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Full Text

Preamble

Explaining the 750 GeV Diphoton Excess from Top/Bottom Partner Cascade Decay in Two-Higgs-Doublet Model Extension

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Abstract

In this paper, we interpret the 750 GeV diphoton excess in the Zee-Babu extension of the two-Higgs-doublet model by introducing a top partner (T)/bottom partner (B). In the alignment limit, the 750 GeV resonance is identified as the heavy CP-even Higgs boson (H), which can be sizably produced via the QCD

process $pp \rightarrow TT$ or $pp \rightarrow BB$ followed by the decay $T \rightarrow Ht$ or $B \rightarrow Hb$. The diphoton decay rate of H is greatly enhanced by the charged singlet scalars predicted in the Zee-Babu extension and the total width of H can be as large as 7 GeV. Under the current LHC constraints, we scan the parameter space and find that such an extension can account for the observed diphoton excess.

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Introduction

Very recently, both the ATLAS data with 3.2 fb^{-1} and the CMS data with 2.6 fb^{-1} [?] have reported an excess of the diphoton resonance (X) around 750 GeV. The local significances of their results are 3.6 and 2.6 in the respective experiments. Combining the 8 and 13 TeV data [?], the observed signal strength ($pp \rightarrow X \rightarrow \gamma\gamma$) is 10.6 fb for ATLAS and 4.47 fb for CMS. Since there are no excesses observed in the dijet [?], $t\bar{t}$ [?], diboson or dilepton channels, understanding such an excess becomes a challenging task. So far, many new physics models have been proposed for this excess [2,5–12], among which a singlet scalar is usually introduced as the 750 GeV resonance.

Different from the previous singlet scalar explanations, we attempt to interpret the 750 GeV resonance as a heavy Higgs boson from a second doublet, which mainly originates from the QCD top partner (T) or bottom partner (B) pair production process followed by the decay $T \rightarrow Ht$ or $B \rightarrow Hb$. Obviously, such a scenario still needs extra particles to enhance the 750 GeV Higgs decay into diphoton. Therefore, we introduce a top partner/bottom partner to the Zee-Babu extension [?] of the two-Higgs-doublet model (ZB-2HDM), where two extra charged singlet scalars can enhance the diphoton decay mode and generate neutrino mass. Considering the LHC Higgs data, our study will be focused on an interesting limit of this model, in which one of the neutral Higgs mass eigenstates is almost aligned with the direction of the scalar field vacuum expectation values. In this limit, the 125 GeV Higgs boson tends to have gauge couplings as in the Standard Model (SM) and is easily consistent with the current Higgs data, while the heavy CP-even Higgs boson has very small couplings or no couplings to the SM particles.

Compared to the direct $gg \rightarrow H$ production from the QCD process $pp \rightarrow H$, there are several benefits for the cascade decay production $pp \rightarrow TT/BB \rightarrow HH + t\bar{t}/b\bar{b}$. Since the production of TT/BB and the decay of H are generally unrelated, it is easy to obtain a large branching ratio of $H \rightarrow \gamma\gamma$ by suppressing the 750 GeV Higgs coupling to the top quark. Although the cascade decays have other objects in the diphoton events, such as additional top or bottom quark jets, the status of whether or not there are other objects in the event is unclear at the moment. So, currently, the cascade decay is still a feasible way to interpret the 750 GeV diphoton excess, although not very likely.

Our work is organized as follows. In Sec. II we present the Zee-Babu extension of the 2HDM with the top/bottom partner. In Sec. III we perform the numerical

calculations and discuss the 750 GeV diphoton production rate and the total width of the resonance in the allowed parameter space. Finally, we give our conclusion in Sec. IV.

II. Model

A. Two-Higgs-Doublet Model

The general Higgs potential is written as [?]

$$V = \mu_1^2(\Phi_1^\dagger\Phi_1) + \mu_2^2(\Phi_2^\dagger\Phi_2) + m_{12}^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \lambda_5$$

Here we focus on the CP-conserving case where all λ_i and m_{12}^2 are real. In the Higgs basis, the two complex scalar doublets with hypercharge $Y = 1$ can be written as

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \rho_1 + iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\rho_2 + iA) \end{pmatrix}$$

The Φ_1 field has the vacuum expectation value (VEV) $v = 246$ GeV, and the VEV of Φ_2 field is zero. The G^0 and G^+ are the Nambu-Goldstone bosons which are eaten by the gauge bosons. The H^+ and A are the mass eigenstates of the charged Higgs boson and CP-odd Higgs boson, and their masses are given by $m_A^2 = m_{H^\pm}^2 + v^2(\lambda_4 - \lambda_5)$. The physical CP-even Higgs bosons h and H are the linear combination of ρ_1 and ρ_2 ,

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix}$$

To satisfy the 125 GeV Higgs data, we focus on the so-called alignment limit [?], which corresponds to $\lambda_6 = 0$ and $\cos\theta = 0$. In this limit, the two CP-even Higgs masses are given by $m_h^2 = 2\lambda_1 v^2$ and $m_H^2 = m_{H^\pm}^2 + v^2(\lambda_4 + \lambda_5)$.

The general Yukawa interactions without tree-level FCNC can be given by [?]

$$\mathcal{L}_Y = \bar{Q}_L(y_u \tilde{\Phi}_1 + \kappa_u \tilde{\Phi}_2)u_R + \bar{Q}_L(y_d \Phi_1 + \kappa_d \Phi_2)d_R + \bar{L}_L(y_\ell \Phi_1 + \kappa_\ell \Phi_2)e_R + \text{h.c.}$$

where $Q_L^T = (u_L, d_L)$, $L_L^T = (\nu_L, \ell_L)$, and $\tilde{\Phi}_{1,2} = i\tau_2 \Phi_{1,2}^*$. y_u , y_d and y_ℓ are 3×3 matrices in family space, and κ_u , κ_d and κ_ℓ are coupling constants. The couplings of neutral Higgs bosons normalized to the SM Higgs boson are given by

$$g_{hVV} = \sin\theta, \quad g_{hf\bar{f}} = \sin\theta + \cos\theta\kappa_f, \quad g_{HVV} = \cos\theta, \quad g_{Hf\bar{f}} = \cos\theta - i\gamma_5\kappa_u, \quad g_{Hd\bar{d}} = -i\gamma_5\kappa_d, \quad g_{H\ell\bar{\ell}} = -i\gamma_5$$

where V denotes Z and W , and f denotes u , d and ℓ .

B. Zee-Babu Extension

In order to enhance the branching ratio of the 750 GeV Higgs boson decay to diphoton, we can suppress the total width by taking a small heavy CP-even Higgs coupling to the top quark. However, in this case the charged Higgs of 2HDM (H^\pm) cannot enhance the diphoton branching ratio sizably. Perturbativity gives the upper bound of the heavy CP-even Higgs coupling to the charged Higgs. A light H^\pm can enhance the $\gamma\gamma$ width, but the decay $H \rightarrow H^\pm W^\mp$ will be open and enhance the total width more sizably. Therefore, some additional particles are needed to enhance the 750 GeV Higgs decay into diphoton, such as vector-like fermions or charged scalars. Since the amplitude for $H \rightarrow \gamma\gamma$ is proportional to the square of the electric charge of the particle in the loop, multi-charged particles can enhance $H \rightarrow \gamma\gamma$ sizably.

Here we take the approach of the Zee-Babu model to introduce two $SU(2)_L$ singlet scalar fields π^+ and χ^{++} with hypercharge 1 and 2 [?], respectively. In addition to enhancing the decay rate of $H \rightarrow \gamma\gamma$ sizably, this model can naturally give rise to small neutrino Majorana mass. The potential of the two singlet scalars can be written as

$$V = m_\pi^2 \pi^+ \pi^- + m_\chi^2 \chi^{++} \chi^{--} + k_1 \Phi_1^\dagger \Phi_1 \pi^+ \pi^- + k'_1 \Phi_1^\dagger \Phi_1 \chi^{++} \chi^{--} + k_2 \Phi_2^\dagger \Phi_2 \pi^+ \pi^- + k'_2 \Phi_2^\dagger \Phi_2 \chi^{++} \chi^{--} + k_3 (\Phi_1^\dagger \Phi_2 + \Phi_2^\dagger \Phi_1)$$

Gauge invariance precludes the singlet Higgs fields from coupling to quarks. The Yukawa couplings of singlets to leptons are

$$\mathcal{L}_\pi = f_{ab} \bar{L}_a^c L_b \pi^+ + g_{ab} \bar{e}_a^c e_b \chi^{++} + \text{h.c.}$$

The trilinear μ term in Eq. (8) breaks lepton number and gives rise to neutrino Majorana mass contributions at the two-loop level. Detailed introductions on neutrino mass can be found in [?]. Here we focus on the charged Higgs couplings to the heavy CP-even Higgs. Since the k_1 and k'_1 terms of Eq. (8) that contain the 125 GeV Higgs couplings to charged Higgs are proportional to $\sin \theta$, we assume k_1 and k'_1 to be very small and ignore them in our calculations. Then, after Φ_1 acquires the VEV, the masses of π^+ and χ^{++} are m_π and m_χ , and the CP-even Higgs couplings to the charged Higgses are determined by k_3 and k_4 terms:

$$h\pi^+\pi^- : k_3 \cos \theta v, \quad H\pi^+\pi^- : k_3 \sin \theta v, \quad h\chi^{++}\chi^{--} : k_4 \cos \theta v, \quad H\chi^{++}\chi^{--} : k_4 \sin \theta v$$

For $\cos \theta = 0$, the couplings of $h\pi^+\pi^-$ and $h\chi^{++}\chi^{--}$ are zero. Considering the constraints of perturbativity and stability of the potential, we simply take $0 < k_3 = k_4 < 4\pi$, and fix $m_\pi = m_\chi = 375$ GeV, which will give the maximal value of the form factor of the scalar loop in the $H \rightarrow \gamma\gamma$ decay.

C. Top/Bottom Partners

Next, we introduce the top partner to interact with Φ_2 in the 2HDM. The Yukawa interaction is given as

$$\mathcal{L}_T = y_T \bar{Q}_{tL} \tilde{\Phi}_2 T_R + m_T \bar{T}_L T_R + m'_T \bar{T}_L t_R + \text{h.c.}$$

where $Q_{tL} = (t_L, b_L)^T$ and t_R are the left-handed $SU(2)$ doublet of the third generation and the right-handed $SU(2)$ singlet of the top quark, respectively, while T_R and T_L are two $SU(2)$ singlet top partners.

We obtain the mass matrix of the top quark and its partner (t, T) :

$$\begin{pmatrix} \bar{t}_L & \bar{T}_L \end{pmatrix} \begin{pmatrix} \frac{y_{tv}}{\sqrt{2}} & m'_T \\ 0 & m_T \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix} + \text{h.c.}$$

In this paper, we assume m'_T to be very small so that there is no mixing between t and T . If Φ_1 has interactions with Q_{tL} and T_R , mixing between t and T would appear, but we do not consider this case. Due to the absence of mixing between t and T , the top partner mass is m_T . Using Eq. (2), Eq. (11) gives the Yukawa interactions:

$$\frac{y_T}{\sqrt{2}} \rho_2 \bar{t}_L T_R - \frac{y_T}{\sqrt{2}} A \bar{t}_L T_R - y_T H^- \bar{b}_L T_R + \text{h.c.}$$

Using Eq. (4), Eq. (13) gives the top partner couplings to the Higgs bosons:

$$h \bar{t}_L T_R = h \bar{T}_R t_L : \frac{y_T}{\sqrt{2}} \cos \theta, \quad H \bar{t}_L T_R = H \bar{T}_R t_L : \frac{y_T}{\sqrt{2}} \sin \theta, \quad A \bar{T}_R t_L = -A \bar{t}_L T_R : i \frac{y_T}{\sqrt{2}} \sin \theta, \quad H^- \bar{b}_L T_R = H^+ \bar{T}_R b_L$$

Due to the absence of mixing between t and T , there are no diagonal couplings of $H\bar{T}T$ and $h\bar{T}T$. For $\cos \theta = 0$, the $h\bar{t}T$ channel will be open, and some simulations on the T channel at the LHC have been studied in [?]. In this paper we will take $\cos \theta = 0$ for which the coupling of $h\bar{t}T$ is absent.

For the singlet T_L and T_R , the general neutral and charged current interactions are [?]

$$\mathcal{L}_T^{NC} = \frac{g}{\cos \theta_W} Z_\mu [\bar{T} \gamma^\mu (\delta g_T^L P_L + \delta g_T^R P_R) T + (\delta g_{Tt}^L \bar{T}_L \gamma^\mu t_L + \text{h.c.})]$$

$$\mathcal{L}_T^{CC} = \frac{g}{\sqrt{2}} W^{+\mu} [c_{\theta_L} \bar{t}_L \gamma_\mu b_L + s_{\theta_L} \bar{T}_L \gamma_\mu b_L] + \text{h.c.}$$

where $c_{\theta_L} = \cos \theta_L$ and $s_{\theta_L} = \sin \theta_L$ with θ_L being the mixing angle of the left-handed top and the partner. In this paper we assume there is no mixing of t and T , namely $s_{\theta_L} = 0$. For this case, Eq. (15) shows that the couplings of $Z\bar{T}t$ and $W^+\bar{T}b$ are zero, and there are no decays of $T \rightarrow Zt$ and $T \rightarrow W^+b$.

Similarly, we can introduce the bottom partner and the Yukawa interaction is given as

$$\mathcal{L}_B = y_B \bar{Q}_{tL} \Phi_2 B_R + m_B \bar{B}_L B_R + m'_B \bar{B}_L b_R + \text{h.c.}$$

where B_R and B_L are two $SU(2)$ singlet bottom partners. When m'_B approaches zero, there is no mixing between b and B . From Eq. (16), we can obtain the bottom partner couplings to Higgses:

$$H\bar{b}_L B_R = H\bar{B}_R b_L : \frac{y_B}{\sqrt{2}} \sin \theta, \quad h\bar{b}_L B_R = h\bar{B}_R b_L : \frac{y_B}{\sqrt{2}} \cos \theta, \quad A\bar{B}_R b_L = -A\bar{b}_L B_R : i \frac{y_B}{\sqrt{2}} \sin \theta, \quad H^+ \bar{t}_L B_R = H^+ \bar{t}_L b_R : i \frac{y_B}{\sqrt{2}} \sin \theta,$$

Similar to the top partner, there are no couplings of $h\bar{b}B$, $h\bar{B}B$, $H\bar{B}B$, $Z\bar{B}b$ and $W^- \bar{B}t$ for $\cos \theta = 0$ and the absence of mixing between b and B .

III. Numerical Calculations and Discussions

The 2HDM is usually described in the physical basis and Higgs basis. In the physical basis, the two Higgs doublets Φ_1 and Φ_2 have non-zero VEVs, and $\tan \beta$ is defined as v_2/v_1 with v_1 and v_2 being the VEVs of the first and second scalar doublets. In the Higgs basis, the VEV of Φ_2 is zero; therefore, the parameter $\tan \beta$ is absent. The coupling constants of the Higgs potential in the Higgs basis as shown in Eq. (1) can be expressed using the coupling constants and $\tan \beta$ in the physical basis [?].

In the Higgs basis, the Yukawa interactions of fermions are parameterized by the κ_u , κ_d and κ_ℓ as shown in Eq. (6) and Eq. (7), which can be mapped to the four traditional types of 2HDMs via the specified values of κ_u , κ_d and κ_ℓ in Table I. However, here we take $\sin \theta = 1$, $\kappa_d = \kappa_\ell = 0$. For this choice, Eq. (7) shows that the 750 GeV Higgs (H) couplings to down-type quarks and leptons are zero, and the coupling to gauge bosons is zero, which can naturally satisfy the bounds from measurements of diboson, dijet and dilepton channels. The 125 GeV Higgs (h) couplings to up-type quarks, down-type quarks, leptons and gauge bosons are the same as the SM Higgs, and the couplings to the new charged Higgs, T and B quarks equal zero for $\sin \theta = 1$. The H coupling to up-type quarks is proportional to κ_u , which can control the width of $H \rightarrow \bar{t}t$ and is taken as a free input parameter. However, the experimental data of the 750 GeV Higgs diphoton rate will give an upper bound on the width of the 750 GeV Higgs.

A. T and B Decay

As discussed above, the partners T and B have no couplings to gauge bosons and the 125 GeV Higgs in the parameter space taken in this paper. Therefore, T and B can hardly be constrained by current experimental data from exotic quark searches by ATLAS [?] and CMS [?]. The main decay modes are $T \rightarrow tA$ and $T \rightarrow tH$ for the T quark, as well as $B \rightarrow bH$, $B \rightarrow bA$ and $B \rightarrow tH^-$ for the B quark. For $m_H = 750$ GeV, the oblique parameters favor m_{H^\pm} and m_A to have degenerate masses, especially when their masses have sizable deviation from 750 GeV.

We take $m_B = 770$ GeV and $m_T = 940$ GeV, and plot their branching ratios versus m_A in Fig. 1 [Figure 1: see original paper]. Since the widths of $T \rightarrow tH$,

$T \rightarrow tA$ and $T \rightarrow bH^+$ are proportional to y_T^2 , their branching ratios are independent of y_T , which also holds for the B quark and y_B . Both $Br(B \rightarrow bH)$ and $Br(T \rightarrow tH)$ are very small when m_A and m_{H^\pm} are much smaller than m_H , and increase with m_A and m_{H^\pm} . For $m_B = 770$ GeV and $m_H = m_A = m_{H^\pm} = 750$ GeV, tH^- is kinematically forbidden, and $Br(B \rightarrow bH)$ and $Br(B \rightarrow bA)$ have nearly the same value of 50%. For $m_T = 940$ GeV and $m_H = m_A = m_{H^\pm} = 750$ GeV, bH^+ dominates over $T \rightarrow tH$ and $T \rightarrow tA$ since the former has an enhanced factor of 2 from the coupling, while $T \rightarrow tH$ and $T \rightarrow tA$ are suppressed by large phase space. Only when m_{H^\pm} and m_A are very close to m_T and m_B do $T \rightarrow tH$ and $B \rightarrow bH$ become the dominant decay modes.

B. The Production Rate of 750 GeV Diphoton Resonance

In order to obtain the maximal production rate, we assume $m_A = m_{H^\pm}$ to be larger than m_B and m_T , which leads to $Br(B \rightarrow H^\pm W^\mp, H^+ H^-) = 1$. Also $H \rightarrow AZ$, $H \rightarrow AA$ and $H \rightarrow H^+ H^-$ are kinematically forbidden for this case. For $m_A = m_{H^\pm}$, λ_4 and λ_5 are determined by m_H and m_{H^\pm} from Eq. (3) and Eq. (5):

$$\lambda_4 = \lambda_5 = \frac{m_H^2 - m_{H^\pm}^2}{v^2}$$

For $m_{H^\pm} > m_H$, λ_4 and λ_5 are negative, which will be constrained by vacuum stability to some extent. As discussed in Sec. II, $\cos\theta = 0$ determines $\lambda_6 = 0$ and $\lambda_1 = m_h^2/(2v^2)$, and λ_2 , λ_3 and λ_7 are free parameters that can be tuned to satisfy theoretical constraints from vacuum stability, unitarity and perturbativity. Refs. [22-25] give the corresponding well-known classical formulas for the constraints on the coupling constants of the physical basis. We employ 2HDMC [?] to perform the theoretical constraints on the coupling constants in the physical basis, and then use the formulas of Eqs. (A16-A22) in Ref. [?] to transform the results into constraints on λ_2 , λ_3 and λ_7 in the Higgs basis, namely expressing λ_2 , λ_3 and λ_7 with the allowed parameters of the physical basis. In Fig. 2 [Figure 2: see original paper], we project the samples allowed by the theoretical constraints on the planes of λ_2 versus m_A , λ_3 versus m_A and λ_7 versus m_A for $m_A = m_{H^\pm}$, $m_H = 750$ GeV and $\cos\theta = 0$.

Fig. 2 shows that λ_2 is required to be larger than 0. With increasing m_A and m_{H^\pm} , the absolute values of λ_4 and λ_5 become large (λ_4 and λ_5 are negative), which favors large λ_3 and λ_7 with a small absolute value.

The widths of $H \rightarrow W^+ W^-$, ZZ , hh , $\bar{b}b$, $\tau\bar{\tau}$ at tree-level are zero for $\cos\theta = 0$ and $\kappa_d = \kappa_\ell = 0$. Therefore, $H \rightarrow \bar{t}t$ is the dominant decay mode for large κ_u . Also the one-loop decays $H \rightarrow gg$, $H \rightarrow \gamma\gamma$, $H \rightarrow Z\gamma$ and $H \rightarrow ZZ$ are considered, and the last three modes can be sizably enhanced by the new charged scalars at one-loop. Since π^+ and χ^{++} are $SU(2)_L$ singlets, when the charged scalars give the dominant contributions to $\gamma\gamma$, there is an approximate

relation:

$$\Gamma(H \rightarrow \gamma\gamma) : \Gamma(H \rightarrow Z\gamma) : \Gamma(H \rightarrow ZZ) = 1 : 0.6 : 0.09$$

We define the production rate of the 750 GeV diphoton resonance as

$$R_{\gamma\gamma} = \sigma(gg \rightarrow B\bar{B}(T\bar{T})) \times Br(B\bar{B}(T\bar{T}) \rightarrow H\bar{b}b(t\bar{t})) \times Br(H \rightarrow \gamma\gamma + X) + \sigma(gg \rightarrow H) \times Br(H \rightarrow \gamma\gamma)$$

At the LHC, the cross sections of $gg \rightarrow B\bar{B}(T\bar{T})$ are approximately 240 (65) fb for $\sqrt{s} = 13$ TeV and 28 (5.5) fb for $\sqrt{s} = 8$ TeV [?] with $m_B = 770$ GeV ($m_T = 940$ GeV). In our calculations, we consider the relevant collider bounds from LHC searches at $\sqrt{s} = 8$ TeV \cite{28-31}: $\sigma_{t\bar{t}} < 550$ fb, $\sigma_{\gamma\gamma} < 2$ fb, $\sigma_{Z\gamma} < 4$ fb, $\sigma_{ZZ} < 12$ fb.

Taking $k_4 = 4\pi$, $m_\pi = m_\chi = 375$ GeV, $m_T = 940$ GeV and $m_B = 770$ GeV, we project the surviving samples on the plane of $R_{\gamma\gamma}$ versus κ_u in Fig. 3 [Figure 3: see original paper]. Since the heavy CP-even Higgs coupling to the top quark is proportional to κ_u , the production rate from $gg \rightarrow H$ increases with κ_u . Since the cross section of $gg \rightarrow B\bar{B}(T\bar{T})$ is independent of κ_u , and the total width of H increases with κ_u , the production rate from the latter dominates over the former for small κ_u , and equals the former for $\kappa_u = 0.8$ (0.42). $R_{\gamma\gamma} > 1$ fb favors κ_u to be smaller than 0.9 for $m_B = 770$ GeV and 0.45 for $m_T = 940$ GeV. Compared to the bottom partner, the top partner mass is required to be larger than 930 GeV to open the decay $T \rightarrow tH$. The $gg \rightarrow T\bar{T}$ cross section with $m_T = 940$ GeV is 65 fb at the LHC with $\sqrt{s} = 13$ TeV, which is much smaller than that of $gg \rightarrow B\bar{B}$ with $m_B = 770$ GeV (240 fb). Therefore, the constraints on $m_T = 940$ GeV are stronger than those on $m_B = 770$ GeV.

For a very small top Yukawa coupling, the total width of the 750 GeV Higgs is very narrow, which leads to a large $Br(H \rightarrow \gamma\gamma)$. Therefore, very small κ_u is mainly excluded by the experimental data of the diphoton rate at $\sqrt{s} = 8$ TeV, and the lower bound of κ_u is 0.14 for $m_B = 770$ GeV and 0.05 for $m_T = 940$ GeV.

In Fig. 4 [Figure 4: see original paper], we project the surviving samples on the planes of κ_4 versus κ_u , Γ_H versus κ_4 and Γ_H versus κ_u . Large $R_{\gamma\gamma}$ favors small κ_u and large k_4 , where the former can suppress the total width of the 750 GeV Higgs, and the latter can enhance the decay $H \rightarrow \gamma\gamma$ via the charged Higgs couplings to the 750 GeV Higgs. $R_{\gamma\gamma} > 2$ fb favors $\kappa_u < 0.46$ and $k_4 > 0.05$ for $m_B = 770$ GeV, and $\kappa_u < 0.24$ and $k_4 > 1.0$ for $m_T = 940$ GeV. For $m_B = 770$ GeV, the total width can reach 7 GeV for $R_{\gamma\gamma} = 2$ fb, and be larger than 2 GeV for $R_{\gamma\gamma} < 6$ fb. For $m_T = 940$ GeV, the total width can reach 2 GeV for $R_{\gamma\gamma} = 2$ fb, and be larger than 0.8 GeV for $R_{\gamma\gamma} < 4$ fb.

With increasing masses of the bottom partner and top partner, the cross section of $gg \rightarrow B\bar{B}(T\bar{T})$ will decrease rapidly and be around 2 fb for $m_B = m_T = 1500$ GeV. For sufficiently small top quark Yukawa coupling of the 750 GeV Higgs, the 750 GeV Higgs will mainly decay into $\gamma\gamma$, $Z\gamma$ and ZZ , and $Br(H \rightarrow \gamma\gamma)$

is around 60%. Therefore, the diphoton production rate of the 750 GeV Higgs will reach 1.2 fb for $m_B = m_T = 1500$ GeV. For m_B and m_T smaller than 1500 GeV, a larger production rate can be obtained. However, the total width of the 750 GeV Higgs is required to be very narrow to enhance the production rate. Therefore, precise measurement of the width at the LHC can serve as a sensitive probe of the bottom partner and top partner.

For the 750 GeV resonance, CMS slightly prefers a narrow width, while ATLAS favors a width of 45 GeV. Such a large width can be obtained by enhancement of κ_u and κ_d which can increase the widths of $H \rightarrow \bar{t}t, \bar{b}b$. However, with increasing total width, the branching ratio of the diphoton mode decreases, which suppresses the diphoton production rate. For the model with one singlet bottom partner ($m_B = 770$ GeV), the total width of the 750 GeV Higgs is required to be smaller than 7 GeV in order to obtain $R_{\gamma\gamma} > 2$ fb. Some additional charged particles need to be introduced to enhance the width of H in order to obtain $R_{\gamma\gamma} > 2$ fb and $\Gamma_H \sim 45$ GeV.

In this paper, we discussed two different scenarios: the singlet top partner and the singlet bottom partner. Besides, one can attempt to introduce the doublet fields:

$$\Psi'_L = \begin{pmatrix} T_L \\ B_L \end{pmatrix}, \quad \Psi'_R = \begin{pmatrix} T_R \\ B_R \end{pmatrix}$$

The Yukawa interactions can be given as

$$\mathcal{L}_{\Psi'} = y_T \bar{\Psi}'_L \tilde{\Phi}_2 t_R + y_B \bar{\Psi}'_L \Phi_2 b_R + m \bar{\Psi}'_L \Psi'_R + m' \bar{Q}_{tL} \Psi'_R + \text{h.c.}$$

In order to avoid experimental constraints from ATLAS and CMS searches for $Wb, T \rightarrow tZ, T \rightarrow th, B \rightarrow Wt, B \rightarrow bZ$ and $B \rightarrow bh$, one can assume that there are no mixings of t and T as well as b and B , namely $m' = 0$. For this case, the T and B have degenerate mass, $m_T = m_B = m$, and the charged current of T and B still appears since they are $SU(2)_L$ doublets:

$$\frac{g}{\sqrt{2}} W^{+\mu} \bar{T} \gamma_\mu B + \text{h.c.}$$

In order to obtain large cross sections of $pp \rightarrow \bar{B}B/\bar{T}T$, one should take small masses of B and T . For $m_T = m_B = 770$ GeV, the 750 GeV diphoton production rate from the $HH\bar{b}b$ process is the same as the model with singlet B_L and B_R . Also the 750 GeV diphoton resonance can originate from $pp \rightarrow \bar{T}T$ followed by the off-shell decays $T \rightarrow t^*H$ and $T \rightarrow W^*B^*$ (including the off-shell 750 GeV Higgs). Since T will partly decay into other objects, the $pp \rightarrow \bar{T}T$ rate is smaller than that of $pp \rightarrow \bar{B}B$. This model predicts the existence of the top partner and bottom partner simultaneously, and the particle spectrum is more complicated than the models with one top partner or one bottom partner studied in this paper.

IV. Conclusion

To accommodate the 750 GeV diphoton excess, we proposed an extension of 2HDM with top and bottom partners. In addition, we took the approach of the Zee-Babu model to introduce two scalar singlets (one singly charged and one doubly charged), which can naturally give a small neutrino Majorana mass and enhance the 750 GeV Higgs decay into diphoton. In this model, the production rate $R_{\gamma\gamma}$ of the 750 GeV diphoton comes from both $B\bar{B}(T\bar{T})$ and $gg \rightarrow H$, where the former dominates over the latter for small top quark coupling with the 750 GeV Higgs, and is comparable to the latter for large top Yukawa coupling.

For $m_B = 770$ GeV, $R_{\gamma\gamma} > 2$ fb favors $\kappa_u < 0.46$ and $k_4 > 0.05$, and the total width of the 750 GeV Higgs can reach 7 GeV for $R_{\gamma\gamma} = 2$ fb. For $m_T = 940$ GeV, $R_{\gamma\gamma} > 2$ fb favors $\kappa_u < 0.24$ and $k_4 > 1.0$, and the total width can reach 2 GeV for $R_{\gamma\gamma} = 2$ fb. To obtain a sufficiently large production rate of the 750 GeV diphoton, the total width tends to decrease with increasing bottom partner and top partner masses. Therefore, precise measurement of the width of the resonance at the LHC can serve as a sensitive probe of these bottom and top partners.

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