Vector-like Quark Interpretation of Excess in Higgs Signal Strength

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Abstract

There is a +2$\sigma$ deviation in the average Higgs-signal strength for all the 7 + 8 + 13 TeV data up to Summer 2018. We find that a slight reduction of the bottom-Yukawa coupling can fit the data better than the standard model. We suggest an extension with a vector-like quark doublet, of which the right-handed component of $b'$ mixes nonnegligibly with the standard model $b$ quark. We show that the mixing would induce a reduction of the bottom Yukawa coupling. Simultaneously, the coupling of the $Z$ boson to the right-handed $b$ quark increases, which could reduce the forward-backward asymmetry of bottom production at LEP and bring it closer to the experimental value.
I. INTRODUCTION

The standard model (SM) like Higgs boson was discovered in 2012 [1, 2]. After Run I at 7 and 8 TeV, the identity of the Higgs boson was very close to the SM one [3, 4]. With more and more measurements of the Higgs-signal strengths for various production and decay channels at a center-of-mass energy of 13 TeV, including the newly established $t\bar{t}H$ production channel [5, 6], and $H \rightarrow b\bar{b}$ [7, 8] and $\tau\tau$ [9, 10] in 2018, the SM-like Higgs boson is further confirmed. The most updated fits to the Higgs-boson couplings in various scenarios have recently been performed [11].

Some very interesting results emerge from the new global fits, which were not realized previously. The combined average signal strength of the Higgs boson now stands at a $+2\sigma$ deviation from the SM value, namely $\mu_{\exp} = 1.10 \pm 0.05$. Note that from the earlier combined signal strength at 7 + 8 TeV, the ATLAS and CMS obtained [12]

$$\mu_{7+8\,\text{TeV}} = 1.09^{+0.11}_{-0.10},$$

which was about $1\sigma$ above the SM. The 13 TeV data continues to show such trend, by combining all production and decay channels [11]:

$$\mu_{13\,\text{TeV}} = 1.10 \pm 0.06.$$

These two results can be combined naively into a total signal strength

$$\mu_{\text{All}} = 1.10 \pm 0.05,$$ (1)

which shows a $2\sigma$ above the SM prediction.

If the overall signal strength continues to about $10\%$ above the SM prediction while the uncertainties continues to reduce, it would pose a threat to the SM Higgs boson. One of the most economical fits to the Higgs-signal strength is to vary the total width of the Higgs boson. In Ref. [11] we found that the best-fit value for the $\Delta \Gamma_{\text{tot}}$ is

$$\Delta \Gamma_{\text{tot}} = -0.285^{+0.18}_{-0.17} \text{ MeV}$$ (2)

which means a reduction of about $0.285/4 = 0.07$ or 7% to the total width.

Naively, it is hard to imagine that one can add any new channels to reduce the total width. Nevertheless, one possibility is to reduce the partial width into $b\bar{b}$ with a reduced bottom-Yukawa coupling, provided that the current uncertainty of $H \rightarrow b\bar{b}$ coupling is of order 20%.
There are a few obvious possibilities that one can consider: (i) a $b'_{L/R}$ singlet vector-like quark model but the left-handed (LH) component would modify the CKM phenomenology significantly, and thus subject to severe constraints. (ii) A $(t', b')_{L/R}$ vector-like quark doublet with hypercharge $Y/2 = 1/6$ (the same as the SM quark doublet) but it would increase the tension with the experimental bottom forward-backward asymmetry at $Z$-pole. In this work, we explore an extension[13] of the SM by adding an $SU(2)$ vector-like quark doublet with a different hypercharge of $Y/2 = -5/6$, of which the upper component $b'_{R}^{-1/3}$ mixes with the SM $b_{R}$ quark while $b'_{L}^{-1/3}$ mixes negligibly with $b_{L}$. In such a way, the right-handed (RH) component of the bottom quark is reduced and thus the bottom-Yukawa coupling is reduced with respect to the SM value. Therefore, it can effectively explain why the average Higgs-signal strength is enhanced.

Historically, the measurement of forward-backward asymmetry $A_{FB}^b$ of the bottom quark at the $Z^0$ pole remains a $-2.4\sigma$ deviation from the SM prediction [14]. In the present context, due to the mixing between $b'_{R}^{-1/3}$ and $b_{R}$ the effective RH coupling of bottom quark to the $Z$ boson is enhanced, such that the $A_{FB}^b$ would decrease[15] in accord with the experimental data. Apparently, the addition of the new vector-like quark doublet can simultaneously explain the Higgs-signal strength $\mu_{Higgs}$ and the forward-backward asymmetry $A_{FB}^b$ in the correspondingly right direction. However, there are other precision constraints that we have to consider, namely, the ratio $R_b$ of the partial width $Z \rightarrow b\bar{b}$ to the total hadronic width, as well as the total hadronic width of the $Z$ boson. We will give details in subsequent sections.

The organization of the paper is as follows. In the next section, we describe the extension of an isospin doublet of vector-like quarks, and modifications to the Higgs and $Z$ couplings. In Sec. III, we fit the parameter $\delta \equiv \Delta/M$, where $\Delta$ measures the mixing and $M$ is approximately the mass of heavy vector-like quark, to the data of Higgs-signal strengths and to $A_{FB}^b$, with or without $R_b$ and $\Gamma_{had}$. We discuss some other potential issues with modifications of the bottom-quark couplings and then conclude.
II. FORMALISM

In this work, we consider the vector-like quark doublet with a hypercharge \( \frac{Y}{2} = -\frac{5}{6} \) denoted by

\[
\mathcal{B}_{L,R} = \begin{pmatrix} b'_{-\frac{1}{3}} \\ p'_{-\frac{4}{3}} \end{pmatrix}_{L,R}, \quad \left( \frac{Y}{2} \right)_{B} = -\frac{5}{6}.
\]

We label electric charges of the new particles \( b', p' \) by superscripts. Since \( b' \) carries the same electric charge as the SM bottom quark \( b \), they can mix. The quark mass matrix of \((b, b')\) receives additional contributions from the following new coupling with the SM Higgs doublet \( H \),

\[
\mathcal{L} \supset g_B \overline{b_L} \tilde{H} b_R + \text{h.c.} = g_B (\overline{b_L}, \overline{p_L}) \begin{pmatrix} -\frac{1}{\sqrt{2}}(v + h) \\ H^* \end{pmatrix} b_R + \text{h.c.},
\]

(3)

where \( \tilde{H} = i\tau_2 H^* \). Note that the vector-like quarks receive their mass \( M \) from some mechanisms, other than the usual electroweak symmetry breaking. We assume \( M \) is of order TeV or more. Then the quark-mass matrix and the interactions with the SM Higgs boson become

\[
\mathcal{L}_Y \supset -(\overline{b_L}, \overline{b'_L}) \begin{pmatrix} m(1 + \frac{h}{v}) \\ 0 \\ 0 \end{pmatrix} \begin{pmatrix} b_R \\ b'_R \end{pmatrix} + \text{h.c.}
\]

(4)

The large mass \( M \) for the vectorial \( \mathcal{B} \) is unrelated to \( H \). It is much larger than the off-diagonal mass \( \frac{g_B v}{\sqrt{2}} \equiv \Delta \). The mass parameter \( m \) accounts for the \( b \)-quark mass in the SM if we ignore \( \Delta \).

A. Mass diagonalization and Modifications to Bottom Yukawa

From the above equation, the mass terms for \( b, b' \) can be written as

\[
\mathcal{L}_{\text{mass}} \supset -(\overline{b_L}, \overline{b'_L}) \begin{pmatrix} m \\ 0 \\ \Delta \\ M \end{pmatrix} \begin{pmatrix} b_R \\ b'_R \end{pmatrix} + \text{h.c.} = -(\overline{b_L}, \overline{b'_L}) \mathcal{M} \begin{pmatrix} b_R \\ b'_R \end{pmatrix} + \text{h.c.}
\]

(5)

where \( \Delta = g_B v / \sqrt{2} \).

We require the following left and right rotations to diagonalize the non-hermitian mass matrix:

\[
\begin{pmatrix} b \\ b' \end{pmatrix}_{L,R} = \begin{pmatrix} \cos \theta_{L,R} & \sin \theta_{L,R} \\ -\sin \theta_{L,R} & \cos \theta_{L,R} \end{pmatrix} \begin{pmatrix} b_m \\ b'_m \end{pmatrix}_{L,R} \equiv \mathcal{U}_{L,R} \begin{pmatrix} b \\ b' \end{pmatrix}_{L,R}
\]

(6)
where the superscript “m” denotes the mass eigenstates. For convenience we will drop the “m” wherever it is understood to be the mass eigenstates. The presence of the zero entry in the upper-right corner of the quark-mass matrix in Eq. (5) suggests that the right rotation angle $\theta_R$ is of order $\frac{\Delta}{M}$, which is much larger than the left rotation angle $\theta_L$ of order $\frac{m\Delta}{M^2}$ for the favorable scenario $\Delta \gg m$. The suppression of $\theta_L/\theta_R$ is of order $m_b/O(\text{TeV}) \sim 10^{-3}$.

More precisely, the non-hermitian mass matrix $M$ is diagonalized by a bi-unitary rotation as

$$U_L^\dagger MU_R = M_{\text{diag}}, \quad (7)$$

which can be turned into

$$U_L^\dagger MM_L U_L = U_R^\dagger M^2 U_R = M_{\text{diag}}^2 = \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix}, \quad (8)$$

with $m_1 < m_2$. Then the hermitian mass matrix squared can be diagonalized and the corresponding eigenvalues and eigenvectors can be calculated exactly:

$$m_{1,2}^2 = \frac{(m^2 + \Delta^2 + M^2) \pm \sqrt{(m^2 + \Delta^2 + M^2)^2 - 4m^2M^2}}{2} \quad (9)$$

$$\sin 2\theta_L = \frac{2m\Delta}{\sqrt{(m^2 + \Delta^2 + M^2)^2 - 4m^2M^2}} \quad (9)$$

$$\sin 2\theta_R = \frac{2\Delta M}{\sqrt{(m^2 + \Delta^2 + M^2)^2 - 4m^2M^2}} \quad (10)$$

In the limit $M, \Delta \gg m$, they can be simplified to

$$m_{1,2}^2 = \frac{m^2}{1 + \frac{\Delta^2}{M^2}}, \quad m_2^2 = \Delta^2 + M^2. \quad (11)$$

The mixing angles can also be simplified as

$$\sin \theta_L \equiv s_L \simeq \frac{m\Delta}{M^2 + \Delta^2}, \quad \cos \theta_L \equiv c_L \simeq 1 - \frac{1}{2} \left( \frac{m\Delta}{M^2 + \Delta^2} \right)^2, \quad (12)$$

and

$$\sin \theta_R \equiv s_R \simeq \frac{\Delta}{\sqrt{M^2 + \Delta^2}}, \quad \cos \theta_R \equiv c_R \simeq \frac{M}{\sqrt{M^2 + \Delta^2}}. \quad (13)$$

In the above, we identify $m_1 = m_b$, the mass of the observed $b$-quark mass, and $m_2 = M_{b'}$ to be the TeV mass of the heavy vector-like quark. Practically, we can take $c_L \simeq 1$ in the
analysis and then we find the $h-b'_{m}-b_{m}$ Yukawa coupling depends only on one parameter of $\delta \equiv \Delta/M$. More precisely, the coupling for $(h/v)b_{L}^{m}b_{R}^{m}$ is given by

$$m_{cL}c_{R} - \Delta s_{L}c_{R} \simeq \frac{m_{b}}{1 + \delta^{2}}c_{R} \simeq m_{b}\frac{1}{\sqrt{1 + \delta^{2}}}c_{R}$$

(14)

where we use $\Delta s_{L} = m\delta^{2}/(1 + \delta^{2})$ and $c_{R}$ is given by Eq. (13) in the $m \to 0$ limit. The result is an overall reduction in the Higgs Yukawa coupling by $C_{b} \equiv c_{R}\sqrt{1 + \delta^{2}}$ from the SM value.

There are also couplings for other off-diagonal elements, as given in this equation:

$$L_{Y} \supset -\frac{h}{v}(b_{L}^{m}, b_{L}^{m}) \left( \begin{array}{cc}
m_{b}(1 + \delta^{2})^{-1/2}c_{R} & m_{b}(1 + \delta^{2})^{-1/2}s_{R} \\
\Delta c_{R} & \Delta s_{R}
\end{array} \right) \left( \begin{array}{c}b_{L}^{m} \\
b_{R}^{m}
\end{array} \right) + H.c.$$  

(15)

We can immediately see that the off-diagonal coupling of $h_{b'_{m}}b_{m}$ will dominate over the other one. Phenomenologically, the so-produced $b'$ will decay into $h + b_{R}$. We shall discuss the collider signature in the Discussion.

In the following we can focus on the effect of RH mixing in numerical analysis.

**B. Modifications to the Z couplings**

In the weak eigenbasis, according to $T_{3f} - Q_{f}x_{w}$, the $Z$ couplings to fermions $b_{L,R}$ and $b'_{L,R}$, are given by

$$-L \supset g_{Z}(b_{L}, b_{L})\gamma^{\mu}Z_{\mu} \left( \begin{array}{cc}
\frac{1}{2} + \frac{1}{3}x_{w} & 0 \\
0 & \frac{1}{2} + \frac{1}{3}x_{w}
\end{array} \right) \left( \begin{array}{c}b_{L} \\
b_{L}'
\end{array} \right)$$

\n
$$+ g_{Z}(b_{R}, b_{R})\gamma^{\mu}Z_{\mu} \left( \begin{array}{cc}
0 & \frac{1}{2} + \frac{1}{3}x_{w} \\
\frac{1}{3}x_{w} & 0
\end{array} \right) \left( \begin{array}{c}b_{R} \\
b_{R}'
\end{array} \right).$$

(16)

After rotating into mass eigenbasis we have

$$-L \supset g_{Z}(b_{L}^{m}, b_{L}^{m})\gamma^{\mu}Z_{\mu} \left( \begin{array}{cc}
-\frac{1}{2}(c_{L}^{2} - s_{L}^{2}) + \frac{1}{3}x_{w} & -c_{L}s_{L} \\
-c_{L}s_{L} & \frac{1}{2}(c_{L}^{2} - s_{L}^{2}) + \frac{1}{3}x_{w}
\end{array} \right) \left( \begin{array}{c}b_{L}^{m} \\
b_{L}''
\end{array} \right)$$

\n
$$+ g_{Z}(b_{R}^{m}, b_{R}^{m})\gamma^{\mu}Z_{\mu} \left( \begin{array}{cc}
\frac{1}{2}s_{R}^{2} + \frac{1}{3}x_{w} & -\frac{1}{2}c_{R}s_{R} \\
-\frac{1}{2}c_{R}s_{R} & \frac{1}{2}s_{R}^{2} + \frac{1}{3}x_{w}
\end{array} \right) \left( \begin{array}{c}b_{R}^{m} \\
b_{R}''
\end{array} \right).$$

(17)

Here the gauge coupling $g_{Z} = g_{2}/\cos\theta_{w}$ and the electroweak mixing $x_{w} = \sin^{2}\theta_{w}$. Note that the $Z$ coupling to the LH $b$ quark is practically the same as the SM coupling for a very
small $s_L \approx \frac{m_A}{M^2}$. On the other hand, the RH $b$ quark coupling is modified by an amount $s_R^2/2 \sim \Delta^2/(2M^2)$.

There are a number of observables that would be modified when the RH coupling to the $Z$ boson is modified:

1. **Total hadronic width.** At tree level, the change to the decay width into $b\bar{b}$ is given by

   $$\delta\Gamma_b^{BSM} = \left[\Gamma^{BSM,b}_{\text{tree}} - \Gamma^{SM,b}_{\text{tree}}\right] \left(1 + \frac{\alpha_s(M_Z)}{\pi}\right).$$

   With this modification the total hadronic width is changed to

   $$\Gamma_{had}^{BSM} = \Gamma_{had}^{SM} + \delta\Gamma_b^{BSM}.$$  \hspace{1cm} (19)

2. **$R_b$.** The $R_b$ is the fraction of hadronic width into $b\bar{b}$, and so it is given by

   $$R_b = \frac{\Gamma^{SM,b}_{had} + \delta\Gamma^{BSM,b}_{had}}{\Gamma^{SM}_{had} + \delta\Gamma^{BSM}_{had}}.$$ \hspace{1cm} (20)

   The value of $R_b$ can increase for a moderate $s_R$ when $s_R \gg s_L$.

3. **$A_{FB}^b$.** There is a large tension in the forward-backward asymmetry of $b$ quark production at the $Z$ resonance,

   $$A_{FB}^b = \frac{3}{4} \times \frac{(g^e)^2_L - (g^e)^2_R}{(g^e)^2_L + (g^e)^2_R} \times \frac{(g^b)^2_L - (g^b)^2_R}{(g^b)^2_L + (g^b)^2_R}.$$ \hspace{1cm} (21)

   Those couplings to the $Z$ boson are basically given by $T_3 - Q x_w$ in SM. For the electron it is simply

   $$\frac{(g^e)^2_L - (g^e)^2_R}{(g^e)^2_L + (g^e)^2_R} = \frac{(-\frac{1}{2} + x_w)^2 - x_w^2}{(-\frac{1}{2} + x_w)^2 + x_w^2},$$

   while for the $b$ quark it is

   $$\frac{(g^b)^2_L - (g^b)^2_R}{(g^b)^2_L + (g^b)^2_R} = \frac{(-\frac{1}{2} + \frac{1}{3} x_w)^2 - \frac{1}{9} x_w^2}{(-\frac{1}{2} + \frac{1}{3} x_w)^2 + \frac{1}{9} x_w^2}.$$ 

   Correspondingly, the modified forward-backward asymmetry is given by

   $$A_{FB}^b = \frac{3}{4} \times \frac{(-\frac{1}{2} + x_w)^2 - x_w^2}{(-\frac{1}{2} + x_w)^2 + x_w^2} \times \frac{(-\frac{1}{2} + \frac{1}{3} x_w)^2 - \frac{1}{9} x_w^2}{(-\frac{1}{2} + \frac{1}{3} x_w)^2 + \frac{1}{9} x_w^2}.$$ \hspace{1cm} (22)
III. FITTING TO DATA

Four data sets are considered in our analysis. They are summarized in the following table.

| Experimental Data                                      | SM values       | $\chi^2$(SM) |
|--------------------------------------------------------|-----------------|--------------|
| Higgs-signal strengths with the average                 | $\mu_{\text{Higgs}} = 1.10 \pm 0.05$ | $\mu^\text{SM} = 1.00$ | 53.81 [11] |
| $(A_{FB}^b)_{\text{EXP}} = 0.0992 \pm 0.0016$         | $0.1030 \pm 0.0002$ | 5.29 [14]    |
| $R_b^{\text{EXP}} = 0.21629 \pm 0.00066$             | $0.21582 \pm 0.00002$ | 0.49 [14]    |
| $\Gamma_{\text{had}} = 1.7444 \pm 0.0020 \text{GeV}$ | $1.7411 \pm 0.0008$ | 2.35 [14]    |

The 125 GeV Higgs-signal strengths include a combined ATLAS+CMS analysis for the 7+8 TeV datasets [12] and all the most updated 13 TeV data summarized in Ref. [11]. The average signal strength is $\mu_{\text{Higgs}} = 1.10 \pm 0.05$ [11]. There are totally 64 data points. The goodness of the SM description for the Higgs data stands at $\chi^2/d.o.f. = 53.81/64$, which gives a $p$-value of 0.814. As explained in Introduction, a reduction in the total Higgs decay width can provide a better description of the Higgs data with $\chi^2/d.o.f. = 51.44/63$, corresponding to a $p$-value of 0.851 [11]. In this work, the reduction in the total width is achieved by a slight reduction in the RH bottom Yukawa coupling. On the other hand, the other three datasets were from the LEPI precision measurements tabulated in PDG [14]. There has been a 2.4σ deviation in the $A_{FB}^b$ while $R_b$ is very much consistent with the SM.

In the following, we present our numerical results on fitting to different combinations of the datasets with variation in $\delta \equiv \Delta/M$ and a fixed or varying $x_w$. We first show the fits with each single dataset listed in the previous table. Figure 1 shows the $\Delta \chi^2$ distribution versus $\delta$ fitting to four single experimental datasets with a fixed $x_w = 0.23154$ [14] and $c_L^2 = 1$. (Note that in the mass hierarchy $m \ll \Delta \ll M$ that we have assumed, $c_L^2$ is practically equal to 1.) The best fit values and uncertainties of $\delta$ for each dataset are listed in Table I from Case-i to iv. We can see that the dataset on Higgs-signal strengths and that on $(A_{FB}^b)_{\text{EXP}}$ prefer a sizable mixing between $b_R$ and $b'_R$, corresponding to the mixing angle equal to $s_R \simeq \delta \simeq 0.25$ and 0.20, respectively. The total hadronic width mildly prefers a mixing with mixing angle equal to $s_R \simeq \delta \simeq 0.14$. However, the $R_b$ is very much consistent with the SM and indicates a very small mixing $s_R \simeq \delta \simeq 0.08$ between $b_R$ and $b'_R$.

Next we come to various combinations of datasets. In Case-v, we perform the fit by
combining all four experimental datasets by varying $\delta \equiv \Delta / M$ with a fixed $x_w = 0.23154$. The result is shown in right-panels of Fig. [I] and Table [I]. The central value of $\delta$ shifts slightly to $\delta \simeq 0.13$, which gives mild improvements to all four datasets. Overall, the $\chi^2$ improves considerably.

**TABLE I.** The best fit points to the experimental datasets: Higgs-signal strengths, $A^b_{FB}$, $R_b$, and $\Gamma_{\text{tot}}$. Note that $\chi^2_{\text{Higgs}}$ includes only the Higgs-signal strength data while $\chi^2_{\text{total}}$ sums over all experimental datasets: $\text{Higgs} + (A^b_{FB})_{\text{EXP}} + R^b_{\text{EXP}} + \Gamma_{\text{had}}$.

| Cases data | SM | i | ii | iii | iv |
|-----------|----|---|----|-----|----|
| $x_w$      | 0.23154 | 0.23154 | 0.23154 | 0.23154 | 0.23154 |
| $\delta \equiv \Delta / M$ | 0.0 | 0.253$^{+0.063}_{-0.090}$ | 0.202$^{+0.036}_{-0.046}$ | 0.0814$^{+0.044}_{-0.046}$ | 0.143$^{+0.036}_{-0.052}$ |
| $C_b \equiv g_{hbb} / g^\text{SM}_{hbb}$ | 1.000 | 0.936$^{+0.037}_{-0.036}$ | 0.959$^{+0.017}_{-0.016}$ | 0.9934$^{+\text{limit}}_{-0.0091}$ | 0.980$^{+0.012}_{-0.012}$ |
| $\chi^2_{\text{Higgs}}$ | 53.81 | 50.99 | 51.39 | 53.27 | 52.35 |
| $A^b_{FB}$ | 0.1030 | 0.0968 | 0.0991 | 0.1024 | 0.1012 |
| $R_b$      | 0.21582 | 0.2208 | 0.2189 | 0.21629 | 0.21731 |
| $\Gamma_{\text{had}}[\text{GeV}]$ | 1.7411 | 1.7523 | 1.7480 | 1.7421 | 1.7444 |
| $\chi^2_{\text{total}}$ | 62.21 | 113.9 | 69.78 | 58.32 | 56.13 |

| Cases data | v | Fit-I | Fit-II |
|-----------|---|------|------|
| $x_w$      | 0.23154 | 0.23109$^{+0.00070}_{-0.00082}$ | 0.23209$^{+0.00031}_{-0.00031}$ |
| $\delta \equiv \Delta / M$ | 0.132$^{+0.022}_{-0.028}$ | 0.253$^{+0.063}_{-0.090}$ | 0.115$^{+0.037}_{-0.027}$ |
| $C_b \equiv g_{hbb} / g^\text{SM}_{hbb}$ | 0.9826$^{+0.0066}_{-0.0063}$ | 0.936$^{+0.037}_{-0.036}$ | 0.9868$^{+0.0055}_{-0.0099}$ |
| $\chi^2_{\text{Higgs}}$ | 52.53 | 50.99 | 52.80 |
| $A^b_{FB}$ | 0.10144 | 0.09922 | 0.09918 |
| $R_b$      | 0.21708 | 0.22082 | 0.21677 |
| $\Gamma_{\text{had}}[\text{GeV}]$ | 1.7439 | 1.7523 | 1.7432 |
| $\chi^2_{\text{total}}$ | 55.88 | 113.6 | 53.68 |
FIG. 1. Case-i to v: $\delta$ is varied while taking $c_L = 1$ and $x_w = 0.23154$. Left-column: $\Delta \chi^2$ distributions versus $\delta \equiv \Delta / M$ and versus $C_b \equiv g_{hbb} / g_{hbb}^{\text{SM}}$ for individual fitting to four experimental datasets: (i) Higgs-signal strength, (ii) $(A_{FB}^b)_{\text{EXP}}$, (iii) $R_b^{\text{EXP}}$, and (iv) $\Gamma_{\text{had}}$, which correspond to Case-i to iv in TABLE I. Right-column: $\Delta \chi^2$ distributions versus $\delta \equiv \Delta / M$ and versus $C_b$ for the combined fitting, which corresponds to Case-v in TABLE I.

In order to see whether such deviations from SM are robust or not, we allow the value of $x_w$ floating together with $\delta$, and perform two fittings, Fit-I and Fit-II. The Fit-I only includes the Higgs-signal strengths and $(A_{FB}^b)^{\text{EXP}}$, because these two datasets would allow a significant deviation from the SM, according to the Cases-i and ii. The best fit point and $\Delta \chi^2$ distribution are shown in Table I and Fig.2. In this case, the best fit point $(\delta, x_w) = (0.25, 0.231)$ gives very good description to the Higgs-signal strengths and $A_{FB}^{\text{EXP}}$, but draws a large deviation in $R_b$ and $\Gamma_{\text{had}}$. For the Fit-II, which includes all four datasets, the best fit values and $\Delta \chi^2$ distributions are shown in Table II and Fig. 3 respectively. The best fit point $(\delta, x_w) = (0.115, 0.232)$ provides the best description for all four datasets - the lowest $\chi^2$ overall.
FIG. 2. **Fit-I:** fitting to the Higgs-signal strengths and \((A^b_{FB})^{\text{EXP}}\) datasets by varying \((\delta, x_W)\).

Upper-panels: \(\Delta \chi^2\) distributions versus \(\delta \equiv \Delta/M\) and versus \(C_b \equiv g_{hbb}/g^{\text{SM}}_{hbb}\). Lower-panels: the parameter-space region with \(\Delta \chi^2 \leq 1\).

So far we observe that the Higgs-signal strengths can be improved substantially by reducing the bottom Yukawa coupling, which is achieved in this work by mixing the RH component \(b'_R\) of a vector-like quark doublet with the SM right-handed bottom quark. So is the forward-backward asymmetry of the bottom quark at the \(Z\) pole. A mixing of order \(s_R \simeq \delta \simeq 0.20 - 0.25\) can achieve the effects. However, such a mixing would deviate \(R_b\) and \(\Gamma_{\text{had}}\) too much. Overall, a mixing of order \(s_R \simeq \delta \simeq 0.12 - 0.13\) would improve the whole picture.

**IV. DISCUSSION**

Note that the left-handed \(b\) quark mixing is extremely small of order \(m_b v/M^2 \sim 10^{-4}\). All the \(B\) decays, including lifetime, branching ratios, \(B^0 - \overline{B^0}\) mixing and angular distributions,
FIG. 3. **Fit-II:** the same as Fig. 2 but fitting to the Higgs-signal strengths, \((A_{FB}^b)_{\text{EXP}}, R_b^{\text{EXP}},\) and \(\Gamma_{\text{had}}\) datasets.

would not be affected. So are the CKM matrix elements, because all these processes involve the left-handed coupling only.

The parameter \(\delta = \Delta/\cal{M} = g_B v/(\sqrt{2}M) = 0.1 - 0.2\) in the above analysis. Assuming \(g_B \sim O(1)\) the mass of the heavy vector-like quark (VLQ) would be of order \(\Delta^2 + M^2 \sim 1 - 2\) TeV. This VLQ is phenomenologically very interesting. It can be directly produced via QCD production processes, such as \(gg, q\bar{q} \rightarrow b'b\) (here \(b'\) is understood to be the mass eigenstate).

Assuming the mixing in the left-hand \(b'\) is negligible compared to the right-handed one, the dominant decays of \(b'\) are

\[b' \rightarrow bh, \quad \text{and} \quad b' \rightarrow bZ\]

with partial widths given by

\[
\Gamma(b' \rightarrow bh) = \left(\frac{\Delta}{v}\right)^2 \frac{M_{b'}}{32\pi} c_R^2 \left(1 - \frac{m_h^2}{M_{b'}^2}\right)^2
\] (23)
\[
\Gamma(b' \to bZ) = \frac{g_2 c_R s_R}{128\pi} \frac{M_{b'}^3}{m_Z^2} \left( 1 + \frac{2m_Z^2}{M_{b'}^2} \right) \left( 1 - \frac{m_Z^2}{M_{b'}^2} \right)^2 .
\] (24)

It is understood that the mass of \(b'\) is approximately \(\sqrt{\Delta^2 + M^2}\) in the leading order. Note that \(s_R \approx \Delta/M\) and \(c_R \approx 1\) in the limit \(\Delta/M \to 0\). The partial width of \(b' \to bZ\) can then be further simplified to

\[
\Gamma(b' \to bZ) = \left( \frac{\Delta}{v} \right)^2 \frac{M_{b'}}{32\pi} \left( 1 + \frac{2m_Z^2}{M_{b'}^2} \right) \left( 1 - \frac{m_Z^2}{M_{b'}^2} \right)^2
\]

Therefore, in the limit \(M_{b'} \gg m_Z, m_h\) these two partial widths are the same. We recall the equivalence theorem that in high energy limit the Higgs boson and longitudinal mode of gauge bosons behave the same.

The collider signature of pair production of \(b\bar{b'}\) via the decay into the \(Z\) boson is rather clean

\[b\bar{b'} \rightarrow (bX)(\bar{b}Z) \rightarrow (bX)(\bar{b}l^+l^-)\]

Such a search for charged lepton pair(s) plus jets has been performed at the 13 TeV LHC \[16\]. Here we perform a rough estimate of the the lower mass limit of \(b'\). The number of events with at least one charged lepton pair is

\[
N = \sigma(pp \rightarrow b\bar{b'}) \times L \times \left( 1 - B^2(b' \rightarrow bh) \right) \times B(Z \rightarrow \ell^+\ell^-) \times \epsilon
\] (25)

where \(\epsilon\) denotes the relevant experimental efficiency collectively. Taking \(L = 36.1\) fb\(^{-1}\), \(B(b' \rightarrow bh) = 0.5\), \(B(Z \rightarrow e^+e^- + \mu^+\mu^-) = 0.067\), and \(\epsilon = 0.5\), and requiring \(N < 4\), we obtain

\[
\sigma(pp \rightarrow b\bar{b'}) \lesssim 4\text{ fb}.
\] (26)

This upper limit on production cross section can be translated to the lower mass limit of \(M_{b'} \gtrsim 1.4\) TeV \[16\].

Further searches of \(b\bar{b'} \rightarrow (bZ)(\bar{b}Z), (bh)(\bar{b}Z), (bh)(bh)\) are possible. The signatures would give 1 or 2 charged lepton pairs at the \(Z\) mass plus multiple \(b\) jets.

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