Enhanced Higgs Pair Signal in the 2HDM with Two Degenerate 125 GeV Higgs Bosons [Postprint]

Authors: Han, X, Wang, L, Yang,JM

Date: 2016-12-28T00:00:00+00:00

Abstract

We discuss a scenario of the type-II two-Higgs-doublet model (2HDM) in which the bb? rate of the Higgs pair production is enhanced due to the two nearly degenerate 125 GeV Higgs bosons (h, H). Considering various theoretical and experimental constraints

Full Text

Higgs Pair Signal Enhanced in the 2HDM with Two Degenerate 125 GeV Higgs Bosons

Xiao-Fang Han[1]**, Lei Wang**[2,1]**, Jin Min Yang**[3]

[1]IFIC, Universitat de València-CSIC, Apt. Correus 22085, E-46071 València, Spain
[2]State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Academia Sinica, Beijing 100190, P. R. China

Abstract

We discuss a scenario of the type-II Two-Higgs-Doublet Model (2HDM) in which the $b\bar{b}\gamma\gamma$ rate of Higgs pair production is enhanced due to two nearly degenerate 125 GeV Higgs bosons (h, H). Considering various theoretical and experimental constraints, we determine the allowed ranges of the trilinear couplings of these two Higgs bosons and calculate the signal rate of $b\bar{b}\gamma\gamma$ from Higgs pair production (hh, hH, HH) at the LHC. We find that in the allowed parameter space, some trilinear Higgs couplings can be larger than the Standard Model (SM) value by an order of magnitude and the production rate of $b\bar{b}\gamma\gamma$ can be greatly enhanced. We also consider a "decoupling" benchmark point where the light CP-even Higgs has an SM-like cubic self-coupling while other trilinear couplings are very small. With detailed simulation of the $b\bar{b}\gamma\gamma$ signal and backgrounds, we find that in such a "decoupling" scenario the hh and hH channels can jointly enhance the statistical significance to 5σ at the 14 TeV LHC with an integrated luminosity of 3000 fb^{-1}.

Introduction

So far, the properties of the 125 GeV Higgs boson discovered by the ATLAS and CMS collaborations [?, ?] agree with Standard Model predictions. However, there is no experimental information on the Higgs self-coupling, which is vital for spontaneous electroweak symmetry breaking. As is well known, Higgs pair production at the LHC may provide a way to probe the Higgs self-coupling. The $b\bar{b}b\bar{b}$ signal from Higgs pair production has the largest rate but suffers from a huge QCD background. The $b\bar{b}\tau^+\tau^-$ channel is swamped by the $b\bar{b}jj$ background [?], where each light-flavored jet can fake a hadronic τ. The detection of these two channels, as well as the $b\bar{b}WW^*$ channel, requires more elaborate strategies such as boosted kinematics and jet substructure techniques [?]. Although the $b\bar{b}\gamma\gamma$ channel has a relatively small rate, it has the cleanest background and thus has attracted more attention [?]. For the Standard Model, the significance for $gg \to b\bar{b}\gamma\gamma$ is only around 2σ at the 14 TeV LHC with an integrated luminosity of 3000 fb^{-1} [?, ?]. Therefore, a collider with higher energy (say 100 TeV) seems necessary to examine the Higgs self-coupling from Higgs pair production.

Higgs pair production can serve as a good probe for new physics. The production rate can be enhanced by modifying the Higgs self-coupling or top quark Yukawa coupling appropriately. It can also be enhanced by new production mechanisms, such as heavy top partner loops in little Higgs models [?], squark loops in SUSY models [?], and the on-shell production of a heavy Higgs decaying into a pair of 125 GeV Higgses in the two-Higgs-doublet model (2HDM) [?, ?]. In this work, we discuss a scenario in the type-II 2HDM [?] where the $b\bar{b}\gamma\gamma$ channel of Higgs pair production is enhanced due to two nearly degenerate 125 GeV Higgs bosons (similar degenerate cases have been discussed in the literature [?], but their impact on Higgs pair signals has not been studied). The mass splitting between these two Higgs bosons is smaller than the detector mass resolution but larger than their widths, so that interference terms can be neglected. First, considering theoretical constraints from vacuum stability, unitarity, and perturbativity, as well as experimental constraints from electroweak precision data, flavor observables, and Higgs data, we determine the allowed ranges of the trilinear couplings of these two Higgs bosons and calculate the $b\bar{b}\gamma\gamma$ production rate at the LHC. Then, focusing on a "decoupling" benchmark point where the light CP-even Higgs has an SM-like cubic self-coupling while other trilinear couplings are very small, we perform a detailed simulation of the $b\bar{b}\gamma\gamma$ signal and its backgrounds at the 14 TeV LHC with an integrated luminosity of 3000 fb^{-1}.

Our work is organized as follows. In Sec. II we recapitulate the type-II 2HDM. In Sec. III we describe our numerical calculations. In Sec. IV, we show the allowed ranges of the various trilinear couplings of the two Higgs bosons and present the simulation results for the $b\bar{b}\gamma\gamma$ signal and its backgrounds at the LHC. Finally, we draw our conclusions in Sec. V.

II. Type-II 2HDM

The general Higgs potential of the 2HDM is written as [?]

$$V = m_{11}^2(\Phi_1^\dagger\Phi_1)+m_{22}^2(\Phi_2^\dagger\Phi_2)-\left[m_{12}^2(\Phi_1^\dagger\Phi_2+\text{h.c.})\right]+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2+\frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2)+\lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger$$

In the type-II 2HDM, a discrete Z_2 symmetry is introduced to set $\lambda_6 = \lambda_7 = 0$ while allowing for a soft-breaking term with $m_{12}^2 \neq 0$. All λ_i and m_{12}^2 are taken to be real in order to avoid explicit CP violation in the Higgs sector.

The two complex scalar doublets have hypercharge $Y = 1$,

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}(v_1+\phi_1^0+ia_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}(v_2+\phi_2^0+ia_2) \end{pmatrix},$$

where v_1 and v_2 are the vacuum expectation values (VEVs) with $v^2 = v_1^2+v_2^2 = (246\ \text{GeV})^2$ and $\tan\beta$ is defined as v_2/v_1. The physical scalar spectrum of this model consists of two neutral CP-even scalars h and H, one neutral pseudoscalar A, and two charged scalars $H^\pm$. This basis can be rotated to the Higgs basis by a mixing angle β, where the VEV of the Φ_2 field is zero. In the Higgs basis, the mass eigenstates are obtained from

$$\begin{aligned} h &= \sin(\beta-\alpha)\phi_1^0+\cos(\beta-\alpha)\phi_2^0, \\ H &= \cos(\beta-\alpha)\phi_1^0-\sin(\beta-\alpha)\phi_2^0, \\ A &= a_2, \\ H^\pm &= \phi_2^\pm, \end{aligned}$$

where the fields on the right-hand side denote the interaction eigenstates in the Higgs basis.

In the Higgs basis, the general Yukawa interactions without tree-level flavor-changing neutral currents are written as [?]

$$\mathcal{L}_Y = -\bar{Q}_L(\kappa_d\Phi_1+\kappa_d'\Phi_2)d_R-\bar{Q}_L(\kappa_u\tilde{\Phi}_1+\kappa_u'\tilde{\Phi}_2)u_R-\bar{L}_L(\kappa_\ell\Phi_1+\kappa_\ell'\Phi_2)\ell_R+\text{h.c.},$$

where $\tilde{\Phi}_i(x) = i\tau_2\Phi_i^*(x)$ and $\kappa_{d,u,\ell}$ are the Yukawa matrices. For the type-II 2HDM, we have

$$\kappa_u' = \cot\beta, \quad \kappa_d = \kappa_\ell = \tan\beta.$$

From Eq. (4) we can obtain the couplings of neutral Higgs bosons normalized to the SM values:

$$\begin{aligned} g_{hVV} &= \sin(\beta-\alpha), \quad g_{HVV} = \cos(\beta-\alpha), \quad g_{AVV} = 0, \\ g_{hff} &= \sin(\beta-\alpha) + \cos(\beta-\alpha)\kappa_f, \\ g_{Hff} &= \cos(\beta-\alpha) - \sin(\beta-\alpha)\kappa_f, \\ g_{Aff} &= i\gamma_5\kappa_f, \end{aligned}$$

where V denotes Z and W, and f denotes u, d, and ℓ. The charged Higgs couplings are written as

$$\mathcal{L}_{H^\pm} = \frac{\sqrt{2}}{v} H^+ \bar{u} \left[\kappa_d V_{\rm CKM} M_d P_R - \kappa_u M_u V_{\rm CKM} P_L\right] d + \frac{\sqrt{2}}{v} H^+ \bar{\nu} \kappa_\ell M_\ell P_R \ell + \text{h.c.},$$

where M_f are the diagonal fermion mass matrices.

III. Numerical Calculations

We employ 2HDMC-1.6.5 [?] to implement theoretical constraints from vacuum stability, unitarity, and coupling-constant perturbativity, and to calculate the oblique parameters (S, T, U) and $\delta\rho$. We use SuperIso-3.4 [?] to implement constraints from B physics and HiggsBounds-4.1.3 [?] to implement exclusion constraints from neutral and charged Higgs searches at LEP, Tevatron, and LHC at 95% confidence level. An in-house code is used to calculate the χ^2 fit to the 125.5 GeV Higgs signal, Δm_{B_s} and Δm_{B_d}. In addition to theoretical constraints, we require the type-II 2HDM to satisfy all experimental data at the 2σ level. The experimental values of electroweak precision data, B physics observables, Δm_{B_s} and Δm_{B_d} are taken from [?].

We generate the 2HDM@NLO model using the tree-level 2HDM model and NLOCT package [?]. The model contains the QCD R_2 vertices and UV counterterms for the 2HDM, which is based on the FeynRules [?] and UFO [?] frameworks. In our simulation, the parton-level signal and background events are generated with MadGraph5 v2.3.0 [?]. For Higgs pair production via gluon-gluon fusion, we take the factorization and renormalization scales as the invariant mass of the Higgs pair. An in-house code is used to transform the results of 2HDMC into the parameter card which is read by MadGraph5 v2.3.0, since there are different bases and mixing angles in the CP-even Higgs sector between the 2HDM@NLO model and 2HDMC. PYTHIA [?] is employed to decay the Higgs bosons following the decay table in the parameter card, and to perform parton showering and hadronization. We perform fast detector simulations and data analysis with Delphes [?] and MadAnalysis5 [?]. Jet reconstruction is done using the anti-k_T algorithm with a radius parameter of $R = 0.5$. The efficiency for b-tagging is taken as 70%. The efficiency of photon tagging and the mistagging rate of QCD jets are assumed to be the default values as in Delphes.

Using the method in [?], we perform a global fit to the 125.5 GeV Higgs data of 29 channels after ICHEP 2014 [?]. Since we assume that the mass splitting of the two CP-even Higgs bosons is smaller than the detector mass resolution, the signal strength for a channel is defined as

$$\hat{\mu}_i = \sum_{H=h,H} \frac{\epsilon_i^{gg}\hat{\mu}_H R_{gg}^H + \epsilon_i^{VBF}\hat{\mu}_H R_{VBF}^H + \epsilon_i^{Vh}\hat{\mu}_H R_{Vh}^H + \epsilon_i^{t\bar{t}}\hat{\mu}_H R_{t\bar{t}}^H}{\epsilon_i^{gg} + \epsilon_i^{VBF} + \epsilon_i^{Vh} + \epsilon_i^{t\bar{t}}},$$

where $R_j^H = (\sigma\cdot \mathrm{BR})_j^H/(\sigma\cdot \mathrm{BR})_j^{\mathrm{SM}}$ with j denoting the partonic process $gg \to H$, VBF, Vh, or $t\bar{t}H$, and ϵ_i^j denotes the assumed signal composition of the partonic process j [**?**], which has the same value for h and H. For an uncorrelated observable i,

$$\chi_i^2 = \frac{(\mu_i^{\exp} - \hat{\mu}_i)^2}{\sigma_i^2},$$

where $\mu_i^{\exp}$ and σ_i denote the experimental central value and uncertainty for the i-th channel. The uncertainty asymmetry is retained in our calculations. For the two correlated observables, we take

$$\chi_{i,j}^2 = \frac{(\mu_i^{\exp} - \hat{\mu}_i)^2}{\sigma_i^2} + \frac{(\mu_j^{\exp} - \hat{\mu}_j)^2}{\sigma_j^2} - 2\rho\frac{(\mu_i^{\exp} - \hat{\mu}_i)(\mu_j^{\exp} - \hat{\mu}_j)}{\sigma_i\sigma_j},$$

where ρ is the correlation coefficient. We sum over χ^2 in the 29 channels and pay particular attention to the surviving samples with $\chi^2 \leq \chi^2_{\min} + 6.18$, where $\chi^2_{\min}$ denotes the minimum value of χ^2. These samples correspond to the 95.4% confidence level region in any two-dimensional plane of the model parameters when explaining the Higgs data (corresponding to the 2σ range).

In our calculations, we take $m_h = 125.5$ GeV and $m_H = 126$ GeV. The input parameters are $\cos(\beta-\alpha)$, $\tan\beta$, the physical Higgs masses (m_A, $m_{H^\pm}$), and the soft-breaking parameter m_{12}^2. Since the Higgs couplings between the two CP-even Higgs bosons are independent of m_A and $m_{H^\pm}$, we take $m_A = m_{H^\pm}$, which is favored by the $\delta\rho$ and oblique parameters. We randomly scan the parameters in the following ranges:

$$\begin{aligned} &0.1 < \cos(\beta-\alpha) < 1, \\ &0.1 < \tan\beta < 50, \\ &200 \text{ GeV} < m_A = m_{H^\pm} < 700 \text{ GeV}, \\ &(400 \text{ GeV})^2 < m_{12}^2 < (400 \text{ GeV})^2. \end{aligned}$$

We take the convention $0 < \cos(\beta-\alpha) < 1$ and $\sin(\beta-\alpha) > 0$. With $\cos(\beta-\alpha) < 0.1$, the couplings between the light CP-even Higgs and the gauge bosons are close to the SM predictions while the corresponding heavy Higgs couplings are very small.

IV. Results and Discussions

After imposing the above-mentioned theoretical and experimental constraints, we find the minimal value of χ^2 is $\chi^2_{\min} \simeq 18.08$, which is slightly larger than the SM value (17.0). The corresponding parameters are $\sin(\beta-\alpha) = 0.99996$, $\tan\beta = 3.094$, $m_h = 125.5$ GeV, $m_H = 126.0$ GeV, $m_A = 448.88$ GeV, $m_{H^\pm} = 448.88$ GeV, and $m_{12}^2 = 4615.4$ GeV^2.

A. Higgs Pair Cross Section and Higgs Trilinear Couplings We define $R_{b\bar{b}\gamma\gamma}$ as the $b\bar{b}\gamma\gamma$ signal event number in the type-II 2HDM normalized to the SM prediction:

$$R_{b\bar{b}\gamma\gamma} = \frac{\sum_{\hat{H}\hat{H}} \sigma(gg \to \hat{H}\hat{H}) \times \mathrm{Br}(\hat{H}\hat{H} \to b\bar{b}\gamma\gamma)}{\sigma(gg \to hh)_{\mathrm{SM}} \times \mathrm{Br}(hh \to b\bar{b}\gamma\gamma)_{\mathrm{SM}}},$$

where $\hat{H}\hat{H}$ denotes hh, hH, or HH. In fact, the contributions from $gg \to HH$ can be neglected since $\mathrm{Br}(H \to \gamma\gamma)$ is much smaller than the SM prediction for $\cos(\beta-\alpha) < 0.1$.

In Fig. 1 [Figure 1: see original paper], we project the surviving samples onto the planes of $\cos(\beta-\alpha)$ versus $\tan\beta$ and m_{12}^2 versus $\tan\beta$, respectively. At the 14 TeV LHC with an integrated luminosity of 3000 fb^{-1}, the significance for the SM is around 2σ for the $b\bar{b}\gamma\gamma$ channel [**?**, **?**]. Therefore, it should be difficult to probe the $b\bar{b}\gamma\gamma$ channel of the type-II 2HDM for $R_{b\bar{b}\gamma\gamma} < 2.0$. As shown in this figure, $R_{b\bar{b}\gamma\gamma} > 2.0$ favors $\tan\beta < 2$ ($\tan\beta < 1.2$ is excluded by Δm_{B_s} and Δm_{B_d}), and 10^5 GeV$^2 < m_{12}^2 < 1.5 \times 10^5$ GeV^2. The Higgs trilinear couplings are sensitive to $\tan\beta$ and m_{12}^2. In addition, the top quark Yukawa coupling is sensitive to $\tan\beta$, as shown in Eq. (6).

To understand the allowed ranges of $R_{b\bar{b}\gamma\gamma}$, we project the surviving samples onto the planes of the Higgs couplings in Fig. 2 [Figure 2: see original paper]. The upper panel of Fig. 2 shows that the light CP-even Higgs trilinear coupling and its coupling to the top quark are restricted to be around the SM predictions, respectively. The absolute value of the heavy CP-even Higgs coupling to the top quark is always suppressed, and allowed to be as low as 0.12 relative to the SM top quark Yukawa coupling. In some parameter space, the absolute values of the Higgs trilinear couplings HHH and HHh are respectively allowed to be as high as 15 and 10 times the SM hhh coupling. The absolute value of the coupling Hhh is always suppressed compared to the SM hhh coupling due to the suppression of $\cos(\beta-\alpha)$. From Fig. 2 we see that $R_{b\bar{b}\gamma\gamma} > 2.0$ favors two different regions. In one region, the Higgs potential is "decoupling," namely the hhh coupling is near the SM prediction while other trilinear couplings HHH, HHh, and Hhh are very small. Therefore, for the $gg \to hH$ production process, the contributions of triangle diagrams will be sizably suppressed since the couplings HHh and Hhh are very small. This will sizably soften the destructive interference between the triangle and box diagrams, leading to enhancement of the $gg \to hH$ cross section. In the other region, the coupling HHh is much larger than the SM hhh coupling, which can make the contributions of the triangle diagrams overcome the box diagrams and enhance the $gg \to hH$ cross section. Fig. 2 shows that $R_{b\bar{b}\gamma\gamma} > 2.0$ favors the absolute value of y_{Htt} to be larger than 0.5, which avoids the $gg \to hH$ cross section being sizably suppressed.

Although the couplings HHH and HHh can be much larger than the SM hhh coupling, the cross section of $gg \to HH$ cannot be enhanced since there is destructive interference between the triangle diagrams mediated by H and h. Conversely, the cross section of $gg \to hh$ is smaller than the SM cross section since the Htt coupling is suppressed. We show the cross sections of hh, hH, and HH in Fig. 3 [Figure 3: see original paper]. This figure shows that the cross section of HH is smaller than 0.6 times the SM hh prediction for most surviving samples. The cross section of hh is around the SM prediction, and the cross section of hH can reach 17 times the SM hh prediction.

B. Simulation Results in a Decoupling Scenario As seen from the preceding section, the cross section of Higgs pair production at the LHC can be sizably enhanced by a large Higgs trilinear coupling in the 2HDM with two nearly degenerate CP-even 125 GeV Higgs bosons, and as a result the Higgs pair signal is observable at the LHC. In the following we consider a "decoupling" scenario in which the light CP-even Higgs has an SM-like cubic self-coupling while other Higgs trilinear couplings of the two CP-even Higgs bosons are very small. In this scenario, the $b\bar{b}hh$, $b\bar{b}hH$, and $b\bar{b}HH$ processes can be neglected since there is no enhancement of Higgs trilinear couplings.

We take a benchmark point with the following parameters: $\sin(\beta - \alpha) = 0.999988$, $\tan\beta = 1.232$, $m_h = 125.5$ GeV, $m_H = 126.0$ GeV, $m_A = 595.65$ GeV, $m_{H^\pm} = 595.65$ GeV, $m_{12}^2 = 12304.0$ GeV^2; $y_{htt} = 0.996$, $y_{Htt} = 0.82$, $y_{hbb} = 1.006$, $y_{Hbb} = 1.228$, $y_{hhh} = 0.99996$, $y_{HHH} = 0.245$, $y_{HHh} = 0.0598$, $y_{Hhh} = 0.00552$; $\mathrm{Br}(H \to \gamma\gamma) = 1.969 \times 10^{-3}$, $\mathrm{Br}(H \to b\bar{b}) = 0.6119$, $\mathrm{Br}(h \to \gamma\gamma) = 9.702 \times 10^{-4}$, $\mathrm{Br}(h \to b\bar{b}) = 0.8385$; $\sigma(hh)_{\mathrm{LO}} = 16.74$ fb, $\sigma(hH)_{\mathrm{LO}} = 50.4$ fb.

Since $\mathrm{Br}(H \to \gamma\gamma)$ is very small, we neglect $gg \to HH \to b\bar{b}\gamma\gamma$ and consider only the $b\bar{b}\gamma\gamma$ signal from hh, hH, and HH production. The main SM backgrounds include non-resonant $b\bar{b}\gamma\gamma$, $t\bar{t}h$ ($t\bar{t} \to b\bar{b} + X$, $h \to \gamma\gamma$), Zh ($Z \to b\bar{b}$, $h \to \gamma\gamma$), and $b\bar{b}h$ ($h \to \gamma\gamma$). We neglect the subdominant reducible backgrounds of $jj\gamma\gamma$ and $t\bar{t}\gamma\gamma$ [?]. QCD corrections are considered by including a k-factor, which is 2.27 for the signal [?], 2.0 for $b\bar{b}\gamma\gamma$ [?], 1.1 for $t\bar{t}h$ [?], 1.33 for Zh [?], and 1.2 for $b\bar{b}h$ [?].

Fig. 4 [Figure 4: see original paper] shows the distributions of some kinematic variables at the LHC with $\sqrt{s} = 14$ TeV for the hh, hH, $b\bar{b}\gamma\gamma$, and $t\bar{t}h$ processes. The results for Zh and $b\bar{b}h$ are not shown since they are subdominant. Based on the distribution differences between the signal and backgrounds, we can improve the signal-to-background ratio by applying kinematic cuts. First, we require the final states to include two isolated photons and two b-jets, and further impose the following cuts:

$$\begin{gathered} p_T^{b_1} > 60 \text{ GeV}, \quad p_T^{b_2} > 25 \text{ GeV}, \quad p_T^{\gamma_1} > 60 \text{ GeV}, \quad p_T^{\gamma_2} > 25 \text{ GeV}, \\ \Delta R_{bb} > 0.4, \quad \Delta R_{\gamma\gamma} > 0.4, \quad \Delta R_{b\gamma} > 0.4, \quad |\eta_b| < 2.5, \quad |\eta_\gamma| < 2.5, \\ M_{bb} > 30 \text{ GeV}, \quad M_{\gamma\gamma} > 30 \text{ GeV}, \quad M_{bb\gamma\gamma} > 350 \text{ GeV}, \end{gathered}$$

where $p_T^{b_1}$ and $p_T^{\gamma_1}$ denote the transverse momentum of the hardest b-jet and photon, and $p_T^{b_2}$ and $p_T^{\gamma_2}$ denote that of the second-hardest b-jet and photon. $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$ is the particle separation with $\Delta\phi$ and $\Delta\eta$ being the separation in azimuthal angle and rapidity, respectively. The cuts on the invariant mass $M_{bb\gamma\gamma}$ and $p_T^{b_1}$ can suppress the backgrounds sizably, especially the largest background $b\bar{b}\gamma\gamma$.

The photon pair is further restricted to have

$$115 \text{ GeV} < M_{\gamma\gamma} < 135 \text{ GeV}, \quad \Delta R_{\gamma\gamma} < 2.0,$$

and the b-quark pair is restricted to have

$$100 \text{ GeV} < M_{bb} < 140 \text{ GeV}, \quad \Delta R_{bb} < 2.0.$$

Since the two photons (two b-quarks) in the signals come from Higgs decays, the signal rates peak at their invariant masses around the Higgs mass with relatively small separation. The cuts in Eqs. (17) and (18) play the dominant role in suppressing the backgrounds.

Finally, we apply additional cuts that specifically suppress the $t\bar{t}h$ background. Since $W^\pm$ decays into charged leptons and jets, the $t\bar{t}h$ background tends to include additional charged leptons and more jets. Therefore, we veto events with

$$p_T^\ell > 20 \text{ GeV} \quad \text{or} \quad p_T^{j_8} > 20 \text{ GeV},$$

where $p_T^{j_8}$ denotes the transverse momentum of the 8th-hardest jet.

The resulting cut flow is shown in Table I . The $b\bar{b}\gamma\gamma$ and $t\bar{t}h$ are the two major backgrounds. After imposing the above cuts, the events from the hH signal are approximately 1.6 times those from hh. Since h and H are degenerate 125.5 GeV Higgs bosons, the total signal events from hh and hH can reach a significance of 5σ at the 14 TeV LHC with an integrated luminosity of 3000 fb^{-1}. If there is sizable mass splitting between h and H, the cuts in Eq. (17) and Eq. (18) will inevitably hurt the hH events and hence suppress the significance. Therefore, the degeneracy between h and H plays a key role in enhancing the significance for such a "decoupling" scenario.

V. Conclusion

In this work we discussed a special scenario in the type-II 2HDM where the $b\bar{b}\gamma\gamma$ channel of Higgs pair production can be enhanced due to two nearly degenerate 125 GeV Higgs bosons. We considered various theoretical and experimental constraints and found that in the allowed parameter space, some trilinear Higgs couplings can be larger than the SM value by an order of magnitude and the $b\bar{b}\gamma\gamma$ signal can be sizably enhanced. We also considered a "decoupling" scenario where the light CP-even Higgs has an SM-like cubic self-coupling while other trilinear Higgs couplings are very small. From a detailed simulation of the $b\bar{b}\gamma\gamma$

signal and backgrounds, we found that the hh and hH production channels can jointly enhance the statistical significance to 5σ at the 14 TeV LHC with an integrated luminosity of 3000 fb^{-1}. Therefore, the degenerate h and H play a vital role in enhancing the significance for probing this Higgs potential "decoupling" scenario.

Acknowledgment

We would like to thank Tao Liu, Olivier Mattelaer, Lei Wu and Shuo Yang for helpful discussions, and Antonio Pich for reading the manuscript and useful suggestions. This work has been supported in part by the Spanish Government and ERDF funds from the EU Commission [Grant No. FPA2011-23778], by the Spanish Centro de Excelencia Severo Ochoa Programme [Grant SEV-2014-0398], and by the National Natural Science Foundation of China under grant Nos. 11275245, 10821504 and 11135003.

[1] S. Chatrchyan et al. [CMS Collaboration], Phys. Lett. B 716, 30 (2012).
[2] G. Aad et al. [ATLAS Collaboration], Phys. Lett. B 716, 1 (2012).
[3] V. Barger, L. L. Everett, C. B. Jacksonand, G. Shaughnessy, Phys. Lett. B 728, 433 (2014).
[4] D. E. FerreiradeLima, A. Papaefstathiou, M. Spannowsky, JHEP 08, 030 (2014); A. Papaefstathiou, L. L. Yang, J. Zurita, Phys. Rev. D 87, 011301 (2013); A. J. Barr, M. J. Dolan, C. Englertand, M. Spannowsky, Phys. Lett. B 728, 308 (2014); D. E. Ferreira de Lima, A. Papaefstathiou, M. Spannowsky, JHEP 1408, 030 (2014); C. Englert, F. Krauss, M. Spannowskyand, J. Thompson, Phys. Lett. B 743, 93 (2015); Z. Kang, P. Ko, J. Li, arXiv:1504.04128.
[5] W. Yao, arXiv:1308.6302.
[6] A. Azatov, R. Contino, G. Panico, M. Son, arXiv:1502.00539.
[7] Q.-H. Cao, B. Yan, D.-M. Zhang, H. Zhang, arXiv:1508.06512.
[8] V. Barger, L. L. Everett, C. B. Jackson, A. D. Peterson, G. Shaughnessy, Phys. Rev. D 90, 095006 (2014).
[9] B. Hespel, D. Lopez-Val, E. Vryonidou, JHEP 1409, 124 (2014); U. Baglio, O. Eberhardt, U. Nierste, M. Wiebusch, Phys. Rev. D 90, 015008 (2014); L.-C. Lu, C. Du, Y. Fang, H.-J. He, H. Zhang, arXiv:1507.02644.
[10] J. Baglio, et al., JHEP 1304, 151 (2013); J. Baglio, arXiv:1408.6066; A. J. Barr, et al., JHEP 1502, 016 (2015); Q. Li, Z. Li, Q.-S. Yan, X. Zhao, Phys. Rev. D 92, 014015 (2015); I. Hinchliffe, et al., arXiv:1504.06108; H.-J. He, J. Ren, W. Yao, arXiv:1506.03302; Z.-L. Han, R. Ding, Y. Liao, arXiv:1506.08996; C.-T. Lu, J. Chang, K. Cheung, J. S. Lee, arXiv:1505.00957; A. Papaefstathiou, arXiv:1504.04621; M. Slawinska, W. v. den Wollenberg, B. v. Eijk, S. Bentvelsen, arXiv:1408.5010.
[11] L. Wang, W. Wang, J. M. Yang, H. Zhang, Phys. Rev. D 76, 017702 (2007); J.-J. Liu, et al., Phys. Rev. D 70, 015001 (2004); C. O. Dib, R. Rosenfeld, A. Zerwekh, JHEP 05, 074 (2006).
[12] U. Ellwanger, arXiv:1306.5541; C. Han, et al., JHEP 1404, 003 (2014); J. Cao, L. Shang, P. Wan, J. M. Yang, JHEP 1304, 134 (2013); S. Dawson, C.

Kao, Y. Wang, Phys. Rev. D 77, 113005 (2008).
[13] L. J. Hall, M. B. Wise, Nucl. Phys. B 187, 397 (1981); J. F. Donoghue, L. F. Li, Phys. Rev. D 19, 945 (1979).
[14] J. F. Gunion, Y. Jiang, S. Kraml, Phys. Rev. Lett. 110, 051801 (2013); P. M. Ferreira, R. Santos, H. E. Haber, J. P. Silva, Phys. Rev. D 87, 055009 (2013); Y. Grossman, Z. Surujon, J. Zupan, JHEP 1303, 176 (2013); M. Chabab, M. C. Peyranere, L. Rahili, Phys. Rev. D 90, 035026 (2014); A. David, J. Heikkila, G. Petrucciani, Eur. Phys. Jour. C 75, 49 (2015).
[15] R. A. Battye, G. D. Brawn, A. Pilaftsis, JHEP 1108, 020 (2011).
[16] A. Pich, P. Tuzon, Phys. Rev. D 80, 091702 (2009).
[17] D. Eriksson, J. Rathsman, O. St ˚ al, Comput. Phys. Commun. 181, 189 (2010); Comput. Phys. Commun. 181, 833 (2010).
[18] F. Mahmoudi, Comput. Phys. Commun. 180, 1579-1673 (2009).
[19] P. Bechtle, et al., Comput. Phys. Commun. 181, 138 (2010); Eur. Phys. Jour. C 74, 2693 (2014).
[20] K. A. Olive etal. [Particle Data Group], Chin. Phys. C 38, 090001 (2014).
[21] C. Degrande, arXiv:1406.3030.
[22] A. Alloul, et al., Comput. Phys. Commun. 185, 2250 (2014).
[23] C. Degrande, et al., Comput. Phys. Commun. 183, 1201 (2012).
[24] J. Alwall, et al., JHEP 1407, 079 (2014); V. Hirschi, O. Mattelaer, arXiv:1507.00020.
[25] T. Sjostrand, S. Mrenna, P. Z. Skands, JHEP 0605, 026 (2006).
[26] J. de Favereau, et al., JHEP 1402, 057 (2014).
[27] E. Conte, B. Fuksand, G. Serret, Comput. Phys. Commun. 184, 222 (2013).
[28] J. R. Espinosa, C. Grojean, M. Muhlleitner, M. Trott, JHEP 1205, 097 (2012); G. Belanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, JHEP 1302, 053 (2013); P. P. Giardino, K. Kannike, M. Raidal, A. Strumia, JHEP 1206, 117 (2012); B. Dumont, S. Fichet, G. Gersdorff, JHEP 1307, 065 (2013); J. Cao, et al., JHEP 1203, 086 (2012); J. S. Lee, P. Y. Tseng, JHEP 1305, 134 (2013).
[29] G. Aad et al. [ATLAS Collaboration], Phys. Rev. D 90, 112015 (2014); Phys. Rev. D 90, 052004; S. Chatrchyan et al. [CMS Collaboration], Eur. Phys. Jour. C 74, 3076 (2014); Phys. Rev. D 89, 092007 (2014); JHEP 1401, 096 (2014); Phys. Rev. D 89, 012003 (2014); JHEP 1405, 104 (2014); Talk by K. Herner, "Studies of the Higgs boson properties at D0" , ICHEP 2014, Spain.
[30] K. Cheung, J. S. Lee, P.-Y. Tseng, Phys. Rev. D 90, 095009 (2014).
[31] D. deFlorian, J.Mazzitelli, Phys. Rev. Lett. 111, 201801 (2013).
[32] S. Dittmaier et al. [LHC Higgs Cross Section group], arXiv:1101.0593.
[33] S. Dawson, C. B. Jackson, L. Reina, D. Wackeroth, Phys. Rev. Lett. 94, 031802 (2005).

Note: Figure translations are in progress. See original paper for figures.