\[ B \rightarrow K\pi \] Puzzle and New Sources of CP Violation in Supersymmetry

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The difference between the CP asymmetries of the \(B^0 \rightarrow K^+\pi^-\) and \(B^+ \rightarrow K^+\pi^0\) decays has been recently confirmed with an evidence larger than \(5\sigma\)'s. We discuss it as a possible signal of new physics associated with new (large) CP violation in the electroweak penguin contributions. We propose a supersymmetry breaking scheme where such new sources of CP violation occur in the flavor non-universal trilinear scalar couplings.

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Establishing that the simple CKM pattern of the Standard Model (SM), with its single CP violating phase, correctly accounts for the vast and complex realm of hadronic flavor phenomena represents a stunning milestone in our endeavor to understand fundamental interactions. Yet, there exists a few sources of tension between experimental data and SM predictions in \(B\) physics \(^[20]\), in particular, but not exclusively, related to CP asymmetries in \(b \rightarrow s\) transitions (see \(^[1,2,3,4]\)) and for update \(^[5]\). Here we focus our attention on the so-called "\(B \rightarrow K\pi\) Puzzle". The recent Belle and Babar Collaborations updates \(^[7]\) on the CP asymmetry in the decays \(B^0 \rightarrow K^+\pi^-\) (together with the consistent CDF data) and \(B^+ \rightarrow K^+\pi^0\),

\[
\mathcal{A}_{CP}(B^0 \rightarrow K^+\pi^-) = -9.7 \pm 1.2\% , \quad (1)
\]

\[
\mathcal{A}_{CP}(B^+ \rightarrow K^+\pi^0) = +5.0 \pm 2.5\% \quad (2)
\]

confirm the existence of a non-vanishing difference between the two CP asymmetries beyond \(5\sigma\) \(^[8]\):

\[
\mathcal{A}_{CP}(B^0 \rightarrow K^+\pi^-) - \mathcal{A}_{CP}(B^+ \rightarrow K^+\pi^0) = (14.7 \pm 2.7\%) \quad (3)
\]

In the SM with naive factorization these two asymmetries are essentially equal. On the other hand, one expects that the "improved" BBNS QCD factorization \(^[3]\) (QCDF) with appropriate \(1/m_b\) corrections (accounting for unknown final state interactions) \(^[10]\) may (even largely) modify such naive expectation. However, even allowing for a considerable freedom in choosing such corrections, QCDF fails to reproduce the above experimental difference by several \(\sigma\)'s \(^[11,12]\). Also alternative approaches to QCDF, namely perturbative QCD (PQCD) \(^[13]\) and Soft Collinear Effective Theory (SCET) \(^[14]\), are in trouble to satisfactorily reproduce the result in Eq\(^[5]\). Only fitting to the experimental data arbitrary contributions corresponding to subleading terms in the power expansion, can one overcome the \(B \rightarrow K\pi\) puzzle; this latter approach, known as General Parametrization \(^[4,15]\), gives up searching for a specific dynamics. Notice that whenever dynamical assumptions are made, discrepancies between theory and experiment in the \(B \rightarrow K\pi\) CP asymmetries arise \(^[16]\).

Hence, even with all the caution needed in interpreting results related to CP asymmetries in purely hadronic exclusive \(B\) decays \(^[4,17]\), one can certainly entertain the possibility that \(B \rightarrow K\pi\) puzzle hints at some physics beyond the SM with new sources of CP violation in addition to the CKM phase \(^[13,19]\). 

As said above, it is true that the \(B \rightarrow K\pi\) puzzle is not the only potential hint for new physics that emerges from rare \(B\) decays. Some tension among values of the parameter \(\sin 2\beta\) which are extracted in different ways from the data has been persisting for some time now and, more recently, a possible evidence for new physics in the CP violating \(b \rightarrow \psi\phi\) decay has been pointed out \(^[11]\). However, the anomaly in the CP asymmetries of the two isospin-related \(B\) decay channels in Eq\(^[2]\) looks peculiarly interesting for the following aspect. The \(B\) decay amplitudes into \(K^+\pi^-\) and \(K^+\pi^0\) differ only by the subleading terms given by the color-suppressed tree contribution \((C)\) and the electroweak penguins \((P_{EW})\). While a resolution of the \(B \rightarrow K\pi\) puzzle through an enhancement of the \(C\) amplitude is unviable \(^[19]\), prospects look more appealing if one tries to invoke a large CP violation from \(P_{EW}\) \(^[19,20]\).

On the other hand, \(P_{EW}\) is essentially real within the SM and has a strong phase very close to the color-allowed tree amplitude \((T)\) \(^[21]\). Hence, making use of \(P_{EW}\) for the resolution of the \(B \rightarrow K\pi\) puzzle entails the presence of new physics beyond the SM with the presence of new sources of CP violation leaking into the electroweak penguins. Indeed, we emphasize that what is actually crucial to overcome the "\(B \rightarrow K\pi\) puzzle" is that \(P_{EW}\) exhibits a large CP violation, but otherwise the new physics electroweak penguins need not be strongly enhanced with respect to the SM ones. This latter observation plays a major role when one tries to account
for the experimental result in Eq. (3) invoking new physics while respecting the vast set of data in rare B physics which represent a stunning confirmation of the SM flavor paradigm encoded in the CKM matrix.

Here we address the above issue in the context of supersymmetric (SUSY) extensions of the SM. If SUSY appears in a context where flavor physics is still fully accounted for by the CKM pattern (the so-called "minimal flavor violation"), then the above CP puzzle remains untouched. It was pointed out that prospects change when one moves to non-minimal flavor SUSY models where the electroweak penguins can be enhanced and new phases may be obtained [11]. It is then compelling to provide an explicit model where the CP puzzle in $B \rightarrow K\pi$ decays is overcome and to study its implications for the flavor changing neutral current (FCNC) phenomenology. This is the aim of the present paper.

We individuate the source of flavor non-minimality in the trilinear scalar terms of the soft SUSY breaking sector, i.e. in the non-universal $A$-terms. Non-universality in the soft breaking terms is a common feature in most superstring inspired SUSY models [22]. Indeed, asking for flavor universality in the SUSY breaking sector of supergravities implies strong constraints on their minimal Kahler potential. Relaxing such constraints, as in several string and D-brane derived models [23], leads to non-degenerate trilinear couplings. It is also worth reminding that non-universal soft SUSY breaking represents an important ingredient, together with new large SUSY CP phases, to produce observable effects in the low-energy CP violating phenomena without exceeding the tough constraint of the experimental electric dipole moments limits [23,24].

The $B \rightarrow K\pi$ decays are driven by the $b \rightarrow s$ transition. The effective Hamiltonian of this transition is given by

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left( C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3}^{10} C_i Q_i ight) + C_{7\gamma} Q_{7\gamma} + C_{8\gamma} Q_{8\gamma} + \left\{ Q_i \rightarrow \bar{Q}_i, C_i \rightarrow \bar{C}_i \right\} \quad (4)$$

where $\lambda_p = V_{pb} V_{ps}^*$, with $V_{pb}$ the unitary CKM matrix elements satisfying the unitarity triangle relation $\lambda_t + \lambda_u + \lambda_c = 0$, and $C_i \equiv C_i(\mu_b)$ are the Wilson coefficients at low energy scale $\mu_b \approx O(m_b)$. The basis $Q_i \equiv Q_i(\mu_b)$ of the relevant local operators renormalized at the same scale $\mu_b$ can be found in Ref. [25]. $Q_{1,2}$ refer to the current-current operators, $Q_{3-6}$ to the QCD penguin operators, and $Q_{7-10}$ to the electroweak penguin operators, while $Q_{7\gamma}$ and $Q_{8\gamma}$ are the magnetic and the chromo-magnetic dipole operators, respectively. In addition, the operators $Q_i \equiv \bar{Q}_i(\mu_b)$ are obtained from $Q_i$ by the chirality exchange $(\bar{q}_1 q_2)_{V \pm A} \rightarrow (\bar{q}_1 q_2)_{V \mp A}$. Notice that in the SM the coefficients $C_i$ identically vanish due to the $V-A$ structure of charged weak currents, while in the Minimal Supersymmetric SM (MSSM) they can receive contributions from both chargino and gluino exchanges.

In our analysis, we adopt the QCDF scheme [9] in evaluating the hadronic matrix elements for exclusive hadronic final states. We assume that the QCD factorization free parameters $\rho_{A,H}$ and $\phi_{A,H}$ are of order one. In this case, the SM contributions to the amplitudes of $B^0 \rightarrow K^+\pi^-$ and $B^+ \rightarrow K^+\pi^0$ can be parameterized as [10]

$$A(B^0 \rightarrow K^+\pi^-) = \lambda_u T e^{i\delta_T} + \lambda_c \left( P e^{i\delta_P} + P_{EW} e^{i\delta_{EW}} \right),$$

$$\sqrt{2} A(B^+ \rightarrow K^+\pi^0) = \lambda_u \left( T e^{i\delta_T} + C e^{i\delta_C} \right) + \lambda_c \left( P e^{i\delta_P} + \rho_{EW} e^{i\delta_{EW}} \right), \quad (5)$$

where the real parameters: $T, C, P, P_{EW},$ and $P_{EW}$ represent color allowed tree, color suppressed tree, QCD penguin, electroweak penguin, and color suppressed electroweak penguin diagrams, respectively. The parameters $\delta_{P,T,C,EW,EW}$ denote the CP conserving (strong) phases of the corresponding amplitudes. In the above expressions, we neglected the small annihilation contribution. Note that in the SM the only source of CP violation for both the B decays under consideration is represented by the phase of the CKM parameter $\lambda_u$, i.e., the penguin contributions are essentially real. As stated above, one finds that the SM contributions to the CP asymmetries of $B^0 \rightarrow K^+\pi^-$ and $B^+ \rightarrow K^+\pi^0$ are very close and with the same sign. Even assuming that the QCD factorization parameter $\rho \gg 1$, the two asymmetries still remain of the same sign [11], at variance with the present experimental result.

We now focus our attention on SUSY models. The relevance of $b \rightarrow s$ transition processes as powerful probes for the presence of low-energy SUSY has been long studied for the most general class of MSSM [4, 26]. Here we stick to the interesting class of MSSM realizations where the source of flavor non-universality resides entirely in the non-universal $A$-terms.

The Wilson coefficients due to the gluino exchange are $C_{7\gamma}^0$ and $C_{8\gamma}^0$, while for the chargino contribution the following Wilson coefficients are important: $C_{7C}^0$, $C_{8C}^0$, $C_{7\gamma}^0$, and $C_{8\gamma}^0$. Note that gluino contributions to $C_{7\gamma}$ and $C_{8\gamma}$ are very small, particularly in this class of model with non-universal $A$-terms and universal squark masses. The complete expressions for these Wilson coefficients can be found in terms of mass insertion approximation in Ref. [11, 27] and in terms of mass eigenstate in Ref. [28]. In our numerical analysis, we use the complete one-loop computation in the mass eigenstate basis.

While for $T$, the SM contribution, $T = T_{SM}$, dominates, sizeable SUSY contributions arise in the penguin sector, $P = P_{SM} + P_{SU SY}$. Notice that the strong CP violating phases associated with $T_{SU SY}$ and $P_{SU SY}$ are in general different from the SM ones.

As said above, we are going to make use of $P_{SU SY}^{EW}$ to account for the isospin breaking difference in the CP asymmetries of Eq. (3). It is then relevant to observe that the electroweak penguins of $B \rightarrow K\pi$ are insensitive to the values of $C_{7\gamma}$ and $C_{8\gamma}$, which give the dominant contributions to the branching ratio of $b \rightarrow s\gamma$. Therefore, the $b \rightarrow s\gamma$ constraint does not pose an immediate threat to our proposal.

In general, the SM and SUSY $B \rightarrow K\pi$ decay amplitudes
can be parametrized as follows:
\[
A_{SM}^\text{SM} = |A_{SM}| e^{i(\theta_{SM} + \delta_{SM})},
\]
\[
A_{SM}^\text{TH} = |A_{SM}| e^{i(-\theta_{SM} + \delta_{SM})},
\]
with similar expression for \(A_{SUSY}^\text{TH}\). Here, \(\delta_{SM(SUSY)}\) is the SM (SUSY) CP conserving phase and \(\theta_{SM(SUSY)}\) is the SM (SUSY) CP violating phase.

The CP asymmetry can be written as
\[
A_{CP} = \frac{2R \sin(\delta_{SM} - \delta_{SUSY}) \sin(\theta_{SM} - \theta_{SUSY})}{1 + R^2 + 2R \cos(\delta_{SM} - \delta_{SUSY}) \cos(\theta_{SM} - \theta_{SUSY})},
\]
where \(R\) is defined as \(R = |A_{SUSY}/A_{SM}|\).

Let us turn to a specific model where to compute the relevant quantities entering the above expression for \(A_{CP}\). We consider a SUSY breaking mechanism giving rise to flavor non-universal trilinear couplings. We parameterize the trilinear matrices \(Y^u_{ij}\) with the so-called “factorizable” \(A\)-terms, \((YA)_{ij} = A_{ij}Y_{ij}\), where \(A_{ij}\) is given by
\[
A_{ij} = \bar{m}_0 \begin{pmatrix} x & y & z \\ x & y & z \end{pmatrix},
\]
with the entries \(x, y\) and \(z\) complex and of order one, while \(Y_{ij}\) are the Yukawa couplings. In general \(A^u\) and \(A^d\) have different structures. Here we assume for simplicity that \(A^{u} = A^{d}\). Again just for simplicity, we consider universality both in the soft scalar mass \(\bar{m}_0\) and gaugino mass \(M_{1/2}\) sectors.

In the super-CKM basis \(Y^A\) reads \(Y^A = Y_{diag}(U.A.V)\), where \(U\) and \(V\) are the left and right rotational matrices that diagonalize the quark mass matrix. The off-diagonal term in the \(LR\) quark mass matrix is proportional to the corresponding quark mass
\[
(\delta_{LR}^q)_{ij} = \frac{m_q}{\bar{m}_0^q} (U.A^q.V)_{ij},
\]
where \(\bar{m}_q\) denotes the average squark mass. Notice that the above choice of the “factorizable” \(A\)-terms implies that the mass insertion \((\delta_{LR}^q)_{11} \approx m_u/\bar{m}_0 \sim \mathcal{O}(10^{-6})\), which is consistent with the stringent neutron EDM constraint \([24]\), even in the presence of large SUSY CP violating phases.

The possibility of exploiting complex nonuniversal \(A\)-terms had been advocated a few years ago in connection with a similar issue of direct CP violation, but in the context of the Kaon system, to account for the size of \(e'/\varepsilon\) \([29]\). Notice that in the present case involving transitions from the third to the second generation, the size of the flavor changing mass insertions can be quite conspicuous. Indeed, \((\delta_{LR}^q)_{32}\), which is relevant for the CP asymmetry of \(B \to K\pi\) mediated by chargino exchange, can be as high as \((\delta_{LR}^q)_{32} \approx m_t/\bar{m}_0 \sim \mathcal{O}(0.1)\). Clearly, the corresponding \((\delta_{LR}^q)_{32}\) in the down-sector is suppressed by the smallness of \(m_t\) compared to \(m_i\) avoiding possible problems with the \(b \to s\gamma\) constraint.

We now come to a quantitative evaluation of the SUSY contributions to the CP asymmetries in our model. In addition to \(\tan \beta\), the free parameters are: \(m_0, m_{1/2}, A_0, |x|, |y|, |z|, \phi_1, \phi_2, \phi_3\), where \(\phi_i\) are the associated phases to the trilinear parameters \(x, y, z\). For simplicity, we assume \(A_0 = m_0\) and set \(m_0 = 300\) GeV, \(m_{1/2} = 500\) GeV and \(\tan \beta = 10\). We vary the other six parameters, taking into account all the relevant constraints imposed on SUSY models, in particular the EDM constraints and the observed limits on the branching ratio of \(B \to s\gamma\). These two constraints are the most important ones to significantly affect our parameter space.

In order to account for the experimental results we ask for the SUSY contributions to be such to give rise to the following two features at variance with respect to what occurs in the SM: i) \(R_{\pi^+K^-}\) should turn out to be larger than \(R_{\pi^0K^-}\), in order to obtain \(|A_{CP}(\pi^+K^-)| > |A_{CP}(\pi^0K^-)|\) and ii) the relative sign between the CP violating and strong phases associated to \(B^0 \to \pi^+K^-\) should be negative, while it should be positive in the \(B^0 \to \pi^0K^-\) case.

In Fig. 1 we display the ratios \(R_{\pi^+K^-}\) and \(R_{\pi^0K^-}\) as function of the trilinear parameter \(z\) for \(x = 1, y = 2\) and \(\phi_i = \mathcal{O}(1)\).

We have checked that for the above choice of the parameter also the second above requirement, namely the fact that the CP violating phases of the amplitudes \(B^0 \to \pi^+K^-\) and \(B^0 \to \pi^0K^-\) have opposite sign, is indeed fulfilled.

The correlation between the two CP asymmetries \(A_{CP}(\pi^+K^-)\) and \(A_{CP}(\pi^0K^-)\) are displayed in Fig. 2.

From this figure, it becomes clear that the experimental results reported in Fig. 2 can be easily accommodated in this class of SUSY models.

In conclusion, we have shown that the presence of new sources of CP violation in the flavor non-universal trilinear scalar terms can originate a (large) phase in the SUSY penguins, in particular in the electroweak ones, leading to a res-
olution of the $B 	o K \pi$ puzzle. Interestingly enough, these sources of CP violation which are linked to the breaking of SUSY could be at the origin of possible deviations from the SM in the two manifestations of direct CP violation in the $K$ and $B$ systems, $\varepsilon'/\varepsilon$ and the $B \to K \pi$ CP violating asymmetries, respectively. The experimental search for other $B$ decay channels (for instance, $B^+ \to J/\psi K^+$ [3]) where the presence of the enhanced CP violation in electroweak penguins can show up is of utmost relevance.

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![FIG. 2: The correlation between the CP asymmetries $A^{CP}(\pi^+ K^-)$ and $A^{CP}(\pi^0 K^-)$ as function of the trilinear parameter $z.$](image-url)