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Puzzles in B physics

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Abstract. I discuss some puzzles observed in exclusive B-meson decays, concentrating on the large difference between the direct CP asymmetries in the $B^0 \to \pi^\mp K^\pm$ and $B^\pm \to \pi^0 K^\pm$ modes, the large $B^0 \to \pi^0\pi^0$ branching ratio, and the large deviation of the mixing-induced CP asymmetries in the $b \to sq\bar{q}$ penguins from those in the $b \to c\bar{c}s$ trees.

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1. Introduction

The B-factories have accumulated enough events, which allow precision measurements of exclusive B-meson decays. These measurements sharpen the discrepancies between experimental data and theoretical predictions within the Standard Model, such that some puzzles have appeared. The recently observed direct CP asymmetries and branching ratios of the $B \to \pi K$, $\pi\pi$ decays [1]

$$\begin{aligned}
&A_{\rm CP}(B^0 \to \pi^\mp K^\pm) = (-10.8 \pm 1.7)\% ,\\
&A_{\rm CP}(B^\pm \to \pi^0 K^\pm) = (4 \pm 4)\% ,\\
&B(B^0 \to \pi^\mp \pi^\pm) = (4.9 \pm 0.4) \times 10^{-6} ,\\
&B(B^0 \to \pi^0 \pi^0) = (1.45 \pm 0.29) \times 10^{-6} ,
\end{aligned} \tag{1}$$

are prominent examples. The expected relations $A_{\rm CP}(B^0 \to \pi^\mp K^\pm) \approx A_{\rm CP}(B^\pm \to \pi^0 K^\pm)$ and $B(B^0 \to \pi^\mp\pi^\pm) \gg B(B^0 \to \pi^0\pi^0)$ obviously contradict to the above data. The weak phase ϕ_1, defined via the Cabibbo–Kobayashi–Maskawa (CKM) matrix element $V_{td} = |V_{td}| \exp(-i\phi_1)$ [2], can be extracted either from the tree-dominated or penguin-dominated modes. It has been estimated that the penguin pollution in the $b \to c\bar{c}s$ trees and the tree pollution in the $b \to sq\bar{q}$ penguins are about 5%. Therefore, it is expected that the measured mixing-induced CP asymmetries $S_{sq\bar{q}}$ are close to $S_{c\bar{c}s} = \sin(2\phi_1) \approx 0.685$ [1]. However, a large deviation $\Delta S \equiv S_{sq\bar{q}} - S_{c\bar{c}s}$ has been measured.

In this talk I will review the recent studies of these subjects, concluding that the $B \to \pi K$ puzzle could be attributed to QCD uncertainty, the $B \to \pi\pi$ puzzle cannot be resolved within the current theoretical development, and the ΔS puzzle might be a promising signal of new physics, if the data persist. I will not discuss another puzzle from the small longitudinal polarization fractions observed in the penguin-dominated $B \to VV$ decays, such as $B \to \phi K^*$ and $B \to \rho K^*$, since they involve different dynamics. A recent summary on this topic is referred to in ref. [3].

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

To explain the $B \to \pi K$ puzzle, it is useful to adopt the topological-amplitude parametrization for two-body nonleptonic B-meson decays [4]. The $B \to \pi K$ amplitudes are written, up to $O(\lambda^2)$, $\lambda \approx 0.22$ being the Wolfenstein parameter, as

$$\begin{aligned} A(B^+ \to \pi^+ K^0) &= P' , \\ \sqrt{2}A(B^+ \to \pi^0 K^+) &= -P' \left[1 + \frac{P'_{\rm ew}}{P'} + \left(\frac{T'}{P'} + \frac{C'}{P'}\right) {\rm e}^{i\phi_3}\right] , \\ A(B^0 \to \pi^- K^+) &= -P' \left(1 + \frac{T'}{P'} {\rm e}^{i\phi_3}\right) , \\ \sqrt{2}A(B^0 \to \pi^0 K^0) &= P' \left(1 - \frac{P'_{\rm ew}}{P'} - \frac{C'}{P'} {\rm e}^{i\phi_3}\right) . \end{aligned} \tag{2}$$

The notations T', C', P', and $P'_{\rm ew}$ stand for the color-allowed tree, color-suppressed tree, penguin, and electroweak penguin amplitudes, respectively, which obey the counting rules [5,6]

$$\frac{T'}{P'} \sim \lambda , \quad \frac{P'_{\rm ew}}{P'} \sim \lambda , \quad \frac{C'}{P'} \sim \lambda^2 . \tag{3}$$

The weak phase ϕ_3 is defined via the CKM matrix element $V_{ub} = |V_{ub}| \exp(-i\phi_3)$ [2]. The data $A_{\rm CP}(B^0 \to \pi^\mp K^\pm) \approx -11\%$ indicate a sizable relative strong phase between T' and P', which verifies our prediction made years ago using the perturbative QCD (PQCD) approach [7]. Since both $P'_{\rm ew}$ and C' are subdominant, the approximate equality for the direct CP asymmetries $A_{\rm CP}(B^\pm \to \pi^0 K^\pm) \approx A_{\rm CP}(B^0 \to \pi^\mp K^\pm)$ is expected, which is, however, in conflict with the data in eq. (1) dramatically.

It is then natural to conjecture a large $P'_{\rm ew}$ [8–12], which signals a new physics effect, a large C' [13–16], which implies a missing mechanism in the Standard Model, or both [17,18]. The large C' proposal seems to be favored by a recent analysis of the $B \to \pi K$, $\pi\pi$ data based on the amplitude parametrization [13]. The PQCD predictions for the $B \to \pi K$, $\pi\pi$ decays in [7,19] were derived from the leading-order (LO) and leading-power formalism. While LO PQCD gives a negligible C', it is possible that this supposedly tiny amplitude receives a significant subleading correction. Hence, before claiming a new physics signal, one should at least examine whether the next-to-leading-order (NLO) effects could enhance C' significantly.

In [20] we calculated the important NLO contributions to the $B \to \pi K$, $\pi\pi$ decays from the vertex corrections, the quark loops, and the magnetic penguins.

Table 1. Branching ratios from PQCD in the NDR scheme in units of $\times 10^{-6}$. The label $\mathrm{LO_{NLOWC}}$ means the LO results with the NLO Wilson coefficients, and +VC, +QL, +MP, and +NLO mean the inclusions of the vertex corrections, the quark loops, the magnetic penguin, and all the above NLO corrections, respectively. The theoretical uncertainties in the parentheses represent those only from the variation of hadronic parameters.

Mode	Data [1]	LO	$\mathrm{LO_{NLOWC}}$	+VC	+QL	+MP	+NLO
$B^\pm \to \pi^\pm K^0$	24.1 ± 1.3	17.0	32.3	30.1	34.2	24.1	$23.6^{+14.5\,(+13.8)}_{-8.4(-8.2)}$
$B^\pm \to \pi^0 K^\pm$	12.1 ± 0.8	10.2	18.4	17.1	19.4	14.0	$13.6^{+10.3\,(+7.3)}_{-5.7(-4.3)}$
$B^0 \to \pi^\mp K^\pm$	18.9 ± 0.7	14.2	27.7	26.1	29.4	20.5	$20.4^{+16.1\,(+11.5)}_{-8.4(-6.7)}$
$B^0 \to \pi^0 K^0$	11.5 ± 1.0	5.7	12.1	11.4	12.8	8.7	$8.7^{+6.0\,(+5.5)}_{-3.4\,(-3.1)}$
$B^0 \to \pi^\mp \pi^\pm$	4.9 ± 0.4	7.0	6.8	6.6	6.9	6.7	$6.5^{+6.7(+2.7)}_{-3.8(-1.8)}$
$B^\pm \to \pi^\pm \pi^0$	5.5 ± 0.6	3.5	4.1	4.0	4.1	4.1	$4.0^{+3.4(+1.7)}_{-1.9(-1.2)}$
$B^0 \to \pi^0 \pi^0$	1.45 ± 0.29	0.12	0.27	0.37	0.29	0.21	$0.29^{+0.50(+0.13)}_{-0.20\,(-0.08)}$

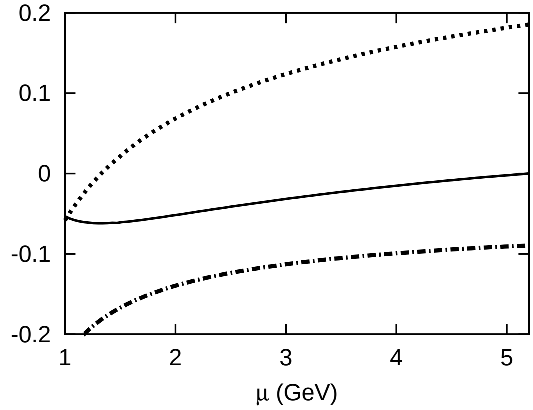

Figure 1. Real part of a_2 for the $B \to \pi K$ decays without the vertex corrections (dotted lines) and with the vertex corrections (solid lines), and imaginary part with the vertex corrections (dot-dashed lines) in the NDR scheme.

Those NLO corrections to the B-meson transition form factors, being overall quantities, are irrelevant. The higher-power corrections, having not yet been under good control, were not considered. We found that the corrections from the quark loops and from the magnetic penguins, being about 10% of the LO penguin amplitude, decrease only the $B \to \pi K$ branching ratios as shown in table 1. The vertex corrections increase C' by a factor of 3, and induce a large phase relative to T'. This result can be understood from the value of the Wilson coefficient $a_2(\mu)$ in figure 1, to which C' is proportional, at the characteristic scale $\mu \approx \sqrt{m_b \Lambda} \approx 1.7$ GeV, m_b being the B quark mass and Λ a hadronic scale. The larger C' renders the total tree amplitude $T' + C'$ more or less parallel to the total penguin amplitude $P' + P'_{\mathrm{ew}}$ in the $B^\pm \to \pi^0 K^\pm$ modes. Hence, it leads to nearly vanishing $A_{\mathrm{CP}}(B^\pm \to \pi^0 K^\pm)$ as

Table 2. Direct CP asymmetries from PQCD in the NDR scheme in percentage.

Mode	Data [1]	LO	$\mathrm{LO_{NLOWC}}$	+VC	+QL	+MP	+NLO
$B^\pm \to \pi^\pm K^0$	-2 ± 4	-1	-1	-1	0	-1	$0 \pm 0\,(\pm 0)$
$B^\pm \to \pi^0 K^\pm$	4 ± 4	-8	-6	-2	-5	-8	$-1^{+3\,(+3)}_{-6\,(-5)}$
$B^0 \to \pi^\mp K^\pm$	-10.8 ± 1.7	-12	-8	-9	-6	-10	$-10^{+7\,(+5)}_{-8\,(-6)}$
$B^0 \to \pi^0 K^0$	2 ± 13	-2	0	-7	0	0	$-7^{+3\,(+1)}_{-4\,(-2)}$
$B^0 \to \pi^\mp \pi^\pm$	37 ± 10	14	19	21	16	20	$18^{+20\,(+7)}_{-12\,(-6)}$
$B^\pm \to \pi^\pm \pi^0$	1 ± 6	0	0	0	0	0	$0 \pm 0\,(\pm 0)$
$B^0 \to \pi^0 \pi^0$	28^{+40}_{-39}	-4	-34	65	-41	-43	$63^{+35\,(+\,9)}_{-34\,(-15)}$

shown in table 2, and the $B \to \pi K$ puzzle is resolved at the 1σ level. Our analysis also confirmed that the NLO corrections are under control in PQCD.

At last, we emphasize that the NLO PQCD predictions for the $B^0 \to \pi^0 K^0$ still fall short a bit compared to the data. It implies a new-physics phase associated with the electroweak penguin amplitude P'_{ew} [9,21–23], such that it becomes orthogonal to the penguin amplitude P', and enhances the $B^0 \to \pi^0 K^0$ branching ratio. That is, we can not exclude the possibility of new physics effects in the $B \to \pi K$ decays.

3. The $B \to \pi\pi$ puzzle

Similarly, the $B \to \pi\pi$ decay amplitudes are parametrized as

$$\sqrt{2}A(B^+ \to \pi^+\pi^0) = -T\left[1 + \frac{C}{T} + \frac{P_{\mathrm{ew}}}{T}\mathrm{e}^{i\phi_2}\right] , \tag{4}$$

$$A(B_d^0 \to \pi^+\pi^-) = -T\left(1 + \frac{P}{T}\mathrm{e}^{i\phi_2}\right) , \tag{5}$$

$$\sqrt{2}A(B_d^0 \to \pi^0\pi^0) = T\left[\left(\frac{P}{T} - \frac{P_{\mathrm{ew}}}{T}\right)\mathrm{e}^{i\phi_2} - \frac{C}{T}\right] , \tag{6}$$

with the power counting rules

$$\frac{P}{T} \sim \lambda , \quad \frac{C}{T} \sim \lambda , \quad \frac{P_{\mathrm{ew}}}{T} \sim \lambda^2 . \tag{7}$$

The hierarchy of the branching ratios $B(B^0 \to \pi^0\pi^0) \sim O(\lambda^2)B(B^0 \to \pi^\mp\pi^\pm)$ is then expected. However, the data in eq. (1) show $B(B^0 \to \pi^0\pi^0) \sim O(\lambda)B(B^0 \to \pi^\mp\pi^\pm)$, giving rise to the $B \to \pi\pi$ puzzle.

As indicated in table 1, the NLO corrections, despite increasing the color-suppressed tree amplitudes significantly, are not enough to enhance the $B^0 \to \pi^0\pi^0$ branching ratio to the measured value. A much larger amplitude ratio $|C/T| \sim 0.8$ must be obtained in order to resolve the puzzle [13]. Nevertheless, the NLO corrections do improve the consistency of our predictions with the data: the predicted

Table 3. $B \to \rho\rho$ branching ratios from PQCD in the NDR scheme in units of 10^{-6}.

Mode	Data [1]	LO	$\mathrm{LO_{NLOWC}}$	+VC	+QL	+MP	+NLO
$B^0 \to \rho^\mp\rho^\pm$	$25.2^{+3.6}_{-3.7}$	27.8	26.1	25.2	26.6	25.9	$25.3^{+25.3\,(+12.1)}_{-13.8\,(-7.9)}$
$B^\pm \to \rho^\pm\rho^0$	19.1 ± 3.5	13.7	16.2	16.0	16.2	16.2	$16.0^{+15.0\,(+\,7.8)}_{-8.1\,(-5.3)}$
$B^0 \to \rho^0\rho^0$	< 1.1	0.33	0.56	1.02	0.62	0.45	$0.92^{+1.10\,(+0.64)}_{-0.56\,(-0.40)}$

Table 4. Branching ratios from QCDF with the input of the SCET jet function in units of 10^{-6}. The data for the $B \to \rho\rho$ decays include all polarizations.

Mode	Data [1]	Default, LO jet	Default, NLO jet	S4, LO jet	S4, NLO jet
$B^\pm \to \pi^\pm\pi^0$	5.5 ± 0.6	6.02	6.24	5.07	5.77
$B^0 \to \pi^\mp\pi^\pm$	4.9 ± 0.4	8.90	8.69	5.22	4.68
$B^0 \to \pi^0\pi^0$	1.45 ± 0.29	0.36	0.40	0.72	1.07
$B^\pm \to \rho_L^\pm\rho_L^0$	19.1 ± 3.5	18.51	19.48	16.61	18.64
$B^0 \to \rho_L^\mp\rho_L^\pm$	$25.2^{+3.6}_{-3.7}$	25.36	24.42	18.48	16.76
$B^0 \to \rho_L^0\rho_L^0$	< 1.1	0.43	0.66	0.92	1.73

$B^0 \to \pi^\pm\pi^\mp$ ($B^0 \to \pi^0\pi^0$) branching ratio decreases(increases). To make sure the NLO effects observed in §2 are reasonable, we have applied the same PQCD formalism to the $B \to \rho\rho$ branching ratios [24], which are also sensitive to the color-suppressed tree contribution. It was found that the NLO PQCD predictions are in agreement with the data of the $B^0 \to \rho^\mp\rho^\pm$ and $B^\pm \to \rho^\pm\rho^0$ branching ratios, and saturate the experimental upper bound of the $B^0 \to \rho^0\rho^0$ branching ratio as shown in table 3. We conclude that it is unlikely to accommodate the measured $B^0 \to \pi^0\pi^0$, $\rho^0\rho^0$ branching ratios simultaneously in PQCD. Therefore, our resolution to the $B \to \pi K$ puzzle makes sense, and the $B \to \pi\pi$ puzzle is confirmed.

It has been claimed that the $B \to \pi\pi$ puzzle is resolved in the QCD-improved factorization (QCDF) approach [25] with an input from soft-collinear effective theory (SCET) [26]: the inclusion of the NLO jet function, the hard coefficient of $\mathrm{SCET_{II}}$, into the QCDF formula for the color-suppressed tree amplitude gives sufficient enhancement of the $B^0 \to \pi^0\pi^0$ branching ratio. It is certainly necessary to investigate whether the new mechanism proposed above deteriorates the consistency of theoretical results with other data. Therefore, we have extended the formalism in [26] to the $B \to \rho\rho$ decays as a check [24]. Because of the end-point singularities present in twist-3 spectator amplitudes and in annihilation amplitudes, these contributions have to be parametrized in QCDF [25]. Different scenarios for choosing the free parameters, labelled by 'default', 'S1', 'S2', 'S3' and 'S4', have been proposed in [27]. As shown in table 4, the large measured $B^0 \to \pi^0\pi^0$ branching ratio can be accommodated by including the NLO jet function, when the parameter scenario S4 is adopted. However, this effect overshoots the upper bound of the $B^0 \to \rho^0\rho^0$ branching ratio very much. We have surveyed the other scenarios, and found the results from S1 and S3 (S2) similar to those from the default (S4). That is, it is also unlikely to accommodate the $B \to \pi\pi$, $\rho\rho$ data simultaneously in QCDF.

There exists an alternative phenomenological application of SCET [28,29], where the jet function, characterized by the scale of $O(\sqrt{m_b \Lambda})$, is regarded as being incalculable. Its contribution, together with other nonperturbative parameters, such as the charming penguin, were then determined by the $B \to \pi\pi$ data. That is, the color-suppressed tree amplitude can not be explained, but the data are used to fit for the phenomenological parameters in the theory. Predictions for the $B \to \pi K$, KK decays were then made based on the obtained parameters and partial $SU(3)$ flavor symmetry [29]. Final-state interaction (FSI) is certainly a plausible resolution to the $B \to \pi\pi$ puzzle, but the estimate of its effect is quite model-dependent. Even opposite conclusions were drawn sometimes. When including FSI either into naive factorization [30] or into QCDF [31], the $B^0 \to \pi^0\pi^0$ branching ratio was treated as an input in order to fix the involved free parameters. Hence, no resolution was really proposed. It has been found that FSI, evaluated in the Regge model, is insufficient to account for the observed $B^0 \to \pi^0\pi^0$ branching ratio [32].

4. The ΔS puzzle

The time-dependent CP asymmetry of the $B^0 \to \pi^0 K_S$ mode is defined as

$$A_{\rm CP}(B^0(t) \to \pi^0 K_S) \equiv \frac{B(\bar{B}^0(t) \to \pi^0 K_S) - B(B^0(t) \to \pi^0 K_S)}{B(\bar{B}^0(t) \to \pi^0 K_S) + B(B^0(t) \to \pi^0 K_S)} = A_{\pi^0 K_S} \cos(\Delta M_d\, t) + S_{\pi^0 K_S} \sin(\Delta M_d\, t)\,, \qquad (8)$$

with the mass difference ΔM_d of the two B-meson mass eigenstates, and the direct asymmetry and the mixing-induced asymmetry,

$$A_{\pi^0 K_S} = \frac{|\lambda_{\pi^0 K_S}|^2 - 1}{1 + |\lambda_{\pi^0 K_S}|^2}\,, \quad S_{\pi^0 K_S} = \frac{2\,{\rm Im}(\lambda_{\pi^0 K_S})}{1 + |\lambda_{\pi^0 K_S}|^2}\,, \qquad (9)$$

respectively. The $B^0 \to \pi^0 K_S$ decay has a CP-odd final state, and the corresponding factor

$$\lambda_{\pi^0 K_S} = -{\rm e}^{-2i\phi_1} \frac{P' - P'_{\rm ew} - C' {\rm e}^{-i\phi_3}}{P' - P'_{\rm ew} - C' {\rm e}^{i\phi_3}}\,. \qquad (10)$$

After obtaining the values of the various topological amplitudes, we computed the mixing-induced CP asymmetries through eq. (10) [20]. Since C' is of $O(\lambda^2)$ compared to P', it is expected that the LO PQCD result of $S_{\pi^0 K_S} \approx 0.70$ is close to $S_{c\bar{c}s} \approx 0.685$ as shown in table 5. It is known that the leading deviation of $\Delta S_{\pi^0 K_S} \equiv S_{\pi^0 K_S} - S_{c\bar{c}s}$ caused by C' is proportional to $\cos(\delta_{C'} - \delta_{P'})$, if $P'_{\rm ew}$ is neglected, where $\delta_{C'}(\delta_{P'})$ is the strong phase of $C'(P')$. Because the vertex corrections induce a large $\delta_{C'}$, C' becomes more orthogonal to P', and $\Delta S_{\pi^0 K_S}$ does not increase much in NLO PQCD. This tendency persists in other $b \to sq\bar{q}$ penguin decays. The mixing-induced CP asymmetry in the $B^0 \to \pi^{\mp}\pi^{\pm}$ can be defined in a similar way. However, the penguin pollution P is of $O(\lambda)$ relative to

Table 5. Mixing-induced CP asymmetries from PQCD in the NDR scheme.

	Data	LO	LO_{NLOWC}	+VC	+QL	+MP	+NLO
$S_{\pi^0 K_S}$	0.31 ± 0.26	0.70	0.73	0.74	0.73	0.73	$0.74^{+0.02\,(+0.01)}_{-0.03\,(-0.01)}$
$S_{\pi\pi}$	-0.50 ± 0.12	-0.34	-0.49	-0.47	-0.51	-0.41	$-0.42^{+1.00\,(+0.05)}_{-0.56\,(-0.05)}$

T in these decays, such that a larger deviation of $S_{\pi\pi}$ from $S_{c\bar{c}s}$ was found. The PQCD results of $S_{\pi\pi}$ are consistent with the data, but those of $S_{\pi^0 K_S}$ are not. Moreover, PQCD predicts $\Delta S_{\pi^0 K_S} > 0$, opposite to the measured value. This result is in agreement with those derived in the literature [15,33,34]. Hence, it is not easy to explain the data of $S_{\pi^0 K_S}$ [35].

5. Conclusion

Many puzzles in exclusive B-meson decays have been observed recently. The data $A_{\text{CP}}(B^\pm \to \pi^0 K^\pm)$ much different from $A_{\text{CP}}(B^0 \to \pi^\mp K^\pm)$ could be resolved in NLO PQCD by taking into account the vertex corrections. We found that there is no satisfactory resolution to the $B \to \pi\pi$ puzzle in the literature: the available proposals are either data fitting, or can not survive the constraints from the $B \to \rho\rho$ data under the current theoretical development. The NLO effects push the deviation $\Delta S_{\pi^0 K_S}$ toward the even larger positive value. Therefore, the measurement of the mixing-induced CP asymmetries in the penguin-dominated modes provides an opportunity of discovering new physics.

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