The dynamical models and the $Z \to b \bar{b}$ asymmetry

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March 25, 2022

Abstract

Motivated by the $3.2\sigma (1.4\sigma)$ deviations between the recent experimental value for $A_{FB}^b(R_b)$ and the standard model (SM) prediction, we examine the effect of new physics (NP) on the $Zbb$ couplings $g_L^b$ and $g_R^b$. First we focus our attention on the dynamical models. Then, using effective lagrangean techniques, we discuss the corrections of NP to $g_L^b$ and $g_R^b$. We find some kinds of NP might explain the recently experimental data about $R_b$ and $A_{FB}^b$. However, the free parameters of these kinds of NP must be severely constrained.

PACS number(s): 12.60Cn,12.60.Nz,13.38.Dg

$^*$This work is supported by the National Natural Science Foundation of China(I9905004), the Excellent Youth Foundation of Henan Scientific Committee(9911), and Foundation of Henan Educational Committee.

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1 Introduction

Most of the experiments are consistent with the predictions of the standard model (SM) with sufficient accuracy. Almost all of the experimental data are quite well explained in the context of the SM. However, in the most recent analysis of the precision electroweak data [1], the $Z \rightarrow b \bar{b}$ forward-backward asymmetry $A_{FB}^b = 0.0990(17)$ is $3.2\sigma$ from the SM fit value, but there is just a hint of a disagreement, at the $1.4\sigma$ level, for the $Z \rightarrow b \bar{b}$ branching ratio $R_b [R_b = 0.21664(68)]$. The result presented by the recent experimental data are very puzzling. Certainly the result could be a statistical fluctuation or from unknown systematic error, but Ref[2] has told us that this seems to be due to new physics (NP) beyond SM. In this note we shall assume that this is a signal of new physics (NP).

The effective $Zb\bar{b}$ vertex can be parameterized in terms of two form factors, the left-handed coupling $g^b_L$ and the right-handed coupling $g^b_R$:

$$\frac{e}{S_w C_w} [g^b_L b_L \gamma^\mu b_L + g^b_R b_R \gamma^\mu b_R]Z_\mu, \quad (1)$$

where $S_w = \sin \theta_w$, $\theta_w$ is the Winberg angle. In order to determine the two form factors separately, we need two independent measurement of the $Zb\bar{b}$ vertex. One is provided by $R_b$ and the other by the forward-backward asymmetry $A_{FB}^b$. The deviations of the experimental data about $R_b$ and $A_{FB}^b$ from the SM predictions may be induced by the corrections of NP to the two form factors $g^b_L$ and $g^b_R$.

In this paper, we shall explore whether the corrections of NP to the two form factors can bring the theoretical predictions closer to the experimental results. We find that some kinds of NP can not fit both $R_b$ and $A_{FB}^b$ within the $1\sigma$ bounds of the recent experimental data at the same time. Some other kinds of NP might explain the recently experimental data about $R_b$ and $A_{FB}^b$. However, the free parameters of these kinds of NP must be severely constrained.
Constraints of the experimental data on $g_L^b$ and $g_R^b$

The two form factors $g_L^b$ and $g_R^b$ can be written as:

$$g_L^b = -\frac{1}{2} + \frac{1}{3}S_w^2 + \delta g_L^b, \quad g_R^b = \frac{1}{3}S_w^2 + \delta g_R^b.$$  \hspace{1cm} (2)

Where $\delta g_{L(R)}^b$ contain the SM and the NP contributions at one loop order:

$$g_L^b = -\frac{1}{2} + \frac{1}{3}S_w^2 + \delta g_L^{b,SM} + \delta g_L^{b,N}, \quad g_R^b = \frac{1}{3}S_w^2 + \delta g_R^{b,SM} + \delta g_R^{b,N}.$$  \hspace{1cm} (3)

Where the SM values are for $m_t = 174 GeV$ and $M_H = 100 GeV$ [3]. In principle, the corrections of NP to the $Zb\bar{b}$ vertex may give rise to one additional form factor, proportional to $\sigma^\mu\nu q^\nu$. This magnetic moment-type form factor arises at one-loop and should be considered as well. However, its contributions to $R_b$ and $A_b^{FB}$ are very small. Thus, we have ignored it.

The corrections of NP to $R_b$ and $A_b^{FB}$ can be expressed in terms of the form factors $\delta g_L^{b,N}$ and $\delta g_R^{b,N}$:

$$\frac{\delta R_b}{R_b^{SM}} = 2(1 - R_b^{SM}) \frac{g_L^{b,SM}\delta g_L^{b,N} + g_R^{b,SM}\delta g_R^{b,N}}{(g_L^{b,SM})^2 + (g_R^{b,SM})^2},$$  \hspace{1cm} (5)

$$\frac{\delta A_b^{FB}}{A_b^{SM}} = \frac{4(g_L^{b,SM})^2(g_R^{b,SM})^2}{(g_L^{b,SM})^4 - (g_R^{b,SM})^4} \left(\frac{\delta g_L^{b,N}}{g_L^{b,SM}} - \frac{\delta g_R^{b,N}}{g_R^{b,SM}}\right).$$  \hspace{1cm} (6)

The $1\sigma$ contours of $R_b$ and $A_b^{FB}$ are plotted in Fig.1. Since $\frac{\delta R_b}{R_b^{SM}}$ is more than one order of magnitude smaller than $\frac{\delta A_b^{FB}}{A_b^{SM}}$, the expression $g_L^{b,SM}\delta g_L^{b,N} + g_R^{b,SM}\delta g_R^{b,N}$ is severely constrained. From this and that $g_L^{b,SM}$ is about 5.5 times larger than $g_R^{b,SM}$ we can see that $\frac{\delta A_b^{FB}}{A_b^{SM}}$ is dominated by the $\frac{\delta g_L^{b,N}}{g_L^{b,SM}}$ term. Thus, we find that the constraints of the $1\sigma$ bounds of $R_b$ and $A_b^{FB}$ on $\delta g_L^{b,N}/g_L^{b,SM}$ and $\delta g_R^{b,N}/g_R^{b,SM}$ can be written as:

$$0.0002 \leq \frac{\delta g_L^{b,N}}{g_L^{b,SM}} + \frac{(g_L^{b,SM})^2\delta g_L^{b,N}}{g_L^{b,SM}} \leq 0.0041, \quad 0.225 \leq \frac{\delta g_R^{b,N}}{g_R^{b,SM}} \leq 0.465.$$  \hspace{1cm} (7)

Thus, if the deviations from the SM values about $R_b$ and $A_b^{FB}$ persist, the corrections to $g_L^b$ and $g_R^b$ from any kind of NP, which can fit both $R_b$ and $A_b^{FB}$ within the $1\sigma$ bounds of the experimental at the same time, must satisfy Eq.(7). This is a very strong constraint.
In the following, we will explore whether the contributions of NP to the $Zb\bar{b}$ couplings $g_{L}^{b,SM}, g_{R}^{b,SM}$ can bring the SM predictions close to the experimental results and see whether there is any kind of NP satisfying Eq.(7). First we will mainly focus our attention on the class of models, in which the electroweak symmetry breaking (EWSB) and the large top mass is dynamically generated by the new strong interactions. In this paper, we will call this class of models as the dynamical models. Then, using effective lagrangean techniques, we discuss the corrections of NP to the form factors $g_{L}^{b}$ and $g_{R}^{b}$. This is a model independent analysis.

3 The dynamical models

To completely avoid the problems arising from the elementary Higgs field, various kinds of dynamical EWSB mechanisms have been proposed, and among which topcolor-assisted technicolor (TC2) theory is an attractive idea. TC2 theory generally predicts the existence of two kinds of new gauge bosons:(a) the extended technicolor (ETC) gauge bosons, (b) the topcolor gauge bosons including the color-octet colorons $B_{\mu}^{A}$ and an extra $U(1)_{Y}$ gauge boson $Z'$. Furthermore, this kind of models predict a number of pseudo Goldstone bosons ($PGB$’s), including the technipions in the technicolor sector and the top-pions in the topcolor sector. All these new particles can give corrections to the form factors $g_{L}^{b}$ and $g_{R}^{b}$.

The main ETC corrections to $g_{L}^{b}$ and $g_{R}^{b}$ are from the ETC gauge boson contributions. It has been shown in Ref.[5] that the negative diagonal ETC gauge boson contribution to $g_{L}^{b}$ is larger than that of the positive sideways gauge boson. There are $\delta g_{L}^{b,E} < 0$ and $\delta g_{R}^{b,E} \simeq 0$. The gauge bosons $B_{\mu}^{A}$ and $Z'$ also have contributions to $g_{L}^{b}$ and $g_{R}^{b}$ and there are $\delta g_{L}^{b,B}/g_{L}^{b,SM} = \delta g_{R}^{b,B}/g_{R}^{b,SM} > 0$, $\delta g_{L}^{b,Z'}/g_{L}^{b,SM} > 0$ and $\delta g_{R}^{b,Z'}/g_{R}^{b,SM} > 0$. Due to the strong coupling between the top-pion and the third generation quarks, the top-pions can give rise to a large positive correction to $g_{L}^{b,SM}$, i.e. $\delta g_{L}^{b,\pi_{t}}/g_{L}^{b,SM} < 0$, $\delta g_{R}^{b,\pi_{t}} \simeq 0$. In Ref.[8] it is found that, by combining all of these corrections to $g_{L}^{b}$ and $g_{R}^{b}$, it is possible that TC2 models can make the theoretical predictions consistent with the experimental...
value of $R_b$. For $A_{FB}^b$, we have:

$$
\frac{\delta A_{FB}^b}{A_{FB}^{b,SM}} = - \frac{4(g_L^{b,SM})^2(g_R^{b,SM})^2}{(g_L^{b,SM})^4 - (g_R^{b,SM})^4} \left[ \frac{\delta g_R^{b,B}}{g_R^{b,SM}} + \frac{\delta g_R^{b,Z'}}{g_R^{b,SM}} \right]
$$

(8)

with

$$
\frac{\delta g_R^{b,B}}{g_R^{b,SM}} = \frac{k_3}{3 \pi} C_2(R) \frac{m_t^2}{M_B^2} \ln \frac{M_B^2}{m_Z^2}, \quad \frac{\delta g_R^{b,Z'}}{g_R^{b,SM}} = \frac{k_1}{6 \pi} (g_R^{b})^2 \frac{m_q^2}{M_Z'^2} \ln \frac{M_Z'^2}{m_Z^2}.
$$

(9)

We have neglected the small $\delta g_L^b$ term in above equations. $k_3$ and $k_1$ are the coloron and the $Z'$ coupling constants, respectively, $M_B$ and $M_{Z'}$ are, respectively, the mass of $B^4$ and $Z'$, $C_2(R) = \frac{4}{3}$ and $Y_R^b = -\frac{2}{3}\left[4\right]$. If we take $k_3 = 2, k_1 = 1\left[9\right]$, and $M_B = M_{Z'} = 500\text{GeV}$, we have $\delta A_{FB}^b \simeq 2.6 \times 10^{-4}$, which is too small to explain the $A_{FB}^b$ experimental deviations from the SM prediction value. Thus, TC2 models cannot fit both $R_b$ and $A_{FB}^b$ within the $1\sigma$ bounds of the recent experimental data. If the deviation persists, TC2 models may be ruled out.

Several years ago, to generate a large top mass, a dynamical model was proposed in Ref.[10] by B. Holdom. The model contains a fourth family, and members of the third and fourth families are composed of two “families” of fermions $f$ and $f'$. The model also predicts the existence of the extra massive gauge boson $\chi$, which is a singlet under unbroken gauge symmetries and with a mass in the few hundred GeV to one TeV range. The gauge boson $\chi$ does not couple to the first and second families. It couples with a vector charge of $g_\chi$ to all members of the $f$ family and with a vector charge of $-g_\chi$ to all members of the $f'$ family. The mechanism producing a large top mass requires that the fourth family quark mass eigenstates $t'$ and $b'$ correspond to Dirac spinors of the form $[f_L, f_R]$, which are nearly degenerate. The $t$ and $b$ quarks correspond to $[f_L, f_R]$, which implies that the gauge boson $\chi$ couples with the same axial coupling to the $t$ and $b$ quarks. The main effects of $\chi$ on the form factors $g_L^b$ and $g_R^b$ come from its mixing with the electroweak gauge boson $Z$, which can be written as [11]:

$$
\delta g_L^{b,\chi} = -\delta g_R^{b,\chi} = -\frac{e}{8 S_w C_w} \left( \frac{m_t}{m_q'} \right)^2,
$$

(10)

where $q' = (t', b')$. If the dynamical $t'$ and $b'$ masses make the main contributions to the
W and Z masses and the associated decay constant is $F \simeq 145 GeV$, then [11]:

$$m_{q'} \approx \sqrt{3F \frac{m_\rho}{2f_\pi}} \approx 1 TeV.$$  \tag{11}

Using Eq.(10) and (11), we can easily obtain $\frac{\delta g_R^{b,\chi}}{g_R^{b,SM}} \simeq 3.7\%$, which is too small to explain the recent experimental data. The reason of generating too small corrections to $g_R^b$ is that EWSB is mainly induced by the dynamical $t'$ and $b'$ masses. If we change this assurance, this problem may be solved. In fact, EWSB may be induced by two or more kinds of new strong interactions at the same time or induced by the elementary scalar field. If we assume that EWSB is driven by the dynamical $t'$ and $b'$ masses and other strong interactions or a Higgs sector, we have:

$$3(xF)^2 + \nu^2 = \nu_w^2,$$  \tag{12}

with $x$ is a free parameter, $\nu_w \approx 246 GeV$ is the electroweak scale and $\nu$ represents the contributions of other strong interactions or a Higgs sector to EWSB. Then, the corrections of gauge boson $\chi$ to $g_L^b$ and $g_R^b$ can be approximately written as:

$$\delta g_L^{b,\chi} \approx -\frac{e}{8 S_w C_w \nu_w} \left( \frac{m_t}{1 TeV} \right)^2.$$  \tag{13}

Using the expression of $\delta g_R^{b,N} / g_R^{b,SM}$ in Eq.(7), we can constraint the free parameter $x$, which is in the range of $0.28 - 0.41$. This means that, to explain the recent experimental data of $A_{FB}^b$, the dynamical $t'$ and $b'$ masses must make only small contributions to EWSB and the associated decay constant is $F_x \approx 40 - 60 GeV$.

The equation (13) gives too large correction to $\delta g_L^b$ as compared to the constraint(7). But, if the scenario described above is indeed correct, it can predict the existence of new scalars with the decay constant $F_x \approx 40 - 60 GeV$. Similar to the top-pions, these new scalars have large Yukawa couplings to the third family quarks. Thus, these new scalars may have large positive contribution to $g_L^b$, which can partly cancel the large negative contributions of the extra gauge boson $\chi$ to $g_L^b$. So this new model might fit both $R_b$ and $A_{FB}^b$ within the 1 $\sigma$ bounds of the experimental data at the same time.

Other type of new models can also explain the recently experimental data. For example, the new model proposed by D. Chang et al [12] is this case. This new model [12]
contains an exotic fourth family of quarks and leptons, which is free of anomalies, together with a heavy Higgs scalar triplet which supplies the neutrinos with Majorana masses. It has been shown [13] that if the top mass \( m_t \) is actually larger than about 230 GeV, and the SM \( b_R \) mixes with the exotic quark \( Q_1 \) of charge \( -\frac{1}{3} \) of the doublet \( (Q_1, Q_4)_R \), where \( Q_4 \) has charge \( -\frac{4}{3} \), then this model can account for all the 1999 precision electroweak data. From Eq.(9) of Ref.[14], we can see that this new model can fit both \( A_{FB}^b \) and \( R_b \) within the 1\( \sigma \) bounds of the recent experimental data for \( 0.035 \leq (\sin \theta_b)^2 \leq 0.072 \), where \( \theta_b \) is the mixing angle of the SM \( b_R \) and the exotic quark \( Q_1 \). The observed ”top quark” phenomenon at the Fermilab are assumed to be due to \( Q_4 \).

4 Model independent analysis with dimension-six operators

In the last several years, many authors [14, 15] have studied the effects of the dimension-six CP conserving \( SU(3)_C \times SU(2)_L \times U(1)_Y \) invariant operators on the observables \( R_b \) and \( A_{FB}^b \) by using effective Lagrangian techniques. In this section, we will use this method to model independent analysis of the corrections of NP to the observables \( R_b \) and \( A_{FB}^b \) and compare them with the recent experimental data.

If we assume that EWSB is dynamical driven by new strong interactions. This kind of NP may predict the existence of the operators \( O_{qB}, O_{bB} \), in the notation of Ref.[16]. These operators arise from the extra \( U(1)_Y \) gauge boson B, which may have significantly contributions to \( g_{L}^{b} \) and \( g_{R}^{b} \). The corrections of the operators \( O_{qB} \) and \( O_{bB} \) to \( g_{L}^{b}, g_{R}^{b} \) can be explicitly written as:

\[
\begin{align*}
\delta g_{L}^{b,B} &= \frac{2 S_{w}^{2} C_{w} C_{qB}}{e \Lambda^{2} k^{2}}, \\
\delta g_{R}^{b,B} &= \frac{2 S_{w}^{2} C_{w} C_{bB}}{e \Lambda^{2} k^{2}},
\end{align*}
\]

(14)

where \( \Lambda \) is the NP scale. \( k = p_{b} + p_{\bar{b}} \) is the momentum of the electroweak gauge boson Z and \( C_{ij} \) are coupling coefficients which represent the coupling strengths of the operators \( O_{ij} \). From Eq.(14), we can see that the experimental measurement values of \( R_b \) and \( A_{FB}^b \) can give severe constrain on the free parameters of NP. If we demand that NP can fit
both $R_b$ and $A_{FB}^b$ with 1σ bounds of the recent experimental data at the same time, the value of the coupling coefficients $C_{ij}$ can be obtained by using Eq.(7). Explicitly

$$0.136 \leq C_{qB} \leq 0.604, \quad 1.61 \leq C_{bB} \leq 3.32.$$  \hfill (15)

In above estimation, we have taken $\Lambda \approx 1T eV$. Thus, as long as Eq.(15) is satisfied, it is possible that this kind of NP models could explain the deviations of the $R_b$ and $A_{FB}^b$ experimental values from the SM predictions.

If we assume that EWSB is driven by elementary scalar fields, the operators $O_{\phi q}^{(1)}$, $O_{\phi q}^{(3)}$ and $O_{\phi b}$ might exist in this kind of NP. Certainly, the operators $O_{\phi q}$ and $O_{\phi b}$ might also exist. However, the contributions of these operators to $R_b$ and $A_{FB}^b$ are proportional to $m_b$ and hence are negligible. The corrections of the operators $O_{\phi q}^{(1)}$, $O_{\phi q}^{(3)}$ and $O_{\phi b}$ to the form factors $g_L^b$ and $g_R^b$ can be written as:

$$\delta g_{L,\phi}^b = -\frac{2S_w C W}{e} \frac{\nu_w m_Z}{\Lambda^2} (C_{\phi q}^{(1)} + C_{\phi q}^{(3)}), \quad \delta g_{R,\phi}^b = \frac{2S_w C W}{e} \frac{\nu_w m_Z}{\Lambda^2} C_{\phi b}. \hfill (16)$$

Using Eq.(7) and (16), we can obtain:

$$-0.108 \leq C_{\phi q}^{(1)} + C_{\phi q}^{(3)} \leq -0.024, \quad 0.287 \leq C_{\phi b} \leq 0.593,$$  \hfill (17)

which is required to have the theoretical values of both $R_b$ and $A_{FB}^b$ to lie within the 1σ bounds of the recent experimental data.

From Eq.(16) and (17), we can see that the contributions of the operators $O_{\phi q}^{(1)}$, $O_{\phi q}^{(3)}$ and $O_{\phi b}$ to $R_b$ and $A_{FB}^b$ are larger than those of the operators $O_{qB}$ and $O_{bB}$. The NP models which can predict the operators $O_{\phi q}^{(1)}$, $O_{\phi q}^{(3)}$ and $O_{\phi b}$ are more severely constrained by the experimental data. However, with appropriate parameter values, all of two kinds of NP models can fit both $R_b$ and $A_{FB}^b$ within the 1σ bounds of the experimental data at the same time.

5 Conclusions

The effective $Zb\bar{b}$ vertex can be parameterized in terms of two form factors $g_L^b$ and $g_R^b$. These two form factors can be determined by the observables $R_b$ and $A_{FB}^b$. Thus, using
the new results of $R_b$ and $A_{FB}^b$, we can obtain the constrains of the experimental data on 
$\delta g_L^{b,N}$ and $\delta g_R^{b,N}$. On this basis, we discuss the contributions of some kinds of NP to $\delta g_L^b$ and $\delta g_R^b$, we find that some models, such as TC2 models, can not fit both $R_b$ and $A_{FB}^b$ within the $1\sigma$ bounds of new experimental data at the same time. However, some kinds of NP, for example, some modification of the model proposed in Ref.[1] might explain the deviations of the new experimental data about observables $R_b$ and $A_{FB}^b$ from the SM predictions. Certainly, in the framework of these kinds of NP, model building must be studied extensively in the future. Lastly, we use effective Lagrangean techniques to model independent analysis of the corrections of NP to the observables $R_b$ and $A_{FB}^b$ and compare them with the recent experimental data. We find that, with appropriate parameter values, some kinds of NP models can fit the experimental data of the observables $R_b$ and $A_{FB}^b$ at the same time.
Figure captions

Fig.1: The $1\sigma$ contours for $R_b$ and $A_{FB}^b$ in the $\delta g_L^b - \delta g_R^b$ plane. The solid line represents that the contribution of NP makes the SM prediction value of $R_b$ and $A_{FB}^b$ to the centre value of the experimental data.
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Fig. 1