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Probing the CP of the Higgs at a $\gamma\gamma$ collider using $\gamma\gamma \to t\bar{t} \to lX$. [1]

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ABSTRACT

We present results of an investigation to study CP violation in the Higgs sector in $t\bar{t}$ production at a $\gamma\gamma$-collider. This is done in a model independent way in terms of six form-factors $\{\Re(S_\gamma), \Im(S_\gamma), \Re(P_\gamma), \Im(P_\gamma), S_t, P_t\}$ which parameterize the CP mixing in Higgs sector. The angular distribution of the decay lepton from $t/\bar{t}$ is shown to be independent of any CP violation in the tbW vertex. Hence it can be used as a diagnostic of the CP mixing. We study how well one can probe different combinations of the form factors by measurements of the combined asymmetries that we construct, in the initial state lepton (photon) polarization and the final state lepton charge, using only circularly polarized photons. We show that the method can be sensitive to loop-induced CP violation in the Higgs sector in the MSSM.

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Abstract

We present results of an investigation to study CP violation in the Higgs sector in $t\bar{t}$ production at a $\gamma\gamma$-collider. This is done in a model independent way in terms of six form-factors $\{\Re(S_\gamma), \Im(S_\gamma), \Re(P_\gamma), \Im(P_\gamma), S_t, P_t\}$ which parameterize the CP mixing in Higgs sector. The angular distribution of the decay lepton from $t/\bar{t}$ is shown to be independent of any CP violation in the tbW vertex. Hence it can be used as a diagnostic of the CP mixing. We study how well one can probe different combinations of the form factors by measurements of the combined asymmetries that we construct, in the initial state lepton (photon) polarization and the final state lepton charge, using only circularly polarized photons. We show that the method can be sensitive to loop-induced CP violation in the Higgs sector in the MSSM.

1 Introduction

While the standard model (SM) has been proved to provide the correct description of fundamental particles and their interactions, direct experimental verification of

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the Higgs sector and a basic understanding of the mechanism for the generation of the observed CP violation is still lacking. Many models with an extended Higgs sector have CP violation in the Higgs sector. In this context there are then two important questions that need to be answered viz., if CP is conserved in the Higgs sector, how well can the CP transformation properties of the, possibly more than one, neutral Higgses be established and if it is violated how is this reflected in Higgs mixing and the couplings. The CP violation in the Higgs sector can be either explicit, spontaneous or loop-induced. The last has been studied in the context of the minimal Supersymmetric Standard Model (MSSM) in great detail recently and arises from loops containing sparticles and nonzero phases of the MSSM parameters μ and A_t.

$\gamma\gamma$ colliders are shown to make possible an accurate determination of the $\gamma\gamma$ width of the Higgs and allow possibilities of search for the H/A of the MSSM at points in parameter space not accessible to LHC. More importantly they provide unique opportunity of determination of CP properties of Higgs using polarized photon beams by studying the dependence of the cross-section on the initial beam polarization [1] as well as the polarization of the $t/\bar{t}$ produced in the final state [2, 3] in the Higgs decay. The last has been studied in a model independent way. In this talk we present results of our studies [4] of the $\gamma\gamma \to \phi \to t\bar{t}$ production followed by decay of the polarized t and develop a strategy to determine the CP properties of the ϕ couplings, by probing the t polarization through the decay l distributions, for which analytical expressions were obtained. Since the top decays rapidly enough the angular distributions of the lepton coming from the top decay can provide a good probe of the initial top polarization and has been shown to work effectively in the analysis of top dipole moment [5] and CP-violating $\gamma\gamma Z$ coupling [6].

2 Formalism and Decay l angular distribution

We perform our calculations in a model independent way. We parametrise the vertices $\mathcal{V}_{t\bar{t}\phi}, \mathcal{V}_{\gamma\gamma\phi}$ of the scalar ϕ with a $t\bar{t}$ and $\gamma\gamma$ pair, in a manner similar to Ref. [2] as

$$\mathcal{V}_{t\bar{t}\phi} = -ie\frac{m_t}{M_W}\left(S_t + i\gamma^5 P_t\right) \tag{1}$$

and

$$\mathcal{V}_{\gamma\gamma\phi} = \frac{-i\sqrt{s}\alpha}{4\pi}\left[S_\gamma(s)\left(\epsilon_1.\epsilon_2 - \frac{2}{s}(\epsilon_1.k_2)(\epsilon_2.k_1)\right) - P_\gamma(s)\frac{2}{s}\epsilon_{\mu\nu\alpha\beta}\epsilon_1^\mu\epsilon_2^\nu k_1^\alpha k_2^\beta\right]. \tag{2}$$

k_1 and k_2 are the four-momenta of colliding photons and $\epsilon_{1,2}$ are photon polarization vectors. S_t, P_t can be real constants without loss of generality whereas S_γ, P_γ are complex form factors. Simultaneous presence of P_t and S_t and/or S_γ and P_γ implies CP violation. For the tbW vertex also we choose the completely general form

$$\Gamma^\mu_{tbW} = -\frac{g}{\sqrt{2}} V_{tb} \left[\gamma^\mu \left(f_{1L} P_L + f_{1R} P_R\right) - \frac{i}{M_W} \sigma^{\mu\nu} (p_t - p_b)_\nu \left(f_{2L} P_L + f_{2R} P_R\right)\right] \quad (3)$$

and similarly for the vertex for $\bar{t}$. In the limit of vanishing b masses, and taking f_{1L} to have the SM value 1, the only nonstandard part of this vertex which gives non-vanishing contribution, is f_{2R}, and similarly $\bar{f}_{2L}$ for the vertex of $\bar{t}$ *viz.* $\bar{\Gamma}^\mu_{tbW}$. For the general $\phi t\bar{t}, \phi\gamma\gamma$ and tbW vertex given above we use the helicity amplitudes to calculate the analytical expression for differential cross-section for $\gamma\gamma \to t\bar{t} \to l^+ b \nu_l \bar{t}$ and hence for the angular distribution of the decay lepton, keeping only the linear terms in $f_{2R}, \bar{f}_{2L}$.

The differential cross-section is given by a matrix product of the production and decay density matrices, integrated over an appropriate phase space. The production and the decay density matrices $\rho^+(\lambda, \lambda'), \Gamma(\lambda, \lambda')$ in the $\gamma\gamma$ c.m. frame and in the t rest frame respectively are given by,

$$\rho^+(\lambda, \lambda') = e^4 \rho'^+(\lambda, \lambda') = \sum \rho_1(\lambda_1, \lambda_1') \rho_2(\lambda_2, \lambda_2') \mathcal{M}(\lambda_1, \lambda_2, \lambda, \lambda_{\bar{t}}) \mathcal{M}^*(\lambda_1', \lambda_2', \lambda', \lambda_{\bar{t}})$$

$$\Gamma(\lambda, \lambda') = g^4 |\Delta(p_W^2)|^2 \; \Gamma'(\lambda, \lambda') = \frac{1}{2\pi} \int d\alpha \sum M_\Gamma(\lambda, \lambda_b, \lambda_{l^+}, \lambda_\nu) \; M^*_\Gamma(\lambda', \lambda_b, \lambda_{l^+}, \lambda_\nu). \quad (4)$$

Here $M_\Gamma, \mathcal{M}$ are the decay and production matrix elements, $\alpha :$ azimuthal angle of b-quark in the rest-frame of t-quark with z-axis pointing in the direction of momentum of lepton and $\rho_{1(2)}$ are the photon density matrices.

The decay l angular distribution can be obtained analytically by integrating the equation for the differential cross-section over $E_l, \cos\theta_t$ and ϕ_l. It can be shown that the effect of the anomalous tbW coupling on l angular distribution, is only an overall factor $1 + 2r - 6\Re(f^\pm)\sqrt{r}$ *independent* of any kinematical variables. The total width of t-quark calculated up-to linear order in the anomalous vertex factors receives the *same* factor. Thus to linear approximation in anomalous tbW couplings the angular distribution of the decay lepton unaltered. Hence this is an observable for which the only source of the CP-violating asymmetry will be the production process[7, 4].

The cross-section $\sigma(\gamma\gamma \to t\bar{t} \to lX)$, depends on the relative polarizations of the two γ's since the ϕ exchange diagram contributes only when both colliding photons have same helicity. Further, the $\gamma\gamma$ collider will be constructed using laser backscattered photons and hence the polarization/energy spectrum of γ depends on laser photon and beam lepton (e^+/e^-) helicities. One has to choose $\lambda_e \lambda_l = -1$ to get a hard photon spectrum, and set $\lambda_{e^-} = \lambda_{e^+}$ to maximize the sensitivity to possible CP-violating interactions coming from the Higgs coupling. For this choice the initial state polarization is completely specified by giving the helicity of (say) the e^-. In the final state one can look either for an l^+ or l^-. Hence, we have four possible polarized cross-sections: $\sigma(+,+)$, $\sigma(+,-)$, $\sigma(-,+)$, $\sigma(-,-)$, where the first index denotes the helicity of the e^- and second the charge of the lepton. We wish to construct asymmetries which will be sensitive to a CP-violating ϕ coupling.

3 Asymmetries of σ w.r.t. initial γ polarization and final l charge.

Using these four available cross-section we can now define six asymmetries w.r.t. the initial e^- polarization and final l charge as,

$$\mathcal{A}_1 = \frac{\sigma(+,+) - \sigma(-,-)}{\sigma(+,+) + \sigma(-,-)}, \mathcal{A}_2 = \frac{\sigma(+,-) - \sigma(-,+)}{\sigma(+,-) + \sigma(-,+)}, \mathcal{A}_3 = \frac{\sigma(+,+) - \sigma(-,+)}{\sigma(+,+) + \sigma(-,+)}$$
$$\mathcal{A}_4 = \frac{\sigma(+,-) - \sigma(-,-)}{\sigma(+,-) + \sigma(-,-)}, \mathcal{A}_5 = \frac{\sigma(+,+) - \sigma(+,-)}{\sigma(+,+) + \sigma(+,-)}, \mathcal{A}_6 = \frac{\sigma(-,+) - \sigma(-,-)}{\sigma(-,+) + \sigma(-,-)}. \quad (5)$$

Due to the different angular dependence of the different contributions, the σ' s are calculated with a cut off on the lepton angle θ_0, to be optimized to increase sensitivity to CP-violating couplings. Out of the six asymmetries, $\mathcal{A}_1$ and $\mathcal{A}_2$ are purely CP-violating. $\mathcal{A}_3$ and $\mathcal{A}_4$ are polarization asymmetries for a given lepton charge. $\mathcal{A}_5$ and $\mathcal{A}_6$ are charge asymmetries for a given polarization which will be zero if $\theta_0 \to 0$. Further, only three of these asymmetries are linearly independent of each other.

To study these further we choose a specific prediction in the MSSM [3] for $\tan\beta = 3$, with all sparticles heavy and maximal phase. The values we choose are: $m_\phi = 500GeV, \Gamma_\phi = 1.9GeV, S_t = 0.33, P_t = 0.15, S_\gamma = -1.3 - 1.2i, P_\gamma = -0.51 + 1.1i$. We choose beam energy $E_b = 310$ GeV for this choice of the Higgs mass and the photon spectra, to maximize the asymmetries. The asymmetries can be as high as 9% for (say) $\mathcal{A}_4$. Even the CP-violating asymmetries can be as high as 3–4%. The CP properties of the Higgs can be determined if one knows all the *six* form-factors $S_t, P_t, \Re(S_\gamma), \Im(S_\gamma), \Re(P_\gamma), \Im(P_\gamma)$. These appear in the production density matrix in eight combinations: the CP-even x_i and CP-odd y_i, $(i = 1, ...4)$ given by $S_t\Re(S_\gamma), S_t\Im(S_\gamma), P_t\Re(P_\gamma), P_t\Im(P_\gamma)$ and $S_t\Re(P_\gamma), S_t\Im(P_\gamma), P_t\Re(S_\gamma), P_t\Im(S_\gamma)$ respectively. The above mentioned asymmetries are functions of x's and y's and thus can be used to extract information on these combinations.

Asymmetries are constructed from the measured cross-sections as,

$$\mathcal{A} = \frac{\sigma_1 - \sigma_2}{\sigma_1 + \sigma_2} = \frac{\Delta\sigma}{\sigma}. \tag{6}$$

The number of events corresponding to the asymmetry are $\mathcal{L}\Delta\sigma$. For the asymmetry to be measurable at all we must have at least $\mathcal{L}\Delta\sigma > f\sqrt{\mathcal{L}\sigma}$, where $f = 1.96$ for 95% c.l. Thus $\frac{\mathcal{L}\Delta\sigma}{f\sqrt{\mathcal{L}\sigma}} = \frac{\sqrt{\mathcal{L}}}{f} \times \frac{\Delta\sigma}{\sqrt{\sigma}}$ can be taken as a measure of the sensitivity. To be more precise, one can compare numerical value for a given asymmetry $\mathcal{A}$ with the expected fluctuation in its value at a given level of confidence, viz., $\frac{\mathcal{A}}{\delta\mathcal{A}} \propto \frac{\Delta\sigma}{\sqrt{\sigma}}$.

With this definition of sensitivity we then look for suitable angular cut in the lab frame which will maximize the sensitivity of the measurement. For $\mathcal{A}_5, \mathcal{A}_6$ the optimal choice of the cut off angle s around $60°$, whereas for the purely CP-violating asymmetries $\mathcal{A}_1, \mathcal{A}_2$ it is $0°$. In view of the experimental cut off at small angles to the beam direction, we choose two different values of angular cuts; $20°$ and $60°$. If for certain values of the form-factors the predicted asymmetries lie within the fluctuation from the values expected in the SM, then it means that this particular set of values for the form factors cannot be distinguished from those in the SM at the luminosity we consider. We then say that this point falls in the blind region of the parameter space. In this region the hypothesis that the actual values of the couplings are different from the SM expectation cannot be tested.

Thus the set of parameters x_i, y_i are said to be inside the blind region at a given luminosity if

$$|\mathcal{A}(\{x_i, y_i\}) - \mathcal{A}_{SM}| \le \delta\mathcal{A}_{SM} = \frac{f}{\sqrt{\sigma_{SM}\mathcal{L}}}\sqrt{1 + \mathcal{A}_{SM}^2}.$$

We took two of the eight possible combinations to be non-zero at a time and studied how well these can be constrained.

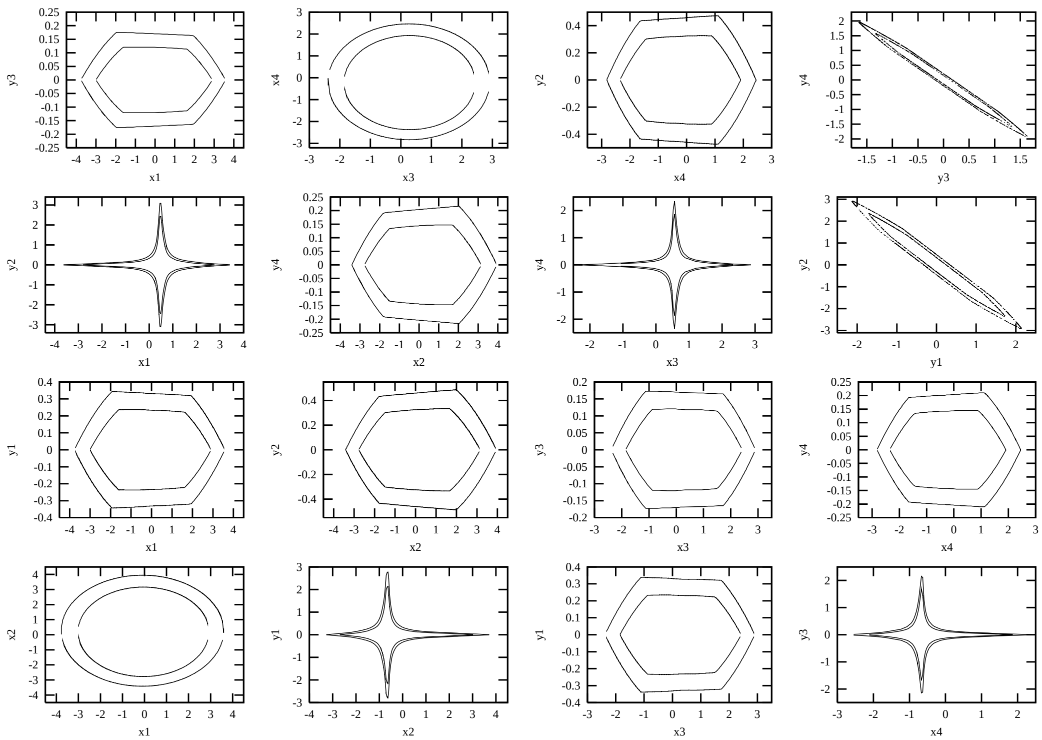

Figure 1: The boundaries of blind regions for various pairs of parameters. Details given in the text

4 How can the asymmetries be used?

Figure 2 shows the boundaries of the blind region as defined above, for various x_i, y_j pairs, for luminosity values of 500 and 1000 fb^{-1}, with beam energy $E_b = 310$ GeV. Both angular cuts, $\theta_0 = 20^\circ$ and 60°, are used to put limits at C.L. of 95%. The larger region corresponds to 500 fb^{-1}, while the smaller corresponds to 1000 fb^{-1}. We see that indeed the asymmetries can probe for nonzero values of the CP-violating parameters $y_j, j = 1, 4$. One may further ask the question whether it is possible to discriminate a particular point in the parameter space of the MSSM predictions against the SM as the correct theory. To be able to do that not only is it necessary that the particular values of x_i, y_j lie outside the blind region for the SM for the pair of parameters under consideration, but further there should be no overlap of this blind region with that around the values x_i^{mssm}, y_j^{mssm} expected for the MSSM point under consideration. The latter can be determined again the same way as that for the SM, using expected values of the asymmetries for the MSSM point. As

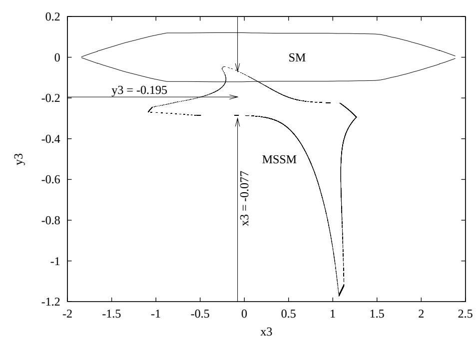

Figure 2: The boundaries of blind regions in the parameter space at 95% c.l. in the $x_3 - y_3$ plane, for a luminosity of 1000 fb^{-1} for $E_b = 310$ GeV. Both angular cuts, $\theta_0 = 20°$ and $60°$, are used for the MSSM point, $x_3 = -0.077,\ y_3 = -0.195$.

Figure 3 shows that one is indeed sensitive to the values of the parameters predicted in MSSM due to loop effects. Since in the analysis done above, we hold values of all the other parameters, other than the two being varied, at the values expected in the model (say the SM) one has to combine different results of Figure 2 to obtain the range to which the various parameters $x_i, y_j, i, j = 1, 4$ can be restricted at a given luminosity. The details of such an analysis are given elsewhere [4].

Since only three out of the possible six asymmetries are linearly independent and there are six independent form factors, it is clear that one needs additional information to extract all of them in a completely model independent way. It has been established [2] that at least *in principle* complete determination of the form factors using the polarization asymmetries of the final state $t/\bar{t}$ is possible if one uses linear polarisation of the γ along with the circular one. Our analysis above has studied the possible accuracy of the determination of these form factors using the combined asymmetries involving the initial lepton (and hence the photon) polarization and the decay lepton charge, for the case of circular polarization of the initial γ. It would be interesting to extend the analysis of the decay l asymmetries, using linearly polarized γ.

5 Summary

We have studied $\gamma\gamma \to \phi \to t\bar{t}$ where ϕ is a scalar which may or may not have definite CP parity. We looked at the process $\gamma\gamma \to t\bar{t} \to l^{\pm}X$, where l^+/l^- comes from decay of $t/\bar{t}$. CP-non-conserving vertices $\mathcal{V}_{\phi\gamma\gamma}, \mathcal{V}_{t\bar{t}\phi}$, can give rise to net polarization asymmetry for the t. The angular distribution for the decay l is used as an analyzer of t polarization and hence of CP violation in the Higgs sector. We have studied this in a model independent way using the $\mathcal{V}_{\phi\gamma\gamma}, \mathcal{V}_{t\bar{t}\phi}$ parametrised in terms of form factors. We first establish that the decay lepton angular distribution is insensitive to any anomalous part the tbW coupling $f^{\pm}$ to first order. We have further constructed combined asymmetries involving the initial lepton (and hence the photon) polarization and the decay lepton charge. These can put strong limits on CP-violating combinations of the form factors y's, when only two combinations are varied at a time. However, the use of only the circularly polarized photons is found to be inadequate for simultaneous determination or constraining of all the form-factors. The analysis thus needs to be extended to include linear polarization of the photons.

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