Gauge Model of Quark-Lepton Nonuniversality

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Abstract

We propose a gauge model where quark-lepton universality is an accidental symmetry which is only approximate, in analogy to the well-accepted notion that strong isospin is accidental and approximate. This is a natural framework for explaining possible small deviations of quark-lepton universality which is applicable to the recently reported apparent nonunitarity of the quark mixing matrix. As a result, small departures from quark-lepton universality are expected in $Z$ decays as well as in the recent neutrino data of the NuTeV collaboration and in future low-energy experiments. New physics is predicted at the TeV scale.
In the standard model of particle interactions, left-handed (right-handed) quarks and leptons are doublets (singlets) under the same $SU(2)_L \times U(1)_Y$ gauge group. This has three important implications: (1) the observed weak-interaction strength of quarks is equal to that of leptons, i.e. $G^q_F = G^l_F$, (2) the observed weak-interaction strength of each generation of quarks and leptons is equal to one another, i.e. $G^e_F = G^\mu_F = G^\tau_F$, and (3) the charged-current strength is equal to the neutral-current strength, i.e. $G^{CC}_F = G^{NC}_F$, if the $SU(2)_L \times U(1)_Y$ gauge symmetry is spontaneously broken only by scalar doublets.

Experimentally, all seem to be in very good agreement with data, but as more precision data become available, it is theoretically desirable to have a natural framework for describing any possible deviations. We should use what we have learned regarding the validity of strong isospin, which is now understood as an accidental approximate symmetry because of the mass-scale hierarchy $m_u, m_d \ll \Lambda_{QCD}$ and not because $m_u = m_d$ (or more precisely $|m_u - m_d| \ll m_u + m_d$) as previously thought. We are thus motivated to propose that quarks and leptons couple to different $SU(2)$’s and $U(1)$’s with different coupling strengths, but their effective low-energy weak-interaction strengths will turn out to be independent of the couplings, and are nearly equal because of a certain mass-scale hierarchy of scalar vacuum expectation values, i.e. $G^q_F \simeq G^l_F$. This remarkable result was first obtained over 20 years ago [1] and applied to generation nonuniversality [1, 2, 3, 4, 5]. Just as this previous proposal required that the $\tau$ lifetime be longer than the standard-model prediction (which is no longer supported by present data), our new proposal of quark-lepton nonuniversality requires that the neutron lifetime be longer, which is exactly what has now been reported [6].

This recent measurement of the neutron $\beta$-decay asymmetry has determined that

$$|V_{ud}| = 0.9713(13),$$

which, together with [7] $|V_{us}| = 0.2196(23)$ and $|V_{ub}| = 0.0036(9)$, implies the apparent
nonunitarity of the quark mixing matrix, i.e.
\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9917(28). \] (2)

However, if the effective \( G_F^{\text{CC}} \) measured in lepton-quark interactions is smaller than that measured in lepton-lepton interactions, i.e. \( \mu \) decay, then the above is expected to be less than one.

Consider the gauge group \( SU(3)_c \times SU(2)_q \times SU(2)_l \times U(1)_q \times U(1)_l \). This differs from our previous proposals by the additional extension of \( U(1)_Y \) to \( U(1)_q \times U(1)_l \). Quarks and leptons are assumed to transform as follows:

\[
(u, d)_L \sim (3, 2, 1, 1/6, 0), \quad u_R \sim (3, 1, 1, 2/3, 0), \quad d_R \sim (3, 1, 1, -1/3, 0);
\]

\[
(v, e)_L \sim (1, 1, 2, 1, 0), \quad e_R \sim (1, 1, 1, 0, -1).
\] (3)

The scalar sector consists of two doublets

\[
(\phi^+_1, \phi^0_1) \sim (1, 2, 1, 1/2, 0), \quad (\phi^+_2, \phi^0_2) \sim (1, 1, 2, 0, 1/2),
\] (5)

one singlet

\[
\chi^0 \sim (1, 1, 1, 1/2, -1/2),
\] (6)

and one self-dual bidoublet

\[
\eta = \frac{1}{\sqrt{2}} \begin{pmatrix} \eta^0 & -\eta^+ \\ \eta^- & \eta^0 \end{pmatrix} \sim (1, 2, 2, 0, 0),
\] (7)

such that \( \eta = \tau_2 \eta^* \tau_2 \). Each column is a doublet under \( SU(2)_q \) and each row is a doublet under \( SU(2)_l \).

Let \( \langle \phi^0_{1,2} \rangle \equiv v_{1,2}, \langle \chi^0 \rangle \equiv w, \) and \( \langle \eta^0 \rangle \equiv u \), then the effective charged-current four-fermion weak coupling strengths at low energy are given by [5]

\[
\left( \frac{4G_F}{\sqrt{2}} \right)^{\text{CC}}_{u} = \frac{u^2 + v_1^2}{(v_1^2 + v_2^2)u^2 + v_1^2v_2^2} = \left( \frac{4G_F}{\sqrt{2}} \right)^{\text{CC}}_{\mu},
\] (8)

\[
\left( \frac{4G_F}{\sqrt{2}} \right)^{\text{CC}}_{lq} = \frac{u^2}{(v_1^2 + v_2^2)u^2 + v_1^2v_2^2} = \left( \frac{4G_F}{\sqrt{2}} \right)^{\text{CC}}_{\beta}.
\] (9)
Note that these expressions are independent of the $SU(2)_q$ and $SU(2)_l$ couplings and quark-lepton universality is obtained in the limit $v_{1,2}^2 \ll u^2$. The effective $G_F$ measured in $d \to u + e + \bar{\nu}_e$ must now be smaller than that in $\mu \to \nu_\mu + e + \bar{\nu}_e$ by the factor $\xi^{-1}$, where [1]

$$\xi \equiv 1 + \frac{v_1^2}{u^2}. \quad (10)$$

Thus the apparent unitarity violation of the quark mixing matrix [Eq. (2)] can be explained with

$$\frac{v_1^2}{u^2} = 0.0042(14). \quad (11)$$

This potential effect was already pointed out over 10 years ago [8], in response to a proposed model [9] where $\xi = 1$ exactly, in which case there is no such effect.

Consider now the effective neutral-current four-fermion weak coupling strengths. They are given by [5]

\[
\left( \frac{4G_F}{\sqrt{2}} \right)_{lq}^{NC} = \frac{u^2w^2}{(v_1^2 + v_2^2)u^2w^2 + v_1^2v_2^2(u^2 + w^2)}, \quad (12)
\]

\[
\left( \frac{4G_F}{\sqrt{2}} \right)_{lq}^{NC} = \frac{u^2w^2 + v_1^2(u^2 + w^2)}{(v_1^2 + v_2^2)u^2w^2 + v_1^2v_2^2(u^2 + w^2)}. \quad (13)
\]

This shows that the effective neutral-current $G_F$ given in Eq. (12) measured in low-energy neutrino-quark scattering should be smaller than the corresponding charged-current $G_F$ given in Eq. (9) by the factor

\[
\frac{(G_F)_{lq}^{NC}}{(G_F)_{lq}^{CC}} = \left( 1 + \frac{v_1^2v_2^2u^2}{u^2[(v_1^2 + v_2^2)u^2 + v_1^2v_2^2]} \right)^{-1} \approx 1 - \left( \frac{v_1^2v_2^2}{v_1^2 + v_2^2} \right) \frac{1}{w^2}. \quad (14)
\]

Similarly, the effective $\sin^2 \theta_W$ will also be shifted. We thus expect small deviations from the Standard Model in precision low-energy neutrino-quark scattering experiments such as NuTeV [10]. On the other hand, the size of these deviations is constrained by the structure of the gauge model and is not enough to explain the recent NuTeV result. We will come back to this after we consider the precision data at the $Z$ resonance.
Let \( g_{1,2,3,4} \) be the gauge couplings of \( SU(2)_q, SU(2)_l, U(1)_q, U(1)_l \) respectively and define
\[
g_{ij}^{-2} \equiv g_i^{-2} + g_j^{-2}
\]. The electromagnetic coupling \( e \) is then given by
\[
\frac{1}{e^2} = \frac{1}{g_1^2} + \frac{1}{g_2^2} + \frac{1}{g_3^2} + \frac{1}{g_4^2},
\] (15)
and the photon in the basis \((W_q^0, W_l^0, B_q, B_l)\) is
\[
A = e(g_{1}^{-1}, g_{2}^{-1}, g_{3}^{-1}, g_{4}^{-1}).
\] (16)

We now consider the following 3 orthonormal states:
\[
Z_1 = e(g_{12}g_{34}^{-1}g_1^{-1}, g_{12}g_{34}^{-1}g_2^{-1}, -g_{34}g_{12}^{-1}g_3^{-1}, -g_{34}g_{12}^{-1}g_4^{-1}),
\] (17)
\[
Z_2 = g_{12}(g_1^{-1}, -g_1^{-1}, 0, 0),
\] (18)
\[
Z_3 = g_{34}(0, 0, g_4^{-1}, -g_3^{-1}).
\] (19)

The resulting \( 3 \times 3 \) mass-squared matrix is then given by
\[
\frac{1}{2} \begin{pmatrix}
(g_{12}g_{34}^2/e^2)(v_1^2 + v_2^2) & (g_{12}g_{34}/eg_{12})(g_1^2v_1^2 - g_2^2v_2^2) & (g_{12}g_{34}/eg_{34})(g_1^2v_1^2 - g_3^2v_3^2) \\
(g_{12}g_{34}/eg_{12})(g_1^2v_1^2 - g_2^2v_2^2) & (g_{12}/g_2^2 + g_2^2)w^2 + \mathcal{O}(v^2) & \mathcal{O}(v^2) \\
(g_{12}g_{34}/eg_{34})(g_1^2v_1^2 - g_3^2v_3^2) & \mathcal{O}(v^2) & (g_3^2g_4^2/g_{34}^2)w^2 + \mathcal{O}(v^2)
\end{pmatrix}.
\] (20)

Whereas \( Z_1 \) couples universally to quarks and leptons, \( Z_2 \) and \( Z_3 \) will distinguish between them. The observed \( Z \) boson is mostly \( Z_1 \) with small mixtures of \( Z_2 \) and \( Z_3 \) of order \( v^2/u^2 \) and \( v^2/w^2 \) respectively.

Define \( r \equiv v_2^2/v_1^2, \ y \equiv g_2^2/(g_1^2 + g_2^2), \ x \equiv g_4^2/(g_3^2 + g_4^2) \), and consider the leptonic decay width
\[
\Gamma_l = \frac{G_F m_e^2}{2 \sqrt{2} \pi} \left( 1 + \frac{3\alpha}{4\pi} \right) \rho_l [1 + (1 - 4 \sin^2 \theta_l)^2]
\] (21)
with the analogous expression for quarks, then a straightforward analysis \([5]\) yields
\[
\Delta \rho_l = -y^2(1 + r) v_1^2 u^2 + \frac{[1 - x^2(1 + r)^2]}{1 + r} v_1^2 w^2,
\] (22)
\[
\Delta \rho_q = \Delta \rho_l - 2[1 - y(1 + r)] v_1^2 u^2 - 2[1 - x(1 + r)] v_1^2 w^2,
\] (23)
\[ \Delta \sin^2 \theta_l = \frac{s^2 y [1 - s^2 y(1 + r)] v_1^2}{c^2 - s^2} + \frac{c^2 [1 - x(1 + r)]}{(c^2 - s^2)(1 + r)} [-s^2 + c^2 x(1 + r)] \frac{v_1^2}{w^2}, \quad (24) \]

\[ \Delta \sin^2 \theta_q = \Delta \sin^2 \theta_l + s^2 [1 - y(1 + r)] \frac{v_1^2}{u^2} - c^2 [1 - x(1 + r)] \frac{v_1^2}{w^2}, \quad (25) \]

where \( c^2 = 1 - s^2 \) and \( s^2 \) may be taken to be any one of the several \( \sin^2 \theta_W \) values measured in various ways (because their differences would be of higher order in the correction). Note that \( \Delta \rho_q - \Delta \rho_l \) and \( \Delta \sin^2 \theta_q - \Delta \sin^2 \theta_l \) shift in the same direction from \( Z_1 - Z_3 \) mixing but in opposite directions from \( Z_1 - Z_2 \) mixing. This allows for the possibility that \( \Delta \rho_q \) and \( \Delta \rho_l \) are equal, but \( \Delta \sin^2 \theta_q \) and \( \Delta \sin^2 \theta_l \) are not, or vice versa. Using the above shifts and the method of Ref. [11], we may then write down the deviations expected from the standard model for all the precision measurements at the \( Z \) resonance [7].

In low-energy neutrino-quark scattering, the effective neutral-current interaction is given by

\[ \mathcal{H}_{int} = \left( \frac{4G_F}{\sqrt{2}} \right)^{NC} \frac{1}{2} \bar{d} \gamma^\mu \left( \frac{1 - \gamma_5}{2} \right) \nu [j_{qL}^{(3)} - (\sin^2 \theta_W)_{lq} j_{qL}^{em}] \mu, \quad (26) \]

where

\[ (\sin^2 \theta_W)_{lq} = \frac{e^2}{g_{12}^2} + \frac{e^2 v_1^2}{g_2^2 u^2} - \frac{e^2 v_1^2}{g_4^2 w^2}. \quad (27) \]

Using Eq. (20), we obtain

\[ \frac{e^2}{g_{12}^2} = s_0^2 \left[ \frac{1}{1 + c^2 (c^2 - s^2)(1 + r)} \frac{[1 - y(1 + r)]^2 v_1^2}{u^2} - [1 - x(1 + r)]^2 \frac{v_1^2}{w^2} \right], \quad (28) \]

where \( s_0^2 \) is defined as usual by

\[ s_0^2(1 - s_0^2) = \frac{\pi \alpha(M_Z)}{\sqrt{2} G_F M_Z^2}. \quad (29) \]

Thus the shift of \( (\sin^2 \theta_W)_{lq} \) from the standard-model prediction using precision data at the \( Z \) resonance is given by

\[ (\Delta \sin^2 \theta_W)_{lq} = \left[ \frac{s^2 c^2}{(c^2 - s^2)} [2y - y^2(1 + r)] + s^2 (1 - y) \frac{v_1^2}{u^2} \right] \frac{v_1^2}{w^2} - \left[ \frac{s^2 c^2}{(c^2 - s^2)} \frac{[1 - x(1 + r)]^2}{1 + r} + c^2 (1 - x) \right] \frac{v_1^2}{w^2}. \quad (30) \]
Using Eq. (14), we then have
\[
\Delta (g_{L}^{\text{eff}})^2 = - \left( \frac{2r}{1+r} \right) \frac{v_1^2}{u^2} \left( g_{L}^{\text{eff}} \right)^2_{SM} - \left( 1 - \frac{10s^2}{9} \right) (\Delta \sin^2 \theta_W)_{lq},
\] (31)
\[
\Delta (g_{R}^{\text{eff}})^2 = - \left( \frac{2r}{1+r} \right) \frac{v_1^2}{u^2} \left( g_{R}^{\text{eff}} \right)^2_{SM} + \frac{10s^2}{9} (\Delta \sin^2 \theta_W)_{lq},
\] (32)
as deviations from the standard model appropriate for the NuTeV measurements.

Parity nonconservation in atomic transitions is governed by the same effective low-energy neutral-current interaction. The shift in the weak charge is given here by
\[
\Delta Q_W = \left( \frac{\Delta G_F}{G_F} \right)_{lq}^{NC} (Q_W)_{SM} - 4Z(\Delta \sin^2 \theta_W)_{lq},
\] (33)
where
\[
\left( \frac{\Delta G_F}{G_F} \right)_{lq}^{NC} = - \left( \frac{v_1^2}{u^2} - \left( \frac{r}{1+r} \right) \frac{v_1^2}{w^2} \right),
\] (34)
which is of the same order of magnitude as the experimental accuracy.

For neutral-current leptonic process such as $\nu_\mu e \rightarrow \nu_\mu e$, we use Eqs. (8) and (13) to obtain
\[
\left( \frac{\Delta G_F}{G_F} \right)_{ll}^{NC} = \left( \frac{1}{1+r} \right) \frac{v_1^2}{w^2},
\] (35)
and the analogs of Eqs. (27) and (30) are now
\[
(\sin^2 \theta_W)_{ll} = \frac{e^2}{g_{12}^2} - \frac{e^2 v_1^2}{g_7^2 u^2} + \frac{e^2 v_1^2}{g_3^2 w^2},
\] (36)
and
\[
(\Delta \sin^2 \theta_W)_{ll} = \left[ \frac{s^2 c^2}{(c^2 - s^2)} \right] \left[ 2y - y^2(1+r) \right] - s^2 y \frac{v_1^2}{w^2} \]
\[
- \left[ \frac{s^2 c^2}{(c^2 - s^2)} \right] \left[ 1 - x(1+r) \right] - c^2 x \frac{v_1^2}{w^2}.
\] (37)
We now perform a global fit to all available experimental observables (22 in number) and obtain the following best-fit values:
\[
\frac{v_1^2}{u^2} = 0.00489, \quad \frac{v_1^2}{w^2} = 0.00238, \quad r = 10.2, \quad y = 0.0955, \quad x = 0.135.
\] (38)
Our results are summarized in Table 1. Details will be given in a forthcoming comprehensive paper.

Table 1: Fit Values of 22 Observables

<table>
<thead>
<tr>
<th>Observable</th>
<th>Measurement</th>
<th>Standard Model</th>
<th>Pull</th>
<th>This Model</th>
<th>Pull</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma_l$ [MeV]</td>
<td>83.985 ± 0.086</td>
<td>84.015</td>
<td>-0.3</td>
<td>83.950</td>
<td>+0.4</td>
</tr>
<tr>
<td>$\Gamma_{inv}$ [MeV]</td>
<td>499.0 ± 1.5</td>
<td>501.6</td>
<td>-1.7</td>
<td>501.2</td>
<td>-1.5</td>
</tr>
<tr>
<td>$\Gamma_{had}$ [GeV]</td>
<td>1.7444 ± 0.0020</td>
<td>1.7425</td>
<td>+1.0</td>
<td>1.7444</td>
<td>-0.0</td>
</tr>
<tr>
<td>$A^0_{fb}$</td>
<td>0.01714 ± 0.00095</td>
<td>0.01649</td>
<td>+0.7</td>
<td>0.01648</td>
<td>+0.7</td>
</tr>
<tr>
<td>$A_l(P_\tau)$</td>
<td>0.1465 ± 0.0032</td>
<td>0.1483</td>
<td>-0.6</td>
<td>0.1482</td>
<td>-0.5</td>
</tr>
<tr>
<td>$R_b$</td>
<td>0.21644 ± 0.00065</td>
<td>0.21578</td>
<td>+1.0</td>
<td>0.21582</td>
<td>+1.0</td>
</tr>
<tr>
<td>$R_c$</td>
<td>0.1718 ± 0.0031</td>
<td>0.1723</td>
<td>-0.2</td>
<td>0.1722</td>
<td>-0.1</td>
</tr>
<tr>
<td>$A^0_{fb}$</td>
<td>0.0995 ± 0.0017</td>
<td>0.1040</td>
<td>-2.6</td>
<td>0.1039</td>
<td>-2.6</td>
</tr>
<tr>
<td>$A^0_{c}$</td>
<td>0.0713 ± 0.0036</td>
<td>0.0743</td>
<td>-0.8</td>
<td>0.0740</td>
<td>-0.8</td>
</tr>
<tr>
<td>$A_b$</td>
<td>0.922 ± 0.020</td>
<td>0.935</td>
<td>-0.7</td>
<td>0.934</td>
<td>-0.6</td>
</tr>
<tr>
<td>$A_c$</td>
<td>0.670 ± 0.026</td>
<td>0.668</td>
<td>+0.1</td>
<td>0.665</td>
<td>+0.2</td>
</tr>
<tr>
<td>$A_l$(SLD)</td>
<td>0.1513 ± 0.0021</td>
<td>0.1483</td>
<td>+1.4</td>
<td>0.1482</td>
<td>+1.5</td>
</tr>
<tr>
<td>$\sin^2\theta_{eff}^\text{kept}(Q_{fb})$</td>
<td>0.2324 ± 0.0012</td>
<td>0.2314</td>
<td>+0.8</td>
<td>0.2322</td>
<td>+0.2</td>
</tr>
<tr>
<td>$m_W$ [GeV]</td>
<td>80.449 ± 0.034</td>
<td>80.394</td>
<td>+1.6</td>
<td>80.390</td>
<td>+1.7</td>
</tr>
<tr>
<td>$\Gamma_W$ [GeV]</td>
<td>2.139 ± 0.069</td>
<td>2.093</td>
<td>+0.7</td>
<td>2.093</td>
<td>+0.7</td>
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<tr>
<td>$g^\nu_e^L$</td>
<td>-0.040 ± 0.015</td>
<td>-0.040</td>
<td>-0.0</td>
<td>-0.039</td>
<td>-0.1</td>
</tr>
<tr>
<td>$g^\nu_e^R$</td>
<td>-0.507 ± 0.014</td>
<td>-0.507</td>
<td>-0.0</td>
<td>-0.507</td>
<td>-0.0</td>
</tr>
<tr>
<td>$(g^\nu_L^eff)^2$</td>
<td>0.3001 ± 0.0014</td>
<td>0.3042</td>
<td>-2.9</td>
<td>0.3032</td>
<td>-2.2</td>
</tr>
<tr>
<td>$(g^\nu_R^eff)^2$</td>
<td>0.0308 ± 0.0011</td>
<td>0.0301</td>
<td>+0.6</td>
<td>0.0299</td>
<td>+0.8</td>
</tr>
<tr>
<td>$Q_W$(Cs)</td>
<td>-72.18 ± 0.46</td>
<td>-72.88</td>
<td>+1.5</td>
<td>-72.26</td>
<td>+0.2</td>
</tr>
<tr>
<td>$Q_W$(Tl)</td>
<td>-114.8 ± 3.6</td>
<td>-116.7</td>
<td>+0.5</td>
<td>-115.7</td>
<td>+0.3</td>
</tr>
<tr>
<td>$\sum_{i=d,s,b}</td>
<td></td>
<td>V_{ui}</td>
<td>^2$</td>
<td>0.9917 ± 0.0028</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

We see that we are able to explain the apparent nonunitarity [6] of the quark mixing matrix and reduce the NuTeV discrepancy [10] while maintaining excellent agreement with precision data at the $Z$ resonance, except for the $b\bar{b}$ forward-backward asymmetry measured at LEP, which is also not explained by the standard model. In fact, the shift of $A^0_{fb}$ is given
in our model by

\[ \Delta A_{fb}^{0,b} = \frac{3}{4} (A_e \Delta A_b + A_b \Delta A_e) = -0.07 \Delta \sin^2 \theta_q - 5.57 \Delta \sin^2 \theta_l. \]  

(39)

Because of the dominant coefficient of the second term, it measures essentially the same quantity as \( A_l \) and there is no realistic means of reconciling the discrepancy of \( \sin^2 \theta_{e,f} \) at the \( Z \) resonance using \( b \bar{b} \) versus using leptons in the final state.

The new polarized \( e^-e^+ \rightarrow e^-e^- \) experiment (E158) [12] at SLAC (Stanford Linear Accelerator Center) is designed to measure the left-right asymmetry which is proportional to \( G_F(1 - 4 \sin^2 \theta_W) \) to an accuracy of about 10%. Using Eq. (38) and the standard-model prediction of \( \sin^2 \theta_W = 0.238 \), our expectation is that the above measurement will shift by only \(-2.2\%\) from its standard-model prediction. The new polarized \( ep \) elastic scattering experiment (Qweak) [13] at TJNAF (Thomas Jefferson National Accelerator Facility) is designed to measure \( Q_W \) of the proton, i.e.

\[ Q^p_W = \left[ 1 + \frac{\Delta G_F}{G_F} \right]^{NC} (1 - 4s^2)_{SM} - 4(\Delta \sin^2 \theta_W)_{lq}, \]  

(40)

to an accuracy of about 4\%. We expect a shift of only +3.0\%. Using Eq. (38), we see also that the scale of new physics, i.e. \( u \) and \( w \), is at the TeV scale. Specifically, using the best-fit values of \( r, y, \) and \( x \), we find \( m_{W_2} \approx m_{Z_2} \approx 1.2 \text{ TeV} \), and \( m_{Z_3} \approx 0.8 \text{ TeV} \).

In conclusion, we have proposed a natural gauge model of quark-lepton nonuniversality as a foil against the standard model for comparison at present and future precision electroweak measurements at both high and low energies. The natural reduction of the effective \( G_F \) in lepton-quark charged-current interactions versus that in lepton-lepton interactions explains the apparent nonunitarity of the quark mixing matrix. Resulting shifts in other electroweak parameters are nontrivial, but a good fit to all precision measurements at the \( Z \) resonance is still obtained, with a small reduction in the observed discrepancy of low-energy neutrino-quark scattering data with the theoretical expectation. New physics at the TeV scale is
mandatory in the form of one new charged gauge boson and two new neutral gauge bosons.

The work of X.L. was supported in part by the China National Natural Science Foundation under Grants No. 19835060 and No. 90103017. The work of E.M. was supported in part by the U. S. Department of Energy under Grant No. DE-FG03-94ER40837.
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