Nonoblique Effects in the $Zb\bar{b}$ Vertex from Extended Technicolor Dynamics

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Extended technicolor theories generate potentially large corrections to the $Zb\bar{b}$ vertex which can be observed in current experiments at the CERN e^+e^- collider LEP.

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There exist no compelling or even consistent theories to explain the origin of the diverse masses and mixings of the quarks and leptons. In this regard, the origin of the large top-quark mass is particularly puzzling. In technicolor models [1], this large top mass is presumably the result of extended technicolor (ETC) [2] dynamics at relatively low energy scales. (This is true so long as there are no additional light scalar particles coupling to ordinary fermions and technifermions [3,4].) Since the magnitude of the Kobayashi-Maskawa matrix element $|V_{tb}|$ is very nearly 1, $SU(2)_W$ gauge invariance insures that the ETC dynamics which generates the top mass also couples to the left-handed component of the bottom quark. In this paper, we point our that this dynamics produces potentially large "nonoblique" [5] effects at the $Zb\bar{b}$ vertex. In particular, if $m_t \gtrsim 100$ GeV and no effect is visible with data currently being obtained at the CERN e^+e^- collider LEP, theories in which the ETC and weak interactions commute [i.e., in which the ETC gauge bosons are $SU(2)_W$ singlets] can be ruled out, with the same confidence as models with excessive flavor-changing neutral currents.

If the top mass is generated by the exchange of an $SU(2)_W$ neutral ETC gauge boson, then this boson carries technicolor and couples with strength $g_{\rm ETC}$ to the current

$$\xi\bar{\psi}_L^i\gamma^\mu T_L^{iw}+(1/\xi)\bar{t}_R\gamma^\mu U_R^w\,, \tag{1}$$

where $\psi_L=(t,b)_L$ is the left-handed tb doublet, $T_L=(U,D)_L$ is a left-handed technifermion weak doublet, and U_R is a corresponding right-handed technifermion weak singlet. The indices i and w are for $SU(2)_W$ and technicolor, respectively. The constant ξ is an ETC-gauge-group–dependent Clebsch-Gordan coefficient and is expected to be of order 1. At energies lower than the mass ($M_{\rm ETC}$) of the ETC gauge boson, the effects of its exchange may be approximated by local four-fermion operators. In particular, the top mass arises from an operator coupling the left- and right-handed pieces of the current (1),

$$-(g_{\rm ETC}^2/M_{\rm ETC}^2)(\bar{\psi}_L^i\gamma^\mu T_L^{iw})(\bar{U}_R^w\gamma_\mu t_R)+\text{H.c.} \tag{2}$$

This may be Fierz-transformed into a product of technicolor-singlet densities,

$$2(g_{\rm ETC}^2/M_{\rm ETC}^2)(\bar{\psi}_L^i t_R)(\bar{U}_R T_L^i)+\text{H.c.} \tag{3}$$

In what follows we will assume (for simplicity) that there is only one doublet of technifermions, that the strong technicolor interactions respect an $SU(2)_L\times SU(2)_R$ chiral symmetry, and therefore that the technicolor F constant (analogous to f_π in QCD) is $v\approx 250$ GeV. Using the rules of naive dimensional analysis [6] we find the top-quark mass is

$$m_t=\frac{g_{\rm ETC}^2}{M_{\rm ETC}^2}\langle\bar{U}U\rangle\approx\frac{g_{\rm ETC}^2}{M_{\rm ETC}^2}(4\pi v^3)\,. \tag{4}$$

Equivalently, the scale of the ETC dynamics responsible for generating the top mass is

$$M_{\rm ETC}\approx(1.4\text{ TeV})g_{\rm ETC}(100\text{ GeV}/m_t)^{1/2}\,. \tag{5}$$

In the absence of fine tuning [3] and as long as $g_{\rm ETC}^2v^2/M_{\rm ETC}^2<1$ (or, equivalently, when $m_t/4\pi v$ is small), the ETC interactions may be treated as a small perturbation on the technicolor dynamics and our estimates are self-consistent. Note that the rules of naive dimensional analysis do not require that $M_{\rm ETC}$ be large, only that $m_t/4\pi v$ be small.

These dimensional estimates are typically modified in "walking technicolor" models [7] where there is an enhancement of operators of the form (3) due to a large anomalous dimension of the technifermion mass operator. The enhancement is important for the ETC interactions responsible for light fermion masses (for which $M_{\rm ETC}$ must be quite high), but will not be numerically significant in the case of the top quark because the ETC scale (5) associated with the top quark is so low. Hence, the results in "walking" theories are expected to be similar to those presented below.

Consider the four-fermion operator arising from the left-handed part of the current (1),

$$-\xi^2(g_{\rm ETC}^2/M_{\rm ETC}^2)(\bar{\psi}_L^i\gamma^\mu T_L^{iw})(\bar{T}_L^{jw}\gamma_\mu\psi_L^j)\,. \tag{6}$$

(Reference [8] lists possible four-fermion operators arising from ETC exchange, with emphasis on model-independent and potentially dangerous ETC contributions to $\delta\rho$.) This may be Fierz-transformed into the form of a product of technicolor-singlet currents and includes

$$-\tfrac{1}{2}\xi^2(g_{\rm ETC}^2/M_{\rm ETC}^2)(\bar\psi_L\gamma^\mu\tau^a\psi_L)(\bar T_L\gamma_\mu\tau^a T_L)\,, \qquad (7)$$

where $g_{\rm ETC}$ and $M_{\rm ETC}$ are as in Eq. (3) and the τ^a are weak isospin Pauli matrices. We will show that this operator can generate sizable deviations in the predictions for the $Zb\bar b$ coupling. There are also operators involving products of weak-singlet left-handed currents, but these operators will not affect the $Zb\bar b$ coupling.

Our analysis of the effects of operator (7) proceeds along the lines of Ref. [9]. Adopting an effective chiral Lagrangian description appropriate below the technicolor chiral-symmetry-breaking scale, we may replace the technifermion current by a sigma-model current [10]:

$$(\bar T_L\gamma_\mu\tau^a T_L)=\tfrac{1}{2}v^2{\rm Tr}(\Sigma^\dagger\tau^a iD_\mu\Sigma)\,, \qquad (8)$$

where $\Sigma=\exp(2i\tilde\pi/v)$ transforms as $\Sigma\to L\Sigma R^\dagger$ under $SU(2)_L\times SU(2)_R$, and the covariant derivative is

$$\partial_\mu\Sigma+i\frac{e}{s_\theta\sqrt2}(W_\mu^+\tau^+ + W_\mu^-\tau^-)\Sigma+i\frac{e}{s_\theta c_\theta}Z_\mu(\tfrac12\tau_3\Sigma-s_\theta^2[Q,\Sigma])+ieA_\mu[Q,\Sigma]\,. \qquad (9)$$

In unitary gauge $\Sigma=1$ and operator (7) becomes

$$\frac{\xi^2}{2}\frac{g_{\rm ETC}^2v^2}{M_{\rm ETC}^2}\bar\psi_L\left(\frac{e}{s_\theta c_\theta}\not Z\frac{\tau_3}{2}+\frac{e}{s_\theta\sqrt2}(\not W^+\tau^+ + \not W^-\tau^-)\right)\psi_L\,. \qquad (10)$$

This yields a correction

$$\delta g_L=-\frac{\xi^2}{2}\frac{g_{\rm ETC}^2v^2}{M_{\rm ETC}^2}\frac{e}{s_\theta c_\theta}(I_3)=\frac{\xi^2}{4}\frac{m_t}{4\pi v}\frac{e}{s_\theta c_\theta} \qquad (11)$$

to the tree-level $Zb\bar b$ couplings

$$g_L=\frac{e}{s_\theta c_\theta}(I_3-Qs_\theta^2)=\frac{e}{s_\theta c_\theta}(-\tfrac12+\tfrac13 s_\theta^2)\,,$$

$$g_R=\frac{e}{s_\theta c_\theta}(\tfrac13 s_\theta^2)\,.$$

Consider the effect of δg_L on the ratio of the $b\bar b$ and hadronic widths of the Z. In any such ratio of widths, all oblique effects and, in particular, any effects from the ρ parameter approximately cancel. The change in this ratio is

$$\delta\left(\frac{\Gamma_{b\bar b}}{\Gamma_{\rm had}}\right)\approx\left(\frac{\Gamma_{b\bar b}}{\Gamma_{\rm had}}\right)\left(\frac{\delta\Gamma}{\Gamma_{b\bar b}}-\frac{\delta\Gamma}{\Gamma_{\rm had}}\right), \qquad (12)$$

where $\delta\Gamma$ is the purely nonoblique correction to the $Zb\bar b$ width,

$$\frac{\delta\Gamma}{\Gamma_{b\bar b}}\approx\frac{2g_L\delta g_L}{g_L^2+g_R^2}\approx-3.7\%\times\xi^2\left(\frac{m_t}{100\ {\rm GeV}}\right). \qquad (13)$$

For a top mass of order 100 GeV, the standard-model predictions [11] are 378 MeV for $\Gamma_{b\bar b}$ and 1734 MeV for $\Gamma_{\rm had}$, and we see that (13) leads to

$$\delta\left(\frac{\Gamma_{b\bar b}}{\Gamma_{\rm had}}\right)\approx-2.9\%\times\xi^2\left(\frac{m_t}{100\ {\rm GeV}}\right)\left(\frac{\Gamma_{b\bar b}}{\Gamma_{\rm had}}\right). \qquad (14)$$

By way of comparison, the corresponding $Zb\bar b$ vertex correction in the one-Higgs-boson standard model gives [12] a correction of approximately 0.5% if $m_t=100$ GeV and 2.0% if $m_t=200$ GeV. The leading standard-model correction is *quadratic* in m_t, whereas the ETC correction is *linear*.

Experiments at LEP currently measure $\Gamma_{b\bar b}/\Gamma_{\rm had}$ to an accuracy of about 5% [13], so a shift on the order of (14) cannot currently be excluded. The measurement of $\Gamma_{b\bar b}/\Gamma_{\rm had}$ should eventually reach 2% [13], at which point it will be possible to either see or exclude the effect in Eq. (14). The similarly large Wtb vertex contribution in Eq. (10) is much more difficult to observe without detailed studies of the top quark.

So far, we have assumed that the ETC and weak interactions commute. In theories with weak-charged gauge bosons, we can make no definite predictions. As before, the ETC boson responsible for generating the top mass can contribute to the $Zb\bar b$ vertex. For example, the operator (3) can arise from the exchange of a weak-doublet ETC gauge boson which couples T_L to t_L^c (the field which is charge conjugate to t_R) and ψ_L to U_L^c. Such a gauge boson will give rise to the $SU(2)_{L+R}$-triplet operator $(\bar U_R\gamma^\mu U_R)(\bar\psi_L\gamma_\mu\psi_L)$. In addition, there may be technicolor-neutral weak-triplet ETC bosons contributing directly to an operator of the form (7). In both of these cases, we would generically expect effects on the $Zb\bar b$ coupling to be of the same order of magnitude as those already described, but the size and sign of the total shift (13) will be model dependent.

It is interesting to note that a correction to the $Zb\bar b$ vertex linear in m_t can also occur in models [14] where fermion masses arise from mixing of ordinary fermions and technibaryons. In this case, the b_L and b_R are partly technibaryons and, as in QCD, the axial technibaryon coupling is renormalized. Then the left- and right-handed couplings receive a correction of the form

$$\delta g_L=(g_L-g_R)[\tfrac12(g_A-1)]\sin^2\alpha\,, \qquad (15)$$

and

$$\delta g_R=(g_R-g_L)[\tfrac12(g_A-1)]\sin^2\beta\,, \qquad (16)$$

where g_A is the axial current renormalization, while α and β are the mixing angles relating the left- and right-handed components of the mass eigenstate b field to the corresponding gauge eigenstate b and technibaryon fields. In this model, the mass of the top is

$$m_t \approx m_{\mathrm{TB}} \sin\alpha \sin\gamma\,, \tag{17}$$

where m_{TB} is the mass of a technibaryon and γ is the mixing angle for the right-handed top. If $\sin\gamma$ and $\sin\alpha$ are of the same order of magnitude, $\sin\alpha \approx (m_t/m_{\mathrm{TB}})^{1/2}$ and

$$\frac{\delta\Gamma}{\Gamma_{b\bar{b}}} \approx (g_A - 1)\frac{m_t}{m_{\mathrm{TB}}}\,. \tag{18}$$

In a QCD-like theory with $g_A \approx 1.25$, and for $m_t = 100$ GeV and $m_{\mathrm{TB}} = 1$ TeV, this results in an effect of order $+2\%$ in $\Gamma_{b\bar{b}}/\Gamma_{\mathrm{had}}$.

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