Published for SISSA by Springer

Received: *December 24, 2013*
Revised: *February 6, 2014*
Accepted: *February 10, 2014*
Published: *March 3, 2014*

LHC diphoton and Z+photon Higgs signals in the Higgs triplet model with Y = 0

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Abstract: We study the implications of the LHC diphoton and Z+photon Higgs signals on the Higgs triplet model with Y=0, which predicts two neutral CP-even Higgs bosons h, H and a pair of charged Higgs $H^{\pm}$. We discuss three different scenarios: (i) the observed boson is the light Higgs boson h; (ii) it is the heavy Higgs boson H; (iii) the observed signal is from the almost degenerate h and H. We find that the inclusive Higgs diphoton rates in the first two scenarios can be enhanced or suppressed compared to the SM value, which can respectively fit the ATLAS and CMS diphoton data within 1σ range. The inclusive ZZ^* rates are suppressed, which are outside 1σ range of ATLAS data and within 1σ range of CMS data. Meanwhile, another CP-even Higgs boson production rate can be suppressed enough not to be observed at the collider. For the third scenario, the Higgs diphoton rate is suppressed, which is outside 1σ range of ATLAS data, and the ZZ^* rate equals to SM value approximately. In addition, we find that the two rates of $h \to \gamma\gamma$ and $h \to Z\gamma$ have the positive correlations for the three scenarios.

Keywords: Higgs Physics, Beyond Standard Model

ArXiv ePrint: 1303.4490

doi:10.1007/JHEP03(2014)010

JHEP03(2014)010

Contents

JHEP03(2014)010

1 Introduction

The CMS and ATLAS collaborations have announced the observation of a new boson around 125.5 GeV [1, 2], which is corroborated by the Tevatron search results [3]. The properties of this particle with large experimental uncertainties are consistent with the SM Higgs boson. Among the various signals, the diphoton and ZZ^* are the cleanest channels of seraching for the Higgs boson. The CMS and ATLAS have presented the constraints [4, 5],

$$\begin{aligned} &R_{\gamma\gamma} = 0.77 \pm 0.27, \qquad &&R_{ZZ^*} = 0.92 \pm 0.28 \ \ \text{(CMS)}, \\ &R_{\gamma\gamma} = 1.6 \pm 0.3, \qquad &&R_{ZZ^*} = 1.5 \pm 0.4 \ \ \text{(ATLAS)}. \end{aligned} \tag{1.1}$$

The CMS collaboration has released their results of the measurement of $Z\gamma$ and set an upper limit on the ratio $R_{Z\gamma} < 10$ [6].

The recent Higgs data has been discussed in the SUSY models [7–27], little Higgs models [28–34] and the extensions of Higgs field models, such as the two-Higgs-doublet model [35–48], the Higgs triplet model (Y=2) [49–57], the models with septuplet [58] and color-octet scalar [59]. In this work, we will study the implications of the LHC diphoton and Z+photon Higgs signals on the Higgs triplet model with Y=0 (HTM0) [60, 61], which predicts two neutral CP-even Higgs bosons h, H and a pair of charged Higgs $H^\pm$. We will discuss three different scenarios: (i) the observed boson is the light Higgs h, and the heavy Higgs H is not observed at the LHC; (ii) it is the heavy Higgs H, and the light Higgs h is not observed at the LEP; (iii) the observed signal is from the almost degenerate h and H. Also we will pay the particular attention to the correlations between $h \to Z\gamma$ and $h \to \gamma\gamma$. Since both of the rates are loop-induced by charged particles, they should be closely correlated. Any new physics effects manifested in the diphoton decay should also alter the $Z\gamma$ decay [54, 62–66]

Our work is organized as follows. In section II we recapitulate the Higgs triplet model with Y=0. In section III we discuss the LHC diphoton Higgs signal and the correlations between $h \to Z\gamma$ and $h \to \gamma\gamma$. Finally, we give our conclusion in section IV.

2 Higgs triplet model with Y=0

In the HTM0, a real SU(2)$_\mathrm{L}$ triplet scalar field Σ with $Y = 0$ is added to the SM Lagrangian in addition to the doublet field Φ. These fields can be written as

$$\Sigma = \tfrac{1}{2}\begin{pmatrix} \delta^0 & \sqrt{2}\delta^+ \\ \sqrt{2}\delta^- & -\delta^0 \end{pmatrix}, \qquad \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}. \tag{2.1}$$

The renormalizable scalar potential can be written as [67]

$$V(\Phi,\Sigma) = -\mu^2\ \Phi^\dagger\Phi\ +\ \lambda_0\ \left(\Phi^\dagger\Phi\right)^2\ -\frac{1}{2}\ M_\Sigma^2 F\ +\ \frac{b_4}{4}F^2\ +\ a_1\ \Phi^\dagger\Sigma\Phi + \frac{a_2}{2}\Phi^\dagger\Phi F \tag{2.2}$$

where $F \equiv \left(\delta^0\right)^2 + 2\delta^+\delta^-$ and all the parameters are real. The Higgs doublet and triplet fields can acquire vacuum expectation values

$$\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v_d \end{pmatrix}, \qquad \langle\Delta\rangle = \frac{1}{2}\begin{pmatrix} v_t & 0 \\ 0 & -v_t \end{pmatrix} \tag{2.3}$$

with $v^2 = v_d^2 + 4v_t^2 \approx (246\ \text{GeV})^2$.

After the spontaneous symmetry breaking, the Lagrangian of eq. (2.2) predicts the four physical Higgs bosons, including two CP-even Higgs bosons h, H and a pair of charged Higgs $H^\pm$. These mass eigenstates are in general mixtures of the doublet and triplet fields. The mass matrixes of neutral and charged Higgs bosons are [67]

$$\mathcal{M}_0^2 = \begin{pmatrix} 2\lambda_0 v_d^2 & -a_1 v_d/2 + a_2 v_d v_t \\ -a_1 v_d/2 + a_2 v_d v_t & 2b_4 v_t^2 + \frac{a_1 v_d^2}{4v_t} \end{pmatrix} \equiv \begin{pmatrix} A & B \\ B & C \end{pmatrix}, \mathcal{M}_\pm^2 = \begin{pmatrix} a_1 v_t & a_1 v_d/2 \\ a_1 v_d/2 & \frac{a_1 v_d^2}{4v_t} \end{pmatrix}. \tag{2.4}$$

The physical mass eigenstates and the unphysical electroweak eigenstates are related by rotations through two mixing angles θ_0 and θ_+:

$$\begin{pmatrix} h \\ H \end{pmatrix} = \begin{pmatrix} \cos\theta_0 & \sin\theta_0 \\ -\sin\theta_0 & \cos\theta_0 \end{pmatrix}\begin{pmatrix} \phi^0 \\ \delta^0 \end{pmatrix}, \tag{2.5}$$

$$\begin{pmatrix} H^\pm \\ G^\pm \end{pmatrix} = \begin{pmatrix} -\sin\theta_\pm & \cos\theta_\pm \\ \cos\theta_\pm & \sin\theta_\pm \end{pmatrix}\begin{pmatrix} \phi^\pm \\ \delta^\pm \end{pmatrix}. \tag{2.6}$$

Where the Goldstone boson $G^\pm$ is eaten by the gauge bosons.

Since the experimental value of the ρ parameter is near unity [68], $4v_t^2/v_d^2$ is required to be much smaller than unity. In our calculation, v_t is taken as 1 GeV. The mixing angle

$\theta_\pm$ is proportional to $\frac{v_t}{v_d}$, therefore it is very small. The charged Higgs mass is given as

$$M_{H^\pm}^2 = a_1 v_t \left(1 + \frac{v_d^2}{4v_t^2}\right). \tag{2.7}$$

The neutral mixing angle θ_0 is given as

$$\begin{aligned} c_0 \equiv \cos\theta_0 &= \frac{1}{\sqrt{2}}\left(1 - \frac{A-C}{\sqrt{(A-C)^2+4B^2}}\right)^{1/2}, \\ s_0 \equiv \sin\theta_0 &= -\frac{1}{\sqrt{2}}\frac{B}{\mid B\mid}\left(1 + \frac{A-C}{\sqrt{(A-C)^2+4B^2}}\right)^{1/2}. \end{aligned} \tag{2.8}$$

Where

$$c_0 > \frac{1}{\sqrt{2}} \text{ for } C > A, \quad c_0 < \frac{1}{\sqrt{2}} \text{ for } \quad C < A, \quad c_0 \to \frac{1}{\sqrt{2}} \text{ for } C \to A. \tag{2.9}$$

The neutral Higgs boson masses are given as

$$\begin{aligned} m_h^2 &= \frac{1}{2}\left(A + C - \sqrt{(A-C)^2+4B^2}\right), \\ m_H^2 &= \frac{1}{2}\left(A + C + \sqrt{(A-C)^2+4B^2}\right). \end{aligned} \tag{2.10}$$

In our calculations, the involved Higgs couplings are listed as [67]

$$\begin{aligned} &hf\bar{f} : -i\frac{m_f}{v_d}c_0, && Hf\bar{f} : i\frac{m_f}{v_d}s_0, \\ &ZZh : \frac{2im_Z^2}{v_d}c_0 g^{\mu\nu}, && ZZH : -\frac{2im_Z^2}{v_d}s_0 g^{\mu\nu}, \\ &W^+W^-h : ig_2^2\left(\frac{1}{2}v_d c_0 + 2v_t s_0\right)g^{\mu\nu}, && W^+W^-H : ig_2^2\left(-\frac{1}{2}v_d s_0 + 2v_t c_0\right)g^{\mu\nu}, \\ &\gamma H^+H^- : ie\left(p'-p\right)^\mu, && ZH^+H^- : i\left(g_2 c_W - \frac{m_Z}{v_d}s_+^2\right)\left(p'-p\right)^\mu, \end{aligned}$$
$$\begin{aligned} H^+H^-h &: -i\left(a_1 c_+ s_+ c_0 - \frac{1}{2}a_1 s_+^2 s_0 + a_2 v_d c_+^2 c_0 + a_2 v_t s_+^2 s_0 + 2b_4 v_t c_+^2 s_0 + 2\lambda_0 v_d s_+^2 c_0\right), \\ H^+H^-H &: -i\left(-a_1 c_+ s_+ s_0 - \frac{1}{2}a_1 s_+^2 c_0 - a_2 v_d c_+^2 s_0 + a_2 v_t s_+^2 c_0 + 2b_4 v_t c_+^2 c_0 - 2\lambda_0 v_d s_+^2 s_0\right). \end{aligned} \tag{2.11}$$

Where $s_+ = \sin\theta_+$ and $c_+ = \cos\theta_+$. All the momenta flow into the vertex.

3 The Higgs diphoton and $Z\gamma$ rates at the LHC

In our calculations, we take m_h, m_H, a_2, b_4 and v_d, v_t as the input parameters, which can determine the values of λ_0, a_1, $m_{H^\pm}$. As mentioned above, v_t is taken as 1 GeV. The perturbativity can give the strong constraints on a_2 and b_4,

$$-2\sqrt{\pi} \le a_2 \le 2\sqrt{\pi}, \qquad -2\sqrt{\pi} \le b_4 \le 2\sqrt{\pi}. \tag{3.1}$$

The electroweak T parameter can give the constraints on the splitting of m_H and $m_{H^\pm}$, $(m_H - m_{H^\pm})^2 < 0.96\ m_W^2$ [67]. Since the coupling $H^\pm \bar{f}_i f_j$ is sizably suppressed by s_+, the search experiments through the top quark decay hardly give the constraints on $H^\pm$. The experimental data at the LEP gives the lower bound of the charged Higgs mass, $m_{H^\pm} > 79.3\,\text{GeV}$ [69, 70].

We discuss three different scenarios: (I) the observed boson is the light Higgs h, $m_h = 125.5\,\text{GeV}$ and $135\,\text{GeV} \leq m_H \leq 500\,\text{GeV}$; (II) it is the heavy Higgs H, $m_H = 125.5\,\text{GeV}$ and $80\,\text{GeV} \leq m_h \leq 110\,\text{GeV}$; (III) the observed signal is from the almost degenerate h and H, $m_h \simeq m_H \simeq 125.5\,\text{GeV}$.

As shown in the eq. (2.11), the h couplings to $f\bar{f}$ and WW are proportional to c_0 while these couplings of H are proportional to s_0. Due to $v_t \ll v_d$ and $s_+ \to 0$, the h couplings to WW and H^+H^- are sensitive to c_0 while these couplings of H are sensitive to s_0. Therefore, the cross sections and the decay widths of $h(H)$ normalized to SM values can be given as

$$\begin{aligned}
\frac{\sigma(\ gg \to h(H)\ )}{\sigma_{\text{SM}}(\ gg \to h(H)\ )} &\simeq \frac{\sigma(\ pp \to jjh(H)\ )}{\sigma_{\text{SM}}(\ pp \to jjh(H)\ )} \\
&\simeq \frac{\sigma(\ pp \to Vh(H)\ )}{\sigma_{\text{SM}}(\ pp \to Vh(H)\ )} \simeq \frac{\sigma(\ pp \to h(H)t\bar{t}\ )}{\sigma_{\text{SM}}(\ pp \to h(H)t\bar{t}\ )} \simeq c_0^2(s_0^2), \\
\frac{\Gamma(\ h(H) \to f\bar{f}\ )}{\Gamma_{\text{SM}}(\ h(H) \to f\bar{f}\ )} &\simeq \frac{\Gamma(\ h(H) \to VV\ )}{\Gamma_{\text{SM}}(\ h(H) \to VV\ )} \simeq \frac{\Gamma(\ h(H) \to gg\ )}{\Gamma_{\text{SM}}(\ h(H) \to gg\ )} \simeq c_0^2(s_0^2),
\end{aligned} \tag{3.2}$$

where V denotes W, Z. Compared to SM, in addition to the modified $ht\bar{t}$ and hWW couplings, the charged Higgs $H^\pm$ will alter the decays $h \to \gamma\gamma$ and $h \to Z\gamma$ via the one-loop. The corresponding expressiones are given in the appendix A.

The Higgs boson $\gamma\gamma$, ZZ^* and $Z\gamma$ rates of HTM0 normalized to the SM values are respectively defined as

$$\begin{aligned}
R_{h(H)}(\gamma\gamma) &= \frac{\sigma(\ pp \to h(H)\ )}{\sigma_{\text{SM}}(\ pp \to h(H)\ )} \frac{Br(\ h(H) \to \gamma\gamma\ )}{Br_{\text{SM}}(\ h(H) \to \gamma\gamma\ )} \\
&\simeq c_0^2(s_0^2) \frac{\Gamma(\ h(H) \to \gamma\gamma\ )}{c_0^2(s_0^2)\Gamma_{\text{SM}}(\ h(H)\ )} \frac{\Gamma_{\text{SM}}(\ h(H)\ )}{\Gamma_{\text{SM}}(\ h(H) \to \gamma\gamma\ )} \simeq \frac{\Gamma(\ h(H) \to \gamma\gamma\ )}{\Gamma_{\text{SM}}(\ h(H) \to \gamma\gamma\ )}, \\
R_{h(H)}(ZZ^*) &= \frac{\sigma(\ pp \to h(H)\ )}{\sigma_{\text{SM}}(\ pp \to h(H)\ )} \frac{Br(\ h(H) \to ZZ^*\ )}{Br_{\text{SM}}(\ h(H) \to ZZ^*\ )} \\
&\simeq c_0^2(s_0^2) \frac{c_0^2(s_0^2)\Gamma_{\text{SM}}(\ h(H) \to ZZ^*\ )}{c_0^2(s_0^2)\Gamma_{\text{SM}}(\ h(H)\ )} \frac{\Gamma_{\text{SM}}(\ h(H)\ )}{\Gamma_{\text{SM}}(\ h(H) \to ZZ^*\ )} \simeq c_0^2(s_0^2), \\
R_{h(H)}(Z\gamma) &= \frac{\sigma(\ pp \to h(H)\ )}{\sigma_{\text{SM}}(\ pp \to h(H)\ )} \frac{Br(\ h(H) \to Z\gamma\ )}{Br_{\text{SM}}(\ h(H) \to Z\gamma\ )} \\
&\simeq c_0^2(s_0^2) \frac{\Gamma(\ h(H) \to Z\gamma\ )}{c_0^2(s_0^2)\Gamma_{\text{SM}}(\ h(H)\ )} \frac{\Gamma_{\text{SM}}(\ h(H)\ )}{\Gamma_{\text{SM}}(\ h(H) \to Z\gamma\ )} \simeq \frac{\Gamma(\ h(H) \to Z\gamma\ )}{\Gamma_{\text{SM}}(\ h(H) \to Z\gamma\ )}.
\end{aligned} \tag{3.3}$$

Where $\sigma(\ pp \to h(H)\ )$ is the total cross section of Higgs boson. The analytic expressions in eq. (3.2) and eq. (3.3) may help us understand the Higgs production and decay well. In our numerical calculations, we take code Hdecay to consider the relevant higher order QCD and electroweak corrections [71].

JHEP03(2014)010

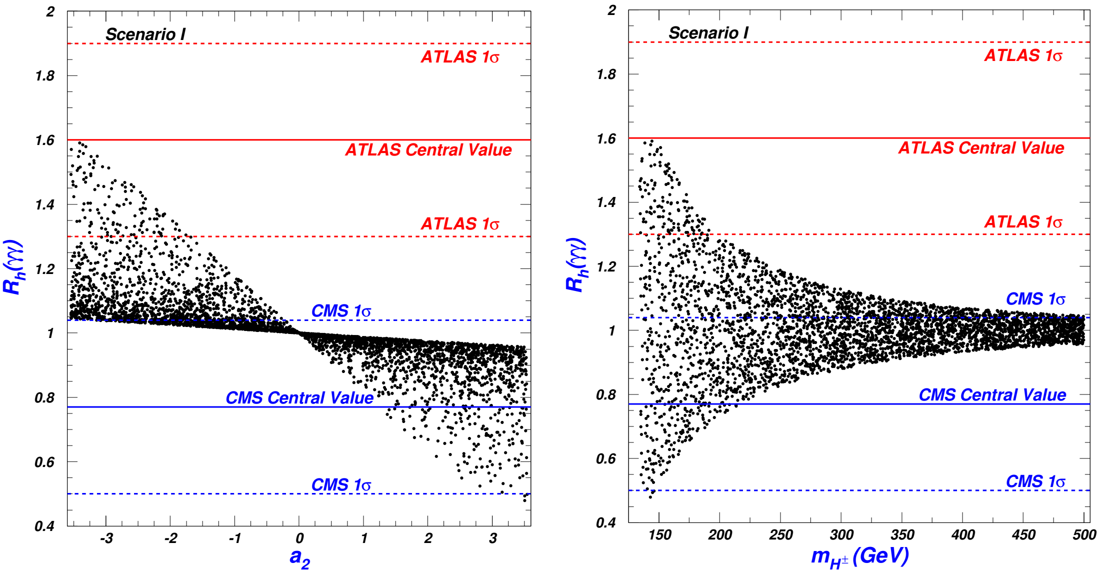

Figure 1. The scatter plots of the parameter space projected on the planes of $R_h(\gamma\gamma)$ versus a_2 and $R_h(\gamma\gamma)$ versus $m_{H^\pm}$, respectively.

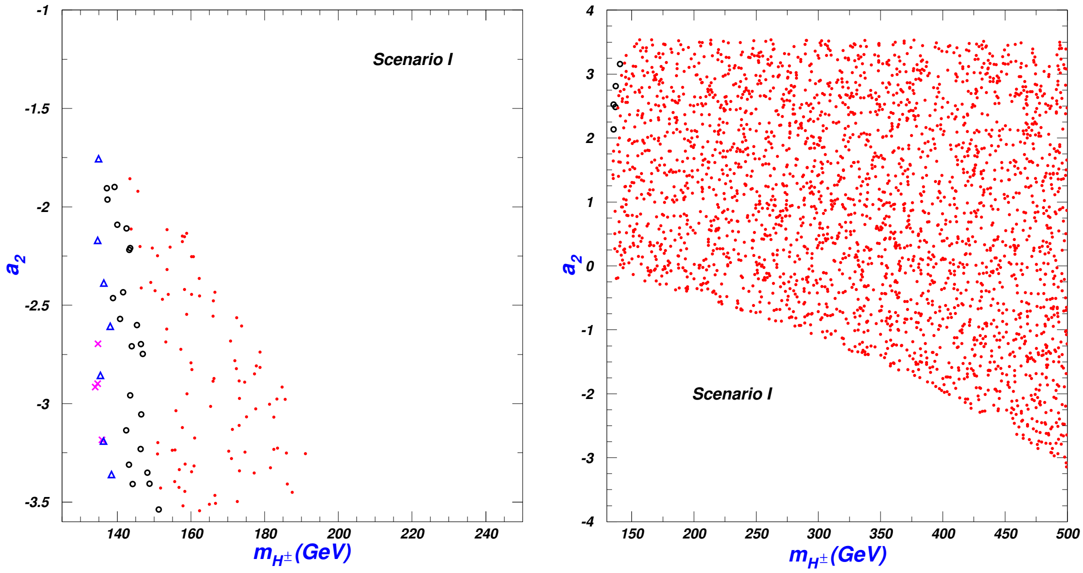

Figure 2. The scatter plots projected on the plane of a_2 versus $m_{H^\pm}$. For the left panel, $R_h(\gamma\gamma)$ is within 1σ range of ATLAS data. $0.86 < c_0^2 < 0.90$ for the crosses (pink), $0.90 \leq c_0^2 < 0.95$ for the triangles (blue), $0.95 \leq c_0^2 < 0.98$ for the circles (black), and $0.98 \leq c_0^2 < 1.0$ for the bullets (red). The right panel is the same as the left panel, but $R_h(\gamma\gamma)$ is within 1σ range of CMS data.

3.1 Scenario I

For the scenario I, the light Higgs h is the observed boson. Since the observed ZZ^* rate is consistent with the SM value, c_0 can not be too small. Also, it is important to make sure that the production rate of H is small enough not to be detected at the LHC. Thus, to obtain a large c_0 and a small s_0, we require $C > A$ (see eq. (2.9)).

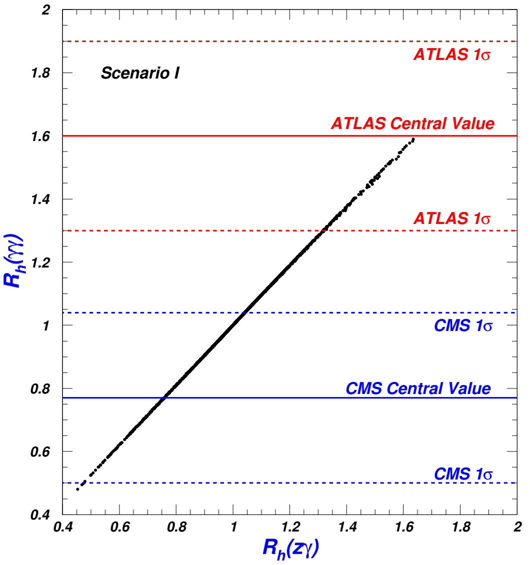

Figure 3. The scatter plots of the parameter space projected on the plane of $R_h(\gamma\gamma)$ versus $R_h(Z\gamma)$.

In figure 1, we plot $R_h(\gamma\gamma)$ versus a_2 and $R_h(\gamma\gamma)$ versus $m_{H^\pm}$, respectively. The h coupling to H^+H^- is sensitive to the parameter a_2, which gives the additional contributions to the decay $h \to \gamma\gamma$ via one-loop. Figure 1 shows that the $H^\pm$ contributions to $R_h(\gamma\gamma)$ can interfere constructively with W contributions for $a_2 < 0$ and interfere destructively for $a_2 > 0$, leading $R_h(\gamma\gamma) > 1$ and $R_h(\gamma\gamma) < 1$, which are respectively favored by the enhanced ATLAS diphoton data and the suppressed CMS data. The magnitude becomes sizable as the increasing of the absolute value of a_2 and the decreasing of $m_{H^\pm}$.

In figure 2, the samples with $R_h(\gamma\gamma)$ being within 1σ range of ATLAS and CMS diphoton data are projected on the plane of a_2 and $m_{H^\pm}$. The left panel shows that the 1σ ATLAS diphoton data favors $-3.6 < a_2 < -1.8$ and $m_{H^\pm} < 190\,\text{GeV}$. While the CMS data favors $a_2 > 0$ and allow a_2 to be smaller than 0 for enough large $m_{H^\pm}$. The left panel shows that, for $R_h(\gamma\gamma)$ is within 1σ range of ATLAS diphoton data, the samples lie in the region of $c_0^2 > 0.86$, and the vast majority of them congregate the region of $c_0^2 > 0.96$. The large $m_{H^\pm}$ favors a large c_0^2. From the right panel, the value of c_0^2 is larger than 0.98 for $R_h(\gamma\gamma)$ is within 1σ range of CMS diphoton data. Due to $R_h(ZZ^*) \simeq c_0^2$ (see eq. (3.3)), the inclusive ZZ^* rate is outside 1σ range of ATLAS data (1.5 ± 0.4), but within 1σ range of CMS data (0.92 ± 0.28). Besides, for such large c_0^2, the corresponding s_0^2 is smaller than 0.14, which will suppress the production rates of H at the LHC sizably (see eqs. (3.2) and (3.3)), leading that H is not detected at the LHC.

Figure 3 shows $R_h(\gamma\gamma)$ versus $R_h(Z\gamma)$. We find that the two rates are positively correlated, and the behavior of $R_h(Z\gamma)$ is similar to that of $R_h(\gamma\gamma)$. Further, the prediction of $R_h(Z\gamma)$ equals to that of $R_h(\gamma\gamma)$ approximately.

3.2 Scenario II

For the scenario II, the heavy Higgs H is the observed boson. The parameter s_0 can not be very small to make the observed ZZ^* rate to be consistent with the experimental data.

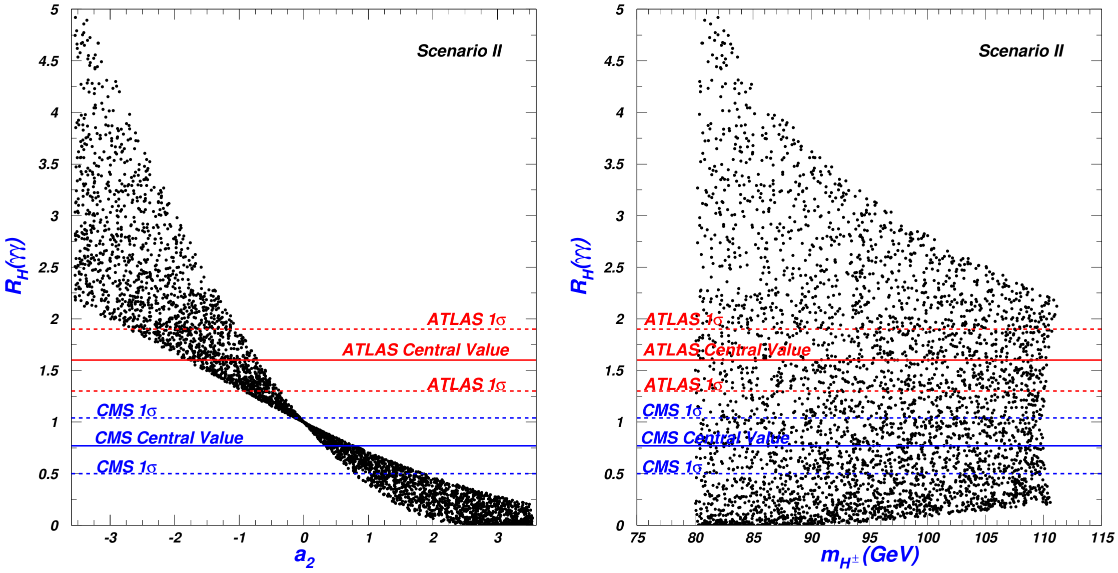

Figure 4. Same as figure 1, but for $R_H(\gamma\gamma)$.

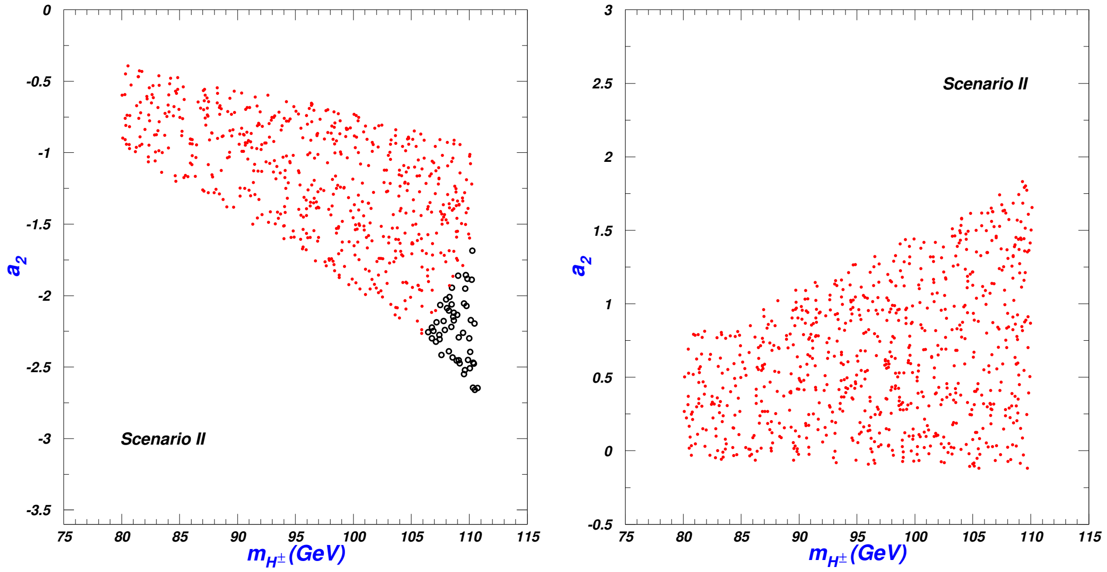

Figure 5. The Scatter plots projected on the plane of a_2 versus $m_{H^\pm}$. For the left panel, $R_H(\gamma\gamma)$ is within 1σ range of ATLAS data. $0.95 \leq s_0^2 < 0.98$ for the circles (black), and $0.98 \leq s_0^2 < 1.0$ for the bullets (red). The right panel is the same as the left panel, but $R_H(\gamma\gamma)$ is within 1σ range of CMS data.

Besides, it is important to make sure that the production rate of h is small enough not to be detected at the LEP. Thus, we require $C < A$ to obtain a large s_0 and a small c_0, (see eq. (2.9)).

In figure 4, we plot $R_H(\gamma\gamma)$ versus a_2 and $R_H(\gamma\gamma)$ versus $m_{H^\pm}$, respectively. Similar to $R_h(\gamma\gamma)$, $R_H(\gamma\gamma)$ is also larger than 1.0 for $a_2 < 0$ and smaller than 1.0 for $a_2 > 0$. $R_H(\gamma\gamma)$ can reach 5.0 for $a_2 \sim -3.5$ and $m_{H^\pm} \sim 80\,\text{GeV}$, which is much larger than $R_h(\gamma\gamma)$ since $m_{H^\pm}$ for the former is smaller than that for the latter.

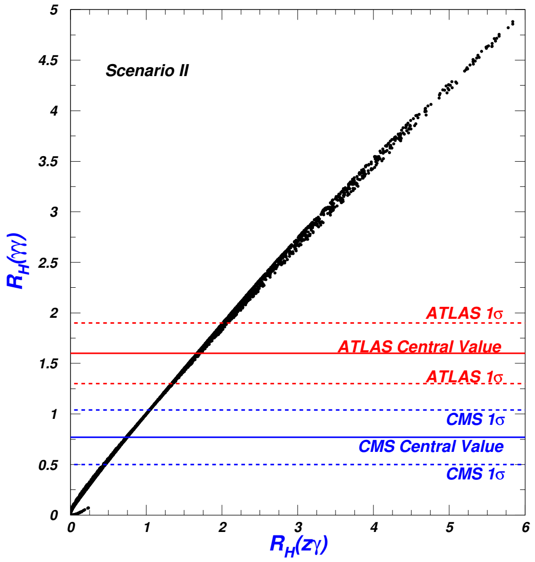

Figure 6. Same as figure 3, but for $R_H(\gamma\gamma)$ versus $R_H(Z\gamma)$.

In figure 5, the samples with $R_H(\gamma\gamma)$ being within 1σ range of ATLAS and CMS diphoton data are projected on the plane of a_2 and $m_{H^\pm}$. Figure 5 shows that $-2.7 < a_2 < -0.4$ and $-0.1 < a_2 < 1.9$ are respectively favored by the 1σ ATLAS and CMS data. The left panel shows that, for $R_H(\gamma\gamma)$ is within 1σ range of ATLAS diphoton data, the samples lie in the region of $s_0^2 > 0.95$, and the vast majority of them congregate the region of $s_0^2 > 0.98$. From the right panel, the value of s_0^2 is larger than 0.98 for $R_H(\gamma\gamma)$ is within 1σ range of CMS diphoton data. The small $m_{H^\pm}$ favors a large s_0^2. Due to $R_H(ZZ^*) \simeq s_0^2$ (see eq. (3.3)), the inclusive ZZ^* rate is outside 1σ range of ATLAS data, but within 1σ range of CMS data. Besides, for such large s_0^2, the corresponding c_0^2 is smaller than 0.05, and the cross section of $e^+e^- \to Zh$ is below the upper limit presented by the LEP [72, 73].

In figure 6, we plot $R_H(\gamma\gamma)$ versus $R_H(Z\gamma)$. Similar to scenario I, the two rates are also positively correlated. Especially for the region favored by the 1σ range of ATLAS and CMS data, the prediction of $R_H(Z\gamma)$ equals to that of $R_H(\gamma\gamma)$ approximately.

3.3 Scenario III

For the scenario III, the observed signal is from the almost degenerate h and H. We assume that the mass splitting of h and H is small enough not to be resolve at current statistics, but large enough so that there is hardly interference between the amplitudes of h and H, $|m_H - m_h| \gg \Gamma(h)$, $\Gamma(H)$ [74]. Therefore, according to eq. (2.10), both the absolute values of $A - C$ and B must be very small, but not to equal to zero exactly. For this case, we can obtain a relation of $m_{H^\pm} \simeq m_h \simeq m_H$ according to eqs. (2.4), (2.7) and (2.10).

In figure 7, we plot $R_h(\gamma\gamma)+R_H(\gamma\gamma)$ versus a_2 and c_0^2, respectively. We find that the Higgs diphoton rate is suppressed compared to SM value, $0.87 < R_h(\gamma\gamma)+R_H(\gamma\gamma) < 0.9$, which is outside 1σ range of ATLAS diphoton data, but within 1σ range of CMS diphoton data. Due to $a_1 > 0$, a_2 must be larger than zero to obtain a very small $\mid B \mid$ ($B = -a_1 v_d/2 + a_2 v_d v_t$). Thus, $R_h(\gamma\gamma)+R_H(\gamma\gamma)$ is smaller than 1.0 since the $H^\pm$ contributions

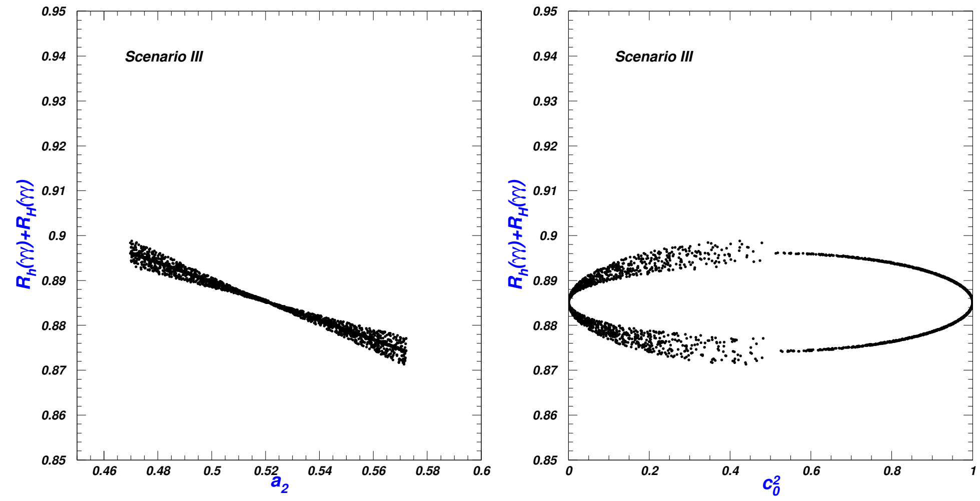

Figure 7. The scatter plots of the parameter space projected on the planes of $R_h(\gamma\gamma) + R_H(\gamma\gamma)$ versus a_2 and c_0^2, respectively.

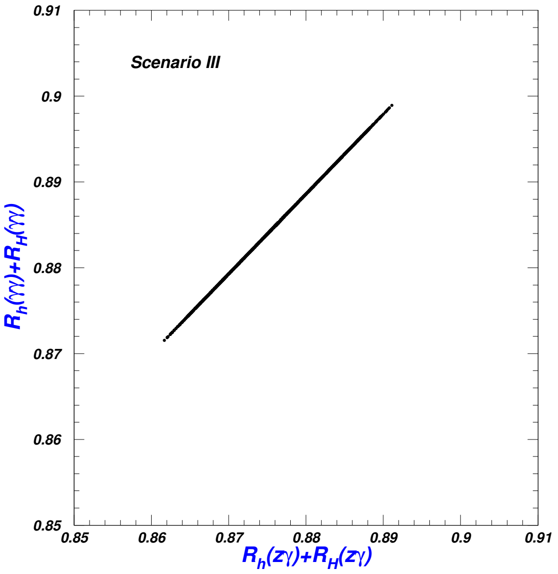

Figure 8. Same as figure 3, but for $R_h(\gamma\gamma) + R_H(\gamma\gamma)$ versus $R_h(Z\gamma) + R_H(Z\gamma)$.

will interfere destructively with the W contributions for $a_2 > 0$. The right panel shows that the large mixing angle θ_0 may appear. The reason is that $\mid A - C \mid$ still may be much smaller than $\mid B \mid$ although $\mid B \mid$ is very small. Due to $R_h(ZZ^*) \simeq c_0^2$ and $R_H(ZZ^*) = s_0^2$ (see eq. (3.3)), the inclusive ZZ^* rate equals to SM prediction value approximately.

In figure 8, we plot $R_h(\gamma\gamma) + R_H(\gamma\gamma)$ versus $R_h(Z\gamma) + R_H(Z\gamma)$. We find that the two rates are also positively correlated, and the correlation is more strong than that of scenario II. $R_h(Z\gamma) + R_H(Z\gamma)$ is allowed to vary in the narrow region $0.86 < R_h(Z\gamma) + R_H(Z\gamma) < 0.89$.

4 Conclusion

In the Higgs triplet model with Y=0, we study the Higgs boson $\gamma\gamma$ and $Z\gamma$ rates at the LHC. We studied three different scenarios: (i) the observed boson is the light Higgs boson h; (ii) it is the heavy Higgs boson H; (iii) the observed signal is from the almost degenerate h and H. We found that, for the first two scenarios, the inclusive Higgs diphoton rates can be enhanced or suppressed compared to the SM value, which is respectively within 1σ range of ATLAS and CMS data. For the scenario I, the ATLAS data favors $-3.6 < a_2 < -1.8$ and $m_{H^\pm} < 190\,\text{GeV}$. The CMS data favors $a_2 > 0$ and allow a_2 to be smaller than 0 for enough large $m_{H^\pm}$. For the scenario II, the ATLAS and CMS diphoton data favor $-2.7 < a_2 < -0.4$ and $-0.1 < a_2 < 1.9$, respectively. For the first two scenarios, the inclusive ZZ^* rates are suppressed, which are outside 1σ range of ATLAS data and within 1σ range of CMS data. For the third scenario, the Higgs diphoton rate is suppressed, which is outside 1σ range of ATLAS data, and the ZZ^* rate equals to SM value approximately. Besides, the two rates of $h \to \gamma\gamma$ and $h \to Z\gamma$ are positively correlated, and they are approximately equal within the 1σ range of ATLAS and CMS diphoton data.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (NNSFC) under grant Nos. 11105116, 11005089, and 11175151.

A The expressions for $\Gamma(h \to \gamma\gamma)$ and $\Gamma(h \to Z\gamma)$

The charged fermion (f), gauge boson (W) and scalar (s) can contribute to the decay widths of $h \to \gamma\gamma$ and $h \to Z\gamma$, which are given by [65, 66, 75]

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 m_h^3}{256\pi^3 v^2}\left|\sum_f N_f^c Q_f^2 y_f A_{1/2}^{\gamma\gamma}(\tau_f) + y_W A_1^{\gamma\gamma}(\tau_W) + Q_s^2 \frac{v\mu_{hss^*}}{2m_s^2} A_0^{\gamma\gamma}(\tau_s)\right|^2, \tag{A.1}$$

$$\begin{aligned}\Gamma(h \to Z\gamma) = \frac{\alpha^2 m_h^3}{128\pi^3 s_W^2 c_W^2 v^2}\left(1 - m_Z^2/m_h^2\right)^3 \Bigg| & N_f^c Q_f y_f \frac{(Q_R^Z + Q_L^Z)}{2} A_{1/2}^{Z\gamma}(\tau_f, \lambda_f) \\ & + Q_W Q_W^Z y_W A_1^{Z\gamma}(\tau_W, \lambda_W) + Q_s Q_s^Z \frac{v g_{hss}}{2m_s^2} A_0^{Z\gamma}(\tau_s, \lambda_s)\Bigg|^2, \end{aligned} \tag{A.2}$$

where $\tau_i = m_h^2/4m_i^2$, $\lambda_i = m_Z^2/4m_i^2$, $Q_W = 1$, $Q_W^Z = c_W^2$. $Q_{f,s}$ are the electric charges of fermion and scalar. N_f^c is the color factor for fermion f. $Q_{R,L(s)}^Z = I_{R,L(s)}^3 - Q_{f(s)} s_W^2$ with $I_{R,L(s)}^3$ being the third isospin components of chiral fermions (scalar). y_f and y_W denote the Higgs couplings to $f\bar{f}$ and WW normalized to the corresponding SM values. g_{hss} is the coupling constant of hss. The loop functions $A_{(0,\,1/2,\,1)}^{\gamma\gamma}$ and $A_{(0,\,1/2,\,1)}^{Z\gamma}$ in eqs. (A.1) and (A.2) are defined as

$$\begin{aligned}
A_0^{\gamma\gamma}(\tau) &= -[\tau - f(\tau)]\tau^{-2}\,, A_{1/2}^{\gamma\gamma}(\tau) = 2[\tau + (\tau-1)f(\tau)]\tau^{-2}\,, \\
A_1^{\gamma\gamma}(\tau) &= -[2\tau^2 + 3\tau + 3(2\tau-1)f(\tau)]\tau^{-2}\,, \\
A_0^{Z\gamma}(\tau,\lambda) &= I_1(\tau,\lambda)\,,\ A_{1/2}^{Z\gamma}(\tau,\lambda) = -2[I_1(\tau,\lambda) - I_2(\tau,\lambda)], \\
A_1^{Z\gamma}(\tau,\lambda) &= [2(1+2\tau)(1-\lambda) + (1-2\tau)]I_1(\tau,\lambda) - 8(1-\lambda)I_2(\tau,\lambda)\,,
\end{aligned} \tag{A.3}$$

where

$$\begin{aligned}
I_1(\tau,\lambda) &= -\frac{1}{(\tau-\lambda)} + \frac{1}{(\tau-\lambda)^2}[f(\tau) - f(\lambda)] + \frac{2\lambda}{(\tau-\lambda)^2}[g(\tau) - g(\lambda)]\,, \\
I_2(\tau,\lambda) &= \frac{1}{(\tau-\lambda)}[f(\tau) - f(\lambda)]\,,
\end{aligned} \tag{A.4}$$

with the functions $f(\tau)$ and $g(\tau)$ given by

$$\begin{aligned}
f(\tau) &= \begin{cases} (\sin^{-1}\sqrt{\tau})^2\,, & \tau \le 1 \\ -\dfrac{1}{4}\left[\log\dfrac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right]^2, & \tau > 1 \end{cases}, \\
g(\tau) &= \begin{cases} \sqrt{\tau^{-1}-1}(\sin^{-1}\sqrt{\tau})\,, & \tau \le 1 \\ \dfrac{\sqrt{1-\tau^{-1}}}{2}\left[\log\dfrac{1+\sqrt{1-\tau^{-1}}}{1-\sqrt{1-\tau^{-1}}} - i\pi\right], & \tau > 1\,. \end{cases}
\end{aligned} \tag{A.5}$$

B The vacuum expectation values

The minimization conditions for the tree-level Higgs potential are

$$\left(-\mu^2 + \lambda_0 v_d^2 - \frac{a_1 v_t}{2} + \frac{a_2 v_t^2}{2}\right) v_d = 0\,, \tag{B.1}$$

$$-M_\Sigma^2 v_t + b_4 v_t^3 - \frac{a_1 v_d^2}{4} + \frac{a_2 v_d^2 v_t}{2} = 0\,. \tag{B.2}$$

Solving the eqs. (B.1) and (B.2) with Mathematica, we can obtain the expressions of v_t and v_d in terms of the Lagrangian parameters. However, their expressions are very complicated and lengthy. Therefore, we assume v_t to be much smaller than 1, and give the approximate solutions for $a_2\mu^2 \ge 2M_\Sigma^2\lambda_0$,

$$v_t = \frac{1}{a_1}\left(-\mu^2 + \frac{a_1^2}{4a_2} + \frac{2M_\Sigma^2\lambda_0}{a_2} + \frac{\sqrt{-128\mu^2 a_2 M_\Sigma^2\lambda_0 + (a_1^2 + 4\mu^2 a_2 + 8M_\Sigma^2\lambda_0)^2}}{4a_2}\right), \tag{B.3}$$

$$v_d = \sqrt{\frac{M_\Sigma^2}{a_2} + \frac{\mu^2}{2\lambda_0} + \frac{a_1^2}{8a_2\lambda_0} + \frac{\sqrt{-128\mu^2 a_2 M_\Sigma^2\lambda_0 + (a_1^2 + 4\mu^2 a_2 + 8M_\Sigma^2\lambda_0)^2}}{8a_2\lambda_0}}, \tag{B.4}$$

and for $a_2\mu^2 \leq 2M_\Sigma^2\lambda_0$,

$$v_t = \frac{1}{a_1}\left(-\mu^2 + \frac{a_1^2}{4a_2} + \frac{2M_\Sigma^2\lambda_0}{a_2} - \frac{\sqrt{-128\mu^2 a_2 M_\Sigma^2\lambda_0 + (a_1^2 + 4\mu^2 a_2 + 8M_\Sigma^2\lambda_0)^2}}{4a_2}\right), \tag{B.5}$$

$$v_d = \sqrt{\frac{M_\Sigma^2}{a_2} + \frac{\mu^2}{2\lambda_0} + \frac{a_1^2}{8a_2\lambda_0} - \frac{\sqrt{-128\mu^2 a_2 M_\Sigma^2\lambda_0 + (a_1^2 + 4\mu^2 a_2 + 8M_\Sigma^2\lambda_0)^2}}{8a_2\lambda_0}}. \tag{B.6}$$

From eqs. (B.3) and (B.5), v_t approaches to 0 for $a_1 \to 0$, which is understandable since a_1 is the coefficient of the only term in the Lagrangian breaking the custodial symmetry.

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