Explicit CP Violation in the MSSM

Through Higgs $\rightarrow \gamma\gamma$

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Abstract

The MSSM with explicit CP violation is studied through the di-photon decay channel of the lightest neutral Higgs boson. Through the leading one-loop order $H_1 \rightarrow \gamma\gamma$ is affected by a large number of Higgs-sparticle couplings, which could be complex. Our preliminary scan over the Supersymmetric parameter space shows that more than 50% average deviations are possible, in either direction, in the corresponding branching ratio, with respect to the case of the CP-conserving MSSM. In particular, our analysis shows that in the presence of a light stop (with mass $\sim 200$ GeV) a CP-violating phase $\phi_\mu \sim 90^\circ$ can render the $H_1 \rightarrow \gamma\gamma$ branching ratio more than 10 times larger, for suitable combinations of the other MSSM parameters.
The mechanism of Electro-Weak Symmetry Breaking (EWSB) is elusive even after the very successful LEP era, although precision measurements hint at a light Higgs particle. It is expected that the soon to be operational Large Hadron Collider (LHC) will be able to make definite statements about the Higgs mechanism. At the same time there are various reasons to think that the Standard Model (SM) is only an effective theory valid up to TeV range, and some richer structure is needed to explain particle dynamics (much) beyond such energy scale. Supersymmetry (SUSY), being the most favoured of all the new physics scenarios proposed so far, is going to be searched for in all possible ways at the LHC. Within the Minimal Supersymmetric Standard Model (MSSM) the scalar potential conserves CP at tree level \[1\]. The reason is that SUSY imposes an additional (holomorphic) symmetry on the Higgs sector of a general two-Higgs doublet model, that entails flavour conservation in tree-level neutral currents and absence of CP-violating scalar-pseudoscalar mixings in the Born approximation. Beyond the latter, recent studies have shown that CP invariance of the Higgs potential may in principle be broken by radiative corrections \[2\], as the Vacuum Expectation Values (VEVs) of the two Higgs doublets can develop a relative phase \[3\]. This type of CP violation is generally referred to as spontaneous CP violation and it requires a light Higgs state as a result of the Georgi-Pais theorem \[4\], but the possibility of the latter has now been essentially ruled out by experiment \[5\].

CP violation can also be explicitly induced in the MSSM, in much the same way as it is done in the SM, by complex Yukawa couplings of the Higgs bosons to (s)quarks. There are several new parameters in the Supersymmetric theory, that are absent in the SM, which could well be complex and thus possess CP-violating phases. Such parameters include: (i) the higgsino mass term $\mu$, (ii) the soft SUSY-breaking gaugino masses $M_a$ ($a = 1, 2, 3$), (iii) the soft bilinear term $B\mu$ and (iv) the soft trilinear Yukawa couplings $A_f$ of the Higgs particles to scalar fermions of flavour $f$.

Each of these parameters can have independent phases. After applying universality conditions at a unification scale $M_X$ the gaugino masses have a common phase and the trilinear couplings are all equal with another common phase. As argued by \[6\], one may deviate from exact universality and consider $A_f$ to be diagonal in flavour space with vanishing first and second generation couplings to avoid problems with the electron, muon and neutron Electric Dipole Moments (EDMs). This leaves four independent phases, those of $\mu, B\mu, M_a$ and $A_f$. However, the two $U(1)$ symmetries of the conformal-invariant part of the MSSM
may be employed to re-phase one of the Higgs doublet fields and the gaugino fields such that $M_a$ and $B_\mu$ are real \cite{7, 8}. We will work within this setup with two independent physical phases, which we take to be $arg(\mu) = \phi_\mu$ and $arg(A_f) = \phi_{A_f}$. As intimated, the CP-violating phases associated with the sfermions of the first and, to a lesser extent, second generations are severely constrained by bounds on the EDMs of the electron, neutron and muon. However, there have been several suggestions \cite{9}–\cite{11} to evade these constraints without suppressing the CP-violating phases. One possibility is to arrange for partial cancellations among various contributions to the EDMs \cite{11}. Another option is to make the first two generations of scalar fermions rather heavy, of order a few TeV, so that the one-loop EDM constraints are automatically evaded. As a matter of fact, one can consider so-called effective SUSY models \cite{10} where decoupling of the first and second generation sfermions are invoked to solve the SUSY Flavour Changing Neutral Current (FCNC) and CP problems without spoiling the naturalness condition. We adopted the latter version of a CP-violating MSSM for our analysis, along with $A_f = 0$ for the first two generation sfermions.

The CP-violating phases $\phi_\mu$ and $\phi_{A_f}$ could in principle be measured directly in the production cross sections and decay widths of (s)particles in high energy colliders \cite{7}, \cite{12} - \cite{17} or indirectly via their radiative effects on the Higgs sector \cite{7, 14}. In this letter we will look at $H_1 \to \gamma\gamma$ which involve the (leading) direct effects of CP violation through couplings of $H_1$ to sparticles in the loops (see Fig. 1) as well as the (subleading) indirect effect through the scalar-pseudoscalar mixing yielding a CP-mixed state, $H_1$. The origin of this CP-mixing is the following. In the Higgs sector, the CP-violating phases mentioned above introduce non-vanishing off-diagonal mixing terms in the neutral Higgs mass matrix, which in the weak basis ($\phi_1, \phi_2, a$), where $\phi_{1,2}$ are the CP-even states and $a$ is the CP-odd state, may schematically be written as \cite{7, 14, 18, 19}

$$\mathcal{M}_H^2 = \begin{pmatrix} \mathcal{M}_S^2 & \mathcal{M}_{SP}^2 \\ \mathcal{M}_{PS}^2 & \mathcal{M}_{P}^2 \end{pmatrix}. \quad (1)$$

Here, $\mathcal{M}_S^2$ is a $2 \times 2$ matrix describing the transition between the CP-even states, $\mathcal{M}_P^2$ gives the mass of the CP-odd state whilst $\mathcal{M}_{PS}^2 = (\mathcal{M}_{SP}^2)^T$ (a $1 \times 2$ matrix) describes the mixing between the CP-even and CP-odd states. The mixing matrix elements are typically proportional to

$$\mathcal{M}_{SP}^2 \propto \Im(\mu A_f) \quad (2)$$
and are dominated by loops involving the top squarks and could be of order $M_Z^2$. As a result, the neutral Higgs bosons of the MSSM no longer carry any definite CP-parities. Rotation from the EW states to the mass eigenvalues,

$$(\phi_1, \phi_2, \alpha)^T = O (H_1, H_2, H_3)^T,$$

is now carried out by a $3 \times 3$ real orthogonal matrix $O$, such that

$$O^T M_H^2 O = \text{diag}(M_{H_1}^2, M_{H_2}^2, M_{H_3}^2)$$

with $M_{H_1} \leq M_{H_2} \leq M_{H_3}$. As a consequence, it is now appropriate to parameterise the Higgs sector of the CP-violating MSSM in terms of the mass of the charged Higgs boson, $M_{H^\pm}$, as the latter remains basically unaffected. (For a detailed formulation of the MSSM Higgs sector with explicit CP violation, see Refs. [7, 18].)

In order to study the effects of the CP-violating phases we focus here on the di-photon decay mode of the lightest neutral Higgs boson, $H_1$. The reason is twofold. Firstly, the di-photon decay mode is the most promising channel for the discovery of a light neutral Higgs state – of mass between, say, $80 - 130$ GeV, at the LHC [20, 21]. Secondly, the dominant CP-violating terms dependent on $\mu$ and $A_f$ (hereafter, $f = b, t, \tau$) enter the perturbative calculation of the di-photon decay width with a coupling strength that is of the same order as that of the CP-conserving ones (of $O(\alpha^3)$). Furthermore, on the technical side, thanks to the narrow width of such a light Higgs state (of 10 MeV at the most), the entire $gg/qq \rightarrow H_1 \rightarrow \gamma \gamma$ process can be factorised into three parts: the production process, the Higgs propagator and the decay channel. Effects of CP violation can show up in this process through the aforementioned couplings in the production, through a possible mixing of Higgs states at one-loop and above in the propagator and through the same couplings in the decay. CP violation entering the production of a Higgs state in gluon-gluon fusion process at hadron colliders was studied first by [22], choosing a parameter space region which is not sensitive to the CP-mixing of the Higgs states, and later by [13, 23], including the presence of CP-mixing of the Higgs states. Effects of CP-mixing in the propagator are discussed separately but in great detail in [16]. A thorough study of the other MSSM Higgs decay channels in presence of CP-violation can be found in [12]-[18],[22]-[25]. We postpone the full analyses of $gg/qq \rightarrow H_1 \rightarrow \gamma \gamma$ including also CP-violating effects in production and propagation to a later work.
In the MSSM a Higgs state decays into two photons through loops of fermions, sfermions, EW gauge bosons, charged Higgses as well as charginos (see Fig. 1). (Expressions for the amplitudes of $H_1 \rightarrow \gamma \gamma$ along with relevant couplings are available in [26] and references therein.) This decay mode of $H_1$ (also $H_2$ and $H_3$) along with its production through gluon-gluon fusion is discussed by Ref. [23]. However, the analysis therein was limited to parameter space regions where CP-violating effects are only due to the changed SM particle (especially $W^{\pm}$) couplings to the $H_1$. Effects of sparticles (made suitably heavy in Ref. [23]) in the loops were negligible. We examine here the complementary region of MSSM parameter space (albeit limitedly to the Higgs decay), wherein sparticle masses are taken light, so that they contribute substantially in the loops. In addition, we will show that, in the presence of non-trivial CP-violating phases, there are regions of MSSM parameter space where the couplings of the decaying Higgs bosons to all sparticles in the loops are strongly modified with respect to the CP-conserving MSSM, thereby inducing dramatic changes on the $H_1 \rightarrow \gamma \gamma$ width and Branching Ratio (BR).

To prove this, we have used the publicly available FORTRAN code CPSuperH [26] version 2 for our analysis. CPSuperH calculates the mass spectrum and decay widths of the neutral and charged Higgs bosons in the most general MSSM including explicitly CP-violating phases. In addition, it computes all the couplings of the neutral Higgs bosons $H_{1,2,3}$ and the charged Higgs boson $H^{\pm}$ to ordinary and Supersymmetric matter. The program is based on the results obtained in Refs. [12–15] and the most recent renormalisation group improved effective-potential approach, which includes dominant higher-order logarithmic and threshold corrections, $b$-quark Yukawa-coupling resummation effects and Higgs boson pole-mass shifts [18, 27].
The free non-SM parameters of the model now include: $|\mu|$, phase of $\mu$ ($\phi_\mu$), charged Higgs mass ($M_{H^\pm}$), soft gaugino masses ($M_a$), soft sfermion masses of the third generation ($M_{(\tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{E}_3)}$), (unified) soft trilinear couplings of the third generation ($|A_f|$), phase of the trilinear coupling ($\phi_{A_f}$). In our scan we have chosen the following very extensive parameter ranges:

$$\tan \beta : 1 - 60, \ |\mu| : 100 - 2000 \text{ GeV}, \ \phi_\mu : 0^\circ - 180^\circ, \ M_{H^\pm} : 100 - 400 \text{ GeV},$$

$$M_2 : 100 - 500 \text{ GeV}, \ M_{(\tilde{Q}_3, \tilde{U}_3, \tilde{D}_3, \tilde{E}_3)} : 100 - 2000 \text{ GeV}, \ |A_f| : 100 - 2000 \text{ GeV}.$$  

We aimed at searching regions in the Supersymmetric parameter space where the variation in the BR($H_1 \to \gamma\gamma$) due to the CP-violating phases is maximised compared to the CP-conserving case. As stated above, the CP-violating effects are proportional to $\Im m(\mu A_f)$, and so we opted to fix $\phi_{A_f}$ to $0^\circ$ and varied only $\phi_\mu$. Besides, $M_1$ and $M_3$ were kept fixed as their variation is of no significance here. Finally, no unification of the soft sfermion masses was assumed, though they were taken in the same range. For this analysis, threshold corrections induced by the exchange of gluinos and charginos in the Higgs-quark-antiquark vertices [28, 29] were not included.

We scanned the above parameter space for 100,000 randomly selected points within the ranges specified above and for each of these we have taken values of $\phi_\mu$ increasing from $0^\circ$ to $180^\circ$ in steps of $20^\circ$. Notice that $\phi_\mu = 0^\circ(180)^\circ$ corresponds to the CP-conserving MSSM point with $\mu = +|\mu|(-|\mu|)$, while any other non-trivial $\phi_\mu$ shows the effect of CP violation. The following experimental constraints from LEP2 and Tevatron [30, 31] were imposed during the scan:

$$m_{\chi^\pm_1} \geq 104 \text{ GeV} \ (\text{LEP2}),$$

$$m_{\tilde{f}} \gtrsim 100 \text{ GeV} \ for \ \tilde{f} = \tilde{l}, \tilde{\nu}, \tilde{t}_1 \ (\text{LEP2}),$$

$$m_{\tilde{b}} \gtrsim 300 \text{ GeV} \ (\text{Tevatron}).$$

Parameter space points violating these constraints were discarded. We only considered points with lightest Higgs mass ($M_{H_1}$) between 90 and 130 GeV, the range in which the $H_1 \to \gamma\gamma$ decay is relevant.

For each point in the scans that survives the various constraints discussed above we asked CPSuperH to print out the mass and $\gamma\gamma$ BR of the lightest Higgs $H_1$. In order to have an
idea of the overall trend followed by the BR for different phases, we first looked at the average behaviour at specific $M_{H_1}$ values. To do this we divided the mass range into bins of size 4 GeV. To find the average sensitivity within each mass bin, we defined the percentage deviation

$$R_{\phi_{\mu}}^i = \frac{\sum_n (BR_{\phi}^{(i,n)} - BR_0^{(i,n)})}{\sum_n BR_0^{(i,n)}} \times 100,$$ (4)

where the summation is over the number of random points ($n$) within a particular bin $i$. We denote the BR in the CP-conserving case by $BR_0$ (specifically, the latter corresponds to the case $\phi_{\mu} = 0^\circ$, however, without any loss or gain of information, we could alternatively have used the limit $\phi_{\mu} = 180^\circ$) and that with a non-vanishing $\phi_{\mu}$ (different from $180^\circ$) by $BR_{\phi}$. This average percentage deviation is plotted in Fig. 2 (left) for the different values of $\phi_{\mu}$ taken in each bin. There is an enhancement in the BR of about 20% for $M_{H_1}$ larger than 110 GeV for moderate values of $\phi_{\mu} \sim 100^\circ$, while there is a suppression of about 40 – 50% for $M_{H_1}$ around 90 – 98 GeV. This change-over from enhancement to suppression for lower $M_{H_1}$ values shows the diminishing role of sparticles in the loop as the mass difference between $2m_f$ and $M_{H_1}$ increases and the effect of a non-zero $\phi_{\mu}$ is effectively more and more through a changed $H_1WW$ coupling. Such suppression is in agreement with the results of [23]. In the mass region of 100 – 110 GeV the effect is apparently very small. However, this is an artifact of the binned averaging, where points with enhanced and suppressed BRs falling in the same mass bin cancel each other. This cancellation is nullified by taking the absolute value of the difference in the numerator of Eq. (4), i.e., before averaging. The result is plotted in Fig. 2 (right). More than 50% deviation is seen for $\phi_{\mu} = 100^\circ$ for $M_{H_1}$ around 104 GeV. Now, it should be noted that these figures represent only the average behaviour. It is therefore possible to find regions of parameter space where the differences are larger (or smaller, for that matter). We did indeed find points with difference in the BR larger than 50 times in our scan in either direction.

A subtlety should be noted in this context though, concerning the derived MSSM masses that also depend on $\phi_{\mu}$ and enter the decay $H_1 \rightarrow \gamma\gamma$ ($M_{H_1}$, $m_{\tilde{b},\tilde{t},\tilde{\tau}}$, $M_{\chi^\pm}$). In fact, all the latter change when going from the CP-conserving case to the CP-violating one. The most crucial one in this respect is $M_{H_1}$. However, we have verified that for the same parameter point (apart from a different $\phi_{\mu}$) the latter always changes less than 2 GeV between the two MSSM configurations. Hence, our 4 GeV wide bins do capture percentage corrections to the
FIG. 2: Scan result showing binned average values of percentage differences in the BR($H_1 \to \gamma\gamma$) between the CP-violating and CP-conserving case (left) as well as the absolute value of it (right) – see Eq. (4) – for various choices of $\phi_\mu$.

BR consistently between the two MSSMs as a function of the lightest Higgs boson mass. (Rare borderline cases are also correctly assigned to the right bin.) Besides, 2 GeV is roughly the di-photon mass resolution in ATLAS [20] (while in CMS it is somewhat better [21]). In short, we imagine an experimental situation in which a Higgs resonance is extracted in $\gamma\gamma X$ samples with the above mass resolution at a time when the other SUSY masses and mixing (including $\tan \beta$) entering the loops of the $H_1 \to \gamma\gamma$ mode have already been measured in real sparticle production with a resolution that does not allow one to distinguish between a CP-conserving and a CP-violating MSSM scenario. Under these conditions, for large enough differences of BRs, a simple measurement of the normalisation of the $\gamma\gamma$ resonance (after background subtraction) may suffice to distinguish between the two envisaged CP scenarios.

To illustrate the validity of this argument, we have selected some specific points from the parameter scan to study the deviations in the BR. While doing this we also wanted to understand the contribution of the different components inducing the CP-violating effect. We specifically looked for points with large trilinear coupling and large $\mu$ values, for the CP-mixing of the Higgs states is proportional to their product (as mentioned in the beginning of this letter). We then considered different cases choosing the soft-mass values such that only one of the sparticles in the loop is light, while all others are heavy (the mass of the charged Higgs boson is varied between 100 GeV and 400 GeV, but for the interesting region
FIG. 3: BR($H_1 \rightarrow \gamma\gamma$) plotted against $M_{H_1}$. Parameters used are: $\tan\beta = 20$, $M_1 = 100$ GeV, $M_2 = M_3 = 1$ TeV, $M_{(Q_3,D_3,L_3,E_3)} = 1$ TeV, $|\mu| = 1$ TeV, $|A_f| = 1.5$ TeV. Left figure has $M_{\tilde{U}_3} = 1$ TeV while right one has $M_{\tilde{U}_3} = 250$ GeV (the latter giving a rather light stop, $m_{\tilde{t}_1} = 200$ GeV).

$M_{H_1} > 115$ GeV it is heavier than 300 GeV), expecting to see the effect due only to the exchange of this light sparticle, alongside the one due to standard matter, $t$, $b$ and $W^\pm$. We also considered the situation when only SM particles are effective, with all the relevant sparticles heavy. We plot the BR against $M_{H_1}$ for $\phi_\mu = 0^\circ$, $90^\circ$, $180^\circ$ for two cases, (i) with all sparticles heavy and (ii) with a light stop of around 200 GeV, in Fig. 3. In case (i) the effect is almost entirely due to the CP-mixing of the Higgs states, entering the BR through the deviation in the couplings of the SM particles with the $H_1$. In case (ii) we also have, in addition to the above, the effect of a light stop, through its CP-violating coupling with the $H_1$ as well as the sensitivity of the stop mass to the CP-violating phases. It is instead found that the effects of light sbottoms, staus and charginos are negligible, so that the BRs in these cases – keeping all other SUSY parameters to be the same – are similar to case (i). This is indeed expected, considering the smaller Yukawa couplings for the corresponding SM particles (with respect to the top) and – in particular – the stringent experimental limit on $m_{\tilde{b}_1}$ from Tevatron. The effect in the case of only heavy sparticles in the loop is exclusively due to the modification of the SM fermion and gauge boson couplings of the CP-mixed Higgs state.

As stated above, the deviations in the $M_{H_1}$ is within 2 GeV for both the cases for the entire range of $\phi_\mu$, as shown in Fig. 4 (left). The larger sensitivity of the BR to $\phi_\mu$ in the case
with light stop can partly be explained through the sensitivity of $m_{\tilde{t}_1}$ to $\phi_\mu$. The variation of $m_{\tilde{t}_1}$ with $\phi_\mu$ is plotted in Fig. 4 (right). Notice that the latter is of the same order as the expected experimental resolution [20, 21], so that it may not be possible to confirm CP-violating effects directly in the stop sector.

In summary, while a full study incorporating the production processes and detector dependent aspects is needed to have a clear quantitative picture, our preliminary analyses indicate that the di-photon channel of the lightest Higgs boson may enable one to distinguish the CP-violating MSSM from the CP-conserving one, so long that some SUSY parameters are measured elsewhere. This is not phenomenologically unconceivable, as the $H_1 \rightarrow \gamma\gamma$ detection mode requires a very high luminosity, unlike the discovery of those sparticles (and the measurement of their masses and couplings) that impinge on the Higgs process studied here. A complete analysis will eventually require to fold the decay process with propagator effects and the appropriate production mode (gluon-gluon fusion and Higgs-strahlung in this case), where similar CP-violating effects may enter.

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