$B_d \to \phi K_S$ CP asymmetries as an important probe of supersymmetry

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The decay $B_d \to \phi K_S$ is a special probe of physics beyond the Standard Model (SM), since it has no SM tree level contribution. Motivated by recent data suggesting a deviation from the SM for its time-dependent CP asymmetry, we examine supersymmetric explanations. Chirality preserving contributions are generally small, unless gluino is relatively light. Higgs contributions are also too small to explain a large asymmetry. Chirality flipping $LR$ and $RL$ gluino contributions actually can provide sizable effects without conflict with all related results. We discuss how various insertions can be distinguished, and argue the needed sizes of mass insertions are reasonable.

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$B \to \phi K$ is a powerful testing ground for new physics. Because it is loop suppressed in the standard model (SM), this decay is very sensitive to possible new physics contributions to $b \to s\bar{s}s$, a feature not shared by other charmless $B$ decays. Within the SM, it is dominated by the QCD penguin diagrams with a top quark in the loop. Therefore the time dependent CP asymmetries are essentially the same as those in $B \to J/\psi K_S$:

$$\sin 2\beta_{\phi K_S} \simeq \sin 2\beta_{J/\psi K_S} + O(\lambda^2).$$

Recently both BaBar and Belle reported the branching ratio and CP asymmetries in the $B_d \to \phi K_S$ decay:

$$B \to \phi K \to \phi K_S.$$

and the angle $\theta_d$ represents any new physics contributions to the $B_d - \overline{B_d}$ mixing angle. They find $\sin 2\beta_{\phi K} = S_{\phi K} = -0.39 \pm 0.41$ [4], which is a 2.7 $\sigma$ deviation from the SM prediction: $\sin 2\beta_{J/\psi K_S} = 0.734 \pm 0.054$ [3]. On the other hand, the measured branching ratio $(8 - 9) \times 10^{-6}$ is not far from the SM prediction. The direct CP asymmetry in $B_d \to \phi K_S$ is also reported by the Belle collaboration: $C_{\phi K_S} = 0.56 \pm 0.43$.

In this paper, we wish to explain the deviation of $\sin 2\beta_{\phi K_S}$ from $\sin 2\beta_{J/\psi K_S}$ within general SUSY models with $R$-parity conservation. (See Refs. [4] for related works.) There are basically two interesting classes of modifications: (i) gluino-mediated $b \to sq\bar{q}$ with $q = u,d,s,c,b$ induced by flavor mixings in the down-squark sector, and (ii) Higgs mediated $b \to s\bar{s}s$ in the large $\tan \beta$ limit ($\propto \tan^3 \beta$ at the amplitude level). In the following, we analyze the effects of these two mechanisms on the branching ratio of $B_d \to \phi K_S$, $S_{\phi K}$, $C_{\phi K}$, $B \to X_s \gamma$ and its direct CP asymmetry, $B_0^0 - \overline{B_0^0}$ mixing, and the correlation of the Higgs mediated $b \to s\bar{s}s$ transition with $B_s \to \mu^+\mu^-$. We will deduce that $LL$ and $RR$ insertions give effects too small to cause an observable deviation between $S_{\phi K}$ and $S_{J/\psi K_S}$, unless the gluino and squarks have masses close to the current lower bounds. Once the existing CDF limit on $B_s \to \mu^+\mu^-$ is imposed...
on the Higgs mediated $b \to s\bar{s}s$, that also provides too small an effect. On the other hand, the down-sector $LR$ and $RL$ insertions can provide a sizable deviation in a robust way consistent with all other data.

In the general MSSM, the squark and the quark mass matrices are not diagonalized simultaneously. There will be gluino mediated FCNC of strong interaction strength, which may even exceed existing limits. It is customary to rotate the effects so they occur in squark propagators rather than in couplings, and to parametrize them in terms of dimensionless parameters. We work in the usual mass insertion approximation (MIA) \( \delta \), where the flavor mixing \( j \to i \) in the down type squarks associated with \( q_B \) and \( q_A \) is parametrized by \( \delta_{AB}^{ij} \). More explicitly,

\[
(\delta_{LL}^{d})_{ij} = \left( V^d_L M_Q^2 V^d_L \right)_{ij} / \tilde{m}^2, \quad \text{etc.}
\]

in the super CKM basis where the quark mass matrices are diagonalized by \( V^d_L \) and \( V^d_R \), and the squark mass matrices are rotated in the same way. Here \( M_Q^2, M_D^2 \) and \( M_{LR}^2 \) are squark mass matrices, and \( \tilde{m} \) is the average squark mass. Because we are considering \( b \to s\bar{s}s \) transitions, we have \( (i, j) = (2, 3) \).

Since the decay $B_d \to \phi K_S$ is dominated by SM QCD penguin operators, the gluino-mediated QCD penguins may be significant if the gluinos and squarks are not too heavy. For $LL$ and $RR$ mass insertions, the gluino-mediated diagrams can contribute to a number of operators already present in the SM, such as those with LH flavor-changing currents \( (O_{3,6}) \) and the magnetic and chromomagnetic operators \( (O_{7r}, O_{8g}) \). On the other hand $LR$ and $RL$ insertions do not generate \( O_{3,6} \). (All operators are explicitly defined in \[8\].) But $RR$ and $RL$ insertions also generate operators with RH flavor-changing currents and so we must consider the operators \( O_{3,6}, O_{7r}, O_{8g} \) which are derived from the untilded operators by the exchange $L \leftrightarrow R$. In the SM, the \( O_{3,6} \) operators are absent and the \( O_{7r,8g} \) operators are suppressed by light quark masses, \( m_q \). But in SUSY, \( O_{7r,8g} \) in particular can be enhanced by \( \tilde{m}/m_q \) with respect to the SM, making them important phenomenologically. Of course, these gluino induced FCNC could also affect $B \to J/\psi K_S$ in principle. But this gold-plated mode for $\sin 2\beta$ is dominated by a tree level diagram in the SM, and the SUSY loop corrections are negligible.

We calculate the Wilson coefficients corresponding to each of these operators at scale $\mu \sim \tilde{m} \sim m_W$; explicit expressions are in Ref. \[8\]. We evolve the Wilson coefficients to $\mu \sim m_S$ using the appropriate renormalization group (RG) equations \[10\], and calculate the amplitude for $B \to \phi K$ using the recent BBNS approach \[8\] for estimating the hadronic matrix elements.

The explicit expressions for $\Gamma(B \to \phi K_S)$ can be found in Refs. \[8,9\]. In the numerical analysis presented here, we fix the SUSY parameters to be \( m_3 = \tilde{m} = 400 \text{ GeV} \). In each of the mass insertion scenarios to be discussed, we vary the mass insertions over the range $|\delta_{AB}^{ij}| \leq 1$ to fully map the parameter space. We then impose two important experimental constraints. First, we demand that the predicted branching ratio for inclusive $B \to X_s \gamma$ fall within the range $2.0 \times 10^{-4} < B(B \to X_s \gamma) < 4.5 \times 10^{-4}$, which is rather generous in order to allow for various theoretical uncertainties. Second, we impose the current lower limit on $M_\chi > 14.9 \text{ ps}^{-1}$.

A new CP-violating phase in $(\delta_{AB}^{d})_{23}$ will also generate CP violation in $B \to X_s \gamma$. The current data on the direct CP asymmetry $A_{\text{CP}}^{\phi \to \gamma}$ from CLEO is \[11\] $A_{\text{CP}}^{\phi \to \gamma} = (-0.079 \pm 0.108 \pm 0.022)(1.0 \pm 0.030)$, which is not particularly constraining. Within the SM, the predicted CP asymmetry is less than $\sim 0.5\%$, so a larger asymmetry would be a clear indication of new physics \[12\].

Remarkably, despite the well-known importance of $B \to X_s \gamma$ for constraining $(\delta_{AB}^{d})_{23}$, we will find in the following that the $B \to \phi K$ branching ratio provides an independent constraint on the $LR$ and $RL$ insertions which is already as strong as that derived from $B \to X_s \gamma$. Where relevant, we will show our predictions for $A_{\text{CP}}^{\phi \to \gamma}$.

Next we consider the case of a single $LL$ mass insertion: $(\delta_{LL}^{d})_{23}$. Our results will hold equally well for a single $RR$ insertion. Though the $LL$ insertion generates all of the operators $O_{3,6,7r,8g}$, qualitatively there are substantial cancellations between their SUSY contributions and so the effect of the $LL$ insertion is significantly diluted. Scanning over the parameter space as discussed previously, we find that $S_{\phi K} > 0.5$ for $m_3 = \tilde{m} = 400 \text{ GeV}$ and for any value of $|\delta_{LL}^{d})_{23}| \leq 1$, the lowest values being achieved only for very large $\Delta M_s$. If we lower the gluino mass down to 250 GeV, $S_{\phi K}$ can shift down to $\sim 0.05$, but only in a small corner of parameter space. Similar results hold for a single $RR$ insertion. Thus we conclude that the effects of the $LL$ and $RR$ insertions on $B \to X_s \gamma$ and $B \to \phi K$ are not sufficient to generate a (large) negative $S_{\phi K}$, unless gluino and squarks are relatively light. Nonetheless, their effects on $B_s - \bar{B}_s$ mixing could still be large and observable, providing a clear signature for $LL$ and $RR$ mass insertions (see Ref. \[8\] for details).

Next we consider the case of a single $LR$ insertion. Scanning over the parameter space and imposing the constraints from $B \to X_s \gamma$ and $\Delta M_s$, we find $|\delta_{LR}^{d})_{23}| \lesssim 10^{-2}$. This is, however, large enough to significantly affect $B \to \phi K_s$, both its branching ratio and CP asymmetries, through the contribution to $C_{15}$. In Fig. (1,a), we show the correlation between $S_{\phi K}$ and $C_{15}$. Since the $LR$ insertion can have a large effect on the CP-averaged branching ratio for $B \to \phi K$ we further impose that $B(B \to \phi K) < 1.6 \times 10^{-5}$ (which is twice the experimental value) in order to include theoretical uncertainties in the BBNS approach related to hadronic physics. Surprisingly, we see that the $B \to \phi K$ branching ratio constrains $(\delta_{LR}^{d})_{23}$ just as much as $B \to X_s \gamma$.

Studying Fig. 1, we can learn much about the viability...
and testability of scenarios with a single LR insertion. For one thing, we can get negative $S_{\phi K}$, but only if $C_{\phi K}$ is also negative (this is excluded by the present data, but only at the 1.4σ level). Conversely, a positive $C_{\phi K}$ implies that $S_{\phi K} > 0.6$. This correlation between $S_{\phi K}$ and $C_{\phi K}$ can be tested at B factories in the near future given better statistics. The correlation between $S_{\phi K}$ and the direct CP asymmetry in $B \to X_s \gamma$ ($= A_{\text{CP}}^{b \to s \gamma}$) is shown in Fig. 1(b). We find $A_{\text{CP}}^{b \to s \gamma}$ becomes positive for a negative $S_{\phi K}$, while a negative $A_{\text{CP}}^{b \to s \gamma}$ implies that $S_{\phi K} > 0.6$. It is also clear from the figure that the present CLEO bound on $A_{\text{CP}}^{b \to s \gamma}$ does not significantly constrain the LR model. Finally, we also find that the deviation of $B_d \to \overline{B}_d$ mixing from the SM prediction is small after imposing the $B_d \to X_s \gamma$ and $B_d \to \phi K_S$ branching ratio constraints. Thus we conclude that a single LR insertion can describe the data on $S_{\phi K}$ but only if the measurement of $C_{\phi K}$ shifts to negative values. This scenario can then be tested by measuring a positive direct CP asymmetry in $B \to X_s \gamma$ and $B_d \to \overline{B}_d$ mixing consistent with the SM.

The last single mass insertion case is that of RL. We find that the RL operator most conveniently describes the current data. For example, in Figs. 2(a) and (b), we show the correlation of $S_{\phi K}$ with $B(B \to \phi K)$ and $C_{\phi K}$, respectively, in the RL dominance scenario. We find that $S_{\phi K}$ can take almost any value between $-1$ and $+1$ without conflict with the observed branching ratio for $B \to \phi K$. We also find that $C_{\phi K}$ can be positive for a negative $S_{\phi K}$, unlike in the LR case. In particular, if we impose the $B(B_d \to \phi K^0)$ constraint, then $|C_{\phi K}| > 0.2$ for $S_{\phi K} < 0$, except in very small regions of parameter space. This could be a useful check on the presence of the RL operator. But the RL operator leaves SM predictions intact in two important observables. First, within the range of allowed $(\delta_{\text{RL}}^{b \to s \gamma})_{23}$, the $B \to \phi K^0$ mixing receives only very small contributions from SUSY. Second, because the RL insertion generates the $\bar{O}_{3,5,6,7,8,9}$ operators while the SM generates only the untilded operators, there is no interference between the phases of the SUSY and SM contributions, and so $A_{\text{CP}}^{b \to s \gamma} = 0$.

The process $B \to X_s \gamma$ actually has a rather unconventional but well-motivated structure in the RL scenario. In Ref. [13], it was found that one can have a strong cancellation between the SM and SUSY contributions to $C_{7 \gamma}$ and $C_{8 \gamma}$, as is expected in the supersymmetric limit. Then the observed branching ratio is due to the $C_{7 \gamma}$ operator, which implied an RL insertion of about the same size as that needed here. Thus this earlier analysis motivates the RL insertion for the present case.

We have considered separate insertions so the effects of each can be seen clearly. In many realistic SUSY models, combinations of various insertions will play a role phenomenologically, and of course we do not mean to imply that only single insertions should occur in nature. A particularly interesting case is one in which the RL and RR operators co-exist. While we do not study this model in detail here, we note that (as discussed in Ref. [13]) if both $(\delta_{\text{RR}}^{b \to s \gamma})_{23}$ and $(\delta_{\text{RL}}^{b \to s \gamma})_{23}$ are nonzero, then $A_{\text{CP}}^{b \to s \gamma}$ can arise as an interference between $C_{7 \gamma}$ and $C_{8 \gamma}$. Then the RR insertion could shift $\Delta M_s$ appreciably, while the RL insertion gives the above result.

Finally we consider a completely different class of contributions to $b \to s s \bar{s}$. At large tan $\beta$, FCNC’s can also be mediated by exchanges of neutral Higgs bosons, as found in $B \to X_s \mu^+ \mu^-$ [14], $B_{s,d} \to \mu^+ \mu^-$ [17], $\tau \to 3 \mu$, etc. [14]. Likewise, $b \to s s \bar{s}$ could be enhanced by neutral Higgs exchange, which is flavor dependent since the Higgs coupling is proportional to the Yukawa couplings. The effective coupling for $b \to s s \bar{s}$ is basically the same with that for $B_s \to \mu^+ \mu^-$ up to a small difference between the muon and the strange quark masses (or their Yukawa couplings). Imposing the upper limit on this decay from CDF [17] during the Tevatron’s Run I, $B(B_s \to \mu^+ \mu^-) < 2.6 \times 10^{-6}$, we can derive a model-independent upper limit on this effective coupling. We find that $S_{\phi K_S}$ cannot be smaller than 0.71 for such couplings, so that we cannot explain the large deviation in $S_{\phi K_S}$ with Higgs-mediated $b \to s s \bar{s}$ alone.
Now let us provide possible motivation for values of $|\langle \delta_{\text{LR,RL}} \rangle_{23}| \lesssim 10^{-2}$, that we find phenomenologically are needed in order to generate $S_{\phi K}$. In particular, at large $\tan \beta$ it is possible to have double mass insertions which give sizable contributions to $|\langle \delta_{\text{LR,RL}} \rangle_{23}|$. First a $\langle \delta_{\text{LL,LL}} \rangle_{23}$ or $\langle \delta_{\text{RR,RR}} \rangle_{23} \sim 10^{-2}$ is generated. The former can be obtained from renormalization group running even if its initial value is negligible at the high scale. The latter may be implicit in SUSY GUT models with large mixing in the neutrino sector [3]. Alternatively, in models in which the SUSY flavor problem is resolved by an alignment mechanism using spontaneously broken flavor symmetries, or by decoupling, the resulting $\text{LL}$ and/or $\text{RR}$ insertions cannot explain the measured CP asymmetry in $B_d \to \phi K_S$. But at large $\tan \beta$, the $\text{LL}$ and $\text{RR}$ insertions can induce the $\text{RL}$ and $\text{LR}$ insertions needed for $S_{\phi K}$ through a double mass insertion [20]:

$$\langle \delta_{\text{LR,RL}} \rangle_{23}^{\text{ind}} = \langle \delta_{\text{LL,RR}} \rangle_{23} \frac{m_b (A_b - \mu \tan \beta)}{m_t^2}.$$ 

One can achieve $\langle \delta_{\text{LR,RL}} \rangle_{23}^{\text{ind}} \sim 10^{-2}$ if $\mu \tan \beta \sim 10^3 \text{GeV}$, which could be natural if $\tan \beta$ is large (for which $A_b$ becomes irrelevant). Note that in this scenario both the $\text{LL}(\text{RR})$ and $\text{LR}(\text{RL})$ insertions would have the same CP violating phase, since the phase of $\mu$ here is constrained by electron and down-quark electric dipole moments. Lastly, one can also construct string-motivated D-brane scenarios in which $\text{LR}$ or $\text{RL}$ insertions are $\sim 10^{-2}$ [3].

In this letter, we considered several classes of potentially important SUSY contributions to $B \to \phi K_S$ in order to see if a significant deviation in its time-dependent CP asymmetry $S_{\phi K}$ could arise from SUSY effects. The Higgs-mediated FCNC effects and models based on the gluino-mediated $\text{LL}$ and $\text{RR}$ insertions both give contributions too small to alter $S_{\phi K}$ significantly. On the other hand, the gluino-mediated contribution with $\text{LR}$ and/or $\text{RL}$ insertions can lead to sizable negative in $S_{\phi K}$ (as reported experimentally) as long as $|\langle \delta_{\text{LR,RL}} \rangle_{23}| \sim 10^{-3} - 10^{-2}$. As a byproduct, we found that nonlepton $B$ decays such as $B \to \phi K$ begin to constrain $|\langle \delta_{\text{LR,RL}} \rangle_{23}|$ as strongly as $B \to X_s \gamma$. Besides producing no measurable deviation in $B^0 - \bar{B}^0$ mixing, the $\text{RL}$ and $\text{LR}$ operators generate definite correlations among $S_{\phi K}$, $C_{\phi K}$ and $A_{\phi \gamma}^\mu$, and our explanation for the negative $S_{\phi K}$ can be easily tested by measuring these other observables. In particular $C_{\phi K}$ can be positive only for an $\text{RL}$ insertion. A pure $\text{RL}$ scenario also predicts a vanishing direct CP asymmetry in $B \to X_s \gamma$. However, if the $\text{RL}$ insertion is accompanied by an $\text{RR}$ insertion, then the resulting direct CP asymmetry in $B \to X_s \gamma$ can be large [12], and the $\text{RR}$ contribution to the $B_s - \bar{B}_s$ mixing can induce significant shifts in $\Delta M_s$ and the phase of $B_s - \bar{B}_s$ mixing. Finally, we also point out that the $|\langle \delta_{\text{LR,RL}} \rangle_{23}| \lesssim 10^{-2}$ can be naturally obtained in SUSY flavor models with double mass insertion at large $\tan \beta$, and in string-motivated models [3].

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