Implications of LEP and SLD data for new physics in $Zb\bar{b}$ couplings

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The combined CERN LEP and SLAC Large Detector (SLD) data on the $b\bar{b}$ forward-backward asymmetry from the Z-pole measurements may imply the presence of new physics in the $Zb\bar{b}$ couplings. In general, the effect of new physics can be parametrized by $SU_C(3) \times SU_L(2) \times U_Y(1)$ invariant higher dimensional operators. By fitting the recently announced LEP and SLD data on A_b and R_b, the size of the coupling strengths of these operators can be determined. We also found that the new physics operators can be divided into two types, depending on their Higgs field content. The ones involving the Higgs field have very mild effects at higher energy colliders, while the other type which do not contain the Higgs field can show significantly large effects on $b\bar{b}$ production at LEP II, $t\bar{t}$ production at the NLC and single top quark production at the Fermilab Tevatron. The preliminary data from the LEP II measurements disfavor the second type of operators.

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I. INTRODUCTION

The continuing agreement between experimental data and theoretical predictions on almost all the electroweak variables has further solidified the standard model (SM). However, there are signs of perhaps something non-standard from the investigation of non-electroweak variables and the indication of the possibilities of new physics from electroweak variables themselves as well. On the one hand, the accumulative and, especially, the recent data on neutrino oscillations have strongly suggested the fact of finite neutrino masses [1] and, therefore, the SM has to be modified. On the other hand, the Z-pole measurements at the CERN e^+e^- collider LEP and SLAC Large Detector (SLD) on the $b\bar{b}$ forward-backward asymmetry give a value of $A_b = [g_L^2(b) - g_R^2(b)]/[g_L^2(b) + g_R^2(b)]$ which deviates from the SM prediction by 2.7σ [2]. If this A_b anomaly is not a statistical or systematic effect, it signals the presence of new physics in association with the $Zb\bar{b}$ coupling. Meanwhile, the experimental value of the related quantity $R_b = \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$, after showing a deviation from the SM value for a few years, now agrees well with the SM prediction [2]. To explain the current experimental values of both A_b and R_b, the required new physics contribution has to shift the left- and right-handed $Zb\bar{b}$ couplings by $\sim -1\%$ and $\sim +30\%$, respectively [3,4]. Recently efforts have been made in exploring the A_b anomaly, either in explaining the effect in specified models [4,5] or in examining its implications for low energy decay processes [6]. The popular low energy supersymmetry (SUSY) and the models in which the third generation feels a different gauge dynamics from the usual weak interaction cannot yield such large anomalous $Zb_R\bar{b}_R$ coupling, as shown in [7] and [8], respectively. These studies

are focused on the theme that has emerged since the discovery of the heavy top quark, that new physics is most likely related to the gauge symmetry breaking sector and, therefore, may affect the interactions of the third family quarks most significantly.

From the overwhelming success of the SM at the electroweak scale, one can conclude that the underlying theory of the new physics can openly manifest only at a higher energy scale. One can envisage that in the scheme of a larger symmetry that encompasses the new physics, after integrating out the heavy degrees of freedom which lie outside the SM spectrum, higher dimensional terms will be present at energies not too far above the electroweak scale and the induced effective terms should preserve the basic SM structure. Then the new physics effects on the $Zb\bar{b}$ couplings can be parametrized by a set of higher dimensional operators [9,10] which are $SU_C(3) \times SU_L(2) \times U_Y(1)$ symmetric before the electroweak symmetry breaking becomes explicit. From the above argument we see that before the electroweak symmetry breaking, the $Zb\bar{b}$ part of the effective Lagrangian can take the general form

$$\mathcal{L}_{Zb\bar{b}}^{eff} = \mathcal{L}_{Zb\bar{b}}^{SM} + \frac{1}{\Lambda^2} \sum_i C_i O_i + O\left(\frac{1}{\Lambda^4}\right) \tag{1}$$

where $\mathcal{L}_{Zb\bar{b}}^{SM}$ is the SM part, Λ is the new physics scale, O_i are dimension-6 SM gauge invariant operators, and C_i are constants which represent the coupling strengths of O_i. We have assumed that operators of higher dimensions than 6 are suppressed by powers of $1/\Lambda^2$, so Eq. (1) is a quite general parametrization of new physics.

Since there are many possible higher dimensional operators O_i, it is important to use various experimental data to constrain the operator form in order to narrow down the directions of the underlying theory. Because the operator O_i can contribute to several vertices after $SU_L(2) \times U_Y(1)$ symmetry breaking, these operators can contribute to and will show correlated effects on several different physical observables. It will become clear later that the new physics effects required to explain A_b will also show up in other observables, such as $b\bar{b}$ production at LEP II, $t\bar{t}$ production at the Next Linear Collider (NLC), and $t\bar{b}$ production at the Tevatron. These effects help to distinguish the possible operator forms required.

This article is organized as follows. In Sec. II we list the contributing dimension-6 operators and derive their induced vertices. In Sec. III we constrain the coupling strengths of the operators using the LEP and SLD Z-pole $Zb\bar{b}$ data. In Sec. IV we investigate the correlated effects of these operators at LEP II, the NLC, and the Tevatron. In Sec. V we present our discussions and the conclusion.

II. OPERATORS AND THEIR INDUCED VERTICES

Assuming CP conservation and ignoring those operators which only lead to anomalous dipole-moment couplings which are suppressed, we have two dimension-6 gauge invariant operators which give rise to anomalous right-handed $Zb\bar{b}$ coupling [9],

$$O_{bB} = [\bar{b}_R \gamma^\mu D^\nu b_R + \overline{D^\nu b_R} \gamma^\mu b_R] B_{\mu\nu}, \qquad (2)$$

$$O_{\Phi b} = i[\Phi^\dagger D_\mu \Phi - (D_\mu \Phi)^\dagger \Phi] \bar{b}_R \gamma^\mu b_R, \qquad (3)$$

and four operators affecting the left-handed $Zb_L\bar{b}_L$ coupling,

$$O_{qW} = \left[\bar{q}_L \gamma^\mu \frac{\sigma^I}{2} D^\nu q_L + \overline{D^\nu q_L} \gamma^\mu \frac{\sigma^I}{2} q_L \right] W^I_{\mu\nu}, \qquad (4)$$

$$O_{qB} = [\bar{q}_L \gamma^\mu D^\nu q_L + \overline{D^\nu q_L} \gamma^\mu q_L] B_{\mu\nu}, \qquad (5)$$

$$O^{(1)}_{\Phi q} = i[\Phi^\dagger D_\mu \Phi - (D_\mu \Phi)^\dagger \Phi] \bar{q}_L \gamma^\mu q_L, \qquad (6)$$

$$O^{(3)}_{\Phi q} = i\left[\Phi^\dagger \frac{\sigma^I}{2} D_\mu \Phi - (D_\mu \Phi)^\dagger \frac{\sigma^I}{2} \Phi \right] \bar{q}_L \gamma^\mu \frac{\sigma^I}{2} q_L. \qquad (7)$$

At the order of C_i/Λ^2, the contributions to R_b and A_b from those operators that only lead to anomalous dipole-moment couplings for $Zb\bar{b}$ are suppressed by a factor m_b/m_Z relative to the contributions of the operators we are considering. We have used the conventional notation: $q_L = (t_L, b_L)$ is $SU_L(2)$ doublet of the third family of quarks, Φ the Higgs boson doublet, B_μ the $U_Y(1)$ gauge field and $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$, W^I_μ ($I=1,2,3$) are the $SU_L(2)$ gauge fields, $W^I_{\mu\nu} = \partial_\mu W^I_\nu - \partial_\nu W^I_\mu + g_2 \epsilon_{IJK} W^J_\mu W^K_\nu$, and σ^I are the Pauli matrices.

After the electroweak symmetry breaking each operator can give rise to a set of vertices which may affect more than one electroweak observable involving the bottom quark and
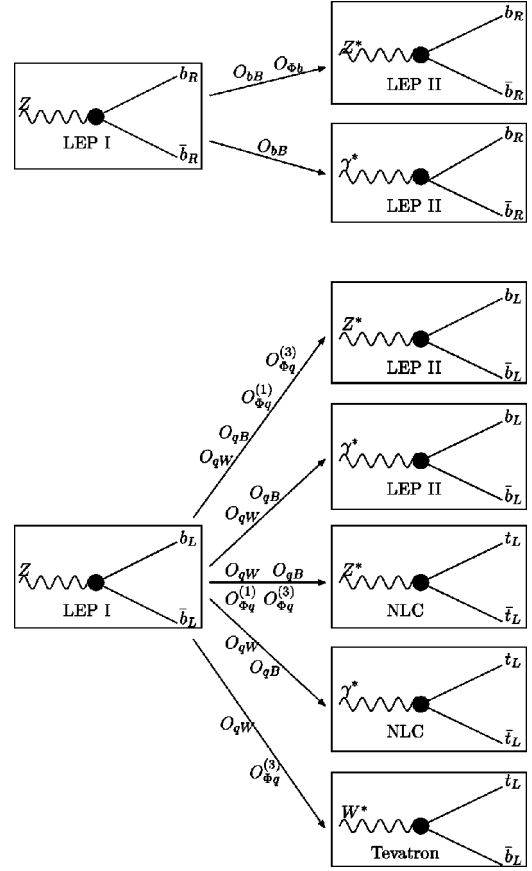

FIG. 1. The diagrams showing the correlated effects of new physics in $Zb\bar{b}$ couplings.

lead to correlated effects among these observables. The two right-handed operators, O_{bB} and $O_{\Phi b}$ in Eqs. (2) and (3), will give rise to anomalous $Zb_R\bar{b}_R$ and $\gamma b_R\bar{b}_R$ couplings. The four left-handed operators given in Eqs. (4)–(7) also involve the top quark and therefore will contribute to both bottom quark and top quark anomalous couplings. The correlated effects of these operators at the various colliders are depicted in Fig. 1.

Denoting the $V^0 q\bar{q}$ ($V^0 = Z, \gamma; q = t, b$) and $Wt\bar{b}$ vertices by

$$\Gamma^\mu_{V^0 q\bar{q}} = -ie g^V \gamma^\mu [P_L(g^V_L + \delta g^V_L) + P_R(g^V_R + \delta g^V_R)], \quad (8)$$

$$\Gamma^\mu_{Wt\bar{b}} = -i\frac{g}{\sqrt{2}} \gamma^\mu P_L(1 + \delta g^W_L), \qquad (9)$$

the SM couplings are g^V_L, g^V_R, and g^W_L, while the anomalous couplings are denoted by δg^V_L, δg^V_R and δg^W_L. Here $P_{L,R} = (1 \mp \gamma_5)/2$, $g^\gamma = 1$, $g^Z = 1/(4s_W c_W)$ with $s_W \equiv \sin \theta_W$ and $c_W \equiv \cos \theta_W$. The SM couplings are given by $g^\gamma_L(q) = g^\gamma_R(q) = e_q$, $g^Z_L(q) = 4I^3_q - 4s^2_W e_q$ and $g^Z_R(q) = -4s^2_W e_q$ with e_q being the electric charge of the quark in units of e and $I^3_q = \pm 1/2$, the weak isospin component. The new physics contributions to δg^V_R from the right-handed operators are given in Table I, and those to δg^V_L and δg^W_L from the left-handed

TABLE I. The anomalous couplings induced by right-handed operators. k is the momentum of the corresponding vector boson.

	O_{bB}	$O_{\Phi b}$
$\delta g_R^Z(b)$	$\dfrac{4s_W^2 c_W}{e}\dfrac{k^2}{\Lambda^2}C_{bB}$	$-\dfrac{4s_W c_W}{e}\dfrac{vm_Z}{\Lambda^2}C_{\Phi b}$
$\delta g_R^\gamma(b)$	$-\dfrac{c_W}{e}\dfrac{k^2}{\Lambda^2}C_{bB}$	0
$\delta g_R^\gamma(t)$	0	0
$\delta g_R^\gamma(t)$	0	0

operators in Table II. The three operators, O_{bB}, O_{qW} and O_{qB}, induce momentum dependent anomalous couplings, and, therefore, their effects will generally be enhanced in higher energy processes.

It should be pointed out that there are no contributions from anomalous t_R couplings in the present considerations. The reason is that the operators which contribute to the t_R coupling are of the form of the operators given in Eqs. (2) and (3), b_R replaced by t_R, and do not involve the bottom quark; we therefore ignore all these operators.

III. CONSTRAINTS FROM THE Z-POLE DATA

The non-standard contributions to R_b and A_b at the Z pole from the anomalous couplings in Eq. (8) can be written as

$$\delta R_b = 2R_b^{SM}(1-R_b^{SM})\left[\frac{g_L^Z(b)\delta g_L^Z(b)+g_R^Z(b)\delta g_R^Z(b)}{[g_L^Z(b)]^2+[g_R^Z(b)]^2}\right],$$
(10)

$$\delta A_b = 2A_b^{SM}\left[\frac{g_L^Z(b)\delta g_L^Z(b)-g_R^Z(b)\delta g_R^Z(b)}{[g_L^Z(b)]^2-[g_R^Z(b)]^2}\right.$$
$$\left.-\frac{g_L^Z(b)\delta g_L^Z(b)+g_R^Z(b)\delta g_R^Z(b)}{[g_L^Z(b)]^2+[g_R^Z(b)]^2}\right].$$
(11)

Here we only keep the lowest order effects of new physics, i.e., $\mathcal{O}(C_i/\Lambda^2)$, which is the interference of new physics terms with the SM contributions, and neglect the interference terms proportional to m_b/m_Z. The SM values of R_b^{SM} and A_b^{SM} are taken to be [3]

$$R_b^{\text{SM}}=0.2158\pm0.0002, \quad A_b^{\text{SM}}=0.9347\pm0.0001, \quad (12)$$

which are the predictions in the SM including radiative corrections. The anomalous couplings $\delta g_L^Z(b)$ and $\delta g_R^Z(b)$ in Eqs. (10) and (11) are obtained from Tables I and II with the Z boson being on mass shell ($k^2=m_Z^2$).

The experimental values for A_b and R_b reported in [2] are

$$R_b^{\text{expt}}(\text{LEP+SLD})=0.21642\pm0.00073, \quad (13)$$

$$A_b^{\text{expt}}(\text{LEP})=0.881\pm0.020,$$
$$A_b^{\text{expt}}(\text{SLD})=0.905\pm0.026,$$
(14)

where the LEP value of A_b is obtained from the measured quantities $A_{\text{FB}}(b)=\frac{3}{4}A_e A_b$ using $A_e=0.1496\pm0.0016$, the combined average of A_e from LEP and SLD. The combined value of A_b from LEP and SLD is then given by $A_b^{\text{expt}}(\text{LEP+SLD})=0.8902\pm0.0158$, which is 2.8σ below the SM prediction. To fit the data on both R_b and A_b the $Zb\bar{b}$ couplings are required to be [4] $g_L^Z(b)/4=-0.4163\pm0.0020$ and $g_R^Z(b)/4=0.0996\pm0.0076$. Comparing with the SM values [11] $g_L^Z(b)/4=-0.4208$ and $g_R^Z(b)/4=0.0774$, obtained by including radiative corrections and taking $m_t=174$ GeV and $m_H=100$ GeV, we find that new physics effects are needed in both $Zb_R\bar{b}_R$ and $Zb_L\bar{b}_L$, which indicates both right- and left-handed higher dimension operators are necessary. If we use only one right- and one left-handed operator at a time to obtain the required modifications to the $Zb_R\bar{b}_R$ and $Zb_L\bar{b}_L$ couplings, we obtain the ranges of strengths of the operators at the 1σ (2σ) level:

$$2.72 \ (1.30)\lesssim\frac{|C_{bB}|}{(\Lambda/\text{TeV})^2}\lesssim5.54 \ (6.96),$$
$$0.48 \ (0.23)\lesssim\frac{|C_{\Phi b}|}{(\Lambda/\text{TeV})^2}\lesssim0.99 \ (1.24),$$
(15)

$$0.51 \ (0.10)\lesssim\frac{|C_{qW}|}{(\Lambda/\text{TeV})^2}\lesssim1.33 \ (1.73),$$
$$0.47 \ (0.09)\lesssim\frac{|C_{qB}|}{(\Lambda/\text{TeV})^2}\lesssim1.21 \ (1.58),$$
(16)

$$0.08 \ (0.02)\lesssim\frac{|C_{\Phi q}^{(1)}|}{(\Lambda/\text{TeV})^2}\lesssim0.22 \ (0.28),$$
(17)

$$0.08 \ (0.02)\lesssim\frac{|C_{\Phi q}^{(3)}|}{(\Lambda/\text{TeV})^2}\lesssim0.22 \ (0.28).$$

Apart from the limits that can be obtained from the electroweak variables the strengths of the operators can also be constrained by the partial wave unitarity condition of the appropriate 2-to-2 scattering processes $b\bar{b}\leftrightarrow b\bar{b}$, $b\bar{b}\leftrightarrow t\bar{t}$ and $t\bar{t}\leftrightarrow t\bar{t}$, which involve the helicity channels $b_+\bar{b}_-$, $b_-\bar{b}_+$, $t_+\bar{t}_-$ and $t_-\bar{t}_+$, with $+$ and $-$ denoting positive and negative helicities [13]. For the three operators, O_{bB}, O_{qW}, and O_{qB}, which give rise to momentum dependent couplings, the unitarity constraints are found to be significant [13], and are given by

$$\frac{|C_{bB}|}{\Lambda^2}<\frac{\sqrt{8\pi}}{s},$$
(18)

TABLE II. The anomalous couplings induced by left-handed operators. k is the momentum of the corresponding vector boson.

	O_{qW}	O_{qB}	$O_{\Phi q}^{(1)}$	$O_{\Phi q}^{(3)}$
$\delta g_L^Z(b)$	$\dfrac{2s_W c_W^2}{e}\dfrac{k^2}{\Lambda^2}C_{qW}$	$\dfrac{4s_W^2 c_W}{e}\dfrac{k^2}{\Lambda^2}C_{qB}$	$-\dfrac{4s_W c_W}{e}\dfrac{v m_Z}{\Lambda^2}C_{\Phi q}^{(1)}$	$-\dfrac{4s_W c_W}{e}\dfrac{v m_Z}{\Lambda^2}C_{\Phi q}^{(3)}$
$\delta g_L^\gamma(b)$	$\dfrac{s_W}{2e}\dfrac{k^2}{\Lambda^2}C_{qW}$	$-\dfrac{c_W}{e}\dfrac{k^2}{\Lambda^2}C_{qB}$	0	0
$\delta g_L^Z(t)$	$-\dfrac{2s_W c_W^2}{e}\dfrac{k^2}{\Lambda^2}C_{qW}$	$\dfrac{4s_W^2 c_W}{e}\dfrac{k^2}{\Lambda^2}C_{qB}$	$-\dfrac{4s_W c_W}{e}\dfrac{v m_Z}{\Lambda^2}C_{\Phi q}^{(1)}$	$\dfrac{4s_W c_W}{e}\dfrac{v m_Z}{\Lambda^2}C_{\Phi q}^{(3)}$
$\delta g_L^\gamma(t)$	$-\dfrac{s_W}{2e}\dfrac{k^2}{\Lambda^2}C_{qW}$	$-\dfrac{c_W}{e}\dfrac{k^2}{\Lambda^2}C_{qB}$	0	0
δg_L^W	$-\dfrac{s_W}{e}\dfrac{k^2}{\Lambda^2}C_{qW}$	0	0	$\dfrac{v^2}{\Lambda^2}C_{\Phi q}^{(3)}$

$$\frac{|C_{qW}|}{\Lambda^2}<\frac{\sqrt{4\pi}}{s}, \qquad (19)$$

and

$$\frac{|C_{qB}|}{\Lambda^2}<\frac{\sqrt{4\pi}}{s}. \qquad (20)$$

Here s is the center-of-mass energy squared for the relevant process. Requiring the unitarity condition to be satisfied for the processes with center-of-mass energy up to the new physics scale, i.e., $\sqrt{s}\approx\Lambda$, we obtain the upper limits on the coupling strengths, which are $|C_{bB}|<\sqrt{8\pi}$, $|C_{qW}|<\sqrt{4\pi}$, and $|C_{qB}|<\sqrt{4\pi}$. They imply that to give the minimal contribution required by the A_b and R_b data the new physics scale cannot be too high. The 1σ (2σ) upper bounds are found to be

$$\Lambda\lesssim 1.4(2.0)\ \text{TeV}\quad(\text{for }O_{bB}), \qquad (21)$$

$$\Lambda\lesssim 2.6(5.9)\ \text{TeV}\quad(\text{for }O_{qW}), \qquad (22)$$

and

$$\Lambda\lesssim 2.8(6.2)\ \text{TeV}\quad(\text{for }O_{qB}). \qquad (23)$$

The upper bounds on the new physics scales for the three momentum-independent operators are much weaker, e.g., $\Lambda\lesssim 10$ (14) TeV at the 1σ (2σ) level for the operator $O_{\Phi b}$.

IV. CORRELATED EFFECTS AT LEP II, THE NLC AND THE TEVATRON

The anomalous couplings in Eqs. (8) and (9) also contribute to the production cross sections for $e^+e^-\rightarrow Z^*$, γ^* $\rightarrow q\bar{q}$ ($q=b,t$) and $u\bar{d}\rightarrow W^*\rightarrow t\bar{b}$ as follows:

$$\delta\sigma(e^+e^-\rightarrow q\bar{q})=\frac{3}{2}\beta_q\Big\{D_{\gamma\gamma}e_e^2[(3-\beta_q^2)e_q(\delta g_L^\gamma+\delta g_R^\gamma)]$$
$$+D_{ZZ}(v_e^2+a_e^2)[(3-\beta_q^2)v_q(\delta g_L^Z+\delta g_R^Z)$$
$$+2\beta_q^2 a_q(\delta g_L^Z-\delta g_R^Z)]+D_{Z\gamma}e_e v_e$$
$$\times\Big[\frac{3-\beta_q^2}{2}[e_q(\delta g_L^Z+\delta g_R^Z)$$
$$+v_q(\delta g_L^\gamma+\delta g_R^\gamma)]+\beta_q^2 a_q(\delta g_L^\gamma-\delta g_R^\gamma)\Big]\Big\}$$

$$(24)$$

and

$$\delta\hat{\sigma}(u\bar{d}\rightarrow t\bar{b})=\frac{g^4}{384\pi}\frac{(\hat{s}-m_t^2)^2}{\hat{s}^2(\hat{s}-m_W^2)^2}[2(2\hat{s}+m_t^2)\delta g_L^W]. \qquad (25)$$

Here s and $\hat{s}$ are the squared center-of-mass energies for $e^+e^-\rightarrow q\bar{q}$ and $u\bar{d}\rightarrow t\bar{b}$, respectively. v_f and a_f represent, respectively, the vector and axial-vector $Zf\bar{f}$ couplings in the SM, i.e., $v_f\equiv(g_L^Z+g_R^Z)/2$ and $a_f\equiv(g_L^Z-g_R^Z)/2$. In Eq. (24) we have defined

$$\beta_q=\sqrt{1-4m_q^2/s}, \qquad (26)$$

$$D_{\gamma\gamma}=\frac{4\pi\alpha^2(s)}{3s}, \qquad (27)$$

$$D_{ZZ}=\frac{G_F^2}{96\pi}\frac{sm_Z^4}{(s-m_Z^2)^2+(s\Gamma_Z/m_Z)^2}, \qquad (28)$$

and

$$D_{Z\gamma} = \frac{G_F\alpha(s)}{3\sqrt{2}} \frac{m_Z^2(s-m_Z^2)}{(s-m_Z^2)^2+(s\Gamma_Z/m_Z)^2}. \tag{29}$$

The anomalous contribution to $R_b \equiv \sigma(e^+e^- \to b\bar{b})/\sigma(e^+e^- \to q\bar{q})$ and the forward-backward asymmetry A_{FB}^b at LEP II are given by

$$\frac{\delta R_b}{R_b^{SM}} = (1 - R_b^{SM})\frac{\delta\sigma(e^+e^- \to b\bar{b})}{\sigma^{SM}(e^+e^- \to b\bar{b})} \tag{30}$$

and

$$\frac{\delta A_{FB}^b}{A_{FB}^{b,\,SM}} = \frac{D_{Z\gamma}e_e a_e(e_b\delta g_L^Z - e_b\delta g_R^Z + g_L^Z\delta g_L^\gamma - g_R^Z\delta g_R^\gamma) + 4D_{ZZ}v_e a_e(g_L^Z\delta g_L^Z - g_R^Z\delta g_R^Z)}{2D_{Z\gamma}e_e a_e e_b a_b + 8D_{ZZ}a_e v_e v_b a_b} - \frac{\delta\sigma(e^+e^- \to b\bar{b})}{\sigma^{SM}(e^+e^- \to b\bar{b})}. \tag{31}$$

The total hadronic cross section for $p\bar{p} \to t\bar{b} + X$ is evaluated by the convolution of the parton cross section and parton distribution functions. Here we use the CTEQ3L parton distribution functions [12] with $\mu = \sqrt{\hat{s}}$. The top quark mass is taken to be 175 GeV. The values of the other parameters are taken to be

$$m_Z = 91.187, \quad m_W = 80.33, \quad G_F = 1.16639 \times 10^{-5} \text{ GeV}^{-2}$$

and $\alpha = 1/128$.

Since the existence of both new right- and left-handed operators is necessary to explain the LEP I data, we again assume that only one pair of the operators given in Eqs. (2)–(7) contributes at a time in obtaining the limits on their contributions. Subject to the limits derived from the data on A_b and R_b, their effect on R_b and A_{FB}^b at LEP II, the $t\bar{t}$ production rate at the NLC, and the single top production cross section $\sigma(p\bar{p} \to t\bar{b} + X)$ at the Tevatron can be evaluated. These effects are summarized in Table III.

A few remarks regarding to the results in Table III are appropriate:

(a) The right-handed operator O_{bB} has large effects on R_b and A_{FB}^b at LEP II due to two reasons: One is that it contributes to the $\gamma^* b_R \bar{b}_R$ coupling and the γ^* intermediate state gives the dominant contribution to $\sigma(e^+e^- \to b\bar{b})$ at LEP II. The other is that the effects of O_{bB} are enhanced by a factor s/m_Z^2, which is 4.3 for $\sqrt{s} = 189$ GeV at LEP II, due to its momentum dependent couplings. The preliminary LEP II data at $\sqrt{s} = 189$ GeV give [14]

$$R_b^{expt} = 0.167 \pm 0.011(\text{stat}) \pm 0.008(\text{syst}), \quad R_b^{SM} = 0.162, \tag{32}$$

$$A_{FB}^{b,expt} = 0.68 \pm 0.21(\text{stat}) \pm 0.04(\text{syst}), \quad A_{FB}^{b,SM} = 0.56. \tag{33}$$

Note the large statistical error in $A_{FB}^{b,expt}$. At the 1σ (2σ) level the new physics effects are limited to the following ranges:

$$-5\%(-14\%) \lesssim \frac{\delta R_b}{R_b^{SM}} \lesssim 11\% \quad (20\%), \tag{34}$$

$$-17\%(-55\%) \lesssim \frac{\delta A_{FB}^b}{A_{FB}^{b,SM}} \lesssim 60\% \quad (98\%). \tag{35}$$

From Table III we see that the minimum contributions of O_{bB}, when it is used together with any one of the left-handed operators, lie outside the allowed ranges in Eqs. (34) and (35) at the 1σ level. Hence the right-handed operator O_{bB} is disfavored unless the central values of both R_b^{expt} and $A_{FB}^{b,expt}$ are modified in the refined LEP II data analysis. The operator $O_{\Phi b}$, which is neither momentum dependent nor contributes to the $\gamma^* b_R \bar{b}_R$ coupling, makes much smaller contributions to R_b and A_{FB}^b at LEP II. As shown in Table III, when $O_{\Phi b}$ is used together with a left-handed operator the deviation from the SM is allowed by the preliminary LEP II data.

(b) The left-handed operator, O_{qW}, when used to fit the anomalous $Zb_L\bar{b}_L$ coupling at the Z pole, can give rise to a sizable effect in the cross section for $p\bar{p} \to t\bar{b} + X$ at the Fermilab Tevatron because its effect on $W^* t\bar{b}$ is enhanced by a factor $\hat{s}/m_Z^2$ ($\sqrt{\hat{s}}$ is the center-of-mass energy of the parton-level process $u\bar{d} \to t\bar{b}$). Moreover, both O_{qW} and O_{qB} can cause large effects in the production rate of $t\bar{t}$ pairs at the NLC because their anomalous $\gamma^* t_L \bar{t}_L$ coupling is enhanced by a factor $s/m_Z^2 \approx 30$ for $\sqrt{s} = 500$ GeV at the NLC. Note that the effect of O_{qB} is about a factor of 2 larger than that of O_{qW}.

(c) Because of the clean environment and anticipated large number of the top quark pair events at the NLC, it is possible to measure the top quark pair production rate at the level of a few percent [15]. So the $t\bar{t}$ production rate decrease caused by O_{qW} (O_{qB}), with the minimum 2σ limit of 3.7% (7.2%), should be observable at the 2σ level. In contrast, as a result of the backgrounds at hadron colliders, it will be challenging to measure the single top quark production rate at the level of a few percent [16] at the Tevatron. The decrease of the single top quark production rate caused by O_{qW}, with the minimum $1\sigma(2\sigma)$ limit of 15% (3%), should be observable at the 1σ level, but probably not at the 2σ level. A detailed Monte Carlo analysis, with the consideration of all possible backgrounds, showed [17] that the

TABLE III. The ranges of correlated effects which are required by the data on A_b and R_b at the Z-pole. No contributions are indicated by ''$-$.''

		LEP II (189 GeV)		NLC (500 GeV)	Tevatron (2 TeV)
		$\dfrac{\delta R_b}{R_b^{SM}}$ (%)	$\dfrac{\delta A_{FB}^b}{A_{FB}^{b,SM}}$ (%)	$\dfrac{\delta\sigma(e^+e^-\to t\bar{t})}{\sigma^{SM}(e^+e^-\to t\bar{t})}$ (%)	$\dfrac{\delta\sigma(P\bar{P}\to t\bar{b}+X)}{\sigma^{SM}(P\bar{P}\to t\bar{b}+X)}$ (%)
O_{bB}, O_{qW}	1σ	$17\sim33$	$-32\sim-65$	$-19\sim-48$	$-15\sim-39$
	2σ	$9.4\sim41$	$-15\sim-81$	$-3.7\sim-63$	$-3.0\sim-51$
O_{bB}, O_{qB}	1σ	$21\sim44$	$-36\sim-77$	$-36\sim-93$	$-$
	2σ	$10\sim55$	$-16\sim-98$	$-7.2\sim-122$	$-$
O_{bB}, $O_{\Phi q}^{(1)}$	1σ	$21\sim42$	$-31\sim-64$	$0.2\sim0.5$	$-$
	2σ	$10\sim52$	$-15\sim-81$	$0.04\sim0.7$	$-$
O_{bB}, $O_{\Phi q}^{(3)}$	1σ	$21\sim42$	$-31\sim-64$	$-0.2\sim-0.5$	$-1.0\sim-2.6$
	2σ	$10\sim52$	$-15\sim-81$	$-0.04\sim-0.7$	$-0.2\sim-3.4$
$O_{\Phi b}$, O_{qW}	1σ	$-3.2\sim-8.8$	$-2.7\sim-5.8$	$-19\sim-48$	$-15\sim-39$
	2σ	$-0.4\sim-12$	$-1.2\sim-7.4$	$-3.7\sim-63$	$-3.0\sim-51$
$O_{\Phi b}$, O_{qB}	1σ	$0.8\sim1.7$	$-7.5\sim-18$	$-36\sim-93$	$-$
	2σ	$0.4\sim2.2$	$-2.1\sim-24$	$-7.2\sim-122$	$-$
$O_{\Phi b}$, $O_{\Phi q}^{(1)}$	1σ	$0.04\sim-0.3$	$-2.6\sim-5.5$	$0.2\sim0.5$	$-$
	2σ	$0.2\sim-0.5$	$-1.1\sim-6.9$	$0.04\sim0.7$	$-$
$O_{\Phi b}$, $O_{\Phi q}^{(3)}$	1σ	$0.04\sim-0.3$	$-2.6\sim-5.5$	$-0.2\sim-0.5$	$-1.0\sim-2.6$
	2σ	$0.2\sim-0.5$	$-1.1\sim-6.9$	$-0.04\sim-0.7$	$-0.2\sim-3.4$

effects of O_{qW} on the single top quark production rate are observable at run 3 or run 2b (30 fb^{-1} luminosity) at the 2σ level for $C_{qW}/(\Lambda/\text{TeV})^2\gtrsim0.5$. Consequently, the effects of O_{qW}, with coupling strength in the 2σ range, $1.73\gtrsim C_{qW}/(\Lambda/\text{TeV})^2\gtrsim0.1$ in Eq. (16), will only marginally be observable in run 3 or run 2b at the Tevatron.

(d) Among the left-handed operators the two operators that involve the Higgs field, $O_{\Phi q}^{(1)}$ and $O_{\Phi q}^{(3)}$, together with the right-handed operator, $O_{\Phi b}$, which also involves the Higgs field, indeed, do provide the required contribution to $Zb_L\bar{b}_L$ coupling but cause only small effects at LEP II, the NLC, and the upgraded Tevatron; only a few percent deviation from the SM in the b forward-backward asymmetry at LEP II.

V. DISCUSSION AND CONCLUSION

We have examined in some detail the possibility of new physics, characterized by higher dimension operators, if the current data on the $Zb\bar{b}$ couplings at the Z pole are taken literally. The dimension-6 operators we considered consist of two right-handed operators and four left-handed ones. Both the right- and left-handed operators are needed to explain the data. We also examined the effects of the eight pairs of operator at high energy colliders, LEP II, NLC, and upgraded Tevatron. Since the operators have sufficiently different behaviors at these higher energy colliders, their effects can mostly be distinguished, as can be seen from Table III. In particular, the preliminary LEP II data disfavor four pairs of

these operators, all of which involve the right-handed operator O_{bB}.

The four pairs which contain the operator $O_{\Phi b}$ also behave differently. The pair $O_{\Phi b}$ and O_{qW} has only small effects on δR_b and δA_{FB}^b but observable effects on $t\bar{t}$ production at the NLC and single top quark production at the upgraded Tevatron. The pair $O_{\Phi b}$ and O_{qB} has a strong effect on $t\bar{t}$ production at the NLC, and an observable effect on δA_{FB}^b, but a negligible effect on δR_b and no observable effects at the Tevatron.

The remaining two pairs, $O_{\Phi b}$, $O_{\Phi q}^{(1)}$ and $O_{\Phi b}$, $O_{\Phi q}^{(3)}$, have very little effect on the high energy quantities under consideration, except for a few percent deviation from the SM in A_{FB}^b. However, since these operators all contain the Higgs field and, therefore, are related to the symmetry breaking sector, they may well have something to do with new physics; at least, our analysis indicates they are the most likely suspects. The $Ht\bar{t}$ production at the NLC, $e^+e^-\to t\bar{t}H$ and $e^+e^-\to b\bar{b}H$, are useful processes for detecting their existence, as these operators can induce anomalous four-point couplings: $Zt\bar{t}H$ and $Zb\bar{b}H$. However, the production rates for such processes depend on the Higgs boson mass, which awaits discover.

In our analyses we have considered one pair of right- and left-handed operators at a time. If the two right-handed operators O_{bB} and $O_{\Phi b}$ are considered together, C_{bB} will be strongly constrained by the LEP II data for the reasons discussed in remark (a) of the previous section. Then the effects

of O_{bB} on the LEP I observables will be suppressed relative to these of $O_{\Phi b}$. Thus $O_{\Phi b}$ will remain to explain the LEP I data and our previous conclusion that $O_{\Phi b}$ is the favored candidate for the right-handed new physics operator in the $Zb\bar{b}$ couplings is not changed. Similarly, if we consider the four left-handed operators together we can obtain a bound on a linear combination of their coupling coefficients from the LEP I data. From top quark pair production at the NLC we can distinguish O_{qW} and O_{qB} from the other two. From single top quark production at the upgraded Tevatron we might also be able to single out O_{qW}. However, it will be difficult to distinguish $O_{\Phi q}^{(1)}$ from $O_{\Phi q}^{(3)}$.

In conclusion, if new physics effects exist in the $Zb\bar{b}$ vertex, as indicated by the current measurements at the Z pole, then (1) the responsible right-handed operator could only be $O_{\Phi b}$, to be consistent with the LEP II data, (2) the responsible left-handed operators can be distinguished by measuring $t\bar{t}$ production rate at the NLC and single top

quark production at the Tevatron, and (3) it is most likely that any new physics in $Zb\bar{b}$ couplings will involve the Higgs sector.

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