A New Strategy to Extract $\boldsymbol{\phi_s}$ from $\boldsymbol{B_s^0 \to K^- K^+}$

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We discuss our recently proposed new strategy to extract the mixing-angle ϕ_s from CP violation in $B_s^0 \to K^- K^+$, $B_d^0 \to \pi^- \pi^+$. This strategy applies the U-spin symmetry only to theoretically well-behaved quantities, thereby allowing for a measurement of ϕ_s with a theoretical precision at the 0.5° level, which matches experimental prospects. It may reveal new sources of CP violation and provides valuable insights into U-spin-breaking effects.

1 Introduction

Non-leptonic B-meson decays offer an interesting laboratory to test the Standard Model (SM) and search for new sources of CP violation. In these studies, the theoretical precision is usually limited by strong interactions. In order to deal with this challenge, QCD flavour symmetries offer a powerful tool. A prime example is the system of the $B_s^0 \to K^- K^+$, $B_d^0 \to \pi^- \pi^+$ decays, which are related by the U-spin symmetry and allow the extraction of the CKM angle γ and the B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s [1,2]. The decay $B_s^0 \to K^- K^+$ is dominated by penguin loop topologies, offering an avenue for New Physics (NP) to enter. The corresponding strategy has already been implemented by the LHCb collaboration [3], reporting results in agreement with the SM.

We show that this method is limited by U-spin-breaking effects, which will preclude us from taking full advantage of the impressive precision that can be achieved in the era of the LHCb upgrade [4] and Belle II [5], unless there is theoretical progress to calculate the corresponding corrections. In view of this situation, we use γ determined from pure $B \to D^{(*)} K^{(*)}$ decays as an input, and propose a new strategy [6,7] to utilise CP violation in $B_s^0 \to K^- K^+$ for the extraction of ϕ_s. A key ingredient is the semileptonic decay $B_s^0 \to K^- \ell^+ \nu_\ell$, allowing us to apply the U-spin symmetry only to theoretically well-behaved quantities, resulting in a future theoretical precision of $\mathcal{O}(0.5°)$ for ϕ_s, matching the anticipated experimental precision.

2 The Original Strategy

In the SM, the $B_s^0 \to K^- K^+$ decay amplitude can be written as [1]

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

where the primes indicate a $\bar{b} \to \bar{s}$ transition, and penguin parameters are defined by

$$d' e^{i\theta'} \equiv \frac{1}{R_b} \left[\frac{P^{(ct)'} + PA^{(ct)'}}{T' + E' + P^{(ut)'} + PA^{(ut)'}}\right]. \tag{2}$$

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Here T' and E' are colour-allowed tree and exchange amplitudes, while $P^{(qt)'} \equiv P^{(q)'} - P^{(t)'}$ and $PA^{(qt)'} \equiv PA^{(q)'} - PA^{(t)'}$ $(q = u, c)$ denote penguin and penguin annihilation topologies, respectively. On the other hand, $R_b \approx 0.4$ and $\epsilon \approx 0.05$ are CKM factors[8]. For the U-spin partner decay $B_d^0 \to \pi^-\pi^+$, we write $A\left(B_d^0 \to \pi^-\pi^+\right) = e^{i\gamma}\mathcal{C}\left[1 - de^{i\theta}e^{-i\gamma}\right]$, where $\mathcal{C}$ and $de^{i\theta}$ are analogous to their $B_s^0 \to K^-K^+$ counterparts. The U-spin flavour symmetry then implies[1]

$$d'e^{i\theta'} = de^{i\theta}. \tag{3}$$

This relation can be exploited to extract γ and ϕ_s from measurements of CP violation in the $B_s^0 \to K^-K^+, B_d^0 \to \pi^-\pi^+$ system[1,2]. Following this strategy, the LHCb collaboration[3] obtained $\gamma = (63.5^{+7.2}_{-6.7})^\circ$, which agrees with determinations from pure tree decays[8]. For the LHCb upgrade, a determination with an experimental uncertainty of $\mathcal{O}(1^\circ)$ is expected[6,7] when full U-spin symmetry is applied. However, allowing for 20% U-spin-breaking corrections through

$$\xi \equiv d'/d = 1.0 \pm 0.2, \quad \Delta \equiv \theta' - \theta = (0 \pm 20)^\circ, \tag{4}$$

gives an uncertainty of $\mathcal{O}(5^\circ)$ on γ. In comparison, the anticipated uncertainty for the future determination of γ from pure tree decays is $\mathcal{O}(1^\circ)$[4,5].

The CP asymmetries of $B_s^0 \to K^-K^+$ allow the determination of

$$\sin\phi_s^{\text{eff}} = \mathcal{A}_{\text{CP}}^{\text{mix}}(B_s \to K^-K^+)/\sqrt{1 - \mathcal{A}_{\text{CP}}^{\text{dir}}(B_s \to K^-K^+)^2}\ , \tag{5}$$

where the "effective" B_s^0–$\bar{B}_s^0$ mixing phase $\phi_s^{\text{eff}} \equiv \phi_s + \Delta\phi_{KK}$ involves the phase shift[9]

$$\tan\Delta\phi_{KK} = \epsilon\left[\frac{2(d'\cos\theta' + \epsilon\cos\gamma)\sin\gamma}{d'^2 + 2\epsilon d'\cos\theta'\cos\gamma + \epsilon^2\cos 2\gamma}\right]. \tag{6}$$

From the recent measurement of CP violation in $B_s^0 \to K^-K^+$[10] the LHCb collaboration[3] obtained $\phi_s = -(6.9^{+9.2}_{-8.0})^\circ$. At the LHCb upgrade, ϕ_s^{eff} can be measured with a precision at the 0.5° level[4]. The determination of ϕ_s is then limited by knowledge of the hadronic parameters that enter $\Delta\phi_{KK}$ in (6). For U-spin-breaking corrections as in (4), we find an uncertainty for $\Delta\phi_{KK}$ of 2.6°, and correspondingly a similar uncertainty on ϕ_s. In comparison, ϕ_s can be determined from $B_s^0 \to J/\psi\phi$ with a future precision of $\mathcal{O}(0.5^\circ)$[11]. Therefore, in order to match the future experimental precision for γ and ϕ_s, ξ would have to be known with an uncertainty at the few percent level, which cannot be accomplished with current theoretical methods.

3 The New Strategy

To make full use of the physics potential of the upgrade era, we proposed a new strategy[6,7] depicted schematically in Fig. 1.

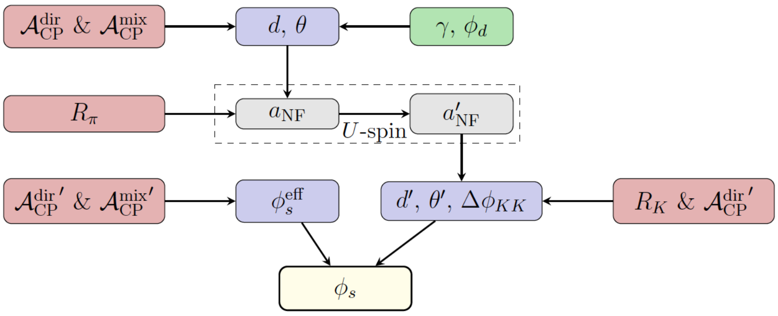

Figure 1 – Schematic picture of the new strategy. $\mathcal{A}_{\text{CP}}^{\text{dir}}$, $\mathcal{A}_{\text{CP}}^{\text{mix}}$ and $\mathcal{A}_{\text{CP}}^{\text{dir}\prime}$, $\mathcal{A}_{\text{CP}}^{\text{mix}\prime}$ are the CP asymmetries of the $B_d^0 \to \pi^-\pi^+$ and $B_s^0 \to K^-K^+$ decays, respectively.

It makes minimal use of the U-spin symmetry, while employing γ and ϕ_d as an input. A new ingredient are semileptonic decay rates, which enter the ratios

$$R_\pi \equiv \frac{\Gamma(B_d \to \pi^-\pi^+)}{d\Gamma(B_d^0 \to \pi^-\ell^+\nu_\ell)/dq^2|_{q^2=m_\pi^2}} = 6\pi^2|V_{ud}|^2 f_\pi^2 X_\pi \, r_\pi \, |a_{\rm NF}|^2, \tag{7}$$

$$R_K \equiv \frac{\Gamma(B_s \to K^-K^+)}{d\Gamma(B_s^0 \to K^-\ell^+\nu_\ell)/dq^2|_{q^2=m_K^2}} = 6\pi^2|V_{us}|^2 f_K^2 X_K \, r_K \, |a'_{\rm NF}|^2. \tag{8}$$

Here $|V_{ud}|$ and $|V_{us}|$ are CKM matrix elements, $f_\pi(f_K)$ denotes the charged pion (kaon) decay constant, and X_π, X_K describe phase-space factors and form-factor ratios. The penguin parameters and γ are encoded in

$$r_\pi = 1 - 2d\cos\theta\cos\gamma + d^2 \ , \ \ r_K = 1 + 2\left(d'/\epsilon\right)\cos\theta'\cos\gamma + \left(d'/\epsilon\right)^2 . \tag{9}$$

Finally, the parameter $a_{\rm NF} = a_{\rm NF}^T(1+r_P)(1+x)$ and its primed counterpart $a'_{\rm NF}$ characterize non-factorizable effects with $r_P \equiv P^{(ut)}/T$ and $x \equiv (E + PA^{(ut)})/(T + P^{(ut)})$.

The $B_d^0 \to \pi^-\pi^+$ CP asymmetries allow a clean determination of the penguin parameters d, θ [1,7]. We may then determine d' and θ' from r_K in (9) by applying the U-spin symmetry to

$$\xi_{\rm NF}^a \equiv \left|\frac{a_{\rm NF}}{a'_{\rm NF}}\right| = \left|\frac{a_{\rm NF}^T}{a_{\rm NF}^{T'}}\right| \left|\frac{1+r_P}{1+r'_P}\right| \left|\frac{1+x}{1+x'}\right|. \tag{10}$$

Finally, we may determine $\Delta\phi_{KK}$ in (6) and extract $\phi_s = \phi_s^{\rm eff} - \Delta\phi_{KK}$.

The theoretical precision is now only limited by the U-spin-breaking corrections to the ratio (10), making our strategy very robust with respect to these corrections. The parameter $a_{\rm NF}^T \equiv 1 + \Delta_{\rm NF}^T$ has been calculated in QCD factorization [12,13], yielding $\Delta_{\rm NF}^T \sim 0.05$. Parameterizing possible U-spin-breaking correction by $\Delta_{\rm NF}^{T'} = \Delta_{\rm NF}^T(1-\xi_{\rm NF}^T)$ leads to

$$a_{\rm NF}^T/a_{\rm NF}^{T'} = 1 + \Delta_{\rm NF}^T\xi_{\rm NF}^T + \mathcal{O}((\Delta_{\rm NF}^T)^2). \tag{11}$$

For 20% U-spin-breaking corrections, i.e. $\xi_{\rm NF}^T \sim 0.2$, we find a correction to (11) at the 1% level. In analogy, we write $r'_P = r_P(1-\xi_r)$ and

$$1 + r_P/1 + r'_P = 1 + r_P\xi_r + \mathcal{O}(r_P^2). \tag{12}$$

Using current data from $B_d^0 \to \pi^-K^+$ and $B_s^0 \to K^-\pi^+$ decays as well as $B^+ \to \pi^+K^0$ and $B^+ \to K^+\overline{K}^0$ modes, we find $|r_P| \sim 0.22$ [7]. Assuming $\xi_r \sim 0.2$ gives a correction at the 5% level. This correction can be further reduced in the future by using measurements of the CP asymmetries of the pure penguin decays $B_d^0 \to K^0\overline{K}^0$ and $B_s^0 \to K^0\overline{K}^0$ [7]. The parameter x involves the exchange and penguin annihilation amplitudes, which can be probed using $B_d^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$ decays. Recently, LHCb measured the branching fractions for these decays [14], which suggest that x lies in the 0.05–0.10 regime [7]. Since x is a small parameter, the structure of $\xi_{\rm NF}^a$ results in a very robust situation with respect to U-spin-breaking effects. Assuming again U-spin-breaking effects of 20% gives only a correction of $\mathcal{O}(3\%)$. Future measurements of the CP asymmetries of $B_d^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$ would allow us to further pin down the contributions to this ratio, thereby avoiding theoretical assumptions on these effects.

Finally, we arrive at a combined uncertainty of $\xi_{\rm NF}^a$ in (10) of 5%. In Fig. 2, we show the error on $\Delta\phi_{KK}$ as a function of the relative error on $\xi_{\rm NF}^a$ and R_K [6]. For the first we assume a perfect experimental situation, while for the latter we only consider experimental uncertainties. Matching the expected precision of the $\phi_s^{\rm eff}$ measurement requires a determination with an uncertainty of 0.5°. This requires a measurement of both R_π and R_K with a relative precision of 5%. Interestingly, the new strategy allows us also to determine the U-spin-breaking parameters ξ and Δ with an uncertainty at the 0.07 level [7], giving insights into U-spin-breaking effects.

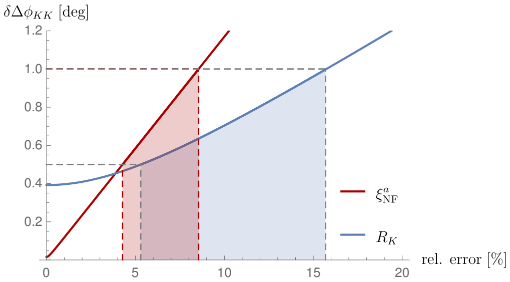

Figure 2 – Illustration of the theoretical and experimental uncertainty of $\Delta\phi_{KK}$.

The $B_s^0 \to K^-\ell^+\nu_\ell$ decay has unfortunately not yet been measured, and usually appears in the context of extracting $|V_{ub}|$. We strongly advocate analyses of this channel at Belle II and LHCb. In view of this lack of data, we demonstrate the power of our new strategy using data from $B_d^0 \to \pi^- K^+$. This decay differs from the required $B_s^0 \to K^- K^+$ channel only through the spectator quarks, and has only tree and penguin contributions. Using current data, we performed the first determination of the U-spin-breaking parameters $\tilde{\xi} \equiv \tilde{d}'/d = 0.87 \pm 0.20$ and $\tilde{\Delta} \equiv \tilde{\theta}' - \theta = (5.8 \pm 8.3)^\circ$, which are fully consistent with the U-spin symmetry. Finally we obtain $\phi_s = \phi_s^{\rm eff} - \Delta\phi_{KK} = -(6.8 \pm 7.9)^\circ$, where the uncertainty is dominated by the current experimental values the $B_s^0 \to K^- K^+$ CP asymmetries. The agreement with the previous LHCb determination is impressive, demonstrating the power of our new strategy.

4 Conclusions

We have presented a new strategy to determine the B_s^0–$\bar{B}_s^0$ mixing phase ϕ_s from CP violation $B_s^0 \to K^- K^+$. It uses γ, as determined from pure tree decays, as an input, exploits CP violation in $B_d^0 \to \pi^-\pi^+$, and utilises semileptonic $B_s^0 \to K^-\ell^+\nu_\ell$ and $B_d^0 \to \pi^-\ell^+\nu_\ell$ modes. The strategy allows us to apply the U-spin symmetry only to a favourable ratio of hadronic parameters which is very robust with respect to U-spin-breaking corrections. Using further experimental data, the theoretical uncertainty of ϕ_s can be reduced to $\mathcal{O}(0.5^\circ)$ [6,7], which matches the precision of this phase from $B_s^0 \to J/\psi\phi$ and related decays. Our strategy offers exciting new opportunities for the LHCb upgrade and Belle II era and may reveal new sources of CP violation.

Acknowledgements

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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