Effect of supersymmetric right-handed flavor mixing on B_s decays

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Motivated by the possibility of $S_{\phi K_S} < 0$, we study the implications for the B_s meson system. In a specific model that realizes $S_{\phi K_S} < 0$ with large s-b mixing, right-handed dynamics, and a new CP phase, we present predictions for CP asymmetries in $B_s \to J/\psi\phi$, K^+K^-, and $\phi\gamma$ decays. Even if the measurement of time-dependent CP asymmetry becomes hampered by very fast B_s oscillation, a finite difference between the decay rates of B_s mass eigenstates may enable the studies of CP violations with untagged data samples. Thus, studies of CP violation in the B_s system would remain useful for the extraction of new physics information.

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I. INTRODUCTION

The current experimental average of mixing-dependent CP asymmetry in $B_d \to \phi K_S$ decay is $S_{\phi K_S} = -0.15 \pm 0.33$ [1]. This constitutes a 2.7σ deviation from $\sin 2\phi_1 = 0.736 \pm 0.049$ as measured in $B_d \to J/\psi K_S$ and other charmonium channels [1]. The standard model (SM) asserts $S_{\phi K_S} = \sin 2\phi_1$ to the percent level. Although there is disagreement between the measurements of Belle [2] and *BABAR* [1] at the 2.1σ level at present, the new physics hint may well be real. On the other hand, the SM also asserts $S_{K_S\pi^0}$, $S_{\eta' K_S} = \sin 2\phi_1$, which seem to be supported by the experimental values. Many new physics (NP) scenarios have been advanced. In particular, it has been pointed out that the new physics interaction should be right handed so that, while $S_{\phi K_S}$ can be negative in sign, $S_{\eta' K_S}$ [3,4] and $S_{K_S\pi^0}$ [5] $\sim \sin 2\phi_1 > 0$ can be maintained.

In our previous work [5], we studied the implications of $S_{\phi K_S} < 0$ for charmless B_d decay modes, in the framework of Abelian flavor symmetry (AFS) combined with supersymmetry (SUSY). We assume that SUSY is at TeV scale, and the AFS scale is not far above the SUSY scale. For the sake of clarity, we introduced three parameters as follows: gluino mass $m_{\tilde g}$, light right-handed squark $\widetilde{sb}_1$ mass $\tilde m_1$ (not independent from squark mass scale $\tilde m$), and just one extra CP violating phase σ. Taking into account contributions from the chromodipole operator, we found that large $\tilde s_R$-$\tilde b_R$ mixing can turn $S_{\phi K_S}$ negative for $\sigma \sim 40°$–$90°$ while, for $\sigma \sim 180°$–$360°$, $S_{\phi K_S}$ is larger than the SM value of 0.74. Combining $b \to s\gamma$ and $B \to \phi K_S$ rates and $S_{\phi K_S} < 0$, the current experimental results seem to suggest $\sigma \sim 65°$. We now extend our study to the B_s system.

The present bound of the mass difference Δm_{B_s} is around $15\ \mathrm{ps}^{-1}$. Compared to $\Delta m_{B_d} = 0.502\ \mathrm{ps}^{-1}$ [6], B_s^0-$\bar B_s^0$ oscillations are already very rapid. As pointed out in [5], the large effect of $S_{\phi K_S} < 0$ calls for rather light $\widetilde{sb}_1$, while $m_{\tilde g}$ cannot be too heavy. It is then found that $\Delta m_{B_s} \gtrsim 70\ \mathrm{ps}^{-1}$ is hard to avoid. Measurement of such fast oscillations at Tevatron Run II now appears hopeless, and it would be challenging even for the next generation LHCb and BTeV experiments. While finding $\Delta m_{B_s} > \Delta m_{B_s}^{\mathrm{SM}}$ itself would constitute evidence beyond SM, a better quantity for revealing NP is the weak phase of B_s^0-$\bar B_s^0$ mixing, i.e., $\sin 2\Phi_{B_s}$. Since the SM predicts $\sin 2\Phi_{B_s} \approx 0$ due to the absence of the Cabibbo-Kobayashi-Maskawa (CKM) phase in $V_{tb}^* V_{ts}/V_{tb} V_{ts}^*$, the measurement of $\sin 2\Phi_{B_s}$ is expected to be a good NP probe. We found that, for $\sigma \sim 65°$, $\sin 2\Phi_{B_s}$ can vary over a very wide range [5]. Although the observation of $\sin 2\Phi_{B_s}$ itself may be hampered by the very fast B_s oscillation, measurement of $\sin 2\Phi_{B_s}$ would shed further light on $\widetilde{sb}_1$ parameters.

Whether the measurement of mixing-dependent CP asymmetries in the B_s system becomes very challenging or not, it is useful to remember that untagged data may provide an alternative handle for studies of CP violation in the B_s system. The general formula for time-dependent CP asymmetry in $B_q \to f$ decay, where f is a CP eigenstate, is given by [7–10]

$$a_{\mathrm{CP}}[B_q(t) \to f] = \frac{\Gamma[\bar B_q(t) \to f] - \Gamma[B_q(t) \to f]}{\Gamma[\bar B_q(t) \to f] + \Gamma[B_q(t) \to f]} = \frac{\mathcal{A}_f \cos\Delta m_{B_q} t + S_f \sin\Delta m_{B_q} t}{\cosh\frac{\Delta\Gamma_q t}{2} + \mathcal{A}_{\Delta\Gamma} \sinh\frac{\Delta\Gamma_q t}{2}}, \quad (1)$$

where $\mathcal{A}_f$, S_f, and $\mathcal{A}_{\Delta\Gamma}$ are expressed in terms of decay amplitudes $A(B \to f)$ and $\bar A(\bar B \to f)$ as

$$\mathcal{A}_f = \frac{|\bar A|^2 - |A|^2}{|\bar A|^2 + |A|^2}, \qquad S_f = \frac{2\xi \mathrm{Im}[\frac{q}{p}\bar A A^*]}{|\bar A|^2 + |A|^2}, \qquad \mathcal{A}_{\Delta\Gamma} = \frac{2\xi \mathrm{Re}[\frac{q}{p}\bar A A^*]}{|\bar A|^2 + |A|^2}, \quad (2)$$

and $|\mathcal{A}_f|^2 + |S_f|^2 + |\mathcal{A}_{\Delta\Gamma}|^2 = 1$. The final state f satisfies $\mathcal{CP}|f\rangle = \xi|f\rangle$, and q/p is related to the weak phases describing B_q^0-$\bar B_q^0$ mixing. Throughout this paper, we set the mass difference $\Delta m_{B_q} > 0$ and define the width difference $\Delta\Gamma_q$ as follows:

$$\Delta m_{B_q} = m_{B_{qH}} - m_{B_{qL}}, \qquad \Delta\Gamma_q = \Gamma_{B_{qH}} - \Gamma_{B_{qL}}, \quad (3)$$

where B^0_{qH} and B^0_{qL} denote the mass eigenstates of the B^0_q system, and Γ_q is the average width. The mass eigenstates can be approximated by the CP eigenstates.

For the B_d system, one has $\Delta\Gamma_d/\Gamma_d \to 0$, and Eq. (1) simplifies to the more familiar form of

$$a_{CP}[B_d(t) \to f] = \mathcal{A}_f \cos\Delta m_{B_d} t + S_f \sin\Delta m_{B_d} t, \quad (4)$$

where $\mathcal{A}_f$ and S_f can be determined by measuring time distributions of flavor tagged data. However, very rapid B^0_s-$\bar{B}^0_s$ oscillations, i.e., $\Delta m_{B_s} \gg \Gamma_s$, may prevent us from distinguishing between an initial B^0_s or $\bar{B}^0_s$. Fortunately, the quantity $\mathcal{A}_{\Delta\Gamma}$ also probes CP violation [as can be seen from Eq. (2)], and can be extracted by using *untagged* B_q data samples,

$$\begin{aligned}\Gamma[f, t] &\equiv \Gamma[B_q(t) \to f] + \Gamma[\bar{B}_q(t) \to f] \\ &\propto e^{-\Gamma_q t}(|A|^2 + |\bar{A}|^2)\cosh\frac{\Delta\Gamma_q t}{2} \\ &\quad\times \left\{1 + \mathcal{A}_{\Delta\Gamma}\tanh\frac{\Delta\Gamma_q t}{2}\right\}. \quad (5)\end{aligned}$$

Unlike $\Delta\Gamma_d/\Gamma_d \to 0$ for B_d, $\Delta\Gamma_s/\Gamma_s$ may be as large as $O(10\%)$ [11]. This makes the study of CP violation in the B_s system hopeful, even if very rapid B^0_s-$\bar{B}^0_s$ oscillations prevent us from extracting S_f from flavor tagged data.

All quantities in Eq. (5) can in principle be measured at hadron colliders. The average width, $\Gamma_s = (\Gamma^{(+)}_{B_s} + \Gamma^{(-)}_{B_s})/2$, can be measured via flavor-specific studies such as semileptonic decays, where both CP even and odd widths $\Gamma^{(\pm)}_{B_s}$ are present. $\Gamma^{(+)}_{B_s}$ can be measured via decays such as $B_s \to J/\psi\phi$, which is dominantly CP even [12]. Thus, one can in principle obtain $|\Delta\Gamma_s/2| = |\Gamma_s - \Gamma^{(+)}_{B_s}|$. It is expected that studies of B_s decays can determine $\Delta\Gamma_s/\Gamma_s$ up to a few percent accuracy [10]. If $\Delta\Gamma_s/\Gamma_s$ is around 10% as asserted, studies with untagged data can be a promising way to measure CP violation.

One remark should be made. As well as Δm_{B_s} and $\sin 2\Phi_{B_s}$, $\Delta\Gamma_s$ is also governed by new CP violating physics [13]. If the NP phase is present, $\Delta\Gamma_s$ is given by $\Delta\Gamma_s/\Delta\Gamma_s^{SM} = \cos 2\Phi_{B_s}$. In our model $\sin 2\Phi_{B_s}$ is sensitive to the model parameters and can vary over a very wide range. Therefore, $\Delta\Gamma_s$ shows the similar sensitivity for the model parameters. Clearly, $\Delta\Gamma_s < \Delta\Gamma_s^{SM}$, if found, it will be evidence of NP beyond the SM, though the measurement becomes harder.

As B_s studies can help confirm and shed further light on new physics that might already be emerging from B_d studies, in this paper we study the impact of light $\widetilde{sb}_1$ on B_s meson decays, with special attention to a new CP phase $\sigma \sim 65°$. We study the measurements that can assist in determining the model parameters. The outline of this paper is as follows. In Sec. II, we recall the necessary features of the new physics model with maximal mixing between right-handed squarks $\tilde{s}_R$ and $\tilde{b}_R$. Results of our analysis are shown in Sec. III, for $B_s \to J/\psi\phi$, K^+K^-, and $\phi\gamma$. The conclusion is given in Sec. IV.

II. MAXIMAL $\tilde{s}_R$-$\tilde{b}_R$ SQUARK MIXING

Within SM we have no direct knowledge of right-handed quark mixings, since the weak interaction probes just the left-handed sector. On the other hand, we are still far from a solution to the flavor problem. SUSY can in principle bring forth extra right-handed dynamics, but it does not address the flavor issue. As one tries to understand the right-handed flavor sector by assuming AFS, near maximal s_R-b_R mixing can be realized. With supersymmetric AFS, furthermore, maximal $\tilde{s}_R$-$\tilde{b}_R$ squark mixing [14,15] brings forth an extra CP violating phase and $s_R\tilde{b}_R\tilde{g}$ couplings. As pointed out in [15], decoupling the d flavor is preferred to evade the constraints from the kaon system as much as possible.

With d flavor decoupled, we can reduce 3×3 down quark mass matrix to 2×2 submatrix relevant to s and b flavors. Normalized to m_b, the down quark mass matrix element $M^{(d)}_{ij}$ has the diagonal terms $M^{(d)}_{33} \simeq 1$ and $M^{(d)}_{22} \simeq \lambda^2$, where $\lambda \simeq 0.22$ is the Wolfenstein parameter. Taking analogy with $V_{cb} \simeq \lambda^2$ gives $M^{(d)}_{23} \simeq \lambda^2$, but $M^{(d)}_{32}$ is unknown for lack of right-handed flavor dynamics. With effective AFS [16], the *Abelian* nature implies $M^{(d)}_{23}M^{(d)}_{32} \sim M^{(d)}_{22}M^{(d)}_{33}$, hence $M^{(d)}_{32} \sim 1$ is deduced. This may be the largest off-diagonal term, but its effects are hidden from our view within the SM. However, introducing SUSY, its effect may be revealed via the superpartners of right-handed quarks.

Decoupling d flavor reduces the down squark mass matrix from 6×6 to 4×4. Focusing on the 2×2 RR submatrix $(\tilde{M}^2_d)^{(sb)}_{RR}$, by the Hermitian nature one finds just one extra CP violating phase, denoted as σ, and we parametrize $(\tilde{M}^2_d)^{(sb)}_{RR}$ as

$$(\tilde{M}^2_d)^{(sb)}_{RR} = \begin{bmatrix} \tilde{m}^2_{22} & \tilde{m}^2_{23}e^{-i\sigma} \\ \tilde{m}^2_{23}e^{i\sigma} & \tilde{m}^2_{33} \end{bmatrix}. \quad (6)$$

The squark mass eigenvalues are $\tilde{m}^2_{1,2} = [\tilde{m}^2_{22} + \tilde{m}^2_{33} \mp \sqrt{(\tilde{m}^2_{22} - \tilde{m}^2_{33})^2 + 4\tilde{m}^4_{23}}]/2$, which are reached by diagonalizing $(\tilde{M}^2_d)^{(sb)}_{RR}$,

$$\begin{aligned}(\tilde{M}^2_d)^{(sb)}_{RR} &= R^\dagger \begin{bmatrix} \tilde{m}^2_1 & 0 \\ 0 & \tilde{m}^2_2 \end{bmatrix} R, \\ R &\equiv \begin{bmatrix} \cos\theta & -\sin\theta e^{-i\sigma} \\ \sin\theta & \cos\theta e^{-i\sigma} \end{bmatrix},\end{aligned} \quad (7)$$

where R absorbs the phase σ and transfers it to the quark-squark-gluino coupling, and θ is a measure of the relative weight of $\tilde{m}_{23}^2$ and $(\tilde{m}_{22}^2 - \tilde{m}_{33}^2)$. Clearly, with $\tilde{m}_{23}^2 \sim \tilde{m}_{22,33}^2$, in general we have one suppressed eigenvalue $\tilde{m}_1^2$ due to level splitting.

Our scenario corresponds to $\tilde{m}_{22}^2 \simeq \tilde{m}_{33}^2 \simeq \tilde{m}_{23}^2 \simeq \tilde{m}^2$ such that a democratic structure is realized for the right-handed squark mass matrix in Eq. (6). The eigenstates, hence, carry both s and b flavors and are called the strange-beauty squarks $\widetilde{sb}_{1,2}$. To achieve this, some fine-tuning is necessary. As a typical case, we take $\tilde{m}_{22}^2 = \tilde{m}_{33}^2 = \tilde{m}^2$ (i.e., $\theta = \pi/4$ and $\tilde{m}_1^2 + \tilde{m}_2^2 = 2\tilde{m}^2$) and consider the ratio $\tilde{m}_{23}^2/\tilde{m}^2 \equiv 1 - \delta$. For small δ, we have $\tilde{m}_1^2/\tilde{m}^2 \approx \delta$ and $\tilde{m}_2^2/\tilde{m}^2 \approx 2 - \delta$, and a low mass $\widetilde{sb}_1$ can be realized. How light $\tilde{m}_1$ can be depends on the fine-tuning one is willing to make. For $\tilde{m} = 1(2)$ TeV, to get $\tilde{m}_1 \simeq 0.2$ TeV the level of tuning is $\lambda^2(\lambda^3)$, which is comparable to what is seen in $V_{\rm CKM}$. As had been shown in [5], $S_{\phi K_S} < 0$ requires $\widetilde{sb}_1$ to be suitably light, and the gluino should not be too heavy. Since we would like to focus on the effects from a light right-handed squark, we fix $\tilde{m}_1 = 0.2$ TeV in the following analysis. We will illustrate the $\tilde{m}$ dependence of our results instead.

In our computations, we use mass the eigenbasis of Eq. (6) for right-handed squarks, since off-diagonal elements are large. However, $(\tilde{M}_d^2)_{LR,RL}^{sb}$ itself is strongly suppressed by down-type quark masses, and off-diagonal elements of $(\tilde{M}_d^2)_{LL}^{sb}$ are λ^2 suppressed. Hence, we also use mass insertion approximation for contributions arising from $q\tilde{q}_L\tilde{g}$, since perturbative expansion is possible.

III. RESULTS FOR B_s

B_s mixing can be studied by flavor-specific decays such as $B_s \to D_s\pi^-$, but we are more interested in CP violating measurables, especially those that could shed light on the potential new physics as hinted by $S_{\phi K_S} < 0$ in the B_d system. In the following, we give results on $B_s \to J/\psi\phi$, K^+K^-, and $\phi\gamma$ as they illustrate different aspects. Since the new physics effect on these decays is our interest, we employ the naive factorization approach for calculation of hadronic matrix elements and assume absence of final state interaction phases.

A. $B_s \to J/\psi\phi$

The decay $B_s \to J/\psi\phi$ is a clean mode for the same reason as $B_d \to J/\psi K_S$, i.e., a single tree amplitude dominates and the relevant CKM matrix element $V_{cb}^* V_{cs}$ is real. Therefore, this decay mode is promising for the extraction of weak phase information related to B_s^0-$\bar{B}_s^0$ mixing, Φ_{B_s}. Since the weak phase of B_s^0-$\bar{B}_s^0$ mixing is basically absent in SM, the values of $\sin 2\Phi_{B_s}$ and $\cos 2\Phi_{B_s}$ are governed by new physics effects. Assuming $(q/p) \equiv e^{2i\Phi_{B_s}}$ with $\mathrm{Re}(q/p)$ positive in sign within the SM, we have

$$\begin{aligned} \sin 2\Phi_{B_s} &\equiv \sin 2(\Phi_{B_s}^{\rm SM} + \Phi_{B_s}^{\rm NP}) = \sin 2\Phi_{B_s}^{\rm NP}, \\ \cos 2\Phi_{B_s} &\equiv \cos 2(\Phi_{B_s}^{\rm SM} + \Phi_{B_s}^{\rm NP}) = \cos 2\Phi_{B_s}^{\rm NP}, \end{aligned} \tag{8}$$

to good accuracy. Figure 1(a) shows our predictions for Δm_{B_s}. As mentioned in the introduction, the large effect of $S_{\phi K_S} < 0$ implies $\Delta m_{B_s} \gtrsim 70\ \mathrm{ps}^{-1}$. The measurement of $\sin 2\Phi_{B_s}$ would be challenging, but it clearly is a good probe of new physics. Furthermore, if $\Delta\Gamma_s/\Gamma_s$ is around 10%, it could also be available for the study of CP violation due to $\cos 2\Phi_{B_s}$. Let us see how these two quantities can be measured via $B_s \to J/\psi\phi$ decay.

In contrast to $B_d \to J/\psi K_S$, the decay product of $B_s \to J/\psi\phi$ consists of two vector mesons, and is not a CP eigenstate. However, angular analysis of $B_s \to J/\psi(l^+l^-)\phi(K^+K^-)$ can distinguish between the CP-even and CP-odd components of the full amplitude, with six measurable components associated with the angles describing the kinematics [8,17]. The current experimental result for the branching fraction is $(9.3 \pm 3.3) \times 10^{-4}$ [6]. Moreover, the CDF collaboration finds $|A_0|^2 \approx 0.61 \pm 0.14$ and $|A_\perp|^2 \approx 0.23 \pm 0.19$ [12], with $|A_0|^2 + |A_\parallel|^2 + |A_\perp|^2 = 1$.

We write the full decay amplitude as follows:

$$\begin{aligned} A(B^0 \to f) &= A_0 g_0 + A_\parallel g_\parallel + iA_\perp g_\perp, \\ \bar{A}(\bar{B}^0 \to f) &= \bar{A}_0 g_0 + \bar{A}_\parallel g_\parallel - i\bar{A}_\perp g_\perp, \end{aligned} \tag{9}$$

where $g_{0(\parallel,\perp)}$ depends on kinematic angles. For $B_s \to J/\psi\phi$, the three polarization amplitudes A_0, $A_\parallel$ (CP even), and $A_\perp$ (CP odd) are expressed as [8]

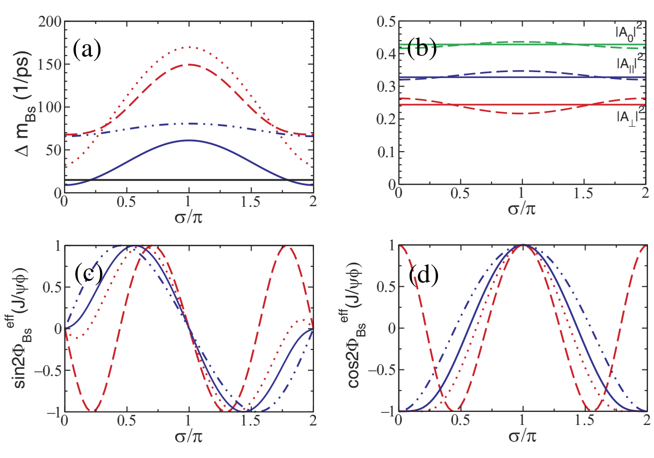

FIG. 1 (color online). (a) Δm_{B_s}, (b) amplitudes $|A_i|^2$, (c) $\sin 2\Phi_{B_s}^{\rm eff}(J/\psi\phi)$, and (d) $\cos 2\Phi_{B_s}^{\rm eff}(J/\psi\phi)$ vs CP phase σ (normalized to π) for $\tilde{m}_1 = 0.2$ TeV. For (a), (c), and (d), solid, dot-dashed (dashed, dotted) lines are for $\tilde{m} = 2, 1$ TeV, $m_{\tilde{g}} = 0.8(0.5)$ TeV. For (b), solid line [and horizontal line in (a)] is the SM expectation, while the dashed line is for $\{m_{\tilde{g}}, \tilde{m}\} = \{0.5, 2\}$ TeV.

$$\frac{A_0}{A_\parallel} = -\frac{1}{\sqrt{2}}\left[x - \frac{2m_{J/\psi}m_\phi}{(m_{B_s}+m_\phi)^2}\frac{A_2}{A_1}\frac{C^b_{J/\psi\phi}}{C^a_{J/\psi\phi}}(x^2-1)\right],$$
$$\frac{A_\perp}{A_\parallel} = \frac{2m_{J/\psi}m_\phi}{(m_{B_s}+m_\phi)^2}\frac{VC^c_{J/\psi\phi}}{A_1 C^a_{J/\psi\phi}}\sqrt{x^2-1}, \tag{10}$$

where $x \equiv p_{J/\psi}\cdot p_\phi/(m_{J/\psi}m_\phi)$, and are sensitive to the form factors $A_1(m^2_{J/\psi})$, $A_2(m^2_{J/\psi})$, and $V(m^2_{J/\psi})$. In the SM the short-distance coefficients $C^{a(b,c)}_{J/\psi\phi}$ are given by

$$C^{a(b,c)}_{J/\psi\phi} = \sqrt{2}G_F V^*_{cb}V_{cs}f_{J/\psi}m_{J/\psi}\left[a_2 - \frac{V^*_{tb}V_{ts}}{V^*_{cb}V_{cs}}(a_3+a_5)\right], \tag{11}$$

where, for example, a_2 is the coefficient of the $O_2 = (\bar{s}_\alpha c_\beta)_{V-A}(\bar{c}_\alpha b_\beta)_{V-A}$ operator. In addition to the SM contributions, we take into account the SUSY contributions due to the q-$\tilde{g}$-$\tilde{q}$ interaction, including the contributions coming from the chromodipole operator associated with $\bar{s}bg$ [18]. Such new effects, in general, can provide differences between $C^{a(b,c)}_f$.

Here we use $\{A_1(m^2_{J/\psi}), A_2(m^2_{J/\psi}), V(m^2_{J/\psi})\} = \{0.42, 0.47, 0.87\}$ based on the central values at $q^2 = 0$ in the light-cone sum rule approach [19]. The theoretical uncertainty is estimated as 15%. Figure 1(b) illustrates the polarization amplitudes. With these form factors, there is 1.3σ deviation from the measurement $|A_0|^2 \sim 0.61$, which is acceptable. It may be experimental, or may be due to sensitivity of form factors. Since this decay is tree dominant, the new physics effect is rather tiny. For example, taking $\{\tilde{m}_1, m_{\tilde{g}}, \tilde{m}\} = \{0.2, 0.5, 2\}$ TeV, the impact is less than 10% [dashed line in Fig. 1(b)]. Despite ambiguities from nonperturbative effects, we find the dominant component, with or without NP effect, is the CP-even state ($|A_0|^2 + |A_\parallel|^2$). In particular, the longitudinal component, i.e., $|A_0|^2$, is found to be dominant.

The absolute branching fraction is sensitive to form factors and also the effective number of colors, $N_c^{\rm eff}$. This is because the decay is color suppressed. For SM expectation, we find $\mathcal{B}_{\rm SM} \sim 7.0(9.4, 12.3)\times 10^{-4}$ for $N_c^{\rm eff} = 2.3(2.2, 2.1)$, while the experimental measurement is $\mathcal{B} \sim (6 \sim 13)\times 10^{-4}$. Throughout this paper, we take the effective number of color to be $N_c^{\rm eff} = 2.3$, giving $a_2 \sim 0.14$.

The direct CP violation asymmetries $A_{J/\psi\phi}$ for each polarization amplitude is

$$\mathcal{A}_f = \frac{|\bar{A}_\lambda|^2 - |A_\lambda|^2}{|\bar{A}_\lambda|^2 + |A_\lambda|^2}, \qquad (\lambda = 0, \parallel, \perp), \tag{12}$$

which are negligibly small because of single tree dominance. Thus, the actual CP probes are $S_{J/\psi\phi}$ and $\mathcal{A}_{\Delta\Gamma}$ of Eq. (2), which should satisfy $|S_{J/\psi\phi}|^2 + |\mathcal{A}_{\Delta\Gamma}|^2 \cong 1$, with equality cross-checked by direct CP violation. This allows us to introduce the terminology of $\sin 2\Phi^{\rm eff}_{B_s}(J/\psi\phi)$ and $\cos 2\Phi^{\rm eff}_{B_s}(J/\psi\phi)$ instead of $S_{J/\psi\phi}$ and $\mathcal{A}_{\Delta\Gamma}$, so we can compare with the CP violating phase induced purely by B_s^0-$\bar{B}_s^0$ mixing, $\sin 2\Phi_{B_s}$ and $\cos 2\Phi_{B_s}$. Let us concentrate on the dominant longitudinal component $|A_0|^2$. We find that, to good approximation,

$$\sin 2\Phi^{\rm eff}_{B_s}(J/\psi\phi) \approx \sin 2\Phi_{B_s},$$
$$\cos 2\Phi^{\rm eff}_{B_s}(J/\psi\phi) \approx \cos 2\Phi_{B_s}, \tag{13}$$

because of $A_{J/\psi\phi} \approx 0$ and $A_0 \approx +\bar{A}_0$. The same result is obtained for measurements done with $A_\parallel$, but for $A_\perp$ there is a sign change. Thus, the weak phase of B_s^0-$\bar{B}_s^0$ mixing can be measured via CP violation studies in the decay $B_s \to J/\psi\phi$, which we illustrate for our model in Figs. 1(c) and 1(d) vs the CP phase σ.

Our results for $\sigma \sim 65°$ are clearly rather different from $\sin 2\Phi^{\rm eff}_{B_s}(J/\psi\phi) \sim 0$ and $\cos 2\Phi^{\rm eff}_{B_s}(J/\psi\phi) \sim 1$ predicted by SM. As noted [5], for $\sigma \sim 65°$, $\sin 2\Phi^{\rm eff}_{B_s}(J/\psi\phi)$ can vary over a rather wide range, so a precision measurement could help pin down σ. It is remarkable that the large effect of $S_{\phi K_S} < 0$ implies $\cos 2\Phi^{\rm eff}_{B_s}(J/\psi\phi) < 0$, that is, $\cos 2\Phi_{B_s} < 0$. The measurements of $\sin 2\Phi^{\rm eff}_{B_s}$ and $\cos 2\Phi^{\rm eff}_{B_s}$ can shed light on our model parameters.

We stress that $\cos 2\Phi^{\rm eff}_{B_s}$ is actually measured via untagged B_s data utilizing the lifetime difference between two B_s mass eigenstates, i.e., Eq. (5). Even if the $\sin 2\Phi^{\rm eff}_{B_s}(J/\psi\phi)$ measurement gets hampered by very fast B_s oscillations, measurement of $\cos 2\Phi^{\rm eff}_{B_s}$ is in principle possible, so long that $\Delta\Gamma_s$ itself can be measured.

B. $B_s \to K^+K^-$

$B_s \to K^+K^-$ decay is dominated by QCD penguins and is similar to $B_d \to K^+\pi^-$, except for the advantage that the final state K^+K^- is a CP (even) eigenstate. The decay amplitude is written as

$$\begin{aligned} iA(\bar{B}_s \to K^+K^-) &= \frac{G_F}{\sqrt{2}} f_K F_0^{B_sK}(m_K^2)(m_B^2 - m_K^2)\Big\{V_{ub}V^*_{us}a_1 \\ &\quad - V_{tb}V^*_{ts}\Big[\Delta a_4 + a_{10} + (\Delta a_6 + a_8)R_P \\ &\quad + \Delta c_{12}\frac{\alpha_s}{4\pi}\frac{m_b^2}{q^2}\tilde{S}_{KK}\Big]\Big\}, \end{aligned} \tag{14}$$

where f_K and $F_0^{B_sK}$ are the decay constant and form factor of the $B_{s(d)} \to K$ transition, respectively, and R_P is a chiral enhancement factor, where we use $R_P = 1.24$. We write $\Delta a_i = a_i - a_i'$ and $\Delta c_{12} = c_{12} - c_{12}'$, where the coefficients a_i' and c_{12}' are related to the NP right-handed dynamics. The CP conserving phases are taken into account via the Bander-Silverman-Soni mechanism (e.g., see [20]). The last term in Eq. (14) is induced by the chromodipole operator, and accompanied by the hadronic factor $\tilde{S}_{KK}/q^2$. We shall use [5] $\tilde{S}_{KK} = -1.58$ as evaluated from naive factorization, and $q^2 = m_b^2/3$ for the virtual gluon momentum emitted by the $b \to s$ chromodipole.

Equation (14) illustrates several problems for extracting CP violating phases from $B_s \to K^+K^-$. In contrast to the clean $B_s \to J/\psi\phi$ mode, the tree contribution is suppressed by $V_{ub}V_{us}^*$ and penguin contributions dominate; hence, the amplitude is sensitive to hadronic parameters. Furthermore, the tree contribution brings in the CKM phase $\phi_3 \equiv \arg V_{ub}^*$. We note, however, that the latter can in principle be extracted from $B_s \to D_s^\pm K^\mp$ decays, independent from the analogous $B_d \to D^\pm K^\mp$ program. The latter should still provide us with information on ϕ_3 if fast B_s oscillations degrade our sensitivity in the $B_s \to D_s^\pm K^\mp$ program. At the moment, especially in the presence of new physics, it is not clear which ϕ_3 value to take. We take $\phi_3 = 60°$ in the following.

The branching fraction is sensitive to the form factor $F_0^{B_sK}$. Figure 2(a) shows our result of the branching fraction, with $F_0^{B_sK} = F_0^{B_dK} = 0.33$. The current upper bound for the rate of $B_s \to K^+K^-$ is

$$\mathcal{B}(B_s \to K^+K^-) < 5.9 \times 10^{-5}, \tag{15}$$

at 90% confidence level [6]. On the other hand, recent results from the Tevatron [21] give

$$\frac{f_{b\to B_s}}{f_{b\to B_d}} \frac{\mathcal{B}(B_s \to K^+K^-)}{\mathcal{B}(B_d \to K^+\pi^-)} = 0.74 \pm 0.20 \pm 0.22, \tag{16}$$

where $f_{b\to B_{s(d)}}$ is the production fraction for $B_{s(d)}$, and

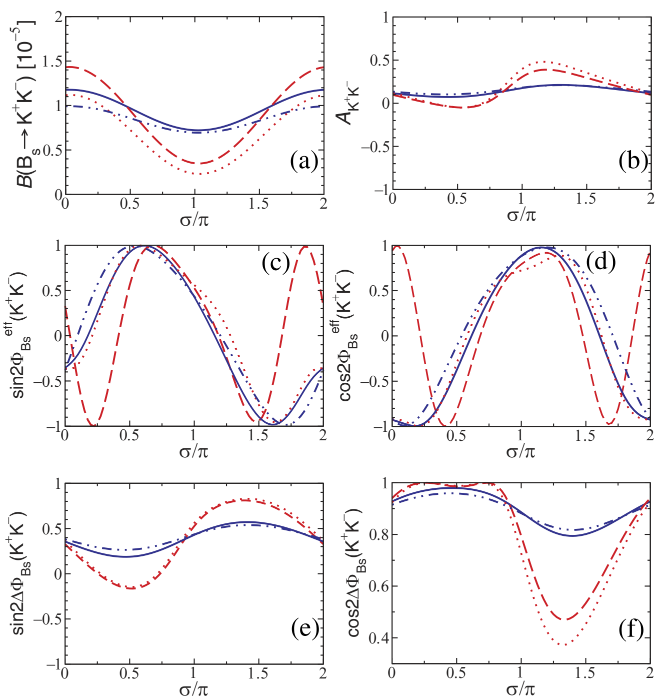

FIG. 2 (color online). For $B_s \to K^+K^-$ (a) branching fraction (see text), (b) $A_{K^+K^-}$, (c) $\sin 2\Phi_{B_s}^{\rm eff}$, (d) $\cos 2\Phi_{B_s}^{\rm eff}$, (e) $\sin 2\Delta\Phi_{B_s}$, and (f) $\cos 2\Delta\Phi_{B_s}$ vs σ, with notation as in Fig. 1(a).

$f_{b\to B_s}/f_{b\to B_d} \approx 0.27$ [6]. This suggests $\mathcal{B}(B_s \to K^+K^-) \sim 3 \times \mathcal{B}(B_d \to K^+\pi^-)$, and seems to prefer $F_0^{B_sK}$ to be 1.5 to 1.8 times larger than the 0.33 value we use.

The quantities $\mathcal{A}_{K^+K^-}$, $S_{K^+K^-}$, and $\mathcal{A}_{\Delta\Gamma}$, which are independent of $F_0^{B_sK}$ but correlated to each other, are illustrated in Figs. 2(b)–2(d). Let us focus on the region $\sigma \sim 65°$. Because $\mathcal{A}_{K^+K^-}$ is tiny, we can still use the same terminology of $\sin 2\Phi_{B_s}^{\rm eff}(K^+K^-)$ and $\cos 2\Phi_{B_s}^{\rm eff}(K^+K^-)$. We see that the decay phase ϕ, defined by $A = |A|e^{i\phi}$, must be rather suppressed, since $\sin 2\Phi_{B_s}^{\rm eff}(K^+K^-)$ and $\cos 2\Phi_{B_s}^{\rm eff}(K^+K^-)$ are quite similar to the $B_s \to J/\psi\phi$ case, i.e., $\sin 2\Phi_{B_s}$ and $\cos 2\Phi_{B_s}$, respectively.

For a more detailed understanding of the decay phase ϕ, we define the difference angle $\Delta\Phi_{B_s}$ between $\Phi_{B_s}^{\rm eff}$ and Φ_{B_s} which are given by (up to discrete ambiguities)

$$\sin 2\Delta\Phi_{B_s} \equiv \sin 2(\Phi_{B_s}^{\rm eff} - \Phi_{B_s}), \quad \cos 2\Delta\Phi_{B_s} \equiv \cos 2(\Phi_{B_s}^{\rm eff} - \Phi_{B_s}). \tag{17}$$

Since Φ_{B_s} is just $\Phi_{B_s}^{\rm eff}(J/\psi\phi)$ to good approximation, one can extract $\Delta\Phi_{B_s}$ by using $\Phi_{B_s}^{\rm eff}(J/\psi\phi)$ instead of Φ_{B_s}. The SM gives $\Delta\Phi_{B_s}^{\rm SM} \sim 10°$. Figures 2(e) and 2(f) illustrate $\sin 2\Delta\Phi_{B_s}$ and $\cos 2\Delta\Phi_{B_s}$, where the vertical range for the latter is from 0.3 to one to reveal better detail. We see that, for $\sigma \sim 65°$, $\sin 2\Delta\Phi_{B_s}$ has turned negative for the lower gluino mass case, and measurement can provide some information. On the other hand, $\cos 2\Delta\Phi_{B_s} \cong 1$, and not much can be learned.

Although the measurement of these quantities may suffer from very fast B_s oscillations, our results for $S_{\phi K_S} < 0$ imply that $\Delta\Phi_{B_s}$ from $B_s \to K^+K^-$ decay can potentially help determine model parameters.

C. $B_s \to \phi\gamma$

For radiative $b \to s\gamma$ transition, the decay rate at leading order is proportional to $|c_{11}|^2$ and $|c'_{11}|^2$, where c_{11}, c'_{11} are the short-distance Wilson coefficients of

$$O_{11}, O'_{11} = \frac{e}{8\pi^2} m_b \bar{s}\sigma^{\mu\nu}(1 \pm \gamma_5)F_{\mu\nu}b. \tag{18}$$

In the SM with purely left-handed interaction, c'_{11} is suppressed by s quark mass hence negligible.

The decay $B_s \to \phi\gamma$ is expected to be the B_s counterpart of the decay $B_d \to K^{*0}\gamma$. The present experimental upper bound on the rate is [6]

$$\mathcal{B}(B_s \to \phi\gamma) < 1.2 \times 10^{-4}, \tag{19}$$

at 90% confidence level. In Fig. 3(a), we illustrate the branching fraction by using $\mathcal{B}(B_s \to \phi\gamma) = \mathcal{B}_{\rm SM}(|c_{11}|^2 + |c'_{11}|^2)/|c_{11}^{\rm SM}|^2$, where $c_{11}^{\rm SM} = -0.31$ and $\mathcal{B}_{\rm SM} \approx 4.8 \times 10^{-5}$ [22].

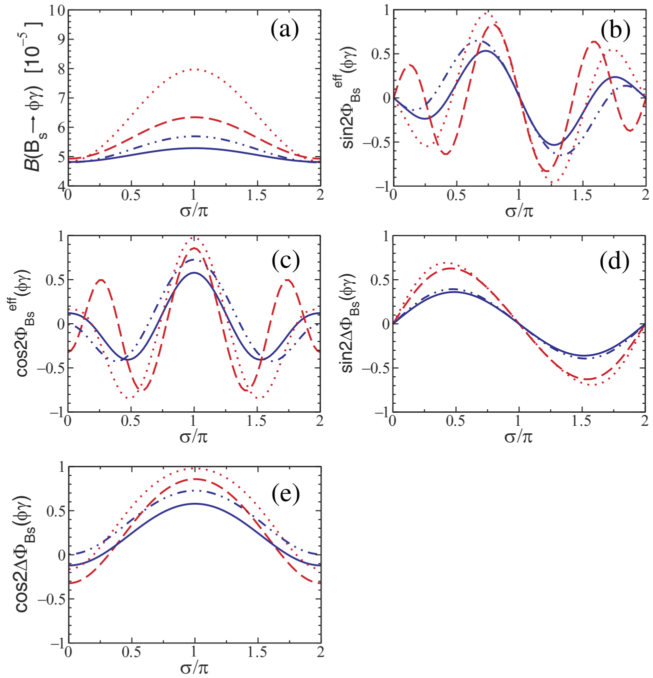

FIG. 3 (color online). For $B_s \to \phi\gamma$, (a) branching fraction, (b) $\sin 2\Phi_{B_s}^{\rm eff}$, (c) $\cos 2\Phi_{B_s}^{\rm eff}$, (d) $\sin 2\Delta\Phi_{B_s}$, and (e) $\cos 2\Delta\Phi_{B_s}$ vs σ, with notation the same as Fig. 1(a).

The quantities of interest are $S_{\phi\gamma}$ and $\mathcal{A}_{\Delta\Gamma}$. As we will show below, nonvanishing values imply the presence of *wrong helicity photons*. It is known that "wrong helicity" photons from the decay $b \to s\gamma$ would indicate new physics [23,24]. In our previous work [5], we studied $S_{K^{*0}(K_S\pi^0)\gamma}$, which was inspired by the recent experimental data on $S_{K_S\pi^0}$ from *BABAR* [1]. It is important to stress that $S_{\phi\gamma}$ and $\mathcal{A}_{\Delta\Gamma}$ are free from hadronic effects such as $\tilde{S}_{K^+K^-}/q^2$ in $B_s \to K^+K^-$. Hadronic effects are largely absorbed in the $B_s \to \phi$ form factor, which cancels out when forming CP ratios.

The photon radiated from $\bar{B}_s(B_s)$ is dominantly left(right)-handed polarized in the SM. Therefore, in the SM, Eq. (1) can be written separately for $\Gamma[\bar{B}_s(t) \to \phi\gamma_L]$ and $\Gamma[B_s(t) \to \phi\gamma_L]$ to good approximation. However, $\phi\gamma_{L(R)}$ is *not* a CP eigenstate *if* the photon polarization is measured. Following Ref. [23], the amplitudes are given by

$$\begin{aligned}\bar{A}(\bar{B}_s \to \phi\gamma_L) &= \bar{a}\cos\Psi e^{i\phi_L},\\ \bar{A}(\bar{B}_s \to \phi\gamma_R) &= \bar{a}\sin\Psi e^{i\phi_R},\\ A(B_s \to \phi\gamma_R) &= -a\cos\Psi e^{-i\phi_L},\\ A(B_s \to \phi\gamma_L) &= -a\sin\Psi e^{-i\phi_R},\end{aligned} \tag{20}$$

where $\cos\Psi(\sin\Psi)$ is the relative amount of left(right)-polarized photons, and $\phi_{L(R)}$ is the associated CP violating phase. The measurement of time-dependent CP asymmetry for this mode treats the photon handedness as unmeasured. Thus, Eq. (1) should be given by [23,24]

$$a_{\rm CP}(t) = \frac{\Gamma[\bar{B}_s(t) \to \phi\gamma] - \Gamma[B_s(t) \to \phi\gamma]}{\Gamma[\bar{B}_s(t) \to \phi\gamma] + \Gamma[B_s(t) \to \phi\gamma]}, \tag{21}$$

where $\Gamma[\bar{B}_s(B_s) \to \phi\gamma]$ sums over the two separate rates for the final states $\phi\gamma_L$ and $\phi\gamma_R$. It is in this way that interference and CP violation can occur.

Assuming $a^2 = \bar{a}^2$, Eq. (21) gives

$$\begin{aligned} S_{\phi\gamma} &= \frac{-2|c_{11}c'_{11}|}{|c_{11}|^2 + |c'_{11}|^2}\sin(2\Phi_{B_s} + \phi_L + \phi_R),\\ \mathcal{A}_{\Delta\Gamma} &= \frac{-2|c_{11}c'_{11}|}{|c_{11}|^2 + |c'_{11}|^2}\cos(2\Phi_{B_s} + \phi_L + \phi_R),\end{aligned} \tag{22}$$

and $\mathcal{A}_{\phi\gamma} = 0$. The observables $S_{\phi\gamma}$ and $\mathcal{A}_{\Delta\Gamma}$ are good probes of right-handed dynamics, as they vanish with c'_{11}. Note that $\mathcal{A}_{\phi\gamma}$, $S_{\phi\gamma}$, and $\mathcal{A}_{\Delta\Gamma}$ do not satisfy $|\mathcal{A}_f|^2 + |S_f|^2 + |\mathcal{A}_{\Delta\Gamma}|^2 = 1$, because in Eqs. (21) and (22) one sums over two distinct components. In fact,

$$\sqrt{S_{\phi\gamma}^2 + \mathcal{A}_{\Delta\Gamma}^2} = \frac{2|c_{11}c'_{11}|}{|c_{11}|^2 + |c'_{11}|^2} \equiv \sin 2\vartheta_{\rm mix} \tag{23}$$

is nothing but the relative interference strength, called $\sin 2\vartheta_{\rm mix}$ [24], between $\bar{B}_s(t) \to \phi\gamma_L$ and $\phi\gamma_R$ decay amplitudes induced by mixing.

Since weak interaction is left handed, the right-handed effect from the SM is always accompanied with mass suppression factor. Hence, $S_{\phi\gamma}^{\rm SM} \approx \mathcal{A}_{\Delta\Gamma}^{\rm SM} \approx 0$, and $\sin\Delta\Phi_{B_s}$ and $\cos\Delta\Phi_{B_s}$ also vanish within SM. We illustrate these quantities in Figs. 3(b)–3(e) within our scenario. Our results for $\sigma \sim 65°$ are clearly rather different from the *zero* value predicted by SM. They can be profitably studied, again if fast B_S mixing can be overcome. Note that $\cos\Delta\Phi_{B_s}$, which can in principle be measured without tagging and vertexing, is not far from zero for $\sigma \sim 65°$, hence not a good discriminant.

IV. CONCLUSION

A hint for new physics has emerged in mixing-dependent CP violation asymmetry in $\bar{B}_d \to \phi K_S$ decay, which seems to be of opposite sign to $\bar{B}_d \to J/\psi K_S$. It is important to cross-check in B_s system.

In an explicit model that combines SUSY and Abelian flavor symmetry, one has maximal $\tilde{s}_R$-$\tilde{b}_R$ squark mixing, with one new associated CP violating phase σ. The maximal mixing could generate one light and flavor mixed $\widetilde{sb}_1$ squark, which could impact on $b \leftrightarrow s$ transitions. The current experimental results, $S_{\phi K_S} < 0$ while $S_{\eta' K_S}$, $S_{K_S\pi^0} > 0$, seem to suggest $\sigma \sim 65°$ with $m_{\widetilde{sb}_1} = 0.2$ TeV and $m_{\tilde{g}} \sim 0.5$ TeV. Studies of mixing-dependent CP asymmetry S_f in the B_s system in as many modes f is of great interest to test the model. However, it would be challenging because of very rapid B_s oscillations implied by the sizable new physics effect in $S_{\phi K_S} < 0$. An alternative approach is to use untagged data to complement the studies of CP violation in the B_s system. This is feasible if $\Delta\Gamma_s/\Gamma_s$ is as large as $O(10\%)$, allowing one to study CP violating asymmetry in rate, $\mathcal{A}_{\Delta\Gamma}$. Thus, it is worthy to investigate CP asymmetries S_f and $\mathcal{A}_{\Delta\Gamma}$ in the B_s system.

We have illustrated such a study for the B_s system that could search for new physics effects and assist the determination of model parameters. We gave the results for $\bar{B}_s \to J/\psi\phi$, K^+K^-, and $\phi\gamma$. We stress that S_f, $\mathcal{A}_{\Delta\Gamma}$, and $\Delta\Phi_{B_s}$ (shift in Φ_{B_s} in specific CP eigenmode relative to $J/\psi\phi$) have good potential to help pin down the model parameters. However, the measurement of these quantities may sometimes be challenging because of fast B_s oscillations. We also emphasize that the mechanism that utilizes the *wrong helicity photon* in $B_s \to \phi\gamma$ decay allows one to study CP violation without hadronic effects that plague the charmless hadronic modes such as $\bar{B}_s \to K^+K^-$.

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