Direct CP asymmetries in three-body B decays

Hsiang-nan Li
Academia Sinica

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Outlines

- Motivation
- Two-hadron distribution amplitudes
- Direct CP asymmetries
- Summary

Motivation

- Recent LHCb data of direct CP asymmetries in localized regions of phase space

$$A_{CP}^{\text{region}}(K^+K^-K^-) = -0.226 \pm 0.020 \pm 0.004 \pm 0.007,$$

for $m^2_{K^+K^-\text{high}} < 15\ \text{GeV}^2$ and $1.2 < m^2_{K^+K^-\text{low}} < 2.0\ \text{GeV}^2$

$$A_{CP}^{\text{region}}(K^-\pi^+\pi^-) = 0.678 \pm 0.078 \pm 0.032 \pm 0.007$$

for $m^2_{K^-\pi^+\text{high}} < 15\ \text{GeV}^2$ and $0.08 < m^2_{\pi^+\pi^-\text{low}} < 0.66\ \text{GeV}^2$

$$A_{CP}^{\text{region}}(K^+K^-\pi^-) = -0.648 \pm 0.070 \pm 0.013 \pm 0.007$$

for $m^2_{K^+K^-} < 1.5\ \text{GeV}^2$

rho resonance

$$A_{CP}^{\text{region}}(\pi^+\pi^-\pi^-) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007$$

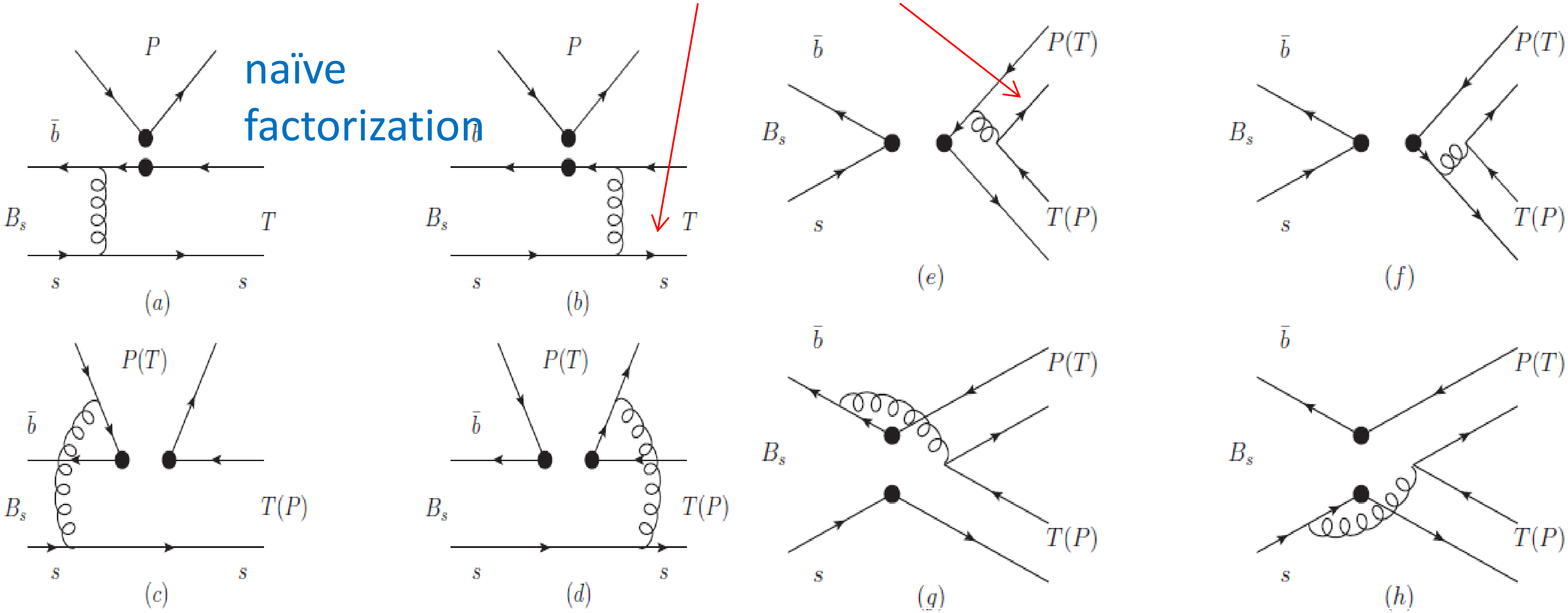
for $m^2_{\pi^+\pi^-\text{high}} > 15\ \text{GeV}^2$ and $m^2_{\pi^+\pi^-\text{low}} < 0.4\ \text{GeV}^2$

Goals

- Develop a theoretical approach to 3-body hadronic B decays
- Understand data of direct CP asymmetries in localized regions, focusing on 3pi, Kpipi
- Predict direct CP asymmetries in other 3-body decay modes
- Predict direct CP asymmetries in whole phase space (resonant + nonresonant) . Very challenging

PQCD for 2-body B decays

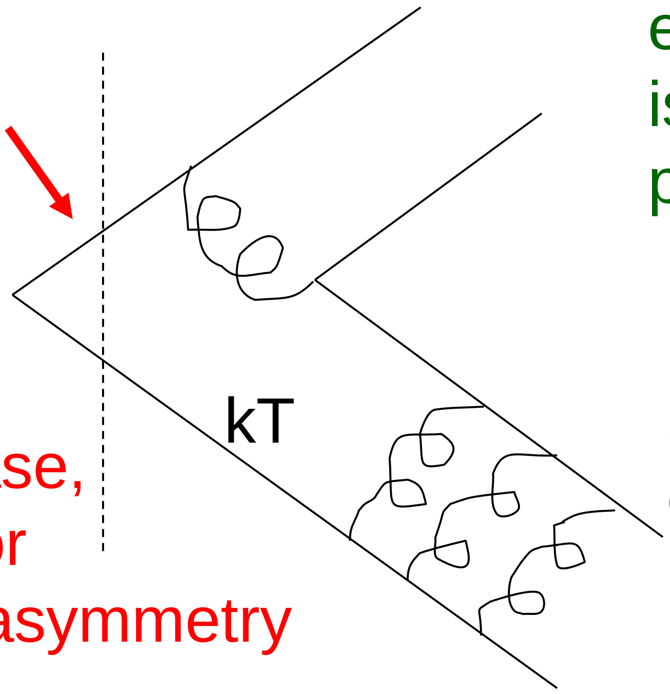
- PQCD approach to 2-body B decays based on kT factorization: b quark decay kernel convoluted with TMD hadron wave functions
- Parton kT smears end-point singularity



Short-distance phase in PQCD

internal
line goes
on-shell

strong phase,
required for
direct CP asymmetry



end-point singularity
is regularized by
parton kT

Sudakov gluons
guarantee finite kT

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

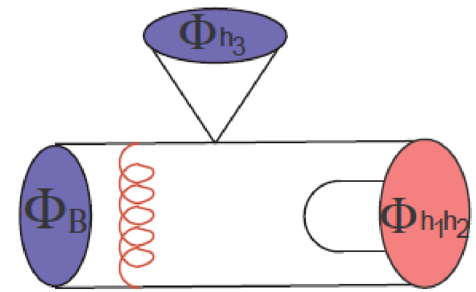
⇨ kT also leads to complex annihilation in PQCD

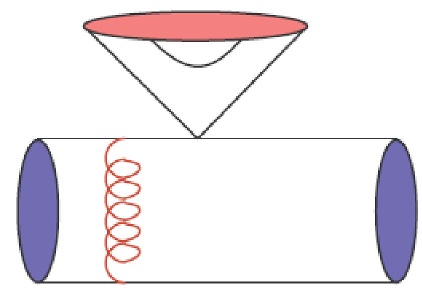
PQCD for 3-body B decays?

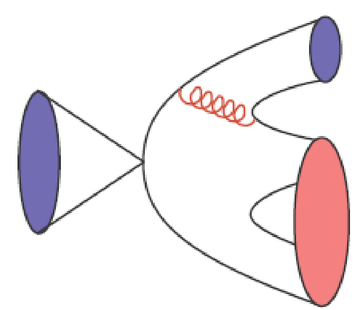
- Straightforward extension involves too many (> 150) diagrams, not practical
- Moreover, two hard-gluon exchange is power suppressed
- One hard-gluon, one soft-gluon exchange dominates, but how to calculate it?
- How to include both resonant and nonresonant contributions in a framework?
- How to obtain strong phases of various sources, especially from rescattering?

Approaches in literature

- Based on parameterizations of
  current-induced process
  transition process
  But, annihilation process?
- Nonfactorizable contribution?
- Resonant via Breit-Wigner then double counting of nonresonant?
- Rescattering strong phases?



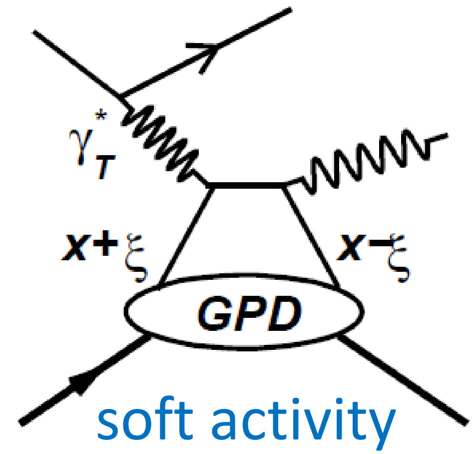




Two-hadron DA

Chen, Li 2003

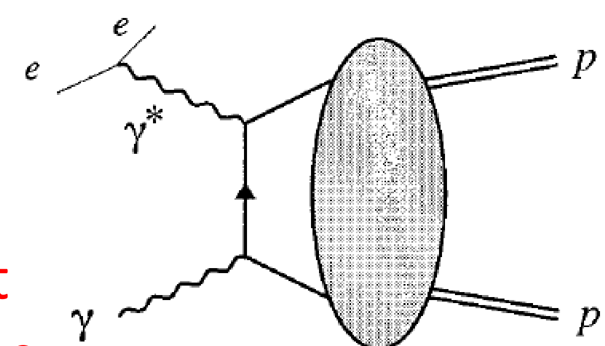
- Inspired by generalized parton distribution (GPD) based on dominance of hand-bag diagram in forward scattering



- Introduce two-hadron distribution amplitude (TDA, crossing of GPD) for dominant region

two hard-gluon power suppressed

one hard, one soft gluon, two hadrons collimate, dominant



Definitions of TDAs

- TDAs for vector, scalar, tensor currents (from Fierz transformation for factorizing quark flow)

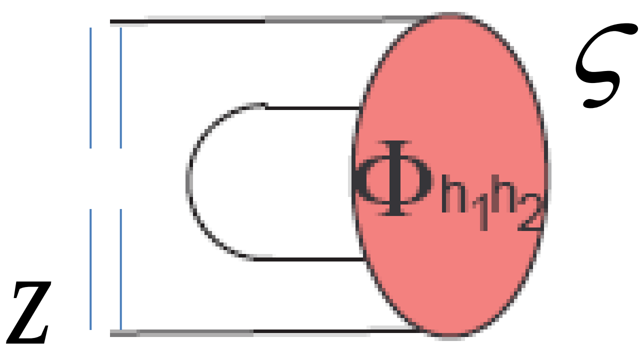
$\sigma^3/2$

$$\Phi_v(z,\zeta,w^2) = \frac{1}{2\sqrt{2N_c}} \int \frac{dy^-}{2\pi} e^{-izP^+y^-} \langle \pi^+(P_1)\pi^-(P_2)|\bar{\psi}(y^-)\ \not{n}_- T\psi(0)|0\rangle\ ,$$

$$\Phi_s(z,\zeta,w^2) = \frac{1}{2\sqrt{2N_c}} \frac{P^+}{w} \int \frac{dy^-}{2\pi} e^{-izP^+y^-} \langle \pi^+(P_1)\pi^-(P_2)|\bar{\psi}(y^-) T\psi(0)|0\rangle\ ,$$

$1/2$

$$\Phi_t(z,\zeta,w^2) = \frac{1}{2\sqrt{2N_c}} \frac{f_{2\pi}^\perp}{w^2} \int \frac{dy^-}{2\pi} e^{-izP^+y^-} \langle \pi^+(P_1)\pi^-(P_2)|\bar{\psi}(y^-) i\sigma_{\mu\nu} n_-^\mu P^\nu T\psi(0)|0\rangle$$



I = 1 with vector, tensor (C-parity odd)
I = 0 with scalar (C-parity even)

Kinematics

- Meson momenta in light-cone coordinates

$$p_B = \frac{m_B}{\sqrt{2}}(1, 1, 0_{\mathrm{T}}), \quad p = \frac{m_B}{\sqrt{2}}(1, \eta, 0_{\mathrm{T}}), \quad p_3 = \frac{m_B}{\sqrt{2}}(0, 1-\eta, 0_{\mathrm{T}})$$

- Two-hadron invariant mass

$$\omega^2 = p^2 \qquad p = \underset{\text{pi+}}{p_1} + \underset{\text{pi-}}{p_2} \qquad \eta = \frac{\omega^2}{m_B^2}$$

- pi+ momentum fraction

$$p_1^+ = \zeta\frac{m_B}{\sqrt{2}}, \quad p_1^- = (1-\zeta)\eta\frac{m_B}{\sqrt{2}}, \quad p_2^+ = (1-\zeta)\frac{m_B}{\sqrt{2}}, \quad p_2^- = \zeta\eta\frac{m_B}{\sqrt{2}}$$

Parameterization of TDAs

- TDAs are normalized to time-like form factors
- Form factors include both resonant and non-resonant contributions
- Up to leading partial wave expansion

$$\propto (p_1 - p_2)^\mu F_\pi$$

$$\Phi_{v,t}(z,\zeta,w^2) = \frac{3F_{\pi,t}(w^2)}{\sqrt{2N_c}} z(1-z)(2\zeta-1)$$

correspond to l = 1
P wave…

$$\Phi_s(z,\zeta,w^2) = \frac{3F_s(w^2)}{\sqrt{2N_c}} z(1-z)$$

correspond to l = 0
S wave…

form factors Fs, Ft, twist-3,
suppressed by a power in PQCD

Complex time-like form factors

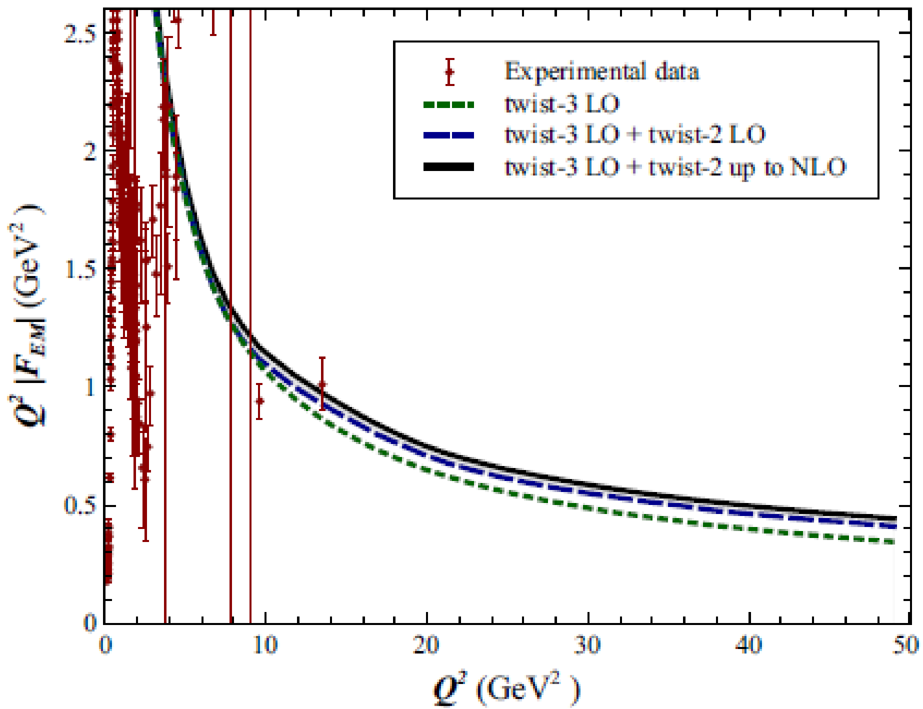
- P and S waves

$$F_\pi(w^2) = \frac{m^2 \exp[i\delta_1^1(w)]}{w^2 + m^2}$$

m=1 GeV

from data

$$m_{J/\psi}^2 |F_\pi(m_{J/\psi}^2)|^2 \sim 0.9 \ \mathrm{GeV}^2$$



$$F_s(w^2) = \frac{m_0^\pi m^2 \exp[i\delta_0^0(w)]}{w^3 + m_0^\pi m^2}$$

$$F_t(w^2) = \frac{m_0^\pi m^2 \exp[i\delta_1^1(w)]}{w^3 + m_0^\pi m^2}$$

Watson theorem

$$F_{s,t}(w^2)/F_\pi(w^2) \sim m_0^\pi / w$$

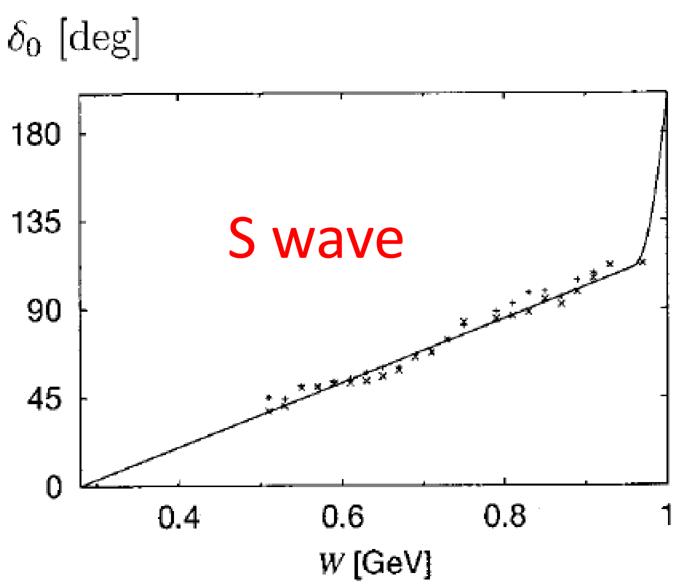
$$\frac{M_\pi^2}{m_u + m_d}$$ =1.4 GeV

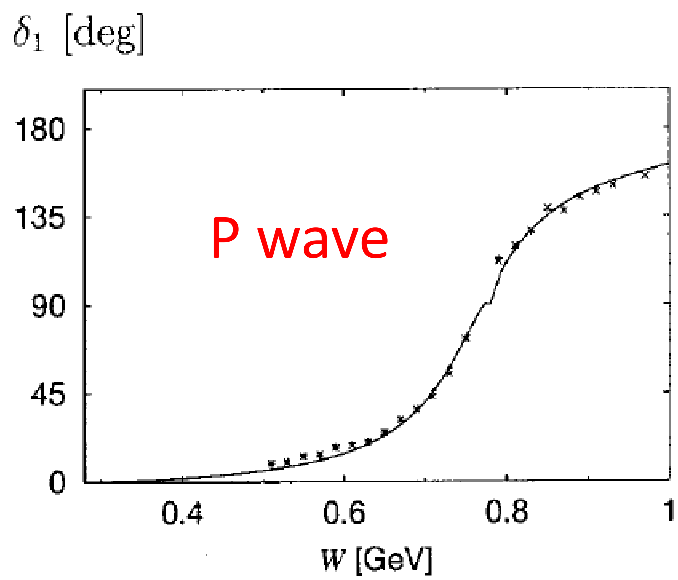
Rescattering phases

- LHCb data of CP asymmetries in localized regions offered a chance to confront theory
- Data for rescattering phases in localized region ($m_{\pi\pi}^2 < 0.4\, GeV^2$) are available

dimensional coefficient

$$\delta_0(w) = \pi(w - 2m_\pi) \qquad \delta_1(w) = 1.4\pi(w - 2m_\pi)^2$$

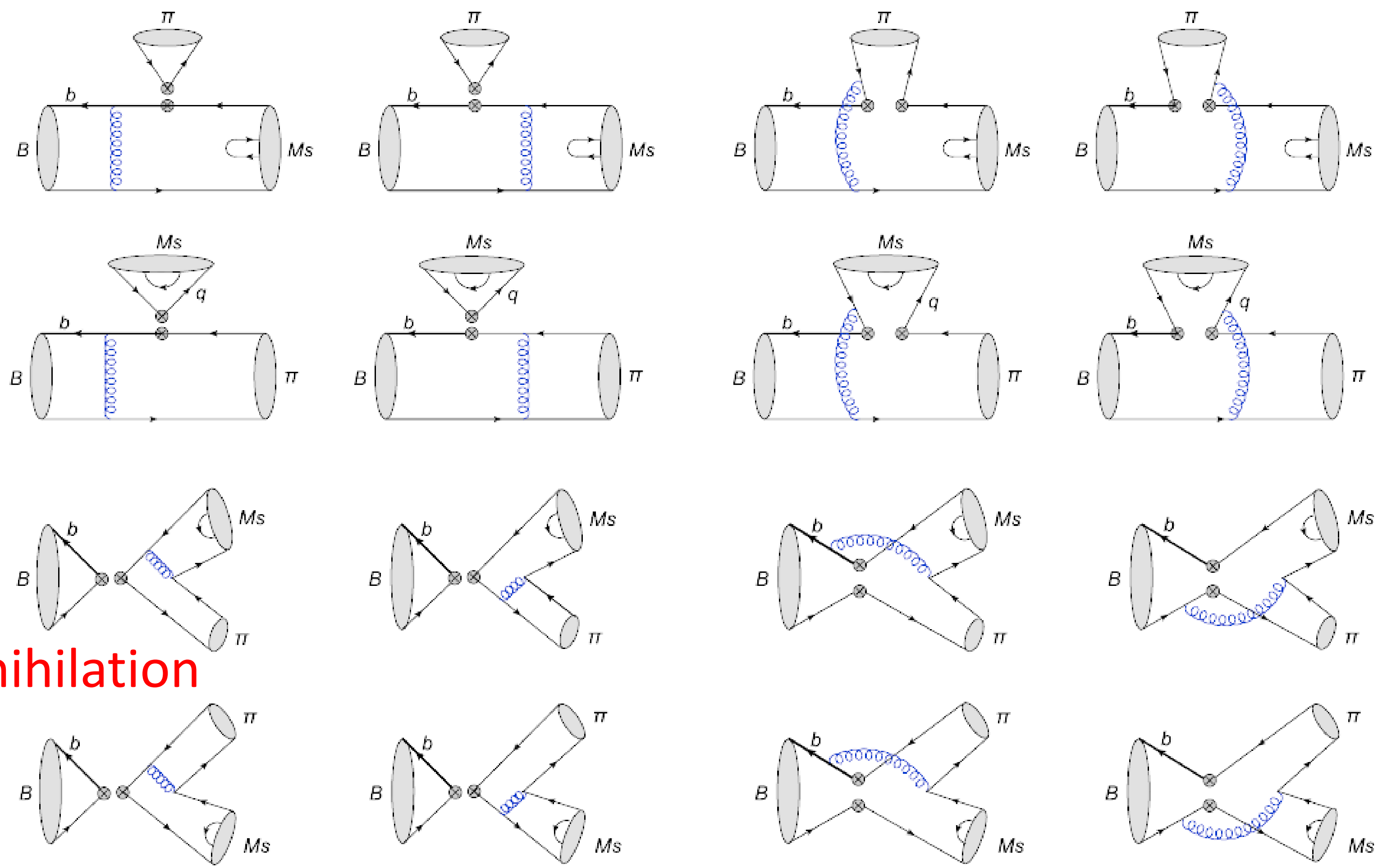




Feynman diagrams

- All inputs are ready, go ahead to calculate 16 diagrams (load 10 times lower)

nonfactorizable



annihilation

Open the box…

- Factorization formula for decay amplitude

$$\mathcal{M} = \Phi_B \otimes H \otimes \Phi_{h_1 h_2} \otimes \Phi_{h_3}$$

- B meson and hadron DAs have been widely adopted in analysis of 2-body decay
- Calculate B+ and B- decays

$$A_{CP}^{reg}(B^\pm \to \pi^\pm \pi^+ \pi^-) = 0.52^{+0.12}_{-0.22}(\omega_B)^{+0.11}_{-0.09}(a_2^\pi)^{+0.03}_{-0.03}(m_0^\pi)$$

+-0.05 +-0.15 +-0.1

- Data $A_{CP}^{\text{region}}(\pi^+\pi^-\pi^-) = 0.584 \pm 0.082 \pm 0.027 \pm 0.007$
- Short-distance phase is important
- P wave phase doubled, Acp increases up to 0.7

$$A_{CP}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-})$$

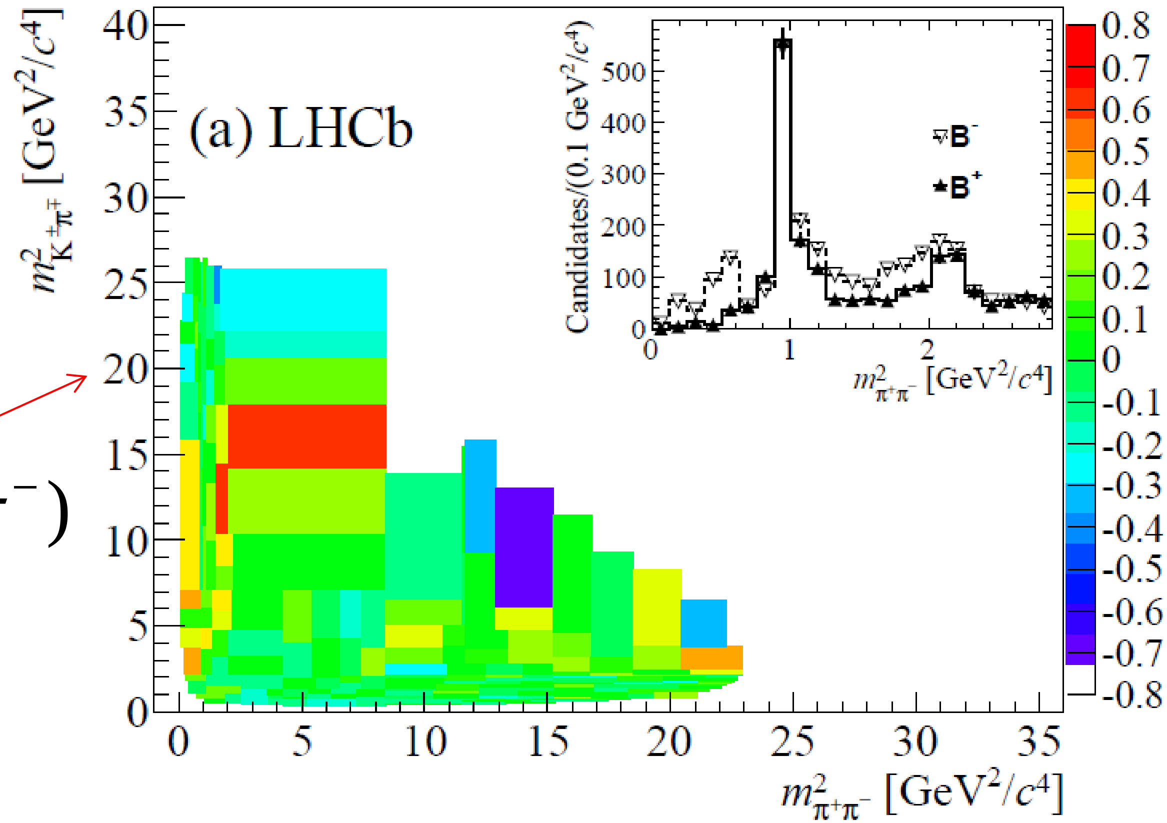
- PQCD (Mishima, Li): $A_{CP}(B^{\pm} \to K^{\pm}\rho^{0}) = 0.71^{+0.25}_{-0.35}$

$$A_{CP}^{\text{region}}(K^{-}\pi^{+}\pi^{-}) = 0.678 \pm 0.078 \pm 0.032 \pm 0.007$$

for $m^2_{K^-\pi^+\text{high}} < 15\ \text{GeV}^2$ and $0.08 < m^2_{\pi^+\pi^-\text{low}} < 0.66\ \text{GeV}^2$

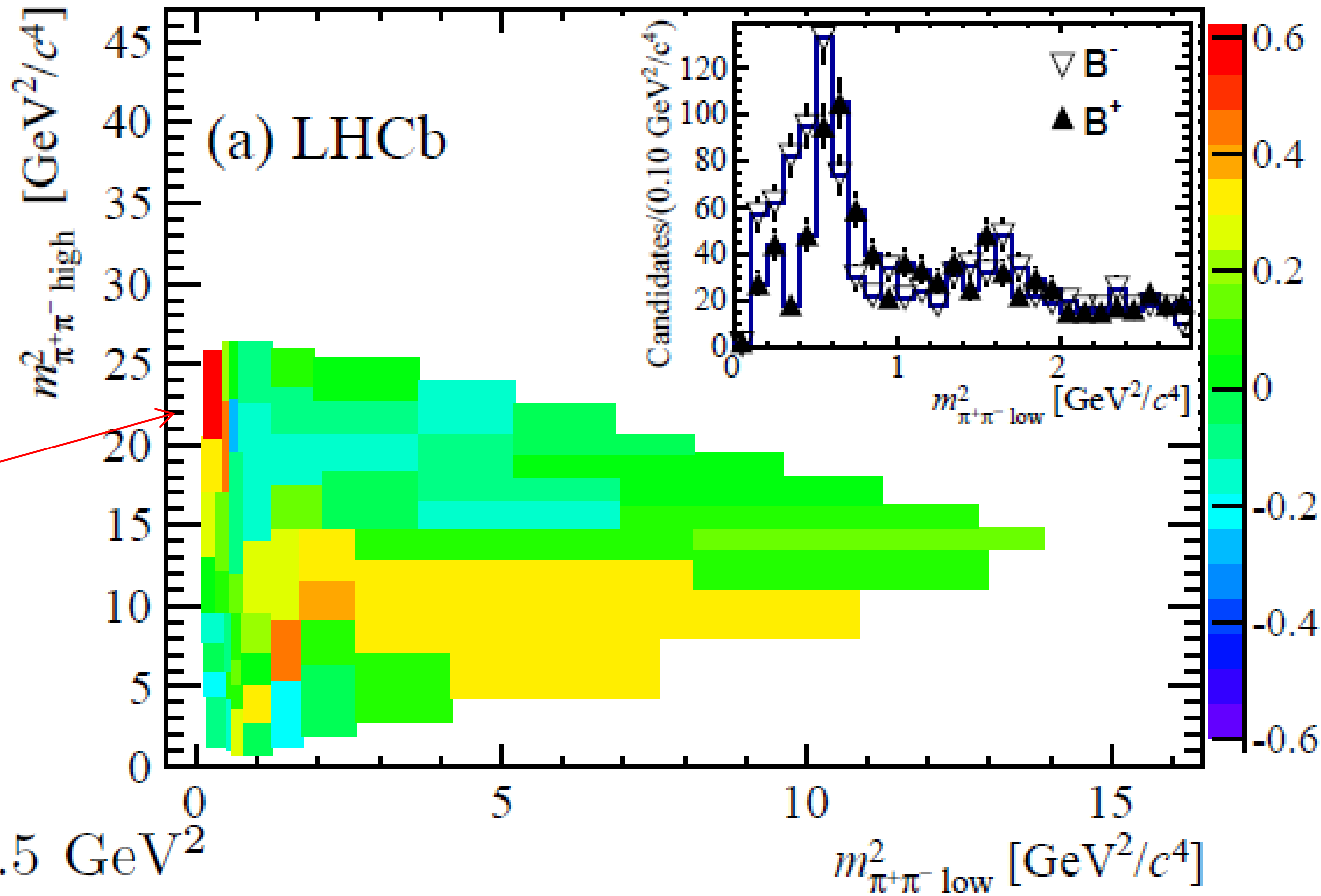
- In the same low pipi invariant mass

$A_{CP}^{reg}(B^{\pm} \to K^{\pm}\pi^{+}\pi^{-})$
$= -0.02$



$$A_{CP}(B^{\pm} \to \pi^{\pm}\pi^{+}\pi^{-})$$

- In higher pipi invariant mass



$A^{reg}_{CP}(\pi^{\pm}\pi^{+}\pi^{-})$
$= 0.63$

$m^2_{\pi^+\pi^-\text{high}} > 20.5\ \text{GeV}^2$

$m^2_{\pi^+\pi^-\text{low}} < 0.4\ \text{GeV}^2$

Summary

- Systematic approach to 3-body B decays based on kT factorization theorem with TDA has been established
- Short-distance and rescattering P-wave phases are equally important for predicting Acp
- Can explain and predict direct CP asymmetries of 3pi and Kpipi in various localized regions of phase space
- A lot of applications are expected

Back-up slides

B meson and hadron DAs

- B meson and hadron DAs have been widely adopted in analysis of 2-body decay

0.45 GeV

$$\phi_B(x,b) = N_B x^2 (1-x)^2 \exp\left[-\frac{1}{2}\left(\frac{x m_B}{\omega_B}\right)^2 - \frac{\omega_B^2 b^2}{2}\right]$$

$$\phi^A_{\pi(K)}(x) = \frac{f_{\pi(K)}}{2\sqrt{2N_c}} 6x(1-x)\left[1 + a_1^{\pi(K)} C_1^{3/2}(2x-1) + a_2^{\pi(K)} C_2^{3/2}(2x-1) + \right.$$

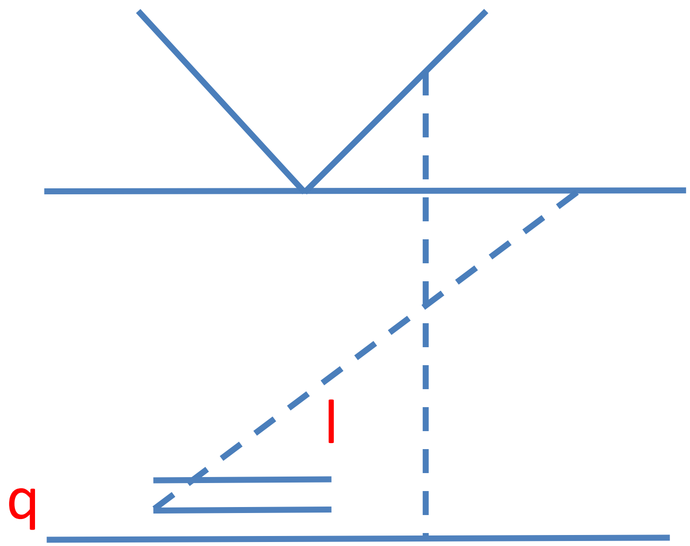
0.25

$$\phi^P_{\pi(K)}(x) = \frac{f_{\pi(K)}}{2\sqrt{2N_c}} \left[1 + \right.$$ higher Gegenbauer terms

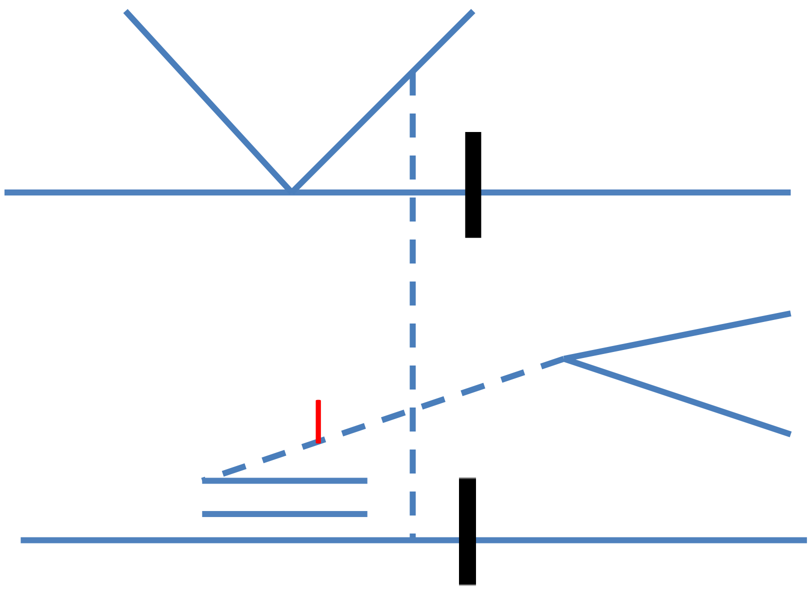
$$\phi^T_{\pi(K)}(x) = \frac{f_{\pi(K)}}{2\sqrt{2N_c}} (1-2x)\left[1 + \right.$$

Factorization of TDA

- Similar to collinear factorization for ordinary hadron DA based on eikonalization and Ward identity for summing collinear attachments



$$\bar{q}(k)\frac{\gamma^{\alpha}(\not{k}+\not{l})}{(k+l)^{2}} \approx \bar{q}(k)\frac{k^{\alpha}}{k\cdot l}$$



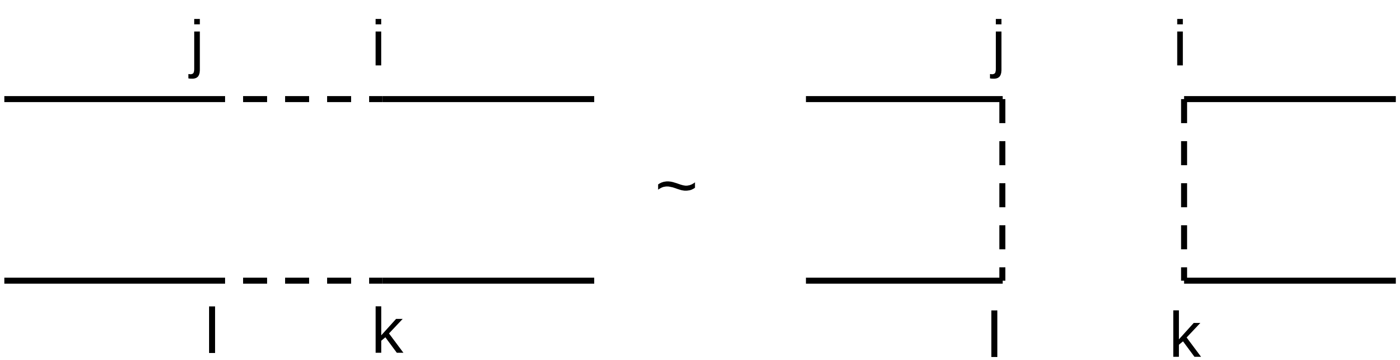
as two hadrons collimate
it is collinear gluon

Fierz transformation

- Insert Fierz identity to break fermion flow

$$I_{ij}I_{lk} \;=\; \frac{1}{4}I_{ik}I_{lj} + \frac{1}{4}(\gamma^\alpha)_{ik}(\gamma_\alpha)_{lj} + \frac{1}{8}(\sigma^{\alpha\beta})_{ik}(\sigma_{\alpha\beta})_{lj} + \frac{1}{4}(\gamma^5\gamma^\alpha)_{ik}(\gamma_\alpha\gamma^5)_{lj} + \frac{1}{4}(\gamma^5)_{ik}(\gamma^5)_{lj}$$

- First 3 projectors contribute, leading to 3 TDAs



C-parity

- C-parity (charge parity) for mesonic state is equivalent to parity

$$C\,|\pi^+\pi^-\rangle = (-1)^L\,|\pi^+\pi^-\rangle$$

- C-parity for quark fields (spinors)

$$\psi^{(c)} = C\psi^\star \qquad C = i\gamma^2$$

$$C^\dagger\gamma^\mu C = -(\gamma^\mu)^\star$$

- C-parity is odd for vector and tensor currents, and even for scalar current