Definite new physics answers to CP asymmetries questions

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Abstract: Supersymmetry exhibits new sources of CP violation. We discuss the implications of these new contributions to CP violation both in the K and B physics. We show that CP violation puts severe constraints on low energy SUSY, but it represents also a promising ground to look for signals of new physics.

1. CP VIOLATION IN SUSY

The strong implications of the presence of generic Supersymmetric (SUSY) soft–breaking terms in Flavor Changing Neutral Current (FCNC) and CP violation phenomena were readily realized in the early 80's with the beginning of the SUSY phenomenological studies. The need of an analog of the GIM mechanism in the scalar sector to suppress too large SUSY contributions to K^0–$\bar{K}^0$ mixing was emphasized and this showed the large potentiality of looking for SUSY signals in FCNC and CP violation experiments. Still, the existence of a single experimental measure of CP violation in nature, namely indirect CP violation in kaon mixing, ε_K, made it impossible to distinguish among a pure Cabibbo–Kobayashi–Maskawa (CKM) origin of CP violation or a large supersymmetric (or more generally new physics) contribution. The actual possibility to disentangle these two options arises with the comparison of different CP violating processes. Specially, the CP asymmetries in B^0 decays to be measured in the B–factories and the improvement of electric dipole moment (EDM) constraints can play a very important role to accomplish this objective.

Recently, the arrival of the first results of B^0 CP asymmetries from the B factories has caused a lot of excitement in the high energy physics community [1].

$$a_{J/\psi} = \begin{cases} 0.59 \pm 0.14 \pm 0.05 & (\text{ Babar}) \\ 0.99 \pm 0.14 \pm 0.06 & (\text{ Belle}) \\ 0.79^{+0.41}_{-0.44} & (\text{ CDF}) \end{cases} \tag{1.1}$$

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The errors in these measurements are still too large to draw any firm conclusion and they have a large overlap with the SM expectations corresponding to $0.6 \leq \sin(2\beta) \leq 0.8$. Nevertheless, there is still room for a sizeable new physics contribution. Next we are going to analyze the consequences of a SUSY contribution to these CP violation observables [2].

2. CP VIOLATION WITH NEW FLAVOR STRUCTURES

It is well known that flavor and CP violation are deeply connected. In particular it is clear that the presence of large SUSY phases is not enough to produce sizeable supersymmetric contributions to these flavor changing observables [3]. However, the presence of non-universality in the SUSY soft breaking terms, expected for instance in string theories, is already enough to generate large supersymmetric contributions to ε'/ε [4], ε_K [5] and possibly to other K and B physics CP violation observables. To show this, 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. In any case, it is important to notice that the minimal situation would correspond to the case where the mixings in either K^{D_L} or K^{U_L} are of the same order as the mixings in K and other possibilities would always involve larger mixings. Hence we take a "minimal" situation where both them are of order K and the Yukawa matrices are Hermitian which implies $K^{A_L} = K^{A_R}$. In any case, given that now $K^{D(U)_L}$ measure the flavor misalignment among, $d(u)_L$–$\tilde{Q}_L$ and we have already used the rephasing invariance of the quarks to make K real, it is evident that we can expect new observable (unremovable) phases in the quark-squark mixings, and in particular in the first two generation sector, i.e.,

$$K^{D_L} = K^{D_R} = \begin{pmatrix} 1 - \lambda^2/2 & \lambda\ e^{i\alpha} & A\ \rho\ \lambda^3 e^{i\beta} \\ -\lambda\ e^{-i\alpha} & 1 - \lambda^2/2 & A\ \lambda^2\ e^{i\gamma} \\ A\ \lambda^3\ (e^{-i(\alpha+\gamma)} - \rho\ e^{-i\beta}) & -A\ \lambda^2\ e^{-i\gamma} & 1 \end{pmatrix} \tag{2.1}$$

where δ_{CKM} would correspond to a combination $\beta - \alpha - \gamma$. Finally, the trilinear matrices, Y^A_d and Y^A_u, are specified in this basis by the SUSY breaking theory as $Y^A_{ij} = A_{ij} \cdot Y_{ij}$.

The next step is to use the MSSM Renormalization Group Equations (RGE) [6] to evolve these matrices from M_{GUT} down to the electroweak scale. The main RGE effects from M_{GUT} to M_W are those associated with the gluino mass and third generation Yukawa couplings. Regarding squark mass matrices, it is well-known that diagonal elements receive important RGE contributions proportional to gluino mass that dilute the mass eigenstate non-degeneracy [5]. Then, in the Super-CKM basis (SCKM), the off-diagonal elements in the sfermion mass matrices will be given by $(K^A \cdot M^2_{\tilde{A}} \cdot K^{A^\dagger})_{i\neq j}$ up to smaller RGE corrections. On the other hand, gaugino effects in the trilinear RGE are always proportional to the Yukawa matrices, not to the trilinear matrices themselves and so they are always diagonal to extremely good approximation in the SCKM basis. Once more, the off-diagonal elements will be approximately given by $(K^A \cdot Y^A_{u,d} \cdot K^{A^\dagger})_{i\neq j}$.

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)[9]. 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 [10].

This can be seen explicitly in a type I string inspired example [8]. In these models, we can write the trilinear couplings at M_{GUT} in matrix notation as,

$$Y^A_{d(u)} = \mathrm{Diag}\left(a_1^Q, a_2^Q, a_3^Q\right) \cdot Y_{d(u)} + Y_{d(u)} \cdot \mathrm{Diag}\left(a_1^{D(U)}, a_2^{D(U)}, a_3^{D(U)}\right) \tag{2.2}$$

As discussed above, gluino RGE effects are again diagonal in the SCKM basis and off-diagonal elements are basically given by the initial conditions. So, using unitarity of K^{D_L} and K^{D_R} it is straight-forward to get,

$$\begin{aligned}(\delta^d_{LR})_{i\neq j} \;=\; & \frac{1}{m^2_{\tilde{q}}}\Big(m_j\ (a_2^Q - a_1^Q)\ K^{D_L}_{i2} K^{D_L\,*}_{j2} \;+\; m_j\ (a_3^Q - a_1^Q) K^{D_L}_{i3} K^{D_L\,*}_{j3} \\ & + m_i\ (a_2^D - a_1^D)\ K^{D_R}_{i2} K^{D_R\,*}_{j2} \;+\; m_i\ (a_3^D - a_1^D)\ K^{D_R}_{i3} K^{D_R\,*}_{j3}\Big)\end{aligned} \tag{2.3}$$

First we must take into account that, owing to the gluino dominance in the squark eigenstates at M_W, $m^2_{\tilde{q}}(M_W) \approx 6\ m^2_{\tilde{g}}(M_{GUT})$. In the kaon system, we can neglect m_d; replacing the values of masses and mixings in Ref. [8],

$$\begin{aligned}(\delta^d_{LR})_{12} &\simeq \frac{m_s}{m_{\tilde{q}}}\ \frac{(a_2^D - a_1^D)}{m_{\tilde{q}}}\ K^{D_L}_{12} K^{D_L\,*}_{22} \\ &\simeq 2.8 \times 10^{-5} \cdot (\Theta_2 e^{-i\alpha_2} - \Theta_3 e^{-i\alpha_3}) \cdot \left(\frac{100\ \mathrm{GeV}}{m_{3/2}}\right)\end{aligned} \tag{2.4}$$

where we have used $\theta \simeq 0.7$. Comparing with the bounds on the MI in [9] we can see that indeed this value could give a very sizeable contribution to ε'/ε[4, 8]. It is important to notice that the phase of $(a_2^D - a_1^D)$ is actually unconstrained by electric dipole moment (EDM) experiments as emphasized in [8]. This result is very important: it means that even if the relative quark-squark flavor misalignment is absent, the presence of non-universal flavor-diagonal trilinear terms is enough to generate large FCNC effects in the Kaon system.

Similarly, in the neutral B system, $(\delta^d_{LR})_{13}$ contributes to the $B_d - \bar{B}_d$ mixing parameter, ΔM_{B_d}. However, in our minimal scenario, $K^{D_L} \approx K$, we obtain,

$$\begin{aligned}(\delta^d_{LR})_{13} &\simeq \frac{m_b}{m_{\tilde{q}}}\ \frac{(a_3^D - a_1^D)}{m_{\tilde{q}}}\ K^{D_L}_{13} K^{D_L\,*}_{33} \\ &\simeq 2.5 \times 10^{-5} \cdot (\Theta_1 e^{-i\alpha_1} - \Theta_3 e^{-i\alpha_3}) \cdot \left(\frac{100\ \mathrm{GeV}}{m_{3/2}}\right),\end{aligned} \tag{2.5}$$

clearly too small to generate sizeable $\tilde{b}$–$\tilde{d}$ transitions, as the bounds in [9] show. Notice that larger effects are still possible in a more "exotic" scenario with a large mixing in $K^{D_L}_{13}$. For instance, with a maximal value, $|K^{D_L}_{13} K^{D_L\,*}_{33}| = 1/2$, we would get $(\delta^d_{LR})_{13} \simeq 2 \times 10^{-3} \cdot (100\ \mathrm{GeV}/m_{3/2})$. Even in this limiting situation, this result is roughly one order of magnitude too small to saturate ΔM_{B_d}, though it could still be observed through the CP asymmetries. Hence in the B system we reach a very different result: it is not enough to have non–universal trilinear terms, large flavor misalignment among quarks and squarks is also required.

A similar analysis can be maid with the chirality conserving mass insertions. In this case, they are,

$$(\delta^d_R)_{ij} \;=\; \frac{1}{m^2_{\tilde{q}}} \left[K^{D_L}_{i2} K^{D_L\,*}_{j2} \,(m^2_{R_2} - m^2_{R_1}) \;+\; K^{D_L}_{i3} K^{D_L\,*}_{j3} \,(m^2_{R_3} - m^2_{R_1}) \right] \tag{2.6}$$

Therefore, in the kaon system, we get,

$$\begin{aligned}(\delta^d_R)_{12} &\simeq \frac{\cos^2\theta(\Theta_1^2 - \Theta_2^2)}{6\sin^2\theta} K^{D_L}_{12} K^{D_L\,*}_{22} \;+\; \frac{\cos^2\theta(\Theta_1^2 - \Theta_3^2)}{6\sin^2\theta} K^{D_L}_{13} K^{D_L\,*}_{23} \\ &\simeq \frac{\cos^2\theta(\Theta_1^2 - \Theta_2^2)}{6\sin^2\theta}\ \lambda\ e^{i\alpha}\end{aligned} \tag{2.7}$$

This value has to be compared with the mass insertion bounds required to saturate ε_K [9], which in this case are, $(\delta^d_R)^{bound}_{12} \leq 0.0032$. Using $\theta \simeq 0.7$, we get,

$$(\delta^d_R)_{12} \simeq 0.035(\Theta_1^2 - \Theta_2^2)\sin\alpha \lesssim 0.0032. \tag{2.8}$$

Hence, it is clear that we can easily saturate ε_K without any special fine–tuning. Indeed, this constraint which is one of the main sources of the so–called Supersymmetric flavor problem, in this generic MSSM amounts to the requirement that $(\Theta_1^2 - \Theta_2^2)\sin\alpha \lesssim 0.1$ with all the different factors in this expression $\Theta_1^2, \Theta_2^2, \sin\alpha \leq 1$ [5].

Now we turn to the CP asymmetries in the B system, here we have,

$$\begin{aligned}(\delta^d_R)_{13} &\simeq \frac{\cos^2\theta(\Theta_2^2 - \Theta_1^2)}{6\sin^2\theta} K^{D_L}_{12} K^{D_L\,*}_{32} \;+\; \frac{\cos^2\theta(\Theta_3^2 - \Theta_1^2)}{6\sin^2\theta} K^{D_L}_{13} K^{D_L\,*}_{33} \\ &\simeq A\ \lambda^3\ \frac{\cos^2\theta}{6\sin^2\theta} \Big[-(\Theta_2^2 - \Theta_1^2)\ e^{i(\alpha+\gamma)} \\ &\qquad + (\Theta_3^2 - \Theta_1^2)\ (e^{-i(\alpha+\gamma)} - \rho\ e^{-i\beta}) \Big] \lesssim 10^{-3},\end{aligned} \tag{2.9}$$

to be compared with the mass insertion bound $(\delta^d_R)^{bound}_{12} \leq 0.098$ required to not over–saturate the B^0 mass difference. Nevertheless, in the presence of large mixing, still possible when flavor in the soft breaking terms has an independent source, we can get $K^{D_A}_{13} K^{D_A\,*}_{33} \simeq 1/2$. In this limiting situation $(\delta^d_A)_{13} \lesssim 0.05$, still reachable through CP asymmetries at the B factories in the presence of a sizeable phase in K^{D_A}. So, we find again that to have observable effects in the B system it is required to have not only the presence of non-universality but also large quark-squark flavor misalignment.

3. CONCLUSIONS AND OUTLOOK

In conclusion we have shown that in the kaon system large SUSY effects are naturally expected in any model with non-universal soft-breaking terms. In this direction, several works can be found in the literature [11, 12] in the mass insertion context. 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.

In summary, given the fact that LEP searches for SUSY particles are close to their conclusion and that for Tevatron it may be rather challenging to find a SUSY evidence, we consider CP violation a potentially precious ground for SUSY searches before the advent of the "SUSY machine", LHC.

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