Higgs pair signal enhanced in the 2HDM with two degenerate 
125 GeV Higgs bosons

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Abstract

We discuss a scenario of the type-II 2HDM in which the \(b\bar{b}\gamma\gamma\) 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, we figure out the allowed ranges of the trilinear couplings of these two Higgs bosons and calculate the signal rate of \(b\bar{b}\gamma\gamma\) from the productions of Higgs pairs (\(hh, hH, HH\)) at the LHC. We find that in the allowed parameter space some trilinear Higgs couplings can be larger than the SM value by an order 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 a SM-like cubic self-coupling while other trilinear couplings are very small. With a detailed simulation on 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 5\(\sigma\) at 14 TeV LHC with an integrated luminosity of 3000 fb\(^{-1}\).

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I. INTRODUCTION

So far the properties of the 125 GeV Higgs boson discovered by the ATLAS and CMS collaborations [1, 2] agree with the Standard Model (SM) predictions. However, there is no experimental information for the Higgs self-coupling, which is vital for the spontaneous electroweak symmetry breaking. As is well known, the Higgs pair production at the LHC may provide a way to probe the Higgs self-coupling. The signal \( bb\bar{b}b \) from the Higgs pair has the largest rate, but suffers from the huge QCD background. The \( bb\tau\bar{\tau} \) channel is swamped by the \( bbjj \) background [3] where each light-flavored jet can fake a hadronic \( \tau \). The detection of these two channels and also the \( bbWW^* \) channel needs more elaborated strategies like boosted kinematics and jet substructure technique [4]. Although the \( bb\gamma\gamma \) channel has a small rate, it has the cleanest background, and thus has attracted more attention [5–10]. For the SM, the significance for \( gg \rightarrow hh \rightarrow bb\gamma\gamma \) is only around 2\( \sigma \) at the 14 TeV LHC with an integrated luminosity of 3000 fb\(^{-1}\) [5, 6]. So a collider with higher energy (say 100 TeV) seems needed to examine the Higgs self-coupling from the Higgs pair production.

The 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 properly. Also, it can be enhanced by some new mechanisms in the production, such as the heavy top partner loops in the little Higgs model [11], the squark loops in the SUSY models [12], and the on-shell production of a heavy Higgs which decays into a pair of 125 GeV Higgses in the two-Higgs-doublet model (2HDM) [8, 9]. In this work, we will discuss a scenario in the type-II 2HDM [13] where the \( bb\gamma\gamma \) channel of the Higgs pair is enhanced due to the two nearly degenerate 125 GeV Higgses (similar degenerate cases have been discussed in the literature [14], but their impact on Higgs pair signals has not been studied). The mass splitting between these two Higgses is smaller than the mass resolution of the detector while larger than their widths so that the interference terms can be neglected. First, considering the theoretical constraints from vacuum stability, unitarity and perturbativity as well as the experimental constraints from the electroweak precision data, flavor observables and Higgs data, we will figure out the allowed ranges of the trilinear couplings of these two Higgses and calculate the \( bb\gamma\gamma \) production rate at the LHC. Then, focusing on a "decoupling" benchmark point where the light CP-even Higgs has a SM-like cubic self-coupling while the other trilinear couplings are very small, we perform a detailed simulation on the \( bb\gamma\gamma \) 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 Higgses and give the simulation results for the \(b\bar{b}\gamma\gamma\) signal and its backgrounds at the LHC. Finally, we draw our conclusion in Sec.V.

II. TYPE-II 2HDM

The general Higgs potential of 2HDM is written as \cite{15}

\[
V = m_{11}^2 (\Phi_1^\dagger \Phi_1) + m_{22}^2 (\Phi_2^\dagger \Phi_2) - \left[ m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) \right] \\
+ \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 + \lambda_3 (\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1) \\
+ \left[ \frac{\lambda_5}{2} (\Phi_1^\dagger \Phi_2)^2 + \text{h.c.} \right] + \left[ \lambda_6 (\Phi_1^\dagger \Phi_1)(\Phi_1^\dagger \Phi_2) + \text{h.c.} \right] \\
+ \left[ \lambda_7 (\Phi_2^\dagger \Phi_2)(\Phi_1^\dagger \Phi_2) + \text{h.c.} \right].
\]  

(1)

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

The two complex scalar doublets have the hypercharge \(Y = 1\),

\[
\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}} (v_1 + \phi_0^1 + ia_1) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}} (v_2 + \phi_0^2 + ia_2) \end{pmatrix},
\]

(2)

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 \(h\) and \(H\), one neutral pseudoscalar \(A\), and two charged scalar \(H^\pm\). This basis can be rotated to the Higgs basis by a mixing angle \(\beta\), where the VEV of \(\Phi_2\) field is zero. In the Higgs basis, the mass eigenstates are obtained from

\[
h = \sin(\beta - \alpha)\phi_1^0 + \cos(\beta - \alpha)\phi_2^0, \\
H = \cos(\beta - \alpha)\phi_1^0 - \sin(\beta - \alpha)\phi_2^0, \\
A = a_2, \quad H^\pm = \phi_2^\pm,
\]

(3)

where the fields in the righ sides denote the interaction eigenstates in the Higgs basis.
In the Higgs basis, the general Yukawa interactions with no tree-level FCNC are written as

\[
L_Y = - \frac{\sqrt{2}}{v} \left[ M'_d \bar{Q}_L (\Phi_1 + \kappa_d \Phi_2) d_R + M'_u \bar{Q}_L (\Phi_1 + \kappa_u \Phi_2) u_R + M'_\ell \bar{L}_L (\Phi_1 + \kappa_\ell \Phi_2) \ell_R \right] + \text{h.c.},
\]

where \( \Phi_i(x) = i \tau_2 \Phi^*_i(x) \) and \( M'_{d,u,\ell} \) 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 Higgs boson

\[
y_v^h = \sin(\beta - \alpha), \quad y_f^H = \sin(\beta - \alpha) + \cos(\beta - \alpha) \kappa_f,
\]

\[
y_v^H = \cos(\beta - \alpha), \quad y_f^H = \cos(\beta - \alpha) - \sin(\beta - \alpha) \kappa_f,
\]

\[
y_v^A = 0, \quad y_u^A = -i \gamma^5 \kappa_u, \quad y_d^A = i \gamma^5 \kappa_d, \quad y_\ell^A = i \gamma^5 \kappa_\ell,
\]

where \( V \) denotes \( Z \) and \( W \), and \( f \) denotes \( u, d \) and \( \ell \). The charged Higgs couplings are written as

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

where \( M_f \) are the diagonal fermion mass matrices.

### III. NUMERICAL CALCULATIONS

We employ 2HDMC-1.6.5 \[17\] to implement the theoretical constraints from the vacuum stability, unitarity and coupling-constant perturbativity, and calculate the oblique parameters \((S, T, U)\) and \(\delta \rho\). We use SuperIso-3.4 \[18\] to implement the constraints from \( B \to X_s \gamma \) and use HiggsBounds-4.1.3 \[19\] to implement the exclusion constraints from the neutral and charged Higgses searches at the LEP, Tevatron and LHC at 95% confidence level. The in-house code is used to calculate \( \chi^2 \) fit to 125.5 GeV Higgs signal, \( \Delta m_{Bs} \) and \( \Delta m_{B_d} \). In addition to the theoretical constraints, we require the type-II 2HDM to satisfy all the experimental data at 2\( \sigma \) level. The experimental values of electroweak precision data, \( B \to X_s \gamma \), \( \Delta m_{Bs} \) and \( \Delta m_{B_d} \) are taken from \[20\].

We generate the 2HDM@NLO model using the tree-level 2HDM model and NLOCT package \[21\]. The model contains the QCD R2 vertex and UV counterterms for the 2HDM, which
is based on the FeynRules \[22\] and UFO \[23\] frameworks. In our simulation, the parton level signal and background events are generated with MadGraph5 \_aMC \_v2.3.0 \[24\]. For the Higgs pair production via gluon-gluon fusion, we take the factorization and renormalization scales as the the invariant mass of the Higgs pair. The in-house code is used to transform the results of 2HDMC into the parameter card which is read by MadGraph5 \_aMC \_v2.3.0 since there are different basis and mixing angles in CP-even Higgs sector between 2HDM@NLO model and 2HDMC. PYTHIA \[25\] is employed to decay the Higgs bosons following the decay table of parameter card, and perform parton shower and hadronization. We perform the fast detector simulations and data analysis with Delphes \[26\] and Madanalysis5 \[27\]. 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 mis-tagging of QCD jets is assumed to the default value as in Delphes.

Using the method in \[28\], we perform a global fit to the 125.5 GeV Higgs data of 29 channels after ICHEP 2014 \[29\]. Since we assume that the mass splitting of the two CP-even Higgses is smaller than the mass resolution of detector, the signal strength for a channel is defined as

$$
\mu_i = \sum_{\hat{H} = h, H} \epsilon_i^{gg\hat{H}} R_{gg\hat{H}} + \epsilon_i^{VBF\hat{H}} R_{VBF\hat{H}} + \epsilon_i^{V\hat{H}} R_{V\hat{H}} + \epsilon_i^{t\bar{t}\hat{H}} R_{t\bar{t}\hat{H}},
$$

where $R_j = (\sigma \times BR)_j / (\sigma \times BR)^{SM}_j$ with $j$ denoting the partonic process $gg\hat{H}$, $VBF\hat{H}$, $V\hat{H}$, or $t\bar{t}\hat{H}$, and $\epsilon_i^j$ denotes the assumed signal composition of the partonic process $j$ \[30\], which has the same value for $h$ and $H$. For an uncorrelated observable $i$,

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

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

$$
\chi^2_{i,j} = \frac{1}{1 - \rho^2} \left[ \frac{(\mu_i - \mu_i^{exp})^2}{\sigma_i^2} + \frac{(\mu_j - \mu_j^{exp})^2}{\sigma_j^2} - 2\rho \frac{(\mu_i - \mu_i^{exp})(\mu_j - \mu_j^{exp})}{\sigma_i \sigma_j} \right],
$$

where $\rho$ is the correlation coefficient. We sum over $\chi^2$ in the 29 channels, and pay particular attention to the surviving samples with $\chi^2 - \chi^2_{\min} \leq 6.18$, where $\chi^2_{\min}$ denotes the minimum of $\chi^2$. These samples correspond to the 95.4% confidence level region in any two-dimension.
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, and the input parameters are $\cos(\beta - \alpha)$, $\tan \beta$, the physical Higgs masses ($m_A$, $m_{H^\pm}$) and the soft breaking parameter $m^2_{12}$. Since the Higgs couplings between the two CP-even Higgses 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 scan randomly the parameters in the following ranges

$$0 \leq \cos(\beta - \alpha) \leq 0.1 , 1 \leq \tan \beta \leq 15,$$

$$200 \text{ GeV} \leq m_A = m_{H^\pm} \leq 700 \text{ GeV}, \quad -(400 \text{ GeV})^2 \leq m^2_{12} \leq (400 \text{ GeV})^2.$$  \hfill (11)

We take the convention $0 \leq \cos(\beta - \alpha) \leq 1$ and $-1 \leq \sin(\beta - \alpha) \leq 1$. With $0 \leq \cos(\beta - \alpha) \leq 0.1$, 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 $\chi^2$ is $\chi^2_{min} \approx 18.08$, which is slightly larger than the SM value (17.0). And the corresponding parameters are

$$\sin(\beta - \alpha) \approx 0.99996, \quad \tan \beta \approx 3.094, \quad m_h = 125.5 \text{ GeV}, \quad m_H \approx 126.0 \text{ GeV},$$

$$m_A = 448.88 \text{ GeV}, \quad m_{H^\pm} = 448.88 \text{ GeV}, \quad m^2_{12} = 4615.4 \text{ GeV}^2.$$  \hfill (12)

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 of type-II 2HDM normalized to the SM prediction

$$R_{b\bar{b}\gamma\gamma} = \frac{\sum \sigma(gg \to \hat{H}\hat{H}) \times Br(\hat{H}\hat{H} \to b\bar{b}\gamma\gamma)}{\sigma(gg \to hh)_{SM} \times Br(hh \to b\bar{b}\gamma\gamma)_{SM}},$$  \hfill (13)

where $\hat{H}\hat{H}$ denotes $hh$, $hH$ or $HH$. In fact, the contributions from $gg \to HH \to b\bar{b}\gamma\gamma$ can be neglected since $Br(H \to \gamma\gamma)$ is much smaller than the SM prediction for $0 \leq \cos(\beta - \alpha) \leq 0.1$.

In Fig. \ref{fig:SurvivingSamples} we project the surviving samples on the planes of $\cos(\beta - \alpha)$ versus $\tan \beta$ and $m^2_{12}$ versus $\tan \beta$, respectively. At the 14 TeV LHC with an integrated luminosity of
FIG. 1: The scatter plots of surviving samples projected on the planes of $\cos(\beta - \alpha)$ versus $\tan \beta$ and $m_{12}^2$ versus $\tan \beta$, respectively. The crosses (red) are for $R_{b\bar{b}\gamma\gamma} \leq 1.2$, and bullets (green) for $1.2 < R_{b\bar{b}\gamma\gamma} \leq 2.0$, and triangles (black) for $R_{b\bar{b}\gamma\gamma} > 2.0$.

3000 $fb^{-1}$, the significance of SM is around $2\sigma$ for the $b\bar{b}\gamma\gamma$ channel \cite{5, 6}. Therefore, it should be difficult to probe the $b\bar{b}\gamma\gamma$ channel of 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 $\Delta m_{B_s}$ and $\Delta m_{B_d}$), $-1 \times 10^5 \text{ GeV}^2 < m_{12}^2 < -3 \times 10^4 \text{ GeV}^2$ and $0 \text{ GeV}^2 < m_{12}^2 < 1.5 \times 10^4 \text{ GeV}^2$. The various Higgs trilinear couplings are sensitive to $\tan \beta$ and $m_{12}^2$. In addition, the top quark Yukawa couplings 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 on the planes of the Higgs couplings in Fig. 2. The upper panel of Fig. 2 shows that the light CP-even Higgs trilinear coupling and its coupling to top quark are restricted to be around the SM predictions, respectively. The absolute value of the heavy CP-even Higgs coupling to 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 value of the Higgs trilinear couplings of $HHH$ and $HHh$ are respectively allowed to be as high as 15 and 10 relative to 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
FIG. 2: Same as Fig. 1 but projected on the planes of $y_t^h$ versus $y_{hhh}$, $y_t^H$ versus $y_{HHH}$, $y_{HHH}$ versus $y_{Hhh}$ and $y_{Hhh}$ versus $y_{HHh}$. All these Higgs trilinear couplings are normalized to the SM $hhh$ coupling.

potential is "decoupling", namely the $hhh$ coupling is near the SM prediction while other trilinear couplings of $HHH$, $HHh$ 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 of $HHh$ and $Hhh$ are very small. This will sizably soften the destructive
FIG. 3: Same as Fig. 1 but projected on the planes of $R_{hH}$ versus $R_{hh}$ and $R_{HH}$ versus $R_{hh}$. Here the ratios denote the production rates via the gluon fusion normalized to the SM cross section of $hh$ production.

interference between the triangle and box diagrams, leading the enhancement of the cross section of $gg \rightarrow hH$. In the other region, the coupling $HHh$ is much larger than the SM $hhh$ coupling, which can make the contributions of the triangle diagrams to overcome the box diagrams, and enhance the cross section of $gg \rightarrow hH$. In addition, the upper-right panel of Fig. 2 shows that $R_{bb\gamma\gamma} > 2.0$ favors the absolute value of $y_t^H$ to be larger than 0.5, which avoids the cross section of $gg \rightarrow hH$ to be sizably suppressed.

Although the couplings of $HHH$ and $HHh$ can be much larger than the SM $hhh$ coupling, the cross section of $gg \rightarrow HH$ can not be enhanced since there are destructive interference between the triangle diagrams mediated by $H$ and $h$. Conversely, the cross section of $gg \rightarrow HH$ is smaller than the SM cross section of $gg \rightarrow hh$ since the $Ht\bar{t}$ coupling is suppressed. We show the cross sections of $hh$, $hH$ and $HH$ in Fig. 3. This figure shows that the cross section of $HH$ is smaller than 0.6 relative 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 of 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 a SM-like cubic self-coupling while other Higgs trilinear couplings of the two CP-even Higgses are very small. In this scenario, the $b\bar{b} \rightarrow hh, hH, HH$ processes can be neglected since there is no enhancement of Higgs trilinear couplings.

We take a benchmark point

$$\sin(\beta - \alpha) \approx -0.999988, \quad \tan \beta \approx 1.232, \quad m_h = 125.5 \text{ GeV}, \quad m_H \approx 126.0 \text{ GeV},$$

$$m_A = 595.65 \text{ GeV}, \quad m_{H^\pm} = 595.65 \text{ GeV}, \quad m_{t_{12}}^2 = 12304.0 \text{ GeV}^2;$$

$$y_{ht} = -0.996, \quad y_{Ht} = 0.82, \quad y_{h\bar{b}b} = -1.006, \quad y_{H\bar{b}b} = -1.228,$$

$$y_{hh} = -0.99996, \quad y_{H\bar{H}H} = 0.245, \quad y_{H\bar{H}h} = 0.0598, \quad y_{HHh} = 0.00552;$$

$$Br(h \rightarrow \gamma\gamma) = 1.969 \times 10^{-3}, \quad Br(h \rightarrow b\bar{b}) = 0.6119,$$

$$Br(H \rightarrow \gamma\gamma) = 9.702 \times 10^{-5}, \quad Br(H \rightarrow b\bar{b}) = 0.8385;$$

$$\sigma(gg \rightarrow hh)_{LO} = 16.74 \text{ fb}, \quad \sigma(gg \rightarrow hH)_{LO} = 50.4 \text{ fb}. \quad (14)$$

Since $Br(H \rightarrow \gamma\gamma)$ is very small, we neglect $gg \rightarrow HH \rightarrow b\bar{b}\gamma\gamma$, and consider the $b\bar{b}\gamma\gamma$ signal from

$$gg \rightarrow hh \rightarrow b\bar{b}\gamma\gamma,$$

$$gg \rightarrow hH \rightarrow b\bar{b}\gamma\gamma. \quad (15)$$

The main SM backgrounds include non-resonant $b\bar{b}\gamma\gamma$, $tt\bar{h}$ ($t\bar{t} \rightarrow b\bar{b} + X, \quad h \rightarrow \gamma\gamma$), $Zh$ ($Z \rightarrow b\bar{b}, \quad h \rightarrow \gamma\gamma$) and $b\bar{b}h$ ($h \rightarrow \gamma\gamma$). We neglect the subdominant reducible backgrounds of $jj\gamma\gamma$ and $t\bar{t}\gamma\gamma$ [8]. The QCD corrections are considered by including a $k$-factor, which is 2.27 for the signal [31], 2.0 for $b\bar{b}\gamma\gamma$ [6], 1.1 for $tt\bar{h}$ [32], 1.33 for $Zh$ [32] and 1.2 for $b\bar{b}h$ [33].

Fig. 4 shows the distributions of some kinematical variables at the LHC with $\sqrt{s} = 14$ TeV for the $hh, hH, b\bar{b}\gamma\gamma$ and $tt\bar{h}$. The results of $Zh$ and $b\bar{b}h$ are not shown since they are subdominant. According to the distribution differences between the signal and backgrounds, we can improve the ratio of signal to backgrounds by making some kinematical cuts. First,
we require the final states to include two isolated photons and two $b$-jets, and further impose
the following cuts

\[ P_T^{b_1} > 60 \text{ GeV}, \quad P_T^{b_2} > 25 \text{ GeV}, \quad P_T^{\gamma_1} > 60 \text{ GeV}, \quad P_T^{\gamma_2} > 25 \text{ GeV}, \]
\[ \Delta R_{bb} > 0.4, \quad \Delta R_{\gamma\gamma} > 0.4, \quad \Delta R_{b\gamma} > 0.4, \]
\[ |\eta_b| < 2.5, \quad |\eta_{\gamma}| < 2.5, \]
\[ M_{bb} > 30 \text{ GeV}, \quad M_{\gamma\gamma} > 30 \text{ GeV}, \quad M_{bb\gamma\gamma} > 350 \text{ GeV}, \]  

(16)

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 \( P_T^{\gamma_2} \) for 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 the azimuthal angle and rapidity respectively. The cuts of the invariant mass of two \( b \)-jets and two photon \( M_{bb\gamma\gamma}, P_T^{b_1} \) and \( P_T^{\gamma_1} \) can suppress the backgrounds sizably, especially the largest background \( b\bar{b}\gamma\gamma \).

The photon pair is further restricted to have

\[ \Delta R_{\gamma\gamma} < 2.0, \quad 115 \text{ GeV} < M_{\gamma\gamma} < 135 \text{ GeV}. \]  

(17)

The \( b \)-quark pair is restricted to have

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

(18)

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

Finally, we make some cuts which can specially suppress the background \( t\bar{t}h \). Since \( W^\pm \) will decay into the charged leptons and jets, the background \( t\bar{t}h \) tends to include additional charged leptons and more jets. Therefore, we will veto the following case

\[ P_T^\ell > 20 \text{ GeV} \quad \text{or} \quad P_T^{j8} > 20 \text{ GeV}, \]

(19)

where \( P_T^{j8} \) denotes the transverse momentum of the 8th hardest jet.

The resulting cut flow is shown in Table. [11] The \( b\bar{b}\gamma\gamma \) and \( t\bar{t}h \) are the two major backgrounds. After imposing the above cuts, the events from signal \( hH \) are approximately 1.6 times of those of \( hh \). Since \( h \) and \( H \) are the degenerate 125.5 GeV Higgses, the total signal events are from \( hh \) and \( hH \), whose significance can reach 5\( \sigma \) at the 14 TeV LHC with an integrated luminosity of 3000 \( fb^{-1} \). If there is sizable mass splitting between \( h \) and \( H \), the
TABLE I: The cut flow for the signal and background event numbers at the 14 TeV LHC with an integrated luminosity of 3000 fb$^{-1}$ for the $b\bar{b}\gamma\gamma$ channel. The two columns labeled 'hh' and 'hH' are for the Higgs pair signal while other columns are for the backgrounds.

| $\sqrt{s} = 14$ TeV, 3 ab$^{-1}$ | hh | hH | $b\bar{b}\gamma\gamma$ | $t\bar{t}h$ | Zh | $b\bar{b}h$ | $S/\sqrt{B}$ |
|-----------------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| after cut in Eq. (16)       | 38.4             | 63.3             | 15999           | 246.8           | 22.5             | 9.8             | 0.8             |
| after cut in Eq. (17)       | 29.9             | 48.1             | 679.5           | 152.5           | 18.4             | 4.7             | 2.7             |
| after cut in Eq. (18)       | 18.7             | 29.9             | 74              | 16.8            | 2.7              | 0.4             | 5.1             |
| after cut in Eq. (19)       | 18.6             | 29.7             | 74              | 10.4            | 2.7              | 0.4             | 5.2             |

cuts in Eq. (17) and Eq. (18) will hurt the events of $hH$ inevitably and hence suppress the significance. Therefore, the degeneracy between $h$ and $H$ plays the 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 the Higgs pair production can be enhanced due to the two nearly degenerate 125 GeV Higgses. 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 and the signal $b\bar{b}\gamma\gamma$ can be sizably enhanced. We also considered a "decoupling" scenario where the light CP-even Higgs has the SM-like cubic self-coupling while other trilinear Higgs couplings are very small. From a detailed simulation on the signal $b\bar{b}\gamma\gamma$ and backgrounds, we found that the $hh$ and $hH$ production channels can jointly enhance the statistical significance to 5$\sigma$ at the 14 TeV LHC with an integrated luminosity of 3000 fb$^{-1}$. Therefore, the degenerate $h$ and $H$ play the vital role in enhancing the significance for probing the Higgs potential "decoupling" scenario.

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