Beyond factorization of B meson decays

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Self-Introduction

- George Sterman's student (88-92)
- Research Interest on B physics stems from the only collaborative paper on Sudakov effects in pion form factor
- Overlap with S. Aoki, F. Essler, M. Galassi, E. Laenen, Magneas, J. Qiu
- Side interests: neutron star (Kuo), QED vacuum (Coker, Pawani, Goldhaber), QCD sum rules (Coriano), small-x physics (R. Ball), joint resummation (Laenen, Sterman, Vogelsang)

Introduction

- Why B physics?

  Constrain standard-model parameters

    CKM matrix elements, weak phases

  Explore heavy quark dynamics

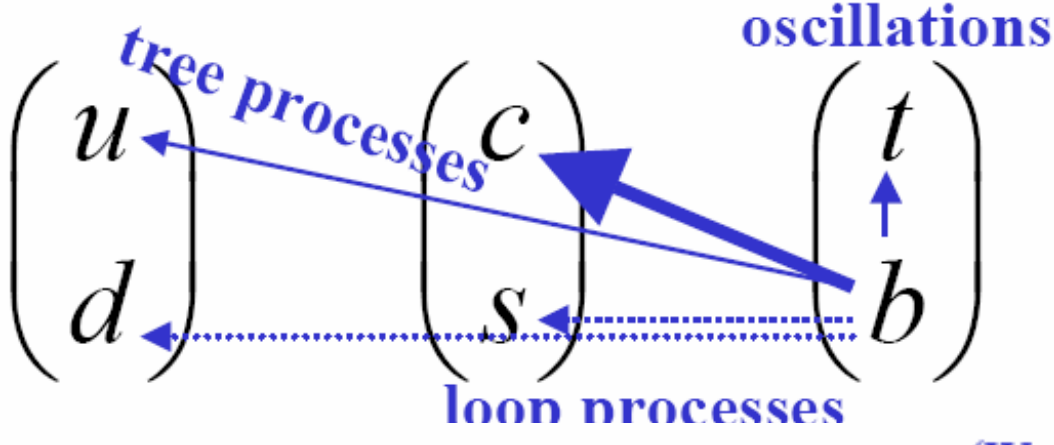
    Form factors, penguins, strong phases

  Search for new physics

    SUSY, 4th generation, Z'…

- Need B factories and critical comparison between data and QCD theories.

Cabbibo-Kobayashi-Maskawa Matrix



(Wolfenstein parametrization)

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + O(\lambda^4)$$

Weak phase, ~~CP~~

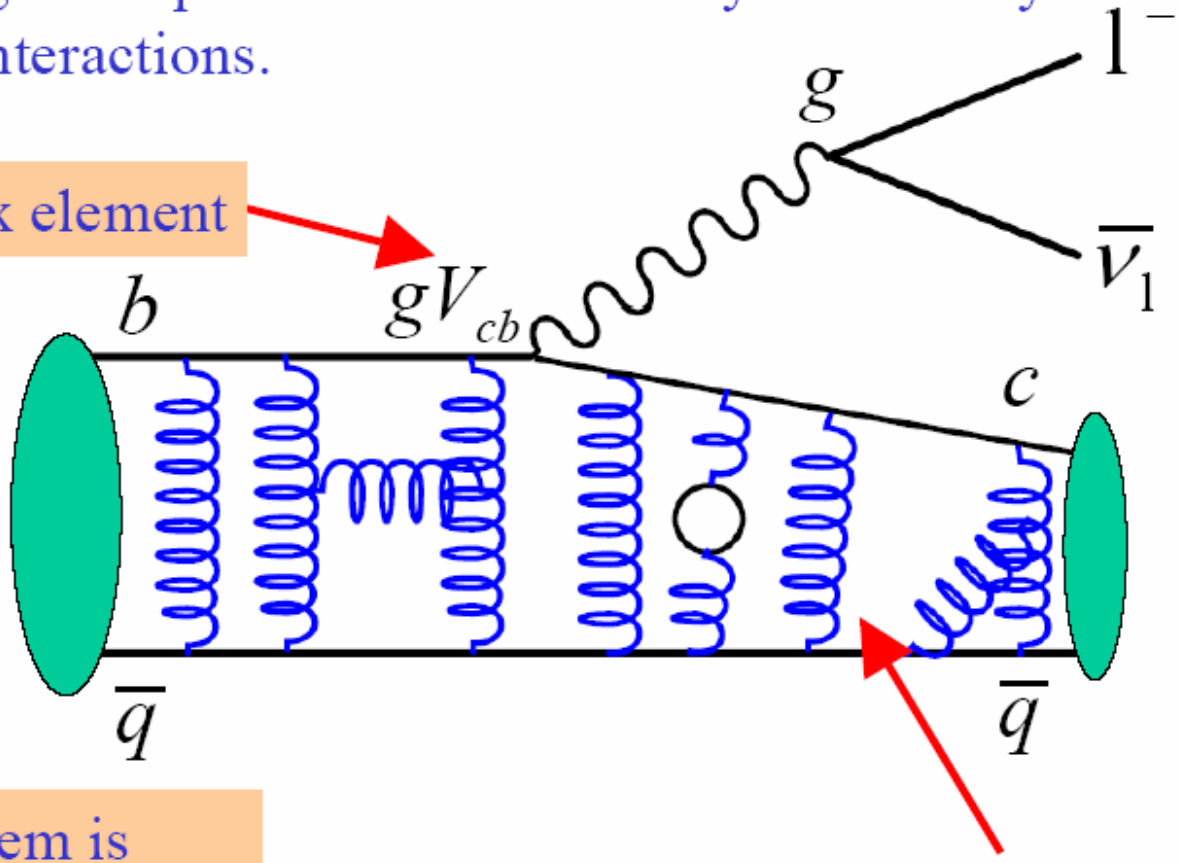
$$; \left(\begin{array}{cc|c} 0.97 & 0.23 & 0.004 \\ -0.23 & 0.97 & 0.04 \\ \hline 0.004 & -0.04 & 1 \end{array}\right)$$

(magnitudes only)

B transition form factors

Underlying weak process is substantially affected by an overlay of strong interactions.

CKM matrix element

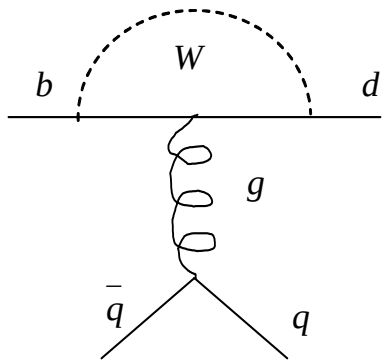


Initial system is bound state: *b*-quark is not at rest in B frame.

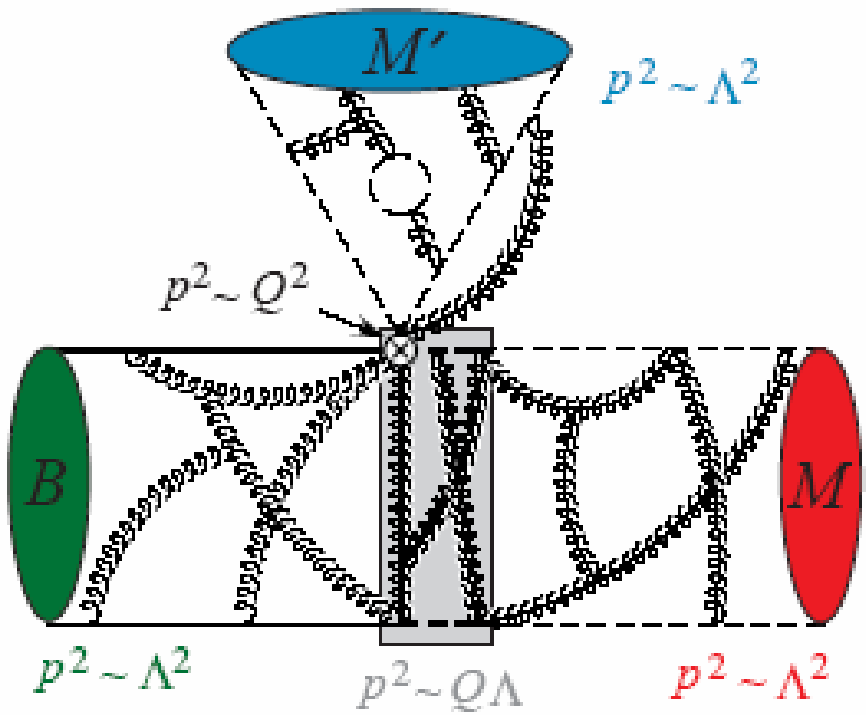
Exchange of gluons is between daughter quark and spectator quark to form the final state meson.

Nonleptonic decays

- Involve scales m_W, m_b, and Λ
- Dynamics with perturbative scales can be organized into weak effective Hamiltonian $H=V_{CKM}\Sigma_i C_i(\mu)O_i(\mu)$
- C_i: Wilson coeff.
- O_i: 4-fermion ope.
- Their μ dependence cancels.



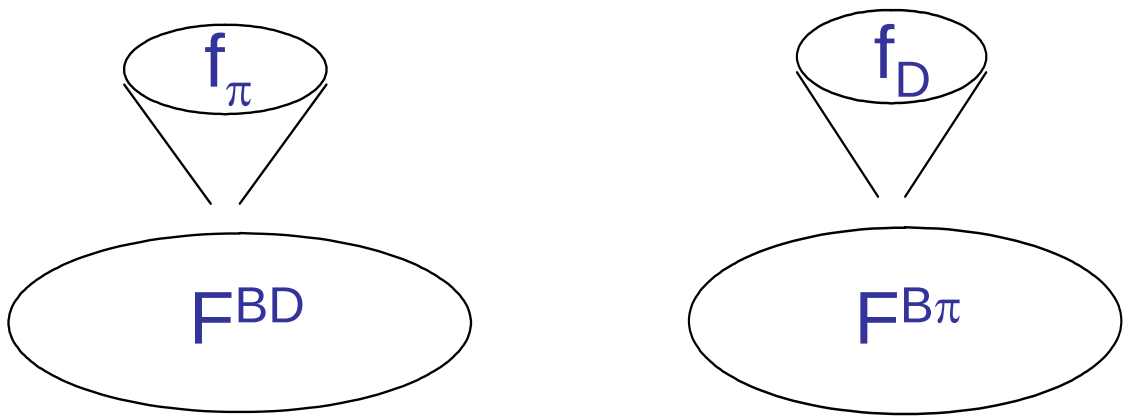
penguin



Factorization assumption

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

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



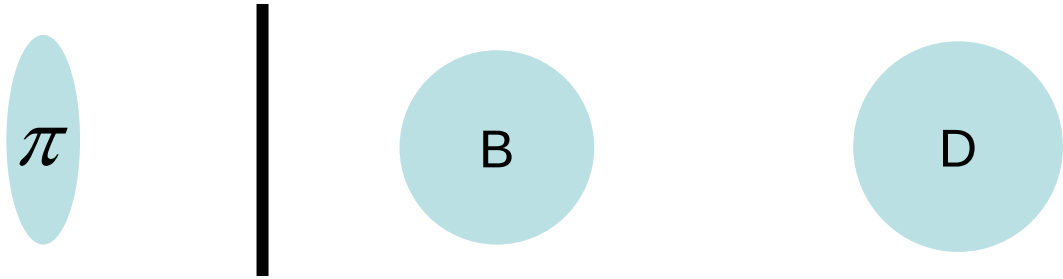
Color-allowed Color-suppressed

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

a_1, a_2 : Wilson coefficients

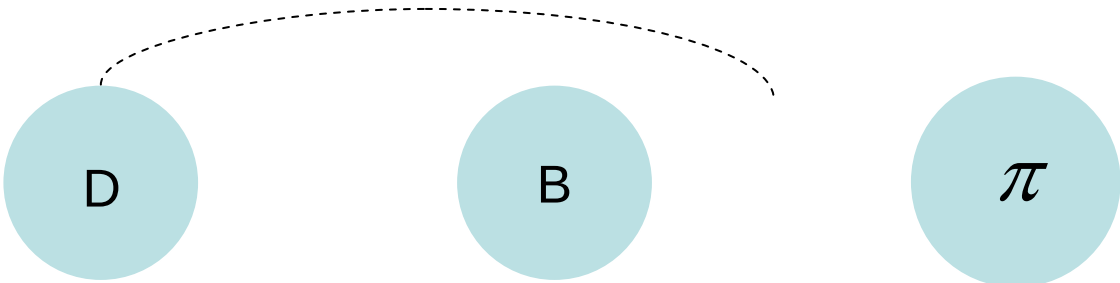
Prof. Stech, Chamonix, France, 2005

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

- FA can not be complete: form factor and decay constant are physical, independent of μ. Predictions depend on μ through $C(\mu)$.
- 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 was used for decades due to slow experimental and theoretical progress.

CP violation (Soni's talk)

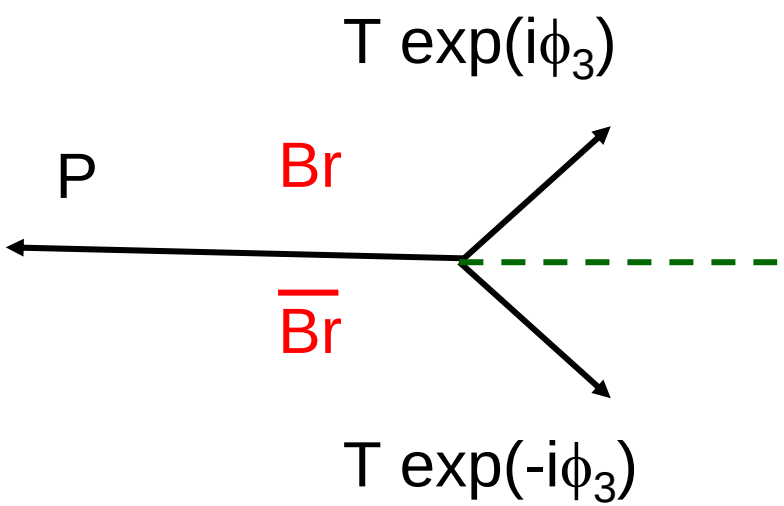
- Thumb only on the right---P violation
- Thumbs on the right of right hand, and on the left of left hand---CP conservation
- God is fair: He gives L to particle and R to antiparticle.
- CP conserved here? ⟶
- If she loses one arm, ~~CP~~ at 10^{-3}

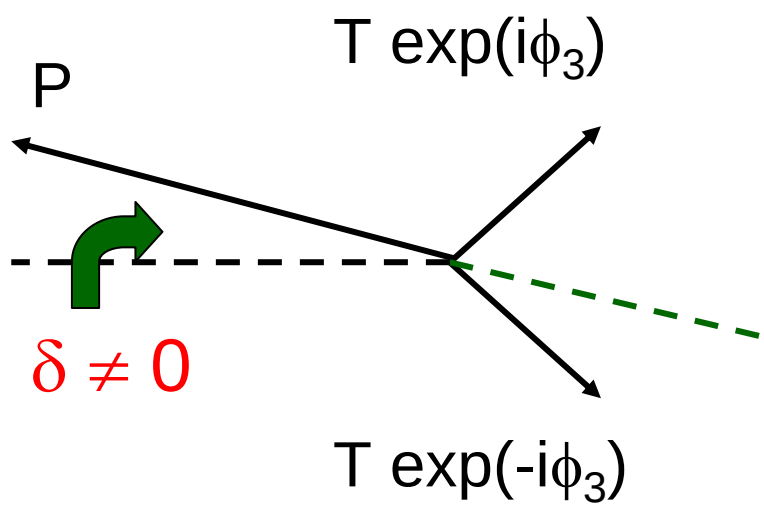
Anti- particle particle

Thousand-hand Guan Yin

Strong phase and ~~CP~~

- To have $A_{CP} \neq 0$, there must be at least two amplitudes, weak phase, strong phase.





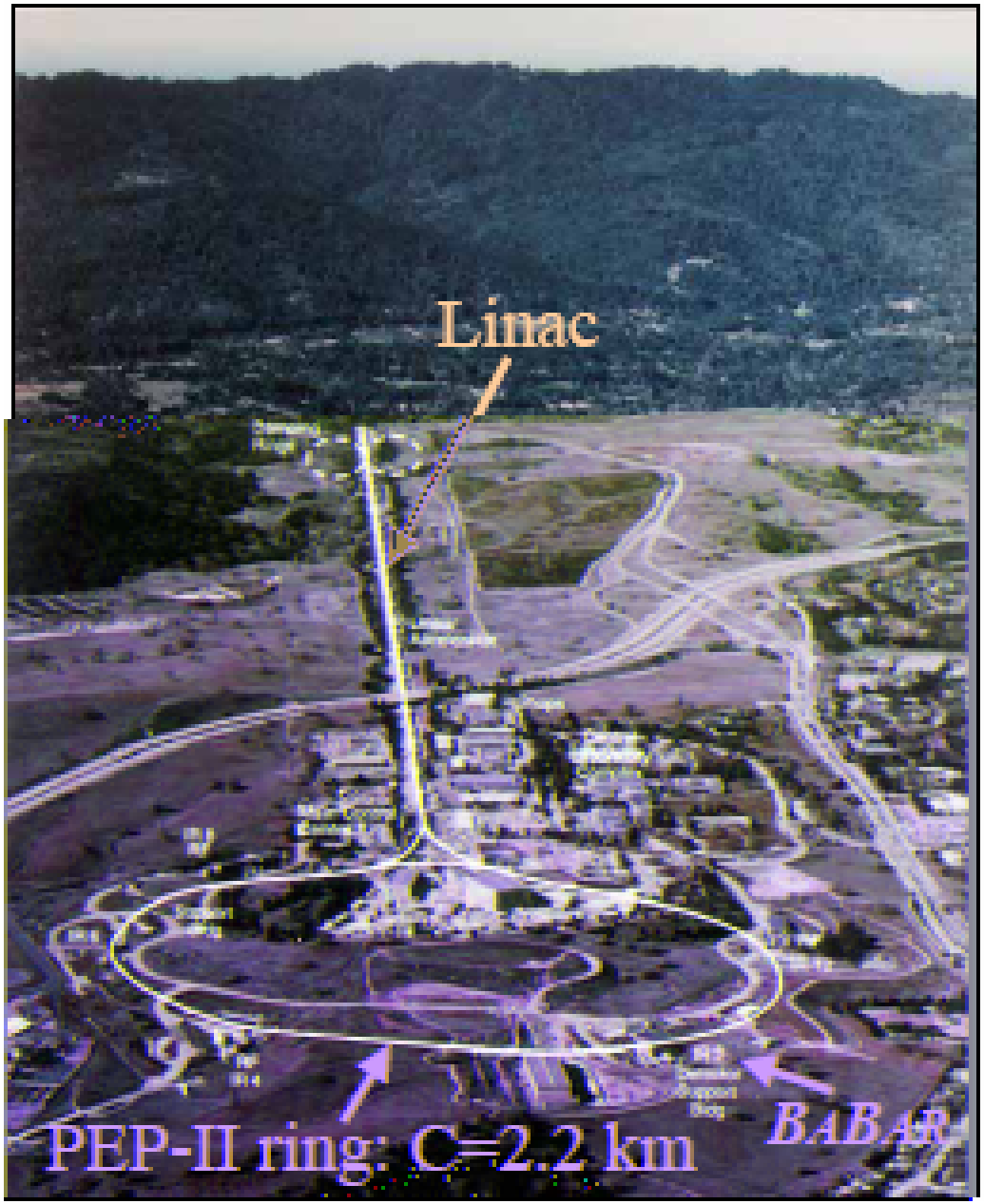
If $\delta=0$ $\overline{Br} = Br$

$\overline{Br} \neq Br$ direct ~~CP~~

Transition in 2000

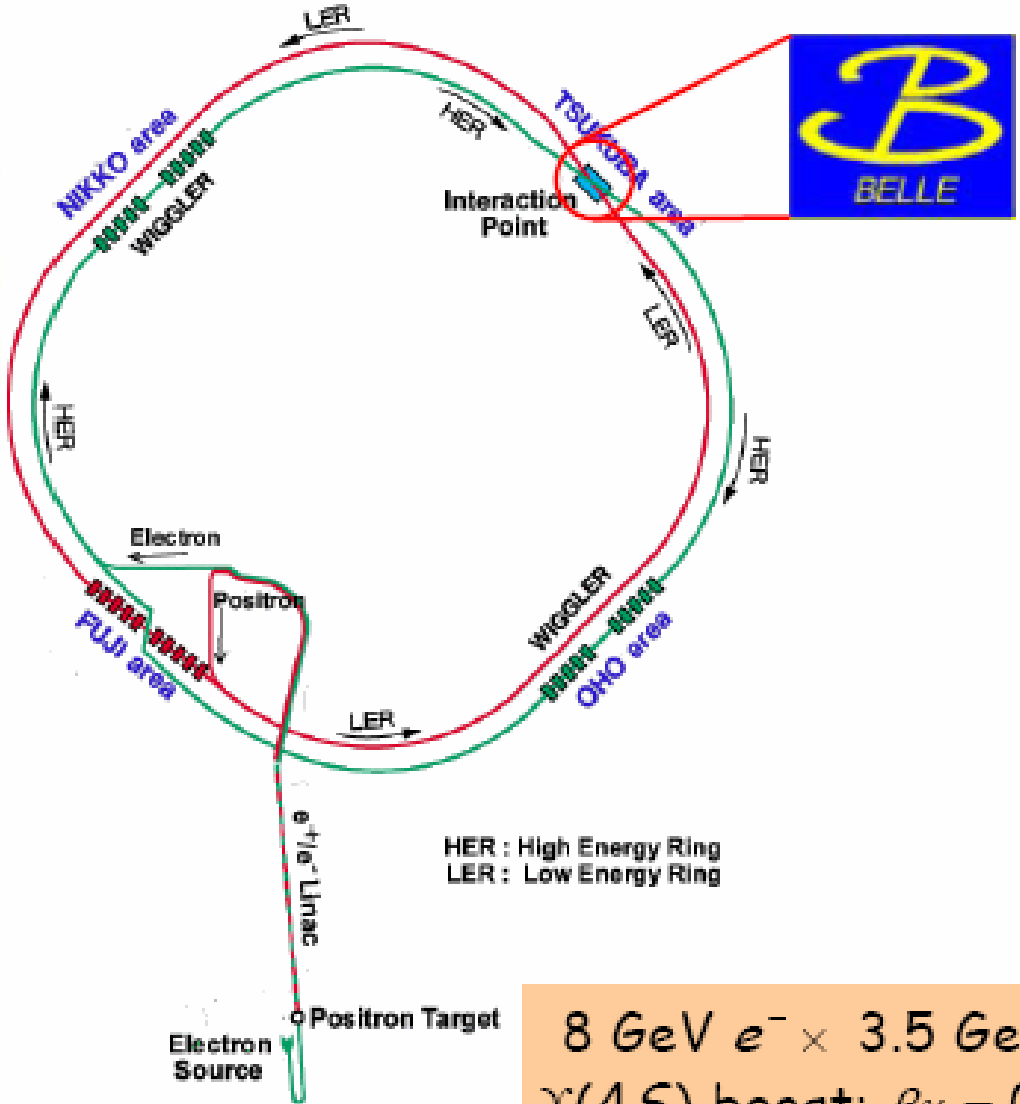
- Great experimental (Babar, Belle) and theoretical (factorization approaches) progress around 2000.
- Rare (including color-suppressed) decays with BR down to 10^{-6} and CP asymmetries can be measured precisely at B factories.
- Explore nonfactorizable and power corrections, or even new physics.
- Theorists need to go beyond FA.

Babar at SLAC



- 1993: start of PEP-II construction
- 1994: start of BABAR construction
- Spring 1999: BABAR moves onto beamline
- Oct 29, 2000 PEP-II achieves design luminosity
- Fall 2003: start trickle injection of beams into PEP-II (5 Hz)
- Spring 2004: PEP-II achieves 3X design luminosity

KEKB & Belle Layout



8 GeV e^- × 3.5 GeV e^+

$\Upsilon(4S)$ boost: $\beta\gamma = 0.425$

±11 mrad crossing angle

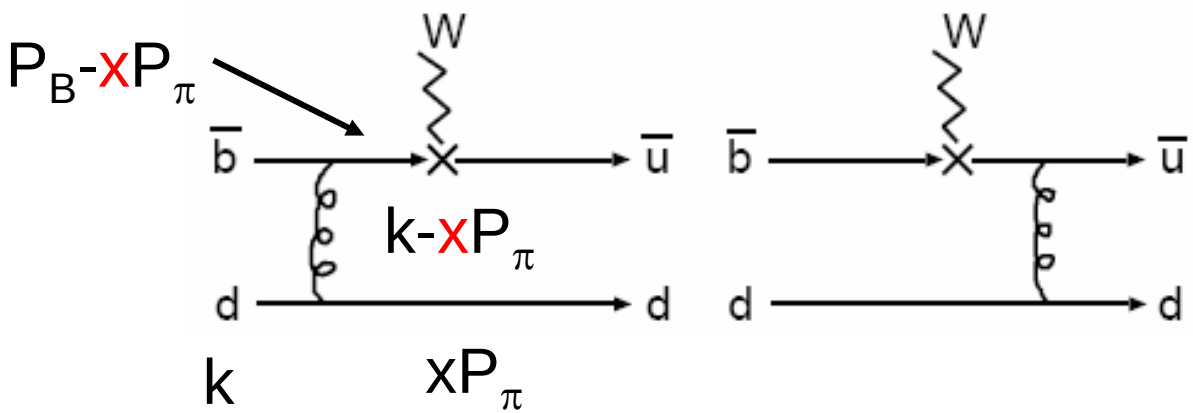
Factorization theorem (Qiu's talk)

- High-energy ($Q \to \infty$) QCD processes involve both perturbative and nonperturbative dynamics.
- Dramatically different dynamics factorize: a hard kernel H(Q), and distribution amplitudes $\phi(\Lambda)$.
- H is process-dependent, but calculable.
- Nonperturbative inputs ϕ are universal (process-independent).

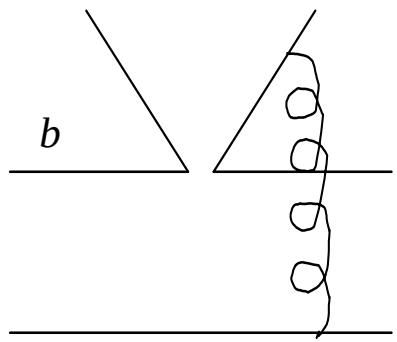
  $\Rightarrow$ Factorization theorem has a predictive power.

End-point singularity

- Naïve application of collinear factorization theorem to form factor gives end-point singularity



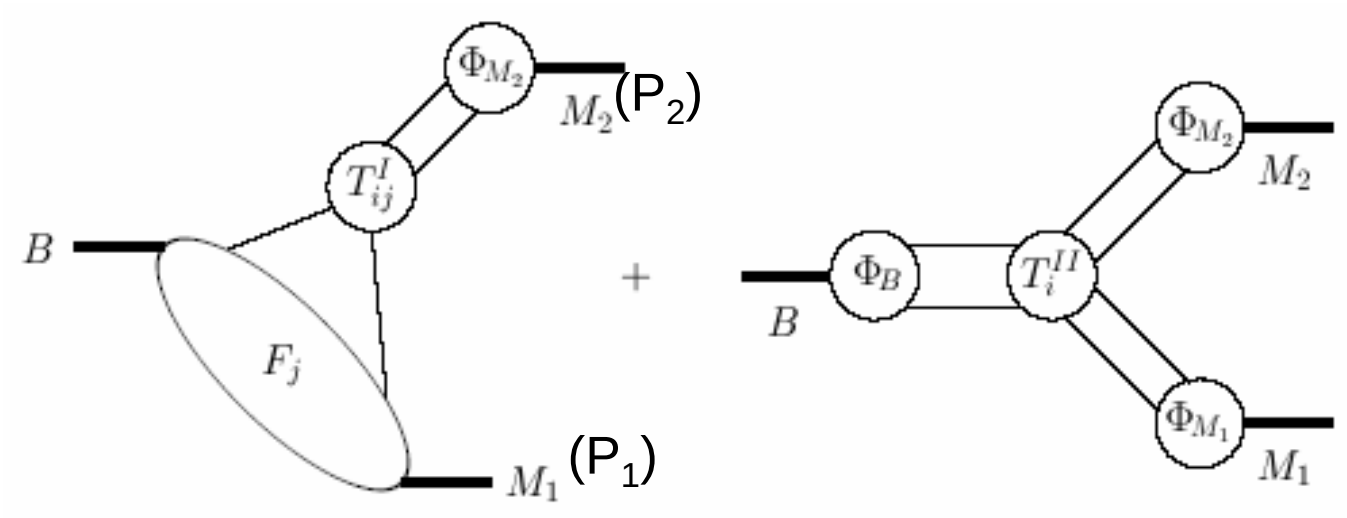
$$\int_0^1 dx \frac{\phi_\pi(x)}{x^2} \to \infty, \qquad \phi_\pi(x) \propto x(1-x)$$



- Non-spectator amplitude is finite at leading twist due to pair cancellation.

QCD-improved factorization

- Treat form factor as input (Buchalla, Beneke, Neubert, Sachrajda 99)

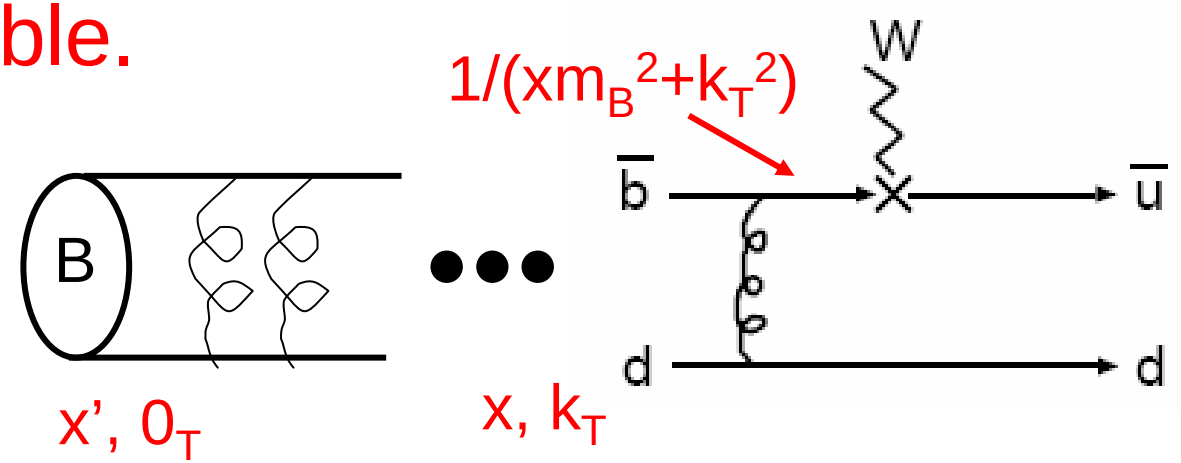


$$A(B \to \pi\pi) \propto \phi_\pi \otimes T^I \otimes F^{B\pi} + \phi_\pi \otimes T^{II} \otimes \phi_B \otimes \phi_\pi$$

- OCDF = FA + QCD corrections
- Predictions for are close to those from FA, small direct CP asymmetries .

K_T factorization

- End-point singularity means that small-x region dominates. Parton k_T is not negligible.



- Collinear gluons modify both longitudinal and transverse momenta of partons.
- Pion form factor (Li, Sterman 92)
- $B \to \pi$ form factor (Li, Yu 95)

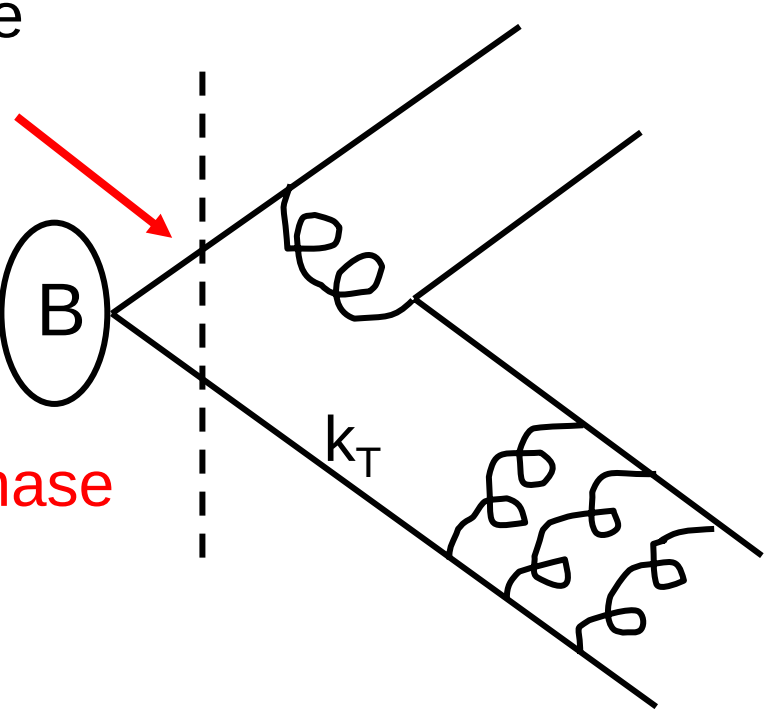
Imaginary annihilation

- Around 90's, inclusive decays (CLEO) and HQET dominated. Few exclusive ($b \to c$) decays, for which FA works well.
- Our works did not catch attention till 99, when B factories began to operate.
- Application to charmless nonleptonic decays gives large imaginary (power-suppressed) penguin annihilation (Keum, Li, Sanda 00), contrary to common belief.
- Predict $A_{CP}(K^+\pi^-) \approx -10\%$, confirmed by data.

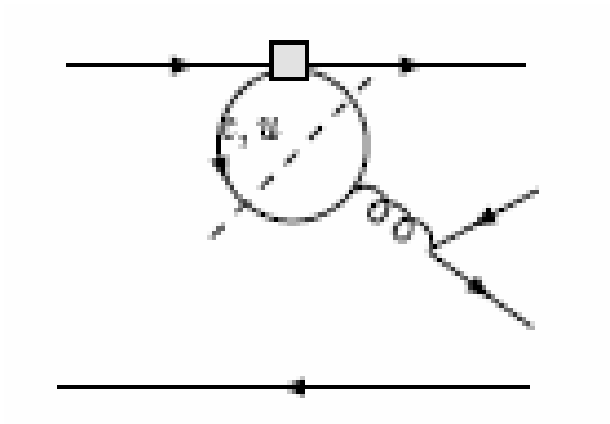
Principle value

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

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

Summary

- Go beyond factorization assumption by means of factorization theorem.
- Critical comparison have revealed puzzles:
  $A_{CP}(K^+\pi^-) \neq A_{CP}(K^+\pi^0)$,
  mixing-induced S(penguin) ≠ S(tree),…
  new physics?
- Need super-B factory
- Apologize for not mentioning soft-collinear effective theory