Supersymmetry contributions to $B \to K\pi$ in the view of recent experimental results

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Abstract

Supersymmetric contributions to the branching ratios and CP asymmetries of $B \to K\pi$ decays are analyzed in the view of recent experimental measurements. We show that supersymmetry can still provide a natural solution to the apparent discrepancy between these results and the standard model expectations. We emphasize that chargino contributions may enhance the electroweak penguin effects that can resolve to the $B \to K\pi$ puzzle. We also point out that a non-universal $A$-terms is an essential requirement for this solution.

1 Introduction

Recently, BaBar [1] and Belle [2] collaborations have reported new experimental results for the branching ratios (BRs) and CP asymmetries of $B \to K\pi$ decays. As in the previous measurements [3], the current results point to a lack of compatibility with the Standard Model (SM) expectations, which is known as the $B \to K\pi$ puzzle. The new average values of the experimental measurements of the BRs and CP asymmetry of the four decay channels [4] are given in Table 1.

| Decay channel | $BR \times 10^{-6}$ | $A_{CP}$  |
|---------------|--------------------|----------|
| $K^+\pi^-$    | 19.83 ± 0.63       | −0.099 ± 0.016 |
| $K^+\pi^0$    | 12.83 ± 0.59       | 0.050 ± 0.025  |
| $K^0\pi^+$    | 23.4 ± 1.06        | 0.007 ± 0.025  |
| $K^0\pi^0$    | 9.89 ± 0.63        | −0.12 ± 0.11   |

Table 1: The new average results for the BRs and CP asymmetries of $B \to K\pi$ decays.
It is important to notice that the updated value of the direct CP asymmetry in $B^0 \rightarrow K^+\pi^-$, $A_{CP}(K^+\pi^-) = -0.099\pm 0.016$, corresponds to a $4.3\,\sigma$ deviation from zero. Also the difference between the CP asymmetries $A_{CP}(K^+\pi^-)$ and $A_{CP}(K^+\pi^0)$ is about $3.2\,\sigma$, which is quite difficult to be accommodated within the SM, as emphasized in Ref.[5]. These results might indicate to a large color-suppressed amplitude or enhanced electroweak penguin as it happens in the supersymmetric (SUSY) extension of the SM [5–7].

From the latest measurements for BRs, one finds that the ratios $R_c, R_n$ and $R$ of $B \rightarrow K\pi$ decays are given by

\begin{align}
R_c & = \frac{2 [BR(B^+ \rightarrow K^+\pi^0) + BR(B^- \rightarrow K^-\pi^0)]}{BR(B^+ \rightarrow K^0\pi^+) + BR(B^- \rightarrow K^0\pi^-)} = 1.096 \pm 0.071, \\
R_n & = \frac{1}{2} \left[ \frac{BR(B^0 \rightarrow K^+\pi^-) + BR(\bar{B}^0 \rightarrow K^-\pi^+)}{BR(B^0 \rightarrow K^0\pi^0) + BR(B^0 \rightarrow K^0\pi^-)} \right] = 1.003 \pm 0.071, \\
R & = \frac{\pi_+^B}{\pi_0^B} \left[ \frac{BR(B^0 \rightarrow K^+\pi^-) + BR(\bar{B}^0 \rightarrow K^-\pi^+)}{BR(B^+ \rightarrow K^0\pi^+) + BR(B^- \rightarrow K^0\pi^-)} \right] = 0.923 \pm 0.051.
\end{align}

It is remarkable that $R_n$ has changed significantly from the previous result, where $R_n$ was given by $R_n = 0.79 \pm 0.08$. It is now very close to one, which makes it more consistent with the SM and SUSY expectations. As discussed in Ref.[5], it was rather difficult to account for the situation $R_n < 1$ and $R_c \gtrsim 1$ in both of the SM and SUSY models. In the SM, the amplitudes of $B \rightarrow K\pi$ imply that $R_n = R_c \simeq 1$. While in SUSY models, it is possible to have a deviation between $R_n$ and $R_c$ and to get $R_n$ less than one. However, it has been realized [5,7] that it is quite unnatural to obtain $R_n \simeq 0.79$ with $R_c \simeq 1.1$, although this may occur in a very small region of the parameter space, as shown in Fig. 2 in Ref.[5].

In this letter we update our previous analysis for the supersymmetric contributions to the $B \rightarrow K\pi$ process. We show that the possible supersymmetric solution to the $B \rightarrow K\pi$ puzzle is still consistent with the new experimental results. In fact with the new measurements for the branching ratios, it is now even easier for SUSY to account for the CP asymmetries of $B \rightarrow K\pi$ decays in a wider region of the parameter space. We point out that chargino contributions can enhance the electroweak penguin effects and account for the new experimental results of the BRs and CP asymmetries. We indicate that the left-right (LR) mixing between the second and third generation of up-squarks can provide the source of the required flavor violation in this process.

The article is organized as follows. In section 2 we analyze the supersymmetric contribution to the BRs of the $B \rightarrow K\pi$ decays. We show that with the new experimental results, the supersymmetric solution to the difference $R_n - R_c$ can take place for more points in the parameter space than before. In section 3 we study the supersymmetric contribution to the CP asymmetries of $B \rightarrow K\pi$ decays in view of the recent experimental results. In section 4 we briefly discuss the possibility of having a large mixing in supersymmetric models. Finally we give our conclusions in section 5.
2 SUSY contribution to $B \rightarrow K \pi$ branching ratios

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

$$H_{\text{eff}}^{B=1} = \frac{G_F}{\sqrt{2}} \sum_{p=u,c} \lambda_p \left( C_1 Q_1^p + C_2 Q_2^p + \sum_{i=3}^{10} C_i Q_i + C_7 Q_7 + C_8 Q_8 \right) + h.c., \quad (4)$$

where $\lambda_p = V_{pb} V_{ps}^*$, $Q_i$ are the relevant local operators and $C_i$ are the Wilson coefficients which can be found in Ref.[5]. The decay amplitudes of $B \rightarrow K \pi$ can be parameterized as follows:

$$A_{B^+ \rightarrow K^0 \pi^+} = \lambda_c A_{\pi K} P \left[ e^{-i\theta_p} + r_A e^{i\delta_A} e^{i\gamma} \right]$$

$$\sqrt{2} A_{B^+ \rightarrow K^+ \pi^0} = \lambda_c A_{\pi K} P [e^{-i\theta_p} + (r_A e^{i\delta_A} + r_C e^{i\delta_C}) e^{i\gamma} + r_{EW} e^{-i\theta_{EW}} e^{i\delta_{EW}}] \quad (5)$$

$$A_{B^0 \rightarrow K^+ \pi^-} = \lambda_c A_{\pi K} P [e^{-i\theta_p} + (r_A e^{i\delta_A} + r_C e^{i\delta_C}) e^{i\gamma} + r_{EW} e^{-i\theta_{EW}} e^{i\delta_{EW}}], \quad (6)$$

$$-\sqrt{2} A_{B^0 \rightarrow K^0 \pi^0} = \lambda_c A_{\pi K} P [e^{-i\theta_p} + (r_A e^{i\delta_A} + r_T e^{i\delta_T} - r_C e^{i\delta_C} e^{i\delta_C}) e^{i\gamma} + r_{EW} e^{-i\theta_{EW}} e^{i\delta_{EW}}$$

$$- r_{EW} e^{-i\theta_{EW}} e^{i\delta_{EW}}],$$

(7)

where $\delta_A, \delta_C, \delta_T, \delta_{EW}, \delta_{EW}^C$ and $\theta_p, \theta_{EW}, \theta_{EW}^C$ are the CP conserving (strong) and the CP violating phase, respectively. Here $T, C, A, P, EW, EW^C$ represent a tree, a color suppressed tree, an annihilation, QCD penguin, electroweak penguin, and suppressed electroweak penguin diagrams, respectively. The parameters $P, r_{EW}, r_{EW}^C$ are defined as

$$P e^{i\theta_p} e^{i\delta_p} = \alpha_4^c - \frac{1}{2} \alpha_{4,EW}^c + \beta_3^c + \beta_{3,EW}^c,$$

$$r_{EW} e^{i\theta_{EW}} e^{i\delta_{EW}} = \left[ \frac{3}{2} (R_{K^*} \alpha_{3,EW}^c + \alpha_{4,EW}^c) \right] / P,$$

$$r_{EW}^C e^{i\theta_{EW}^C} e^{i\delta_{EW}^C} = \left[ \frac{3}{2} (\alpha_{4,EW}^c - \beta_{3,EW}^c) \right] / P.$$ (9)

Detailed definitions for these parameters in terms of the relevant Wilson coefficients of the QCD and electroweak penguins can be found in Ref.[5]. In this case, one can expand $R_c$ and $R_n$ in terms of $r_T, r_{EW}$ and $r_{EW}^C$ as follows [5]:

$$R_c \simeq 1 + r_T^2 - 2 r_T \cos(\gamma + \theta_p) + 2 r_{EW} \cos(\theta_p - \theta_{EW}) - 2 r_T r_{EW} \cos(\gamma + \theta_{EW}), \quad (10)$$

$$R_c - R_n \simeq 2 r_T r_{EW} \cos(\gamma + \theta_p - \theta_{EW}) - 2 r_T r_{EW}^C \cos(\gamma + 2 \theta_{EW} - \theta_{EW}^C), \quad (11)$$

where $r_c \simeq r_T$ has been assumed [5]. It interesting to note that within the SM, where $\theta_p = \theta_{EW} = \theta_{EW}^C = 0$ and $r_{EW}^C \simeq 0.01 << r_{EW} \simeq 0.1$, one obtains

$$(R_c - R_n) \big|_{SM} \simeq \mathcal{O}(0.01), \quad (12)$$

which is not consistent with the experimental results.
For gluino mass $m_{\tilde{g}} = 500$ GeV, average squark mass $m_{\tilde{q}} = 500$ GeV, light stop mass $m_{\tilde{t}_R} = 150$ GeV, $M_2 = 200$ GeV, $\mu = 400$ GeV and $\tan \beta = 10$, the SUSY contributions to the $r_{\text{EW}}$ and $r_{\text{EW}}^C$ are given by [5]

$$r_{\text{EW}}^{\text{SUSY}} \simeq r_{\text{EW}}^{\text{SM}} \left[ 1 + 0.053 \tan \beta (\delta_{LL}^u)^{32} - 2.78 (\delta_{LR}^d)^{23} + 1.11 (\delta_{LR}^u)^{32} \right]. \quad (13)$$

and

$$(r_{\text{EW}}^C)^{\text{SUSY}} \simeq (r_{\text{EW}}^C)^{\text{SM}} \left[ 1 + 0.134 \tan \beta (\delta_{LL}^u)^{32} + 26.4 (\delta_{LR}^d)^{23} + 1.62 (\delta_{LR}^u)^{32} \right]. \quad (14)$$

It is worth mentioning that the $r_{\text{EW}}$ and $r_{\text{EW}}^C$ dependence on the down mass insertions $(\delta_{LR}^d)^{23}$ is due to the gluino contribution, mainly via the chromomagnetic operator $Q_{8g}$. While the up mass insertions $(\delta_{LL}^u)^{32}$ and $(\delta_{LR}^u)^{32}$ are due to the chargino contributions (penguin diagrams with chargino in the loop), in particular through $Q_{7\gamma}$, $Q_{8g}$ and Z-penguin, for more details see Ref.[5].

The mass insertion $(\delta_{LR}^d)^{23}$ is constrained by the branching ratio of $b \to s \gamma$, such that $|(\delta_{LR}^d)^{23}| \lesssim 10^{-2}$. Also the mass insertion $(\delta_{LL}^u)^{32}$ can be restricted by $b \to s \gamma$, however this constraints depend on the value of $\tan \beta$ and the phase of this mass insertion, as discussed in details in Ref.[5]. Finally, the $(\delta_{LR}^u)^{32}$ mass insertion is essentially unconstrained and can be of order one. Therefore, as can be seen from Eq.(14), $r_{\text{EW}}^C$ can not be enhanced much in SUSY models and its typical value is of order $O(10^{-2})$ as in the SM, especially in the scenario of dominant mass insertion $(\delta_{LR}^u)^{32}$, which we will adopt in our analysis.

In this case, it is quite safe to neglect the effect of $r_{\text{EW}}^C$ respect to $r_{\text{EW}}$. Therefore, the difference $R_c - R_n$ can be of order 0.1 if $r_r r_{\text{EW}}$ is of order 0.05 and $\cos(\gamma + 2 \theta_P - \theta_{\text{EW}}) \simeq 1$. Since $r_r$ is dominated by the SM values and it is given [5] by $r_r^{\text{SM}} \simeq 0.2$, a value of order 0.25 is required for $r_{\text{EW}}$ to have $R_c - R_n \simeq 0.1$. As can be seen from Eq.(13), such value of $r_{\text{EW}}$ can be obtained with $(\delta_{LR}^u)^{32} \sim O(1)$. It is important to mention that with the previous experimental result for $R_c - R_n$ which was of order 0.2, it was not possible to saturate this difference with single mass insertion contribution and simultaneous contributions from two mass insertions at least are required [7].

### 3 SUSY contribution to $B \to K\pi$ CP asymmetry

The direct CP asymmetry of $B^0 \to K^+\pi^-$ decay is defined as

$$A_{CP}(K^+\pi^-) = \frac{|A(B^0 \to K^+\pi^-)|^2 - |A(\bar{B}^0 \to K^-\pi^+)|^2}{|A(B^0 \to K^+\pi^-)|^2 + |A(\bar{B}^0 \to K^-\pi^+)|^2}, \quad (15)$$

with similar expressions for the asymmetries $A_{CP}(K^0\pi^-)$, $A_{CP}(K^-\pi^0)$ and $A_{CP}(\bar{K}^0\pi^0)$. As is known, a necessary condition to generate a CP asymmetry is that the corresponding
process should have at least two interfering amplitudes with different weak and strong phases. Using the above parametrization in Eqs.(5-8), one finds

\[ A_{CP}(K^+\pi^-) \simeq -2r_T \sin \delta_T \sin(\theta_P + \gamma), \]  
\[ A_{CP}(K^0\pi^+) \simeq -2r_A \sin \delta_A \sin(\theta_P + \gamma), \]  
\[ A_{CP}(K^0\pi^-) \simeq 2r_{\text{ew}} \sin \delta_{\text{ew}} \sin(\theta_P - \theta_{\text{ew}}), \]  
\[ A_{CP}(K^+\pi^0) \simeq -2r_T \sin \delta_T \sin(\theta_P + \gamma) - 2r_{\text{ew}} \sin \delta_{\text{ew}} \sin(\theta_P - \theta_{\text{ew}}), \]  

where we have neglected \( r_{\text{ew}}^C \) respect to \( r_{\text{ew}} \) and \( r_T \). Also we ignored the higher order terms. Here some comments, that can be concluded from the above approximated expressions for the CP asymmetries, are in order:

1. Within the SM, where \( \theta_P = \theta_{\text{ew}} = 0, r_T \simeq 0.2 \) and \( r_{\text{ew}} \simeq 0.1 \), one finds that

\[ A_{CP}(K^+\pi^0) = A_{CP}(K^+\pi^-), \]  

which is not supported by the recent data reported in Table 1.

2. In the SM, the CP asymmetry \( A_{CP}(K^0\pi^0) \) is expected to be close to zero. This may contradict the recent results indicate that \( A_{CP}(K^0\pi^0) \simeq -0.12 \pm 0.11 \).

3. The CP asymmetry \( A_{CP}(K^0\pi^+) \) seems consistent with the SM since \( r_A \simeq \mathcal{O}(0.01) \).

4. It is remarkable that the values of the SUSY CP violating phases \( \theta_P \) and \( \theta_{\text{ew}} \) would play important role in accommodating the experimental measurements of these CP asymmetries.

Now, let us discuss the SUSY contributions to the CP asymmetries \( A_{CP}(K\pi) \). As can be seen from Table 1, the CP asymmetry \( A_{CP}(K^0\pi^0) \) measurement includes a large uncertainty. Therefore, in our analysis for the supersymmetric contributions, we will focus on \( A_{CP}(K^+\pi^-) \) and \( A_{CP}(K^+\pi^0) \). Nonetheless, we will derive the corresponding \( A_{CP}(K^0\pi^0) \) in the region of the SUSY parameter space that leads to a consistent results with experimental measurements. Concerning the \( A_{CP}(K^0\pi^+), \) since \( r_A \) receives negligible SUSY contribution, it remains, as in the SM, of order 0.01. Thus, with a proper value of \( \delta_A \) one can easily get the measured small value \( A_{CP}(K^+\pi^0) \).

In Figs. 1 and 2, we present our numerical results for the CP asymmetries \( A_{CP}(K^+\pi^-) \) and \( A_{CP}(K^+\pi^0) \) as functions of the absolute value and the phase of the dominant mass insertion (\( \delta_{LR}^{\text{ew}} \)), respectively. We have scanned over the relevant strong phases: \( \delta_T \in [-\pi,0] \) and \( \delta_{\text{ew}} \in [0,\pi] \). We have used \( \gamma \simeq \pi/3 \), which gives the best fit for the SM results with the CP experimental measurements. It turns out that \( \sin(\theta_P + \gamma) \) is usually negative, there for a negative \( \sin \delta_T \) is needed to compensate this sign and leads to a negative \( A_{CP}(K^+\pi^-) \), in agreement with the experimental data. In our numerical analysis,
the QCD factorization approximation have been used to estimate the hadronic matrix elements, as in Ref. [5].

From Fig. 1, one can see that within the range of input values used for the strong phases, the predicted results of $A_{CP}(K^+\pi^-)$ in supersymmetric models are always negative. Thus, the experimental results at 1 $\sigma$ level, i.e., $A_{CP}(K^+\pi^-) \in [-0.115, -0.083]$ can be naturally accommodated with $\langle |(\delta^u_{LR})_{32}| \rangle > 0.05$, and no constraint can be imposed on the phase of this mass insertion, although negative region, i.e. $0 < \text{Arg}[(\delta^u_{LR})_{32}] < -\pi/2$, seems more favored.

Furthermore, Fig. 2 implies that the CP asymmetry $A_{CP}(K^+\pi^0)$ can be in its experimental range $[0.025, 0.075]$ when $\langle |(\delta^u_{LR})_{32}| \rangle \gtrsim 0.1$. Also from the second plot in this figure,
one can observe that negative values for the phase of \( (\delta_{LR}^u)_{23} \) are favored, consistently with the conclusion deduced from the result of the asymmetry \( A_{CP}(K^+\pi^-) \).

Now, let us examine the CP asymmetry \( A_{CP}(K^0\pi^0) \) in this region favored by the asymmetries \( A_{CP}(K^+\pi^-) \) and \( A_{CP}(K^+\pi^0) \). It turns out that at \( |(\delta_{LR}^u)_{23}| \simeq 0.4 \) and \( \text{Arg}(\delta_{LR}^u)_{23} \simeq 0(\pm 1) \), which lead to consistent results for both of \( A_{CP}(K^+\pi^-) \) and \( A_{CP}(K^+\pi^0) \) with their experimental measurements, one can easily obtain \( A_{CP}(K^0\pi^0) \simeq -0.1 \), in agreement with the experimental result given in Table 1.

4 Large mixing in SUSY models

As shown in the previous sections, a large mixing between third and second generation of up-squarks is required in order to provide a solution to the \( B \to K\pi \) puzzle. One may ask, is it possible to generate such a large mixing between LR-squarks in SUSY models at electroweak scale without contradicting any other flavor changing neutral current constrains.

In fact, generally there are two ways to obtain a large LR mixing that may lead to \( (\delta_{LR}^u)_{32} \sim 0(1) \). The first way is through non-universal trilinear \( A \)-terms. In this case, \( (\delta_{LR}^u)_{23} \) is given by

\[
(\delta_{LR}^u)_{23} \simeq \frac{1}{\tilde{m}^2} \left[ V_{uL}^+ (Y^u A^u) V_{uR} \right]_{23},
\]

where \( V_{uL,R} \) are the diagonalization of the up quark mass matrix and \( \tilde{m} \) is the average squark mass. Therefore, with a non-hierarchal Yukawa couplings and \( A \)-terms of order \( \tilde{m} \), it is quite plausible to obtain \( (\delta_{LR}^u)_{32} \) of order \( 0(1) \). However, in order to avoid the stringent constraints from the electric dipole moment experimental limits, the \( A \)-term should be Hermitian or it must have a specific pattern. This type of non-universal \( A \)-terms is a salient feature of soft SUSY breaking terms in string or brane inspired models [8].

The second approach for generating large LR mixing is through the non-universal soft scalar masses and large \( \tan\beta \). The simplest example of this class of SUSY models is the one suggested in Ref.[9] as a minimal of non-minimal flavor SUSY model. In these models, the soft SUSY breaking terms are universal except for the third generation squark masses. As explained in Ref.[9], an effective \( (\delta_{LR}^u)_{32} \) mass insertion can be obtained as follows:

\[
(\delta_{LR}^u)_{32} \simeq (\delta_{LL}^u)_{32} (\delta_{LR}^u)_{22},
\]

where the mass insertion \( (\delta_{LR}^u)_{22} \) is approximately given by \( m_c A_c / \tilde{m}^2 \). Here \( m_c \) is the charm quark mass and \( A_c \) is the associate trilinear coupling. Therefore, in order to have \( (\delta_{LR}^u)_{22} \simeq 1 \), the value of \( A_c \) at the weak scale should be of order \( \tilde{m}^2 \), which seems unnatural. Furthermore, since the mass insertion \( (\delta_{LL}^u)_{32} \) is constrained by the branching ratio of \( b \to s\gamma \) to be \( \lesssim 0.1 \), one finds that in this case the resulting mass insertion \( (\delta_{LR}^u)_{32} \)
is less than 0.1. In this respect, one may conclude that the non-universal $A$-terms is an essential requirement in order to have a supersymmetric solution for the $B \rightarrow K\pi$ puzzle.

5 Conclusions

In this letter we have updated our analysis for the supersymmetric contributions to the branching ratios and CP asymmetries of $B \rightarrow K\pi$ decays in the light of recent experimental measurements. We have shown that the new experimental results for the branching ratios allow supersymmetry to become a natural solution for the $B \rightarrow K\pi$ puzzle in a wider region of the parameter space. We have found that within SUSY models with large LR mixing between second and third generation of up-squarks, the chargino contributions can enhance electroweak penguin and accommodate the experimental results for both of the branching ratios and CP asymmetries of $B \rightarrow K\pi$. Finally we emphasized that the non-universal soft SUSY breaking $A$-terms may be the only way to generate the required mixing, which is necessary for this supersymmetric solution.

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