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Pair production of Two Higgs Doublet Model light Higgs bosons in $\gamma\gamma$ collisions

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ABSTRACT

We study the production of a pair of light, neutral, CP-even Higgs bosons in photon–photon collisions within the general Two Higgs Doublet Model (THDM). This is a process for which the lowest order contribution in both, the Standard Model and the THDM, appears at one loop. We find that the cross section for this process can be much larger in the THDM than in the Standard Model and the number of events expected at the Photon Collider will allow a determination of some of the parameters in the scalar potential.

The study of the electroweak symmetry breaking mechanism is one of the most important topics for future collider experiments. The recent global fits to electroweak precision measurements suggest that a light Higgs boson can be discovered in the near future at LHC (or possibly even at the Tevatron) [1]. Once such a particle is discovered the task will be to measure its properties and to investigate the level of agreement with the Standard Model expectations, to either verify the Standard Model Higgs mechanism or to necessitate the introduction of new physics concepts. This task will be better addressed at future e^+e^- colliders. Also, the Photon Collider can provide complementary experimental data to study the properties of the Higgs boson.

The simplest extension of the Standard Model Higgs sector is obtained by introducing a second Higgs doublet. In the most general case, such a THDM leads to unacceptable large CP-violation and tree-level Flavor Changing Neutral Currents (FCNC). CP is conserved by the restriction to real parameters, and tree level FCNC contributions are suppressed by imposing a symmetry $\Phi_1 \to -\Phi_1$. With these restrictions, there are still two types of THDMs [2]. They differ in the way the Higgs doublets are coupled to the fermions. In Type-I, only one Higgs doublet couples to the fermions, while in Type-II the neutral components of the first Higgs doublet couple to up-type fermions and the neutral components of the second Higgs doublet couple to down-type fermions. Indeed, the Higgs sector in the Minimal Supersymmetric Standard Model belongs to this second type of a THDM. In both cases, after electroweak symmetry breaking, the model is left with 5 scalar bosons: two neutral, CP-even bosons (h^0 and H^0), one neutral CP-odd boson (A^0), and a pair of charged Higgs particles ($H^\pm$).

The phenomenology of an extended Higgs sector has been extensively studied in the literature, but most of the work has been devoted to the Minimal Supersymmetric Standard Model, where supersymmetry imposes significant restrictions to the structure of the scalar potential [3,4]. Concerning the general THDM it has been shown that precise measurements of the decay widths $h^0 \to b\bar{b}$, $h^0 \to \gamma\gamma$, $h^0 \to \gamma Z$ can provide crucial information on the scalar potential parameters [5,6], as well as B decays and electroweak precision data [7]. Double Higgs boson production at the LHC can also be used to probe deviations from the Standard Model value of the triple Higgs coupling [8]. Triple Higgs boson production processes in e^+e^- collisions at ILC appear as promising channels to study the Higgs potential due to the large number of events expected [9]. The processes $e^+e^- \to \phi_i\phi_j Z$ with $\phi_i = h^0$, H^0, A^0 or $H^\pm$ [10] as well as the quantum corrections to $e^+e^- \to H^+H^-$ [11] have also been shown to be of interest in the determination of the Higgs self-coupling parameters.

In this Letter we assume the CP-conserving THDM and discuss the production of a pair of the lightest CP-even Higgs boson h^0 in photon–photon collisions, $\gamma\gamma \to h^0h^0$, as expected at the Photon Collider. We are going to restrict our discussion to the particularly interesting case where h^0 couples to gauge bosons and fermions as the Standard Model Higgs particle (H) does. For such a situation, the experimental signatures of h^0 are in general very similar to the ones of H making the experimental distinction between both models a challenging task. Since pair production of Higgs bosons in $\gamma\gamma$ processes is loop-induced in both models, either standard and non-standard contributions appear at the same level, thus advocating this process as a particular sensitive tool to probe the type of the Higgs sector.

The organization of the Letter is the following. We will first recall the structure of the THDM and its free parameters, which define the couplings that enter the amplitude for $\gamma\gamma \to h^0h^0$. Next, we will briefly discuss the Standard Model predictions for

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the $\gamma\gamma \to HH$ cross section and number of events expected at the Photon Collider. This yields the reference values that will be used for comparison with our results for THDM Higgs bosons, which we will present thereafter, with emphasis on the mass of the charged Higgs boson. In our calculations we have used the packages FormCalc and FeynArts [12].

The most general potential for the extension of the scalar sector of the Standard Model to include two $SU(2)_L$ doublets, Φ_1 and Φ_2, with $Y = 1$ reads as follows [3],

$$\begin{aligned} V = {} & \lambda_1\left(\Phi_1^\dagger\Phi_1 - v_1^2\right)^2 + \lambda_2\left(\Phi_2^\dagger\Phi_2 - v_2^2\right)^2 \\ & + \lambda_3\left[\left(\Phi_1^\dagger\Phi_1 - v_1^2\right) + \left(\Phi_2^\dagger\Phi_2 - v_2^2\right)\right]^2 \\ & + \lambda_4\left[(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) - (\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)\right] \\ & + \lambda_5\left[\mathrm{Re}(\Phi_1^\dagger\Phi_2) - v_1 v_2 \cos\xi\right]^2 + \lambda_6\left[\mathrm{Im}(\Phi_1^\dagger\Phi_2) - v_1 v_2 \sin\xi\right]^2 \\ & + \lambda_7\left[\mathrm{Re}(\Phi_1^\dagger\Phi_2) - v_1 v_2 \cos\xi\right]\left[\mathrm{Im}(\Phi_1^\dagger\Phi_2) - v_1 v_2 \sin\xi\right]. \end{aligned} \tag{1}$$

The corresponding Lagrangian violates CP unless we take $\lambda_7 = \xi = 0$ and the rest of the parameters as real. Except for the term proportional to λ_5 this CP-conserving potential is symmetric under the discrete transformation $\Phi_1 \to -\Phi_1$. This symmetry cancels all the contributions to FCNC processes. The term proportional to λ_5 breaks the symmetry only in a soft way via a dimension-two term. So, one can allow λ_5 to be different from zero without entering into conflict with the experimental data on FCNC processes. The parameters v_1 and v_2 in Eq. (1) are the vacuum expectation values of the Higgs fields:

$$\langle\Phi_1\rangle = \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \qquad \langle\Phi_2\rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}. \tag{2}$$

From the experimental value of the W boson mass we can fix the sum $v_1^2 + v_2^2$. In this way we are left with seven free parameters: λ_i with $i = 1, \ldots, 6$ and $\tan\beta = v_2/v_1$.

We denote the masses of the physical particle spectrum by M_{h^0}, M_{H^0}, M_{A^0}, M_{H^+}; thereby, we choose h^0 as the lighter and H^0 as the heavier one of the CP-even neutral bosons. The particle masses can be written in terms of the parameter set $\lambda_1, \ldots, \lambda_6$, $\tan\beta$. Alternatively, one can use a more easily measurable set of parameters to fix the model: M_{h^0}, M_{H^0}, M_{A^0}, M_{H^+}, λ_5, $\tan\beta$ and α, where most of the parameters in the potential have been replaced by the masses of the physical bosons and the mixing angle α between the two CP-even neutral fields. Just a single parameter, λ_5, is kept in this set as a remnant of the original couplings in Eq. (1). The relations between both sets of parameters can be found in Ref. [13]. When translating from the first to the second set of parameters, one has to take into account the restrictions imposed on the values of λ_i from perturbative unitarity.

Before proceeding with the THDM, we set the reference scale and briefly review and update the results of Ref. [14] for the Standard Model reaction $\gamma\gamma \to HH$. Since the Higgs boson does not directly couple to photons, the lowest order amplitude for this process is of one loop order, just as in the case of single Higgs production in two-photon collisions or the decay $H \to \gamma\gamma$ [6,15]. The relevant set of diagrams are shown in Fig. 1 in a generic way. The particles running in the triangles and boxes (a)–(c) can be all the charged particles of the Standard Model, but the dominant contributions are obtained from the t quark and W boson. The diagrams (d)–(i), however, only receive loop contributions from the W boson and Goldstone bosons. It is interesting to point out that the triple Higgs vertex appears in the diagrams (b), (e) and (i).

The production cross section for a Higgs boson mass $m_H = 120$ GeV is shown in Fig. 2 as a function of the center-of-mass energy $E_{\gamma\gamma}$ in the relevant range for the Photon Collider. Other parameter values are $m_t = 171.4$ GeV and $M_W = 80.40$ GeV. The red line corresponds to the configuration where both photons have the same helicity, while the green line corresponds to the case where the two photons have opposite helicity. At these energies, near threshold, the configuration with the same helicity dominates. That is because only in this configuration the two Higgs bosons can be produced in an s-wave state. This cross section shows some sensitivity to the top quark mass; indeed one can observe the effects of the $t\bar{t}$ threshold in the change of slope in the red curve, but the dependence with the t quark mass is too small to be observable at the Photon Collider for values of the mass within the present experimental error. Convoluting these cross sections with the expected luminosities at the Photon Collider [17] one can expect 39 events per year.

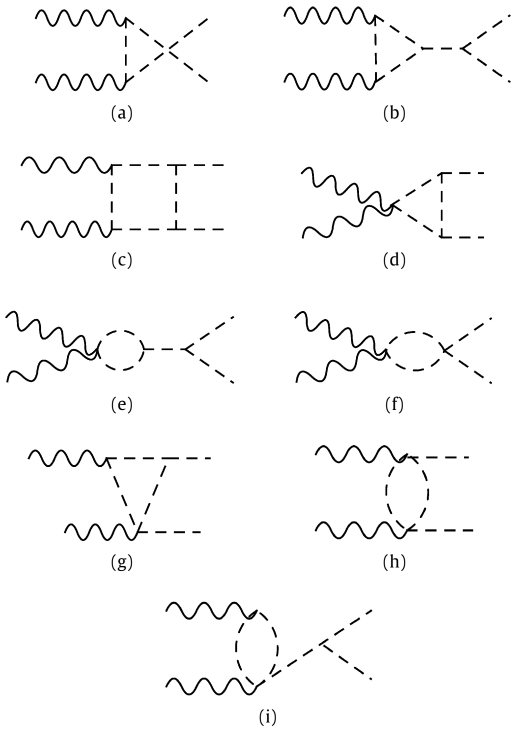


Fig. 1. Diagrams contributing to neutral Higgs boson pair production. In the Standard Model the particles in the loops in diagrams (a)–(d) can be all the charged particles, while in diagrams (d)–(i) can only be W bosons and Goldstone bosons. In the THDM one can have in addition charged Higgs bosons in all loops and a heavy neutral Higgs in the s-channel in diagrams (b), (e) and (i).

The general CP-conserving Two Higgs Doublet Models introduce two types of modifications into the Standard Model calculation. First, the same set of generic diagrams contribute, but the couplings of the Higgs boson to the Standard Model particles and the triple Higgs $h^0h^0h^0$ coupling change. In particular, the couplings of the Higgs boson to the fermions depend on the type of THDM we consider. Second, new diagrams contribute to the process: (i) diagrams that have the same form as the ones shown in Fig. 1, but the particles running in the loops are now charged Higgs bosons, and (ii) new diagrams similar to (b) and (e) with a heavy neutral Higgs boson in the s-channel also contribute. Since the neutral CP-odd Higgs boson does not contribute to this process, our results will be independent of the mass M_{A^0}.

In the following we restrict our discussion to the case where

$$\alpha = \beta - \frac{\pi}{2}. \tag{3}$$

This is a particularly interesting situation because the lightest Higgs boson couples to the Standard Model Particles just in the same way as the standard Higgs boson does. The differences between the Standard Model Higgs boson, H, and the lightest THDM neutral Higgs boson, h^0, only appear at the one-loop level. Since

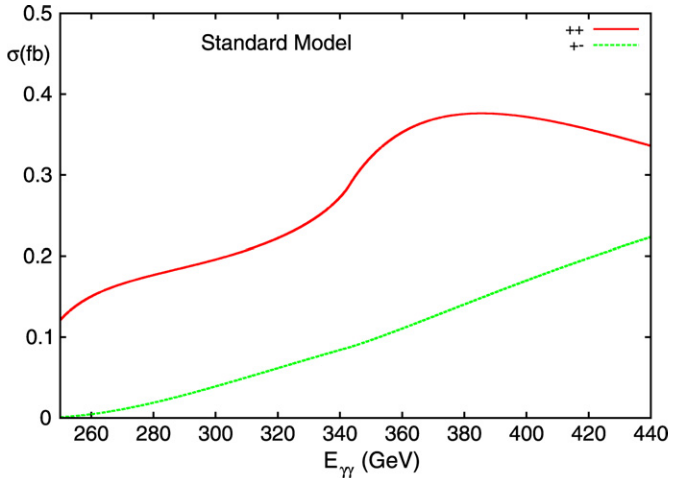


Fig. 2. Standard Model cross section as a function of the two-photon center-of-mass energy for the cases where the two photons have the same helicity (red line) and opposite helicity (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

the lowest order contribution to $\gamma\gamma \to hh$ is also of one-loop order, this process becomes most appropriate to distinguish between the two models.

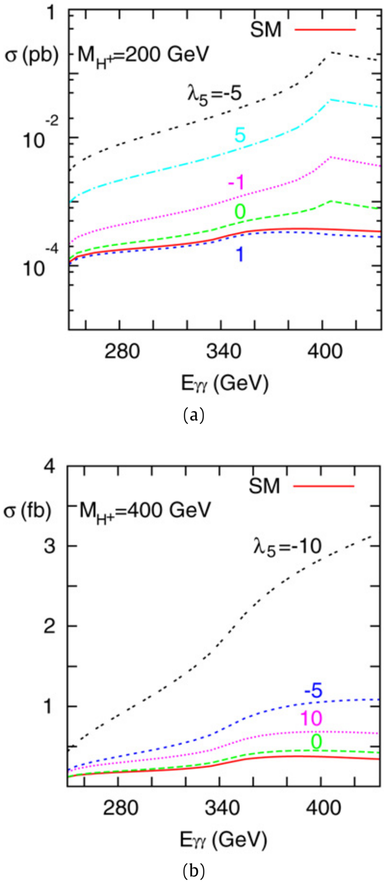
Introducing the relation (3) for the THDM parameters has several consequences. First, since the coupling of h^0 to fermions is the same as for the standard H, it is independent of the type of the THDM. Hence our results apply for both types of THDMs. Second, the triple coupling $h^0h^0H^0$ vanishes, so no diagrams containing a H^0 contribute to our process. This makes our results independent of the mass of the heavy neutral Higgs boson. Third, the only new contributions are those with charged Higgs bosons in the loops of Fig. 1. The relevant couplings for these diagrams are:

$$\begin{aligned} &h^0H^+H^- \to -\frac{ig}{2M_W}\left(M_{h^0}^2 + 2M_{H^+}^2 - \frac{4\lambda_5 M_W^2}{g^2}\right),\\ &h^0h^0H^+H^- \to -\frac{ig^2}{4M_W^2}\left(M_{h^0}^2 + 2M_{H^+}^2 - \frac{4\lambda_5 M_W^2}{g^2}\right), \end{aligned} \tag{4}$$

with the $SU(2)$ gauge coupling g. These self couplings turn out to be independent of $\tan\beta$. In summary, our results for the cross-section for $\gamma\gamma \to h^0h^0$ depend only on three parameters: M_{h^0}, M_{H^+}, and λ_5. Certainly, if we relax relation (3) between the angles α and β, the cross section becomes dependent on the type of the THDM and on all the parameters except M_{A^0}. But differences to the Standard Model will then appear already at the tree level.

First we consider the case of a "light" charged Higgs boson, which means that its mass is low enough for $H^\pm$ to be pair produced and, thus, discovered at a Linear Collider or the LHC. So, by the time of a Photon Collider, the mass M_{H^+} would be known and the only relevant unknown parameter would be λ_5. Strictly speaking, this discussion is only meaningful for a THDM of Type-I because in the THDM Type-II one has a bound of $M_{H^+} \geqslant 295$ GeV from $b \to s\gamma$ decays [16]. This bound is valid for any value of $\tan\beta > 2$.

In the left plot of Fig. 3 we display the $\gamma\gamma \to h^0h^0$ cross section as a function of the center-of-mass energy $E_{\gamma\gamma}$ of the two photons for the configuration where the photons have the same helicity, which yields the largest cross section. We have chosen, as an example, a mass $M_{H^+} = 200$ GeV and a range of values of λ_5 from $\lambda_5 = -5$ to $\lambda_5 = 5$ (well within the allowed range). The cross section turns out to be very sensitive to the value of λ_5, particularly for negative values. One obtains an increase as large as three orders of magnitude for $\lambda_5 = -5$. This is not very surprising because the vertex $H^+H^-h^0$ in Eq. (4) appears twice in the diagrams in Fig. 1, i.e., λ_5 appears squared in the amplitude.



(a)

(b)

Fig. 3. Cross-section for $\gamma\gamma \to h^0h^0$ for the helicity configuration in which both photons have the same helicity, as a function of the $\gamma\gamma$ center-of-mass energy.

There are also values of the parameters for which the effects are very small. Indeed, from Eq. (4) it is clear that the triple and quartic couplings $H^+H^-h^0$ and $H^+H^-h^0h^0$ vanish when the relation

$$2M_{H^+}^2 + H_{h^0}^2 - \frac{M_W^2 s_W^2}{\pi\alpha}\lambda_5 = 0 \tag{5}$$

holds, thus reducing the differences between the Standard Model predictions and the THDM predictions to the effects of the diagrams containing charged Higgses and Goldstone bosons in the loops.

The differences between the cross sections in the THDM and the Standard Model are reduced when the mass of the charged Higgs boson is increased. We show, as an example, the cross section for the case of $M_{H^+} = 400$ GeV in Fig. 3, right plot. Still, even for such a higher charged Higgs mass, the effects can be observable for a wide range of λ_5.

The predicted number of h^0h^0 pairs for the Photon Collider as a function of λ_5 is shown in Fig. 4 for different values of M_{H^+}. Taking into account all possible helicity configurations convoluted with the respective luminosities given in Ref. [17]. It is interesting to observe that for negative values of λ_5 the difference between the SM and the THDM predictions is large even for rather large values of the charged Higgs mass, whereas for positive values of λ_5 the THDM cross section approaches the SM result rather quickly, in such a way that for M_{H^+} larger than about 700 GeV it will be very difficult to differentiate between the models. The reason is that the relation (5) cannot be satisfied for $\lambda_5 < 0$, thus keeping the $H^+H^-h^0$ and $H^+H^-h^0h^0$ couplings always rather large, while

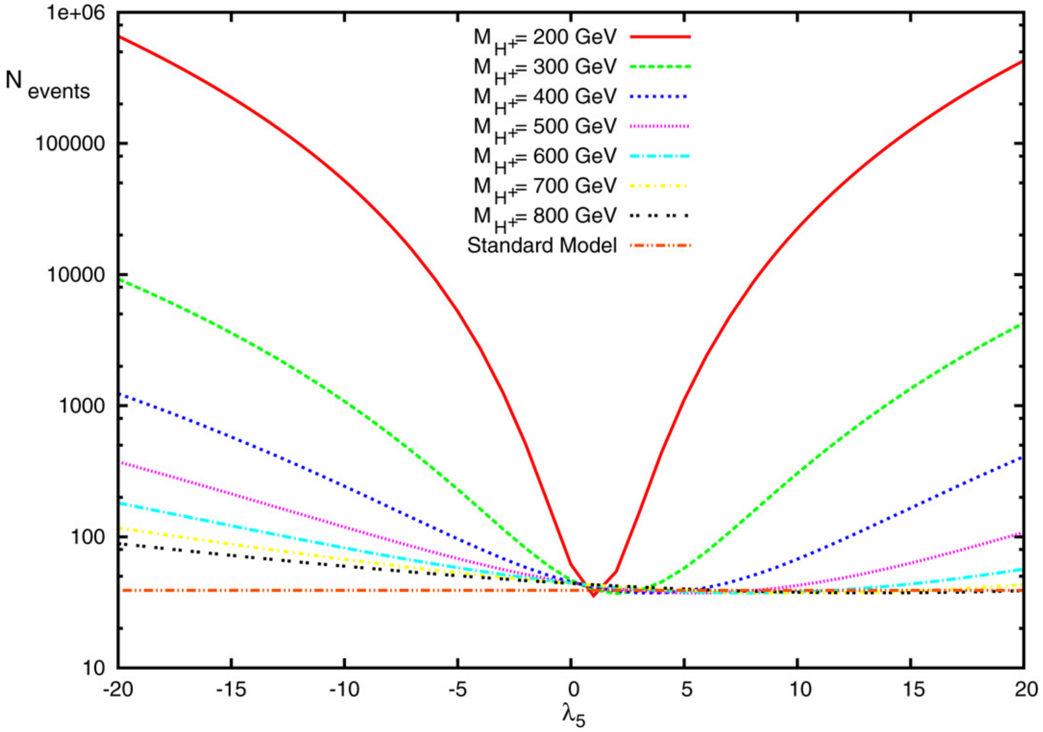


Fig. 4. Total number of events in the THDM as a function of λ_5 for different values of the charged Higgs boson mass. The horizontal line represents the Standard Model prediction for the number of events.

for $\lambda_5 > 0$ these couplings become much smaller by partial compensation of the two terms.

To summarize, we have studied the process $\gamma\gamma \to h^0 h^0$, where h^0 is the lightest, neutral, CP-even Higgs boson in the general Two Higgs Doublet Model. We have focussed our study to the intricate case where the h^0 couplings to the standard particles are the same as the couplings of the Standard Model Higgs boson. This means that tree level cross sections are the same in both models and differences appear only at higher order. Since pair production of neutral Higgs bosons in two-photon collisions is loop-induced, this is a very suitable place to look for differences between the SM and THDM predictions. We have found that for a wide range of values of M_{H^+} and λ_5 (and independent of the residual model parameters, i.e., M_{H^0}, M_{A^0}, and $\tan\beta$) the cross section in the THDM is much larger than in the Standard Model. Using the predicted two-photon luminosities for the Photon Collider, the expected number of events, for negative values of the parameter λ_5 and values of the charged Higgs boson mass up to ~ 800 GeV, should be large enough to distinguish between the models and to allow a determination of these parameters.

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