New Strategy to Explore CP Violation with $B_s^0 \rightarrow K^- K^+$

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Abstract

The $U$-spin symmetry provides a powerful tool to extract the angle $\gamma$ of the Unitarity Triangle and the $B_s^0$-$\bar{B}_s^0$ mixing phase $\phi_s$ from CP violation in the $B_s^0 \rightarrow K^- K^+$, $B_d^0 \rightarrow \pi^- \pi^+$ system. LHCb has obtained first results with uncertainties at the $7^\circ$ level. Due to $U$-spin-breaking corrections, it will be challenging to reduce the uncertainty below $\mathcal{O}(5^\circ)$ at Belle II and the LHCb upgrade. We propose a new strategy, using $\gamma$ as input and utilizing $B_s^0 \rightarrow K^- \ell^+ \nu_\ell$, $B_d^0 \rightarrow \pi^- \ell^+ \nu_\ell$ decays, which allows an extraction of $\phi_s$ with a future theoretical precision of up to $\mathcal{O}(0.5^\circ)$, thereby matching the experimental prospects. Since $B_s^0 \rightarrow K^- K^+$ is dominated by penguin topologies, new sources of CP violation may be revealed.
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 [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 direct CP violation. In the case of neutral $B_d$ mesons $(q = d, s)$, interference between $B^0_d \rightarrow f$ and $\bar{B}^0_d \rightarrow f$ transitions through $B^0_d - \bar{B}^0_d$ mixing may generate mixing-induced CP violation [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 $B^0_d \rightarrow K^-K^+$ mode is one of the most prominent non-leptonic $B$ 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 $B^0_s \rightarrow K^-K^+$ channel is related to $B^0_d \rightarrow \pi^-\pi^+$ through the $U$-spin flavor symmetry of strong interactions, relating down and strange quarks to each other. Exploiting this feature, the hadronic non-perturbative parameters of $B^0_s \rightarrow K^-K^+$, which suffer from large theoretical uncertainties, can be related to their counterparts in $B^0_d \rightarrow \pi^-\pi^+$, allowing the extraction of the angle $\gamma$ of the Unitarity Triangle and the $B^0_s - \bar{B}^0_s$ mixing phase $\phi_s$ [5,7].

A variant of this $U$-spin method was proposed in [8], combining it with the $B \rightarrow \pi\pi$ isospin analysis [9], which reduces the sensitivity to $U$-spin-breaking effects.

Using their first measurement of CP violation in $B^0_s \rightarrow K^-K^+$ [10], the LHCb collaboration [11] obtained

$$\gamma = (63.5^{+7.2}_{-6.7})^\circ, \quad \phi_s = -(6.9^{+9.2}_{-8.6})^\circ.$$  \hspace{1cm} (1)

In this analysis, the strategies proposed in [5] and [8] were found to agree with each other and previous studies [12] for $U$-spin-breaking effects of up to 50%. For even larger corrections of $(50-100)%$, the $B \rightarrow \pi\pi$ system stabilizes the situation.

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

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 will show, it is challenging to reduce the uncertainty below $O(5^\circ)$. We propose a new strategy to exploit the physics potential of $B^0_s \rightarrow K^-K^+$, $B^0_s \rightarrow \pi^-\pi^+$ in the high-precision era of $B$ physics. It employs semi-leptonic $B^0_s \rightarrow K^-\ell^+\nu_\ell$, $B^0_d \rightarrow \pi^-\ell^+\nu_\ell$ decays as new ingredients and applies the $U$-spin symmetry only to theoretically well-behaved quantities. This method will eventually allow a measurement of $\phi_s$ from CP violation in $B^0_s \rightarrow K^-K^+$ 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 $B^0_d \to K^0 \pi^+$ 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 $B^0_d \to K^0 \pi^+$ decay amplitude can be written as

$$A\left(B^0_d \to K^0 \pi^+\right) = e^{i\gamma}\sqrt{C'} \left[1 + \frac{1}{\epsilon} d' e^{i\phi} e^{-i\gamma}\right],$$  

(2)

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

$$C' = \lambda^3 A R_b \left[T' + E' + P^{(ut)} + P^{(ut')}\right],$$  

(3)

$$d'e^{i\phi} = \frac{1}{R_b} \left[\frac{P^{(ct)} + P^{(ct')} - P^{(ct)}}{T' + E' + P^{(ut')} + P^{(ut)}}\right].$$  

(4)

with

$$P^{(qt)} = P^{(qt')}, \quad P^{(at)} = P^{(at')}, \quad P^{(aq)} = P^{(aq')} - P^{(a)}.$$  

(5)

Here $T'$ is a colour-allowed tree and $E'$ an exchange amplitude, while $P^{(qt)}$ and $P^{(at)}$ denote penguin and penguin annihilation topologies, respectively, with $q = u, c, t$ quarks in the loops. Finally, $A \equiv |V_{cb}|/\lambda^3 \approx 0.8$, $R_b \equiv (1 - \lambda^2/2)|V_{ub}/V_{cb}| \approx 0.4$ and $\epsilon \equiv \lambda^2/(1 - \lambda^2) \approx 0.05$ are CKM factors involving the Wolfenstein parameter $\lambda \equiv |V_{us}| \approx 0.22$ [13]. The exchange and penguin annihilation topologies are expected to play a minor role on the basis of dynamical arguments [18–20].

The amplitude of the $b \to d$ mode $B^0_d \to \pi^- \pi^+$ reads

$$A\left(B^0_d \to \pi^- \pi^+\right) = e^{i\gamma}C \left[1 - de^{i\phi} e^{-i\gamma}\right],$$  

(6)

where the hadronic parameters $C$ and $de^{i\phi}$ are defined in analogy to their $B^0_d \to K^- K^+$ counterparts. The $U$-spin symmetry implies the following relations [3]:

$$d'e^{i\phi} = de^{i\phi},$$  

(7)

$$C' = C.$$  

(8)

Due to $B^0_q - \bar{B}^0_q$ oscillations, we obtain time-dependent decay rate asymmetries which probe direct and mixing-induced CP violation, described by $A^{\text{dir}}_{CP}(B_q \to f)$ and $A^{\text{mix}}_{CP}(B_q \to f)$, respectively [2]. In the case of $B^0_d \to K^- K^+$ and $B^0_d \to \pi^- \pi^+$, these observables depend on in addition to $\gamma$ and $d' e^{i\phi}$ and $d e^{i\phi}$; the $A^{\text{mix}}_{CP}(B_q \to f)$ involve also the $B^0_d - \bar{B}^0_d$ mixing phases $\phi_q$.

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

At the LHCb upgrade, $\gamma$ 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] because factorizable $U$-spin-breaking corrections cancel [5]. In Table I we collect expected measurements of the CP asymmetries at the LHCb upgrade. Assuming the $U$-spin relation $d' = d$, we get an experimental uncertainty of $\gamma$ of $1^{\circ}$, as illustrated in Fig. 1. Allowing for $U$-spin-breaking corrections as

$$\xi \equiv \frac{d'}{d} = 1 \pm 0.2, \quad \Delta \equiv \theta' - \theta = (0 \pm 20)^\circ,$$  

(9)

where only $\xi$ affects the determination of $\gamma$, gives an uncertainty of $O(5\circ)$. The CP asymmetries of $B^0_d \to K^- K^+$ allow the determination of the following “effective” mixing phase [22]:

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

(10)

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

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

(11)
At the LHCb upgrade, $\phi^{\text{eff}}$ can be measured with a precision at the 0.50% level \cite{4}. Using $\gamma = (70 \pm 1)^\circ$ and the CP asymmetries of $B^0_d \to \pi^-\pi^+$ as input, $d$ and $\theta$ can be extracted. If we assume $U$-spin-breaking corrections as given by \cite{9} when converting the $B^0_d \to \pi^-\pi^+$ parameters into their $B^0_s \to K^-K^+$ counterparts, we obtain an uncertainty for $\Delta \phi_{KK}$ of 2.6$\circ$, which affects the determination of $\phi_s = \phi^{\text{eff}} - \Delta \phi_{KK}$ correspondingly.

In order to match the future experimental precision, $\xi$ 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 $\gamma$ as an input, assuming $\gamma = (70 \pm 1)^\circ$ as determined from pure tree decays in the era of Belle II and the LHCb upgrade \cite{3,4}. Moreover, we use $\phi_d$ as an input, which can be extracted from $B^0_{d,s} \to J/\psi KS$ decays taking penguin contributions into account, assuming $\phi_d = (43.2 \pm 0.6)^\circ$ \cite{10}. The CP asymmetries of $B^0_d \to \pi^-\pi^+$ allow then a theoretically clean determination of the hadronic parameters $d$, $\theta$ and $C$. We shall focus on the determination of $\phi_s$ from \cite{10} which requires knowledge of the hadronic phase shift $\Delta \phi_{KK}$ in \cite{11}.

The ratios of non-leptonic decay rates to differential semileptonic rates allow us to probe non-factorizable effects of strong interactions \cite{23-28}. In analogy to the analysis of $B \to D\bar{D}$ decays in \cite{29}, we introduce

$$R_{\pi} = \frac{\Gamma(B_d \to \pi^-\pi^+)}{d\Gamma(B^0_d \to \pi^-\ell^+\nu_\ell)/dq^2|_{q^2=m^2_K}} = 6\pi^2|V_{ud}|^2 f^2_{\pi\pi} \pi_{\pi\pi} |a_{NF}|^2,$$  \hspace{1cm} (12)

where $|V_{ud}|$ is a CKM matrix element, $f_{\pi\pi}$ denotes the charged pion decay constant,

$$X_{\pi} = \left[\frac{(m^2_{B_d} - m^2_{\pi})^2}{m^2_{B_d}(m^2_{B_d} - 4m^2_{\pi})}\right] \left[\frac{F^0_{0\pi}(m^2_{\pi})}{F^0_{0\pi}(m^2_{\pi})}\right]^2$$  \hspace{1cm} (13)

depends on the meson masses and form factors,

$$r_{\pi} = 1 - 2d \cos \theta \cos \gamma + d^2,$$  \hspace{1cm} (14)

and

$$a_{NF} = a_{NF}^T (1 + r_P)(1 + x)$$  \hspace{1cm} (15)

characterizes non-factorizable effects with

$$r_P \equiv \frac{P^{(ut)}}{T}, \quad x \equiv \frac{E + PA^{(ut)}}{T + P^{(ut)}}.$$  \hspace{1cm} (16)

The deviation of $a_{NF}^T$ from one characterizes non-factorizable 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” \cite{30}. The framework of QCD factorization sets a stage for the theoretical description \cite{31,32}, where two-loop next-to-next-to-leading-order vertex corrections were calculated \cite{33}:

$$a_{NF}^{T} = 1 \pm 0.029 + (0.011 \pm 0.023)i.$$

In analogy to \cite{12}, we introduce

$$R_K = \frac{\Gamma(B_s \to K^-K^+)}{d\Gamma(B^0_s \to K^-\ell^+\nu_\ell)/dq^2|_{q^2=m^2_K}} = 6\pi^2|V_{us}|^2 f^2_K X_K r_K |a_{NF}|^2,$$  \hspace{1cm} (18)

where

$$r_K = 1 + 2 \left(\frac{d'}{\epsilon}\right) \cos \theta' \cos \gamma + \left(\frac{d'}{\epsilon}\right)^2,$$  \hspace{1cm} (19)

and $X_K$ can be obtained from \cite{13} through straightforward replacements.

From the CP asymmetries of $B^0_s \to \pi^-\pi^+$ we may determine $R_{\pi}$. The ratio of $R_K$ and $R_{\pi}$ yields then

$$r_K = r_{\pi} R_K R_{\pi} \frac{|V_{us}| f_K}{|V_{us}| f_K} \frac{X_{\pi}}{X_K} \frac{a_{NF}}{a_{NF}^T},$$  \hspace{1cm} (20)

which allows us to determine the observable in \cite{19} by applying the $U$-spin symmetry to the following ratio:

$$\xi_{NF}^T = \frac{a_{NF}}{a_{NF}^T} = \frac{a_{NF}^T}{a_{NF}} \left[\frac{1 + r_P}{1 + r_P'}\right] \left[\frac{1 + x}{1 + x'}\right].$$  \hspace{1cm} (21)

Experimental data for charged kaon and pion leptonic decays allow the determination of $|V_{us}|/|f_K|/|V_{ud}| f_{\pi} = 0.27599 \pm 0.00337$ with impressive precision \cite{34}. The double ratio of form factors in $X_{\pi}/X_K$ is given with excellent precision by one, which is also in agreement with

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Illustration of the new strategy to extract $\phi_s$ from CP violation in $B^0 \to K^-K^+$. The $A^{\text{dir}}_{CP}$, $A^{\text{mix}}_{CP}$ and $A_{CP}^{\text{dir}'}$, $A_{CP}^{\text{mix}'}$ denote the direct, mixing-induced CP asymmetries of the $B^0_d \to \pi^-\pi^+$ and $B^0_s \to K^-K^+$ decays, respectively.}
\end{figure}
the kinematic constraint implemented by lattice calculations \[35, 36\]. Using \(A_{\text{CP}}^{\text{dir}}(B_s \to K^- K^+) = A_{\text{CP}}^{\text{dir}}\), which depends on \(d', \theta'\) and \(\gamma\) \[35\], we may determine \(d'\) and \(\theta'\):

\[
d' = e^{2} \left[ r_{K} + \cos 2\gamma \pm \left( r_{K} + \cos 2\gamma \right)^{2} - \left( r_{K} - 1 \right)^{2} - \left( r_{K} A_{\text{CP}}^{\text{dir}} / \tan \gamma \right)^{2} \right]^{1/2}.
\]  

(22)

\[
\sin \theta' = \frac{\varepsilon r_{K} A_{\text{CP}}^{\text{dir}}}{2d' \sin \gamma}, \quad \cos \theta' = \frac{\varepsilon^{2} \left( r_{K} - 1 \right) - d'^{2}}{2ed' \cos \gamma}.
\]  

(23)

Finally, we determine \(\Delta \phi_{KK}\) through \[11\], which allows the extraction of \(\phi_{s} = \phi_{s}^{\text{eff}} - \Delta \phi_{KK}\) from the CP asymmetries of \(B_{s}^{0} \to K^{+} K^{-}\) entering \[10\]. This method is illustrated in the flowchart in Fig. 2.

The theoretical precision of this method is limited by the \(U\)-spin-breaking corrections to \[21\]. Writing \(a_{\text{NF}}^{T(\gamma)} = 1 + \Delta_{\text{NF}}^{\gamma}\) with \(\Delta_{\text{NF}}^{\gamma} = \Delta_{\text{KF}}^{\gamma}(1 - \xi_{\text{NF}}^{\gamma})\) yields

\[
a_{\text{NF}}^{T(\gamma)} = 1 + \Delta_{\text{NF}}^{\gamma} \xi_{\text{NF}}^{\gamma} + \mathcal{O}((\Delta_{\text{NF}}^{\gamma})^{2}).
\]  

(24)

The numerical value in \[17\] corresponds to \(\Delta_{\text{NF}}^{\gamma} \sim 0.05\). Consequently, \(\xi_{\text{NF}} \sim 0.2\), i.e. \(U\)-spin-breaking corrections of 20\% corresponds to a correction at the 1\% level to \[24\]. In the case of \(r_{P}\) defined in \[16\], we write in analogy \(r_{P}' = r_{P}(1 - \xi_{r_{P}})\), which gives

\[
1 + r_{P} = 1 + r_{P} \xi_{r_{P}} + \mathcal{O}(r_{P}^{2}).
\]  

(25)

Using data, we expect \(r_{P} \sim 0.3\), which agrees with general expectations \[18, 19\]. Assuming \(\xi_{r_{P}} \sim 0.2\) yields a correction at the 5\% level. A similar structure arises for the \(U\)-spin-breaking ratio of \((1 + x)/(1 + x')\), which involves the exchange and penguin annihilation amplitudes \[16\]. These topologies are expected to play a minor role. Experimental data for \(B_{d}^{0} \to K^{+} K^{-}\) and \(B_{s}^{0} \to \pi^{+} \pi^{-}\) decays allow us to constrain these contributions \[6, 37\]. Making assumptions for \(x, x'\) in analogy to the discussion for \(r_{P}, r_{P}'\) would give a correction at the 5\% level.

Combining all these non-factorizable \(U\)-spin-breaking effects, we estimate the corresponding error of \(\xi_{\text{NF}}^{\gamma}\) in \[21\] as 10\%. Since \(r_{K} \gg 1\), as can be seen in \[19\], we obtain \(d' \sim \sqrt{r_{K}} \propto |a_{\text{NF}}^{T(\gamma)}|\). Since \[11\] gives \(\Delta \phi_{KK} \sim -10^\circ\) for \(d' \sim 0.6\), we conclude that this 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 \[37\]. In Fig. 3 we illustrate the error of \(\Delta \phi_{KK}\). We observe that a precision of 0.5\% requires a measurement of both \(R_{K}\) 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.

**IV. PICTURE FROM CURRENT DATA**

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

\[
d' e^{i\theta'} = d' e^{i\theta'},
\]  

(27)
where $\tilde{d}$, $\tilde{\theta}$ are the $B^0_d \rightarrow \pi^- K^+$ counterparts of $d'$, $\theta'$. As replacement for $R_K$ we introduce

$$\tilde{R}_K \equiv \frac{\Gamma(B^0_d \rightarrow \pi^- K^+)}{\Gamma(B^0_d \rightarrow \pi^- \ell^+ \nu_\ell)/dq^{2l^2q^2=m^2_K}}.$$  (28)

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 $\gamma = (70 \pm 7)^\circ$, $\phi_d = (43.2 \pm 1.8)^\circ$, $A_{CP}^{d} (B^0_d \rightarrow \pi^- K^+) = 0.082 \pm 0.006$ and the CP asymmetries of $B^0_d \rightarrow \pi^- \pi^+$ in Table II we obtain

$$d = 0.58 \pm 0.16, \quad \theta = (151.4 \pm 7.6)^\circ$$  (29)
$$\tilde{d} = 0.51 \pm 0.03, \quad \tilde{\theta} = (157 \pm 2)^\circ,$$  (30)

which yield

$$\tilde{\xi} = \frac{\tilde{d}}{d} = 0.88 \pm 0.20, \quad \tilde{\Delta} = \tilde{\theta} - \theta = (5.5 \pm 8.3)^\circ.$$  (31)

Here the uncertainties correspond only to the input parameters. The agreement between (29) and (30) is remarkable, strongly disfavoring the anomalously large $U$-spin-breaking corrections of $(50–100)\%$ considered in [11].

The current CP asymmetries of $B^0_s \rightarrow K^- K^+$ give $\phi_s^{\text{eff}} = (-17.6 \pm 7.9)^\circ$. Employing (27) results in

$$\Delta \phi_{KK} = -(10.7 \pm 6.0)^\circ.$$  (32)

Consequently, we obtain

$$\phi_s = \phi_s^{\text{eff}} - \Delta \phi_{KK} = -(6.9 \pm 7.9)^\circ,$$  (33)

where the uncertainty is fully dominated by experiment. This value of $\phi_s$ is in perfect agreement with [11].

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 $B^0_s$–$B^0_d$ mixing phase $\phi_s$ from the $B^0_s \rightarrow K^- K^+$, $B^0_d \rightarrow \pi^- \pi^+$ system. The novel ingredients are the semileptonic $B^0_s \rightarrow K^- \ell^+ \nu_\ell$ and $B^0_d \rightarrow \pi^- \ell^+ \nu_\ell$ 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 $\phi_s$ from the CP violation in $B^0_s \rightarrow K^- K^+$ with a theoretical precision as high as $O(0.5^\circ)$, which matches the experimental prospects, and offers powerful tests of the $U$-spin symmetry. As there is currently no measurement of the $B^0_s \rightarrow K^- \ell^+ \nu_\ell$ decay available, we used the $B^0_s \rightarrow \pi^- K^+$ mode to illustrate the new strategy and obtain a very promising picture from the current data. We strongly advocate experimental analyses of $B^0_s \rightarrow K^- \ell^+ \nu_\ell$ and dedicated determinations of the $R_K$ and $R_\pi$ ratios. The comparison of $\phi_s$ extracted from the penguin-dominated $B^0_s \rightarrow K^- K^+$ 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.

Acknowledgements

We would like to thank Kristof De Bruyn for very useful discussions. This work is supported by the Foundation for Fundamental Research on Matter (FOM) and by the Deutsche Forschungsgemeinschaft (DFG) within research unit FOR 1873 (QFET).
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