Spontaneous CP violation in supersymmetric models

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Abstract

We briefly comment on the question of spontaneous CP violation for several models of weak interactions. We focus on one of the minimal extensions of the Standard Model where spontaneous CP violation is viable, the next-to-minimal supersymmetric standard model (NMSSM), with two Higgs doublets and a gauge singlet. We analyse the most general Higgs potential without a discrete $Z_3$ symmetry, and derive an upper bound on the mass of the lightest neutral Higgs boson. We estimate $\epsilon_K$ by applying the mass insertion approximation, finding that in order to account for the observed CP violation in the neutral kaon sector a non-trivial flavour structure in the soft-breaking $A$ terms is required and that the upper bound on the lightest Higgs-boson mass becomes stronger. We also discuss the implications of electric dipole moments of the electron and the neutron in SUSY models with SCPV.

1 Introduction

The origin of CP violation remains a fundamental open question in particle physics. In spite of the standard model success in accommodating the experimental value of $\epsilon_K$ and $\epsilon'/\epsilon$ through the Cabibbo-Kobayashi-Maskawa mechanism, an alternative scenario is to assume that rather than being explicitly broken at the Lagrangian level, CP is a symmetry of the Lagrangian, which is spontaneously broken by the vacuum \footnote{See \cite{ref1}.}. We begin with a brief overview of several possible scenarios for spontaneous CP violation (SCPV): the standard model (SM), multi-Higgs doublet models and the minimal supersymmetric standard model (MSSM).

As in Reference \footnote{See \cite{ref2}.}, we shall discuss in detail spontaneous CP breaking at the tree level in the context of supersymmetry, most specifically in an extension of the MSSM with one gauge singlet field ($N$) besides the two Higgs doublets ($H_{1,2}$), the so-called next-to-minimal supersymmetric standard model (NMSSM). In this class of models CP violation is caused by the phases associated with the vacuum expectation values of the Higgs fields, thus the reality of the CKM matrix is automatic and not an \textit{ad hoc} assumption. In
summary, we will investigate whether or not one can achieve spontaneous breaking of CP whilst generating the observed amount of $\epsilon_K$ and having Higgs-boson masses that are consistent with experimental data.

2 Spontaneous CP violation: standard model and beyond

As previously discussed, and although nearly 40 years have passed since the first experimental evidence of CP violation, we are still far from having a complete theoretical framework that can fully account for both the origin of the CP symmetry break and the measured CPV observables.

In the SM, CP is explicitly broken at the Lagrangian level through complex Yukawa couplings. In the interaction basis, and prior to electroweak symmetry breaking, the charged current and Yukawa terms in the Lagrangian can be written as

$$
\mathcal{L}^{int} = -\bar{u}^0_L h_u \phi u_R^0 - \bar{d}^0_L h_d \phi d_R^0 + i \frac{g}{\sqrt{2}} \bar{u}^0_L \gamma^\mu d_R^0 W^+_\mu + \text{H.c.} ,
$$

where $h_u,d$ are generic $3 \times 3$ complex Yukawa matrices. After $SU(2)_L \times U(1)_Y$ is broken to $U(1)_{em}$, CP violation arises from the misalignment of mass and charged-current interaction eigenstates. In the physical quark basis, the Lagrangian now reads

$$
\mathcal{L}^{phys} = -\bar{u}_L M^\text{diag}_u u_R - \bar{d}_L M^\text{diag}_d d_R + i \frac{g}{\sqrt{2}} \bar{u}_L \gamma^\mu V^\text{CKM}_L d_R W^+_{\mu} + \text{H.c.} .
$$

The Cabibbo-Kobayashi-Maskawa matrix ($V^\text{CKM}$) can be parametrized by 3 real angles and one physical phase, $\delta^\text{CKM}$, which is the only source of CP violation in the SM. So far, the KM mechanism has been able to account for the experimental values of the CP violating parameters in the $K$ and $B$ sectors. Nevertheless, it is not clear whether this mechanism of “hard” CP violation is the only existing scenario, or if the SM contributions are the dominant or even the only ones. Further motivation to discuss other scenarios of CP violation stems from the fact that within the SM the amount of CP violation is not enough to generate the observed baryon asymmetry of the Universe.

A possible way to overcome this problem is to increase the number of CP violating sources in the theory. As an example, one can refer to models with vector-like quarks [5], Left-Right symmetric models [6], extensions of the SM Higgs sector, and the minimal supersymmetric standard model (MSSM). In fact, the MSSM adds 40 new phases, arising from both gauge and flavour sectors, that explicitly violate CP, and these have been the object of extensive studies.

On the other hand, and instead of increasing the number of “hard” CPV phases, one can adopt an alternative scenario where CP is spontaneously (or “softly”) broken. In
this framework, CP is originally a symmetry of the Lagrangian which is broken at the same time as the electroweak symmetry due to complex scalar vacuum expectation values (VEV’s)\(^\dagger\). Invariance of \( \mathcal{L} \) under a generic CP transformation requires that the Yukawa couplings of Eq. (1) are real (for a complete discussion see Reference [4]). In this case, and assuming the whole theory to be CPT invariant, the Poincaré group (\( \mathcal{P} \)) is also a symmetry group of the Lagrangian.

Although it is a very appealing mechanism, spontaneous CPV is not always viable. Let us review the status of SCPV in the SM and some of its minimal extensions.

a) Standard model

As we will shortly see, in the SM, and in generic \( SU(2)_L \times U(1)_Y \) gauge theories with only one Higgs doublet (\( \phi \)), SCPV cannot occur. The SM Higgs VEV that breaks electroweak symmetry can be generically written as a complex space-time constant quantity,

\[
\langle 0 | \phi(x_\mu) | 0 \rangle = \begin{pmatrix} 0 \\ v e^{i\alpha} \end{pmatrix}.
\]

Nevertheless, this vacuum is trivially CP invariant, as one can promptly verify by considering a generic CP transformation for the scalar Higgs field:

\[
(\mathcal{CP}) \, \phi(t, \tau) \, (\mathcal{CP}^\dagger) = e^{i\beta} \phi(t, -\tau),
\]

where the phase \( \beta \) that appears in the above transformation is arbitrary. It is clear that by taking \( \beta = 2\alpha \), the vacuum is indeed CP invariant. To overcome this, one is naturally led to extend the Higgs content of the model.

b) Extensions of the SM: multi-Higgs doublet models

A general problem of multi-Higgs doublet models is the existence of flavour-changing neutral Yukawa interactions, arising from the addition of scalar particles (Higgs bosons, in this case) whose Yukawa couplings are not flavour diagonal. Typically, these interactions give excessive contributions to neutral meson mixing observables, and in order to satisfy the experimental constraints on \( K^0 - \bar{K}^0 \), \( D^0 - \bar{D}^0 \), \( B^0 - \bar{B}^0 \) mixing and some rare decays, one has to find a way to suppress them. Either one assumes that the additional neutral scalars are sufficiently heavy to decouple (with masses of order TeV), or the existence of some mechanism to suppress the non-diagonal couplings. Clearly the latter is the most appealing and natural way to avoid conflict with experiment. For the case of two Higgs doublets, and as originally shown in Ref. [7], the only way to achieve natural flavour conservation (NFC), is by imposing that each of the scalar doublets only couples to either up or down type quarks. This can be achieved by imposing a discrete or reflexion

\(^\dagger\)Note that due to Lorentz invariance only scalar fields may have non-vanishing VEV’s.
symmetry on the scalar potential, for example a Z\textsubscript{2} symmetry. Albeit, once such a symmetry is imposed, SCPV cannot be obtained.

One can further increase the number of Higgs doublets: in the Branco model \cite{8}, which contains three doublets, and has NFC, CP can be spontaneously broken and scalar particle interactions are the only source of CP violation. It is also worth mentioning that SCPV can occur in models where, instead of just enlarging the Higgs sector, one has additional fermions or an extended gauge sector (e.g. extended Left-Right symmetric models, models with additional heavy exotic fermions, etc.).

c) Extensions of the SM: supersymmetric models

The MSSM appears as an appealing scenario for SCPV, since it has by construction two Higgs doublets and NFC is automatic. Still, it is well known that due to supersymmetric constraints on the Higgs potential one cannot obtain SCPV at the tree level. The reason why this occurs is analogous to that of the non-supersymmetric two-Higgs doublet model.

The possibility of having radiatively induced SCPV in the MSSM has been already ruled out for this scenario leads to the existence of a very light Higgs boson, which is incompatible with the present experimental data. It is therefore of interest to consider simple extensions of the MSSM such as a model with at least one gauge singlet field (\(N\)) besides the two Higgs doublets (\(H\textsubscript{1,2}\)), the so-called next-to-minimal supersymmetric standard model (NMSSM), and to ask if one can achieve spontaneous breaking of CP in such a class of models.

3 Spontaneous CPV in the NMSSM

3.1 The Higgs potential

We consider the most general form of the superpotential given by 

\[ W = W_{\text{fermion}} + W_{\text{Higgs}}. \]

In addition to the usual MSSM terms, one finds new contributions in \(W_{\text{Higgs}}\):

\[ W_{\text{Higgs}} = -\lambda \hat{N} \hat{H}_1 \hat{H}_2 - \frac{k}{3} \hat{N}^3 - r \hat{N} - \mu \hat{H}_1 \hat{H}_2, \quad (5) \]

where \(\hat{N}\) is a singlet superfield. Decomposing the SUSY soft-breaking terms as \(L_{\text{SB}} = L_{\text{SB}}^{\text{fermion}} + L_{\text{SB}}^{\text{Higgs}}\), additional soft terms will appear in \(L_{\text{SB}}^{\text{Higgs}}\)

\[-L_{\text{SB}}^{\text{Higgs}} = m^2_{H_i} H_i^a H_i^a + m^2_{N_i} N_i^a N_i^a - \left( B \mu \varepsilon_{ab} H_1^a H_2^b + A \lambda N \varepsilon_{ab} H_1^a H_2^b + \frac{A_k}{3} N^3 + A_r N + \text{H.c.} \right). \quad (6)\]

In the above equations \(i, j = 1, 2, 3\) denote generation indices, \(a, b = 1, 2\) are SU(2) indices, and \(\varepsilon\) is a completely antisymmetric \(2 \times 2\) matrix with \(\varepsilon_{12} = 1\). In the above expression, \(\hat{H}_1^a\) and \(\hat{H}_2^a\) denote the Higgs doublets of the minimal supersymmetric standard model.
and $\hat{N}$ is a singlet field. The matrices $h_U, h_D$, and $h_E$ give rise to the usual Yukawa interactions which generate the masses of quarks and leptons. As pointed out before, and since in models of SCPV CP is conserved at the Lagrangian level, these matrices are real.

In order to solve the so-called ‘$\mu$ problem’ of the MSSM, a discrete $Z_3$ symmetry was originally imposed on the superpotential, which naturally leads to $\mu = r = 0$. Nevertheless, in this case the NMSSM has no spontaneous CP violation [5]. As it can be seen from Eq. (5) we do not require the superpotential to be invariant under a discrete $Z_3$ symmetry. In our analysis we do not relate the soft SUSY-breaking parameters to some common unification scale, but rather take them as arbitrary at the electroweak scale. In what follows we shall assume that the tree-level potential is CP conserving and set all parameters (soft squark and Higgs masses, bilinear and trilinear soft breaking terms) to be real, but allow complex vacuum expectation values for the neutral Higgs fields which emerge after spontaneous symmetry breaking:

$$\langle H^0_i \rangle = v_i e^{i\theta_i}/\sqrt{2} ; \quad \langle N \rangle = v_3 e^{i\theta_3}/\sqrt{2}.$$  

(7)

After deriving the CP-invariant neutral scalar potential, we find that only the following phase combinations appear: $\phi_D = \theta_1 + \theta_2$, $\phi_N = \theta_3$. Hence, and without loss of generality we shall set $\theta_1 = 0$. We have found that an acceptable mass spectrum can be easily obtained with the exact values depending on the set of parameters we choose. As it can be seen in Figure 1 a), not only the large singlet phase solution is allowed, but it is indeed favoured. The maximal possible value of the Higgs-boson mass can differ from that of the
MSSM for the case of large values of the coupling constant $\lambda$ as depicted in Figure 1 b).

For low values of $\lambda$, corrections to the tree level Higgs-boson mass are significant and depend mainly on the SUSY scale that we take for the squarks, with $\text{max}(m_{H^0})$ ranging from 105 to 130 GeV, as the typical SUSY scale varies from 300 to 1000 GeV. Finally, we point out that the SM and MSSM Higgs boson mass limits obtained at LEP do not necessarily apply to the NMSSM (see, e.g. [10]) since due to some singlet admixture the lightest neutral Higgs boson may have a reduced coupling to the $Z^0$ and thus even escape detection.

### 3.2 Brief overview of the model

In the scenario we are considering, CP invariance is imposed on the Lagrangian, and hence all couplings are real. In particular, the Yukawa couplings in Eq. (1) are arbitrary real matrices in flavour space. After spontaneous symmetry breaking, the up and down quarks acquire masses,

$$m_U = h_U \frac{v_2}{\sqrt{2}} e^{-i\phi_D}, \quad m_D = h_D \frac{v_1}{\sqrt{2}}.$$  \hfill(8)

As it can be seen from the above equation, the overall phase $\phi_D$ can be rotated away by means of a phase transformation on $u_R$, i.e. $u_R \rightarrow u'_R = e^{-i\phi_D} u_R$. Recalling that the $W$-boson interactions are purely left-handed, this phase does not appear in charged weak interactions. Therefore, in this model the CKM matrix is real and there is no CP violation stemming from the SM through the CKM mechanism. This is a consequence of having real Yukawa couplings and overall phases that can be reabsorbed in the right-handed fields (which are not involved in $W^\pm$ boson exchange). As we will soon discuss, CP violation will arise solely from the relative phases in the VEV’s of the neutral Higgs fields, $\phi_D$ and $\phi_N$, which appear in the scalar quark, gaugino and Higgsino mass matrices, as well as in some of the vertices.

In the squark sector, working in the ‘super-CKM’ basis, we find complex contributions to the squark mass terms, which can be generically written as

$$M^2_{\tilde{q}} = \begin{pmatrix} M^2_{\tilde{q}_{LL}} & M^2_{\tilde{q}_{LR}} \\ M^2_{\tilde{q}_{RL}} & M^2_{\tilde{q}_{RR}} \end{pmatrix}, \quad \tilde{q} = \tilde{U}, \tilde{D}. \hfill(9)$$

In particular, we focus on the $LR$ submatrices of the up and down squark squared masses:

$$M^2_{U_{LR}} = M^2_{U_{RL}} = V_L U^* V_R \frac{v_2}{\sqrt{2}} - \mu_{\text{eff}} \cot \beta e^{i\phi_D} m^\text{diag}_U; \quad (U \rightarrow D), \hfill(10)$$
where \( Y_{ij}^U \equiv A_{ij}^U h_{ij}^U \) (no sum over \( i, j \)), \( \mu_{\text{eff}} \equiv \mu + l \frac{\Delta A_U}{\sqrt{2}} e^{i\phi_N} \). As we shall see in the next section, a non-universal flavour structure in the \( A \) terms, i.e. \( A_{ij}^U \neq \text{constant} \), is indispensable for having sizable supersymmetry contributions to CP violation in the kaon sector.

In the chargino sector (defining \( m_{\tilde{W}} = M_2 \), \( m_{\tilde{H}} = |\mu_{\text{eff}}| \), and \( \varphi = \arg (\mu_{\text{eff}}) \)) the following weak basis interaction Lagrangian arises:

\[
-\mathcal{L}_{\text{int}} = m_{\tilde{W}} \overline{W} W + m_{\tilde{H}} \overline{H} H + \frac{g}{\sqrt{2}} (v_1 e^{-i\varphi} \overline{W}_R \tilde{H}_L + v_2 e^{i\varphi} \overline{W}_L \tilde{H}_R + \text{H.c.}).
\]  

(11)

4 Implications of indirect CP violation for the NMSSM

The next step in the discussion of the viability of SCPV in the NMSSM consists in addressing whether or not one can have CP violation in \( K^0 - \bar{K}^0 \) mixing, and the possible implications on the upper bound of the lightest Higgs-boson mass. Accordingly, we will compute the box-diagram contributions to \( \epsilon_K \) by applying the mass insertion approximation. The effective Hamiltonian governing \( \Delta S = 2 \) transitions can be written as

\[
H_{\text{eff}} = \sum_i c_i O_i,
\]

and the CP observable \( \epsilon_K \) is then given by:

\[
\epsilon_K \simeq \frac{e^{i\pi/4}}{\sqrt{2}} \frac{\text{Im} \mathcal{M}_{12}}{\Delta m_{K}}, \text{ where } \mathcal{M}_{12} = \frac{\langle K^0 | H_{\text{eff}} | \bar{K}^0 \rangle}{2m_K}.
\]  

(12)

In the presence of SUSY contributions the Wilson coefficients \( c_i \) can be decomposed as

\[
c_i = c_i^W + c_i^{H^\pm} + c_i^{\tilde{\chi}^\pm} + c_i^{\tilde{\chi}_1^0} + c_i^{\tilde{\chi}_2^0}.
\]

Recalling that the \( V_{\text{CKM}} \) matrix is real one has no \( W \) boson or charged Higgs contributions. Regarding gaugino mediated diagrams, and in the approximation of retaining only a single mass insertion in an internal squark line, we find that in the present scenario with low tan \( \beta \), we have a \( c_i^{\tilde{\chi}^\pm} \) dominance. As for the local operators \( O_i \), [12], the \( \Delta S = 2 \) transition is largely governed by the \( V-A \) four-fermion operator \( O_1 = \overline{d} \gamma^\mu P_L s \overline{d} \gamma_\mu P_L s \). Therefore, we consider only the non-standard contributions to the Wilson coefficient \( c_1 \), which are dominated by the diagrams depicted in Figure 2. In the limit of degenerate left-handed up-type squarks, keeping only leading top-quark contributions and using the orthogonality of the \( V_{\text{CKM}} \), we find that the imaginary part of the neutral kaon mass matrix off-diagonal element is

\[
\text{Im} \mathcal{M}_{12} = \frac{2G_F^2 f_K^2 m_K m_{W}^4}{3\pi^2 \langle m_{\tilde{q}} \rangle^8} (V^*_{td} V_{ts}) m_t^2 |e^{i\phi_D} m_{\tilde{W}} + \cot \beta m_{\tilde{H}}| \Delta A_U \sin(\varphi_D - \phi_D) (M_Q^2)_{12} I_L.
\]  

(13)

In the above formula, \( I_L \) is the loop function (see Ref. [2]) and \( \Delta A_U \equiv A_{13}^U - A_{23}^U \). From inspection of Eq. (13), it is straightforward to conclude that in order to get a non-vanishing \( \text{Im} \mathcal{M}_{12} \) we need a theory of non-universal \( A_U \) terms (i.e. \( \Delta A_U \neq 0 \); i.e., it is not possible to saturate the observed CP violation in the \( K \)-meson system in the context of SUSY with
a real CKM matrix and universal $A_U$ terms. In Table 1 we present the results for the absolute value of $\epsilon_K$ for various sets of SUSY parameters and low $\tan \beta$.

| $|\epsilon_K|$ | $\phi_D$ | $\phi_N$ | $m_{H^0}$ | $\langle m_{\tilde{q}} \rangle$ | $m_{\tilde{q}_R}$ | $\tan \beta$ | $\lambda$ | $v_3$ |
|---|---|---|---|---|---|---|---|---|
| (10$^{-3}$) | (rad) | (rad) | (GeV) | (GeV) | (GeV) | | | (GeV) |
| 3.24 | 4.71 | 1.57 | 99 | 252 | 235 | 6.7 | -0.03 | 327 |
| 3.03 | 0.89 | 1.75 | 97 | 261 | 168 | 6.6 | +0.33 | 387 |
| 2.75 | 4.71 | 4.71 | 99 | 232 | 201 | 9.2 | -0.02 | 221 |
| 2.42 | 1.96 | 4.08 | 94 | 299 | 174 | 5.1 | -0.06 | 352 |
| 2.10 | 4.67 | 4.75 | 98 | 279 | 220 | 7.8 | +0.01 | 142 |
| 2.02 | 4.68 | 4.71 | 92 | 250 | 152 | 7.4 | +0.02 | 371 |
| 2.01 | 4.18 | 4.73 | 96 | 280 | 232 | 4.6 | -0.01 | 238 |
| 1.31 | 1.12 | 4.72 | 100 | 273 | 241 | 9.6 | -0.01 | 238 |
| 1.29 | 2.35 | 4.70 | 99 | 258 | 230 | 6.1 | -0.13 | 363 |

Table 1: Numerical values of $|\epsilon_K|$ in the low $\tan \beta$ region for certain sets of model parameters that satisfy the minimisation condition of the Higgs potential.

In order to saturate the observed value of $|\epsilon_K|$ and to obey present experimental limits on the sparticle spectrum, one has to take $\Delta A_U$ of order 500 GeV. Values of $A_U^i$ ($i = 1, 2$) around the TeV scale do not significantly affect the mass spectrum of the theory.

\footnote{For our numerical calculations, we have used the nominal values $(M^2_{\tilde{q}_{12}}/\langle m_{\tilde{q}} \rangle)^2 = 0.08$, $V_{ts} = -0.04$, $V_{td} = 0.0066$, $m_t = 175$ GeV and $\Delta A_U = 500$ GeV.}
and can account for values of the left-right mass insertions \((\delta_{LR}^U)_{ij}\) which are consistent with present experimental bounds \([14]\).

The large CP phases appearing in Table \([1]\) hint to potential problems with the electric dipole moments (EDM’s) of the electron and neutron. From the computation of the contributions to the EDM’s of electron and neutron mediated by photino and gluino for the sets of parameters displayed in Table \([1]\), we find that compatibility with the present experimental results of \(d_n < 6.3 \times 10^{-26} \text{e cm (90\% C.L.) and } d_e = 1.8 \times 10^{-27} \text{e cm}\) \([13]\), requires that the photino and gluino masses should satisfy \(0.5 \text{ TeV} \lesssim m_{\tilde{\gamma}} \lesssim 2 \text{ TeV}\) and \(2 \text{ TeV} \lesssim m_{\tilde{g}} \lesssim 6 \text{ TeV}\). Such a hierarchy in the soft gaugino masses appears to be rather unnatural since the masses of the squarks and \(W\)-ino are typically of the order 100–300 GeV in this model. Moreover, masses of the superpartners of about 1 TeV may be in conflict with the cosmological relic density. Finally, one should point out that the above-mentioned hierarchy for the spartners leads to an unacceptable scenario for the lightest supersymmetric particle (LSP). In this case, the LSP would be either charged or have a non-zero lepton number.

5 Conclusions

In this talk we have addressed the viability of spontaneous CP violation in the context of some minimal extensions of the SM. In particular, we have studied spontaneous CP violation in the NMSSM, demonstrating that it is possible to generate sufficient CP violation in order to account for the magnitude of \(\epsilon_K\). We have shown that the minimisation of the most general Higgs potential leads to an acceptable mass spectrum which is accompanied by large CP-violating phases. Regarding CP violation in \(K^0-\bar{K}^0\) mixing we have discussed that saturating \(\epsilon_K\) requires a rather low SUSY scale with \(M_{\text{SUSY}} \approx 300 \text{ GeV}\) (i.e. light squark and \(W\)-ino masses) and a non-trivial flavour structure of the soft SUSY-breaking trilinear couplings \(A_i^{ij\alpha}\) \((i = 1, 2)\). As a consequence, the parameter space is severely constrained and the mass of the lightest Higgs boson is further diminished, and it turns out to be no greater than \(\sim 100 \text{ GeV}\) for the case of low \(\tan \beta\) \((\lesssim 10)\). We have also argued that the large phase solution presents a potential conflict with the severe constraints on the EDM’s of electron and neutron. Therefore, the implications of the EDM bounds on the parameter space, together with the implied LSP scenario, will be a great challenge for SUSY models with spontaneous CP violation (at least for minimal models as the one here discussed).

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