Large Direct $CP$ Violation in $B \to \phi\phi X_s$ Decays

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Abstract

We present a novel method to search for a new $CP$-violating phase in the $b \to s\bar{s}s\bar{s}$ transition using $B \to \phi\phi X_s$ decays, where $X_s$ represents a final state with a specific strange flavor such as $K^\pm$, $K^{*\pm}$ or $K^{\pm}\pi^{\mp}$. Direct $CP$ violation can be enhanced due to an interference between an amplitude beyond the standard model (SM) and the SM decay amplitude through the $\eta_c$ resonance. We find that the $CP$ asymmetry can be as large as 0.4 within the present experimental bounds on the $b \to s\bar{s}s$ transition. These decays provide a very clean experimental signature and the background is expected to be small in particular at $e^+e^-$ $B$ factories. A simulation study for the $B^{\pm} \to \phi\phi K^{\pm}$ decay shows that the statistical significance of $CP$ violation can exceed 5 standard deviations with $10^9$ $B$ mesons.

Key words: $B$ decay, direct $CP$ violation, new physics

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The phenomenon of $CP$ violation is one of the major unresolved issues in our understanding of elementary particles today. In the standard model (SM), $CP$ violation arises from an irreducible complex phase, the Kobayashi-Maskawa (KM) phase [1], in the Cabibbo-Kobayashi-Maskawa (CKM) weak-interaction quark mixing matrix [1,2]. Recent observations of direct $CP$ violation in the neutral $K$ meson system [3,4] and mixing-induced $CP$ violation in the neutral $B$ meson system [5,6] strongly support the KM mechanism. Despite this success, additional $CP$-violating phases are inevitable in most of theories involving new physics (NP) beyond the SM [7]. Some of them allow large deviations from the SM predictions in $B$ meson decays. Examples of such theories include supersymmetric grand-unified theories with the see-saw mechanism that can accommodate the large neutrino mixing [8]. Therefore it is of fundamental importance to measure $CP$ asymmetries that are sensitive to the difference between the SM and NP. Additional sources of $CP$ violation are also highly desirable to understand the origin of the matter-antimatter asymmetry of the universe; detailed studies have found no way that $CP$ violation in the SM alone could explain the baryogenesis [9]. Many methods to search for a new source of $CP$ violation in $B$ meson decays have been proposed until now. One of the most promising ways among them is to compare the mixing-induced $CP$ asymmetries in the $B \to \phi K_S^0$ decay [10], which is dominated by the $b \to s\bar{s}s$ transition that is known to be sensitive to possible NP effects, with those in the $B^0 \to J/\psi K_S^0$ decay [11]. Recent measurements by Belle [12] and BaBar [13] collaborations yield values smaller than the SM expectation; a difference by 2.6 standard deviations is obtained when two results are combined. The other charmless decays $B^0 \to \eta' K_S^0$ and $B^0 \to K^+ K^- K_S^0$, which are mediated by $b \to s\bar{s}s$, $s\bar{u}u$ and $s\bar{d}d$ transitions, also provide additional information [12,13]. The present world average with $B^0 \to \phi K_S^0$, $\eta' K_S^0$ and $K^+ K^- K_S^0$ combined is different from the average with $B^0 \to J/\psi K_S^0$ and related modes by 3.1 standard deviations [14]. Possible implications of these measurements are discussed in the literature [15].

In this Letter, we propose a novel method to search for a new $CP$-violating phase in the hadronic $b \to s$ transition using $B^\pm \to \phi \phi X_s^\pm$ decays [16]. Here $X_s^\pm$ represents a final state with a specific strange flavor such as $K^\pm$ or $K^{*\pm}$. These non-resonant direct decay amplitudes are dominated by the $b \to s\bar{s}\bar{s}$ transition. A contribution from the $b \to u\bar{u}s$ transition followed by rescattering into $s\bar{s}s$ is expected to be small because of the CKM suppression and the OZI rule [17]. In these decays, when the invariant mass of the $\phi\phi$ system is within the $\eta_c$ resonance region, they interfere with the $B^\pm \to \eta_c (\to \phi\phi) X_s^\pm$ decay that is dominated by the $b \to c\bar{c}s$ transition. The decay width of $\eta_c$ is sufficiently large [18,19] to provide a sizable interference. Within the SM, this interference does not cause sizable direct $CP$ violation because there is no weak phase difference between the $b \to s\bar{s}s\bar{s}$ and the $b \to c\bar{c}s$ transitions. On the other hand, a NP contribution with a new $CP$-violating phase can create a large weak phase difference. Thus large $CP$ asymmetries can appear
only from NP amplitudes, and an observation of direct CP violation in these
decays is an unambiguous manifestation of physics beyond the SM.

Although the same argument so far is applicable to the \( B^\pm \to \phi X_s^\pm \) decays, there is no guaranteed strong phase difference that is calculable reliably for these decays. In contrast, the Breit-Wigner resonance provides the maximal strong phase difference in the case of \( B^\pm \to (\phi\phi)_{m-m_{\eta_c}} X_s^\pm \) decays. CP violation that arises from interference between a resonant and a nonresonant amplitude was initially studied in top-quark decays [20] and in radiative \( B^\pm \) decays [21]. The charmonium width effect on the SM direct CP asymmetries in \( B \) decays was first considered in \( B^\pm \to \eta_c(\chi_c0)\pi^\pm \) decays [22] and was also used in subsequent theoretical studies [23].

Experimentally, an evidence for the decay \( B^\pm \to \eta_cK^\pm \) was first reported by the CLEO collaboration [24]. Recently Belle [19] has also reported the first observation of the \( B^0 \to \eta_cK^{*0} \) decay. This implies that other modes such as \( B^+ \to \eta_cK^{*+} \) will also be seen with a similar branching fraction, so that we will be able to study semi-inclusive \( B^\pm \to \eta_cX_s^\pm \) transitions experimentally. The semi-inclusive branching fraction of \( B^\pm \to \eta_cX_s^\pm \) is not yet measured, but is theoretically expected to be comparable to the branching fraction of the semi-inclusive decay \( B^\pm \to J/\psi X_s^\pm \) [25].

We derive the rates and the asymmetry of the decays \( B^\pm \to (\phi\phi)_{m-m_{\eta_c}} X_s^\pm \) based on the formalism described in the study of \( B^\pm \to \eta_c(\chi_c0)\pi^\pm \) decays [22]. The distribution of two \( \phi \)'s is determined with two kinematical variables; one is the invariant mass of the \( \phi\phi \) system, \( m \), and the other is the angle \( \theta \) between the \( B \)-meson momentum and the momentum of one of two \( \phi \)'s in the center-of-mass frame of the \( \phi\phi \) system. To have the interference between resonant and direct amplitudes, \( m \) should be in the \( \eta_c \) resonance region. To be specific, we require in this study that the difference between \( m \) and \( \eta_c \) mass (\( M \)) should satisfy \( |m - M| < 3\Gamma \), where \( \Gamma \) is the width of the \( \eta_c \) resonance [26]. The differential decay rate normalized with the total \( B^\pm \) decay rate is then given by the following equation:

\[
\frac{1}{\Gamma_B} \frac{d\Gamma^\pm}{dz} = \frac{(M+3\Gamma)^2}{(M-3\Gamma)^2} \int ds |R(s) + D^\pm(s, z)|^2 ,
\]

where \( R(s) \) is the resonant amplitude, \( D^\pm(s, z) \) is the direct amplitude of the \( B^\pm \to \phi\phi X_s^\pm \) decay, \( \Gamma_B \) is the total \( B \) decay rate, \( s \equiv m^2 \) and \( z \equiv \cos \theta \).

The resonant amplitude \( R(s) \) is given by

\[
R(s) \equiv A(B^\pm \to \eta_c X_s^\pm \to \phi\phi X_s^\pm) = \frac{a_R\sqrt{M\Gamma}}{(s-M^2)+i\Gamma} ,
\]
where $a_R$ is a product of the weak decay amplitude of $B^\pm \to \eta_cX_s^\pm$ and the real part of the $\eta_c$ decay amplitude to $\phi\phi$.

The direct amplitude $D^\pm$ is separated into contributions from the SM, $D_{SM}$, and from NP, $D_{NP}^\pm$,

$$D^\pm(s \approx M^2, z) \equiv D_{SM}(s \approx M^2, z) + D_{NP}^\pm(s \approx M^2, z),$$

$$D_{SM}(s \approx M^2, z) \equiv \frac{a_D(z)}{\sqrt{M\Gamma}} e^{i\delta},$$

$$D_{NP}^\pm(s \approx M^2, z) \equiv \frac{a_{NP}(z)}{\sqrt{M\Gamma}} e^{i\delta'} e^{\pm i\Theta_{NP}},$$

where $a_D(z)$ is a real part of the SM direct amplitude, $\delta$ ($\delta'$) is a strong phase difference between the resonant amplitude and the SM (NP) direct amplitude, $a_{NP}(z)$ is a real part of the NP amplitude and $\Theta_{NP}$ is a new $CP$-violating phase. If $\delta \neq \delta'$ holds, direct $CP$ violation can also occur from an interference between the SM and NP direct amplitudes. We do not take this case in our study and assume $\delta = \delta'$ in the following discussion.

The difference between the decay rates of $B^+$ and $B^-$ is given by

$$\frac{1}{\Gamma_B} \left( \frac{d\Gamma^+}{dz} - \frac{d\Gamma^-}{dz} \right) \equiv \gamma^-(z) \approx -4\pi a_R a_{NP}(z) \cos \delta \cdot \sin \Theta_{NP}. \quad (6)$$

Similarly the sum of two decay rates is given by

$$\frac{1}{\Gamma_B} \left( \frac{d\Gamma^+}{dz} + \frac{d\Gamma^-}{dz} \right) \equiv \gamma^+(z) \approx 2\pi a_R^2 + 24a_D^2(z)(r^2 + 2r \cos \Theta_{NP} + 1)
-4\pi a_R a_D(z)(r \cos \Theta_{NP} + 1) \sin \delta, \quad (7)$$

where $r \equiv a_{NP}(z)/a_D(z)$ is the amplitude ratio of NP to the SM. The $z$ dependence of $r$ reflects the spin components of the $\phi\phi$ system, which can be determined at $B$ factories in the future from the differential decay rates in the mass-sideband region below the $\eta_c$ resonance. Although only a pseudo-scalar component in the direct transition interferes with the $\eta_c$ resonance, the effect of other components can be estimated by such a measurement. Thus, for simplicity, we assume that the direct transition is dominated by a pseudo-scalar component and ignore the $z$ dependence of $r$ in the following discussion.

The maximum asymmetry is realized when $\cos \delta \simeq 1$ is satisfied. Assuming that $\delta$ is small following the discussion by Eilam, Gronau and Mendel [22],
the differential partial rate asymmetry is
\[ A_{CP}(z) \equiv \frac{\gamma^-(z)}{\gamma^+(z)} \approx \frac{-4\pi a_R a_{NP}(z) \sin \Theta_{NP}}{2\pi a_R^2 + 24a_D^2(z)(r^2 + 2r \cos \Theta_{NP} + 1)}. \] (8)

As a measure of CP violation, we define the following CP-asymmetry parameter:
\[ A_{CP} \equiv \sqrt{\int_{-1}^{1} dz \gamma^-(z)^2} / \sqrt{\int_{-1}^{1} dz \gamma^+(z)^2}. \] (9)

The numerator of \( A_{CP} \) can be expressed with the branching fraction of the resonance \((2\pi a_R^2)\) and that of NP in the resonance region \((B_{NP})\):
\[ \int_{-1}^{1} dz \gamma^-(z)^2 = (2\pi a_R^2) \cdot B_{NP} \cdot \frac{2\pi}{3} \sin^2 \Theta_{NP}, \] (10)

where
\[ 2\pi a_R^2 \approx B(B^\pm \to \eta_c X_s^\pm) \cdot B(\eta_c \to \phi \phi), \] (11)

and
\[ B_{NP} \equiv \frac{1}{M} \int_{(M-3\Gamma)^2}^{(M+3\Gamma)^2} ds \int_{-1}^{1} dz a_{NP}^2(z). \] (12)

The inclusive branching fraction \( B(B^\pm \to \eta_c X_s^\pm) \) has not been measured and only an upper limit of 0.9% is available [18]. Therefore we take theoretical expectations that range from 0.3% to 0.7%, depending on the estimation of the ratio of \( B(B \to \eta_c X) \) to \( B(B \to J/\psi X) \) [25]. For \( B(\eta_c \to \phi \phi) \), we take the present world average of \((0.71 \pm 0.28)\% \) [18]. As a result we obtain \( 2\pi a_R^2 = (2 \sim 5) \times 10^{-5} \).

There is no direct experimental bound on the \( B \to \phi \phi X_s \) decay (see Note added in the end of this Letter). A bound on the \( B \to \phi X_s \) decay \((2.2 \times 10^{-4} \) at 90\%C.L.) is available [27]. The search, however, was devoted only for energetic \( \phi \) mesons above \( p_\phi > 2.1 \) GeV/c. On the other hand, the momentum of \( \phi \) mesons in the \( B \to \phi \phi X_s \) decay is lower; it should be less than 2.2 GeV/c. Consideration on other experimental bounds also leads to a weak limitation on \( b \to sg \) [28]; \( B(b \to sss) \sim 1\% \) is still allowed, while the estimation of \( B(b \to sss) \) within the SM is \( \sim 0.2\% \) [29]. Since there is no reliable way to
calculate the hadronic matrix element of the multi-body decay $B \to \phi \phi X_s$, we use an event generator that is based on the LUND fragmentation model [30] for the estimation of $\mathcal{B}_{\text{NP}}$. We start from the $b \to sg^* \to s\bar{s}s$ transition that mainly produces soft $\phi$ mesons. We find that it is possible to assume $\mathcal{B}(b \to sg^* \to s\bar{s}s) \sim 1\%$ without conflicting the existing experimental results such as the branching ratio of the exclusive $B \to \phi K$ decay [31]. We use the default value of the $s\bar{s}$ popping probability in JETSET 7.4 [30], which is consistent with the ratio of the branching fractions between $B \to J/\psi K\phi$ and $B \to J/\psi K$ [32]. We estimate $\mathcal{B}_{\text{NP}}$ to be $\sim 5 \times 10^{-6}$ for $\mathcal{B}(b \to sg^* \to s\bar{s}s) = 1\%$. Estimations of the corresponding branching fraction within the SM typically yield smaller values than this estimation. For example, the branching fraction of $B \to \phi X_s$ is expected to be around $10^{-4}$. With an additional $s\bar{s}$ popping and with the aforementioned simulation, we obtain $\mathcal{B}(B \to \phi X_s)_{\text{SM}} \sim 3 \times 10^{-7}$ in the $\eta_c$ mass region. Also from the expected $\mathcal{B}(b \to s\bar{s}s)$ in the SM, we obtain $\sim 9 \times 10^{-7}$. Thus $r^2 \sim 5$ holds for $\mathcal{B}(b \to sg^* \to s\bar{s}s) = 1\%$. Note that, even in this case, an observation of non-resonant $B \to \phi X_s$ decays in the $\eta_c$ mass sideband region alone can not establish physics beyond the SM because of the difficulty in estimating branching fractions of multi-body hadronic decays.

The evaluation of the denominator of $\mathcal{A}_{CP}$ is straightforward with the estimations mentioned above. We obtain the following result for $\mathcal{B}(b \to sg^* \to s\bar{s}s) \sim 1\%$ and $2\pi a_R^2 = 2 \times 10^{-5}$:

$$
\mathcal{A}_{CP} \cong \frac{\mathcal{B}_{\text{NP}}}{\sqrt{\mathcal{B}(B^\pm \to \eta_c X^\pm) \cdot \mathcal{B}(\eta_c \to \phi\phi) + 2(1 + 2r^{-1}\cos \Theta_{\text{NP}} + r^{-2})\mathcal{B}_{\text{NP}}} \times \sqrt{\frac{\pi}{3}} \cdot |\sin \Theta_{\text{NP}}| \sim 0.40 \cdot |\sin \Theta_{\text{NP}}|} .
$$

(13)

A large $CP$ asymmetry of 0.4 is allowed. The asymmetry is roughly proportional to $|r|$. Therefore it can be sizable even with $r^2 < 1$; for example, $\mathcal{A}_{CP} \sim 0.1$ is allowed for $r^2 = 0.3$.

A $CP$ asymmetry proportional to $\sin \phi_3$ ($\phi_3 = 59^\circ \pm 13^\circ$ [18]) may arise within the SM due to an interference between the resonant amplitude and a SM contribution from the $b \to u\bar{u}s$ transition followed by rescattering into $s\bar{s}s$. The effect is expected to be small since the $b \to u\bar{u}s$ decay amplitude is CKM-suppressed, and the rescattering amplitude is also suppressed by the OZI rule. From the measured branching fractions for $B^+ \to K^+K^-K^+$ and $B^+ \to K^+K^-\pi^+$ together with the additional $O(\lambda)$ suppression, where $\lambda = 0.2229 \pm 0.0022$ is the sine of the Cabibbo angle [18], the fraction of the $b \to u\bar{u}s$ transition in the $B^+ \to K^+K^-K^+$ decay amplitude is estimated to be $\sqrt{0.0222 \pm 0.005}$ in Ref. [33]. Using this information and with a modest assumption on a rescattering amplitude ratio $\mathcal{A}(u\bar{u} \to \phi\phi)/\mathcal{A}(u\bar{u} \to K^+K^-) \lesssim 0.3$ from the OZI rule, we estimate the $CP$ asymmetry to be less than 0.9%. Thus we conclude that the $CP$ asymmetry within the SM is most likely below 1%.
We perform Monte Carlo simulation for the \( B^\pm \to \phi\phi K^\pm \) decay and estimate statistical errors on the \( CP \) asymmetry parameter. For this decay mode, the background level is expected to be small enough to be neglected [34]. The reconstruction efficiency and the \( \phi\phi \) mass resolution are estimated using a GEANT-based detector simulator for the Belle detector [35]. We obtain \( \sim 300 \) events for \( N_B = 10^9 \), where \( N_B \) is the number of charged \( B \) mesons recorded by a detector. We perform an unbinned maximum-likelihood fit to the differential decay rate distribution, which is proportional to \( |R(s) + D^\pm(s, z)|^2 \), instead of integrating the distribution. We choose the following two free parameters in the fit: \( A_{CP}^0 \equiv -2r(a_D/a_R)\sin\Theta_{NP} \) and \( B \equiv a_B^2(r^2 + 2r \cos \Theta_{NP} + 1) \). \( A_{CP}^0 \) is the \( CP \) asymmetry in the Breit-Wigner term. \( B \) is proportional to the branching ratio of the non-resonant \( B^\pm \to \phi\phi K^\pm \) decay below the \( \eta_c \) mass region. The statistical error for \( A_{CP}^0 \) is estimated to be \( \delta A_{CP}^0 \sim 0.06 \). Figure 1 shows the 5\( \sigma \) search regions for \( N_B = 10^9 \) (dotted line) and for \( N_B = 10^{10} \) (solid line), which will be accessible at next-generation high-luminosity \( e^+e^- B \) factories. Direct \( CP \) violation will be observed in a large parameter space above a 5\( \sigma \) significance.

The new \( CP \)-violating phase \( \Theta_{NP} \) also affects time-dependent \( CP \)-violating asymmetries \( A_{CP}(t) = S \sin(\Delta m_d t) + A \cos(\Delta m_d t) \) in \( B^0 \to \phi K_S^0 \) and related decays. Here \( \Delta m_d \) is the mass difference between the two \( B^0 \) mass eigenstates, and \( S \) and \( A \) are parameters for mixing-induced \( CP \) violation and direct \( CP \) violation, respectively. Ignoring a strong phase difference between the amplitude of NP (\( A_{NP} \)) and SM (\( A_{SM} \)), we obtain

\[
S = \frac{\sin 2\phi_1 + 2\rho \sin(2\phi_1 + \Theta_{NP}) + \rho^2 \sin(2\phi_1 + 2\Theta_{NP})}{1 + \rho^2 + 2\rho \cos \Theta_{NP}}
\]

(14)

where \( \rho \equiv A_{NP}/A_{SM} \) is an amplitude ratio of NP to the SM and \( \phi_1 \) is one of the angles of the unitarity triangle. In particular, a difference in \( S \) between \( B^0 \to \phi K_S^0 \) and \( B^0 \to J/\psi K_S^0 \) decays, i.e. \( \Delta S \equiv S(\phi K_S^0) - S(J/\psi K_S^0) \neq 0 \), would be a clear signal of the new phase since \( S(J/\psi K_S^0) = \sin 2\phi_1 \) is held to a good approximation. We define expected statistical significance of the deviation from the SM by \( A_{CP}^0/\delta A_{CP}^0 \) for the \( B^\pm \to \phi\phi K^\pm \) decay and by \( \Delta S/\delta \Delta S \) for the \( B^0 \to \phi K_S^0 \) decay, where \( \delta \Delta S \) is an expected statistical error of \( \Delta S \) extrapolated from the latest result by the Belle experiment [12]. Although \( r^2 \) is not necessarily equal to \( \rho^2 \), both decays are governed by the same \( b \to s\bar{s}s \) transition. Therefore it is reasonable to choose \( r^2 = \rho^2 \) for comparison. Figure 2 shows the resulting significance for \( 10^{10} B \) mesons and with \( r^2 = \rho^2 = 0.5 \). The significance for \( \Delta S \) largely depends on the sign of \( \Theta_{NP} \), which is not the case for the \( B^\pm \to \phi\phi K^\pm \) decay. The sign dependence arises from an asymmetric range for \( \Delta S \); to a good approximation, we have \( -1 - \sin 2\phi_1 \leq \Delta S \leq -1 + \sin 2\phi_1 \) where \( \sin 2\phi_1 = +0.736 \pm 0.049 \) [14]. Therefore the \( B^\pm \to \phi\phi K^\pm \) decay plays a unique role in searching for a new \( CP \)-violating phase.
In the above estimation, we use parameters that have uncertainties. However, they can in principle be measured precisely if a sufficient number of B mesons are produced. In our estimation, we assume efficiencies and background levels that have been achieved with the Belle detector at the KEK B factory. They depend on the actual detector performance and beam conditions, which might be different at a next-generation B factory with the higher luminosity. Detailed simulation studies as well as some extrapolation from data at current B factories will be needed for further quantitative evaluation.

Experimental sensitivities can be improved by adding more final states. The technique to reconstruct $X_s$, which has been successfully adopted for the measurements of semi-inclusive $B \to X_s \ell\ell$ transitions [36], can be used for this purpose. Flavor-specific neutral B meson decays, such as $B^0 \to \phi\phi K^{*0}(\to K^+\pi^-)$, and other charmonia such as the $\chi_{c0} \to \phi\phi$ decay can also be included. The method proposed in this Letter is also applicable to other beauty hadrons. Examples include $B_s \to \eta_c(\to \phi\phi)\phi$ and $\Lambda_b \to \eta_c(\to \phi\phi)\Lambda$.

In summary, we have investigated $B \to \phi\phi X_s$ decays as a probe for a new $CP$-violating phase in the $b \to s\bar{s}s\bar{s}s$ transition. Large $CP$ violation may arise from an interference between $B^+ \to \eta_c(\to \phi\phi)X_s^+$ and a contribution of the physics beyond the SM to the non-resonant decay $B^+ \to \phi\phi X_s^+$. We find that the direct $CP$ asymmetry can be as large as 0.4. The experimental signature will be very clean in particular at $e^+e^-$ B factories; when $10^9$ charged B mesons are available, the statistical error on the $CP$ asymmetry parameter is estimated to be $\sim$0.06. The statistical significance of $CP$ violation in the $B^\pm \to \phi\phi K^{\pm}$ decay can exceed 5 standard deviations. An even better sensitivity will be expected by including other final states. We also find that this result is comparable to the expected sensitivity with mixing-induced $CP$ violation in the $B^0 \to \phi K^0_S$ decay. Thus $B \to \phi\phi X_s$ decays will be useful to search for $CP$ violation beyond the SM in the $b \to s\bar{s}s\bar{s}s$ transition at high-luminosity $e^+e^-$ B factories.

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Note added.–After finishing this study and as we were preparing the manuscript, the Belle Collaboration announced evidence for $B \to \phi\phi K$ decays [37]. The signal purity is close to 100% when the $\phi\phi$ invariant mass is within the $\eta_c$.
mass region, as assumed in our study. The results are still limited by small
statistics; using the measured branching fractions of the $B \to \phi\phi K$ decay
within and below the $\eta_c$ mass region, we find that the maximal $CP$ asymmetry of $A_{\text{CP}} \sim 0.4$ is still allowed. The same paper also reports $B(\eta_c \to \phi\phi) = (1.8^{+0.8}_{-0.6} \pm 0.7) \times 10^{-3}$, which is smaller than the current world average. We repeat the fit procedure described in this Letter with the above branching fraction. Although the smaller value for $B(\eta_c \to \phi\phi)$ results in the smaller number of signal events, the $CP$ asymmetry from the interference between the resonant and the new-physics amplitudes becomes larger. We find that the change in $B(\eta_c \to \phi\phi)$ does not largely affect the significance; the difference is less than 10% for $r^2 = 0.5$ and $\sin \Theta_{NP} = 1$.

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Fig. 1. Expected sensitivities on direct $CP$ violation in the $B^\pm \to \phi \phi K^\pm$ decay for $10^9 B$ mesons (dotted line) and $10^{10} B$ mesons (solid line). In the regions above the curves, direct $CP$ violation can be measured with a $5\sigma$ significance or larger.

Fig. 2. Expected statistical significance of deviations from the SM for direct $CP$ violation in the $B^\pm \to \phi \phi K^\pm$ decay with $r^2 = 0.5$ (solid line) and for time-dependent $CP$ violation in the $B^0 \to \phi K_S^0$ decay with $|A_{NP}/A_{SM}|^2 = 0.5$ (dashed line). For each case, significance is calculated with $10^{10} B$ mesons.