Constraints on Top Couplings in Models with Exotic Quarks

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(Received 24 August 1998)

The extension of the standard model with exotic quark singlets and doublets introduces large flavor changing neutral couplings between ordinary fermions. We derive inequalities which translate the precise determination of the diagonal Z couplings, in particular, at LEP, into stringent bounds on the off-diagonal ones. The resulting limits can be saturated in minimal extensions with one vector doublet or singlet. In this case, 23 and 6 single top events, respectively, are predicted at LEP2 for an integrated luminosity of 500 pb^{-1} per experiment. [S0031-9007(99)08551-8]

The agreement of the standard model (SM) with present data places strong constraints on new physics [1,2]. However, these are much less stringent for the top quark. Indeed, the only model-independent limits on anomalous top couplings are the direct ones from the Fermilab Tevatron, $B(t \to qZ) \leq 0.33$, $B(t \to q\gamma) \leq 0.032$ at 95% C.L. [3]. These limits will be improved, up to a factor of ~ 20 eventually, after the Tevatron run beginning in the next millennium. One can also consider generic indirect limits [4], but they are usually too restrictive because possible interference effects with contributions of other heavy states, natural in many models (see Ref. [5]), are not taken into account. On the other hand, effective vertices are often suppressed by coupling constant and mass scale factors in well-defined theories. Present Tevatron limits are weak enough to allow for the production of ~ 630 clean single top $t\bar{q} + \bar{t}q$ events at the CERN e^+e^- collider LEP2 assuming a total luminosity of 500 pb^{-1} per experiment at 200 GeV [6]. However, the expected rate of such events is negligible in the SM and many of its extensions. Models with extra scalars (or gauge bosons) can have large flavor changing neutral (FCN) top couplings with ordinary fermions, but their observation at LEP2 would require a new boson with a mass close to threshold, to be exchanged in the s channel, and with a relatively large coupling to e^+e^-. These models, e.g., two Higgs doublet models [7], need also extra symmetries, at first sight unnatural, to allow a large and harmless boson coupling to electrons. Then, there seems to be a gap between present direct limits and expected single top production at e^+e^- colliders in the context of simple SM extensions. In this Letter we point out that these events can be produced at LEP2 in models with exotic quarks [5,8], although their rate is further constrained by a set of inequalities obeyed by these models.

Vectorlike or mirror quarks appear in many grand unified and string theories, such as those based on E_6. Mixing with these heavy fermions is the best way to enhance the top signal without producing new particles if the new quarks have masses above threshold. Heavy vectorlike fermions decouple, and their indirect effects become small under the natural assumptions of multiplet degeneracy and mass scaling. At any rate, the induced mixing between ordinary quarks cannot be arbitrarily large because there are stringent direct limits on the FCN couplings of the five light flavors [9]. Moreover, we will derive simple inequalities in this class of SM extensions relating the off-diagonal Z couplings to the diagonal ones. They translate the precise determination of the u, c quark couplings into stronger constraints on Ztq couplings than present or future direct Tevatron bounds. We will prove that the limits deduced in this way can be saturated in the simplest SM extensions with one vectorlike quark doublet or singlet, leading to a sizable production of single top events at LEP2. For the top quark these inequalities provide a simple and novel method to estimate to a good approximation the allowed size of the Ztq coupling, with the advantage that there is no need to perform global fits to particular models.

The class of models proposed extends the SM quark content to include vectorlike doublets [left- and right-handed doublets under SU(2)$_L$], vectorlike singlets (left- and right-handed singlets), and mirror quarks, which are left-handed singlets and right-handed doublets. The doublets can have electric charges $(\frac{2}{3}, -\frac{1}{3})$, $(\frac{5}{3}, \frac{2}{3})$, or $(-\frac{1}{3}, -\frac{4}{3})$, although only exotic quarks with standard charges appear in the simplest grand unified and string models, as, for instance, in E_6 with extra $27 + \overline{27}$ representations. For simplicity we will first restrict ourselves to doublets with standard charges and generalize the results later. Let us consider any of these extensions, with N standard quark families, n vectorlike doublets, n_u up and n_d down vectorlike singlets, and N' mirror quark families. The total number of up-type quarks $\mathcal{N}_u = N + N' + n + n_u$ and down-type quarks $\mathcal{N}_d = N + N' + n + n_d$ does not need to be equal in general (by "up" and "down" we will mean charges $\frac{2}{3}$ and $-\frac{1}{3}$, and *not* weak isospin $\frac{1}{2}$ and $-\frac{1}{2}$). In any of these models, the gauge neutral current Lagrangian in the weak

eigenstate basis can be written in matrix notation as

$$\mathcal{L}_Z = -\frac{g}{2c_W}(\bar{u}_L^{(d)}\gamma^\mu u_L^{(d)} + \bar{u}_R^{(d)}\gamma^\mu u_R^{(d)}$$
$$- \bar{d}_L^{(d)}\gamma^\mu d_L^{(d)} - \bar{d}_R^{(d)}\gamma^\mu d_R^{(d)} - 2s_W^2 J_{\rm EM}^\mu)Z_\mu ,$$
$$(1)$$

with $(u_L^{(d)}, d_L^{(d)})$ and $(u_R^{(d)}, d_R^{(d)})$ doublets under SU(2)$_L$ of dimension $N + n$ and $N' + n$, respectively. The charged and Higgs currents are also modified, but we ignore them for the moment. The mixing of weak eigenstates with the same chirality and different isospin originates FCN couplings in the mass eigenstate basis, where the Lagrangian in Eq. (1) reads

$$\mathcal{L}_Z = -\frac{g}{2c_W}(\bar{u}_L X^{uL}\gamma^\mu u_L + \bar{u}_R X^{uR}\gamma^\mu u_R$$
$$- \bar{d}_L X^{dL}\gamma^\mu d_L - \bar{d}_R X^{dR}\gamma^\mu d_R - 2s_W^2 J_{\rm EM}^\mu)Z_\mu .$$
$$(2)$$

Here $u = (u, c, t, T, \ldots)$ and $d = (d, s, b, B, \ldots)$ are $\mathcal{N}_u$ and $\mathcal{N}_d$ dimensional vectors, respectively. The diagonal Zqq couplings of up- and down-type mass eigenstates $q = u, d$ are $c_{L(R)}^q = \pm X_{qq}^{L(R)} - 2Q_q s_W^2$, with the plus (minus) sign for up- (down-) type quarks (we will always drop u, d superscripts if not needed). If $q_{L(R)}$ is a pure up or down quark singlet, $X_{qq}^{L(R)} = 0$, whereas for a pure doublet $X_{qq}^{L(R)} = 1$. In both cases FCN couplings between $q_{L(R)}$ and other quarks vanish for $q_{L(R)}$ is a weak interaction eigenstate and has a definite isospin. In general $q_{L(R)}$ has singlet and doublet components and $0 < X_{qq}^{L(R)} < 1$, implying nonzero FCN couplings for $q_{L(R)}$. These arguments are made quantitative writing the unitary transformations between the mass and weak interaction eigenstates, $q_L^0 = \mathcal{U}^{qL}q_L$, $q_R^0 = \mathcal{U}^{qR}q_R$, with $\mathcal{U}^{qL}$ and $\mathcal{U}^{qR}$ $\mathcal{N}_q \times \mathcal{N}_q$ unitary matrices and $q_{L,R}^0 = (q_{L,R}^{(d)}, q_{L,R}^{(s)})$ weak interaction eigenstates (doublets $q_{L,R}^{(d)}$ and singlets $q_{L,R}^{(s)}$). Then, it follows from Eqs. (1) and (2) that

$$X_{\alpha\beta}^{uL} = (\mathcal{U}_{i\alpha}^{uL})^*\mathcal{U}_{i\beta}^{uL}, \qquad X_{\alpha\beta}^{uR} = (\mathcal{U}_{j\alpha}^{uR})^*\mathcal{U}_{j\beta}^{uR},$$
$$X_{\sigma\tau}^{dL} = (\mathcal{U}_{k\sigma}^{dL})^*\mathcal{U}_{k\tau}^{dL}, \qquad X_{\sigma\tau}^{dR} = (\mathcal{U}_{l\sigma}^{dR})^*\mathcal{U}_{l\tau}^{dR},$$
$$(3)$$

where (i, k) and (j, l) sum over the left- and right-handed doublets, respectively, $\alpha, \beta = u, c, t, T, \ldots$ and $\sigma, \tau = d, s, b, B, \ldots$. From these equations we obtain all the information on Z couplings. To simplify the notation, let q, q' be two mass eigenstates with the same electric charge and chirality and X the corresponding coupling matrix X^{uL}, X^{uR}, X^{dL}, or X^{dR}. Equation (3) implies that the matrix elements $X_{qq'}$ are bounded, $|X_{qq'}| \leq 1$, and that the diagonal elements are positive, $X_{qq} \geq 0$. In particular, if q is a weak eigenstate, $X_{qq} = \pm 2T_{3q}$, with the plus (minus) sign for up- (down-) type quarks. Using the Schwarz inequality it is straightforward to show that for $q \neq q'$

$$|X_{qq'}|^2 \leq (1 - X_{qq})(1 - X_{q'q'}),\qquad (4)$$

$$|X_{qq'}|^2 \leq X_{qq}X_{q'q'}.\qquad (5)$$

These inequalities translate the determination of the diagonal Zqq and $Zq'q'$ couplings, X_{qq} and $X_{q'q'}$, into a bound on the off-diagonal coupling Zqq', $X_{qq'}$. In other words, Eqs. (4) and (5) relate the isospin of q, q' with the FCN coupling Zqq'. Even if we do not know $X_{q'q'}$ we still can learn about the $X_{qq'}$ coupling from our knowledge of X_{qq}. This is particularly useful in the case of the top quark, since the bounds derived can be saturated in the simplest extensions with exotic fermions. Also we can set limits on the coupling of a light quark q to a new unknown quark q'. From Eqs. (4) and (5) follows that if $X_{qq} = 0, 1$, the FCN couplings involving q vanish (in this case q is a weak eigenstate), independently of the particular SM extension considered. Conversely, if $X_{qq} \neq 0, 1$, there must exist nonzero FCN couplings for q, as can be shown from Eq. (3) observing that $X^2 = X$, $X^\dagger = X$.

In order to apply Eqs. (4) and (5) it is necessary to review present experimental results on the diagonal Z couplings to quarks $c_{L,R}^q$. The Z couplings to the lightest quarks u, d are measured in atomic parity violation and in the SLAC polarized-electron experiment [1]. The determination of c_L^u, c_R^u, and c_L^d is accurate, whereas the error in c_R^d is very large (see Table I). The precision data taken at LEP and SLC provide accurate determinations of the Zcc and Zbb couplings at M_Z (see Table II). The ratio R_c is mainly a measure of $|c_L^c|^2 + |c_R^c|^2$ and the forward-backward (FB) asymmetry $A_{\rm FB}^{0,c}$ of $(|c_L^c|^2 - |c_R^c|^2)/(|c_L^c|^2 + |c_R^c|^2)$. From these data the moduli of $c_{L,R}^c$ can be extracted but not their sign. This opens an interesting possibility that, although already settled experimentally, makes the measurement of $A_{\rm FB}^c$ off the Z pole at LEP2 very important. Of the two sign choices for c_R^c, the negative value corresponds to the usual isospin assignment for the right-handed charm quark as an almost pure singlet, whereas the positive sign can be achieved with a large mixing ($\sim 60\%$) with a new right-handed doublet T_R^0. This ambiguity has been settled by a combination of the low energy measurements of $A_{\rm FB}^c$ at PEP (29 GeV) and PETRA (35 and 44 GeV) [10]. The data are consistent with the negative sign within 0.4σ, whereas the deviation is 4.2σ for the positive sign. Recent measurements at LEP2 [11] have large statistical uncertainties but already show a preference for a negative

TABLE I. Diagonal couplings measured in atomic parity violation experiments. We use $s_W^2 = 0.232 \pm 0.001$.

Experimental value	$X_{qq}^{L(R)} = \pm(c_{L(R)}^q + 2Q_q s_W^2)$
$c_L^u = 0.656 \pm 0.032$	$X_{uu}^L = 0.965 \pm 0.032$
$c_R^u = -0.358 \pm 0.026$	$X_{uu}^R = -0.049 \pm 0.026$
$c_L^d = -0.880 \pm 0.022$	$X_{dd}^L = 1.035 \pm 0.022$
$c_R^d = -0.054^{+0.154}_{-0.096}$	$X_{dd}^R = 0.209^{+0.096}_{-0.154}$

TABLE II. R_c, R_b and asymmetries.

Quantity	Data	SM fit
R_c	0.1735 ± 0.0044	0.1723
$A_{\rm FB}^{0,c}$	0.0709 ± 0.0044	0.0736
R_b	$0.216\,56 \pm 0.000\,74$	0.2158
$A_{\rm FB}^{0,b}$	0.0990 ± 0.0021	0.1030

c_R^c (0.3σ) rather than for a positive one (1.6σ). This raises the question of whether there is any other experimental reason to exclude the large T_R^0-c mixing. A large T_R^0 component in the c quark is disfavored by the ρ parameter as long as none of the d, s, b quarks has a large right-handed doublet B_R^0 component [12]. Mixing with the d, b quarks would lead to unacceptably large right-handed charged current couplings, but mixing with the s quark is allowed. (FCN currents between light quarks can be made to vanish if only one of them mixes with the doublet [8].) Only the off-peak asymmetry for the strange quark is sensitive to the sign of c_R^s, but present data $A_{\rm FB}^{0,s} = 0.131 \pm 0.035 \pm 0.013$ [13] do not exclude either sign. In summary, the only strong indication that c_R, s_R are indeed isosinglets and do not have a large doublet component is provided by the low energy measurement of $A_{\rm FB}^c$. However, this results from the average of inconclusive measurements, so a precise determination of the off-peak asymmetry at LEP2 will be welcome. The analysis for the b quark is similar: the off-peak asymmetry and the ρ parameter fix the sign ambiguity and the B_R^0 component in the b mass eigenstate must be small [14]. The value of c_R^d in Table I is compatible with the two sign assignments but again the ρ parameter and the measured value of c_R^u force a small B_R^0-d mixing. Table III summarizes the values of $c_{L(R)}^q$ and $X_{qq}^{L(R)}$ obtained from R_b, R_c, $A_{\rm FB}^{0,b}$, $A_{\rm FB}^{0,c}$, and their correlation matrix in Ref. [2] assuming small mixing with the new quarks, as required by the SM isospin assignments.

In Tables I and III we observe that the values of X_{uu}^R, X_{dd}^L, X_{cc}^R, and X_{bb}^R are unphysical. This is worst for X_{bb}^R, which is 2σ away from the physical region $[0, 1]$, a direct consequence of the 2σ discrepancy between the measured and the SM values of $A_{\rm FB}^{0,b}$. [This discrepancy can be explained in models with doublets of charges $(-\frac{1}{3}, -\frac{4}{3})$ [14], where the value of X_{bb}^R is physical as discussed below.] A more careful application of the inequalities is then necessary, since directly using the values in Tables I

TABLE III.   Diagonal couplings from Table II. For the b quark we also include the radiative correction $+0.0014$ to s_W^2.

Experimental value	$X_{qq}^{L(R)} = \pm(c_{L(R)}^q + 2Q_q s_W^2)$
$c_L^c = 0.690 \pm 0.013$	$X_{cc}^L = 0.998 \pm 0.013$
$c_R^c = -0.321 \pm 0.019$	$X_{cc}^R = -0.013 \pm 0.019$
$c_L^b = -0.840 \pm 0.005$	$X_{bb}^L = 0.996 \pm 0.005$
$c_R^b = 0.194 \pm 0.018$	$X_{bb}^R = -0.039 \pm 0.018$

and III is not appropriate. Instead, we define the 90% C.L. upper limit on $X_{qq'}$ as the value x such that the probability of finding $X_{qq'} \leq x$ *within* the physical region is 0.9. With this definition and a Monte Carlo generator for the Gaussian distributions of R_b, R_c, $A_{\rm FB}^{0,b}$, $A_{\rm FB}^{0,c}$ (correlated) and $X_{uu}^{L,R}$, $X_{dd}^{L,R}$ (assuming no correlation) we obtain the bounds in Table IV, where we also quote present direct limits [3,9]. Alternatively, we can shift the unphysical values in Tables I and III to the physical region and find the 90% C.L. upper limit as defined above, obtaining the bounds given in parentheses.

A few comments are in order. (i) The more restrictive bounds on left-handed currents are estimated using Eq. (4), whereas for right-handed currents Eq. (5) gives a stronger constraint. (ii) These bounds are not all independent and thus cannot be simultaneously saturated, e.g., X_{tc}^R and X_{tu}^R cannot have both their largest value. (iii) The couplings of the top quark have not yet been measured, and we assume the factors $(1 - X_{tt}^L)$ and X_{tt}^R in Eqs. (4) and (5) to be both equal to unity. The factors $(1 - X_{ss}^L)$ and X_{ss}^R are also set equal to one because the measurement of $A_{\rm FB}^{0,s}$ alone does not provide any useful constraint. (iv) The inequalities also allow one to set new nontrivial limits on the FCN couplings of the ordinary and new heavy quarks T, B. These limits can be read from Table IV making the replacement $t \to T$, $s \to B$. Finally, it is worth noticing that the constraints on top couplings obtained from the inequalities are more restrictive than those from top decays at Tevatron.

The limits obtained on top FCN couplings can be saturated in the simplest extensions of the SM, namely, the addition of a vectorlike doublet or singlet. In the model with an additional isodoublet the bound $X_{ct}^R \leq 0.16$ can be saturated choosing the projection of the new right-handed doublet T^0 on the mass eigenstates u, c, t, T to be $\mathcal{U}_{T^0\alpha}^{uR} = (0, 0.16, 0.99, 0)$. The projection of its partner B^0 on the mass eigenstates can be chosen as

TABLE IV.   Experimental limits on FCN couplings and bounds deduced from coupling inequalities in models with exotic quarks of standard charges. The bounds in parentheses are obtained with an alternative method of estimating the probability, explained in the text.

Coupling	X^L	X^R	Source
uc	1.2×10^{-3}	1.2×10^{-3}	δm_D
	$0.033\ (0.035)$	$0.019\ (0.028)$	inequalities
ut	0.84	0.84	$t \to uZ$
	$0.28\ (0.28)$	$0.14\ (0.21)$	inequalities
ct	0.84	0.84	$t \to cZ$
	$0.14\ (0.15)$	$0.16\ (0.18)$	inequalities
ds	4.1×10^{-5}	4.1×10^{-5}	$K^+ \to \pi^+ \nu \overline{\nu}$
	$0.14\ (0.19)$	$0.62\ (0.61)$	inequalities
db	1.1×10^{-3}	1.1×10^{-3}	δm_B
	$0.0081\ (0.017)$	$0.062\ (0.086)$	inequalities
sb	1.9×10^{-3}	1.9×10^{-3}	$B^0 \to \mu^+ \mu^- X$
	$0.076\ (0.11)$	$0.12\ (0.17)$	inequalities

$\mathcal{U}^{dR}_{B^0\sigma} = (0, \epsilon, 0, \sqrt{1 - \epsilon^2})$. The ρ parameter prefers a sizable B^0-s mixing ϵ but $b \to s\gamma$ requires a negligible value $O(10^{-3})$. Then the experimental constraints on FCN currents are satisfied and the right-handed currents between ordinary quarks remain small. The analysis for $X^R_{ut} \leq 0.14$ can be performed similarly. These bounds lead to 23 and 18 $t\bar{q} + \bar{t}q$ events, respectively, at LEP2.

In the extension of the SM with one extra singlet T^0 of charge $\frac{2}{3}$, there are no right-handed charged currents and all FCN couplings vanish except those for left-handed up-type quarks. This model and the analogous model with an extra charge $-\frac{1}{3}$ singlet have been analyzed extensively in the literature [5,15], and we will not repeat their discussion here. However, it is worth noting that in these models the relationship between charged and neutral currents further restricts the allowed size of the FCN couplings. Present limits on Cabbibo-Kobayashi-Maskawa matrix elements [1] imply $X^L_{ct} \leq 0.082$, $X^L_{ut} \leq 0.046$, leading to 6 and 2 $t\bar{q} + \bar{t}q$ events at LEP2.

Now we will extend the analysis with the inclusion of quark doublets with nonstandard charges $(\frac{5}{3}, \frac{2}{3})$ or $(-\frac{1}{3}, -\frac{4}{3})$, which we will simply refer to as "nonstandard doublets." The weak interaction eigenstates are in this case $q^0_{L,R} = (q^{(d)}_{L,R}, q^{(n)}_{L,R}, q^{(s)}_{L,R})$, with $q^{(n)}_{L,R}$ the nonstandard doublets which have diagonal couplings $-\bar{u}^{(n)}_{L,R}\gamma^\mu u^{(n)}_{L,R}$ and $+\bar{d}^{(n)}_{L,R}\gamma^\mu d^{(n)}_{L,R}$ in Eq. (1). The form of the Lagrangian in the mass eigenstate basis remains the same for the quarks with standard charges, counting the new quarks in $\mathcal{N}_u$ and $\mathcal{N}_d$. One major difference is that this time the diagonal couplings are not positive definite, but still $|X_{qq'}| \leq 1$, and $X_{qq} = \pm 2T_{3q}$ for states with definite isospin. Moreover, while Eq. (4) remains true, Eq. (5) is no longer valid and must be replaced by

$$|X_{qq'}|^2 \leq (1 + X_{qq})(1 + X_{q'q'}). \quad (6)$$

The reason of this replacement becomes clear if we consider the meaning of Eqs. (4) and (5). For instance, applied to up-type quarks they express the fact that a mass eigenstate with the highest ($\frac{1}{2}$) or the lowest (0) isospin is a weak eigenstate whose FCN couplings must vanish. With the addition of nonstandard doublets, the lowest isospin for charge $\frac{2}{3}$ quarks is $-\frac{1}{2}$, thus the replacement of Eq. (5) by Eq. (6). (For charge $-\frac{1}{3}$ quarks the argument is similar.) The bounds obtained from Eq. (6) are much less restrictive and clearly cannot be saturated due to the other experimental constraints (charged currents, neutral meson mixing, and oblique corrections), and a global fit is needed to find the largest allowed value of the FCN couplings in each particular model. However, the bounds on $X^L_{qq'}$ couplings in Table IV obtained using Eq. (4) are still valid, as long as the highest (lowest) isospin for left-handed up (down) quarks is $\frac{1}{2}$ ($-\frac{1}{2}$).

Finally, some concluding remarks. If the top quark is indeed observed at LEP2, this will provide a strong indication for the existence of new heavy quark doublets, because the maximum $t\bar{q} + \bar{t}q$ production rate with only new heavy singlets is 4 times smaller. In any case, the Next Linear Collider with its expected integrated luminosity of 100 fb^{-1} at $\sqrt{s} = 500$ GeV will allow one to disentangle X^L_{tq} and X^R_{tq} [16]. On the other hand, the absence of top events at LEP2 will improve the limits on $X^{L,R}_{tq}$ to a common value of 0.033. This number is to be compared with the bound obtained after the next Tevatron run if the decay $t \to qZ$ is not observed, eventually $|X^{L,R}_{tq}| \leq 0.19$. Thus, in the next two years LEP2 will either detect Ztc couplings or set on them the most stringent bounds before the next generation of colliders. In fact, the first quoted results at LEP2 [17] improve by a factor of 2 the present Tevatron limit.

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