$h\gamma\gamma$ coupling in Higgs Triplet Model

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We investigate Higgs boson decay into two photons in the type-II seesaw model. The rate of $h \to \gamma\gamma$ gets suppressed/enhanced in this model compared to the Standard Model (SM) due to the presence of the singly and doubly charged Higgs $H^{\pm}$ and $H^{\pm\pm}$.

1 Introduction

One of the main goals of the LHC is the search for the scalar Higgs bosons and the exploration of the mechanism which is responsible for the electroweak symmetry breaking. However, in order to establish the Higgs mechanism as the correct one for electroweak symmetry breaking, we need to measure the Higgs couplings to fermions and to gauge bosons as well as the self-interaction of Higgs bosons. If those measurements are precise enough, they can be helpful in discriminating between the models through their sensitivity to quantum correction effects.

It is now well known, that at the LHC the branching ratio $h \to \gamma\gamma$ can be extracted with a precision of the order 15% at the high luminosity option of LHC [1] while at the International Linear Collider (ILC) it can be exctacted with about 23-25% for Higgs mass arround 120 GeV [2]. In the case where the $\gamma\gamma$ option of ILC is available, with the 1% accuracy measurement of the branching ratio of $h \to b\bar{b}$ at ILC, the width $\Gamma(h \to \gamma\gamma)$ can be determined with 2% accuracy from $\gamma\gamma \to h^* \to b\bar{b}$ process, for Higgs mass of 120 GeV [2]. Therefore, precise calculation of $\Gamma(h \to \gamma\gamma)$ within different beyond Standard Model (SM) is highly needed.

Recently, the ATLAS and CMS experiments have already probed the Higgs boson in the mass range 110–600 GeV, and excluded a Standard Model (SM) Higgs in the range 141–476 GeV at the 95%C.L. through a combined analysis of all decay channels and up to $\sim 2.3\text{fb}^{-1}$ integrated luminosity per experiment, [3]. Very recently, CMS and ATLAS exclude with 4.9fb^{-1} datasets 1 to 2–3 times the SM diphoton cross-section at the 95%C.L. in most of the mass range 110–130 GeV, and report an excess of events around 123–127 GeV in the diphoton channel, corresponding to an exclusion of 3 and 4 times the SM cross-section respectively for CMS [4] and ATLAS [5]. Furthermore, they exclude a SM Higgs in small, though different, portions of this mass range, (112.7)114–115(.5) GeV for ATLAS and 127–131 GeV for CMS, at the 95%C.L.

The SM Higgs sector, extended by one weak gauge triplet of scalar fields (hereafter dubbed DTHM), is a very promising setting to account for neutrino masses through the so-called type II seesaw mechanism. This Higgs sector, containing two CP-even, one CP-odd, one charged and one doubly-charged Higgs scalars, can be tested directly at the LHC or

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ILC, provided that the Higgs triplet mass scale M_Δ and the soft lepton-number violating mass parameter μ are of order or below the weak-scale [6, 7]. Moreover, in most of the parameter space [and apart from an extremely narrow region of μ], one of the two CP-even Higgs scalars is generically essentially SM-like and the other an almost decoupled triplet, irrespective of their relative masses, [6].

It follows that if all the Higgs sector of the model is accessible to the LHC or ILC, one expects a neutral Higgs state with cross-sections very close to the SM in all Higgs production and decay channels to leading electroweak order, except for the di-photon channel. Indeed, in the latter channel, loop effects of the other Higgs states can lead to substantial enhancements which can then be readily analyzed in the light of the experimental exclusion limits as argued above.

In this paper we will analyze the decay $h \to \gamma\gamma$ in the framework of DTHM. This effect will mainly come from singly and doubly charged Higgs boson contributions. We will show that DTHM can account for the excess in the di-photon cross-section reported by ATLAS/CMS, but it can also account for a deficit in the di-photon cross-section without modifying the gluon fusion rate as well as the other channels like $h \to b\bar{b}, \tau^+\tau^-, WW^*, ZZ^*$.

2 Higgs sector of DTHM

The scalar sector of the DTHM model consists of the standard Higgs doublet H and a colorless Higgs triplet Δ with hypercharge $Y_H = 1$ and $Y_\Delta = 2$ respectively. Their matrix representation are given by:

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix} \quad \text{and} \quad H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \tag{1}$$

The most general $SU(2)_L \times U(1)_Y$ gauge invariant renormalizable potential $V(H, \Delta)$ is given by [6, 7]:

$$\begin{aligned} V &= -m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + M_\Delta^2 Tr(\Delta^\dagger \Delta) + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta) \\ &+ \lambda_2 (Tr\Delta^\dagger \Delta)^2 + \lambda_3 Tr(\Delta^\dagger \Delta)^2 + \lambda_4 H^\dagger \Delta \Delta^\dagger H + [\mu(H^T i\tau_2 \Delta^\dagger H) + hc] \end{aligned} \tag{2}$$

Once EWSB takes place, the neutral components of the Higgs doublet and Higgs triplet acquire vacuum expectation values [6]. The DTHM is fully specified by seven independent parameters which we will take: λ, $\lambda_{i=1\ldots4}$, μ and v_t. These parameters respect a set of dynamical constraints originating from the potential, particularly perturbative unitarity and boundedness from below constraints [6]. The model spectrum contains seven physical Higgs states: a pair of CP even states (h, H) with $m_h < m_H$, one CP odd Higgs boson A, one simply charged Higgs $H^\pm$ and one doubly charged state $H^{\pm\pm}$.

The mass of the SM-Higgs like h is fixed more or less by λ parameter while the charged Higgs state masses, given below, will depend strongly on λ_4 and μ:

$$m_{H^\pm}^2 = \frac{(v_d^2 + 2v_t^2)[2\sqrt{2}\mu - \lambda_4 v_t]}{4v_t} \tag{3}$$

$$m_{H^{\pm\pm}}^2 = \frac{\sqrt{2}\mu v_d^2 - \lambda_4 v_d^2 v_t - 2\lambda_3 v_t^3}{2v_t} \tag{4}$$

For a recent and comprehensive study of the DTHM, in particular concerning the distinctive properties of the mixing angle between the neutral components of the doublet and triplet Higgs fields and its correlation with μ parameter, we refer to [6].

3 $h \to \gamma\gamma$

The low SM Higgs mass region, $[110, 140]$ GeV, is the most challenging for LHC searches. In this mass regime, the main search channel through the rare decay into a pair of photons as well as the decay into $\tau^+\tau^-$. The Higgs decay into two photons is only possible through loops. The theoretical predictions for its decay rate is well known in the SM for long time. Following the ref [6], we will see how singly charged ($H^\pm$) and doubly charged ($H^{\pm\pm}$) Higgs states of the DTHM could enhance or suppress the two photons decay rate. Furthermore, since one or the other of the two CP-even neutral Higgs bosons h, H present in the DTHM can behave as a purely SM-like Higgs depending on the μ parameter which fixes the regime under consideration (see [6]), we will refer to the SM-like state generically as H in the following. In the present paper, we will concentrate only on h as the SM-like Higgs, for the other case we refer to [8] for details.

The decay $h \to \gamma\gamma$ is mediated at 1-loop level by the virtual exchange of the SM fermions, the SM gauge bosons and the new charged Higgs states. Detailed analytic expression for the partial width $\Gamma(h \to \gamma\gamma)$ can be found in [8]. Note that the structure of the $H^\pm$ and $H^{\pm\pm}$ contributions is the same except for the fact that the $H^{\pm\pm}$ contribution is enhanced by a relative factor four in the amplitude since $H^{\pm\pm}$ has an electric charge of ± 2 units. For the following discussion we denote $A_0^h(H^\pm)$, $A_0^h(H^{\pm\pm})$ and $A_1^h(W)$ respectively the singly charged Higgs, doubly charged Higgs and the W boson contributions to $h \to \gamma\gamma$.
The coupling of the SM-like higgs to the new charged Higgs states is given by:

$$g_{hH^{++}H^{--}} \approx -\bar{\epsilon}\lambda_1 v_d, \quad g_{hH^+H^-} \approx -\bar{\epsilon}(\lambda_1 + \frac{\lambda_4}{2})v_d \tag{5}$$

where $\bar{\epsilon}$ is the sign of s_α, the mixing between doublet and triplet components, in the convention where c_α is always positive.

As well known, the decay width of $h \to \gamma\gamma$ in the SM is dominated by the W loops which can also interfere destructively with the subdominant top contribution. In the DTHM, the signs of the couplings $g_{hH^+H^-}$ and $g_{hH^{++}H^{--}}$, and thus those of the $H^\pm$ and $H^{\pm\pm}$ contributions to $\Gamma(h \to \gamma\gamma)$, are fixed respectively by the signs of $2\lambda_1 + \lambda_4$ and λ_1, Eqs.(5, 5). However, the combined perturbative unitarity and potential boundedness from below (BFB) constraints derived in [6] confine λ_1, λ_4 to small regions. For instance, in the case of vanishing $\lambda_{2,3}$, λ_1 is forced to be positive while λ_4 can have either signs but still with bounded values of $|\lambda_4|$ and $|2\lambda_1 + \lambda_4|$. Moreover, since we are considering scenarios where $\mu \sim \mathcal{O}(v_t)$, negative values of λ_4 can be favored by the experimental bounds on the (doubly)charged Higgs masses, Eqs. (3,4). For definiteness we stick in the following to $\lambda_1 > 0$, although the sign of λ_1 can be relaxed if $\lambda_{2,3}$ are non-vanishing. Also in the considered mass range for $h, H^\pm$ and $H^{\pm\pm}$, the charged state contributions $A_0^h(H^\pm, H^{\pm\pm})$ are real-valued and take positive values in the range $0.3 - 1$. An increasing value of λ_1 will thus lead to contributions of $H^\pm$ and $H^{\pm\pm}$ that are constructive among each other but destructive with respect to the sum of W boson and top quark contributions. [Recall that for the W contributions, $\mathcal{R}eA_1^h(W)$ takes negative values in the range -12 to -7.] As we will see in the next section, this can either reduce tremendously the branching ratio into di-photons, or increase it by an amount that can be already constrained by the present ATLAS/CMS results.

We show in Fig. 1 (upper panel) the $Br(h \to \gamma\gamma)$ as a function of λ_1, illustrated for several values of λ_4 and $\lambda = 0.45$, $v_t = 1$ GeV. In this plot, the lightest CP-even state h carries 99% of the SM-like Higgs component, with an essentially fixed mass $m_h \approx 114$–115 GeV over the full range of values considered for λ_1 and λ_4.

As can be seen from this plot, $\mathrm{Br}(h \to \gamma\gamma)$ is very close to the SM prediction [$\approx 2 \times 10^{-3}$] for small values of λ_1, irrespective of the values of λ_4. Indeed in this region the di-photon decay is dominated by the SM contributions, the $H^{\pm\pm}$ contribution being shutdown for vanishing λ_1, while the sensitivity to λ_4 in the $H^{\pm}$ contribution, is suppressed by a large $m_{H^\pm}$ mass, $m_{H^\pm} \approx 164$–237 GeV for $-1 < \lambda_4 < 1$, cf. Eq.(5). Increasing λ_1 (for fixed λ_4) enhances the $g_{hH^\pm H^\mp}$ and $g_{hH^{\pm\pm}H^{\mp\mp}}$ couplings. The destructive interference between the SM loop contributions and those of $H^{\pm}$ and $H^{\pm\pm}$ becomes then more and more pronounced. The leading DTHM effect is mainly due to the $H^{\pm\pm}$ contribution, the latter being enhanced with respect to $H^{\pm}$ by a factor 4 due to the doubled electric charge, but also due to a smaller mass than the latter in some parts of the parameter space, $m_{H^{\pm\pm}} \approx 110$–$266$ GeV. It is obvious that the amplitude for $h \to \gamma\gamma$ is essentially linear in λ_1, since $m_{H^\pm}$ and $m_{H^{\pm\pm}}$, Eqs. (3, 4), do not depend on λ_1 while the dependence on this coupling through m_h is screened by the mild behavior of the scalar functions $A^h_{0,1/2,1}$. Furthermore, the latter functions remain real-valued in the considered domain of Higgs masses. There exists thus necessarily values of λ_1 where the effect of the destructive interference is maximized leading to a tremendous reduction of $\Gamma(h \to \gamma\gamma)$. Since all the other decay channels remain SM-like, the same reduction occurs for $\mathrm{Br}(h \to \gamma\gamma)$. The different dips seen in Fig. 1 are due to such a severe cancelation between SM loops and $H^{\pm}$ and $H^{\pm\pm}$ loops, and they occur for λ_1 values within the allowed unitarity & BFB regions. Increasing λ_1 beyond the dip values, the contributions of $H^{\pm\pm}$ and $H^{\pm}$ become bigger than the SM contributions and eventually come to largely dominate for suf-

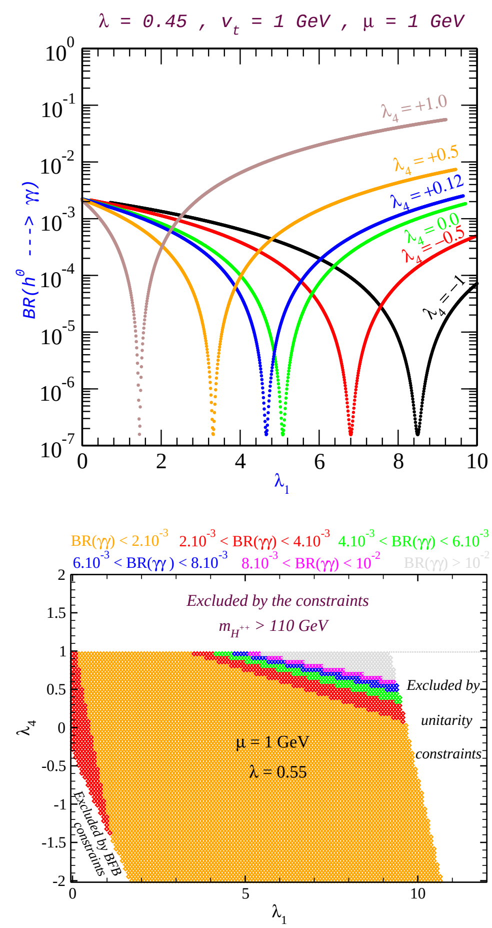

Figure 1: upper panel: $Br(h \to \gamma\gamma)$ as a function of λ_1 for various values of λ_4 and $\lambda = 0.45$ corresponding to $m_h \approx 115$ GeV. Lower panel: Scatter plot in the (λ_1, λ_4) plane showing $Br(h \to \gamma\gamma$. In both panel: $\lambda = 0.55$, $\lambda_3 = 2\lambda_2 = 0.2$ and $v_t = \mu = 1$ GeV, h is SM-like and $m_h \approx 127$ GeV.

ficiently large λ_1. There is however another interesting effect when λ_4 increases. Of course the locations of the dips depend also on the values of λ_4, moving them to lower values of λ_1 for larger λ_4. Thus, for larger λ_4, there is a place, within the considered range of λ_1, for a significant increase of $\mathrm{Br}(h \to \gamma\gamma)$ by even more than one order of magnitude with respect to the SM prediction. This spectacular enhancement is due to the fact that larger λ_4 leads to smaller $H^{\pm\pm}$ and $H^{\pm}$ which can efficiently boost the reduced couplings that scale like the inverse second power of these masses. For instance varying λ_4 between -1 and 1 in the upper panel case, decreases $H^{\pm\pm}$ from 266 to 110 GeV, which modify the $\mathrm{Br}(h \to \gamma\gamma)$ by 2 orders of magnitude with respect to the SM value.

In Fig. 1, we show a scatter plot for $\mathrm{Br}(h \to \gamma\gamma)$ in the (λ_1, λ_4) plane illustrating more generally the previously discussed behavior, for $m_h = 127$ GeV, imposing unitarity and BFB constraints as well as the lower bounds $m_{H^{\pm}} \gtrsim 80$ GeV and $m_{H^{\pm\pm}} \gtrsim 110$ GeV on the (doubly-)charged Higgs masses[a]. One retrieves the gradual enhancement of $\mathrm{Br}(h \to \gamma\gamma)$ in the regions with large and positive $\lambda_{1,4}$. The largest region (in yellow) corresponding to $\mathrm{Br}(h \to \gamma\gamma) \lesssim 2 \times 10^{-3}$ encompasses three cases: –the SM dominates –complete cancelation between SM and $H^{\pm}$, $H^{\pm\pm}$ loops –$H^{\pm}$, $H^{\pm\pm}$ loops dominate but still leading to a SM-like branching ratio.

Besides the branching ratio of $h \to \gamma\gamma$, and in order to compare our predictions with CMS and ATLAS data, we will consider the following observable relevant for LHC:

$$R_{\gamma\gamma}(h) = \frac{(\Gamma(h \to gg) \times \mathrm{Br}(h \to \gamma\gamma))^{DTHM}}{(\Gamma(h \to gg) \times \mathrm{Br}(h \to \gamma\gamma))^{SM}} \tag{6}$$

The above ratio has the advantage that all the leading QCD corrections as well as PDF uncertainties drop out. Moreover, $R_{\gamma\gamma}$ can be viewed as an estimate of the ratio of DTHM to SM of the gluon fusion Higgs production cross section with a Higgs decaying into a photon pair. One should, however, keep in mind the involved approximations: assuming only one intermediate (Higgs) state, one should take the ratio of the parton-level cross-sections $\sigma(gg \to \gamma\gamma)$ in both models, which are given by $\mathrm{Br}(h \to gg) \times \mathrm{Br}(h \to \gamma\gamma)$. Using instead the ratio $R_{\gamma\gamma}$ as defined in Eq. (6) relies on the fact that in the SM-like Higgs regime of DTHM, the branching ratios of all Higgs decay channels are the *same* as in the SM, except for $h \to \gamma\gamma$ (and $h \to \gamma Z, gg$) where they can significantly differ, but remain very small compared to the other decay channels, so that $\Gamma(h \to \mathrm{all})^{DTHM}/\Gamma(h \to \mathrm{all})^{SM} \approx 1$.

In Figs. 2 we illustrate the effects directly in terms of the ratio $R_{\gamma\gamma} \approx \sigma^{\gamma\gamma}/\sigma^{\gamma\gamma}_{\mathrm{SM}}$ defined in Eq.(6). We also show on the upper plot Figs. 2 the present experimental exclusion limits corresponding to these masses, taken from [5]. As can be seen from Fig.2, one can easily accommodate, for $m_h \approx 125\mathrm{GeV}$, a SM cross-section, $R_{\gamma\gamma}(m_h = 125\mathrm{GeV}) = 1$, or a cross-section in excess of the SM, e.g. $R_{\gamma\gamma}(m_h = 125\mathrm{GeV}) \sim 3$–4, for values of λ_1, λ_4 within the theoretically allowed region. The excess reported by ATLAS and CMS in the diphoton channel can be readily interpreted in this context. However, one should keep in mind that all other channels remain SM-like, so that the milder excess observed in WW^* and ZZ^* should disappear with higher statistics in this scenario. This holds independently of which of the two states, h or h, is playing the role of the SM-like Higgs.

[a] Recently, CMS puts a lower limit of 313 GeV on $H^{\pm\pm}$ from $H^{\pm\pm}$ decaying leptonically. This limit can be reduced down to 100 GeV if one takes into account the decay channels $H^{\pm\pm} \to W^{\pm}W^{\pm *}$ as well as $H^{\pm\pm} \to H^{\pm}W^{\pm *}$ [7,9].

We comment now on another scenario, in case the reported excess around $m_h \approx 125$ GeV would not stand the future accumulated statistics. Fig.1(upper panel) shows different dips in $Br(h \to \gamma\gamma)$ corresponding to the case of $m_h \approx 115$ GeV. The ratio $R_{\gamma\gamma}$ would have similar behavior as reported in Fig.1(upper panel) since $\Gamma(h \to gg)$ will be quite similar both in SM and DTHM. Then, the large deficit for $R_{\gamma\gamma}$ in parts of the (λ_1, λ_4) parameter space opens up an unusual possibility: the exclusion of a SM-like Higgs, such as the one reported by ATLAS in the 114–115 GeV range, does not exclude the LEP events as being real SM-like Higgs events in the same mass range! This is a direct consequence of the fact that in the model we consider, even a tremendous reduction in $\sigma^{\gamma\gamma} = \sigma^h \times \text{Br}(h \to \gamma\gamma)$ leaves all other channels, and in particular the LEP relevant cross-section $\sigma(e^+e^- \to Zh)$ essentially identical to that of the SM.

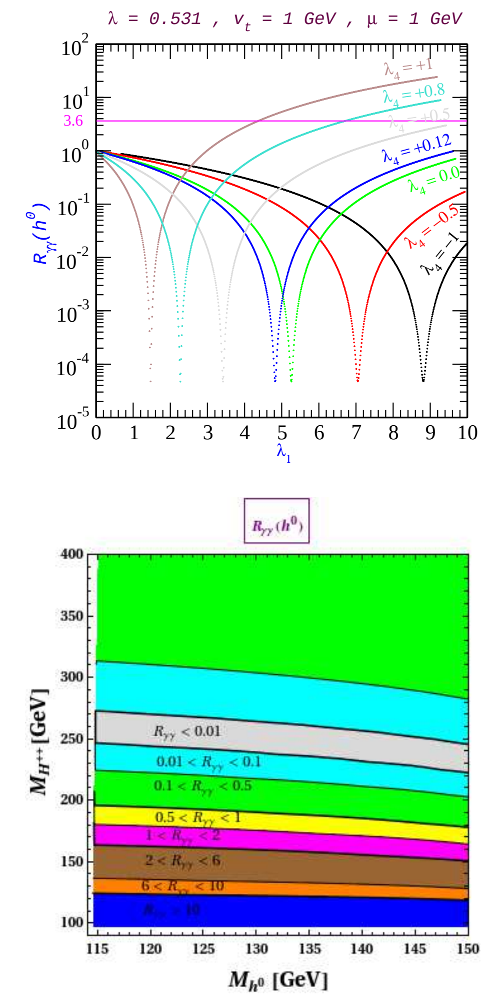

Figure 2: Upper panel: $R_{\gamma\gamma}$ as a function of λ_1 for various values of λ_4, with $\lambda = 0.53$ (h is SM-like and $m_h = 124$–125 GeV), $\lambda_3 = 2\lambda_2 = 0.2$ and $v_t = 1$ GeV; The horizontal lines indicate the ATLAS exclusion limits [5]. Lower panel: Scatter plots in the $(m_h, m_{H^{\pm\pm}})$ plane, showing domains of $R_{\gamma\gamma}$ values, we scan in the domain $.45 < \lambda < 1.2, -5 < \lambda_4 < 3$ with $\lambda_1 = 8$, $\lambda_3 = 2\lambda_2 = 0.2$ and $v_t = \mu = 1$ GeV.

Last but not least, exclusion limits or a signal in the diphoton channel can be translated into constraints on the masses of $H^{\pm\pm}$ and $H^{\pm}$. We show in Figs. 2(lower panel) the correlation between m_h and $m_{H^{\pm\pm}}$ for different ranges of $R_{\gamma\gamma}$. Obviously, the main dependence on m_h drops out in the ratio $R_{\gamma\gamma}$ hence the almost horizontal bands in the plots. There remains however small correlations which are due to the model-dependent relations between the (doubly-)charged and neutral Higgs masses that can even be magnified in the regime of h SM-like. In this plot we take large value for $\lambda_1 = 8$ which give $R_{\gamma\gamma} > 1$ for light $m_{H^{\pm\pm}}$. For low values of λ_1, as we learn from previous discussion, the ratio $R_{\gamma\gamma}$ remains below 1 even for increasing $H^{\pm\pm}$ and $H^{\pm}$ masses. The reason is that these masses become large when λ_4 is large (and negative) for which the loop contribution of $H^{\pm}$ does not vanish, as can be easily seen from Eqs. (3, 5).

4 Discussion and Conclusions

The lightest neutral CP-even Higgs boson h of DTHM, has the same tree-level couplings to the SM weak bosons Z and $W^{\pm}$, leptons and quarks, as the SM Higgs boson. For these reasons, the main production mode for such a Higgs is the usual gluon fusion, W fusion or Higgsstrahlung processes at LHC or Higgsstrahlung and W fusion processes at ILC. As a matter of fact, the cross sections from all production modes are expected to be of the same size as the SM Higgs. Moreover, Higgs boson h should have the same branching ratios to those SM particles to which it couples at tree level as the SM Higgs except for a small suppression due to the mixing of the doublet with the triplet component. The loop-induced decays, however, receive contributions from the charged states of the model. This is indeed the case for the decays $h \to \gamma\gamma, \gamma Z$ but not for $h \to gg$. Therefore, it is expected that the loop mediated processes $h \to \gamma\gamma, \gamma Z$ would have some large deviation from its SM values but the total width of SM-like Higgs boson are nearly identical to the SM Higgs one. Any deviations from the SM case concerning the SM-like Higgs boson production and decay at the LHC and/or ILC are expected to come solely from the branching ratio into two photons and not from the production cross sections or decays into the other conventional channels unless if the sensitivity of those measurements are of comparable size with radiative corrections.

To conclude, we have discussed a possible enhancement/suppression of the partial decay width $\Gamma(h \to \gamma\gamma)$ in the DTHM for light charged states $H^{\pm}$ and $H^{\pm\pm}$. The partial decay width $\Gamma(h \to \gamma\gamma)$ depends on the potential via the couplings $hH^{\pm}H^{\mp}$, $hH^{\pm\pm}H^{\mp\mp}$. This means that a possible enhancement depends on the parameter space of the scalar potential. Restricting the parameter space of the DTHM with perturbative unitarity as well as vacuum stability constraints would restricts the possible enhancement of $\Gamma(h \to \gamma\gamma)$. In large area of parameter space of the DTHM, the deviations in the decay width for $h \to \gamma\gamma$ from the corresponding SM values can be quite large, therefore $h \to \gamma\gamma$ can be used to distinguish between DTHM and SM through the precise measurement program planed at ILC and its $\gamma\gamma$ option.

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