A Novel PQCD Approach in Charmless B-meson Decays

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Abstract. We discuss a novel perturbative QCD approach on the exclusive non-leptonic two body B-meson decays. We briefly review its ingredients and some important theoretical issues on the factorization approaches. We show numerical results which is compatible with recent experimental data for the charmless B-meson decays.

INTRODUCTION

The aim of the study on weak decay in B-meson is two folds: (1) To determine precisely the elements of CKM matrix and to explore the origin of CP-violation in low energy scale, (2) To understand strong interaction physics related to the confinements of quarks and gluons within hadrons.

Both tasks complement each other. An understanding of the connection between quarks and hadron properties is a necessary prerequisite for a precise determination of CKM matrix elements and CP-violating phases, so called KM-phase[1].

The theoretical description of hadronic weak decays is difficult since nonperturbative QCD interactions are involved. This makes it difficult to interpret correctly data from asymmetric B-factories and to seek the origin of CP violation. In the case of B-meson decays into two light mesons, we can explain roughly branching ratios by using the factorization approximation [2, 3]. Since B-meson is quite heavy, when it decays into two light mesons, the final-state mesons are moving so fast that it is difficult to exchange gluons between final-state mesons. Therefore the amplitude can be written in terms of the product of weak decay constant and transition form factors by the factorization (color-transparancy) argument. In this approach we cannot calculate non-factorizable contributions and annihilation contributions even though which is not dominant. Because of this weakness, violation of CP symmetry cannot be predicted correctly.

Recently two different QCD approaches beyond naive and general factorization assumption [2, 3, 4, 5] was proposed: (1) QCD-factorization in heavy quark limit [6, 7] in

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which non-factorizable terms and $a_i$ are calculable in some cases. (2) A Novel PQCD approach [8, 9, 10] including the resummation effects of the transverse momentum carried by partons inside meson. In this talk, I discuss some important theoretical issues in the PQCD factorization and numerical results for charmless B-decays.

**INGREDIENTS OF PQCD**

*Factorization in PQCD.* The idea of pertubative QCD is as follows: When heavy B-meson decays into two light mesons, the hard process is dominant. Since two light mesons fly so fast with large momentum, it is reasonable assumptions that the final-state interaction is not important for charmless B-decays and hard gluons are needed to boost the resting spectator quark to get large momentum and finally to hadronize a fast moving final meson. So the dominant process is that one hard gluon is exchanged between specator quark and other four quarks.

Let’s start with the lowest-order diagram of $B \rightarrow K\pi$. The soft divergences in the $B \rightarrow \pi$ form factor can be factorized into a light-cone B meson wave function, and the collinear divergences can be factorized into a pion distribution amplitude. The finite pieces of them is absorbed into the hard part. Then in the natural way we can factorize amplitude into two pieces: $G \equiv H(Q,\mu) \otimes \Phi(m,\mu)$ where H stands for hard part which is calculable with a perturbative way, and $\Phi$ is wave functions which belong to the non-perturbative physics.

PQCD adopt the three scale factorization theorem [11] based on the perturbative QCD formalism by Brodsky and Lepage [12], and Botts and Sterman [13], with the inclusion of the transverse momentum components which was carried by partons inside meson.

We have three different scales: electroweak scale: $M_W$, hard interaction scale: $t \sim O\left(\sqrt{\Lambda m_b}\right)$, and the factorization scale: $1/b$ where $b$ is the conjugate variable of parton transverse momenta. The dynamics below $1/b$ is completely non-perturbative and can be parameterized into meson wave functions which is universal and process independent. In our analysis we use the results of light-cone distribution amplitudes (LCDAs) by Ball [14, 15] with light-cone sum rule.

The amplitude in PQCD is expressed as

$$A \sim C(t) \times H(t) \times \Phi(x) \times \exp\left[-s(P,b)-2\int_{1/b}^{t} \frac{d\mu}{\mu} \gamma_q(\alpha_s(\mu)) \right] \quad (1)$$

where $C(t)$ are Wilson coefficients, $\Phi(x)$ are meson LCDAs and variable $t$ is the factorized scale in hard part.

*Sudakov Suppression Effects.* When we include $k_\perp$, the double logarithms $\ln^2(Pb)$ are generated from the overlap of collinear and soft divergence in radiative corrections to meson wave functions, where P is the dominant light-cone component of a meson momentum. The resummation of these double logarithms leads to a Sudakov form factor $\exp[-s(P,b)]$ in Eq.(1), which suppresses the long distance contributions in the large $b$ region, and vanishes as $b > 1/\Lambda_{QCD}$. 

This suppression renders \( k_{\perp}^2 \) flowing into the hard amplitudes of order

\[
k_{\perp}^2 \sim O(\bar{\Lambda}M_B) .
\]  

(2)

The off-shellness of internal particles then remain of \( O(\bar{\Lambda}M_B) \) even in the end-point region, and the singularities are removed. This mechanism is so-called Sudakov suppression.

Du et al. have studied the Sudakov effects in the evaluation of nonfactorizable amplitudes [16]. If equating these amplitudes with Sudakov suppression included to the parametrization in QCDF, it was observed that the corresponding cutoffs are located in the reasonable range proposed by Beneke et al. [7]. Sachrajda et al. have expressed an opposite opinion on the effect of Sudakov suppression in [17]. However, their conclusion was drawn based on a very sharp \( B \) meson wave function, which is not favored by experimental data.

Here I would like to comment on the negative opinions on the large \( k_{\perp}^2 \sim O(\bar{\Lambda}M_B) \). It is easy to understand the increase of \( k_{\perp}^2 \) from \( O(\bar{\Lambda}^2) \), carried by the valence quarks which just come out of the initial meson wave functions, to \( O(\bar{\Lambda}M_B) \), carried by the quarks which are involved in the hard weak decays. Consider the simple deeply inelastic scattering of a hadron. The transverse momentum \( k_{\perp} \) carried by a parton, which just come out of the hadron distribution function, is initially small. After infinite many gluon radiations, \( k_{\perp} \) becomes of \( O(Q) \), when the parton is scattered by the highly virtual photon, where \( Q \) is the large momentum transfer from the photon. The evolution of the hadron distribution function from the low scale to \( Q \) is described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equation [18, 19]. The mechanism of the DGLAP evolution in DIS is similar to that of the Sudakov evolution in exclusive \( B \) meson decays. The difference is only that the former is the consequence of the single-logarithm resummation, while the latter is the consequence of the double-logarithm resummation.

By including Sudakov effects, all contributions of the \( B \rightarrow \pi \) form factor comes from the region with \( \alpha_s/\pi < 0.3 \) [9] as shown in Figure 1. It indicate that our PQCD results are well within the perturbative region.
Threshold Resummation. The other double logarithm is \( \alpha_s \ln^2(1/x) \) from the end point region of the momentum fraction \( x \) [20]. This double logarithm is generated by the corrections of the hard part in Figure 2. This double logarithm can be factored out of the hard amplitude systematically, and its resummation introduces a Sudakov factor \( S_t(x) = 1.78|x(1-x)|^c \) with \( c = 0.3 \) into PQCD factorization formula. The Sudakov factor from threshold resummation is universal, independent of flavors of internal quarks, twists and topologies of hard amplitudes, and decay modes.

Threshold resummation[20] and \( k_\perp \) resummation [21, 13, 22] arise from different subprocesses in PQCD factorization and suppresses the end-point contributions, making PQCD evaluation of exclusive \( B \) meson decays reliable. If excluding resummation effects, the PQCD predictions for the \( B \to K \) form factors are infrared divergent. If including only \( k_\perp \) resummation, the PQCD predictions are finite. However, the two-parton twist-3 contributions are still huge, so that the \( B \to K \) form factors have an unreasonably large value \( F_{BK} \sim 0.57 \) at maximal recoil. The reason is that the double logarithms \( \alpha_s \ln^2 x \) have not been organized. If including both resummations, we obtain the reasonable result \( F_{BK} \sim 0.35 \). These studies indicate the importance of resummations in PQCD analyses of \( B \) meson decays. In conclusion, if the PQCD analysis of the heavy-to-light form factors is performed self-consistently, there exist no end-point singularities, and both twist-2 and twist-3 contributions are well-behaved.

Power Counting Rule in PQCD. The power behaviors of various topologies of diagrams for two-body nonleptonic \( B \) meson decays with the Sudakov effects taken into account has been discussed in details in [23]. The relative importance is summarized below:

\[
\text{emission} : \text{annihilation} : \text{nonfactorizable} = 1 : \frac{2m_0}{M_B} : \frac{\Lambda}{M_B},
\]

with \( m_0 \) being the chiral symmetry breaking scale. The scale \( m_0 \) appears because the annihilation contributions are dominated by those from the \((V-A)(V+A)\) penguin operators, which survive under helicity suppression. In the heavy quark limit the annihilation and nonfactorizable amplitudes are indeed power-suppressed compared to the factorizable emission ones. Therefore, the PQCD formalism for two-body charmless nonleptonic \( B \) meson decays coincides with the factorization approach as \( M_B \to \infty \). However, for the physical value \( M_B \sim 5 \text{ GeV} \), the annihilation contributions are essential. In Table 1 we can easily check the relative size of the different topology in Eq.(3) by the penguin
TABLE 1. Amplitudes for the $B^0_d \rightarrow K^+\pi^-$ decay where $F$ ($M$) denotes factorizable (non-factorizable) contributions, $P$ ($T$) denotes the penguin (tree) contributions, and $a$ denotes the annihilation contributions. Here we adopted $\phi_3 = 80^0$ and $R_b = \sqrt{(p^2 + \eta^2)} = 0.38$.

| Amplitudes | Left-handed gluon exchange | Right-handed gluon exchange | Total |
|------------|-----------------------------|-----------------------------|-------|
| $Re(f_{\pi F}^T)$ | $7.07 \cdot 10^{-2}$ | $3.16 \cdot 10^{-2}$ | $1.02 \cdot 10^{-1}$ |
| $Im(f_{\pi F}^T)$ | $-$ | $-$ | $-$ |
| $Re(f_{\pi F}^P)$ | $-5.52 \cdot 10^{-3}$ | $-2.44 \cdot 10^{-3}$ | $-7.96 \cdot 10^{-3}$ |
| $Im(f_{\pi F}^P)$ | $-$ | $-$ | $-$ |
| $Re(f_B F_a^P)$ | $4.13 \cdot 10^{-4}$ | $-6.51 \cdot 10^{-4}$ | $-2.38 \cdot 10^{-4}$ |
| $Im(f_B F_a^P)$ | $2.73 \cdot 10^{-3}$ | $1.68 \cdot 10^{-3}$ | $4.41 \cdot 10^{-3}$ |
| $Re(M_T)$ | $7.06 \cdot 10^{-3}$ | $-7.17 \cdot 10^{-3}$ | $-1.11 \cdot 10^{-4}$ |
| $Im(M_T)$ | $-1.10 \cdot 10^{-2}$ | $1.35 \cdot 10^{-2}$ | $2.59 \cdot 10^{-3}$ |
| $Re(M_P)$ | $-3.05 \cdot 10^{-4}$ | $3.07 \cdot 10^{-4}$ | $2.17 \cdot 10^{-6}$ |
| $Im(M_P)$ | $4.50 \cdot 10^{-4}$ | $-5.29 \cdot 10^{-4}$ | $-7.92 \cdot 10^{-5}$ |
| $Re(M_P)$ | $2.03 \cdot 10^{-5}$ | $-1.37 \cdot 10^{-4}$ | $-1.16 \cdot 10^{-4}$ |
| $Im(M_P)$ | $-1.45 \cdot 10^{-5}$ | $-1.27 \cdot 10^{-4}$ | $-1.42 \cdot 10^{-4}$ |

contribution for W-emission ($f_{\pi F}^P$), annihilation($f_B F_a^P$) and non-factorizable($M_P^P$) contributions.

Note that all the above topologies are of the same order in $\alpha_s$ in PQCD. The nonfactorizable amplitudes are down by a power of $1/m_b$, because of the cancellation between a pair of nonfactorizable diagrams, though each of them is of the same power as the factorizable one. I emphasize that it is more appropriate to include the nonfactorizable contributions in a complete formalism. The factorizable internal-W emission contributions are strongly suppressed by the vanishing Wilson coefficient $a_2$ in the $B \rightarrow J/\psi K^{(*)}$ decays [24], so that nonfactorizable contributions become dominant. In the $B \rightarrow D\pi$ decays, there is no soft cancellation between a pair of nonfactorizable diagrams, and nonfactorizable contributions are significant [24].

In QCDF the factorizable and nonfactorizable amplitudes are of the same power in $1/m_b$, but the latter is of next-to-leading order in $\alpha_s$ compared to the former. Hence, QCDF approaches FA in the heavy quark limit in the sense of $\alpha_s \rightarrow 0$. Briefly speaking, QCDF and PQCD have different counting rules both in $\alpha_s$ and in $1/m_b$. The former approaches FA logarithmically ($\alpha_s \propto 1/\ln m_b \rightarrow 0$), while the latter does linearly ($1/m_b \rightarrow 0$).

**IMPORTANT THEORETICAL ISSUES**

*End Point Singularity and Form Factors.* If calculating the $B \rightarrow \pi$ form factor $F_{B\pi}$ at large recoil using the Brodsky-Lepage formalism [12, 25], a difficulty immediately occurs. The lowest-order diagram for the hard amplitude is proportional to $1/(x_1 x_2^3)$, $x_1$ being the momentum fraction associated with the spectator quark on the $B$ meson side. If the pion distribution amplitude vanishes like $x_3$ as $x_3 \rightarrow 0$ (in the leading-twist, *i.e.*, twist-2 case), $F_{B\pi}$ is logarithmically divergent. If the pion distribution amplitude is a
constant as $x_3 \to 0$ (in the next-to-leading-twist, i.e., twist-3 case), $F^{B\pi}$ even becomes linearly divergent. These end-point singularities have also appeared in the evaluation of the nonfactorizable and annihilation amplitudes in QCDF mentioned above.

When we include small parton transverse momenta $k_{\perp}$, we have

$$\frac{1}{x_1 x_2^2 M_B^4} \rightarrow \frac{1}{(x_3 M_B^2 + k_{\perp}^2) \left[x_1 x_3 M_B^2 + (k_{\perp} - k_{3\perp})^2\right]}$$

(4)

and the end-point singularity is smeared out.

In PQCD, we can calculate analytically space-like form factors for $B \to P, V$ transition and also time-like form factors for the annihilation process [23, 26].

**Strong phases.** While strong phases in FA and QCDF come from the Bander-Silverman-Soni (BSS) mechanism[27] and from the final state interaction (FSI), the dominant strong phase in PQCD come from the factorized annihilation diagram[8, 9, 10]. It has been argued that the two sources of strong phases in the FA and QCDF approaches are in fact strongly suppressed by the charm mass threshold and by the end-point behavior of meson wave functions.

**Dynamical Penguin Enhancement vs Chiral Enhancement.** As explained before, the hard scale is about 1.5 GeV. Since the RG evolution of the Wilson coefficients $C_{4,6}(t)$ increase drastically as $t < M_B^2/2$, while that of $C_{1,2}(t)$ remain almost constant, we can get a large enhancement effects from both wilson coefficients and matrix elements in PQCD.

In general the amplitude can be expressed as

$$\text{Amp} \sim [a_{1,2} \pm a_4 \pm m_0^{PV}(\mu)a_6] \cdot <K\pi|O|B>$$

(5)

with the chiral factors $m_0^{P}(\mu) = m_0^2/[m_1(\mu) + m_2(\mu)]$ for pseudoscalar meson and $m_0^{V} = m_V$ for vector meson. To accommodate the $B \to K\pi$ data in the factorization and QCD-factorization approaches, one relies on the chiral enhancement by increasing the mass $m_0$ to as large values about 3 GeV at $\mu = m_b$ scale. So two methods accomodate large branching ratios of $B \to K\pi$ and it is difficult for us to distinguish two different methods.
in $B \rightarrow PP$ decays. However we can do it in $B \rightarrow PV$ because there is no chiral factor in LCDAs of the vector meson.

We can test whether dynamical enhancement or chiral enhancement is responsible for the large $B \rightarrow K\pi$ branching ratios by measuring the $B \rightarrow \phi K$ modes. In these modes penguin contributions dominate, such that their branching ratios are insensitive to the variation of the unitarity angle $\phi_3$. According to recent works by Cheng et al. [28], the branching ratio of $B \rightarrow \phi K$ is $(2 - 7) \times 10^{-6}$ including 30% annihilation contributions in QCD-factorization approach. However PQCD predicts $10 \times 10^{-6}$ [23, 29].

**Fat Imaginary Penguin in Annihilation.** There is a folklore that annihilation contribution is negligible compared to W-emission one. In this reason annihilation contribution was not included in the general factorization approach and the first paper on QCD-factorization by Beneke et al. [6]. In fact there is a suppression effect for the operators with structure $(V - A)(V - A)$ because of a mechanism similar to the helicity suppression for $\pi \rightarrow \mu\nu$. However annihilation from the operators $O_{5,6,7,8}$ with the structure $(S - P)(S + P)$ via Fiertz transformation survive under the helicity suppression and can get large imaginary value. The real part of factorized annihilation contribution becomes small because there is a cancellation between left-handed gluon exchanged one and right-handed gluon exchanged one as shown in Table 1. This mostly pure imaginary value of annihilation is a main source of large CP asymmetry in $B \rightarrow \pi^+\pi^-$ and $K^+\pi^-$. In Table 5 we summarize the CP asymmetry in $B \rightarrow K(\pi)\pi$ decays.

**NUMERICAL RESULTS**

*Branching ratios and Ratios of CP-averaged rates.* The PQCD approach allows us to calculate the amplitudes for charmless B-meson decays in terms of ligh-cone distribution amplitudes up to twist-3. We focus on decays whose branching ratios have already been measured. We take allowed ranges of shape parameter for the B-meson wave function as $\delta_B = 0.36 - 0.44$ which accomodate to reasonable form factors, $R^{B\pi}(0) = 0.27 - 0.33$ and $R^{BK}(0) = 0.31 - 0.40$. We use values of chiral factor with $m_0^0 = 1.3 GeV$ and $m_0^K = 1.7 GeV$. Finally we obtain branching ratios for $B \rightarrow K(\pi)\pi$ [23, 30], $K\phi$ [23, 29] and $K^*\pi$, which is well agreed with present experimental data (see Table 2 and 3).

**Table 3.** Branching ratios of $B \rightarrow \phi K^{(*)}$ decays with $\phi_3 = 80^\circ$, $R_B = 0.38$. Here we adopted $m_0^0 = 1.3 GeV$ and $m_0^K = 1.7 GeV$. $R_B = \sqrt{\rho^2 + \eta^2}$ and unit is $10^{-6}$. (Aug/2001 data)

| Decay Channel | CLEO       | BELLE      | BABAR      | PQCD       |
|---------------|------------|------------|------------|------------|
| $\phi K^\pm$ | $5.5^{+2.1}_{-1.8} + 0.6$ | $11.2^{+2.2}_{-2.0} + 0.14$ | $7.7^{+1.6}_{-1.4} + 0.8$ | $10.2^{+3.9}_{-3.1}$ |
| $\phi K^0$   | $< 12.3$   | $8.9^{+3.4}_{-2.7} + 1.0$    | $8.1^{+3.1}_{-2.5} + 0.8$ | $9.6^{+3.7}_{-2.0}$  |
| $K^*0 \pi^\pm$ | $7.6^{+3.5}_{-3.0} + 1.6$ | $19.4^{+4.2}_{-3.9} + 2.1^{+3.5}_{-6.8}$ | $15.5 + 3.4 + 1.5$ | $12.2^{+2.4}_{-2.0}$ |
| $K^\pm \pi^\mp$ | $22^{+8+4}_{-6-5}$ | $-$         | $-$         | $9.6^{+2.0}_{-1.6}$ |
TABLE 4. Ratios of CP-averaged rates in $B \to K\pi, \pi\pi$ decays with $\phi_3 = 80^0, R_b = 0.38$. Here we adopted $m^0_\pi = 1.3$ GeV, $m^K_0 = 1.7$ GeV and $R_b = \sqrt{(\rho^2 + \eta^2)}$. (Aug/2001 data)

| Quantity                                      | CLEO     | PQCD     | BBNS     |
|-----------------------------------------------|----------|----------|----------|
| $\frac{Br(\pi^+\pi^-)}{Br(\pi^+K^+)}$      | 0.25 ± 0.10 | 0.30 − 0.69 | 0.5 − 1.9 |
| $\frac{Br(\pi^0K^+)}{2Br(\pi^0\pi^0)}$     | 0.59 ± 0.27 | 0.78 − 1.05 | 0.9 − 1.4 |
| $\frac{\tau(B^\pm)}{\tau(B^0)} \frac{Br(\pi^\mp K^0)}{Br(\pi^\mp \pi^0)}$ | 1.27 ± 0.47 | 0.77 − 1.60 | 0.9 − 1.3 |

In order to reduce theoretical uncertainties from decay constant of B-meson and from light-cone distribution amplitudes, we consider rates of CP-averaged branching ratios, which is presented in Table 4. While the first ratio is hard to be explained by QCD factorization approach with $\phi_3 < 90^0$, our prediction can be reached to 0.30.

**CP Asymmetry of $B \to \pi\pi, K\pi$.** Because we have a large imaginary contribution from factorized annihilation diagrams in PQCD approach, we predict large CP asymmetry ($\sim 20\%$) in $B^0 \to \pi^+\pi^-$ decays and about $-15\%$ CP violation effects in $B^0 \to K^+\pi^-$. The detail prediction is given in Table 5. The precise measurement of direct CP asymmetry (both magnitude and sign) is a crucial way to test factorization models which have different sources of strong phases. Our predictions for CP-asymmetry on $B \to K(\pi)\pi$ have a totally opposite sign to those of QCD factorization.

TABLE 5. CP-asymmetry in $B \to K\pi, \pi\pi$ decays with $\phi_3 = 40^0 \sim 90^0, R_b = 0.38$. Here we adopted $m^0_\pi = 1.3$ GeV, $m^K_0 = 1.7$ GeV and $R_b = \sqrt{(\rho^2 + \eta^2)}$. (Aug/2001 data)

| $A_{CP}(\%)$ | Experiment | Theory | CFMPS[31] (|$A_{CP}$|) |
|--------------|------------|--------|------------------|
| $\pi^+K^-$   | $-4.8 \pm 6.8$ (BaBar) $-7 \pm 8 \pm 2$ | $-12.9 \sim -21.9$ $5 \pm 9$ | $17 \pm 6$ |
| $\pi^0K^-$   | $-9.6 \pm 11.9$ | $-10.0 \sim -17.3$ $7 \pm 9$ | $18 \pm 6$ |
| $\pi^-K^0$   | $-4.7 \pm 13.9$ | $-0.6 \sim -1.5$ $1 \pm 1$ | $3 \pm 3$ |
| $\pi^+\pi^-$ | $-25 \pm 48$     | $15.0 \sim 30.0$ $-6 \pm 12$ | $58 \pm 29$ |
Determination $\phi_3$ in $B \rightarrow \pi\pi, K\pi$. Some years ago, many authors[32, 33, 34] have derived a bound on $\phi_3$ from rates of branching ratios on $B \rightarrow K(\pi)\pi$. The ratio $R_K$ is given by

$$R_K \equiv \frac{Br(B^0 \rightarrow K^\pm \pi^\mp)}{Br(B^{\pm} \rightarrow K^{0} \pi^{\pm})} = 1.0 + \frac{2 \lambda^2 R_b}{a_K} \cos \phi_3$$

where $\lambda = 0.22$, $R_b = 0.41 \pm 0.07$ and $a_K = (a_4 + 2a_6 r_K)/a_1$. As shown in Figure 3, arbitrary $\phi_3$ is allowed due to large experimental uncertainties in present data ($0.95 \pm 0.30$). We expect more precise measurement of $R_K$ to determine $\phi_3$ in future within 2-3 years.

**SUMMARY AND OUTLOOK**

In this paper I have discussed ingredients of PQCD approach and some important theoretical issues with numerical results by comparing experimental data. A new PQCD factorization approach provides a useful theoretical framework for a systematic analysis on non-leptonic two-body B-meson decays. This approach explain sucessfully present experimental data upto now and will be tested more thoroughly with more precise data in near future.
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