# Hadronic $B$ Decays in PQCD

Satoshi Mishima
*School of Natural Sciences, Institute for Advanced Study, Princeton, NJ 08540, U.S.A.*

I review recent progress on exclusive hadronic $B$ meson decays in the perturbative QCD approach, with focus on puzzles in the branching ratios and the CP asymmetries of the $B \to \pi K$ and $B \to \pi\pi$ modes, and polarization fractions in $B \to VV$ modes.

## 1. Introduction

$B$ factory experiments have accumulated a lot of data and have reported many interesting results [1]. Some observables, mixing-induced CP asymmetries for $b \to s$ penguin modes, branching ratios and direct CP asymmetries for $B \to \pi K$ and $\pi\pi$, and polarization fractions for penguin-dominated $B \to VV$ modes, have exhibited some deviations from naïve expectations in the Standard Model.

It is necessary to go beyond naïve estimations for understanding the observed deviations. The perturbative QCD (PQCD) approach [2, 3] is one of the theoretical attempts to include subdominant contributions, such as spectator and annihilation diagrams, and higher-order corrections. PQCD has applied to various two-body $B$ decays at leading order (LO) in $\alpha_s$ and has made reasonable predictions for various decay modes. Recently, the important next-to-leading-order (NLO) contributions were evaluated in the $B \to \pi K$, $\pi\pi$, and $\rho\rho$ decays to investigate the discrepancies between the LO PQCD predictions and the data [4, 5].

This talk is organized as follows: In Sec. 2, I briefly review the PQCD factorization formula. I discuss the branching ratios and the CP asymmetries of the $B \to \pi K$ and $\pi\pi$ decays with the NLO corrections in Sec. 3. The LO PQCD predictions of the polarization fractions are presented in Sec. 4. Section 5 is a summary.

## 2. PQCD Factorization Theorem

Most of the calculations of $B$ decay amplitudes rely on the factorization of decay amplitudes into a product of short-distance and long-distance physics. QCD-improved factorization (QCDF) [6] and soft-collinear effective theory (SCET) [7] are based on collinear factorization theorem, but PQCD is based on $k_T$ factorization theorem.

Employing collinear factorization theorem, some decay amplitudes involve a singularity arising from the end-point region of parton momentum fractions. An end-point singularity implies that a decay amplitude is dominated by soft dynamics and cannot be factorized. Such soft contributions are regarded as phenomenological parameters, which can be fitted from

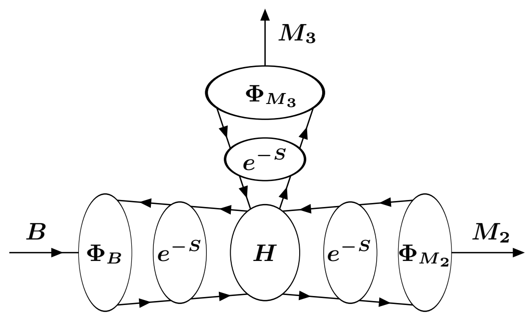


Figure 1: Factorization of hadronic two-body $B$ meson decays in the PQCD approach.

the experimental data.

In the PQCD approach with $k_T$ factorization theorem, the Sudakov factor ensures the absence of the end-point singularities [8]. All amplitudes can be factorizable into parton distribution amplitudes $\Phi$, the Sudakov factors $e^{-S}$, and a hard kernel $H$:

$$\mathcal{A}(B \to M_2 M_3) \;=\; \Phi_{M_2} \otimes \Phi_{M_3} \otimes H \otimes e^{-S} \otimes \Phi_B \;, \quad (1)$$

where $\otimes$ stands for convolutions in both longitudinal and transverse momenta of partons [9]. The schematic picture of the factorization theorem is given in Fig. 1. The distribution amplitudes, which are universal in the processes under consideration, are determined from experiments, the light-cone QCD sum rules, lattice calculations, or other theoretical methods. The hard kernel is characterized by a hard scale $Q \sim \sqrt{\bar{\Lambda} m_b}$, where $\bar{\Lambda}$ is a hadronic scale and $m_b$ the $b$ quark mass [10–12], and can be evaluated as an expansion in powers of $\alpha_s(Q)$ and $\bar{\Lambda}/Q$. The hard kernels of the spectator and annihilation contributions, as well as the emission contribution, are calculable and start from $O(\alpha_s)$. PQCD predicts a large direct CP asymmetry in $B^0 \to \pi^\mp K^\pm$ as a result of a large strong phase arising from annihilation penguin diagrams [2].

## 3. $B \to \pi K$ and $\pi\pi$ Puzzles

The current data of the direct CP asymmetries of $B \to \pi K$ and the branching ratios of $B \to \pi\pi$ [1],

$$A_{CP}(B^\pm \to \pi^0 K^\pm) \;=\; (4 \pm 4)\% \;,$$

$$\begin{aligned} A_{CP}(B^0 \to \pi^\mp K^\pm) &= (-10.8 \pm 1.7)\% , \\ \mathrm{Br}(B^0 \to \pi^\pm \pi^\mp) &= (4.9 \pm 0.4) \times 10^{-6} , \\ \mathrm{Br}(B^0 \to \pi^0 \pi^0) &= (1.45 \pm 0.29) \times 10^{-6} , \quad (2) \end{aligned}$$

have been inconsistent with the expected relations

$$\begin{aligned} A_{CP}(B^\pm \to \pi^0 K^\pm) &\approx A_{CP}(B^0 \to \pi^\mp K^\pm) , \\ \mathrm{Br}(B^0 \to \pi^\pm \pi^\mp) &\gg \mathrm{Br}(B^0 \to \pi^0 \pi^0) . \quad (3) \end{aligned}$$

These relations can be understood in the topological-amplitude decompositions [13]:

$$\begin{aligned} \mathcal{A}(B^+ \to \pi^+ K^0) &= P' \\ \sqrt{2}\mathcal{A}(B^+ \to \pi^0 K^+) &= -P' - P'_{ew} - (T' + C')\, e^{i\phi_3} , \\ \mathcal{A}(B^0 \to \pi^- K^+) &= -P' - T' e^{i\phi_3} , \\ \sqrt{2}\mathcal{A}(B^0 \to \pi^0 K^0) &= P' - P'_{ew} - C' e^{i\phi_3} , \quad (4) \end{aligned}$$

and

$$\begin{aligned} \mathcal{A}(B^0 \to \pi^+ \pi^-) &= -T - P e^{i\phi_2} , \\ \sqrt{2}\mathcal{A}(B^+ \to \pi^+ \pi^0) &= -T - C - P_{ew} e^{i\phi_2} , \\ \sqrt{2}\mathcal{A}(B^0 \to \pi^0 \pi^0) &= -C + (P - P_{ew})\, e^{i\phi_2} , \quad (5) \end{aligned}$$

where $T^{(\prime)}$, $C^{(\prime)}$, $P^{(\prime)}$, and $P_{ew}^{(\prime)}$ stand for the color-allowed tree, color-suppressed tree, penguin, and electroweak penguin amplitudes, respectively, and $\phi_2$ and $\phi_3$ are the weak phase defined by $V_{ub} = |V_{ub}| \exp(-i\phi_3)$, $V_{td} = |V_{td}| \exp(-i\phi_1)$, and $\phi_2 = 180^\circ - \phi_1 - \phi_3$. Assuming the hierarchies, $P' > T'$, $P'_{ew} > C'$ for $B \to \pi K$ and $T > C$, $P > P_{ew}$ for $B \to \pi\pi$ [14–16], the relations in Eq. (3) can be derived. The current data seem to require a large electroweak penguin amplitude [16–22], a large color-suppressed tree amplitude [23–26], or both of them [27–29].

The LO PQCD predictions follow the naïve expectations as shown in Tables I and II [2, 3, 30]. Because

Table I Branching ratios for the $B \to \pi K$ and $\pi\pi$ decays in units of $10^{-6}$.

| **Mode** | **Data** [1] | **LO** [30] | **NLO** [4, 5] |
|---|---|---|---|
| $B^\pm \to \pi^\pm K^0$ | $24.1 \pm 1.3$ | $14.4 \sim 26.3$ | $23.6^{+14.5}_{-\ 8.4}$ |
| $B^\pm \to \pi^0 K^\pm$ | $12.1 \pm 0.8$ | $7.9 \sim 14.2$ | $13.6^{+10.3}_{-\ 5.7}$ |
| $B^0 \to \pi^\mp K^\pm$ | $18.9 \pm 0.7$ | $12.7 \sim 19.3$ | $20.4^{+16.1}_{-\ 8.4}$ |
| $B^0 \to \pi^0 K^0$ | $11.5 \pm 1.0$ | $4.5 \sim 8.1$ | $8.7^{+\ 6.0}_{-\ 3.4}$ |
| $B^0 \to \pi^\mp \pi^\pm$ | $4.9 \pm 0.4$ | $5.9 \sim 11.0$ | $6.5^{+\ 6.7}_{-\ 3.8}$ |
| $B^\pm \to \pi^\pm \pi^0$ | $5.5 \pm 0.6$ | $2.7 \sim 4.8$ | $4.0^{+\ 3.4}_{-\ 1.9}$ |
| $B^0 \to \pi^0 \pi^0$ | $1.45 \pm 0.29$ | $0.10 \sim 0.65$ | $0.29^{+0.50}_{-0.20}$ |

LO PQCD predicts a negligible $C^{(\prime)}$, NLO contributions may enhance $C^{(\prime)}$ sufficiently. Recently, the most important NLO contributions from the vertex corrections, the quark loops, and the magnetic penguin were calculated in the PQCD approach [4, 5]. The sum of

Table II Direct CP asymmetries for the $B \to \pi K$ and $\pi\pi$ decays in percentage.

| **Mode** | **Data** [1] | **LO** [30] | **NLO** [4, 5] |
|---|---|---|---|
| $B^\pm \to \pi^\pm K^0$ | $-2 \pm 4$ | $-1.5 \sim -0.6$ | $0 \pm 0$ |
| $B^\pm \to \pi^0 K^\pm$ | $4 \pm 4$ | $-17.3 \sim -10.0$ | $-1^{+3}_{-6}$ |
| $B^0 \to \pi^\mp K^\pm$ | $-10.8 \pm 1.7$ | $-21.9 \sim -12.9$ | $-10^{+7}_{-8}$ |
| $B^0 \to \pi^0 K^0$ | $2 \pm 13$ | $-1.03 \sim -0.90$ | $-7^{+3}_{-4}$ |
| $B^0 \to \pi^\mp \pi^\pm$ | $37 \pm 10$ | $16.0 \sim 30.0$ | $18^{+20}_{-12}$ |
| $B^\pm \to \pi^\pm \pi^0$ | $1 \pm 6$ | $0.0$ | $0 \pm 0$ |
| $B^0 \to \pi^0 \pi^0$ | $28^{+40}_{-39}$ | $20.0 \sim 40.0$ | $63^{+35}_{-34}$ |

the latter two reduces the LO penguin amplitudes by about 10% in the $B \to \pi K$ decays and affects the CP asymmetries little. The vertex corrections enhance $C'$ by a factor of three and rotate the phase of $C'$, so that $T' + C'$ is parallel to $P' + P'_{ew}$. Thus, the direct CP asymmetry of $B^\pm \to \pi^0 K^\pm$ vanishes as shown in Table II.

To compare the predicted $B \to \pi K$ branching ratios with the data, it is useful to consider the ratios

$$\begin{aligned} R &= \frac{\mathrm{Br}(B^0 \to \pi^\mp K^\pm)}{\mathrm{Br}(B^\pm \to \pi^\pm K^0)} \frac{\tau_{B^+}}{\tau_{B^0}} = 0.85 \pm 0.06 , \\ R_c &= 2\, \frac{\mathrm{Br}(B^\pm \to \pi^0 K^\pm)}{\mathrm{Br}(B^\pm \to \pi^\pm K^0)} = 1.00 \pm 0.08 , \\ R_n &= \frac{1}{2} \frac{\mathrm{Br}(B^0 \to \pi^\mp K^\pm)}{\mathrm{Br}(B^0 \to \pi^0 K^0)} = 0.82 \pm 0.08 . \quad (6) \end{aligned}$$

As shown in Fig. 2, the PQCD predictions for $R$ and $R_c$ are consistent with the data, whereas that for $R_n$ is larger than the data [4]. The larger $R_n$ is due to the smaller $B^0 \to \pi^0 K^0$ branching ratio, which might imply a significant $P'_{ew}$. However, the discrepancy is not serious at this moment, because the theoretical uncertainty is representative and the actual uncertainty could be larger.

The enhanced $C'$ also affects the mixing-induced CP asymmetry of $B^0 \to \pi^0 K_S$, given by

$$S_{\pi^0 K_S} = \frac{2\,\mathrm{Im}(\lambda_{\pi^0 \mathrm{K_S}})}{1 + |\lambda_{\pi^0 \mathrm{K_S}}|^2} , \quad (7)$$

with

$$\lambda_{\pi^0 K_S} = -e^{-2i\phi_1} \frac{P' - P'_{ew} - C' e^{-i\phi_3}}{P' - P'_{ew} - C' e^{i\phi_3}} . \quad (8)$$

$S_{\pi^0 K_S}$ may deviate from $S_{c\bar{c}s} = \sin(2\phi_1)$ in $b \to c\bar{c}s$ modes. Therefore, it is essential to include the NLO corrections in the calculation of $S_{\pi^0 K_S}$. It was found that the predicted possible deviation of $S_{\pi^0 K_S}$ is still small, $S_{\pi^0 K_S} - S_{c\bar{c}s} = 0.06^{+0.02}_{-0.03}$ [4]. Moreover, PQCD predicts a positive deviation, opposite to the observed one.

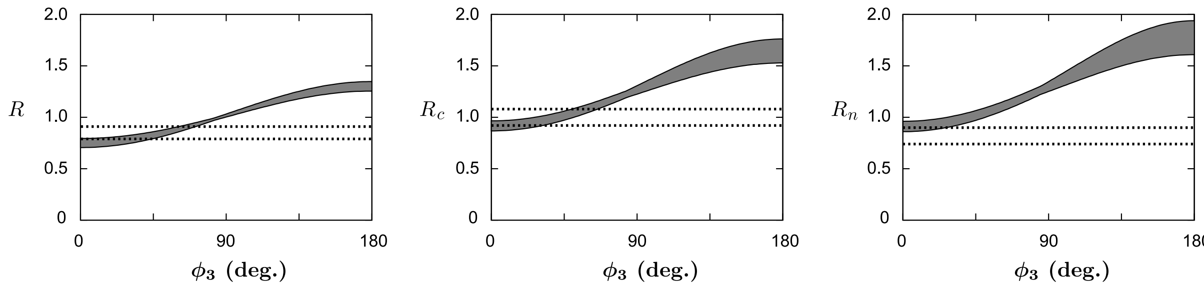


Figure 2: $R$, $R_c$, and $R_n$ as functions of $\phi_3$ from NLO PQCD with the bands representing the theoretical uncertainty [4]. The two dashed lines denote $1\sigma$ bounds from the data.

$C$ for $B \to \pi\pi$, as well as $C'$ for $B \to \pi K$, is enhanced by the vertex corrections, but it is insufficient to accommodate the $B^0 \to \pi^0\pi^0$ branching ratio to the measured value [4]. NLO PQCD predicts $|C/T| \approx 0.2$ for $B \to \pi\pi$, though a much larger $|C/T| \approx 0.8$ is required to explain the observed $B^0 \to \pi^0\pi^0$ branching ratio [25].

The same NLO PQCD formalism was applied to the $B \to \rho\rho$ decays [5], which are sensitive to the color-suppressed tree contribution. The predicted $B \to \rho\rho$ branching ratios are listed in Table III. The LO results differ from those in the previous LO analyses [31, 32] slightly due to the different choices of the hard scale and parameters. The NLO PQCD predictions for the $B^0 \to \rho^\mp\rho^\pm$ and $B^\pm \to \rho^\pm\rho^0$ branching ratios are consistent with the data. Because the decay amplitudes for $B \to \rho\rho$ are similar to those for $B \to \pi\pi$, the branching ratio of $B^0 \to \rho^0\rho^0$ is expected to be larger than that of $B^0 \to \pi^0\pi^0$ due to the meson decay constants $f_\rho > f_\pi$. In fact, the NLO predictions follow this expectation, and the central value of the predicted $B^0 \to \rho^0\rho^0$ branching ratio has almost reached the experimental upper bound. The NLO PQCD analysis has thus confirmed that it is unlikely to accommodate both the $B^0 \to \pi^0\pi^0$ and $B^0 \to \rho^0\rho^0$ branching ratios to the data simultaneously. Hence, the $B \to \pi\pi$ puzzle is confirmed in the PQCD approach. All proposed resolutions to the $B \to \pi\pi$ puzzle should survive the constraints from the $B^0 \to \rho^0\rho^0$ data.

Table III Branching ratios for the $B \to \rho\rho$ decays in units of $10^{-6}$ [5].

| **Mode** | **BABAR** [1] | **Belle** [1] | **LO** | **NLO** |
|---|---|---|---|---|
| $B^0 \to \rho^\mp\rho^\pm$ | $30 \pm 4 \pm 5$ | $22.8 \pm 3.8^{+2.3}_{-2.6}$ | 27.8 | $25.3^{+25.3}_{-13.8}$ |
| $B^\pm \to \rho^\pm\rho^0$ | $17.2 \pm 2.5 \pm 2.8$ | $31.7 \pm 7.1^{+3.8}_{-6.7}$ | 13.7 | $16.0^{+15.0}_{-\ 8.1}$ |
| $B^0 \to \rho^0\rho^0$ | $< 1.1$ | — | 0.33 | $0.92^{+1.10}_{-0.56}$ |

I comment on $B \to \pi K$ and $\pi\pi$ results in other theoretical approaches. In QCDF, $C^{(\prime)}$ is enhanced by the NLO jet function obtained from SCET and the large $B^0 \to \pi^0\pi^0$ branching ratio can be explained [34]. However, the inclusion of the NLO jet function overshoots the $B^0 \to \rho^0\rho^0$ branching ratio and deteriorates the predictions for the $B^\pm \to \pi^0K^\pm$ and $B^0 \to \pi^\mp K^\pm$ direct CP asymmetries [5]. In SCET, incalculable soft contributions are regarded as phenomenological parameters, which can be fitted from the experimental data. It was found that the charming penguin, which is one of the phenomenological parameters, is large as $|C^{(\prime)}/T^{(\prime)}| \approx 1$ [35–37]. Consequently, the large $B^0 \to \pi^0\pi^0$ branching ratio can be realized. The $B^0 \to \rho^0\rho^0$ branching ratio should be checked in the same formalism. The ratio $C^{(\prime)}/T^{(\prime)}$ is, however, real in the leading-power SCET formalism, and therefore the $B^\pm \to \pi^0K^\pm$ and $B^0 \to \pi^\mp K^\pm$ direct CP asymmetries can not be explained at the same time [35–37].

## 4. Polarizations in $B \to VV$

In the naïve factorization approximation, the longitudinal and transverse polarization fractions, $R_L$ and $R_{\parallel,\perp}$, respectively, in $B \to VV$ modes obey the power-counting rules [38],

$$R_L \sim 1 - O(m_V^2/m_B^2)\ , \quad R_{\parallel,\perp} \sim O(m_V^2/m_B^2)\ , \tag{9}$$

where $m_B$ is the mass of the $B$ meson and $m_V$ that of the emitted vector meson from the weak vertex. The data of the longitudinal polarization fractions are given by [1]

$$\begin{aligned} R_L(B^0 \to \rho^+\rho^-) &= 0.967^{+0.023}_{-0.028}\ , \\ R_L(B^+ \to \rho^+\rho^0) &= 0.96 \pm 0.06\ , \\ R_L(B^+ \to K^{*+}\rho^0) &= 0.91^{+0.23}_{-0.21}\ , \\ R_L(B^+ \to K^{*0}\rho^+) &= 0.48^{+0.09}_{-0.08}\ , \\ R_L(B^+ \to \phi K^{*+}) &= 0.50 \pm 0.07\ , \\ R_L(B^0 \to \phi K^{*0}) &= 0.48 \pm 0.04\ . \end{aligned} \tag{10}$$

The polarization fractions for tree-dominated modes, $B \to \rho\rho$, satisfy Eq. (9). However, those for penguin-dominated modes, $B \to \phi K^*$ and $K^{*0}\rho^+$, obviously conflict with the naïve expectations.

For the penguin-dominated modes, the polarization fractions could be modified by sub-leading contributions. The penguin annihilation contribution from the

$(S-P)(S+P)$ operators, which follows $R_L \sim R_\parallel \sim R_\perp$, could decrease the longitudinal fraction [38]. In LO PQCD, the spectator and penguin annihilation contributions help to reduce $R_L$ as shown in Table IV, but it is not enough to explain the $B \to \phi K^*$ and $K^{*0}\rho^+$ data [39–41]. $R_L$ for $B^+ \to K^{*+}\rho^0$ remains as $R_L \sim 0.85$, which is consistent with the data, because this process involves additional tree amplitudes. The tree-dominated modes, which are insensitive to the sub-leading corrections, follow the naïve counting rules in Eq. (9) [5, 31]. Therefore, only the penguin-dominated modes $B \to \phi K^*$ and $K^{*0}\rho^+$ have exhibited anomalies in the measured polarization fractions.

Table IV Polarization fractions in $B \to \phi K^*$, (I) without spectator and annihilation contributions, and (II) with spectator and annihilation contributions [39].

| **Mode** | | $R_L$ | $R_\parallel$ | $R_\perp$ | $\phi_\parallel$ **(rad)** | $\phi_\perp$ **(rad)** |
|---|---|---|---|---|---|---|
| $B^0 \to \phi K^{*0}$ | (I) | 0.923 | 0.040 | 0.035 | $\pi$ | $\pi$ |
| | (II) | 0.750 | 0.135 | 0.115 | 2.55 | 2.54 |
| $B^+ \to \phi K^{*+}$ | (I) | 0.923 | 0.040 | 0.035 | $\pi$ | $\pi$ |
| | (II) | 0.748 | 0.133 | 0.111 | 2.55 | 2.54 |

There have been several mechanisms proposed to explain the observed $B \to \phi K^*$ polarizations. In PQCD, it was proposed that the $B \to K^*$ form factor $A_0$, associated with the longitudinal polarization, may be smaller than the central value of the LO PQCD prediction [42]. Postulating a smaller value, $A_0 \approx 0.3$, which does not contradict to any existing measurements, $R_L$ for $B \to \phi K^*$ decreases to 0.6. Another mechanism in PQCD was proposed in Ref. [32]. Adopting a modified definition of the hard scale, which is a source of theoretical uncertainty, $R_L$ for $B \to \phi K^*$ could approach to 0.6. However, $R_L$ for $B^+ \to K^{*0}\rho^+$ becomes about 0.8, which is inconsistent with the data. This is because the sign of the real part of the annihilation amplitude for $B^+ \to K^{*0}\rho^+$ is opposite to that for $B \to \phi K^*$ [32]. Small $R_L$ for the penguin-dominated modes might come from the complicated QCD dynamics, but it is important to explain both the $B \to \phi K^*$ and $K^{*0}\rho^+$ data.

## 5. Summary

In this talk, I have summarized the recent works on exclusive hadronic $B$ meson decays in the PQCD approach, concentrating on the observed deviations in the branching ratios and the CP asymmetries of the $B \to \pi K$, $\pi\pi$ modes, and the polarization fractions of penguin-dominated $B \to VV$ modes, which are sensitive to subdominant contributions.

Including the important NLO contributions, the color-suppressed tree amplitude is enhanced by the vertex corrections, and therefore the predicted direct CP asymmetries of the $B \to \pi K$ modes become consistent with the experimental data. However, it is unlikely to accommodate both the $B^0 \to \pi^0\pi^0$ and $B^0 \to \rho^0\rho^0$ branching ratios to the measured ones simultaneously.

The polarization fractions of the penguin-dominated $B \to VV$ modes deviate from the naïve power-counting rules, including the spectator and annihilation contributions. However, it is not enough to explain the observed data. A small longitudinal fraction for $B \to \phi K^*$ might come from QCD uncertainty, but it is necessary to explain both the $B \to \phi K^*$ and $K^{*0}\rho^+$ data. NLO corrections to the polarization fractions should be studied in future work.

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