On CP Violation in SUSY

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Abstract

We discuss some new features of CP violating and FCNC processes in the low-energy SUSY context distinguishing : i) models where the presence of SUSY does not introduce any new flavour structure in addition to the usual CKM mixings of the Standard Model (SUSY flavour blindness) and ii) models where the breaking of SUSY and its transmission from the hidden to the observable sector are not flavour blind.

1 CP VIOLATION IN SUSY

Supersymmetry introduces CP violating phases (for a more extended review on the subject, see [1]) in addition to $\delta_{\rm CKM}$ and, even if one envisages particular situations where such extra–phases vanish, the phase $\delta_{\rm CKM}$ itself leads to new CP–violating contributions in processes where SUSY particles are exchanged. CP violation in B decays has all potentialities to exhibit departures from the SM CKM picture in low–energy SUSY extensions, although, as we will discuss, the detectability of such deviations strongly depends on the regions of the SUSY parameter space under consideration.

In any MSSM, at least two new "genuine" SUSY CP–violating phases are present. They originate from the SUSY parameters μ, M, A and B. The first of these parameters is the dimensionful coefficient of the $H_u H_d$ term of the superpotential. The remaining three parameters are present in the sector that softly breaks the N=1 global SUSY. M denotes the common value of the gaugino masses, A is the trilinear scalar coupling, while B denotes the bilinear scalar coupling. In our notation, all these three parameters are dimensionful. Two combinations of the phases of these four parameters are physical [2]. We use here the commonly adopted choice:

$$\varphi_A = \arg\left(A^* M\right), \qquad \varphi_B = \arg\left(B^* M\right). \tag{1}$$

where also $\arg\left(B\mu\right) = 0$, i.e. $\varphi_\mu = -\varphi_B$.

The main constraints on φ_A and φ_B come from their contribution to the electric dipole moments of the neutron and of the electron. For instance, the effect of φ_A and φ_B on the electric and chromoelectric dipole moments of the light quarks (u, d, s) lead to a contribution to d_N^e of order [3]

$$d_N^e \sim 2\left(\frac{100\mathrm{GeV}}{\tilde{m}}\right)^2 \sin\varphi_{A,B} \times 10^{-23}\mathrm{e\,cm}, \tag{2}$$

where $\tilde{m}$ here denotes a common mass for squarks and gluinos. The present experimental bound, $d_N^e < 1.1 \times 10^{-25}$ e cm, implies that $\varphi_{A,B}$ should be $< 10^{-2}$, unless one pushes SUSY masses up to $\mathcal{O}(1$ TeV).

In view of the previous considerations, most authors dealing with the MSSM prefer to simply put φ_A and φ_B equal to zero. Actually, one may argue in favor of this choice by considering the soft breaking sector of the MSSM as resulting from SUSY breaking mechanisms which force φ_A and φ_B to vanish. For instance, it is conceivable that both A and M originate from one same source of $U(1)_R$ breaking. Since φ_A "measures" the relative phase of A and M, in this case it would "naturally"vanish. In some specific models, it has been shown [4] that through an analogous mechanism also φ_B may vanish.

If $\varphi_A = \varphi_B = 0$, then the novelty of SUSY in CP violating contributions merely arises from the presence of the CKM phase in loops where SUSY particles run [2, 5]. The crucial point is that the usual GIM suppression, which plays a major role in evaluating ε_K and ε'/ε in the SM, in the MSSM case (or more exactly in the CMSSM) is replaced by a super–GIM cancellation which has the same "power" of suppression as the original GIM. Again, also in the CMSSM, as it is the case in the SM, the smallness of ε_K and ε'/ε is guaranteed not by the smallness of δ_{CKM}, but rather by the small CKM angles and/or small Yukawa couplings. By the same token, we do not expect any significant departure of the CMSSM from the SM predictions also concerning CP violation in B physics. As a matter of fact, given the large lower bounds on squark and gluino masses, one expects relatively tiny contributions of the SUSY loops in ε_K or ε'/ε in comparison with the normal W loops of the SM.

Several analyses in the literature tackle the above question or, to be more precise, the more general problem of the effect of light $\tilde{t}$ and χ^+ on FCNC processes [6]. In this case sizeable contributions can still occur. The generic situation concerning CP violation in the MSSM case with $\varphi_A = \varphi_B = 0$ and exact universality in the soft–breaking sector can be summarized in the following way: the MSSM does not lead to any significant deviation from the SM expectation for CP–violating phenomena as d_N^e, ε_K, ε'/ε and CP violation in B physics; the only exception to this statement concerns a small portion of the MSSM parameter space where a very light $\tilde{t}$ ($m_{\tilde{t}} < 100$ GeV) and χ^+ ($m_\chi \sim 90$ GeV) are present. In this latter particular situation, sizeable SUSY contributions to ε_K are possible and, consequently, major restrictions in the ρ–η plane can be inferred. Obviously, CP violation in B physics becomes a crucial test for this MSSM case with very light $\tilde{t}$ and χ^+. Interestingly enough, such low values of SUSY masses are at the border of the detectability region at LEP II.

More generally, for models where the breaking of SUSY and its transmission from the hidden to the observable sectors are completely insensitive to the flavour structure (flavour blind SUSY models), the following relevant statement can be proved [7]. In the absence of the CKM phase, a general MSSM with all possible phases in the soft–breaking terms, but no new flavor structure beyond the usual Yukawa matrices, can never give a sizeable contribution to ε_K, ε'/ε or hadronic B^0 CP asymmetries. However, we will see in the next section, that as soon as one introduces some new flavor structure in the soft SUSY–breaking sector, even if the CP violating phases are flavor independent, it is indeed possible to get sizeable CP contribution for large SUSY phases and $\delta_{CKM}=0$. Hence a new result in hadronic B^0 CP asymmetries in the framework of supersymmetry would be a direct proof of the existence of a completely new flavor structure in the soft–breaking terms. This means that B–factories will probe the flavor structure of the supersymmetry soft–breaking terms even before the direct discovery of the supersymmetric partners [7].

2 CP VIOLATION WITH NEW FLAVOR STRUCTURES

In contrast with the situation we have seen in the previous section, the presence of non–universality in the SUSY soft breaking terms, expected in string theories is already enough to generate large supersymmetric contributions to ε'/ε [8] and ε_K [9].

In the following, we work in a generic MSSM: the supersymmetry soft–breaking terms as given at the scale M_{GUT} have a completely general flavor structure, although we assume all of them of the order of a single scale, $m_{3/2}$. In this framework, to define our MSSM, all we have to do is to write the full set of soft–breaking terms. This model includes, in the quark sector, 7 different structures of flavor, $M^2_{\tilde{Q}}$, $M^2_{\tilde{U}}$, $M^2_{\tilde{D}}$, Y_d, Y_u, Y^A_d and Y^A_u. At the supersymmetry breaking scale, M_{GUT}, the natural basis is the basis where all the squark mass matrices, $M^2_{\tilde{Q}}, M^2_{\tilde{U}}, M^2_{\tilde{D}}$, are diagonal. In this basis, the Yukawa matrices are, $v_1\, Y_d = K^{D_L\,\dagger} \cdot M_d \cdot K^{D_R}$ and $v_2\, Y_u = K^{D_L\,\dagger} \cdot K^\dagger \cdot M_u \cdot K^{U_R}$, with M_d and M_u diagonal quark mass matrices, K the Cabibbo–Kobayashi–Maskawa (CKM) mixing matrix and K^{D_L}, K^{U_R}, K^{D_R} unknown, completely general, 3×3 unitary matrices.

Once we specify these 7 matrices, our MSSM model is fully defined at the M_{GUT} scale. However, experimentally measurable quantities involve the sfermion mass matrices at the electroweak scale. So, the next step is to use the MSSM Renormalization Group Equations (RGE) [10, 11] to evolve these matrices down to the electroweak scale. Below the electroweak scale, it is more convenient to work in the SCKM basis where the same unitary transformation is applied to both quarks and squarks so that quark mass matrices are diagonalized. The main RGE effects from M_{GUT} to M_W are those associated with the gluino mass and third generation Yukawa couplings.

After RGE running, flavor–changing effects in the SCKM basis can be estimated by the insertion of flavor–off–diagonal components of the mass–squared matrices normalized by an average squark mass, the so–called mass insertions (MI)[13]. In first place, we will analyze the LR MI. Due to the trilinear terms structure, the LR sfermion matrices are always suppressed by $m_q/m_{\tilde{q}}$, with m_q a quark mass and $m_{\tilde{q}}$ the average squark mass. In any case, this suppression is compulsory to avoid charge and color breaking and directions unbounded from below [14]. In particular, it is required that $(Y_d^A)_{ij} \lesssim \sqrt{3} m_{\tilde{q}}\, max\{m_i, m_j\}/v_1$, which in turn implies that $(\delta^d_{LR})_{i\neq j} \lesssim \sqrt{3}\, max\{m_i, m_j\}/m_{\tilde{q}}$. So we must impose, as model independent upper bounds,

$$\begin{aligned} (\delta^d_{LR})_{12} \quad &\lesssim \quad \sqrt{3}\, \frac{m_s}{m_{\tilde{q}}} \simeq 3.2 \times 10^{-4} \cdot \left(\frac{500\ GeV}{m_{\tilde{q}}}\right) \\ (\delta^d_{LR})_{13} \quad &\lesssim \quad \sqrt{3}\, \frac{m_b}{m_{\tilde{q}}} \simeq 0.01 \cdot \left(\frac{500\ GeV}{m_{\tilde{q}}}\right) \end{aligned} \tag{3}$$

where we take all quark masses evaluated at M_Z. The phenomenological MI bounds given are stronger only for $Im(\delta^d_{LR})_{12}$. Hence, this means that there is still room to saturate ε'/ε with LR mass insertions. However, these bounds imply that, under general circumstances, it is not possible to saturate simultaneously ε_K and ε'/ε with a single $(\delta^d_{LR})_{12}$. In any case, we must remember that these are only upper bounds and a definite model is required if one wants to have a direct estimate of the value of these quantities. For instance such a computation is performed in a type I string inspired example [12]. In these models, with $K^{D_L} \simeq K$ (CKM),

$$(\delta^d_{LR})_{12} \quad \simeq \quad \frac{m_s}{m_{\tilde{q}}}\, \frac{(a_2^Q - a_1^Q)}{m_{\tilde{q}}}\, K_{12} K_{22}{}^* \simeq 4 \times 10^{-5} \cdot \left(\frac{500\ GeV}{m_{\tilde{q}}}\right) \tag{4}$$

Therefore, even if the relative quark–squark flavor misalignment is only of the same size of CKM mixings, the presence of non–universal flavor–diagonal trilinear terms is enough to generate large FCNC effects in the Kaon system. However, in the B system we arrive to a very different result: it is not at all enough to have non–universal trilinear terms, but, it is also required to have large flavor misalignment among quarks and squarks.

The situation for the LL and RR mass insertions is less defined due to the absence of any theoretical prejudice on these mass matrices at M_{GUT}.

In the presence of non–universality, sizeable SUSY contributions to the kaon mass difference are expected. Regarding CP violation observables, with large phases in the K^{D_A} matrices, big contributions to ε_K arise [9] (notice $m^2_{\tilde{D}_{A_i}}$ are always real numbers). This is again equivalent to our result for the LR transitions: even if the sfermion mass matrices at M_{GUT} are flavor diagonal, large FCNC effects are produced in the K system with family non–universal masses.

As for the B system, it is found that to have observable effects it is required to have not only the presence of non-universality, but also large quark-squark flavor misalignment.

In summary, in gluino mediated transitions large effects are expected in the Kaon system in the presence of non-universal squark masses even with a "natural" CKM–like mixing. However in the B system, due to the much lower sensitivity to supersymmetric contributions, observable effects are expected only with approximately maximal $\tilde{b}$–$\tilde{d}$ mixings.

Finally we add a short comment on the relation between the large neutrino mixing and possibly large CP violating effects in B physics in the context of SUSY GUT's [15]. In this case the large effect in B physics is due to a maximal $\tilde{b}$–$\tilde{s}$ mixing in the sector of right-handed down squarks.

In see-saw models of neutrino masses a la SUSY SO(10) the observed large mixing in atmospheric neutrinos naturally leads to large b-s transitions. If the associated new CP phase turns out to be large, this SUSY contribution can drastically affect the CP violation in some of the B decay channels yielding the β and γ angles of the unitarity triangle. They can even produce sizeable CP asymmetries in some decay modes which are not CP violating in the standard model context. Hence the observed large neutrino mixing makes observations of low energy SUSY effects in some CP violating decay channels potentially promising in spite of the agreement between the SM and data in K and B physics so far.

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