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Explaining 750 GeV diphoton excess from top/bottom partner cascade decay in two-Higgs-doublet model extension

Xiao-Fang Han [a], Lei Wang [b,a,*], Lei Wu [c], Jin Min Yang [d,e], Mengchao Zhang [d]

[a] Department of Physics, Yantai University, Yantai 264005, China
[b] IFIC, Universitat de València-CSIC, Apt. Correus 22085, E-46071 València, Spain
[c] ARC Centre of Excellence for Particle Physics at the Terascale, School of Physics, The University of Sydney, NSW 2006, Australia
[d] Institute of Theoretical Physics, Academia Sinica, Beijing 100190, China
[e] Department of Physics, Tohoku University, Sendai 980-8578, Japan

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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 $pp \to T\bar{T}$ or $pp \to B\bar{B}$ followed by the decay $T \to Ht$ or $B \to Hb$. 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.

1. Introduction

Very recently, both the ATLAS data with 3.2 fb^{-1} and the CMS data with 2.6fb^{-1} [1] have reported an excess of the diphoton resonance (X) around 750 GeV. The local significances of their results are 3.6σ and 2.6σ in the respective experiments. Combining the 8 and 13 TeV data [2], the observed signal strength $\sigma_X \times Br(X \to \gamma\gamma)$ is 10.6 ± 2.9 fb for the ATLAS and 4.47 ± 1.86 fb for the CMS. Since there are no excesses observed in the dijet [3], $t\bar{t}$ [4], 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.

Differently from the previous singlet scalar explanations, we attempt to interpret the 750 GeV resonance as a heavy Higgs boson from a second doublet, which is mainly originating from the QCD top partner (T) or bottom partner (B) pair production process followed by the decay $T \to Ht$ or $B \to Hb$. Obviously, such a scenario still needs the extra particles to enhance the 750 GeV Higgs decay into diphoton. Therefore, we introduce a top partner/bottom partner to the Zee–Babu extension [13] of the two-Higgs-doublet model (ZB-2HDM), where two extra charged singlet scalars can enhance the decay of diphoton mode and generate the 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 the 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 the very small couplings or no couplings to the SM particles.

Compared to the direct $gg \to H$ production process, there are several benefits for the production of H from the QCD process $pp \to T\bar{T}/B\bar{B} \to HH + t\bar{t}/b\bar{b}$. Since the production of T/B and the decay of H are generally unrelated, it is easy to obtain a large branching ratio of $H \to \gamma\gamma$ by suppressing the 750 GeV Higgs coupling to the top quark. Although the cascade decays have other objects in the diphoton events, such as the 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. 2 we present the Zee–Babu extension of the 2HDM with the top/bottom partner. In Sec. 3 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. 4.

* Corresponding author at: Department of Physics, Yantai University, Yantai 264005, China.
E-mail address: leiwang@ytu.edu.cn (L. Wang).

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2. Model

2.1. Two-Higgs-doublet model

The general Higgs potential is written as [14]

$$
\begin{aligned}
V = {} & \mu_1^2(\Phi_1^\dagger\Phi_1) + \mu_2^2(\Phi_2^\dagger\Phi_2) + \left[\mu_3^2(\Phi_1^\dagger\Phi_2 + \text{h.c.})\right] \\
& + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) \\
& + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\
& + \left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right] + \left[\lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right] \\
& + \left[\lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + \text{h.c.}\right]. \qquad (1)
\end{aligned}
$$

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 the hypercharge $Y = 1$ can be written as

$$
\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \rho_1 + iG_0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\rho_2 + iA) \end{pmatrix}. \qquad (2)
$$

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

$$
m_A^2 = m_{H^\pm}^2 + v^2(\frac{1}{2}\lambda_4 - \lambda_5). \qquad (3)
$$

The physical CP-even Higgs bosons h and H are the linear combination of ρ_1 and ρ_2,

$$
\begin{pmatrix} \rho_1 \\ \rho_2 \end{pmatrix} = \begin{pmatrix} \sin\theta & \cos\theta \\ \cos\theta & -\sin\theta \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}. \qquad (4)
$$

To satisfy the 125 GeV Higgs data, we focus on the so-called *alignment limit* [15], which corresponds to $\lambda_6 = 0$ and $\cos\theta = 0$. In this limit, the two CP-even Higgs masses are given as

$$
m_h^2 = 2\lambda_1 v^2, \quad m_H^2 = m_{H^\pm}^2 + v^2(\frac{1}{2}\lambda_4 + \lambda_5). \qquad (5)
$$

The general Yukawa interactions without the tree-level FCNC can be given by [16]

$$
\begin{aligned}
-\mathcal{L} = {} & y_u\, \overline{Q}_L\, (\tilde{\Phi}_1 + \kappa_u \tilde{\Phi}_2)\, u_R + y_d\, \overline{Q}_L\, (\Phi_1 + \kappa_d\, \Phi_2)\, d_R \\
& + y_l\, \bar{L}_L\, (\Phi_1 + \kappa_\ell\, \Phi_2)\, e_R + \text{h.c.}, \qquad (6)
\end{aligned}
$$

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

$$
\begin{aligned}
& y_V^h = \sin\theta, \quad y_f^h = \sin\theta + \cos\theta\kappa_f, \\
& y_V^H = \cos\theta, \quad y_f^H = \cos\theta - \sin\theta\kappa_f, \\
& y_V^A = 0, \quad y_u^A = -i\gamma^5\kappa_u, \quad y_{d,\ell}^A = i\gamma^5\kappa_{d,\ell}, \qquad (7)
\end{aligned}
$$

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

2.2. 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, for this case the charged Higgs of 2HDM ($H^\pm$) cannot enhance the branching ratio of diphoton sizably. The perturbativity will give the upper bound of the heavy CP-even Higgs coupling to the charged Higgs. A light $H^\pm$ can enhance the width of $H \to \gamma\gamma$, but the decay $H \to H^\pm W^\mp$ 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 the vector-like fermions or the charged scalars. Since the amplitude of $H \to \gamma\gamma$ is proportional to the square of electric charge of the particle in the loop, the multi-charged particle can enhance $H \to \gamma\gamma$ sizably.

Here we take the approach of Zee–Babu model to introduce two $SU(2)_L$ singlet scalar fields π^+ and χ^{++} with hypercharge 1 and 2 [13], respectively. In addition to enhancing the decay rate of $H \to \gamma\gamma$ sizably, this model can naturally give rise to the small neutrino Majorana mass.

The potential of the two singlet scalars can be written as

$$
\begin{aligned}
V = {} & m_\pi^2 \pi^+\pi^- + m_\chi^2 \chi^{++}\chi^{--} + k_1\Phi_1^\dagger\Phi_1\pi^+\pi^- \\
& + k_1'\Phi_1^\dagger\Phi_1\chi^{++}\chi^{--} + k_2\Phi_2^\dagger\Phi_2\pi^+\pi^- + k_2'\Phi_2^\dagger\Phi_2\chi^{++}\chi^{--} \\
& + k_3(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1)\pi^+\pi^- + k_4(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1)\chi^{++}\chi^{--} \\
& + k_5(\pi^+\pi^-)^2 + k_6(\chi^{++}\chi^{--})^2 + (\mu\pi^-\pi^-\chi^{++} + h.c.). \qquad (8)
\end{aligned}
$$

The gauge invariance precludes the singlet Higgs fields from coupling to the quarks. The Yukawa coupling of singlets to leptons arel1

$$
\mathcal{L} = f_{ab}\bar{L_{La}^C}L_{Lb}\pi^+ + g_{ab}\bar{E_{Ra}^C}E_{Rb}\chi^{++} + h.c.. \qquad (9)
$$

The trilinear μ term in Eq. (8) breaks the lepton number and gives rise to the neutrino Majorana mass contributions at the two-loop level. The detailed introductions on the neutrino mass can be found in [13]. 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 the 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,

$$
\begin{aligned}
& h\pi^+\pi^- : -k_3\cos\theta v, \quad h\chi^{++}\chi^{--} : -k_4\cos\theta v, \\
& H\pi^+\pi^- : k_3\sin\theta v, \quad H\chi^{++}\chi^{--} : k_4\sin\theta v. \qquad (10)
\end{aligned}
$$

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 $0 \lesssim k_3 = k_4 \lesssim 4\pi$, and fix $m_\pi = m_\chi = 375$ GeV, which will give the maximal value of the form factor of scalar loop in the $H \to \gamma\gamma$ decay.

2.3. Top/bottom partners

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

$$
-\mathcal{L} = y_T\, \bar{Q}_{tL}\, \widetilde{\Phi}_2 T_R + m_T \bar{T}_L T_R + m_T' \bar{T}_L t_R + h.c., \qquad (11)
$$

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

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

$$\left(\bar{t}_L \ \bar{T}_L\right) \begin{pmatrix} m_t & 0 \\ m'_T & m_T \end{pmatrix} \begin{pmatrix} t_R \\ T_R \end{pmatrix}. \quad (12)$$

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

$$\frac{y_T}{\sqrt{2}}\rho_2 \bar{t}_L T_R - i\frac{y_T}{\sqrt{2}}A\bar{t}_L T_R - y_T H^- \bar{b}_L T_R + h.c.. \quad (13)$$

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

$$\begin{aligned} &H\bar{t}_L T_R = H\bar{T}_R t_L : \ \frac{y_T}{\sqrt{2}}\sin\theta \\ &h\bar{t}_L T_R = h\bar{T}_R t_L : \ -\frac{y_T}{\sqrt{2}}\cos\theta \\ &A\bar{t}_L T_R = -A\bar{T}_R t_L : \ i\frac{y_T}{\sqrt{2}} \\ &H^-\bar{b}_L T_R = H^+\bar{T}_R t_L : y_T. \end{aligned} \quad (14)$$

Due to the absence of the mixing of t and T, there are not the diagonal couplings of $H\bar{T}T$ and $h\bar{T}T$. For $\cos\theta \neq 0$, the $T \to th$ channel will be open, and some simulations on the channel at the LHC have been studied in [17]. 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 [18]

$$\begin{aligned} \mathcal{L}^{NC} = &\frac{g}{c_W} Z_\mu \bar{t}\left[(\frac{1}{2} - \frac{2}{3}s_W^2 + \delta g_L^t)P_L + (-\frac{2}{3}s_W^2)P_R\right] t \\ &+ \frac{g}{c_W} Z_\mu \bar{T}\left[(\frac{1}{2} - \frac{2}{3}s_W^2 + \delta g_L^T)P_L + (-\frac{2}{3}s_W^2)P_R\right] T \\ &+ \frac{g}{c_W} Z_\mu \bar{T}\left[\delta g_L^{Tt} P_L\right] t + h.c., \\ \mathcal{L}^{CC} = &\frac{g}{\sqrt{2}} W^{\mu+} c_{\theta_L}\, \bar{t}\, \gamma_\mu P_L\, b + \frac{g}{\sqrt{2}} W^{\mu+} s_{\theta_L}\, \bar{T}\, \gamma_\mu P_L\, b + h.c.. \end{aligned} \quad (15)$$

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. $\delta g_L^t = -\frac{s_{\theta L}^2}{2}$, $\delta g_L^T = -\frac{c_{\theta L}^2}{2}$ and $\delta g_L^{Tt} = \frac{s_{\theta_L} c_{\theta_L}}{2}$. In this paper we assume that there is no mixing of t and T, namely $s_{\theta_L} = 0$. For this case, the Eq. (15) shows that the couplings of $Z\bar{T}t$ and $W^+\bar{T}b$ are zero, and there are no decays of $T \to Zt$ and $T \to W^+ b$.

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

$$-\mathcal{L} = y_B\, \bar{Q}_{tL}\, \Phi_2 B_R + m_B \bar{B}_L B_R + m'_B \bar{B}_L b_R + h.c., \quad (16)$$

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

$$\begin{aligned} &H\bar{b}_L B_R = H\bar{B}_R b_L : \ \frac{y_B}{\sqrt{2}}\sin\theta \\ &h\bar{b}_L B_R = h\bar{B}_R b_L : \ -\frac{y_B}{\sqrt{2}}\cos\theta \\ &A\bar{b}_L B_R = -A\bar{B}_R b_L : \ -i\frac{y_B}{\sqrt{2}} \\ &H^+\bar{t}_L B_R = H^-\bar{B}_R t_L : -y_B. \end{aligned} \quad (17)$$

Table 1
The specified values of κ_u, κ_d and κ_ℓ for the four traditional types of 2HDMs.

	Type I	Type II	Lepton-specific	Flipped
κ_u	$1/\tan\beta$	$1/\tan\beta$	$1/\tan\beta$	$1/\tan\beta$
κ_d	$1/\tan\beta$	$-\tan\beta$	$1/\tan\beta$	$-\tan\beta$
κ_ℓ	$1/\tan\beta$	$-\tan\beta$	$-\tan\beta$	$1/\tan\beta$

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

3. Numerical calculations and discussions

The 2HDM is usually described in the physical basis and Higgs basis. In the physical basis, the two Higgs doublet Φ_1 and Φ_2 have the non-zero VEVs, and $\tan\beta$ is defined as v_2/v_1 with v_1 and v_2 being the VEV of the first and second scalar doublet. In the Higgs basis, the VEV of Φ_2 is zero, therefore, the parameter $\tan\beta$ is absent. The coupling constants of Higgs potential in the Higgs basis as shown in the Eq. (1), can be expressed using the coupling constants and $\tan\beta$ in the physical basis [19].

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), and which can be mapped to the four traditional types of 2HDMs via the κ_u, κ_d and κ_ℓ specified in Table 1.

However, here we take $\sin\theta = 1$, $\kappa_d = \kappa_\ell = 0$. For this choice, the Eq. (7) shows that the 750 GeV Higgs (H) couplings to the down-type quark and lepton are zero, and the coupling to gauge boson is zero, which can naturally satisfy the bounds from the measurements of the diboson, dijet and dilepton. The 125 GeV Higgs (h) couplings to up-type quark, down-type quark, lepton and gauge boson are the same as the SM Higgs, and the couplings to the new charged Higgs, T and B quark equal to zero for $\sin\theta = 1$. The H coupling to the up-type quark is proportional to κ_u, which can control the width of $H \to \bar{t}t$ and is taken as a free input parameter. However, the experimental data of the 750 GeV Higgs diphoton rate will give the upper bound of the width of the 750 GeV Higgs.

3.1. *T and B decay*

As discussed above, the partners T and B have no couplings to the gauge bosons and the 125 GeV Higgs in the parameter space taken in this paper. Therefore, T and B can be hardly constrained by the current experimental data of the exotic quark from the ATLAS [20] and CMS [21] searches. The main decay modes are $T \to tH$, $T \to tA$ and $T \to bH^+$ for the T quark, as well as $B \to bH$, $B \to bA$ and $B \to tH^-$ for the B quark. For $m_H = 750$ GeV, the oblique parameters favor $m_{H^\pm}$ and m_A to have the degenerate mass, especially for that their mass 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. Since the widths of $T \to tH$, $T \to tA$ and $T \to bH^+$ are proportional to y_T^2, their branching ratios are independent on y_T, which also holds for the B quark and y_B. Both $Br(B \to bH)$ and $Br(T \to tH)$ are very small for 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, $B \to tH^-$ is kinematically forbidden, and $Br(B \to bH)$ and $Br(B \to bA)$ have the same value and equal to 50% nearly. For $m_T = 940$ GeV and $m_H = m_A = m_{H^\pm} = 750$ GeV, $T \to bH^+$ dominates over $T \to tH$ and $T \to tA$ since the former has an enhanced factor of 2 from the coupling, and $T \to tH$ and $T \to tA$ are suppressed by a large phase space. Only for $m_{H^\pm}$ and m_A are very closed

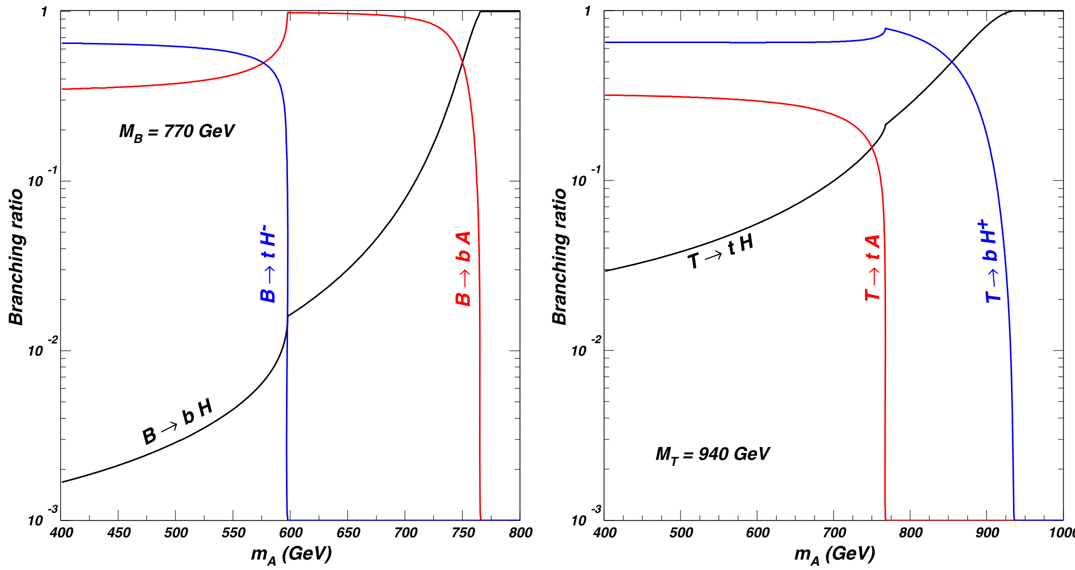

Fig. 1. The branching ratios of T and B versus m_A with $m_{H^\pm} = m_A$ and $m_H = 750$ GeV.

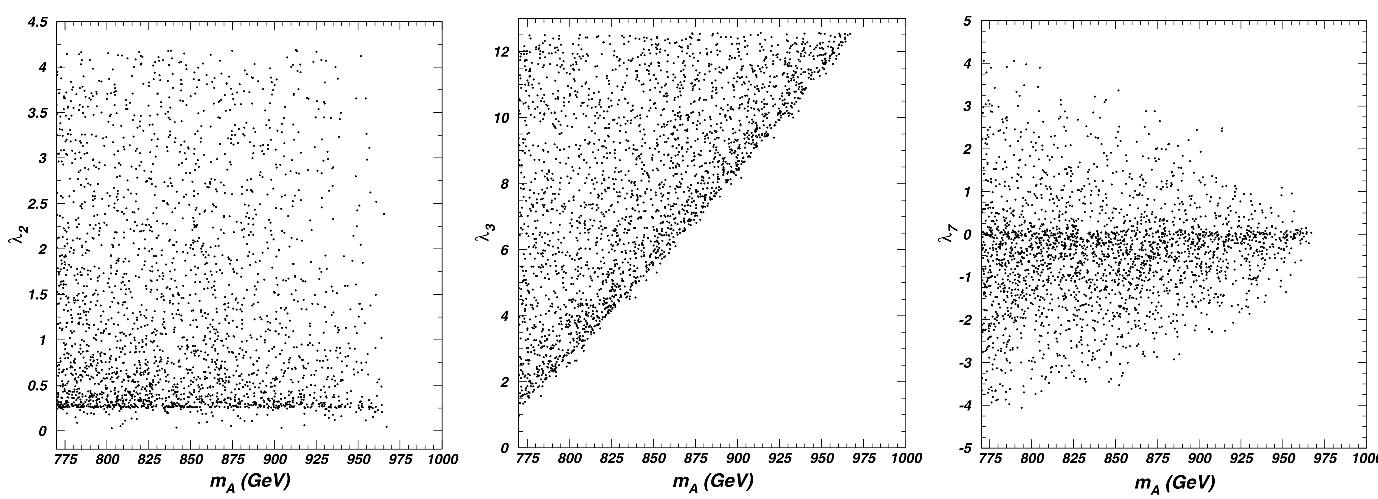

Fig. 2. The samples allowed by the theoretical constraints from the vacuum stability, unitarity and perturbativity for $m_A = m_{H^\pm}$, $m_H = 750$ GeV and $\cos\theta = 0$.

to m_T and m_B, $T \to tH$ and $B \to bH$ are the dominant decay modes.

3.2. 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 $Br(B \to bH) = Br(T \to tH) = 1$. Also $H \to AZ$, $H \to H^\pm W^\mp$, $H \to AA$ and $H \to H^+H^-$ 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 the Eq. (3) and Eq. (5),

$$\frac{\lambda_4}{2} = \lambda_5 = \frac{m_H^2 - m_{H^\pm}^2}{2v^2}. \tag{18}$$

For $m_{H^\pm} > m_H$, λ_4 and λ_5 are negative, which will be constrained by the vacuum stability to some extent. As discussed in the Section 2, $\cos\theta = 0$ determines $\lambda_6 = 0$ and $\lambda_1 = \frac{m_h^2}{2v^2}$, and λ_2, λ_3 and λ_7 are the free parameters, which can be tuned to satisfy theoretical constraints from the vacuum stability, unitarity and perturbativity. Refs. [22–25] give the corresponding well-known classical formulas for the constrains on the coupling constants of the physical basis. We employ 2HDMC [26] to perform the theoretical constraints on the coupling constants in the physical basis, and then use the formulas of Eqs. (A16)–(A22) in the Ref. [19] to transform the results into the 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 the Fig. 2, 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 the increasing of 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 the large λ_3 and the λ_7 with a small absolute value.

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

$$\Gamma(H \to \gamma\gamma) : \Gamma(H \to Z\gamma) : \Gamma(H \to ZZ) = 1 : 0.6 : 0.09. \tag{19}$$

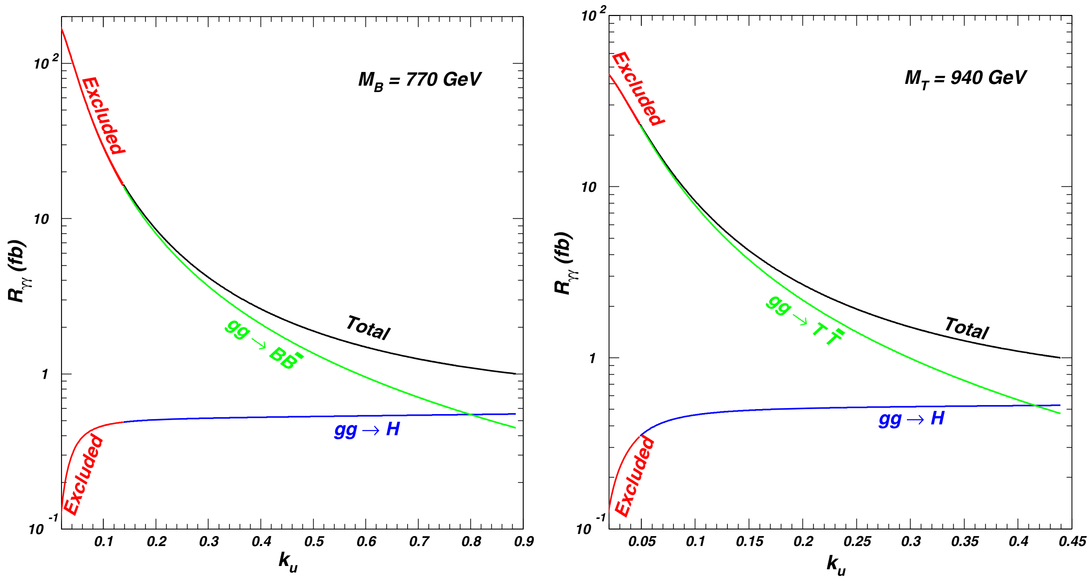

Fig. 3. The diphoton production rate of the 750 GeV Higgs versus k_u for $m_B = 770$ GeV and $m_T = 940$ GeV. The 750 GeV Higgs coupling to the new charged Higgs (k_4) is fixed as 4π, and $m_\pi = m_\chi = 375$ GeV.

We define the production rate of the 750 GeV diphoton,

$$\begin{aligned} R_{\gamma\gamma} \equiv\ & \sigma(gg \to B\bar{B}\ (T\bar{T})) \times Br(B\bar{B}\ (T\bar{T}) \to HHb\bar{b}\ (t\bar{t})) \\ & \times Br(HH \to \gamma\gamma + X) \\ & + \sigma(gg \to H) \times Br(H \to \gamma\gamma) \\ =\ & \sigma(gg \to B\bar{B}\ (T\bar{T})) \times Br(HH \to \gamma\gamma + X) \\ & + \sigma(gg \to H) \times Br(H \to \gamma\gamma). \end{aligned} \quad (20)$$

At the LHC, the cross sections of $gg \to B\bar{B}$ ($T\bar{T}$) with $m_B =$ 770 GeV ($m_T = 940$ GeV) are approximate 240 (65) fb for $\sqrt{s} =$ 13 TeV and 28 (5.5) fb for $\sqrt{s} = 8$ TeV [27].

In our calculations, we consider the relevant collider bounds from LHC searches at $\sqrt{s} = 8$ TeV [28–31]:

$$\sigma_{t\bar{t}} < 550 \text{ fb}, \quad \sigma_{\gamma\gamma} < 2 \text{ fb}, \\ \sigma_{Z\gamma} < 4 \text{ fb}, \quad \sigma_{ZZ} < 12 \text{ fb}. \quad (21)$$

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. Since the heavy CP-even Higgs coupling to top quark is proportional to κ_u, the production rate from $gg \to H$ increases with κ_u. Since the cross section of $gg \to B\bar{B}$ ($T\bar{T}$) is independent on κ_u, and the total width of 750 GeV Higgs increases with κ_u, the production rate from $gg \to B\bar{B}$ ($T\bar{T}$) decreases with increasing of κ_u. The production rate from latter dominates over the former for the small κ_u, and equals to 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 $T \to tH$. The cross section of $gg \to T\bar{T}$ with $m_T = 940$ GeV is 65 fb at the LHC with $\sqrt{s} = 13$ TeV, which is much smaller than that of $gg \to B\bar{B}$ with $m_B = 770$ GeV, 240 fb. Therefore, the constraints on $m_T = 940$ GeV are more strong than those on $m_B = 770$ GeV.

For a very small top Yukawa coupling, the total width of 750 GeV Higgs is very narrow, which leads a large $Br(H \to \gamma\gamma)$. Therefore, the very small κ_u is mainly excluded by the experimental data of the diphoton rate at the $\sqrt{s} = 8$ 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, 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. The large $R_{\gamma\gamma}$ favors a small κ_u and a large k_4, and the former can suppress the total width of the 750 GeV Higgs, and the latter can enhance the decay $H \to \gamma\gamma$ 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 the increasing of the mass of bottom partner and top partner, the cross section of $gg \to B\bar{B}$ ($T\bar{T}$) will decrease rapidly and be around 2 fb for $m_B = m_T = 1500$ GeV. For the enough small top quark Yakawa coupling of the 750 GeV Higgs, the 750 GeV Higgs will mainly decay into $\gamma\gamma$, $Z\gamma$ and ZZ, and $Br(H \to \gamma\gamma)$ 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 are smaller than 1500 GeV, the more large 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, the precise measurement of width at the LHC can be as a sensitive probe of the bottom partner and top partner.

For the 750 GeV resonance, the CMS slightly prefers a narrow width, and the ATLAS favors a width of 45 GeV. Such large width can be obtained by the enhancement of κ_u and κ_d which can enhance the widths of $H \to \bar{t}t$, $\bar{b}b$. However, with the increasing of the total width, the branching ratio of the diphoton mode decreases, which will suppress 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 be introduced to enhance the width of $H \to \gamma\gamma$ in order to obtain $R_{\gamma\gamma} > 2$ fb and $\Gamma_H \simeq 45$ GeV.

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

$$\Psi'_L = \begin{pmatrix} T_L \\ B_L \end{pmatrix}, \quad \Psi'_R = \begin{pmatrix} T_R \\ B_R \end{pmatrix}. \quad (22)$$

The Yukawa interactions can be given as

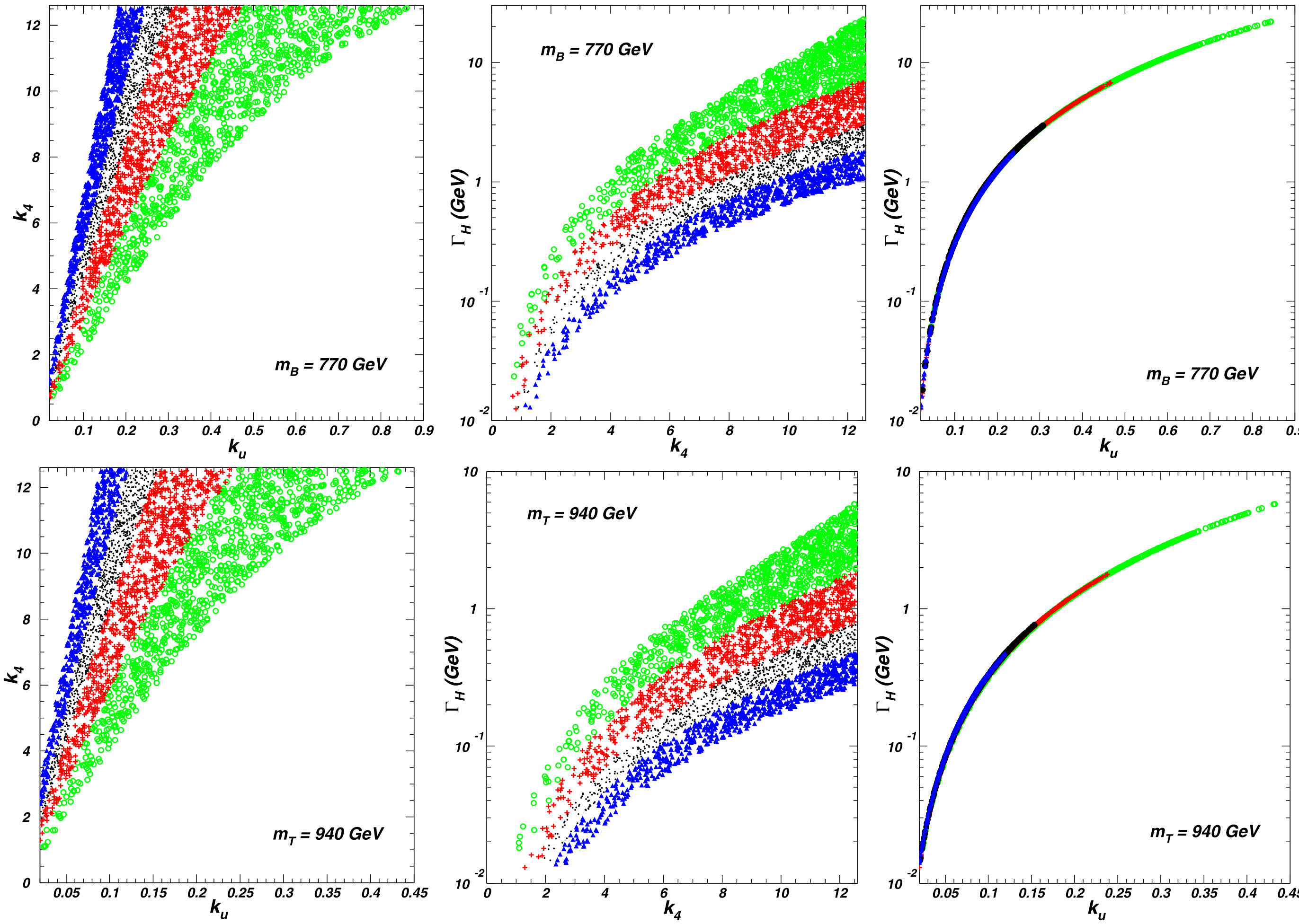

Fig. 4. The surviving samples projected on the planes of κ_4 versus κ_u, Γ_H versus κ_4 and Γ_H versus κ_u for $m_B = 770$ GeV and $m_T = 940$ GeV, with 1 fb $< R_{\gamma\gamma} < 2$ fb for the circles (green), 2 fb $< R_{\gamma\gamma} < 4$ fb for the pluses (red), 4 fb $< R_{\gamma\gamma} < 6$ fb for the bullets (black) and 6 fb $< R_{\gamma\gamma} < 10$ fb for the triangles (blue). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

$$-\mathcal{L} = y_T\,\bar{\Psi}'_L\,\widetilde{\Phi}_2 t_R + y_B\,\bar{\Psi}'_L\,\Phi_2 b_R + m\bar{\Psi}'_L\Psi'_R + m'\,\bar{Q}_{tL}\Psi'_R + h.c.. \tag{23}$$

In order to avoid the experimental constraints of the ATLAS and CMS searches for the $T \to Wb$, $T \to tZ$, $T \to th$, $B \to Wt$, $B \to bZ$ and $B \to bh$, 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 the degenerate mass,

$$m_T = m_B = m, \tag{24}$$

and the charged current of T and B still appears since they are the doublets of $SU(2)_L$,

$$\mathcal{L}^{CC} = \frac{g}{\sqrt{2}} W^{\mu+}\bar{T}\,\gamma_\mu\,B + h.c.. \tag{25}$$

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

4. Conclusion

To accommodate the 750 GeV diphoton excess, we proposed an extension of 2HDM with the top and bottom partners. In addition, we took the approach of Zee–Babu model to introduce two scalar singlets (one is singly charged, and the other is 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 is from both $gg \to B\bar{B}$ $(T\bar{T})$ and $gg \to H$, and the former dominates over the latter for a small top quark coupling with the 750 GeV Higgs, and is comparable to the latter for a 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 enough large production rate of the 750 GeV diphoton, the total width tends to decrease with the increasing of the bottom partner and top partner masses. Therefore, the precise measurement of the width of the resonance at the LHC can be as a sensitive probe of these bottom partner and top partner.

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