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New strategy to explore CP violation with $B_s^0 \to K^- K^+$

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The U-spin symmetry provides a powerful tool to extract the angle γ of the Unitarity Triangle and the B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s from CP violation in the $B_s^0 \to K^- K^+$, $B_d^0 \to \pi^- \pi^+$ system. LHCb has obtained first results with uncertainties at the 7° level. Due to U-spin-breaking corrections, it will be challenging to reduce the uncertainty below $\mathcal{O}(5°)$ at Belle II and the LHCb upgrade. We propose a new strategy, using γ as input and utilizing $B_s^0 \to K^- \ell^+ \nu_\ell$, $B_d^0 \to \pi^- \ell^+ \nu_\ell$ decays, which allows an extraction of ϕ_s with a future theoretical precision of up to $\mathcal{O}(0.5°)$, thereby matching the experimental prospects. Since $B_s^0 \to K^- K^+$ is dominated by penguin topologies, new sources of CP violation may be revealed.

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I. INTRODUCTION

Decays of B mesons offer an interesting laboratory to search for signals of physics beyond the Standard Model (SM). In particular the penguin sector is sensitive to new heavy particles, which may enter the corresponding loop diagrams or cause flavor-changing neutral currents at the tree level (see for example [1]). Such new interactions are usually associated with new sources of CP violation, which would manifest themselves in CP-violating decay rate asymmetries.

These CP asymmetries are induced through interference effects. Interference between different decay contributions, such as tree and penguin topologies, results in CP violation directly at the decay-amplitude level. This is referred to as direct CP violation. In the case of neutral B_q^0 mesons ($q = d,\ s$), interference between $B_q^0 \to f$ and $\bar{B}_q^0 \to f$ transitions through B_q^0–$\bar{B}_q^0$ mixing may generate mixing-induced CP violation (see for example [2]). In order to detect footprints of New Physics (NP) in the era of Belle II [3] and the LHCb upgrade [4], the SM picture of the CP asymmetries has to be understood with highest precision, where the main challenge is related to the impact of strong interactions.

The $B_s^0 \to K^- K^+$ mode is one of the most prominent nonleptonic B decays, receiving contributions from tree and penguin topologies. Due to the specific pattern of the quark-flavor mixing in the SM, which is encoded in the Cabibbo–Kobayashi–Maskawa (CKM) matrix [2], the latter loop processes play the dominant role.

The $B_s^0 \to K^- K^+$ channel is related to $B_d^0 \to \pi^- \pi^+$ through the U-spin flavor symmetry of strong interactions, relating down and strange quarks to each other. Exploiting this feature, the hadronic nonperturbative parameters of $B_s^0 \to K^- K^+$, which suffer from large theoretical uncertainties, can be related to their counterparts in $B_d^0 \to \pi^- \pi^+$, allowing the extraction of the angle γ of the Unitarity Triangle and the B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s [5–7]. A variant of this U-spin method was proposed in [8], combining it with the $B \to \pi\pi$ isospin analysis [9], which reduces the sensitivity to U-spin-breaking effects.

Using their first measurement of CP violation in $B_s^0 \to K^- K^+$ [10], the LHCb Collaboration [11] obtained

$$\gamma = (63.5^{+7.2}_{-6.7})°, \qquad \phi_s = -(6.9^{+9.2}_{-8.0})°. \tag{1}$$

In this analysis, the strategies proposed in [5,8] were found to agree with each other and previous studies [6,7] for U-spin-breaking effects of up to 50%. For even larger corrections of (50%–100%), the $B \to \pi\pi$ system stabilizes the situation.

Using pure tree decays $B \to D^{(*)} K^{(*)}$ [12,13], γ can be extracted in a theoretically clean way (for an overview, see [14]). Current data yield the averages $\gamma = (73.2^{+6.3}_{-7.0})°$ [15] and $(68.3 \pm 7.5)°$ [16], which agree with (1) and have similar uncertainties. The phase ϕ_s takes the SM value $\phi_s^{\rm SM} = -(2.1 \pm 0.1)°$ [17] and can be determined through $B_s^0 \to J/\psi\phi$ and similar decays which are dominated by tree topologies [18,19]; penguin contributions limit the theoretical precision (see [20] and references therein). The Particle Data Group (PDG) gives the average $\phi_s = -(0.68 \pm 2.2)°$ [21], which has an uncertainty about four times smaller than (1). In the future, the uncertainty for γ from tree decays can be reduced to $\mathcal{O}(1°)$ [3,4], while ϕ_s can be determined from $B_s^0 \to J/\psi\phi$ and penguin control channels with a precision at the 0.5° level [20].

The experimental results in (1) suggest significant room for improvement. However, the theoretical precision is limited by U-spin-breaking corrections to penguin topologies. As we show, it is challenging to reduce the uncertainty below $\mathcal{O}(5°)$. We propose a new strategy to exploit the physics potential of $B_s^0 \to K^-K^+$, $B_d^0 \to \pi^-\pi^+$ in the high-precision era of B physics. It employs semileptonic $B_s^0 \to K^-\ell^+\nu_\ell$, $B_d^0 \to \pi^-\ell^+\nu_\ell$ decays as new ingredients and applies the U-spin symmetry only to theoretically well-behaved quantities. This method will eventually allow a measurement of ϕ_s from CP violation in $B_s^0 \to K^-K^+$ with a theoretical precision at the 0.5° level, thereby matching the expected experimental precision. It has the exciting potential to reveal CP-violating NP contributions to the penguin-dominated $B_s^0 \to K^-K^+$ mode and provides valuable insights into strong interaction dynamics through the determination of U-spin-breaking parameters.

II. THE ORIGINAL STRATEGY

Before focusing on the new method, it is instructive to have a look at the original strategy [5–7]. In the SM, the $B_s^0 \to K^-K^+$ decay amplitude can be written as

$$A(B_s^0 \to K^-K^+) = e^{i\gamma}\sqrt{\epsilon}\mathcal{C}'\left[1 + \frac{1}{\epsilon}d'e^{i\theta'}e^{-i\gamma}\right], \tag{2}$$

where the primes indicate a $\bar{b} \to \bar{s}$ transition, and

$$\mathcal{C}' = \lambda^3 A R_b[T' + E' + P^{(ut)'} + PA^{(ut)'}] \tag{3}$$

$$d'e^{i\theta'} \equiv \frac{1}{R_b}\left[\frac{P^{(ct)'} + PA^{(ct)'}}{T' + E' + P^{(ut)'} + PA^{(ut)'}}\right] \tag{4}$$

with

$$P^{(qt)'} \equiv P^{(q)'} - P^{(t)'}, \qquad PA^{(qt)'} \equiv PA^{(q)'} - PA^{(t)'}. \tag{5}$$

Here, T' is a color-allowed tree and E' an exchange amplitude, while $P^{(q)'}$ and $PA^{(q)'}$ denote penguin and penguin annihilation topologies, respectively, with $q = u$, c, t quarks in the loops. Finally, $A \equiv |V_{cb}|/\lambda^2 \approx 0.8$, $R_b \equiv (1-\lambda^2/2)|V_{ub}/(\lambda V_{cb})| \approx 0.4$ and $\epsilon \equiv \lambda^2/(1-\lambda^2) \approx 0.05$ are CKM factors involving the Wolfenstein parameter $\lambda \equiv |V_{us}| \approx 0.22$ [15]. The exchange and penguin annihilation topologies are expected to play a minor role on the basis of dynamical arguments [22–24].

The amplitude of the $\bar{b} \to \bar{d}$ mode $B_d^0 \to \pi^-\pi^+$ reads

$$A(B_d^0 \to \pi^-\pi^+) = e^{i\gamma}\mathcal{C}[1 - de^{i\theta}e^{-i\gamma}], \tag{6}$$

where the hadronic parameters $\mathcal{C}$ and $de^{i\theta}$ are defined in analogy to their $B_s^0 \to K^-K^+$ counterparts. The U-spin symmetry implies the following relations [5]:

$$d'e^{i\theta'} = de^{i\theta}, \tag{7}$$

$$\mathcal{C}' = \mathcal{C}. \tag{8}$$

Due to B_q^0–$\bar{B}_q^0$ oscillations, we have time-dependent decay rate asymmetries which probe direct and mixing-induced CP violation, described by $\mathcal{A}_{\rm CP}^{\rm dir}(B_q \to f)$ and $\mathcal{A}_{\rm CP}^{\rm mix}(B_q \to f)$, respectively [2]. In the case of the decays at hand, we have the following expressions [5]:

$$\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^-K^+) = \frac{2\epsilon d'\sin\theta'\sin\gamma}{d'^2 + 2\epsilon d'\cos\theta'\cos\gamma + \epsilon^2}, \tag{9}$$

$$\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^-K^+) = \left[\frac{d'^2\sin\phi_s + 2\epsilon d'\cos\theta'\sin(\phi_s+\gamma) + \epsilon^2\sin(\phi_s+2\gamma)}{d'^2 + 2\epsilon d'\cos\theta'\cos\gamma + \epsilon^2}\right]; \tag{10}$$

the CP asymmetries of $B_d^0 \to \pi^-\pi^+$ follow by replacing $\epsilon \to -1$, $d' \to d$, $\theta' \to \theta$ and $\phi_s \to \phi_d$.

The main application of this system is usually the determination of γ, using the ϕ_q as input. However, if only ϕ_d is employed, also ϕ_s can be extracted. In view of the large uncertainties of the current LHCb measurement of the $B_s^0 \to K^-K^+$ CP asymmetries (see Table I), the results in (1) are governed by the CP asymmetries of $B_d^0 \to \pi^-\pi^+$ and the ratio of the branching ratios of $B_s^0 \to K^-K^+$ and $B_d^0 \to \pi^-\pi^+$ [6,7]. The latter is affected by U-spin-breaking corrections to (8) which involve nonperturbative decay constants and form factors.

At the LHCb upgrade, γ can be extracted by using only the CP asymmetries. In this case, the U-spin relation $d' = d$ is sufficient, which is more favorable than (8) as factorizable U-spin-breaking corrections cancel [5]. In Table I, we give a scenario for the CP asymmetries at the LHCb upgrade, using the expected uncertainties given in [4]. As the current uncertainties of the $B_s^0 \to K^-K^+$ CP asymmetries are still very large, we use the U-spin relation (7) with (9) and (10) to calculate the corresponding central values. Assuming the U-spin relation $d' = d$, we obtain the constraints shown in Fig. 1, leading to an experimental

TABLE I. Summary of the current and future measurements. For the upgrade scenario, we use (d, θ) following from the CP asymmetries of $B_d^0 \to \pi^-\pi^+$ to calculate the central values of the $B_s^0 \to K^-K^+$ CP asymmetries with the U-spin symmetry.

Observable	Current [21,25]	LHCb upgrade [4]
$\mathcal{A}_{\rm CP}^{\rm dir}(B_d \to \pi^-\pi^+)$	-0.31 ± 0.05	-0.31 ± 0.008
$\mathcal{A}_{\rm CP}^{\rm mix}(B_d \to \pi^-\pi^+)$	0.66 ± 0.06	0.66 ± 0.008
$\mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^-K^+)$	0.14 ± 0.11	0.087 ± 0.008
$\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^-K^+)$	-0.30 ± 0.13	-0.19 ± 0.008

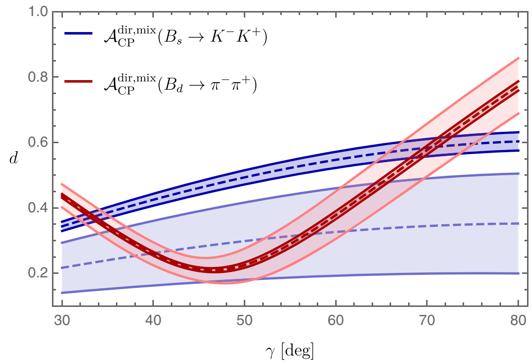

FIG. 1. Illustration of the γ determination from the *CP* asymmetries of the $B_d^0 \to \pi^-\pi^+$, $B_s^0 \to K^-K^+$ decays: current situation (wide bands), LHCb upgrade as specified in Table I (narrow bands).

uncertainty of γ of $\mathcal{O}(1°)$. Allowing for U-spin-breaking corrections as

$$\xi \equiv d'/d = 1 \pm 0.2, \qquad \Delta \equiv \theta' - \theta = (0 \pm 20)°, \qquad (11)$$

where only ξ affects the determination of γ, gives an uncertainty of $\mathcal{O}(5°)$.

The *CP* asymmetries of $B_s^0 \to K^-K^+$ allow the determination of the following "effective" mixing phase [26]:

$$\sin\phi_s^{\rm eff} = \frac{\mathcal{A}_{\rm CP}^{\rm mix}(B_s \to K^-K^+)}{\sqrt{1 - \mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^-K^+)^2}}, \qquad (12)$$

where $\phi_s^{\rm eff} \equiv \phi_s + \Delta\phi_{KK}$ with

$$\tan\Delta\phi_{KK} = \epsilon\left[\frac{2(d'\cos\theta' + \epsilon\cos\gamma)\sin\gamma}{d'^2 + 2\epsilon d'\cos\theta'\cos\gamma + \epsilon^2\cos 2\gamma}\right]. \qquad (13)$$

At the LHCb upgrade, $\phi_s^{\rm eff}$ can be measured with a precision at the 0.5° level [4]. Assuming U-spin-breaking corrections as given by (11) gives an uncertainty for $\Delta\phi_{KK}$ of 2.6°, which affects the determination of $\phi_s = \phi_s^{\rm eff} - \Delta\phi_{KK}$ correspondingly.

In order to match the future experimental precision on γ and ϕ_s, ξ would have to be known with an uncertainty at the few percent level. Unless there is theoretical progress, this precision is out of reach, and the impressive experimental prospects at the LHCb upgrade cannot be fully exploited.

III. THE NEW STRATEGY

Our goal is to make minimal use of the U-spin symmetry. We employ γ as an input, assuming $\gamma = (70 \pm 1)°$ as determined from pure tree decays in the era of Belle II and the LHCb upgrade [3,4]. Moreover, we use ϕ_d as an input, which can be extracted from $B_{d,s}^0 \to J/\psi K_{\rm S}$ decays taking penguin contributions into account, assuming $\phi_d = (43.2 \pm 0.6)°$ [20]. The *CP* asymmetries of $B_d^0 \to \pi^-\pi^+$ allow then a theoretically clean determination of the hadronic parameters d, θ and $\mathcal{C}$. We focus on the determination of ϕ_s from (12) which requires knowledge of the hadronic phase shift $\Delta\phi_{KK}$ in (13).

The ratios of nonleptonic decay rates to differential semileptonic rates allow us to probe nonfactorizable effects of strong interactions [27–32] and were applied to $B \to D\bar{D}$ decays in [33]. We introduce

$$R_\pi \equiv \frac{\Gamma(B_d \to \pi^-\pi^+)}{d\Gamma(B_d^0 \to \pi^-\ell^+\nu_\ell)/dq^2|_{q^2=m_\pi^2}} = 6\pi^2|V_{ud}|^2 f_\pi^2 X_\pi r_\pi |a_{\rm NF}|^2, \qquad (14)$$

where $|V_{ud}|$ is a CKM matrix element, f_π denotes the charged pion decay constant and

$$X_\pi = \left[\frac{(m_{B_d}^2 - m_\pi^2)^2}{m_{B_d}^2(m_{B_d}^2 - 4m_\pi^2)}\right]\left[\frac{F_0^{B_d\pi}(m_\pi^2)}{F_1^{B_d\pi}(m_\pi^2)}\right]^2 \qquad (15)$$

depends on the meson masses and form factors, which are defined through

$$\langle\pi^+(k)|\bar{u}\gamma_\mu b|\bar{B}_d^0(p)\rangle = F_0^{B\pi}(q^2)\left(\frac{M_B^2 - M_\pi^2}{q^2}\right)q_\mu + F_1^{B\pi}(q^2)\left[(p+k)_\mu - \frac{M_B^2 - M_\pi^2}{q^2}q_\mu\right], \qquad (16)$$

with $q \equiv p - k$. Moreover,

$$r_\pi = 1 - 2d\cos\theta\cos\gamma + d^2, \qquad (17)$$

and

$$a_{\rm NF} = a_{\rm NF}^T(1 + r_P)(1 + x) \qquad (18)$$

characterizes nonfactorizable effects with

$$r_P \equiv \frac{P^{(ut)}}{T}, \qquad x \equiv \frac{E + PA^{(ut)}}{T + P^{(ut)}}. \qquad (19)$$

The deviation of $a_{\rm NF}^T$ from one characterizes nonfactorizable contributions to T. From the theoretical point of view, this color-allowed tree amplitude is most favorable, while the penguin topologies are challenging, with issues such as "charming penguins" [34]. The framework of QCD factorization sets a stage for the theoretical description [35,36], where two-loop next-to-next-to-leading-order vertex corrections were calculated [37]:

$$a_{\rm NF}^T = 1.000^{+0.029}_{-0.069} + (0.011^{+0.023}_{-0.050})i. \qquad (20)$$

In analogy to (14), we introduce

$$R_K \equiv \frac{\Gamma(B_s \to K^- K^+)}{d\Gamma(B_s^0 \to K^- \ell^+ \nu_\ell)/dq^2|_{q^2=m_K^2}} = 6\pi^2 |V_{us}|^2 f_K^2 X_K r_K |a'_{\rm NF}|^2, \tag{21}$$

where

$$r_K = 1 + 2(d'/\epsilon)\cos\theta' \cos\gamma + (d'/\epsilon)^2, \tag{22}$$

and X_K can be obtained from (15) through straightforward replacements.

From the CP asymmetries of $B_d^0 \to \pi^-\pi^+$, we may determine r_π. The ratio of R_K and R_π yields then

$$r_K = r_\pi \frac{R_K}{R_\pi}\left(\frac{|V_{ud}|f_\pi}{|V_{us}|f_K}\right)^2 \frac{X_\pi}{X_K}|\xi_{\rm NF}^a|^2, \tag{23}$$

where

$$\xi_{\rm NF}^a \equiv \left|\frac{a_{\rm NF}}{a'_{\rm NF}}\right| = \left|\frac{a_{\rm NF}^T}{a_{\rm NF}^{T'}}\right|\left|\frac{1+r_P}{1+r'_P}\right|\left|\frac{1+x}{1+x'}\right|. \tag{24}$$

Applying the U-spin symmetry to $\xi_{\rm NF}^a$ in (24) allows us to determine r_K in (22). As we show in detail, the structure of (24) is theoretically favorable, as it is very robust with respect to U-spin-breaking corrections. Experimental data for charged kaon and pion leptonic decays allow the determination of $|V_{us}|f_K/|V_{ud}|f_\pi = 0.27599 \pm 0.00037$ with impressive precision [38]. The double ratio of form factors in X_π/X_K is given with excellent precision by one, which is also in agreement with the kinematic constraint implemented by lattice calculations [39,40].

Using (9), which depends on d', θ' and γ [5], we may now determine d' and θ':

$$d' = \epsilon\left[r_g \pm \sqrt{r_g^2 - (r_K-1)^2 - (r_K \mathcal{A}_{\rm CP}^{\rm dir'}/\tan\gamma)^2}\right]^{1/2}$$

$$\sin\theta' = \frac{\epsilon r_K \mathcal{A}_{\rm CP}^{\rm dir'}}{2d'\sin\gamma}, \qquad \cos\theta' = \frac{\epsilon^2(r_K-1) - d'^2}{2\epsilon d'\cos\gamma}, \tag{25}$$

where $r_g \equiv r_K + \cos 2\gamma$ and $\mathcal{A}_{\rm CP}^{\rm dir'} \equiv \mathcal{A}_{\rm CP}^{\rm dir}(B_s \to K^-K^+)$. Finally, we determine $\Delta\phi_{KK}$ through (13), which allows the extraction of $\phi_s = \phi_s^{\rm eff} - \Delta\phi_{KK}$ from the CP asymmetries of $B_s^0 \to K^+K^-$ entering (12). This method is illustrated in the flowchart in Fig. 2.

The theoretical precision is limited by the U-spin-breaking corrections to (24). In the following, we assume U-spin-breaking corrections of 20% to demonstrate the sensitivity of our new strategy. Writing $a_{\rm NF}^{T(')} = 1 + \Delta_{\rm NF}^{T(')}$ with $\Delta_{\rm NF}^{T'} = \Delta_{\rm NF}^T(1-\xi_{\rm NF}^T)$ yields

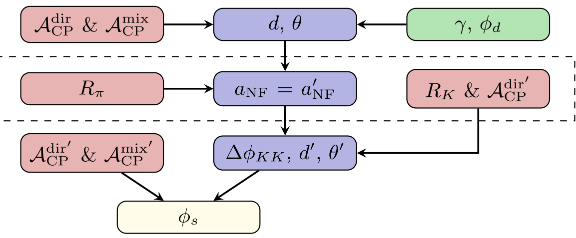

FIG. 2. Illustration of the new strategy to extract ϕ_s from CP violation in $B_s^0 \to K^-K^+$. The $\mathcal{A}_{\rm CP}^{\rm dir}$, $\mathcal{A}_{\rm CP}^{\rm mix}$ and $\mathcal{A}_{\rm CP}^{\rm dir'}$, $\mathcal{A}_{\rm CP}^{\rm mix'}$ denote the direct, mixing-induced CP asymmetries of the $B_d^0 \to \pi^-\pi^+$ and $B_s^0 \to K^-K^+$ decays, respectively. The dashed box highlights the novel steps in our method.

$$\frac{a_{\rm NF}^T}{a_{\rm NF}^{T'}} = 1 + \Delta_{\rm NF}^T \xi_{\rm NF}^T + \mathcal{O}((\Delta_{\rm NF}^T)^2). \tag{26}$$

The numerical value in (20) corresponds to $\Delta_{\rm NF}^T \sim 0.05$. Consequently, $\xi_{\rm NF}^T \sim 0.2$, i.e. U-spin-breaking corrections of 20%, corresponds to a correction at the 1% level to (26). In the case of r_P, defined in (19), we write in analogy $r'_P = r_P(1-\xi_r)$, which gives

$$\frac{1+r_P}{1+r'_P} = 1 + r_P\xi_r + \mathcal{O}(r_P^2). \tag{27}$$

Using current data from $B_d^0 \to \pi^-K^+$ and $B_s^0 \to K^-\pi^+$, as well as $B^+ \to \pi^+K^0$ and $B^+ \to K^+\bar{K}^0$, we expect $r_P \sim 0.3$ [41], which agrees with general expectations [22,23]. Assuming $\xi_r \sim 0.2$ yields a correction at the 5% level. In the future one can use the decays $B_d^0 \to K^0\bar{K}^0$ and $B_s^0 \to K^0\bar{K}^0$ to pin down $r_P^{(\prime)}$. A similar structure arises for the U-spin-breaking ratio of $(1+x)/(1+x')$, which involves the exchange and penguin annihilation amplitudes (19). These topologies are expected to play a minor role and can be probed through $B_d^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$ decays, with values of x in the 0.2 regime [6,41]. Consequently, in analogy to the discussion for r_P, r'_P, we obtain a correction at the 5% level. Recent LHCb data [42] suggest an even smaller value for x in the 0.05–0.10 regime [41], which is even more favorable for our new strategy.

Combining all these nonfactorizable U-spin-breaking effects, we estimate the corresponding error of $\xi_{\rm NF}^a$ in (24) as 10%. This error estimate is very robust with respect to U-spin-breaking effects, because $\Delta_{\rm NF}^T$, r_P and x are small parameters. Since $r_K \gg 1$, as can be seen in (22), we obtain $d' \sim \epsilon\sqrt{r_K} \propto |a_{\rm NF}/a'_{\rm NF}|$. Since (13) gives $\Delta\phi_{KK} \sim -10°$ for $d' \sim 0.6$, we conclude that the new method allows the determination of this phase with a theoretical precision at the 1° level. Using experimental data, this error can be controlled in a more sophisticated way, and even a regime of 0.5° appears achievable in the upgrade scenario [41]. A comparison with the original strategy, where 20% U-spin-breaking effects led to a precision of 3°, shows the

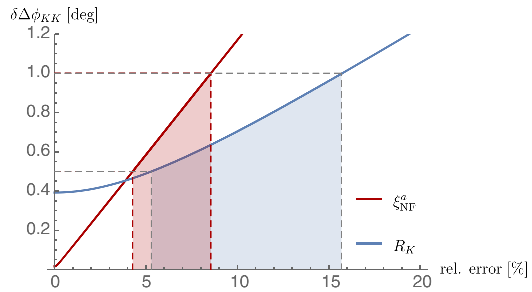

FIG. 3. Illustration of the error on $\Delta\phi_{KK}$. For the dependence on the U-spin-breaking parameter $\xi^a_{\rm NF}$ in (24), we assume a perfect experimental situation, while a perfect theoretical situation is assumed for the dependence on the relative error of R_K, assuming a precision for R_π of 5%.

power of our new strategy. Moreover, in the upgrade era we may explore the U-spin-breaking effects directly through data, thereby avoiding any theoretical assumptions on these effects. In Fig. 3, we illustrate the error of $\Delta\phi_{KK}$. We observe that a precision of 0.5° requires a measurement of both R_π and R_K with a relative precision of 5% in an ideal theoretical situation. A measurement of R_K with a relative precision of 15% would allow a precision of 1°, which would already be an impressive achievement.

The U-spin-breaking parameter ξ in (11), which limits the precision of the original method, can be written as

$$\xi = \xi^a_{\rm NF}\left|\frac{T_{\rm fact}}{T'_{\rm fact}}\right|\left|\frac{P^{(ct)'}+PA^{(ct)'}}{P^{(ct)}+PA^{(ct)}}\right|. \tag{28}$$

In contrast to $\xi^a_{\rm NF}$ in (24), ξ involves penguin amplitudes with internal top and charm quarks, where also "charming penguins" enter [34]. Since the leading U-spin-breaking corrections are associated with these contributions, the uncertainty is significantly larger than in the case of $\xi^a_{\rm NF}$, which governs the new strategy.

Another key feature of this method is that we may actually determine both ξ and Δ from the data, thereby allowing valuable insights into the U-spin symmetry at work. Assuming future determinations of R_K, R_π and $\xi^a_{\rm NF}$ with 5% precision, ξ can be extracted with an uncertainty at the 0.07 level.

The $B^0_s \to K^-\ell^+\nu_\ell$ decay has unfortunately not yet been measured. We strongly advocate analyses of this channel at Belle II and LHCb, aiming at a direct measurement of the ratio R_π/R_K which is required for our method. It is interesting to note that the ratio f_s/f_d of the $B^0_{s,d}$ fragmentation functions, which is a key ingredient for measurements of branching ratios of B^0_s mesons at hadron colliders [43], cancels in (21).

IV. PICTURE FROM CURRENT DATA

In view of the lack of data for the determination of R_K, we consider $B^0_d \to \pi^-K^+$, which arises if we replace the spectator strange quark of $B^0_s \to K^-K^+$ by a down quark. This channel has only penguin and tree contributions. If we neglect the exchange and penguin annihilation topologies in $B^0_s \to K^-K^+$ and use the $SU(3)$ flavor symmetry, we get the following relation [6]:

$$d' e^{i\theta'} = \tilde{d}' e^{i\tilde{\theta}'}, \tag{29}$$

where $\tilde{d}'$, $\tilde{\theta}'$ are the $B^0_d \to \pi^-K^+$ counterparts of d', θ'. As replacement for R_K, we introduce

$$\tilde{R}_K \equiv \frac{\Gamma(B^0_d \to \pi^-K^+)}{d\Gamma(B^0_d \to \pi^-\ell^+\nu_\ell)/dq^2|_{q^2=m_K^2}}. \tag{30}$$

In the ratio $R_\pi/\tilde{R}_K$ the semileptonic decay rates cancel up to a small corrections due to the different kinematical points.

Using the current values $\gamma = (70 \pm 7)^\circ$, $\phi_d = (43.2 \pm 1.8)^\circ$, $\mathcal{A}^{\rm dir}_{\rm CP}(B^0_d \to \pi^-K^+) = 0.082 \pm 0.006$ [25] and the CP asymmetries of $B^0_d \to \pi^-\pi^+$ in Table I, we obtain

$$d = 0.58 \pm 0.16, \qquad \theta = (151.4 \pm 7.6)^\circ \tag{31}$$

$$\tilde{d}' = 0.50 \pm 0.03, \qquad \tilde{\theta}' = (157.2 \pm 2.2)^\circ, \tag{32}$$

which yield

$$\tilde{\xi} \equiv \tilde{d}'/d = 0.87 \pm 0.20, \qquad \tilde{\Delta} \equiv \tilde{\theta}' - \theta = (5.8 \pm 8.3)^\circ. \tag{33}$$

Here, the uncertainties correspond only to the input parameters. The agreement between (31) and (32) is remarkable, strongly disfavoring the anomalously large U-spin-breaking corrections of (50%–100%) considered in [11].

The current CP asymmetries of $B^0_s \to K^-K^+$ give $\phi_s^{\rm eff} = (-17.6 \pm 7.9)^\circ$. Employing (29) results in

$$\Delta\phi_{KK} = -(10.8 \pm 0.6)^\circ. \tag{34}$$

Consequently, we obtain

$$\phi_s = \phi_s^{\rm eff} - \Delta\phi_{KK} = -(6.8 \pm 7.9)^\circ, \tag{35}$$

where the uncertainty is fully dominated by experiment. This value of ϕ_s is in excellent agreement with (1).

The analysis of the currently available data demonstrates impressively the power of the new strategy.

V. CONCLUSIONS

We have proposed a new strategy to extract the B^0_s–$\bar{B}^0_s$ mixing phase ϕ_s from the $B^0_s \to K^-K^+$, $B^0_d \to \pi^-\pi^+$ system. The novel ingredients are the semileptonic $B^0_s \to$

$K^-\ell^+\nu_\ell$ and $B_d^0 \to \pi^-\ell^+\nu_\ell$ decays, allowing us to limit the application of the U-spin symmetry to theoretically favorable color-allowed tree amplitudes and robust quantities. This method provides a future determination of ϕ_s from the CP violation in $B_s^0 \to K^-K^+$ with a theoretical precision as high as $\mathcal{O}(0.5°)$, which matches the experimental prospects and offers powerful tests of the U-spin symmetry. As there is currently no measurement of the $B_s^0 \to K^-\ell^+\nu_\ell$ decay available, we used the $B_d^0 \to \pi^-K^+$ mode to illustrate the new strategy and obtain a very promising picture from the current data. We strongly advocate experimental analyses of $B_s^0 \to K^-\ell^+\nu_\ell$ and dedicated determinations of the R_K and R_π ratios. The comparison of ϕ_s extracted from the penguin-dominated $B_s^0 \to K^-K^+$ decay with the SM prediction and alternative measurements may reveal new sources of CP violation. This strategy offers exciting new opportunities for the era of Belle II and the LHCb upgrade.

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