Explicit CP violation in the MSSM Higgs sector

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Abstract

We analysed the sensitivity of the process $gg \to H_1 \to \gamma\gamma$ to the explicitly CP-violating phases $\phi_\mu$ and $\phi_A$ in the Minimal Supersymmetric Standard Model (MSSM) at the Large Hadron Collider (LHC), where $H_1$ is the lightest Supersymmetric Higgs boson. We conclude that depending on these phases, the overall production and decay rates of $H_1$ can vary up to orders of magnitude compared to the CP-conserving case.

Keywords: Supersymmetry, CP Violation, Higgs Production
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1 Introduction

In the MSSM, the Higgs potential conserves Charge & Parity (CP) at tree level \cite{1}. Beyond the latter, CP violation can manifest itself through complex Yukawa couplings of the Higgs bosons to (s)fermions. There are several new parameters in the SUSY theory that are absent in the SM, which could well be complex and thus possess CP-violating phases. However, the CP-violating phases associated with the sfermions of the first and, to a lesser extent, second

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generations are severely constrained by bounds on the Electric Dipole Moments (EDMs) of the electron, neutron and muon \[2\]–\[5\].

By building on the results of Refs. \[6, 7\] (for the production) and \[8]–\[11\] (for the decay), we recently examined the LHC phenomenology of the $gg \rightarrow H_1 \rightarrow \gamma\gamma$ process (where $H_1$ labels the lightest neutral Higgs state of the CP-violating MSSM), which involves the (leading) direct effects of CP violation through couplings of the $H_1$ to sparticles in the loops as well as the (subleading) indirect effects through scalar-pseudoscalar mixing yielding the CP-mixed state $H_1$. Here we summarize the results of \[12\] focusing especially on the effects of a light stop in the production of a cp-mixed $H_1$ by gluon fusion and its decay into two photons.

2 CP violation in the di-photon search channel

Explicit CP violation arises in the Higgs sector of the MSSM when various related couplings become complex. As a result, the physical Higgs bosons are no more CP eigenstates, but a mixture of them. CP-violating effects in the combined production and decay process enter through:

1. Complex $H_1$-$\tilde{f}$-$\tilde{f}^*$ couplings at production level.
2. Complex $H_1$-$\tilde{f}$-$\tilde{f}^*$ couplings at decay level.
3. Mixing in the propagator.

The leading contribution to Higgs production in gluon fusion is at the one loop level. Similarly the leading contribution to di-photon decay channel is also at one loop level, as shown in Fig. 1.

Figure 1: Leading order Feynman diagram for $gg \rightarrow H_1 \rightarrow \gamma\gamma$ including the effect of mixing in the propagator.

The propagator is considered in the following way. A CP-mixed Higgs particle, $H_i$, produced through gluon fusion, can be converted into another mass eigenstate, $H_j$, through loops of fermion or gauge boson (see Fig. 1). The lightest of the three $H_j$ states is taken to be $H_1$ here. This $H_1$ decays then through the di-photon channel. The propagator matrix is obtained from the self-energy of the Higgs particles computed at one-loop level, where we used the expressions provided by \[13\] which include off-diagonal absorptive parts. The matrix inversion required is done numerically using the Lapack \[14\] package. All the relevant couplings and masses are obtained from CPSuperH version 2 \[15\]. Cross section amplitude
of the full process shown in Fig. 1, and the parton level cross section itself are then computed numerically.

It was observed in [11] that the only significant contribution to the cross section is made by the phase of a light stop in the decay loops. Therefore, assuming a similar trend for the production mode also, we have considered a few sample parameter space points and studied the effect of CP violation, in particular the significance of a light stop in the loops, ignoring the effects of other sfermions, in order to illustrate the typical effects of CP-violation in the MSSM.

We fix the following MSSM parameters which do not play a role in CP violation studies:

\[ M_1 = 100 \text{ GeV}, \quad M_2 = M_3 = 1 \text{ TeV}, \quad M_{Q_3} = M_{D_3} = M_{L_3} = M_{E_3} = M_{\text{SUSY}} = 1 \text{ TeV}. \]

We consider the case of all the third generation tri-fermion couplings being unified into one single quantity, \( A_f \). All the soft masses are taken to be at some unification scale, whose representative value adopted here is 1 TeV. When considering the light stop case we take a comparatively light value for \( M_{U_3} \sim 250 \text{ GeV} \), which corresponds to a stop mass of around 200 GeV, otherwise \( M_{U_3} \) is set to 1 TeV. In the Higgs scalar-pseudoscalar coupling the product of \( \mu A_f \) and the sum of their phases is relevant rather than \( \mu \) or \( A_f \) separately. Hence, we have kept \( \phi_{A_f} = 0 \) and studied the effect of CP violation by varying \( \phi_\mu \) alone. In our numerical analysis we have varied these parameters between 1 TeV and 2 TeV. \( M_{H^+} \) is varied between 100 and 300 GeV. The mass of the lightest Higgs particle is then in the range of 100–130 GeV. It was noticed that only large \( \tan \beta \) case produce significant differences, so we take a representative value of \( \tan \beta = 20 \) to see the effect of the other parameters.

### 3 Results

In order to show the dependence on phase, we plotted a quantity \( \Delta \sigma / \sigma_0 \), with \( \Delta \sigma \) being the difference in the magnitude of cross section for \( \phi_\mu \) set to a given value and \( \phi_\mu = 0 \), and \( \sigma_0 \) being the cross section for \( \phi_\mu = 0 \), in Fig. 2 against \( M_{H^+} \). We have considered \( \mu = 1 \text{ TeV} \) and \( A_f = 1 \text{ TeV} \). Clearly, there is appreciable variation of the cross section with \( \phi_\mu \). Comparing the two cases of light and heavy stops, it is clear that the Higgs-stop-stop coupling is significant, with the difference in cross sections being noticably large with a light stop.

Figure 3 illustrates similar studies with \( A_f = 1.5 \text{ TeV}, \mu = 1 \text{ TeV} \) (left) and \( A_f = 1 \text{ TeV}, \mu = 1.5 \text{ TeV} \) (right), in particular showing how significantly the result depends on \( A_f \) and \( \mu \). In general, we may expect the difference between the CP-conserving and CP-violating cases to depend quite sensitively on \( A_f \) and \( \mu \), more so in the presence of a light stop.

Therefore, we conclude that the discovery of a light MSSM Higgs boson (with mass below 130 GeV or so) at the LHC may eventually enable one to disentangle the CP-violating case from the CP-conserving one, so long that the relevant SUSY parameters entering \( gg \to H_1 \to \gamma \gamma \) are measured elsewhere, in particular \( m_{\tilde{t}_1} \). This is not phenomenologically unconceivable, as this Higgs detection mode requires a very high luminosity, unlike the discovery of those sparticles (and the measurement of their masses and couplings) that enter the loops.
Figure 2: $\Delta \sigma/\sigma_0$ for the process ($pp \to H_1 \to \gamma\gamma$) at the LHC plotted against the charged Higgs mass for different $\phi_\mu$ values. The relevant MSSM variables are set as follows: $\tan\beta = 20$, $A_f = 1$ TeV, $\mu = 1$ TeV, with $M_{U_3} = 1$ TeV (left plot) and $M_{U_3} = 250$ GeV (right plot).

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Figure 3: $\Delta \sigma/\sigma_0$ for the process ($pp \to H_1 \to \gamma\gamma$) at the LHC plotted against the charged Higgs mass for different $\phi_\mu$ values, with $A_f = 1.5$ TeV and $\mu = 1$ TeV (left plot) and $A_f = 1$ TeV and $\mu = 1.5$ TeV (right plot), for $M_{U_3} = 250$ GeV.

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