

REVIEW ARTICLE

Distinguish models mimicking the SM Higgs^{*}

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The new particle around 125 GeV observed at the LHC is almost consistent with the standard model Higgs boson, except that the diphoton decay mode may be excessive. We summarize a number of possibilities. We propose to use the vector-boson fusion to test the underlying model for electroweak symmetry breaking. Using the well known dijet-tagging technique to single out the vector-boson fusion mechanism, we investigate potential of vector-boson fusion to discriminate a number of models suggested to give an enhanced inclusive diphoton production rate.

Keywords Higgs boson, vector-boson fusion, diphoton, electroweak symmetry breaking

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Contents

1	Introduction	285
2	Models	286
2.1	Standard model Higgs boson	286
2.2	Two-Higgs-doublet model (2HDM)	286
2.3	Supersymmetric Higgs boson: MSSM	287
2.4	Fermiophobic Higgs	287
2.5	The radion	288
2.6	Inert Higgs doublet model (IHDM)	288
3	Vector-boson fusion (VBF)	289
4	Decay branching ratios	289
5	Production rates in vector-boson fusion	290
6	Conclusions	291
	Acknowledgements	292
	References and notes	292

1 Introduction

We summarize a few models that have been suggested to explain the newly observed particle of about 125 GeV at the Large Hadron Collider (LHC) [1, 2]. It is of very high expectation that the observed particle is the long-sought Higgs boson, which was proposed in 1960s [3–5].

Before the LHC era there have been many speculations of the breaking of electroweak symmetry. The so-called gauge hierarchy problem requires that new physics has to come in around TeV scale in order to satisfy the naturalness argument in particle physics. Historically, there are two categories of models: one with a strongly-coupled electroweak symmetry breaking (EWSB) sector and one with a weakly-coupled EWSB sector. The most studied model for strong EWSB is the technicolor-type model [6] while that for weakly-coupled EWSB model is the supersymmetry [7]. In technicolor models, the standard model (SM) is simply an effective model below TeV scale, at which the theory is replaced by another strong dynamics. Therefore, the cutoff scale now becomes just TeV. On the other hand, supersymmetric models predict another set of particles, which differ from their SM counter parts by a half-integral spin. Quadratically divergent contributions to the Higgs boson radiative corrections are cancelled among the SM particles and the corresponding supersymmetric particles.

If the Superconducting Super Collider (SSC) was built the Higgs boson could have been discovered in early 2000s with perhaps a short running of the machine. Since the Higgs boson has been hiding for such a long time,

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many interesting alternatives were proposed in the last 10–15 years. Around the turn of the century extra dimension models became very popular, not to mention there have been a large number of varieties – large extra dimension [8], universal extra dimension [9], Randall–Sundrum models [10], etc. There are also the little Higgs type models [11]. In contrast to supersymmetry the new particles have the spin as their SM counter parts. Contributions to the Higgs boson radiative corrections are cancelled among the SM particles and the corresponding new particles. Perhaps, more and more models would have been proposed if the Higgs boson kept hiding. Would not it be more fascinating for theorists?

In the past few years, the high energy community has been very excited with a number of experimental anomalies from the Tevatron, LHC, and dark matter (DM) experiments. The long-time inconsistency among the DAMA results [12] (also the CoGeNT [13]) and the other direct detection experiments [14, 15] has motivated a number of unconventional dark matter models. The top-quark forward-backward asymmetry observed by the CDF and DØ collaborations is rather puzzling too [16–18]. Many models such as flavor-changing Z' , unusual W' , axigluon, etc. [19] were proposed, but the new LHC results seem ruled out almost all of these models [20]. The CDF Wjj anomaly in 2011 [21] also stimulated a large number of theoretical or phenomenological models to account for the observation [22]. However, with non-observation of the resonance from DØ and CMS [23, 24] the excitement gradually died out.

The discovery of the Higgs boson was jointly announced in July 2012 by ATLAS [1] and CMS [2]. All the observed channels, WW , ZZ and $\gamma\gamma$ are consistent with the predictions of the SM Higgs boson, except that the $\gamma\gamma$ rate is somewhat higher than expectation. The $b\bar{b}$ and $\tau\tau$ channels are not confirmed yet, because of large uncertainties.

The diphoton production rate is about a factor of 1.3–2 higher than that of the standard model Higgs boson. Nevertheless, the observed rates are consistent with either the SM Higgs boson or some other Higgs models. A large number of models have been put forward to account for the observed particle at 125 GeV, including the SM, MSSM, NMSSM, UMSSM and other MSSM-extended models, fermiophobic Higgs, 2HDM, RS radion, inert-Higgs doublet, triplet Higgs models, etc.

The $H \rightarrow \gamma\gamma$ events collected by CMS and ATLAS can be divided into two categories: *inclusive* $\gamma\gamma X$ and *exclusive* $\gamma\gamma jj$. Presumably, the inclusive $\gamma\gamma X$ events include all production channels such as gluon fusion, vector-boson fusion, associated production, etc, among which gluon fusion dominates for production of the SM Higgs boson and most of the models considered in this talk,

except for the fermiophobic Higgs boson. On the other hand, exclusive $\gamma\gamma jj$ events mainly come from vector-boson fusion and associated production, which can be further disentangled by jet-tagging techniques.

The disadvantage of gluon fusion is that it is not clear what particles and their masses running in the triangle loop. In some models, the contribution from a particular charged particle can increase or decrease the diphoton decay width, depending on the relative signs. On the other hand, the advantage of using WW fusion is that the production diagram is clean and directly testing the couplings of hWW and hZZ . The WW fusion can be extracted by the presence of two energetic forward jets. We can impose selection cuts to select jets in forward rapidity and high energy region [25, 26].

We summarize all the models and find the parameter space of each model that have been proposed to explain the excess in the inclusive Higgs diphoton events, and attempt in distinguishing the models using the exclusive $\gamma\gamma jj$ channel in vector-boson fusion (VBF) [27]. The exclusive VBF events with $\gamma\gamma jj$ in the final state are selected using the forward jet-tagging techniques which will be explained shortly. We will first choose the parameter-space region of each model that can account for the excess in the inclusive diphoton rate, and then in that region of parameter space we calculate the exclusive $jj\gamma\gamma$ VBF production rates. We found that the exclusive $\gamma\gamma jj$ production rate in VBF channel can give more information to help in distinguishing a number of popular models.

The organization of this paper is as follows. We briefly highlight a number of models in the next section, and the WW fusion and selection cuts in Section 3. We give the decay branching ratios in Section 4 and production rates in Section 5. We conclude in Section 6.

2 Models

2.1 Standard model Higgs boson

The SM Higgs boson [3] is still the most favorable candidate to interpret the observed boson, though the experimental data showed slightly excess in inclusive $\gamma\gamma X$ events over the prediction of the SM Higgs boson [1, 2]. Production of the SM Higgs boson is dominated by gluon fusion, which is an order of magnitude larger than the next important mechanism – VBF.

2.2 Two-Higgs-doublet model (2HDM)

There are two Higgs doublets instead of just one in the 2HDM. In order to avoid dangerous tree level flavor-changing neutral currents, the popular 2HDMs are im-

posed a discrete symmetry. In this review, we focus on the type II, which has the same Higgs sector as the MSSM. The Higgs sector consists of two Higgs doublets

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix}$$

where the subscripts u, d denote the right-handed quark singlet field that the Higgs doublet couples to. The electroweak symmetry is broken when the Higgs doublet fields develop the VEVs. Physically, there are two CP-even, one CP-odd, and a pair of charged Higgs bosons after EWSB. The Yukawa couplings and masses for fermions can be obtained from the following Yukawa interactions after EWSB

$$\mathcal{L}_{\text{Yuk}} = -y_u \bar{Q}_L u_R \tilde{H}_u - y_d \bar{Q}_L d_R H_d + h.c.$$

where $\tilde{H}_u = i\tau_2 H_u^*$. The parameters of the model in the CP-conserving case include

$$m_h, m_H, m_A, m_{H^\pm}, \tan \beta \equiv \frac{v_u}{v_d}, \alpha$$

where α is the mixing angle between the two CP-even Higgs bosons. The couplings of the two lighter and heavier CP-even Higgs bosons h and H respectively and the CP-odd Higgs boson A to the top, bottom quarks, and taus are given by, with a common factor of $-igm_f/(2m_W)$ being suppressed

	$t\bar{t}$	$b\bar{b}$	$\tau^-\tau^+$
h :	$\cos \alpha / \sin \beta$	$-\sin \alpha / \cos \beta$	$-\sin \alpha / \cos \beta$
H :	$\sin \alpha / \sin \beta$	$\cos \alpha / \cos \beta$	$\cos \alpha / \cos \beta$
A :	$-i \cot \beta \gamma_5$	$-i \tan \beta \gamma_5$	$-i \tan \beta \gamma_5$

Other relevant couplings in WW fusion are those to gauge bosons given by

$$\begin{aligned} hW^+W^- : & \quad ig m_W \sin(\beta - \alpha) g^{\mu\nu} \\ hZZ : & \quad ig m_Z \frac{\sin(\beta - \alpha)}{\cos \theta_W} g^{\mu\nu} \end{aligned}$$

Dominant production of the light CP-even Higgs boson h at the LHC is via gluon fusion, similar to the SM Higgs boson with the top quark running in the loop; however, in the large $\tan \beta$ region the bottom-quark contribution can also be substantial. Since the bottom-Yukawa coupling can be substantially enhanced, the gluon fusion cross section can be larger than the SM. On the other hand, since the couplings of the h to the WW and ZZ are simply the SM values multiplied by $\sin(\alpha - \beta)$, WW fusion cross sections are in general smaller than the SM.

The overall diphoton production rate $\sigma(gg \rightarrow h) \times B(h \rightarrow \gamma\gamma)$ in gluon fusion can easily vary between 0.5–2 of the SM prediction depending on parameters [28]. It was shown in Ref. [28] that the enhancement in branch-

ing ratio can be obtained roughly along $\sin \alpha$ near zero for all $\tan \beta$ in the type II model.

2.3 Supersymmetric Higgs boson: MSSM

In order to achieve a mass of 125 GeV for the lighter CP-even Higgs boson, a very large radiative correction is needed, which essentially comes from top-stop loop. The approximate formula for the lighter CP-even Higgs boson is given by [29]

$$\begin{aligned} m_h^2 \approx & m_Z^2 \cos^2(2\beta) + \frac{3m_t^4}{4\pi^2 v^2} \\ & \cdot \left[\frac{1}{2} X_t + t + \frac{1}{16\pi^2} \left(\frac{3m_t^2}{2v^2} - 32\pi\alpha_s \right) t (X_t + t) \right] \end{aligned} \quad (1)$$

where

$$\begin{aligned} X_t &= \frac{2(A_t - \mu \cot \beta)^2}{M_{\text{SUSY}}^2} \left[1 - \frac{(A_t - \mu \cot \beta)^2}{12M_{\text{SUSY}}^2} \right] \\ t &= \frac{M_{\text{SUSY}}^2}{m_t^2} \end{aligned} \quad (2)$$

and $M_{\text{SUSY}} \sim 1$ TeV is the SUSY scale. A large A_t is needed to generate a large correction. Here we use $m_{Q_3} = m_{U_3} = 850$ GeV, $A_t = 1.4$ TeV, $m_A = 1$ TeV, and $\tan \beta = 60$. The reason behind such a large $\tan \beta$ is the stau contribution to the diphoton branching ratio explained below [29].

The decay into diphoton is more involved in SUSY models. All charged particles, including squarks, sleptons, charginos, charged Higgs boson can flow in the triangle loop. With the present constraints from experiments, the production rate into diphoton in the MSSM can hardly be enhanced by more than a factor of 1.5 [29], by pushing one of the stau to be very light. Without loss of generality we choose

$$\begin{aligned} m_{L_3} &= m_{e_3} = 200 - 450 \text{ GeV}, \quad \text{and} \\ \mu &= 200 - 1000 \text{ GeV} \end{aligned} \quad (3)$$

in which we can scan for the diphoton production rate $\sigma(gg \rightarrow h)B(h \rightarrow \gamma\gamma)$ to be larger than the SM rate. The region essentially gives a light stau, which can enhance the $B(h \rightarrow \gamma\gamma)$. We scan the region according to Eq. (3) and require the mass of the lighter CP-even Higgs boson around 125 GeV and the diphoton production rate larger than the SM value¹⁾. There are also studies for various extensions of the MSSM [31–33].

2.4 Fermiophobic Higgs

With the name “fermiophobic” (FP) the Higgs boson

¹⁾ There is another possibility that the heavier CP-even Higgs boson can be at around 125 GeV and its diphoton production rates can be enhanced relative to the SM one [30]. We will not pursue this further here.

only couples to the vector bosons at tree level, though higher-loop corrections can induce small couplings to fermions. In this case, the Yukawa couplings and masses of fermions are generated by some other mechanisms, which are not of concern in this review.

The coupling strength of the FP Higgs boson to vector bosons is the same as that of the SM Higgs boson. We write the interactions as

$$\mathcal{L}_{\text{FP}} = -gm_W h_{\text{FP}} W_\mu^+ W^{-\mu} - \frac{gm_Z}{2 \cos \theta_W} h_{\text{FP}} Z_\mu Z^\mu \quad (4)$$

Since the FP Higgs boson does not couple to quarks, it cannot be produced dominantly by gluon fusion at hadronic colliders, but only through the vector-boson fusion and the associated production with a W/Z boson. The corresponding production cross sections are the same as the VBF of the SM Higgs boson. Nevertheless, the FP Higgs boson lighter than 130 GeV has a much larger branching ratio into diphoton, such that it can still account for the observed diphoton rate at the LHC [34]. There are two reasons: (i) the FP Higgs boson decay into fermions is highly suppressed with only the loop-induced couplings, and (ii) the decay into photons is via a loop of W boson without the negative interference from the top quark. Thus, the branching ratio into diphoton can be enhanced by more than an order of magnitude. Overall, the diphoton production rate at the LHC is comparable to the SM Higgs boson, as was used to account for the observed boson [34].

2.5 The radion

The RS model [10] used a warped 5D space-time, a slice of the symmetric space AdS_5 , to explain the gauge hierarchy problem. The extra dimension φ is a single S^1/Z_2 orbifold with one hidden and one visible 3-brane localized at $\varphi = 0$ and π , respectively. A stabilization mechanism was proposed in Ref. [35] by adding a bulk scalar field propagating in the background solution which can generate a potential to stabilize the modulus field. As a consequence, the lightest excitation mode of the modulus field is the radion, which has a mass of the order of 100 GeV to a TeV, and the strength of its coupling to the SM fields is of the order of $O(1/\text{TeV})$ [36].

The interactions of the stabilized modulus (radion) ϕ with the SM particles on the visible brane are completely determined by 4-dimensional general covariance, given by

$$\mathcal{L}_{\text{radion}} = \frac{\phi}{\Lambda_\phi} T_\mu^\mu(\text{SM}) \quad (5)$$

where $\Lambda_\phi = \langle \phi \rangle$ is of the order of TeV and T_μ^μ is the trace of the SM energy-momentum stress tensor, given by

$$T_\mu^\mu(\text{SM}) = -2m_W^2 W_\mu^+ W^{-\mu} - m_Z^2 Z_\mu Z^\mu$$

$$+ \sum_f m_f \bar{f} f + (2m_h^2 h^2 - \partial_\mu h \partial^\mu h) + \cdots \quad (6)$$

The coupling of the radion to a pair of gluons (photons) is induced at one loop level, with the dominated contributions coming from the heavy top quark (top quark and W) as well as from the trace anomaly in QCD (QED). In addition, $gg \rightarrow \phi$ gets substantial enhancement from the trace anomaly [37]. For the decay of the radion, it is dominated by the gg mode instead of $b\bar{b}$ at the low mass region, while its diphoton branching ratio is merely a fraction of the SM value of $h_{\text{SM}} \rightarrow \gamma\gamma$.

Overall, the diphoton production rate $\sigma(gg \rightarrow \phi) \times B(\phi \rightarrow \gamma\gamma)$ can be larger than the SM rate if the scale Λ_ϕ is small enough. If we are not concerned about naturalness, the scale Λ_ϕ can be as small as 0.8 TeV. Here we fix the scale Λ_ϕ to be 0.8–0.99 TeV, which can enhance the diphoton production rate in gluon fusion by a factor of 1.5–1.0 [38, 39] relative to the SM rate.

2.6 Inert Higgs doublet model (IHDM)

IHDM is a special case of 2HDM, in which one of the doublets takes on the role of the SM Higgs doublet, while the other one is inert which means that it entirely decouples from the SM leptons, quarks, and gauge bosons. Physically, there are 2 CP-even scalars (h, S), 1 CP-odd scalar (A), and a pair of charged Higgs ($H^\pm$). The h plays the role of the SM Higgs boson while the others are inert. A list of parameters of the model includes $m_h, m_S, m_A, m_{H^\pm}, \mu_2$, and λ_2 .

Production via gluon fusion and via WW fusion are the same as the SM Higgs boson. However, the decay into $\gamma\gamma$ receives additional contributions from the $H^\pm$ running in the loop. If kinematically allowed the Higgs boson h can also decay into $H^+ H^-$, AA , and SS . For simplicity and to achieve a large enough branching ratio into $\gamma\gamma$ we set the masses of $S, A, H^\pm$ to be above the threshold ($m_h/2$). In this model, the coupling between the charged Higgs boson and the SM Higgs boson h is given by

$$g_{hH^+H^-} = -i \frac{e}{m_W \sin \theta_W} (m_{H^\pm}^2 - \mu_2^2) \quad (7)$$

It is clear that from this equation the sign of the charged Higgs contribution to the triangular loop can be positive or negative, depending on the sizes of $m_{H^\pm}$ and μ_2 . Thus, if we set $m_{H^\pm} = \mu_2$, the charged Higgs contribution vanishes and so the diphoton branching ratio becomes the same as the SM one.

It was shown in Ref. [40] that in gluon fusion the diphoton production rate is determined by the product of gluon-fusion cross section and the $\gamma\gamma$ branching ratio, which can be varied from about 0.5 to 2. It was shown in Ref. [40] that when $m_{H^\pm}^2 < \mu_2^2$ the diphoton branching

ratio is enhanced. Together with other theoretical constraints one can find the region to be $|\mu_2| \approx 100 - 200$ GeV and $m_{H^\pm} < |\mu_2|$.

3 Vector-boson fusion (VBF)

The most distinguished feature of VBF at hadronic colliders is the appearance of two energetic forward jets separated by a large $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, where η is the pseudo-rapidity and ϕ is the azimuth angle. The Feynman diagram is shown in Fig. 1. Each of the initial quarks radiates a W/Z boson, which further annihilates into the Higgs boson. The unique feature of this process is that “the W/Z bosons participating in the fusion process are close to on-shell [41], and irrespective whether the W/Z is longitudinal or transverse, the scattered quark carries almost all the energy of the incoming quark and goes in the forward direction.” [25, 26]. Based on this feature we impose the following experimental cuts in selecting the dijet events coming dominantly from the VBF:

$$E_{T_j} > 30 \text{ GeV}, \quad |\eta_j| < 4.7, \quad \Delta R_{jj} > 3.5 \quad (8)$$

and

$$\begin{aligned} (\text{Ejcut}) \quad E_{j_1} &> 500 \text{ GeV}, \quad \text{or} \\ (\text{Mjjcut}) \quad M_{jj} &> 350 \text{ GeV} \end{aligned} \quad (9)$$

where the subscript “1” denotes the most energetic jet. In the cut of Eq. (9), we choose either the energy of the most energetic jet $E_{j_1} > 500$ GeV or the invariant mass of the jet pair $M_{jj} > 350$ GeV.

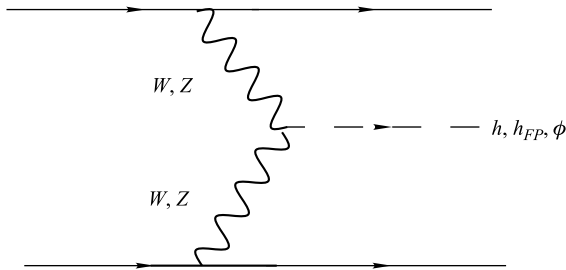


Fig. 1 A Feynman diagram showing the vector-boson fusion into SM Higgs, FP Higgs or radion.

The vector-boson fusion is well-known that it allows to probe the direct coupling between the vector bosons and the Higgs boson or other particles under consideration. This is in contrast to the gg fusion, because any colored particles can flow in the triangular loop and affect the production rate. For example, in MSSM all squarks can circulate inside the loop.

4 Decay branching ratios

Here we list the decay branching ratio into $\gamma\gamma$ for the SM

Higgs boson, fermiophobic Higgs boson, and the radion of mass 125 GeV, IHDM, 2HDM, and the MSSM Higgs boson in Table 1. The branching ratio of a FP Higgs boson into diphoton can be an order of magnitude larger than that of the SM Higgs boson, because it does not decay into fermions. That is the reason why it can account for the observed 125 Higgs boson at the LHC, even though its gluon fusion production cross section is very small. The case of the radion is opposite to the FP Higgs. The diphoton branching ratio of the radion is a few times smaller than that of the SM, while its production rate via gg fusion is substantially enhanced.

Table 1 Decay branching ratio $B(h \rightarrow \gamma\gamma)$ for the SM Higgs boson h_{SM} , the fermiophobic Higgs boson h_{FP} , the radion ϕ , the inert Higgs doublet model, the two Higgs doublet model, and the MSSM.

Parameter space			$B(h \rightarrow \gamma\gamma)$
SM			2.3×10^{-3}
FP			1.5×10^{-2}
Radion	$\Lambda_\phi = 0.8\text{--}1 \text{ TeV}$		0.57×10^{-3}

	μ_2/GeV	$m_{H^\pm}/\text{GeV}$	$B(h \rightarrow \gamma\gamma)$
IHDM1	200	70	6.7×10^{-3}
IHDM2	200	100	3.3×10^{-3}
IHDM3	200	150	2.5×10^{-3}
IHDM4	200	200	2.3×10^{-3}
IHDM5	150	70	4.2×10^{-3}
IHDM10	100	90	2.4×10^{-3}

	$\sin \alpha$	$\tan \beta$	$B(h \rightarrow \gamma\gamma)$
2HDM1	0	1.5	3.8×10^{-3}
2HDM2	0	5	6.5×10^{-3}
2HDM3	0	10	6.8×10^{-3}
2HDM4	0	20	6.9×10^{-3}

MSSM					
	$m_{L_3}=m_{E_3}$	μ	m_h	$B(h \rightarrow \gamma\gamma)$	$\frac{\sigma(gg \rightarrow h)B(h \rightarrow \gamma\gamma)}{\sigma(gg \rightarrow h_{\text{SM}})B(h_{\text{SM}} \rightarrow \gamma\gamma)}$
BP1	250	400	127.0	2.4×10^{-3}	1.02
BP2	250	500	126.2	2.9×10^{-3}	1.19
BP3	250	536	125.4	3.6×10^{-3}	1.45
BP4	300	536	126.8	2.4×10^{-3}	1.005
BP5	300	700	125.4	2.8×10^{-3}	1.15
BP6	300	763	123.7	3.4×10^{-3}	1.38
BP7	350	700	126.6	2.4×10^{-3}	0.999
BP8	350	800	125.8	2.5×10^{-3}	1.03
BP9	350	927	123.9	2.7×10^{-3}	1.11

The choice for the parameters of the IHDM such that the diphoton branching ratio is enhanced relative to the SM one: $|\mu_2| \approx 100\text{--}200$ GeV and $m_{H^\pm} < |\mu_2|$. The branching ratios into $\gamma\gamma$ for the light CP-even Higgs boson in the 2HDM can be enhanced along $\sin \alpha \approx 0$ and $\tan \beta = 5\text{--}20$.

In the MSSM, we choose the region where the lighter CP-even Higgs boson is around 125 GeV (123–128 GeV) and the diphoton production rate $\sigma(gg \rightarrow h)B(h \rightarrow \gamma\gamma)$

is equal to or larger than the SM value. As explained above the stop sector must be heavy in order to achieve a mass of 125 GeV for the lighter CP-even Higgs boson. First, we fix the $m_{Q_3} = m_{U_3} = 850$ GeV and $A_t = 1.4$ TeV with $\tan\beta = 60$ and $m_A = 1$ TeV. Second, we vary $m_{E_3} = m_{L_3}$ and μ to achieve a light stau so as to enhance the diphoton production rate. We show in Fig. 2 the region in the plane of $(m_{E_3} = m_{L_3}, \mu)$ that the $m_h = 123\text{--}128$ GeV and the ratio $\sigma(gg \rightarrow h)B(h \rightarrow \gamma\gamma)/\sigma(gg \rightarrow h_{\text{SM}})B(h_{\text{SM}} \rightarrow \gamma\gamma)$ is larger than 1.

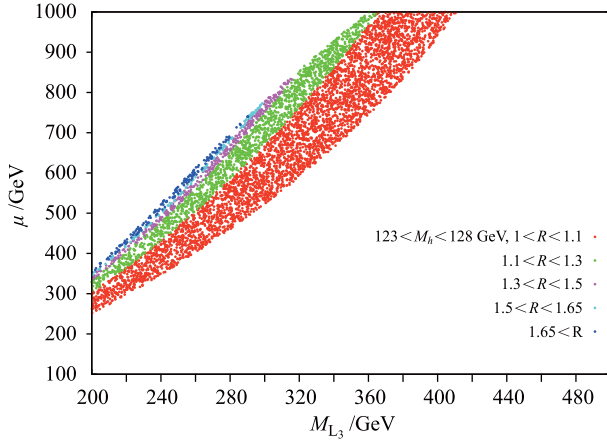


Fig. 2 The parameter space region where $m_h = 123\text{--}128$ GeV and $R = \sigma(gg \rightarrow h)B(h \rightarrow \gamma\gamma)/\sigma(gg \rightarrow h_{\text{SM}})B(h_{\text{SM}} \rightarrow \gamma\gamma)$ is larger than 1. The other fixed parameters are $m_{Q_3} = m_{U_3} = 850$ GeV, $A_t = 1.4$ TeV, $\tan\beta = 60$ and $m_A = 1$ TeV.

5 Production rates in vector-boson fusion

We calculate the VBF cross sections for $pp \rightarrow jjh$ for various models under consideration. We impose the selection cuts for energetic forward jets as in Eqs. (8) and (9). We let the Higgs boson decay into $\gamma\gamma$, and impose the following cuts on the photons:

$$\begin{aligned} E_{T_\gamma} &> 30 \text{ GeV}, \quad |\eta_\gamma| < 2.5 \\ |m_{\gamma\gamma} - m_h| &< 3.5 \text{ GeV} \end{aligned} \quad (10)$$

We present numerical results in detector-simulation level by employing the PYTHIA-PGS (PYTHIA v6.420, PGS4(090401)) package inside MADGRAPH [42]. More details can be found in Refs. [42, 43]. The numerical results for LHC-7, LHC-8, and LHC-14 are listed in Table 2 for the SM, FP, radion, IHDM, 2HDM, and the MSSM.

It would be more transparent to show the production rate relative to the SM one

$$\frac{\sigma(pp \rightarrow jjX) \times B(X \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow jjh_{\text{SM}}) \times B(h_{\text{SM}} \rightarrow \gamma\gamma)} \quad (11)$$

where X stands for the SM Higgs or any other Higgs-like candidate in various models. We found that this ratio is quite robust against various cuts [Mjcut or Ejcut as in

Table 2 Production rates in fb at PGS level for $pp \rightarrow jjh \rightarrow jj\gamma\gamma$ at LHC-7 (LHC-8, LHC-14).

	Photon cuts and Ejcut	Photon cuts and Mjcut
SM	0.15 (0.19, 0.61)	0.33 (0.41, 1.1)
FP	1.03 (1.27, 4.12)	2.24 (2.78, 7.35)
Radion	0.0038 (0.0047, 0.014)	0.0076 (0.0095, 0.026)
IDHM1	0.44 (0.56, 1.79)	0.97 (1.21, 3.23)
IDHM2	0.22 (0.28, 0.88)	0.48 (0.59, 1.59)
IDHM3	0.16 (0.21, 0.67)	0.36 (0.45, 1.21)
IDHM4	0.15 (0.19, 0.62)	0.33 (0.41, 1.11)
IDHM5	0.28 (0.35, 1.12)	0.61 (0.76, 2.03)
IDHM10	0.16 (0.20, 0.64)	0.35 (0.43, 1.16)
2HDM1	0.17 (0.22, 0.70)	0.38 (0.47, 1.25)
2HDM2	0.41 (0.52, 1.66)	0.90 (1.11, 2.99)
2HDM3	0.44 (0.56, 1.79)	0.97 (1.20, 3.23)
2HDM4	0.45 (0.58, 1.85)	1.00 (1.24, 3.33)
MSSM BP	Photon cuts and Ejcut	Photon cuts and Mjcut
BP1	0.19 (0.28, 0.83)	0.44 (0.57, 1.47)
BP2	0.22 (0.33, 0.97)	0.52 (0.66, 1.76)
BP3	0.29 (0.40, 1.18)	0.63 (0.82, 2.10)
BP4	0.19 (0.28, 0.85)	0.43 (0.56, 1.46)
BP5	0.22 (0.32, 0.92)	0.50 (0.65, 1.65)
BP6	0.27 (0.38, 1.07)	0.61 (0.75, 1.90)
BP7	0.20 (0.26, 0.85)	0.43 (0.53, 1.47)
BP8	0.21 (0.29, 0.85)	0.44 (0.59, 1.48)
BP9	0.22 (0.30, 0.92)	0.49 (0.59, 1.66)

Eq. (9)] and against the energy of the collision.

In the upper panel of Fig. 3, we first show the ratio for the *inclusive* diphoton production rate $\frac{\sigma(X) \times B(X \rightarrow \gamma\gamma)}{\sigma(h_{\text{SM}}) \times B(h_{\text{SM}} \rightarrow \gamma\gamma)}$ of each model, which is dominated by gluon fusion, except for the FP Higgs boson. The parameter space of each model is chosen such that this inclusive diphoton rate is equal to or larger than the SM rate except for the FP Higgs boson which has no free parameter. For the same parameter space, we show in the lower panel the ratio for the *exclusive* $jj\gamma\gamma$ production rate $\frac{\sigma(pp \rightarrow jjX) \times B(X \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow jjh_{\text{SM}}) \times B(h_{\text{SM}} \rightarrow \gamma\gamma)}$ for each model. The figure is valid for LHC-7, LHC-8 and LHC-14, and for using either Mjcut cut on both forward jets or Ejcut cut on the most energetic jet.

It is clear that the models can be employed to explain the excess in the inclusive diphoton rates in some parameter space region, but for the same region of parameter space the ratio of exclusive VBF production would be different among the models. The FP Higgs would be a number of times larger than the SM in the VBF channel, but the RS radion would give negligible exclusive VBF production. On the other hand, the IHDM, 2HDM, and the MSSM would give similar ratios in both inclusive and exclusive production. The 2HDM can give a somewhat smaller ratio in the exclusive VBF.

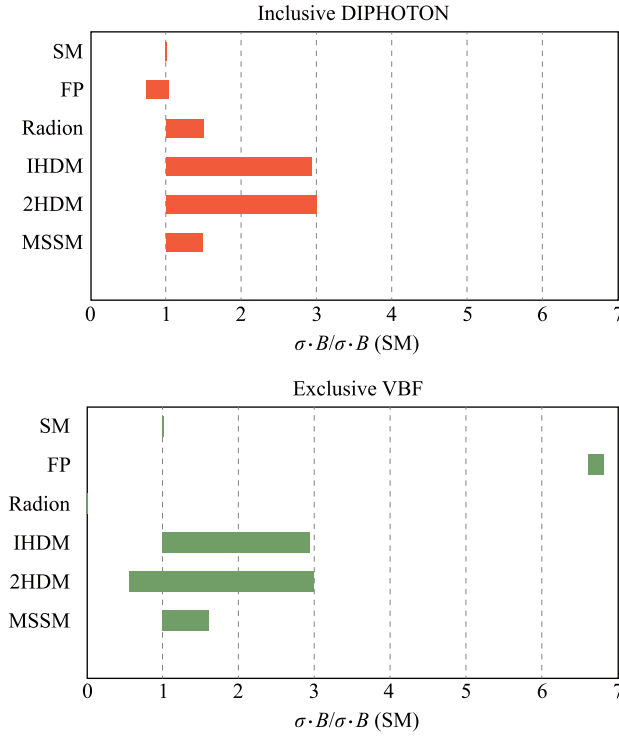


Fig. 3 Upper: The ratio of *inclusive* diphoton production rates $\frac{\sigma(X) \times B(X \rightarrow \gamma\gamma)}{\sigma(h_{SM}) \times B(h_{SM} \rightarrow \gamma\gamma)}$ for various models. The parameter space is chosen such that the ratio is equal to or larger than 1, except for the FP Higgs boson which has no free parameter. Lower: The ratio of the *exclusive* $jj\gamma\gamma$ production rate $\frac{\sigma(pp \rightarrow jjX) \times B(X \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow jjh_{SM}) \times B(h_{SM} \rightarrow \gamma\gamma)}$ for each model in the corresponding parameter space.

Background discussion.

The dominant backgrounds to $h \rightarrow \gamma\gamma$ consist of i) the irreducible background from the prompt diphoton production, and ii) the reducible backgrounds from $pp \rightarrow \gamma + j$ and $pp \rightarrow jj$, when one or more of the jets hadronize into (typically neutral) pions and deposit energy in the electromagnetic calorimeter. These reconstructed objects are generally referred to as fake photons. Isolation is a very useful tool to reject the non-prompt background coming from electromagnetic showers originating in jets, because these fake photons are often accompanied by single and multiple π^0 s. The signal from $h \rightarrow \gamma\gamma$ will be identified as a sharp peak in the $m_{\gamma\gamma}$ distribution, where the background is in continuum.

Given that we have obtained the event rates of each model in the tables, which have been under experimental cuts and simulations (PGS), it is straightforward to estimate the required luminosity to probe various scenarios. The continuum background at the 7 TeV and 8 TeV LHC in VBF channel has been obtained in Refs. [44] and [2]. Since the SM Higgs boson has been seen above the background with some significance level in the VBF channel in the current LHC runs (about 5 fb^{-1} at 7 TeV and about 5 fb^{-1} at 8 TeV), the scenarios with

higher event rates than the SM Higgs boson should be detectable. The projected integrated luminosity at the end of 2012 is about $10\text{--}15 \text{ fb}^{-1}$ for each experiment. It would not be a problem to investigate the scenarios in the VBF channel.

6 Conclusions

The likelihood for a new discovery is rather high. Nevertheless, whether this new particle is the SM Higgs boson is not an easy question to answer. Here the scenario of this 125 GeV particle produced by vector-boson fusion, instead of gluon fusion as the dominant production mechanism for the standard model Higgs boson, is studied in details. By using the forward dijet tagging technique, one can single out the vector-boson fusion mechanism. We studied a number of popular new physics models that have been employed to interpret the observed particle at 125 GeV, including fermiophobic Higgs boson, the Randall–Sundrum radion, inert-Higgs-doublet model, two-Higgs-doublet model, and the MSSM. Since the inclusive diphoton channel showed an excess over the SM predictions, we first selected the parameter space of each model that can give an inclusive diphoton rate larger than or equal to the SM rate. Then, we calculate the exclusive $jj\gamma\gamma$ diphoton production rate in VBF for that parameter space. If the diphoton mode excess seen at LHC-7 can be firmly established by the new LHC-8 data, it will be the utmost task to identify the nature of this particle. Perhaps, it is simply the SM Higgs boson with some level of statistical fluctuation, but it could also be the RS radion [38, 39], fermiophobic Higgs boson [34], the light CP-even Higgs boson of the 2HDM [28], the Higgs boson of the IHDM [40], or one of the CP-even Higgs bosons in other extensions of the MSSM [31–33], all of which can allow an enhancement to the $\gamma\gamma$ production rate. On the other hand, the vector-boson fusion, as singled out by the dijet tag, provides useful information in helping to differentiate among various models. It is not hard by browsing through Fig. 3 to conclude the following:

- If a similar rate is seen in inclusive production but no large excess is seen in the exclusive VBF production it would unlikely be a fermiophobic Higgs boson.
- If a similar rate or excess is seen in inclusive production but some events are seen in exclusive VBF production rate, it would unlikely be the RS radion.
- If moderate excess is seen in both inclusive production and exclusive VBF production, it could be the Higgs boson of the IHDM, 2HDM, or the MSSM. However, if the excess is over 60% it will pose severe challenge to the MSSM.

It seems easy to rule out either fermiophobic Higgs boson or RS radion, providing that we see no large excess or some events in VBF channel, respectively. However, it is still difficult to distinguish the other models when the inclusive and exclusive rates are similar to or slightly larger than the SM values. If the production rate of the diphoton mode at 125 GeV lines up with the SM prediction eventually, it is still premature to conclude this is coming from the SM Higgs boson. Other alternatives in MSSM, NMSSM, or other SUSY models can also be mimicking the SM Higgs boson, depending on the parameter space of the new physics model. In any case, once the signals at 125 GeV are confirmed further studies including all possible decay modes are to be taken into account in order to discriminate these many alternatives beyond the standard model.

Vector-boson fusion is the next most important production mechanism that must be taken into account to fully identify the newly discovered particle.

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