Nonuniversal correction to $Z \to b\bar{b}$ and flavor-changing neutral current couplings

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A nonuniversal interaction, which involves only the heavy quarks (t_L, b_L) and t_R, modifies the neutral current couplings and induces flavor-changing neutral currents (FCNC's). The size of the FCNC effect depends crucially on the dynamics of the fermion mass generation. In this paper, we study the effect of the nonuniversal interaction on $Zb\bar{b}$, $Zb\bar{s}$, $Zd\bar{s}$, and $Zd\bar{b}$, by using an effective Lagrangian technique and assuming the quark mass matrices in the form of a generalized Fritzsch *Ansatz.* We point out that, if fitting $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ to the CERN LEP data within 1σ, the induced FCNC couplings are very close to the allowed bounds of several rare decays.

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Recently the Collider Detector at Fermilab (CDF) Collaboration [1] presented evidence for a top quark with a mass $m_t \sim$175 GeV. Since m_t is of the order of Fermi scale, the top quark couples strongly to the electroweak symmetry-breaking sector and may play a key role in probing new physics beyond the standard model. The new physics we have in mind is a nonuniversal interaction acting on only the top quark multiplet and it can be manifest in top quark production processes at the hadron and next generation linear colliders. It can also affect the partial width of $Z \to b\bar{b}$ measured at the CERN e^+e^- collider LEP because the $\mathrm{SU}(2)_L$ group places (t_L, b_L) into a common doublet. The experimentally observed value for the ratio $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$ is higher than the standard model expectation. This would be an indication of the nonuniversal interaction, if it is more than a statistical fluctuation.

It is well known that a nonuniversal interaction will induce flavor-changing neutral currents (FCNC's) among the light fermions [2–5]. However, the size of the FCNC effects depends crucially on the quark mass mixing matrices. So one can not predict quantitatively the induced FCNC effect without specifying the mass matrices. At present it seems too early to attempt an actual solution to the issue of mass generation. However, there has been a great amount of activity in looking for the relation between fermion masses and their mixing matrix elements, as commonly referred to as texture studies. One expects that a "successful" *Ansatz* can provide clues to the dynamics of the fermion mass generation.

In recent years, most studies on the implication of fermion mass *Ansatz* were focused on grand unification theories with and without supersymmetry. In this paper we take a phenomenological, model-independent approach to new physics beyond the standard model, i.e., the effective Lagrangian technique, and consider the implication of the fermion mass *Ansatz* on the induced FCNC effect. Specifically, we will use one variation of the Fritzsch [6] *Ansatz* to study the correlated effects of new physics on $Zb\bar{b}$ and $Zb\bar{s}$, etc. We will point out that when fitting R_b to the LEP data within 1σ, the induced FCNC couplings are very close to the allowed bounds of several rare decays. Our results show that the new physics associated with top quark may be revealed by the presence of FCNC processes.

We first discuss $Z \to b\bar{b}$. Following the general approach, we assume that anomalous, nonuniversal interaction is $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ invariant. Hence the b quark will participate in any t quark interactions when the left-handed doublet is involved. This can result in a modification of the $Zb\bar{b}$ vertex. We can parametrize the modification by introducing a parameter κ_j, which shifts the standard model tree level coupling g_j to the effective coupling g_j^{eff},

$$g_j^{\text{eff}} = g_j(1 + \kappa_j) , \tag{1a}$$

where $j = L$ (R) denotes the left (right) hand, and g_j are the standard model coupling strengths of the neutral current:

$$g_L = -\frac{1}{2} + \frac{1}{3}\sin^2\theta_W, \quad g_R = \frac{1}{3}\sin^2\theta_W . \tag{1b}$$

The contributions of the new physics to the $Z \to b\bar{b}$ width are proportional to g_L^2 and g_R^2. Since $g_L^2 \gg g_R^2$, we will neglect the modification to the right-handed interaction in this article. Defining $\delta\Gamma$ to be the purely nonuniversal correction of the new physics beyond the standard model to the $Z \to b\bar{b}$ width, $\Gamma_{b\bar{b}}$, we have

$$\frac{\delta\Gamma}{\Gamma_{b\bar{b}}} \simeq 2\frac{g_L^2\kappa_L}{g_L^2 + g_R^2} \simeq 2\kappa_L . \tag{2}$$

Then the R_b becomes

$$R_b \sim R_b^{\text{SM}}\left(1 + \frac{\delta\Gamma}{\Gamma_{b\bar{b}}}\right) \sim R_b^{\text{SM}}(1 + 2\kappa_L) , \tag{3}$$

where the standard model value is $R_b^{\text{SM}} = 0.2157$ for $m_t = 175$ GeV and $m_H = 300$ GeV. The experimental value of R_b measured at LEP is $R_b = 0.2192 \pm 0.0018$ [7], which is roughly within 2σ of the standard model expectation. A positive κ_L would improve the situation.

In general, κ_L can be viewed as functions of q^2 [8], where q is the four-momentum of the Z boson, and at LEP, $q^2 = m_Z^2$. Expanding κ_L in terms of q^2, we have

$$\kappa_L = \kappa_L^0 + q^2\text{-dependent terms} . \tag{4}$$

Gauge invariant operators describing κ_L have been con-

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structed explicitly in effective Lagrangian with a nonlinear [2] realization of $SU(2)_L \times U(1)_Y$. In this paper we use an effective Lagrangian with a linearization [9] of $SU(2)_L \times U(1)_Y$ for the discussion. The new physics effects are parametrized by a set of higher dimension operators $\mathcal{O}^i$, which are required to be invariant under the standard model gauge symmetry and contain only the standard model fields. The new physics effects on the light fermions are assumed to be negligible, so the higher dimension operators involve only (t_L, b_L), t_R, the gauge and scalar bosons. For dimension 6, there are two operators which generate directly[1] a κ_L^0 in Eq. (4) [10,11]:

$$\mathcal{O}^1 = i[\phi^\dagger D_\mu \phi - (D_\mu\phi)^\dagger \phi]\bar{\Psi}_L \gamma^\mu \Psi_L \ , \tag{5a}$$

$$\mathcal{O}^2 = i[\phi^\dagger \vec{\tau} D_\mu \phi - (D_\mu\phi)^\dagger \vec{\tau}\phi]\bar{\Psi}_L \gamma^\mu \vec{\tau}\Psi_L \ , \tag{5b}$$

where ϕ is the doublet Higgs field of the standard model and $\Psi_L^T = (t,b)_L$. Let us introduce the effective Lagrangian $\mathcal{L}^{\rm eff}$, containing higher dimension operators given in Eqs. (5):

$$\mathcal{L}^{\rm eff} = \mathcal{L}^{\rm SM} + \frac{1}{\Lambda^2}(c_1\mathcal{O}^1 + c_2\mathcal{O}^2) \ , \tag{6}$$

where c_i, $i = 1,2$, are real parameters, which determine the strength of the contributions of the operators, $\mathcal{L}^{\rm SM}$ is the standard model Lagrangian, and Λ is the cutoff of the effective theory.

After electroweak symmetry breaking, the anomalous couplings for $Zb\bar{b}$ and $Zb\bar{s}$, etc., from $\mathcal{L}^{\rm eff}$ are contained in

$$\frac{g}{\cos\theta_W}\begin{pmatrix}\bar{d}\\ \bar{s}\\ \bar{b}\end{pmatrix}_L^T U_L^{\dagger(d)}\begin{pmatrix}0 & & \\ & 0 & \\ & & \delta_L\end{pmatrix} U_L^{(d)}\gamma_\mu \begin{pmatrix}d\\ s\\ b\end{pmatrix}_L Z^\mu \ , \tag{7}$$

where

$$\delta_L = \frac{v^2}{\Lambda^2}(c_1 + c_2) \ , \tag{8}$$

and $v \simeq 250$ GeV, $U_L^{(d)}$ is a unitary rotation matrix diagonalizing the left-handed down quarks. The Cabibbo-Kabayashi-Maskawa (CKM) mixing matrix for the charged weak current is

$$V = (U_L^{(u)})^\dagger U_L^{(d)} \ , \tag{9}$$

where $U_L^{(u)}$ is the rotation matrix for the left-handed up quarks. Note that in the standard model, which corresponds to $\mathcal{L}^{\rm eff}$ in the limit $\Lambda \to \infty$, the individual $U_{L,R}^{(u)}$ and $U_{L,R}^{(d)}$ are not measurable, but only V in Eq. (9) is.

The relative size of the $Zb\bar{b}$ to the FCNC couplings, $Zb\bar{s}$, etc., in Eq. (7) depends on the rotation matrix $U_L^{(d)}$. The elements of $U_L^{(d)}$ can be evaluated once the corresponding mass matrix is given. In the literature a widely used *Ansatz* is the one suggested by Fritzsch [6] and its variations. The latter is given by

$$M^{(q)} = \begin{pmatrix} 0 & x_q e^{i\alpha_q} & 0 \\ x_q e^{-i\alpha_q} & \omega_q & y_q e^{i\beta_q} \\ 0 & y_q e^{-i\beta_q} & z_q \end{pmatrix} \ , \tag{10}$$

where x_q, y_q, ω_q, and z_q are real parameters and $q = u(d)$ denotes the up (down) type quarks. The original Fritzsch *Ansatz* is given by putting $\omega_q = 0$, which predicts a too small top quark mass $m_t \leq 90$ GeV [12]. Here we consider one variation [13] which can have an acceptable top quark mass $m_t \leq 190$ GeV, and fits the current experimental data on the CKM matrix. In the variation [13], the rotation matrix $U^{(q)} (= U_L^{(q)} = U_R^{(q)})$ is given by

$$\begin{pmatrix} 1 & -\left(\frac{m_1}{m_2}\right)^{1/2} & \left(\frac{m_1 m_2 (m_2 + w_q)}{m_3^3}\right)^{1/2} \\ \left(\frac{m_1}{m_2}\right)^{1/2} e^{-i\alpha_q} & e^{-i\alpha_q} & \left(\frac{m_2 + w_q}{m_3}\right)^{1/2} e^{-i\alpha_q} \\ -\left(\frac{m_1(m_2+w_q)}{m_2 m_3}\right)^{1/2} e^{-i(\alpha_q+\beta_q)} & -\left(\frac{m_2+w_q}{m_3}\right)^{1/2} e^{-i(\alpha_q+\beta_q)} & e^{-i(\alpha_q+\beta_q)} \end{pmatrix} \ , \tag{11}$$

where m_1, m_2, and m_3 correspond to m_u, m_c, and m_t for $q = u$, and m_d, m_s, and m_b for $q = d$, and $w_u = m_c$, $w_d = 0$, α_q and β_q are responsible for CP violation phase in the CKM matrix.

In Table I, we give the theoretical values of FCNC couplings and the corresponding experimental upper limits. One can see that if fitting R_b to LEP data within 1σ, the induced FCNC couplings are close to the allowed bounds

TABLE I. Theoretical prediction on FCNC couplings, and corresponding experimental upper limits taken from Ref. [15]. $\tilde{\kappa}_L = U_L^{\dagger(d)}{\rm diag}[0,0,\delta_L]U_L^{(d)}$. The elements of $U_L^{(d)}$ are calculated by taking the central values of the down quark masses evaluated at $\mu = 1$ GeV, $m_s/m_b = 0.33$, $m_d/m_s = 0.051$. For $Z \to b\bar{b}$, $\tilde{\kappa}_L^{bb} = \delta_L$, and using definition of κ_L in Eq. (1a) we have $\delta_L = g_L\kappa_L$, so $(R_b - R_b^{\rm SM})/R_b^{\rm SM} = 2\delta_L/g_L$.

$\lvert\tilde{\kappa}_L^{ij}\rvert$	Predictions	Limits and processes
$\lvert\tilde{\kappa}_L^{ds}\rvert$	$\lvert 7.5 \times 10^{-3} \times \delta_L\rvert$	3×10^{-4}(K^0-$\bar{K}^0$ mixing)
$\lvert\tilde{\kappa}_L^{ds}\rvert$	$\lvert 7.5 \times 10^{-3} \times \delta_L\rvert$	2×10^{-5}($K_L \to \bar{\mu}\mu$)
$\lvert\tilde{\kappa}_L^{db}\rvert$	$\lvert 0.041 \times \delta_L\rvert$	4×10^{-4}(B_d-$\bar{B}_d$ mixing)
$\lvert\tilde{\kappa}_L^{bs}\rvert$	$\lvert 0.182 \times \delta_L\rvert$	2×10^{-3}($B \not\to l^+l^-X$)

[1]We are not considering the operators that can affect $Zb\bar{b}$ indirectly by loop effects.

of several rare decays.[2] For example, assuming a positive κ_L and fitting R_b to the experimental data within 1σ, we have $|\tilde{\kappa}_L^{ds}| \geq (1.2 \sim 2.6) \times 10^{-5}$, which lies in the experimental limit of $K_L \to \bar{\mu}\mu$.

In our calculations we have not considered the q^2-dependent terms in Eq. (4), which are generally proportional to m^2/Λ^2 where m is a typical mass of a process under consideration, while the operators in Eqs. (5) give rise to terms proportional to v^2/Λ^2. Therefore, the momentum-dependent terms are generally suppressed at low energies. We should point out that if an *Ansatz* different from that of (11) is used, the magnitudes of anomalous $Zb\bar{b}$, $Zb\bar{s}$, etc., maybe changed [14]. Thus the future data on $Zb\bar{b}$ and $Zb\bar{s}$, etc., will provide an experimental test on various fermion mass *Ansätze*.

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[2]We realize that there are uncertainties in the numerical values of the rotation matrix elements caused by the uncertainties in the values of fermion masses, CKM mixing angles, and the analytical approximation used in Ref. [13].

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