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Measuring Higgs CP properties through top quark production at a photon collider

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Abstract. We study resonant effects of heavy Higgs bosons on the top-pair production process at a photon linear collider. Observables which can be obtained by circular polarization of colliding photons and polarization measurement through the angular distribution of the top quark decays are useful not only for measuring the Higgs CP parity but also resolving degeneracy of Higgs bosons.

Keywords. Higgs, Beyond the Standard Model

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1. Introduction

The Higgs sector of the Standard Model (SM) can be extended by additional Higgs multiplets. In such models, neutral CP-even Higgs boson(s)(H) as well as neutral CP-odd Higgs boson(s) (A) appear. Models like the minimal supersymmetric extension of the SM (MSSM) are expected to have almost degenerate masses for H and A if they are heavy in comparison with m_Z.

On the other hand, a photon collider can be an ideal device for production of neutral Higgs bosons H and A. Its reach for the mass of Higgs bosons is about 80% of the parent e^+e^- collider. Even if the heavy neutral Higgs bosons can not be detected at the LHC, and even if they are too heavy to be detected at the e^+e^- collider, it may be possible to detect them at a photon collider [1].

In this talk, we study observables which can be obtained by circular polarization of colliding photons and polarization measurement through the angular distribution of the top quark decays in the $\gamma\gamma \to t\bar{t}$ process at a photon collider. It will be shown that special linear combinations for these observables are useful for measuring the Higgs CP parity and for resolving degeneracy of heavy neutral Higgs bosons [2].

2. Observables for the process $\gamma\gamma \to t\bar{t}$

When the $\gamma\gamma$ collision energy reaches around mass of the Higgs bosons H and A, the helicity amplitudes for the process $\gamma_{\lambda_1}\gamma_{\lambda_2} \to t_\sigma\bar{t}_{\overline{\sigma}}$ can be expressed as

$$M^{\sigma\overline{\sigma}}_{\lambda_1\lambda_2} = [M_H]^{\sigma\overline{\sigma}}_{\lambda_1\lambda_2} + [M_A]^{\sigma\overline{\sigma}}_{\lambda_1\lambda_2} + [M_t]^{\sigma\overline{\sigma}}_{\lambda_1\lambda_2}\,, \tag{1}$$

where the first term $M_{H,A}$ stands for the s-channel H, A-exchange amplitudes and the latter term M_t stands for the t- and u-channel top-quark-exchange amplitudes. The resonant helicity amplitudes are calculated by using the lowest-dimensional effective Lagrangian of the form

$$L_{\phi\gamma\gamma} = \frac{1}{m_\phi}\left(b^H_\gamma A_{\mu\nu}A^{\mu\nu} + b^A_\gamma \widetilde{A}_{\mu\nu}A^{\mu\nu}\right)\phi. \tag{2}$$

By considering the decay angular distribution of $t\bar{t}$ pairs, we can derive the convoluted four observables, Σ_1 to Σ_4,

$$\Sigma_i(\sqrt{\hat{s}}) = \int d\sqrt{\hat{s}} \sum_{\lambda_1,\,\lambda_2} \left(\frac{1}{L_{0.8}}\frac{dL^{\lambda_1\lambda_2}}{d\sqrt{\hat{s}}}\right)\left(\frac{3\beta}{32\pi\hat{s}}\int S^i_{\lambda_1\lambda_2}(\Theta,\sqrt{\hat{s}})d\cos\Theta\right), \tag{3}$$
$$\text{for } \; i = 1-4,$$

where $\hat{s}$ is the total energy-squared in the rest frame of $\gamma\gamma$ collisions and the functions $S^i_{\lambda_1\lambda_2}$ contain all the information about the $\gamma\gamma \to t\bar{t}$ helicity amplitudes:

$$\begin{aligned} S^1_{\lambda_1\lambda_2} &= \left|M^{RR}_{\lambda_1\lambda_2}\right|^2, \qquad S^2_{\lambda_1\lambda_2} = \left|M^{LL}_{\lambda_1\lambda_2}\right|^2, \\ S^3_{\lambda_1\lambda_2} &= 2\Re\left[M^{RR}_{\lambda_1\lambda_2}\left(M^{LL}_{\lambda_1\lambda_2}\right)^*\right], \quad S^4_{\lambda_1\lambda_2} = 2\Im\left[M^{RR}_{\lambda_1\lambda_2}\left(M^{LL}_{\lambda_1\lambda_2}\right)^*\right], \end{aligned} \tag{4}$$

the $\gamma\gamma$ luminosity integrated over $z \geq 0.8z_m$ is denoted by $L_{0.8}$ and the luminosity distribution for each $\gamma\gamma$ helicity combination is expressed by $dL^{\lambda_1\lambda_2}/d\sqrt{\hat{s}}$.

For the collider parameters, we here use $E_e = 250$ GeV, $P_l = -1.0$, $P_e = 0.9$ and $x = 4.8$, where colliding photons are highly polarized to be + around $\sqrt{\hat{s}} = 400$ GeV. In this case, among the four combinations for $\lambda_1\lambda_2$, the $++$ combination largely dominates aroud $\sqrt{\hat{s}} = 400$ GeV, and the quantities S^{1-4} in (4) can be expressed by $M_{H,A}$ and M_t which are the abbreviated notation for $[M_{H,A}]^{RR}_{++}$ and $[M_t]^{RR}_{++}$;

$$\begin{aligned} S^1_{++} = {} & |M_t|^2 + |M_A|^2 + |M_H|^2 \\ & + 2M_t\Re[M_A] + 2M_t\Re[M_H] + 2\Re[M^*_A M_H], \end{aligned} \tag{5}$$

$$\begin{aligned} S^2_{++} = {} & \left(\frac{1-\beta}{1+\beta}\right)^2 |M_t|^2 + |M_A|^2 + |M_H|^2 \\ & + 2\frac{1-\beta}{1+\beta}M_t\Re[M_A] - 2\frac{1-\beta}{1+\beta}M_t\Re[M_H] - 2\Re[M^*_A M_H], \end{aligned} \tag{6}$$

$$\begin{aligned} S^3_{++} = {} & 2\frac{1-\beta}{1+\beta}|M_t|^2 + 2|M_A|^2 - 2|M_H|^2 \\ & + 2\left(\frac{1-\beta}{1+\beta}+1\right)M_t\Re[M_A] + 2\left(\frac{1-\beta}{1+\beta}-1\right)M_t\Re[M_H], \end{aligned} \tag{7}$$

$$\begin{aligned} S^4_{++} = {} & 2\left(\frac{1-\beta}{1+\beta}-1\right)M_t\Im[M_A] + 2\left(\frac{1-\beta}{1+\beta}+1\right)M_t\Im[M_H] \\ & + 4\Im[M^*_A M_H], \end{aligned} \tag{8}$$

where β is the velocity of the top quarks.

3. Measuring Higgs CP parity

If we assume that the top-quark decays are essentially described by the SM amplitudes, it is straightforward to extract all the four observables Σ_1 to Σ_4 which are proportional to $S^1_{\lambda_1\lambda_2} - S^4_{\lambda_1\lambda_2}$. As you see in (5)–(8), S^2, S^3 and S^4 include the terms which differ in sign for H and A. Therefore, if we observe the difference between H and A, it is possible to determine the Higgs CP parity from the observables [2] [3].

The observables are also sensitive to the complex phase of the $\gamma\gamma H$ and $\gamma\gamma A$ vertices. Since variation in the phase modifies the magnitudes of the observables and the $\sqrt{\hat{s}}$ values where the observables have peaks and bottoms, we can recieve new information about the Higgs couplings to new heavy charged particles which give extra contribution to the $\gamma\gamma H$ and/or $\gamma\gamma A$ vertices [2].

4. Resolving degeneracy of Higgs bosons

In the above discussion, we studied four observables separately. Once they are derived individually, we can obtain their arbitrary linear combinations. The most powerful combinations for probing the CP parity of Higgs bosons are $\Sigma_1 + \Sigma_2 + \Sigma_3$ and $\Sigma_1 + \Sigma_2 - \Sigma_3$ which are approximately proportional to

$$S^1_{++} + S^2_{++} + S^3_{++} = \left(\frac{2}{1+\beta}\right)^2 |M_t|^2 + 4\,|M_A|^2 + 4\frac{2}{1+\beta} M_t \Re\,[M_A]\,, \tag{9}$$

$$S^1_{++} + S^2_{++} - S^3_{++} = \left(\frac{2\beta}{1+\beta}\right)^2 |M_t|^2 + 4\,|M_H|^2 + 4\frac{2\beta}{1+\beta} M_t \Re\,[M_H]\,. \tag{10}$$

The former combination receives contribution only from the CP-odd resonance, while the latter only from the CP-even resonance when CP is conserved. It is therefore straightforward to separate the CP-even and CP-odd resonances, even when their masses are degenerate.

The four observables Σ_1 to Σ_4 and the linear combination $\Sigma_1 + \Sigma_2 \pm \Sigma_3$ are shown in Fig.1. When we draw the figure, we adopt a MSSM prediction as an example where the parameters are taken as follows: $m_A = 400$ GeV, $\tan\beta = 3$, $m_{\tilde{f}} = 1$ TeV, $M_2 = 500$ GeV, $\mu = -500$ GeV. Then we find

$$\begin{aligned} m_A &= 400\ \mathrm{GeV},\ \ \Gamma_A = 1.75\ \mathrm{GeV}, && (11)\\ &\mathrm{Br}\ (A \to \gamma\gamma) = 1.53 \times 10^{-5},\ \ \mathrm{Br}(A \to t\bar{t}) = 0.946, \\ m_H &= 403.8\ \mathrm{GeV},\ \ \Gamma_H = 0.79\ \mathrm{GeV}, && (12)\\ &\mathrm{Br}\ (H \to \gamma\gamma) = 0.99 \times 10^{-5},\ \ \mathrm{Br}(H \to t\bar{t}) = 0.742 \end{aligned}$$

for the above parameters [4]. In the left four figures, contributions from both H and A bosons whose masses are almost degenarate can be found. It may be impossible to tell existence of two Higgs bosons under the energy resolution of the detector from those observables. On the other hand, in the right two figures, contributions from the H and A bosons are resolved. Then it is obvious that both H and A bosons exist around $\sqrt{\hat{s}} = 400$ GeV.

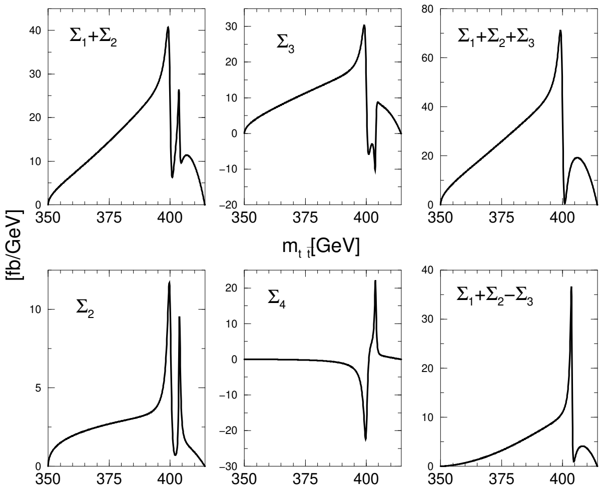

Figure 1. The observables Σ_1 to Σ_4 and $\Sigma_1 + \Sigma_2 \pm \Sigma_3$.

References

[1] M.M. Muhlleitner, M. Kramer, M. Spira and P.M. Zerwas, *Phys. Lett.* **B508**, 311 (2001); D.M. Asner, J.B. Gronberg and J.F. Gunion, *Phys. Rev.* **D67**, 035009 (2003).

[2] E. Asakawa and K. Hagiwara, *Eur. Phys. J.* **C31**, 351 (2003).

[3] E. Asakawa, J. Kamoshita, A. Sugamoto and I. Watanabe, *Eur. Phys. J.* **C14**, 335 (2000).

[4] A. Djouadi, J. Kalinowski and M. Spira, *Comm. Phys. Commun. Res.* **108**, 56 (1998).