Probing Higgs Sector CP Violation with Top Quarks at a Photon Linear Collider

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Abstract
We investigate for two-Higgs doublet models with intrinsic CP violation in the scalar potential CP-nonconserving effects in unpolarized $\gamma\gamma \rightarrow tt$ for a range of neutral Higgs boson masses which includes resonant $\varphi$ production and the subsequent decay of $\varphi \rightarrow tt$. The importance of taking into account, even in the resonant case, the interference with the nonresonant background is shown. Further, we propose and calculate three asymmetries which efficiently trace CP-violating effects in $\gamma\gamma \rightarrow tt$ using semileptonic $tt$ decays.

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1. Introduction

CP-violating interactions beyond the Kobayashi-Maskawa mechanism and their high-energy phenomenology have been investigated rather intensely in recent years. This was (and is) motivated to some extent by proposals of efficient non-standard model scenarios for generating the cosmological baryon asymmetry at the electroweak phase transition (for a review, see [1]). An extended Higgs boson sector – as predicted by many extensions of the Standard Model (SM) – provides such interactions in a natural way [2,3]. In the case of Higgs sector CP violation one expects, in particular, a spectrum of neutral Higgs particles with indefinite CP parity. This can be traced through large Yukawa couplings to heavy fermions, notably to top quarks [4,5,6,7,8,9,10,11,12,13,14,15,16,17].

A “Compton collider” [18] which is considered as an option in the context of the present discussion of high-energy $e^+e^-$ linear colliders, would provide, among other things, an interesting possibility to produce neutral Higgs bosons and to study their quantum numbers [19,20]. In this letter we investigate, in the framework of two-Higgs doublet extensions of the SM with explicit CP violation in the Higgs potential [3,4,21,22], CP-violating effects in unpolarized† $\gamma\gamma \to t\bar{t}$ which includes, for neutral Higgs boson masses above the $t\bar{t}$ threshold, resonant $\phi$ production and the subsequent decay of $\phi \to t\bar{t}$. If $\phi$ is not a CP eigenstate, a CP-violating spin-spin correlation is induced in the decay $\phi \to t\bar{t}$ (and in the decays into other fermions, respectively) already at the Born level which can be as large as 0.5, as pointed out in [9] (see also [11,15], and for absorptive effects see [15,16,23,24,25]). However, the narrow-width approximation does not apply for a Higgs boson with mass above the $t\bar{t}$ threshold and interference with the non-resonant $\gamma\gamma \to t\bar{t}$ amplitude decreases this spin-spin correlation significantly, as shown below. As we wish to consider also the case of light Higgs bosons $\phi$ below the $t\bar{t}$ threshold we have computed, for the above models, the complete set of CP-nonconserving contributions to $\gamma\gamma \to t\bar{t}$ in one-loop approximation. Apart from the above spin-spin correlation we determine also a polarization asymmetry which projects onto absorptive CP effects. In addition we propose and calculate three asymmetries with which this polarization asymmetry and the above-mentioned spin-spin correlation can be traced efficiently in semileptonic $t\bar{t}$ decays.

† CP asymmetries for polarized $\gamma\gamma \to \phi \to t\bar{t}$ were investigated in [8]. They apply if the polarizations of both photons are adjustable.
2. CP violation in $\gamma \gamma \rightarrow t\bar{t}$

We first discuss signatures of CP violation in the reaction

$$\gamma(p_1) + \gamma(p_2) \rightarrow t(k_1) + \bar{t}(k_2), \quad (2.1)$$

where the momenta are defined in the photon-photon CM frame. We consider only unpolarized photon beams. The initial state of (2.1) then forms a CP eigenstate. The process may be described by the density matrix:

$$R_{\alpha\alpha',\beta\beta'}(p, k) = \sum' \langle t(k_1, \alpha')\bar{t}(k_2, \beta')|T|\gamma(p_1)\gamma(p_2)\rangle^* \langle t(k_1, \alpha)\bar{t}(k_2, \beta)|T|\gamma(p_1)\gamma(p_2)\rangle \quad (2.2)$$

where the $\sum'$ denotes averaging over the $\gamma\gamma$ polarizations, $\alpha, \alpha', \beta, \beta'$ are spin indices, and $p = p_1, k = k_1$. Note that $R$ is an even function of the three-momentum $p$ due to Bose symmetry of the two-photon state. The squared matrix element for the process $\gamma\gamma \rightarrow t\bar{t} \rightarrow X$ is then given, in the narrow-width approximation for the $t$ quark, by $\text{tr}(R_{\rho t}\rho\bar{t})$, where $\rho_t$ and $\rho\bar{t}$ are the decay density matrices for polarized $t$ and $\bar{t}$ decay, respectively.

The general structure of CP-violating contributions to the production density matrix $R$ can be determined easily. For unpolarized photons one finds that CP-violating dispersive contributions must be of the form [9,12]

$$\hat{k} \cdot (s_+ \times s_-)h_e(y),$$
$$\hat{p} \cdot (s_+ \times s_-)h_o(y), \quad (2.3)$$

where $s_+, s_-$ are the spin operators of $t$ and $\bar{t}$, respectively, and $h_e(y), h_o(y)$ are even and odd functions of the cosine of the scattering angle, $y = \hat{p} \cdot \hat{k}$. Note that QCD- or QED-induced absorptive parts of the scattering amplitude of the process (2.1) cannot induce $t\bar{t}$ spin-spin correlations: they generate a polarization of $t$ and $\bar{t}$ normal to the scattering plane of the reaction (2.1) [9,26]. CP-violating absorptive contributions to $R$ are of the form

$$\hat{k} \cdot (s_+ - s_-)f_e(y),$$
$$\hat{p} \cdot (s_+ - s_-)f_o(y), \quad (2.4)$$

where $f_e$ and $f_o$ are even and odd functions of $y$, respectively.

We now discuss the salient features of neutral Higgs sector CP violation. For definiteness we consider two-doublet extensions of the SM with explicit CP violation in the Yukawa couplings (which leads to the Kobayashi-Maskawa phase) and in the Higgs potential [3,4,21,22]. As a consequence the three physical neutral Higgs boson states $\varphi_j, j = 1, 2, 3$ are in general states with indefinite CP
parity; i.e., they couple both to scalar and pseudoscalar quark and lepton currents with strength $a_j m_f / v$ and $\tilde{a}_j m_f / v$, respectively, where $m_f$ is the fermion mass and $v \simeq 246$ GeV. For the top quark we have

$$a_{jt} = d_{2j} / \sin \beta, \quad \tilde{a}_{jt} = -d_{3j} \cot \beta,$$

where $\tan \beta = v_2 / v_1$ is the ratio of the moduli of the vacuum expectation values of the two doublets, and $d_{2j}, d_{3j}$ are the matrix elements of a $3 \times 3$ orthogonal matrix which describes the mixing of the neutral Higgs states of definite CP parity. Only the CP=+1 components of the mass eigenstates $\varphi_j$ couple to the $W$ and charged Higgs bosons at the tree level. (For notation and details, see [4]).

CP violation requires that the neutral Higgs bosons are not mass-degenerate. In the following we assume that the masses of $\varphi_{2,3}$ are much larger than the mass of $\varphi_1$ and also larger than the photon-photon CM energy. Then the effect of $\varphi_{2,3}$ on the quantities discussed below is negligible.

The Born amplitude for the reaction (2.1) and the contributions from $\varphi$ exchange at one loop are depicted in Fig.1. (Note that there is no CP-violating contribution from the Kobayashi-Maskawa phase to this order in perturbation theory.) Figs.1b – 1e represent CP-violating contributions which are proportional to the coupling $a_{1t} \tilde{a}_{1t}$. A remark concerning Fig.1e is in order: the CP-violating $\varphi_j$ exchange contributions to the self energy of the top quark are of the form $\Sigma_{CP}(p^2) = m_t f(p^2) \gamma_5$. The function $f(p^2)$ is actually finite if one sums over all $\varphi_j$ and takes into account the orthogonality properties of the mixing matrix $d_{ij}$. For the sake of simplicity and in the spirit of the previous discussion, we keep only the contribution from $\varphi_1$. We use an on-shell definition of the top mass. This induces a counterterm with Lorentz structure $m_t f(m_t^2) \gamma_5$, which has to be taken into account in Fig.1e.

If the mass of $\varphi$ is close to the $\gamma \gamma$ CM energy, the contributions Fig.1f–1h become resonant. (Fig.1f represents four amplitudes: two CP-conserving ones with couplings $a_{1t}^2$ and $\tilde{a}_{1t}^2$, respectively, and two CP-violating ones with couplings $a_{1t} \tilde{a}_{1t}$. Likewise, Figs.1g,h represent two amplitudes where $\varphi$ couples to the scalar top current and two amplitudes with $\varphi$ coupling to the pseudoscalar current.) Even in the resonant case interference of these terms with the Born amplitude is non-negligible because of the finite width of $\varphi$ [9]. We compute this width in the two-doublet model by summing the partial widths for $\varphi \to W^+ W^-, ZZ, t \bar{t}$, assuming that the charged Higgs is heavy. (For definiteness we take in the following $m_{H^\pm} = 500$ GeV.)

The CP-conserving part of the density matrix (2.2) is determined from the squared Born amplitude Fig.1a, the interference of Fig.1a with the CP-even amplitudes of Fig.1f,g,h and the square of the sum of Figs.1f,g,h. The CP-odd part of $R$ results from the interference of the Born diagram with the CP-odd terms from Figs.1b – 1h and the interference of the CP-even and -odd amplitudes of
Figs. 1f – 1h. For Higgs boson masses of the order of 100 GeV or larger neutral Higgs sector CP violation is so far not very stringently constrained by low-energy phenomenology, which includes the experimental upper bounds on the electric dipole moments of the electron and neutron. Below and in the next section we evaluate CP-asymmetries for the following set of parameters:

\[
d_{i1} = \frac{1}{\sqrt{3}}, \quad i = 1, 2, 3; \quad \tan \beta = 0.5
\]  

(2.6)

and

\[
d_{i1} = \frac{1}{\sqrt{3}}, \quad i = 1, 2, 3; \quad \tan \beta = 1.0
\]  

(2.7)

(Values of \(\tan \beta\) as small as 0.5 can be accommodated by phenomenology [27].) Set (2.6) is used to exhibit the maximal order of magnitude of the asymmetries below within the two-doublet models.

For illustrative purposes we have plotted in Figs. 2, 3 two basic CP-odd correlations at the parton level, using the above parameter set (2.7), \(m_t = 175\) GeV, and \(m_\phi = 400\) GeV. (The correlations are normalized such that \(1 \rangle = 1\.) Figs. 2, 3 show the longitudinal polarization asymmetry \(\langle \hat{k} \cdot (s_+ - s_-) \rangle\) and the spin-spin correlation \(\langle \hat{k} \cdot (s_+ \times s_-) \rangle\), respectively, as a function of the photon-photon CM energy \(\sqrt{s_{\gamma\gamma}}\). The spin-spin correlation is largest slightly below \(\sqrt{s_{\gamma\gamma}} = m_\phi\), but then changes sign due to the interference of the various amplitudes. Only in the unrealistic limit \(\Gamma_\phi/m_\phi \rightarrow 0\) the naive Born level result mentioned in Sect. 1 would be recovered [9]. For \(\tan \beta = 0.5\) the correlations shown in Figs. 2, 3 increase roughly by a factor of two.

3. CP asymmetries for semileptonic \(t\bar{t}\) decays

In this section we evaluate a few asymmetries which efficiently trace the “basic” CP-odd quantities (2.3) and (2.4) in the final states into which \(t\) and \(\bar{t}\) decay. We define a sample \(A\) as consisting of \(t\bar{t}\) pairs where the \(t\) decays semileptonically and the \(\bar{t}\) decays hadronically:

\[
t \rightarrow \ell^+ + \nu_\ell + b \\
\bar{t} \rightarrow W^- + \bar{b} \rightarrow q + \bar{q'} + \bar{b},
\]  

(3.1)

The sample \(B\) is defined by the charge conjugated decay channels of the \(t\bar{t}\) pairs with respect to sample \(A\).

We concentrate here on the above decay modes, since they are especially suited for our CP studies: In each event we have one lepton which is known to be a good analyser of the top spin \(^\dagger\), and in the same event we may reconstruct the momentum of the other top quark from its hadronic decay products. Note that in the \(e^+e^-\) (or \(e^-e^-\)) laboratory system, the top quark pairs are in

\(^\dagger\) We use the distributions for the decays of polarized \(t \rightarrow \ell, t \rightarrow W, \ldots\) in the form as given in [28,29].
general not produced back to back, since the backscattered photons carry different energy fractions which cannot be determined event by event. Thus only the rest system of one of the top quarks may be reconstructed unambiguously in each of the above samples. Purely hadronic decays which would allow in principle for a reconstruction of both top and antitop momenta might also be considered. Because flavour-tagging for \( W \rightarrow q\bar{q}' \) is probably inefficient, the reconstructed directions of flight of the \( W^+(W^-) \) must then act as analysers of the \( t(\bar{t}) \) spin. However, they have a lower analyser quality than the charged lepton. The channels where both \( t \) and \( \bar{t} \) decay semileptonically could also be used for CP studies. However, apart from having a smaller branching ratio the momentum (direction) of the top cannot be reconstructed for these modes. This leads, generally speaking, to a decrease in sensitivity to the effects which we are after.

Therefore we confine ourselves to the event samples \( A \) and \( B \). First we consider the observables:

\[
O_1 = (q_{L+}^T \times q_{W-}^T) \cdot \hat{k}_{L+}^T \quad \text{for sample } A, \\
\bar{O}_1 = (q_{L-}^T \times q_{W+}^T) \cdot \hat{k}_{L-}^T \quad \text{for sample } B.
\]  

(3.2)

Here, the upper index “\( L \)” refers to the overall laboratory system and the asterisk denotes the \( \bar{t}(t) \) rest system. A CP-odd “asymmetry” may be defined through the sum

\[
A_1 = \langle O_1 \rangle_A + \langle \bar{O}_1 \rangle_B. 
\]  

(3.3)

\( A_1 \) traces the CP-odd spin-spin correlations defined in (2.3).

We also define, for the same samples, the observables

\[
O_2 = E_{L+}^{L+}, \\
\bar{O}_2 = E_{L-}^{L-}, \\
O_3 = q_{L+}^T \cdot \hat{k}_{L+}^T, \\
\bar{O}_3 = q_{L-}^T \cdot \hat{k}_{L-}^T
\]  

(3.4)

(3.5)

and the CP asymmetries

\[
A_2 = \langle O_2 \rangle_A - \langle \bar{O}_2 \rangle_B, 
\]  

(3.6)

\[
A_3 = \langle O_3 \rangle_A - \langle \bar{O}_3 \rangle_B. 
\]  

(3.7)

The quantities (3.6) and (3.7) probe CP violation generated by the asymmetries in the \( t \) and \( \bar{t} \) polarizations in the production plane (2.4).

To calculate the above correlations, we have to convolute the “partonic” differential cross section for \( \gamma\gamma \rightarrow t\bar{t} \) and \( t\bar{t} \rightarrow A \) or \( B \) with the distribution function for the backscattered laser photons.
We neglect the transverse momenta of the Compton photons, which is a very good approximation [18]. The differential distributions are of the form \( \text{tr}(R \rho_t \rho_{\bar{t}}) \), where the decay distributions \( \rho_t \) and \( \rho_{\bar{t}} \) are taken from [28,29]. We then obtain the asymmetries (3.3), (3.6), (3.7) as integrals over some elements of the density matrix \( R \) defined in (2.2). For example,

\[
A_2 = \frac{4}{3} \left( 1 + \frac{2}{2 + 4 \omega} \right) \int_0^{x_{\max}} dx_1 N(x_1) \int_0^{x_{\max}} dx_2 N(x_2) \int_{-1}^{1} dy \frac{\beta E}{16 \pi} \times \beta E \frac{x_1 + x_2}{2 \sqrt{x_1 x_2}} \left( y b_{1CP}^2 + b_{2CP}^2 \right).
\]

Here \( N(x) \) is the normalized distribution of photons with energy fraction \( x = E_\gamma/E_{\text{beam}} \), \( \omega = m_W^2/m_t^2 \), \( s \) denotes the squared \( e^+e^- \) CM energy, and \( \sigma_0 \) is the effective cross section for \( \gamma\gamma \rightarrow t\bar{t} \), i.e., the \( \gamma\gamma \rightarrow t\bar{t} \) cross section folded with the photon distribution functions. Further, \( E \) is the energy and \( \beta = \sqrt{1 - m_t^2/E^2} \) is the velocity of the top quark in the \( \gamma\gamma \) CM system. The distributions turn out to be essentially flat as functions of the cosine \( y \) of the scattering angle in the \( \gamma\gamma \) CM frame. Therefore we do not apply a cut in this variable. The functions \( b_{1,2}^CP \) are the CP-violating absorptive contributions to the density matrix \( R \).

For \( N(x) \) we take the leading order result, as given e.g. in [18,30]. The maximal energy fraction of a photon \( x_{\max} \) is determined by the laser energy,

\[
x_{\max} = \frac{z}{1 + z} \quad \text{with} \quad z = \frac{4 E_{\text{beam}} E_{\text{laser}}}{m_e^2}.
\]

We choose the laser energy \( E_{\text{laser}} \) for a given beam energy \( E_{\text{beam}} \) such that \( z \) reaches its maximal value, \( z_{\max} = 2(1 + \sqrt{2}) \), which is determined by the threshold of the undesirable production of \( e^+e^- \) pairs through annihilation of a backscattered photon with a laser photon. Thus we have \( x_{\max} \approx 0.8284 \).

Formulas analogous to (3.8) hold also for the other asymmetries. In order to estimate the statistical sensitivity of \( A_i \) \((i = 1, 2, 3)\), we have computed the ratios \( A_i/\Delta A_i \), where \( \Delta A_i \equiv \Delta O_i \approx \sqrt{\langle O_i^2 \rangle_A} \approx \sqrt{\langle O_i^2 \rangle_B} \). The corresponding signal-to-noise ratios \( S_i \) are given by

\[
S_i = \frac{|A_i|}{\Delta A_i} \times \sqrt{N_{\text{event}}}, \quad (3.10)
\]

where

\[
N_{\text{event}} = R_{A,B} \mathcal{L} \sigma_0 \quad (3.11)
\]

with the integrated luminosity \( \mathcal{L} \) of the Compton collider and the branching ratios \( R_{A,B} \) for the decay modes \( A, B \).
Figs. 4-6 show the three ratios $A_i/\Delta A_i$, $i = 1, 2, 3$ for different Higgs masses $m_\phi$ at a fixed $e^+e^-$ collider energy $\sqrt{s} = 500$ GeV. In each figure, the dashed line corresponds to the parameter set (2.6) and the full line to the parameter set (2.7). The asymmetries exhibit extrema when the Higgs mass is close to the $t\bar{t}$ threshold due to large interference effects, and additional extrema when the Higgs mass is close to the maximal $\gamma\gamma$ energy. Even for a Higgs with mass above the maximal $\gamma\gamma$ energy, there remains a significant interference effect that might be detectable.

For the most sensitive of our asymmetries, $A_3$, we also determined, for a given Higgs mass, the collider energy that maximizes the signal-to-noise ratio. The results are listed in Table 1 for the parameter set (2.7). In brackets we also give the numbers for set (2.6). We use only semileptonic top decays into electrons and muons, i.e., $R_{A,B} = 4/27$. For example, at $m_\phi = 400$ GeV, one gets the largest sensitivity for a collider energy of 490 GeV. For an integrated luminosity of 100 fb$^{-1}$ we then find a statistical significance $S_3$ of 3.1(4.9). This indicates the exciting possibility of probing Higgs sector CP-violation.

4. Conclusions

A high luminosity “Compton collider” would offer an interesting opportunity to study in detail the neutral Higgs sector and in particular CP violation beyond the Kobayashi-Maskawa mechanism which is possible in multi-Higgs extensions of the standard model. In this paper we have computed for two-doublet models the complete CP-violating contributions to unpolarized $\gamma\gamma \rightarrow t\bar{t}$ in one-loop approximation. The dispersive contributions give rise to CP odd spin-spin correlations which can reach values of the order of ten percent. Longitudinal polarization asymmetries of similar magnitude are induced by CP-violating absorptive contributions. We have further proposed and calculated three CP asymmetries for semileptonic $t\bar{t}$ decays which efficiently trace the CP odd effects considered. We find that for quite a broad window of Higgs masses, a high luminosity Compton collider operating at an $e^+e^-$ CM energy of $\sqrt{s} = 500 - 600$ GeV would allow for the possibility to probe CP-violating effects from an extended Higgs sector.

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References

[1] A.G. Cohen, D.B. Kaplan, and A.E. Nelson, Ann. Rev. Nucl. Part. Sci. 43 (1993) 27.
[2] T.D. Lee, Phys. Rev. D8 (1973); J. Liu and L. Wolfenstein, Nucl. Phys. B289 (1987) 1; G.C. Branco and M.N. Rebelo, Phys. Lett. B160 (1985) 117.
[3] S. Weinberg, Phys. Rev. D42 (1990) 860.
[4] W. Bernreuther, T. Schröder, and T.N. Pham, Phys. Lett. B279 (1992) 389.
[5] B. Grzadkowski and J. Gunion, Phys. Lett. B289 (1992) 440.
[6] C.R. Schmidt and M.E. Peskin, Phys. Rev. Lett. 69 (1992) 410.
[7] D. Atwood and A. Soni, Phys. Rev. D45 (1992) 2405; S. Bar-Shalom et al. SLAC preprint SLAC-PUB-6765 (1995).
[8] B. Grzadkowski and J. Gunion, Phys. Lett. B294 (1992) 361.
[9] W. Bernreuther and A. Brandenburg, Phys. Lett. B314 (1993) 104.
[10] D. Chang and W.-Y. Keung, Phys. Lett. B305 (1993) 261.
[11] D. Chang, W.-Y. Keung, and I. Phillips, Phys. Rev. D48 (1993) 3225.
[12] W. Bernreuther and A. Brandenburg, Phys. Rev. D49 (1994) 4481.
[13] W. Bernreuther and P. Overmann, Z. Phys. C61 (1994) 599.
[14] A. Pilaftsis and M. Nowakowski, Int. J. Mod. Phys. A9 (1994) 1097; ibid. A9 (1994) 5849 (E).
[15] X.G. He, J.P. Ma, and B.H.J. McKellar, Mod. Phys. Lett. A9 (1994) 205; Phys. Rev. D49 (1994) 4548.
[16] B. Grzadkowski, Phys. Lett. B338 (1994) 71.
[17] J.P. Ma and B.H.J. McKellar, Melbourne preprint UM-P-94/50 (1994).
[18] I.F. Ginzburg et al., Nucl. Instrum. Meth. 205 (1983) 47; ibid. 219 (1984) 5; V.I. Telnov, Nucl. Instrum. Meth. 294 (1990) 72.
[19] $e^+e^- \text{ Collisions at 500 GeV: The Physics Potential}$, ed. by P.M. Zerwas, DESY publication DESY 92-123A,B, Hamburg 1992, DESY 93-123C (1993); Physics and Experiments with Linear Colliders, ed. by R. Orava, P. Eerola, and M. Nordberg (World Scientific, Singapore), Vols. I, II (1992).
[20] M. Krümer, J. Kühn, M. Stong, and P. Zerwas, Z. Phys. C64 (1994) 21.
[21] A. Mendez and A. Pomarol; Phys. Lett. B272 (1991) 313.
[22] C.D. Froggatt, R.G. Moorehouse, and I.G. Knowles, Nucl. Phys. B386 (1992) 63.
[23] A. Skjold and P. Osland, Phys. Lett. B329 (1994) 305.
[24] T. Arens, U.D.J. Giesler, and L.M. Sehgal, Phys. Lett. B339 (1994) 127.
[25] T. Arens and L.M. Sehgal, Aachen preprint PITHA-94-37 (1994).
[26] W. Bernreuther, J.P. Ma, and B.H.J. McKellar, Phys. Rev. D51 (1995) 2475.
[27] F. Cornet, W. Hollik, and W. Mösle, Nucl. Phys. **B428** (1994) 61.

[28] W. Bernreuther, O. Nachtmann, P. Overmann, T. Schröder, Nucl. Phys. **B388** (1992) 53; ibid. **B406** (1993) 516 (E).

[29] J.P. Ma, A. Brandenburg, Z. Phys. **C56** (1992) 97.

[30] J.H. Kühn, E. Mirkes, and J. Steegborn, Z. Phys. **C57** (1993) 615.
Figure Captions

Figure 1: Feynman diagrams for $\gamma\gamma \rightarrow t\bar{t}$. In (a) the Born diagram is shown, (b) to (h) depict the relevant one-loop $\varphi$ exchange diagrams. In (g) and (h), we show the contributions due to $W$ boson, charged Higgs $H$, Goldstone boson $G$ and ghost $\eta$ propagation around the loop. Diagrams with crossed photon lines are not shown.

Figure 2: Longitudinal polarization asymmetry $\langle \hat{k} \cdot (s_+ - s_-) \rangle$ as a function of the photon-photon CM energy for $m_\varphi = 400$ GeV, $m_t = 175$ GeV and parameter set (2.7).

Figure 3: Spin-spin correlation $\langle \hat{k} \cdot (s_+ \times s_-) \rangle$ as a function of the photon-photon CM energy for the same choice of parameters as in Fig. 2.

Figure 4: The quantity $A_1/\Delta A_1$ for different Higgs masses $m_\varphi$ at $\sqrt{s} = 500$ GeV. The dashed line corresponds to parameter set (2.6), the full line to parameter set (2.7).

Figure 5: Same as Fig.4, but for $A_2/\Delta A_2$.

Figure 6: Same as Fig.4, but for $A_3/\Delta A_3$. 
Table Caption

Table 1: Optimal collider energies $\sqrt{s_{\text{opt}}}$, number of events $N_{\text{event}}$ for samples $A, B$ (cf. 3.1) and statistical significance $S_3$ of the asymmetry $A_3$ for some Higgs masses $m_\phi$. In computing $N_{\text{event}}$ and $S_3$ only semileptonic $t$ decays into $e$ and $\mu$ are taken into account; i.e., we take $R_{A,B} = 4/27$. To obtain the optimal collider energy, the parameter set (2.7) is used. The numbers for parameter set (2.6) at the same energies are given in brackets.
Table 1

| $m_{\phi}$ [GeV] | $\sqrt{s_{\text{opt}}}$ [GeV] | $N_{\text{event}} / (\mathcal{L} / (100 \text{ fb}^{-1}))$ | $S_3 / \sqrt{\mathcal{L} / (100 \text{ fb}^{-1})}$ |
|------------------|------------------|---------------------------------|---------------------------------|
| 100              | 690              | 4.46(4.28) $\times 10^3$        | 1.2(2.8)                        |
| 150              | 690              | 4.46(4.27) $\times 10^3$        | 1.2(2.8)                        |
| 200              | 690              | 4.44(4.24) $\times 10^3$        | 1.2(3.0)                        |
| 250              | 670              | 4.15(3.88) $\times 10^3$        | 1.4(3.3)                        |
| 300              | 630              | 3.42(3.13) $\times 10^3$        | 1.7(4.2)                        |
| 325              | 590              | 2.64(2.31) $\times 10^3$        | 2.1(5.2)                        |
| 350              | 540              | 1.60(1.42) $\times 10^3$        | 3.0(7.3)                        |
| 375              | 620              | 3.27(3.17) $\times 10^3$        | 2.7(5.9)                        |
| 400              | 490              | 0.88(1.11) $\times 10^3$        | 3.1(4.9)                        |
| 425              | 520              | 1.48(1.70) $\times 10^3$        | 3.1(5.1)                        |
| 450              | 550              | 2.13(2.31) $\times 10^3$        | 2.8(4.7)                        |
| 475              | 580              | 2.74(2.92) $\times 10^3$        | 2.6(4.2)                        |
| 500              | 610              | 3.32(3.44) $\times 10^3$        | 2.3(3.8)                        |
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