Physics Letters B 672 (2009) 354–360

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Higgs boson pair production at a photon–photon collision in the two Higgs doublet model

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ARTICLE INFO

Article history:
Received 31 August 2008
Received in revised form 5 January 2009
Accepted 24 January 2009
Available online 27 January 2009
Editor: T. Yanagida

PACS:
12.60.Fr
14.70.Bh
14.80.Cp

Keywords:
Higgs self-coupling
Photon collider
New physics

ABSTRACT

We calculate the cross section of Higgs boson pair production at a photon collider in the two Higgs doublet model. We focus on the scenario in which the lightest CP even Higgs boson (h) has the Standard Model like couplings to the gauge bosons. We take into account the one-loop correction to the hhh coupling as well as additional one-loop diagrams due to charged Higgs bosons to the $\gamma\gamma \to hh$ helicity amplitudes. It is found that the full cross section can be enhanced by both these effects to a considerable level. We discuss the impact of these corrections on the hhh coupling measurement at the photon collider.

The Higgs sector is the last unknown part of the Standard Model (SM) for elementary particles. Discovery of the Higgs boson and the measurement of its properties at current and future experiments are crucial to establish our basic picture for spontaneous electroweak symmetry breaking (EWSB) and the mechanism of particle mass generation. The Higgs mechanism would be experimentally tested after the discovery of a new scalar particle by measuring its mass and the coupling to the weak gauge bosons. The mass generation mechanism for quarks and charged leptons via the Yukawa interaction is also clarified by the precise determination of both the fermion masses and the Yukawa coupling constants. If the deviation from the SM relation between the mass and the coupling is found, it can be regarded as an evidence of new physics beyond the SM. The nature of EWSB can be revealed through the experimental reconstruction of the Higgs potential, for which the measurement of the Higgs self-coupling is essential [1–5]. The structure of the Higgs potential depends on the scenario of new physics beyond the SM [6,7], so that the experimental determination of the triple Higgs boson coupling can be a probe of each new physics scenario. Furthermore, the property of the Higgs potential would be directly related to the aspect of the electroweak phase transition in the early Universe, which could have impact on the problem of the electroweak baryogenesis [8].

It is known that the measurement of the triple Higgs boson coupling is rather challenging at the CERN Large Hadron Collider (LHC), requiring huge luminosity. A study has shown that at the SLHC with the luminosity of 3000 fb^{-1}, expected accuracy would be about 20–30% for the mass (m_h) of the Higgs boson (h) to be around 170 GeV [1,2]. At the international linear collider (ILC), the main processes for the hhh measurement are the double Higgs boson production mechanisms via the Higgs-strahlung and the W-boson fusion [3,4]. If the collider energy is lower than 1 TeV, the double Higgs strahlung process $e^+e^- \to Zhh$ is important for a light Higgs boson with the mass of 120–140 GeV, while for higher energies the W-boson fusion process $e^+e^- \to hh\nu\bar{\nu}$ becomes dominant due to its t-channel nature [5]. 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 $< m_h <$ 200 GeV), it has not yet been known how accurately the hhh coupling can be measured by the electron–positron collision.

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0370-2693/$ – see front matter
doi:10.1016/j.physletb.2009.01.050

The photon collider is an option of the ILC. The possibility of measuring the hhh coupling via the process of $\gamma\gamma \to hh$ has been discussed in Ref. [9], where the cross section has been calculated at the one-loop level, and the dependence on the triple Higgs boson coupling constant is studied. In Ref. [10] the statistical sensitivity to the hhh coupling constant has been studied especially for a light Higgs boson mass in relatively low energy collisions. Recently, these analyses have been extended for wider regions of the Higgs boson masses and the collider energies. It has been 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 [11].

Unlike the double Higgs production processes $e^+e^- \to Zhh$ and $e^+e^- \to hh\nu\bar{\nu}$ in e^+e^- collisions, $\gamma\gamma \to hh$ is an one-loop induced process. When the origin of the shift in the hhh coupling would be due to one-loop corrections by new particles, it may also affect the amplitude of $\gamma\gamma \to hh$ directly through additional one-particle-irreducible (1PI) one-loop diagrams of $\gamma\gamma h$ and $\gamma\gamma hh$ vertices.

In this Letter, we consider the new particle effect on the $\gamma\gamma \to hh$ cross sections in the two Higgs doublet model (THDM), in which additional CP-even, CP-odd and charged Higgs bosons appear. It is known that a non-decoupling one-loop effect due to these extra Higgs bosons can enhance the hhh coupling constant by $\mathcal{O}(100)\%$ [6]. 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). We find 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. We consider how the new contribution to the cross section of $\gamma\gamma \to hh$ would affect the measurement of the triple Higgs boson coupling at a $\gamma\gamma$ collider.

In order to examine the new physics effect on $\gamma\gamma \to hh$, we calculate the helicity amplitudes in the THDM. We impose a discrete symmetry to the model to avoid flavor changing neutral current in a natural way [12]. The Higgs potential is then given by

$$\begin{aligned} V_{\text{THDM}} &= \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 - \left(\mu_3^2\Phi_1^\dagger\Phi_2 + \text{h.c.}\right) \\ &\quad + \lambda_1|\Phi_1|^4 + \lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 \\ &\quad + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left\{\left(\Phi_1^\dagger\Phi_2\right)^2 + \text{h.c.}\right\}, \end{aligned} \tag{1}$$

where Φ_1 and Φ_2 are two Higgs doublets with hypercharge $+1/2$. We here include the soft breaking term for the discrete symmetry by the parameter μ_3^2. In general, μ_3^2 and λ_5 are complex, but we here take them to be real for simplicity. We parameterize the doublet fields as

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

where vacuum expectation values (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 $\sin(\beta - \alpha) = 1$. We do not specify the type of Yukawa interactions [13], because it does not much affect the following discussions.

Throughout this Letter, 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 the Higgs bosons are[1]

$$m_h^2 = \left\{\lambda_1\cos^4\beta + \lambda_2\sin^4\beta + 2(\lambda_3+\lambda_4+\lambda_5)\cos^2\beta\sin^2\beta\right\}v^2, \tag{3}$$

$$m_H^2 = M^2 + \frac{1}{8}\left\{\lambda_1 + \lambda_2 - 2(\lambda_3+\lambda_4+\lambda_5)\right\}(1-\cos 4\beta)v^2, \tag{4}$$

$$m_A^2 = M^2 - \lambda_5 v^2, \tag{5}$$

$$m_{H^\pm}^2 = M^2 - \frac{\lambda_4+\lambda_5}{2}v^2, \tag{6}$$

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 $M \to \infty$.

There are several important constraints on the THDM parameters from the data. The LEP direct search results give the lower bounds $m_h > 114$ GeV in the SM-like limit and m_H, m_A, $m_{H^\pm} \gtrsim$ 80–90 GeV [14]. In addition, the rho parameter data at the LEP requires the approximate custodial symmetry in the Higgs potential. This implies that $m_{H^\pm} \simeq m_A$ or $\sin(\beta-\alpha) \simeq 1$ and $m_{H^\pm} \simeq m_H$. The Higgs potential is also constrained from the tree level unitarity [15,16], the triviality and the vacuum stability [17], in particular for the case where the non-decoupling effect is important as in the discussion here. For $M \sim 0$, masses of the extra Higgs bosons H, A and $H^\pm$ are bounded from above by about 500 GeV for $\tan\beta = 1$, when they are degenerated [15]. With non-zero M, these bounds are relaxed depending on the value of M. The constraint from $b \to s\gamma$ gives a lower bound on the mass of $H^\pm$ depending on the type of Yukawa interaction; i.e., in Model II [13], $m_{H^\pm} > 295$ GeV (95% CL) [18]. Recent data for $B \to \tau\nu$ can also give a constraint on the charged Higgs mass especially for large values of $\tan\beta$ in Model II [19,20]. In the following analysis, we do not include these constraints from B-physics because we do not specify type of Yukawa interactions.

In the THDM with $\sin(\beta-\alpha) = 1$, the one-loop helicity amplitudes for the initial photon helicities ℓ_1 and ℓ_2 ($\ell_i = +1$ or -1) are given as

$$\mathcal{M}^{\text{1-loop}}_{\text{THDM}}(\ell_1, \ell_2) = \mathcal{M}(\ell_1, \ell_2, \lambda_{hhh}) + \Delta\mathcal{M}(\ell_1, \ell_2, \lambda_{hhh}), \tag{7}$$

where $\lambda_{hhh} = -3m_h^2/v$, $\mathcal{M}(\ell_1, \ell_2, \lambda_{hhh})$ is the SM amplitude given in Ref. [9], and $\Delta\mathcal{M}(\ell_1, \ell_2, \lambda_{hhh})$ represents additional one-loop contributions from the charged Higgs boson loop to the $\gamma\gamma \to hh$ cross section. We note that λ_{hhh} has the same form as in the SM when $\sin(\beta-\alpha) = 1$. Due to the parity we have $\mathcal{M}_{\text{THDM}}(\ell_1, \ell_2) = \mathcal{M}_{\text{THDM}}(-\ell_1, -\ell_2)$, so that there are independent two helicity amplitudes.

The Feynman diagrams which contribute to $\Delta\mathcal{M}$ are shown in Fig. 1. $\Delta\mathcal{M}$ is given for each helicity set for $\sin(\beta-\alpha) \simeq 1$ as

[1] For the case without the SM-like limit, see Ref. [7] for example.