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Utilising $B \to \pi K$ Decays at the High-Precision Frontier

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$B \to \pi K$ decays have received a lot of attention over the last two decades, with puzzling patterns in the previous data. They form a particularly interesting set of decays as they are dominated by QCD penguin topologies. Electroweak penguin amplitudes also play a significant role, giving a contribution at the level of the tree topologies. We find a discrepancy in the correlation between the CP asymmetries of $B_d^0 \to \pi^0 K_S$. A modified electroweak penguin sector offers an attractive avenue for new particles to enter. We provide a new method to determine the electroweak penguin parameters, and apply it to current data for charged $B \to \pi K$ decays. It uses an isospin relation and requires only $SU(3)$ input to fix a normalization. A central role is played by the mixing-induced CP asymmetry of $B_d^0 \to \pi^0 K_S$. The implementation of our strategy in the high-precision era of B-physics has the exciting potential to establish New Physics in the electroweak penguin sector.

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1. Introduction

Decays of the type $B \to \pi K$ have been in the spotlight for over two decades ([1, 2] and references therein). This is a particularly interesting class of decays because the leading contributions come from QCD penguin topologies; the tree topologies are suppressed by the CKM matrix element V_{ub}. Moreover, electroweak (EW) penguin amplitudes give contributions at the same level as the tree topologies.

The decay $B_d^0 \to \pi^0 K_S$ is the only $B \to \pi K$ channel with a mixing-induced CP asymmetry. Moreover, all $B \to \pi K$ decays may have direct CP violation. The correlation between the CP asymmetries of the $B_d^0 \to \pi^0 K_S$ mode has revealed a discrepancy in the past, which could be explained by a modified EW penguin sector [2]. We have a fresh look at this correlation, and present a new method to pin down the parameters governing the EW penguin contributions [3].

2. The $B \to \pi K$ System

The EW penguin topologies contributing to $B_d^0 \to \pi^- K^+$ and $B^+ \to \pi^+ K^0$ are colour-suppressed and play a minor role. On the other hand, the $B_d^0 \to \pi^0 K^0$ and $B^+ \to \pi^0 K^+$ channels have also contributions from colour-allowed EW penguin toplogies. These effects are described by the following parameter, which can be calculated using the $SU(3)$ flavour symmetry [4, 1]:

$$q e^{i\phi} e^{i\omega} \equiv -\left(\frac{\hat{P}_{EW} + \hat{P}_{EW}^{\mathrm{C}}}{\hat{T} + \hat{C}}\right) \stackrel{\mathrm{SM}}{=} \frac{-3}{2\lambda^2 R_b}\left(\frac{C_9 + C_{10}}{C_1 + C_2}\right) R_q = (0.68 \pm 0.05) R_q. \tag{2.1}$$

Here $\phi(\omega)$ is a CP-violating (CP-conserving) phase, and $\hat{P}_{EW}(\hat{T})$ and $\hat{P}_{EW}^{\mathrm{C}}(\hat{C})$ are colour-allowed and colour-suppressed EW penguin (tree) amplitudes, respectively. Note that ω vanishes in the $SU(3)$ limit, and that its smallness is a model-independent result [5]. Furthermore, $\lambda \equiv |V_{us}| = 0.22$, R_b is a side of the unitarity triangle (UT), and the C_i are Wilson coefficients. The deviation of R_q from 1 parametrizes $SU(3)$-breaking corrections. We will use $R_q = 1.0 \pm 0.3$, while progress in lattice QCD can bring the uncertainty down to ± 0.05 in the future [2].

The hadronic parameters that describe the tree and QCD penguin topologies can be determined using $B \to \pi\pi$ data, where contributions from EW penguins are tiny, employing the $SU(3)$ flavour symmetry [1, 2]. Allowing for non-factorizable $SU(3)$-breaking corrections of 20% we obtain [3]

$$r_{\mathrm{c}} e^{i\delta_{\mathrm{c}}} \equiv \frac{\hat{T} + \hat{C}}{P'} = (0.17 \pm 0.06) e^{i(1.9 \pm 23.9)^\circ}, \quad r e^{i\delta} \equiv \frac{\hat{T} - \hat{P}_{tu}}{P'} = (0.09 \pm 0.03) e^{i(28.6 \pm 21.4)^\circ}, \tag{2.2}$$

where $\hat{P}_{tu}$ is the difference between QCD penguin amplitudes with t and u quarks, and $P' \propto P_{tc}$. In an analysis of $B_{d,s} \to \pi\pi, KK, \pi K$ modes, no indications of anomalously large non-factorizable $SU(3)$-breaking corrections were found [6].

The direct CP asymmetries $A_{\mathrm{CP}}^f \equiv \left(|\bar{A}_f|^2 - |A_f|^2\right) / \left(|\bar{A}_f|^2 + |A_f|^2\right)$, as well as the branching ratios, are ingredients of a sum rule [7], which vanishes in the SM up to corrections of $\mathcal{O}(r_{(\mathrm{c})}^2)$ [3]. The current experimental data [8] are in agreement with the SM pattern. Since the uncertainty of $A_{\mathrm{CP}}^{\pi^0 K^0}$ is still large, we use the sum rule to predict $A_{\mathrm{CP}}^{\pi^0 K^0} = -0.14 \pm 0.03$ [3].

The mixing-induced CP asymmetry $S_{\mathrm{CP}}^{\pi^0 K_S}$ enters the time-dependent rate asymmetry as

$$\frac{\Gamma(\bar{B}_d^0(t) \to \pi^0 K_S) - \Gamma(B_d^0(t) \to \pi^0 K_S)}{\Gamma(\bar{B}_d^0(t) \to \pi^0 K_S) + \Gamma(B_d^0(t) \to \pi^0 K_S)} = A_{\mathrm{CP}}^{\pi^0 K_S} \cos(\Delta M_d t) + S_{\mathrm{CP}}^{\pi^0 K_S} \sin(\Delta M_d t), \tag{2.3}$$

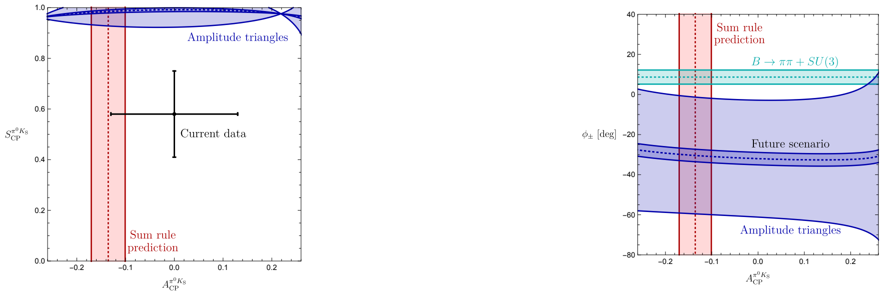

Figure 1: Left: Correlation between the CP asymmetries of $B_d^0 \to \pi^0 K_S$. Right: $\phi_\pm$ as a function of $A_{CP}^{\pi^0 K_S}$.

where ΔM_d is the mass difference between the B_d mass eigenstates. We have

$$S_{CP}^{\pi^0 K_S} = \sin(\phi_d - \phi_{00})\sqrt{1-(A_{CP}^{\pi^0 K_S})^2}, \tag{2.4}$$

where $\phi_d = (43.2 \pm 1.8)^\circ$ is the CP-violating B_d^0–$\bar{B}_d^0$ mixing phase [2]. The key quantity is the angle $\phi_{00} \equiv \arg(\bar{A}_{00}A_{00}^*)$ between $A_{00} \equiv A(B_d^0 \to \pi^0 K^0)$ and its CP-conjugate $\bar{A}_{00}$, which can be expressed in terms of the hadronic parameters in Eq. (2.2) as follows [3]:

$$\tan\phi_{00} = 2(r\cos\delta - r_c\cos\delta_c)\sin\gamma + 2r_c\,(\cos\delta_c - 2\tilde{a}_C/3)\,q\sin\phi + \mathcal{O}(r_{(c)}^2). \tag{2.5}$$

Here $\tilde{a}_C \equiv a_C\cos(\Delta_C + \delta_c)$ parametrizes the small colour-suppressed EW penguin contributions.

3. Correlations Between the CP Asymmetries of $B_d^0 \to \pi^0 K_S$

The amplitudes of the $B \to \pi K$ decays satisfy the following isospin relation [1, 2]:

$$\begin{aligned} 3A_{3/2} &\equiv \sqrt{2}A(B_d^0 \to \pi^0 K^0) + A(B_d^0 \to \pi^- K^+) = \sqrt{2}A(B^+ \to \pi^0 K^+) + A(B^+ \to \pi^+ K^0) \\ &= -(\hat{T}+\hat{C})e^{i\gamma} + (\hat{P}_{EW} + \hat{P}_{EW}^{C}) = -(\hat{T}+\hat{C})\left(e^{i\gamma} - qe^{i\phi}e^{i\omega}\right). \end{aligned} \tag{3.1}$$

Here $A_{3/2} \equiv |A_{3/2}|e^{i\phi_{3/2}}$ is an isospin $I = 3/2$ amplitude, where $\gamma = (70 \pm 7)^\circ$ is the corresponding UT angle, and $|\hat{T}+\hat{C}|$ can be determined from the $B \to \pi\pi$ system using the $SU(3)$ relation [9]:

$$|\hat{T}+\hat{C}| = R_{T+C}\,|V_{us}/V_{ud}|\,\sqrt{2}|A(B^+ \to \pi^+\pi^0)|. \tag{3.2}$$

The $SU(3)$-breaking effects are given by $R_{T+C} = 1.2 \pm 0.2$, where the central value is obtained in factorization and the uncertainty allows for non-factorizable corrections [2, 10].

The cleanest way to determine ϕ_{00} is from the amplitude triangles corresponding to the isospin relation for the neutral decays in Eq. (3.1). It requires only $SU(3)$ input from R_{T+C} and R_q, and no topologies have to be neglected [2]. From Eq. (2.4), we can then determine $S_{CP}^{\pi^0 K_S}$ as a function of $A_{CP}^{\pi^0 K_S}$. There is a fourfold ambiguity in the determination of ϕ_{00}, which can be resolved using the neutral $B \to \pi K$ data as discussed in Refs. [2, 3]. Finally, we obtain the correlation shown in the left panel of Fig. 1, which is more constrained than in previous work [2] due to a better determination of γ. We observe a discrepancy between the data and the correlation at the 2.5σ level.

In the right panel of Fig. 1, we show a new constraint, obtained from the angle $\phi_\pm \equiv \arg(\bar{A}_\pm A_\pm^*)$ between $A_\pm \equiv A(B_d^0 \to \pi^- K^+)$ and its CP-conjugate $\bar{A}_\pm$. For $\phi = 0^\circ$, which includes the SM, we

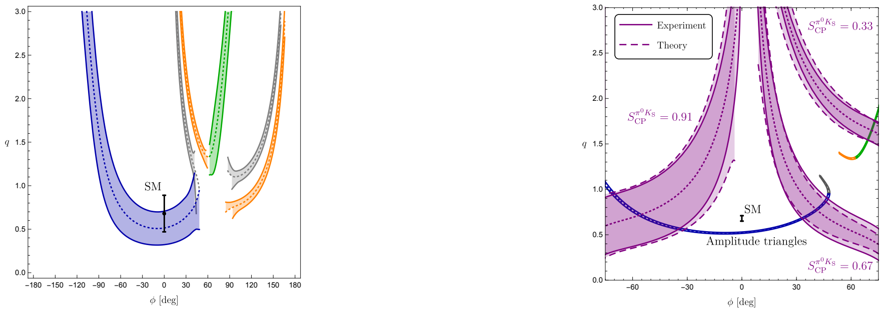

Figure 2: Contours in the ϕ–q plane for charged $B \to \pi K$ data following from the isospin relation in Eq. (3.1). The left panel shows current data, whereas the right one corresponds to future scenarios.

obtain $\phi_{\pm}|_{\phi=0} = 2r\cos\delta\sin\gamma + \mathscr{O}(r^2) = (8.7 \pm 3.5)^{\circ}$, where the numerical value follows from Eq. (2.2). We can also extract this angle from the amplitude triangles. The tension between these two constraints shows that also the correlation itself is not in agreement with the SM. We could obtain a consistent picture in Fig. 1 if the mixing-induced CP asymmetry of $B_d^0 \to \pi^0 K_{\rm S}$ moved up by $\sim 1\sigma$ and $\mathscr{B}r(\pi^0 K^0)$ went down by $\sim 2.5\sigma$. On the other hand, Fig. 1 may be a hint of NP, where a modified EW penguin sector is a particularly interesting scenario.

4. Determination of the Electroweak Penguin Parameters

The isospin relation in Eq. (3.1) can also be used to obtain contours in the ϕ–q plane [3]. This analysis may be done for the neutral and charged decays separately. It requires us to fix the relative orientation of the triangles, which is done through $S_{\rm CP}^{\pi^0 K_{\rm S}}$ in the case of the neutral decays, and with the angle between $A(B^+ \to \pi^+ K^0)$ and its CP conjugate, which is of $\mathscr{O}(1^{\circ})$, for the charged decays. Since the current uncertainty of $S_{\rm CP}^{\pi^0 K_{\rm S}}$ is still large [8], we perform the analysis for the charged decays, yielding the contours in the left panel of Fig. 2. This method requires $SU(3)$ input only to determine $|\hat{T} + \hat{C}|$ from Eq. (3.2), and no topologies have to be neglected.

In order to determine the values of q and ϕ we need further information. This can be obtained by converting a measurement of $S_{\rm CP}^{\pi^0 K_{\rm S}}$ into a value of ϕ_{00}. Eq. (2.5) then yields a contour in the ϕ–q plane, using the hadronic parameters in Eq. (2.2). As the strong phases enter only as $\cos\delta_{(c)}$, this expression is very insensitive to variations of these parameters, thereby having a theoretically favourable structure. Furthermore, the small contributions from colour-suppressed EW penguins can be included through data [3].

In view of the large current uncertainty of $S_{\rm CP}^{\pi^0 K_{\rm S}}$, we study three scenarios. In the right panel of Fig. 2, we give again the contours from the amplitudes triangles, now assuming perfect measurements and progress on the calculation of R_{T+C} [2]. In addition, we show the contours from $S_{\rm CP}^{\pi^0 K_{\rm S}}$, where we consider a precision of ± 0.04 for the CP asymmetries of $B_d^0 \to \pi^0 K_{\rm S}$ at the end of Belle II [11], and include 20% non-factorizable $SU(3)$-breaking corrections for the hadronic parameters entering Eq. (2.5). We give separately the experimental and theoretical uncertainties, and observe that we can match the experimental precision with theory. Moreover, we see that $S_{\rm CP}^{\pi^0 K_{\rm S}}$ provides complementary information on q and ϕ, allowing the determination of these parameters.

5. Conclusions

We have performed a state-of-the-art $B \to \pi K$ analysis, finding a tension with the SM in the correlation of the $B_d^0 \to \pi^0 K_S$ CP asymmetries. In order to clarify this intriguing picture, either data have to move to confirm the SM, or we may have NP, where a modified EW penguin sector provides a particularly interesting scenario. We present a new strategy to determine the EW penguin parameters q and ϕ with unprecedented precision at future B-physics experiments. It has the potential to resolve this puzzling situation and reveal new sources of CP violation.

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