Higgs boson pair production at the Photon Linear Collider in the two Higgs doublet model

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We calculate the cross section of the lightest Higgs boson pair production at the Photon Linear Collider in the two Higgs doublet model. We focus on the scenario in which the lightest Higgs boson has the standard model like couplings to gauge bosons. We take into account the one-loop correction to the hhh coupling as well as additional one-loop diagrams due to charged bosons to the $\gamma\gamma \to hh$ helicity amplitudes. We discuss the impact of these corrections on the hhh coupling measurement at the Photon Linear Collider.

1   Introduction

The Higgs sector is the last unknown part of the standard model (SM). In the SM, the tree level Higgs self-coupling $\lambda_{hhh} = 3m_h^2/v$ and $\lambda_{hhhh} = 3m_h^2/v^2$ are uniquely determined by the Higgs boson mass m_h, where v is vacuum expectation value (VEV) of the Higgs boson. The effective Higgs potential is written as

$$V = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\tilde{\lambda}_{hhh}h^3 + \frac{1}{4!}\tilde{\lambda}_{hhhh}h^4 + \cdots , \tag{1}$$

where the effective Higgs self-couplings $\tilde{\lambda}_{hhh}$ and $\tilde{\lambda}_{hhhh}$ are given by precision measurement of hhh and $hhhh$ couplings. If the deviation from the SM tree level Higgs self-coupling (λ_{hhh} and λ_{hhhh}) is found, it can be regarded as an evidence of new physics beyond the SM. The origin of the spontaneous electroweak symmetry breaking (EWSB) would be experimentally tested after the discovery of a new scalar particle by measuring its mass and self-couplings. The Higgs self-coupling measurement is one of main purposes at the International Linear Collider (ILC). The structure of the Higgs potential depends on the scenario of new physics beyond the SM, so that precision measurement of the hhh coupling can be a probe of each new physics scenario[1, 2].

The 8th general meeting of the ILC physics working group, 1/21, 2009

It is known that the measurement of the triple Higgs boson coupling is rather challenging at the CERN Large Hadron Collider (LHC). At the SLHC with luminosity of 3000 fb^{-1}, the hhh coupling can be determined with an accuracy of 20-30% for 160 GeV $\leq m_h \leq$ 180 GeV[3, 4]. At the ILC, the main processes for the hhh measurement are the double Higgs boson production mechanisms via the Higgs-strahlung and the W-boson fusion[5, 6]. At the ILC with a center of mass energy of 500 GeV, the double Higgs strahlung process $e^+e^- \rightarrow Zhh$ is dominant. On the other hand, W-boson fusion process $e^+e^- \rightarrow hh\nu\bar{\nu}$ becomes dominant due to its t-channel nature at 1 TeV or higher energies[7]. Sensitivity to the hhh coupling in these processes becomes rapidly worse for greater Higgs boson masses. In particular, for the intermediate mass range (140 GeV $\leq m_h \leq$ 200 GeV), it has not yet been known how accurately the hhh coupling can be measured by the electron-positron collision. The Photon Linear Collider (PLC) is an optional experiment of the ILC. The possibility of measuring the hhh coupling via the process of $\gamma\gamma \rightarrow hh$ has been discussed in Ref. [8]. In Ref. [9] the statistical sensitivity to the hhh coupling constant has been studied especially for a light Higgs boson mass in relatively low energy collisions.

In this paper, we study the double Higgs production process at the PLC. In Sect. 2, we discuss the statistical sensitivity to the hhh coupling constant via the process of $e^-e^- \rightarrow \gamma\gamma \rightarrow hh$ at the PLC in the SM. In Sect. 3, we study the new particle effects on the $\gamma\gamma \rightarrow hh$ process in the two Higgs doublet model (THDM).

2 The statistical sensitivity to the hhh coupling constant

We study the statistical sensitivity to the hhh coupling constant for wide regions of the Higgs boson masses and the collider energies at the PLC. The $\gamma\gamma \rightarrow hh$ process is an one-loop induced process. The Feynman diagrams for this process in the SM are given in Ref. [8]. There are two types of diagrams, which are the pole diagrams and the box diagrams. The amplitude of the pole diagrams describes as $\mathcal{M}_{\text{pole}} \propto \tilde{\lambda}_{hhh}/s$, where $\sqrt{s}$ is the center of mass energy of the $\gamma\gamma$ system. It is suppressed by $1/s$ at the high energy region, so that the statistical sensitivity to the hhh coupling becomes rapidly worse for this region. On the other hand, the box diagrams do not depend on the hhh coupling.

In Fig. 1, we present the statistical sensitivity on the Higgs self-coupling constant at the PLC. We modify the triple Higgs coupling constant as $\tilde{\lambda}_{hhh} = \lambda_{hhh}(1 + \delta\kappa)$, where $\delta\kappa$ represents deviation from the SM prediction. We assume that the efficiency of the particle tagging is 100% with an integrated luminosity of 1/3 ab^{-1} and E_{ee} is the center of mass energy of the e^-e^- system. We plot $\delta\kappa$ based on statistical error of the event number in the $e^-e^- \rightarrow \gamma\gamma \rightarrow hh$ process in the SM. Namely, $\delta\kappa$ is determined by

$$|N(\delta\kappa) - N(\delta\kappa = 0)| = \sqrt{N(\delta\kappa = 0)}, \qquad (2)$$

for assumed luminosity. Notice that $\delta\kappa$ is not symmetric with respect to $\delta\kappa = 0$ because there is interference between pole and box diagrams. The cases for $\delta\kappa > 0$ and $\delta\kappa < 0$ are shown separetly. The left [right] figure shows the sensitivity as a function of m_h [E_{ee}]. It is found that when the collision energy is limited to be lower than 500-600 GeV the statistical sensitivity to the hhh coupling can be better for the process in the $\gamma\gamma$ collision than that in the electron-positron collision for the Higgs boson with the mass of 160 GeV[10].
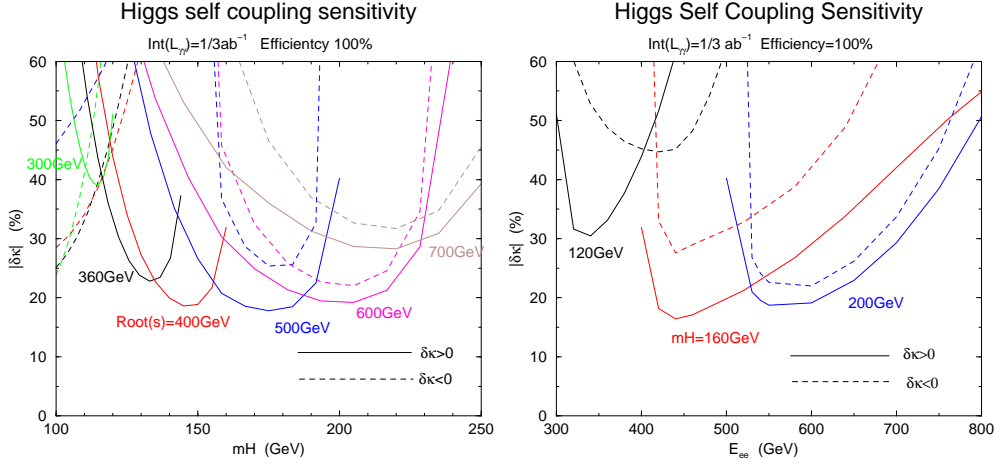
Figure 1: The statistical sensitivity to the hhh coupling constant at the PLC. In the left [right] figure, the statistical sensitivity is shown as a function of m_h [E_{ee}] for each value of E_{ee} [m_h]. Solid [Dotted] lines correspond to $\delta\kappa > 0$ [$\delta\kappa < 0$] case.

3 The $\gamma\gamma \to hh$ process in the THDM

We consider the new particle effects on the $\gamma\gamma \to hh$ process in the THDM, in which additional CP-even, CP-odd and charged Higgs boson appear. It is known that non-decoupling loop effect of extra Higgs bosons shift the hhh coupling value from the SM by $\mathcal{O}(100)\%$[1]. In the $\gamma\gamma \to hh$ helicity amplitudes, there are additional one-loop diagrams by the charged Higgs boson loop to the ordinary SM diagrams (the W-boson loop and the top quark loop). It is found that both the charged Higgs boson loop contribution to the $\gamma\gamma \to hh$ amplitudes and the non-decoupling effect on the hhh coupling can enhance the cross section from its SM value significantly[11].

In order to study the new physics effect on $\gamma\gamma \to hh$ process, we calculate the helicity amplitudes in the THDM. The THDM Higgs potential is given by

$$
\begin{aligned}
V_{\text{THDM}} &= \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 - (\mu_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\
&\quad + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left\{(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}\right\},
\end{aligned} \tag{3}
$$

where Φ_1 and Φ_2 are two Higgs doublets with hypercharge $+1/2$. The Higgs doublets are parametrized as

$$
\Phi_i = \begin{bmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{bmatrix}, \quad (i = 1, 2), \tag{4}
$$

where VEVs v_1 and v_2 satisfy $v_1^2 + v_2^2 = v^2 \simeq (246 \text{ GeV})^2$. The mass matrices can be diagonalized by introducing the mixing angles α and β, where α diagonalizes the mass matrix of the CP-even neutral bosons, and $\tan\beta = v_2/v_1$. Consequently, we have two CP-even (h and H), a CP-odd (A) and a pair of charged ($H^\pm$) bosons. We define α such that h is the SM-like Higgs boson when $\sin(\beta - \alpha) = 1$.

The 8th general meeting of the ILC physics working group, 1/21, 2009

We concentrate on the case with so called the SM-like limit $[\sin(\beta - \alpha) = 1]$, where the lightest Higgs boson h has the same tree-level couplings as the SM Higgs boson, and the other bosons do not couple to gauge bosons and behave just as extra scalar bosons. In this limit, the masses of Higgs bosons are

$$
\begin{aligned}
m_h^2 &= \{\lambda_1 \cos^4 \beta + \lambda_2 \sin^4 \beta + 2(\lambda_3 + \lambda_4 + \lambda_5) \cos^2 \beta \sin^2 \beta\} v^2, & (5) \\
m_H^2 &= M^2 + \frac{1}{8}\{\lambda_1 + \lambda_2 - 2(\lambda_3 + \lambda_4 + \lambda_5)\}(1 - \cos 4\beta) v^2, & (6) \\
m_A^2 &= M^2 - \lambda_5 v^2, & (7) \\
m_{H^\pm}^2 &= M^2 - \frac{\lambda_4 + \lambda_5}{2} v^2, & (8)
\end{aligned}
$$

where $M(=|\mu_3|/\sqrt{\sin\beta\cos\beta})$ represents the soft breaking scale for the discrete symmetry, and determines the decoupling property of the extra Higgs bosons. When $M \sim 0$, the extra Higgs bosons H, A and $H^\pm$ receive their masses from the VEV, so that the masses are proportional to λ_i. Large masses cause significant non-decoupling effect in the radiative correction to the hhh coupling. On the other hand, when $M \gg v$ the masses are determined by M. In this case, the quantum effect decouples for $M \to \infty$.

It is known that in the THDM λ_{hhh} can be changed from the SM prediction by the one-loop contribution of extra Higgs bosons due to the non-decoupling effect (when $M \sim 0$). In the following analysis, we include such an effect on the cross sections. The effective hhh coupling $\Gamma_{hhh}^{\mathrm{THDM}}(\hat{s}, m_h^2, m_h^2)$ is evaluated at the one-loop level as[1]

$$
\Gamma_{hhh}^{\mathrm{THDM}}(\hat{s}, m_h^2, m_h^2) \simeq \frac{3m_h^2}{v}\left[1 + \sum_{\Phi=H,A,H^+,H^-} \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^3 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2}\right]. \quad (9)
$$

The exact one-loop formula for $\Gamma_{hhh}^{\mathrm{THDM}}$ is given in Ref. [2], which has been used in our actual numerical analysis.

In Fig. 2, we plot the cross sections of $\gamma\gamma \to hh$ for the helicity set $(+, +)$ as a function of the photon-photon collision energy $E_{\gamma\gamma}$. The five curves correspond to the following cases,

(a) THDM 2-loop: the cross section in the THDM with additional one-loop corrections to the hhh vertex, $\Gamma_{hhh}^{\mathrm{THDM}}$.

(b) THDM 1-loop: the cross section in the THDM with the tree level hhh coupling constant λ_{hhh}.

(c) SM 2-loop: the cross section in the SM with additional top loop correction to the hhh coupling $\Gamma_{hhh}^{\mathrm{SM}}$ given in Ref. [2].

(d) SM 1-loop: the cross section in the SM with the tree level hhh coupling constant $\lambda_{hhh}^{\mathrm{SM}}$ $(= \lambda_{hhh}$ for $\sin(\beta - \alpha) = 1)$.

(e) For comparison, we also show the result which corresponds to the SM 1-loop result with the effective hhh coupling $\Gamma_{hhh}^{\mathrm{THDM}}$.

In the left figure, there are three peaks in the case (a) (THDM 2-loop). The one at the lowest $E_{\gamma\gamma}$ is the peak just above the threshold of hh production. There the cross section
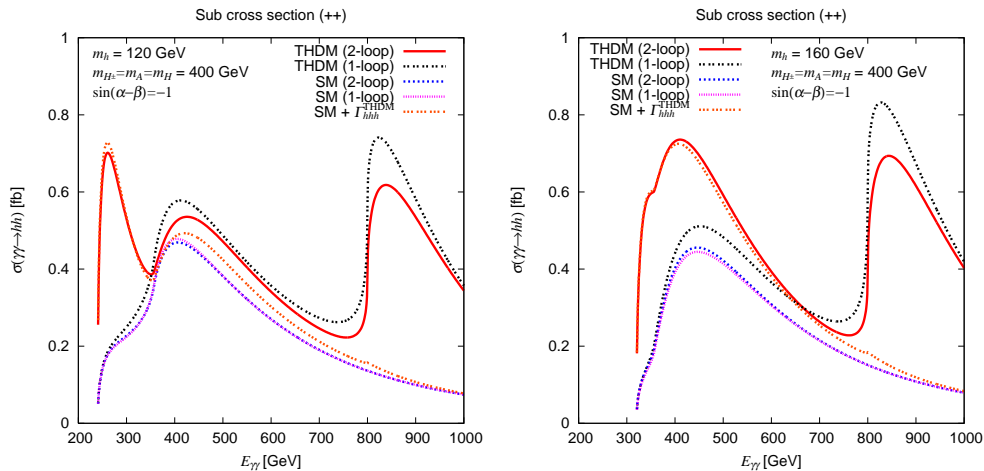
Figure 2: The cross section $\hat{\sigma}(+, +)$ for the sub process $\gamma\gamma \to hh$ with the photon helicity set $(+, +)$ as a function of the collision energy $E_{\gamma\gamma}$. In the left [right] figure the parameters are taken to be $m_h = 120$ [160] GeV for $m_\Phi(\equiv m_H = m_A = m_{H^\pm}) = 400$ GeV, $\sin(\beta - \alpha) = 1$, $\tan\beta = 1$ and $M = 0$.

is by about factor three enhanced as compared to the SM prediction due to the effect of $\Delta\Gamma_{hhh}^{\text{THDM}}/\Gamma_{hhh}^{\text{SM}}$ ($\sim 120\%$) because of the dominance of the pole diagrams in $\gamma\gamma \to hh$. The second peak at around $E_{\gamma\gamma} \sim 400$ GeV comes from the top quark loop contribution which is enhanced by the threshold of top pair production. Around this point, the case (a) can be described by the case (e) (SM+$\Gamma_{hhh}^{\text{THDM}}$). For $E_{\gamma\gamma} \sim 400\text{-}600$ GeV, the cross section in the case (a) deviates from the case (c) (SM 2-loop) due to both the charged Higgs loop effect and the effect of $\Delta\Gamma_{hhh}^{\text{THDM}}/\Gamma_{hhh}^{\text{SM}}$. The third peak at around $E_{\gamma\gamma} \sim 850$ GeV is the threshold enhancement of the charged Higgs boson loop effect, where the real production of charged Higgs bosons occurs. The contribution from the non-pole one-loop diagrams are dominant. In the right figure, we can see two peaks around $E_{\gamma\gamma} \sim 350\text{-}400$ GeV and 850 GeV. At the first peak, the contribution from the pole diagrams is dominant so that the cross section is largely enhanced by the effect of $\Delta\Gamma_{hhh}^{\text{THDM}}/\Gamma_{hhh}^{\text{SM}}$ by several times 100% for $E_{\gamma\gamma} \sim 350$ GeV. It also amounts to about 80% for $E_{\gamma\gamma} \sim 400$ GeV. For $E_{\gamma\gamma} < 600\text{-}700$ GeV, the result in the case (e) gives a good description of that in the case (a). The second peak is due to the threshold effect of the real H^+H^- production as in the left figure.

In Fig. 3, the full cross section of $e^-e^- \to \gamma\gamma \to hh$ is given from the sub cross sections by convoluting the photon luminosity spectrum[8]. In our study, we set $x = 4E_b\omega_0/m_e^2 = 4.8$ where E_b is the energy of electron beam, ω_0 is the laser photon energy and m_e is the electron mass. In order to extract the contribution from $\hat{\sigma}(+, +)$ that is sensitive to the hhh vertex, we take the polarizations of the initial laser beam to be both -1, and those for the initial electrons to be both $+0.45$. The full cross section for $m_\Phi = 400$ GeV has similar energy dependences to the sub cross section $\hat{\sigma}(+, +)$ in Fig. 2, where corresponding energies are rescaled approximately by around $\sqrt{s} \sim E_{\gamma\gamma}/0.8$ due to the photon luminosity spectrum. For smaller m_Φ, the peak around $\sqrt{s} \sim 350$ GeV becomes lower because of
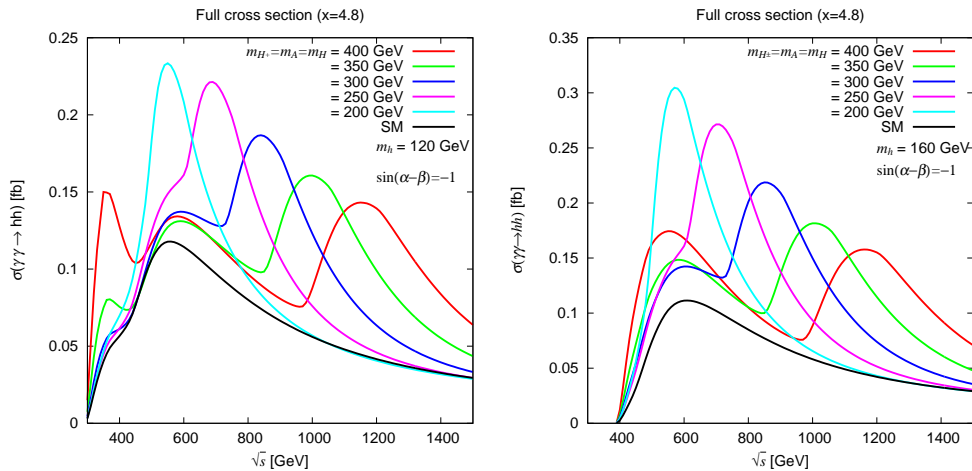
Figure 3: The full cross section of $e^-e^- \to \gamma\gamma \to hh$ as a function of $\sqrt{s}$ for each value of $m_\Phi (= m_H = m_A = m_{H^\pm})$ with $\sin(\beta - \alpha) = 1$, $\tan\beta = 1$ and $M = 0$. The case for $m_h = 120\ [160]$ GeV is shown in the left [right] figure.

smaller $\Delta\Gamma_{hhh}^{\mathrm{THDM}}/\Gamma_{hhh}^{\mathrm{SM}}$.

In Fig. 4, five curves correspond to the cases (a) to (e) in Fig. 2. In the left figure, one can see that the cross section is enhanced due to the enlarged $\Gamma_{hhh}^{\mathrm{THDM}}$ for larger values of m_Φ which is proportional to m_Φ^4 (when $M \sim 0$). This implies that the cross section for these parameters is essentially determined by the pole diagram contributions. The effect of the charged Higgs boson loop is relatively small since the threshold of charged Higgs boson production is far. Therefore, the deviation in the cross section from the SM value is smaller for relatively small m_Φ (10-20% for $m_\Phi < 300$ GeV due to the charged Higgs loop effect) but it becomes rapidly enhanced for greater values of m_Φ ($\mathcal{O}(100)$ % for $m_\Phi > 350$ GeV due to the large $\Delta\Gamma_{hhh}^{\mathrm{THDM}}$). A similar enhancement for the large m_Φ values can be seen in the right figure. The enhancement in the cross section in the THDM can also be seen for $m_\Phi < 250$ GeV, where the threshold effect of the charged Higgs boson loop appears around $\sqrt{s} \sim 600$ GeV in addition to that of the top quark loop diagrams. For $m_\Phi = 250$-400 GeV, both contributions from the charged Higgs boson loop contribution and the effective hhh coupling are important and enhance the cross section from its SM value by 40-50%.

4 Conclusions

In this paper, we have analysed the new physics loop effects on the cross section of $\gamma\gamma \to hh$ in the THDM with SM-like limit including the next to leading effect due to the extra Higgs boson loop diagram in the hhh vertex. Our analysis shows that the cross section can be largely changed from the SM prediction by the two kinds of contributions; i.e., additonal contribution by the charged Higgs boson loop effect, and the effective one-loop hhh vertex $\Gamma_{hhh}^{\mathrm{THDM}}$ enhanced by the non-decoupling effect of extra Higgs bosons. The cross section strongly depends on m_h and $\sqrt{s}$ and also on m_Φ. The approximation of the full cross
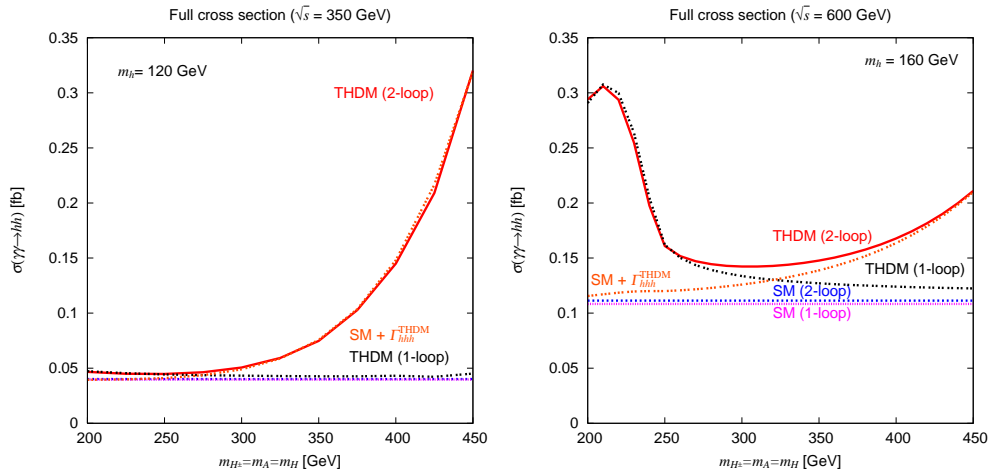
Figure 4: In the left [right] figure, the full cross section of $e^-e^- \to \gamma\gamma \to hh$ at $\sqrt{s} = 350$ GeV [600 GeV] for $m_h = 120$ [160] GeV is shown as a function of $m_\Phi (= m_H = m_A = m_{H^\pm})$ with $\sin(\beta - \alpha) = 1$, $\tan\beta = 1$ and $M = 0$.

section in the case (a) (THDM 2-loop) by using the result in the case (e) (SM+$\Gamma_{hhh}^{\text{THDM}}$) is a good description for $\sqrt{s} \ll 2m_\Phi/0.8$. On the other hand, in a wide region between threshold of top pair production and that of charged Higgs boson pair production, both the contributions (those from charged Higgs boson loop effect and from $\Gamma_{hhh}^{\text{THDM}}$) are important. In the region below the threshold of the real production of extra Higgs bosons, cross section is largely enhanced from the SM value by the effects of the charged Higgs boson loop and the effective $\Gamma_{hhh}^{\text{THDM}}$ coupling. These New Physics effects would be detectable at the future Photon Linear Collider.

5 Acknowledgments

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The 8th general meeting of the ILC physics working group, 1/21, 2009

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