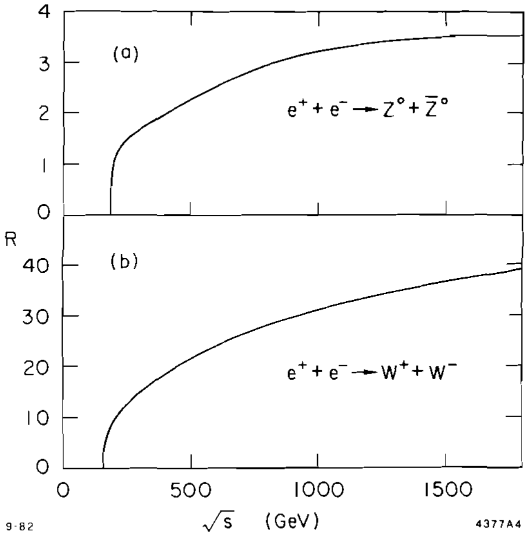
$$e^+e^-\rightarrow Z^\circ Z^\circ: \ \frac{d\sigma}{d\Omega} = \frac{\alpha^2}{s}\left(\frac{\beta}{2}\right)\left[\frac{4m_z^2sut+(t^2+u^2)(ut-m_z^4)}{u^2t^2}\right] \qquad (2.19)$$

$$\times \left[\frac{(v_e^2+a_e^2)^2 + 4(v_ea_e)^2}{(16\sin^2\theta_W\cos^2\theta_W)^2}\right]$$

$$t = m_z^2 - (s/2)\,(1 - \beta\cos\theta)$$

$$u = m_z^2 - (s/2)\,(1 + \beta\cos\theta)$$

This reaction also has forward and backward peaks. The magnitude of the cross section is strongly dependent[2.5] on $\sin\theta_W$ because of the last term in Eq. 2.19. Figure 2.4a shows the behavior of R for $\sin^2\theta_W$=0.22. Thus contrary to fermion pair production, R increases with $\sqrt{s}$ here.



2.4. R versus total energy for (a) $e^++e^-\rightarrow Z^\circ+\bar{Z}^\circ$, and (b) $e^++e^-\rightarrow W^++W^-$.

The reaction

$$e^++e^- \rightarrow W^++W^- \qquad (2.20)$$

occurs[2.4,2.5] through a complicated cancellation of the three diagrams in Fig. 2.3b. The differential cross section peaks when θ, the angle between the e^- and W^-, is small. For large s

$$e^++e^-\rightarrow W^++W^-: \ \sigma = \frac{\pi\alpha^2}{2\sin^4\theta_W}\ \frac{1}{s}\left(\ell n\ \frac{s}{m_W^2} - 5/4\right) \qquad (2.21)$$

As with $e^+e^- \rightarrow Z^\circ Z^\circ$ R increases as $\ell n\ (s/m_W^2)$, however the ℓn behavior has a different origin. Figure 2.4b gives the behavior of R versus energy.

In Table 2.2 we summarize the behavior of R as a function of energy for the processes we have discussed.

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° are corrected for radiation.

$\sqrt{s}$ (GeV)	$\ell^+\ell^-$	$\nu\bar{\nu}$	$q\bar{q}$ charge$=\frac{2}{3}$	$q\bar{q}$ charge$=\frac{1}{3}$	Z°Z°	W^+W^-
40	1.00	.02	1.33	.33	.0	.0
93(Z°)	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

Finally we remark on the two-virtual photon process

$$\begin{aligned} &e^+ + e^- \rightarrow e^+ + e^- + \gamma_{\text{virtual}} + \gamma_{\text{virtual}} \\ &\gamma_{\text{virtual}} + \gamma_{\text{virtual}} \rightarrow \text{leptons, quarks, or bosons} \end{aligned} \qquad (2.22)$$

The main characteristics of this process are:

(i) the total cross section increases as $\ell n\, s$;

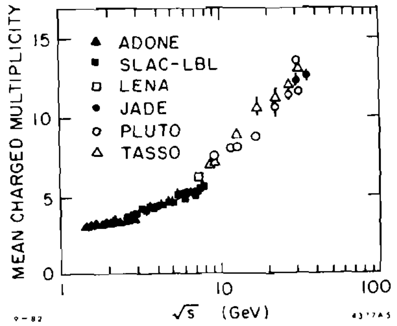
(ii) the total cross section is dominated by $m_{\gamma\gamma} << \sqrt{s}$ where $m_{\gamma\gamma}$ is the invariant mass of the two photons;

(iii) the total cross section is also dominated by small $p_{T\gamma\gamma}$, where $p_{T\gamma\gamma}$ is the transverse momentum of the $\gamma\gamma$ system;

(iv) hence events from this process are identified and separated from other events by $m_{\gamma\gamma}$ and $p_{T\gamma\gamma}$ criteria.

Reference 2.7 gives more details.

b. e^+e^- Multiplicities: Figure 2.5 gives the measured charged particle multiplicity in e^+e^- annihilation.[2.6] One of the ways to fit the data over the entire $\sqrt{s}$ range is to use the QCD inspired expression



2.5. Mean charged multiplicity versus total energy for e^+e^- annihilation.

$$\langle N_{ch}\rangle = N_0 + a\, e^{b\sqrt{\ell n(s/\Lambda^2)}} \qquad (2.23a)$$

The rough rule

$$\langle N_{ch}\rangle = 2.3\, s^{1/4}, \quad s \text{ in GeV}^2 \qquad (2.23b)$$

gives the same values of $\langle N_{ch}\rangle$ over the energy range in Table 2.3. However we feel that these fits are driven by the rapid change in $d\langle N_{ch}\rangle/d\sqrt{s}$ over the energy range in Fig. 2.5; and may not be a good way to extrapolate. Therefore we also fit the large $\sqrt{s}$ data in Fig. 2.5 with

$$\langle N_{ch}\rangle = -1.0 + 2.0\, \ell n\, s \qquad (2.23c)$$

Table 2.3: Various extrapolations for $\langle N_{ch}\rangle$ in e^+e^- annihilation; s is in GeV²

$\sqrt{s}$ (GeV)	$-1.0+2.0\,\ell n\, s$	$2.3\, s^{1/4}$	Eq. 2.23a
100	17	23	23
500	24	51	52
1000	27	73	72
2000	29	103	98

Here and in the rest of this paper we shall assume that the π^0 multiplicity is given by

$$\langle N_{\pi^0}\rangle \approx \langle N_{ch}\rangle/2 \qquad (2.24)$$

c. Quark jets in e^+e^- Interactions: All our present knowledge of quark hadronic jets comes from e^+e^- data below $\sqrt{s}\approx 36$ GeV. We must depend on this data to visualize how quark jets can be studied and used at higher e^+e^- energies. And we must extrapolate this knowledge into very high energy $\bar{p}p$ and pp interactions to see if we can detect and use quark jets in hadron-hadron physics. We are interested in two issues. First, what is the angular size of a jet? This is relevant to how easily a jet can be found, particularly in hadron-hadron interactions. The second issue is: how well can the invariant mass of a jet be measured?

A round estimate of the angular size of a jet can be made as follows. In e^+e^- interactions at $\sqrt{s}$= 30 GeV the total particle multiplicity is about 20, hence the average particle momentum is 1.5 GeV/c. In a jet the average transverse momentum relative to the jet axis is about 350 MeV/c. Thus we expect the conical half angle of a 15 GeV jet to be

$$\theta_{jet}\,(15\text{ GeV}) = (.35/1.5)\text{ rad} \approx 13° \qquad (2.25a)$$

A more refined measure is to use the sphericity, Fig. 2.6.

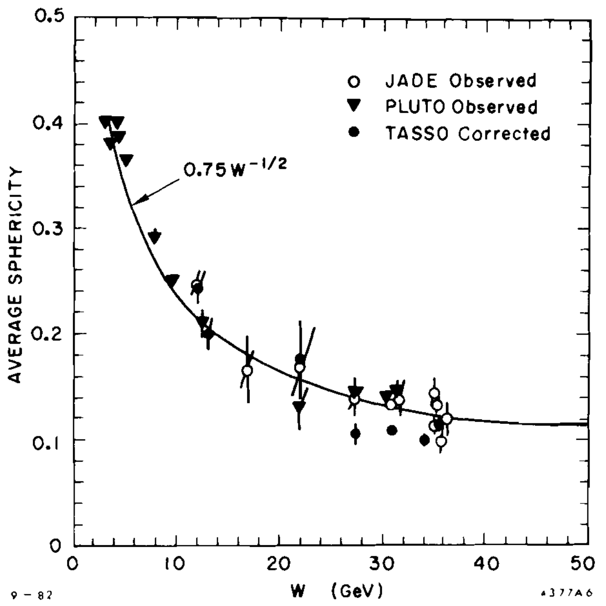
$$S = \frac{3}{2}\min\frac{\sum_i p_{t,i}^2}{\sum_i p_i^2} \qquad (2.26)$$

Here p_i is the momentum of particle i in the jet and $p_{t,i}$ is its transverse momentum relative to the jet axis. Then define[2.8,2.9]

$$\sin\theta_{jet,sph} = \sqrt{2S/3} \qquad (2.27)$$

This yields for a 15 GeV jet

$$\theta_{jet,sph}\,(15\text{ GeV}) = 16° \qquad (2.25)$$



2.6. Average sphericity versus total energy for e^+e^- annihilation. From Ref. 2.9.

An alternative measure of the angular size of the jet uses the energy distribution. We define $\theta_{jet,E}$ (P_E) where $\theta_{jet,E}$ is the conical half angle which contains a percentage P_E of the total jet energy. Table 2.4 gives some examples.

Table 2.4: $\theta_{jet,E}$ (50%) for u,d,s,c quarks and for t quarks, assuming m_t=25 GeV and the jet model describe in Ref. 2.10.

$\sqrt{s}$ (GeV)	$\theta_{jet,E}$ (50%)	
	u,d,s,c quarks	t quark
29	30°	-
89	4°	22°

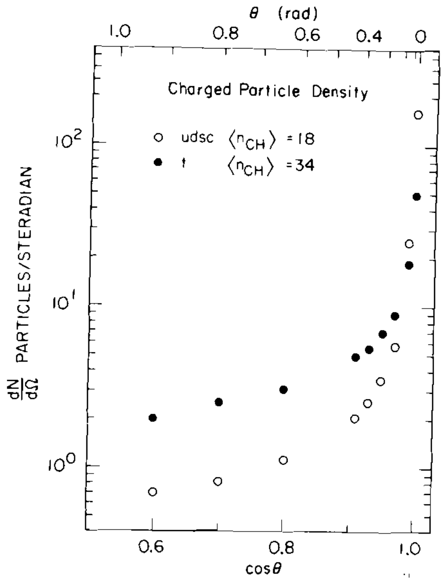
The next question is what happens at higher energy. Over the known range (Fig. 2.6), the sphericity and hence θ_{jet} is decreasing. There are some grounds for arguing that θ_{jet} will continue to decrease as the $\sqrt{s}$ increases. We note that the average value of p_i increases as $\sqrt{s}/\langle N_{ch}\rangle$, while the average value of $p_{t,i}$ increases at a slower rate.

On the other hand as the $\sqrt{s}$ increases we expect that each jet emits a larger fraction of secondary quark and gluon jets which broaden the basic jet. Therefore we will be conservative and assume a constant measure of the jet size of

$$\theta_{jet} \lesssim 20° \qquad (2.28)$$

A related question is the expected width of a jet from a t quark. All of the above considerations were based on the natural mixture of the light quarks and b quark at e^+e^- energies near 30 GeV. The t quark jet will certainly be broader.[2.10] Figure 2.7 is an example.

The measurement of the invariant mass of a jet is a process with which we have little experience at present. The goal is to determine



2.7. Average charged particle density per unit solid angle from a model calculation at the energy of the Z°. The t quark mass is assumed to be 19 GeV/c^2. From Ref. 2.10.

$$m^2_{jet} = \left(\sum_i E_i\right)^2 - \left(\sum_i \vec{p}_i\right) \qquad (2.29)$$

where the sum is over all particles in the jet. The errors come from:

a) uncertainties as to which particles are in the jet;
b) loss of undetected particles such as neutrinos and neutrons;
c) errors in measuring $\vec{p}_i$

Furthermore one has to rely on calorimetric measurements for the photon measurements, and perhaps for the charged particle measurements. This general problem is too complicated to discuss in this paper.

d. W and Z Jets in e^+e^- Interactions: The decays:

$$\begin{aligned} W^\pm &\to q + q' \to \text{hadrons} \\ Z° &\to q + \bar{q} \to \text{hadrons} \end{aligned} \qquad (2.30)$$

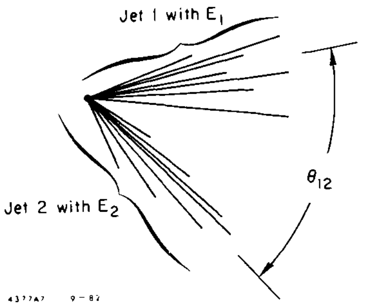
will often lead to a pair of jets, Fig. 2.8, which in turn allows the identification of the W or Z through a mass measurement. If E_1 and E_2 are the respective jet energies and θ_{12} is the angle between them

$$m_W \approx 2E_1E_2\,(1-\cos\theta_{12}) \qquad (2.31)$$

An analysis of the measurement shows that the controlling error is $\Delta\theta$, the error in θ_{12}. In the case of a symmetric decay, $E_1=E_2=E_W/2$, and $\theta_{12}=2m_W/E_W$. Using m_W=80 GeV

$$\frac{\Delta m}{m} \approx \Delta\theta \left(\frac{E_W}{160}\right), \quad E_W \text{ in GeV} \qquad (2.32)$$

The error $\Delta\theta$ depends upon how well each jet axis can be determined; $\Delta\theta \approx 40$ mrad seems attainable. Hence



2.8. Sketch of a W decaying into two quark jets.

$$\frac{\Delta m}{m} \sim 2.5\times10^{-4}\ E_W, \quad E_W \text{ in GeV} \qquad (2.33)$$

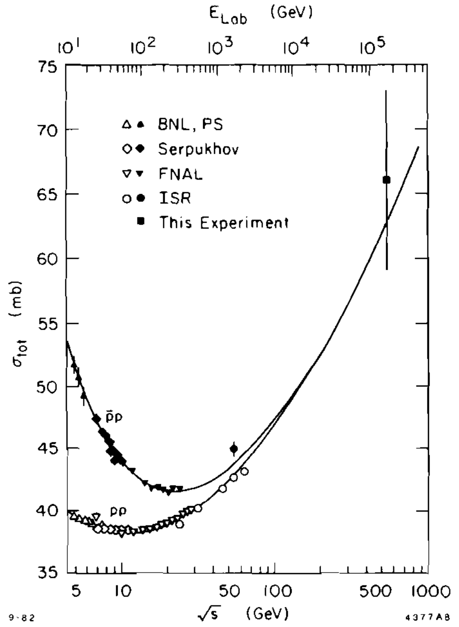
In the unsymmetric decay the error is larger. However, at least some of the time, the measurement of the invariant mass of a pair of quark jets will allow a determination as to whether they come from a W or Z°. But it is not possible to distinguish a W from a Z° by this method.

C. General Behavior of Hadron-Hadron Interactions for $0.5 \gtrsim \sqrt{s} \gtrsim 40$ TeV

a. $\bar{p}p$ and pp Cross Sections: Figure 2.9 shows the measured pp and $\bar{p}p$ total cross sections.[2.11] To estimate σ_{tot} at higher energies we use $\sigma_{\bar{p}p,tot} \approx \sigma_{pp,tot}$ and assume the extrapolation

$$\sigma_{tot} = -1.1 + 23.1 \log_{10} \sqrt{s};\ s \text{ in GeV} \qquad (2.34)$$

Then the following is predicted

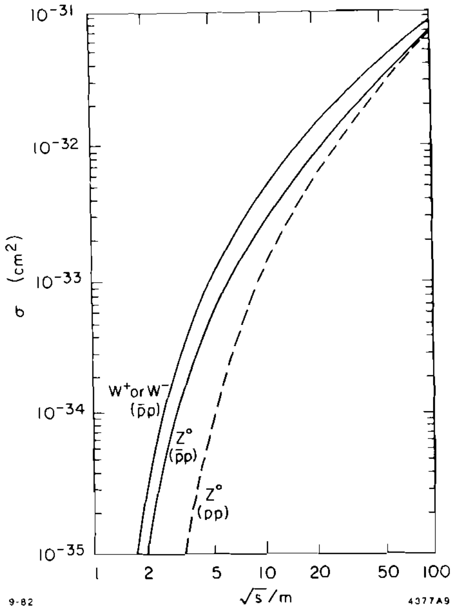


2.9. Total cross sections for pp and $\bar{p}p$. From Ref. 2.11.

$\sqrt{s}$ TeV	σ_{tot} (mb)	
1	68	(2.35)
2	75	
10	91	
40	105	

The $W^{\pm}$ and Z° inclusive cross sections[2.12] are given in Fig. 2.10. The production mechanism is

$$q + \bar{q} \rightarrow W^{\pm} \text{ or } Z^{\circ} \qquad (2.36)$$



2.10. Calculated production cross section for W and Z° boson in pp and $\bar{p}p$ collisions. From Ref. 2.12.

From Fig. 2.10 and its extrapolation we estimate:

$\sqrt{s}$ (TeV)	$(\sigma_{Z^\circ}/\sigma_{tot})\ \bar{p}p$	
1	5×10^{-8}	(2.37)
10	1×10^{-6}	
40	5×10^{-6}	

The W cross section is a little larger and the respective pp cross sections are a little smaller.

b. pp and $\bar{p}p$ Multiplicities: Multiplicity studies at the CERN ISR[2.13] and SPS[2.14,2.15] colliders indicate that the most suitable equation for the total charged multiplicity is

$$\langle N_{ch}\rangle = .88 + .44\ \ell n\ s + .118\ (\ell n\ s)^2 \qquad (2.38)$$

This equation predicts

$\sqrt{s}$ (TeV)	$\langle N_{ch}\rangle$	
1	30	
10	49	(2.39)
40	63	

Here we are assuming that $\langle N_{ch}\rangle_{pp} \approx \langle N_{ch}\rangle_{\bar{p}p}$. We shall also assume $\langle N_{\pi^\circ}\rangle \approx \langle N_{ch}\rangle/2$.

Since many of the produced particles are clustered around the beam line, most searches for new types of particles will avoid the forward and backward directions. Restricting our attention to colliders with equal energy beams, this means that the region

$$15^\circ \lesssim \theta \lesssim 165^\circ \tag{2.40}$$

is of most interest. Here θ is the angle between a particle and one of the beam directions. We recall that the rapidity parameter y is defined by

$$y = \frac{1}{2} \ln \left(\frac{E+p_\parallel}{E-p_\parallel}\right) \tag{2.41a}$$

and when the particle mass is ignored we get the pseudorapidity

$$y_{ps} = \ln \left(\frac{1+\cos\theta}{\sin\theta}\right) \tag{2.41b}$$

Hence the y_{ps} range of interest is

$$-2 < y_{ps} < 2$$

At the ISR energy of $\sqrt{s}$ = 60 GeV, the mean charged particle multiplicity per unit rapidity near $\theta=90^\circ$, $\langle dN_{ch}/dy \rangle_{90^\circ}$ is 2.0 for pp collisions[2.13], at the SPS $\bar{p}p$ collider[2.14] it is 3.0 for $\sqrt{s}$=540 GeV. Ignoring the pp-$\bar{p}$p difference, this yields

$$\langle dN_{ch}/dy \rangle_{90^\circ} \sim 0.23 \ln s \tag{2.42}$$

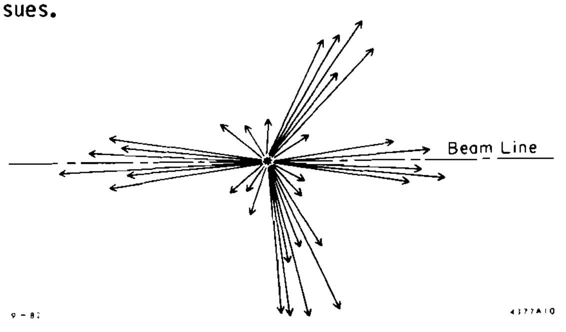
This leads to the following predictions:

$\sqrt{s}$ (TeV)	$\langle N_{ch} \rangle$ in $\lvert y \rvert < 2$
1	13
2	15
10	17
40	19

(2.43)

We note that the distribution of N_{ch} in the small y region is quite assymmetric about $\langle N_{ch} \rangle$, there is a substantial tail at large values of N_{ch}.

c. Jets in pp and $\bar{p}$p Interactions: We are just beginning to study hadron jets in pp or $\bar{p}$p interactions in the same ways that jets are studied in e^+e^- interactions. Figure 2.11 illustrates the problems. In the forward and backward regions there are clusters of particles associated with small p_t phenomena. Over the central region of 5 or 6 units of rapidity there are scattered 15-20 charged particles (see Eq. 2.43) and half that number of π°'s. A jet may be difficult to see in that background. And even if the jet is seen, that background will make it more difficult to measure the types of jet properties discussed in Secs. 2Bc and 2Bd. The studies on jet phenomena being carried out at the SPS $\bar{p}$p collider will illuminate these issues.



2.11. Sketch of jets in hadron-hadron collisions at a collider.

Nevertheless it is useful to try to estimate the jet production cross section[2.16] as is done in Fig. 2.12. These curves can be used as follows. Consider pp at $\sqrt{s}$=1000 GeV and suppose one is interested in a jet of 100 GeV invariant mass. Then $p_\perp$ of order 100 GeV must be involved and

$$d\sigma/d\Omega\, dp_\perp \sim 10^{-8}\ \text{mb/GeV} \tag{2.44a}$$

Using $\Delta p_\perp \sim$ 100 GeV and $\Delta\Omega \sim 10$ for $30^\circ < \theta < 150^\circ$,

$$\sigma(m_{jet} = 100\ \text{GeV}) \sim 10^{-5}\ \text{mb} \tag{2.44b}$$

and is very small compared to σ_{tot}.

D. General Behavior of ep Interactions for $0.2 \lesssim \sqrt{s} \lesssim 3.3$ TeV

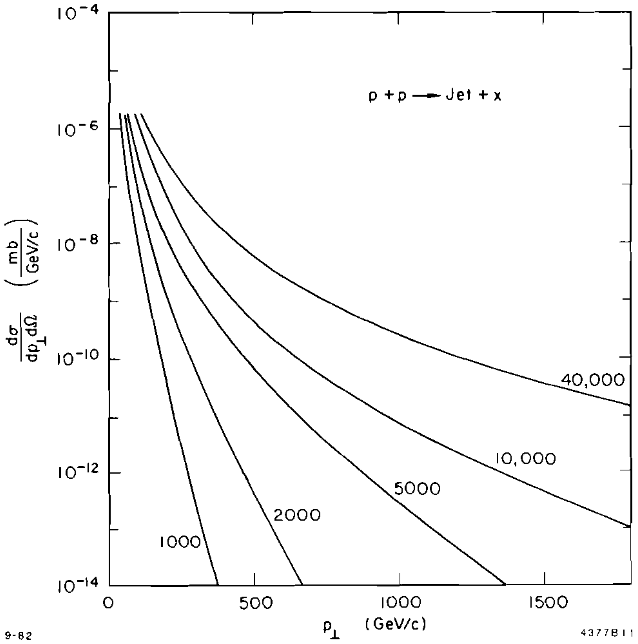
We now consider ep interactions restricting our discussion to colliders with the following energy ranges:

e Energy (GeV)	p Energy (TeV)	$\sqrt{s}$ (TeV)	Reference
10	1.0	0.2	2.17
30	0.3	0.2	2.18
30	0.8	0.3	2.19
140	20.0	3.3	2.20

a. ep Kinematics: The basic ep kinematics are illustrated in Fig. 2.13. The four-momentum carried by the exchanged vector boson is q, and P is the four momentum of the incident proton. The invariant mass at the hadronic vertex, $\sqrt{s_{had}}$, is given by

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

In our metric q^2 is negative and $|q^2| = 2q\cdot P - s_{had}$. Hence $2q\cdot P$ is the maximum value of $|q^2|$, and we define



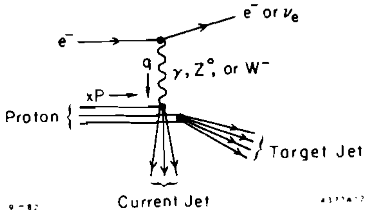
2.12. Calculated cross section for jet production in pp collisions. From Ref. 2.16.

$$x = \frac{|q^2|}{2q\cdot P}\ ; \quad 0<x<1 \tag{2.46}$$

It is conventional to define

$$\nu = q\cdot P/m_{\text{proton}} \tag{2.47}$$

As shown in Fig. 2.13, 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. We do not know in what fraction of the events we will be able to actually see separated jets. Problems arise similar to the problems of seeing jets in hadron-hadron collisions. However there is the great advantage that we know the direction and energy of the current jet since its four-momentum is q+xP. In neutral current events, Eqs. 2.50a and 2.50b, we can measure q well and hence determine x. Charged current events, Eq. 2.50c, are not so straightforward, but q and x can still be determined with a proper detector.



2.13. Diagram for ep inelastic scattering.

b. ep Cross Sections: In the standard model there are three processes which occur in ep interactions

$$e^- + p \rightarrow e^- + \text{anything via photon } (\gamma) \text{ exchange} \tag{2.50a}$$

$$e^- + p \rightarrow e^- + \text{anything via } Z^\circ \text{ exchange} \tag{2.50b}$$

$$e^- + p \rightarrow \nu_e + \text{anything via } W^- \text{ exchange} \tag{2.50c}$$

The first two processes involve neutral currents, the third involves a charged current.

The cross section for the γ exchange process has the form[2.21],

$$\frac{d\sigma}{dq^2 d\nu} = \frac{\alpha^2}{q^4} f(s,q^2,\nu) \tag{2.51}$$

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.

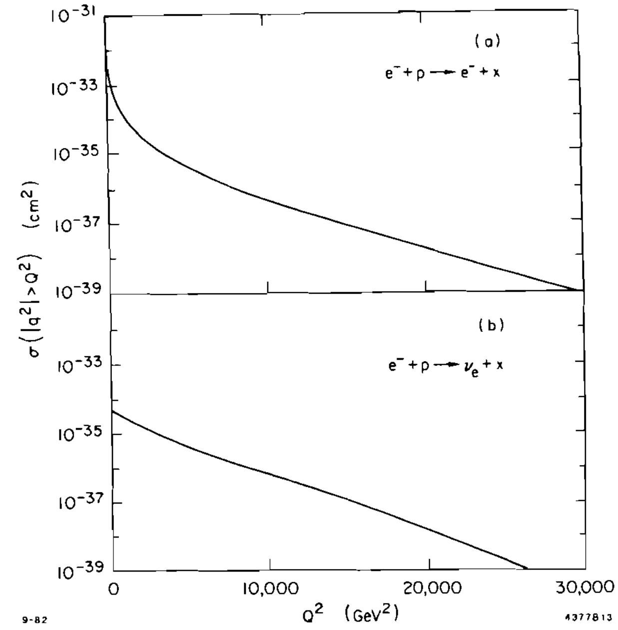
Then

$$q^2 \approx 0 \qquad \sigma_{\text{tot,ep}} \sim 0.02\ \sigma_{\text{tot},\gamma p} \sim 2 \times 10^{-30}\ \text{cm} \tag{2.52}$$

Here we have used $\sigma_{\text{tot},\gamma p} \sim 0.1$ mb. Most ep events will be in this domain. Incidentally, the energy distribution of these almost real photons will be

$$dN_\gamma/dE_\gamma \sim 1/E_\gamma \tag{2.53}$$

Figure 2.14 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. Hence the interesting large $|q^2|$ cross sections are about 10^{-5} of the total cross section in Eq 2.52.



2.14. Integrated cross sections for inclusive ep interactions.

3. New Leptons of Conventional Types

A. Introduction

We begin our discussion of the physics which might exist beyond the standard model by considering new leptons[3.1,3.2] of conventional type. Our definition of a conventional lepton is:

(i) No strong interaction
(ii) Conventional weak interactions where applicable
(iii) Point particle
(iv) Half integer spin
(v) Some type of lepton conservation rule.

The point particle requirement (iii) makes it possible to calculate production cross sections and lifetimes. Composite leptons are discussed in Sec. 11, however we shall occasionally note in this section some consequences of a lepton being composite.

Our discussion is centered on the type of lepton conservation rule obeyed by the lepton and its partners.

B. Types and Signatures

a. Stable Single Leptons: Consider a charged, $L^\pm$, or neutral, L°, lepton with a unique conserved lepton number; that number not being possessed by any other particle. Then the lepton is stable; and it can only be produced with its antiparticle. For example in e^+e^- annihilation

$$e^+ + e^- \rightarrow L^+ + L^- \tag{3.1}$$

and in production via hadron decay

$$h \to L^+ + L^- + \text{other particles} \qquad (3.2)$$

b. Lepton with Partners, Masses Less than the W Mass: The known leptons, called sequential leptons, consist of charged-neutral pairs:

$$\begin{matrix} e^- & \nu_e \\ \mu^- & \nu_\mu \\ \tau^- & \nu_\tau \end{matrix} \qquad (3.3)$$

Here only the particles are shown. Each partner in a pair has the same unique, conserved lepton number. This constrains the production processes for example

$$e^+ + e^- \to \mu^+ + \mu^- \qquad (3.4)$$

$$h \to \mu^- \to \nu_\mu + \text{other particles} \qquad (3.5)$$

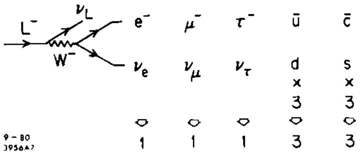
The decay process, which must be via the weak interaction, is illustrated by the decay modes of the τ.

$$\text{pure leptonic:} \quad \tau^- \to \nu_\tau + \ell^- + \nu_\ell; \quad \ell = e, \mu \qquad (3.6a)$$

$$\text{semi-leptonic:} \quad \tau^- \to \nu_\tau + (\text{hadrons})^- \qquad (3.6b)$$

This pattern in which the decay mode consists of a partner of the decaying lepton plus leptons or hadrons extends to all leptons discussed in this subsection. The restriction to lepton masses less than the W mass prevents decay modes containing W or Z particles.

The branching fractions, B, can be estimated using the elementary fermion counting method of Fig. 3.1. We assume:



3.1. Schematic for approximate calculation of branching fractions for the decay modes of a charged lepton. The top quark or other proposed fundamental fermions are assumed to be more massive than the L^-.

(i) $\text{mass}_{L^-} \gg \text{mass}_\tau$, mass_c quark

(ii) $\text{mass}_{L^-} < \text{mass}_t$ quark

(iii) the Standard Model

Then neglecting all masses except the L^- mass, m_{L^-},

$$B(L^- \to \nu_L\, \ell^- \bar{\nu}_\ell) = 1/9, \quad \ell = e, \mu, \tau \qquad (3.7a)$$

$$B(L \to \nu_L \text{ hadrons}) = 2/3 \qquad (3.7b)$$

The decay width is

$$\Gamma(L^- \to \text{all}) \approx \frac{G_F^2 m_{L^-}^5}{192\pi^3} \cdot \frac{1}{B(L^- \to \nu_L \ell \bar{\nu}_\ell)} \approx \frac{9 G_F^2 m_L^5}{192\pi^3} \qquad (3.8a)$$

In terms of the μ lifetime $T_\mu = 2.2\ 10^{-6}$s, the L^- lifetime is

$$T_{L^-} \approx \frac{T_\mu}{9} \left(\frac{m_\mu}{m_{L^-}}\right)^5 \qquad (3.8b)$$

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. Thus we may consider an L^--L° pair with

$$\text{mass}_{L^\circ} \text{ of same order as mass}_{L^-} \qquad (3.9a)$$

Indeed we might have

$$\text{mass}_{L^\circ} > \text{mass}_{L^-} \qquad (3.9b)$$

It is instructive to note that for this case, L° decays via

$$L^\circ \to L^- + \ell^+ + \nu_\ell; \quad \ell = e, \mu, \tau \qquad (3.9c)$$

$$L^\circ \to L^- + (\text{hadrons})^+; \qquad (3.9d)$$

and the L^- may be stable. We can also consider pairs of neutral leptons L°-$L^{\circ\prime}$ with the same lepton number. If L° is more massive, possible decay modes are

$$\begin{aligned} &L^\circ \to L^{\circ\prime} + \ell^+ + \ell^-, \quad \ell = e, \mu, \tau \\ &L^\circ \to L^{\circ\prime} + \nu_\ell + \bar{\nu}_\ell \\ &L^\circ \to L^{\circ\prime} + (\text{hadrons})^\circ \end{aligned} \qquad (3.10)$$

Pairs of charged leptons L^--$L^{-\prime}$ may have electromagnetic decays and are discussed later.

Finally 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 $L^{\circ\prime}$-L^--L° with

$$\text{mass}_{L^{\circ\prime}} > \text{mass}_{L^-} > \text{mass}_{L^\circ} \qquad (3.11)$$

The semi-leptonic decay modes would be

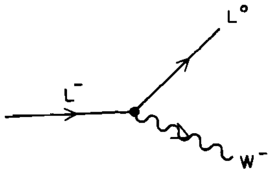
$$\begin{aligned} &L^{\circ\prime} \to L^- + (\text{hadrons})^+ \\ &L^{\circ\prime} \to L^\circ + (\text{hadrons})^\circ \\ &L^- \to L^\circ + (\text{hadrons})^- \end{aligned} \qquad (3.12)$$

Another way to look for massive neutral leptons is suggested by the possibility of a fourth family with a massive neutrino $\nu' \equiv L^\circ$ in the Standard Model framework. Then, just as Cabibbo mixing allows the strange quark to decay to lighter generations, one expects here $\nu' \to \ell^- +$hadrons, with $\ell^- = e^-, \mu^-, \tau^-$. By analogy with $\tau^\pm \to \nu_\tau + \pi^\pm$, here we expect $\nu' \to \ell^- \pi^+$ (and $\bar{\nu}' \to \ell^+ \pi^-$). The associated lifetimes can be scaled from those of the τ, with an unknown mixing angle factor to allow for the generation change. Since $\nu' \bar{\nu}'$ will couple to the Z° with a normal branching ratio, one could hope to find ν' in any reaction where Z°'s are produced. It is important to look in $\mu^-\pi^+$, $e^-\pi^+$, $\mu^+\pi^-$, $e^+\pi^-$ for signals of new neutral leptons.

c. Leptons with Partners, Masses Larger than the W Mass:: Consider an L^--L° pair with

$$\text{mass}_{L^-} - \text{mass}_{L^\circ} \gg \text{mass}_W \qquad (3.13)$$

Then the decay mode (Fig. 3.2)



3.2. Diagram for the decay of a charged lepton into a W assuming that the difference between the masses of the L^- and L° is greater than the mass of the W.

$$L^- \rightarrow L^\circ + W^- \tag{3.14}$$

has the width

$$\Gamma(L^- \rightarrow L^\circ + W^-) \approx \frac{G_F}{4\pi} \frac{(m_L^2 - m_W^2)^2 m_W^2}{m_L^3} (1 + m_L^2/2m_W^2) \tag{3.15}$$

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

$$\Gamma \approx G_F m_L^3/8\pi. \tag{3.16}$$

Similar considerations apply to an L°-$L^{\circ\prime}$ pair and the decay mode

$$L^\circ \rightarrow L^{\circ\prime} + Z^\circ \tag{3.17}$$

d. Excited Charged Leptons: A traditional speculation in lepton physics concerns excited charged leptons; for example an excited electron e'^- would have:

$$\begin{array}{ll} \text{(i)} & \text{mass}_{e'} > \text{mass}_e \\ \text{(ii)} & \text{lepton number } e'^- = \text{lepton number } e^- \end{array} \tag{3.18}$$

This concept is particularly attractive in composite models of leptons in which the L' would be an excited state of the L.

Condition (ii) allows the electromagnetic decay

$$L^- \rightarrow L^{-\prime} + \gamma \tag{3.19}$$

with width Γ_{em}. Weak decays

$$\begin{array}{l} L^- \rightarrow L^{-\prime} + \ell^+ + \ell^-, \quad L^{-\prime} + \nu_\ell + \bar{\nu}_\ell, \\ L^{-\prime} + (\text{hadrons})^+ \end{array} \tag{3.20}$$

with width Γ_{wk} can also occur. The ratio Γ_{em}/Γ_{wk} depends on the model, it is not necessary that $\Gamma_{em} >> \Gamma_{wk}$. There is further discussion in Sec. 3E.

e. Leptons with Other Charges: We have been assuming that the lepton charge is 0 or ±1; however, one can speculate about multiply charged or fractionally charged leptons. We do not discuss the former in the interests of brevity; the latter are in other papers in the Proceedings.

C. Present Knowledge of Leptons

1. Charged Leptons. As is well known,[3.1,3.2] no charged leptons have been found beyond the e, μ, and τ. The most definitive searches have used e^+e^- annihilation and the lower limits on the masses are

$$m_{\text{charged lepton}} \gtrsim 15 \text{ GeV}/c^2 \tag{3.21}$$

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.

2. Neutral Leptons. We know very little about the existence of neutral leptons[3.1] beyond the existence of the ν_e and ν_μ, and the very probable existence of the ν_τ. The reason for our ignorance is that the definite search method

$$e^+ + e^- \rightarrow Z^\circ \rightarrow L^\circ + \bar{L}^\circ \tag{3.22}$$

has too small a cross section at the energies of existing e^+e^- colliders. Searches have been made for various special kinds of neutral leptons such as

(i) an L° associated with a μ;
(ii) an L° associated with an e;
(iii) a stable L° produced in pp collisions;
(iv) an L° produced in a K or D meson decay.

But there are no general searches and an L° with a mass as low as several hundred MeV/c^2 could exist and not have been detected.

D. Heavy Lepton Searches at e^+e^- Colliders

a. Lepton Mass < W or Z Mass: We have a great deal of experience in searching for charged leptons[3.2-3.2] via

$$e^+ + e^- \rightarrow \gamma_{\text{virtual}} \rightarrow L^+ + L^- \tag{3.23a}$$

It is easy to extend that experience to

$$e^+ + e^- \rightarrow Z^\circ \rightarrow L^+ + L^-; \tag{3.23b}$$

and to neutral lepton production

$$e^+ + e^- \rightarrow Z^\circ \rightarrow L^\circ + \bar{L}^\circ \tag{3.24}$$

These processes have very distinctive signatures. We restrict our discussion in this section 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.

$$m_{L^-} > m_{L^\circ} \quad \begin{array}{ll} L^- \rightarrow L^\circ + \ell^- + \bar{\nu}_\ell: & \text{1 prong} \\ L^- \rightarrow L^\circ + \text{hadrons:} & \text{hadron cluster} \end{array} \tag{3.25a}$$

$$m_{L^\circ} > m_{L^-} \quad \begin{array}{ll} L^\circ \rightarrow L^- + \ell^+ + \bar{\nu}_\ell: & \text{2 prong} \\ L^\circ \rightarrow L^- + \text{hadrons:} & L^- + \text{hadron cluster} \end{array} \tag{3.25b}$$

$$m_{L^-} > m_{L'^-} \quad \begin{array}{ll} L^- \rightarrow L'^- + \ell^+ + \ell^-: & \text{3 prong} \\ L^- \rightarrow L'^- + \nu_\ell + \bar{\nu}_\ell: & \text{1 prong} \\ L^- \rightarrow L'^- + \text{hadrons:} & L'^- + \text{hadron cluster} \end{array} \tag{3.25c}$$

$$L^\circ \rightarrow L'^\circ + \ell^+ + \ell^-: \quad \text{2 prong}$$

$$m_{L^\circ} > m_{L'^\circ} \quad L^\circ \rightarrow L'^\circ + \nu_\ell + \bar{\nu}_\ell: \quad \text{missing momentum} \quad (3.25d)$$

$$L^\circ \rightarrow L'^\circ + \text{hadrons}: \quad \text{hadronic cluster}$$

Finally, by generation mixing one can have the useful mode

$$L^\circ \rightarrow \ell^- \pi^+$$

if $m_{L^\circ} > m_e + m_\pi$. The concepts underlying these signatures are discussed in Sec. 3Bb.

Table 3.1 gives R values, and event rates for lepton pair production at $\sqrt{s} < 2m_W$. We assume an average luminosity of 10^{31} cm^{-2} s^{-1} and that the facility runs for physics 10^7 s/yr. The event rates at the Z° are of course magnificent, but even below and above the Z° they are adequate. The Standard Model is assumed.

Table 3.1: R values and produced lepton pair rates for $e^+e^- \rightarrow L\bar{L}$ 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° peak.

$\sqrt{s}$ (GeV)	L^+L^-		$L^\circ\bar{L}^\circ$	
	R	Events/yr	R	Events/yr
40	1.00	5,400	0.016	90
93 (Z°)	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. 3.25a 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 cluster events, or μ+hadron cluster 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° 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.

b. Lepton Mass > W or Z Mass. We now consider $\sqrt{s} > 2m_W$ so that one can produce lepton pairs with

$$m_L > m_W \text{ or } m_Z \tag{3.26}$$

Then the decay modes

$$\begin{aligned} &L^- \rightarrow W^- + L^\circ: && \text{W jet + missing momentum} \\ &L^- \rightarrow Z^\circ + L'^-: && \text{Z jet} + L'^- \\ &\bar{L}^\circ \rightarrow W^- + L^+: && \text{W jet} + L^+ \\ &L^\circ \rightarrow Z^\circ + L'^\circ: && \text{Z jet + missing momentum} \end{aligned} \tag{3.27}$$

can occur. As discussed in Sec. 3Bc, they dominate over a broad lepton mass range. These provide very distinctive signatures. For example

$$e^+ + e^- \rightarrow L^+ + L^- \rightarrow L^\circ + \bar{L}^\circ + W^+ + W^- \tag{3.28}$$

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

$$e^+ + e^- \rightarrow L^\circ + \bar{L}^\circ \rightarrow L^+ + L^- + W^+ + W^- \tag{3.29}$$

is very distinctive.

The major background, particularly for the reaction in Eq. 3.28, comes from

$$e^+ + e^- \rightarrow W^+ + W^- \tag{3.30}$$

As described in Sec. 2Ba this process has an R value of several multiples of 10. However there are several ways to drastically reduce the background:

(i) an acollinear requirement on the jet directions;
(ii) a missing energy requirement; and
(iii) since the reaction in Eq. 3.30 has a forward peak, a requirement that the jet axes have $|\cos\theta| \lesssim 0.9$.

The background from the two-virtual-photon processes

$$e^+ + e^- \rightarrow e^+ + e^- + W^+ + W^-, \qquad e^+ + e^- + Z^\circ + \bar{Z}^\circ \tag{3.31}$$

can be eliminated by requiring that the missing momentum not point along the beam line. Finally the γγ, γZ°, μ^+, μ^-, τ^+, τ^- and quark-antiquark final states offer little background.

Table 3.2 gives R values and event rates for $\sqrt{s}>0.2$ TeV. To reach energies above 0.2 TeV we have assumed an e^+e^- linear collider with an average luminosity of 10^{33} cm^{-2} s^{-1}. Studies at this conference and other studies have indicated that this luminosity is required to give such a facility its full potential. We use, as before, 10^7 s/yr.

Table 3.2: R values and produced lepton pair rates for $e^+ + e^- \rightarrow L\bar{L}$ with $\sqrt{s} > .2$ TeV. $\mathcal{L}=10^{33}$ cm^{-2} s^{-1} and 10^7 s/year is assumed. The Standard Model is used with the conventional coupling constants.

$\sqrt{s}$ TeV	L^+L^-		$L^\circ\bar{L}^\circ$	
	R	Events/yr	R	Events/yr
0.2	1.27	28,000	0.50	11,000
0.7	1.18	2100	0.32	570
2.0	1.17	250	0.31	70

We reach the same conclusion as we did in the previous section for $m_L > m_W$ or m_Z, e^+e^- colliders provide a definitive way to look for heavy leptons.

E. Heavy Lepton Searches at ep Colliders

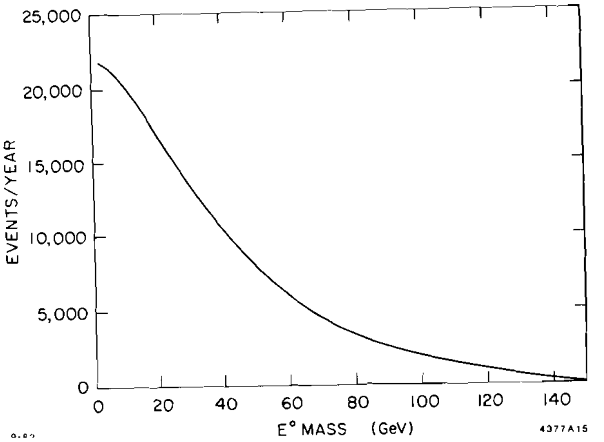
a. Electron Associated Heavy Leptons. The ep collider offers a powerful way[2.17-2.20] to search for charged or neutral heavy leptons which have the lepton number of the e. The reaction

$$e^- + p \rightarrow E^- + \text{anything} \tag{3.32}$$

can occur through γ or neutral weak current exchange, while

$$e^-+p \rightarrow E^\circ + \text{anything} \qquad (3.33)$$

can occur through charged weak current exchange. Figure 3.3 shows the E° yield per year for an ep collider[2.17] with 10 GeV e's and 1 TeV p's. (The average luminosity is 10^{32} cm^{-2} s^{-1} for 10^7 s per year.) This prediction assumes the usual magnitude of the e^--E°-W^- weak coupling.



3.3. Events per day for the production of a proposed E° heavy lepton for 10 GeV electrons colliding with 1000 GeV protons. An integrated luminosity of 10^{39} cm^{-2} per year is assumed.

b. Virtual Photoproduction of Heavy Leptons. The principle mechanism for the production of more general types of leptons is virtual photoproduction

$$e^-+p \rightarrow e^-+\gamma_{\text{virtual}} + \text{anything}$$
$$\gamma_{\text{virtual}} \rightarrow L^+ + L^- \qquad (3.34)$$

Unfortunately this cross section becomes very small[3.1] 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. Hence, as far as we can tell at present, ep colliders do not provide a general method for searching for heavy leptons.

F. Heavy Lepton Searches at pp and $\bar{p}p$ Colliders

a. Lepton Production Via Quark-Antiquark Annihilation. The general production mechanism is quark-antiquark annihilation:

$$q+\bar{q} \rightarrow \gamma_{\text{virtual}} \rightarrow L^+ + L^-$$

$$q+\bar{q} \rightarrow Z^\circ_{\text{virtual}} \rightarrow L^+ + L^- \text{ or } L^\circ + \bar{L}^\circ \qquad (3.35)$$

$$q+\bar{q}' \rightarrow W^-_{\text{virtual}} \rightarrow L^- + \bar{L}^\circ$$

We consider leptons with masses above 50 GeV/c^2 since lighter leptons will be found in Z° studies. When the $q\bar{q}$ energy, $\sqrt{s_{qq}}$, is of the order 100 GeV or more the cross section for these processes is just the high energy weak cross section, $\sigma \sim G_F^2\, s_{q\bar{q}}/4\pi \sim 10^{-34}$ cm^2

To estimate the cross section for

$$p+p(\bar{p}) \rightarrow L+\bar{L} + \text{anything} \qquad (3.36)$$

σ must be multiplied by the probability of finding a $q\bar{q}$ pair of sufficient energy in pp or $p\bar{p}$. This probability is certainly < 0.25, hence the relevant cross sections are less than 10^{-35} cm^2. Therefore

$$\sigma_{L\bar{L}}/\sigma_{tot} \lesssim 10^{-10} \qquad (3.37)$$

The signatures of the $L\bar{L}$ pair are those discussed in Sec. 3D, but they are obscured by the hadronic background in the same event. This difficulty combined with the very small signal-to-noise ratio of Eq. 3.37 has discouraged planning for heavy lepton searches at hadron-hadron colliders. Certainly more work on this subject is needed, but the problems to be overcome are very severe.

b. Lepton Production Via Particle Decay. Heavy leptons can also be produced at hadron-hadron colliders via the decay of a heavy particle:

$$W^- \rightarrow L^- + \bar{L}^\circ \qquad (3.38)$$

$$Z^\circ \rightarrow L^+ + L^- \qquad (3.39)$$

$$h \rightarrow L^- + \bar{L}^\circ + \text{hadrons} \qquad (3.40)$$

The first two processes limit the lepton mass to less than 40 or 45 GeV/c^2, and in general the signatures are obscure. This obscurity occurs 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, $Z^\circ \rightarrow L^+ + L^-$ is a superb signture.) The third process has the added difficulty of being speculative, no heavy h is known at present. Summarizing, the processes in Eqs. 3.38-3.40 are interesting, but they do not offer a definitive way to search for heavy leptons.

G. Heavy Lepton Searches in Fixed Target Experiments

a. Searches in Charged Particle Beams. The simplest type of search is to carefully 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.

b. Searches in Lepton-Nucleon Collisions. The interaction of electron, muon or neutrino beams with a fixed target offers the possibility of the production of heavy leptons[3.1,3.5-3.7] associated with those leptons. For example, one can look for an $L^\pm$ lepton with the lepton number of the ν_μ using[3.5]

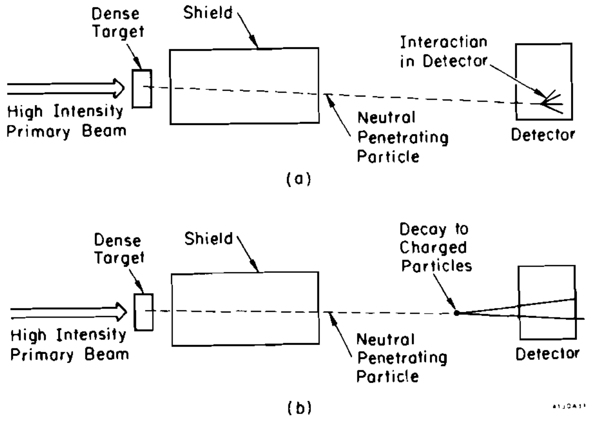
$$\nu_\mu + N \rightarrow L^\pm + \text{hadrons}$$
$$L^\pm \rightarrow \nu_\mu + e^\pm + \nu_e\ (\bar{\nu}_e) \qquad (3.41)$$

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

$$m \lesssim \sqrt{E_p/2}\ \text{GeV/c}^2, \quad E \text{ in GeV} \qquad (3.42)$$

where E_p is the primary beam energy.

c. Beam Dump Experiments. 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. 3.4a, 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°, are detected in a massive detector through their weak interaction. Or the penetrating particle might decay before reaching the detector, Fig. 3.4b, and the decay products be observed in the detector.



3.4. Schematic drawing of beam dump experiments.

The methods for detecting an L° in the detector are illustrated by proposals[3.1,3.8,3.9] to detect the τ neutrino, ν_τ, in proton beam dump experiments. The proposals use

$$p+N \to F^- + \text{hadrons}$$

$$F^- \to \tau^- + \bar{\nu}_\tau \qquad (3.43)$$

$$\tau^- \to \nu_\tau + \text{charged particles}$$

Here F is the charmed meson. More τ's arise from b quark decay. The neutrinos from π and K decay would overwhelm the ν_τ signal unless the majority of the π's and K's interact before they decay. Therefore the entire proton beam must be dumped in thick target, Fig. 3.4a. There are still some problems with the prompt ν_e's and ν_μ's from D mesons and other charmed particle semileptonic decays; but the detection of the ν_τ appears feasible, either through direct bubble chamber measurement of the track of the τ^- in

$$\nu_\tau + N \to \tau^- + \text{hadrons} \qquad (3.44)$$

or through detection of a large missing transverse momentum when the τ in Eq. 3.44 decays.

In electron beam dump experiments the presumed production mechanism would be real or virtual photoproduction of a charged particle pair

$$\gamma + N \to A^+ + A^- + \text{hadrons}, \qquad (3.45a)$$

or direct coupling to a neutral particle $e^+ + e^- \to A^\circ$, and the subsequent decay of the A in the dump or shield

$$A \to L^\circ + ? \text{ or } A^\circ \to \gamma\gamma,\ e^+e^- \qquad (3.45b)$$

The particle A might be a hadron or lepton. Other more indirect or unconventional production processes might be envisaged.

H. Summary

We may summarize this section as follows:

(i) e^+e^- collisions provide general and definitive ways to search for heavy leptons
(ii) ep collisions are valuable in searches for e-related leptons, but they do not provide general search methods.
(iii) Hadron-hadron collisions do not provide general search methods because the production cross sections are small or uncertain and/or the signal can be obscured by a much larger background.
(iv) Fixed target experiments provide a number of ways to search for specific types of heavy leptons.

4. New Quarks of Conventional Type

A. Introduction

In this section we consider heavier members of the known quark family -- the u,d,s,c,b quarks. We also assume that the top, t, quark has been found; although we shall sometimes use t quark searches as examples. We define these conventional type quarks as follows:

(i) their strong interaction obeys quantum chromodynamics;
(ii) their decay occurs only through the weak interaction.
(iii) their charge is ±1/3 or ±2/3;
(iv) they are point particles; and
(v) they have spin 1/2.

B. Decay Modes and Signatures

a. Quark Mass < W mass. Here we simply build upon our knowledge of how the known quarks decay[4.1]. For example

$$c \to s+u+\bar{d} \qquad (4.1)$$

$$c \to s+e^+ + \nu_e$$

$$c \to s+\mu^+ + \nu_\mu$$

Then a new heavy quark Q decays via

$$Q \to q+f+\bar{f}' \qquad (4.2)$$

Here q is another quark with $m_Q > m_q$

The conventional requirement that flavor changing currents be charged demands

$$|\text{charge}_Q - \text{charge}_q| = 1 \qquad (4.3)$$

The $f\bar{f}'$ pair represents fermion-antifermion pairs such as $u\bar{d}$, $e^+\nu_e$, or $\mu^+\nu_\mu$.

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

$$\begin{array}{l} Q \to q_1 + f_1 + \bar{f}'_1 \\ \quad \lfloor\!\to q_2 + f_2 + \bar{f}'_2 \\ \qquad \lfloor\!\to \cdots \end{array} \qquad (4.4)$$

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.

If charged Higgs bosons exist (or their equivalents such as bosons from Technicolor), heavy quarks will instead decay into them, via

$$Q \to q + H^{\pm} \ .$$

For example, a t quark will decay via $t \to b + H^+$ if $m_t > m_b + m_H$. The charged Higgs decay is only semiweak, giving $\Gamma \sim G_F$ rather than G_F^2, so it will always dominate when allowed.

There is no basic reason to insist on the cascade model of Eq. 4.4. As long as we are considering new heavier quarks we might consider a type with a single decay to a very light quark

$$Q \to q_{\text{light}} + f + \bar{f}' \qquad (4.5)$$

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

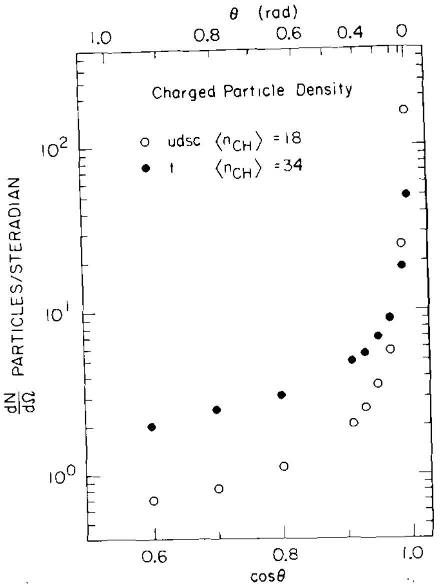
Finally we might relax the flavor changing charged currents requirement of Eq. 4.3 and allow

$$\text{charge}_Q = \text{charge}_q \qquad (4.6)$$

This is also discussed in Sec. 10.

The determination that a jet comes from a new heavy quark is a complicated problem that has not yet been demonstrated in practice, and is too involved to discuss here. We only mention some considerations:

(i) The observation of a well defined jet is very useful.
(ii) The mass of the Q quark can be indicated by a measurement of the jet mass or at least by a measurement of the jet angular width. Figure 4.1 provides an example.
(iii) Leptons with large p_t relative to the jet axis may also be used to indicate the large mass of the Q.
(iv) 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.
(v) W and Z jets may provide a large background from which the Q jet must be extracted.



4.1. Average charged particle density per unit solid angle from a model calculation at the energy of the Z°. The t quark mass is assumed to be 19 GeV/c^2. From Ref. 2.10.

b. Quark Mass > W Mass or Z° Mass. As with leptons (see Sec. 3Bc), when

$$m_Q > m_W \text{ or } m_Z \qquad (4.7)$$

the decays

$$Q \to W^+ + q \qquad (4.8a)$$

$$Q \to Z^\circ + q \qquad (4.8b)$$

will occur and will dominate the decay modes. In the decay in Eq. 4.8b we have allowed a flavor changing neutral current. These decay modes have striking signature when the jet configuration allows the q quark jet to be distinguished from the W or Z jet.

c. Quarkonium. We are all well acquainted with the identification of a new quark q through the discovery of its vector meson bound state $V(Q\bar{Q})$[4.2]. The ψ and Υ provide case histories. There has also been extensive discussion of toponium[4.3], the $(t\bar{t})$ bound state. There are two traditional methods for finding and studying the $V(q\bar{q})$:

(i) In e^+e^- annihilation one looks for

$$e^+ + e^- \to V(Q\bar{Q}) \to \text{hadrons} \qquad (4.9a)$$

$$e^+ + e^- \to V(Q\bar{Q}) \to \ell^+ + \ell^-; \quad \ell = e, \mu \qquad (4.9b)$$

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

(ii) In hadron-hadron collisions one looks for

$$\begin{array}{l} h + h \to V(Q\bar{Q}) + \text{anything} \\ \qquad\quad \lfloor\!\to \ell^+ + \ell^-, \quad \ell = e, \mu \end{array} \qquad (4.10)$$

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

As we shall discuss next both of these methods have difficulties at very high energies, but in the energy range where these methods work, they are very powerful. Reference 4.4 presents more details.

C. Production and Detection of Heavy Quarks in e^+e^- Collisions

a. Quarkonium Searches. The traditional method is to vary the total energy, $E=\sqrt{s}$, in steps somewhat smaller than the observed width, Γ_{obs}, of the V. This is called an energy scan. This observed width is a convolution of the natural width of the resonance, Γ_V, and the machine produced width of the beams, δ_E. Roughly

$$\delta_E \sim 10^{-3}\ E \qquad (4.11)$$

Hence as m_V increases, Γ_{obs} increases at least as fast as $E=m_V$. Furthermore at $m_V \approx 60$ GeV, Γ_V begins to increase rapidly because of the weak interactions.[2.3,4.4] The result of these effects is that the crucial quantities

$$r_{V,had} = [\sigma(e^+e^- \rightarrow V \rightarrow \text{hadrons})/\sigma(e^+e^- \rightarrow \text{hadrons})]_{E=m_V} \qquad (4.12)$$

$$r_{V,\mu\mu} = [\sigma(e^+e^- \rightarrow V \rightarrow \mu^+\mu^-)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)]_{E=m_V}$$

decrease as m_V increases. Several studies[4.4,4.5] show that it is too time consuming to search for $V(q\bar{q})$ by an e^+e^- energy scan if

$$m_V \gtrsim 80\ \text{GeV}, \qquad (4.13)$$

unless one has prior knowledge of a localized E region which would contain m_V. Hence an unguided e^+e^- energy scan limits heavy quark searches to

$$m_Q \lesssim 40\ \text{GeV} \qquad (4.14)$$

Therefore we must consider methods in which

$$e^+ + e^- \rightarrow Q + \bar{Q} \qquad (4.15)$$

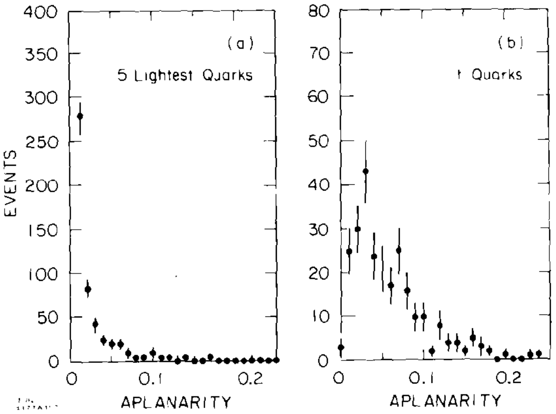
is detected at $E > 2m_q$.

b. Quark Mass $<$ W Mass. Table 4.1 gives the production rates for a new heavy quark, Q, with $m_q \lesssim m_W$. The primary background is the production of the lighter quarks, assumed to be the u,d,s,c,b and t. In Sec. 4Ba we gave a very general discussion of how the $e^+e^- \rightarrow Q+\bar{Q}$ signal can be distinguished from the background. Here we present an example which has been worked out in detail[4.6]

Table 4.1: R and production rates for $e^+e^- \rightarrow Q\bar{Q}$ assuming the Standard Model and $\sin^2\theta_W=0.22$. The Z° values are corrected for radiation. $\mathcal{L}=10^{31}$ and 10^7s/yr is assumed.

$\sqrt{s}$ (GeV)	Q Charge = ±2/3		Q Charge = ±1/3	
	R	Events/year	R	Events/year
40	1.33	7,200	0.33	1,800
93(Z°)	395.	400,000	505.	510,000
200	2.37	510	1.54	330

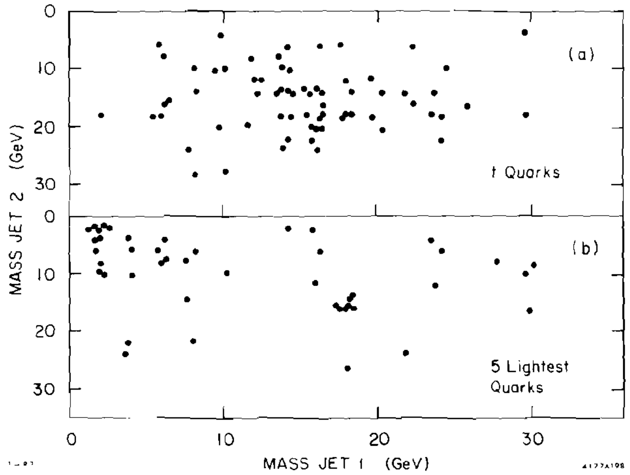
Consider how to find at the Z° a t quark with a mass of 19 GeV/c^2. The signal/background = .36. This is a difficult case because $\sqrt{s} >> 2m_t$. (If $2m_t$ were close to $\sqrt{s}$, there would be a marked effect on the average sphericity, which is an easily studied parameter.) Figure 4.2 shows the comparative aplanarity, A, for a two jet event; A is defined in Eqn. 4.16. Define σ_i as the eigenvalue of the sphericity tensor with respect to axis i; that is it is the sum of $p_T{}^2$ with respect to that axis. Axis 2 is the jet axis. A very narrow jet has $\sigma_3 \approx 0$ and $\sigma_1 \approx 2$, hence $A \approx 0$ in that case.



4.2. Model calculation for aplanarity of (a) light quarks and (b) a 19 GeV/c^2 top quark in e^+e^- annihilation, two-jet events at the Z°. From Ref. 4.6.

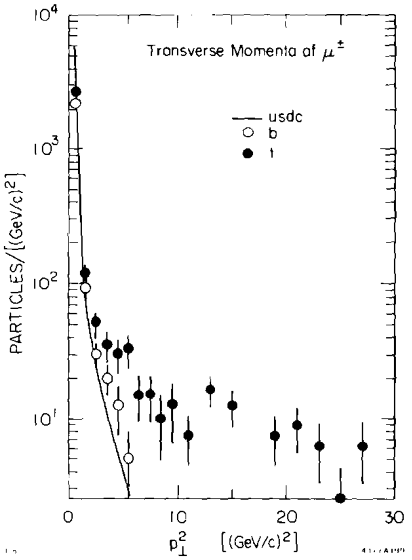
$$A = 1.5\ (\sigma_3 + \sigma_1 - \sigma_2)/(\sigma_3 + \sigma_1 + \sigma_2) \qquad (4.16)$$

A requirement that $A > 0.04$ increases the signal/background to 1.6. Next a scatter plot of the reconstructed jet masses is made, Fig. 4.3, and events are selected with both masses greater than 10 GeV/c^2. Now the signal/background = 4; and the final $t\bar{t}$ selection efficiency is 20%.



4.3. Model calculation for measured masses of jets in e^+e^- annihilation, two-jet events for (s) a 19 GeV/c^2 top quark and (b) for light quarks at the Z°. From Ref. 4.6.

An alternative method for finding $t\bar{t}$ events in this example is to look for a lepton with large $p_\perp$ relative to the jet axis. Figure 4.4 shows the muon case[4.6], again m_t=19 GeV/c^2 and the search is at the Z°. By requiring $p_\perp > 2.06$ GeV/c the signal/



4.4. Model calcuation for the transverse momenta of muons produced in e^+e^- annihilation, two-jet events at the Z°. From Ref. 4.6.

background = 4, and the tt selection efficiency is 25%.

Applying these methods to the general case of a heavy quark Q, we expect to attain similar signal/background ratios. The selection efficiencies will probably be less, perhaps 5-20%. But even the 5% efficiency provides sufficient numbers of events when applied to the production rates in Table 4.1.

The remaining question is how to find the Q mass from the Q and $\overline{Q}$ jets. One method is to reconstruct the invariant mass using calorimetric measurements of the vector momentum of each particle in the jet. Even in the case of a two jet event this method looks difficult[4.6]. The assignment of particles to a jet becomes increasingly uncertain as the angle between the particle momentum and the jet axis increases. Additional errors come from the measurement errors of the calorimeter and the loss of neutrinos.

An alternative way is to look for the $Q\overline{Q}$ threshold by doing what we call a smart energy scan. Such a scan has two aspects.

(i) The event selection criteria used at the initial energy to find the $Q+\overline{Q}$ are applied at all energies.

(ii) One scans downward in energy in large steps. As soon as the $Q+\overline{Q}$ signal disappears one scans upward in energy in smaller steps, and so forth.

c. Quark Mass > W or Z Mass. As discussed in Sec. 4Bc as m_Q rises above m_W, the dominant decay mode becomes

$$Q \to W^+ + q \tag{4.17a}$$

and we obtain the distinctive signature:

$$e^+ + e^- \to \underset{\lfloor\to W^+ + q}{Q} + \underset{\lfloor\to W^- + q}{\overline{Q}} \tag{4.17b}$$

of 2W jets plus 2 quark jets. The primary background is the process

$$e^+ + e^- \to W^+ + W^-, \tag{4.18}$$

Similar considerations apply to

$$Q \to Z^\circ + q \tag{4.19}$$

Table 4.2 gives the production rates for an e^+e^- collider.

Table 4.2: R and production rates for $e^+e^- \to Q\overline{Q}$ assuming the Standard Model and $\sin^2\theta_W = 0.22$. $\mathcal{L} = 10^{33}$ and 10^7s/year is assumed.

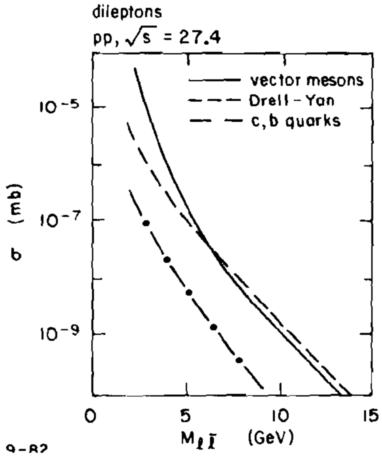
$\sqrt{s}$ (GeV)	Q Charge = ±2/3		Q Charge = ±1/3	
	R	Events/year	R	Events/year
200	2.37	51,000	1.54	33,000
700	1.97	3,500	1.11	2,000
2000	1.95	420	1.09	240

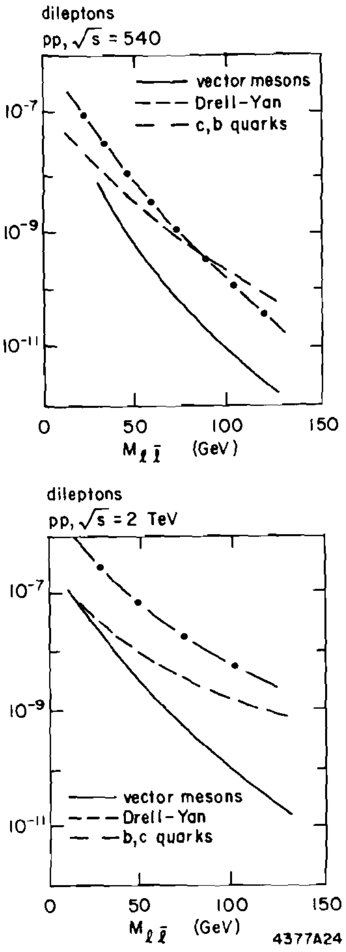
D. Production and Detection of Heavy Quarks at pp and p̄p Colliders

1. Quarkonium Detection. As discussed in Sec. 4Bc the traditional, and very successful, way to find $V(Q\overline{Q})$ produced in hadron-hadron collisions is to look for

$$V \to e^+ + e^-,\ \mu^+ + \mu^- \tag{4.20}$$

Unfortunately when $m_V > 50$ GeV/c^2, the $V \to \ell^+\ell^-$ signal may become lost in an $\ell^+\ell^-$-background from the decay of b quark pairs, from the decay of c quark pairs, and from the Drell-Yan process. This is illustrated in Fig. 4.5. Therefore this method is limited to

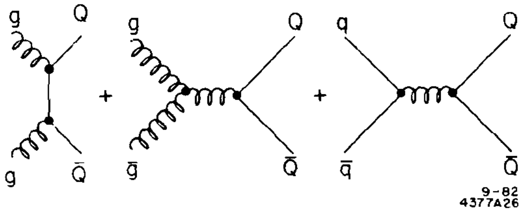




4.5. Calculations of dilepton cross sections in pp collisions. From Ref. 4.7.

$$m_Q \lesssim 25 \text{ GeV}/c^2 \qquad (4.21)$$

2. Heavy Quark Production and Backgrounds. Figure 4.6 shows the three basic processes for producing $Q\bar{Q}$ pairs in pp or $p\bar{p}$ collisions.



4.6. Diagrams for heavy quark production in hadron-hadron collisions.

Perturbative QCD predicts[4.8] the cross sections and event rates in Table 4.3 for pp collisions. Cross sections for $\bar{p}p$ collisions are somewhat larger.

Table 4.3: Total cross sections and event rates for $Q\bar{Q}$ pair production in pp collisions. $\mathcal{L}=10^{32}$ cm^{-2} s^{-1} and 10^7 s/yr is assumed. From Ref. 4.8.

Q Mass (GeV)	$\sqrt{s}$ = 1 TeV		$\sqrt{s}$ = 2 TeV		$\sqrt{s}$ = 10 TeV		$\sqrt{s}$ = 40 TeV	
	σ (mb)	Events per yr	σ (mb)	Events per yr	σ (mb)	Events per yr	σ (mb)	Events per yr
100	5×10^{-7}	500,000	7×10^{-6}	7,000,000	3×10^{-4}	300,000,000		
200	1×10^{-9}	1,000	1×10^{-7}	100,000	2×10^{-5}	20,000,000	2×10^{-4}	200,000,000
400			3×10^{-10}	300	8×10^{-7}	800,000	2×10^{-5}	20,000,000
800					2×10^{-8}	20,000	1×10^{-6}	1,000,000
1600					1×10^{-10}	100	6×10^{-8}	60,000
3200							1×10^{-9}	1,000

To find a heavy quark Q by the simplest method one would look for jets which could be distinguished from the jets of gluons and lighter quarks. Figure 2.12 presents[4.8] a calculation of the background of these gluon and light quark jets. To estimate a signal/background ratio consider m_Q=100 GeV/c^2 at $\sqrt{s}$ = 2000 GeV. For such a mass a $p_\perp \approx$ 100 GeV/c is required. Then

$$d\sigma_{jet}/d\Omega \, dp_\perp \approx 5\times10^{-7} \text{ mb} \qquad (4.22a)$$

We use $\Delta p_\perp \approx$ 100 GeV/c and $\Delta\Omega \approx$ 5. Hence

$$\sigma_{jet} \sim 2\times10^{-5} \text{ mb} \qquad (4.22b)$$

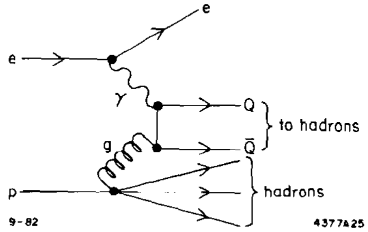
comparing this to the total cross section in Table 4.3 and multiplying by .4 for the solid angle acceptance, we find

$$\text{signal/background} \sim 0.05 \qquad (4.22c)$$

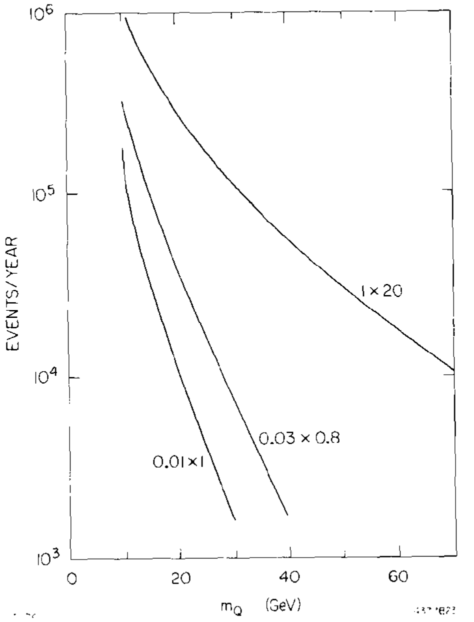
for m_Q = 100 GeV at $\sqrt{s}$ = 2000 in pp collisions. Given the difficulties we have already discussed in distinguishing a heavy quark jet from other jets, this may be a serious problem. We might consider requiring a charm meson with a secondary vertex in the jet. This would improve the signal/background ratio; but it will decrease the event rate. It is clear that more thinking needs to be done on how to find heavy quarks in hadron-hadron colliders.

E. Heavy Quark Searches at ep Colliders

In ep collisions the dominant process for heavy quark production is the interaction of the virtual photon with a gluon, Fig. 4.7. In such a process it is difficult for the photon-gluon system to attain a large invariant mass, hence the attainable m_Q range is limited. Figure 4.8 presents a rough calculation[4.9]. Colliders with s < 0.3 TeV are limited to m_Q<50 GeV/c^2. Even a very high energy collider, 1 TeV e's and 20 TeV p's, m_Q is limited to m_Q<100 GeV/c^2. These calculations are very recent and more work is certainly worthwhile on heavy quark production at ep colliders.



4.7. Diagram for production of heavy quarks in ep collisions.



4.8. Events per year for production of heavy quarks in ep collisions. The numbers attached to each curve give the electron energy and proton energy respectively in TeV. A luminosity of 10^{39} cm^{-2} per year is assumed.

F. Summary

This section is summarized as follows:

(i) The discovery of new heavy quarks with masses above about 40 GeV/c^2 depends primarily upon the identification of hadronic jets from the decay of these quarks. Such jets must be separated from light quark jets, gluon jets, W jets of other background jets.

(ii) e^+e^- colliders are the definitive way to look for new heavy quarks provided they have sufficient luminosity and energy.

(iii) Hadron-hadron colliders offer sufficient event rates for the search for new heavy quarks. However the separation of the heavy quark signal from the background may be difficult.

(iv) e-p colliders appear to offer a relatively small mass range in which to search for new heavy quarks.

5. Deviations From Standard Model Predictions

As discussed in the introduction, we are assuming that the SM is a correct description of basic physics for E<100 GeV. Nevertheless, it is incomplete, and new physics should appear. One way new physics can appear is as new particles, and that is discussed in detail for (i) further generations, in Secs 3 and 4, and (ii) for new kinds of particles suggested by Technicolor, supersymmetry, and constituent ideas, in several sections below. A second way to find new physical effects is through the appearance of (often small) deviations from SM predictions. In this section we will emphasize several of those. They are mostly well-known places to look, and there is some overlap with the "Testing the Standard Model" report, but for completeness and because of our different perspective we thought it appropriate to include this discussion.

(A) The Standard Model prediction for the Z° mass is discussed in detail in the "Testing the Standard Model" section, including the very important effects of radiative corrections. A shift in M(Z°) from mixing with higher mass Z°'s is one way we could get a clue to new physics. At least four approaches allow such a shift: (i) If there are horizontal gauge interactions there will be additional (electrically neutral) gauge bosons. They will in general mix with the Standard Model Z°, e.g. through fermion loops, and shift its mass. (ii) Grand Unified Models with symmetry breaking at intermediate scales will have additional U(1) groups and thus additional Z°'s; mixing may occur. (iii) Constituent models can produce several Z° states with non-zero overlap integrals. (iv) Left-right symmetric models will have additional Z°'s that will mix, often producing large shifts in m(Z°).

(B) If a shift is observed in m(Z°) only, its interpretation is unclear. For example, if the shift is downward of order 2% it will cancel most of the expected increase due to radiative corrections. Since several mechanisms that shift m(Z°) do not affect $m(W^\pm)$ [e.g. (i) and (ii) above], it would be very valuable to also have a measurement of $m(W^\pm)$. This can be done at an e^+e^- machine when $e^+e^-\to W^+W^-$ is possible, by fitting to the shape of the cross section. It may be possible at a hadron collider by comparing $W^\pm\to\mu^\pm\nu$, $e^\pm\nu$ with a single lepton spectrum from $Z^\circ\to\mu^+\mu^-$, e^+e^-, as discussed in the "Testing the Standard Model" report. The uncertainties in this method are statistical, experimental systematics, theoretical systematics since Z° production is via $\bar{u}u+\bar{d}d$, while $W^\pm$ production is via $u\bar{d}$, $\bar{u}d$, and different background effects. A 1% measurement may be a reasonable goal.

(C) The ρ parameter, $\rho=m_W^2/m_Z^2 \cos^2\theta_W$, is an extremely important probe of physics beyond the Standard Model (see ref. 5.1 for some review of its significance and references to other work). If $\rho\neq 1$ we learn either that there is SU(2) breaking at a higher mass scale, or that Higgs particles (fundamental or dynamical) occur in other than doublet representations.

(D) The importance of $\Gamma_{TOT}(Z^\circ)$ and $\Gamma(Z^\circ \to$ undetected neutrals) are well known -- since they are calculable quantities in the Standard Model, their values will tell us about any open decay channels to presently unknown particles. There are contributions to $\Gamma(Z^\circ\to$undetected neutrals) from any massless or light neutrinos (see "Testing the Standard Model" for details), and possible contributions from other new states. The supersymmetric scalar partners of left-handed neutrinos would contribute (with possible phase space corrections if they have mass); there is little restriction on their masses at present, although it appears $m(\tilde{\nu}) > m_\tau$ so as not to noticeably affect semileptonic τ decay. Gluino pairs contribute[5.2] at the 10^{-5} level, and photino pairs less, so they do not affect the interpretation.

(E) It is also well known that the rates and angular distributions for $e^+e^-\to W^+W^-$ and $q\bar{q}\to W^\pm\gamma$ are sensitive probes of the structure of gauge theories. One study[5.1] on the sensitivity to heavier Higgs has been done, but little effort has otherwise been made to see the effect of other ideas on these reactions. In particular, any object that couples to $q\bar{q}$ and to $W^{\pm}\gamma$ will appear in the s-channel of $q\bar{q}\to W^{\pm}\gamma$ at hadron colliders. Such objects occur in Technicolor, but the Technicolor contribution is small compared to the Standard Model one; other effects might enter, e.g. in constituent models.

(F) The neutral current interactions of u and d quarks, and of e,μ, and ν_μ have been well measured, and there is some data on those of ν_e and τ. More precise information on all of these, and any information on s,b,t is very desirable. Just as discussed for the existence of additional Z°'s under point (A) above, the interactions of such Z°'s lead to additional neutral currents which could appear mainly for heavier fermions, but could still appear at the 10% level for the light quarks and leptons.

As Hung and Sakurai have emphasized[5.2], the factorization constraint of the Standard Model is a very important test. It arises because in the Standard Model the two parameters ρ and $\sin^2\theta_W$ describe over a dozen observables. At present accuracy such a description is indeed possible, which is a great success of the Standard Model. New physics which influences some interactions more than it does others will cause factorization violations at some level. An interesting aspect of factorization tests is their programmatic nature, requiring data in νN reactions, νe reactions, e^+e^-reactions, atomic physics parity violation, etc. It is important to ensure that ultimately data is available from all these sources to allow the needed comparisons.

A related neutral current test is the value of the parameter C defined by

$$\pounds^{eff} = \frac{4G_F}{\sqrt{2}} [(J_\mu^3 - \sin^2\theta_W \, J_\mu^{EM})^2 + C(J_\mu^{EM})^2]$$

which would signify a deviation from the Standard Model neutral current. Presently $C/\sin^4\theta_W < 1/3$, and a better limit is needed. At present only e^+e^-reactions can measure C well, as such an interaction is parity conserving and only present when electrically charged particles interact.

(G) Additional Z° and $W^{\pm}$ states are another way that new affects might show up. If we assume that their couplings to quarks and leptons are unchanged, and take also the same branching ratio to $\mu^+\mu^-$ (which is optimistic since additional decays will be available), then requiring 100 events of $Z°\to\mu^+\mu^-$ or 1000 events of $W\to\mu\nu$ will allow finding a new state in the process shown

Process	$\sqrt{s}$	$\int \pounds dt$	Mass
$e^+e^-\to Z°$	$2E_{beam}$	10^{36}-10^{38}	scan up to $\sqrt{s}$
ep	200 GeV	10^{38}	$\lesssim 300$
pp	800 GeV	10^{40}	$m_Z \lesssim 320$, $m_W \lesssim 300$
$\bar{p}p$	10 TeV	10^{37}	$m_Z \lesssim 360$
	10 TeV	10^{39}	$m_Z \lesssim 1740$
	2 TeV	10^{37}	$m_Z \lesssim 230$, $m_W \lesssim 150$

The methods for searching directly for additional Z°'s or W's are straightforward. At hadron-hadron colliders one simply looks for the same signatures as are proposed for the standard Z° and W. The sensitivity depends on the expected production cross section. If it is the same as for the standard Z° and W, Fig. 2.10 may be used. In e^+e^- colliders one scans through the available energy range for an $e^+e^- \to Z°'$ peak in the total cross sections or for an $e^+e^- \to W'^+ + W'^-$ threshold in cross section. As an example, to search for a Z°' in the 250 GeV to 1000 GeV range, a scan[5.1] with an integrated luminosity of 10^{37} cm^{-2} is required. This assumes the e^+e^- collider is a linear machine with a relatively large energy spread of ±5%, and that $e^+e^-\to Z°'$ has the standard cross section. A collider with a luminosity of 10^{33} cm^{-2} s^{-1} would allow searches for Z°'s with 0.01 of the standard production cross section.

(H) QCD test are equally important, but harder to perform at high accuracy. Constituent ideas would lead to large QCD "violations"; a number of these are described in the contribution of Eichten, Leveille, and Peskin. Perhaps the most important puzzle in the Standard Model QCD is the strong CP problem -- why is CP conserved in strong interaction when one can write a piece in $\pounds$ that does not conserve CP? The resolution of this problem may be an important insight to going Beyond the Standard Model.

6. Grand Unified Theories

Much of what should be covered in this section is well treated in other sections of the proceedings, so we will only give a brief description. The reports of Mann, Shrock, and Lanou should be consulted.

The main quantities to measure or search for to either test the predictions of grand unification, or to probe physics on the grand unification mass scale, are:

(A) Proton decay
(B) n-$\bar{n}$ oscillations
(C) monopoles
(D) $\sin^2\theta_W$
(E) the baryon asymmetry of the universe
(F) ν masses
(G) lepton nonconservation, double β-decay.

The measurement of $\sin^2\theta_W$ is discussed in detail in the "Testing the Standard Model" section of the proceedings. Proton decay and ν masses are extremely general phenomena, as we have discussed in the introduction --if they do not occur in nature there must be a (presently unknown) reason. Monopoles, and n-$\bar{n}$ oscillations could occur in nature, would fit easily into grand unified theories, and would greatly help in leading toward the correct theory.
All of these are extremely important to pursue, and should be a part of a full program.

7. Higgs Physics Beyond the Standard Model

The standard model requires the existence of a single, electrically neutral, color singlet, scalar, fundamental boson. If that is the only Higgs boson, its couplings to fermions and gauge bosons are fixed because of its role in giving them mass, but its own mass is essentially arbitrary.

As discussed above, there is not yet any understanding of the physical origin of mass, or the physics of Higgs bosons. There is no good criterion for what constitutes a simple Higgs sector. For example, since there are three families of quark doublets and of lepton doublets, perhaps the simplest approach is to have three families of Higgs doublets. As a further example, in the Standard Model both fermions and gauge bosons get their mass from one Higgs vacuum expectation value; but with such different mass scales perhaps more than one vacuum expectation value should be involved -- that requires two (or more) Higgs doublets.

Essentially the only experimental restriction on the Higgs sector is that $\rho = M_W^2/M_Z^2 \cos^2\theta_W \simeq 1$. To make $\rho \neq 1$ it is sufficient to have SU(2) breaking, or appropriately chosen Higgs particles that are not doublets; the closeness of ρ to unity is an important constraint on any model[5.1], but one can construct models with Higgs particles in other multiplets and with SU(2) breaking and with $\rho \simeq 1$.

There are a number of specific reasons (as well as the general ones mentioned above) why more than one Higgs doublet[7.1] might exist. The most interesting approaches so far to give a physical basis to scalar bosons, Technicolor and Supersymmetry (both discussed below), both require two or more Higgs doublets. Left-right symmetric theories have additional Higgs bosons. If the strong CP problem is solved by the Peccei-Quinn mechanism two doublets are needed. It may be that a theory in which quark mixing angles can be calculated in terms of quark masses requires two or more doublets. Unfortunately, none of these arguments is compelling yet. Nevertheless, it is important to look for experimental clues to Higgs phenomena in a variety of places.

If additional Higgs multiplets are part of the theory, two new phenomena occur in general.

(i) Physical charged Higgs bosons exist; their mass is not calculable without a model.

(ii) Couplings of Higgs bosons to fermions can vary from the simplest form ($g_{Hf\bar{f}} = m_f g/m_W$ where g is the gauge coupling). Consequently, it is important to obtain experimental limits on charged and neutral Higgs couplings.

Additional neutral Higgs will also occur, but searching for them is essentially the same as for the Standard Model Higgs, so we will not discuss that further.

Charged Higgs particles can show up directly in two ways.

(i) Since they are charged scalars they are produced in e^+e^- reactions with $\beta^3/4$ units of R and a $\sin^2\theta$ production distribution. Presumably e^+e^- machines can always do definitive experiments to find or exclude charged Higgs up to $m_H < E_{beam}$, although there may be some restrictions on sensitivity to various decay modes. Decay modes are expected to be dominated by those with heavier fermions, e.g. $t\bar{b}$, $c\bar{b}$, $c\bar{s}$, $\tau\nu$. Perhaps those modes that mix generations are suppressed by mixing angles (so maybe $\Gamma_{c\bar{s}} > \Gamma_{c\bar{b}}$). More quantitatively, at a vertex $f \to H^\pm + f'$, the coupling can depend on $m_f = m$ and on $m_{f'} = m'$. It is not known whether $g \sim m + m'$ or $g \sim \sqrt{mm'}$; both have been used. The latter would apparently uncouple $H^\pm$ from lepton channels such as $\tau\nu$ since m_ν is so small or zero. Possibly a mixing angle factor involving the CKM angles θ_2, θ_3 occurs if the coupling changes generations, such as $b \to cH^-$. Since there are no convincing arguments about charged Higgs couplings, experiments should consider any of these modes as possibly dominant. While charged Higgs may be difficult to detect, e^+e^- should be the cleanest way to search. Several sections of the proceedings contain discussions of detecting charged Higgs bosons in e^+e^- at $\sqrt{s} \simeq m_{Z^\circ}$ and $\sqrt{s} > m_{Z^\circ}$. Presently various arguments from data at e^+e^- machines (SPEAR, CESR, PETRA, PEP) exclude charged Higgs of mass $\lesssim$ 13 GeV/c in most decay modes.

(ii) If charged Higgs exist in the right mass range, with any quarks or leptons appropriately heavier, then they may couple members of a doublet, e.g.

$$t \to b + H^+.$$

Because this decay is semiweak it will dominate the usual $t \to b f\bar{f}$. In that case, if the mass range is such that they are not accessible at an e^+e^- machine, perhaps they could be found or studied at a hadron machine. At present we know of no detailed studies of this process including backgrounds and detector limitations.

So far we have spoken of detecting the Higgs bosons as particles. They could also appear[7.2] as exchanged currents, just as $W^\pm Z^\circ$ do. We would detect scalar (or pseudoscalar) currents. Unfortunately, because they are expected to couple proportional to the mass of fermions, their contributions may typically be weaker by a factor $m_f^2/4\, m_H^2$ than usual vector currents (the 1/4 is for spin). [The muon g-2 places limited restrictions, while β-decay and μ-decay hardly are constraining so far. Comparison of $\pi(K) \to \mu\nu$, $e\nu$ gives the same m_e^2/m_μ^2 ratio as the V-A currents if the Higgs couples proportional to mass, and simply renormalizes f_π.] If the coupling is proportional to mass it would give violations of $e/\mu/\tau$ or d/s/b or u/c/t universality.

At present there are essentially no model independent restrictions on neutral Higgs masses. For charged Higgs, the absence of a decay $\tau^+ \to \nu H^+$ requires $m_{H^\pm} > m_\tau$, and the apparent absence of $b \to cH^-$, uH^- requires $m_{H^\pm} > m_b - m_c$ or $m_{H^\pm} > m_b$.

Finally, although they happened not to be discussed in detail at this study, we mention the important question of axions for completeness. Axions arise whenever global symmetries in a theory are broken. There are no model-independent statements about their masses or couplings. They are essentially very light fundamental scalar or pseudoscalar bosons, and should be searched for wherever possible.

8. Technicolor (TC)

A) Survey of Theory

The physics of scalar bosons and their role in generating mass for fermions and gauge bosons is not understood. However, the need for some new physics associated with the scalar bosons will not go away. One approach[8.1] to making a fundamental gauge theory that provides the needed mechanisms is to introduce new fundamental fermions (Technifermions) a new QCD-like force (called Technicolor or Hypercolor), and a new SU(2)-like interaction (Extended Technicolor, or sideways force). Then the dynamics and the symmetry structure of the new sector provide the basis for generating mass. Although there are no fundamental scalars, a number of scalar, pseudoscalar, and spin 1 bosons are generated either as (Pseudo)-Goldstone Bosons of the broken symmetries of the new sector or as dynamical states.

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, and with the general arguments of our introduction and the comments of Peskin elsewhere in these proceedings. Without any committment to a particular Technicolor model, it seems to be a useful goal to aim toward physics facilities which would allow the main states that arise in Technicolor to be found experimentally if they exist. While the Technicolor states are composites, they will appear to be pointlike objects until probed at momentum transfers on the scale of the Technicolor theory, about 1 TeV.

Precisely which states arise is model dependent, but the general pattern is easy to see. The new Technifermions (F) are assumed to carry their technicolor quantum number, and in addition ordinary color, $SU(2)_L$, and $U(1)$ quantum numbers. To make technicolor-singlet states from $\overline{F}F$ one can combine them in the available pairs. Allowing F to include color triplet states (Q) and color singlet states (L), and assuming all are electroweak doublets, gives [recall, $\overline{3}\otimes 3=8\oplus 1$, $2\otimes 2=3\oplus 1$] color singlets [$\overline{L}L$, $(\overline{Q}Q)_1$], color triplets [$\overline{L}Q$, $\overline{Q}L$], and color octets [$(\overline{Q}Q)_8$], all bosons, with spins 0 and 1 expected. While it is not logically necessary to have both technifermions Q,L and to have the technifermions carry color and SU(2) quantum number, it seems to be very hard to give masses to ordinary fermions in any other picture. By analogy with QCD, the spin 1 states (like the ρ and the ω) are expected to have a mass about that of the mass scale of the theory, which has to be about 1 TeV to get m_W, m_Z correct. The spin 0 bosons initially arise as Goldstone bosons and they are massless. If they had no other interactions they would stay massless, but because some of them are colored and charged they get mass -- but in amounts approximately calculable from the standard model, because only ordinary color and charge are involved. Other sources of mass are present in the model, and could give a few GeV of mass or conceivably up to 50 GeV in some cases.

The reader can consult the references[8.1,8.2,8.3] to study the full list of particles and for discussions of expected masses and decays. Since we are treating Technicolor as an approach to suggest interesting things to study, we will leave many details for the literature. Here we focus on five states. See also the contribution of K. Lane to these proceedings.

B) Neutral Higgs-like Bosons

There are light, color singlet, electrically neutral (pseudo) scalars that are like the usual Higgs boson. In the TC theory they cannot be too heavy (say $M_0<40$ GeV, perhaps much less) and might be expected in 1-10 GeV range. Searching for them is just like searching for a normal neutral Higgs, except that the useful $Z^\circ Z^\circ H^\circ$ coupling (which allows a search for H° in $e^+e^- \rightarrow \{{\mu^+\mu^- \atop e^+e^-}\}H^\circ$ in the Standard Model) is absent here (see Lane's discussion).

C) Charged Higgs-like Bosons

There are light, charged, color singlet bosons; they are indistinguishable from fundamental charged Higgs bosons. Their mass should be $m_{\pm}<40$ GeV and might be expected in the 5-20 GeV range. See the discussion above in Section 6 concerning their production and decay properties. They are also considered in some detail in other sections of the proceedings. If such states do not exist it is a very serious constraint on Technicolor ideas, and probably excludes most approaches. [But, beyond the Standard Model there are essentially no decisive negative results; only finding a signal is definitive.]

D) The η_T

If the technifermions are colored, they will form color octet (pseudo) Goldstone bosons (usually called the technieta, η_T). (See Dimopoulos, Ref. 8.1, and ref. 8.2.) These states start out massless but get about 250 GeV of mass from color interactions. That number is more firm than others because masses add quadratically for bosons, and even 50 GeV of mass from other sources hardly shifts it. Further, since the η_T is a color octet pseudoscalar,

(i) its coupling to the vector gauge bosons (gluons) is calculable analagously to the coupling of π° to $\gamma\gamma$, so its production cross section can be calculated,

(ii) since it is a color octet its cross section is large.

Thus even though it is heavy, η_T is copiously produced at hadron machines.

Further, because of its connection to mass generation the η_T is expected to couple more strongly to heavier states, so its dominant decay should be to the heaviest quark pair, e.g. $t\overline{t}$. If t-quark jets can be selected with sufficient efficiency, the effective mass of $t\overline{t}$ may show an η_T peak. The kind of cuts and detector needed to carry out such an analysis has been studied in some detail by Baltay et al., and is described in their report in these proceedings; they show production cross sections including scaling violations for a range of masses and energies. While further analysis is needed, especially concerning the properties of the Monte Carlo results they use to estimate and reject background, their current view is optimistic that an η_T signal could be found at a high intensity hadron collider if it were present in the data at the expected level, even if $m_t \simeq 20$ GeV; as m_t increases the situation improves. It is worth noting that the production cross section for η_T, $d\sigma/dy \sim (\Gamma/m^3)\, G(x_1)\, G(x_2)$, where Γ is the partial width for $\eta_T \rightarrow gg$, m is the η_T mass, and G the gluon distribution function. Since the partial width Γ is itself proportional to m3, $d\sigma/dy$ depends on m only through phase space and the gluon distributions functions. Thus comparison of η_T production rates at different machines depends only on these standard quantities and is qualitatively quite reliable.

An η_T is expected to have other interesting decays that can be used for detection or study. In particular[8.2] $\eta_T \rightarrow G+Z^\circ$ should occur at about 1/2%, and $G+\gamma$ at about 1/6%. If 10^5 η_T are produced in 10^7 sec at a high intensity collider, a 1/2% decay gives 500 events, and $Z^\circ+G$ should be a very clear signature.

E) Leptoquarks

In Technicolor there are leptoquark states.[8.1,8.2] These are spinless bosons which are color triplets, so they are pair produced in hadron collisions. They have charges q=5/3,... so they give 25/36 β^3 units of R in e^+e^-reactions. They get less mass than the color octets, with m expected to be about 150 GeV.

Their decay will be to a lepton and a quark. Again, models suggest they have couplings proportional to mass, so they couple to the heaviest states, but that may not hold. Decays include $t\tau$, $t\nu$, $t\mu$, $c\tau$, $c\mu$, $c\nu$,... Some of these are very good signatures and may allow the leptoquarks to be found even with their modest production cross sections. Both the signatures with a charged lepton and those with a ν may be valuable, the latter giving large missing energy and p_T.

Above their threshold in e^+e^- (>300 GeV?) it seems likely that leptoquarks can be found, although no study of backgrounds and signatures has yet been done. At hadron colliders a study of how to detect them has been begun but more work is needed.

F) Spin 1 Technicolor Particles

The theory has spin one bound states like the ρ,ω. They come in color octets (as the pseudoscalars) and color singlets (these correspond to the pseudoscalars that combine with $W^\pm$, Z° to give them mass). They will occur as s-channel resonances in e^+e^- and in $q\bar{q}$ or gg, giving large effects for $\sqrt{s} \sim 1$ TeV [it is conceivable their masses are smaller than the scale of the theory, e.g. by as much as a factor of 2, but there is no good way to estimate their masses.] They will have a number of interesting decays, such as W^+W^-, $Z^\circ Z^\circ$, $W^\pm g$, $Z^\circ g$, $Z^\circ W^+ g$ and would give dramatic effects.

The color singlet states give of order 10 units of R in e^+e^- collisions, corresponding to $\sigma \sim 1$ pb. With $\mathcal{L}=10^{33}/\text{cm}^2$ sec this gives 10^4 events in 10^7 sec and can be studied; if $\mathcal{L}$ drops to 10^{30}, it becomes very difficult, as the W^+W^- background is significant. Similarly, in hadron reactions, while one can produce the color octet ρ and take advantage of the larger color couplings, one still finds a cross section of only about 8 pb. [That is easily understood -- qualitatively one has

$$\left.\frac{d\sigma}{dy}\right)_{y=0} \simeq 4\pi\ (2J+1)(\Gamma_{q\bar{q}}/m^3)\ q(x)\bar{q}(x)$$

where the first two factors are from the s-channel resonance formula, and ρ_T is coupled to the two hadrons by quark distributions. For J=1, $\Gamma_{qq}/m \simeq 10^{-3}$, m=1 TeV, and evaluating the quark distributions at x=1 TeV/40 TeV for a 40 TeV collider (so $q(x) \simeq 0.4$), gives $d\sigma/dy)_{y=0} \simeq 2.5$ pb.] Then a 40 TeV collider with $\mathcal{L}=10^{30}/\text{cm}^2$sec would have 80 events in 10^7 sec. With the $W^\pm$,Z° background 10^4 times larger this is probably too small to see, and certainly too small to study. And, arising from an s-channel, colored resonance it is one of the largest effects that can be expected from 1 TeV physics. This example clearly illustrates the need for high luminosity machines to do TeV physics.

G. Summary

If nature had a structure like that suggested by Technicolor ideas, important contributions to finding the particle states can be made by both e^+e^- and hadron colliders. The charged Higgs and leptoquarks can probably be detected at e^+e^- machines up to the energy limit $m < \sqrt{s}/2$. Hadron colliders can probably do well on η_T, may be able to study charged Higgs if they occur in heavy quark decay, and may be able to detect leptoquark states; more detailed study is needed in the latter two cases. The light neutral Higgs are hard to find. They may have dominant decays to heavy quarks such as $c\bar{c}$ or $b\bar{b}$, in which case sophisticated high resolution detectors might allow a signal to be found. The best method may require detecting the Wilczek mechanism $V \to P^\circ\gamma$ on a quarkonium state $V=\Upsilon$ or $t\bar{t}$, so perhaps an e^+e^- machine that can sit on the Υ is a high priority to look for light neutral Higgs. Future TeV e^+e^- or hadron colliders can study the 1 TeV region, which might be quite rich, but high luminosity will be needed.

9. Supersymmetry

A) Survey of Theory

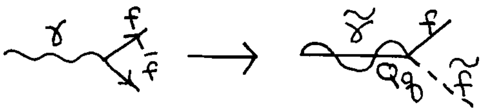
As discussed above, Technicolor is one idea to explain in part why the standard model works, and what the physics of mass generation and scalar bosons is about. The other approach that can incorporate scalar bosons as part of the theory is supersymmetry, in which every fermion has an associated boson. In the eyes of many theorists supersymmetry is particularly beautiful because (1) a local gauge theory of supersymmetry can be related to gravity, so that one can hope for a framework including all the known forces of nature, and hope for relating the cosmological constant to particle physics; (2) one can make models which are both supersymmetric and grand-unified and which show promise for understanding widely separated mass scales; and (3) it has fewer divergences than a general field theory and many quantities are not renormalized. For a recent review see Ref. 9.1, and see the contribution of Hinchliffe and Littenberg for more details.

Supersymmetry must be a broken symmetry or each of the familiar particles would have a partner of the same mass, charge, color, etc but 1/2 unit less spin. That is not observed. The scale of supersymmetry breaking is unknown, so we do not know what masses the new particles should have. However, if supersymmetry provides the explanation for the gauge boson mass scale of order 100 GeV, whatever mechanisms are operating to give masses on that scale will presumably operate on many of the particles that have very small masses before the symmetry is broken. Thus if nature is supersymmetric one can hope to find partners of photons, gluons, quarks, leptons, $W^\pm$, Z° all with mass within a factor of 2-3 either way from m_Z. The simplest ideas would produce lighter states, with all the above having mass well below m_Z. As always, there are no guarantees -- a negative result does not exclude a supersymmetric world at a higher mass scale. A positive result would be a great breakthrough.

Since the partners of the fermions, and particularly the partners of the massless gauge bosons, could be quite light, searching seriously for supersymmetric partners is appropriate even today. We will discuss four kinds of particles. All of the couplings of the partners can be deduced from those of the normal particles by taking the usual vertices and replacing any pair of particles by their supersymmetric partners. A partner will be devoted by a ~. As in other sections, we are viewing the supersymmetric particles as general probes of unknown phenomena; we leave some details for the literature and we do not give a general discussion of supersymmetry phenomenology. We also note that Fayet[9.2] has suggested an additional, light, vector boson from an additional U(1) symmetry in a supersymmetry model; there is not yet evidence against the existence of this state, and it is best looked for in precision low energy experiments.

B) Photinos ($\tilde{\gamma}$)

They are the partners of photons, and are spin 1/2 fermions. They couple as shown to a fermion of



charge Qq. They will interact in a detector by hitting a quark and exciting a scalar quark

$\tilde{\gamma}+q \to \tilde{q} \to q+\tilde{g}$

which decays to a quark and a gluino (the gluon partner). The gluino in turn decays and eventually a lightest supersymmetry particle escapes. Since the scalar quark is presumed to have mass of order m_Z, the photino interaction[9.3] cross section is typically somewhat larger than a ν cross section. Thus a photino may interact in a beam dump detector but will escape a typical collider detector. [If there is a lighter supersymmetry particle, e.g, the Goldstone fermion G, the photino will decay $\tilde{\gamma}\to\gamma G$, with a lifetime set by the scale of supersymmetry breaking and by the photino mass. If it decays, some detectors might see the photon.]

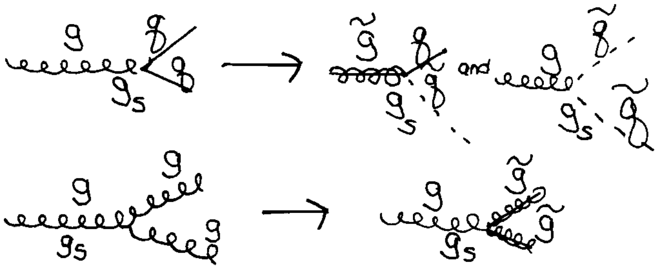
Direct production of photinos is difficult to arrange. They are produced by e exchange in $e^+e^-\to\tilde{\gamma}\tilde{\gamma}$, but $\sigma\sim s\alpha^2/\tilde{m}_e^4$ which is a typical weak cross section (since $\tilde{m}_e$ is large) and thus too small, unless very high luminosity is available. If photinos are seen most likely it will be from the sequence where gluinos are produced and the photinos appear as gluino decay products. The photino mass is unknown. Naively one would expect it to be of order α/α_s times a gluino mass. Since the gluino mass is at least several GeV (see below), one might expect photino masses above perhaps 1/4 GeV.

To summarize: photinos are hard to produce directly but they will occur in the decay of other supersymmetry particles. They will interact in beam dump detectors but not in collider detectors, so they carry away energy and momentum at the latter.

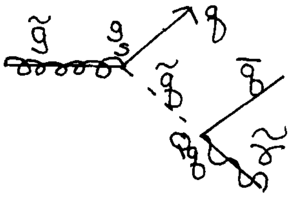
C) Gluinos ($\tilde{g}$)

These are the spin 1/2 partners of gluons. Since they are colored they couple to gluons strongly, and with the large color octet Clebsch-Gordon coefficient, so they are very strongly produced, which makes them potentially of great experimental interest[9.4,9.5]. Their decay signatures are useable.

To find the gluino couplings we start from the normal QCD couplings and change particles to their supersymmetry partners in pairs.

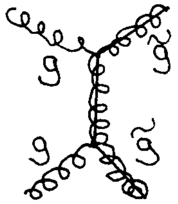


From these diagrams and those for photinos we see that the gluino will have the decay mode $q\bar{q}\tilde{\gamma}$ (Qq is the charge of the quark, e.g. 2/3 e). [In global



supersymmetry there is also the decay $\tilde{g}\to gG$ where G is the Goldstone fermion. The $q\bar{q}\tilde{\gamma}$ mode usually will dominate, and illustrates all our points, so we only discuss it here. All alternatives are discussed in Ref. 9.5]

Using the above diagrams, gluons could be pair-produced from any hadrons by coupling to the gluons in the hadrons.



The gluino cross sections come out to be 10-20 times those for quarks of the same mass. (See the contribution of Hinchliffe and Littenberg to the proceedings.)

One can show using the above information and existing data that the gluinos will decay with lifetimes less than a few cm, and that they should have been observed if they were lighter than a few GeV in mass (otherwise the cross section to produce them gets too small). The Florence, Michigan, Ohio State, Washington, Wisconsin beam dump experiment at FNAL has recently published the best limits, with $\tilde{m}_g>3.5$-6 GeV depending on various alternatives. Such masses always refer[9.5] to the kinematical mass that affects the production cross section -- that includes some constituent mass as the gluinos bind (presumably with gluons) to make color singlets. That number would be of order 1 GeV if only the color were relevant -- the reader can make his own estimate.

Experiments at higher energy machines can be sensitive to much higher gluino masses. The ISR with experiments in progress can go to masses in the 7-10 GeV range (H. Gordon et al., BNL research note). The SPS collider can search for masses up to about 25 GeV. Littenberg has analyzed the situation at hadron colliders including both production and detection of a signal, and suggests (see his contribution to the proceedings) that one can achieve sensitivies as shown in the table (the upper limit on gluino mass is shown in GeV/c^2):

$\mathcal{L}$	10^{30}	10^{32}	10^{34}
$\sqrt{s}$ (TeV)			
0.8	65	115	150
2	75	220	350
10	200	600	1300
40	500	1200	>2100

For the bottom rows the backgrounds are guessed, while for the top two rows they come from the ISAJET Monte Carlo.

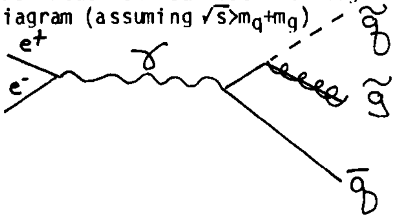
The signatures are discussed in detail in Hinchliffe and Littenberg's contribution to the proceedings. Basically the tools one has at a collider are that the $\tilde{g}$ decay includes the $\tilde{\gamma}$ that escapes, so one has a noncoplanar event with a p_T unbalance, but no prompt charged lepton as would be the case with a missing ν.

Beam dump experiments produce a $\tilde{g}$ in the dump and then detect the photino (from the $\tilde{g}$ decay) in the detector. Longo and Leveille have looked at the cross sections and kinematics and estimate that a 20 TeV fixed target experiment could find $\tilde{g}$ up to about a 20-40 GeV mass, depending on whether $\tilde{\gamma}$ was required to interact or whether one could see the photon from $\tilde{\gamma}\to\gamma G$. If $\tilde{g}$ were found in the appropriate range this would be a valuable way to study $\tilde{\gamma}$ interactions, and would give information about scalar quarks and about the scale of supersymmetry breaking as well.

Gluinos may be produced in e^+e^- collisions via the reactions[2.3,9.6]

$$e^+ + e^- \to q + \bar{\tilde{q}} + \tilde{g}, \quad \bar{q} + \tilde{q} + \tilde{g}$$

Such reactions can occur through the following diagram (assuming $\sqrt{s} > m_q + m_g$)



The experimental problem is to distinguish this reaction from $e^+ + e^- \to q + \bar{q} + g$. The primary signature is large missing momentum from the $\tilde{g}$ to $\tilde{\gamma}$ decay, as in hadron-hadron searches for gluinos. In addition, one might hope that the $\bar{q}\tilde{q}\tilde{g}$ system had different jet and angular distribution properties, compared to the $\bar{q}qg$ system.

Gluinos would also show up in deep inelastic processes with an effect on α_s and on scaling violations. Explicit predictions for high energy ep machines do not seem available; the most recent treatment is in ref. 9.7 and the literature can be traced from there.

(D) Scalar Leptons ($\tilde{\ell}$).

The scalar leptons associated with e, μ, τ are the easiest supersymmetry partners to search for. They are produced at any e^+e^-machine with 1/4 β^3 units of R, up to the kinematic limit. They decay into the associated lepton and a photino with 100% branching ratio, $\tilde{\ell}\to\ell\tilde{\gamma}$. The photino escapes, so one has events with e pairs or μ pairs or τ pairs, but half the energy is missing and the leptons are acoplanar and not colinear. Present limits for $\tilde{e}$ and $\tilde{\mu}$ are about 16 GeV from PETRA.

Both ℓ_L and ℓ_R have a scalar partner. In principle they can have different mass. With ℓ=e,μ,τ there can be six scalar charged leptons. They may be approximately degenerate if their mass originates from a flavor-independent mechanism. There are indications that that might be required to avoid flavor changing neutral current effects, but that is model dependent and may be avoidable by symmetry arguments.

(E) Scalar quarks ($\tilde{q}$).

There is a scalar quark for q_L and for q_R. They are produced in $e^+e^-$with $\beta^3 q^2/4$ units of R, where q is the quark charge. As for scalar leptons, degeneracy could occur. They may be considerably harder to detect because of the background from semileptonic decays of quarks, but they should be detectable with careful analysis up to the kinematic limits at e^+e^-machines.

Scalar quarks can be produced with gluinos up to high masses at hadron colliders; see Littenberg and Hinchliffe for details. Using similar analyses to those for gluinos, there is a good possibility they can be found up to high masses.

(F) Summary

What masses should be expected for supersymmetry partners? Can the machines under discussion cover an interesting range? The mass range is not known, and the answers to these questions are matters of conjecture. However, as mentioned in the introduction to this section, many points of view would put scalar lepton and quark masses and W,Z partner masses within about a factor of two of m_Z, so that is certainly an interesting range. Scalar leptons have the fewest interactions so they might have masses of order 1/2 m_Z. Gluinos are potentially the most interesting as they are Majorana fields and thus are often protected from having mass by global symmetries -- to avoid having very light gluinos, model builders must explicity break these global symmetries in their Lagrangians. Even then some gluino mass contributions can be suppressed, so the range up to m_Z is an extremely interesting range for gluino masses (and many existing models have gluino masses of order 1 GeV).

Finding whether nature is supersymmetric is of the greatest importance. In a few years e^+e^- machines will allow detection of scalar leptons up to 1/2 m_Z. Existing hadron machines will allow searches for gluino masses up to perhaps 25 GeV, and planned hadron machines will allow searches to above 100 GeV by the end of the decade. A 10 TeV hadron collider with $\mathcal{L}$ above 10^{32}/cm^2 sec, or a $\sqrt{s}$ = 500 GeV e^+e^-collider would probably give definitive results if supersymmetry has any "low energy" manifestations at all.

10. The Flavor Problem

Technicolor and supersymmetry are attempts at solutions to fundamental questions, but the flavor problem is still just a problem, with no serious potential explanations in sight. It is decades old, since the recognition that the muon was essentially a heavier electron.

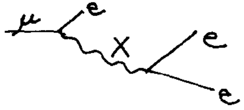
It is clear that two kinds of experimental data would help to clarify the problem.

(i) Today we know of three families. [This assumes the standard model as described above. For one interesting alternative approach see the contribution of R. Holman to the proceedings.] Finding out whether there are more flavors is of great interest. One method is to search for them directly, looking for new lepton and quark flavors; this is discussed in Secs. 3 and 4 above. A second method is the ν counting experiment where the decay $Z^\circ \to$(non-interacting objects) is measured.

(ii) All theoretical approaches that incorporate several flavors lead to interactions which produce some flavor changing neutral interactions (FCNI). In many cases the natural size of the FCNI is larger than the present experimental limits. One can make models in which transitions involving light flavors ($s \to d$, $\mu \to e$) are suppressed by a symmetry, while transitions involving heavy flavors ($b \to s$, $\tau \to \mu$) give branching ratios of order 10^{-4} to 10^{-5}. If (when?) FCNI are found, they may provide the clues we need to make progress; if they are not found and the limits get increasingly strigent, their absence is also a powerful requirement.

It is very important to realize that the flavor problem may not be best approached by going to higher energies but rather by more intense and cleaner "low energy" sources and by better detectors. Assuming FCNI are mediated by heavy bosons, branching ratios of the order of 10^{-9} are significantly more sensitive than looking for transitions at higher energies (including the effect of the growth of the cross sections with energy).

To see that consider $\mu \to eee$ as a prototype reaction. Suppose it is mediated by a boson x.



Then, by comparison with the usual decay $\mu \to e\nu\bar{\nu}$, one can define $G_X = g^2/8M_X^2$, assume the same gauge coupling g, and so one expects

$$BR_{eee} = G_X^2/G_F^2 \lesssim 10^{-10}.$$

The latter number is chosen as a typical sensitivity that will exist in decay experiments in the next few years, if no effect is found. Now consider a high energy process such as $e^+e^- \to \mu^+e^-$ or $ep \to \mu X$, where one can take advantage of the growth with energy of the primary cross section to get a higher rate. Up to factors of order 1, one finds a cross section

$$\sigma \approx G_X^2 s$$

for any such process. Using $G_X^2 < 10^{-10}\, G_F^2$, and s (or Q^2) $\approx 10^5$ GeV^2, one has $\sigma < 10^{-42}$ cm^2. Even for $\mathcal{L} = 10^{33}$ and 10^7 sec, this is 10^{-2} events, too little by far. To achieve higher sensitivity than low energy decays, an experiment will need $Q^2 \mathcal{L} T > 10^{49}$ GeV^2/cm^2.

For heavy fermions (t,b,τ,c) the current results are rate-limited. For s,μ interactions most present experiments are detector-limited, though in a few years it may be possible to utilize more intense beams.

It is extremely important to keep open our options for better experiments looking for flavor transitions. They could come from many sources. More intense and cleaner K,μ beams are one way. Higher luminosity e^+e^- colliders that are τ,c and b factories are another. Higher energy fixed target programs may contain interesting possibilities -- e.g. a dedicated Σ^+ beam at FNAL that would allow $\Sigma^+ \to p\mu e$ to be studied with a sensitivity of 10^{-11} to 10^{-12} might be worthwhile. Hadron colliders are copious sources of heavy quarks and τ's; over 10^{10} b-quarks and over 10^9 τ's are expected per year at a hadron collider with $\mathcal{L} = 10^{32}$/cm^2-sec. The problem there is to be able to study them experimentally; see the analysis of rare b decays by Plattner et al., in these proceedings, where they argue that sensitivities of 10^{-5} to 10^{-6} can be achieved for b-quark decays at an intense hadron collider.

11. Composite Quarks and Leptons?

In the past, every level of matter has turned out to be composite. The signal for that, e.g. for elements or for hadrons, was a proliferation of states. Today some people, seeing this situation repeat in the fairly large number of quark colors and flavors and lepton flavors, believe the same thing may be happening again. There is of course no logical necessity for it to happen, and others believe we may be studying a final level of matter. The possibility of quark confinement in the Standard Model introduces a new aspect to the picture and the three generations may someday appear as a simple situation. In any case, experiment will significantly illuminate the situation in the next decade.

An extensive report discussing the extent to which various machines probe compositeness has been written for the proceedings by Peskin, Eichten, Leveille, and collaborators. Consequently, here we only mention the subject in an introductory way; the reader should turn to their report. One important result they have is that because in e^+e^- reactions one is comparing an electromagnetic process, of order α, to a hypothetical new strong process with a distance scale Λ, then the sensitivity is enhanced and one can effectively reach Λ values given by $(Q^2/\Lambda^2\alpha) \sim 1$. Detailed analysis then gives $\Lambda > 0.75$ TeV for e^+e^-, and similar remarks for ν reactions give $\Lambda > 2.5$ TeV, all from present data. Machines of the next few years will significantly extend these bounds.

Another way effects related to compositeness could show up is in small currents of anomalous space-time or isospin properties, such as a magnetic moment term for the electron coupling, or an axial vector, isoscalar weak current. The subgroup report describes some of these, and we discuss some such currents in other sections. If such currents are found, they can arise from a number of sources, and distinguishing them will be an exciting process. Understanding possible effects of quark and lepton compositeness is a subject which deserves considerable further work -- the information in the present study is a useful beginning.

12. Anomalous Currents

The approach to a great deal of what has been studied above is to look for new physics by finding new particles. An equally good method is to find new currents or interactions.

To mention some examples, if point-like Higgs bosons exist they can mediate charged or neutral transitions. These will then be scalar (or pseudoscalar) currents. In the simplest models they would have a strength $mm'/4m_H^2$ relative to V-A currents or electromagnetic currents, where m and m' are appropriate fermion masses and m_H the Higgs mass. In a deep inelastic process they introduce a cross section term proportional to $x^2y^2/(m_H^2+Q^2)^2$, which can be separated from the usual $A+B(1-y)^2$ terms. In general they provide a 1-y term in any weak or electromagnetic deep inelastic cross section. An interesting problem is to study how to separate 1-y terms which arise from threshold effects, scalar currents, and expected QCD scaling violations. In a Drell-Yan process they lead to a cosθ term in the angular distribution of the lepton pair, by interfering with the photon contribution. In μ decay they give $\eta \neq 0$ and $\xi \neq 1$. These questions are discussed in some detail in Ref. 7.2. All simple models give very small effects.

An amusing example is a possible lepton-quark coupling. This might come from the technicolor leptoquarks, or from a vector boson. Constituent models have such states. Most constraints one can think of [e.g. g-2, $\pi^\circ \rightarrow e^+e^-$, ν reactions, Drell-Yan or e^+e^-angular distributions] do not provide severe restrictions in a model independent way. Ordinary β decay may provide the best constraints since an interaction that coupled d to e^- (or d to $\overline{\nu}_e$) would give a non-local source for the $e\nu_e$ pair; an interaction which couples d to ν may be allowed at quite a high strength. Thus anomalous effects could show up in high energy or in precision low energy experiments.

The most widely discussed examples of non-V-A currents are the V+A, right-handed charged currents. They occur naturally if one wants parity violation to arise spontaneously from a parity conserving fundamental theory rather than appear by assumption as in the standard model. Present limits on right-handed currents are typically at the 10% level. All constraints are model dependent; some can be evaded by assuming the leptonic couplings of the right-handed currents are only to heavy "neutrinos" so they do not show up in leptonic and semi-leptonic decays. For these the searches at ep colliders will be valuable new probes. Others can be evaded by assuming the right-handed currents do not couple to the s-d vertex, or that the CKM mixing angle matrix for the right-handed currents is orthogonal to the CKM mixing angle matrix for the left-handed currents. Existing constraints are important restrictions on theories and models, but do not imply any definitive results about nature. Right-handed currents are currently being searched for[12.1] in μ decay. At ep colliders with polarized beams they can be detected up to the kinematic limits of the machines.

Indeed, while we have in many sections seen that for most new particle searches the best results could be expected at e^+e^- or hadron machines, for new interactions the ep colliders do best. For both scalar and for right-handed currents they can look with good sensitivity. Some of this is quantitatively documented in specific comments on ep collisions in these proceedings, but more work needs to be done in this area.

While ep colliders can look for new interactions with good sensitivty, in general low energy interactions and decays will also be likely places to look for new interactions. Examples where new results could be found in the next few years include finding parity violation in hydrogen, deuterium, and heavier atoms; measuring the decay distributions of τ's and b's better in case right-handed couplings are stronger to heavier fermions; better measurements of $d\sigma/dy$ in νq and νe reactions; and precision measurements in μ,K, and charm decay.

Finally, we mention the important subject of CP violation. So far it has been observed only in K decay. While it can be incorporated into the standard model, just as mass generation can, it is not understood. Nothing new about ways to approach that problem has been included in these proceeding, not because it is not important, but because of time limitations and because the interests of the working groups did not actively cover CP violation. To fully explore the topic a wide variety of results may ultimately be necessary. For example, while detecting a neutron electric dipole moment would be a great breakthrough, without further experiments in other systems we would not know even whether the result was due to CP violation in the strong interactions or in the weak interactions. Even the parameterization of weak CP violation can be via the quark mass and mixing angles, or via the Higgs sector, or via interference of left-handed and right-handed currents that are not in phase -- these can all be distinguished experimentally, eventually.

13. Unexpected Objects and Phenomena

In other sections of this paper our disucssion of physics beyond the standard model is guided by our experience, by current theoretical ideas, and by current theoretical speculations. However as experiments move beyond the standard model we may encounter objects or phenomena which are foreign to our experience or which are not called for in current theoretical thinking. In this section we catalog some examples of such objects or phenomana.

A. Unexpected Elementary Particles

Some examples are:

a) Isolated fractionally charged particles, either quarks or leptons. The experimental situation is still unresolved with respect to isolated or free fractional charge.[13.1-13.3]

b) Tachyons, that is, particles which travel faster than the velocity of light.[13.2,13.4]

c) Heavy stable or long-lived particles.

d) Particles whose properties do not fit into the expected particle type categories of quarks, leptons, intermeidate bosons, gluons, etc.

e) Particles with large electric charges or large spins.

f) Particles with non-exponential lifetimes.

B. Unexpected Elementary Particle Phenomena

Some examples are:

a) Events with unusually large multiplicities or unusual relative numbers of hadrons or leptons.

b) Unexpected increases or decreases in total cross sections.

c) Violation of our most sacred conservation rules, namely charge conservation, angular momentum conservation, four-momentum conservation, and CPT invariance.

d) Violation of time reversal invariance in a new sector of particle physics.

e) Violations of general quantum mechanical ideas such as unitarity and analyticity.

f) Unexpected phenomena in low p_T physics, such as gross violations of Feynman scaling in inclusive reactions.

14. What if there is no Standard Model Z°?

Another direction in which we might find ourselves is that the standard model is only a low energy phenomenological theory, and the fundamental gauge bosons $W^{\pm}, Z^\circ$ do not exist. We should know whether nature is like this within about a year; before then, it may be worthwhile to think a little about what kind of machines would be most useful if we need to choose.

There are at least two approaches one can discuss. First, the low energy theory could be purely an effective four-Fermi interaction, with cross sections that grow like s. While the cross sections will get large at very high energies[14.1], they do not get large fast -- at $\sqrt{s} \approx m_{Z^\circ}$ the weak and the single photon point cross sections are about equal, so the net interaction rate is of order 10^{-3} that on the Z°. At higher c.m. energies the cross section rises correspondingly.

Second, models with composite Z° and $W^{\pm}$ have been constructed, and one approach to them is described in the contribution of Abbott, Fahri, and Tye to the proceedings. Here there is a "Z°" resonance, somewhat higher in mass but within a factor of two, and a large number of additional interesting states.

From the point of view of physics facilities, probably the crucial thing to have available, if there is no standard model Z°, is one which can scan up to an appropriate mass for Z° states, or automatically search a continuum of masses. If there are Z° states, at least one will couple normally to e^+e^-, $\mu^+\mu^-$, $u\bar{u}$, $d\bar{d}$ since these neutral current couplings are measured, but additional states could couple differently.

While we do not expect to need to modify our thinking along the above lines, it is certainly a possible outcome, and it probably would affect what constitutes an optimum research program.

15. Understanding Luminosity vs. Energy for Hadron Colliders

It was frequently observed during the study that the event rate was not always larger for proposed facilities with higher energy than for those with higher luminosity at lower energy. One can easily understand this as a general phenomenon. The $\mathcal{L}$-$\sqrt{s}$ relation is a fairly universal curve.

The essential point is that the total rate is of the form

$$\sigma(s) = \int dx_1 dx_2\, F(x_1)\, F'(x_2)\, \hat{\sigma}\, (\hat{s}),$$

where x_1, x_2 measure the fraction of the hadron momenta carried by the partons 1,2; F and F' are the distribution functions giving the probability of having the parton carry that momentum fraction; $\hat{\sigma}$ is the cross section for the partons to collide and give the final state of interest; and $\hat{s} \approx x_1 x_2 s$, with $\hat{s}$ the square of the constituent c.m. energy, s the square of the total c.m. energy.

For gluons the dominant behavior of F is qualitatively as $(1-x)^5$, for valence quarks as $(1-x)^3$, for sea quarks as $(1-x)^7$. This is Q^2 dependent and is modified by scaling violations, but not too much. Then for the two types of collisions gluon-gluon or valence quark-sea quark, the product $FF' \sim (1-x)^{10}$.

Three types of behavior of $\hat{\sigma}$ are of interest. For production of a single particle, $\hat{\sigma} \sim \delta(\hat{s}-m^2)$. For a hard scattering, including pair production, $\hat{\sigma} \sim \text{constant}/\hat{s}$. For a pointlike cross section, e.g. a short distance constituent interchange, $\hat{\sigma} \sim \hat{s}$. Since $\hat{s} \approx x_1 x_2 s$, these have slightly different x dependence in the integrand for different $\hat{\sigma}$, but in all cases the $(1-x)^{10}$ dominates.

For single production of a particle of mass m, $x \approx m/\sqrt{s}$. For pair production, $x \approx 2m/\sqrt{s}$. For large p_T production, $x \approx 2p_T/\sqrt{s}$.

Suppose we ask for <u>constant event production rate.</u> If we increase s, we decrease x and we increase $(1-x)^{10}$, so σ goes up (phase space effects are correctly included in the actual calculations as well). The event production rate per second is $\sigma\mathcal{L}$. We can also increase $\sigma\mathcal{L}$ by leaving $\sqrt{s}$ fixed and increasing $\mathcal{L}$. Because of the characteristic behavior of σ with s, the $\sigma\mathcal{L}$ curve is about the same for most reactions.

The $\sigma\mathcal{L}$ curve is shown in Fig. 15.1, calculated with full scaling violations, all x dependence, etc. While this figure is very useful for understanding the trade off between $\mathcal{L}$, $\sqrt{s}$, several caveats must be kept in mind:

(a) It is necessary to check that the total event rate is large enough to see the signal (e.g. at least 100 events/experiment or whatever is appropriate).

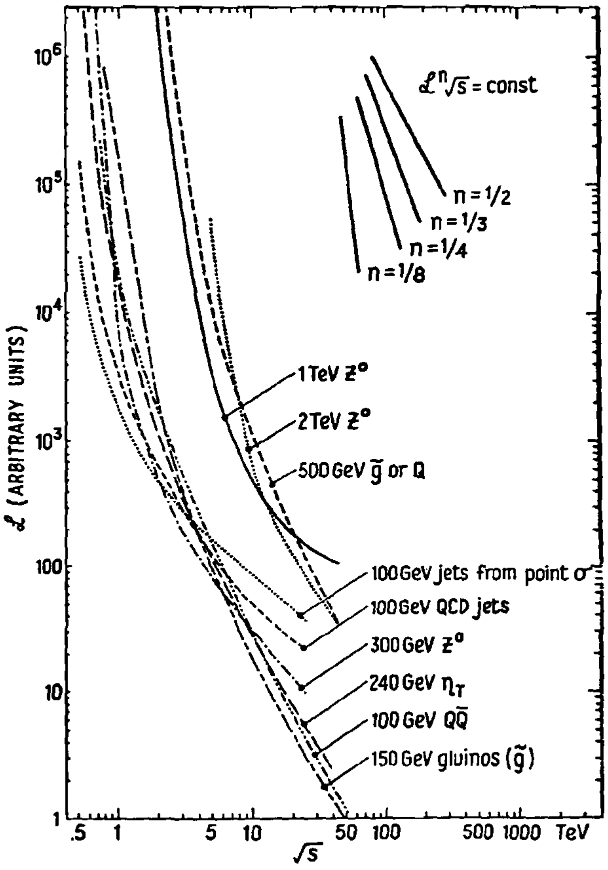


Fig. 15.1. This figure shows curves of constant production physics. (See text for details.)

(b) If the threshold for the process in question is at an energy above the machine's top energy, no increase in $\mathcal{L}$ will help.

(c) Only the production rate is considered here. If $\mathcal{L}$ gets too large the experiment may not be do-able. Even at useable $\mathcal{L}$, the background problems may be worse at higher $\mathcal{L}$ than at larger $\sqrt{s}$. Alternatively, the event multiplicity is larger at high energies.

In spite of these qualifications the lessons of Fig. 15.1 are important to keep in mind.

There is another aspect of the relation between luminosity and energy that should be discussed. On the whole the traditional reaction of the particle physics community has been to go to higher energy. It is not obvious that that will always be the right decision. One can imagine worlds in which intense sources of second and third generation quarks and leptons that allow detailed studies of their rare decays could be the crucial experimental ingredients to success, or in which high statistics study of 100 GeV physics would be more informative than low statistics study of 1 TeV physics. Of course, one can imagine the opposite as well. An obvious example is if higher energy brings new physics with cross sections larger than we expect. Then the curves in Fig. 15a are not relevant. This is, of course, just one aspect of the adventure of going into the unknown territory of higher energies. If choices are necessary for budgetary reasons, our point is that the luminosity frontier should be considered as well as the energy frontier.

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