Possible Supersymmetric Solution to the Discrepancy between $B \to \phi K_S$ and $B \to \eta' K_S$ CP Asymmetries

S. Khalil[1,2] and E. Kou[1]

[1]*IPPP, University of Durham, South Road, Durham DH1 3LE, United Kingdom*

[2]*Ain Shams University, Faculty of Science, Cairo, 11566, Egypt*

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We present a possible supersymmetric solution to the discrepancy between the observed mixing CP asymmetries in $B \to \phi K_S$ and $B \to \eta' K_S$. We show that, due to the different parity in the final states of these processes, their supersymmetric contributions from the R sector have opposite signs, which naturally leads to $S_{\phi K_S} \neq S_{\eta' K_S}$. We also consider the proposed mechanisms to solve the puzzle of the observed large branching ratio of $B \to \eta' K$ and their impact on $S_{\eta' K_S}$.

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While in the standard model (SM), all the CP violating phenomena have to be explained by a single phase in the Cabibbo-Kobayashi-Maskawa matrix, the supersymmetric (SUSY) models include additional new sources of CP violation. Since these new effects can manifest themselves in the CP asymmetries of various B-meson decays, the recently observed large discrepancy among the CP asymmetries of $B \to J/\psi K_S$, $B \to \phi K_S$, and $B \to \eta' K_S$ have raised high expectations for indirectly unveiling low energy SUSY [1].

The measurement of the angle of the unitarity triangle $\beta(\phi_1)$ by the so-called golden mode $B \to J/\psi K_S$ [2,3],

$$S_{J/\psi K_S} = \sin 2\beta(2\phi_1) = 0.734 \pm 0.054, \qquad (1)$$

is in good agreement with the other measurements based on the SM analysis. Accordingly, it has been shown that the effect from the SUSY particles in the box diagram which leads to the $B^0 - \overline{B}^0$ mixing is typically small [4]. On the contrary, in summer 2002, the B factory experiments reported a surprising result for the measurement of β by using the $B \to \phi K_S$ process. Since in the SM, $B \to J/\psi K_S$ and $B \to \phi K_S$ have the same $B^0 - \overline{B}^0$ mixing part and do not have any additional CP violating phase in the decay process, the same value of $\sin 2\beta$ was expected to be extracted from them. Thus, the discovered large discrepancy [3,5]

$$S_{\phi K_S} = -0.39 \pm 0.41 \qquad (2)$$

has created quite a stir. Several efforts to explain this experimental data, in particular, by using SUSY models, have been made. In Ref. [6], it has been shown that these phenomena can be understood without contradicting the smallness of the SUSY effect on $B \to J/\psi K_S$ in the framework of the mass insertion approximation, which allows us to perform a model independent analysis of the SUSY breakings [7]. In this approximation, SUSY contributions are proportional to the mass insertions $(\delta^d_{ij})_{AB}$, where i, j and A, B are the generation and chirality indices, respectively. While the measurement of $B \to J/\psi K_S$ implies the smallness of $(\delta^d_{13})_{AB}$, $(A, B = L, R)$, the different generation mass insertion contributing to the $B \to \phi K_S$ process, $(\delta^d_{23})_{AB}$, can deviate $S_{\phi K_S}$ from $S_{J/\psi K_S}$. In this Letter, we discuss another measurement of $\sin 2\beta$ [3,8]:

$$S_{\eta' K_S} = 0.33 \pm 0.34, \qquad (3)$$

which has been thought to be problematic [1]. Since $B \to \eta' K_S$ gets contributions from $(\delta^d_{23})_{AB}$, $S_{\eta' K_S}$ and $S_{\phi K_S}$ were expected to display similar discrepancy from $S_{J/\psi K_S}$. We first show that, although the magnitude of the SUSY contributions to these processes are indeed similar, $B \to \eta' K_S$ has an opposite sign in the coefficient for the RL and RR mass insertions, which can naturally explain the experimental data. In fact, there is another open question on the $B \to \eta' K$ process, the observed unexpectedly large branching ratio [9]. We further investigate the proposed new mechanisms to enhance the branching ratio of $B \to \eta' K$ and their impact on $S_{\eta' K_S}$.

The effective Hamiltonian for the $\Delta B = 1$ processes induced by gluino exchanges can be expressed as

$$H^{\Delta B=1}_{\rm eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V^*_{ts} \sum_{i=3-6,g} [C_i O_i + \tilde{C}_i \tilde{O}_i], \qquad (4)$$

where the operators $\tilde{O}_i$ can be obtained from O_i by exchanging $L \leftrightarrow R$. The Wilson coefficients C_i and $\tilde{C}_i$ are proportional to $\delta_{LL,LR}$ and $\delta_{RR,RL}$, respectively. The definition of the operators and Wilson coefficients (and the effective Wilson coefficients below) can be found in Ref. [6]. Employing the naive factorization approximation [10], where all the color factor N is assumed to be 3, the amplitude for the $B \to \phi K$ process can be expressed as

$$\overline{A}(\phi K) = -\frac{G_F}{\sqrt{2}} V_{tb} V^*_{ts} \sum_{i=3}^{6} [C^{\rm eff}_i + \tilde{C}^{\rm eff}_i] \langle \phi \bar{K}^0 | O_i | \bar{B}^0 \rangle,$$

where we used

$$\langle \phi \bar{K}^0 | O_i | \bar{B}^0 \rangle = \langle \phi \bar{K}^0 | \tilde{O}_i | \bar{B}^0 \rangle. \qquad (5)$$

On the other hand, the amplitude for $B \to \eta' K$ can be written by

$$\bar{A}(\eta' K) = \frac{G_F}{\sqrt{2}} V_{ub} V_{us}^* \left[\sum_{i=1}^{2} C_i^{\rm eff} \right] \langle \eta' \bar{K}^0 | O_i | \bar{B}^0 \rangle - \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left[\sum_{i=3}^{6} (C_i^{\rm eff} - \tilde{C}_i^{\rm eff}) \right] \langle \eta' \bar{K}^0 | O_i | \bar{B}^0 \rangle,$$

where we used

$$\langle \eta' \bar{K}^0 | O_i | \bar{B}^0 \rangle = -\langle \eta' \bar{K}^0 | \tilde{O}_i | \bar{B}^0 \rangle, \quad (6)$$

which is derived by the fact that the decay constant of η' is sensitive to the chirality of the quarks. The tree contributions to $B \to \eta' K_S$ are found to be less than 1% and can be ignored.

Numerical results on the ratio between SM and SUSY amplitudes for $m_{\tilde{g}} \simeq m_{\tilde{q}} = 500$ GeV are obtained as [6]

$$\left(\frac{A^{\rm SUSY}}{A^{\rm SM}} \right)_{\phi K_S} \simeq (0.23 + 0.04i)[(\delta_{LL}^d)_{23} + (\delta_{RR}^d)_{23}] + (95 + 14i)[(\delta_{LR}^d)_{23} + (\delta_{RL}^d)_{23}], \quad (7)$$

$$\left(\frac{A^{\rm SUSY}}{A^{\rm SM}} \right)_{\eta' K_S} \simeq (0.23 + 0.04i)[(\delta_{LL}^d)_{23} - (\delta_{RR}^d)_{23}] + (99 + 15i)[(\delta_{LR}^d)_{23} - (\delta_{RL}^d)_{23}], \quad (8)$$

where a parameter q^2 is chosen to be $m_b^2/4$. The variation of q^2 within the range of $m_b^2/6 < q^2 < m_b^2/3$ causes $\pm 30\%$ of theoretical uncertainty (see Ref. [6] for more detailed discussions on q^2 dependence). This problem of the unphysical q^2 dependence was recently solved by new technology, the so-called QCD factorization (QCDF) approach [13]. Our result is consistent with the one using QCDF within the errors caused by the coefficients with the higher Gegenbauer terms [14]. The small imaginary parts in Eqs. (7) and (8) are the strong phases which come from the QCD correction terms in the effective Wilson coefficient in Ref. [10]. The different sign for the contributions from the O_i and $\tilde{O}_i$ in $B \to \eta' K_S$ [see Eq. (6)] gives the minus sign for the coefficients of the RL and RR mass insertions in Eq. (8). It is important to mention that this sign flip is not due to using the naive factorization approximation and would not be influenced by any other QCD corrections. Note that the absolute value of the mass insertion $(\delta_{AB}^d)_{23}$, which is relevant to the $b \to s$ transition, is constrained by the experimental results for the branching ratio of the $B \to X_S \gamma$ decay: $|(\delta_{LL,RR}^d)_{23}| < 1$, $|(\delta_{LR,RL}^d)_{23}| \lesssim 1.6 \times 10^{-2}$ [15].

We found that the coefficients for each mass insertion are almost the same in $B \to \phi K$ and $B \to \eta' K$, apart from the signs. Accordingly, we reparametrize these ratios as

$$\left(\frac{A^{\rm SUSY}}{A^{\rm SM}} \right)_{\phi K_S} \equiv R_\phi e^{i\delta_{12}} e^{i\theta_\phi} = \delta_L e^{i \arg \delta_L} + \delta_R e^{i \arg \delta_R}, \quad (9)$$

$$\left(\frac{A^{\rm SUSY}}{A^{\rm SM}} \right)_{\eta' K_S} \equiv R_{\eta'} e^{i\delta_{12}} e^{i\theta_{\eta'}} \simeq \delta_L e^{i \arg \delta_L} - \delta_R e^{i \arg \delta_R}, \quad (10)$$

where $\theta_{\phi(\eta')}$ and δ_{12} are CP violating and conserving phase differences between SM and SUSY, respectively. δ_L and δ_R include the contributions proportional to the mass insertions $(\delta_{LL,LR}^d)_{23}$ and $(\delta_{RR,RL}^d)_{23}$, respectively. Using these parameters, the mixing CP asymmetry is given as [6]

$$S_{\phi K_S(\eta' K_S)} = \frac{\sin 2\beta + 2R_{\phi(\eta')} \cos\delta_{12} \sin(\theta_{\phi(\eta')} + 2\beta) + R_{\phi(\eta')}^2 \sin(2\theta_{\phi(\eta')} + 2\beta)}{1 + 2R_{\phi(\eta')} \cos\delta_{12} \cos\theta_{\phi(\eta')} + R_{\phi(\eta')}^2},$$

where we use $\sin 2\beta = 0.73$ in our analysis. As can be seen from the above formulas, the strong phase enters only as $\cos\delta_{12}$ and the small strong phases found in Eqs. (7) and (8) lead to $\cos\delta_{12} = 0.99$. Thus, we use $\cos\delta_{12} = 1$ in the following.

Here let us recall our main conclusions on $S_{\phi K_S}$ in Ref. [6]. $S_{\phi K_S}$ as a function of θ_ϕ behaves as a $\sin\theta_\phi$ curve taking the value $S_{\phi K_S} = 0.73$ at the origin and bounded above by 1. A typical behavior of $S_{\phi K_S}$ with $R_\phi = 0.5$ and $\cos\delta_{12} = 1$ is shown as the solid line in Fig. 1. In the following, we use this result as a reference and fix $R_\phi = 0.5$ and also focus on the region $-3\pi/4 \leq \theta_\phi \leq -\pi/2$, where $S_{\phi K_S}$ becomes negative.

Now let us discuss the $B \to \eta' K_S$ process and see if we can explain the puzzle of the observed mixing CP asymmetries: $S_{\phi K_S} \leq 0$ while $S_{\eta' K_S} \gtrsim S_{J/\psi K_S}$. First, we show our result without including the contributions from these new mechanisms suggested to enhance the branching ratio of $B \to \eta' K$ in order to see explicitly the different behaviors of $S_{\phi K_S}$ and $S_{\eta' K_S}$ due to the minus sign in Eq. (10). Having some possible SUSY models in mind, we perform a case-by-case study in the following.

Case 1: $|\delta_R| \gg |\delta_L|$.—Equations (9) and (10) lead to

$$R_\phi e^{i\theta_\phi} = |\delta_R| e^{i \arg \delta_R}, \quad (11)$$

$$R_{\eta'} e^{i\theta_{\eta'}} = |\delta_R| e^{i(\arg \delta_R + \pi)}. \quad (12)$$

The CP asymmetry $S_{\eta' K_S}$ as a function of $\arg\delta_R (= \theta_\phi)$ is shown as a dashed line in Fig. 1. $|\delta_R|$ is fixed to have $R_\phi = |\delta_R| = 0.5$. As can be seen from this figure, $S_{\eta' K_S}$ is always larger than the experimental data in Eq. (3) where $S_{\phi K_S}$ is within the experimental range. Note that the $|\delta_L|$ dominated models give the same curve as $S_{\phi K_S}$.

Case 2: $|\delta_L| = |\delta_R|$—In this case, Eqs. (9) and (10) are reduced to

$$R_{\phi K_S} e^{i\theta_\phi} = 2|\delta_L| \cos\frac{\Delta\theta}{2} e^{i(\arg\delta_L + \arg\delta_R)/2}, \quad (13)$$

$$R_{\eta' K_S} e^{i\theta_{\eta'}} = 2|\delta_L| \sin\frac{\Delta\theta}{2} e^{i(\arg\delta_L + \arg\delta_R + \pi)/2}, \quad (14)$$

where $\Delta\theta = \arg\delta_L - \arg\delta_R$. We depict $S_{\eta' K_S}$ as a function of $(\arg\delta_L + \arg\delta_R)/2 (= \theta_\phi)$ for $\Delta\theta = \pi/10$ as the dotted line in Fig. 1. We fix $|\delta_L|$ so as to have $R_\phi = 0.5$. The $\pi/2$ shift appearing in Eq. (14) can be clearly seen in the plot. It is also remarkable that in this case, not only the phase shift between θ_ϕ and $\theta_{\eta'}$ but also the amplitude difference which is given in terms of $\Delta\theta$ differentiate the behavior of $S_{\phi K_S}$ and $S_{\eta' K_S}$. In particular, for small $\Delta\theta$, no matter what the value of $|\delta_L|$ is, $S_{\eta' K_S}$ takes a value close to $\sin 2\beta$.

Case 3: $\arg\delta_L = \arg\delta_R$—In this case, we have

$$R_\phi e^{i\theta_\phi} = (|\delta_L| + |\delta_R|) e^{i \arg\delta_L}, \quad (15)$$

$$R_{\eta'} e^{i\theta_{\eta'}} = \Delta|\delta| e^{i\arg\delta_L}, \quad (16)$$

where $\Delta|\delta| = |\delta_L| - |\delta_R|$. We show our results for $S_{\eta' K_S}$ in terms of $\arg\delta_L (= \theta_\phi)$ in Fig. 1 for $R_\phi = |\delta_L| + |\delta_R| = 0.5$ and $\Delta|\delta| = 0.2$ (dashed-dotted line). We found that the experimental bound gives a constraint of $0 \lesssim \Delta|\delta| \lesssim 0.4$.

Case 4: $\arg\delta_R = \arg\delta_L + \pi/2$—In this case, we have

$$R_\phi e^{i\theta_\phi} = \sqrt{|\delta_L|^2 + |\delta_R|^2} e^{i(\arg\delta_L + \alpha)}, \quad (17)$$

$$R_{\eta'} e^{i\theta_{\eta'}} = \sqrt{|\delta_L|^2 + |\delta_R|^2} e^{i(\arg\delta_L - \alpha)}, \quad (18)$$

where $\tan\alpha = |\delta_R|/|\delta_L|$. In Fig. 1, we plot the result of $S_{\eta' K_S}$ as a function of $\arg\delta_L + \alpha (= \theta_\phi)$ for $R_\phi = \sqrt{|\delta_L|^2 + |\delta_R|^2} = 0.5$ with $\alpha = 5\pi/4$ (dashed–double-dotted line). With the phase shift of 2α, one can have both $S_{\phi K_S}$ and $S_{\eta' K_S}$ within their experimental range.

We should comment that the above model independent analysis can be realized in well known SUSY models. For example, the SUSY models with Hermitian flavor structure [16] are a realization of case 2 with $\Delta\theta = \pi$. Also, the SUSY seesaw models [17] correspond to case 1. Therefore, case 1 can accommodate these models.

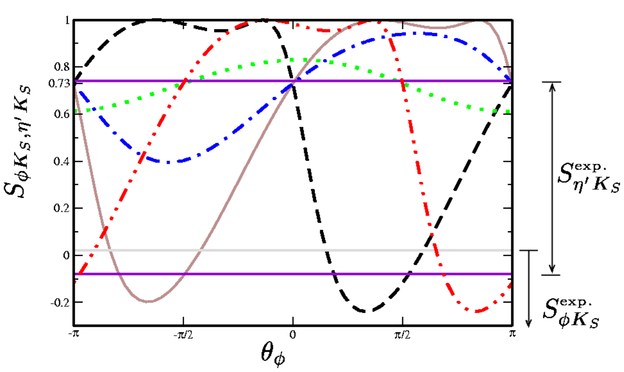

FIG. 1 (color online). $S_{\phi K_S}$ (solid line) and $S_{\eta' K_S}$ versus θ_ϕ for $R_\phi = 0.5$ (dashed line for case 1, dotted line for case 2, dashed-dotted line for case 3, and dashed–double-dotted line for case 4).

As mentioned, another large discrepancy is observed in the branching ratio of the $B \to \eta' K$ process [9]:

$$Br^{\rm exp}(B \to \eta' K) = (55^{+19}_{-16} \pm 8) \times 10^{-6}, \quad (19)$$

which is 2 to 5 times larger than the standard model calculation [18]. Since such a large deviation is observed only in the $B \to \eta' K$ process, the new mechanisms based on the peculiarity of η' meson, for instance, intrinsic charm [19] or gluonium contents of η' [20], have been investigated. We discuss in the following the SUSY effects to the branching ratio and the impacts of those new mechanisms on the mixing *CP* asymmetry $S_{\eta' K_S}$.

Let us first discuss the SUSY contributions and also the uncertainties from various SM parameters. In general, the SUSY contributions can be written as

$$Br(B \to \eta' K) = Br_{\rm SM}(B \to \eta' K) \times [1 + 2\cos(\theta_{\eta'} - \delta_{12}) R_{\eta'} + R_{\eta'}^2].$$

Note that this equation can be applied to $B \to \phi K$ by replacing the indices. The input parameters which are used in our above analysis lead to $Br_{\rm SM}(B \to \eta' K) = 13 \times 10^{-6}$. In fact, this value is sensitive, especially to the s quark mass and the value of q^2 in our calculation. For instance, $m_s = 0.08$ GeV and $q^2 = m_b^2/2$ give $Br_{\rm SM}(B \to \eta' K) = 36 \times 10^{-6}$. However, such a small value of m_s enhances the branching ratio of some similar processes such as $B \to \pi K$ [18] and also a larger q^2 is disfavored by analysis of $S_{\phi K_S}$ [6]. A maximum enhancement from SUSY contributions can be obtained by $\theta_{\eta'} = n\pi$, $n = 0, 1 \ldots$ and $\cos\delta_{12} = 1$, which lead to $Br(B \to \eta' K) = 2.25 \times Br_{\rm SM}(B \to \eta' K)$ for $R_{\eta'} \simeq 0.5$. Interestingly, our solution to reproduce the experimental result of $S_{\phi K_S}$ and $S_{\eta' K_S}$ requires a shift between θ_ϕ and $\theta_{\eta'}$, which may suppress the leading SUSY contribution to the branching ratio for $B \to \phi K$. Thus, it is possible to enhance $B \to \eta' K$ without changing the prediction for $B \to \phi K$ too much. On the other hand, the other similar processes such as $B \to \pi K$ require more attention. Apart from its tree contributions, $B \to \pi K$ obtains as large SUSY contributions as $B \to \eta' K$. Therefore, we must not ignore the limitation given by these similar processes, which will be revealed as soon as more precise experimental data from those processes is available.

Now we turn to the new mechanisms proposed to enhance $Br(B \to \eta' K)$ and its impacts on $S_{\eta' K_S}$. We rewrite the amplitude in the following way:

$$A(\eta' K) = A^{\rm SM}_{\eta' K_S} + A^{\rm SUSY}_{\eta' K_S} + G^{\rm SM} + G^{\rm SUSY}, \quad (20)$$

where $G^{\rm SM}$ and $G^{\rm SUSY}$ are the new mechanism contributions to SM and SUSY, respectively. Accordingly, the branching ratio including the contributions from both

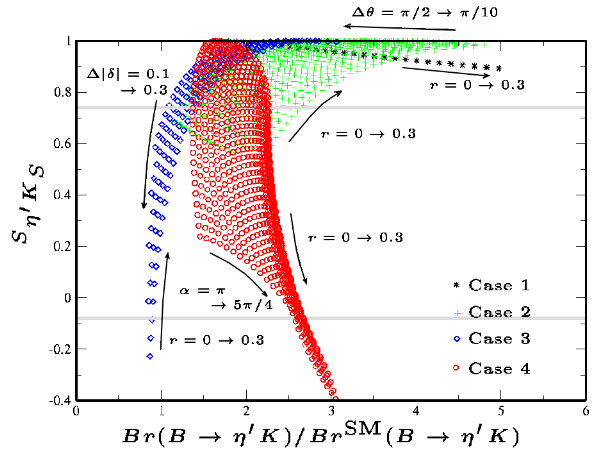

FIG. 2 (color online). A case-by-case study for the branching ratio of $B \to \eta' K$ versus the mixing CP asymmetry $S_{\eta' K_S}$. We assume that $R_\phi \simeq 0.5$ and $\theta_\phi \simeq -5\pi/8$, which lead to $S_{\phi K_S} \simeq -0.2$. The parameter r represents the spectator gluonium contribution in SM.

SUSY and new mechanisms is modified to

$$Br(B \to \eta' K) = Br_{\rm SM}(B \to \eta' K)(1+r)^2 \times [1 + 2\cos(\theta'_{\eta'} - \delta_{12})R'_{\eta'} + R'^2_{\eta'}],$$

where $r \equiv G^{\rm SM}/A^{\rm SM}_{\eta' K_S}$ and $R'_{\eta'} e^{i\theta'_{\eta'}} = (A^{\rm SUSY}_{\eta' K_S} + G^{\rm SUSY})/(A^{\rm SM}_{\eta' K_S} + G^{\rm SM})$. Note that $Br_{\rm SM}(B \to \eta' K)$ does not include the new mechanism contributions. Having the gluonium contributions in mind, we parametrize the SUSY contributions from the new mechanism as

$$\frac{G^{\rm SUSY}}{G^{\rm SM}} = a[(\delta^d_{LL})_{23} + (\delta^d_{RR})_{23}] + b[(\delta^d_{LR})_{23} + (\delta^d_{RL})_{23}],$$

where $[\delta^d_{LL(LR)}]_{23}$ and $[\delta^d_{RR(RL)}]_{23}$ have the same coefficient due to the penguin process and also the same sign since the amplitude is proportional to only the $B - K$ transition form factor. Thus, Eq. (8) is modified to

$$R'_{\eta'} e^{i\theta'_{\eta'}} \simeq \left(\frac{0.23 + ar}{1+r}\right)(\delta^d_{LL})_{23} + \left(\frac{101 + br}{1+r}\right)(\delta^d_{LR})_{23} - \left(\frac{101 - br}{1+r}\right)(\delta^d_{RL})_{23} - \left(\frac{0.23 - ar}{1+r}\right)(\delta^d_{RR})_{23}. \quad (21)$$

Although the quantitative estimation of r is difficult at the moment, the parameters a and b could be computed for a given mechanism. For the intrinsic charm contribution, we have $a = b = 0$ since it come from a tree diagram. For the spectator gluonium contribution $[G^{\rm SUSY}/G^{\rm SM} \simeq \sqrt{2}/(V_{tb}V^*_{ts}G_F)C^{\rm SUSY}_g/C^{\rm SM}_g]$, we obtain $a = -1.2$ and $b = -585$ at the LL order. The spectator gluonium process means that the weak $b \to sg$ transition (chromomagnetic operator O_g) accompanied by one gluon emission from spectator is followed by two gluon fusion into gluonium in η' [21,22]. Using these values in Eq. (21), we find that as r increases $|\delta_L|_{\eta'}$ is reduced and $|\delta_R|_{\eta'}$ is enlarged. In fact, this does not disturb our previous explanation for the discrepancy between $S_{\phi K_S}$ and $S_{\eta' K_S}$, especially because the signs in front of $|\delta_R|_\phi$ and $|\delta_R|_{\eta'}$ remain different, which was a crucial point. In Fig. 2, we show the result for the branching ratio versus $S_{\eta' K_S}$ for cases 1–4 including the spectator gluonium contribution. We fix $R_\phi = 0.5$ and $\theta_\phi = -5\pi/8$ in order to have $S_{\phi K_S} \simeq -0.2$. As can be seen from this figure, we can have both the CP asymmetry of $B \to \eta' K_S$ and its branching ratio within the experimental limits in a significant range of SUSY parameter space.

To conclude, we have considered possible supersymmetric contributions to the CP asymmetry $S_{\phi K_S}$ and $S_{\eta' K_S}$. We showed that the discrepancy between their measurements can be naturally resolved by considering the different parity sensitivity of these processes to the SUSY contributions from the R sector. We also studied the observed large branching ratio of $B \to \eta' K$. We have considered the new mechanisms proposed to enhance $Br(B \to \eta' K)$ and their impact on $S_{\phi K_S} - S_{\eta' K_S}$ correlation.

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