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# Supersymmetric CP Violation: Higgs and Flavor

D. A. Demir [a]

[a]Theoretical Physics Institute, University of Minnesota, Minneapolis, MN 55455

The phenomenolical implications of the flavor–blind and flavor–sensitive supersymmetric (SUSY) CP phases are analyzed by considering the SUSY Higgs sector and the neutral kaon system. It is shown that the production and decays of the Higgs bosons are significantly affected by their CP–violating mixings. On the other hand, the pure SUSY CP violation is shown to be insufficient for saturating the CP violation in the neutral kaon system given the existing experimental bounds on the branching fraction of the $b \to s\gamma$ decay.

## 1. Introduction

In the minimal standard model (SM) of electroweak interactions both flavor violation and CP violation are encoded in the CKM matrix. In softly broken supersymmetry (SUSY), however, the soft–breaking terms provide novel sources for both CP (via the phases of the $\mu$ parameter, gaugino masses $M_{3,2,1}$, and rest of the soft masses) and flavor (via the generation–changing entries of the $3\times 3$ soft (mass)$^2$s $\widetilde{M}_Q^2, \widetilde{M}_U^2, \cdots$ and the triscalar couplings $A_u, A_d, \cdots$) violations [1]. Therefore, the flavor–changing neutral current processes (*e.g.*, $\epsilon_K$, $\epsilon_B$, $B$ decays $\cdots$) and those observables sensitive to the CP parity breaking (*e.g.*, Higgs boson mixings, electric dipole moments (EDM), P–wave mesons, $\cdots$) provide a viable ground for testing the SM at the loop level, and searching for the signatures of weak–scale SUSY.

In this talk the two problems, flavor and CP violations in SUSY, will be discussed separately by first analyzing the SUSY Higgs sector (with flavor–blind phases), and next working out the question of pure SUSY CP violation in the neutral kaon system (with flavor–sensitive phases). In the discussions the phase and flavor structure of the squark (mass)$^2$ matrix, shown schematically in Fig. 1, will be frequently referred. For the Higgs sector, the flavor structure is irrelevant, and the discussions will focus on the dominant one–loop contributions coming from top quark and squark sectors. When analyzing the kaon system, however, the flavor structure will be taken minimal

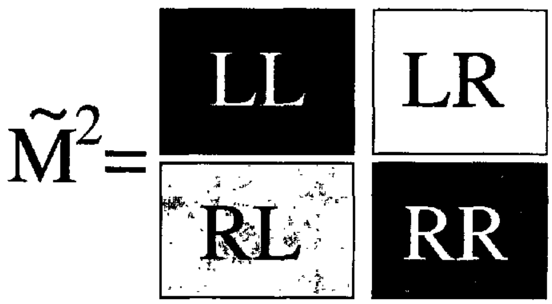


Figure 1. The schematic form of the squark (mass)$^2$ matrix with $3\times 3$ subblocks. The flavor violation comes from the off–diagonal entries of (*i*) the LL and RR blocks (by preserving the chirality), and (*ii*) the LR and RL blocks (by changing the chirality). The CP violation arises in (*i*) these off–diagonal entries (flavor–sensitive), and (*ii*) the diagonal entries of the LR and RL blocks (flavor–blind).

(with most general SUSY soft phases) by choosing, at the GUT scale, squark soft masses diagonal and the trilinear couplings proportional to the Yukawa matrices. SUSY contributes via the soft phases $\varphi_\mu = \mathrm{Arg}[\mu]$, $\varphi_A = \mathrm{Arg}[A]$ where the CKM matrix is taken real, and the strong CP problem is assumed to be evaded by a SUSY version [2] of the Peccei–Quinn mechanism.


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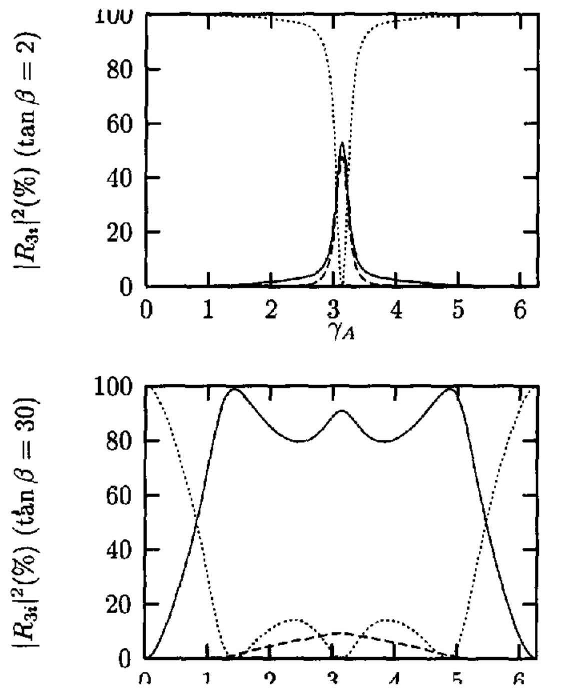


Figure 2. The percentage CP–even ($i = 1,2 \equiv$ solid, dashed) and CP–odd ($i = 3 \equiv$dotted) compositions of $H_3$ for $\tan\beta = 2$ (up) and $\tan\beta = 30$ (down).

## 2. Flavor–insensitive SUSY CP Violation: The Higgs Sector

For probing the effects of the flavor–blind SUSY phases, the EDMs of particles and the Higgs sector provide a viable ground. Here the main concern is on the Higgs sector, and the discussions below will cover the effects of the SUSY phases on the CP parities, masses and couplings of the Higgs bosons.

The tree level Higgs potential is CP–conserving for which the spectrum includes two CP–even Higgs bosons $H_1$ and $H_2$ (with masses $m_{H_1} < m_{H_2}$), and a CP–odd scalar $H_3$. As they possess definite CP parities, it is possible to observe and select these Higgs bosons at, for instance, NLC [3] using $e^+e^- \to Z^\star \to H_{1,2}Z^\star$ and $e^+e^- \to Z^\star \to H_{1,2}H_3$. This clear aspect of the tree level picture is spoiled after taking into account the radiative corrections with finite SUSY CP phases. It is convenient to use the effective potential approach for computing the one–loop effective potential $V_{1-loop} = V_{tree}\left(\Phi_1^0, \Phi_2^0\right) + \Delta V$ with

$$\Delta V = \frac{1}{64\pi^2}\mathrm{Str}\left[M^4\left\{\log\frac{M^2}{Q^2} - \frac{3}{2}\right\}\right] \qquad (1)$$

where $Q$ is the renormalization scale, $\Phi_1^0$, $\Phi_2^0$ are the neutral components of the SUSY Higgs doublets, and $M^2 \equiv M^2\left(\Phi_1^0, \Phi_2^0\right)$ is the field–dependent $(\text{mass})^2$ matrix. The analysis of the masses $M_H^2 = \partial^2 V_{1-loop}/2\partial\varphi_i\partial\varphi_j$, $\varphi_i \in \left\{\Re[\Phi_1^0] - v_1, \Re[\Phi_2^0] - v_2], \Im[\Phi_1^0], \Im[\Phi_2^0]\right\}$ and mixings of the Higgs bosons is performed in [4,5] where the RGE improvement of the $V_{tree}$ parameters is done in [6], a radiatively–induced, $\tan\beta$–enhanced additional phase is derived in [7], the effects of the charginos are taken into account in [8], a reanalysis of [4] by taking into account the strong CP problem [2] is done in [9], and finally the collider signatures are discussed in [10].

The radiative corrections are dominated by the top quark, and $\mathrm{LR}_{33} = m_t\left(A_t\Phi_2^0 - \mu^\star\Phi_1^{0\star}\right)$ and $\mathrm{RL}_{33} = \mathrm{LR}_{33}^\star$ entries of Fig. 1 corresponding to top squarks [4]. The Higgs $(\text{mass})^2$ matrix in $\left\{\Re[\Phi_1^0] - v_1, \Re[\Phi_2^0] - v_2], \sin\beta\Im[\Phi_1^0] + \cos\beta\Im[\Phi_2^0]\right\}$ basis is such that $(i)$ the dependece on the SUSY phases is via $\gamma_A = \varphi_\mu + \varphi_{A_t}$ only, $(ii)$ the radiative corrections to 11, 12, 21, 22, 33 entries reduce to their nonvanishing counterparts in the CP–conserving SUSY when $\gamma_A \to 0$, and $(iii)$ the radiative corrections to 13 and 23 entries are, however, strictly proportional to $\sin\gamma_A$, and thus, vanish identically for $\gamma_A \to 0$. Though all radiative corrections depend on $\gamma_A$ the very existence of CP violation is dictated by the nonzero 13 and 23 entries generating a mixing between the opposite–CP basis elements. For instance, the 13 element add a CP–odd component to the lightest Higgs $H_1$ which can eventually affect its production and decay processes.

One of the most striking effects of SUSY CP violation arises in the CP compositions of the Higgs bosons. Generally, when the pseudoscalar

Higgs of the CP–conserving theory is heavier than $\sim 2\ M_Z$, the CP–odd composition of the lightest Higgs never exceeds 1%. Therefore, practically $H_1$ remains CP–even to an excellent approximation. On the other hand, the heavier Higgs bosons $H_2$ and $H_3$ have no definite CP parities, and thus, their decays and productions at colliders involve new channels. Indeed, the tree level predictions for the NLC search strategy mentioned before are now modified to include a wider signature $e^+e^- \rightarrow Z^\star \rightarrow H_{1,2,H_3} Z^\star$ and $e^+e^- \rightarrow Z^\star \rightarrow H_i^{even} H_j^{odd}$ $(i \neq j)$ [10]. Besides the final state signature, the rates for Higgs boson decays to fermions are significantly modified, for instance, $\Gamma[H_3 \rightarrow \bar{u}u] \sim (\Gamma[H_3 \rightarrow \bar{u}u])_{tree} + \zeta_3 \tan^2\beta$, $\zeta_3$ being the CP–even composition of $H_3$ [4].

Another important effect of the SUSY CP phases stems from the fact that $|LR_{33}|$ and $|RL_{33}|$ depend on $\gamma_A$, and the mass of the light (heavy) stop decreases (increases) as $\gamma_A$ ranges from 0 to $\pi$. This then clearly enhances the raditaive corrections such that $m_{H_1}(\gamma_A = \pi) > m_{H_1}(\gamma_A = 0)$ though there is no violation of the existing upper bound. The very existence of the SUSY phases allow the tree level pseudoscalar Higgs $H_3$ to couple identical squarks, and this, in general, enhances the radiative corrections to $Z^\star hA$ type vertices [10] being a crucial point for Higgs search at the NLC [3].

The points made in these last two paragraphs are illustrated in Fig. 2 for the parameter values $m_Q^2 = m_U^2 = (500\ \mathrm{GeV})^2$; $|A_t| = 1.3$ TeV; $|\mu| = \mu = 250$ GeV; $M_A = 200$GeV for both low and high $\tan\beta$ regimes. At $\gamma_A = 0$ $H_3$ is a pure pseudoscalar, and however, as $\gamma_A$ increases its CP–odd composition starts decreasing whereas simultaneously its $\Re[\Phi_1^0] - v_1$ composition increases (Though not shown here, the lightest Higgs has $\sim$ 100% $\Re[\Phi_2^0] - v_2$ composition therefore, for heavy Higgs bosons only $\Re[\Phi_1^0] - v_1$ remains as active CP–even component.). This happens rather gradually for $\tan\beta = 2$ until $\gamma_A = \pi$ at which these CP compositions change quite fast and $H_3$ becomes a pure scalar boson. This interchange of scalar–pseudoscalar property is more gradual for $\tan\beta = 30$ where $|\mu|\cot\beta \ll |A_t|$. However, in both cases a pseudoscalar Higgs at $\gamma_A = 0$ changes its CP parity for larger values of $\gamma_A$, even it possesses a completely opposite parity at certain points.

The results summarized above are based on the sparticle mass spectrum where $(i)$ the squarks of first two generations are $\gtrsim$ TeV, and $(ii)$ the top squarks weigh significantly below TeV with a large left–right mixing. The former suppresses the one–loop EDMs whereas the second one enhances the CP–violating mixings in the Higgs $(\mathrm{mass})^2$ matrix. One can relax this hierarchy of masses by allowing for all generations to weigh well below TeV in which case the existing EDM bounds must be taken into account. A recent study [11] in this direction shows that the CP violation effects in the Higgs sector can be enhanced only when different contributions to EDMs cancel. However, even if the first two generations of squarks are heavy enough to suppress the one–loop EDMs there can still $(i)$ exist two–loop contributions [12] which can violate the bounds at large $\tan\beta$, and $(ii)$ the production rate for the P–wave bottomonium can be affected via the $b$–quark EDM [13]. While the former can be avoided by choosing $\tan\beta \lesssim 30$ the latter requires an explicit check especially in the parameter space of [11].

## 3. Flavor–sensitive SUSY CP Violation: $b \rightarrow s\gamma$ versus $\varepsilon_K$

This section deals with the effects of SUSY CP phases on the flavor–changing neutral current processes, in particular, the correlation between the $\varepsilon_K$ [14] and $\mathrm{BR}(b \rightarrow s\gamma)$ [15]. While the former exists only when there is CP violation in the underlying model, the latter exists in the CP–conserving limit, too. Therefore, the question of how these two are correlated in SUSY can shed light on the flavor structure needed in the squark mass matrix of Fig. 1. An analysis in this direction has already been carried out in [16] pointing out the need for novel flavor structures beyond the minimal one based on the CKM hierarchy.

Since the CKM matrix is taken real, the entire CP violation must be generated by the SUSY phases. Using the known values of the CKM entries and the quark masses at the weak scale, $Q = M_Z$, the renormalization group running of the Yukawa matrices up to the unification scale $Q = M_G$ produces the flavour structure needed for the soft terms: $(i)$ All squark and slepton soft masses are strictly diagonal $M^2_{Q,U,D,L,E}(M_G) = m^2_{Q,U,D,L,E}1$ with no universality, $(ii)$ Neither Higgs nor gaugino masses are universal, $M^2_{H_{1,2}}(M_G) = m^2_{H_{1,2}}$, $M_{3,2,1}(M_G) = m_{3,2,1}e^{i\varphi_{3,2,1}}$, $(iii)$ All triscalar coupling matrices are proportional to the corresponding Yukawa matrices $A_{U,D,E}(M_G) = a_{U,A,E}e^{i\varphi_{U,D,E}}Y_{U,D,E}(M_G)$ with no universality assumption, again. Therefore, the GUT scale initial conditions have minimal flavor structure and most general CP violation potential.

Central to the discussions below is the LL entry of the $(\text{mass})^2$ matrix in Fig. 1

$$\begin{aligned} \mathrm{LL}^f &= m_Q^2(M_Z) + M_f M_f^\dagger \\ &+ \cos 2\beta \left[(I_f - Q_f)\, M_Z^2 + Q_f\, M_W^2\right] \quad (2) \end{aligned}$$

where $f = u, d$ so that $m_Q^2(M_Z)$ is common to both up and down sectors, and it is the main quantity carrying information about the SUSY flavor structure. The renormalization group equation (RGE) for $m_Q^2(Q)$ is linear, and therefore, one can write $m_Q^2(M_Z)$ as a linear combination of the GUT scale initial conditions (See Appendix A of [17]). The entries of $\widetilde{\Delta} \equiv m_Q^2(M_Z) - \left(m_Q^2(M_Z)\right)^T$ gives the stregth of CP violation in the flavor-changing entries of LL block in Fig. 1. In fact, by an approximate estimate of the RGEs, one can show rather generally that [16]

$$\widetilde{\Delta}_{i<j} \sim 10^{-2} \left|\left[Y_D Y_D^T, Y_U Y_U^T\right]\right|_{ij} m_\alpha m_\beta e^{i\theta_{\alpha\beta}} \quad (3)$$

where $m_\alpha \in \{m_3, m_2, m_1, a_U, a_D, a_E\}$, and $\theta_{\alpha\beta} = \varphi_\alpha - \varphi_\beta$. Clearly this expressesion itself separates the flavor and CP violations: $(i)$ The commutator of $Y_D Y_D^T$ and $Y_U Y_U^T$ determines entirely the flavor structure, and $(ii)$ The bilinear of the soft masses determine the size of the SUSY CP violation. Using the numerical values of the Yukawa matrices (in down-quark diagonal basis, for instance) one finds

$$\widetilde{\delta}_{12;13;23} \sim \tan^2\beta \, \left(10^{-12}; 10^{-8}; 10^{-7}\right) \, e^{i\phi} \quad (4)$$

where $\phi$ is a typical SUSY phase, and $\widetilde{\delta}_{ij} \equiv 3\widetilde{\Delta}_{i<j}/\mathrm{Tr}[\mathrm{LL}]$ represents the CP-violating part of the associated mass insertion, $\delta_{ij}$. This estimate is valid for all trilinear couplings and gaugino masses irrespective of which one has what size of soft phase. Moreover, these rough estimates agree with the exact solution within an order of magnitude [16,17]. The CP violation effects in the RR sector of Fig. 1 are much smaller because $(i)$ the RGEs involve the corresponding Yukawas only which $(ii)$ make RR block nearly real in the super-CKM basis. The derivations here simply show that the sfermion mass matrices keep the same structure and size as found in the constrained SUSY though the GUT-scale initial conditions for the soft masses are of most general form. With such a flavor structure the genuiely SUSY contributions due to gluinos and neutralinos satisfy all constraints imposed by the flavor-changing neutral current experiments are satisfied [18]. The LL block also contributes to the chargino diagrams where the flavor flip comes from the CKM matrix. However, the explicit analysis of the neutal kaon mixing shows that such chirality-preserving contributions are five orders of magnitude below the saturation point. Therefore, even if the most general SUSY phases with most general nonuniversal initial conditions are allowed, the pure SUSY CP violation cannot saturate the flavor-changing neutral current data via the chirality-preserving contributions.

After showing the insufficiency of the LL block, there remains the LR block to analyze. In this sector, all entries are proportional to the corresponding quark masses, and the gluino and neutralino contributions are suppressed by the down quark masses with no possibility of $\tan\beta$-enhancement. The digonal entries of the LR box (as in the Higgs sector), however, can directly contribute to the chargino diagram where the flavor flip occurs via the CKM matrix. Especially with light enough stops and charginos the flavor-blind LR contributions are expected to be important. To see if it can saturate the kaon mixing with a real CKM matrix one must take into account $b \to s\gamma$ bounds. Just the topologies of $K^0$-$\overline{K^0}$ mixing diagrams and $b \to s\gamma$ diagrams suggest the relation

$$|\text{chirality changing, complex coefficient for } \varepsilon_K|$$

$$\sim \left(\frac{m_s}{M_W}\right)^2 \times |\text{ dipole coefficient}, C_7|^2 \quad (5)$$

which establishes a direct correlation between $\varepsilon_K$ and $b \to s\gamma$ though the former vanishes unless there is a source for CP violation whereas the latter does not. This rough relation has been checked in [17] by an explicit numerical analysis, and the result is that for $\epsilon_K$ be saturated the BR($b \to s\gamma$) must exceed the present CLEO bound by four orders of magnitude. An analysis of the $B^0$–$\overline{B^0}$ mixings arrives at the same conclusion in that the resulting predictions are too small to be observable at the B factories [16,17]. To conclude, given the existing BR($b \to s\gamma$) [15] it is impossible to saturate $\epsilon_K$ [14] when CP violation is of pure SUSY origin. The finite phase in the CKM matrix, $\delta_{CKM} \sim \mathcal{O}(1)$, is needed in any case. Another interesting case where BR($b \to s\gamma$) plays a decisive role is the formation of P–wave bottomonium via the $b$–quark EDM having no dependence on the CKM elements [13].

## 4. Conclusion

This talk has concentrated on the effects of SUSY CP violation in flavor–conserving and flavor–violating processes.

As mentioned and illustrated, the SUSY CP violation can have important effects on the Higgs boson system provided that the diagonal entries of LR boxes are large enough. They can effect the signatures of both the production and decay processes to be tested in future colliders of sufficient center–of–mass energy [3].

On the other hand, the CP violation potential of SUSY with minimal flavor scheme is far from being sufficient to saturate $\varepsilon_K$ given the BR($b \to s\gamma$) constraint. Therefore, the novel flavor violation schemes are needed in order for SUSY to saturate the flavor–changing neutral current data with and without CP violation properties.

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