General theoretical introduction

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Outlines

- Introduction
- Factorization assumption
- QCD-improved factorization
- Perturbative QCD factorization
- Soft-collinear effective theory
- (Light-cone) QCD sum rules
- Quark diagram parametrization
- Summary

In this talk…

- Simple ideas only
- For data, Smith’s talk
- For numbers, Stewart’s talk
- For new physics, Kou’s talk

Introduction

- Why B physics?

  Constrain standard-model parameters

    CKM matrix elements, weak phases

  Explore heavy quark dynamics

    Form factors, penguins, strong phases

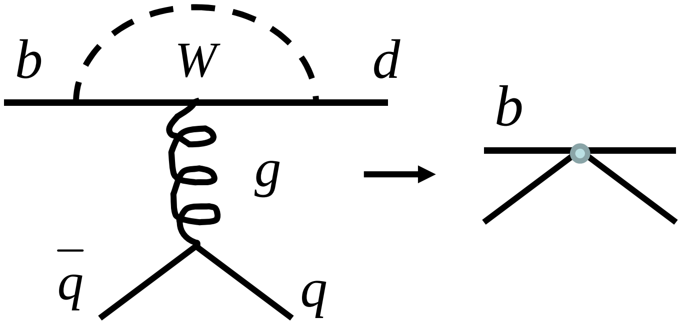
  Search for new physics

    SUSY, 4th generation, Z'…

- Need critical comparison between data and QCD theories.

Hadronic B decays

- Involve three scales m_W, m_b, and Λ
- Scale m_W is integrated out. QCD dynamics is organized into weak effective Hamiltonian $H=V_{CKM}\Sigma_i C_i(\mu)O_i(\mu)$, $m_b < \mu < m_W$
- C_i: Wilson coefficients
- O_i: 4-fermion operators
- Their μ dependence cancels.



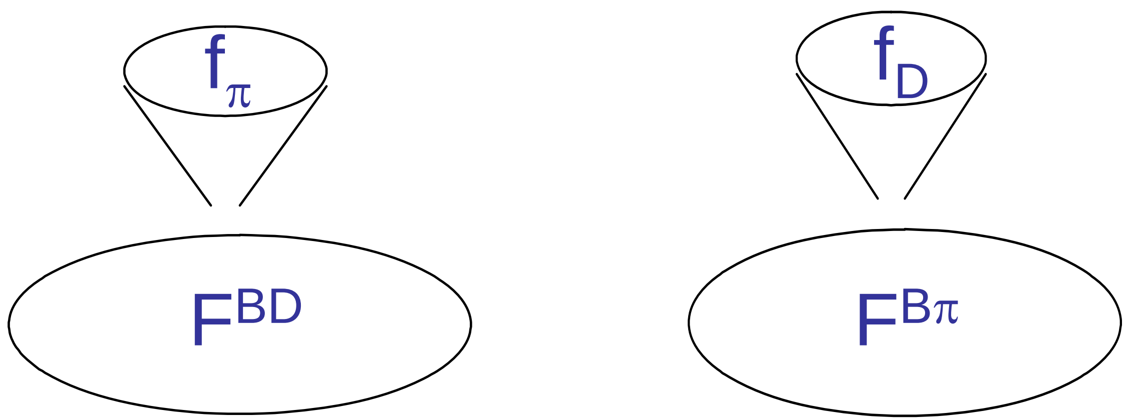
penguin operator

Factorization assumption

Decay amplitude

$$A = \langle D\pi|H_{eff}|B\rangle \sim C(\mu)\, \langle D\pi|O(\mu)|B\rangle$$

FA was proposed to deal with the hadronic matrix element (Bauer, Stech, Wirbel 85).



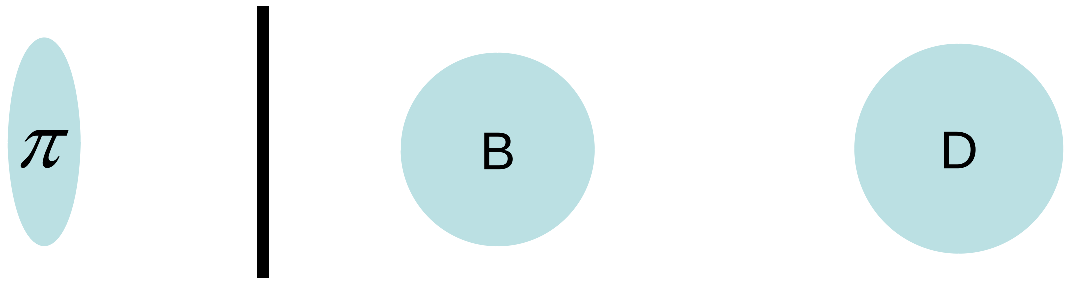
Color-allowed

Color-suppressed

$$A(B \to D\pi) \propto a_1 f_\pi F^{BD} + a_2 f_D F^{B\pi}$$

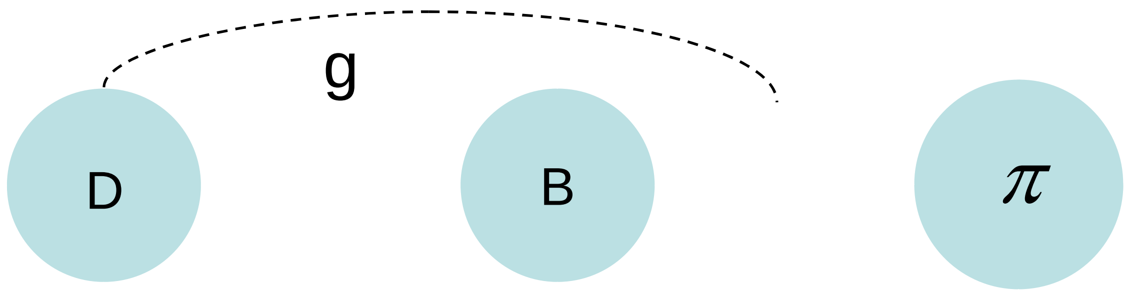
a_1, a_2 : Wilson coefficients or fitting parameters

Color transparency



Lorentz contraction
small color dipole

decoupling in space-time
from the BD system



large corrections in color-suppressed modes due
to heavy D, large color dipole

Incompleteness of FA

- Form factor and decay constant are physical, independent of μ. Predictions depend on μ through $a_{1,2}(\mu)$.
- Nonfactorizable contributions must exist, especially in color-suppressed modes. They may be small in color-allowed decays, which are insensitive to μ.
- Power corrections, like strong phases, are crucial for CP violation.
- FA can not be a complete model.

Beyond FA?

- Generalized naïve factorization, beyond FA phenomenologically (Ali et al, Cheng et al)
- Parameterize nonfactorizable correction

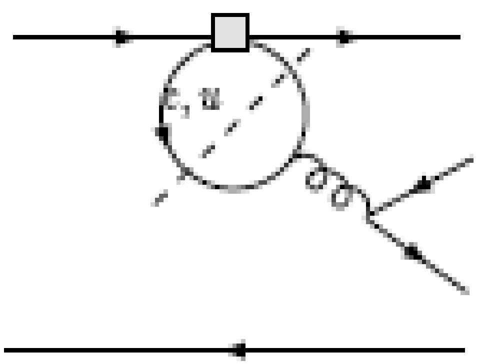
$$a_1 \to a_1 + \chi_1, \quad a_2 \to a_2 + \chi_2$$

- Fine tune mode-dependent parameters χ
- Equivalently, effective number of colors in

$$a_{1(2)} = C_{2(1)} + C_{1(2)}/N_C \qquad N_C \to N_C^{eff} = 2 \sim 6$$

- Strong phase from BSS

  only and important source?
- Go beyond FA theoretically

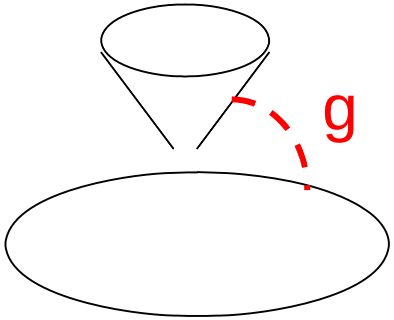


QCD-improved factorization

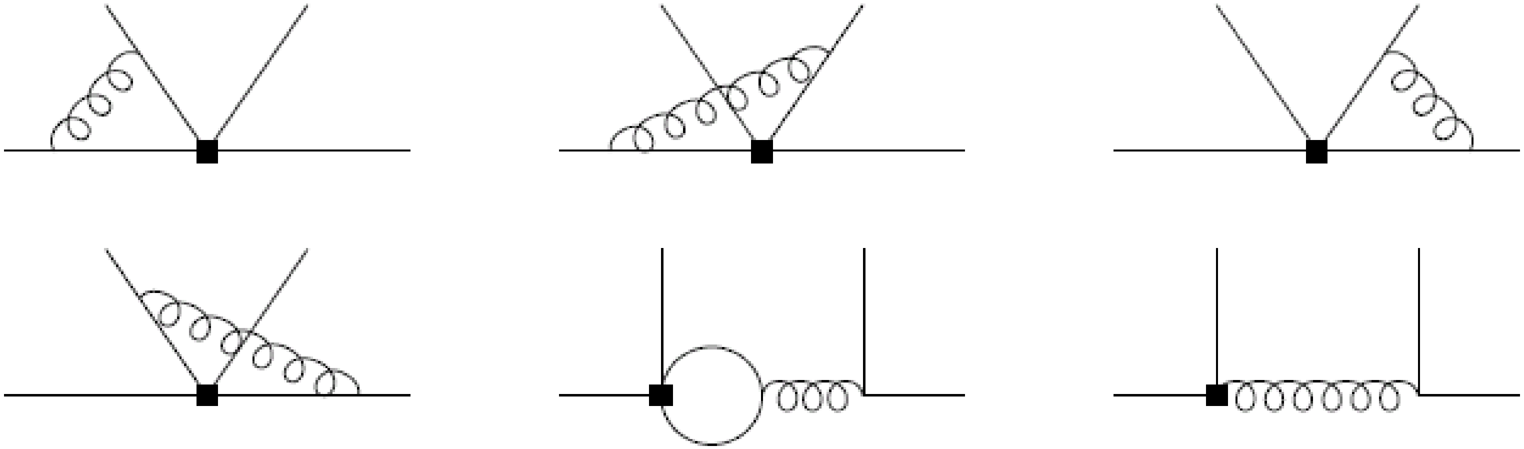
QCD corrections to FA

Higher-order corrections

- Color transparency hints addition of (nonfactorizable) hard gluons



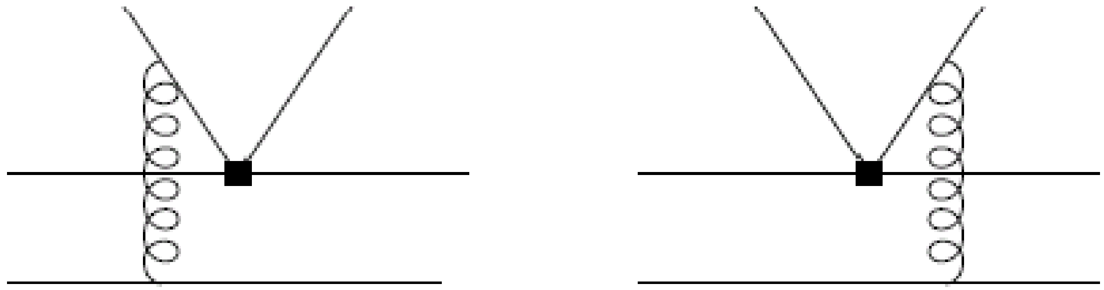
- In terms of Feynman diagrams,



- Soft divergences cancel
- These diagrams weaken μ dependence in Wilson coefficients, and generate strong phases

More higher-order diagrams

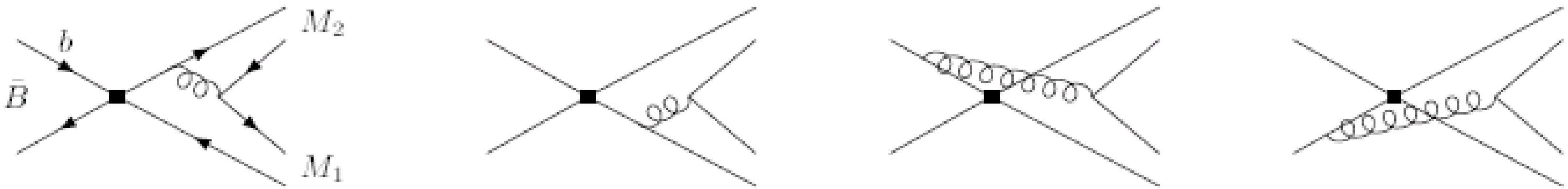
- Hard gluons can also be added to form the following nonfactorizable diagrams



- Feynman rules of these two diagrams (quark and anti-quark propagators) differ by a minus sign in soft region

Higher-power corrections in $1/m_B$

- Annihilation contribution



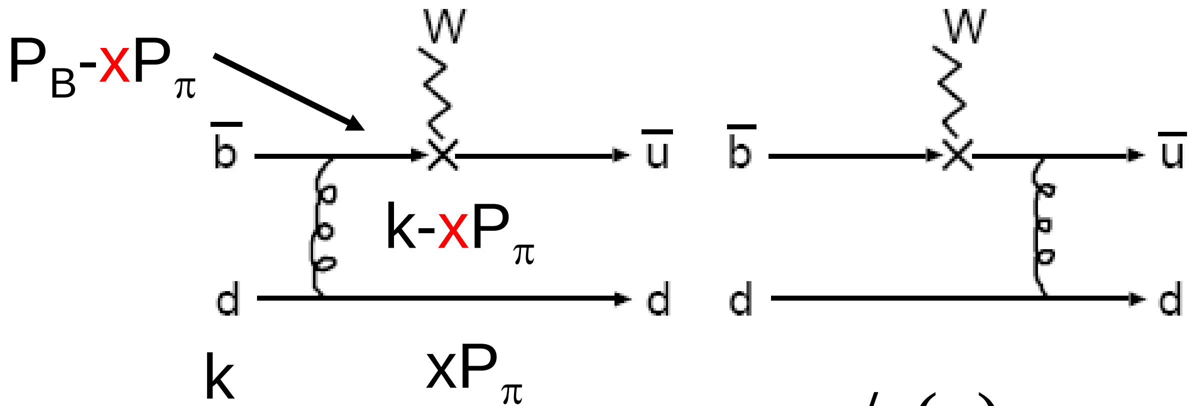
- Twist-3 nonfactorizable contribution
- They contain end-point singularity, not calculable, despite of the appearance of coupling constant in their parameterization

$$x_C = \alpha_S \ln \frac{m_B}{\bar{\Lambda}} \left(1 + \rho_H e^{i\delta_H}\right), \quad \alpha_S \ln \frac{m_B}{\bar{\Lambda}} \left(1 + \rho_A e^{i\delta_A}\right)$$

- Predictions (default) or fitting (S1,S2,…,G)?

End-point singularity

- Application of collinear factorization to B meson transition form factor gives end-point singularity



$$\int_0^1 dx \frac{\phi_\pi(x)}{x^2} \to \infty, \quad \phi_\pi(x) \propto x(1-x)$$

- End-point singularities in annihilation and nonfactorizable contributions have the same origin

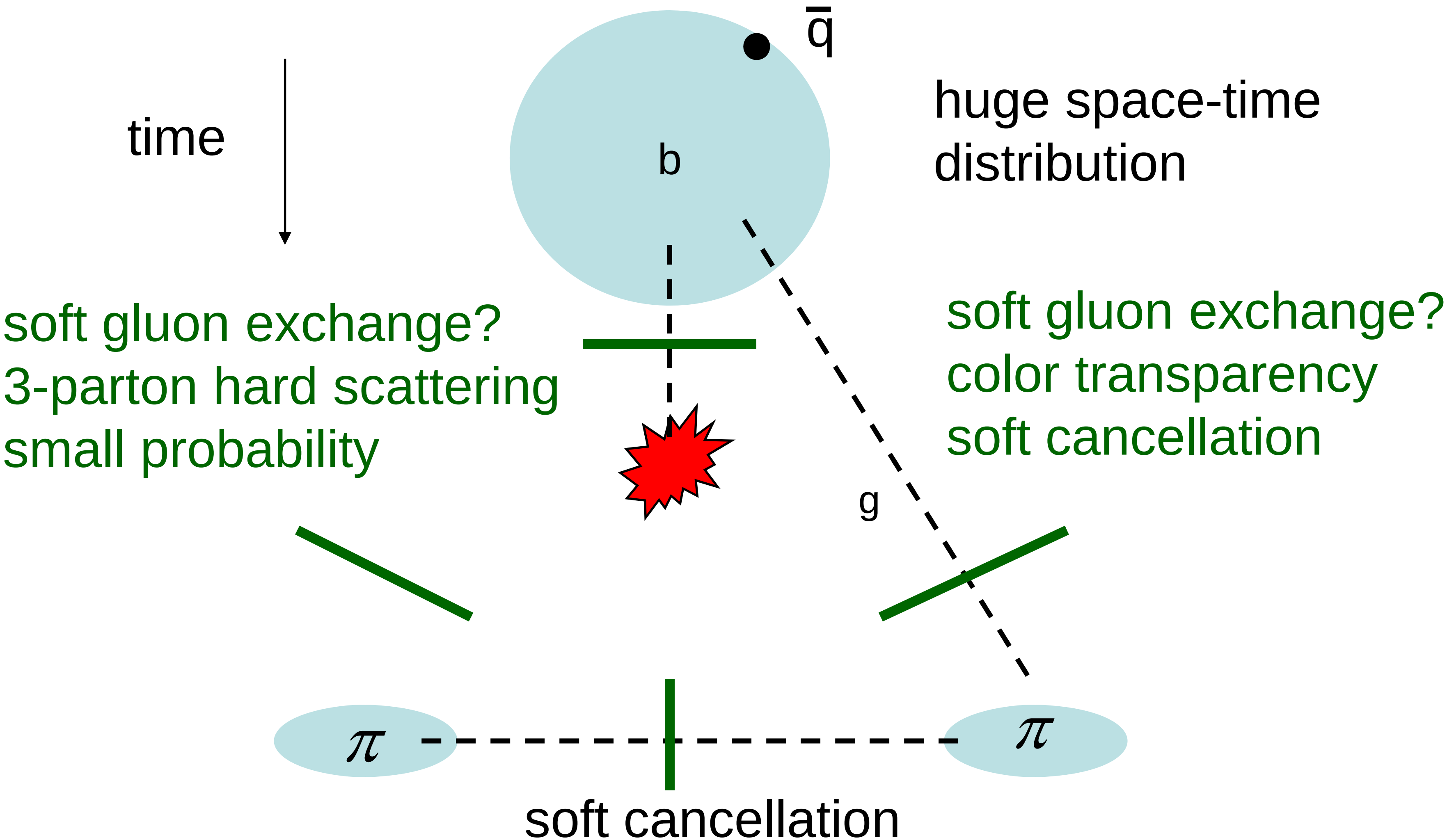
PQCD factorization

starting from factorization theorem

motivated by removing end-point singularity

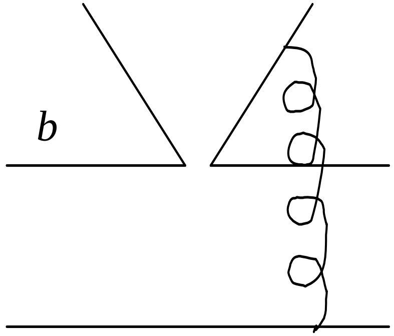
Factorization theorem

- With hard scattering (large energy release)



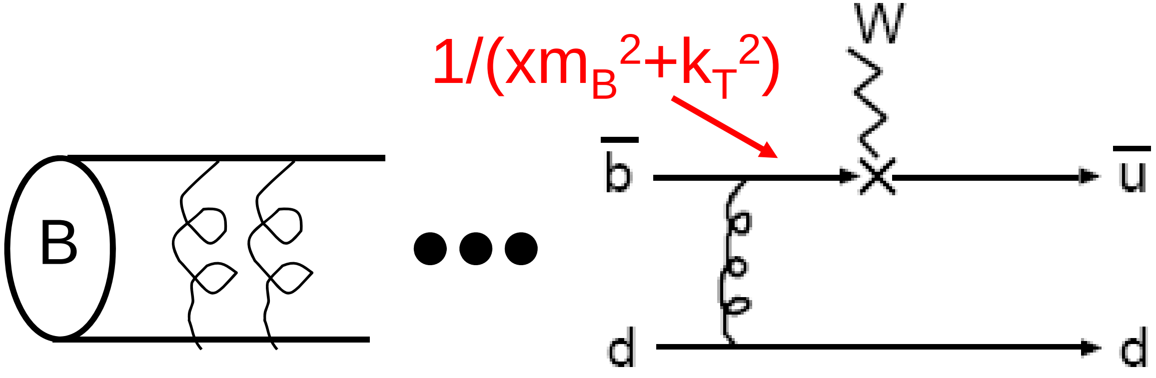
Factorization assumption vs factorization theorem

- FA   FT
- of process   of dynamics
- $A(B\text{->}M_1M_2)\sim f_{M2}F^{BM1}$ $\sim \phi_B{*}\phi_{M1}{*}\phi_{M2}{*}H$
- Vac->M_2, B->M_1 nonpert   pert
- Factorizable: in the above form
- Nonfactorizable: not in the above form
- This nonfactorizable amplitude is factorizable (calculable).



k_T factorization

- Singularity implies small x. Parton k_T not negligible. Develop k_T factorization.
- Many gluon exchanges generate k_T



$$\int_0^1 dx \frac{\phi_\pi(x)}{x^2 m_B^2} \rightarrow \int_0^1 dx \frac{\phi_\pi(x)}{x(x m_B^2 + k_T^2)}$$

- k_T distribution governed by Sudakov factor

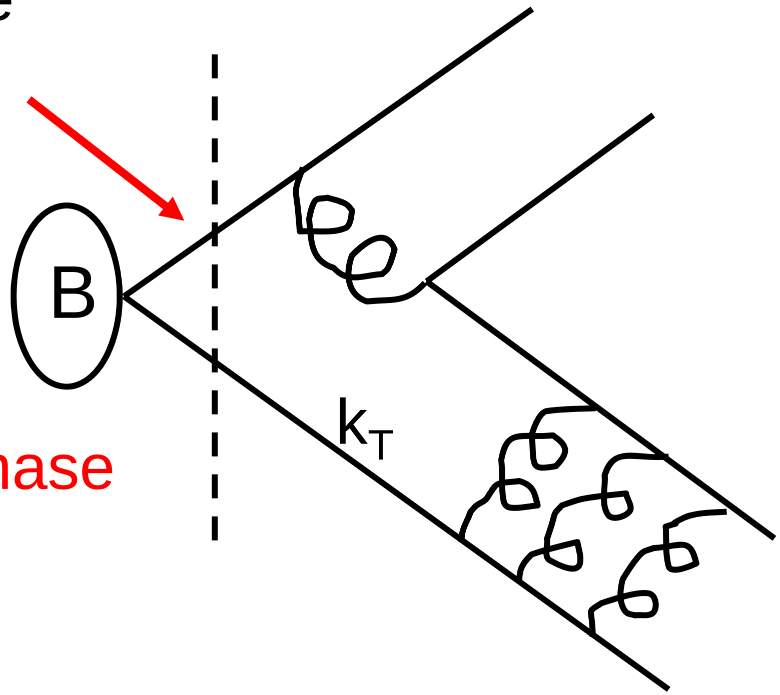
Imaginary annihilation

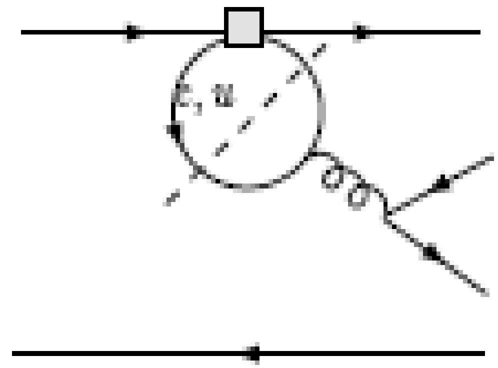
principle value

$$\frac{1}{xm_B^2 - k_T^2 + i\epsilon} = \frac{P}{xm_B^2 - k_T^2} - i\pi\delta(xm_B^2 - k_T^2).$$

loop line
can go
on-shell

strong phase





Bander-Silverman-Soni mechanism, strong phase source in FA

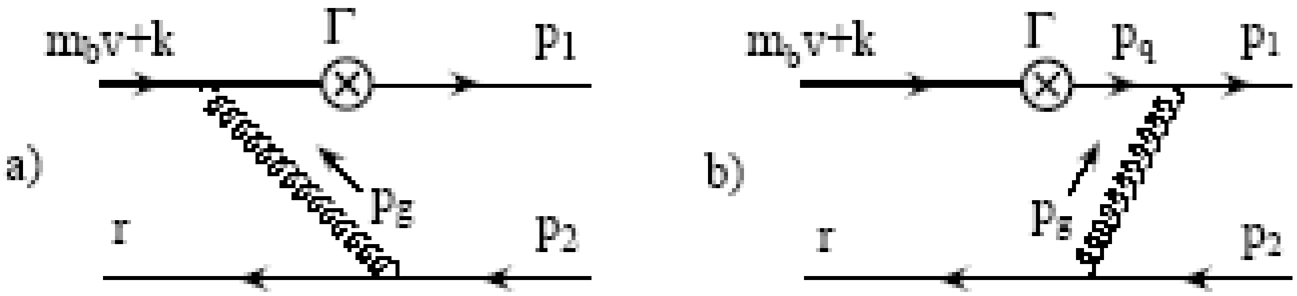
loop with the weight factor from k_T distribution function

Soft-collinear effective theory

based on collinear factorization
but formulated via OPE

B -> π form factor

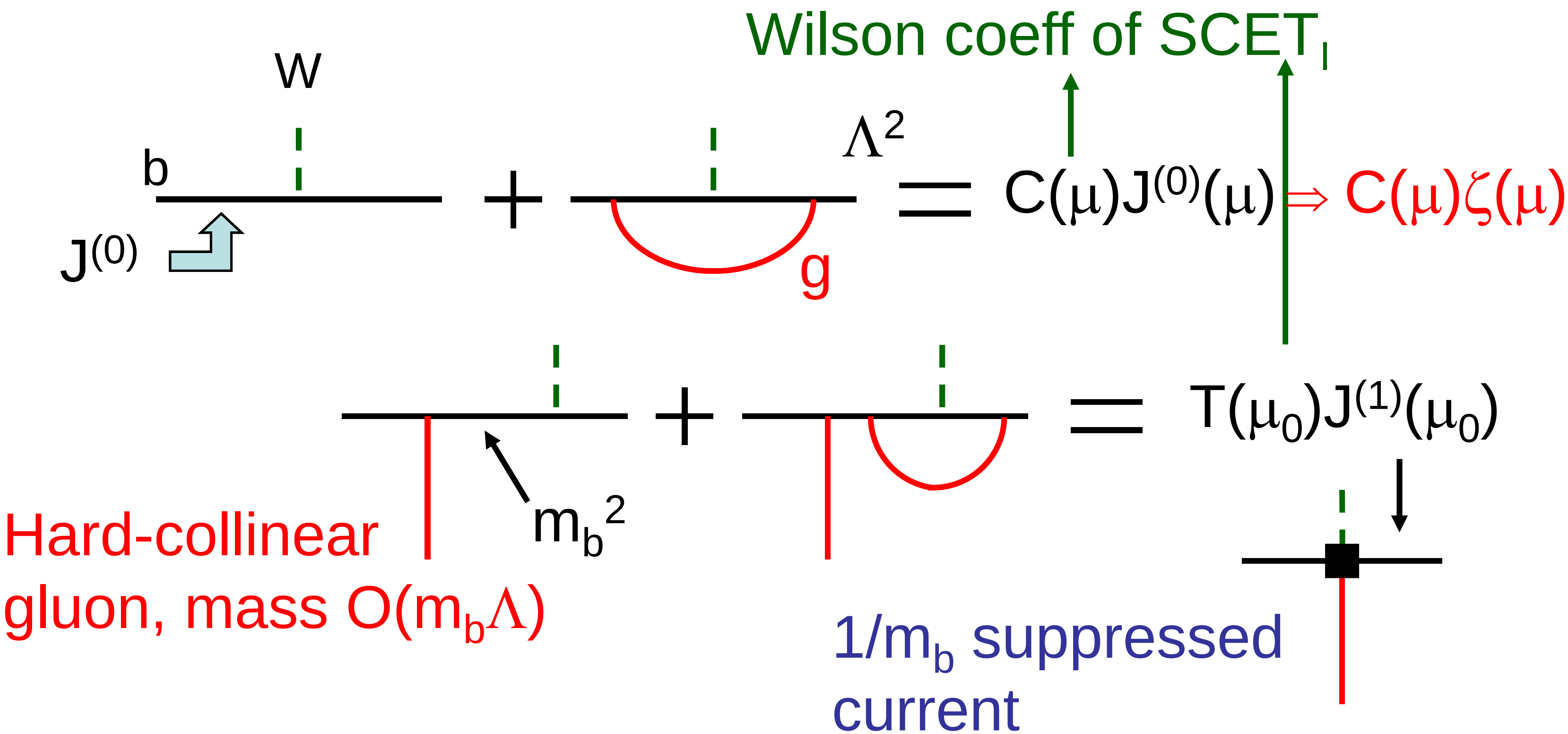
- Kinematics



- Soft spectator in B, r ~ Λ
- If $p_2 \sim m_b$, $p_g^2=(p_2-r)^2=-2r.p_2 \sim$ $O(m_b\Lambda)$
- Then the internal quark is off-shell by $(m_b v+k+p_g)^2-m_b^2 \sim$ $O(m_b^2)$
- Two scales below m_w : $m_b\Lambda$ and m_b^2, separated matching at these two scales

SCET$_I$

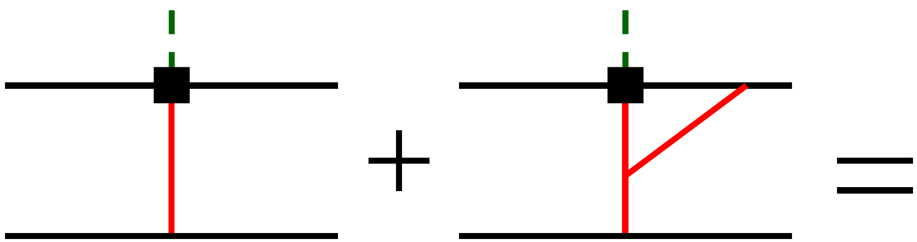
- Full theory -> SCET$_I$: integrate out the lines off-shell by m_b^2



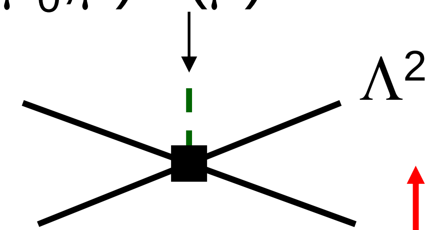
$\mathrm{SCET}_{\mathrm{II}}$

- $\mathrm{SCET}_{\mathrm{I}}$ -> $\mathrm{SCET}_{\mathrm{II}}$: integrate out the lines off-shell by $m_b\Lambda$

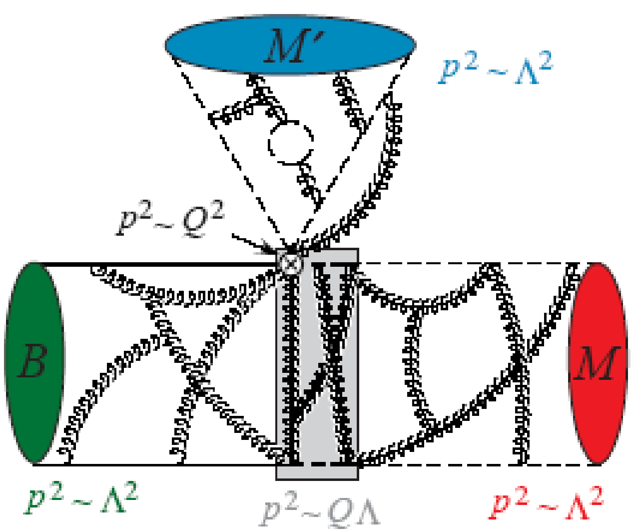
Jet=Wilson coeff of $\mathrm{SCET}_{\mathrm{II}}$



$= J(\mu_0,\mu)O(\mu)$



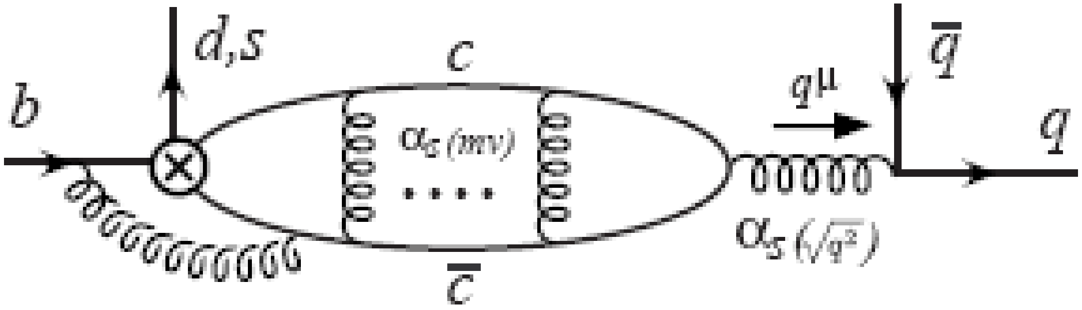
$\Rightarrow T(\mu_0)J(\mu_0,\mu)\phi_M(\mu)\phi_B(\mu)$



Sandwiched by the light meson and B meson states

Charming penguin (Bauer et al)

- At leading power, no large source of strong phases in SCET (no annihilation) .
- Long-distance $O(1/m_b)$ charming penguin is introduced, parameterized as Acc.



- With nonperturbative Acc, apply SCET as QCD-improved parametrization.

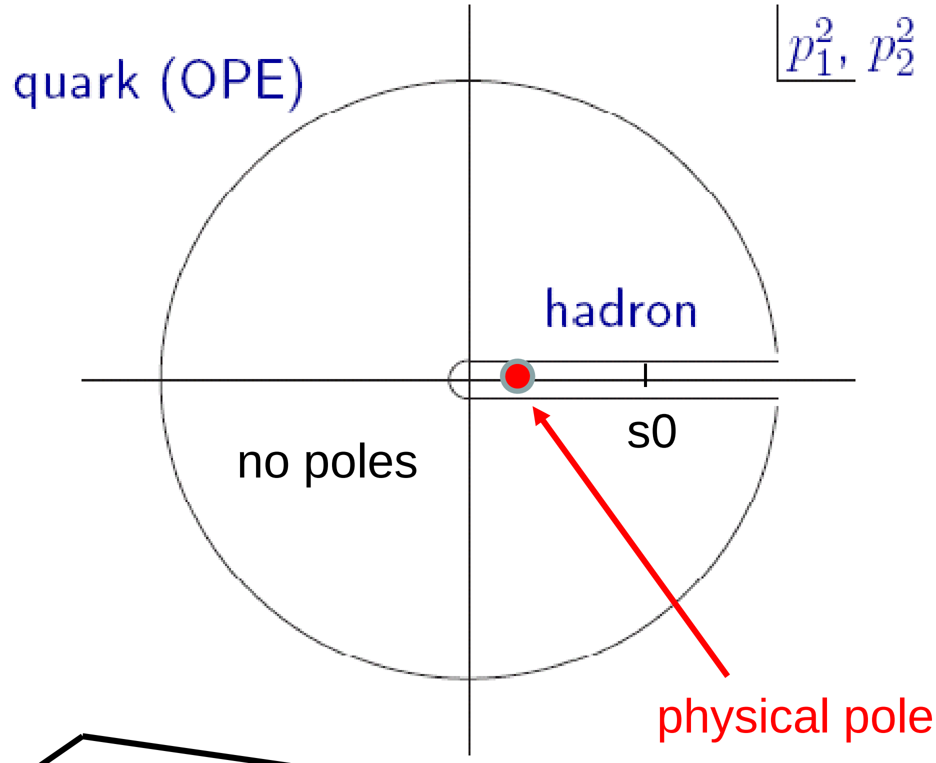
(Light-cone) QCD sum rules

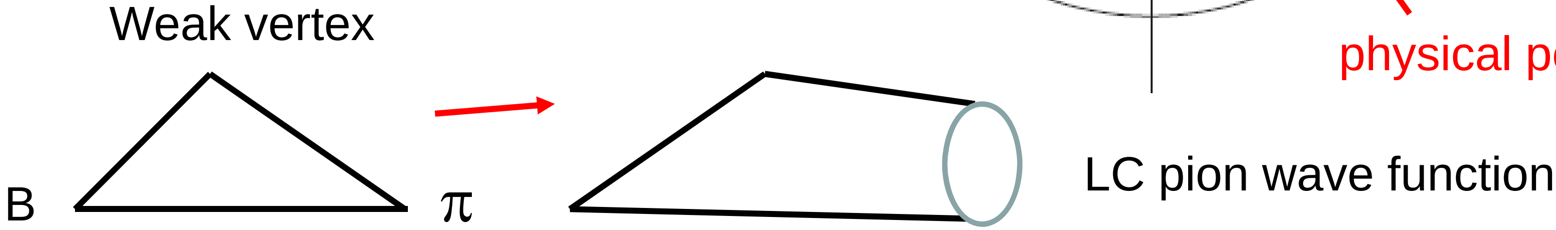
based on quark-hadron duality

different from factorization

Quark-hadron duality

- “Nonperturbative” averaged over duality interval s0 = “perturbative”
- Light-cone QSR approximates QSR by local current ⇒ nonlocal current on light cone



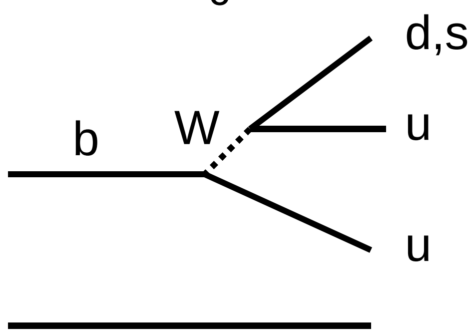


Quark-diagram parametrization

also different from factorization

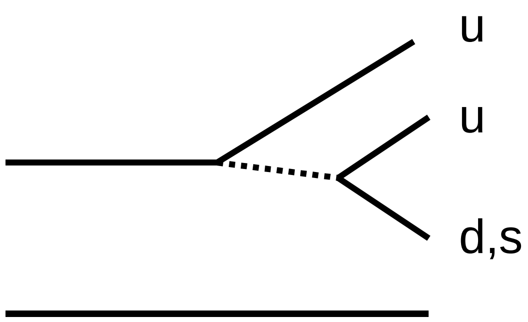
Quark amplitudes

2 color traces $\Rightarrow N_c^2$

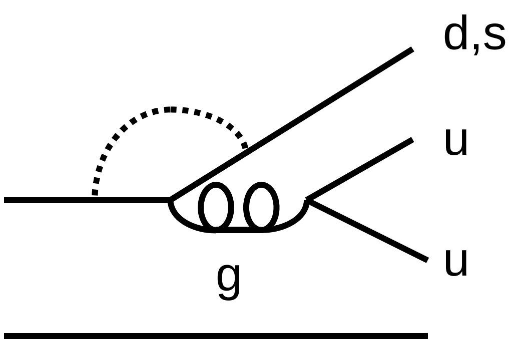


Color-allowed tree T

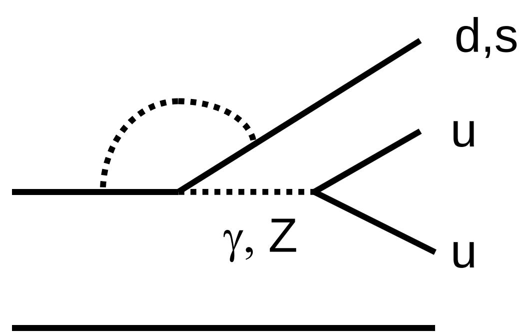
1 color trace $\Rightarrow N_c$



Color-suppressed tree C



QCD penguin P



Electroweak penguin P_{ew}

$\pi\pi$ parametrization

$$\begin{aligned}
\sqrt{2}A(B^+ \to \pi^+\pi^0) &= -T\left[1 + \frac{C}{T} + \frac{P_{ew}}{T}e^{i\phi_2}\right] , \\
A(B_d^0 \to \pi^+\pi^-) &= -T\left(1 + \frac{P}{T}e^{i\phi_2}\right) , \\
\sqrt{2}A(B_d^0 \to \pi^0\pi^0) &= T\left[\left(\frac{P}{T} - \frac{P_{ew}}{T}\right)e^{i\phi_2} - \frac{C}{T}\right] ,
\end{aligned}$$

$$\frac{P}{T} \sim \lambda , \quad \frac{C}{T} \sim \lambda , \quad \frac{P_{ew}}{T} \sim \lambda^2 .$$ tree-dominant

$(C_4/C_2)(V_{td}V_{tb}/V_{ud}V_{ub})/1 \sim (\lambda^2/1)(\lambda^3/\lambda^4) \sim \lambda$

$K\pi$ parametrization

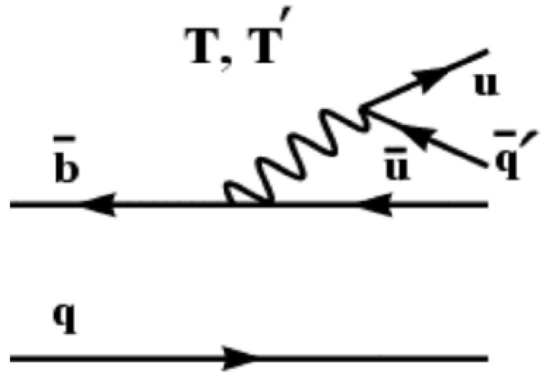
$$
\begin{aligned}
A(B^+ \to K^0\pi^+) &= P' \,, \\
A(B_d^0 \to K^+\pi^-) &= -P'\left(1 + \frac{T'}{P'}e^{i\phi_3}\right) \,, \\
\sqrt{2}A(B^+ \to K^+\pi^0) &= -P'\left[1 + \frac{P'_{ew}}{P'} + \left(\frac{T'}{P'} + \frac{C'}{P'}\right)e^{i\phi_3}\right] \,, \\
\sqrt{2}A(B_d^0 \to K^0\pi^0) &= P'\left(1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

$$
\frac{T'}{P'} \sim \lambda \,, \qquad \frac{P'_{ew}}{P'} \sim \lambda \,, \qquad \frac{C'}{P'} \sim \lambda^2
$$

$(C_2/C_4)(V_{us}V_{ub}/V_{ts}V_{tb}) \sim (1/\lambda^2)(\lambda^5/\lambda^2) \sim \lambda$

Flavor symmetry

- Predictive power from flavor symmetry
- SU(3) relates u,d,s interchange



q = u,d,s
q′= d,s

- U-spin relates d,s interchange

$$B_d^0 \rightarrow K^+\pi^- \text{ and } B_s^0 \rightarrow \pi^+K^-$$

$$B_s^0 \rightarrow K^+K^- \text{ and } B_d^0 \rightarrow \pi^+\pi^-$$

- Difficult to estimate symmetry breaking

Summary

- Able to go beyond factorization assumption by including QCD corrections.
- No end-point singularity in PQCD (k_T factorization) and SCET (zero-bin subtraction), so transition form factors, and $1/m_B$ contributions are calculable.
- External lines are off-shell on OPE side of QSR. Soft contribution in QSR has a definition different from those in factorization approaches.

Summary

- Predictive power of factorization approaches comes from universality of nonperturbative inputs (meson wave functions), but that of quark diagram parametrization from flavor symmetry.

Back-up

Effective theory

- An effective theory by integrating out high energy (E) modes.
- Effective degrees of freedom: collinear fields, soft fields,…
- Express an amplitude in 1/E in terms of the effective operators.
- The Wilson coefficients of these operators are the hard kernels.
- The matrix element of the (nonlocal) operators are DAs or form factors.
- Convenient for deriving factorization theorem.

Wilson coefficients

- Is $J(\alpha_s(m_b\Lambda))$, the Wilson coefficient of $SCET_{II}$, calculable?
- No from Bauer, Pirjol, Rothstein, Stewart, but yes from Beneke and Yang.

$\Rightarrow$Different phenomenological applications of SCET

- C, T (Wilson coefficients of $SCET_I$) and J have been computed up to NLO. See Beneke and Yang, hep-ph/0508250.

Decay amplitude

- SCET factotrization formula for B->M_1M_2

Wilson coeff of $\mathrm{SCET_I}$

Color-allowed

$$A(\bar{B} \to M_1 M_2) = \lambda_c^{(f)} A_{c\bar{c}}^{M_1 M_2} + \frac{G_F m_B^2}{\sqrt{2}} \Big\{ f_{M_2}\, \zeta^{B M_1}$$

Color-suppressed

$$\times \int_0^1 du\, T_{2\zeta}(u)\, \phi^{M_2}(u) + f_{M_1}\, \zeta^{B M_2} \int_0^1 du\, T_{1\zeta}(u)\, \phi^{M_1}(u)$$

Jet function

$$+ \frac{f_B f_{M_1} f_{M_2}}{m_b} \int_0^1 du \int_0^1 dx \int_0^1 dz \int_0^\infty dk_+\, J(z, x, k_+) \Big[T_{2J}(u, z)$$

$$\times \phi^{M_1}(x) \phi^{M_2}(u) + T_{1J}(u, z) \phi^{M_2}(x) \phi^{M_1}(u) \Big] \phi_B^+(k_+) \Big\},$$

factorizable

Wilson coeff of $\mathrm{SCET_I}$

Annihilation in QCDF, $SCET_O$, PQCD

- Applied to charmless nonleptonic decays, scalar penguin annihilation is treated as:
- Parameter in QCDF due to end-point singularity (nonfactorizable), $X_A = \ln(m_B/\Lambda)[1+\rho_A \exp(i\phi_A)]$
- What mechanism generates ϕ_A?
- Factorizable in $SCET_O$, but real (ALRS 06). Strong phase appears at $\alpha_s^2\Lambda/m_b$.
- Phase generated without k_T expansion (Chay, Li, Mishima)