Report of the Electroweak Interactions Theoretical Issues Working Group

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ABSTRACT

An interesting component of the physics program at Fermilab during the next ten years will be the precision verification of the standard model, rather than its extension. While there is a window for finding Z' gauge bosons, it is unlikely that it is possible to discover the standard model Higgs boson. Measurements of $W+\gamma$ rates can place limits on non-standard gauge boson couplings. QCD will be further tested by observation of W or Z plus multiple jets, a signal which is also interesting as a background to new particle searches. Precision measurements of the W and Z masses and the forward-backward asymmetry in Z decays can put limits on new physics.

1. Introduction

Until at least the late 1990's, the machine operating at Fermilab is likely to be a hadronic collider operating in the energy range 2 - 3.6 TeV, with a luminosity of at most 10^{39} cm^2/year. With such a device we may be unable to sail off into the uncharted domains which it is envisioned that the SSC will explore. For example, as is shown below, it is unlikely that we will be able to find the Higgs boson even if nature is cooperative. Instead, we will learn in detail about the physics which we now have only a limited understanding: gauge boson self couplings, CP violations, and precise values of standard model parameters, for example. This physics may turn out to be nearly as interesting as the more flamboyant phenomena one hopes to study at the SSC.

The topics presented to this working group were not chosen to be a complete exploration of the prospects for electroweak physics at Fermilab in the 1990's. In particular, two important subjects were not discussed by this group at all. We did not cover Charm and Bottom decays, which are interesting because they will test the understanding of the weak interaction operators at moderate energy. The B meson especially is expected to exhibit CP violation. Fortunately, this was covered by I. Bigi, working with the collider group [1]. Signals for supersymmetric particles were also explored under the aegis of the collider group, by H. Baer [2].

This paper is in several sections, each of which summarizes a talk presented to this working group. They are organized in reverse order of conventionality of the physics.

2. E_6 Gauge Boson Search*

Of the many possible Grand Unified Theories, the one with E_6 as the gauge group [3] is especially interesting, because there is a class of compactifications of the heterotic superstring which yields it as the group of grand unification [4]. Since E_6 is a rank six group, it is possible that there are one or two extra Z bosons. Many authors have examined the properties and low energy phenomenology of these new particles [5].

For the purposes of this discussion it is not necessary to go into the details of the structure of E_6 models. The results here are sensitive to only two simple assumptions. First, we note that in an E_6 model, the fermions transform as a **27**, which means that there must be twelve per generation which remain undiscovered. For these purposes we assume that all these particles are lighter than the Z', so that none of the decay channels are closed.

The second assumption concerns the coupling of the new gauge boson. At high energies, the coupling is fixed – it is simply given by the one coupling strength of the E_6 gauge group. The physics at low energies is a function of the way in which the symmetry breaks; in particular it depends on whether the different $U(1)$'s all split off from E_6 at the same scale or not. The pattern of breakdown is $E_6 \rightarrow SO(10) \times U(1) \rightarrow SU(5) \times U(1) \times U(1)$. If these two steps happen at different scales then the running of the coupling will make the relationship between the couplings more complex. Here the assumption is that the extra Z's split off all at once.

The results are that present CDF searches can exclude Z''s up to a mass of about 270-360 GeV. With Tevatron upgrades the excluded range increases: with 100 pb^{-1} at 2 TeV the reach is 520-630 GeV; with 100 pb^{-1} at 3.6 TeV the reach is 0.8-1.0 TeV; with 1000 pb^{-1} at 3.6 TeV the reach is 1.2-1.4 TeV; with 500 pb^{-1} at 8 TeV the reach is 1.8-2.2 TeV.

The assumption that the new fermions are light compared to the Z' is pes-

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*This material in this section was presented by J. Rosner. See also his summary talk in these proceedings.

simistic; if they are heavy then the branching fraction into the fermions we see is increased. On the other hand, if the two breaking scales are very different then the coupling of the Z' may be somewhat reduced.

3. Testing Three-Point Couplings of Gauge Bosons†

The discovery of the W and Z bosons at their expected masses convinced physicists of the usefulness of the standard model of electroweak interactions. However, in a crucial sense, the most important aspect of the standard model has never been checked. The central feature of the standard model is that it is a *gauge* theory, and the W, Z, and γ are the gauge bosons. Unfortunately, no process involving the three- or four-point vertices at tree level has ever been observed. A pessimist might therefore assert that it is possible that the true theory of electroweak interactions is not a gauge theory at all, and that the apparent correctness of the predictions of the standard model has been entirely fortuitous.

A great deal of research has been done on this possibility [6]. In this work [7] only the couplings of the W to the photon are considered, in the processes $q\bar{q}' \to W\gamma$ ($W\gamma$ production) and $q\bar{q}' \to W \to f\bar{f}'\gamma$ (radiative W decays). Among the Feynman diagrams for both these processes is one in which the photon is emitted from the W. This diagram involves the three-point coupling $WW\gamma$; therefore the gauge nature of the theory will be directly tested.

In both of the processes considered, every W line is coupled to fermions on at least one end. Since the fermions are assumed to be massless, this ensures that effectively $\partial^\mu W_\mu = 0$. Therefore, the most general form of the $WW\gamma$ coupling which respects Lorentz and electromagnetic gauge invariance is [8]

$$\mathcal{L}_{WW\gamma} = -ie\Big\{ \left(W^\dagger_{\mu\nu}W^\mu A^\nu - W^\dagger_\mu A_\nu W^{\mu\nu}\right) + (1+\Delta\kappa)W^\dagger_\mu W_\nu F^{\mu\nu} + \frac{\lambda}{M_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu F^{\nu\lambda} + \tilde{\kappa}W^\dagger_\mu W_\nu \tilde{F}^{\mu\nu} + \frac{\tilde{\lambda}}{M_W^2}W^\dagger_{\lambda\mu}W^\mu_\nu \tilde{F}^{\nu\lambda}\Big\},$$

where A^μ and W^μ are the photon and W fields respectively, $W^{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, and $\tilde{F}_{\mu\nu} = (1/2)\epsilon_{\mu\nu\rho\sigma}F^{\rho\sigma}$. The electronic charge is e and M_W is the W boson mass.

The first term in this Lagrangian represents the minimal coupling of the W to the photon and its coefficient is fixed by the charge of the W. Within the standard model, at tree level, $\Delta\kappa$, λ, $\tilde{\kappa}$, $\tilde{\lambda}$ are all zero. The $\tilde{\kappa}$ and $\tilde{\lambda}$ terms violate P and CP, while the others preserve all the discrete symmetries. The non-observation of a neutron electric dipole moment forces $\tilde{\kappa} < O(10^{-3})$, a value which would be undetectable at the Tevatron [9].

After the W decays, the $W\gamma$ production process leads to the same final state as the radiative W decay. The hadronic decay modes of the W will be difficult to

†The material in this section was presented by U. Baur.

observe because of the QCD background. The signal is, therefore,

$$p\bar{p} \rightarrow e^{\pm} + \gamma + \not{p}_T,$$

where $\not{p}_T$ represents the missing transverse momentum carried off by the neutrino.

It would be easy to separate radiative W decays from $W\gamma$ production if it were possible make a cut demanding that the mass of the $e\nu\gamma$ be close to the W mass. Unfortunately, because of the non-observation of the neutrino, $M_{e\nu\gamma}$ cannot be determined unambiguously and instead the cluster transverse mass [10] is used

$$M_T^2(e,\gamma,\not{p}_T) = \left[\left(M_{e\gamma}^2 + |\vec{p}_{T\gamma} + \vec{p}_{Te}|^2\right)^{\frac{1}{2}} + \not{p}_T\right]^2 - |\vec{p}_{T\gamma} + \vec{p}_{Te} + \vec{\not{p}}_T|^2.$$

Events which satisfy

$$M_T(e,\gamma,\not{p}_T) < 90\mathrm{GeV}$$

are identified as radiative W decays, the rest are taken to be $W\gamma$ events.

In a real-world detector, it will be necessary to impose cuts to account for detector resolution limitations. Here, the following were imposed:

$$p_{T\gamma} > 10\mathrm{GeV}, \quad \Delta R_{e\gamma} > .7,$$
$$\not{p}_T > 20\mathrm{GeV}, \quad |\eta_e| < 2,$$

where η is the pseudo-rapidity, ϕ is the azimuthal angle, and $\Delta R = \left((\Delta\phi)^2 + (\Delta\eta)^2\right)^{1/2}$.

In addition, there is a background caused by W + jet production with the jet misidentified as a photon. These events contain jets which hadronize with a leading π^0, which carries away most of the jet energy. In the CDF detector only a small fraction $P_{\gamma/j}$ of the jet events with $p_{Tjet} > 50$ GeV are misidentified as a photon. The results below are given for $P_{\gamma/j} = 5 \times 10^{-3}$ and 5×10^{-4}.

When the coefficients $\Delta\kappa$, λ, or $\tilde{\lambda}$ are nonzero, the shape of the spectrum of M_T is changed, especially at large M_T. Shown in Table 1 are the 90% confidence level bounds which can be achieved at the upgraded Tevatron (1.8 TeV, 100 pb^{-1}) using this effect. The entries in this table represent the bounds one gets when only one coupling at a time is assumed to be different from zero. In the case of the radiative W decay, the effect of the non-standard couplings is to change the shape of the distribution of the angle between the photon and electron in the W rest frame. Radiative W decay is less sensitive to the nonstandard couplings because the effect of these terms grows with energy. The bounds derived from radiative W decays are weaker than those of Table 1 by about a factor of 2 to 8.

One might expect that the coefficients of these operators are suppressed by a power v^2/Λ^2, where $v = 250$ GeV. In this case the numbers of Table 1 represent a scale $\Lambda \approx 350$ TeV.

Table 1

	$\Delta\kappa$		λ		$\bar{\lambda}$	
$P_{\gamma/j}$	5×10^{-3}	5×10^{-4}	5×10^{-3}	5×10^{-4}	5×10^{-3}	5×10^{-4}
	+1.50	+1.23	+0.46	+0.38	+0.46	+0.39
	-1.41	-1.13	-0.47	-0.40	-0.46	-0.39

90% confidence level bounds for the anomalous couplings derivable from the $W\gamma$ production process at the upgraded Tevatron (1.8 TeV, 100 pb^{-1}). Only one coupling at a time is assumed different from zero.

4. Two Gauge Boson Physics at the Upgraded Tevatron‡

The study of events containing two gauge bosons will be of tremendous interest at LEP-II and the SSC. At these machines, these events will not only probe the couplings of the W and Z to each other, as discussed above, but they also are sensitive to the symmetry breaking sector. Can the upgraded Tevatron do this physics?

The closed form matrix elements may be used to compute the numbers of two gauge boson events at proton colliders [11]. At the 3.6 TeV, 1000 pb^{-1} machine, there are 60 WZ events in which both gauge bosons decay leptonically, and both have rapidity less than 2.5. While this is probably too few to allow a detailed test of the three-gauge-boson vertices, it will allow the standard model to be checked at some level. Changing the vertices away from their standard model forms tends to destroy gauge cancelations, and the numbers of events are thereby increased.

There are also 400 WW events in which one W decays to $e\nu$ and the other decays to $\mu\nu$ and both W's have rapidity less than 2.5. These are difficult to observe, since it now appears that the top quark is heavier than the W, and so there is a large rate for $t\bar{t}\to W^+bW^-\bar{b}$.

5. Finding the Standard Model Higgs Boson at the Upgraded Tevatron §

At a hadron collider, the dominant production method for Higgs bosons is the gluon-fusion mechanism [12]. Though the Higgs boson does not couple to gluons at tree level, the coupling at one-loop through the quark triangle can be quite appreciable; for certain ranges of Higgs boson and top quark masses the triangle diagram is the dominant production mechanism. Gluon fusion works best when $M_H = 2m_t$, in the sense that for fixed M_H the production cross section as a function of m_t has a local maximum at $M_H/m_t = 2$. For heavy Higgs bosons this mechanism works less and less well: if we fix $M_H/m_t = 2$ and take M_H to infinity the rate goes to zero.

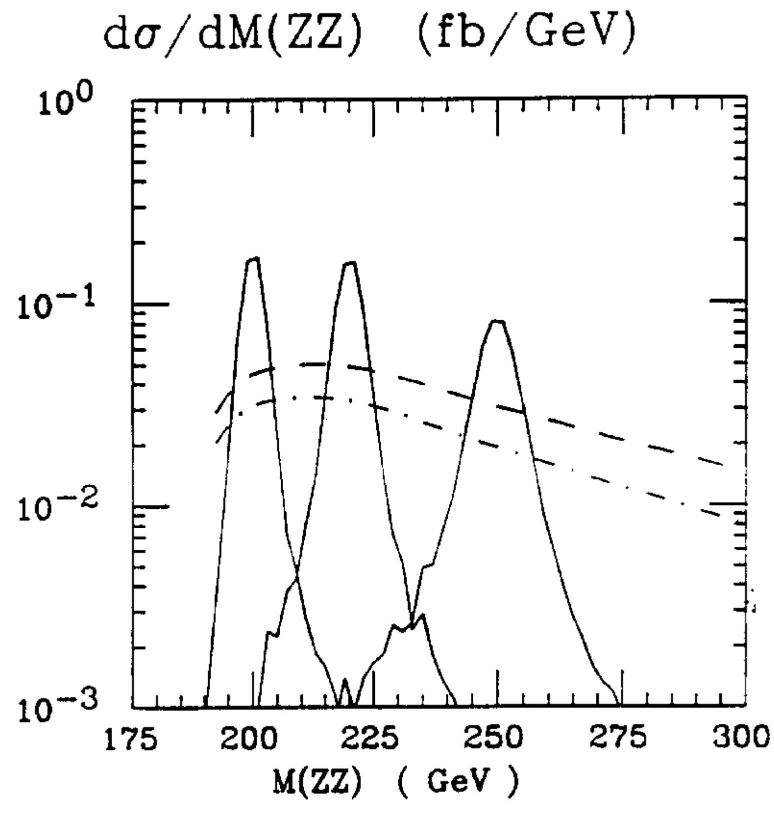
For the purposes of this work, we take what amounts to the best possible case for the 3.6 TeV proton-antiproton collider. Suppose that the top quark weighs 100

‡This material was presented by U. Baur and C.-P. Yuan.

§The material in this section was presented by V. Barger and T. Han

GeV, and the Higgs boson is in the range 200-250 GeV, so that it is nearly twice the top mass. The dominant decay mode of the Higgs boson is then to gauge boson pairs, which are relatively easy to see. Because of the background from $t\bar{t} \rightarrow W^+bW^-\bar{b}$, the W^+W^- mode is not useful, so the ZZ modes must be used. If it is assumed that the Z cannot be found in its hadronic decay channels, then the remaining possibilities are $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ (where $\ell = e, \mu$) or $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$, for which the signal is two leptons plus missing transverse momentum. The advantage of the latter signal is that it has a branching ratio which is roughly six times larger than the former. Unfortunately it suffers from a substantial background of Z + jet events, and the cuts necessary to remove this background reduce the advantage of this mode considerably [13]. The four lepton mode is clean, but suffers from a low rate: $BR(ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-) = 4.4 \times 10^{-3}$.

Figure 1



The cross section for $ZZ \rightarrow 4\ell$ events as a function of M_{ZZ}. The solid curves are for $H \rightarrow ZZ$, with M_H = 200, 220, and 250 GeV, with a top quark mass of 100 GeV. The dashed line is the continuum ZZ background in a $p\bar{p}$ machine, while the dot-dashed line is that in a pp machine. See the text for the cuts imposed.

There is an irreducible background from ZZ continuum production, which yields the 60 events discussed in section IV above. This cannot be entirely eliminated, but it is somewhat mitigated by placing a cut on the pseudorapidity of the Z's; here $|\eta_Z| < 2.5$. Also, since the peak of the distribution of the transverse momentum of the signal Z's occurs at above 40 GeV, a cut which demands $p_{TZ} > 25$ GeV will improve the signal to background ratio.

The solid lines in Figure 1 show the cross section as a function of M_{ZZ} for $M_H = 200, 220, 250$ GeV, with the above cuts imposed. The dashed line shows the cross section after cuts for continuum ZZ production in a $p\bar{p}$ collider, while the dotdash show this background in a pp collider. Here the momentum of the Z has been smeared to simulate a realistic detector; a gaussian with $\sigma = 0.15\sqrt{E}$ was used. The signal curves are a factor of three above the backgrounds. However, with 100 pb^{-1} there are no events in the signal. With 1000 pb^{-1} of data there would be one or two events in the signal, but in the range 200-250 GeV there are a slightly greater number in the background. The signal events are all within 10 GeV of each other, but this is unlikely to be sufficient to provide convincing proof of the existence of the Higgs boson signal.

With a $p\bar{p}$ machine of 8 TeV energy and 500 pb^{-1}/year luminosity, the situation is improved somewhat. For example, for the 220 GeV Higgs boson, there will be 2 to 3 four-lepton events in a 8 GeV wide bin, and only .7 background events in that bin. The neutrino mode has 26.7 events over a background of 11.8 events. This would be a clear signal, if the Z plus jet background can be beaten.

6. W, Z, OR γ Plus 1, 2, OR 3 Jets‖

The production of events with multiple jets at a hadron collider is an interesting test of QCD, and events with a gauge boson and multiple jets will be common enough to be observed. More importantly perhaps, since it now appears that the top quark is heavier than the W, the leading decay of the top quark is $t \to W^+b$. The process W + multiple jets will be a background [14] to $t\bar{t} \to W^+bW^-\bar{b} \to e\nu$ + jets. The process Z + multiple jets is also a background to exotic particle searches, for example leptoquarks, (these are bosons whose signature is $p\bar{p} \to \ell_q\bar{\ell}_q \to (\nu d)(\bar{\nu}\bar{d}) \to \not{p}_T$ + jets [15]), leptoquarkinos (in $p\bar{p} \to \tilde{\ell}_q\bar{\tilde{\ell}}_q \to (\nu d)(\bar{\nu}\bar{d}) \to \not{p}_T$ + jets [15]), or leptogluons (color octet fermions, whose signature is $p\bar{p} \to \nu_8\nu_8 \to (\nu g)(\nu g) \to \not{p}_T$ + jets [16]). It is evident that a complete calculation of gauge boson plus jets is of considerable phenomenological interest.

The amplitudes for gauge boson plus one or two jets was calculated at tree level in reference [17], and to next to leading order in reference [18]. Recently V + 3 jets (where $V = W$, Z or γ) has been calculated [19,20]. The results of this section [21] are based on a FORTRAN program which calculates all the tree level amplitudes for W, Z, or γ + 3, 4, or 5 partons [19].

For the results below cuts are imposed to separate the signal from various

‖The material in this section was presented by V. Barger and T. Han backgrounds. One demands that the transverse momentum of charged leptons and jets be larger than 15 GeV, and that their rapidity be less than 2.5. The separation ΔR (as defined above in section II) between jets or between jets and leptons must be 0.7. The transverse mass (also defined in section II) of the leptons must be at least 50 GeV in events with a W, and events with a Z must have $M_{ee} > 50$ GeV. The detector resolution is assumed to be $0.15\sqrt{E/(1 \text{ GeV})}$ for the e, μ, and $0.80\sqrt{E/(1 \text{ GeV})}$ for the jets.

Table 2 shows the numbers of events for W or Z plus 1, 2, or 3 jets, assuming a machine of 1.8 TeV and 100 pb^{-1}. The branching $W \to e\nu$ or $Z \to ee$ is included. Unfortunately there are large uncertainties in these numbers caused by the ambiguity in the choice of scale. In particular, since the gauge boson plus three jet cross sections depend on α_S^3, the results can be made to vary by as much as a factor of 3 with reasonable choices of scale.

The numbers of Table 2 clearly indicate that the detectors at Fermilab will be able to see this type of event. As a test of perturbative QCD these events are interesting in their own right, and it is important to understand them as a possible background to new physics.

Table 2

n jets	$W(\to e\nu) + n$ jets	$Z(\to ee) + n$ jets
1	20000	2000
2	3000	340
3	420	60

Numbers of events for $W \to e\nu + n$ jets and $Z \to ee + n$ jets. The machine is assumed to be a $p\bar{p}$ collider with an energy of 1.8 TeV and the integrated luminosity is 100 pb^{-1}.

7. KM Matrix and the Top Quark Mass**

In the standard model, the source of CP violation is the phase in the KM matrix, which relates the weak eigenstates of the quarks to their mass eigenstates [22]. In processes like $K^0 - \bar{K}^0$ mixing, the diagrams involve the top quark propagator, and the amount of CP violation depends rather strongly on the top quark mass. In principle, therefore, if one knew all the elements of the KM matrix, and if one could calculate the hadronic matrix elements of weak operators in the kaon, and if one had perfect experimental observation of $K^0 - \bar{K}^0$ oscillations then it would be possible to uniquely predict the mass of the top quark.

In the real world one lacks perfect information about all of these three inputs, and so the calculation gives only a range of allowed top quark masses. During this workshop a recent analysis of the KM parameters [23] has been updated. This material is well covered in J. Rosner's summary talk and space considerations prevent including it again here.

**This material was presented by J. Rosner, C. S. Kim, and C.-P. Yuan

This analysis tends to favor a relatively large value for m_t. There is at present a rather large discrepancy between the two best measurements of ϵ'/ϵ [24,25], which prevents one from making too definitive a prediction. The most pessimistic bound is simply that the top quark is heavier than 78 GeV, the same as the recent bound given by CDF [26]. More work, both experimental and theoretical, is needed.

8. Bounds on the Top Quark Mass in Models with Higgs Triplets††

The standard model has a relationship between the coupling constants of the gauge group and the masses of the gauge boson. This is expressed in the statement that

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1,$$

where $\tan(\theta_w) = g'/g$, the ratio of the coupling strengths. This relationship is observed to hold experimentally [27,28].

That ρ is 1 does not follow from the gauge symmetry alone, and it is possible to construct models which have arbitrary values for ρ. Instead, it derives from a extra symmetry possessed by the standard model, the "custodial $SU(2)$" ($SU(2)_C$) [29]. The $SU(2)_L$ gauge coupling g, the Higgs potential, and the vacuum expectation value (VEV) of the doublet in the standard model all respect the $SU(2)_C$ symmetry, while the $U(1)_Y$ gauge coupling g' and non-degenerate fermion mass terms (*i.e.* such that $m_u \neq m_d$) do not. Non-standard Higgs potentials may or may not violate the custodial symmetry. For example the VEVs of $SU(2)_L$ triplets break the custodial $SU(2)$, and they generate corrections to $\rho = 1$ at tree level. In a model with two doublets the VEVs respect $SU(2)_C$ but the potential in general does not, and there are corrections to ρ at one loop [30].

Here we consider the corrections caused by the VEV of a Higgs triplet. There are two possible assignments of hypercharge, $Y = 0$ and $Y = 2$. The particle content of the former is $(t^+ \; t^0 \; - t^-)$, where t^+ is the complex conjugate of t^-. The particles in the $Y = 2$ triplet are $(t^{++} \; t^+ \; t^0)$. Higgs triplet fields cannot be the whole story in these models; there must also be Higgs doublet fields in order to give the fermions mass. If ϵ is the ratio of the VEV of the triplet to the VEV of the doublet $\epsilon = v_3/v_2$, then in the $Y = 0$ model we have

$$\Delta\rho_{Y=0} = 4\epsilon,$$

and in the $Y = 2$ model,

$$\Delta\rho_{Y=2} = -2\epsilon.$$

Hereafter we assume that the the triplet VEV is known, $\epsilon = 0.05$.

As mentioned above, non-degenerate quark mass terms also generate corrections to $\rho = 1$. In the standard model only the top-bottom mass splitting is

†† The results of this section were presented by D. Morris.

sufficiently sizeable to cause detectable corrections to ρ. Neglecting the mass of the bottom quark [31],

$$\Delta\rho_t = \frac{3\alpha}{16\pi^2 \sin^2\theta_W}\left(\frac{m_t}{m_Z}\right)^2 .$$

(There is also a much smaller correction from the ordinary doublet Higgs boson. The conclusions presented here do not depend much on its mass; however, for definiteness, hereafter $M_H = 100$ GeV.) If one knows the W and Z masses exactly, the top mass can be deduced.

Suppose that the Z mass is known very well, $M_Z = 91.00 \pm .01$ GeV. If the mass of the W were measured to be $80.2 \pm .1$ GeV, as one could expect to do with the 100 pb^{-1}/year upgrade of the Tevatron, then the corresponding 1σ range of top quark mass allowed in the standard model would be from 150 to 180 GeV. In the $Y = 2$ triplet model with $\epsilon = .05$, the top quark is less than 195 but more than 170 GeV, while in the $Y = 0$ model, 125 GeV $< m_t <$ 160 GeV. These ranges overlap, so it is not possible to uniquely distinguish these models from one another via this measurement.

With the proposed upgrade to 3.6 TeV and 1000 pb^{-1}/year, the mass of the W can be perhaps be measured twice as well. If its mass were found to be 80.20 ± 0.05, then the comparable ranges for the top quark mass would be 155 GeV $< m_t <$ 170 GeV in the standard model, 175 GeV $< m_t <$ 190 GeV in the $Y = 2$ triplet model, and 135 GeV $< m_t <$ 150 GeV in the $Y = 0$ triplet model. These ranges no longer overlap, and the three models can be distinguished.

This is a simple example of the measurement of the standard model parameter giving information about the physics beyond the standard model.

9. Bounds on Non-Standard Physics from Electroweak Radiative Correction ‡‡

In the standard model at tree level, there are several ways to define the weak mixing angle θ_W. The ratio of the gauge boson masses [28] is

$$\frac{m_W^2}{m_Z^2} = 1 - \sin^2\theta_W.$$

The forward-backward asymmetry at the Z is

$$A_{FB} \propto 1 - 4\sin^2\theta_W,$$

or one can use the low energy neutrino-electron scattering to define θ_W. The equality of these definitions is only good at tree level. At one loop, radiative corrections will contribute differently to these processes, and they will not give the same value of θ_W.

‡‡This section presents results of M. Golden and L. Randall.

Whether this discrepancy is important or not will depend on the accuracy to which the different processes can be measured. During the next decade, it may be possible to measure the Z mass to 25 MeV or better, and the W may be measured to 50 MeV [32]. If we denote the weak mixing angle derived from the first of the above definitions, the gauge boson masses, by $\theta_{(1)}$, then the error on this measurement will be

$$\delta \sin^2 \theta_{(1)} = 0.0015.$$

The measurement of the forward-backward asymmetry at the Z will yield an error in measuring the weak mixing angle as defined in the second definition above $\delta\theta_{(2)}$ about the same size [33]. Thus the error of the difference will be

$$\delta(\sin^2 \theta_{(1)} - \sin^2 \theta_{(2)}) \approx 0.002.$$

A radiative correction will be important only if it is smaller than this quantity.

The typical size of a one-loop radiative correction is $(\alpha/4\pi)O(1)$. Since this is a smaller than the number above, it is unimportant unless it gets enhanced. There are three ways to do this. First, one may have a large breaking of the custodial symmetry of the last section. There is a correction to $\sin^2 \theta_{(1)} - \sin^2 \theta_{(2)}$ from the top-bottom splitting [31,34]. Here and below, define $\Delta = \sin^2 \theta_{(1)} - \sin^2 \theta_{(2)}$. From the top,

$$\Delta = \frac{\alpha}{4\pi} \left(\frac{3}{4 \sin^2 \theta_W} \right) \left(\frac{m_t}{m_W} \right)^2.$$

For large top mass this effect will be clearly visible.

A second way to enhance the radiative corrections is to have a large number of new particles. For example, the correction to Δ from a new doublet of very heavy degenerate quarks is [35,34]

$$\Delta = \frac{\alpha}{4\pi} \left(-\frac{1}{2} \right).$$

By itself this would be too small to observe, but if there were, say, eight new ultraheavy doublets, the effect would be appreciable. This could place bounds on models with many new undiscovered particles.

One may also enhance the radiative effects by causing coupling constants to run. The definition of $\theta_{(1)}$ is based a measurement at zero momentum, while the forward-backward asymmetry measurement is made at M_Z. Thus the shift in α_{EM} caused by the effects of the light quarks is responsible for a non-zero value of Δ even in the standard model with a light top. New light particles could have a similar effect.

There are also other ways to observe corrections to electroweak parameters. A recent paper suggested that the standard model could be "ununified", with separate $SU(2)$ gauge groups for the left-handed quarks and leptons [36],

$SU(2)_{qL} \times SU(2)_{\ell L} \times U(1)_Y$. In this model there exist new W and Z gauge bosons, mixed with the familiar ones with a mixing angle ϕ. This model is especially interesting to test at the tevatron because the corrections to the couplings of the light W and Z to the leptons go like $\sin^4 \phi$, but the couplings of the quarks are corrected by $\sin^2 \phi$. In this model there are corrections to the forward-backward asymmetry and the W mass at tree-level, and these may be used to constrain this model [37].

The accurate measurement of the standard model parameters may provide strong hints about the physics at energies which will be unreachable during the 1990's.

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