

Spontaneous CP Violation in the Next-to-Minimal Supersymmetric Standard Model

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ABSTRACT: We re-examine spontaneous CP violation (SCPV) at the tree level in the context of the next-to-minimal supersymmetric standard model (NMSSM) with two Higgs doublets and a gauge singlet field. 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 ϵ_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

As first proposed by T.D.Lee [1], an alternative scenario for the breaking of CP is to assume that it is a symmetry of the Lagrangian which is only spontaneously broken by the vacuum. In Ref. [2] we study the spontaneous breaking of CP at the tree level within the context of supersymmetry (SUSY). We consider a simple 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 *ad hoc* assumption. The purpose of our

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[†]A.M.T. acknowledges support by ‘Fundação para a Ciência e Tecnologia’ under grant PRAXIS XXI BD/11030/97.

work is to ask if one can achieve spontaneous breaking of CP whilst generating the observed amount of ϵ_K and having Higgs-boson masses that are consistent with experimental data.

2. 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_{Higgs} , given by:

$$W_{\text{Higgs}} = -\lambda \widehat{N} \widehat{H}_1 \widehat{H}_2 - \frac{k}{3} \widehat{N}^3 - r \widehat{N} - \mu \widehat{H}_1 \widehat{H}_2, \quad (2.1)$$

where \widehat{N} is a singlet superfield. Decomposing the SUSY soft-breaking terms as $\mathcal{L}_{\text{SB}} = \mathcal{L}_{\text{SB}}^{\text{fermion}} + \mathcal{L}_{\text{SB}}^{\text{Higgs}}$, additional soft terms will appear in $\mathcal{L}_{\text{SB}}^{\text{Higgs}}$

$$-\mathcal{L}_{\text{SB}}^{\text{Higgs}} = m_{H_i}^2 H_i^{a*} H_i^a + m_N^2 N^* N - \left(B \mu \epsilon_{ab} H_1^a H_2^b + A_\lambda N \epsilon_{ab} H_1^a H_2^b + \frac{A_k}{3} N^3 + A_r N + \text{H.c.} \right). \quad (2.2)$$

In this analysis, we do not require the superpotential to be invariant under a discrete Z_3 symmetry (which would imply $\mu = r = 0$), nor do we relate the soft SUSY-breaking parameters to some common unification scale, but rather take them as arbitrary at the electroweak scale. Throughout we shall assume that the tree-level potential is CP conserving and take all parameters real, but allow complex vacuum expectation values (VEV's) for the neutral Higgs fields which emerge after spontaneous symmetry breaking: $\langle H_i^0 \rangle = v_i e^{i\theta_i} / \sqrt{2}$ and $\langle N \rangle = v_3 e^{i\theta_3} / \sqrt{2}$. After deriving the CP-invariant neutral scalar potential, it turns out that only the following phase combinations are relevant: $\phi_D = \theta_1 + \theta_2$, $\phi_N = \theta_3$.

We find that an acceptable mass spectrum can be easily obtained, with the exact values

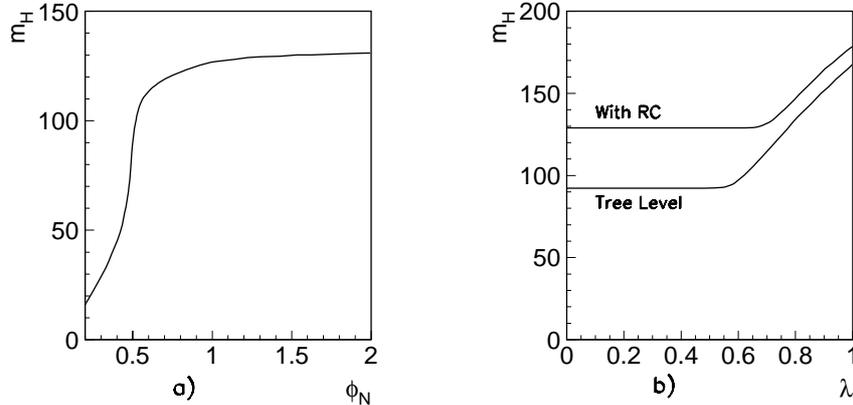


Figure 1: Maximum value of the lightest Higgs-boson mass (in GeV) as a function of the CP-violating phase ϕ_N (in radians) (a), and as a function of the singlet coupling λ at the tree level and after including radiative corrections (at one-loop level) for $M_{\text{SUSY}} = 1$ TeV (b).

depending on the set of parameters we choose. As it can be seen in Figure 1 a), the large singlet phase solution is 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 λ

as depicted in Figure 1 b). For low values of λ , corrections to the tree level Higgs-boson mass are significant and depend mainly on the SUSY scale that we take for the squarks, with $\max(m_{H^0})$ 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., Ref. [3]) since due to some singlet admixture the lightest neutral Higgs boson may have a reduced coupling to the Z^0 [4] and thus even escape detection.

3. Brief overview of the model

In the scenario we are considering, CP invariance is imposed on the lagrangian, and hence all couplings are real. Moreover, the V_{CKM} is naturally real [2]. Even so, the phases associated with the VEV's, ϕ_D and ϕ_N , 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 LR submatrices of the up and down squark squared masses.

$$M_{\tilde{U}LR}^2 = M_{\tilde{U}RL}^{2\dagger} = V_L^U Y_U^* V_R^{U\dagger} \frac{v_2}{\sqrt{2}} - \mu_{\text{eff}} \cot \beta e^{i\phi_D} m_U^{\text{diag}}; \quad (U \rightarrow D), \quad (3.1)$$

where $Y_U^{ij} \equiv A_U^{ij} h_q^{ij}$, (no sum over i, j), $\mu_{\text{eff}} \equiv \mu + \lambda \frac{v_3}{\sqrt{2}} e^{i\phi_N}$.

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:

$$- \mathcal{L}_{\text{int}} = m_{\tilde{W}} \bar{\tilde{W}} \tilde{W} + m_{\tilde{H}} \bar{\tilde{H}} \tilde{H} + \frac{g}{\sqrt{2}} (v_1 e^{-i\varphi} \bar{\tilde{W}}_R \tilde{H}_L + v_2 e^{i\phi_D} \bar{\tilde{W}}_L \tilde{H}_R + \text{H.c.}). \quad (3.2)$$

4. Implications of indirect CP violation for the NMSSM

To explore the consequences of SCPV on the upper bound of the lightest Higgs-boson mass we take into account CP violation in $K^0 - \bar{K}^0$ mixing. To accomplish this, we will compute the box-diagram contributions to ϵ_K by applying the mass insertion approximation. Let us start with the effective Hamiltonian governing $\Delta S = 2$ transitions, which can be written as $H_{\text{eff}} = \sum_i c_i \mathcal{O}_i$. In the presence of SUSY contributions the Wilson coefficients c_i can be decomposed as: $c_i = c_i^W + c_i^{H^\pm} + c_i^{\tilde{\chi}^\pm} + c_i^{\tilde{g}} + c_i^{\tilde{\chi}^0}$. Given that the V_{CKM} matrix is real, 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. Regarding the local operators \mathcal{O}_i [5], the $\Delta S = 2$ transition is largely governed by the $V-A$ four-fermion operator $\mathcal{O}_1 = \bar{d}\gamma^\mu P_L s \bar{d}\gamma_\mu P_L s$. 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_{CKM} , we find that the imaginary part of the neutral kaon mass matrix off-diagonal element is

$$\text{Im } \mathcal{M}_{12} = \frac{2G_F^2 f_K^2 m_K m_W^4}{3\pi^2 \langle m_{\tilde{q}} \rangle^8} (V_{td}^* V_{ts}) m_t^2 \left| e^{i\phi_D} m_{\tilde{W}} + \cot \beta m_{\tilde{H}} \right| \Delta A_U \sin(\varphi_\chi - \phi_D) (M_Q^2)_{12} I_L. \quad (4.1)$$

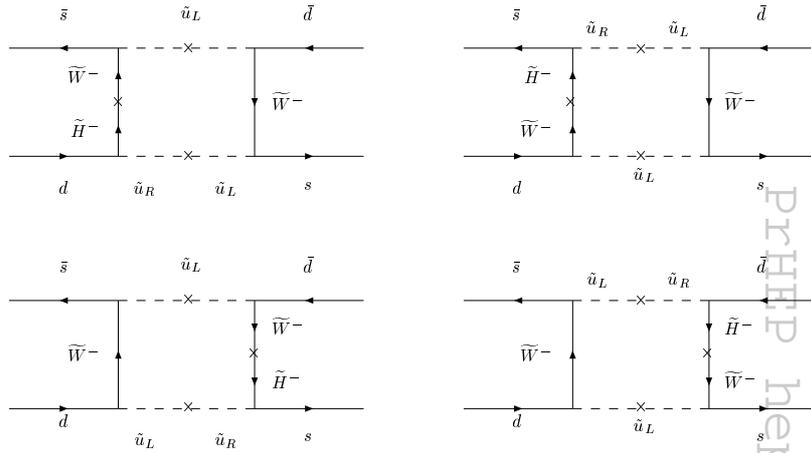


Figure 2: The main contributions to ϵ_K in the mass insertion approximation with W -ino and Higgsino exchange.

In the above formula, I_L is the loop function (see Ref. [2]) and $\Delta A_U \equiv A_U^{13} - A_U^{23}$. From inspection of Eq. (4.1), 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. $\Delta A_U \neq 0$); in other words, 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. Our results for the absolute value of ϵ_K for various sets of SUSY parameters and low $\tan \beta$ are reported in Table 1¹. From Eq. (4.1) it is clear that there is a linear dependence of ϵ_K on the relative difference

$ \epsilon_K $ (10^{-3})	ϕ_D (rad)	ϕ_N (rad)	m_{H^0} (GeV)	$\langle m_{\tilde{q}} \rangle$ (GeV)	$m_{\tilde{t}_R}$ (GeV)	$\tan \beta$	λ	v_3 (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.

ΔA_U . In order to saturate the observed value of $|\epsilon_K|$ [6] and to obey present experimental limits on the sparticle spectrum, one has to take ΔA_U of order 500 GeV. Values of A_U^{i3} ($i = 1, 2$) around the TeV scale do not significantly affect the mass spectrum of the theory, and can account for values of the left-right mass insertions $(\delta_{LR}^U)_{i3}$ which are consistent with present experimental bounds [7].

¹For our numerical calculations, we have used the nominal values $(M_{\tilde{Q}}^2)_{12} / \langle m_{\tilde{q}} \rangle^2 = 0.08$, $V_{ts} = -0.04$, $V_{td} = 0.0066$, $m_t = 175$ GeV and $\Delta A_U = 500$ GeV.

From Table 1, it is clear that we are in the presence of large CP phases, and hence potential problems with the electric dipole moments (EDM's) of the electron and neutron. Given the analytic results for the contributions to the EDM's of electron and neutron mediated by photino and gluino [5], together with the sets of parameters displayed in Table 1 and the present experimental results of $d_n < 6.3 \times 10^{-26} e \text{ cm}$ (90% C.L.) and $d_e = 1.8 \times 10^{-27} e \text{ cm}$ [6], the photino and gluino masses are required to 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 is 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, note 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 would have a non-zero lepton number.

5. Conclusions

In this work, we have studied spontaneous CP violation in the context of the NMSSM, demonstrating that it is possible to generate sufficient CP violation in order to account for the magnitude of ϵ_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. We have discussed that in order to account for the observed CP violation in $K^0-\bar{K}^0$ mixing 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_U^{i3} ($i = 1, 2$) are required. 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 it may be difficult to reconcile the large-phase solution with the severe constraints on the EDM's of electron and neutron. Therefore, the implications of the EDM bounds on the parameter space will be a great challenge for SUSY models with spontaneous CP violation.

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