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Charged Higgs Production in Association with W Boson at Photon Colliders *

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It is important to explore the Higgs sector in order to identify the model beyond the standard model. We study the charged Higgs production in the $\gamma\gamma$ mode of a linear collider (LC) with 1000 GeV center of mass energy. We show that the cross sections for the $\gamma\gamma \to H^\pm W^\mp$ processes can be significantly enhanced in the two Higgs doublet model (THDM). The cross section can reach $0.1 - 100$ fb which is comparable to other charged Higgs boson production processes at a photon collider. While for other processes the cross sections are too small for $m_H^\pm \geq 500$ GeV, $0.1-100$ fb can be expected in the $\gamma\gamma \to H^\pm W^\mp$ processes for $m_H^\pm \geq 570$ GeV when $m_{A^0} = 800$ GeV. Therefore, even if the charged Higgs bosons can not be detected at the Large Hadron Collider (LHC), and even if the charged Higgs bosons are too heavy to be detected in other charged Higgs boson production processes at the LC, it may be possible to detect them in this process.

1. INTRODUCTION

The Higgs sector of the standard model (SM) can be extended by additional Higgs multiplets. In models with additional isospin $SU(2)$-doublets, 2 neutral and a pair of charged Higgs bosons for each additional doublet are newly included as physical Higgs bosons. Then, searches for the Higgs bosons and measurements of their properties are indispensable for understanding the mechanism of electroweak symmetry breaking and also physics beyond the SM.

The decay of a Higgs boson into another Higgs boson is worthwhile to study, because we can observe two kinds of Higgs bosons simultaneously. It is also important in the study of strategies for the detection of Higgs bosons. However, this type of decay is hard to occur in the decoupling region of the minimal supersymmetric standard model (MSSM) because quartic coupling constants in the Higgs potential whose linear combination is related to the mass difference among heavy Higgs bosons are restricted to the electroweak gauge coupling constants g and g'. On the other hand, in the general extended Higgs sector, such as the THDM, this type of decays can be allowed within some constraints. Therefore, to study the decay of a Higgs boson into another Higgs boson may bring us a opportunity to distinguish between the MSSM and such a model [1] as well as to affect detection strategy for Higgs bosons.

In this talk, we concentrate on the decay of a heavy neutral Higgs boson into a charged Higgs boson in the THDM. For production of heavy neutral Higgs bosons, a photon collider can be an ideal device where neutral Higgs bosons are produced in the s-channel via loops of charged particles. Its reach for the mass of Higgs bosons is about 80% of the parent e^+e^- collider. Even if the charged Higgs bosons can not be detected at the LHC, and even if the charged Higgs bosons are too heavy to be detected in other charged Higgs boson production processes at the LC [2, 3], it may be possible to detect them in this decay of neutral Higgs bosons at a photon collider.

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*This talk was given by E. Asakawa.

2. THE TWO HIGGS DOUBLET MODEL

We consider the THDM model with a (softly broken) discrete symmetry under the transformation $\Phi_1 \to \Phi_1$ and $\Phi_2 \to -\Phi_2$, where Φ_i are the Higgs isodoublets with hypercharge 1/2. The Higgs potential at the tree level is given by

$$\begin{aligned} V(\Phi_1, \Phi_2) &= m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2\Phi_1^\dagger\Phi_2 - m_3^{*2}\Phi_2^\dagger\Phi_1 \\ &\quad + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \frac{\lambda_5^*}{2}(\Phi_2^\dagger\Phi_1)^2 \end{aligned} \quad (1)$$

where m_1^2, m_2^2 and λ_1 to λ_4 are real. Since we consider the case of no CP violation in the Higgs sector, m_3^2 and λ_5 are also real though they are generally complex. The potential has its minimum at $\Phi_i = (0, v_i/\sqrt{2})^T$ $(i = 1, 2)$. The 8 parameters in the potential can transform into the masses of the Higgs bosons, m_{h^0},m_{H^0},m_{A^0} and $m_{H^\pm}$, the mixing angles α and β, the vacuum expectation value $v = \sqrt{v_1^2 + v_2^2} = \sqrt{2^{-\frac{1}{2}}G_F^{-1}}$, and the soft-breaking scale of the discrete symmetry $M^2 \equiv m_3^2/(\sin\beta\cos\beta)$. Using these physical parameters, the quartic coupling constants $\lambda_1 - \lambda_5$ can be written as

$$\lambda_1 = \frac{1}{v^2\cos^2\beta}(-\sin^2\beta M^2 + \sin^2\alpha m_{h^0}^2 + \cos^2\alpha m_{H^0}^2), \quad (2)$$

$$\lambda_2 = \frac{1}{v^2\sin^2\beta}(-\cos^2\beta M^2 + \cos^2\alpha m_{h^0}^2 + \sin^2\alpha m_{H^0}^2), \quad (3)$$

$$\lambda_3 = -\frac{M^2}{v^2} + 2\frac{m_{H^\pm}^2}{v^2} + \frac{1}{v^2}\frac{\sin 2\alpha}{\sin 2\beta}(m_{H^0}^2 - m_{h^0}^2), \quad (4)$$

$$\lambda_4 = \frac{1}{v^2}(M^2 + m_{A^0}^2 - 2m_{H^\pm}^2), \quad (5)$$

$$\lambda_5 = \frac{1}{v^2}(M^2 - m_{A^0}^2). \quad (6)$$

3. The $\gamma\gamma \to H^\pm W^\mp$ processes

In the THDM including the MSSM, the processes $\gamma\gamma \to H^\pm W^\mp$ are loop-induced processes, which consist of the triangle-type and box-type diagrams in the leading order. The triangle diagrams lead to the s-channel exchanges of neutral Higgs bosons ($\phi = h^0, H^0, A^0$). Since the quark contributions in loops tend to cancel between the triangle-type and box-type diagrams in the case insensitive to the s-channel Higgs resonance [4], the resonant ϕ production process can dominate around the resonance. In this talk, we consider the case where the peaked energy distribution of $\gamma\gamma$ collision is adjusted to mass of a neutral Higgs boson followed by decay into a charged Higgs boson and a W boson.

From Eqs. (5) and (6) we see that the mass splitting between the CP-odd Higgs boson A^0 and the charged Higgs boson $H^\pm$ is determined by λ_4 and λ_5 only:

$$m_{A^0}^2 - m_{H^\pm}^2 = \frac{v^2}{2}(\lambda_4 - \lambda_5). \quad (7)$$

Let us consider the A^0 resonant production followed by the decay into $H^\pm$ and $W^\mp$ in the THDM. It is notable that, in the MSSM, $\lambda_4 = -g^2/2$ and $\lambda_5 = 0$ lead to $m_{A^0}^2 - m_{H^\pm}^2 = -m_W^2$ which can not induce the resonant A^0 production in the $\gamma\gamma \to H^\pm W^\mp$ processes.

The vertex which induces the A^0 decay into $H^\pm$ and $W^\mp$ at the tree level can be written as

$$\mathcal{V}_{H^\pm W^\mp A^0} = \frac{g}{2}(p_{A^0} - p_{H^\pm}), \quad (8)$$

where p_{A^0} and $p_{H^\pm}$ are the momentum of A^0 and $H^\pm$ in the in-coming directions to the vertex. The helicity amplitude for the process $\gamma(\lambda_1)\gamma(\lambda_2) \to A^0 \to H^\pm W^\mp$ where we sum over the helicities of the out-going W boson is given by the multiplication of the Higgs-$\gamma\gamma$ vertex function $\mathcal{A}^{\lambda_1\lambda_2}$, the Higgs propagator $\mathcal{B}$ and the decay part $\mathcal{C}$:

$$\mathcal{M}^{\lambda_1\lambda_2} = \mathcal{A}^{\lambda_1\lambda_2} \cdot \mathcal{B} \cdot \mathcal{C}. \tag{9}$$

Each part can be written as

$$\mathcal{A}^{\lambda_1\lambda_2} = \frac{(\lambda_1+\lambda_2)}{2}\frac{\alpha g}{8\pi}\frac{m_{A^0}^2}{m_W}\sum_i I^i_{A^0}, \tag{10}$$

$$\mathcal{B} = \frac{-1}{s_{\gamma\gamma} - m_{A^0}^2 + i m_{A^0}\Gamma_{A^0}}, \tag{11}$$

$$\mathcal{C} = g\frac{m_{A^0}}{m_W}E_W\beta_W, \tag{12}$$

where λ_1 and λ_2 denote the helicities of the colliding photons. $\sqrt{s_{\gamma\gamma}}$ and Γ_{A^0} are the $\gamma\gamma$ collision energy and the total decay width of A^0, and the functions $I^i_{A^0}$ can be found in Ref. [5]. E_W and β_W are the energy and the velocity of the W boson in the center-of-mass frame of $\gamma\gamma$ collision, respectively.

The cross section for arbitrary initial photon helicities is given by

$$\widehat{\sigma}^{\lambda_1\lambda_2}_{\gamma\gamma\to H^\pm W^\mp} = \frac{\bar{\beta}}{16\pi s_{\gamma\gamma}}|\mathcal{M}^{\lambda_1\lambda_2}|, \tag{13}$$

where $\bar{\beta} \equiv \sqrt{1 - 2\frac{m_{H^\pm}^2+m_W^2}{s_{\gamma\gamma}} + \frac{(m_{H^\pm}^2-m_W^2)^2}{s_{\gamma\gamma}^2}}$. The cross section for the process is evaluated by convoluting with the $\gamma\gamma$ luminosity;

$$\sigma_{ee\to\gamma\gamma\to H^\pm W^\mp} = \int d\sqrt{s}_{\gamma\gamma}\sum_{\lambda_1\lambda_2}\frac{1}{\mathcal{L}}\frac{d\mathcal{L}^{\lambda_1\lambda_2}}{d\sqrt{s}_{\gamma\gamma}}\widehat{\sigma}^{\lambda_1\lambda_2}_{\gamma\gamma\to H^\pm W^\mp}(\sqrt{s}_{\gamma\gamma}), \tag{14}$$

where we use the $\gamma\gamma$ luminosity derived from the tree-level formula of the backward Compton scattering [6] for $x = 4.8$ assuming complete polarization for laser photons ($P_l = -1.0$) and 90% polarization for electrons ($P_e = 0.9$). In our numerical evaluation, the center-of-mass energy of a parent e^+e^- collider $\sqrt{s}_{ee}$ is assumed to be 1000 GeV and $m_{A^0} = 800$ GeV which is the maximum value possible to reach at $\sqrt{s}_{ee} = 1000$ GeV.

Fig. 1 shows the allowed values of $m_{H^\pm}$ and m_{H^0} from various constraints, for $m_{A^0} = 800$ GeV, $\tan\beta = 7$ and $\alpha = -0.146$. M values are scanned between 0 and m_{A^0}. While the magenta circles indicate the allowed values by the rho parameter measurement [7], the allowed values by theoretical constraints (the requirment of vacuum stability [8] and perturbative unitarity [9] at the tree level) are shown by the turquoise crosses. As a result, we find that $m_H^\pm \geq 570$ GeV is allowed, and to assume $m_{H^0} = m_{H^\pm}$ in the numerical evalution is reasonable.

Table I: Parameters

$\tan\beta$	1.5	7	30	40
m_{A^0} [GeV]	800.0	800.0	800.0	800.0
m_{H^0} [GeV]	$m_{H^\pm}$	$m_{H^\pm}$	$m_{H^\pm}$	$m_{H^\pm}$
m_{h^0} [GeV]	97.7	119.6	121.4	121.54
M [GeV]	$0.0 - m_{A^0}$	$0.0 - m_{A^0}$	$0.0 - m_{A^0}$	$0.0 - m_{A^0}$
α	-0.600	-0.146	-0.0337	-0.0251

The cross sections for four reference choices of $\tan\beta$ ($\tan\beta = 1.5$, 7, 30 and 40) are shown in Fig. 2. The parameters used for evaluating each case are listed in Table I. The M values allowed by the above constraints are dependent on m_{H^0}. In the numerical evalution, the relevant values of M between 0 to m_{A^0} are used. The dependence of the cross sections on the choices of the M values is insignificantly small.

Though the cross sections for the $\gamma\gamma \to H^\pm W^\mp$ process are less than 0.1 fb in the MSSM [2], the cross sections for the $\gamma\gamma \to A^0 \to H^\pm W^\mp$ process amount to $0.1 - 100$ fb in general. Such cross section values are comparable with

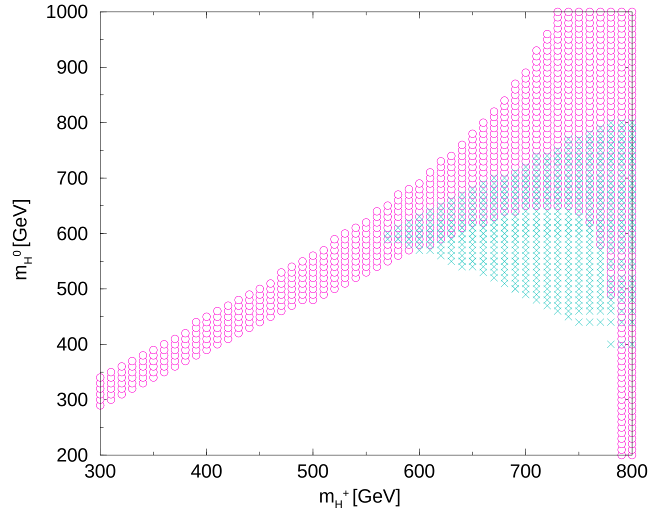

Figure 1: The allowed region for $m_{H^\pm}$ and m_{H^0}. The magenta circles (turquoise crosses) show the allowed region by the rho parameter measurement (theoretical constraints). $m_{A^0} = 800$ GeV, $\tan\beta = 7$, $\alpha = -0.146$.

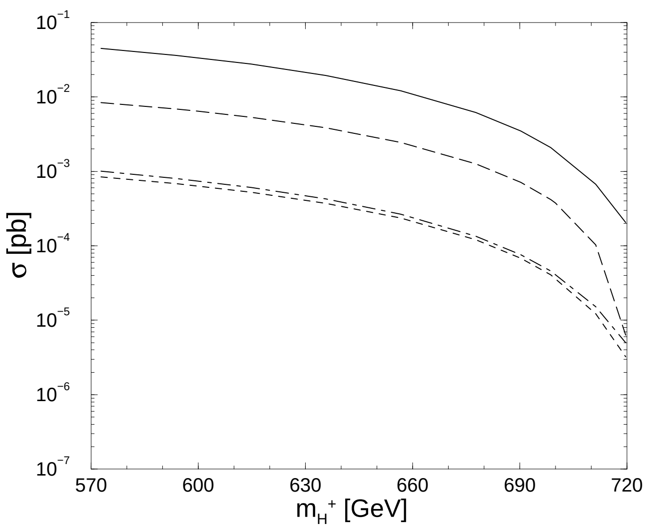

Figure 2: The cross sections for $\gamma\gamma \to A^0 \to H^\pm W^\mp$. $m_{A^0} = 800$ GeV, $\sqrt{s}_{ee} = 1000$ GeV. The solid (dashed, dotted and dat-dashed) curve indicates the case for $\tan\beta = 1.5$ (7, 30 and 40).

the ones for other charged Higgs boson production processes at a photon collider [2]. While for other processes the cross sections are too small for $m_H^\pm \geq 500$ GeV, $0.1 - 100$ fb can be expected in the $\gamma\gamma \to A^0 \to H^\pm W^\mp$ process for $m_H^\pm \geq 570$ GeV.

4. SUMMARY

In the THDM, the decay of a Higgs boson into another Higgs boson can be allowed within experimental and theoretical constraints, though this type of decay is hard to occur in the decoupling region of the MSSM. To study this type of decay may bring us an opportunity to distinguish between the MSSM and such a model [1], as well as to affect detection strategies for Higgs bosons.

The $\gamma\gamma \to A^0 \to H^\pm W^\mp$ processes have been considered here. The A^0 resonant production in the processes can be realized in the THDM. For $\sqrt{s}_{ee} = 1000$ GeV, it is possible to produce the A^0 bosons whose mass is less than 800 GeV at a photon collider. We have studied the case where $\sqrt{s}_{ee} = 1000$ GeV and $m_{A^0} = 800$ GeV.

Though the cross sections for the $\gamma\gamma \to H^{\pm}W^{\mp}$ processes are less than 0.1 fb in the MSSM, the cross sections for the $\gamma\gamma \to A^0 \to H^{\pm}W^{\mp}$ processes in the THDM can reach $0.1 - 100$ fb. It is important that such cross section values can be realized for $m_H^{\pm} \geq 570$ GeV where the values for other charged Higgs boson production processes are too small. Therefore, even if the charged Higgs bosons are too heavy to be detected in other charged Higgs boson production processes at the LC, it may be possible to detect them in this process.

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