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Probing CP-violating Higgs contributions in $\gamma\gamma \to f\bar{f}$

ROHINI M GODBOLE[1], SABINE KRAML[2], SAURABH D RINDANI[3] and RITESH K SINGH[4,*]
[1]Center for High Energy Physics, Indian Institute of Science, Bangalore 560 012, India
[2]Theory Division, Department of Physics, CERN, Switzerland
[3]Physical Research Laboratory, Ahmedabad 380 009, India
[4]Laboratoire de Physique Théoretique, 91405 Orsay Cedex, France
*E-mail: ritesh.singh@th.u-psud.fr

Abstract. We discuss the use of fermion polarization for studying neutral Higgs bosons at a photon collider. To this aim we construct polarization asymmetries which can isolate the contribution of a Higgs boson ϕ in $\gamma\gamma \to f\bar{f}$, $f = \tau/t$, from that of the QED continuum. This can help in getting information on the $\gamma\gamma\phi$ coupling in case ϕ is a CP eigenstate. We also construct CP-violating asymmetries which can probe CP mixing in case ϕ has indeterminate CP. Furthermore, we take the MSSM with CP violation as an example to demonstrate the potential of these asymmetries in a numerical analysis. We find that these asymmetries are sensitive to the presence of a Higgs boson as well as its CP properties over a wide range of MSSM parameters.

Keywords. CP-violating Higgs; polarization; photon collider.

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At a photon collider, fermion-pair production proceeds through the standard QED t-channel as well as through s-channel Higgs mediation. The Higgs boson, ϕ, in general can be CP violating as the case in the MSSM with nonvanishing CP phases. The QED vertex $\gamma f\bar{f}$ conserves chirality, whereas the $\phi f\bar{f}$ coupling mixes different chiralities and hence it can affect, in principle, the polarization of the produced fermions. With unpolarized photons in the initial state, the QED contribution leads to unpolarized fermions in the final state. The same is true for the Higgs exchange should the Higgs boson(s) be a CP eigenstate; CP violation (CPV) in the Higgs sector leads to a net, though very small, polarization of the fermions, even with the unpolarized initial beams. With polarized initial-state photons, the QED contribution alone gives rise to a finite polarization. The additional chirality-mixing contribution from the Higgs boson exchange diagram causes a change in this polarization for both, the CP-conserving and the CP-violating, cases. It is thus possible to construct observables involving the polarizations of the initial-state

Table 1. Polarization observables, interactions and the form-factor combinations that they can probe.

Observable	Type of interaction	Combinations probed
P_f^U	P/CP violating	y_i's
$\delta P_f^+ = P_f^{++} - (P_f^{++})^{\rm QED}$	Chirality mixing	x_i's, y_i's
$\delta P_f^- = P_f^{--} - (P_f^{--})^{\rm QED}$	Chirality mixing	x_i's, y_i's
$\delta P_f^{\rm CP} = P_f^{++} + P_f^{--}$	P/CP violating	y_i's

photons and those of the final-state fermions (τ/t), which can probe the Higgs boson couplings, including possible CP violation in the Higgs sector.

The fermion polarization is defined as the fractional surplus of positive helicity fermions over negative helicity ones, $P_f^{ij} = (N_+^{ij} - N_-^{ij})/(N_+^{ij} + N_-^{ij})$, where the superscript ij stands for the polarizations of the parent e^+e^- beams $(P_e, P_{\bar{e}})$ of the ILC. N_+ and N_- stand for the number of fermions with positive and negative helicities, respectively. The polarization of anti-fermions, $\bar{P}_f^{ij}$, is defined analogously; conservation of linear and angular momenta implies $P_f^{ij} = \bar{P}_f^{ij}$.

We know that the chirality mixing amplitudes in pure QED are proportional to the fermion mass m_f. Hence these are small for light fermions. Further, the Higgs-exchange diagram contributes only when the helicities of the colliding photons are equal; at the same time the QED contribution can be suppressed by choosing $\lambda_1 = \lambda_2$. For the case of the polarized, peaked photon spectrum [1] this amounts to choosing $(P_e, P_{\bar{e}}) = (\pm, \pm)$ for the parent e^+/e^- beams.

The final-state fermion polarization with unpolarized initial state, P_f^U, is zero should the Higgs boson have a definite CP quantum number. Nonzero values of P_f^U only arise for $y_i \neq 0$, thus it is a signal of CP violation in the Higgs sector. For polarized initial states, the final-state fermion polarization is always nonzero. Regardless of whether CP is violated or not, any deviation of P_f^{++} and P_f^{--} from their QED predictions probes the Higgs boson contribution. Moreover, since P-invariance implies $P_f^{++} = -P_f^{--}$ for the QED contribution, $P_f^{++} + P_f^{--} \neq 0$ is a signal of CP violation. The polarization observables are summarized in table 1. Here note that $\delta P_f^{\rm CP} = \delta P_f^+ + \delta P_f^-$. In the following, we choose δP_f^- and $\delta P_f^{\rm CP}$ as the independent observables.

We demonstrate the utility of our polarization observables, by performing a numerical analysis for $\gamma\gamma \to \tau^+\tau^-$ and $\gamma\gamma \to t\bar{t}$ in the CPX scenario [2]. We vary $M_{H^\pm} = 150$–500 GeV and $\tan\beta = 3$–40 and consider different phases Φ_A. The Higgs boson masses, couplings and widths are computed with both CPsuperH [3] and FeynHiggs [4]. For the polarized photon beams, we use the ideal Compton-backscattered photon spectrum of [1]. The beam energy $E_{\rm b}$ for the parent e^+e^- collider is chosen such that the peak in the spectrum of the $\gamma\gamma$ invariant mass corresponds to the relevant Higgs boson mass(es). This choice explores the ultimate potential of the polarization observables; we call it the 'peak E_B' choice. In general, $P_f^U \neq 0$ would be a clear signal of CPV. However, P_f^U is found to be very small, well below experimental sensitivity. So we have to work with polarized beams and consider δP_f^- and $\delta P_f^{\rm CP}$.

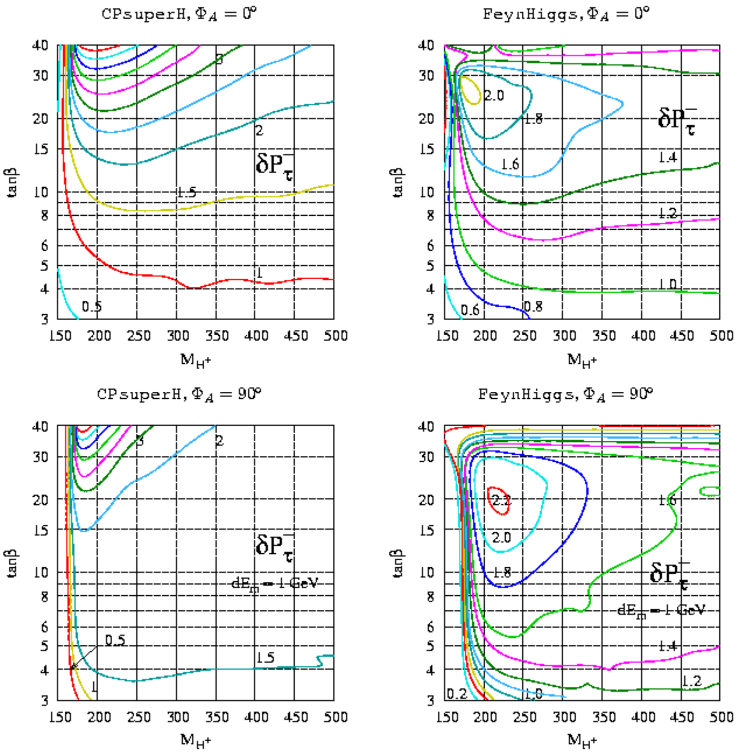

Figure 1. Contours of constant δP_τ^- in units of 10^{-2} in the $\tan\beta$–$M_{H^\pm}$ plane for the CPX scenario with $\Phi_A = 0°$ (top panel) and $\Phi_A = 90°$ (bottom panel) with dE_m = 1 GeV. The left panels show the results obtained with CPsuperH, the right panels those obtained with FeynHiggs.

Let us start with $f = \tau$. Due to the small τ mass, the contribution to the τ polarization from the Higgs boson exchange diagram is very small unless one puts a cut on the $\tau^+\tau^-$ invariant mass. We use a cut $|m_{\tau\tau} - M_{H_1}| \leq \max(\mathrm{d}E_m,\ 5\,\Gamma_{H_1})$ with dE_m = 1 GeV. In figure 1 we show δP_τ^- for both CPsuperH and FeynHiggs for zero and maximal phase Φ_A. The $e^\pm$ beam energy is chosen such that $\sqrt{s_{\gamma\gamma}}$ at the peak of the photon spectrum is equal to the mass of the lightest Higgs boson H_1. The deviation in the polarization due to the H_1 exchange is large for both $\Phi_A = 0$ and 90°. δP_τ^- increases with $\tan\beta$ because the τ Yukawa coupling increases. However, it turns out that $\delta P_\tau^+ \simeq \delta P_\tau^-$, so that $\delta P_\tau^{\mathrm{CP}} \simeq 0$ over all the $\tan\beta$–$M_{H^\pm}$ plane. The difference between CPsuperH and FeynHiggs in figure 1 can be traced to somewhat different predictions of the masses, couplings and decay widths as a result of the different approximations used in the two programs.

In the case of $t\bar{t}$ production, it is the heavier Higgs bosons $H_{2,3}$ which contribute. Since the masses of $H_{2,3}$ are in general close to each other, we choose the beam energy such that the mean value $(M_{H_2} + M_{H_3})/2$ matches with $\sqrt{s_{\gamma\gamma}}$ at the peak of the photon spectrum. We find that the top polarization is sensitive not only to the

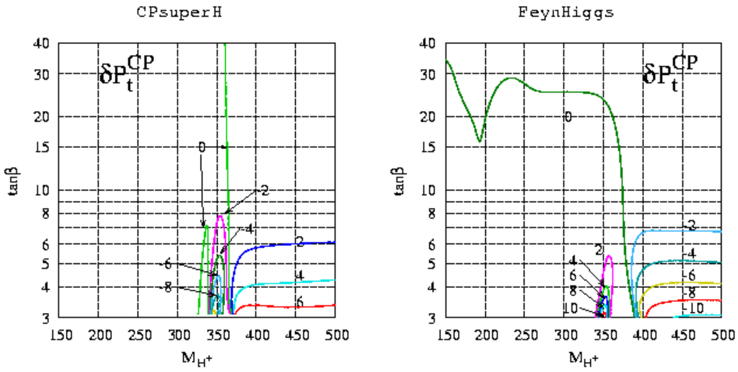

Figure 2. Contours of constant $\delta P_t^{\rm CP}$ in units of 10^{-2} in the $\tan\beta$–$M_{H^\pm}$ plane for the CPX scenario with $\Phi_A = 90°$. The left panel shows the results obtained with CPsuperH, the right panel those obtained with FeynHiggs.

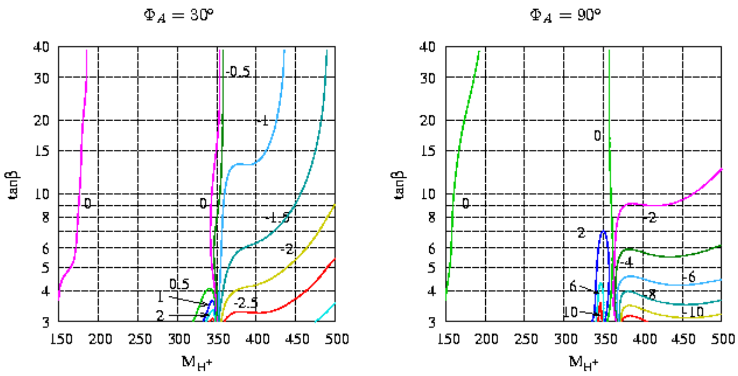

Figure 3. Contours of constant $\mathcal{A}_3$ for $\Phi_A = 30°$ and $90°$; computed with CPsuperH.

Higgs contribution in general ($\delta P_t^{\pm}$) but also to CP violation ($\delta P_t^{\rm CP}$). In figure 2 we show contours of constant $\delta P_t^{\rm CP}$ in the $\tan\beta$–$M_{H^\pm}$ plane for $\Phi_A = 90°$. Of course one needs $M_{H^\pm} \geq 2m_t$. Since the top Yukawa coupling decreases with $\tan\beta$, $\delta P_t^{\rm CP}$ is only sizable for small values of $\tan\beta$. Note that due to the large top-quark mass, no cut on the $t\bar{t}$ invariant mass is needed to increase the sensitivity. The difference in the sign of $\delta P_t^{\rm CP}$ in the two panels in figure 2 is due to different conventions in CPsuperH and FeynHiggs leading to the opposite signs of y_i, $i = 1, ..., 4$, for the same input MSSM parameters. Further, we also investigate the asymmetries defined at the level of leptons as constructed in ref. [5]. These are sensitive to the CP violation in the Higgs sector. We show the corresponding countours in figure 3 for $\Phi_A = 30°$ and $90°$. We see that the lepton asymmetry $\mathcal{A}_3$ is large and observable for small $\tan\beta$, large $m_{H^\pm}$, only for large enough CP phase Φ_A.

In summary, the polarization of heavy fermions is a good probe of the coupling of the Higgs boson including CP violation. We have analyzed this in the MSSM with CPV in the CPX scenario. We find that the polarization of τ-leptons may be used to probe the couplings of the lightest Higgs boson, especially in the large $\tan\beta$ region. The t-quark polarization, which is sensitive to the contribution of the two heavier Higgs bosons, can be used in the low $\tan\beta$ and large $M_{H^\pm}$ region of the MSSM parameter space.

References

[1] I F Ginzburg, G L Kotkin, S L Panfil, V G Serbo and Valery I Telnov, *Nucl. Instrum. Methods* **A219**, 5 (1984)
[2] M Carena, J R Ellis, A Pilaftsis and C E M Wagner, *Phys. Lett.* **B495**, 155 (2000)
[3] J S Lee *et al*, *Comput. Phys. Commun.* **156**, 283 (2004)
[4] S Heinemeyer, *Eur. Phys. J.* **C22**, 521 (2001)
[5] Rohini M Godbole, Saurabh D Rindani and Ritesh K Singh, *Phys. Rev.* **D67**, 095009 (2003)