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Electroweak Limits on Non-Universal Z' Bosons

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Abstract

Many types of physics beyond the standard model include an extended electroweak gauge group. If these extensions are associated with flavor symmetry breaking, the gauge interactions will not be flavor-universal. In this note we update the bounds placed by electroweak data on the existence of flavor non-universal extensions to the standard model in the context of topcolor assisted technicolor (TC2), noncommuting extended technicolor (NCETC), and the ununified standard model (UUM). In the first two cases the extended gauge interactions couple to the third generation fermions differently than to the light fermions, while in the ununified standard model the gauge interactions couple differently to quarks and leptons. The extra $SU(2)$ triplet of gauge bosons in NCETC and UUM models must be heavier than about 3 TeV, while the extra Z boson in TC2 models must be heavier than about 1 TeV.

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1 Introduction

Precision electroweak data place bounds on possible extensions of the electroweak gauge group. If these extensions are associated with flavor symmetry breaking, the gauge interactions will not be flavor-universal [1, 2, 3, 4, 5, 6]. Three particular models which contain such flavor non-universal gauge interactions are topcolor assisted technicolor (TC2) [3], noncommuting extended technicolor (NCETC)[4], and the ununified standard model (UUM)[2, 7]. In the first two cases the extended gauge interactions couple to the third generation fermions differently than to the light fermions, while in the ununified standard model the gauge interactions couple differently to quarks and leptons.

In this note we update the bounds [8, 9, 10] placed by precision data on the existence of the extra neutral Z boson in TC2 models and the extra $SU(2)$ triplet of gauge bosons in NCETC and UUM models. We also consider the bounds arising from the search for contact interactions in scattering experiments, and from requiring the absence of large flavor-changing neutral currents* (for CKM-like values of the various mixing angles).

We find that the the extra Z in TC2 models must be heavier than about 2 TeV for generic values of the gauge coupling. However, the TC2 limits illustrate that, for specific values of the parameters, cancellations can limit the size of deviations of Z-pole observables – allowing for a Z' as light as 730 GeV. In such a case, off-shell measurements become important. Specifically, limits on contact interactions at LEPII imply that the TC2 Z' must be heavier than about 1 TeV. Note that these limits hold regardless of the assumed flavor structure of the quark mixing matrices – unlike the potentially stronger but more model-dependent limits from B-meson mixing.

In contrast, the extra $SU(2)$ triplet of gauge bosons in NCETC and UUM models must be somewhat heavier, with masses always greater than about 3 TeV. For these models, the limits from Z-pole observables are stronger than those from contact interactions at LEP II or from flavor-changing neutral currents.

2 Z' Bosons in TC2 Models

2.1 TC2 models

In technicolor models [12], electroweak symmetry breaking occurs when a new asymptotically free gauge theory (technicolor) spontaneously breaks the chiral symmetries of the new fermions to which it couples (technifermions). Small fermion masses can be generated if the technicolor group is embedded in a larger extended technicolor (ETC) gauge interaction felt by ordinary and technifermions alike [13]. The key feature of topcolor-assisted technicolor models [3] is that an additional, larger, component of the top quark mass is dynamically generated by extended color interactions (topcolor [14]) at a scale of order 1 TeV. The topcolor interactions may be flavor non-universal (as in classic TC2 [3]) or flavor-universal [15]. In either case, a non-universal extended hypercharge group is often invoked [3, 16] to ensure that the top quark condenses and receives a large mass while the bottom quark does not.

The electroweak gauge symmetry in TC2 models is therefore $SU(2)_L \times U(1)_1 \times U(1)_2$. Here $U(1)_1$ is a weak gauge interaction and $U(1)_2$ is the, presumably strong, interaction with isospin-violating quark couplings that facilitates top-quark, but not bottom-quark, condensation. The required pattern of electroweak gauge symmetry breaking is more complicated than that in ordinary

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*Related precision electroweak and flavor-changing neutral current bounds on generic Z' bosons may be found in [11].

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technicolor models; it generally involves two scales (rather than just one) to break the $SU(2)_L \times U(1)_1 \times U(1)_2$ symmetry down to $U(1)_{em}$. The required pattern of breaking is:

$$SU(2)_L \otimes U(1)_1 \otimes U(1)_2$$
$$\downarrow \quad u$$
$$SU(2)_L \otimes U(1)_Y$$
$$\downarrow \quad v$$
$$U(1)_{em},$$

where hypercharge, $Y = Y_1 + Y_2$, is equal to the sum of the generators of the two $U(1)$'s.

The gauge couplings may be written

$$g = \frac{e}{\sin\theta}, \quad g_1' = \frac{g'}{\cos\phi} = \frac{e}{\cos\phi\cos\theta}, \quad g_2' = \frac{g'}{\sin\phi} = \frac{e}{\sin\phi\cos\theta}, \tag{2.1}$$

in terms of the usual weak mixing angle θ and a new mixing angle ϕ. It is convenient to rewrite the neutral gauge bosons in terms of the photon,

$$A^\mu = \cos\theta\,(\cos\phi\,B_1^\mu + \sin\phi\,B_2^\mu) + \sin\theta\,W_3^\mu, \tag{2.2}$$

which couples to electric charge Q with strength e, a field

$$Z_1^\mu = -\sin\theta\,(\cos\phi\,B_1^\mu + \sin\phi\,B_2^\mu) + \cos\theta\,W_3^\mu, \tag{2.3}$$

which couples as the standard model Z would couple, to $T_3 - Q\sin^2\theta$ with strength $\frac{e}{\sin\theta\cos\theta}$ and the field

$$Z_2^\mu = -\sin\phi\,B_1^\mu + \cos\phi\,B_2^\mu, \tag{2.4}$$

which couples to the current $Y' = Y_2 - \sin^2\phi Y$ with strength $\frac{e}{\cos\theta\sin\phi\cos\phi}$. In this basis, using the relation $Q = T_3 + Y$ and the fact that Q is conserved, the mass-squared matrix for the Z_1 and Z_2 can be written as:

$$M_Z^2 = \left(\frac{e}{2\sin\theta\cos\theta}\right)^2 \left(\begin{array}{cc} <T_3T_3> & \frac{\sin\theta}{\sin\phi\cos\phi}<T_3Y'> \\ \frac{\sin\theta}{\sin\phi\cos\phi}<T_3Y'> & \frac{\sin^2\theta}{\sin^2\phi\cos^2\phi}<Y'Y'> \end{array}\right), \tag{2.5}$$

where, from the charged-W masses we see that $<T_3T_3> = v^2 \approx (250\,\mathrm{GeV})^2$.

As discussed in [8], in natural TC2 models [17] the expectation value leading to $Z_1 - Z_2$ mixing, $<T_3Y'>$, can be calculated *entirely* in terms of the gauge couplings, v, and the Y_2 charges of the left- and right-handed top quark. Using the definition of Y', we see that

$$<T_3Y'> = <T_3Y_2> - \sin^2\phi <T_3Y> . \tag{2.6}$$

Since $Y = Q - T_3$ and Q is conserved, the last term is equal to $+\sin^2\phi <T_3T_3>$. Furthermore in natural TC2 models, since the technifermion Y_2-charges are assumed to be isospin symmetric, the technifermions do not contribute to the first term. The only contribution to the first term comes from the top-quark condensate

$$\frac{<T_3Y_2>}{<T_3T_3>} = 2(Y_2^{t_L} - Y_2^{t_R})\frac{f_t^2}{v^2}, \tag{2.7}$$

2

where f_t is the analog of f_π for the top-condensate and is equal to [18]

$$f_t^2 \approx \frac{N_c}{8\pi^2} m_t^2 \log\left(\frac{M^2}{m_t^2}\right) \tag{2.8}$$

in the Nambu—Jona-Lasinio [19] approximation, and M is the mass of the extra color-octet gauge bosons (colorons) arising in the extended color interactions. For $m_t \approx 175$ GeV and $M \approx 1$ TeV, we find $f_t \approx 64$ GeV.

If we define

$$x \equiv \frac{\sin^2\theta}{\sin^2\phi\cos^2\phi} \frac{<Y'Y'>}{<T_3T_3>} \propto \frac{u^2}{v^2}, \tag{2.9}$$

and

$$\epsilon \equiv 2\frac{f_t^2}{v^2}\left(Y_2^{t_L} - Y_2^{t_R}\right), \tag{2.10}$$

the $Z_1 - Z_2$ mass matrix can be written as

$$M_Z^2 = M_Z^2|_{\text{SM}} \begin{pmatrix} 1 & \tan\phi\sin\theta\left(1+\frac{\epsilon}{\sin^2\phi}\right) \\ \tan\phi\sin\theta\left(1+\frac{\epsilon}{\sin^2\phi}\right) & x \end{pmatrix}. \tag{2.11}$$

In the large-x limit the mass eigenstates are

$$Z \approx Z_1 - \frac{\tan\phi\sin\theta}{x}\left(1+\frac{\epsilon}{\sin^2\phi}\right)Z_2 \tag{2.12}$$

$$Z' \approx \frac{\tan\phi\sin\theta}{x}\left(1+\frac{\epsilon}{\sin^2\phi}\right)Z_1 + Z_2 \tag{2.13}$$

The shifts in the Z coupling to $f\overline{f}$ (with $e/(\cos\theta\sin\theta)$ factored out) are therefore given by:

$$\delta g^f \approx -\frac{\sin^2\theta}{x\cos^2\phi}\left(1+\frac{\epsilon}{\sin^2\phi}\right)\left[Y_2^f - \sin^2\phi Y^f\right]. \tag{2.14}$$

Mixing also shifts the Z mass, and gives a contribution to the T parameter [20] equal to:

$$\alpha T \approx \frac{\tan^2\phi\,\sin^2\theta}{x}\left(1+\frac{\epsilon}{\sin^2\phi}\right)^2. \tag{2.15}$$

The shifts in the Z-couplings and mass are sufficient to describe electroweak phenomenology on the Z-peak. For low-energy processes, in addition to these effects we must also consider the effects of Z'-exchange. To leading order in $1/x$, these effects may be summarized by the four-fermion interaction [8]

$$-\mathcal{L}_{\text{NC}}^{Z'} = \frac{4G_F}{\sqrt{2}}\frac{\sin^2\theta}{x\sin^2\phi\cos^2\phi}\left(J_{Y_2} - \sin^2\phi J_Y\right)^2, \tag{2.16}$$

where J_{Y_2} and J_Y are the Y_2- and hypercharge-currents, respectively. It is useful to note that if ϵ is negative, then all the Z pole mixing effects (equations (2.14) and (2.15)) vanish when $\sin^2\phi = -\epsilon$, although the low-energy effects of Z' exchange do not.

An important consistency check is whether the Landau pole of the strongly-coupled $U(1)_2$ gauge interaction lies sufficiently far above the symmetry-breaking scale to render the theory self-consistent. In [15], it was shown that a factor of 10 separation of scales is ensured for $\kappa_1 < 1$ where

$$\kappa_1 \equiv \frac{\alpha_{em}}{\cos^2\theta_W}\left(\frac{g_2}{g_1}\right)^2 \tag{2.17}$$

3

and g_1 (g_2) is the coupling of the $U(1)$ group under which the first and second (third) generation fermions are charged. Since the ratio of coupling constants is defined to be the cotangent of the gauge boson mixing angle ϕ, the constraint on κ_1 will be met if

$$\sin^2 \phi > \left[1 + \frac{\cos^2 \theta_W}{\alpha_{em}} \right]^{-1} \approx 0.01 \quad . \tag{2.18}$$

This condition is satisfied for the values of $\sin^2 \phi$ considered in our analysis.

2.2 Precision EW Constraints

In the presence of the enlarged electroweak gauge group in TC2 models, the predicted properties of the Z^0 resonance and of the low-energy weak interactions are altered. Quantities affected at the Z pole include the width (Γ_Z), decay asymmetries (A_{LR}, A_{FB}^e, A_{FB}^μ, A_{FB}^τ, $A_e(P_\tau)$, $A_\tau(P_\tau)$, A_{FB}^b, A_{FB}^c, $\mathcal{A}_b$, $\mathcal{A}_c$), peak hadronic cross-section (σ_h), and partial-width ratios (R_b, R_c, R_e, R_μ, R_τ). Other affected observables are the W mass, the rates of deep-inelastic neutrino-nucleon scattering (g_L^2, g_R^2) and the degree of atomic parity violation ($Q_W(Cs)$). We have used the general approach of ref. [21] to calculate how the presence of the Z' modifies the predicted values of the electroweak observables whose measured and SM values are listed in Table 1. The formulae for these leading (tree-level) alterations are presented in Appendix A as functions of the mixing angle, ϕ, and the ratio of squared vevs, $1/x$.

We have performed global fits of the electroweak data to the expressions in Appendix A, allowing $1/x$ and ϕ to vary. More precisely, at each value of ϕ we determined a best-fit value of $1/x$, along with one-sigma errors, and used the relation between $1/x$ and $M_{Z'}$ from eqn. (2.11) to translate that into a 95% c.l. lower bound[†] on $M_{Z'}$. Figure 1 summarizes these results. We find that the mass of the Z' boson can be below 1 TeV for $0.0744 \leq \sin^2 \phi \leq 0.0834$, with a minimum value of about 730 GeV. This is more than a factor of two tighter than the bound set in ref. [8]. The goodness-of-fit[‡] for the TC2 model with the Z' lying on the lower-bound curve is 4.2%, somewhat lower than the 5.6% result when we fit the SM predictions to the same data.

2.3 Contact Interactions at LEP II

The LEP experiments have recently published limits on contact interactions [22] which may be used to set a lower bound[§] on $M_{Z'}$. Following the notation of [26], they write the effective Lagrangian for the four-fermion contact interaction in the process $e^+ e^- \to f \bar{f}$ as

$$\mathcal{L}_{\text{contact}} = \frac{g^2}{\Lambda^2 (1 + \delta)} \sum_{i,j=L,R} \eta_{ij} (\bar{e}_i \gamma_\mu e_i)(\bar{f}_j \gamma^\mu f_j) \tag{2.19}$$

where $\delta = 1$ if f is an electron and $\delta = 0$ otherwise. The values of the coefficients η_{ij} set the chirality structure of the interaction being studied; the LEP analysis always takes one of the η_{ij} equal to 1 and sets the others to zero. Following the convention [26] of taking $g^2/4\pi = 1$, they determine a lower

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[†]The standard deviation on which the confidence level is based takes the number of free parameters into account as well as the number of measured quantities.

[‡]The goodness-of-fit expresses the likelihood that the measurements would give a χ^2/d.o.f. this large if the model is correct. Again, the number of d.o.f. equals the number of measurements minus the number of free parameters.

[§]Limits have also been set by the Tevatron experiments, but since these involve only fermions of the first and second generations, the expression for $M_{Z'}$ analogous to the RHS of eqn. (2.21) is suppressed by a factor of $\cos\phi/\sin\phi$ which renders the associated bound weaker than that from LEP data [25].
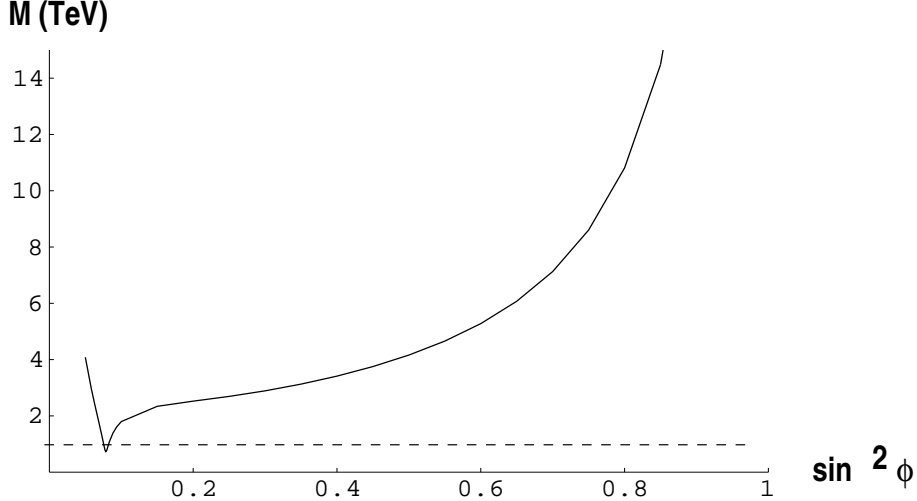
Figure 1: Lower bounds on the Z' boson mass at 95% CL in TC2 models as a function of mixing angle. The solid curve is the lower bound from precision electroweak data; the dashed line is the lower bound from LEP II contact interaction studies.

bound on the scale Λ associated with each type of new physics. In fact, they determine separate limits Λ^+ and Λ^- for each case, depending on whether constructive or destructive interference is assumed. Of particular interest to us for TC2 models are their limits on contact interactions where the final-state fermions are the third-generation fermions τ or b.

At energies well below the mass of the TC2 Z' boson, its exchange in the process $e^+e^- \to f\bar{f}$ where f is a τ lepton or b-quark may be approximated by the contact interaction

$$\mathcal{L}_{NC} \supset \frac{e^2}{\cos^2\theta\, M_{Z'}^2} \left(\frac{c_\phi}{s_\phi} Y_{e_i}(\bar{e}_i\gamma_\mu e_i) \right) \left(\frac{s_\phi}{c_\phi} Y_{f_j}(\bar{f}_j\gamma^\mu f_j) \right) \; , \tag{2.20}$$

based on the Z'-fermion couplings implied by eqns. (2.4,2.13). Comparing this with the contact interactions studied by LEP (2.19), we find

$$M_{Z'} = \Lambda^{sgn[Y_{e_i}Y_{f_j}]} \sqrt{\frac{\alpha_{em}}{\cos^2\theta} |Y_{e_i}Y_{f_j}|} \; . \tag{2.21}$$

Thus, when the produced fermions are tau leptons or right-handed τ-leptons, the LEP limit on Λ^+ is the relevant one; when left-handed b-quarks are produced, the limit on Λ^- rules.

By using the LEP limits on contact interactions in equation (2.21), we find that the strongest lower bound on $M_{Z'}$ comes from production of right-handed tau leptons. LEP sets the limit [22] $\Lambda_{RR}^+ \geq 10.9$ TeV. This translates to the lower bound $M_{Z'} \geq 1.09$ TeV, independent of the mixing angle ϕ. Comparing this with the bounds from precision electroweak data derived in the previous subsection, we see that the region of lower Z' mass (down to 730 GeV) previously allowed at $\sin\phi \approx 0.0784$ is now eliminated.

2.4   Contrasting Limits from B-meson mixing

Recent work in the literature [27, 28, 3] has shown that lower bounds on the mass of the Z' boson in TC2 models may be extracted from limits on neutral B-meson mixing. These limits turn out to
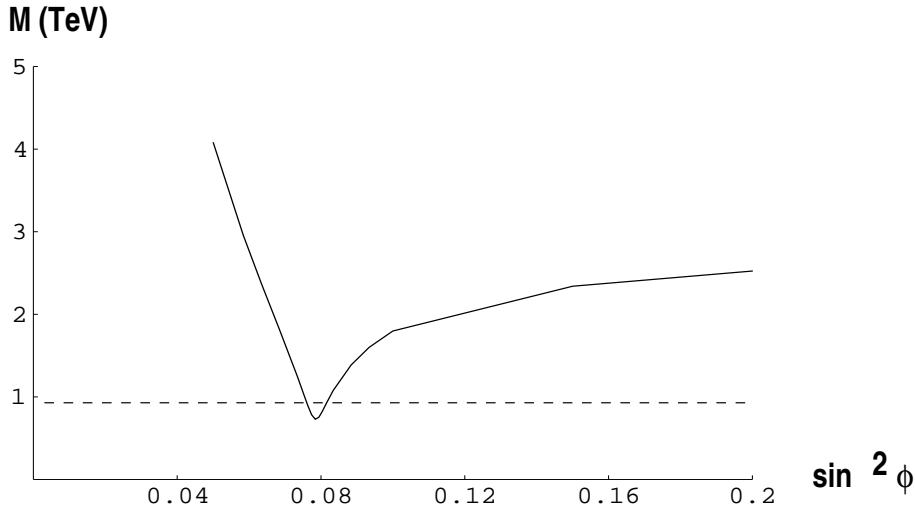
Figure 2: Close-up view of lower bounds on TC2 Z' boson mass at 95% CL as a function of mixing angle. Solid curve is lower bound from precision electroweak data; dashed line is lower bound from LEP II contact interaction studies.

be quite sensitive to the flavor structure of the model. For example, ref. [28] shows that in classic TC2 models [3] in which all quark mixing is confined to the left-handed down-quark sector, one must have $M_{Z'} > 6.8$ TeV (9.6 TeV) if ETC does (does not) contribute to the Kaon CP-violation parameter ϵ. This is a stricter limit than we have found over much of the parameter space of the model. Ref. [29] shows that in flavor-universal TC2 models [15], if one makes the same assumption about the flavor structure, the corresponding lower limit on the Z' mass is merely 590 GeV (910 GeV) – that is, weaker than our bounds. Moreover, changing the assumed flavor structure alters the implied limits. In contrast, our electroweak and contact-interaction limits hold for all models with the gauge and fermion sector described at the start of this section.

3   Weak Bosons in NCETC

In extended technicolor models [13], fermion masses are generated because the ETC gauge bosons couple the ordinary quarks and leptons to the technifermion condensate. The large mass of the top quark arises through ETC dynamics at a relatively low scale, not far above the scale of electroweak symmetry breaking. The defining characteristic of non-commuting extended technicolor (ETC) models [4, 9] is that the ETC interactions do not commute with the $SU(2)_L$ interactions of the standard model. That is, the weak interactions are partially embedded in the ETC gauge group. Providing masses for one family of ordinary fermions (say, the third family) then requires a pattern of gauge symmetry breaking with three distinct scales:

$$G_{ETC} \otimes SU(2)_{light} \otimes U(1)'$$
$$\downarrow \quad f$$
$$G_{TC} \otimes SU(2)_{heavy} \otimes SU(2)_{light} \otimes U(1)_Y$$
$$\downarrow \quad u$$
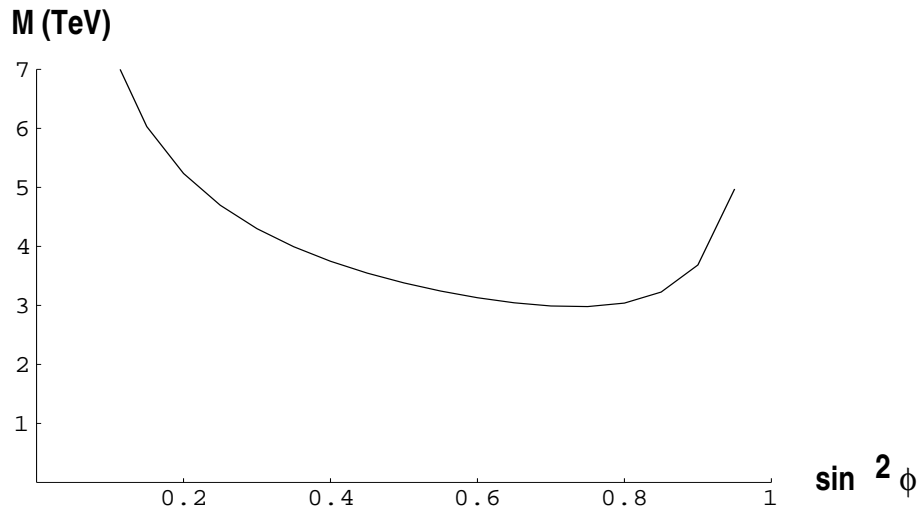$$G_{TC} \otimes SU(2)_L \otimes U(1)_Y$$
$$\downarrow \quad v$$

6

M (TeV)

7
6
5
4
3
2
1

0.2   0.4   0.6   0.8   1

$\sin^2 \phi$

Figure 3: Lower bound on heavy NCETC Z' boson mass at 95% CL as a function of mixing angle.

M (TeV)

7
6
5
4
3
2
1

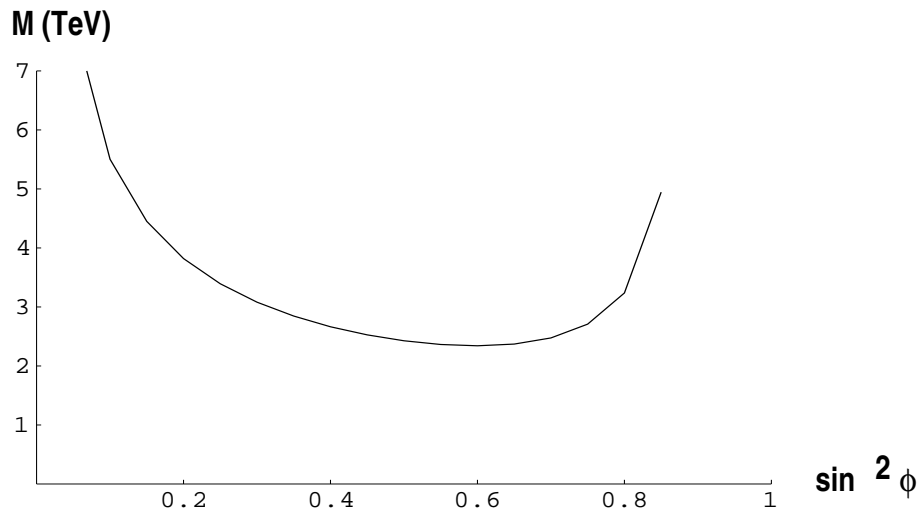0.2   0.4   0.6   0.8   1

$\sin^2 \phi$

Figure 4: Lower bound on light NCETC Z' boson mass at 95% CL as a function of mixing angle.

$$G_{TC} \otimes U(1)_{em},$$

The ETC gauge group is broken to technicolor and an $SU(2)_{heavy}$ subgroup at the scale f. The $SU(2)_{heavy}$ gauge group is effectively the weak gauge group for the third generation[¶] in these non-commuting ETC models, while the $SU(2)_{light}$ is the weak gauge group for the two light generations. The two $SU(2)$'s are mixed (i.e. they break down to a diagonal $SU(2)_L$ subgroup) at the scale u. Finally electroweak symmetry breaking is accomplished at the scale v, as is standard in technicolor theories.

The two simplest possibilities for the $SU(2)_{heavy} \times SU(2)_{light}$ transformation properties of the order parameters that produce the correct combination of mixing and breaking of these gauge groups are:

$$\langle \varphi \rangle \sim (2,1)_{1/2}, \quad \langle \sigma \rangle \sim (2,2)_0 , \qquad \text{``heavy case''} , \tag{3.1}$$

and

$$\langle \varphi \rangle \sim (1,2)_{1/2}, \quad \langle \sigma \rangle \sim (2,2)_0 , \qquad \text{``light case''} . \tag{3.2}$$

Here the order parameter $\langle \varphi \rangle$ is responsible for breaking $SU(2)_L$ while $\langle \sigma \rangle$ mixes $SU(2)_{heavy}$ with $SU(2)_{light}$. We refer to these two possibilities as "heavy" and "light" according to whether $\langle \varphi \rangle$ transforms non-trivially under $SU(2)_{heavy}$ or $SU(2)_{light}$.

The heavy case, in which $\langle \varphi \rangle$ couples to the heavy group, is the choice made in [4], and corresponds to the case in which the technifermion condensation responsible for providing mass for the third generation of quarks and leptons is also responsible for the bulk of electroweak symmetry breaking (as measured by the contribution made to the W and Z masses). The light case, in which $\langle \varphi \rangle$ couples to the light group, corresponds to the opposite scenario: here the physics responsible for providing mass for the third generation *does not* provide the bulk of electroweak symmetry breaking. In this respect, the light case is akin to multiscale technicolor models [32, 33] and top-color assisted technicolor [3].

The gauge couplings may be written

$$g_{light} = \frac{e}{\sin \phi \sin \theta} , \quad g_{heavy} = \frac{e}{\cos \phi \sin \theta} , \quad g' = \frac{e}{\cos \theta} , \tag{3.3}$$

where θ is the usual weak angle and ϕ specifies the strength of the additional interactions. Charge is given by $Q = T_{3l} + T_{3h} + Y$ and the photon eigenstate, by

$$A^\mu = \sin \theta \sin \phi \, W_{3l}^\mu + \sin \theta \cos \phi \, W_{3h}^\mu + \cos \theta X^\mu , \tag{3.4}$$

where $W_{3l,h}$ are the neutral gauge-bosons in $SU(2)_{light,heavy}$ and X is the gauge-boson of $U(1)_Y$. It is convenient to discuss the mass eigenstates in the rotated basis

$$
\begin{aligned}
W_1^\pm &= s \, W_l^\pm + c \, W_h^\pm , \\
W_2^\pm &= c \, W_l^\pm - s \, W_h^\pm , \\
Z_1 &= \cos \theta \, (s \, W_{3l} + c \, W_{3h}) - \sin \theta \, X , \\
Z_2 &= c \, W_{3l} - s \, W_{3h} ,
\end{aligned}
$$

$$\tag{3.5}$$
$$\tag{3.6}$$
$$\tag{3.7}$$
$$\tag{3.8}$$

in which the gauge covariant derivatives separate neatly into standard and non-standard pieces

$$
\begin{aligned}
D^\mu =\ & \partial^\mu + ig \left(T_l^\pm + T_h^\pm \right) W_1^{\pm \, \mu} + ig \left(\frac{c}{s} T_l^\pm - \frac{s}{c} T_h^\pm \right) W_2^{\pm \, \mu} \\
& + i \frac{g}{\cos \theta} \left(T_{3l} + T_{3h} - \sin^2 \theta \, Q \right) Z_1^\mu + ig \left(\frac{c}{s} T_{3l} - \frac{s}{c} T_{3h} \right) Z_2^\mu .
\end{aligned}
\tag{3.9}
$$

[¶]Experimental limits on the heavy gauge bosons of topflavor models [5, 6] which have an identical electroweak gauge structure but use fundamental higgs bosons to effect mass generation are considered in [31, 30].

where $g \equiv \frac{e}{\sin\theta}$. The breaking of $SU(2)_L$ results in mixing of Z_1 and Z_2, as well as a mixing of $W_1^\pm$ and $W_2^\pm$. The mass-squared matrix for the Z_1 and Z_2 is:

$$M_Z^2 = \left(\frac{ev}{2\sin\theta}\right)^2 \begin{pmatrix} \frac{1}{\cos^2\theta} & \frac{-s}{c\cos\theta} \\ \frac{-s}{c\cos\theta} & \frac{x}{s^2c^2} + \frac{s^2}{c^2} \end{pmatrix}, \qquad \text{[heavy case]} \tag{3.10}$$

$$M_Z^2 = \left(\frac{ev}{2\sin\theta}\right)^2 \begin{pmatrix} \frac{1}{\cos^2\theta} & \frac{c}{s\cos\theta} \\ \frac{c}{s\cos\theta} & \frac{x}{s^2c^2} + \frac{c^2}{s^2} \end{pmatrix}. \qquad \text{[light case]} \tag{3.11}$$

In these expressions, $x = u^2/v^2$, and the mass-squared matrix for W_1 and W_2 is obtained by setting $\cos\theta = 1$ in the above matrix. In the limit of large x, the light gauge boson mass eigenstates are

$$W^L \approx W_1 + \frac{cs^3}{x}W_2, \qquad Z^L \approx Z_1 + \frac{cs^3}{x\cos\theta}Z_2 \qquad \text{[heavy case]} \tag{3.12}$$

$$W^L \approx W_1 - \frac{c^3s}{x}W_2, \qquad Z^L \approx Z_1 - \frac{c^3s}{x\cos\theta}Z_2. \qquad \text{[light case]} \tag{3.13}$$

The heavy bosons W^H (Z^H) are the orthogonal combinations of W_1 and W_2 (Z_1 and Z_2); their masses are approximately $M_{W,Z}^H \approx \frac{\sqrt{x}}{sc}M_W^0$ where M_W^0 is the tree-level W-boson mass in the Standard Model.

In addition, the extended-technicolor interactions responsible for giving mass to the third-generation of of quarks and leptons is expected to give rise to shifts in the couplings to the left-handed bottom δg_L^b and the left-handed leptons $\delta g_L^\tau = \delta g_L^{\nu_\tau}$. More precisely, the associated change in the Zff coupling is of the form $\delta g(e/\sin\theta\cos\theta)$.

The presence of the extra electroweak bosons and possible ETC vertex corrections alters the predicted values of electroweak observables. The quantities whose values are affected are indicated separately for the heavy and light cases of NCETC in Table 1. In light NCETC, the same quantities are affected as in TC2 models; in heavy NCETC, the value of A_e [23], the ratio of G_F^2 as inferred from $\tau \to e$ vs. $\mu \to e$, is also altered. Expressions for the predicted shifts from SM values are discussed in Appendix B.

We performed separate global fits of the electroweak data to the parameters δg_b, $\delta g_\tau \equiv \delta g_{\nu_\tau}$, and $1/x$ for a range of values of mixing angle ϕ. At each value of ϕ we fixed the coupling shifts to their best-fit values and used the calculated one-sigma error on $1/x$ to determine a minimum allowed mass for the Z' and W' at 95% c.l. The resulting exclusion curves are shown in Figures 3 and 4.

In heavy NCETC, the extra weak bosons are allowed to be lightest when the mixing angle is at a value near $\sin^2\phi = 0.75$. At this point, the best-fit values for the other model parameters are

$$\begin{aligned} \delta g_b &= -0.0015 \pm 0.00089 \\ \delta g_\tau &= -0.00061 \pm 0.00066 \\ 1/x &= 0.00166 \pm 0.0011 \end{aligned} \tag{3.14}$$

The corresponding best-fit value for the Z' mass is 4.55 TeV, while the minimum allowed value of the Z' mass at 95% c.l. is 2.98 TeV. The goodness of fit is 6.6%, as compared with 7.3% when we fit the SM predictions to the same set of data.

In light NCETC, the Z' and W' can be least massive when the mixing angle is at a value near $\sin^2\phi = 0.60$. At this point, the best-fit values for the other model parameters are

$$\begin{aligned} \delta g_b &= -0.00080 \pm 0.00085 \\ \delta g_\tau &= -0.00017 \pm 0.00076 \\ 1/x &= -0.0013 \pm 0.0031 \end{aligned} \tag{3.15}$$

Note that the best-fit value of 1/x corresponds to an unphysical value for the Z' or W' mass. We therefore take the maximum (positive) value of 1/x at the 2σ level (*i.e.* 1/x=+0.00491) and use the relation $M_W^H \approx \frac{\sqrt{x}}{sc} M_W^0$ to determine the minimum $M_{W'}$ value of 2.3 TeV. Fixing 1/x at this maximum positive value, we performed a two-parameter fit to the couplings, obtaining best-fit values of

$$
\begin{aligned}
\delta g_b &= 0.00039 \pm 0.00061 \\
\delta g_\tau &= 0.0010 \pm 0.00048
\end{aligned}
\tag{3.16}
$$

The goodness of fit is 2.9%, as compared with 5.6% when we fit the SM predictions to the same set of data.

At energies well below the mass of the NCETC Z' boson, its exchange in the process $e^+ e^- \to f\bar{f}$ where f is a τ lepton or b-quark may be approximated by the contact interaction

$$
\mathcal{L}_{NC} \supset \frac{e^2}{\sin^2\theta\, M_{Z'}^2} \left(-\frac{c_\phi}{2s_\phi} (\bar{e}_L \gamma_\mu e_L) \right) \left(\frac{s_\phi}{2c_\phi} (\bar{f}_L \gamma^\mu f_L) \right) \;,
\tag{3.17}
$$

based on the Z'-fermion couplings in eqn.(3.9). As noted earlier, this Z' couples only to left-handed fermions to first approximation. Comparing this with the contact interactions studied by LEP (2.19), we find

$$
M_{Z'} = \Lambda^+ \sqrt{\frac{\alpha_{em}}{4\sin^2\theta}} \;.
\tag{3.18}
$$

The LEP limits from tau lepton production ($\Lambda_{LL}^+ \geq 11.4$ TeV) and from b-quark production ($\Lambda_{LL}^+ \geq 11.8$) TeV are comparable. Using eqn. (3.18), we find $M_{Z'} \geq 1.1$ TeV, a weaker bound than that provided by the precision electroweak data. Again, hadron collider limits, being suppressed by $\cos\phi/\sin\phi$ are even weaker.

Neutral B-meson mixing has also been used [29] to set lower bounds on the Z' mass in these models. If all quark mixing is assumed to occur in the left-handed down sector, a lower limit of order a TeV results – far weaker than the limits we have set using the precision electroweak data. The B-mixing limit is also, as noted in ref. [29], highly dependent on the flavor structure assumed for the model.

4 Weak Bosons in the Ununified Standard Model

As described in ref. [2, 7, 10], this model is based on the electroweak gauge group $SU(2)_q \times SU(2)_\ell \times U(1)$. Left-handed quarks and leptons transform as doublets under $SU(2)_q$ and $SU(2)_\ell$, respectively; right-handed quarks and leptons transform as singlets[‖] under both $SU(2)$ gauge groups. The $U(1)$ is the hypercharge group of the standard model. The gauge couplings may be written

$$
g_l = \frac{e}{\sin\phi\sin\theta}, \quad g_h = \frac{e}{\cos\phi\sin\theta}, \quad g' = \frac{e}{\cos\theta},
\tag{4.1}
$$

in terms of the usual weak mixing angle θ_W and a new mixing angle ϕ.

The electroweak gauge group spontaneously breaks to $U(1)_{em}$ which is generated by $Q = T_{3q} + T_{3\ell} + Y$. This symmetry breaking occurs when two scalar fields, Φ and Σ, transforming respectively as $(1,2)_{1/2}$ and $(2,2)_0$ acquire the vacuum expectation values (vev's)

$$
\langle \Phi \rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}, \quad \langle \Sigma \rangle = \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix} \;.
\tag{4.2}
$$

[‖]See [7] for comments on the use of additional fermions to cancel the $SU(2)_q^2 \times U(1)$ and $SU(2)_\ell^2 \times U(1)$ anomalies.
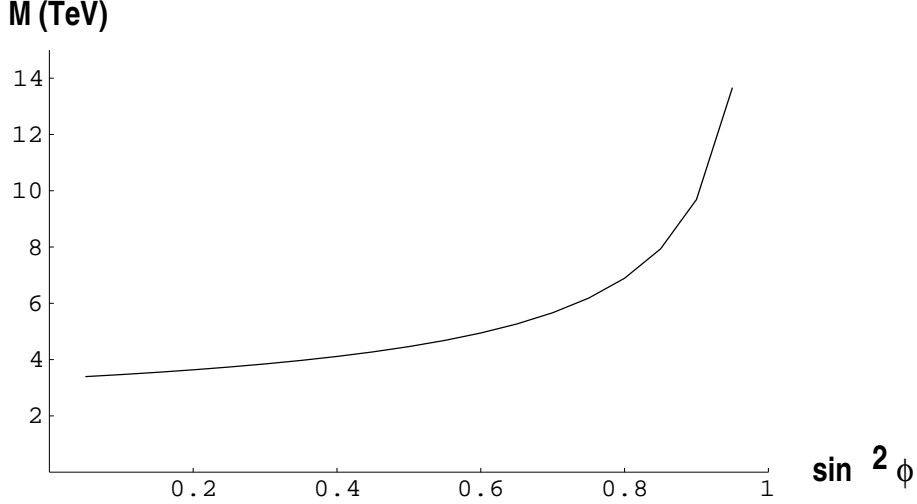
Figure 5: Lower bound on UUM Z' boson mass at 95% CL as a function of mixing angle.

The vev of Σ breaks the two $SU(2)$'s down to the diagonal $SU(2)_W$ of the standard model. Thus this theory reproduces the phenomenology of the standard model for $u \gg v$.

In the limit of large $x \equiv u^2/v^2$, the light gauge boson mass eigenstates are

$$W^L \approx W_1 + \frac{s^3 c}{x} W_2 \,, \quad Z^L \approx Z_1 + \frac{s^3 c}{x \cos\theta} Z_2 \,. \tag{4.3}$$

and they couple to fermions as, respectively,

$$\frac{e}{\sin\theta} \left(T_q^\pm + T_\ell^\pm + \frac{s^2}{x} \Big(c^2 T_q^\pm - s^2 T_\ell^\pm \Big) \right)$$

$$\frac{e}{\sin\theta \cos\theta} \left(T_{3q} + T_{3\ell} - \sin^2\theta \, Q + \frac{s^2}{x} \Big(c^2 T_{3q} - s^2 T_{3\ell} \Big) \right) \,. \tag{4.4}$$

In this approximation, the heavy eigenstates have a mass given by $\frac{M_W^H}{M_W^0} \approx \frac{M_Z^H}{M_Z^0} \approx \frac{\sqrt{x}}{sc}$. where M_W^0 is the tree-level W-boson mass in the Standard Model.

The presence of the extra W and Z bosons in this model leads to predicted deviations in the values of electroweak observables. The list of affected quantities is indicated in the last column of Table 1. Note that while quarks and leptons couple differently to the electroweak bosons in the model, generation universality is preserved so that the "leptonic" values of A_{FB} and R are relevant rather than the distinct values measured for each lepton species; likewise it is the value of σ_h which assumes lepton universality which is relevant here. The formulas for the predicted shifts from SM predictions are discussed in Appendix C.

We performed a global fit of the electroweak data to the model's predictions and determined a 95% c.l. lower bound on $M_{Z'}$ as a function of the mixing angle ϕ, as shown in Figure 5. The mass of the heavy Z' and W' states must always be at least 3.4 TeV, with the limit being stronger as $\sin\phi$ increases. The quality of fit for the Ununified Model on the limit curve is 2.9%, as compared with 4.1% when we fit the predictions of the SM to the same data.

In this model, limits on contact interactions tend to provide much weaker bounds on the Z' mass than the precision electroweak data. The strongest limits from contact interactions arise from

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the process $e_L^+ e_L^- \to \bar{b}_L b_L$, for which (based on eqn. (4.4))

$$M_{Z'} = \Lambda^+ \sqrt{\frac{\alpha_{em}}{4 \sin^2 \theta}}.$$ (4.5)

LEP finds [22] $\Lambda_{LL}^+ \geq 11.8$ TeV, implying $M_{Z'} \geq 1.1$ TeV. The $M_{Z'}$ limit from $e_L^+ e_L^- \to \ell_L^+ \ell_L^-$, for which LEP finds $\Lambda_{LL}^- \geq 9.8$ TeV, is suppressed by a factor of $\sin \phi / \cos \phi$ because only leptons are involved. Tevatron limits on quark compositeness have the potential to be stronger because they are enhanced by a factor of $\cos \phi / \sin \phi$; but the existing D0 bound [34] $\Lambda^- \geq 2.2$ TeV implies only $M_{Z'} \geq 900$ GeV even when $\sin^2 \phi = 0.05$.

5   Conclusions

In this note we update the bounds [8, 9, 10] placed by electroweak data on the existence of flavor non-universal extensions to the standard model in the context of topcolor assisted technicolor (TC2), noncommuting extended technicolor (NCETC), and the ununified standard model (UUM).

    We find that the the extra Z in TC2 models must be heavier than about 2 TeV for generic values of the gauge coupling. However, for values of the new gauge boson mixing angle near $\sin \phi \approx 0.0784$, cancellations among parameters limit the size of deviations of Z-pole observables, weakening the precision electroweak limits. In this region of parameter space, a stronger lower bound on the Z' mass comes from limits on contact interactions at LEP II, which imply that the TC2 Z' must be greater than about 1 TeV. For TC2 models, limits on the Z' mass from flavor-changing neutral currents have been found to be quite model-dependent, in contrast with the limits reported here. We note that a lower bound of order a TeV on the TC2 Z' mass is consistent with the goal of providing sufficient dynamical electroweak symmetry breaking without fine-tuning [3].

    The extra $SU(2)$ triplet of gauge bosons in NCETC and UUM models must be somewhat heavier, with masses always greater than about 3 TeV. The limits on these models from Z-pole observables are significantly stronger than those from contact interactions at LEP II or from flavor-changing neutral currents. In the context of NCETC, a lower bound of order 3 TeV on the masses of the extra SU(2) gauge-bosons implies that the scale of the ETC interactions responsible for generating the top-quark mass must also be greater than about 3 TeV. As noted in [9], this implies that the ETC interactions must be strongly-coupled and that fine-tuning is required in order to accommodate a top-quark mass of 175 GeV. Using the estimates in [9], we see that the strong ETC coupling must be adjusted to of order a few percent or less.

Appendix A: Corrections for TC2

The full list of electroweak corrections to standard model predictions in TC2 is:

$$\Gamma_Z = (\Gamma_Z)_{SM} \left(1 + \left[-0.0390 \tan^2 \phi + 0.0520 \sec^2 \phi + 0.00830 \csc^2 \phi \sec^2 \phi \right] \frac{1}{x} \right)$$ (A.1)

$$A_{LR} = (A_{LR})_{SM} + \left[1.986 \tan^2 \phi - 0.202 \sec^2 \phi + 0.00366 \csc^2 \phi \sec^2 \phi \right] \frac{1}{x}$$ (A.2)

$$A_{FB}^e = (A_{FB}^e)_{SM} + \left[0.474\tan^2\phi - 0.483\sec^2\phi + 0.000875\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.3}$$

$$A_{FB}^\mu = (A_{FB}^\mu)_{SM} + \left[0.474\tan^2\phi - 0.483\sec^2\phi + 0.000875\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.4}$$

$$A_{FB}^\tau = (A_{FB}^\tau)_{SM} + \left[0.474\tan^2\phi - 0.214\sec^2\phi + 0.0139\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.5}$$

$$\sigma_h = (\sigma_h)_{SM}\left(1 - \left[0.0152\tan^2\phi - 0.105\sec^2\phi + 0.00830\csc^2\phi\sec^2\phi\right]\frac{1}{x}\right) \tag{A.6}$$

$$R_b = (R_b)_{SM}\left(1 - \left[0.0440 + 0.190\sec^2\phi - 0.0146\csc^2\phi\sec^2\phi\right]\frac{1}{x}\right) \tag{A.7}$$

$$R_c = (R_c)_{SM}\left(1 - \left[0.0944 - 0.0625\sec^2\phi + 0.00432\csc^2\phi\sec^2\phi\right]\frac{1}{x}\right) \tag{A.8}$$

$$R_e = (R_e)_{SM}\left(1 + \left[.200\tan^2\phi + 0.0325\sec^2\phi - 0.00378\csc^2\phi\sec^2\phi\right]\frac{1}{x}\right) \tag{A.9}$$

$$R_\mu = (R_\mu)_{SM}\left(1 + \left[0.200\tan^2\phi + 0.0325\sec^2\phi - 0.00378\csc^2\phi\sec^2\phi\right]\frac{1}{x}\right) \tag{A.10}$$

$$R_\tau = (R_\tau)_{SM}\left(1 + \left[0.200\tan^2\phi - -.316\sec^2\phi + 0.0235\csc^2\phi\sec^2\phi\right]\frac{1}{x}\right) \tag{A.11}$$

$$A_e(P_\tau) = (A_e(P_\tau))_{SM} + \left[1.986\tan^2\phi - 0.202\sec^2\phi + 0.00366\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.12}$$

$$A_\tau(P_\tau) = (A_\tau(P_\tau))_{SM} + \left[1.986\tan^2\phi - 1.592\sec^2\phi + 0.113\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.13}$$

$$A_{FB}^b = \left(A_{FB}^b\right)_{SM} + \left[1.414\tan^2\phi - 0.157\sec^2\phi + 0.00365\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.14}$$

$$A_{FB}^c = (A_{FB}^c)_{SM} + \left[1.105\tan^2\phi - 0.113\sec^2\phi + 0.00204\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.15}$$

$$\mathcal{A}_b = (\mathcal{A}_b)_{SM} + \left[0.161\tan^2\phi - 0.129\sec^2\phi + 0.00912\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.16}$$

$$\mathcal{A}_c = (\mathcal{A}_c)_{SM} + \left[0.867\tan^2\phi - 0.0883\sec^2\phi + 0.00160\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.17}$$

$$M_W = (M_W)_{SM}\left(1 - \left[0.165\tan^2\phi - 0.0258\sec^2\phi + 0.00101\csc^2\phi\sec^2\phi\right]\frac{1}{x}\right) \tag{A.18}$$

$$g_L^2(\nu N \to \nu X) = \left(g_L^2\right)_{SM} + \left[0.0576\tan^2\phi - 0.0194\sec^2\phi + 0.00121\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.19}$$

$$g_R^2(\nu N \to \nu X) = \left(g_R^2\right)_{SM} + \left[-0.0196\tan^2\phi + 0.00666\sec^2\phi - 0.0000350\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.20}$$

$$Q_W(Cs) = (Q_W(Cs))_{SM} + \left[16.57\tan^2\phi - 5.655\sec^2\phi - 0.00206\csc^2\phi\sec^2\phi\right]\frac{1}{x} \tag{A.21}$$

Appendix B: Corrections for NCETC

The formulae for corrections to most of the variables used in our fits are given in [9]. Those for the few additional variables used here are below.

`Heavy Case`

$$R_c = (R_c)_{SM} \left(1 - 1.01(\delta g_L^b)^{ETC} + \left[0.505s^4 + 1.40s^2c^2 - 0.121(1 - s^4) \right] \frac{1}{x} \right) \tag{B.1}$$

$$\mathcal{A}_b = (\mathcal{A}_b)_{SM} - 0.293(\delta g_L^b)^{ETC} + \left[-0.146s^4 - 0.208(1 - s^4) \right] \frac{1}{x} \tag{B.2}$$

$$\mathcal{A}_c = (\mathcal{A}_c)_{SM} + \left[-0.785s^2c^2 - 1.123(1 - s^4) \right] \frac{1}{x} \tag{B.3}$$

$$A_e = 1 - \frac{2}{x} \tag{B.4}$$

`Light Case`

$$R_c = (R_c)_{SM} \left(1 - 1.01(\delta g_L^b)^{ETC} + \left[-1.01s^2c^2 - 1.784c^4 \right] \frac{1}{x} \right) \tag{B.5}$$

$$\mathcal{A}_b = (\mathcal{A}_b)_{SM} - 0.293(\delta g_L^b)^{ETC} + \left[0.146s^2c^2 + 0.208c^4 \right] \frac{1}{x} \tag{B.6}$$

$$\mathcal{A}_c = (\mathcal{A}_c)_{SM} + \left[1.908c^4 \right] \frac{1}{x} \tag{B.7}$$

Appendix C: Corrections for the UUM

The formulae for corrections to most of the variables used in our fits are given in [10]. Those for the few additional variables used here are below.

$$R_c = (R_c)_{SM} \left(1 + \left[0.073s^2c^2 + 0.121s^4 \right] \frac{1}{x} \right) \tag{C.1}$$

$$\mathcal{A}_b = (\mathcal{A}_b)_{SM} + \left[0.1467s^2c^2 + 0.208s^4 \right] \frac{1}{x} \tag{C.2}$$

$$\mathcal{A}_c = (\mathcal{A}_c)_{SM} + \left[0.7855s^2c^2 + 1.123s^4 \right] \frac{1}{x} \tag{C.3}$$

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Quantity	Experiment	SM	TC2	NCETC (heavy)	NCETC (light)	UUM
Γ_Z	2.4952 ± 0.0023	2.4962	*	*	*	*
A_{LR}	0.1514 ± 0.0022	0.1482	*	*	*	*
A^e_{FB}	0.0145 ± 0.0025	0.0165	*	*	*	
A^μ_{FB}	0.0169 ± 0.0013	0.0165	*	*	*	
A^τ_{FB}	0.0188 ± 0.0017	0.0165	*	*	*	
A^ℓ_{FB}	0.0171 ± 0.0010	0.0165				*
σ^{non}_h	41.541 ± 0.037	41.480	*	*	*	
σ^{univ}_h	41.540 ± 0.033	41.481				*
R_b	0.21646 ± 0.00065	0.215768	*	*	*	*
R_c	0.1719 ± 0.0031	0.1723	*	*	*	*
R_e	20.804 ± 0.050	20.741	*	*	*	
R_μ	20.785 ± 0.033	20.741	*	*	*	
R_τ	20.764 ± 0.045	20.741	*	*	*	
R_ℓ	20.767 ± 0.025	20.741				*
$A_e(P_\tau)$	0.1498 ± 0.0049	0.1482	*	*	*	
$A_\tau(P_\tau)$	0.1439 ± 0.0043	0.1482	*	*	*	
$A_\ell(P_\tau)$	0.1465 ± 0.0033	0.1482				*
A^b_{FB}	0.0994 ± 0.0017	0.1039	*	*	*	*
A^c_{FB}	0.0707 ± 0.0034	0.0743	*	*	*	*
$\mathcal{A}_b$	0.922 ± 0.020	0.935	*	*	*	*
$\mathcal{A}_c$	0.670 ± 0.026	0.668	*	*	*	*
M_W (LEP II)	80.450 ± 0.039	80.394	*	*	*	*
M_W (Tevatron)	80.454 ± 0.060	80.394	*	*	*	*
g^2_L	0.3005 ± 0.0014	0.3042	*	*	*	*
g^2_R	0.0310 ± 0.0011	0.0301	*	*	*	*
$Q_W(Cs)$	-72.39 ± 0.59	-72.89	*	*	*	*
A_e	1.0012 ± 0.0053	1.0		*		

Table 1: Experimental and predicted SM values of electroweak observables. Experimental values of most quantities are from [22]; the experimental value of M_W(Tevatron) and of A_e, the ratio of G^2_F as inferred from the decays of $\tau \to e$ vs. $\mu \to e$, are from [23]; the experimental values of g^2_L and g^2_R are from [24]. The theoretical SM values are from [22]. The value of σ_h labeled "'univ" ("non") was derived (without) assuming lepton universality. In each of the last four columns, a * indicates that the predicted value of the observable in the relevant model differs from that in the SM (see Appendices); thus, 22 observables were used in the TC2 and light ETC fits; 23 in the heavy ETC fit, and 17 in the UUM fit.