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Explaining 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 $pp \to T\bar{T}$ 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.

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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.