Resolution of the $B \to \pi\pi, \pi K$ puzzles

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Hsiang-nan Li and S.M., arXiv:0901.1272

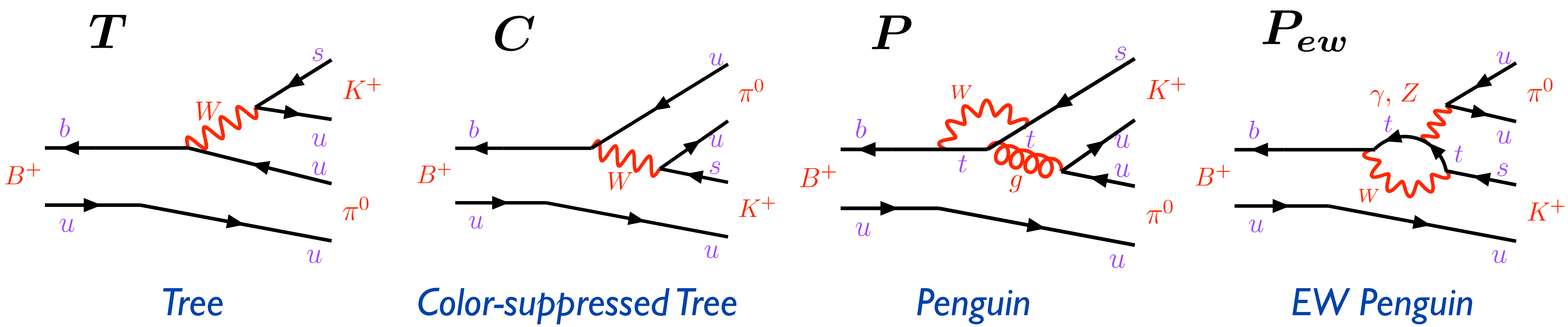
Outline:

1. $B \to \pi K$ and $B \to \pi\pi$ puzzles
   - Large color-suppressed tree amplitude
2. PQCD approach
3. Resolution in PQCD
   - Soft factor
   - Modified factorization formula
4. Summary

1. $B \to \pi K$ and $B \to \pi\pi$ Puzzles

- Topological decomposition:

Gronau, Hernandez, London, Rosner (94)



$$
\begin{aligned}
A(B^0 \to \pi^- K^+) &= -P' - T' e^{i\phi_3} \\
\sqrt{2} A(B^+ \to \pi^0 K^+) &= -(P' + P'_{ew}) - (T' + C') e^{i\phi_3}
\end{aligned}
$$

$$
\begin{aligned}
A(B^0 \to \pi^+ \pi^-) &= -T - P e^{i\phi_2} \\
\sqrt{2} A(B^+ \to \pi^+ \pi^0) &= -(T + C) - P_{ew} e^{i\phi_2} \\
\sqrt{2} A(B^0 \to \pi^0 \pi^0) &= -C + (P - P_{ew}) e^{i\phi_2}
\end{aligned}
$$

$B \to \pi K$ and $B \to \pi\pi$ Puzzles

- Naive estimate:

$B \to \pi K$: $P' > T',\ P'_{ew} > C'$

$B \to \pi\pi$: $T > C,\ P > P_{ew}$

⇒ $A_{\rm CP}(\pi^\mp K^\pm) \approx A_{\rm CP}(\pi^0 K^\pm)$

$B(\pi^+\pi^-) \gg B(\pi^0\pi^0)$

Gronau, Hernandez, London, Rosner (94)

- Theoretical Predictions vs. Data: *HFAG (09)*

$[10^{-2}]$	Data	QCDF	SCET	PQCD
$A_{\rm CP}(\pi^\mp K^\pm)$	$-9.8^{+1.2}_{-1.1}$	$4.5^{+1.1+2.2+0.5+8.7}_{-1.1-2.5-0.6-9.5}$	input	-10^{+7}_{-8}
$A_{\rm CP}(\pi^0 K^\pm)$	5.0 ± 2.5	$7.1^{+1.7+2.0+0.8+9.0}_{-1.8-2.0-0.6-9.7}$	-18 ± 8	-1^{+3}_{-6}

$[10^{-6}]$	Data	QCDF	PQCD
$B(\pi^\mp\pi^\pm)$	5.16 ± 0.22	$8.9^{+4.0+3.6+0.6+1.2}_{-3.4-3.0-1.0-0.8}$	$6.5^{+6.7}_{-3.8}$
$B(\pi^\pm\pi^0)$	$5.59^{+0.41}_{-0.40}$	$6.0^{+3.0+2.1+1.0+0.4}_{-2.4-1.8-0.5-0.4}$	$4.0^{+3.4}_{-1.9}$
$B(\pi^0\pi^0)$	1.55 ± 0.19	$0.3^{+0.2+0.2+0.3+0.2}_{-0.2-0.1-0.1-0.1}$	$0.29^{+0.50}_{-0.20}$

QCDF: Beneke, Neubert(03)
SCET: Bauer, Rothstein, Stewart(05)
PQCD: Li, S.M., Sanda(05); Li, S.M.(06)

Theory errors are correlated.

Large C (or Pew) is required!

SM or NP ? *Gronau,Rosner(03); Yoshikawa(03); Buras et al.(04); Chiang et al.(04); Ciuchini et al.(04); He,McKellar(04); S.M,Yoshikawa(04) and many others*

2. kT Factorization (PQCD) Approach

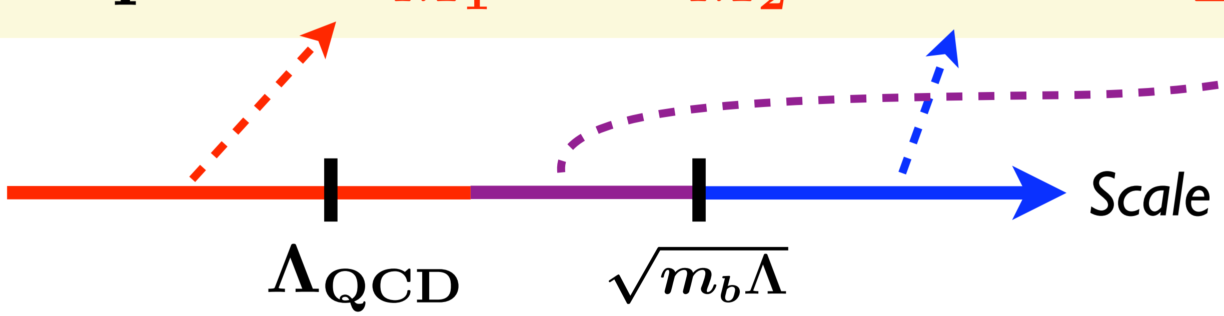
- kT factorization is an appropriate tool for the processes that involve significant contributions from small x. ➡ *applied to DIS, D-Y, etc.*

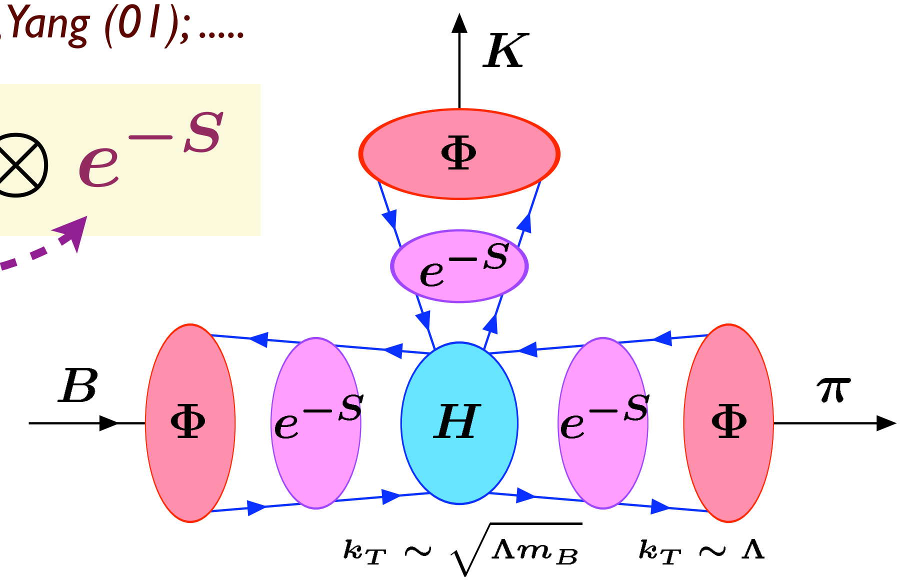
  Botts, Sterman(89); Catani et al.(90,91); Ralston, Pire (90); Huang et al.(91); Collins, Ellis(91); Levin et al.(91); Li, Sterman(92); Jakob, Kroll (93); .....

- Factorization for B decays:

  Chang, Li (97); Yeh, Li (97); Keum, Li, Sanda (01); Lu, Ukai, Yang (01); .....

$$\text{Amp.} \sim \Phi_{M_1} \otimes \Phi_{M_2} \otimes H \otimes \Phi_B \otimes e^{-S}$$





- kT is of $O(\sqrt{m_b\Lambda})$ in a hard kernel H due to the Sudakov evolution.

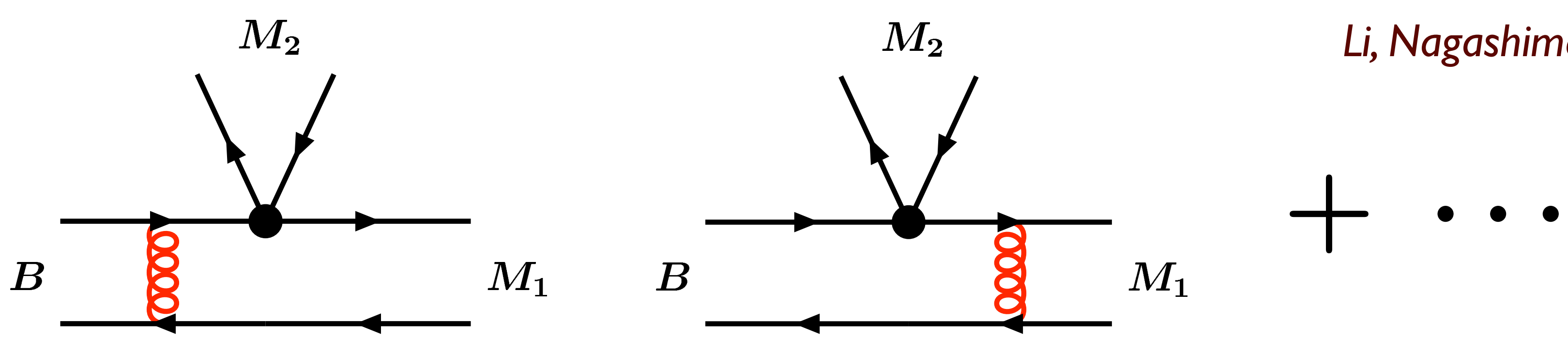
➡ ensures absence of end-point singularities in H.

3. Resolution in PQCD

Key: Factorization for spectator diagrams

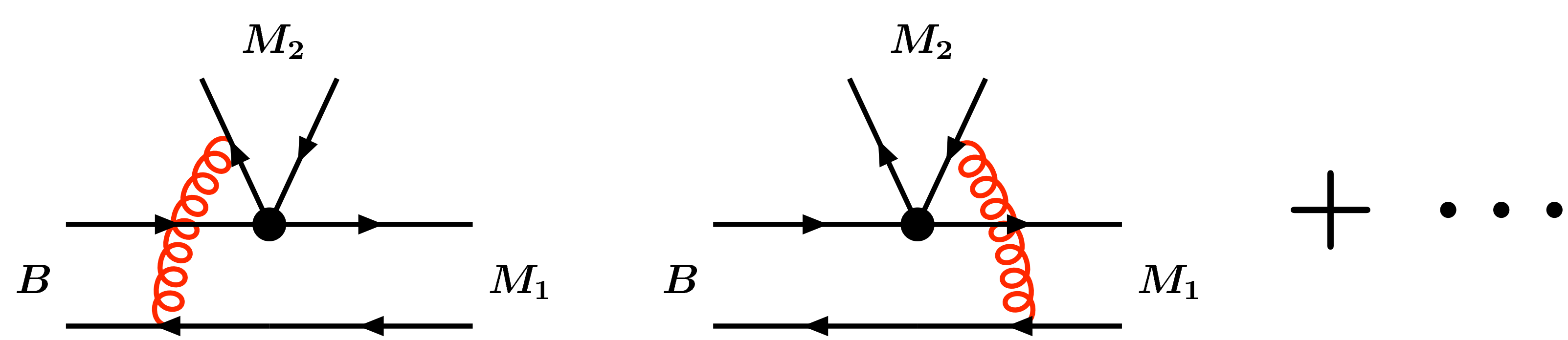
- In kT factorization (PQCD), the factorization has been proved in the following diagrams:

Li, Nagashima (03)



$$\mathbf{Amp.} \sim \Phi_{M_1} \otimes \Phi_{M_2} \otimes H \otimes \Phi_B \otimes \mathbf{(Sudakov)}$$

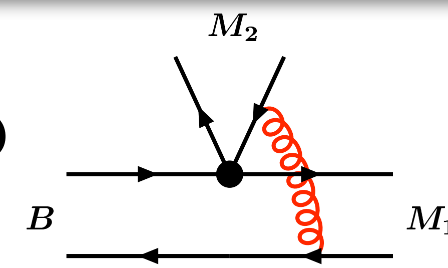
- However, the factorization has not been proved for

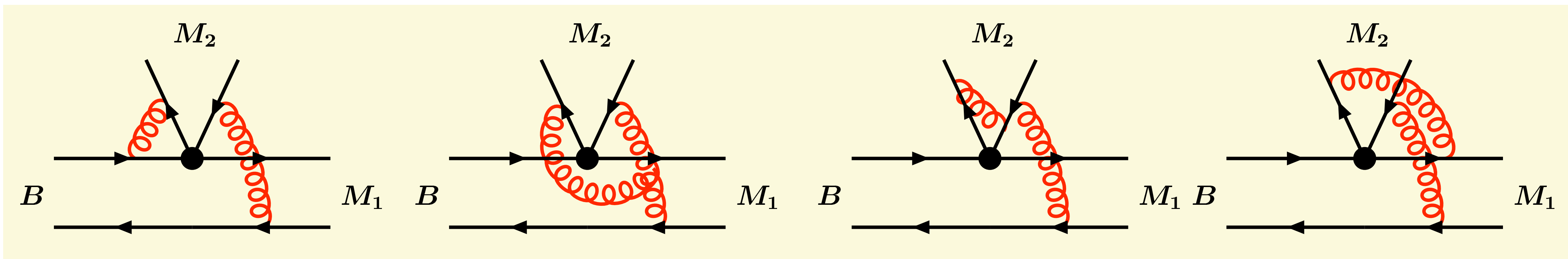


So far, we have assumed the same factorization formula as the above.

Radiative Corrections

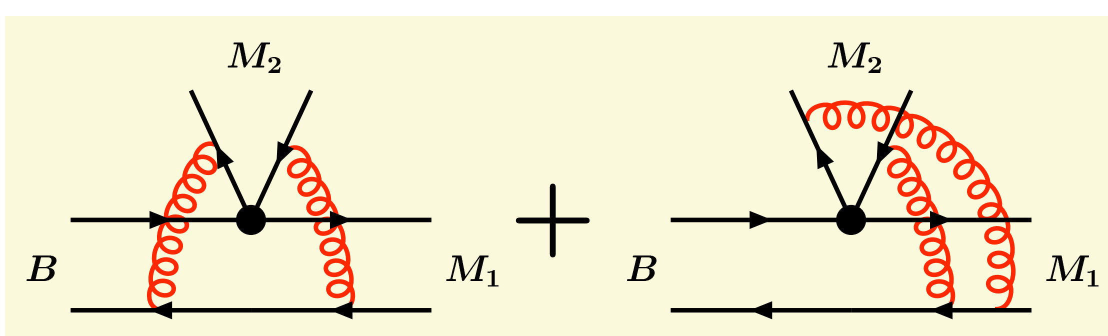
Li, S.M. (09)

- Radiative corrections to 



➡ Collinear div's associated with M_2 are factorizable (eikonal lines) into the M_2 meson wave function.

- The sum of remaining corrections gives **a soft divergence** at $\ell^\mu = (\ell^+, \ell^-, \ell_T) \sim (0, 0, 0_T)$.



$$\propto \; i\frac{\alpha_s}{\pi} C_F \int \frac{d^2\ell_T}{\ell_T^2} \mathcal{M}_a^{(\mathrm{LO})}(\ell_T) \; \rightarrow \; \mathrm{div.}$$

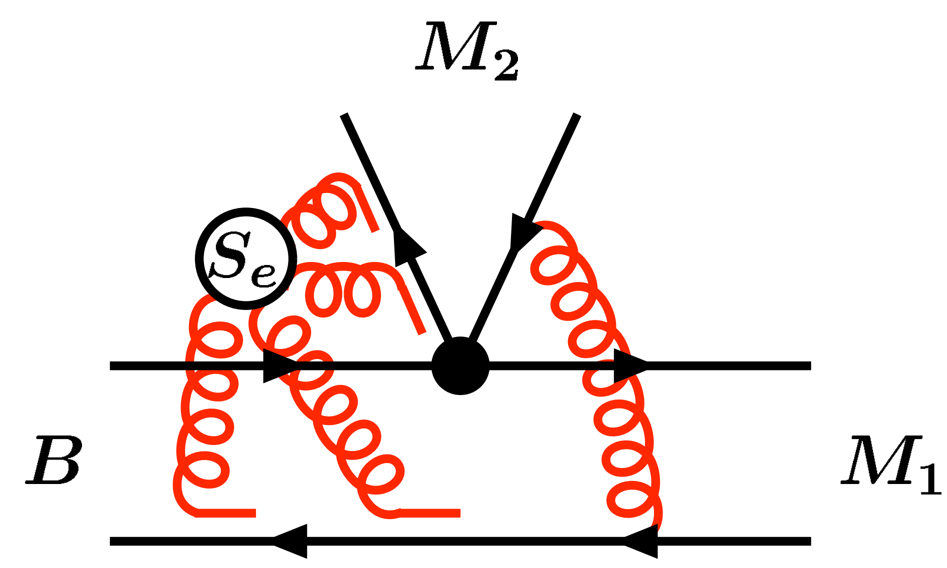
LO amplitude

Soft Factor

Li, S.M. (09)

- A similar soft divergence was found in hadron-hadron collisions. Collins, Qiu (07); Collins (07)

- The residual soft divergence can be factorized into a soft factor, S_e, using the eikonal approximation. Li, S.M. (09); Chang, Li (09)

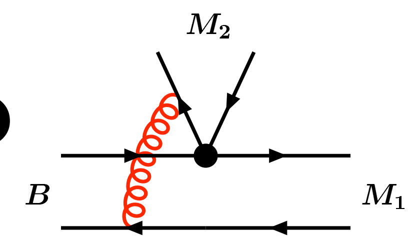


- The soft factor has a dynamical origin similar to that of a meson wave function: the former (latter) absorbs the soft (collinear) gluons.

  ⇨ *can be studied by nonpert. methods or by using data, but we treat it as a parameter in this work.*

Soft Contribution to C

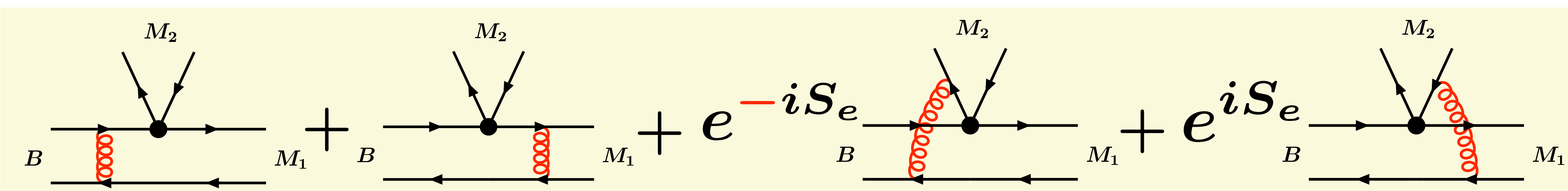
Li, S.M. (09)

- Calculating higher orders, the divergence can be summed into $e^{iS_e}\mathcal{M}_a^{(\mathrm{LO})}$.
- Similarly, corrections to 

give $e^{-iS_e}\mathcal{M}_b^{(\mathrm{LO})}$.
- "Modified" factorization formula:

$$\mathbf{Amp.} \sim \Phi_{M_1} \otimes \Phi_{M_2} \otimes H \otimes \Phi_B \otimes (\mathbf{Sudakov}) \otimes e^{\pm iS_e}$$

- The presence of S_e may convert a destructive interference into a constructive one.

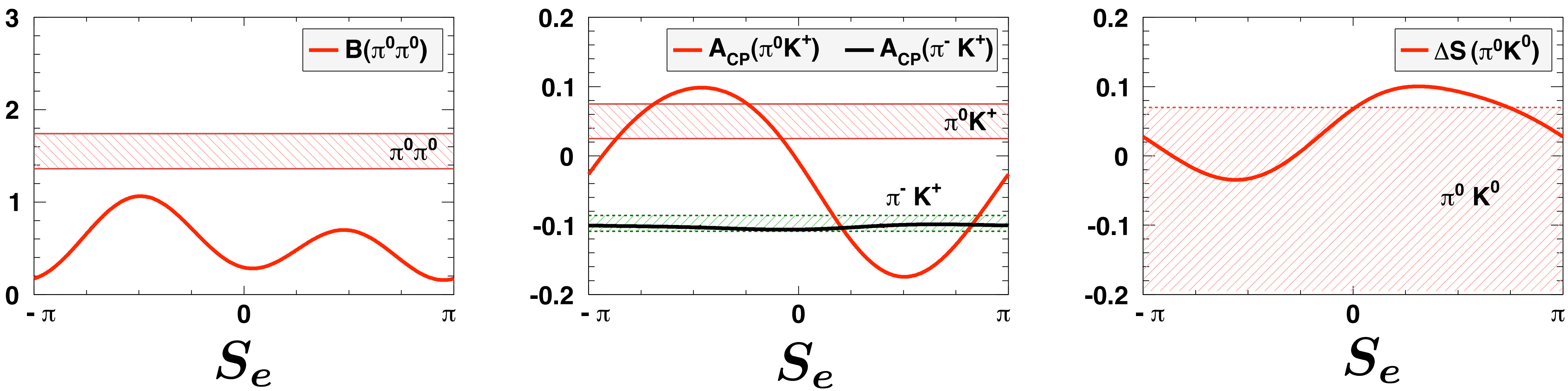


small in C (large in T, P) *almost cancel if Se=0*

- C could be enhanced, while T and P are unchanged.

Resolution of the $B \to \pi\pi, \pi K$ puzzles

Li, S.M. (09)



- $S_e(\pi\pi) \approx S_e(\pi K)$.
- $B(\pi^0\pi^0)$ can be enhanced.
- The difference between $A_{\rm CP}(\pi^\mp K^\pm)$ and $A_{\rm CP}(\pi^0 K^\pm)$ can be enlarged.
- The $B \to \pi\pi, \pi K$ puzzles can be resolved simultaneously for $S_e \sim -\pi/2$. $\dashrightarrow$ $\frac{C}{T} \approx 0.5\, e^{-2.2i}$
- We predict a bit smaller $S(\pi^0 K_S)$.

4. Summary

- There exist uncanceled soft divergences in the spectator diagrams in k_T factorization (PQCD).
- The soft div. can be factorized in a soft factor.

The $B \to \pi\pi,\ \pi K$ puzzles can be resolved simultaneously for $S_e \sim -\pi/2$.

- A difference between $B \to \pi^0\pi^0$ and $B \to \rho^0\rho^0$ is discussed in our paper *arXiv:0901.1272.*

Backup Slides

Sum Rules in $B \to \pi K$

Gronau,Rosner(05); Gronau(05)

$$A_{\rm CP}(\pi^{\mp}K^{\pm}) \approx A_{\rm CP}(\pi^0 K^{\pm})$$

- Including C,

$$A_{\rm CP}(\pi^{\mp}K^{\pm}) \approx A_{\rm CP}(\pi^0 K^{\pm}) + A_{\rm CP}(\pi^0 K^0)$$

- Including other subleading contributions,

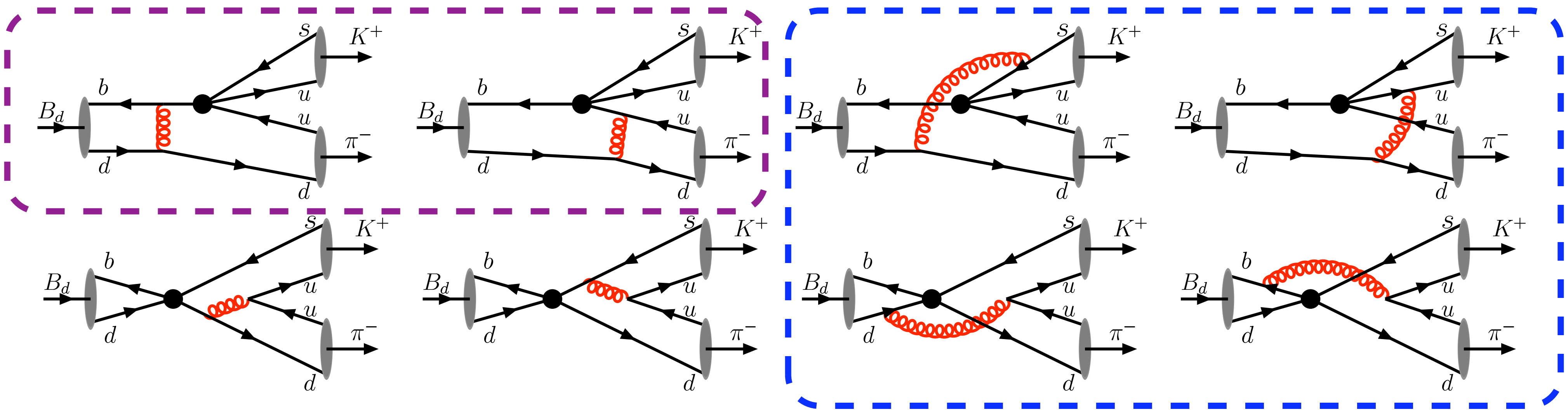
$$A_{\rm CP}(\pi^{\mp}K^{\pm}) + A_{\rm CP}(\pi^{\pm}K^0) \approx A_{\rm CP}(\pi^0 K^{\pm}) + A_{\rm CP}(\pi^0 K^0)$$

$[10^{-2}]$	Data *HFAG (09)*
$A_{CP}(B^{\pm} \to \pi^{\pm}K^0)$	0.9 ± 2.5
$A_{CP}(B^{\pm} \to \pi^0 K^{\pm})$	5.0 ± 2.5
$A_{CP}(B^0 \to \pi^{\mp}K^{\pm})$	$-9.8^{+1.2}_{-1.1}$
$A_{CP}(B^0 \to \pi^0 K^0)$	-1 ± 10

We need Super B factories.

PQCD Approach

- LO diagrams: $O\left(\alpha_s(\sqrt{m_b\Lambda})\right)$

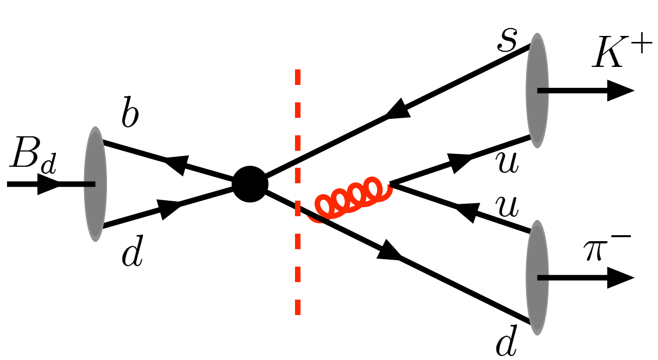


Leading (naive factorization)

Subleading

- Penguin annihilation with $(1-\gamma_5)\otimes(1+\gamma_5)$ -type operator generates a large strong phase.

Keum, Li, Sanda (01)



$$\frac{1}{xM_B^2-|k_T|^2+i\epsilon} = \mathrm{P}\left[\frac{1}{xM_B^2-|k_T|^2}\right] - i\pi\,\delta(xM_B^2-|k_T|^2)$$

- Main sources of uncertainties are non-pert. inputs, i.e. meson distribution amplitudes.

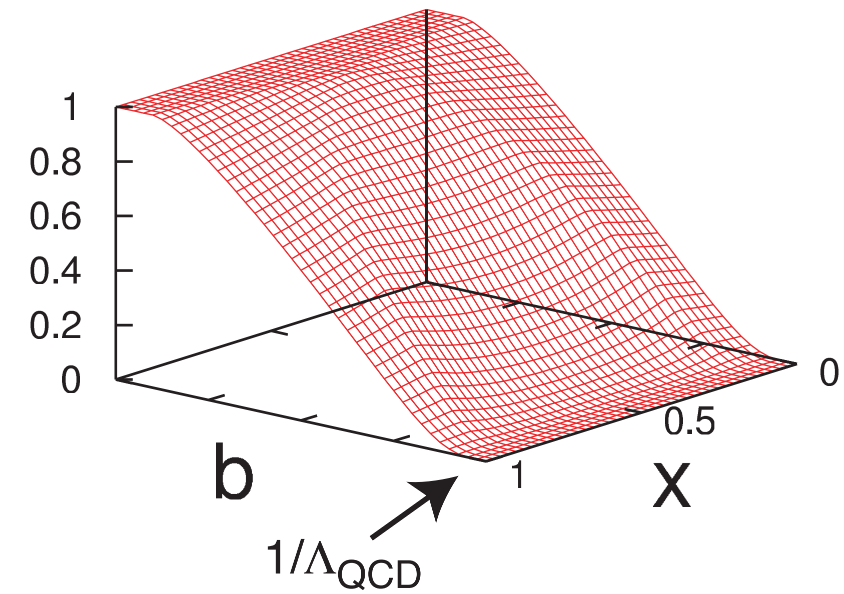
Sudakov Suppression in PQCD

- Keeping k_T, large double logarithms are generated from the overlap of collinear and soft divergences: $\alpha_s \ln^2(M_B/k_T)$
- The double logarithms can be resummed using a resummation technique. *Botts, Sterman (89)*

⇨ Sudakov factor

- Sudakov factor suppresses a small k_T (large b) region.

Li, Sterman (92)



b is the conjugate space of k_T.

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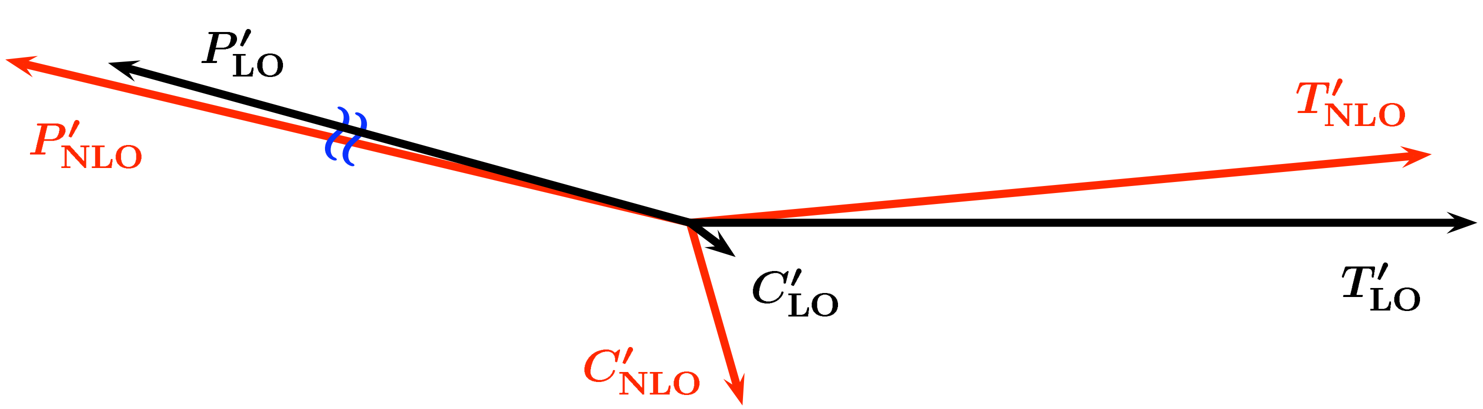
PQCD predictions for $B \to \pi K$

PQCD (k_T factorization) without the soft factor

- LO PQCD predicts $A_{CP}(\pi^{\mp} K^{\pm}) \approx A_{CP}(\pi^0 K^{\pm})$.
- Including important NLO corrections, $A_{CP}(\pi^0 K^{\pm})$ approaches to the data, but not enough. *Li, S.M., Sanda (05)*

$$\begin{cases} A_{CP}(\pi^{\mp} K^{\pm}) \sim 2\,\mathrm{Im}\,[T'/P']\sin\phi_3 \sim -10\% \\ A_{CP}(\pi^0 K^{\pm}) \sim 2\,\mathrm{Im}\,[(T'+C')/P']\sin\phi_3 \sim -1\% \end{cases}$$



C' is still smaller than T, but Im[(T+C)/P] vanishes!

$B \to \rho^0\rho^0$

- $B \to \rho^0\rho^0$ is similar to $B \to \pi^0\pi^0$ at the quark level, but its prediction is consistent with the data.

$[10^{-6}]$	Data	QCDF	PQCD
$B(\rho^\mp\rho^\pm)$	$24.2^{+3.1}_{-3.2}$	$25.5^{+1.5+2.4}_{-2.6-1.5}$	$25.3^{+25.3}_{-13.8}$
$B(\rho^\pm\rho^0)$	$24.0^{+1.9}_{-2.0}$	$20.0^{+4.0+2.0}_{-1.9-0.9}$	$16.0^{+15.0}_{-8.1}$
$B(\rho^0\rho^0)$	$0.73^{+0.27}_{-0.28}$	$0.9^{+1.5+1.1}_{-0.4-0.2}$	$0.92^{+1.10}_{-0.56}$
	HFAG (09)	*Cheng,Yang (08)*	*Li, S.M. (06)*

⇨ Can we explain the large C, under the constraint from $B(\rho^0\rho^0)$?

Pion vs. Rho meson

Nussinov, Shrock (08); Duraisamy, Kagan (08)

- Key: How to accommodate the simultaneous role of the pion as a $q\bar{q}$ state like ρ and an almost massless NG boson?
- The valence $q\bar{q}$ pair must be close enough to reduce the confinement effect. $(r < 1/\Lambda_{\rm QCD})$ If the pair is separated far apart, the linear potential will give the pion a high mass.
- $r_\pi \approx 1/\Lambda_{\rm QCD}$ is accounted for by a soft cloud of higher Fock states:

$$|\pi\rangle \sim |q\bar{q}\rangle + |q\bar{q}g\rangle + |q\bar{q}q\bar{q}\rangle + \cdots \quad \Leftrightarrow \quad \text{NG boson}$$

- Assumption: The soft effect in S_e is significant (negligible) in the decays with $\pi(\rho)$.