Possible large direct CP violations in charmless B meson decays: Summary report on the PQCD method

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(Received 5 October 2002; published 19 March 2003)

We discuss the perturbative QCD approach for the exclusive two body B meson decays to light mesons. We briefly review its ingredients and some important theoretical issues on the factorization approach. We show numerical results which are compatible with present experimental data for charmless B meson decays. In particular, we predict the possibility of large direct CP violation effects in $B^0\to\pi^+\pi^-$ $[(23\pm7\%)]$ and $B^0\to K^+\pi^-$ $[(-17\pm5\%)]$. In the last section we investigate two methods to determine the weak phases ϕ_2 and ϕ_3 from $B\to\pi\pi, K\pi$ processes. We obtain bounds on ϕ_2 and ϕ_3 from present experimental measurements.

DOI: 10.1103/PhysRevD.67.054009 PACS number(s): 13.25.Hw, 11.10.Hi, 12.38.Bx, 13.25.Ft

I. INTRODUCTION

The aim of the study on weak decay in B mesons is twofold: (1) to determine precisely the elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix [1,2] and to explore the origin of CP violation at a low energy scale: (2) to understand the strong interaction physics related to the confinement of quarks and gluons within hadrons.

The two tasks complement each other. An understanding of the connection between quarks and hadron properties is a necessary prerequisite for a precise determination of the CKM matrix elements and the CP-violating Kobayashi-Maskawa (KM) phase [2].

The theoretical description of hadronic weak decays is difficult since the nonperturbative QCD interaction is involved. This makes it difficult to seek the origin of CP violation at asymmetric B factories. In the case of B meson decays into two light mesons, the factorization approximation [3–6] offers some understanding of branching ratios. In the factorization approximation, it is argued that because the final-state mesons are moving so fast it is difficult to exchange gluons. So soft final-state interactions can be neglected (the color-transparency argument [7,8]), and we can express the amplitude in terms of a product of decay constants and transition form factors. These amplitudes are real. This predicts vanishing CP asymmetries. In this approach, we cannot calculate nonfactorizable contributions and annihilation contributions.

Recently two different QCD approaches beyond the naive and general factorization assumption were proposed: (1) QCD-factorization in the heavy quark limit [9,10] in which nonfactorizable terms and a_i are calculable in some cases; (2) the perturbative (PQCD) approach [11–13] including the resummation effects of the transverse momentum carried by partons inside the meson. In this article, we discuss some important theoretical issues in PQCD factorization and numerical results for charmless B decays.

II. INGREDIENTS OF PQCD

A. Factorization in PQCD

The idea of perturbative QCD is as follows. When a heavy B-meson decays into two light mesons, it can be shown that the hard process is dominant. A hard gluon exhange is needed to boost the spectator quark (which is almost at rest) to large momentum so that it can pair up with the fast moving quark to form a meson. Also, it can be shown that the final-state interaction, if any, is calculable, i.e., soft gluon exchanges between final-state hadrons are negligible.

So the process is dominated by one hard gluon exchanged between a spectator quark and the quarks involved in the weak decay. It can be shown that all possible diagrams contributing to the decay amplitude can be cast into a convolution of this hard amplitude and meson wave functions.

Let us start with the lowest-order diagram for $B\to K\pi$. There are diagrams that have infrared divergences. It can be shown that the divergent parts can be absorbed into the light-cone wave functions. Their finite pieces are absorbed into the hard part. Then in a natural way we can factorize the amplitude into two pieces: $G\equiv H(Q,\mu)\otimes\Phi(m,\mu)$ where H contains the hard part of the dynamics and is calculable using perturbation theory. Φ repesents a product of wave functions which contains all the nonperturbative dynamics.

Based on the perturbative QCD formalism developed by Brodsky and Lepage [15] and Botts and Sterman [16], the three-scale factorization theorem can be proved [14], including the transverse momentum components which are carried by partons inside the meson.

We have three different scales: the electroweak scale M_W, the hard interaction scale $t\sim O(\bar{\Lambda} m_b)$, and the factorization scale $1/b$ where b is the conjugate variable of the parton transverse momenta. The dynamics below $1/b$ is completely nonperturbative and can be parametrized into meson wave functions which are universal and process independent. In our analysis we use the results of light-cone distribution amplitudes (LCDAs) by Ball [17,18] obtained with light-cone sum rule.

The ampltitude in PQCD is expressed as

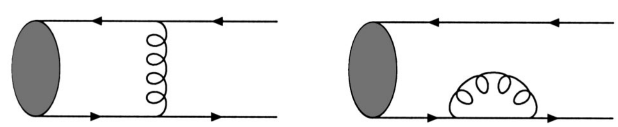

FIG. 1. The diagrams generating double logarithm corrections for the Sudakov resummation.

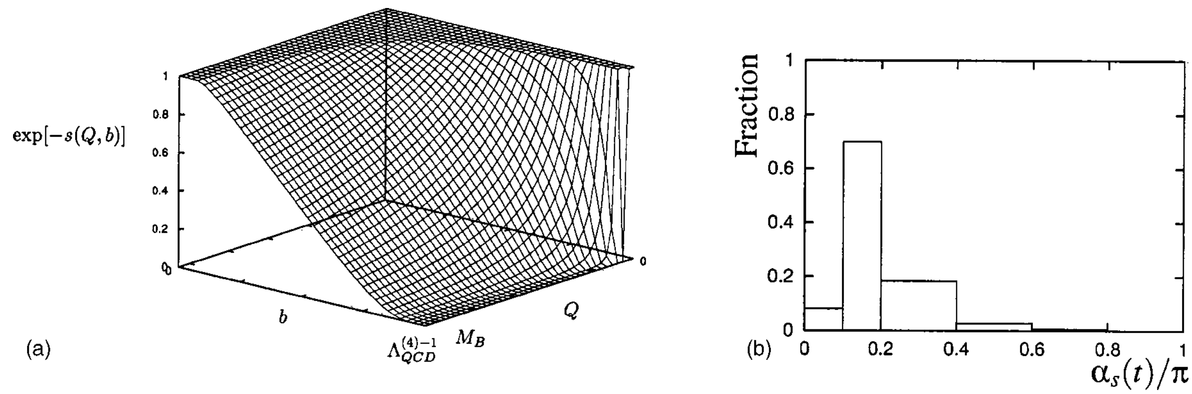

FIG. 2. (a) Sudakov suppression factor. (b) Fractional contribution to the $B\to\pi$ transition form factor $F^{B\pi}$ as a function of $\alpha_s(t)/\pi$.

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

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

B. Sudakov suppression effects

There is a set of diagrams that contain powers of double logarithms $\ln^2(Pb)$ (See Fig. 1). They come from the overlap of the collinear and soft divergence in the radiative corrections to the meson wave functions, where P is the dominant light-cone component of the meson momentum.

Fortunately they can be summed. The summation 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 $b > 1/\Lambda_{QCD}$.

The Sudakov factor can be understood as follows. Even a single gluon emission does not allow the formation of an exclusive final state. So the exclusive two-body decays are proportional to the probability that no gluon is emitted during the hard process. The Sudakov factor leads to this probability. When two quarks are far apart (i.e., large b, thus small $k_\perp$), their colors are no longer shielded. So when the quarks undergo hard scattering they cannot help but emit soft gluons. Since the Sudakov factor suppresses the small $k_\perp$ region, $k_\perp^2$ flowing into the hard amplitudes become large:

$$\langle k_\perp^2\rangle \sim O(\bar{\Lambda} M_B) \tag{2}$$

and the singularities are removed.

In earlier analysis, $k_\perp$ and the Sudakov factor were neglected and it was found that the amplitude is infrared singular. It is clear that such a naive analysis is in error.

Thanks to the Sudakov effect, all contributions to the $B\to\pi$ form factor come from the region with $\alpha_s/\pi < 0.3$ [12] as shown in Fig. 2. This indicates that our PQCD results are well within the perturbative region.

C. Threshold resummation

The other double logarithm is $\alpha_s \ln^2(1/x)$ from the end point region of the momentum fraction x [19]. This double logarithm is generated by the corrections of the hard part in Fig. 3. 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 $c \sim 0.3$ into the PQCD factorization formula. The Sudakov factor from threshold resummation is universal, independent of the flavors of internal quarks, the twists and topologies of the hard amplitudes, and the decay modes.

Threshold resummation [19] and $k_\perp$ resummation [16,20,21] arise from different subprocesses in PQCD factorization and suppress the end point contributions, making PQCD evaluation of exclusive B meson decays reliable. We point out that these resummation effects are crucial. Without these resummation effects, the PQCD predictions for the $B\to K$ form factors are infrared divergent. The $k_\perp$ resummation renders the amplitudes finite, and suppresses two-parton twist-3 contributions to reasonable values.

D. 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 have been discussed in detail in [22]. The relative importance is summarized below:

$$\text{emission:annihilation:nonfactorizable} = 1 : \frac{2m_0}{M_B} : \frac{\bar{\Lambda}}{M_B}, \tag{3}$$

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

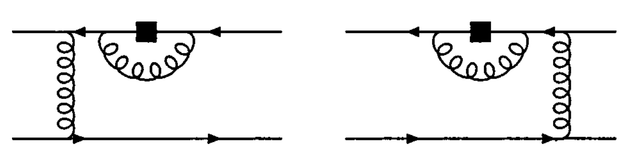

FIG. 3. The diagrams generating double logarithm corrections for the threshold resummation.

TABLE I. Amplitudes for the $B_d^0 \to \pi^+\pi^-$ decay where $F(M)$ denotes factorizable (nonfactorizable) contributions, $P(T)$ denotes the penguin (tree) contributions, and a denotes the annihilation contributions. Here we adopted $\phi_3 = 80°$, $R_b = \sqrt{\rho^2+\eta^2} = 0.38$, $m_0^\pi = 1.4$ GeV, and $\omega_B = 0.40$ GeV.

Amplitude	Twist-2 contribution	Twist-3 contribution	Total
$\mathrm{Re}(f_\pi F^T)$	3.44×10^{-2}	5.00×10^{-2}	8.44×10^{-2}
$\mathrm{Im}(f_\pi F^T)$	–	–	–
$\mathrm{Re}(f_\pi F^P)$	-1.26×10^{-3}	-4.76×10^{-3}	-6.02×10^{-3}
$\mathrm{Im}(f_\pi F^P)$	–	–	–
$\mathrm{Re}(f_B F_a^P)$	2.52×10^{-6}	-3.33×10^{-4}	-3.30×10^{-4}
$\mathrm{Im}(f_B F_a^P)$	8.72×10^{-7}	3.81×10^{-3}	3.81×10^{-3}
$\mathrm{Re}(M^T)$	7.26×10^{-4}	-1.39×10^{-6}	-7.25×10^{-4}
$\mathrm{Im}(M^T)$	-1.62×10^{-3}	-2.91×10^{-4}	1.33×10^{-3}
$\mathrm{Re}(M^P)$	-1.67×10^{-5}	1.47×10^{-7}	-1.66×10^{-5}
$\mathrm{Im}(M^P)$	-3.52×10^{-5}	6.56×10^{-6}	-2.87×10^{-5}
$\mathrm{Re}(M_a^P)$	-7.37×10^{-5}	2.50×10^{-6}	-7.12×10^{-5}
$\mathrm{Im}(M_a^P)$	-3.13×10^{-5}	-2.04×10^{-5}	-5.17×10^{-5}

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 $M_B \sim 5$ GeV, the annihilation contributions are essential. In Table I and II we can easily check the relative size of the different topologies in Eq. (3) by the penguin contribution for W emission ($f_\pi F^P$), annihilation ($f_B F_a^P$) and nonfactorizable (M^P) contributions, as shown in Fig. 4. In particular, we show the relative size of the different twisted light-cone distribution-amplitudes for each topology. Actually the twist-3 contributions are larger than the twist-2 contributions.

Note that all the above topologies are of the same order in α_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, although 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

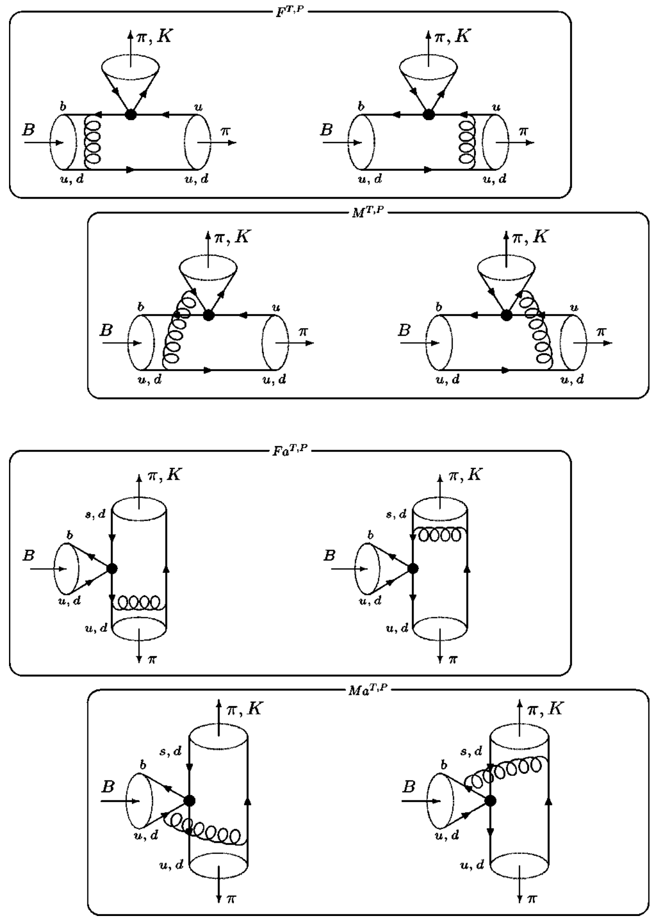

FIG. 4. Feynman diagrams for $B \to \pi\pi$ and $K\pi$ decays.

TABLE II. Amplitudes for the $B_d^0 \to K^+\pi^-$ decay where $F(M)$ denotes factorizable (nonfactorizable) contributions, $P(T)$ denotes the penguin (tree) contributions, and a denotes the annihilation contributions. Here we adopted $\phi_3 = 80°$, $R_b = \sqrt{(\rho^2+\eta^2} = 0.38$.

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

Wilson coefficient a_2 in the $B \to J/\psi K^{(*)}$ decays [23], so that nonfactorizable contributions become dominant [24]. In the $B \to D\pi$ decays, there is no soft cancellation between a pair of nonfactorizable diagrams, and nonfactorizable contributions are significant [23,25].

In QCD factorizaion (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 α_s compared to the former. Hence, QCDF approaches the factorization approach (FA) in the heavy quark limit in the sense of $\alpha_s \to 0$. Briefly speaking, QCDF and PQCD have different counting rules both in α_s and in $1/m_b$. The former approaches FA logarithmically ($\alpha_s \propto 1/\ln m_b \to 0$), while the latter approaches linearly ($1/m_b \to 0$).

III. THE COMPARISON OF PQCD AND QCDF

A. End point singularity and form factors

If calculating the $B \to \pi$ form factor $F^{B\pi}$ at large recoil using the Brodsky-Lepage formalism [15,26], a difficulty immediately occurs. The lowest-order diagram for the hard amplitude is proportional to $1/(x_1 x_3^2)$, 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 $x_3 \to 0$ (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 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

$$\frac{1}{x_1 x_3^2 M_B^4} \quad \to \quad \frac{1}{(x_3 M_B^2 + k_{3\perp}^2)[x_1 x_3 M_B^2 + (k_{1\perp} - k_{3\perp})^2]} \tag{4}$$

and the end point singularity is smeared out.

In PQCD, we can calculate analytically spacelike form factors for the $B \to P,V$ transition and also timelike form factors for the annihilation process [22,27].

B. Strong phases

While strong phases in FA and QCDF come from the Bander-Silverman-Soni mechanism [28] and from the final-state interaction, the dominant strong phase in PQCD comes from the factorizable annihilation diagram [11–13] (see Fig. 5). In fact, the two sources of strong phases in the FA and QCDF approaches are strongly suppressed by the charm mass threshold and by the end point behavior of meson wave functions. So the strong phase in QCDF is almost zero without soft annihilation contributions.

C. Dynamical penguin enhancement vs chiral enhancement

As explained before, the hard scale is about 1.5 GeV. Since the renormalization group evolution of the Wilson coefficients $C_{4,6}(t)$ increases drastically as $t < M_B/2$, while that of $C_{1,2}(t)$ remains almost constant, we can get large enhancement effects from both Wilson coefficents and matrix elements in PQCD.

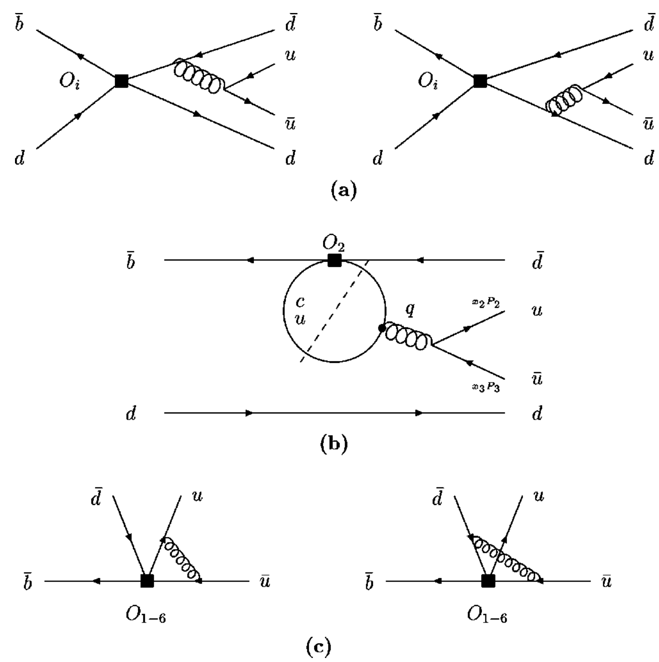

FIG. 5. Different sources of the strong phase: (a) Factorizable annihilation, (b) BSS mechanism, and (c) final-state interaction.

In general the amplitude can be expressed as

$$\text{Amp} \sim [a_{1,2} \pm a_4 \pm m_0^{P,V}(\mu) a_6] \cdot \langle K\pi | O | B \rangle \tag{5}$$

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

We can test whether dynamical enhancement or chiral enhancement is responsible for the large $B \to K\pi$ branching ratios by measuring the $B \to \phi K$ modes. In these modes penguin contributions dominate, such that their branching ratios are insensitive to the variation of the unitarity angle ϕ_3. According to recent work by Cheng *et al.* [29], the branching ratio of $B \to \phi K$ is $(2-7) \times 10^{-6}$ including 30% annihilation contributions in the QCD factorization approach. However, PQCD predicts 10×10^{-6} [22,34]. For $B \to \phi K^*$ decays, QCDF gets about 9×10^{-6} [30], but PQCD has 15×10^{-6} [35]. Because of these small branching ratios for $B \to PV$ and VV decays in the QCD factorization approach, they cannot globally fit the experimental data for $B \to PP$, VP, and VV modes simultaneously with the same sets of free parameters (ρ_H, ϕ_H) and (ρ_A, ϕ_A) [31].

TABLE III. Branching ratios of $B\to\pi\pi$, $K\pi$, and $K\overline{K}$ decays with $\phi_3=80°$, $R_b=\sqrt{\rho^2+\eta^2}=0.38$. Here we adopted $m_0^\pi=1.3$ GeV and $m_0^K=1.7$ GeV. Unit is 10^{-6}. (07/2002 data).

Decay channel	Cleo	Belle	BaBar	PQCD
$\pi^+\pi^-$	$4.3^{+1.6}_{-1.4}\pm0.5$	$5.4\pm1.2\pm0.5$	$4.7\pm0.6\pm0.2$	$7.0^{+2.0}_{-1.5}$
$\pi^+\pi^0$	$5.4^{+2.1}_{-2.0}\pm1.5$	$7.4\pm2.3\pm0.9$	$5.5^{+1.0}_{-0.9}\pm0.6$	$3.7^{+1.3}_{-1.1}$
$\pi^0\pi^0$	<5.2	<6.4	<3.4	0.3 ± 0.1
$K^\pm\pi^\mp$	$17.2^{+2.5}_{-2.4}\pm1.2$	$22.5\pm1.9\pm1.8$	$17.9\pm0.9\pm0.7$	$15.5^{+3.1}_{-2.5}$
$K^0\pi^\mp$	$18.2^{+4.6}_{-4.0}\pm1.6$	$19.4\pm3.1\pm1.6$	$17.5^{+1.8}_{-1.7}\pm1.3$	$16.4^{+3.3}_{-2.7}$
$K^\pm\pi^0$	$11.6^{+3.0+1.4}_{-2.7-1.3}$	$13.0\pm2.5\pm1.3$	$12.8^{+1.2}_{-1.1}\pm1.0$	$9.1^{+1.9}_{-1.5}$
$K^0\pi^0$	$14.6^{+5.9+2.4}_{-5.1-3.3}$	$8.0\pm3.2\pm1.6$	$8.2^{+3.1}_{-2.7}\pm1.2$	8.6 ± 0.3
$K^\pm K^\mp$	<1.9	<0.9	<0.6	0.06
$K^\pm\overline{K}^0$	<5.1	<2.0	<1.3	1.4
$K^0\overline{K}^0$	<13	<4.1	<7.3	1.4

D. Fat imaginary penguin in annihilation

There is a folklore that the annihilation contribution is negligible compared to that of W emission. For this nonreason the annihilation contribution was not included in the general factorization approach and the first paper on QCD factorization by Beneke *et al.* [9]. 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 $\pi\to\mu\nu_\mu$. However, annihilation effects from the operators $O_{5,6,7,8}$ with the structure $(S-P)(S+P)$ via Fierz transformation possess no such helicity suppression, and in addition they lead to large imaginary values. The real part of the factorized annihilation contribution becomes small because there is a cancellation between the left- and right-hand-side gluon effects as shown in Table I. This mostly purely imaginary annihilation amplitude is a main source of large CP asymmetry in $B\to\pi^+\pi^-$ and $K^+\pi^-$. In Table VII below we summarize the CP asymmetry in $B\to K(\pi)\pi$ decays.

IV. NUMERICAL RESULTS

A. 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 light-cone distribution amplitudes up to twist 3. We focus on decays whose branching ratios have already been measured. We take the allowed range of the shape parameter for the B-meson wave function as $\omega_B=0.36$–0.44, which accommodates reasonable form factors $F^{B\pi}(0)=0.27$–0.33 and $F^{BK}(0)=0.31$–0.40. We use values of the chiral factor with $m_0^\pi=1.3$ GeV and $m_0^K=1.7$ GeV. It can be seen that the branching ratios for $B\to K(\pi)\pi$ [11–13,32], $\rho(\omega)\pi$ [33], $K\phi$ [22,34] $K^*\phi$ [35] and $K^*\pi$ [36] are in reasonable agreement with present experimental data (see Tables III–VI).

In order to reduce theoretical uncertainties from the decay constant of the B meson and from light-cone distribution amplitudes, we consider rates of CP-averaged branching ratios, which are presented in Table VII.

TABLE IV. Branching ratios of $B\to\rho\pi$ and $\omega\pi$ decays with $\phi_2=75°$, $R_b=\sqrt{\rho^2+\eta^2}=0.38$. Here we adopted $m_0^\pi=1.3$ GeV and $\omega_B=0.4$ GeV. Unit is 10^{-6}. (07/2002 data).

Decay Channel	Cleo	Belle	BaBar	PQCD
$\rho^\pm\pi^\mp$	$27.6^{+8.4}_{-7.4}\pm4.2$	$20.8^{+6.0+2.8}_{-6.3-3.1}$	$28.9\pm5.4\pm4.3$	27.0
$\rho^0\pi^\pm$	$10.4^{+3.3}_{-3.4}\pm2.1$	$8.0^{+2.3+0.7}_{-2.0-0.7}$	$24\pm8\pm3$	5.4
$\rho^0\pi^0$	–	<5.3	<10.6	0.02
$\omega\pi^\pm$	$11.3^{+3.3}_{-2.9}\pm1.4$	$4.2^{+2.0}_{-1.8}\pm0.5$	$6.6^{+2.1}_{-1.8}\pm0.7$	5.5
$\omega\pi^0$	–	–	<3.0	0.01

TABLE V. Branching ratios of $B\to\phi K^{(*)}$ decays with $\phi_3=80°$, $R_b=\sqrt{\rho^2+\eta^2}=0.38$. Here we adopted $m_0^\pi=1.3$ GeV and $m_0^K=1.7$ GeV. Unit is 10^{-6}. (07/2002 data).

Decay channel	Cleo	Belle	BaBar	PQCD
$\phi K^\pm$	$5.5^{+2.1}_{-1.8}\pm0.6$	$11.2^{+2.2}_{-2.0}\pm0.14$	$7.7^{+1.6}_{-1.4}\pm0.8$	$10.2^{+3.9}_{-2.1}$
ϕK^0	<12.3	$8.9^{+3.4}_{-2.7}\pm1.0$	$8.1^{+3.1}_{-2.5}\pm0.8$	$9.6^{+3.7}_{-2.0}$
$\phi K^{*\pm}$	$10.6^{+6.4+1.8}_{-4.9-1.6}$	<36	$9.7^{+4.2}_{-3.4}\pm1.7$	$16.0^{+5.2}_{-3.4}$
ϕK^{*0}	$11.5^{+4.5+1.8}_{-3.7-1.7}$	$15^{+8}_{-6}\pm3$	$8.6^{+2.8}_{-2.4}\pm1.1$	$14.9^{+4.9}_{-3.4}$

B. CP Asymmetry of $B\to\pi\pi,K\pi$

Because we have a large imaginary contribution from factorized annihilation diagrams in the PQCD approach, we predict large CP asymmetry ($\sim25\%$) in $B^0\to\pi^+\pi^-$ decays and about -15% CP violation effects in $B^0\to K^+\pi^-$. The detailed prediction is given in Table VIII. 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 from those of QCD factorization.

V. DETERMINATION OF ϕ_2 AND ϕ_3 IN $B\to\pi\pi,K\pi$

One of the most exciting aspects of present-day high-energy physics is the exploration of CP violation in B-meson decays, allowing us to overconstrain both sides and three weak phases ϕ_1 $(=\beta)$, ϕ_2 $(=\alpha)$, and ϕ_3 $(=\gamma)$ of the unitarity triangle of the CKM matrix and to check the possibility of new physics.

TABLE VI. Branching ratios of $B\to K^*\pi$ decays with $\phi_3=80°$, $R_b=\sqrt{\rho^2+\eta^2}=0.38$. Here we adopted $m_0^\pi=1.2-1.6$ GeV and $\omega_B=0.36-0.44$ GeV. Unit is 10^{-6}. (07/2002 data).

Decay channel	Cleo	Belle	BaBar	PQCD
$K^{*0}\pi^\pm$	$7.6^{+3.5}_{-3.0}\pm1.6$	$16.2^{+4.1}_{-3.8}\pm2.4$	$15.5\pm3.4\pm1.8$	$10.0^{+5.3}_{-3.5}$
$K^{*\pm}\pi^\mp$	$16^{+6}_{-5}\pm2$	–	–	$9.1^{+4.9}_{-3.2}$
$K^{*\pm}\pi^0$	–	–	–	$3.2^{+1.9}_{-1.2}$
$K^{*0}\pi^0$	–	–	–	$2.8^{+1.6}_{-1.0}$

TABLE VII. Ratios of CP-averaged rates in $B\to K\pi,\pi\pi$ decays with $\phi_3=80°$, $R_b=0.38$. Here we adopted $m_0^\pi=1.3$ GeV and $m_0^K=1.7$ GeV.

Quantity	Experiment	PQCD	QCDF [37]
$\frac{\mathrm{Br}(\pi^+\pi^-)}{\mathrm{Br}(\pi^\pm K^\mp)}$	0.25 ± 0.04	0.30–0.69	0.5–1.9
$\frac{\mathrm{Br}(\pi^\pm K^\mp)}{2\mathrm{Br}(\pi^0 K^0)}$	1.05 ± 0.27	0.78–1.05	0.9–1.4
$\frac{2\,\mathrm{Br}(\pi^0 K^\pm)}{\mathrm{Br}(\pi^\pm K^0)}$	1.25 ± 0.22	0.77–1.60	0.9–1.3
$\frac{\tau(B^+)}{\tau(B^0)}\frac{\mathrm{Br}(\pi^\mp K^\pm)}{\mathrm{Br}(\pi^\pm K^0)}$	1.07 ± 0.14	0.70–1.45	0.6–1.0

The "gold-plated" mode $B_d\to J/\psi K_s$ [39] which allows us to determine ϕ_1 without any hadron uncertainty was recently measured by the BaBar and Belle Collaborations [40]: $\phi_2=(25.5\pm4.0)°$. There are many other interesting channels with which we may achieve this goal by determining ϕ_2 and ϕ_3 [41].

In this paper, we focus on the $B\to\pi^+\pi^-$ and $K\pi$ processes, providing promising strategies to determine the weak phases of ϕ_2 and ϕ_3, by using the perturbative QCD method.

A. Extraction of ϕ_2 from $B\to\pi^+\pi^-$

Even though isospin analysis of $B\to\pi\pi$ can provide a clean way to determine ϕ_2, it might be difficult in practice because of the small branching ratio of $B^0\to\pi^0\pi^0$. In reality in order to determine ϕ_2, we can use the time-dependent rate of $B^0(t)\to\pi^+\pi^-$ including sizable penguin contributions. The amplitude can be written by using the c-convention notation:

$$A(B^0\to\pi^+\pi^-)=V_{ub}^*V_{ud}A_u+V_{cb}^*V_{cd}A_c+V_{tb}^*V_{td}A_t,$$
$$=V_{ub}^*V_{ud}(A_u-A_t)+V_{cb}^*V_{cd}(A_c-A_t),$$
$$=-(|T_c|e^{i\delta_T}e^{i\phi_3}+|P_c|e^{i\delta_P}). \tag{6}$$

TABLE VIII. CP asymmetry in $B\to K\pi,\pi\pi$ decays with $\phi_3=40°-90°$, $R_b=0.38$. Here we adopted $m_0^\pi=1.3$ GeV and $m_0^K=1.7$ GeV.

Direct $A_{CP}(\%)$	Belle (07/02)	BaBar (07/02)	PQCD	QCDF [38]
π^+K^-	$-6\pm9^{+6}_{-2}$	$-10.2\pm5.0\pm1.6$	$-12.9\sim-21.9$	5 ± 9
π^0K^-	$-2\pm19\pm2$	$-9.0\pm9.0\pm1.0$	$-10.0\sim-17.3$	7 ± 9
$\pi^-\bar{K}^0$	$46\pm15\pm2$	-4.7 ± 13.9	$-0.6\sim-1.5$	1 ± 1
$\pi^+\pi^-$	$94^{+25}_{-31}\pm9$	$30\pm25\pm4$	$16.0\sim30.0$	-6 ± 12
$\pi^+\pi^0$	$30\pm30^{+6}_{-4}$	$-3\pm18\pm2$	0.0	0.0

The penguin term carries a different weak phase from the dominant tree amplitude, which leads to a generalized form of the time-dependent asymmetry:

$$A(t)\equiv\frac{\Gamma(\bar{B}^0(t)\to\pi^+\pi^-)-\Gamma(B^0(t)\to\pi^+\pi^-)}{\Gamma(\bar{B}^0(t)\to\pi^+\pi^-)+\Gamma(B^0(t)\to\pi^+\pi^-)}$$
$$=S_{\pi\pi}\sin(\Delta mt)-C_{\pi\pi}\cos(\Delta mt) \tag{7}$$

where

$$C_{\pi\pi}=\frac{1-|\lambda_{\pi\pi}|^2}{1+|\lambda_{\pi\pi}|^2},\quad S_{\pi\pi}=\frac{2\,\mathrm{Im}(\lambda_{\pi\pi})}{1+|\lambda_{\pi\pi}|^2} \tag{8}$$

satisfy the relation $C_{\pi\pi}^2+S_{\pi\pi}^2\leqslant1$. Here

$$\lambda_{\pi\pi}=|\lambda_{\pi\pi}|e^{2i(\phi_2+\Delta\phi_2)}=e^{2i\phi_2}\left[\frac{1+R_ce^{i\delta}e^{i\phi_3}}{1+R_ce^{i\delta}e^{-i\phi_3}}\right] \tag{9}$$

with $R_c=|P_c/T_c|$ and the strong phase difference between penguin and tree amplitudes $\delta=\delta_P-\delta_T$. The time-dependent asymmetry measurement provides two equations for $C_{\pi\pi}$ and $S_{\pi\pi}$ in terms of three unknown variables R_c, δ, and ϕ_2.

When we define $R_{\pi\pi}=\overline{Br}(B^0\to\pi^+\pi^-)/\overline{Br}(B^0\to\pi^+\pi^-)|_{tree}$, where $\overline{Br}$ stands for a branching ratio averaged over B^0 and $\bar{B}^0$, the explicit expressions for $S_{\pi\pi}$ and $C_{\pi\pi}$ are given by

$$R_{\pi\pi}=1-2R_c\cos\delta\cos(\phi_1+\phi_2)+R_c^2, \tag{10}$$

$$R_{\pi\pi}S_{\pi\pi}=\sin2\phi_2+2R_c\sin(\phi_1-\phi_2)\cos\delta-R_c^2\sin2\phi_1, \tag{11}$$

$$R_{\pi\pi}C_{\pi\pi}=2R_c\sin(\phi_1+\phi_2)\sin\delta. \tag{12}$$

If we know R_c and δ, then ϕ_2 can be determined by the experimental data on $C_{\pi\pi}$ versus $S_{\pi\pi}$.

Since PQCD provides $R_c=0.23^{+0.07}_{-0.05}$ and $-41°<\delta<-32°$, the allowed range of ϕ_2 at the present stage is determined by $55°<\phi_2<100°$ as shown in Fig. 6.

According to the power counting rule in the PQCD approach [22], the factorizable annihilation contribution with large imaginary part becomes subdominant and gives a negative strong phase from $-i\pi\delta(k_\perp^2-xM_B^2)$. Therefore we have a relatively large strong phase in contrast to QCD factorization ($\delta\sim0°$) and predict a large direct CP-violation effect in $B^0\to\pi^+\pi^-$ with $A_{cp}(B^0\to\pi^+\pi^-)=(23\pm7)\%$, which will be tested by a more precise experimental measurement within two years. Since the data of the Belle Collaboration [42] are located outside the allowed physical regions, we considered only the recent BaBar measurement [43] with 90% C.L. interval taking into account the systematic errors

$$S_{\pi\pi}=0.02\pm0.34\pm0.05\quad[-0.54,\ +0.58],$$

$$C_{\pi\pi}=-0.30\pm0.25\pm0.04\quad[-0.72,\ +0.12].$$

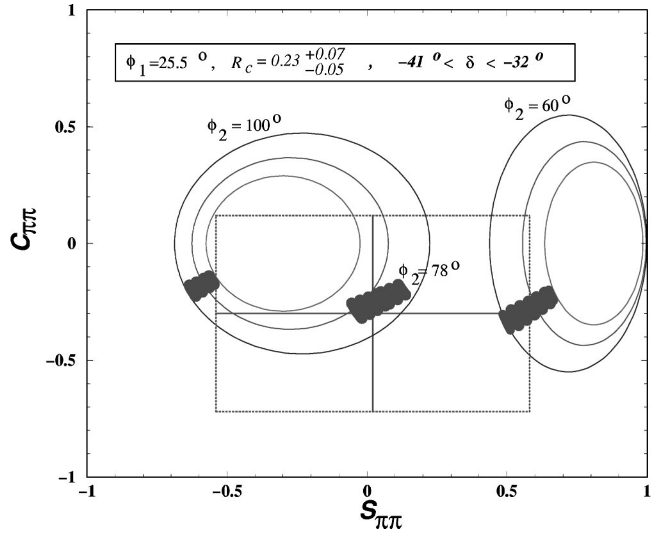

FIG. 6. Plot of $C_{\pi\pi}$ versus $S_{\pi\pi}$ for various values of ϕ_2 with $\phi_1 = 25.5\,°$, $0.18 < R_c < 0.30$, and $-41\,° < \delta < -32\,°$ in the PQCD method. Here we consider the allowed experimental ranges of the BaBar measurement within 90% C.L. Dark areas are allowed regions in the PQCD method for different ϕ_2 values.

The central point of the BaBar data corresponds to $\phi_2 = 78\,°$ in the PQCD method.

Denoting by $\Delta\phi_2$ the deviation of ϕ_2 due to the penguin contribution, derived from Eq. (9), it can be determined with known values of R_c and δ by using the relation $\phi_3 = 180 - \phi_1 - \phi_2$. In Fig. 7 we show the PQCD prediction of the relation $\Delta\phi_2$ versus ϕ_2. For allowed regions of $\phi_2 = (55$–$100)\,°$, we have $\Delta\phi_2 = (8$–$16)\,°$. The main uncertainty comes from the uncertainty of $|V_{ub}|$. The nonzero value of $\Delta\phi_2$ demonstrates sizable penguin contributions in $B^0 \to \pi^+\pi^-$ decay.

B. Extraction of ϕ_3 $(=\gamma)$ from $B^0 \to K^+\pi^-$ and $B^+ \to K^0\pi^+$

By using the tree-penguin interference in $B^0 \to K^+\pi^-$ $(\sim T' + P')$ versus $B^+ \to K^0\pi^+$ $(\sim P')$, the *CP*-averaged

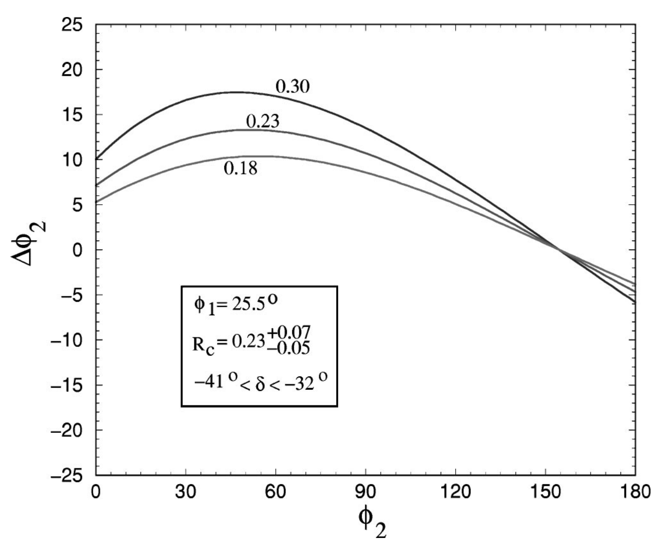

FIG. 7. Plot of $\Delta\phi_2$ versus ϕ_2 with $\phi_1 = 25.5\,°$, $0.18 < R_c < 0.30$, and $-41\,° < \delta < -32\,°$ in the PQCD method.

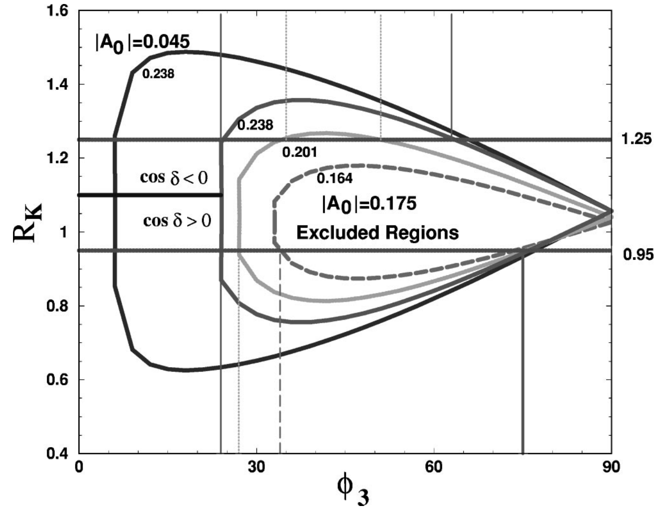

FIG. 8. Plot of R_K versus ϕ_3 with $r_K = 0.164$, 0.201, and 0.238.

$B \to K\pi$ branching fraction may lead to nontrivial constraints on the ϕ_3 angle [44]. In order to determine ϕ_3, we need one more useful piece of information on *CP*-violating rate differences [45]. Let us introduce the following observables :

$$R_K = \frac{\overline{Br}(B^0 \to K^+\pi^-)\,\tau_+}{\overline{Br}(B^+ \to K^0\pi^+)\,\tau_0} = 1 - 2r_K \cos\delta\cos\phi_3 + r_K^2 \geqslant \sin^2\phi_3, \tag{13}$$

$$A_0 = \frac{\Gamma(\overline{B}^0 \to K^-\pi^+ - \Gamma(B^0 \to K^+\pi^-)}{\Gamma(B^- \to \overline{K}^0\pi^-) + \Gamma(B^+ \to \overline{K}^0\pi^+)} = A_{cp}(B^0 \to K^+\pi^-)R_K = -2r_K \sin\phi_3 \sin\delta, \tag{14}$$

where $r_K = |T'/P'|$ is the ratio of the tree to penguin amplitudes in $B \to K\pi$ decays and $\delta = \delta_{T'} - \delta_{P'}$ is the strong phase difference between tree and penguin amplitudes. After eliminate $\sin\delta$ in Eqs. (8) and (9), we have

$$R_K = 1 + r_K^2 \pm \sqrt{(4r_K^2\cos^2\phi_3 - A_0^2\cot^2\phi_3)}. \tag{15}$$

Here we obtain $r_K = 0.201 \pm 0.037$ from the PQCD analysis [12] and $A_0 = -0.110 \pm 0.065$ by combining recent BaBar measurements on the *CP* asymmetry of $B^0 \to K^+\pi^-$: $A_{cp}(B^0 \to K^+\pi^-) = -(10.2 \pm 5.0 \pm 1.6)\%$ [43] with a present world averaged value of $R_K = 1.10 \pm 0.15$ [46].

As shown in Fig. 8, we can constrain the allowed range of ϕ_3 with a 1σ range of world averaged R_K as follows.

For $\cos\delta > 0$, $r_K = 0.164$ we can exclude $0\,° \leqslant \phi_3 \leqslant 6\,°$ and $24\,° \leqslant \phi_3 \leqslant 75\,°$.

For $\cos\delta > 0$, $r_K = 0.201$ we can exclude $0\,° \leqslant \phi_3 \leqslant 6\,°$ and $27\,° \leqslant \phi_3 \leqslant 75\,°$.

For $\cos\delta > 0$, $r_K = 0.238$ we can exclude $0\,° \leqslant \phi_3 \leqslant 6\,°$ and $34\,° \leqslant \phi_3 \leqslant 75\,°$.

For $\cos\delta < 0$, $r_K = 0.164$ we can exclude $0\,° \leqslant \phi_3 \leqslant 6\,°$.

For $\cos\delta < 0$, $r_K = 0.201$ we can exclude $0\,° \leqslant \phi_3 \leqslant 6\,°$ and $35\,° \leqslant \phi_3 \leqslant 51\,°$.

For $\cos\delta<0$, $r_K=0.238$ we can exclude $0°\leq\phi_3\leq6°$ and $24°\leq\phi_3\leq62°$.

From Table II, we obtain $\delta_{P'}=157°$, $\delta_{T'}=1.4°$ and the negative value of $\cos\delta$: $\cos\delta=-0.91$. Therefore the maximum value of the excluded region for ϕ_3 strongly depends on the uncertainty of $|V_{ub}|$. When we take the central value of $r_K=0.201$, ϕ_3 is allowed within the range of $51°\leq\phi_3\leq129°$, because of the symmetric property between R_K and $\cos\delta$, which is consistent with the result from the model-independent CKM fit in the (ρ,η) plane.

VI. SUMMARY AND OUTLOOK

In this paper we have discussed the ingredients of the PQCD approach and some important theoretical issues by comparing experimental data with numerical results. The PQCD factorization approach provides a useful theoretical framework for a systematic analysis of nonleptonic two-body *B*-meson decays. This method successfully explains present experimental data. In particular, PQCD predicted large direct *CP* asymmetries in $B^0\to\pi^+\pi^-,K^+\pi^-$ decays, which will be crucial for distinguishing our approach from others in future precise measurements.

We discussed two methods to determine the weak phases ϕ_2 and ϕ_3 within the PQCD approach through (1) time-dependent asymmetries in $B^0\to\pi^+\pi^-$ $[(23\pm7)\%]$, (2) $B\to K\pi$ $[(-17\pm5)\%]$ processes via the penguin-tree interference. We can get interesting bounds on ϕ_2 and ϕ_3 from present experimental measurements. More detailed work on other methods in $B\to\pi\pi,K\pi$ [47] and $D^{(*)}\pi$ processes will appear elsewhere [48].

ACKNOWLEDGMENTS

We wish to acknowlege the fruitful collaboration with members of PQCD working group and joyful discussions with S. J. Brodsky. This work was supported in part by a Grant-in Aid of Special Project Research (Physics of *CP* Violation) and by a Grant-in Aid for Scientific Exchange from the Ministry of Education, Science and Culture of Japan. Y.Y.K. thanks H. Y. Cheng and M. Kobayashi for their hospitality and encouragement.

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