QCD aspects of exclusive B decays

Hsiang-nan Li
Institute of Physics, Academia Sinica, Taipei

Oct. 06-11, 2003
ICFP2 at KIAS

- Introduction
- Naive Factorization
- QCD Theories
  QCD-improved Factorization
  Perturbatiove QCD
  Soft-Collinear Effective Theory
  Light-cone Sum Rules
- Comparison: QCDF vs. PQCD
- Summary

Introduction

- exclusive B meson decays are important for extracting the Standard Model parameters (CKM matrix elements and weak phases...) and for exploring new physics.
- nonleptonic B meson decays are complicated due to strong dynamics, which must be well understood in order to achieve the above goals.
- the naive factorization assumption has many theoretical drawbacks. To match the increasing experimental precision, QCD theories for nonletonic B meson decays are necessary.
- will discuss QCD-improved Factorization (QCDF), perturbatiove QCD (PQCD), soft-collinear effective theory (SCET), light-cone sum rules (LCSR).
- will not discuss charming penguins, additional parameters in QCDF (Ciuchini et al.), and intrinsic charms, a higher Fock state in PQCD (Gardner and Brodsky).
- will compare the theoretical basis and the phenomenological implications from QCDF and PQCD.
- for explicit QCDF predictions, Du's talk.

for explicit PQCD predictions, Keum's talk.

- for details of SCET, Chay's talk.
- will comment on LCSR.

Naive Factorization (BSW)

- The effective weak Hamiltonian for $B \to D\pi$,

$$\mathcal{H}_{\rm eff} = \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* \Big[C_1(\mu) O_1(\mu) + C_2(\mu) O_2(\mu) \Big]$$

$$O_1 = (\bar{d}b)_{V-A} (\bar{c}u)_{V-A} \; , \qquad\qquad O_2 = (\bar{c}b)_{V-A} (\bar{d}u)_{V-A}$$

- Class-1 (color-allowed) topology: the $\bar{B}^0 \to D^+\pi^-$ mode.
- Class-2 (color-suppressed) topology: the $\bar{B}^0 \to D^0\pi^0$ mode.
- Under FA,

$$A(\bar{B}^0 \to D^+\pi^-) = i \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* (m_B^2 - m_D^2) \, f_\pi \, F_0^{BD}(m_\pi^2) \, a_1(D\pi)$$

$$\sqrt{2}\, A(\bar{B}^0 \to D^0\pi^0) = -i \frac{G_F}{\sqrt{2}} V_{cb} V_{ud}^* (m_B^2 - m_\pi^2) \, f_D \, F_0^{B\pi}(m_D^2) \, a_2(D\pi)$$

$$a_1 = C_2(\mu) + C_1(\mu) \frac{1}{N_c} \; , \quad a_2 = C_1(\mu) + C_2(\mu) \frac{1}{N_c}$$

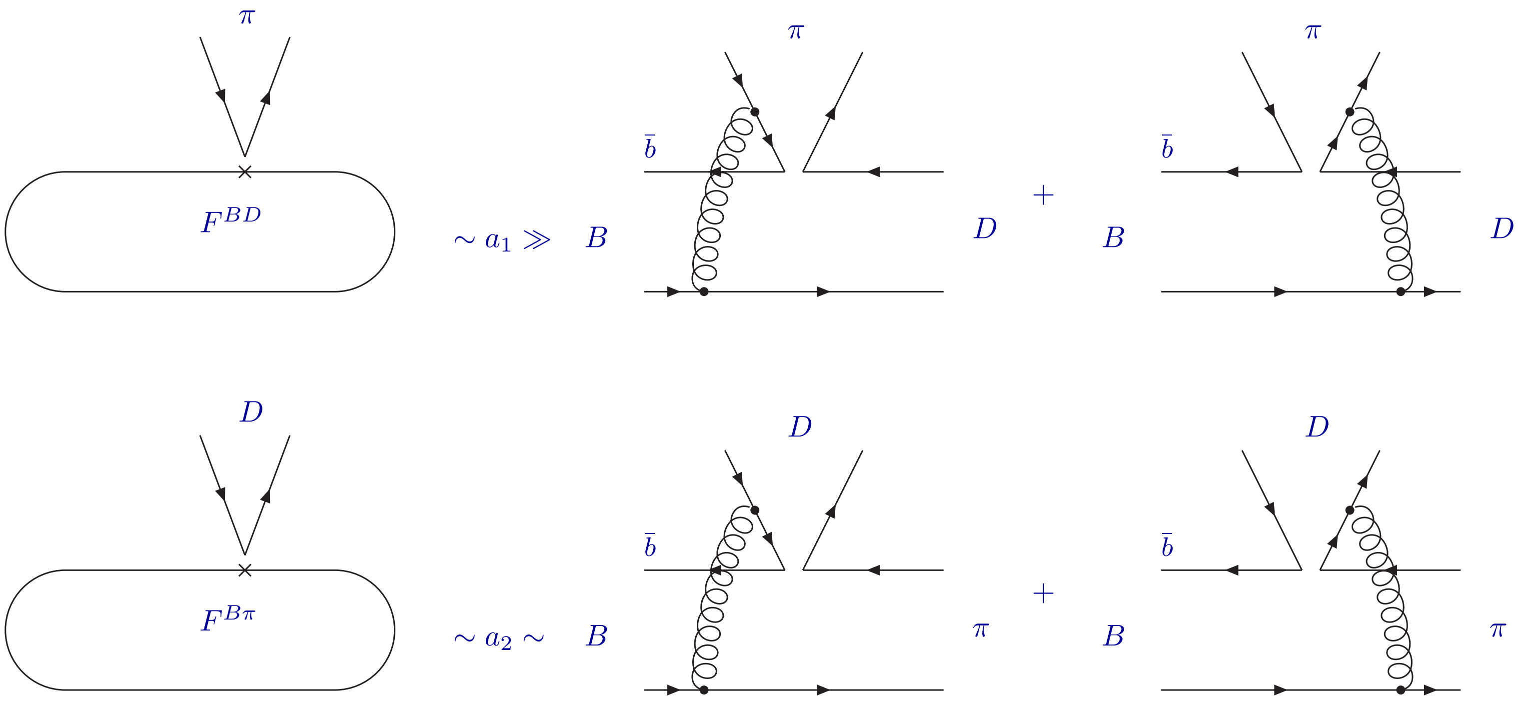
- $a_1(D\pi) \sim O(1)$ and $a_2(D\pi) \sim O(1/N_c)$ depend on the color and Dirac structures of the operators, but otherwise are postulated to be universal.
- $|a_1| \approx 1.1 \pm 0.1$ from the class-1 decays $\bar{B}^0 \to D^{(*)+} M^-$, $M = \pi, \rho, a_1, D_s$, and D_s^*.
- $|a_2| \approx 0.2$–0.3 from the class-2 decays $\bar{B} \to \bar{K}^{(*)} M$, $M = J/\psi$ and $\psi(2S)$ (Cheng and Yang).

• a_2 from the class-2 modes $\bar{B}^0 \to D^{0(*)}M^0$ gives (Neubert and Petrov; Cheng)

$$|a_2(D\pi)| \sim 0.35 - 0.60 \Rightarrow Arg(a_2/a_1)(D\pi) = 59^\circ$$
$$|a_2(D^*\pi)| \sim 0.25 - 0.50 \Rightarrow Arg(a_2/a_1)(D^*\pi) = 63^\circ$$

• the sizeable relative strong phases between class-1 and class-2 amplitudes indicate a failure of FA: a strong nonuniversality of nonfactorizable effects.

• it is easy to understand the failure:



QCD Theories

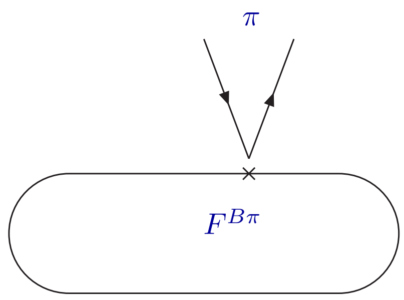
- naive factorization does not work for color-suppressed decays.
- also the scale dependence is explicit and strong phases are not complete in naive factorization.

⇒ need QCD theories to calculate subleading contributions.

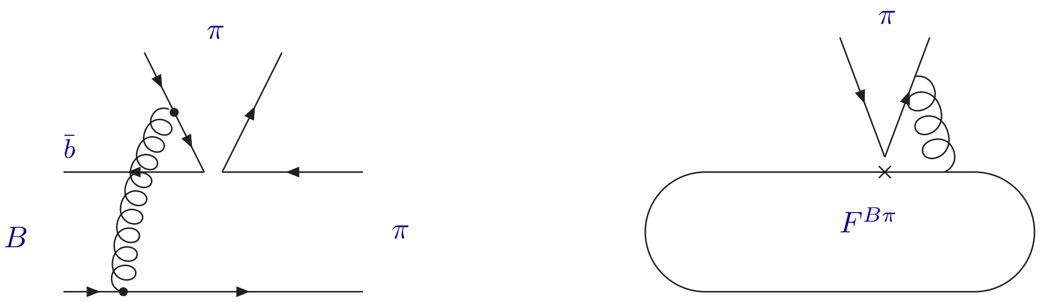
✦ QCDF

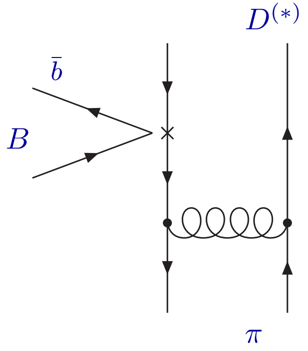
- calculate subleading corrections to naive factorization (Buchalla, Beneke, Neubert and sachrajda).

$O(1)$:



$O(\alpha_s)$:



$O(\alpha_s m_0/m_B)$: 

• B meson transition form factors are not calculable due to end-point singularities.

• end-point singularities also appear in nonspectator amplitudes (twist-3 level) and in annihilation amplitudes.

• need to introduce arbitrary infrared cutoffs,

$$\alpha_s \ln \frac{m_b}{\Lambda} \left(1 + \rho_{H,A} e^{i\delta_{H,A}}\right) . \tag{1}$$

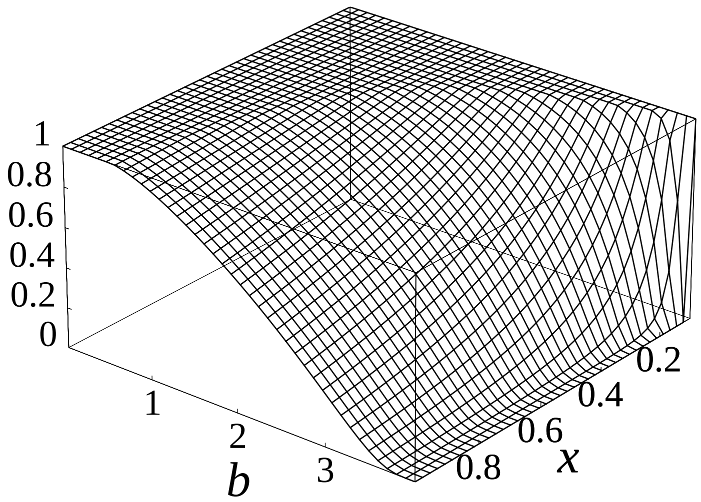
⇒ meaning of theoretical errors from the postulation $0 \leq \rho_{H,A} \leq 1$ is not clear....

• an alternative use of QCDF: global fit to data to determine weak phases and $\rho_{H,A}$ (see Du's talk).

⇒ weak constraint on the weak phases (Ciuchini).

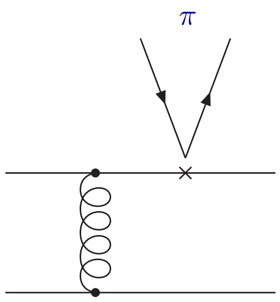
✦ PQCD

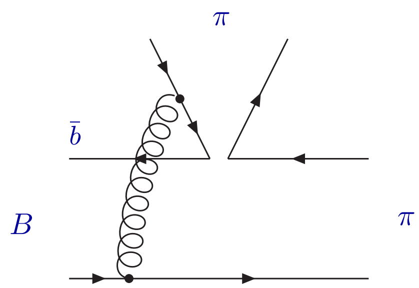
- our opinion is that end-point singularities are not physical, and imply the breakdown of collinear factorization.
- formulate exclusive B meson decays in k_T factorization $\Rightarrow$ include parton k_T. (Keum, Kurimoto, Li, Sanda, Lu, Yang, ...)
$\Rightarrow$ end-point singularities are smeared into large $\ln(xm_b/k_T)$, x: parton momentum fraction
- resum large logarithms to all orders (Li, Sterman)
$\Rightarrow$ Sudakov factor $S(xm_b, k_T)$, the parton distribution in k_T.



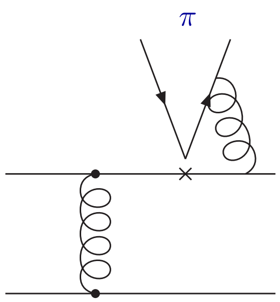
- B meson transition form factors are calculable.
- all topologies are calculable. There is no arbitrary parameter.

$O(\alpha_s)$:

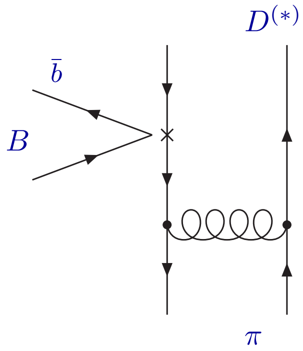




$O(\alpha_s^2)$:



$O(\alpha_s m_0/m_B)$:



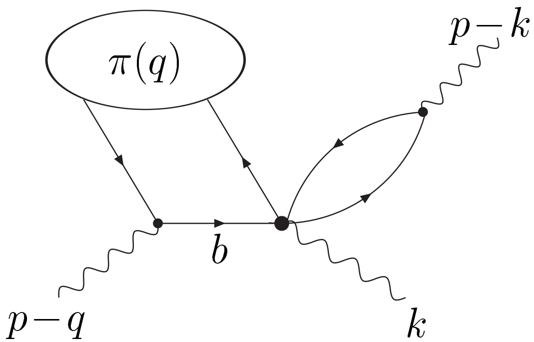
✦ SCET

- formulate collinear factorization theorem of exclusive B meson decays in terms of effective operators (Bauer, Fleming, Pirjol, Stewart, Chay, Kim).
- integrating out short-distance fluctuations, which appear in Wilson coefficients, and long-distance fluctuations are described by new effective degrees of freedom.
- The effective fields contain collinear quarks and gluons ($\xi_{n,p}$, $A^\mu_{n,q}$), massless soft quarks and gluons (q_s, A^μ_s), and massless ultrasoft (usoft) quarks and gluons (q_{us}, A^μ_{us}),....
- SCET is equivalent to the diagrammatic approach: one makes the power counting of the effective operators in the former, and of the Feynman diagrams in the latter.
- The calculation of Wilson coefficients in SCET is the same as in the latter.
- $\lambda = \sqrt{\Lambda/E} \Leftrightarrow$ SCET I and $\lambda = \Lambda/E \Leftrightarrow$ SCET II.

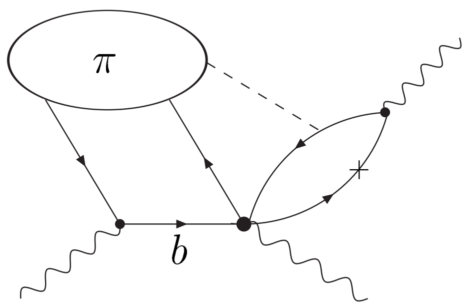
Type	Momenta $(+,-,T)$	Field Scaling	Operators
collinear	$p^\mu \sim (1,\lambda^2,\lambda)$	$\xi_{n,p} \sim \lambda$ $(A^+_{n,p},\ A^-_{n,p},\ A^T_{n,p}) \sim (1,\lambda^2,\lambda)$	$\bar{\mathcal{P}},\ W \sim \lambda^0$ $\mathcal{P}^\mu_T \sim \lambda$
soft	$p^\mu \sim (\lambda,\lambda,\lambda)$	$q_{s,p} \sim \lambda^{3/2}$ $A^\mu_{s,p} \sim \lambda$	$S_n \sim \lambda^0$ $\mathcal{P}^\mu \sim \lambda$
usoft	$k^\mu \sim (\lambda^2,\lambda^2,\lambda^2)$	$q_{us} \sim \lambda^3$ $A^\mu_{us} \sim \lambda^2$	$Y_n \sim \lambda^0$

✦ LCSR

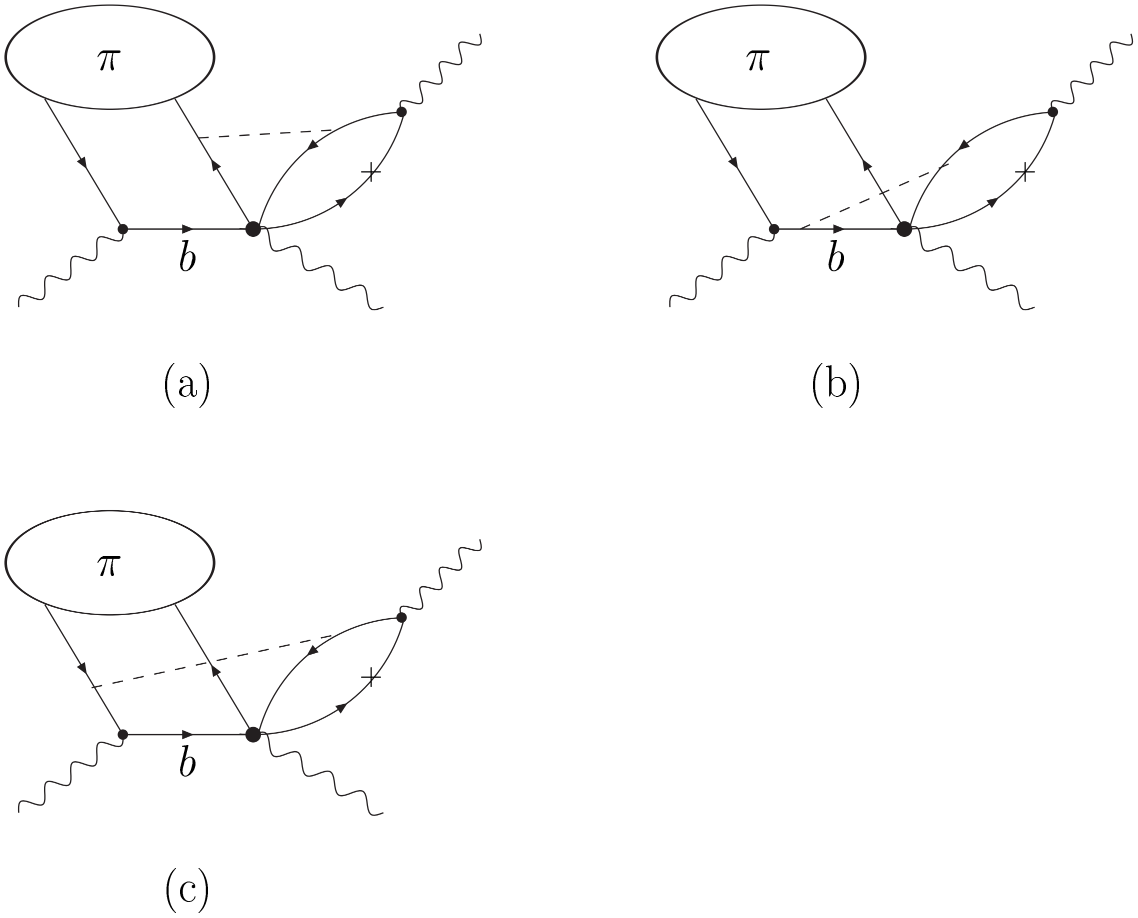
- based on quark-hadron duality (Liu's talk). The light meson bound state is approximated by the first few Fock states (Khodjamirian, Mannel, Melic, Urban)
- factorizable amplitudes (a): the same as form factors.
- nonfactorizable amplitudes: not from two-loop diagrams, but from twist-3 meson distribution amplitudes (b), which are small.
- need two-loop calculations, such as nonfactorizable contributions and annihilation contributions, which are essential for reducing the scale dependence and for generating strong phases.



(a)



(b)



Two-loop nonfactorizable contributions.
(a) and (b) vertex corrections, and (c) nonspectator correction.

Comparison: QCDF vs. PQCD

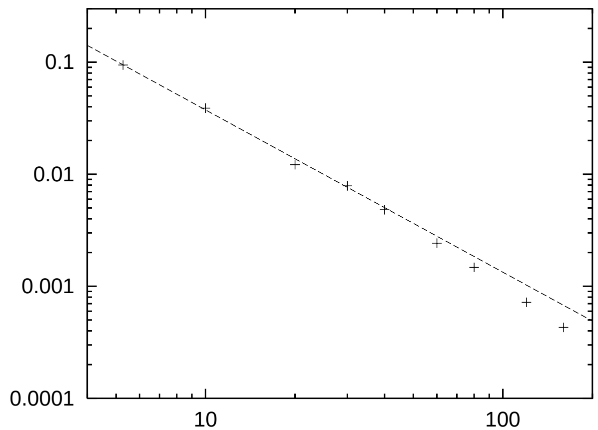
- Same power scaling of factorizable (F) and nonfactorizable (NF) amplitudes:

$$F \sim \frac{1}{m_b^{3/2}} \ \ \text{from HQET in QCDF}$$

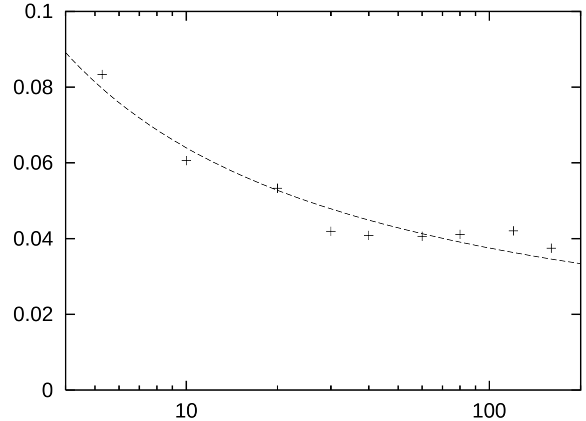
$$F \sim \frac{f_B}{\text{hard scale}} \sim \frac{m_b^{-1/2}}{m_b} \sim \frac{1}{m_b^{3/2}} \ \ \text{in PQCD}$$

$$\frac{NF}{F} \sim \alpha_s \sim \ln^{-1} m_b \ \ \text{in QCDF}$$

$$\frac{NF}{F} \sim \ln^{-1} m_b \ \ \text{due to pair cancellation in PQCD}$$



Power behavior of F.



NF/F in PQCD.

✦ Differences

• penguin enhancement (m_0: chiral enhacement scale; μ: characteristic scale)

QCDF: chiral enhancement in PP modes, $m_0 \sim 3$ GeV, $\mu \sim m_b$.

PQCD: dynamical enhancement in PP, VP, VV modes, $m_0 \sim 1.3$ GeV, $\mu \sim \sqrt{m_b \Lambda} \sim 1.7$ GeV.

• penguin enhancement mechanism can not be distinguished in PP modes.

• predictions for VP branching ratios differ by

$$\frac{\mathrm{Br(PQCD)}}{\mathrm{Br(QCDF)}} \sim 2.$$

• strong phases and CP asymmetries

QCDF: important source from the $O(\alpha_s)$ weak vertex correction.

PQCD: important source from the $O(2m_0/m_b)$ annihilation amplitude.

$$\frac{A_{CP}(\mathrm{PQCD})}{A_{CP}(\mathrm{QCDF})} \sim -4.$$

Summary

• great progress has been made in developing QCD theories of exclusive B meson decays recently.

• the advantage of QCDF is its explicit factorization picture in the heavy quark limit. Talking about the treatment of leading contribtuions, it is most complete among all approaches.

the end-point singularity at subleading level makes QCDF less predictive. Another challenge comes from the explanation of the possible large direct CP asymmetries.

• PQCD is free of end-point singularities, has no arbitrary parameters, and is most phenomenologically successful (except for the $B \to \pi^0\pi^0$ branching ratio and the $B \to \phi K^*$ polarization).

should calculate NLO corrections to check whether PQCD predictions are stable.

• SCET provides asystematic framework for constructing collinear factorization formulas at large recoil.

how to implement SCET to get predictions needs to be studied.

• the advantage of LCSR is that both soft and hard contributions can be analyzed in the same framework.

the urgent subject is to include the two-loop nonfactorizable and annihilation contributions.