Measuring the Higgs CP property at a Photon Linear Collider

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Abstract. We study measurement of the CP property of the Higgs boson at a photon linear collider. One method where we take advantage of interference between Higgs-production and background amplitudes is proposed. A broad peak of the photon energy spectrum is helpful in observing the energy dependence of the interference effects. Numerical results for the process $\gamma\gamma \to t\bar{t}$ are shown as an example.

I INTRODUCTION

In the Standard Model (SM), the electroweak symmetry breaking results in a physical neutral CP-even Higgs boson. There also exist various models extended by increasing Higgs fields, such as the multi-Higgs doublet model where there are extra two neutral and two charged physical Higgs bosons for each additional doublet. If CP is a good symmetry in the Higgs sector, one of the extra neutral bosons is CP-even and the other is CP-odd. If CP is not invariant, all of the Higgs states which have same quantum numbers except for the CP property can be mixed in their mass eigenstates. Then, physical Higgs bosons do not have definite CP parity.

One of the notable advantages of a photon linear collider (PLC) is to provide information about the CP property of the Higgs boson by use of linear polarizations of colliding photons. Defining $J_z = 0$ two-photon states as $|++\rangle$ and $|--\rangle$ where $\pm$ indicate their helicities with $\hbar$ units, the CP transformation leads to the other states: $CP|++\rangle = |--\rangle$, $CP|--\rangle = |++\rangle$. Then, the CP eigenstates are $(|++\rangle + |--\rangle)$ and $(|++\rangle - |--\rangle)$; the former is a $J_z = 0$ component of parallel polarized photons and couples to a CP-even Higgs boson (H) , and the latter is of perpendicularly polarized photons and couples to a CP-odd one (A). However, because colliding beams at PLC are generated by the Compton back-scattering between high energy electrons and laser photons, the energy spectrum of $\sqrt{s}_{\gamma\gamma}$ distributes broadly and the degrees of polarizations depend strongly on $\sqrt{\tau} \equiv \sqrt{s}_{\gamma\gamma}/\sqrt{s}_{ee}$, where $\sqrt{s}_{\gamma\gamma}$ and $\sqrt{s}_{ee}$ are the center-of-mass energy of $\gamma\gamma$ collisions and $e^{\pm}e^{-}$ collisions at parent LC. In the case of the 500 GeV LC, linear polarizations can be used effectively for relatively light Higgs bosons whose masses are less than about a few hundred GeV. For heavier Higgs bosons, it is necessary that the electron energy is raised or we use other methods, conventionally.

We propose one method where we take advantage of interference between Higgs-production and background amplitudes with circular polarized beams. A broad peak of the $\sqrt{s_{\gamma\gamma}}$ spectrum in the range where the degrees of circular polarizations become large is helpful to the method, because we have an interest in the energy dependence of the interference effects.

II CP INVARIANT CASE

As an example, we consider the process $\gamma\gamma \to t\bar{t}$ which receives contribution from the Higgs-exchanged s-channel diagram and the top-quark-exchanged t, u-channel ones. The helicity-dependent cross sections are expressed as

$$\frac{d\sigma^{\lambda_1\lambda_2\sigma\overline{\sigma}}}{d\Omega} \propto \left|\mathcal{M}_{\phi}^{\lambda_1\lambda_2\sigma\overline{\sigma}}\right|^2 + \left|\mathcal{M}_{cont}^{\lambda_1\lambda_2\sigma\overline{\sigma}}\right|^2 + 2\ Re\left[\mathcal{M}_{\phi}^{\lambda_1\lambda_2\sigma\overline{\sigma}}\mathcal{M}_{cont}^{\lambda_1\lambda_2\sigma\overline{\sigma}}\right], \tag{1}$$

where $\mathcal{M}_\phi$ and $\mathcal{M}_{cont}$ are the helicity amplitudes of Higgs resonance ($\phi = H$ or A) and top continuum processes, $\lambda_{1,2}$ denote the helicities of colliding photons in

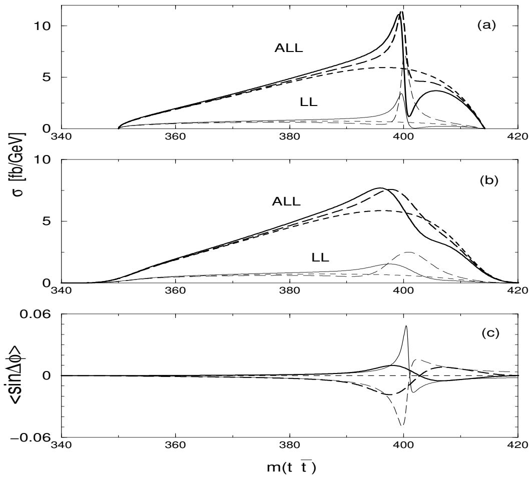

FIGURE 1. The $m(t\bar{t})$ dependence of the cross sections for $\gamma\gamma \to t\bar{t}$. The energy and polarization dependence of the $\gamma\gamma$ luminosity has been considered (we set the highest laser frequency, $x = 4.83$ at $\sqrt{s_{ee}} = 500$ GeV, and $P_e P_L = -1.$). Short-dashed curves show QED predictions, while solid (long-dashed) curves show predictions when A (H) of 400 GeV is produced. In (a) and (b), the thick lines are for total events and the thin lines are for events where final top-pairs are left-handed. Gaussian smearing with $\Delta m(t\bar{t}) = 3$ GeV is applied in (b). Azimuthal decay angular correlation is shown in (c) with (without) the smearing by thick (thin) lines.

$\hbar$ units, σ and $\overline{\sigma}$ the final t and $\overline{t}$ helicities in the center-of-mass frame in $\hbar/2$ (we also write -1 $(+1)$ as L (R).).

Let us notice interference terms in the above cross sections. From helicity-dependence of $\mathcal{M}_\phi$ [1], we find

$$\begin{aligned} sgn\left[\mathcal{M}_\phi^{\lambda\lambda RR}\mathcal{M}_{cont}^{\lambda\lambda RR}\right] &= -sgn\left[\mathcal{M}_\phi^{\lambda\lambda LL}\mathcal{M}_{cont}^{\lambda\lambda LL}\right] \quad \text{for } H, \\ sgn\left[\mathcal{M}_\phi^{\lambda\lambda RR}\mathcal{M}_{cont}^{\lambda\lambda RR}\right] &= \quad sgn\left[\mathcal{M}_\phi^{\lambda\lambda LL}\mathcal{M}_{cont}^{\lambda\lambda LL}\right] \quad \text{for } A. \end{aligned} \tag{2}$$

Then, it is possible to distinguish H from A by observing this difference in the cross section with circular polarized photons. Numerical results are shown in Fig. 1 (a,b). For definiteness, we use the MSSM (minimal SUSY SM) prediction for the total and partial widths for A adopted in ref. [1]. It is found that little interference is observed for H (long-dashed curves) because the interference effects for final $t_L\overline{t}_L$ and $t_R\overline{t}_R$ events cancel each other. On the other hand, the effects for A (solid curves) can be large due to additive interference for both events.

There is another observable sensitive to CP parity. When the decay of a top quark is taken into account, the cross sections for the processes $\gamma_{\lambda_1}\gamma_{\lambda_2} \to bW^+\overline{b}W^-$ can be written by

$$\begin{aligned} \frac{d\sigma_{bW}^{\lambda_1\lambda_2}}{d\Omega} \propto \sum_{\lambda,\overline{\lambda}} \Big\{ & \left|\mathcal{M}^{\lambda_1\lambda_2 LL}\right|^2 \left|\mathcal{D}_L^\lambda\right|^2 \left|\overline{\mathcal{D}}_L^{\overline{\lambda}}\right|^2 + \left|\mathcal{M}^{\lambda_1\lambda_2 RR}\right|^2 \left|\mathcal{D}_R^\lambda\right|^2 \left|\overline{\mathcal{D}}_R^{\overline{\lambda}}\right|^2 \\ & + 2\ Re\left[\mathcal{M}^{\lambda_1\lambda_2 LL}\mathcal{M}^{\lambda_1\lambda_2 RR*}\right]\ Re\left[\mathcal{D}_L^\lambda\overline{\mathcal{D}}_L^{\overline{\lambda}}\mathcal{D}_R^{\lambda*}\overline{\mathcal{D}}_R^{\overline{\lambda}*}\right] \\ & - 2\ Im\left[\mathcal{M}^{\lambda_1\lambda_2 LL}\mathcal{M}^{\lambda_1\lambda_2 RR*}\right]\ Im\left[\mathcal{D}_L^\lambda\overline{\mathcal{D}}_L^{\overline{\lambda}}\mathcal{D}_R^{\lambda*}\overline{\mathcal{D}}_R^{\overline{\lambda}*}\right]\Big\}. \end{aligned} \tag{3}$$

Here, the decay amplitudes for the processes $t_\sigma \to b_- W_\lambda^+$ and $\overline{t}_{\overline{\sigma}} \to \overline{b}_+ W_{\overline{\lambda}}^-$ are defined as $\mathcal{D}_\sigma^\lambda$ and $\overline{\mathcal{D}}_{\overline{\sigma}}^{\overline{\lambda}}$, the explicit forms of which are in the appendix of ref. [2]. We notice the azimuthal angles of b and $\overline{b}$ in the t and $\overline{t}$ rest frame. Describing them as ϕ and $\overline{\phi}$, they appear in the third and fourth terms in Eq. 3:

$$\begin{aligned} Re\left[\mathcal{D}_L^\lambda\overline{\mathcal{D}}_L^{\overline{\lambda}}\mathcal{D}_R^{\lambda*}\overline{\mathcal{D}}_R^{\overline{\lambda}*}\right] &\propto \cos(\phi-\overline{\phi}), \\ Im\left[\mathcal{D}_L^\lambda\overline{\mathcal{D}}_L^{\overline{\lambda}}\mathcal{D}_R^{\lambda*}\overline{\mathcal{D}}_R^{\overline{\lambda}*}\right] &\propto \sin(\phi-\overline{\phi}). \end{aligned} \tag{4}$$

Therefore, we obtain

$$\langle\sin(\phi-\overline{\phi})\rangle = \frac{\displaystyle\int \sin(\phi-\overline{\phi})\ \frac{d\sigma_{bW}^{\lambda_1\lambda_2}}{d\Omega}\ d\Omega}{\displaystyle\int \frac{d\sigma_{bW}^{\lambda_1\lambda_2}}{d\Omega}\ d\Omega} \propto Im\left[\mathcal{M}^{\lambda_1\lambda_2 LL}\mathcal{M}^{\lambda_1\lambda_2 RR*}\right]. \tag{5}$$

When colliding photons are polarized to be $+1$, $Im\left[\mathcal{M}^{++LL}\mathcal{M}^{++RR*}\right] \simeq Im\left[\mathcal{M}_\phi^{++LL}\mathcal{M}_{cont}^{++RR*}\right]$ is satisfied considering $\left|\mathcal{M}_{cont}^{++RR}\right| \gg \left|\mathcal{M}_{cont}^{++LL}\right|$. Since the

Higgs-production amplitudes $\mathcal{M}_H^{++LL}$ and $\mathcal{M}_A^{++LL}$ have opposite signs in the MSSM-type models, $\langle \sin(\phi - \overline{\phi}) \rangle$ tells us the CP parity of the Higgs boson. A numerical calculation is shown in Fig. 1(c). Though the quantity turns out to be rather small because of cancellation between the contributions from longitudinally and transversely polarized W's, we can recover the sensitivity to the CP parity by taking account of W-decay distributions.

III CP NON-INVARIANT CASE

When the CP symmetry is not conserved in the Higgs potential, the helicity amplitudes for the Higgs-production are denoted by

$$\mathcal{M}_\phi^{\lambda_1\lambda_2\sigma\overline{\sigma}} = \frac{e\,\alpha}{4\pi}\frac{m_t}{m_W}\frac{s}{s - m_\phi^2 + im_\phi\Gamma_\phi}\,[\,a_\gamma + \lambda_1 b_\gamma]\,[\,\sigma\beta_t a_t - ib_t]\,\delta_{\lambda_1\lambda_2}\delta_{\sigma\overline{\sigma}}\,. \tag{6}$$

where a_γ and a_t are proportional to the CP-even components of vertices, $\phi\gamma\gamma$ and $\phi t\bar{t}$, b_γ and b_t to the CP-odd components. Since $\{a_\gamma, b_\gamma\}$ or/and $\{a_t, b_t\}$ have non-zero values simultaneously, they induce complicated interference. Moreover, the amplitudes include six parameters for vertices; a_γ, b_γ are complex, whereas a_t, b_t are real. Therefore, we need at least six observables to determine the CP property completely and are urged to use linear polarizations as well. All observables obtained from various polarizations (including the mixture of linear and circular ones) are exhibited in ref. [3].

IV CONCLUSIONS

We have discussed measurement of the CP property of the Higgs boson at PLC. It has been found that we can extract information about the CP property of the Higgs boson from the observation of interference effects between Higgs-production and background amplitudes. If the Higgs boson have definite CP parity, this method can be powerful in high $\sqrt{\tau}$ region where linear polarizations of colliding photons become useless conventionally.

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