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Diphoton rate in the Inert Doublet Model with a 125 GeV Higgs boson

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An improved analysis of the diphoton decay rate of the Higgs boson in the Inert Doublet Model is presented together with critical discussion of the results existing in the literature. For Higgs boson mass M_h equal 125 GeV, and taking into account the following constraints: vacuum stability, existence of the Inert vacuum, perturbative unitarity, electroweak precision tests and the LEP bounds, we found regions in the parameter space where the diphoton rate is enhanced. The resulting regions were confronted with the allowed values of the Dark Matter mass. We found that significant enhancement in the two photon decay of the Higgs boson is only possible for constrained values of scalar couplings $\lambda_3 \sim hH^+H^-$, $\lambda_{345} \sim hHH$ and masses of the charged scalar and the Dark Matter particle. The enhancement above 1.3 demands the masses of $H^\pm$ and H to be less than 135 GeV (and above 62.5 GeV) and $-1.46 < \lambda_3, \lambda_{345} < -0.24$.

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I. INTRODUCTION

Recently a Higgs-like boson has been discovered at the Large Hadron Collider (LHC) [1]. Although most of the measurements of its properties are in agreement with the hypothesis of the Standard Model (SM) Higgs particle, there may be some indications that the discovered boson is not a SM Higgs boson. For example, the signal strength in the decay channel $h \to \gamma\gamma$, $R_{\gamma\gamma}$, which is proportional to $\mathrm{Br}(h \to \gamma\gamma)$, is equal to 1.8 ± 0.3 [2]. This can be accounted for in the framework of Two Higgs Doublet Models (2HDM), in particular in the Inert Doublet Model (IDM).

The diphoton decay rate in the IDM was considered in Ref. [3–6]. In the parameter region studied in Ref. [3] no enhancement was found, while in Ref. [4] the possibility of modifying the total decay width of the Higgs boson due to the invisible decays into Dark Matter (DM) was not taken into account. In Ref. [5, 6] not entire parameter space was investigated as the mass parameter of the potential was taken with only one sign, the DM particle was assumed to be lighter than the Higgs boson and the mass of DM was constrained ($M_H < 150$ GeV). The diphoton decay rate was also considered in the context of the electroweak phase transition in Ref. [7].

We present an independent analysis of the diphoton Higgs decay mode in IDM which improves the points mentioned above and makes use of the recent experimental data [1]. We point out that the gg Higgs decay width is the same as in the SM. The paper is organized as follows: in Section II we briefly review the model, describe the constraints taken into account and present the method of the analysis. In Section III possible sources of modifications of the diphoton production rate in the IDM with respect to the SM are discussed. The resulting constraints for masses and selfcouplings are presented in Section IV and a short summary can be found in Section V. The Appendix A contains a derivation of the conditions for $R_{\gamma\gamma} > 1$, while in the Appendix B formulas for all Higgs boson decay widths are given.

II. SETUP OF THE ANALYSIS

A. Model

We consider the IDM [3, 8, 9], which is a 2HDM with two SU(2) doublets ϕ_S, ϕ_D with hypercharge $Y = 1$ and the following potential :

$$\begin{aligned} V = &-\tfrac{1}{2}\left[m_{11}^2(\phi_S^\dagger\phi_S) + m_{22}^2(\phi_D^\dagger\phi_D)\right] \\ &+\tfrac{1}{2}\left[\lambda_1(\phi_S^\dagger\phi_S)^2 + \lambda_2(\phi_D^\dagger\phi_D)^2\right] \\ &+\lambda_3(\phi_S^\dagger\phi_S)(\phi_D^\dagger\phi_D) + \lambda_4(\phi_S^\dagger\phi_D)(\phi_D^\dagger\phi_S) \\ &+\tfrac{1}{2}\lambda_5\left[(\phi_S^\dagger\phi_D)^2 + (\phi_D^\dagger\phi_S)^2\right]. \end{aligned} \quad (1)$$

The parameters m_{11}^2, m_{22}^2 and $\lambda_1 \ldots \lambda_4$ are real numbers and without loss of generality we take $\lambda_5 < 0$ [10–12]. The potential V is invariant under a $\mathbb{Z}_2$-type symmetry transformation, called D, which changes the sign of the ϕ_D doublet and leaves all other fields unchanged.

We consider a D-symmetric vacuum state (called the Inert vacuum), which corresponds to the following vacuum expectation values $\langle\phi_S\rangle = \begin{pmatrix} 0 \\ v/\sqrt{2} \end{pmatrix}$, $\langle\phi_D\rangle = 0$.

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The masses of the physical scalars read:

$$\begin{aligned} M_h^2 &= m_{11}^2 = \lambda_1 v^2, \\ M_{H^\pm}^2 &= \tfrac{1}{2}(\lambda_3 v^2 - m_{22}^2), \\ M_A^2 &= \tfrac{1}{2}(\lambda_{345}^{-} v^2 - m_{22}^2) = M_{H^\pm}^2 + \tfrac{1}{2}\lambda_{45}^{-} v^2, \\ M_H^2 &= \tfrac{1}{2}(\lambda_{345} v^2 - m_{22}^2) = M_{H^\pm}^2 + \tfrac{1}{2}\lambda_{45} v^2, \end{aligned}$$

where $\lambda_{345} = \lambda_3 + \lambda_4 + \lambda_5$, $\lambda_{345}^{-} = \lambda_3 + \lambda_4 - \lambda_5$, $\lambda_{45}^{-} = \lambda_4 - \lambda_5$, $\lambda_{45} = \lambda_4 + \lambda_5$. The parameters λ_3 and λ_{345} are proportional to the hH^+H^- and hHH couplings, respectively. The only parameter of the potential, which is absent in this formulas is the parameter λ_2, related to the quartic selfcouplings among the scalars, eg. $HHHH$ or H^+H^-HH.

Since solely the ϕ_S doublet takes part in the Spontaneous Symmetry Breaking (SSB), only h is a Higgs boson. The remaining scalars are often called inert scalars[1] as they do not contribute to SSB.

In the IDM the Yukawa interactions are set to Type I, with the ϕ_S doublet coupled to fermions. Thus h is SM-like, i.e. it couples to fermions (at the tree-level) just like the SM Higgs and so does to the gauge bosons. We assume that it corresponds to the boson discovered at the LHC in 2012 [1] and set $M_h = 125\,\text{GeV}$.

Since the D symmetry is exact in the IDM, it renders the lightest neutral D-odd particle stable providing a good Dark Matter (DM) candidate [13]. Without loss of generality we assume that the DM particle is the H scalar, so $\lambda_{45} < 0$.[2]

B. Constraints

In our analysis we took into account the following constraints [14]:

Vacuum stability: For a stable vacuum state to exist it is necessary that the potential V is bounded from below, which leads to [8]:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 + \sqrt{\lambda_1\lambda_2} > 0, \quad \lambda_{345} + \sqrt{\lambda_1\lambda_2} > 0.$$

Perturbative unitarity: For the theory to be perturbatively unitary it is required that the eigenvalues Λ_i of the high-energy scattering matrix fulfill the condition $|\Lambda_i| < 8\pi$, [14, 15]. In particular, we got $\lambda_1, \lambda_2 < 8.38$.

Existence of the Inert vacuum: The Inert vacuum can be realized only if the following conditions are fulfilled [10, 16]:

$$M_h^2,\ M_H^2,\ M_A^2,\ M_{H^\pm}^2 \geqslant 0, \quad \frac{m_{11}^2}{\sqrt{\lambda_1}} > \frac{m_{22}^2}{\sqrt{\lambda_2}}.$$

From the existence of the Inert vacuum and the Higgs boson with mass $M_h = 125\,\text{GeV}$, and unitarity bounds on λ_2, follows a bound on m_{22}^2 [14]:

$$m_{22}^2 \lesssim 9 \cdot 10^4\,\text{GeV}^2. \tag{2}$$

H as DM candidate: We assume that H is the DM candidate, so $M_H < M_A, M_{H^\pm}$. Studies of the DM in the IDM [13] show that if H is to account for the observed relic density of DM, it should have mass in one of the three regions: $M_H < 10\,\text{GeV}$, $40\,\text{GeV} < M_H < 80\,\text{GeV}$ or $M_H > 500\,\text{GeV}$. We will not impose these bounds from the very beginning, but we will discuss the consistency of our results with these constraints.

Electroweak Precision Tests (EWPT): We demand that the values of S and T parameters calculated in the IDM (using formulas from [9]) lie within 2σ ellipses in the S,T plane, with the following central values [17]: $S = 0.03 \pm 0.09$, $T = 0.07 \pm 0.08$, with correlation equal to 87%.

LEP: We use the LEPI and LEPII bounds on the scalar masses [18, 19]:

$$M_{H^\pm} + M_H > M_W, \quad M_{H^\pm} + M_A > M_W,$$
$$M_H + M_A > M_Z, \quad 2M_{H^\pm} > M_Z, \quad M_{H^\pm} > 70\,\text{GeV}$$

and exclude the region where: $M_H < 80\,\text{GeV}$ and $M_A < 100\,\text{GeV}$ and $M_A - M_H > 8\,\text{GeV}$.

We will refer to the set of the conditions described above as "the constraints" for simplicity.

C. Method of the analysis

We scanned randomly the parameter space of the IDM, taking into account the constraints and letting the parameters to vary in the following regimes:

$$\begin{aligned} M_h &= 125\,\text{GeV}, \\ 70\,\text{GeV} \leqslant M_{H^\pm} &\leqslant 800\ (1400)\,\text{GeV}, \\ 0 < M_A &\leqslant 800\ (1400)\,\text{GeV}, \\ 0 < M_H &< M_A, M_{H^\pm}, \\ -25 \cdot 10^4\ (-2 \cdot 10^6)\,\text{GeV}^2 \leqslant m_{22}^2 &\leqslant 9 \cdot 10^4\,\text{GeV}^2, \\ 0 < \lambda_2 &\leqslant 10. \end{aligned}$$

The allowed region in the parameter space depends on the choice of minimal value of m_{22}^2, which is not constrained. We considered two regimes for m_{22}^2. For the wider of them larger masses of dark scalars are allowed, up to 1400 GeV (values in brackets).

In the parameter space fulfilling the constraints we determine regions for which $R_{\gamma\gamma} > 1$.

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[1] They are also called dark scalars (D-scalars).

[2] It does not lead to the limitation of the mass of the Higgs boson, as DM particle is the lightest of the D-odd scalars, not of all scalars, as was assumed in Ref. [5].

III. $R_{\gamma\gamma}$

To study the diphoton rate observed at the LHC we define the quantity $R_{\gamma\gamma}$ as follows [5]:

$$R_{\gamma\gamma} := \frac{\sigma(pp \to h \to \gamma\gamma)^{\mathrm{IDM}}}{\sigma(pp \to h \to \gamma\gamma)^{\mathrm{SM}}} \approx \frac{[\sigma(gg \to h)\mathrm{Br}(h \to \gamma\gamma)]^{\mathrm{IDM}}}{[\sigma(gg \to h)\mathrm{Br}(h \to \gamma\gamma)]^{\mathrm{SM}}} = \frac{\mathrm{Br}(h \to \gamma\gamma)^{\mathrm{IDM}}}{\mathrm{Br}(h \to \gamma\gamma)^{\mathrm{SM}}}. \quad (3)$$

Above we used the fact that the gluon fusion is the dominant channel of Higgs production. Moreover, in the IDM $\sigma(gg \to h)^{\mathrm{IDM}} = \sigma(gg \to h)^{\mathrm{SM}}$, so $R_{\gamma\gamma}$ reduces to the ratio of branching ratios.

In the IDM this ratio can be modified with respect to the SM, since the charged scalar exchanged in loops gives extra contribution to the $h \to \gamma\gamma$ amplitude [3–5]. In addition, the total decay width of the Higgs boson can be modified due to existence of invisible decay channels $h \to HH$ and $h \to AA$ [3, 5]. In different regions of parameters, different effects dominate.

Many channels contribute to the total decay width of the Higgs boson h. The most important ones for mass $M_h = 125\,\mathrm{GeV}$ are: $b\bar{b}$, $c\bar{c}$, $\tau^+\tau^-$, ZZ^*, WW^*, $\gamma\gamma$, $Z\gamma$, gg, HH, AA. To compute the decay widths we used the formulas from Ref. [20–22]. For completeness they are summarized in the Appendix B. The partial widths of the tree-level h decays into SM particles, and also of the loop mediated decay into gg are in IDM equal to the corresponding ones in the SM.

In Fig. 1 the h branching ratios of are presented as functions of m_{22}^2. Three different cases are considered: decay channels $h \to AA$ and $h \to HH$ are open (with $M_H = 50\,\mathrm{GeV}$, $M_A = 60\,\mathrm{GeV}$, left panel), $h \to AA$ is closed and $h \to HH$ is open ($M_A > 63\,\mathrm{GeV}$, $M_H = 60\,\mathrm{GeV}$, middle panel), both $h \to AA$ and $h \to HH$ are closed ($M_H = 75\,\mathrm{GeV}$, $M_A > 63\,\mathrm{GeV}$, right panel).

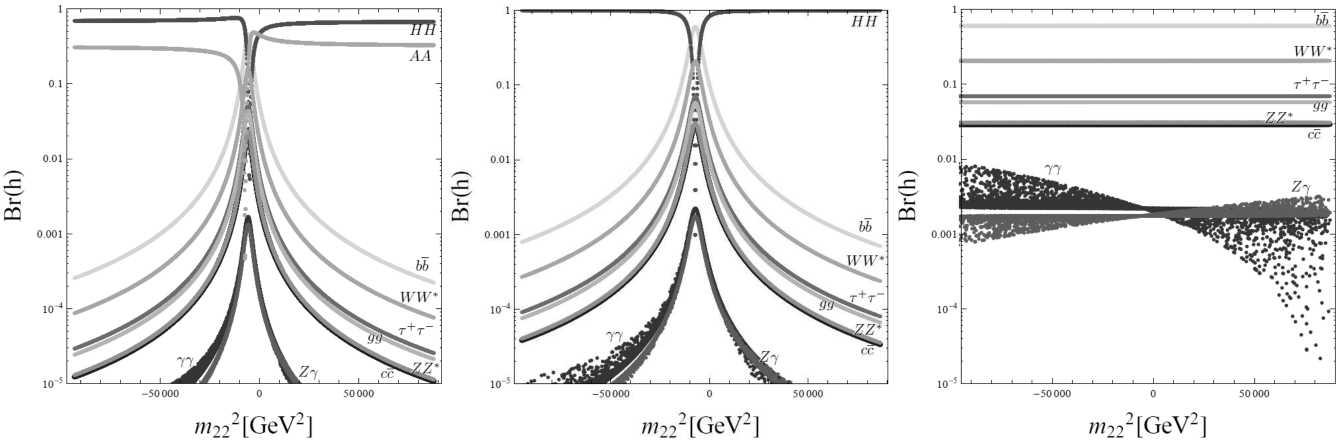

FIG. 1. (Color online) Branching ratios for h with mass 125 GeV. Left panel: decay channels $h \to HH$ and $h \to AA$ are open ($M_H = 50\,\mathrm{GeV}$, $M_A = 60\,\mathrm{GeV}$), middle panel: $h \to HH$ open ($M_H = 60\,\mathrm{GeV}, M_A > 63\,\mathrm{GeV}$), right panel: no invisible h decay channels allowed ($M_H = 75\,\mathrm{GeV}, M_A > 63\,\mathrm{GeV}$).

It appears, that when invisible decay channels $h \to HH$ and $h \to AA$ are open ($M_H < M_h/2$, $M_A < M_h/2$), their partial widths $\Gamma(h \to HH)$, $\Gamma(h \to AA)$ dominate over the partial widths of decays into SM particles. It will be shown, that in these cases the total decay width of the Higgs boson is so big that always $\mathrm{Br}(h \to \gamma\gamma)^{\mathrm{IDM}} < \mathrm{Br}(h \to \gamma\gamma)^{\mathrm{SM}}$.

When $M_H > M_h/2$ (and therefore also $M_A > M_h/2$) the invisible decay channels are closed. Then all the branching ratios are constant (Fig. 1, right panel), with the exception of $\mathrm{Br}(h \to \gamma\gamma)$, which varies significantly with m_{22}^2. We will analyze this case below.

If the decay channels $h \to HH$ and $h \to AA$ are kinematically closed, the total width of h is barely modified with respect to the SM case, since the branching ratio of $h \to \gamma\gamma$, which is the only process that receives contributions from dark scalars, is of the order of 10^{-4}. Thus $R_{\gamma\gamma}$, Eq. (3), reduces to the ratio of the partial width in the IDM to the one in the SM, namely

$$\widetilde{R}_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)^{\mathrm{IDM}}}{\Gamma(h \to \gamma\gamma)^{\mathrm{SM}}}. \quad (4)$$

In the IDM, the dominate partial decay width of the Higgs boson to $\gamma\gamma$ is given by [3–5, 20]:

$$\Gamma(h \to \gamma\gamma)^{\mathrm{IDM}} = \frac{G_F \alpha^2 M_h^3}{128\sqrt{2}\pi^3} \Bigg| \underbrace{\frac{4}{3} A_{1/2}\left(\frac{4M_t^2}{M_h^2}\right) + A_1\left(\frac{4M_W^2}{M_h^2}\right)}_{\mathcal{M}^{\mathrm{SM}}} + \underbrace{\frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} A_0\left(\frac{4M_{H^\pm}^2}{M_h^2}\right)}_{\delta\mathcal{M}^{\mathrm{IDM}}} \Bigg|^2,$$

where $\mathcal{M}^{\mathrm{SM}}$ denotes the contribution from the SM and $\delta\mathcal{M}^{\mathrm{IDM}}$ is the extra contribution present in the IDM, $\mathcal{M}^{\mathrm{IDM}} = \mathcal{M}^{\mathrm{SM}} + \delta\mathcal{M}^{\mathrm{IDM}}$.[3]

The form factors are defined as follows [23]:

$$\begin{aligned} A_0(\tau) &= -\tau[1 - \tau f(\tau)], \\ A_{1/2}(\tau) &= 2\tau[1 + (1-\tau) f(\tau)], \\ A_1(\tau) &= -[2 + 3\tau + 3\tau(2-\tau) f(\tau)] \end{aligned}$$

and

$$f(\tau) = \begin{cases} \arcsin^2\left(\frac{1}{\sqrt{\tau}}\right) & \text{for } \tau \geqslant 1, \\ -\frac{1}{4}\left[\log\left(\frac{1+\sqrt{1-\frac{1}{\tau}}}{1-\sqrt{1-\frac{1}{\tau}}}\right) - i\pi\right]^2 & \text{for } \tau < 1. \end{cases}$$

The $h \to \gamma\gamma$ enhancement is of interest to us, so we consider the inequality $\widetilde{R}_{\gamma\gamma} > 1$, which corresponds to :

$$|\mathcal{M}^{\mathrm{SM}} + \delta\mathcal{M}^{\mathrm{IDM}}|^2 > |\mathcal{M}^{\mathrm{SM}}|^2, \tag{5}$$

where $\mathcal{M}^{\mathrm{SM}}$ is fixed for $M_h = 125\,\mathrm{GeV}$.[4] Inequality (5) can be solved analytically (the full derivation is given in Appendix A), giving the result that $R_{\gamma\gamma} > 1$ is possible only when:

$$\begin{aligned} & m_{22}^2 < -2M_{H^\pm}^2 \quad \text{or} \\ & m_{22}^2 > \frac{aM_h^2}{1 - \left(\frac{2M_{H^\pm}}{M_h}\right)^2 \arcsin^2\left(\frac{M_h}{2M_{H^\pm}}\right)} - 2M_{H^\pm}^2, \end{aligned} \tag{6}$$

where $a = \mathrm{Re}\mathcal{M}^{\mathrm{SM}}$. This two conditions correspond to two possible cases: when the contribution of the charged scalar loop interferes constructively or destructively with the SM contributions, respectively. In the latter case the contribution from the charged scalar has to be at least twice as big as the SM term [4]. Since both of the functions in Eq. (6) are monotonic (with respect to $M_{H^\pm}$) we can get overall bounds on m_{22}^2 with use of the LEPII bound on mass of the charged scalar. Substituting $M_{H^\pm} = 70\,\mathrm{GeV}$ and $M_h = 125\,\mathrm{GeV}$ to these bounds yields: $m_{22}^2 < -9.8 \cdot 10^3\,\mathrm{GeV}^2$ or $m_{22}^2 \gtrsim 1.8 \cdot 10^5\,\mathrm{GeV}^2$. Taking into account the bound (2) we are left with the only option (constructive interference):

$$m_{22}^2 < -9.8 \cdot 10^3\,\mathrm{GeV}^2. \tag{7}$$

The conditions (6) can be translated into conditions for the hH^+H^- coupling (λ_3) with the use of the expression for the mass of the charged scalar, $M_{H^\pm}^2 = \frac{1}{2}(\lambda_3 v^2 - m_{22}^2)$, giving the condition $\lambda_3 < 0$.

IV. RESULTS

In this section we present the regions in the parameter space allowed by the constraints (Sec. II B) and the condition $R_{\gamma\gamma} > 1$. Points with $R_{\gamma\gamma} < 1$ are displayed in Fig. 2-5 in dark green/gray and with $R_{\gamma\gamma} > 1$ in light green/gray.

In Fig. 2 the regions of masses allowed in the IDM by the constraints for the narrow m_{22}^2 range (Sec. II.C) are presented. We show separately the regions where the enhancement in the $h \to \gamma\gamma$ channel occurs. We have found that the $R_{\gamma\gamma}$ enhancement is only possible when $M_H > M_h/2$ and $M_A > M_h/2$. It means that the partial widths of invisible decays increase the total width of the Higgs boson so much that the enhancement with respect to the SM case is impossible (this is in agreement with results of Ref. [5]).[5]

The signal in the $h \to \gamma\gamma$ channel can be enhanced with respect to SM up to almost 3.4 times, which can be inferred from Fig. 3, where the dependence of $R_{\gamma\gamma}$ on M_H and $M_{H^\pm}$ is presented.

Fig. 2 and 3 seem to suggest that $R_{\gamma\gamma} > 1$ is only possible for $M_{H^\pm} \lesssim 350\,\mathrm{GeV}$ (compare with the bound $M_{H^\pm} \lesssim 200\,\mathrm{GeV}$ from [5]). However, it is not the case. If we allow for wider m_{22}^2 range, then we get larger $M_{H^\pm}$ for which $R_{\gamma\gamma} > 1$.[6] This fact is illustrated in the upper panel of Fig. 4, where the results of the scan with wider range of m_{22}^2, are presented. It can be seen that $R_{\gamma\gamma} > 1$

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[3] Above we do not include the contributions from the bottom and charm quark loops as well as from the τ loop, as we have checked that they are negligible. We take $M_W = 80.399\,\mathrm{GeV}$ and $M_t = 173\,\mathrm{GeV}$ from the Particle Data Group (PDG) analysis [22].

[4] If the contributions from light quarks are neglected, $\mathcal{M}^{\mathrm{SM}}$ is real, but we treat it as a complex number, to keep the reasoning general.

[5] Fig. 2 (upper panel) differs from Fig. 1 (left panel) of Ref. [5] as in Ref. [5] the DM particle (H) was assumed to be lighter than the Higgs boson ($M_H < 150\,\mathrm{GeV}$), which decreased the size of the allowed region and also constrained the values of m_{22}^2, which resulted in tighter upper bounds on the masses of $H^\pm$ and A.

[6] In Ref. [5] m_{22}^2 (or $\mu_2^2 = -1/2 m_{22}^2$) was limited by setting $M_H < 150\,\mathrm{GeV}$.

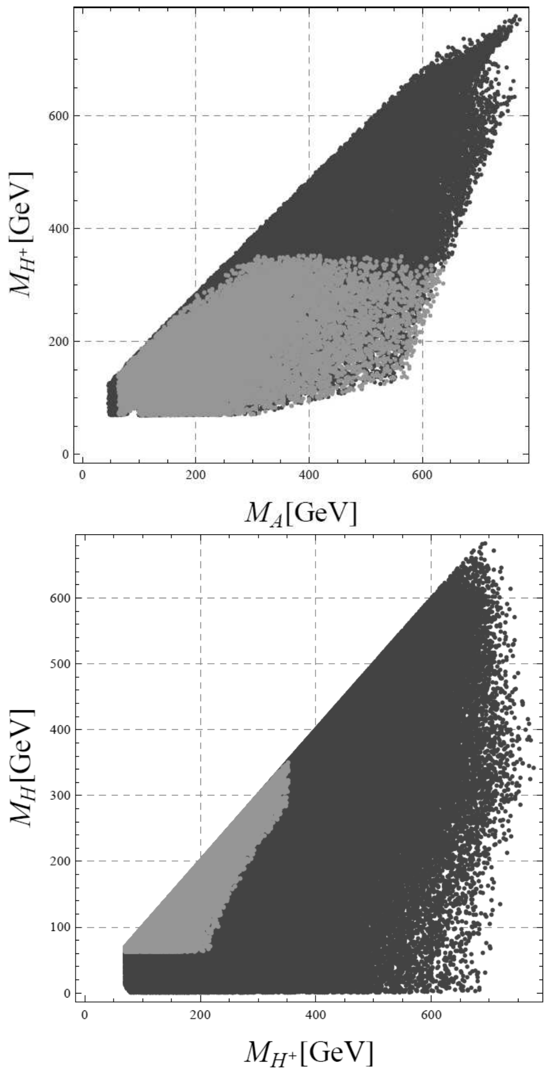

FIG. 2. (Color online) Regions in the $(M_A, M_{H^\pm})$ (upper panel) and $(M_{H^\pm}, M_H)$ (lower panel) planes allowed by the constraints for $-25 \cdot 10^4\,\mathrm{GeV}^2 \leqslant m_{22}^2 \leqslant 9 \cdot 10^4\,\mathrm{GeV}^2$. Points with $R_{\gamma\gamma} < 1$ ($R_{\gamma\gamma} > 1$) are displayed in dark green/gray (light green/gray).

for $M_{H^\pm}$ up to 1 TeV. Regions fulfilling $\widetilde{R}_{\gamma\gamma} > 1$ (light shaded region) and $\widetilde{R}_{\gamma\gamma} > 1.3$ (dark shaded region) are also shown.

It can be seen from Fig. 3 (upper panel) that substantial enhancement ($R_{\gamma\gamma} > 1.3$) appears for relatively light charged scalar, $M_{H^\pm} \lesssim 135\,\mathrm{GeV}$. Moreover, $R_{\gamma\gamma} > 1.3$ is only possible in a region $m_{22}^2 \gtrsim -1.3 \cdot 10^5\,\mathrm{GeV}^2$ (see Fig. 4, upper panel), hence the upper bound on $M_{H^\pm}$ does not change if we allow for very big negative m_{22}^2.

Fig. 3 shows that if $R_{\gamma\gamma} < 1.3$ also the DM particle has to be light: $M_H \lesssim 135\,\mathrm{GeV}$. So we conclude that substantial enhancement is only possible for:

$$\begin{aligned} 62.5\,\mathrm{GeV} &< \ M_H \ < 135\,\mathrm{GeV}, \\ 70\,\mathrm{GeV} &< M_{H^\pm} < 135\,\mathrm{GeV}. \end{aligned}$$

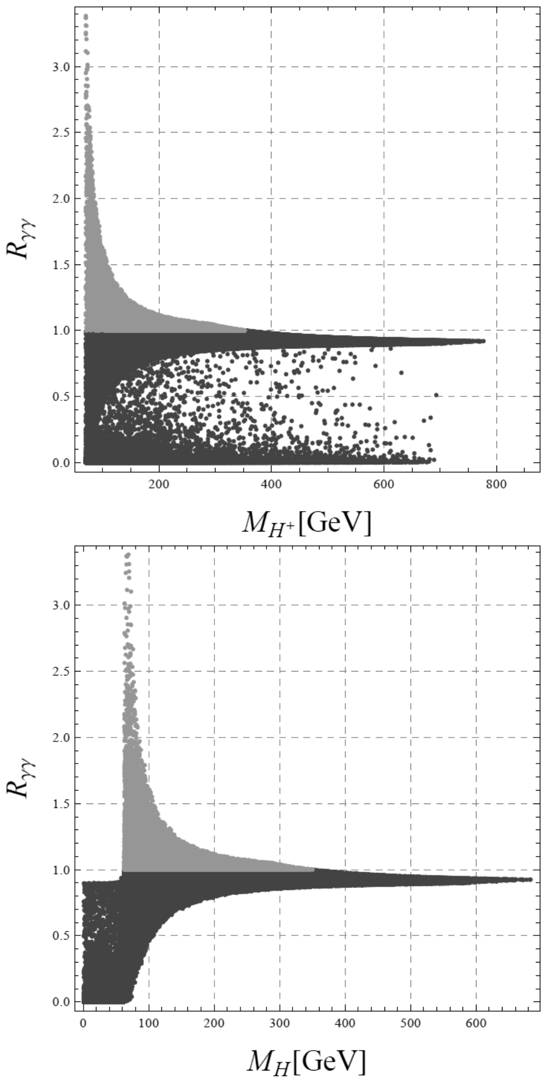

FIG. 3. (Color online) Values of $R_{\gamma\gamma}$ allowed by the constraints for $-25 \cdot 10^4\,\mathrm{GeV}^2 \leqslant m_{22}^2 \leqslant 9 \cdot 10^4\,\mathrm{GeV}^2$ as a function of masses: $M_{H^\pm}$ (upper panel) and M_H (lower panel). Points with $R_{\gamma\gamma} < 1$ ($R_{\gamma\gamma} > 1$) are displayed in dark green/gray (light green/gray).

This reasoning is general and will give upper bounds on $M_{H^\pm}$ and M_H if enhancement of $h \to \gamma\gamma$ decay with respect to SM, $R_{\gamma\gamma} > 1$, is definitely confirmed by data.

From the upper panel of Fig. 4 it is also visible that additional region fulfilling $R_{\gamma\gamma} > 1$ would be allowed if m_{22}^2 could be greater than $9 \cdot 10^4\,\mathrm{GeV}^2$.[7] However this is not allowed for the Inert vacuum, Eq. (6). This shows the important role of the conditions determining existence of

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[7] In Ref. [5] the conditions determining the existence of the Inert vacuum were not taken into account, so a region with $R_{\gamma\gamma} > 1$ and $m_{22}^2 > 0$ would appear in that analysis - only by choosing maximal value of DM particle, M_H, this unphysical region was fortunately avoided.

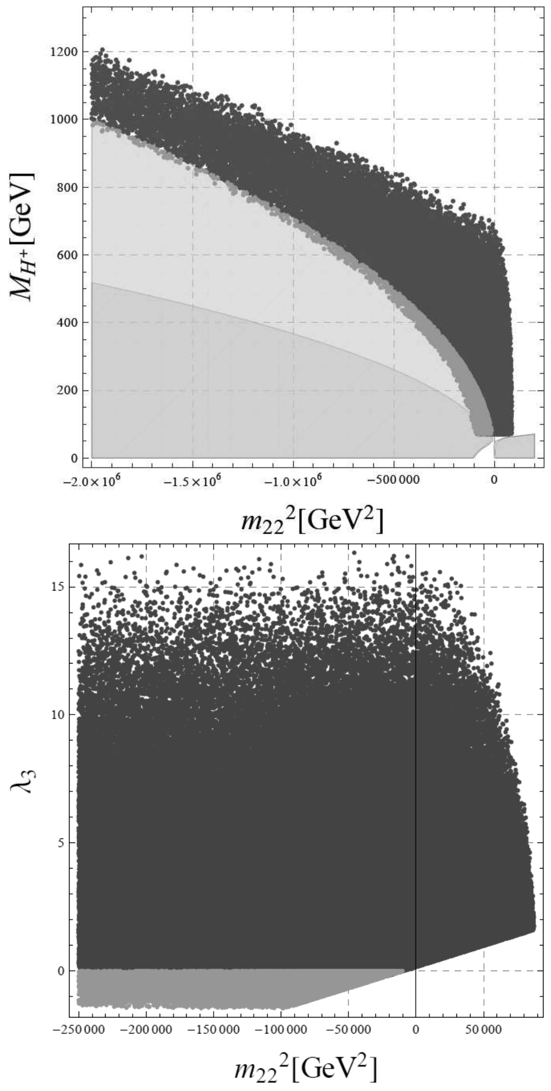

FIG. 4. (Color online) Upper panel: regions where $\widetilde{R}_{\gamma\gamma} > 1$ ($\widetilde{R}_{\gamma\gamma} > 1.3$) (see Eq. (4)) are displayed as light (dark) shaded. Results of the scan for the region $-2 \cdot 10^6\,\mathrm{GeV}^2 \leqslant m_{22}^2 \leqslant 9 \cdot 10^4\,\mathrm{GeV}^2$ with $R_{\gamma\gamma} < 1$ ($R_{\gamma\gamma} > 1$) are displayed in dark (light) green/gray. There is an overlap of the light green and shaded regions. Lower panel: region allowed by the constraints for $-25 \cdot 10^4\,\mathrm{GeV}^2 \leqslant m_{22}^2 \leqslant 9 \cdot 10^4\,\mathrm{GeV}^2$ in the (m_{22}^2, λ_3) plane. Points with $R_{\gamma\gamma} < 1$ ($R_{\gamma\gamma} > 1$) displayed in dark green/gray (light green/gray).

the Inert vacuum in constraining the parameter space and a need of taking them into account.

In the lower panel of Fig. 4 we present the allowed region in the (m_{22}^2, λ_3) plane ($\lambda_3 \sim hH^+H^-$ coupling) and confirm the conclusion of Ref. [5] that the enhanced diphoton production rate is possible only for $\lambda_3 < 0$.

$R_{\gamma\gamma}$ as a function of the coupling λ_3 is shown in Fig. 5 (upper panel) and λ_2 (lower panel), respectively. It can be seen once more that $R_{\gamma\gamma} > 1$ for $\lambda_3 < 0$ and as a consequence, since $M_H < M_{H^\pm}$, also $\lambda_{345} < 0$ with quite stringent lower bounds on both of the couplings:

$$\lambda_3, \lambda_{345} > -1.5.$$

If in addition $R_{\gamma\gamma} > 1.3$, then:

$$-1.46 < \lambda_3, \lambda_{345} < -0.24.$$

On contrary, $R_{\gamma\gamma} > 1$ is possible for all values of λ_2 (lower panel of Fig. 5).[8]

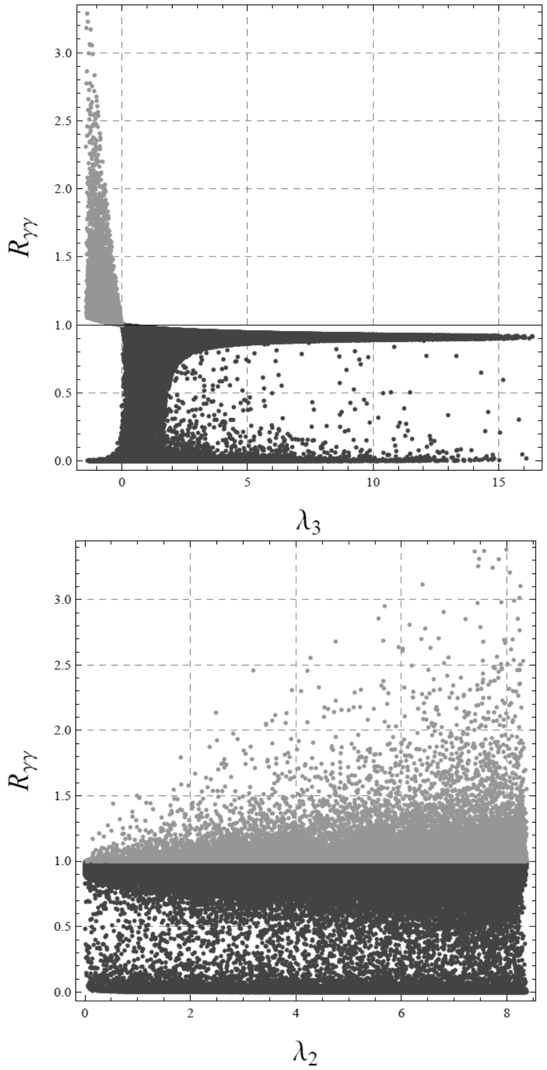

FIG. 5. (Color online) Values of $R_{\gamma\gamma}$ allowed by the constraints for $-25 \cdot 10^4\,\mathrm{GeV}^2 \leqslant m_{22}^2 \leqslant 9 \cdot 10^4\,\mathrm{GeV}^2$ as a function of the couplings: λ_3 (upper panel), λ_2 (lower panel). Points with $R_{\gamma\gamma} < 1$ ($R_{\gamma\gamma} > 1$) displayed in dark green/gray (light green/gray).

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[8] It does not agree with the observation of Ref. [4] which stated that $R_{\gamma\gamma} > 1$ for $-\lambda_3 \gg 1$ and only for big values of λ_2.

V. SUMMARY

We analyzed the diphoton decay rate of the Higgs boson in the IDM, for $M_h = 125$ GeV, and presented a critical discussion of the results existing in the literature. The following conditions were taken into account: vacuum stability, existence of the Inert vacuum, perturbative unitarity, electroweak precision tests, the LEP bounds. The importance of the condition determining the existence of the Inert vacuum should be underlined as it significantly constraints the parameter space where $R_{\gamma\gamma} > 1$ (excludes positive values of m_{22}^2). For the case of closed invisible decay channels of the Higgs boson we give analytical solution of the inequality $\widetilde{R}_{\gamma\gamma} > 1$ and for the general case we found the conditions using the random scan.

We showed that the enhancement in the diphoton channel, with respect to the SM, is not possible if the invisible decay channels are open, confirming the results of Ref. [5]. If the DM particle is heavier than $M_h/2$, then IDM can account for a Higgs boson with enhanced diphoton rate, while its remaining decay channels (apart from $h \to Z\gamma$), in particular other loop induced decay $h \to gg$, stay SM-like.

The enhancement is only possible for $m_{22}^2 < -9.8 \cdot 10^3\,\mathrm{GeV}^2$ ($\lambda_3 < 0$) and maximal $R_{\gamma\gamma}$ value reaches 3.4, for $M_{H^\pm} \sim 70\,\mathrm{GeV}$ and $M_H \sim 80\,\mathrm{GeV}$. Substantial enhancement can be realized only if the charged scalar is light. $R_{\gamma\gamma} > 1.3$ implies $M_{H^\pm} \lesssim 135\,\mathrm{GeV}$, then also $62.4\,\mathrm{GeV} < M_H \lesssim 135\,\mathrm{GeV}$, which would exclude the light and heavy DM scenarios. In this case also stringent constraints on scalar couplings arise: $-1.46 < \lambda_3, \lambda_{345} < -0.24$.

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Appendix A: Derivation of the solution of $R_{\gamma\gamma} > 1$ for $M_H > M_h/2$

We are to solve the following inequality for $M_h = 125\,\mathrm{GeV}$

$$|\mathcal{M}^{\rm SM} + \delta\mathcal{M}^{\rm IDM}|^2 > |\mathcal{M}^{\rm SM}|^2, \tag{A1}$$

while $\mathcal{M}^{\rm SM}$ is fixed. Let us use the following definitions: $a = \mathrm{Re}\mathcal{M}^{\rm SM}$, $b = \mathrm{Im}\mathcal{M}^{\rm SM}$ and $c = \delta\mathcal{M}^{\rm IDM} = \frac{2M_{H^\pm}^2+m_{22}^2}{2M_{H^\pm}^2}A_0(\tau)$, where $\tau = \frac{4M_{H^\pm}^2}{M_h^2}$, $\tau > 1$. Parameter $c \in \mathbb{R}$, because $f\left(\frac{4M_{H^\pm}^2}{M_h^2}\right) = \arcsin^2\left(\frac{M_h}{2M_H}\right)$ for $M_H > M_h/2$. Hence the inequality (A1) can be written as: $|a + ib + c|^2 > |a + ib|^2$ and is equivalent to $c(c + 2a) > 0$.

There are two possibilities: $c > 0$ and $c+2a > 0$ or $c < 0$ and $c + 2a < 0$. One can compute that $a \approx -6.53 < 0$ so the two cases reduce to: $c > -2a$ or $c < 0$.

$c > -2a$ if and only if $\frac{2M_{H^\pm}^2+m_{22}^2}{2M_{H^\pm}^2}A_0(\tau) > -2a$. $A_0(\tau) = -\tau + \tau^2\arcsin^2(1/\tau)$, so $A_0(\tau) > 0$ for $\tau > 1$. Therefore we have:

$$m_{22}^2 > \frac{aM_h^2}{1 - \left(\frac{2M_{H^\pm}}{M_h}\right)^2 \arcsin^2\left(\frac{M_h}{2M_{H^\pm}}\right)} - 2M_{H^\pm}^2.$$

$c > 0$ in two cases: either if $2M_{H^\pm}^2 + m_{22}^2 > 0$ and $A_0(\tau) < 0$, or if $2M_{H^\pm}^2 + m_{22}^2 < 0$ and $A_0(\tau) > 0$. As $A_0(\tau) > 0$, the first option is excluded and the other reduces to $m_{22}^2 < -2M_{H^\pm}^2$.

Finally, there are two regions where enhancement in the $h \to \gamma\gamma$ channel is possible:

$$m_{22}^2 < -2M_{H^\pm}^2 \quad \text{or}$$

$$m_{22}^2 > \frac{aM_h^2}{1 - \left(\frac{2M_{H^\pm}}{M_h}\right)^2 \arcsin^2\left(\frac{M_h}{2M_{H^\pm}}\right)} - 2M_{H^\pm}^2,$$

Appendix B: Decay widths of the Higgs boson

Below we summarize the decay widths of the Higgs boson following [20–22].

1. $h \to q\bar{q}$

$$\begin{aligned}\Gamma(h \to q\bar{q}) =& \frac{3G_F}{4\sqrt{2}\pi}M_h\overline{m}_q^2(M_h)\Bigg\{1 + 5.67\frac{\overline{\alpha}_s(M_h)}{\pi} + \\ &+ \Bigg[37.51 - 1.36N_f - \frac{2}{3}\log\frac{M_h^2}{m_t^2} + \\ &+ \left(\frac{1}{3}\log\frac{\overline{m}_q^2(M_h)}{M_h^2}\right)^2\Bigg]\frac{\overline{\alpha}_s^2(M_h)}{\pi^2}\Bigg\}.\end{aligned}$$

$N_f = 5$ is the number of active light quark flavors. The running quark mass defined at the scale M_h [21]:

$$\begin{aligned}\overline{m}_q(M_h) =& \overline{m}_q(m_q)\left(\frac{\overline{\alpha}_s(M_h)}{\overline{\alpha}_s(m_q)}\right)^{12/(33-2N_f)} \times \\ &\times \frac{1 + c_{1q}\overline{\alpha}_s(M_h)/\pi + c_{2q}\overline{\alpha}_s^2(M_h)/\pi^2}{1 + c_{1q}\overline{\alpha}_s(m_q)/\pi + c_{2q}\overline{\alpha}_s^2(m_q)/\pi^2},\end{aligned}$$

where for the bottom quark $c_{1b} = 1.17$, $c_{2b} = 1.50$ and for the charm quark $c_{1c} = 1.01$, $c_{2c} = 1.39$. The running strong coupling constant is approximated at the one loop level (for energy scales around M_h, where the number of active light quarks can be taken constant) [22]:

$$\overline{\alpha}_s(M_h) = \frac{\overline{\alpha}_s(M_Z)}{1 + \frac{33-2N_f}{12\pi}\overline{\alpha}_s(M_Z)\log\frac{M_h^2}{M_Z^2}}.$$

The values of quark masses and values of the strong coupling are taken from PDG [22]: $\overline{m}_b(m_b) = 4.18\,\mathrm{GeV}$, $\overline{m}_c(m_c) = 1.273\,\mathrm{GeV}$, $\overline{\alpha}_s(M_Z) = 0.118$, $\overline{\alpha}_s(m_b) = 0.223$, $\overline{\alpha}_s(m_c) = 0.38$.

2. $h \to \tau^+\tau^-$

$$\Gamma(h \to \tau^+\tau^-) = \frac{G_F N_c}{4\sqrt{2}\pi} M_h m_\tau^2 \left(1 - \frac{4m_\tau^2}{M_h^2}\right)^{3/2}.$$

3. $h \to VV^*$

$$\Gamma(h \to VV^*) = \frac{3G_F^2}{16\pi^3} M_V^4 M_h \delta_V R_T(x),$$

where $\delta_W = 1$, $\delta_Z = \frac{7}{12} - \frac{10}{9}\sin^2\theta_W + \frac{40}{9}\sin^4\theta_W$,

$$\begin{aligned} R_T(x) =& \frac{3(1 - 8x + 20x^2)}{\sqrt{4x - 1}} \arccos\left(\frac{3x - 1}{2x^{3/2}}\right) + \\ &- \frac{1 - x}{2x}\left(2 - 13x + 47x^2\right) - \frac{3}{2}(1 - 6x + 4x^2)\log x \end{aligned}$$

and $x = \frac{M_V^2}{M_h^2}$.

4. $h \to Z\gamma$

$$\begin{aligned} \Gamma(h \to Z\gamma) =& \frac{G_F^2 \alpha}{64\pi^4} M_W^2 M_h^3 \left(1 - \frac{M_Z^2}{M_h^2}\right)^3 \times \\ & \times \left| 2\frac{1 - \frac{8}{3}\sin^2\theta_W}{\cos\theta_W} A_{1/2}^h\left(\frac{4m_t^2}{M_h^2}, \frac{4m_t^2}{M_Z^2}\right) + \right. \\ & + A_1^h\left(\frac{4M_W^2}{M_h^2}, \frac{4M_W^2}{M_Z^2}\right) + \frac{2M_{H^\pm}^2 + m_{22}^2}{2M_{H^\pm}^2} \times \\ & \left. \times (1 - \sin^2\theta_W) I_1(\frac{4M_{H^\pm}^2}{M_h^2}, \frac{4M_{H^\pm}^2}{M_Z^2}) \right|^2, \end{aligned}$$

where:

$$\begin{aligned} A_{1/2}^h(\tau,\lambda) &= I_1(\tau,\lambda) - I_2(\tau,\lambda), \\ A_1^h(\tau,\lambda) &= \cos\theta_W \left\{ 4\left(3 - \frac{\sin^2\theta_W}{\cos^2\theta_W}\right) I_2(\tau,\lambda) + \right. \\ & \left. + \left[\left(1 + \frac{2}{\tau}\right)\frac{\sin^2\theta_W}{\cos^2\theta_W} - \left(5 + \frac{2}{\tau}\right)\right] I_1(\tau,\lambda) \right\}, \\ I_1(\tau,\lambda) &= \frac{\tau\lambda}{2(\tau - \lambda)} + \frac{\tau^2\lambda^2}{2(\tau - \lambda)^2}\left[f(\tau) - f(\lambda)\right] + \\ & + \frac{\tau^2\lambda}{(\tau - \lambda)^2}\left[g(\tau^{-1}) - g(\lambda^{-1})\right], \\ I_2(\tau,\lambda) &= -\frac{\tau\lambda}{2(\tau - \lambda)}\left[f(\tau) - f(\lambda)\right] \end{aligned}$$

and

$$g(\lambda) = \begin{cases} \sqrt{\frac{1}{\tau} - 1}\arcsin\sqrt{\tau} & \text{for } \tau \geqslant 1, \\ \frac{\sqrt{1 - \frac{1}{\tau}}}{2}\log\frac{1 + \sqrt{1 - \frac{1}{\tau}}}{1 - \sqrt{1 - \frac{1}{\tau}}} & \text{for } \tau < 1. \end{cases}$$

In IDM there is no coupling of H^+H^- to the Z boson, so there is no contribution from the charged scalar loop.

5. $h \to gg$

$$\Gamma(h \to gg) = \frac{G_F \alpha_s^2 M_h^3}{36\sqrt{2}\pi^3}\left|\frac{3}{4} A_{1/2}\left(\frac{4m_t^2}{M_h^2}\right)\right|^2.$$

6. $h \to \varphi\varphi$ ($\varphi = H, A$)

$$\Gamma(h \to \varphi\varphi) = \frac{G_F}{16\sqrt{2}\pi}\frac{M_Z^4}{M_h}\lambda_{h\varphi\varphi}^2\sqrt{1 - 4\frac{M_\varphi^2}{M_h^2}},$$

where $\lambda_{hHH} = \lambda_{345}$ and $\lambda_{hAA} = \lambda_{345}^-$.

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