Fermi National Accelerator Laboratory

FERMILAB-CONF-90/29-T
February, 1990

TEVATRON COLLIDER PHYSICS *

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Abstract

The physics of hadron colliders is briefly reviewed. Issues for further study are presented. Particular attention is given to the physics opportunities for a high luminosity (≥ 100 pb^{-1}/experiment/run) Upgrade of the Tevatron Collider.

1 Introduction

This workshop is dedicated to the study of the physics opportunities at Fermilab in the 1990's. The operation of the Tevatron Collider at significantly increased luminosity will provide a major source of these opportunities. The total integrated luminosity in the 1990's at $\sqrt{s} = 2$ TeV should be in excess of *one inverse femtobarn* and by 1995 a typical integrated luminosity (per experiment per run) may well be in excess of 100 pb^{-1}. The plans for the Tevatron Upgrade are discussed in detail by S. Holmes[1)].

As far as can be foreseen in 1989, the three generation standard model will be as healthy in the 1990's as it is today. Thus, much attention will be focused on finding top, searching for the Higgs boson, pinning down the KM matrix elements through mixing and CP violation measurements, and more precisely testing the gauge structure of the standard model.

In the following Sections, both the standard model and some possible extensions are discussed. Within the standard model I touch on tests of QCD, what can be learned from single and pair production of Electroweak bosons, the signals and associated discovery reach for top, and b physics potential. Beyond the standard model I explore the possibilities of new gauge bosons ($W^{\pm\prime}$ and $Z^{0\prime}$), enlarging the

*Talk presented at Physics at Fermilab in the 1990's, Breckenridge, CO, August 15-24, 1989.

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

symmetries via supersymmetry, new dynamics replacing the standard Higgs, and composite quarks and/or leptons.

2 Precision Tests of QCD

In hadron colliders the fundamental collisions of interest at high energy are the subprocesses with the constituents of the proton and antiproton as the initial states. There are three basic features of these interactions that give hadron colliders their unique character. First, many different subprocesses can be studied. Unlike e^+e^- colliders subprocesses for a variety of initial states (u, d, s, c, b, or t quarks, and gluons) are accessible in the same experiment. Second, the energy of the subprocess, $\sqrt{\hat{s}}$, is not fixed. Therefore by increasing the luminosity, higher subprocess energies can be studied at fixed hadron collider center of mass energy. Finally, QCD predicts the behaviour of the distribution function of the various partons as a function of subprocess energy as well as the subprocess cross section itself.

Processes involving high momentum transfer are calculable and testable. Theory predicts both the basic parton cross sections and the Q^2 evolution of the structure functions which determine the parton luminosities for the initial quarks and gluons in the subprocess. Final state quarks and gluons are identified experimentally as well collimated jets of hadrons.

Comparisons between theory and experiment for a variety of jet physics have been very successful both at CERN S$\bar{p}p$S ($\sqrt{s} = 630\,GeV$) and the Tevatron ($\sqrt{s} = 1.8$ TeV). One such comparison between theory and experiment for inclusive jet production is shown in Fig. 1.

The behaviour expected by theory agrees very well with the experimental data. In particular, the scale variation (Q^2) as a function of $\sqrt{s}$ is in agreement with theoretical expectations. Other tests of the theory such as the dijet angular distribution or the ratio of 2/3/4 jet events also agree with QCD expectations.

In all respects the qualitative agreement between QCD and the observed jet phenomena in hadron collisions is spectacular. The emphasis for the coming decade will shift to precision tests. Thus the experimental imperative will be to reduce the systematic errors in jet measurements. The associated theoretical issue is how to match perturbative calculations (beyond leading order) to the measured cross sections.

Some of the precision tests which will be important in the coming years are the production of electroweak gauge bosons at high transverse momentum and Drell-Yan production. Another example is the direct photon production process. This last process is interesting because the energy of the photon can be measured very accurately experimentally and the complete next to leading order ($\alpha\alpha_s^2$) calculation of the cross section is available[4)]. The main problem theoretically is that the experimental requirement of photon isolation is difficult to implement in a natural way in the order ($\alpha\alpha_s^2$) QCD calculation.

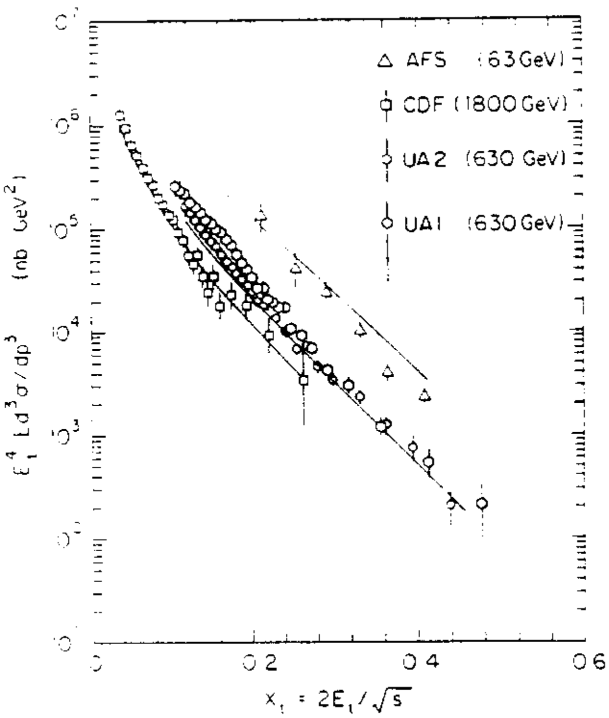

Figure 1: Scaled jet cross section as a function of $x_t = 2E_t/\sqrt{s}$ for CDF, UA1, UA2, and AFS experiments. QCD predictions using Duke and Owens structure functions Set II[2)] with a process scale $Q^2 = E_t^2/2$. From F. Abe et al.[3)].

The accurate measurement of various structure functions in hadron colliders is likely to become a major activity in the coming decade. For example, the gluon distribution can be probed using measurements of heavy quark pair production, especially bottom pair production. The charm distribution can be probed through the parton subprocess,

$$c + g \rightarrow c + \gamma. \tag{1}$$

In following sections, I will discuss some examples of how the more accurate knowledge of these distributions will be useful.

3 W and Z Physics

The production rates for the electroweak bosons $W^{\pm}$ and Z^0 are substantial at the Tevatron collider. The mass of the Z^0 is measured both in hadron interactions at the Tevatron and S$\bar{p}p$S colliders and in e^+e^- collisions at SLC and LEP. It is encouraging to observe the accuracy in the measurement of the Z^0 mass obtained by CDF at the Tevatron[5)],

$$90.9 \pm 0.3 \pm 0.2\,\text{GeV} \quad (\text{CDF}).$$

Of course, the most precise measurement of the Z^0 mass will come from LEP. Presently, the most accurate measurement for the $W^{\pm}$ mass is from CDF[6],

$$80.0 \pm 0.2\,(\mathrm{stat}) \pm 0.3\,(\mathrm{energyscale}) \pm 0.5\,(\mathrm{syst})\,\mathrm{GeV} \quad (\mathrm{CDF}).$$

The cross sections for single and pair production of electroweak bosons are given in Table 1 of Section 6. With a integrated luminosity of 100 pb^{-1} about 2×10^6 $W^{\pm}$ and 6×10^5 Z^0 will be produced.

There are two important measurements for single EW boson production. First is the ratio of the partial rate into electron neutrino via the W to the partial rate into electron positron via the Z,

$$\begin{aligned} R &= \frac{\sigma(\bar{p}p \to W \to e\nu)}{\sigma(\bar{p}p \to Z \to e^+e^-)} \\ &= \frac{\Gamma(W \to e\nu)}{\Gamma(Z \to e^+e^-)}\frac{\Gamma(Z)}{\Gamma(W)}R_\sigma, \end{aligned} \tag{2}$$

where

$$R_\sigma = \frac{\sigma(\bar{p}p \to W)}{\sigma(\bar{p}p \to Z)}. \tag{3}$$

The expectation for R as a function of the top quark mass, m_t, and the number of neutrinos, N_ν, as determined by Martin, Roberts and Stirling[7], is shown in Fig. 2.

The sensitivity to the mass of top and the number of neutrinos arises due to their contribution to the width of the W and Z. Hence the preliminary value of R reported by CDF[6],

$$R = 10.3 \pm 0.8\ (\mathrm{stat}) \pm 0.5\ (\mathrm{sys}), \tag{4}$$

constrains the number of generations and the range of top masses. The measurement of the Z width at LEP and SLC rules out both a fourth generation and a top mass much below $M_Z/2$. The limits on top masses from existing searches at CDF rule out top masses which allow the $W \to t + \bar{b}$ decay if top decays in the way predicted in the three generation standard model. The measurement of R is sensitive to top masses between $M_Z/2$ and $M_W - m_b$ independent of decay mode.

One nonstandard decay mode which is natural in both technicolor and supersymmetric alternatives to the standard model is the decay,

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

to a charged Higgs and a bottom quark. If top is lighter than the W, then this decay mode dominates, the present method of looking for top in final states with electrons or muons fails, and the existing bounds disappear.

Therefore, it is essential to improve the accuracy of this measurement in the future. More generally, R is a measure of the ratio of W/Z widths. Combined with a

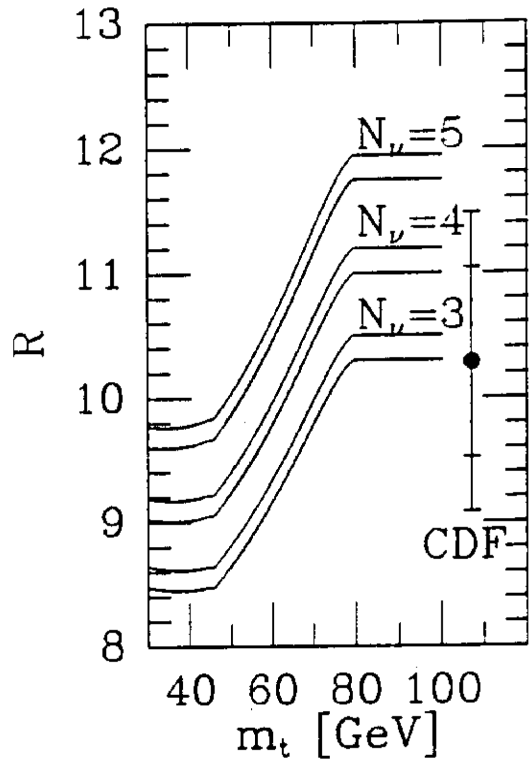

Figure 2: Comparison of data and theory for the R ratio.

precise measurement of the Z width as expected at LEP. An accurate measurement of the W width can be extracted. If the combined statistical and systematic errors on the measurement of R can be reduced to ± 0.1 in a $100 pb^{-1}$ run, the ratio of W/Z widths will be measured to one percent. Thus this ratio will be known as well as the Z width itself. The statistics is dominated by the number of $Z^0 \to l^+ l^-$ decays observed, and it is easy to determine that this error can be reduced to less than one percent. The systematic errors are more difficult, and extensive study will be required to estimate how much these errors can be reduced. There are also theoretical uncertainties in the ratio R_σ. The main uncertainties in R_σ are:

1. Uncertainty in the ratio of the valence up to valence down distributions at values of x relevant to W production. The present structure functions vary significantly in that region. A number of proposals have been made to improve these uncertainties, including a method of Berger et al.[8)] to use a measurement of the asymmetry of W production to directly determine the required ratio of distributions.

2. Uncertainty in the contribution of the charm quark to the production of W^+ from the $c + \bar{s}$ initial state and to the production of Z^0 from the $c\bar{c}$ initial state. The net effect on R_σ is about 4 ± 2 percent at present. As discussed in the previous section, one might try to directly measure the charm quark distribution function in hadron colliders by observing the a charm quark associated with a

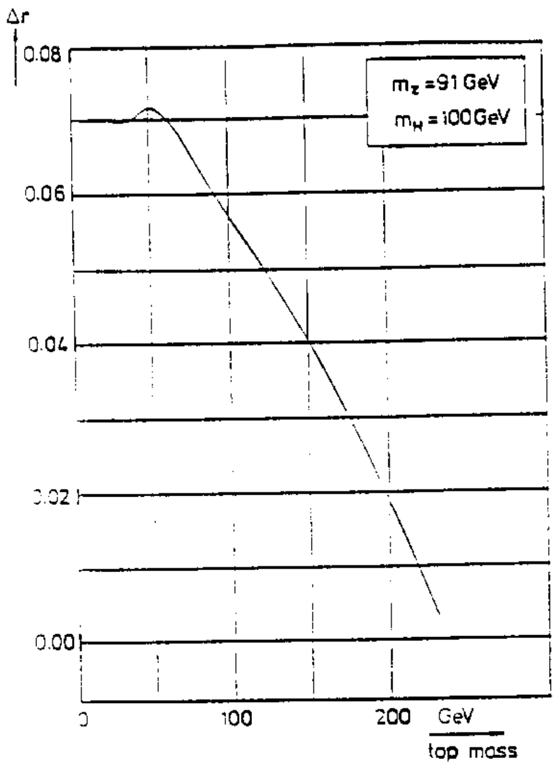

Figure 3: δR versus m_t for M_Z= 91 GeV and m_H = 100 GeV.

high transverse energy photon final state.

It is probable that the errors in the ratio R_σ due to theoretical uncertainties can be reduced over time to under one percent.

The second important measurement for single EW boson production is the mass difference between the W and the Z. In the standard model the radiative corrections modify the relation between the parameters of the model. Defining $\sin^2(\theta_w)$ ala Marciano and Sirlin[9],

$$\begin{aligned} \sin^2(\theta_w) &\equiv 1 - \frac{M_W^2}{M_Z^2} \\ &= \frac{1}{2}\left[1 - \sqrt{1 - \frac{1}{1-\delta r}(\frac{74.562\,\mathrm{GeV}}{M_Z})^2}\right]. \end{aligned} \quad (5)$$

The radiative corrections are contained in the factor δr which is a function of both the top mass and the Higgs mass. The dependence on the top mass is large, as shown in Fig. 3. The dependence on the Higgs mass is logarithmic and weak.

The resulting constraint on the top mass as a function of the measured values of the W and Z masses is shown in Fig. 4.

Assuming the uncertainty in the measurement of $M_Z - M_W$ can be reduced to ±100 MeV, then the mass of top will be constrained to within ±10 GeV.

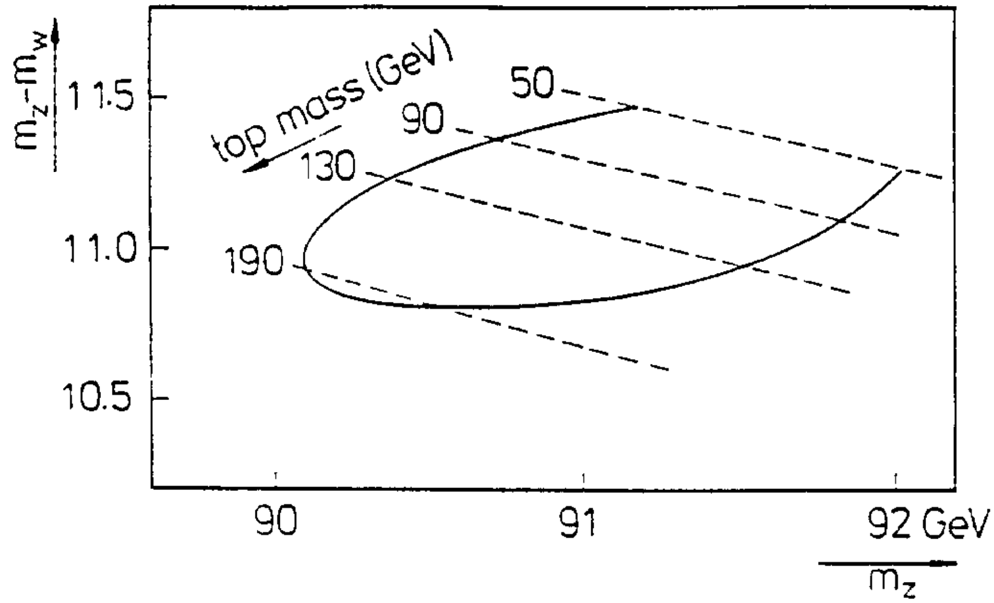

Figure 4: Relation between $M_Z - M_W$ and the top mass as a function of M_Z. The dashed curves are labeled by the associated top mass. The solid curve gives the bounds on the standard model parameters obtained by combining data from the $\bar{p}p$, e^+e^- and νq sectors[10].

Furthermore, at this level of accuracy, the measurement of M_W becomes a very sensitive probe of possible physics beyond the standard model. The feasibility of measuring the mass difference to this precision requires further study.

4 Top Discovery

Top is the only remaining undiscovered fermion in the standard model. Its mass is a fundamental parameter of the standard model. The current bounds on top imply that the top mass is not significantly less than the W mass. Such a heavy top is interesting from both the theoretical and practical viewpoint. I will mention some of the theoretical aspects at the end of this Section. However from a purely practical viewpoint the heavier the top mass the more interesting a top factory becomes. The kinematic range available to explore new physics in top decays is substantial for heavy top. Rare decays look particularly interesting if the top mass turns out to be 160 GeV or more. But first I will review the production and detection of top as a function of its mass.

There are two main production mechanisms for top. First, if kinematically allowed, top can be produced in the decay products of EW bosons produced in hadron collisions. For the CERN S$\bar{p}p$S energy the $W^\pm$ decay is the dominant production mode for top with a mass below 80 GeV. Second, since the top quark is colored, top pairs can be produced from a two gluon or quark-antiquark initial state via the strong interactions. This mechanism is the dominant mechanism at

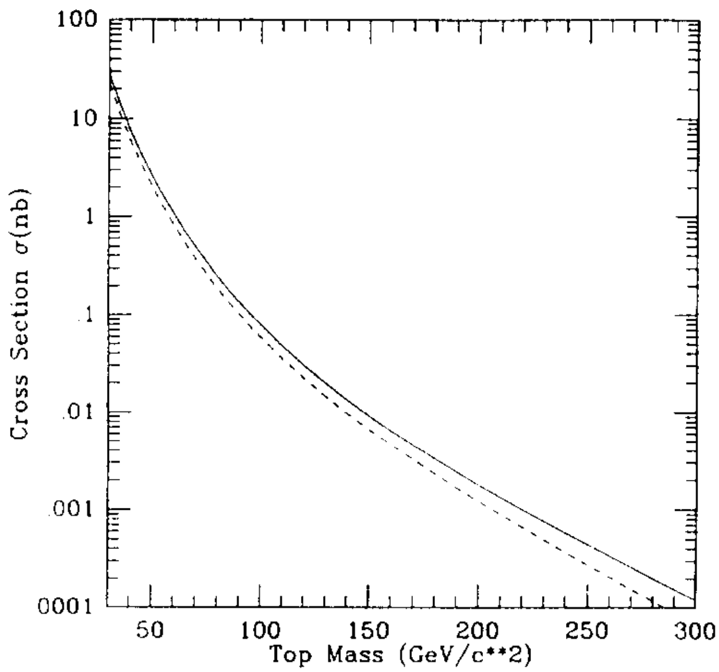

Figure 5: The total cross section for top pair production as a function of m_t. The solid curve is for $\sqrt{s}$ = 2 TeV and the dashed curve is for $\sqrt{s}$ = 1.8 TeV. EHLQ structure functions[11] with Λ = 290 MeV were used.

Tevatron energies (and above) even for top masses below M_W. For m_t above M_W, only gluon fusion contributes.

The rate of top production due to the gluon fusion mechanism is shown in Fig. 5 as a function of top mass.

At $\sqrt{s} = 1.8$ TeV, with an integrated luminosity of $5pb^{-1}$, 1000 top pairs are produced up to a top mass of 85 GeV and 100 top pairs are produced up to a top mass of 120 GeV. At $\sqrt{s} = 2$ TeV, with an integrated luminosity of $100pb^{-1}$, 1000 top pairs are produced up to a top mass of 160 GeV and 100 top pairs are produced up to a top mass of 250 GeV.

There are two principal modes in which to search for top. The bounds on top mass obtained by either method assumes the standard model decay branching ratios.

One method triggers on a pair of isolated leptons. If each top quark decays semileptonically, then the signature is two leptons well isolated from the jets associated with the hadron decay products. In particular, for 40 GeV $\leq m_t \leq M_W$, the $e^{\pm}\mu^{\mp}$ mode is essentially background free and provides an ideal signature. Because the combined branching rate for this mode is only 2%, the reach is somewhat limited. The present CDF bound based on this method is[12],

$$28 \leq m_t \leq 72\, GeV.$$

The other method of searching for top triggers on one charged lepton, some number of jets and missing energy. This method is sensitive to the case in which one top quark decays semileptonically and the other nonleptonically. The branching ratio for the final state with an electron, antineutrino, and two or more jets is 14%. However, this mode has a background from the production of a high transverse momentum W accompanied by QCD jets. This background has been calculated for W plus two jets[13,14] and W plus three jets[14]. The rate for W plus four jets is being calculated at this time. The present CDF bound based on this method is[12],

$$40 \leq m_t \leq 77\,\mathrm{GeV}.$$

For $M_W < m_t \leq 120$ GeV the background from W plus two jets is serious. The processes which produce W plus two jets are,

$$\begin{aligned} q + \bar{q} &\rightarrow W + g + g \\ q + g &\rightarrow W + q + g \\ g + g &\rightarrow W + q + \bar{q}. \end{aligned}$$

The theoretical rate for this background has been calculated by Mangano and Parke[13]. For a 90 GeV top mass the signal to background ratio is approximately one.

For heavier m_t the top decays more frequently produce an event with three or four observable jets. Since the rate for W plus three jets is expected to be approximately 1/5 that for W plus two jets, the signal to background improves considerably. Therefore with increasing luminosity the range for a top discovery will improved dramatically in this mode. For 100 pb^{-1} at $\sqrt{s} = 2$ TeV, the discovery limit for top will exceed 220 GeV.

A good vertex detector could also aid in the identification of heavy top in the lepton, missing energy and jets mode. If four jets are observed, two of them should be primary b quarks.

Finally, it is interesting to speculate on the theoretical implications of heavy top. There are many theoretical ideas which suggest the possibility of a heavy top[15]. One basic element of a number of these speculations is the observation that the one loop contribution to the parameters in the scalar potential is opposite for fermions to the contributions for the EW bosons and the Higgs scalar itself. For example, the logarithmic corrections for the scalar self interaction λ as a function of the mass scale probed (denoted M here) can be expressed as,

$$\lambda(M) = \lambda(v) + B \log M/v.$$

where v is the vacuum expectation value of the scalar field ($\simeq 125\,GeV$) and,

$$v^4 B \simeq (2M_W^4 + M_Z^4) - 4\sum_f m_f^4 + m_H^4.$$

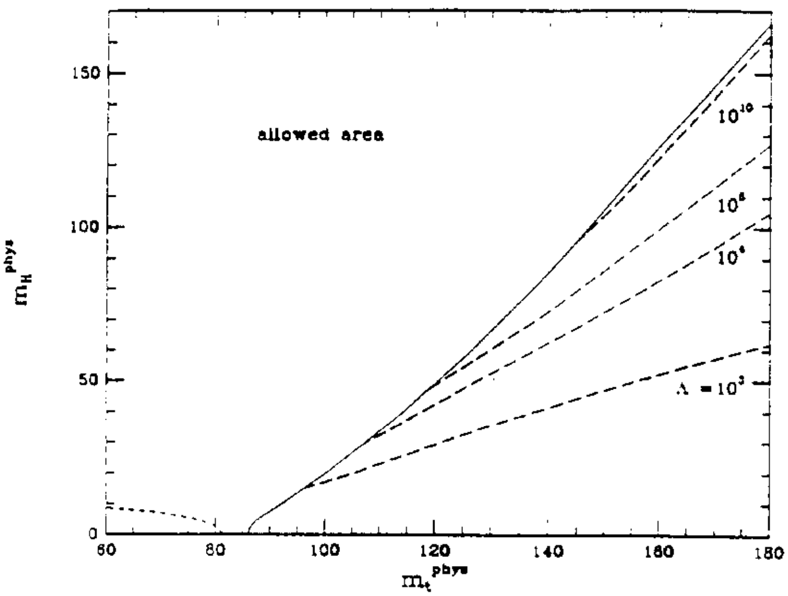

Figure 6: The vacuum stability bounds for different cutoffs ($M = \Lambda$ here). The solid curve is for $\Lambda = 10^{15}$ GeV and the dashed curves represent lower cutoffs. The lower bound for top masses below the W mass is the standard Linde-Weinberg bound and is shown as a dotted line. See Lindner, Sher, and Zaglauer[16)] for details.

If $B < 0$, λ becomes negative and the scalar potential becomes unstable at some scale $M > v$.

Only the top quark gives a significant negative contribution to B. Since the top mass and the Higgs mass are the only undetermined parameters in the standard model, the requirement that B is positive up to some scale M implies a lower bound on the Higgs mass as a function of the top mass for large top masses. The bounds computed by Lindner, Sher and Zaglauer[16)] are shown in Fig. 6.

5 Bottom Production

To study b physics such as mixing, rare decays, and CP violation requires large event rates. The benchmark in b physics is provided by CESR. A peak luminosity of $\mathcal{L} = 10^{32}$ cm^{-2} sec^{-1} has already been attained. This luminosity allows the production of 10^6 $b\bar{b}$ pairs per year on the $\Upsilon 4S$ peak. After the CESRII upgrade a one year run will collect 10^7 $b\bar{b}$ pairs. Of course, for the study of B_s and baryons containing b quarks, fixed target and the Z factories will dominate. Hence, for hadron colliders to be competitive they need to have very high rates, in excess of 10^8 $b\bar{b}$ pairs per year.

The total cross section for b production in $\bar{p}p$ collisions is subject to some theoretical uncertainties. Principally these uncertainties are due to large order $\alpha_s{}^3$ contributions, and sensitivity to the gluon structure functions at small x where they are not well known. Nonetheless, it is clear that with 100 pb^{-1} at $\sqrt{s} = 2$ TeV, at least 10^{10} $b\bar{b}$ pairs will be produced per run.

What studies should be done with all these produced b's? There are many important physics milestones on the way to the eventual study of CP violation in the B meson system. Some of these milestones are:

1. Map out the dynamics of $b\bar{b}$ production.

2. Identify reconstructable final states for B_d and B_s mesons.

3. Look for secondary vertices associated with the decay chain $b \to c \to s$.

4. Study mixing in the same/opposite sign dimuons. Can the impact parameter dependence of the ratio be studied with a good vertex detector.

5. Study rare decay modes.

At the SSC both the luminosity of the machine and the production cross section increase by approximately a factor of ten. To be able to handle the b physics environment at the SSC, the study of b physics in hadron colliders needs to begin in earnest *now*.

6 Electroweak Pair Production

The electroweak gauge boson pair cross sections are important probes of the gauge couplings and the nature of the EW symmetry breaking. The single and pair production cross sections are shown in Table 1.

From the production rates in Table 1 the possibility of studying W^+W^-, $W^\pm Z^0$, and Z^0Z^0 processes does not look encouraging even with 100pb^{-1} of integrated luminosity. Less than 1000 events will be produced in all these modes.

The situation for detection is also bleak. The four jet background overwhelms the EW pair signal with both EW bosons decaying into hadrons. For the opposite case of both EW bosons decaying into leptons, the rates are too small

Table 1: Total cross sections for single and pair production of electroweak gauge bosons. No rapidity cuts were imposed. For $W^\pm\gamma$ the photon energy was required to be more than 10 GeV. All cross sections are in *picobarns* .

$\sqrt{s}$	Process					
(TeV/c^2)	$W^\pm$	Z^0	W^+W^-	$W^\pm Z^0$	Z^0Z^0	$W^+\gamma$
1.8	1.9×10^4	5.9×10^3	6.1	1.2	0.8	15
2.0	2.1×10^4	6.5×10^3	7.5	1.8	0.9	16

even with 100pb^{-1} of integrated luminosity. For the case of one hadronic and one leptonic decay, the rates are too small for all but the production of W^+W^-. In this remaining case the possibility of detection depends on the *background* from top decays. If top is heavier than the W, then top decays present a serious background to observation of W^+W^- pairs. If the top mass is between 85 and 100 GeV, the situation is hopeless. However for very heavy top there is some possibility that the W^+W^- pairs might be observed in the kinematic range below the $\bar{t}t$ production threshold. This possiblity merits further study.

In any case it is still possible to see new physics effects which produce dramatic changes in the EW pair cross sections, e.g. a large resonance in W^+W^- or $W^{\pm}Z^0$. I will come back to this point in Section 9.

A more promising class of processes to study at the Tevatron is the associated production of a W or Z with a photon. For example, the cross section $u + \overline{d} \rightarrow W^+ + \gamma$ given in lowest order by,

$$s^2 \frac{d\sigma_{q\bar{q}'}}{dtdu} = \sqrt{2}/3\alpha(G_F M_W^2)\frac{(Q_1 u + Q_2 t)^2}{ut(s - M_W^2)^2}, \tag{6}$$

$$[sM_W^2 - ut + 1/2(u+t)^2]\delta(s + t + u - M_W^2) \tag{7}$$

where $Q_1 = 2/3$ and $Q_2 = 1/3$. This cross section vanishes at,

$$\cos\theta_{W+} = -\frac{Q_1 - Q_2}{Q_1 + Q_2} = -1/3. \tag{8}$$

This radiation zero is sensitive to the specific form of the $W^+W^-\gamma$ coupling dictated by the gauge theory[17)]. It is therefore sensitive to an anomalous magnetic moment of the W. However, this cross section can be used to bound any anomalous magnetic moment only if this radiation zero survives the order α_s corrections. The complete order α_s QCD corrections to the cross section and differential distributions for this process have recently been calculated[18)]. Since the radiation zero survives, it is worthwhile to study the sensitivity of the Upgrade to an anomalous magnetic moment for the W.

7 New Electroweak Bosons

New $W^{\pm}$ and Z^0 bosons are required in almost any model which enlarges the electroweak gauge group beyond the $SU(2)_L \otimes U(1)_Y$ of the standard model. One class contains left-right symmetric models[19)] based on gauge groups containing,

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_Y, \tag{9}$$

which restores parity invariance at high energies. These models require an additional charged gauge boson. Other models, notably the electroweak sector derived from $SO(10)$ or E_6 unified theories, exhibit additional $U(1)$ invariances. These will

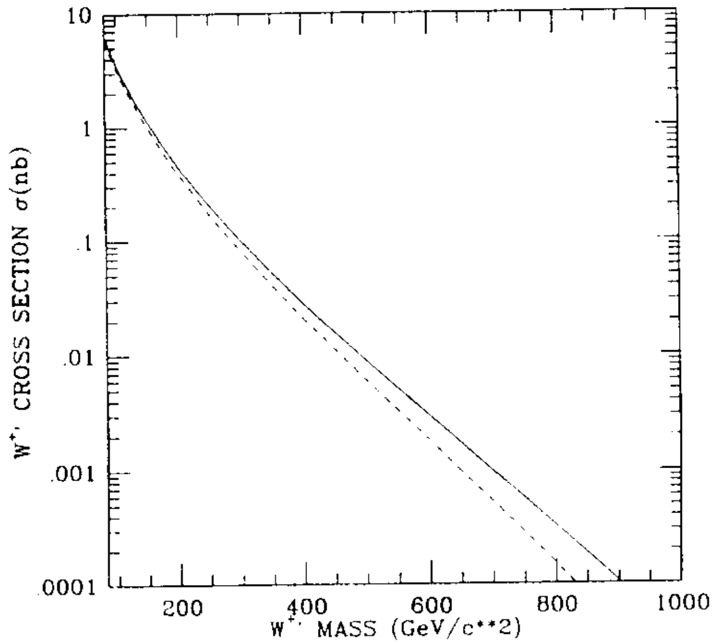

Figure 7: Total cross section, σ (nb), for production of a new charged gauge boson, $W'^{\pm}$, in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV (solid line), and 2.0 TeV (dashed line). The EHLQ structure functions[11] with $\Lambda = 290$ MeV were used. The same couplings as the standard $W^{\pm}$ are assumed.

contain an extra neutral gauge boson[20]. All these models have new gauge coupling constants which are of the order of the $SU(2)_L$ coupling of the standard model. In order to be consistent with existing limits from deep inelastic leptoproduction experiments, the mass of any new gauge boson must be at least a few hundred GeV/c^2.

Assuming a new charged gauge boson, W', with the same coupling strengths as the ordinary W, we obtain the cross section for production in $\bar{p}p$ collisions shown in Fig. 7 at the Tevatron collider.

For a new neutral gauge boson, Z'^0, with the same coupling strengths as the ordinary Z, the production cross sections are similar to the corresponding W^+ cross sections.

Again assuming standard model couplings, the discovery of new intermediate neutral gauge boson, a Z'^0, will require at least 100 produced events. The discovery of a new intermediate charged gauge boson, a $W^{\pm}$, will require at least 200 produced events for the sum of the W'^+ and W'^- final states. For $\sqrt{s} = 1.8$ TeV and an integrated luminosity of 5pb^{-1}, the discovery limits are 390 GeV for a Z'^0 and 400 GeV for a W'. For $\sqrt{s} = 2$ TeV and an integrated luminosity of 100pb^{-1}, the discovery limits are 670 GeV for a Z'^0 and 730 GeV for a W'.

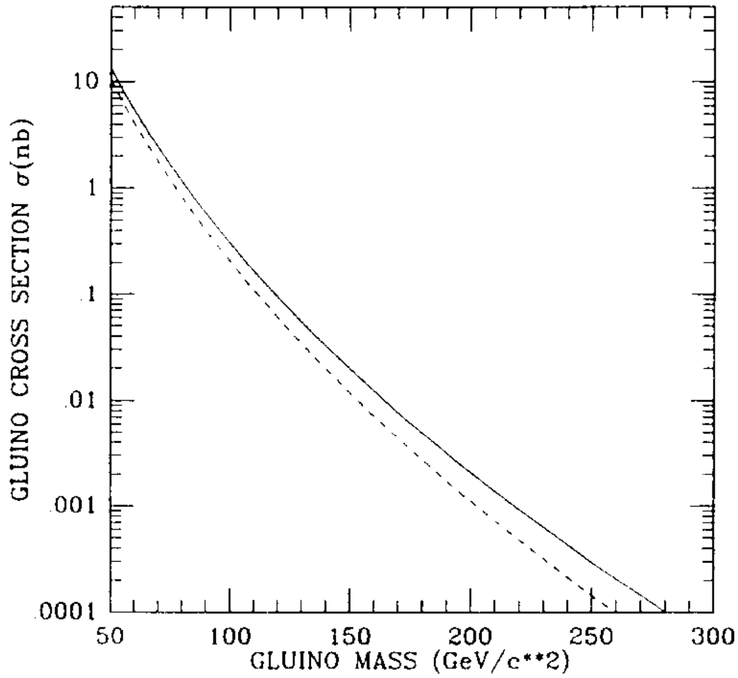

Figure 8: Gluino pair production cross section in nanobarns. All squark masses are assumed large relative to the gluino mass. The cross section for $\sqrt{s} = 2$ TeV and $\sqrt{s} = 1.8$ TeV are denoted by solid and dashed curves respectively. EHLQ structure functions[11)] with $\Lambda = 290$ MeV were used.

8 Supersymmetry

In supersymmetric theories there is a symmetry which pairs fermions and bosons in the same supermultiplet. If supersymmetry occurs in nature, this symmetry must be broken, since the superpartners of the ordinary fermions and gauge bosons are not yet observed. The superpartners of the usual quark and gluon are a scalar color triplet squark and a spin 1/2 color octet gluino. They can be produced via the usual strong interactions. The cross section for gluino pair production is shown in Fig. 8.

In the simplest decay pattern, the gluino decays into a gluon and the lightest mass neutral superpartner (the neutralino), or into a squark and quark. The squark decays into a gluino and quark or into a neutralino and quark. The particular decay mode depends on whether the squark or gluino is heavier. The neutralino escapes the detector without interactions, leaving missing energy as its only signature.

Using this missing energy signal, CDF has put limits on the possible masses for gluinos and squarks as shown in Fig. 9.

From the present 5pb^{-1} run the discovery limit for a squark or gluino should increase to 140 GeV and with an integrated luminosity of 100pb^{-1} the discovery limit

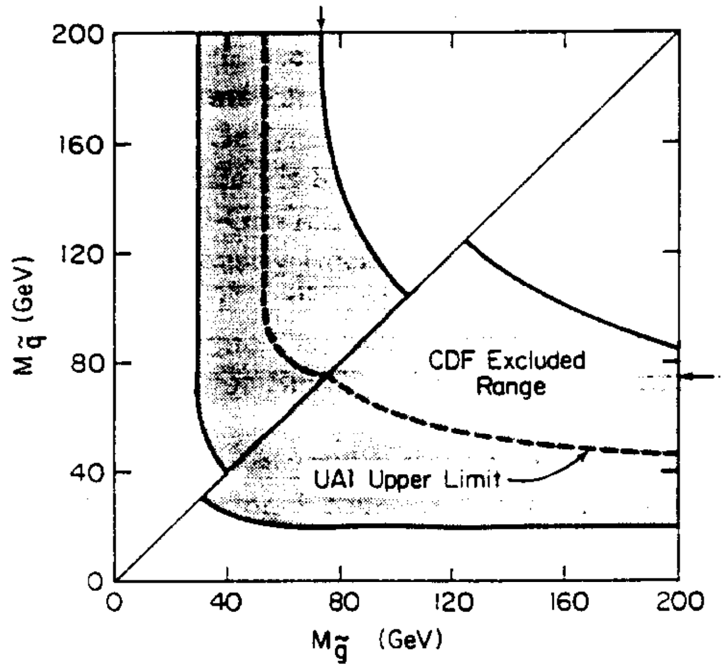

Figure 9: Gluino and light squark mass limits from CDF resulting from the 1987 Tevatron collider run.

will be extended to $210\,GeV$.

It might even be possible to observe some of the superpartners that can't be produced strongly ($\tilde{e}, \tilde{\nu}_e, \tilde{\mu}, \tilde{\nu}_\mu, \tilde{\tau}, \tilde{\nu}_\tau, \tilde{W}, \tilde{Z}, \tilde{\gamma}, \tilde{H}^0$) at the Upgraded Tevatron. Because of the very high luminosity at the Upgrade, Drell-Yan and virtual W and Z processes may extend the discovery potential for some of these superpartners to masses inaccessible to Z^0 decays at e^+e^- colliders. This possibility deserves study.

9 A New Dynamics

If new strong dynamics at the TeV scale replaces the standard model scalar sector, then it is reasonable to expect that some "low" energy signals of this new physics might exist. The two options for such a new dynamics are:

- Replace the Higgs sector only. The original example is Technicolor[22)]. More recently a modification of the usual Technicolor, called Walking Technicolor[23)], has renew interest in this dynamics. It relieves the problems with flavor changing neutral currents found in the original version of Technicolor.
- Composite quarks/leptons. If there is a new dynamics that replaces the Higgs sector, it is possible that quarks and/or leptons are also composite with a dynamics at the same scale, i.e. in the few TeV range.

How can these ideas be tested at the Tevatron operating at high luminosity?

9.1 Walking Technicolor

Walking Technicolor models naturally allow two scales of new dynamics [24]. The technifermions are assumed to be left-handed doublets and right-handed singlets under the weak interactions. Under the Technicolor group, assume that one set of Technifermions are in the fundamental representation (R_1), and the other in a higher dimensional representation (R_2). Define Λ_i as the characteristic scale of chiral symmetry breaking for the Technifermions in Technicolor representation R_i. Then with some reasonable assumptions, the dynamics of these models can be calculated. The results are:

- $\Lambda_1 \ll \Lambda_2$
- Λ_2 is set by the scale of electroweak symmetry breaking.
- The Technihadrons containing only T_1 Technifermions are potentially observable at Tevatron energies.

With regard to the last point, the most easily observable Technihadrons containing T_1 Technifermions are the Technirho ρ_1, a $\overline{T}_1 T_1$ state with $J^{CP} = 1^{--}$, and the Technipion π_1, a $\overline{T}_1 T_1$ state with $J^{CP} = 0^{+-}$. Both these particles are triplets under $SU(2)_L$. The ρ_1 state can be produced in hadron collisions through the process,

$$q + \overline{q} \rightarrow (\text{virtual}) W^{\pm}, Z^0, \text{or} \gamma \rightarrow \rho_1. \quad (10)$$

The ρ_1 decays mainly into pairs of Technipions, one Technipion and one EW gauge boson, or a pair of EW bosons depending on whether $m_{\rho_1} > 2m_{\pi_1}$, $m_{\pi_1} + \mathrm{M_W} < m_{\rho_1} < 2m_{\pi_1}$, or $2M_W < m_{\rho_1} < m_{\pi_1} + \mathrm{M_W}$. By comparison, the π_1 is expected to decay to the heaviest quark pair allowed.

In a specific model one finds that, for $m_{\rho_1} = 250$ GeV, the π_1 has a mass of 130 GeV, so $\rho_1 \rightarrow \pi_1 + \mathrm{M_W}$ is the dominate decay of the Technirho ρ_1. The width of the Technirho is approximately 450 MeV. The total cross section at $\sqrt{s} = 1.8$ TeV for the $\rho_1^{\pm}$ decaying into $W^{\pm}$ plus anything is 4.4 pb while the cross section for the ρ_1^0 decaying into Z^0 plus anything is 1.8 pb . Such a resonance should be observable above the $W^{\pm}(Z^0)$ plus two jet background at the Upgraded Tevatron.

9.2 Composite Quarks/Leptons

If quarks are composite, then the interaction between quarks at low energies relative to the scale of their compositeness contains a contact term in addition to the usual QCD gluon exchange interaction[25]. One possible form of this new contact interaction is,

$$\frac{4\pi}{\Lambda^{*2}} \eta \overline{q} \gamma^{\mu} \frac{(1-\gamma_5)}{2)} q \overline{q} \gamma_{\mu} \frac{(1-\gamma_5)}{2)} q. \quad (11)$$

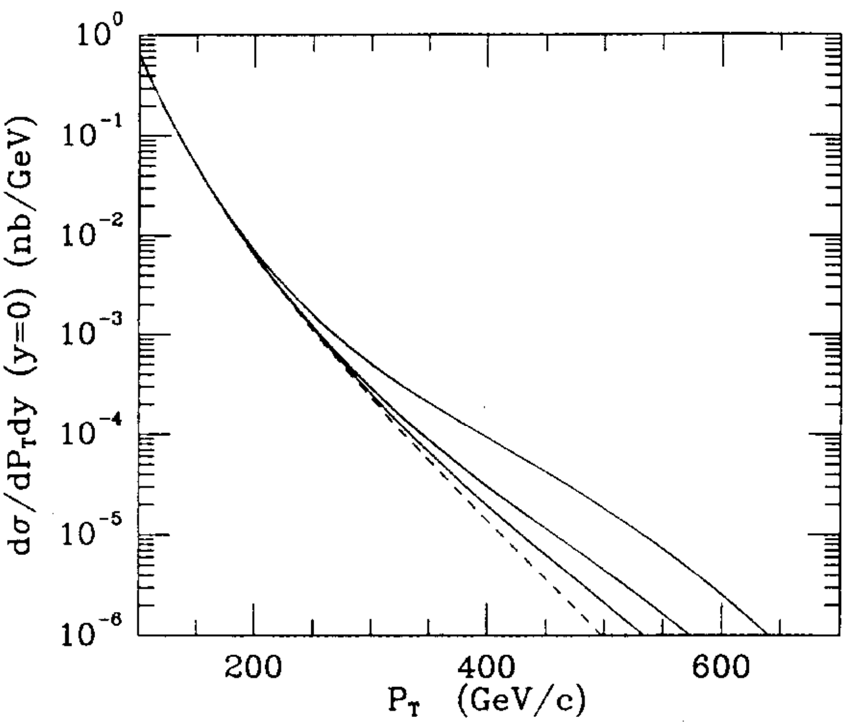

Figure 10: The effect of quark compositeness on the jet differential cross section as a function of jet p_T. The dashed curve is the QCD result for $\sqrt{s} = 2$ TeV, while the upper, middle and lower solid curves represent the compositeness scales $\Lambda^* = 1$, 1.5 and 2.0 TeV respectively. EHLQ structure functions[11)] with $\Lambda = 290$ MeV were used.

The low energy signal for this contact interaction is a modification of the jet differential cross section at high transverse momentum. The effects of various scales of quark compositeness Λ^{*2} are shown in Fig. 10.

If both quarks and leptons are composite, a new type of contact term can arise[25)],

$$\frac{4\pi}{\Lambda^{*2}}\eta\bar{l}\gamma^{\mu}\frac{(1-\gamma_5)}{2}l\bar{q}\gamma_{\mu}\frac{(1-\gamma_5)}{2}q. \tag{12}$$

The modification of the Drell-Yan cross section again produces a large enhancement

Table 2: The discovery limits for observation of the effects of quark compositeness in hadron collisions at the Tevatron.

Process Probed	$\sqrt{s} = 1.8$ TeV 5 pb^{-1}	$\sqrt{s} = 2$ TeV 100 pb^{-1}
Quark Substructure	1.0 TeV	2.3 TeV
Drell-Yan contact term	1.2 TeV	2.7 TeV

for high subprocess energy ($\sqrt{\hat{s}}$) even for rather large values of Λ^*. The resulting discovery limits for the present run and a typical run with the Upgraded Tevatron are shown in Table 2.

10 Summary

For most of the next decade the Tevatron Collider will provide the highest energy parton collisions in the world. The Upgrade will greatly increase the luminosity of the $p\bar{p}$ collisions, and thus make even higher parton level energies available. The physics that can be explored at the Tevatron in the 1990's is rich and varied.

For the strong interactions, the agreement between QCD theory and experiment is spectacular. The major push of the 1990's will be precision tests of QCD. Experimentally this means reducing the systematic errors in measuring the energy of jets and better determinations of the structure functions for gluons, charmed quarks, and the ratio of u_v/d_v quarks. On the theoretical side, the ability to match theoretical calculations to experimental cross sections needs improvement.

The electroweak interactions will also be probed in fundamental ways in hadron collisions. Dramatic improvements in the ability to measure M_W and M_Z at CDF and UA2 open the possibility of precision tests of the EW sector in hadron colliders. Within the standard model this will lead to strong constraints on the possible values for the top mass. Finally the question of what accuracy in the measurement of the W - Z mass difference is required to put meaningful bounds on physics beyond the standard model should be studied.

The detailed study of $W^+W^-, W^{\pm}Z^0$, and Z^0Z^0 pairs will be difficult unless there is a resonance or other large deviation from the standard model expectations. The $W^{\pm}\gamma$ final state can be used to bound the anomalous magnetic moment of the $W^{\pm}$.

The study of heavy quark physics will be a major element of the physics of the 1990's. With an integrated luminosity of ≥ 100 pb^{-1}, the discovery of a standard top is assured at the Tevatron if $m_t \leq 200$ GeV. For heavy top, $m_t > M_W$, there is a theoretical lower bound on the Higgs boson mass. This bound increases as the top mass increases. The study of b physics in colliders is just beginning. The physics potential is great. With an integrated luminosity of 100 pb^{-1}, 10^{10} $b\bar{b}$ pairs are produced.

There is also considerable potential to glimpse physics beyond the standard model. For new gauge bosons (charged or neutral) which couple to the usual quarks with electroweak strength, the discovery limits should be 400 GeV from the present data and 730 GeV with 100 pb^{-1}. Superpartners of the ordinary quarks and gluons, squarks and gluinos, have discovery limits of up to 140 GeV in the present run and 210 GeV with a 100 pb^{-1} run.

A more radical departure from the standard model replaces the scalar sector with a new dynamics such as walking technicolor. In walking technicolor models with two scales, the physics of the lower scale may produce a technirho resonance in the W^+W^- and $W^\pm Z^0$ channels with a mass in the range of 250 to 400 GeV. Such a resonance would be observable in the Upgraded Tevatron.

Finally, what if quarks and leptons are composite? The discovery limit for the scale of quark compositeness is 1.0 TeV from the present run and 2.3 TeV with 100 pb^{-1}. A contact term in the Drell-Yan process associated with quark and lepton compositeness can also be probed up to 1.2 TeV in the present run and 2.7 TeV with 100 pb^{-1}.

The decade of the 1990's at the Tevatron will bring much progress in our understanding of the standard model and most likely some hints about what lies beyond as well.

References

1. Holmes, S., these proceedings.
2. Duke, D. W. and Owens, J. F., Phys. Rev. D **30**, 49 (1984).
3. Abe, F. et al., Phy. Rev. Lett. **62**, 613 (1989).
4. Aurenche, P. et al., Nucl. Phys. **B297**, 661 (1988).
5. Abe, F. et al., Phy. Rev. Lett. **63**, 720 (1989).
6. Campbell, M., "W and Z Results From CDF", presented at the *XIV International Symposium on Leptons and Photon Interactions*, Stanford, California, August 6-12, 1989.
7. Martin, A. D., Roberts, R., and Sterling, J., Mod. Phys. Lett. **A12**, 1135 (1989); Phys. Lett. **228B**, 149 (1989).
8. Berger, E., Halzen, F., Kim, C. S., and Willenbrock, S., Phys. Rev. D **40**, 83 (1989); presented by C.S. Kim at this Workshop.
9. Marciano, W.J. and Sirlin, A., Phys. Rev. D **22**, 2695 (1989).
10. Haidt, D., invited talk at the *XII International Workshop on Weak Interactions and Neutrinos*, Ginosar, Israel, April 1989; DESY Preprint 89-073 (1989).
11. Eichten, E., Hinchliffe, I., Lane, K.D. and Quigg, C., Rev. Mod. Phys. **56**, 579 (1984).
12. Sinervo, P., "Searches for New Particles at CDF", presented at the *XIV International Symposium on Leptons and Photon Interactions*, Stanford, California, August 6-12, (1989); Univ. of Penn. preprint UPR-0171E (1989).

13. Mangano, M. and Parke, S., Fermilab Pub 89/106-T (1989).

14. Berends, F.A., Giele, W.T. and Kuijf, H., Nucl. Phys. **B321**, 39 (1989); Berends, F.A., Giele, W.T., Kuijf, H., Kleiss, R., and Stirling, W.J., Phys. Lett. **B244**, 237 (1989).

15. See for example, Bardeen, W.A., Hill, C., and Lindner, M., Fermilab-Pub-89/127-T (1989), to appear in Phys. Rev. D.

16. Lindner, M., Sher, M. and Zaglauer, H., Phys. Lett. **B228**, 139 (1989).

17. Brodsky, S.J., and Brown, R.W. Phys. Rev. Lett. **49**, 966 (1982); Brown, R.W., Kowalski, K.L. and Brodski, S., Phys. Rev. D **28**, 624 (1983).

18. Smith, J., Thomas, D., van Neerven, W. L., preprint CPT-89/P.2239 (1989), to appear in Z. Phys. C.

19. For a general survey of Left-Right symmetric models see Mohapatra, R.N., *Unification and Supersymmetry*, Springer-Verlag, New York, 1986.

20. For an example in E6 see Rosner, J., Phys. Rev. D **35**, 2244 (1987).

21. Abe, F. et al., Phy. Rev. Letts. **62**, 1825 (1989).

22. Weinberg, S., Phys. Rev. D **13**, 974 (1976); **19**, 1277 (1979); Susskind, L. Phys. Rev. D **20**, 2619 (1979).

23. Holdem, B., Phys. Rev. D **24** (1981); Phys. Lett. **B150**, 301 (1985); Appelquist, T., Karabali, D. and Wijewardhana, L.C.R., Phys. Rev. Lett. **57**, 957 (1986); Appelquist, T. and Wijewardhana, L.C.R., Phys. Rev. D **35**, 774 (1987); ibid. **36**, 568 (1987).

24. Eichten, E. and Lane. K. D., Phys. Lett. **B222**, 274 (1989).

25. Eichten, E., Lane, K.D., and Peskin, M.E., Phys. Rev. Lett. **50**, 811 (1983).