Top-phobic heavy Higgs boson
as the 750 GeV diphoton resonance

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Abstract

A hint of a new resonance at a mass of 750 GeV has been observed in the diphoton channel of LHC Run 2 at $\sqrt{s} = 13$ TeV. The signal rate is too large to interpret it as a new Higgs boson in the context of weakly-coupled renormalizable models. One way is to reduce its total decay rate, which is possible if the CP-even heavy Higgs boson $H^0$ in the aligned two Higgs doublet model becomes top-phobic. To ensure sufficient gluon fusion production, we introduce vector-like quarks (VLQ). The Higgs precision data as well as the exclusion limits from no excesses in other 8 TeV LHC searches of $Z\gamma$, $b\bar{b}$, $\tau^+\tau^-$, and $jj$ channels are simultaneously included. In Type I, top-phobic $H^0$ cannot explain the 750 GeV diphoton signal and the Higgs precision data simultaneously since the universal Yukawa couplings of the up-type and down-type VLQs always make more contribution to $h^0$ than to $H^0$. In Type II, small Yukawa coupling of the up-type VLQ but sizable Yukawa coupling for the down-type VLQ is shown to explain the signal while satisfying other LHC exclusion limits.
I. INTRODUCTION

Very recently the ATLAS [1] and CMS [2] collaborations have announced hints of a new diphoton resonance at a mass of 750 GeV, based on the 3.2 fb$^{-1}$ and 2.6 fb$^{-1}$ data at $\sqrt{s} = 13$ TeV respectively. The local significance of the diphoton excess is 3.6$\sigma$ for the ATLAS and 2.6$\sigma$ for the CMS. Including the look-elsewhere effect between 500 GeV and 4 TeV in the ATLAS data and between 200 GeV and 2 TeV in the CMS data, a global significance becomes less than 2.3$\sigma$ for the ATLAS and 2$\sigma$ for the CMS. The observed excesses in the diphoton invariant mass spectrum correspond to the production cross section times branching ratio of $2.4 - 4.8$ fb according to the total decay width of the resonance particle. Two signal rates of the ATLAS and CMS are compatible with each other.

While the excess of the data can yet be regarded as a statistical fluctuation which would be gone away with more data, it can be really the signal of a new particle. In this study, we explore a possibility that this diphoton excess is due to a decay of a new boson. In the literature, there are many studies in this direction [3–92]. By virtue of the Landau-Yang theorem [93], the new boson cannot be a spin-1 particle. A spin-2 particle such as a heavy graviton is unlikely because it has universal couplings proportional to the energy-momentum tensor, and should have left similar excesses in other final states like $\ell^+\ell^-$. Therefore we consider the best possibility that the resonance is a spin-0 particle.

A strong candidate for the new spin-0 particle is a heavy neutral Higgs boson coming from physics beyond the Standard Model (SM) such as two Higgs doublet models (2HDM) and minimal supersymmetric SM. However the usual heavy Higgs boson in the context of weakly-coupled renormalizable models has a difficulty in explaining the unexpectedly large diphoton signal rate. For example, usual heavy Higgs bosons $H^0$ and $A^0$ in the 2HDM require more than three copies of vector-like quarks (VLQs) with exotically high electric charges to explain the observed $\sigma \cdot B$ [6]. There are three ways to enhance the signal rate: (i) increasing the production cross section, (ii) increasing the diphoton decay rate, and/or (iii) decreasing the total decay rate. Methods (i) and (ii) have been extensively studied in the literature for various new physics models. However the method (iii) has not been much focused yet, which is actually one competent way to obtain the relatively large diphoton signal.

We shall show that this possibility can be naturally achieved in one of the most popular new physics models, the aligned 2HDM. Among five physical Higgs boson degrees of freedom (the light CP-even scalar $h^0$, the heavy CP-even scalar $H^0$, the CP-odd pseudoscalar $A^0$, and two charged Higgs bosons $H^\pm$), we consider the case that $H^0$ is the 750 GeV state and $h^0$ is the observed Higgs boson. In the alignment limit, $h^0$ has the same couplings as the SM Higgs boson. The sum rule prohibits the couplings of $H^0$ with $VV$ ($V = W^\pm, Z^0$). The
dominant decay channel becomes into $t\bar{t}$, and the diphoton branching ratio is still very small even without the $VV$ mode: $B(H^0 \rightarrow \gamma\gamma) \sim \mathcal{O}(10^{-6})$ if the $H^0-t\bar{t}$ coupling is SM-like. But this $t\bar{t}$ decay mode can be suppressed by increasing the tan $\beta$ parameter since the top Yukawa coupling of $H^0$ in the aligned 2HDM is inversely proportional to tan $\beta$. Then $H^0$ becomes top-phobic. In what follows, the top-phobic Higgs boson is meant by $H^0$ with the partial decay rate $\Gamma(H^0 \rightarrow t\bar{t})$ below one percent of the SM value.

If there exist only SM fermions, however, small $H-t\bar{t}$ vertex necessarily suppresses the gluon fusion production which occurs radiatively through the top quark loop. New colored particles are required. We introduce vector-like quarks (VLQs) whose couplings to $H^0$ play a dominant role in the gluon fusion production as well as the loop-induced decay to diphoton [94]. Since the same VLQs also contribute to the loop-induced couplings of $h^0$ to $gg$ and $\gamma\gamma$, a consistency check with the Higgs precision data is necessary. Moreover one should consider simultaneously that no excesses for the comparable mass scale have been observed in any other channels like $Z\gamma$, $b\bar{b}$, $\tau^+\tau^-$, $jj$, $ZZ$, and $W^+W^-$. So our main question is whether the top-phobic $H^0$ in the aligned 2HDM can be the observed 750 GeV state while satisfying these LHC data. In addition, we also study the phenomenological characteristics of this top-phobic $H^0$ at the 13 TeV LHC.

The paper is organized as follows. We describe the top-phobic heavy Higgs boson of the aligned 2HDM in Sec. II. We introduce VLQs and demonstrate their contributions to the effective couplings of $H^0/h^0$ to $gg$ and $\gamma\gamma$. The gain due to the top-phobic nature of $H^0$ is to be also discussed. In Sec. III we perform a parameter scan to account for the signal rate while imposing various constraints. The numerical results on the final allowed parameter space shall be presented. In Sec. IV we draw our conclusions.

II. TOP-PHOBIC HEAVY HIGGS BOSON IN THE ALIGNED 2HDM WITH VLQ

A. Review of 2HDM and top-phobic $H^0$

We consider a 2HDM with CP invariance and softly broken $Z_2$ symmetry [95]. There are two Higgs doublet fields, $\Phi_1$ and $\Phi_2$, which develop nonzero vacuum expectation values (VEVs) $v_1$ and $v_2$ respectively. There are five physical Higgs boson degrees of freedom: the light CP-even scalar $h^0$, the heavy CP-even scalar $H^0$, the CP-odd pseudoscalar $A^0$, and two charged Higgs bosons $H^\pm$. The SM Higgs field is a mixture of $h^0$ and $H^0$ as

$$H^{SM} = s_{\beta-\alpha}h^0 + c_{\beta-\alpha}H^0,$$

where we take $s_x = \sin x$, $c_x = \cos x$, and $t_x = \tan x$ for simplicity of notation, $\alpha$ is the mixing angle between $h^0$ and $H^0$, and $t_\beta = v_2/v_1$. Although the current LHC Higgs precision data
can also be explained by $H^0$ \textbf{[96-103]}, the observed 125 GeV state is set to be $h^0$. We take the alignment limit \textbf{[104]}, $s_{\beta-\alpha} = 1$, so that $h^0$ has the same couplings as the SM Higgs boson \textbf{[105]}.

We consider the case where the 750 GeV state is the heavy CP-even Higgs boson $H^0$:

$$M_H = 750 \text{ GeV}. \quad (2)$$

We also assume that the pseudoscalar $A^0$ and the charged Higgs $H^\pm$ are so heavy that they do not affect the neutral Higgs decays and productions. In this study we do not consider the $H^0-h^0-h^0$ coupling, although it can impose many interesting implications. In the alignment limit, the $H^0-V-V$ ($V = W^\pm, Z^0$) couplings vanish. The Yukawa couplings are different according to the $Z_2$ charges of the SM fermions, which determine the types of 2HDM. In Type I and Type II, the normalized Yukawa couplings by the SM values are

Type I: $\hat{y}_t^H = \hat{y}_b^H = \hat{y}_\tau^H = -\frac{1}{t_\beta}$, \quad (3)

Type II: $\hat{y}_t^H = -\frac{1}{t_\beta}$, $\hat{y}_b^H = \hat{y}_\tau^H = t_\beta$.

In both Type I and Type II, large $t_\beta$ yields the top-phobic $H^0$, for which we require $\Gamma(H^0 \to t\bar{t})/\Gamma(H^0_{\text{SM}} \to t\bar{t}) \leq 1\%$. Note that large $t_\beta$ leads to small $\alpha$ in the alignment limit. In Type II, $\hat{y}_b^H$ and $\hat{y}_\tau^H$ are proportional to $t_\beta$: too large $t_\beta$ is to be excluded by the $\tau^+\tau^-$ resonance searches at the 8 TeV LHC \textbf{[112, 118]}.

B. Contributions of Vector-like Quarks

To provide sufficient gluon fusion production of the top-phobic $H^0$, we need new contributions to the triangular loops for the $H^0-g-g$ vertex. For the purpose, we take into account extra VLQs consisting of $Q_{L/R}$, $U_{L/R}$, and $D_{L/R}$. The $SU(3)_c \times SU(2)_L \times U(1)_Y$ quantum numbers of $Q_{L/R}$, $U_{L/R}$, $D_{L/R}$ are $(3, 2, -5/3)$, $(3, 1, -2/3)$, and $(3, 1, -8/3)$, respectively. The $SU(2)$ doublet $Q_{L/R}$ is presented by

$$Q_{L/R} = \begin{pmatrix} U' \\ D' \end{pmatrix}_{L/R}. \quad (4)$$

The interactions of VLQs are described by

$$\mathcal{L} = Y_{f_L} Q_{L} D_{R} H_d + Y_{f_R} Q_{R} D_{L} H_d + Y_{f_L} Q_{L} U_{R} H_u + Y_{f_R} Q_{R} U_{L} H_u + m_Q Q_{L} Q_{R} - m_U U_{L} U_{R} - m_D D_{L} D_{R} + h.c., \quad (5)$$

where $\tilde{H}_u = i \tau_2 H_u^*$. In Type I, $H_u = H_d = \Phi_2$, and in Type II, $H_u = \Phi_2$ and $H_d = \Phi_1$. For simplicity, we assume $Y_{f_L} = Y_{f_R} = Y_{f_L} = Y_{f_R} = Y_{f_D}$. In addition, there exist Yukawa
interactions such as \( \bar{q}_L U_R H_u + h.c. \) in Type I and Type II as well as \( \bar{Q}_L d_R \tilde{H}_d + h.c. \) in Type II, where \( q_L \) and \( d_R \) are the SM quark doublet and down-type quark singlet respectively. When the two Higgs doublet fields acquire VEVs, those terms give rise to mixing between \( d_L \) and \( U'_L \), and \( d_R \) and \( U_R \), respectively. Flavor changing neutral currents coming from various experiments constrain mixing parameters and coupling constants. It is beyond the scope of this work to study those constraints in detail, and thus we simply assume that they are small enough.

There exist upper bounds on the masses of VLQs from the direct searches at the Tevatron and LHC. If the main decay mode of VLQs includes the third generation quarks such as \( Vb \) and \( Vt \), the mass bounds for VLQs are rather strong: \( M_{VLQ} \gtrsim 400 - 600 \) GeV \cite{120}. If VLQs mix only with lighter generations, the mass bounds become less than 400 GeV \cite{120}. In what follows, we take the lighter mass of VLQs to be around 400 GeV, which is possible by assuming that the VLQs dominantly decay into light quarks.

After the two Higgs doublet fields acquire VEVs, the mass matrices of the VLQs are given by

\[
\mathcal{M}_U = \begin{pmatrix} m_Q & \frac{y_{fU} v_u}{\sqrt{2}} \\ \frac{y_{fU} v_u}{\sqrt{2}} & -m_U \end{pmatrix}, \quad \mathcal{M}_D = \begin{pmatrix} m_Q & \frac{y_{fD} v_d}{\sqrt{2}} \\ \frac{y_{fD} v_d}{\sqrt{2}} & -m_D \end{pmatrix}, \tag{6}
\]

where \( v_u = v_d = v s_\beta \) in Type I while \( v_u = v s_\beta \) and \( v_d = v c_\beta \) in Type II. Then the Yukawa couplings in the mass eigenstates \( U_i \) and \( D_i \) \((i = 1, 2)\) are

\[
-L = \begin{cases} 
(c_a h + s_a H)(y_{fU} \sum_i \bar{U}_i U_i + y_{fD} \sum_i \bar{D}_i D_i); & \text{in Type I}
\end{cases}
\]

\[
\begin{cases} 
(c_a h + s_a H) y_{fU} \sum_i \bar{U}_i U_i + (-s_a h + c_a H) y_{fD} \sum_i \bar{D}_i D_i; & \text{in Type II.}
\end{cases} \tag{7}
\]

Here \( y_{fU} \) and \( y_{fD} \) are the Yukawa couplings in the mass eigenstates, given by

\[
y_{fU,D} = \frac{1}{\sqrt{2}} Y_{fU,D} s \theta_{U,D}, \tag{8}
\]

where \( \theta_{U,D} \) are the mixing angles of \( \mathcal{M}_{U,D} \) in Eq. (6).

The new VLQs contribute to Higgs decay rates to \( \gamma \gamma \) and \( gg \) at one loop level. In order to incorporate the NNLO QCD and NLO EW corrections to the \( h^0/H^0 \) production and decay, we take the well-known SM Higgs boson results for the gluon fusion production cross section and decay rates, and multiply them by the relative factor \( c^{h/H}_{jj} \) \((j = g, \gamma)\):

\[
c^{h/H}_{jj} = \frac{\Gamma(h/H \rightarrow jj)}{\Gamma(H_{SM} \rightarrow jj)}; \tag{9}
\]

where \( M_{H_{SM}} = 125 \) GeV for \( c^h_{jj} \) and \( M_{H_{SM}} = 750 \) GeV for \( c^H_{jj} \).
The decay rates of $h^0$ and $H^0$ into $\gamma\gamma$ and $gg$ in the VLQ-2HDM are

$$\Gamma(h/H \to \gamma\gamma) = \frac{\alpha^2 m_{h/H}^3}{256\pi^3 v^2} \left| \sum_{i=t,b,\tau} N_C Q_i^2 y_i^{h/H} A_{1/2}(x_i^{h/H}) + \epsilon_{V_i}^0 A_1(x_W^{h/H}) + N_C A_{\gamma\gamma}^{h/H} \right|^2,$$

$$\Gamma(h/H \to gg) = \frac{\alpha^2 m_{h/H}^3}{128\pi^3 v^2} \left| \sum_{i=t,b} y_i^{h/H} A_{1/2}(x_i^H) + A_{gg}^{h/H} \right|,$$

where $c_V^h = s_\beta - \alpha$, $c_V^H = c_\beta - \alpha$, $x_i^h = (m_k/2m_i)^2$ and the loop functions $A_{1/2}^H(x)$ and $A_1^H(x)$ are referred to Ref. [121]. $A_{\gamma\gamma,gg}^{h,H}$ are the VLQ contributions. The contributions of the heavy charged Higgs bosons are ignored.

In Type I, $A_{\gamma\gamma,gg}^{h,H}$ are

$$\text{Type I: } A_{\gamma\gamma,gg}^h = c_\alpha \sum_i \left\{ B_{\gamma\gamma,gg}^U y_{fu}^{V_i} v m_{U_i} A_{1/2}(x_{U_i}^h) + B_{\gamma\gamma,gg}^D y_{fd}^{V_i} v m_{D_i} A_{1/2}(x_{D_i}^h) \right\},$$

$$A_{\gamma\gamma,gg}^H = s_\alpha \sum_i \left\{ B_{\gamma\gamma,gg}^U y_{fu}^{V_i} v m_{U_i} A_{1/2}(x_{U_i}^H) + B_{\gamma\gamma,gg}^D y_{fd}^{V_i} v m_{D_i} A_{1/2}(x_{D_i}^H) \right\},$$

where $B_{\gamma\gamma}^{U,D} = Q_{j_{U,D}}^2$ and $B_{gg}^{U,D} = 1$. Note that the VLQ contributions to $h^0$ and $H^0$ are the same except for $c_\alpha$ and $s_\alpha$ factors. Since $\alpha \ll 1$ for the top-phobic $H^0$ in the alignment limit, VLQ contribution to $h^0$ is much larger than that to $H^0$. Type I cannot explain both Higgs precision data and 750 GeV diphoton excess, simultaneously.

In Type II, the VLQ contributions to the amplitudes are

$$\text{Type II: } A_{\gamma\gamma,gg}^h = \sum_{i=1,2} \left\{ c_\alpha B_{\gamma\gamma,gg}^U y_{fu}^{V_i} v m_{U_i} A_{1/2}(x_{U_i}^h) - s_\alpha B_{\gamma\gamma,gg}^D y_{fd}^{V_i} v m_{D_i} A_{1/2}(x_{D_i}^h) \right\},$$

$$A_{\gamma\gamma,gg}^H = \sum_{i=1,2} \left\{ s_\alpha B_{\gamma\gamma,gg}^U y_{fu}^{V_i} v m_{U_i} A_{1/2}(x_{U_i}^H) + c_\alpha B_{\gamma\gamma,gg}^D y_{fd}^{V_i} v m_{D_i} A_{1/2}(x_{D_i}^H) \right\}.$$

It is clearly seen that since $\alpha \ll 1$, $y_{fu}$ contribution is dominant to the Higgs precision data while $y_{fd}$ contribution is dominant to the 750 GeV diphoton data. Large signal rate of $gg \to H \to \gamma\gamma$ requires sizable $y_{fd}$ but the SM-like Higgs data do small $y_{fu}$. This feature combined with large $t_\beta$ has an important implication on the VLQ mass matrices in Eq. [6]. In Type II, the off-diagonal elements of $\mathcal{M}_U$ and $\mathcal{M}_D$ become smaller than the diagonal elements if we assume $m_{Q,U,D} \gtrsim 400$ GeV. The mixing is subdominant.

### C. Enhanced diphoton rate of the top-phobic $H^0$

One of the main reasons why the possible 750 GeV state with $\sigma \cdot B \approx 2.4 - 4.8$ fb cannot be the SM-like Higgs boson is the extremely small diphoton branching ratio of $H_{750}^{\text{SM}}$ [118]. In order to dramatically enhance it, we take the alignment limit and the top-phobic $H^0$, which
prohibits the decays into $VV$ and suppresses the decay into $t\bar{t}$ respectively. In Fig. 1, we present the gain of the top-phobic $H^0$ relative to the SM Higgs boson at a mass of 750 GeV through their ratio of the diphoton branching ratio, the signal rate, and the gluon fusion production cross section as a function of $Y_{fD}$. Here $R(O) \equiv O/O_{SM}$. We set $m_Q = 500$ GeV, $m_U = 800$ GeV, $m_D = 380$ GeV, $Y_{fU} = 0.5$, $R(\Gamma_{H\rightarrow t\bar{t}}) = 1\%$, and $c_{\beta-\alpha} = 0.03$ (solid line), 0 (dashed line). All of three $R(B_{\gamma\gamma}^H)$, $R(\sigma_{gg\rightarrow H})$, and $R(\sigma \cdot B)$ have quite similar results for two $c_{\beta-\alpha}$’s. Small deviation from the alignment does not yield dramatic changes in the results.

It is clear to see that $\text{B}(H \rightarrow \gamma\gamma)$ can be significantly enhanced if $Y_{fD} \gtrsim 2$. This is mainly attributed to the suppressed decay rate into $t\bar{t}$. On the while, the gluon fusion production cross section is smaller than the SM value if $Y_{fD} \lesssim 5$, since the small top Yukawa coupling of $H^0$ suppresses the $g\cdot g\cdot H^0$ vertex at one loop level. When $Y_{fD} \gtrsim 5$, the VLQ contribution becomes compatible with the top quark contribution for the SM Higgs boson. In combination, $\sigma \cdot B$ can increase by an order of magnitude if $Y_{fD} \gtrsim 4$.

III. NUMERICAL RESULTS

The main question of this study is whether the top-phobic $H^0$ in the aligned VLQ-2HDM can explain the possible 750 GeV state while satisfying the other LHC constraints. We consider the following three classes of observations:
1. **The diphoton resonance at 750 GeV**: Based on the ATLAS and CMS combined results of 8 TeV and 13 TeV, we accept the best-fit results by varying the total width $\Gamma$ and $\sigma \cdot B$ through a Poissonian likelihood analysis [5]. We fix the new particle mass at 750 GeV. The allowed value of $\sigma \cdot B$ is different according to $\Gamma$. Since the top-phobic $H^0$ in the alignment limit has small total decay width like $\Gamma \sim 5$ GeV we have $\sigma \cdot B = 2.4_{-1.30}^{+1.35}$ fb. Note that if the width is large like $\Gamma = 30$ GeV, the best-fit value increases to be $\sigma \cdot B = 4.8_{-2.3}^{+2.1}$ fb.

2. **Higgs precision data**: We impose the constraints from the Higgs precision data, particularly the ATLAS [108] and CMS [109, 110] measurements of the signal strength of $\mu_{ggF}$:

$$
\mu_{ggF}^{\gamma\gamma} = \begin{cases} 
1.32 \pm 0.38 & \text{(ATLAS)}; \\
0.85^{+0.19}_{-0.16} & \text{(CMS)}. 
\end{cases}
$$

3. **Exclusion from no observation of new resonance searches at the 8 TeV LHC**: We consider the following upper bounds on the signal rate of the 750 GeV $H^0$:

(a) $\sigma(pp \to H \to Z\gamma) \leq 4$ fb [111];

(b) $\sigma(pp \to H \to \tau^+\tau^-) \leq 12$ fb [112].

(c) $\sigma(pp \to H \to b\bar{b}) \leq 1$ pb [113];

(d) $\sigma(pp \to H \to jj) \leq 12$ pb [114];

(e) $\sigma(pp \to H \to ZZ) \leq 20$ fb [115].

When computing the signal rates, we use the SM results of the gluon fusion production cross section at $\sqrt{s} = 13$ TeV of $\sigma(H_{SM}) = 0.85$ pb [117]. The diphoton signal rate is $c_{gg}^H \times \sigma(H_{SM}) \times B(H \to \gamma\gamma)$. The NNLO QCD and NLO EW corrections are naturally included. We do not consider the interference with the continuum background [116].

Figure 2 shows the 95% C.L. allowed parameter space ($Y_{f_D}, Y_{f_U}$) in Type II by the LHC diphoton excess at 750 GeV (pale red region), the Higgs precision data (green region), and the $\tau^+\tau^-$ data from the 8 TeV LHC (grey region). We have set $m_Q = 500$ GeV, $m_U = 800$ GeV, $m_D = 380$ GeV, $c_{\beta-\alpha} = 0$, and $R(\Gamma_{H \to t\bar{t}}) = 1\%$. One copy of $Q_{L/R}$, $U_{L/R}$ and $D_{L/R}$ is included. The large diphoton signal rate of the 750 GeV state requires sizable $Y_{f_D}$ around 5, but remains almost insensitive to $Y_{f_U}$. This is attributed to small $\alpha$ in Eq. [12].

The allowed region by the Higgs precision data is denoted by the green region. As discussed before, the Higgs precision data is sensitive to $Y_{f_U}$ but not to $Y_{f_D}$. The diphoton signals of the 750 GeV and 125 GeV states play complementary roles in determining $Y_{f_U}$.
FIG. 2. Allowed region in the parameter space \((Y_{f_D}, Y_{f_U})\) in Type II VLQ-2HDM. We have set \(m_Q = 500\text{ GeV}, m_U = 800\text{ GeV}, m_D = 380\text{ GeV}, c_{\beta-\alpha} = 0,\) and \(\mathcal{R}(\Gamma_{H \rightarrow t\bar{t}}) = 1\%\). The pale red region explains the 750 GeV diphoton signal, the green one by the Higgs precision data, and the grey one by \(gg \rightarrow H \rightarrow \tau^+\tau^-\) at the 8 TeV LHC.

and \(Y_{f_D}\): the former fixes \(Y_{f_D} \sim 5\) and the latter \(Y_{f_U} \lesssim 1\). We also present the most sensitive exclusion limit from the LHC8 data, \(gg \rightarrow H \rightarrow \tau^+\tau^-\), by the grey region. Large \(Y_{f_D}\) enhances the gluon fusion production cross section and large \(t_\beta\) increases the branching ratio of \(H \rightarrow \tau^+\tau^-\). \(Y_{f_D} \approx 6\) is excluded. More data in the \(\tau^+\tau^-\) channel at the LHC13 will play a crucial role in probing the model. The other exclusion limits in the channels of \(Z\gamma, b\bar{b}, jj\) and \(ZZ\) are all satisfied in the presented parameter space. The final combined allowed region is the red region bounded by solid lines.

Brief comments on the perturbativity of the Yukawa couplings are in order here. Rather large value of \(Y_{f_D} \sim 5\) may cause worry about dangerously large contribution of the next order loop. Note that \(Y_{f_D}\) is the Yukawa coupling in the weak basis. What matters in the perturbation calculation is the Yukawa couplings in the mass basis, \(y_{f_D}\). The maximum value of \(y_{f_D}\) in the combined allowed region (bounded red region) is much small like \(\sim 0.85\). The reduction is because of the small mixing angle \(\theta_D\) in Eq. (8). One loop level calculation for \(H-\gamma-\gamma\) and \(H-g-g\) vertices is sufficient.

Other important model parameters are the masses of VLQs. The benchmark point in Fig. 2 is for \(m_Q = 500\text{ GeV}, m_U = 800\text{ GeV},\) and \(m_D = 380\text{ GeV},\) which enhances the \(H^0-\gamma-\gamma\) vertex by setting \(m_{D_{1,2}}\) near \(m_H/2\) while reduces the \(h^0-\gamma-\gamma\) vertex by rather large \(m_U\). In Fig. 3 we show the dependence of the VLQ masses on the final allowed region. The bounded
FIG. 3. The final allowed region in the parameter space \( (Y_{fD}, Y_{fU}) \). The benchmark point (bounded by solid line) is for \( m_Q = 500 \text{ GeV}, m_U = 800 \text{ GeV}, m_D = 380 \text{ GeV}, c_{\beta-\alpha} = 0, \) and \( R(\Gamma_{H \to t\bar{t}}) = 1\% \). The red region is for \( m_Q = 400 \text{ GeV} \) while the other parameters are the same as the benchmark point, the yellow region for \( m_U = 400 \text{ GeV} \), and the blue region for \( m_D = 500 \text{ GeV} \).

region by solid lines is the allowed region for the benchmark point. The red region is for smaller \( m_Q = 400 \text{ GeV} \) but the other parameters are the same as the benchmark point. In this case, both \( m_{D_1} \) and \( m_{D_2} \) are near the threshold \( m_H/2 \), enhancing the amplitude relative to the case significantly below or above the threshold. Smaller \( Y_{fD} \) can explain the 750 GeV diphoton signal. The yellow region is for smaller \( m_U = 400 \text{ GeV} \) but the same \( m_Q,D \). The up-type VLQs do not affect the 750 GeV diphoton signal, which has almost the same allowed value of \( Y_{fD} \) for lighter \( m_U \). On the contrary, the Higgs precision data get larger contribution and thus smaller \( Y_{fU} (\lesssim 0.7) \) is required. The blue region is for larger \( m_D = 500 \text{ GeV} \): \( Y_{fD} \approx 6 \) is needed. In summary, the VLQ mass dependence is not strong unless the VLQ masses are much heavier than 500 GeV.

Finally we present the branching ratios of the top-phobic \( H^0 \) (left panel) as well as the LHC 13 prospect of various signal rates (right panel) in Fig. 4. The parameter setting is the same as in Fig. 2. For \( Y_{fU} \) and \( Y_{fD} \), we take the values of the final allowed regions and show the maximum and minimum values for each observable. The diphoton branching ratio is highly enhanced, of the order of \( 10^{-3} \). The dominant decay mode is into \( b\bar{b} \) since the \( b \) quark
We take $m_Q = 500$ GeV, $m_U = 800$ GeV, $m_D = 380$ GeV, $c_{\beta - \alpha} = 0$ and $\mathcal{R}(\Gamma_{H \rightarrow t\bar{t}}) = 1\%$. For $Y_{f_U}$ and $Y_{f_D}$, we take the values in the final allowed region of Fig. 2.

Yukawa coupling is enhanced by $t_{\beta}$. The next dominant mode is $t\bar{t}$: the SM top Yukawa coupling itself is large. The third important mode is the $\tau^+\tau^-$ channel.

The LHC 13 prospects on $\sigma(gg \rightarrow H) \cdot B$ in the $b\bar{b}$, $t\bar{t}$, $\tau^+\tau^-$ and $\gamma\gamma$ channels for the top-phobic $H^0$ are presented in the right panel. As can be seen from the branching ratio, the $b\bar{b}$ has the largest signal rate of about 400 fb and the $t\bar{t}$ has the second largest rate $\sim 110$ fb. However huge QCD backgrounds shall make it difficult to measure the signal in these hadronic channels. The $\tau^+\tau^-$ signal rate about 60 fb is very promising at the 13 TeV LHC.

IV. CONCLUSION

A hint of a new resonance at a mass of 750 GeV has been observed in the diphoton channel of LHC Run 2 at $\sqrt{s} = 13$ TeV. We have investigated if a top-phobic heavy neutral Higgs boson in the aligned two Higgs doublet model can be responsible for the diphoton excess. The relatively large signal rate observed at 13 TeV is efficiently accounted for by reducing the total decay width and thus increasing the diphoton branching ratio. One good example is the top-phobic $H^0$ in the aligned 2HDM. We also introduced vector-like quarks so that their couplings to the top-phobic Higgs guarantee sufficient gluon fusion production. We have showed that in Type I the top-phobic $H^0$ cannot explain the 750 GeV diphoton signal rate since the universal Yukawa couplings of up-type ($Y_{f_U}$) and down-type ($Y_{f_D}$) VLQs always yield more contribution to $h^0$ than to $H^0$. In Type II, we found that $Y_{f_U}$ mainly
contributes to $h^0$ while $Y_{f_D}$ to $H^0$. There exists the allowed parameter region of $Y_{f_U} \lesssim 1$ and $Y_{f_D} \sim 5$ which explains the 750 GeV diphoton excess as well as the Higgs precision data and the exclusion limits from the 8 TeV LHC searches in the $Z\gamma$, $b\bar{b}$, $\tau^+\tau^-$, $jj$, $W^+W^-$, and $ZZ$ channels. The $\tau^+\tau^-$ resonance searches at the 8 TeV LHC begin to constrain the model. The dependence of the VLQ masses was shown to be moderate.

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