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AN ANALYSIS OF NON–OBLIQUE CORRECTIONS TO THE $Zb\bar{b}$ VERTEX

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ABSTRACT

We present a model–independent analysis of the $Zb\bar{b}$ vertex, with the aim of constraining contributions of new physics to the left- and right–handed couplings of the b. We find that the left–handed coupling of the b is quite narrowly constrained by present data, but that the right–handed coupling is still largely unconstrained.

1. Introduction

Recently there has been increasing interest in extensions of the Standard Model (SM) which predict sizable corrections to the $Zb\bar{b}$ vertex. This interest is motivated in part by the fact that a deviation from the SM prediction of $R_b = \Gamma_{b\bar{b}}/\Gamma_{\rm had}$ has been observed at LEP. This quantity is particularly well suited for detecting non–SM vertex corrections since the leading QCD corrections cancel, to leading order, in the ratio. However, since a shift in the couplings of the b will also affect observables such as $R_Z = \Gamma_{\rm had}/\Gamma_{\ell^+\ell^-}$ and $\sigma^0_{\rm had}$, it is important to analyze all the precision electroweak data in a systematic fashion for possible signatures of such corrections.

2. Sensitivity to oblique and non–oblique corrections

In the standard renormalization scheme where α, G_μ, and m_Z are used as input to fix the theory, electroweak observables get their dependence on oblique corrections through the ρ parameter and $\sin^2\theta_{\rm eff}$. If we denote the contribution of new physics to these two quantities as $\delta\rho$ and δs^2, respectively, we have

$$\rho = [\rho]_{\rm SM} + \delta\rho,$$

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$$\sin^2\theta_{\rm eff} \;=\; [\sin^2\theta_{\rm eff}]_{\rm SM} + \delta s^2, \tag{1}$$

where $[\mathcal{O}]_{\rm SM}$ denotes the Standard Model prediction of the observable $\mathcal{O}$.

The left and right handed couplings of the b quark to the Z are given by

$$g_L^b = [g_L^b]_{\rm SM} + \frac{1}{3}\,\delta s^2 + \delta g_L^b, \quad g_R^b = [g_R^b]_{\rm SM} + \frac{1}{3}\,\delta s^2 + \delta g_R^b, \tag{2}$$

where we have included possible non–oblique corrections from new physics, δg_L^b and δg_R^b. Assuming that there are no other non–oblique corrections from new physics, we can calculate the dependence of various observables on $\delta\rho$, δs^2, δg_L^b, and δg_R^b. It is convenient to define the following linear combinations of δg_L^b and δg_R^b:

$$\begin{aligned} \xi_b &\equiv (\cos\phi_b)\delta g_L^b - (\sin\phi_b)\delta g_R^b, \\ \zeta_b &\equiv (\sin\phi_b)\delta g_L^b + (\cos\phi_b)\delta g_R^b, \end{aligned} \tag{3}$$

where $\phi_b \equiv \tan^{-1}|g_R^b/g_L^b| \approx 0.181$. By expanding $\Gamma_{b\bar{b}}$ and $A_b \equiv [(g_L^b)^2 - (g_R^b)^2]/[(g_L^b)^2 + (g_R^b)^2]$ about the point $\delta s^2 = \xi_b = \zeta_b = 0$, we find

$$\begin{aligned} \Gamma_{b\bar{b}} &= [\Gamma_{b\bar{b}}]_{\rm SM}\left(1 + \delta\rho - 1.25\,\delta s^2 - 4.65\,\xi_b\right), \\ A_b &= [A_b]_{\rm SM}\left(1 - 0.68\,\delta s^2 - 1.76\,\zeta_b\right). \end{aligned} \tag{4}$$

All the other observables get their dependence on δg_L^b and δg_R^b through either $\Gamma_{b\bar{b}}$ or A_b so they will depend on either ξ_b or ζ_b, but not both. The observables that depend on $\Gamma_{b\bar{b}}$ are:

$$\begin{aligned} \Gamma_Z &= [\Gamma_Z]_{\rm SM}\left(1 + \delta\rho - 1.06\,\delta s^2 - 0.71\,\xi_b\right), \\ \sigma^0_{\rm had} &= [\sigma^0_{\rm had}]_{\rm SM}\left(1 + 0.11\,\delta s^2 + 0.41\,\xi_b\right), \\ R_Z \equiv \Gamma_{\rm had}/\Gamma_{\ell^+\ell^-} &= [R_Z]_{\rm SM}\left(1 - 0.85\,\delta s^2 - 1.02\,\xi_b\right), \\ R_b \equiv \Gamma_{b\bar{b}}/\Gamma_{\rm had} &= [R_b]_{\rm SM}\left(1 + 0.18\,\delta s^2 - 3.63\,\xi_b\right), \\ R_c \equiv \Gamma_{c\bar{c}}/\Gamma_{\rm had} &= [R_c]_{\rm SM}\left(1 - 0.35\,\delta s^2 + 1.02\,\xi_b\right). \end{aligned} \tag{5}$$

Note that only Γ_Z depends on $\delta\rho$. All of the other observables can be expressed as ratios of widths, so that the ρ dependence cancels between numerator and denominator. We will ignore Γ_Z in the following in order to keep the number of parameters at a manageable level. In an analogous way, we find

$$A_{\rm FB}^b = \frac{3}{4}A_e A_b = [A_{\rm FB}^b]_{\rm SM}\left(1 - 55.7\,\delta s^2 - 1.76\,\zeta_b\right). \tag{6}$$

The relationship between our parameters and others that have appeared in the literature is as follows. The parameter ϵ_b introduced in Ref. 1 is related to δg_L^b by

$$\epsilon_b = [\epsilon_b]_{\rm SM} - 2\delta g_L^b. \tag{7}$$

The parameters δ_{bV} and η_b introduced in Ref. 2 are related to ξ_b and ζ_b by

$$\begin{aligned} \delta_{bV} &= [\delta_{bV}]_{\rm SM} - 4.65\,\xi_b, \\ \eta_b &= [\eta_b]_{\rm SM} - 1.76\,\zeta_b. \end{aligned} \tag{8}$$

Table 1. Experimental measurements and Standard Model predictions for various observables

Observable	Experiment	SM prediction
$\sin^2\theta_{\rm eff}$	0.2317 ± 0.0007 (LEP) 0.2294 ± 0.0010 (SLD)	0.2320
$\sigma^0_{\rm had}$	41.49 ± 0.12 (nb)	41.43 ± 0.03
R_Z	20.795 ± 0.040	20.74 ± 0.04
R_b	0.2202 ± 0.0020	0.2157
R_c	0.1583 ± 0.0098	0.1711
$A^b_{\rm FB}$	0.0967 ± 0.0038	0.0957
A_b	0.99 ± 0.14	0.934

3. Determination of ξ_b and ζ_b

In order to constrain ξ_b and ζ_b, we must first compute nominal Standard Model values for the various observables. This in turn requires that we specify nominal values for the top and Higgs masses. In the following, we use $m_t = 175$ GeV and $m_H = 300$ GeV. It is also necessary to specify the value of α_s used in computing the QCD corrections. Here we will use $\alpha_s = 0.120 \pm 0.006$, which is the value determined from hadronic event shapes, jet rates, and energy correlations.[3] We use this value rather than the 0.123 ± 0.006 determined using lineshape data because it is independent of the Z lineshape parameters we will be using in this analysis. For the top and Higgs masses given above, the Standard Model predictions for the relevant observables are summarized in Table 1, together with the most recent experimental determinations.[4] The errors on $[\sigma^0_{\rm had}]_{\rm SM}$ and $[R_Z]_{\rm SM}$ are due to the uncertainty in α_s.

The LEP value of $\sin^2\theta_{\rm eff}$ is the average over the *leptonic* asymmetries only; since the $b\bar{b}$ asymmetries are sensitive to vertex corrections as well as shifts in the value of $\sin^2\theta_{\rm eff}$, they should be handled separately.

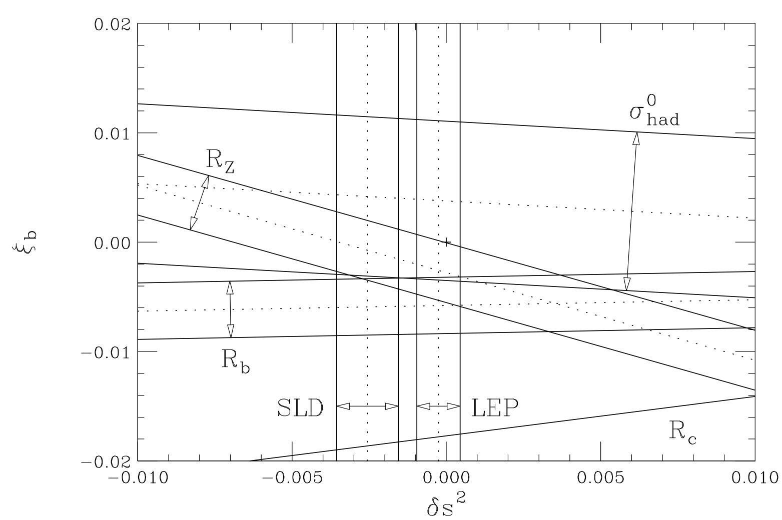

Fig. 1. The 1–σ limits placed on ξ_b and δs^2.

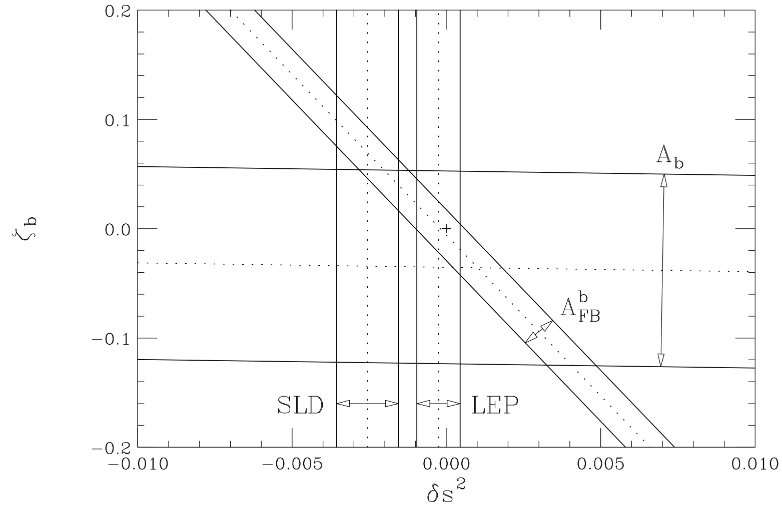

Fig. 2. The 1–σ limits placed on ζ_b and δs^2.

The constraints imposed by the various observables are illustrated in Figures 1 and 2. In Fig. 1, we show the experimentally preferred $1-\sigma$ bands in the $\delta s^2 - \xi_b$ plane, and in Fig. 2 we show the corresponding figure for the $\delta s^2 - \zeta_b$ plane.

A fit to the data with δs^2, ξ_b, and ζ_b as parameters, including the correlation of -0.4 between R_b and R_c, yields

$$\begin{aligned} \delta s^2 &= -0.0009 \pm 0.0006, \\ \xi_b &= -0.003 \ \ \pm 0.002, \\ \zeta_b &= \ \ \ 0.018 \ \ \pm 0.027. \end{aligned} \tag{9}$$

The 2–dimensional projections of the allowed regions onto the δs^2–ξ_b and δs^2–ζ_b planes are shown in Figs. 3 and 4.

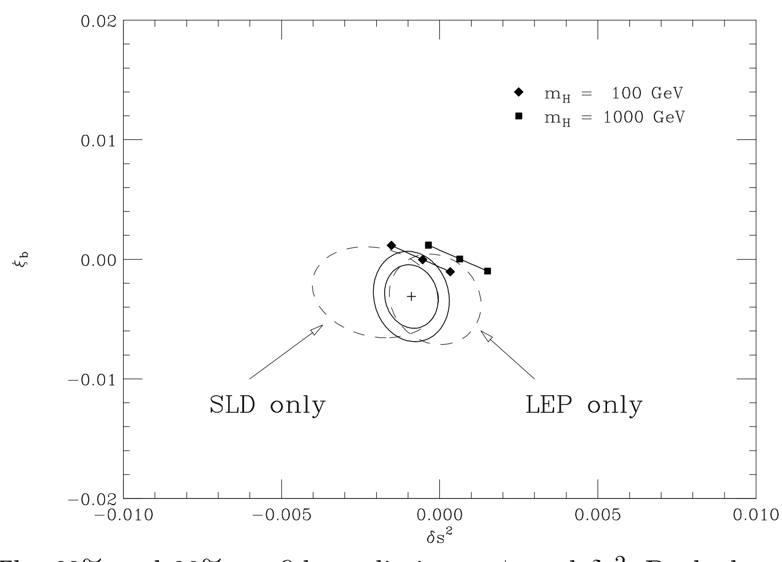

Fig. 3. The 68% and 90% confidence limits on ξ_b and δs^2. Dashed contours show the positions of the 90% limit when only the LEP or SLD value of $\sin^2\theta_{\rm eff}$ is used. The SM points are plotted for $m_t = 150$, 175, and 200 GeV. Larger m_t correspond to smaller δs^2.

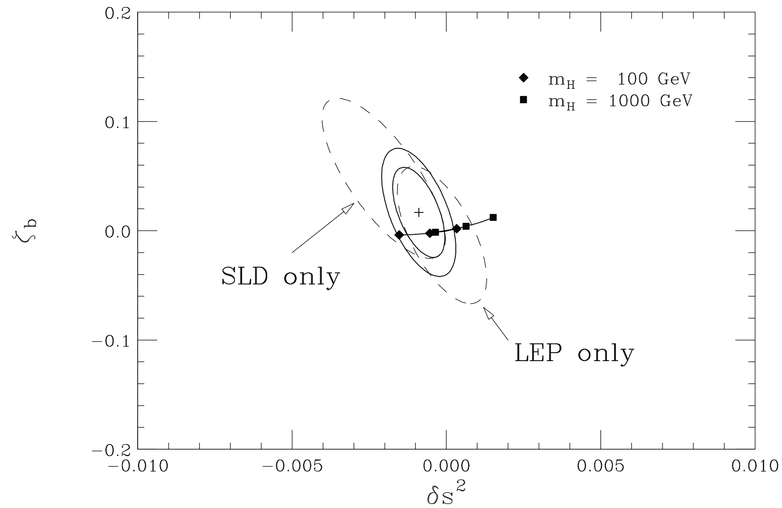

Fig. 4. The 68% and 90% confidence limits on ζ_b and δs^2. The meaning of the dashed contours and SM points are the same as in Fig. 3.

In terms of δg_L^b and δg_R^b, Eq. 9 translates into

$$\delta g_L^b = -0.000 \pm 0.005, \quad \delta g_R^b = \quad 0.018 \pm 0.027. \tag{10}$$

We see from this that the left–handed coupling of the b is very tightly constrained by present data, while the right–handed coupling is more weakly constrained. This leaves considerable freedom for models containing extra right–handed gauge bosons or extended Higgs sectors, which would tend to modify the right–handed coupling of the b. It is also important to note that many observables, in addition to R_b, are sensitive to shifts in the couplings of the b.

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