PHYSICAL REVIEW D **94,** 033010 (2016)

Higgs precision study of the 750 GeV diphoton resonance and the 125 GeV standard model Higgs boson with Higgs-singlet mixing

Kingman Cheung,[1,2,3] P. Ko,[4] Jae Sik Lee,[5] Jubin Park,[5] and Po-Yan Tseng[1]

[1]*Department of Physics, National Tsing Hua University, Hsinchu 300, Taiwan*
[2]*Division of Quantum Phases and Devices, School of Physics, Konkuk University, Seoul 143-701, Republic of Korea*
[3]*Physics Division, National Center for Theoretical Sciences, Hsinchu 300, Taiwan*
[4]*School of Physics, KIAS, Seoul 130-722, Republic of Korea*
[5]*Department of Physics, Chonnam National University, 300 Yongbong-dong, Buk-gu, Gwangju 500-757, Republic of Korea*

(Received 21 March 2016; published 26 August 2016)

We interpret the potential observation of the 750 GeV diphoton resonance at the LHC in models, in which an $SU(2)$ isospin-singlet scalar boson mixes with the standard model (SM) Higgs boson through an angle α. Allowing the singlet scalar boson to have renormalizable couplings to vectorlike leptons and quarks and introducing sizable decay width of the 750 GeV diphoton resonance into non-SM particles such as dark matters, we can explain the large production cross section $\sigma(H_2) \times B(H_2 \to \gamma\gamma)$ as well as the apparent large total width of the boson without conflicts from the results obtained by previous global fits to the SM Higgs boson data.

DOI: 10.1103/PhysRevD.94.033010

I. INTRODUCTION

The biggest triumph of the LHC Run I was the discovery of the standard model (SM) like Higgs boson with mass about 125 GeV [1,2]. The signal-strength data and the spin-parity of the observed 125 GeV particle have all indicated that it is very close to the SM Higgs boson [3,4]. After a shutdown for 2 years, the Run II started with a high expectation. Just with an accumulated luminosity of about 3 fb^{-1} at $\sqrt{s} = 13$ TeV, both ATLAS [5] and CMS [6] showed a hint of a new particle at about 750 GeV decaying into a photon pair. The particle is likely to be a scalar boson or a spin-2 particle. We focus on the scalar boson scenario in this paper.

With a luminosity of 3.2 fb^{-1}, the ATLAS Collaboration found a resonance structure at $M_X \approx 750$ GeV with a local significance of $\sim 3.64\sigma$, but corresponding to 1.88σ when the look-elsewhere-effect is taken into account [5]. The CMS Collaboration also reported a similar though smaller excess with a luminosity of 2.6 fb^{-1} at $M_X \approx 760$ GeV with a local significance of 2.6σ but a global significance less than 1.2σ [6]. Also, in the analysis of ATLAS a total width of about 45 GeV is preferred [5].

These data could be summarized as follows:

$$\begin{aligned} \text{ATLAS}: \; M_X = 750 \text{ GeV}, \quad & \sigma_{\text{fit}}(pp \to X \to \gamma\gamma) \approx 10 \pm 3 \text{ fb}; \quad (95\% \text{ CL}), \quad \Gamma_X \approx 45 \text{ GeV} \\ \text{CMS}: \; M_X = 760 \text{ GeV}, \quad & \sigma_{\text{fit}}(pp \to X \to \gamma\gamma) \approx 9 \pm 7 \text{ fb}; \quad (95\% \text{CL}) \end{aligned}$$

The uncertainties shown are 1.96σ corresponding to 95% C.L. Note that we estimate the best-fit cross section from the 95% C.L. upper limits given in the experimental paper, by subtracting the "expected" limit from the "observed" limit at $M_X = 750(760)$ GeV for ATLAS (CMS).

Although this hint for a new resonance is still very preliminary, it has stimulated a lot of phenomenological activities, bringing in a number of models for interpretation. The first category is the Higgs-sector extensions, including adding singlet Higgs fields [7–9], two-Higgs-doublet models and the MSSM [10]. But in general it fails to explain the large production cross section of $pp \to H \to \gamma\gamma$ in the conventional settings, unless additional particles are added, for example, vectorlike fermions [7–10]. Another category is the composite models [11] that naturally contain heavy fermions, through which the production and the diphoton decay of the scalar boson can be enhanced. Other possibilities are also entertained, such as axion [12], sgoldstini [13], radion/dilaton [14], and other models [15]. More general discussion of the diphoton resonance or its properties can be found in Refs. [16]. The generic feature of the suggested interpretations is to enhance the production cross section of $pp \to H \to \gamma\gamma$, where H is the 750 GeV scalar or pseudoscalar boson, by additional particles running in the $H\gamma\gamma$ decay vertex and/or Hgg production vertex. Another generic feature, though not realized in the CMS data, is the relatively broad width of the particle, which motivates the idea that this particle is window to the dark sector or dark matter [8,9].

A possible interpretation for this 750 GeV particle can be an $SU(2)$ isospin-singlet scalar. In this interpretation, a general feature is that the singlet s mixes with the SM Higgs doublet $H_{\rm SM}$ through an angle α due to the cubic and quartic potential terms such as $\mu s H_{\rm SM}^\dagger H_{\rm SM} + \lambda s^2 H_{\rm SM}^\dagger H_{\rm SM}$. Further, we note that the singlet may also have renormalizable couplings to new vectorlike leptons and quarks [17]. We assume after mixing the lighter boson is the observed SM-like Higgs boson H_1 at 125 GeV while the heavier one H_2 is the one hinted at 750 GeV. Thus, the 750 GeV scalar boson H_2 opens the window to another sector containing perhaps dark matter (DM) and other exotic particles.

In our previous global fits to the Higgs-portal type models with the SM Higgs mixing with a singlet scalar boson with all the Higgs boson data from Run I [18], we have constrained the parameter space of a few models with a singlet scalar. In the Higgs-portal singlet-scalar models with hidden sector DM, there are no new contributions to the $h\gamma\gamma$ and hgg vertices beyond the SM contributions, and the mixing angle α is constrained to $\cos\alpha > 0.86$ at 95% C.L. However, in those models with vectorlike leptons (quarks) the mixing angle can be relaxed to $\cos\alpha > 0.83(0.7)$ at 95% C.L.

The implication is that the 750 GeV scalar boson H_2 can be produced in gg fusion as if it were a 750 GeV SM Higgs boson but with a suppression factor $\sin^2\alpha$ if there are no vectorlike quarks running in the H_2gg vertex. Additional contributions arise when there are vectorlike quarks running in the loop. Similarly, the decay of the scalar boson H_2 behaves like a 750 GeV SM Higgs boson with each partial width suppressed by $\sin^2\alpha$ if there are no vectorlike leptons or quarks running in the H_2gg and $H_2\gamma\gamma$ vertices. If this is the case the branching ratio $B(H_2 \to \gamma\gamma) \sim 10^{-6}$, which is too small to explain the resonance. In this work, we consider vectorlike leptons and vectorlike quarks that can enhance the $H_2 \to \gamma\gamma$ decay substantially to give a large production cross section for $pp \to H_2 \to \gamma\gamma$.

Vectorlike fermions are quite common in a number of extensions of the SM with various motivations. Although we can introduce vectorlike fermions in an *ad hoc* and phenomenological way in order to explain the 750 GeV diphoton excess, their existence can be understood at theoretically deeper levels. They appear naturally in models with new chiral $U(1)$ gauge symmetries in order to cancel gauge anomalies [19–21], in non-Abelian gauge extensions such as $SU(3)_C \times SU(3)_L \times U(1)_Y$ model (the so-called 3-3-1 model where gauge anomalies cancel when three generations of fermions are considered) [22], or in flavor models for fermion masses and mixing [23], to name a few explicit models in the context of 750 GeV diphoton excess. In such models, one can in particular forbid large bare masses of the vectorlike fermions if they are chiral under this new $U(1)$ gauge symmetries, and thus motivate their masses fall into the range we need to accommodate the 750 GeV diphoton excess.

In this paper, we interpret the 750 GeV diphoton resonance by introducing an $SU(2)$ singlet taking fully account of its mixing with the SM doublet. We show that the large production cross section can be explained if the singlet scalar has renormalizable couplings to the vectorlike leptons and quarks. We further show the possibly large total width can be accommodated if H_2 substantially decay into non-SM particles such as dark matters.

The organization is as follows. In the next section, we describe briefly the framework of the SM Higgs mixing with a singlet scalar that couples to new vectorlike fermions. In Sec. III, we present the numerical results for the 750 GeV resonance including the constraints from the properties of the 125 GeV SM Higgs-like scalar boson. Then we conclude in Sec. IV.

II. HIGGS-SINGLET MIXING FRAMEWORK

If there are extra vectorlike fermions with renormalizable couplings to a singlet scalar s,[1] these models generically contain two interaction eigenstates states of h denoting the remnant of the SM Higgs doublet and s the singlet. The two mass eigenstates $H_{1,2}$ are related to the states h and s through an $SO(2)$ rotation as follows:

$$H_1 = h\cos\alpha - s\sin\alpha; \qquad H_2 = h\sin\alpha + s\cos\alpha \tag{1}$$

with $\cos\alpha$ and $\sin\alpha$ describing the mixing between the interaction eigenstates h and s. In the limit of $\sin\alpha \to 0$, $H_1(H_2)$ becomes the pure doublet (singlet) state. In this work, we are taking H_1 for the 125 GeV boson discovered at the 8-TeV LHC run and H_2 for the 750 GeV state hinted at the early 13-TeV LHC run. We are taking $\cos\alpha > 0$ without loss of generality. For the detailed description of this class of models and also Higgs-portal models, we refer to Refs. [17,18].

In this class of models, the singlet field s does not directly couple to the SM particles, but only through the mixing with the SM Higgs field at renormalizable level. And the Yukawa interactions of h and s are described by

$$-\mathcal{L}_Y = h \sum_{f=t,b,\tau} \frac{m_f}{v} \bar{f} f + s \sum_{F=Q,L} g^S_{s\bar{F}F} \bar{F} F, \tag{2}$$

with f denoting the 3rd-generation SM fermions and F the extra vectorlike fermions (VLFs): vectorlike quarks (VLQs) and vectorlike leptons (VLLs). Then the couplings of the two mass eigenstates $H_{1,2}$ to the SM and extra fermions are given by

[1]This singlet scalar s could be a remnant of new gauge symmetry breaking. In that case, s may carry a new quantum number different from the SM gauge charges [24].

$$-\mathcal{L}_Y = H_1\left[\cos\alpha\sum_{f=t,b,\tau}\frac{m_f}{v}\bar{f}f - \sin\alpha\sum_{F=Q,L} g^S_{s\bar{F}F}\bar{F}F\right] + H_2\left[\sin\alpha\sum_{f=t,b,\tau}\frac{m_f}{v}\bar{f}f + \cos\alpha\sum_{F=Q,L} g^S_{s\bar{F}F}\bar{F}F\right]. \quad (3)$$

The couplings of $H_{1,2}$ to two gluons, following the conventions and normalizations of Ref. [25], are given by

$$S^g_{H_1} = \cos\alpha S^{g(\mathrm{SM})}_{H_1} - \sin\alpha S^{g(Q)}_{H_1} \equiv \cos\alpha\sum_{f=t,b}F_{sf}(\tau_{1f}) - \sin\alpha\sum_Q g^S_{s\bar{Q}Q}\frac{v}{m_Q}F_{sf}(\tau_{1Q}),$$
$$S^g_{H_2} = \sin\alpha S^{g(\mathrm{SM})}_{H_2} + \cos\alpha S^{g(Q)}_{H_2} \equiv \sin\alpha\sum_{f=t,b}F_{sf}(\tau_{2f}) + \cos\alpha\sum_Q g^S_{s\bar{Q}Q}\frac{v}{m_Q}F_{sf}(\tau_{2Q}), \quad (4)$$

where $\tau_{ix} = M^2_{H_i}/4m^2_x$. We note that $S^{g(\mathrm{SM})}_{H_1} \simeq 0.651 + 0.050i$ for $M_{H_1} = 125.5$ GeV and $S^{g(\mathrm{SM})}_{H_2} \simeq 0.291 + 0.744i$ for $M_{H_2} = 750$ GeV. In the limit $\tau \to 0$, $F_{sf}(0) = 2/3$. The mass of extra fermion F may be fixed by the relation $m_F = v_s g^S_{s\bar{F}F} + m^0_F$ where v_s denotes the VEV of the singlet s while m^0_F is generated from a different origin other than v_s as in $-\mathcal{L}_{\mathrm{mass}} \supset m^0_F\bar{F}F$. We note that, when $m^0_Q = 0$, each contribution from a VLQ is not suppressed by $1/m_Q$ but by the common factor $1/v_s$.

Similarly, the couplings of $H_{1,2}$ to two photons are given by

$$S^\gamma_{H_1} = \cos\alpha S^{\gamma(\mathrm{SM})}_{H_1} - \sin\alpha S^{\gamma(F)}_{H_1} \equiv \cos\alpha\left[2\sum_{f=t,b,\tau}N_C Q^2_f F_{sf}(\tau_{1f}) - F_1(\tau_{1W})\right] - \sin\alpha\left[2\sum_F N_C Q^2_F g^S_{s\bar{F}F}\frac{v}{m_F}F_{sf}(\tau_{1F})\right],$$
$$S^\gamma_{H_2} = \sin\alpha S^{\gamma(\mathrm{SM})}_{H_2} + \cos\alpha S^{\gamma(F)}_{H_2} \equiv \sin\alpha\left[2\sum_{f=t,b,\tau}N_C Q^2_f F_{sf}(\tau_{2f}) - F_1(\tau_{2W})\right] + \cos\alpha\left[2\sum_F N_C Q^2_F g^S_{s\bar{F}F}\frac{v}{m_F}F_{sf}(\tau_{2F})\right], \quad (5)$$

where $N_C = 3$ and 1 for quarks and leptons, respectively, and $Q_{f,F}$ denote the electric charges of fermions in the unit of e. In the limit $\tau \to 0$, $F_1(0) = 7$. We note that $S^{\gamma(\mathrm{SM})}_{H_1} \simeq -6.55 + 0.039i$ for $M_{H_1} = 125.5$ GeV and $S^{\gamma(\mathrm{SM})}_{H_2} \simeq -0.94 - 0.043i$ for $M_{H_2} = 750$ GeV.

The production cross section of H_2 via the gluon-fusion process is given by

$$\sigma(gg \to H_2) = \frac{|S^g_{H_2}|^2}{|S^{g(\mathrm{SM})}_{H_2}|^2}\sigma_{\mathrm{SM}}(gg \to H_2) \quad (6)$$

with $\sigma_{\mathrm{SM}}(gg \to H_2) \approx 800$ fb denoting the corresponding SM cross section for $M_{H_2} = 750$ GeV at $\sqrt{s} = 13$ TeV [26]. Note that the relation in Eq. (6) only holds at leading order.

The total decay width of H_2 can be cast into the form

$$\Gamma(H_2) = \sin^2\alpha\Gamma_{\mathrm{SM}}(H_2) + \Delta\Gamma^{H_2}_{\mathrm{vis}} + \Delta\Gamma^{H_2}_{\mathrm{inv}}, \quad (7)$$

where $\Gamma_{\mathrm{SM}}(H_2) \simeq 250$ GeV for the SM-like H_2 with $M_{H_2} = 750$ GeV.[2] And $\Delta\Gamma^{H_2}_{\mathrm{vis}}$ and $\Delta\Gamma^{H_2}_{\mathrm{inv}}$ denote additional partial decay widths of H_2 into visible and invisible particles, respectively. The quantity $\Delta\Gamma^{H_2}_{\mathrm{vis}}$ includes the decays into H_1H_1 by definition and, if it is allowed kinematically, into extra vectorlike fermions as well as those into $\gamma\gamma$, gg through the one-loop processes induced by the extra VLQs and/or VLLs. The quantity $\Delta\Gamma^{H_2}_{\mathrm{inv}}$ may include the H_2 decay into invisible particles such as dark matters, or H_2 decays into a pair of Nambu-Goldstone bosons such as Majorons which appear in models for neutrino mass generations (see Refs. [28,29] for example), or dark radiation (or fractional cosmic neutrinos) which appear when global dark $U(1)$ symmetry is spontaneously broken [30].

The partial decay width of H_2 into two photons is given by

$$\Delta\Gamma^{H_2\to\gamma\gamma}_{\mathrm{vis}} = \frac{M^3_{H_2}\alpha^2}{256\pi^3 v^2}\left[|S^\gamma_{H_2}|^2 - \sin^2\alpha|S^{\gamma(\mathrm{SM})}_{H_2}|^2\right] \quad (8)$$

and that into two gluons is

$$\Delta\Gamma^{H_2\to gg}_{\mathrm{vis}} = \left[1 + \frac{\alpha_s}{\pi}\left(\frac{95}{4} - 7\right)\right]\frac{M^3_{H_2}\alpha^2_s}{32\pi^3 v^2} \times \left[|S^g_{H_2}|^2 - \sin^2\alpha|S^{g(\mathrm{SM})}_{H_2}|^2\right] \quad (9)$$

with $\alpha_s = \alpha_s(M_{H_2})$.

III. NUMERICAL RESULTS

In our numerical analysis, we shall restrict ourselves to the case $2m_F > M_{H_2}$ so that $H_2 \to F\bar{F}$ decays are kinematically forbidden and $S^{g(Q),\gamma(F)}_{H_1,H_2}$ are all real. In this case, one may carry out a model-independent study on the

[2] For $M_{H_2} = 750$ GeV, $\Gamma_{\mathrm{SM}}(H_2 \to WW) \simeq 145$ GeV, $\Gamma_{\mathrm{SM}}(H_2 \to ZZ) \simeq 71.9$ GeV, and $\Gamma_{\mathrm{SM}}(H_2 \to t\bar{t}) \simeq 30.6$ GeV. [27].

750 GeV diphoton resonance with the following varying parameters:

$$\sin\alpha, \quad S^{g(Q)}_{H_2}, \quad S^{\gamma(F)}_{H_2}, \quad \Gamma^{\text{non-SM}}_{H_2}, \quad \eta^{g(Q)}, \quad \eta^{\gamma(F)}, \tag{10}$$

where

$$\Gamma^{\text{non-SM}}_{H_2} \equiv \Gamma(H_2 \to H_1 H_1) + \Delta\Gamma^{H_2}_{\text{inv}}. \tag{11}$$

Here the parameters $\eta^{g(Q)}$ and $\eta^{\gamma(F)}$ are defined as in

$$S^{g(Q)}_{H_1} \equiv \eta^{g(Q)} S^{g(Q)}_{H_2}, \qquad S^{\gamma(F)}_{H_1} \equiv \eta^{\gamma(F)} S^{\gamma(F)}_{H_2}. \tag{12}$$

We note that $\eta^{g(Q)}$ and $\eta^{\gamma(F)}$ take values between 2/3 and 1 for the following reasons:

$$S^{g(Q)}_{H_1} = \sum_Q g^S_{s\bar{Q}Q} \frac{v}{m_Q} F_{sf}(\tau_{1Q}) \simeq \frac{2}{3} \sum_Q g^S_{s\bar{Q}Q} \frac{v}{m_Q},$$
$$\frac{2}{3} \sum_Q g^S_{s\bar{Q}Q} \frac{v}{m_Q} \le S^{g(Q)}_{H_2} = \sum_Q g^S_{s\bar{Q}Q} \frac{v}{m_Q} F_{sf}(\tau_{2Q}) \le \sum_Q g^S_{s\bar{Q}Q} \frac{v}{m_Q}, \tag{13}$$

if we have $g^S_{s\bar{Q}Q} > 0$ for all Q's.[3]

Since $|S^{g(Q),\gamma(F)}_{H_1}|$ is larger than $\frac{2}{3}|S^{g(Q),\gamma(F)}_{H_2}|$, the parameters $S^{g(Q),\gamma(F)}_{H_2}$ cannot be arbitrarily large without affecting the LHC data on 125 GeV Higgs boson when $\sin\alpha \neq 0$. For example, the quantities

$$C^{g,\gamma}_{H_1} = |S^{g,\gamma}_{H_1}| / |S^{g,\gamma(\text{SM})}_{H_1}| \tag{14}$$

cannot significantly deviate from 1 [3]. If $\sin\alpha |S^{g(Q)}_{H_1}|$ and $\sin\alpha |S^{\gamma(F)}_{H_1}|$ are required to be within the $\pm 10\%$ range of the corresponding SM values, one might have

$$|S^{g(Q)}_{H_2}| \lesssim \frac{0.1}{|\sin\alpha|}, \qquad |S^{\gamma(F)}_{H_2}| \lesssim \frac{1}{|\sin\alpha|}, \tag{15}$$

when $\eta^{g(Q)} = \eta^{\gamma(F)} = 2/3$. Therefore, we again restricted ourselves to the case of $|\sin\alpha| \lesssim 0.1$ in order to have $|S^{g(Q)}_{H_2}| \gtrsim \mathcal{O}(1)$ and $|S^{\gamma(F)}_{H_2}| \gtrsim \mathcal{O}(10)$.

[3] In this study, we take the more conventional choice of $g^S_{s\bar{F}F} > 0$ for the Yukawa-type coupling between s and VLFs. In general, it may be possible to have negative $g^S_{s\bar{F}F}$ for some VLFs in specific models and the parameters $\eta^{g(Q),\gamma(F)}$ can take any values in principle. However, we shall fully investigate such a case in a later work [31].

When $\sin\alpha \sim 0$, we have numerically

$$\sigma(gg \to H_2) \sim 1250 |S^{g(Q)}_{H_2}|^2 \text{ fb},$$
$$\Gamma(H_2 \to \gamma\gamma) \sim 4.67 \times 10^{-5} |S^{\gamma(F)}_{H_2}|^2 \text{ GeV},$$
$$\Gamma(H_2 \to gg) \sim 8.88 \times 10^{-2} |S^{g(Q)}_{H_2}|^2 \text{ GeV},$$
$$\sigma(gg \to H_2) \times B(H_2 \to \gamma\gamma) \sim 11.8 \frac{(|S^{g(Q)}_{H_2} S^{\gamma(F)}_{H_2}|/90)^2}{(\Gamma_{H_2}/40 \text{ GeV})} \text{ fb} \tag{16}$$

where $\Gamma_{H_2} \sim \Gamma(H_2 \to \gamma\gamma) + \Gamma(H_2 \to gg) + \Gamma(H_2 \to H_1 H_1) + \Delta\Gamma^{H_2}_{\text{inv}}$.

First of all, to have $\Gamma(H_2 \to \gamma\gamma) \sim 40$ GeV, one needs $|S^{\gamma(F)}_{H_2}|^2 \sim 10^6$ which requires unlikely large value of $Q_F \gtrsim 10$ with $g^S_{s\bar{F}F} \sim 1$ and $m_F = 400 - 500$ GeV. If $Q_F \sim \mathcal{O}(1)$, $\Gamma(H_2 \to \gamma\gamma)$ is significantly smaller than 1 GeV since $|S^{\gamma(F)}_{H_2}|^2 \propto Q_F^4$. On the other hand, to have $\Gamma(H_2 \to gg) \sim 40$ GeV, one needs $|S^{g(Q)}_{H_2}|^2 \sim 4 \times 10^2$ which results in $\sigma(gg \to H_2) \sim 5 \times 10^5$ fb leading to enormous number of dijet events with $B(H_2 \to gg) \sim 1$. Therefore, one may need to have

$$\Gamma_{H_2} \sim \Gamma^{\text{non-SM}}_{H_2} \sim 40 \text{ GeV}. \tag{17}$$

Second, we note that $|S^{g(Q)}_{H_2} S^{\gamma(F)}_{H_2}| \sim 90$ to accommodate $\sigma(gg \to H_2) \times B(H_2 \to \gamma\gamma) \sim 10$ fb. Our representative choice of $S^{g(Q)}_{H_2} = 3$ can be easily realized if there are about 6 VLQs with $m_Q \sim 400$–500 GeV and $g^S_{s\bar{Q}Q} \sim 1$. Usually $|S^{\gamma(F)}_{H_2}|$ is larger than $|S^{g(Q)}_{H_2}|$ enhanced by the $2N_C Q_F^2$ factor together with additional contributions from VLLs. Therefore $S^{\gamma(F)}_{H_2} = 10 \times S^{g(Q)}_{H_2} = 30$ could be a reasonable choice.

Bearing all these observations, in Fig. 1, we show the decay width Γ_{H_2} (upper left), the cross section $\sigma(gg \to H_2) \times B(H_2 \to \gamma\gamma)$ (upper right), and the ratios $C^{g,\gamma}_{H_1}$ (lower) as functions of $\sin\alpha$ taking $S^{g(Q)} = 3$, $S^{\gamma(F)} = 10 \times S^{g(Q)} = 30$, and $\Gamma^{\text{non-SM}}_{H_2} = 40$ GeV. In the lower frames, the solid (dashed) lines are for $\eta^{g(Q)} = \eta^{\gamma(F)} = 2/3(1)$. We observe that the suggested scenario comfortably explains the properties of the 750 GeV diphoton resonance without any conflict with the precision data on 125 GeV Higgs. A full model-independent precision analysis of the 125-GeV Higgs and 750-GeV resonance data is to be addressed in a future publication [31].

Though we have concentrated on the case of $|\sin\alpha| < 0.1$, we find our solution with $S^{g(Q)} = 3$ and $S^{\gamma(F)} = 30$ remains to be valid up to $|\sin\alpha| \sim 0.4$ which is still allowed according to our global fits to the Higgs-portal

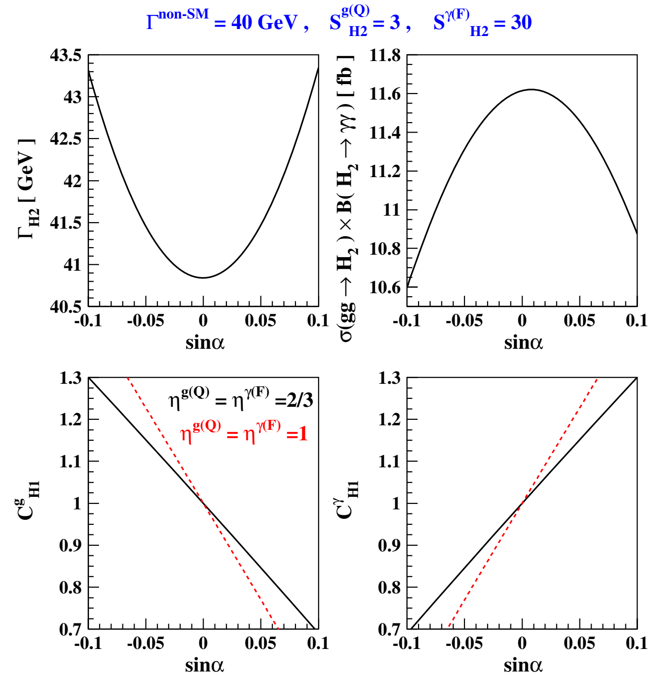

FIG. 1. The decay width Γ_{H_2} (upper left), $\sigma(gg\to H_2)\times B(H_2\to\gamma\gamma)$ (upper right), and the ratios $C_{H_1}^{g,\gamma}$ (lower) as functions of $\sin\alpha$. We have taken $S^{g(Q)}=3$, $S^{\gamma(F)}=10\times S^{g(Q)}=30$, and $\Gamma_{H_2}^{\text{non-SM}}=40$ GeV. In the lower frames, the solid (dashed) lines are for $\eta^{g(Q)}=\eta^{\gamma(F)}=2/3(1)$.

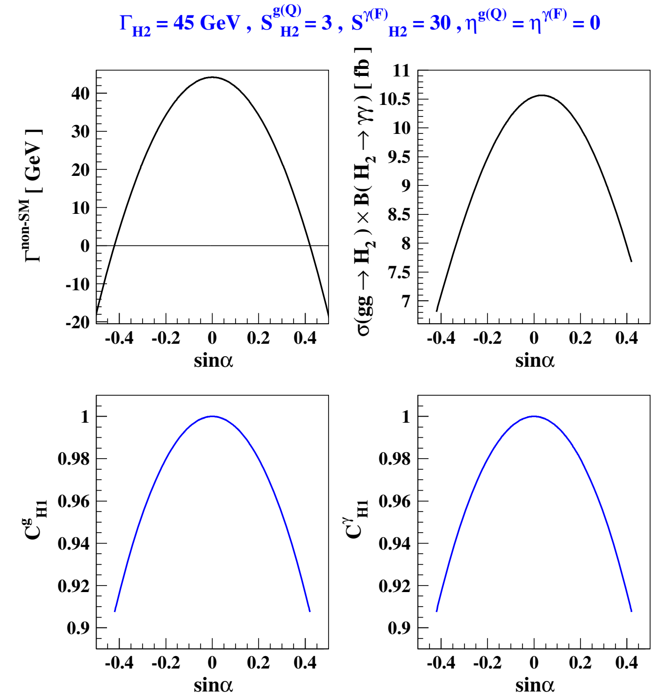

FIG. 2. The non-SM decay width $\Gamma_{H_2}^{\text{non-SM}}$ (upper left), $\sigma(gg\to H_2)\times B(H_2\to\gamma\gamma)$ (upper right), and the ratios $C_{H_1}^{g,\gamma}$ (lower) as functions of $\sin\alpha$. We have taken $S_{H_2}^{g(Q)}=3$, $S_{H_2}^{\gamma(F)}=30$, and $\Gamma_{H_2}=45$ GeV. In the upper-right and lower frames, the physical condition $\Gamma_{H_2}^{\text{non-SM}}>0$ is imposed.

type models [18], see Fig. 2. We fix $\Gamma_{H_2}=45$ GeV and tune $\Gamma_{H_2}^{\text{non-SM}}$ to accommodate it. And a general possibility of having $\eta^{g(Q))}=\eta^{\gamma(F)}=0$ is considered to satisfy the results of the global fits to the 125 GeV Higgs boson data. In this case, we note that $\sigma(gg\to H_2)\times B(H_2\to\gamma\gamma)\propto\cos^4\alpha$ and $C_{H_1}^{g,\gamma}=\cos\alpha$.

In the following, we would like to comment on H_2 decays into WW, ZZ, $t\bar{t}$, and gg. First, let us consider the case where H_2 is produced through the SM-singlet VLQs which only have couplings to g and γ. In this limit of no interactions between VLQs with the W/Z boson, H_2 decays into WW, ZZ, and $t\bar{t}$ through its SM Higgs component at the tree level while the decay into gg proceeds through the VLQ loops. In this case, the cross section times branching ratios are

$$\sigma(gg\to H_2)\times B(H_2\to WW)\simeq 400\ \text{fb}\left(\frac{S_{H_2}^{g(Q)}}{3}\right)^2\left(\frac{\sin\alpha}{0.1}\right)^2\left(\frac{40\ \text{GeV}}{\Gamma_{H_2}}\right)\left(\frac{\sigma_{\text{SM}}(gg\to H_2)}{800\ \text{fb}}\right),$$
$$\sigma(gg\to H_2)\times B(H_2\to ZZ)\simeq 200\ \text{fb}\left(\frac{S_{H_2}^{g(Q)}}{3}\right)^2\left(\frac{\sin\alpha}{0.1}\right)^2\left(\frac{40\ \text{GeV}}{\Gamma_{H_2}}\right)\left(\frac{\sigma_{\text{SM}}(gg\to H_2)}{800\ \text{fb}}\right),$$
$$\sigma(gg\to H_2)\times B(H_2\to t\bar{t})\simeq 90\ \text{fb}\left(\frac{S_{H_2}^{g(Q)}}{3}\right)^2\left(\frac{\sin\alpha}{0.1}\right)^2\left(\frac{40\ \text{GeV}}{\Gamma_{H_2}}\right)\left(\frac{\sigma_{\text{SM}}(gg\to H_2)}{800\ \text{fb}}\right),$$
$$\sigma(gg\to H_2)\times B(H_2\to gg)\simeq 200\ \text{fb}\left(\frac{S_{H_2}^{g(Q)}}{3}\right)^4\left(\frac{40\ \text{GeV}}{\Gamma_{H_2}}\right)\left(\frac{\sigma_{\text{SM}}(gg\to H_2)}{800\ \text{fb}}\right). \tag{18}$$

Given that the current upper limits on production of a resonance into a ZZ, WZ, or WW pair is about 150–200 fb for $M_X=750$ GeV at $\sqrt{s}=13$ TeV [32], our scenario is more or less safe if $|\sin\alpha|\lesssim 0.1$. At $\sqrt{s}=13$ TeV, the search for dijet resonances did not cover the dijet mass range below 1 TeV, and we did not find any search for $t\bar{t}$ resonances.

On the other hand, at $\sqrt{s}=8$ TeV, the gluon-fusion production cross section for a SM Higgs boson of 750 GeV is about 150 fb [33]. A combined search for WW, WZ, ZZ resonances has placed at upper limit of $\sigma(pp \to G^*) \times B(G^* \to VV)$ at slightly less than 100 fb for $M_{G^*} \approx 750$ GeV [34]. Therefore, the parameter regions of $|\sin\alpha| \lesssim 0.1$ are perfectly safe with this 8 TeV search. Another search for $t\bar{t}$ resonances put an upper limit of $\sigma(pp \to X) \times B(X \to t\bar{t})$ at about 0.5–1 pb for a few models [35], which is again very safe for our scenario. Yet, another search for dijet resonances [36] only covered the mass range from 0.85 TeV and up. At 0.85 TeV, the production rate limit is 1–2 pb, which hardly affects our scenario.

In general there can exist interactions between VLFs and W/Z bosons. To be specific, we consider the case in which VLQs share the SM $SU(2)$ and $U(1)_Y$ interactions. Then, in the limit of very small $\sin\alpha$, the decay of H_2 into WW as well as those into ZZ, $Z\gamma$ and $\gamma\gamma$ are dominated by the loops of VLQs. These loop-induced decay modes, especially the WW mode, are more model dependent than those into two gluons and two photons and we consider two representative scenarios for the interactions between VLQs with W/Z bosons.

In the scenario where VLQs are $SU(2)$ singlets with only hypercharge interactions, they do not couple to the W boson. While their interactions with the photon and the Z boson are described by

$$\mathcal{L}_{\rm VLQ} = -eQ_{\rm VLQ}\bar{Q}\gamma^\mu Q A_\mu - \frac{e}{s_W c_W}(-Q_{\rm VLQ}s_W^2)\bar{Q}\gamma^\mu Q Z_\mu, \tag{19}$$

where we are taking $e > 0$ with $s_W \equiv \sin\theta_W$, $c_W \equiv \cos\theta_W$, and $t_W = s_W/c_W$. We find that the effective vertices involving $H_2\gamma\gamma$, $H_2Z\gamma$, and H_2ZZ can be written as, up to an overall constant,

$$\mathcal{L} \propto H_2(F_{\mu\nu}F^{\mu\nu} + t_W F_{\mu\nu}Z^{\mu\nu} + t_W^2 Z_{\mu\nu}Z^{\mu\nu}), \tag{20}$$

and the ratio $\Gamma(H_2 \to ZZ):\Gamma(H_2 \to Z\gamma):\Gamma(H_2 \to \gamma\gamma)$ is approximately given by

$$\Gamma(H_2 \to ZZ):\Gamma(H_2 \to Z\gamma):\Gamma(H_2 \to \gamma\gamma) \approx t_W^4 : 2t_W^2 : 1, \tag{21}$$

ignoring the Z-boson mass in the final state. Taking $t_W \approx 0.55$, the ratio is $0.09:0.6:1$. For $\sigma(pp \to H_2 \to \gamma\gamma) \sim 10$ fb, we have $\sigma(pp \to H_2 \to ZZ) \approx 0.9$ fb and $\sigma(pp \to H_2 \to Z\gamma) \approx 6$ fb which correspond to 1.4 ZZ events and 130 $Z\gamma$ events using $Z \to \ell^+\ell^-$ with an accumulated luminosity of 300 fb^{-1} in the future LHC.

In another scenario, we place one pair of VLQs U and D in an $SU(2)$ doublet as $(U,D)^T = (U,D)_L^T + (U,D)_R^T$ which carries hypercharge Y. Then the electric charges are given by $Q_U = T_{3U} + Y$ and $Q_D = T_{3D} + Y$ and we have $Q_U - Q_D = 1$ independently of the hypercharge Y. Note we are taking $T_{3U} = -T_{3D} = 1/2$. In this case the interactions of the VLQs with gauge bosons are given by

$$\begin{aligned}\mathcal{L}_{\rm VLQ} = &-e(Q_U\bar{U}\gamma^\mu U + Q_D\bar{D}\gamma^\mu D)A_\mu \\ &- \frac{e}{s_W c_W}[\bar{U}\gamma^\mu U(T_{3U} - Q_U s_W^2) \\ &+ \bar{D}\gamma^\mu D(T_{3D} - Q_D s_W^2)]Z_\mu \\ &- \frac{e}{\sqrt{2}s_W}(\bar{U}\gamma^\mu D W_\mu^+ + \bar{D}\gamma^\mu U W_\mu^-).\end{aligned} \tag{22}$$

We note the couplings to the Z boson are purely vectorlike and proportional to the factors $T_{3U,3D} - Q_{U,D}s_W^2$ which are different from the SM case where only the left-handed quarks are participating in the $SU(2)$ interaction. It is possible to make a precise prediction in a simpler case in which, for example, $Y = 0$[4]:

$$\begin{aligned}&\Gamma(H_2 \to WW):\Gamma(H_2 \to ZZ):\Gamma(H_2 \to \gamma Z):\Gamma(H_2 \to \gamma\gamma) \\ &\quad\approx \frac{1}{2s_W^4(Q_U^2 + Q_D^2)^2} : \frac{1}{t_W^4} : \frac{2}{t_W^2} : 1,\end{aligned} \tag{23}$$

ignoring the W- and Z-boson masses. Taking $s_W^2 \approx 0.23$ and $Q_{U,D}^2 = 1/4$, we find the ratio is $38:11:6.6:1$. For $\sigma(pp \to H_2 \to \gamma\gamma) \sim 10$ fb, we have $\sigma(pp \to H_2 \to WW) \approx 380$ fb, $\sigma(pp \to H_2 \to ZZ) \approx 110$ fb, and $\sigma(pp \to H_2 \to Z\gamma) \approx 66$ fb which correspond to 5400 WW events, 180 ZZ events, and 1400 $Z\gamma$ events using $Z \to \ell^+\ell^-$ and $W \to \ell\nu$ with an accumulated luminosity of 300 fb^{-1} in the future LHC. This scenario is much more promising to probe compared to the previous one.

Before concluding, we would like to make a comment on the LHC constraints on VLQs. The VLQs have been actively searched for at the LHC. For example, the ATLAS and CMS collaborations carried out searches recently at $\sqrt{s} = 13$ TeV [38,39] and there was another one at 8 TeV [40]. The lower limits on VLQ mass range from about 750 GeV to about 1.7 TeV, depending on decay channels. Such channels include VLQ $\to bW, Zt, Ht$. Note that all the particles in the final states are visible and energetic because the mass differences between the VLQ and decay products are assumed to be large enough. Furthermore, the branching ratio into a chosen decay channel is assumed 100%. However, if the VLQ decays into invisible particles, e.g., dark matter, and other SM particles, and also if the mass difference between the VLQ and dark matter is small, then the energy available for the visible particles would be small. In these cases, the search would be more subtle and the constraints on VLQ can be significantly relaxed, such that a VLQ of mass as low as 400 GeV might evade the LHC constraints.

[4]We find a complete agreement between our results and those presented in Ref. [37]. A more detailed study considering various scenarios will be presented in Ref. [31].

IV. CONCLUSIONS

The hint of a potential 750 GeV particle observed by ATLAS and CMS is very intriguing. At the surface value of the large production cross section, it is hard to interpret it in the conventional Higgs extension models, such as 2HDMs or MSSM. However, if the additional particles exist, e.g. vectorlike fermions which are allowed to run in the $H_2\gamma\gamma$ and H_2gg vertex, it is possible to explain the large cross section and relatively large total width of the particle.

In this work, we have investigated the models with a singlet scalar that has renormalizable couplings to the vectorlike leptons and quarks, taking fully account of the doublet-singlet mixing. We have used the allowed parameter space regions that we obtained in recent global fits to the Higgs boson data. In the allowed space, we actually find solutions to the 750 GeV boson with $|\sin\alpha| \lesssim 0.1$, $\Gamma_{H_2} \sim \Gamma(H_2 \to H_1H_1) + \Delta\Gamma^{H_2}_{\rm inv} \sim 40$ GeV, and $|S^{g(Q)}_{H_2} S^{\gamma(F)}_{H_2}| \sim 90$. It remains to be seen if this excess will survive more data accumulation in the near future. Should the fitted cross section from the LHC experiments increase or decrease in the future, we can simply modify the product $|S^{g(Q)}_{H_2} S^{\gamma(F)}_{H_2}|$ to fit to it. If the 750 GeV excess turns out to be a new particle, new vectorlike fermions may accompany and could be of utterly importance at the LHC Run II.

As shown in this work, when the total decay width of the 750 GeV diphoton resonance is sizable, it would decay dominantly into invisible particles, which could give rise to monojet events with an addition gluon radiated from the initial-state gluons. Monojet events have been searched actively at the LHC, e.g., at $\sqrt{s} = 13$ TeV [41] and at $\sqrt{s} = 8$ TeV [42] by ATLAS (CMS has similar results), in which the 95% C.L. upper limits on monojet production cross sections due to DM are given. Let us focus on the 13 TeV data and, to be more specific, on a particular selection cut—IM1 ($E_T > 250$ GeV and $P_{T_j} > 250$ GeV). It gives an upper limit of $\sigma \times \text{Acceptance} \times \text{Efficiency} = 553$ fb. On the other hand, the production cross section of H_2 via gluon fusion is $\sigma(gg \to H_2) \sim 10^4$ fb, see the first equation in Eq. (16). In order to radiate an additional energetic gluon from the initial-state gluons, the cross section would decrease by a factor of $\alpha_s/2\pi \sim 10^{-2}$. Therefore, we expect a cross section of order 10^2 fb for monojet production which is obviously below the current experimental upper limit. We find that the case at 8 TeV would be similar. Therefore, the current production of H_2, which decays dominantly into DM, would still be consistent with the monojet searches at the LHC.[5]

ACKNOWLEDGMENTS

This work is supported in part by National Research Foundation of Korea (NRF) Research Grant No. NRF-2015R1A2A1A05001869, and by the NRF grant funded by the Korea government (MSIP) (No. 2009-0083526) through Korea Neutrino Research Center at Seoul National University (PK). The work of K. C. was supported by the MoST of Taiwan under Grants No. NSC 102-2112-M-007-015-MY3.

[5]Also this channel is dependent on the UV completion of DM models as well as DM being scalar, fermion or vector boson for scalar mediator cases (for example, see Ref. [43] for the Higgs portal DM case).

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