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Author
Agashe, K.

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A Consistent Model of Electroweak Data Including $Z \to b\bar{b}$ and $Z \to c\bar{c}$

K. Agashe, M. Graesser, I. Hinchliffe, and M. Suzuki
Physics Division

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A Consistent Model of Electroweak Data Including $Z \to b\bar{b}$ and $Z \to c\bar{c}$ [1]

K. Agashe, M. Graesser, I. Hinchliffe, M. Suzuki
Theoretical Physics Group
E. O. Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

Abstract

We have performed an overall fit to the electroweak data with the generation blind $U(1)$ extension of the Standard Model. As input data for fitting we have included the asymmetry parameters, the partial decay widths of Z, neutrino scattering, and atomic parity violation. The QCD coupling α_s has been constrained to the world average obtained from all data except the Z width. On the basis of our fit we have constructed a viable gauge model that not only explains R_b and R_c but also provides a much better overall fit to the data than the Standard Model. Despite its phenomenological viability, our model is unfortunately not simple from the theoretical viewpoint. Atomic parity violation experiments strongly disfavor more aesthetically appealing alternatives that can be grand unified.

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The observation at LEP[1] that the decay widths of the Z to $b\bar{b}$ and $c\bar{c}$ do not agree with the Standard Model expectations [2] has led to a flurry of theoretical activity [3, 4, 5, 6, 7, 8]. Various possible explanations have been considered. Most of these explanations suffer from at least one defect. Either they do not present a complete phenomenologically viable model or they present an overall fit that ignores some other experimental data. In this paper we present a model that, while aesthetically distasteful, is phenomenologically viable and has a much better overall fit to data than the Standard Model. As input data we use the various asymmetries and partial widths as measured on the Z resonance as well as other data that are constraining.

The outline of the paper is as follows. We start with a general analysis of the data. We modify the couplings in a generation independent fashion by mixing the Z boson to a second neutral boson X. We show that such modifications can lead to a good fit to the data, which is quantified in terms of the total χ^2. On the basis of this analysis, we construct an explicit model with the X that decouples from leptons. The model is not supersymmetric and requires the existence of new quarks to ensure anomaly cancellation. We comment on the constraints that the non-observation of such particles and the new gauge boson itself place on the model. We repeat the χ^2 fit by varying parameters of our model to show how much improvement the model attains over the Standard Model.

It is important that any model that purports to explain the problems in the $b\bar{b}$ and $c\bar{c}$ decay widths of the Z does not introduce problems with other processes. Quantities that are measured precisely at the Z are [1], the mass of the Z, the forward-backward asymmetry for leptons (A^{ℓ}_{FB}), for charm (A^{c}_{FB}) and for bottom (A^{b}_{FB}) quarks; the asymmetries measured in tau decay (A_τ and A_e), the total width of the Z (Γ_Z), the hadronic production cross section (σ^0_h), the ratio of the hadronic to leptonic width (R_ℓ), the fraction of the hadronic width that goes into charm quarks (R_c) and bottom quarks (R_b); as well as the left-right beam polarization asymmetry (A_{LR}) and left-right forward-backward asymmetries for charm ($A_c(LR)$) and bottom quarks ($A_b(LR)$) [9]. In addition there are other important pieces of data. The first of these is α_s that we constrain to be equal to the world average [10] obtained from all data except the Z width; we include the measurements from jet counting at the Z [11] since these measurements are independent of the couplings of the quarks to the Z itself. Very important are data from lower energy experiments, particularly the measurement of parity violation in cesium (Q_W^{Cs}) [12] and thallium (Q_W^{Tl}) [13] atoms which severely constrain the vector couplings of the Z to up and down quarks. The W mass (M_W) [14] severely constrains any shifts in the gauge boson mass spectra and finally measurements from neutral current interaction of neutrinos [15] constrain the couplings of up and down quarks to the Z at lower energies. We shall include all of these data in our fit. Models that can be favored by the Z data alone are disfavored when the rest of the data are included.

The measured values of $R_b = 0.2219 \pm 0.0017$ and $R_c = 0.1540 \pm 0.0074$ deviate by 3.67σ and 2.46σ, respectively, from the Standard Model predictions. The value of R_c is 10% lower than the Standard Model value. It is difficult to explain these discrepancies by models based on radiative corrections [3]. Since $R_q \propto g_L^{q2} + g_R^{q2}$, where $g_{L(R)}^q$ is the left-handed (right-handed) coupling of the quark to the Z boson, we need shifts in these couplings due to new physics to resolve the R_b and R_c anomalies. If the new physics affects only the b and c quark couplings, such shifts are difficult to reconcile with the otherwise good agreement with the Standard Model for the following reason. Since the QCD corrections to the partial decay widths cancel to good accuracy in R_b and R_c, a shift in R_b and R_c changes the total hadronic decay rate into

$$\Gamma_{had} = \Gamma_{had}^0 \times \left(1 + \frac{\alpha_s(M_Z)}{\pi} + O(\alpha_s^2)\right) \times \left(1 + \frac{\delta R_b + \delta R_c}{1 - R_b^{exp} - R_c^{exp}}\right), \qquad (1)$$

where $\delta R_b \equiv R_b^{exp} - R_b^{SM}$, $\delta R_c \equiv R_c^{exp} - R_c^{SM}$, and Γ_{had}^0 denotes the Standard Model value of Γ_{had} before the QCD correction. With $\alpha_s(M_Z) = 0.12$, this change would shift Γ_Z by -11σ from the measured value and, in terms of

R_l, by -14σ. If instead $\alpha_s(M_Z)$ is extracted by fitting Γ_{had} to its measured value, $\alpha_s(M_Z)$ would have to be 0.186 ± 0.042, in disagreement with the world average of 0.118 ± 0.003. A natural resolution of this problem involves postulating the new physics for other quarks too. In particular, if the new physics is generation blind, the model is free from the fine tuning problem of flavor changing neutral currents, which is a common difficulty in the class of models [5, 6] that introduce new physics only in the heavy generations.

The simplest way to accommodate these features is to add another $U(1)$ factor to $SU(2) \times U(1)_Y$ of the Standard Model [5, 7, 8]. Mixing between the gauge boson X of this extra $U(1)$ with the Z boson of the Standard Model can produce the shifts in the $Zq\bar{q}$ couplings that are necessary to explain R_b, R_c and α_s. The most general generation-blind $U(1)_X$ current that is consistent with $SU(2) \times U(1)_Y$ can be written as

$$J_X^\mu = g_X(q_Q\overline{Q}\gamma^\mu Q + q_U\overline{U}\gamma^\mu U + q_D\overline{D}\gamma^\mu D + q_L\overline{L}\gamma^\mu L + q_E\overline{E}\gamma^\mu E + \cdots), \quad (2)$$

where Q and L represent the left-handed quark and lepton doublets, and U, D and E are the right-handed up-type quarks, down-type quarks and charged leptons, respectively. Summation over generations is understood, and the contributions from particles other than those of the Standard Model have been suppressed. Since $U(1)_X$ charges always enter multiplied by g_X, we normalize them to $q_Q = -1$ so that five parameters, g_X and four charge ratios, specify the $U(1)_X$ current. At tree level the $Z - X$ mixing occurs by Higgs doublets that carry $U(1)_X$ charges. We assume that there is no higher dimensional Higgs multiplet of $SU(2)$. Loop diagrams generate both mass and kinetic energy mixing. We parametrize the mass mixing at the Z mass as

$$M^2 = \begin{pmatrix} \frac{1}{4}g_Z^2 v^2 & \kappa g_Z g_X v^2 \\ \kappa g_Z g_X v^2 & g_X^2 V_X^2 \end{pmatrix} \quad (3)$$

where $g_Z = g_2/\cos\theta_W$ with g_2 being the $SU(2)$ coupling and $v^2 = (\sqrt{2}G_F)^{-1}$ at tree level. The kinetic energy is defined to be diagonal at the Z mass.

The gauge eigenstates (Z,X) are related to the mass eigenstates (Z_M, X_M) by

$$\begin{aligned} Z &= Z_M \cos\alpha - X_M \sin\alpha \\ X &= X_M \cos\alpha + Z_M \sin\alpha \end{aligned} \tag{4}$$

where $\tan 2\alpha = -2\kappa g_Z g_X v^2/(g_X^2 V_X^2 - g_Z^2 v^2/4)$. The coupling of the Standard Model quark of flavor i to the Z gauge boson is given by $J^\mu = g_Z q_i(\overline{q}\gamma^\mu q)$ with $q_i \equiv (T_{3L} - Q\sin^2\theta_W)_i$. The lighter mass eigenstate Z_M is identified with the experimentally observed Z boson. The mixing between Z and X shifts the coupling to the observed Z from the Standard Model value by $\delta q_i = (g_X/g_Z)q_{Xi}\sin\alpha + q_i(\cos\alpha - 1)$, where q_{Xi} is the $U(1)_X$ charge of quark i. If $M_X \gg M_Z$, the mixing angle is given by $\sin\alpha = -\kappa g_Z v^2/(g_X V_X^2)$ and therefore $\delta q_i = -\kappa q_{Xi}(v/V_X)^2$. In this approximation there are two parameters κ, V_X for mixing and four $U(1)_X$ charge ratios that are fitted to the data. When M_X is comparable with M_Z, exact diagonalization must be done and the gauge coupling g_X is included as an independent parameter.

Since the Z gauge boson is not a mass eigenstate, the tree-level relation $M_Z^2 = g_Z^2 v^2/4$ is no longer valid. However, the mass relation $M_W^2 = g^2 v^2/4$ is not affected. The shift in M_Z can be expressed as a shift in the ρ parameter [16] . Since the Z mass is measured more accurately than the W mass, we use the W mass relative to the Z mass as experimental information in comparing theoretical predictions with the data. The decrease in M_Z is translated into an increase in M_W and a decrease in $\sin^2\theta_W$. In the large M_X approximation,

$$\frac{\delta M_W^2}{M_W^2} = -\frac{\delta M_Z^2}{M_Z^2}\frac{\cos^2\theta_W}{\cos^2\theta_W - \sin^2\theta_W}, \tag{5}$$

$$\frac{\delta \sin^2\theta_W}{\sin^2\theta_W} = \frac{\delta M_Z^2}{M_Z^2}\frac{\cos^2\theta_W}{\cos^2\theta_W - \sin^2\theta_W}, \tag{6}$$

with $\delta M_Z^2/M_Z^2 = -(M_X \sin\alpha/M_Z)^2$.

Atomic parity violation experiments constrain the vector couplings of the up and the down type quarks. For a heavy atom with atomic number Z and neutron number N, these experiments measure the charge

$Q_W = -2((2Z+N)C_{1u} + (2N+Z)C_{1d})$, where C_{1q} is defined in [17]. The measured [12, 13] and predicted [18, 19] Q_W charges for cesium (Z=55, N=78) and thallium (Z=81, N=124) are:

$$\begin{array}{ll} Q_W(Cs) = -71.04 \pm 1.81, & Q_W(Cs)^{SM} = -73.14 \; (1.16\sigma) \\ Q_W(Tl) = -114.2 \pm 3.8, & Q_W(Tl)^{SM} = -116.3 \; (0.55\sigma). \end{array} \tag{7}$$

Both experiments agree on the sign of the difference between the measured value and the Standard Model prediction. These measurements strongly constrain any new physics that would further decrease the Q_W charge and hence limit the values of the $U(1)_X$ charges the quarks can have.

We perform a minimum χ^2 analysis fitting both the shifts in the vector and axial couplings of Z and the shifts in M_W and $\sin^2\theta_W$ to the 18 observables discussed above. Although the SLD measurement [9] of A_{LR} is inconsistent with the LEP measurement, we find no reason to exclude either measurement from the fit. Electroweak radiative corrections [15, 20] are incorporated in the Standard Model values of these observables. In computing the electroweak radiative corrections, we use $\alpha_s = 0.118$, $m_t = 175$ GeV and $1/\alpha(M_Z) = 128.75$. The new physics requires a nonminimal Higgs sector. The radiative corrections due to Higgs loops are numerically very small. Therefore we approximate the Higgs correction with that of the Standard Model by choosing two values (100 GeV and 400 GeV) for the Higgs mass. The momentum dependence of $Z-X$ mixing due to radiative corrections is not included in the fit since it is model dependent. It should be examined for consistency after a model is built.

In performing the fit we restrict to $V_X > 550$ GeV (see later) and allow the leptons to have arbitrary $U(1)_X$ charges. We diagonalize the $Z-X$ mass matrix exactly. The minimum χ^2 is 13 for $M_H = 100$ GeV and the preferred value of the $U(1)_X$ charges of the leptons is zero. Setting these charges to zero, we have four parameters. With fourteen degrees of freedom, our best χ^2 is 13 for $M_H = 100$ GeV and 15 for $M_H = 400$ GeV. For comparison, the χ^2 for the Standard Model is 30 for $M_H = 100$ GeV. The $U(1)_X$ charges are

$q_U = 4.44 \pm 1.62$ and $q_D = 4.25 \pm 2.73$ for $M_H = 100$ GeV, and $q_U = 2.38 \pm 1.09$ and $q_D = 1.33 \pm 0.74$ for $M_H = 400$ GeV. For $m_H = 100$ GeV, the ρ parameter prefers the X boson to be nearly degenerate with the Z. If we restrict, for example, $M_X > 115$ GeV, the preferred charges are $q_U = 3.28 \pm 1.02$ and $q_D = 2.59 \pm 1.18$ with $\chi^2 = 16$. The errors correspond to $\chi^2 = \chi^2_{min} + 1$. See Table 1 for the experimental and fitted values of the observables.

We now build a model based on our analysis. Since the leptons carry no $U(1)_X$ charge, there are three logical possibilities in constructing a two-doublet Higgs model: (1) $q_U = 2q_L - q_D$; (2) $q_U = q_Q$; and (3) $q_D = q_Q$. We note that the fitted $U(1)_X$ charges are inconsistent with these possibilities. If the atomic parity violation data are excluded, only case (3) is favored by the remaining data; the χ^2 is 15 (15) for $m_H = 100$ (400) GeV and for 13 degrees of freedom (for comparison, the χ^2 for the Standard Model without these data is 28 for 16 degrees of freedom). When the atomic parity violation data are included, the χ^2 is 17 (20) for 15 degrees of freedom. To obtain the best χ^2, however, we must fine tune Z and X to be nearly degenerate. For $M_X = 115$ GeV, for instance, the χ^2 increases to 23 (24). We think that such a high degree of fine tuning in the Z and X masses is unnatural. If loops of added particles generate a strong q^2 dependence such that q_D/q_Q varies from 1 at $q^2 = M_Z^2$ to -1 at $q^2 = 0$, it can avoid the fine tuning. Since such q^2 dependence is unlikely, we reject $q_Q = q_D$ and introduce three Higgs doublets. [2] Anomaly cancellation is challenging and requires many more fermions than in the Standard Model.

A model looks more natural if the $U(1)_X$ charge ratios are rational numbers. Though this is by no means a requirement, we restrict to this possibility. We find that the fitted charges can accommodate such a choice: $q_Q = -1$, $q_U = 2$ and $q_D = 1$. Three Higgs doublets H_u, H_d and H_l are introduced

[2] Recently Babu *et al* [8] proposed supersymmetric grand unified $U(1)$ extension models for R_b and R_c. They imposed $q_Q = q_D$ on all models to accommodate supersymmetry and did not consider atomic parity violation. If atomic parity violation is taken into account, their models would be viable only when Z and X are nearly degenerate.

to give masses to the up quarks, down quarks and leptons. Their $U(1)_X$ charges are $q_{H_u} = -3$, $q_{H_d} = -2$ and $q_{H_l} = 0$. Since the $U(1)_X$ charges of the Standard Model fermions are not vector-like, the $U(1)_X$ gauge symmetry is anomalous and new quarks must be added to cancel the anomalies. We add three generations of Standard Model-like quarks with opposite $U(1)_Y$ and $U(1)_X$ charges: Q'_L = (**2**, -1/6, 1), $\tilde{U}_R$ = (**1**, -2/3, -2), $\tilde{D}_R$ = (**1**, 1/3, -1) under $SU(2) \times U(1)_Y \times U(1)_X$. These new quarks, in turn, generate anomalies under $SU(2) \times U(1)_Y$ and their chiral partners must be added to make $SU(2) \times U(1)_Y$ vector-like: Q'_R = (**2**, -1/6, 0), $\tilde{U}_L$= (**1**, -2/3, 0), $\tilde{D}_L$= (**1**, 1/3, 0). (See Table 2.) Since twelve quark flavors have been added to cancel anomalies, the QCD coupling is no longer asymptotically free. Using the one-loop β function, we have checked that the coupling remains perturbative up to the Planck scale.

The new quarks should be heavier than about 200 GeV to avoid detection at Fermilab. They can acquire mass through the Higgs doublets:

$$\lambda_1 \overline{Q'}_L \tilde{U}_R H_u^c + \lambda_2 \overline{Q'}_R \tilde{D}_L H_l^c + \lambda_3 \overline{Q'}_L \tilde{D}_R H_d^c + \lambda_4 \overline{Q'}_R \tilde{U}_L H_l, \tag{8}$$

where the superscript c denotes charge conjugation. The masses generated by these couplings should be of the order of the Standard Model quark masses. To make the new quarks heavier, we must introduce additional singlet Higgs couplings. These singlet Higgs fields break $U(1)_X$ at a scale larger than the electroweak scale. Two Higgs singlets ϕ and ϕ' are introduced with the $U(1)_X$ charges $q_\phi = -1$ and $q_{\phi'} = -2$ so that the new quarks acquire mass through

$$\lambda_5 \overline{Q'}_R Q'_L \phi + \lambda_6 \overline{\tilde{U}}_R \tilde{U}_L \phi' + \lambda_7 \overline{\tilde{D}}_R \tilde{D}_L \phi \tag{9}$$

When the singlet mass contribution of Eq.(9) is much larger than the contribution of Eq.(8), the new quarks are nearly degenerate within a multiplet and a shift in the T parameter [21] is negligible. Note that in the large singlet mass limit the $U(1)_Y$ current of the new quarks is a pure vector. Therefore a shift in the S parameter [21] is also suppressed by the ratio of the doublet mass to the singlet mass.

Since five Higgs fields (H_u, H_d, H_l, ϕ and ϕ') develop *vevs*, we must ensure that they do not result in an unabsorbed Nambu-Goldstone boson or an axion. We introduce self-interactions among the Higgs multiplets to eliminate accidental global symmetries that may break down spontaneously. Since two neutral gauge bosons of $SU(2)\times U(1)_Y \times U(1)_X$ absorb two Nambu-Goldstone modes, we add appropriate interactions among Higgs fields to give mass to the three remaining modes. The following couplings suffice:

$$\lambda_8 \phi^2 \phi'^c + \lambda_9 H_u^c H_l^c \phi \phi' + \lambda_{10} H_d H_l^c \phi'^c \tag{10}$$

The new quarks can be 3 or $\bar{3}$ of $SU(3)$. If $(Q', \tilde{U}, \tilde{D})$ are assigned to color triplets, there is an accidental discrete symmetry, $Q \to Q$, $Q' \to -Q'$ etc., that prevents the lightest new quark from decaying. Then the lightest baryonic bound state of the new quarks might be abundant enough to have been detected in exotic matter searches [22]. When they are assigned to color antitriplets, we can introduce another scalar singlet $\tilde{\phi}$ and allow the new quarks to decay into Q and $\tilde{\phi}$ through the coupling $QQ'\tilde{\phi}$. However, the following mass terms are then allowed by the gauge symmetries:

$$M_1 Q_L^T C Q'_L + M_2 U_R^T C \tilde{U}_R + M_3 D_R^T C \tilde{D}_R, \tag{11}$$

where C is the charge conjugation matrix. These terms result in mixing between the Standard Model quarks and the new quarks. They may be forbidden by imposing the discrete symmetry mentioned above. We assign an odd parity to $\tilde{\phi}$ under this symmetry to maintain the $QQ'\tilde{\phi}$ coupling. Since $\tilde{\phi}$ is a singlet carrying no $U(1)_Y$ or $U(1)_X$ charge and is stable, it can escape detection in terrestrial experiments. The $\tilde{\phi}$ particle could have been produced in the early Universe and could contribute to the mass density. The mass and coupling of $\tilde{\phi}$ can be adjusted so that it does not overclose the Universe [23].

We now examine the property of the X boson in our model and some of its phenomenological implications. The parameter κ in the $Z-X$ mass matrix is given by

$$\kappa = \frac{2v_d^2 - 3v_u^2}{2v^2}, \tag{12}$$

where $\langle H_u \rangle = v_u/\sqrt{2}$, $\langle H_d \rangle = v_d/\sqrt{2}$ and $\langle H_l \rangle = v_l/\sqrt{2}$ with $\sqrt{v_u^2 + v_d^2 + v_l^2} = v = 247$ GeV. Introducing $\langle \phi \rangle = V/\sqrt{2}$, $\langle \phi' \rangle = V'/\sqrt{2}$ and $5\tilde{V}^2 \equiv V^2 + 4V'^2$, the parameter V_X^2 is given by $5\tilde{V}^2 + 9v_u^2 + 4v_d^2$. If the Yukawa couplings appearing in Eq.(9) are O(1), the *vevs* V and V' should be greater than v so that the new quarks are heavier than the Standard Model quarks. This implies a lower limit $\tilde{V} \geq 250$ GeV (or equivalently $V_X \gtrsim 550$ GeV) that is imposed in performing the fit. We restrict g_X such that $M_X > M_Z$. Since the $U(1)_X$ charges of the up quarks are large, we restrict $g_X \leq 0.5$ to ensure that the coupling strength of the X boson to up quarks $(g_L^2 + g_R^2)g_X^2/4\pi = 5g_X^2/4\pi$ remains perturbative.

Although loop corrections can generate kinetic energy mixing between Z and X, such mixing is equivalent to the mass mixing at any fixed q^2. It makes a small difference only when extrapolation is made to different q^2 which is relevant when fitting to the low-energy experiments. However, we checked that in this model the $Z - X$ mixing parameters vary by a negligible amount over this range, and so we may ignore the extrapolation in the $U(1)_X$ current.

We make a fit to the 18 observables with our model by varying three independent parameters, which we choose to be g_X, κ and V_X. We diagonalize the mass matrix exactly. For $M_H = 400$ GeV, for instance, the best fit is $\chi^2 = 16$ with $g_X = 0.15$, $\kappa = -0.05$ and $V_X = 970$ GeV. It turns out that the χ^2 is not very sensitive to g_X. Varying g_X over the range between 0.1 and 0.5, we find that χ^2 increases only by 1.5. Thereofre we shall fix g_X to 0.15 hereafter. The 95% C.L. range is -0.01 to -0.22 for κ and 790 GeV to 2700 GeV for V_X. No fine tuning is needed for v_l and v_u/v_d to produce $\kappa = -0.05$. But, if we want the t-quark Yukawa coupling to be O(1), v_u must be a substantial fraction of v so that a tuning at the level of 10 % is required for v_u/v_d.

Since the off-diagonal mass matrix element is small, the mass of the X boson is equal to $g_X V_X$ in a good approximation except when it is very close to M_Z. Therefore the 90 % (95 %) C.L. range for M_X is from 119 GeV to 334 GeV (119 GeV to 405 GeV) for $M_H = 400$ GeV ($g_X = 0.15$). As noted earlier, for $M_H = 100$ GeV, the ρ parameter favors smaller values for M_X, which lowers the upper limit of the 90% (95%) C.L. range for M_X to 225 GeV (270 GeV) and pushes the lower limit of the range for M_X very close to M_Z. When Z and X are nearly degenerate, the decay widths must be included in the $Z-X$ mass matrix. Then κ becomes a complex number and the contribution of the off-diagonal width Γ_{ZX} to the real part of the mixing angle α is $\sim (g_X/g_Z)\Gamma_{ZX}\Gamma_X/(4(\Delta M)^2 + (\Gamma_X)^2)$, where $\Delta M = M_X - M_Z$. To keep the mixing small, the X boson must be heavier than the Z boson by at least a few times Γ_X. The X boson can be produced in $p\overline{p}$ collisions at the Tevatron and detected in the dijet final state. For $g_X = 0.15$, the expected production rate is considerably below the limit set by the CDF group [24] for all values of M_X. For larger values of g_X the X boson may be detectable. For $g_X = 0.5$, the values of $M_X \lesssim 750$ GeV are excluded. For $g_X = 0.3$, the region 320 GeV $\lesssim M_X \lesssim$ 520 GeV is excluded.

To summarize, on the basis of an overall fit to all electroweak data we have built a viable $U(1)$ extension of the Standard Model. While the fit to data has been greatly improved, the model lacks aesthetic appeal. The X boson may be accessible by the experiments at Fermilab in the future.

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Table 1: Experimental [1, 9, 12, 13, 14, 15] and fitted values of observables. Correlations between the data were included in the fit. Column labeled "Fit" shows fitted values of observables for arbitrary $U(1)_X$ quark charges (14 d.o.f.). Column labeled "Model" gives fitted values for the model discussed in the text (16 d.o.f.). All fitted values are for $g_X = 0.15$. The χ^2 for the Standard Model is 30 (18 d.o.f.) for $M_H = 100$ GeV.

Observables	Measured value	Fit	Model	Fit	Model
		$M_H = 100$ GeV		$M_H = 400$ GeV	
Γ_Z(GeV)	2.4963 ± 0.0032	2.499	2.500	2.499	2.500
R_ℓ	20.788 ± 0.032	20.77	20.79	20.76	20.78
σ_h^0(nb)	41.488 ± 0.078	41.46	41.44	41.45	41.44
R_b	0.2219 ± 0.0017	0.2210	0.2208	0.2211	0.2204
R_c	0.1540 ± 0.0074	0.1617	0.1631	0.1624	0.1634
A_{FB}^b	0.0997 ± 0.0031	0.1023	0.1038	0.1015	0.1014
$A_b(LR)$	0.841 ± 0.053	0.9150	0.9280	0.9275	0.9281
A_{FB}^c	0.0729 ± 0.0058	0.0810	0.0779	0.0769	0.0757
$A_c(LR)$	0.606 ± 0.090	0.7238	0.696	0.703	0.693
A_τ	0.1418 ± 0.0075	0.1491	0.1490	0.1459	0.1457
A_e	0.1390 ± 0.0089	0.1491	0.1490	0.1459	0.1457
A_{LR}	0.1551 ± 0.0040	0.1491	0.1490	0.1459	0.1457
A_{FB}^ℓ	0.0172 ± 0.0012	0.0167	0.0166	0.0160	0.0159
$Q_W(Cs)$	-71.04 ± 1.81	-71.40	-73.04	-71.03	-72.03
$Q_W(Tl)$	-114.2 ± 3.8	-114.0	-116.6	-113.5	-115.0
g_L^2	0.2980 ± 0.0044	0.299	0.299	0.300	0.300
g_R^2	0.0307 ± 0.0047	0.0290	0.0293	0.0279	0.0280
M_W (GeV)	80.33 ± 0.15	80.40	80.40	80.36	80.36
χ^2		13	16	15	16

Table 2: $SU(3) \times SU(2) \times U(1)_Y \times U(1)_X$ quantum numbers for matter fields in our model.

Fields	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_X$
Q_L	$\mathbf{3}$	$\mathbf{2}$	1/6	-1
U_R	$\mathbf{3}$	$\mathbf{1}$	2/3	+2
D_R	$\mathbf{3}$	$\mathbf{1}$	-1/3	+1
Q'_L	$\bar{\mathbf{3}}$	$\mathbf{2}$	-1/6	+1
$\tilde{U}_R$	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3	-2
$\tilde{D}_R$	$\bar{\mathbf{3}}$	$\mathbf{1}$	+1/3	-1
Q'_R	$\bar{\mathbf{3}}$	$\mathbf{2}$	-1/6	0
$\tilde{U}_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	-2/3	0
$\tilde{D}_L$	$\bar{\mathbf{3}}$	$\mathbf{1}$	+1/3	0
H_u	$\mathbf{1}$	$\mathbf{2}$	-1/2	-3
H_d	$\mathbf{1}$	$\mathbf{2}$	+1/2	-2
H_l	$\mathbf{1}$	$\mathbf{2}$	+1/2	0
ϕ	$\mathbf{1}$	$\mathbf{1}$	0	-1
ϕ'	$\mathbf{1}$	$\mathbf{1}$	0	-2
$\tilde{\phi}$	$\mathbf{1}$	$\mathbf{1}$	0	0

Ernest Orlando Lawrence Berkeley National Laboratory
One Cyclotron Road | Berkeley, California 94720

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