Theoretical status of $B \to \pi K$

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Outline:

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   - $B \to \pi K$ and $B \to \pi\pi$ puzzles
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4. SM tests in $B \to \pi K$
5. Summary

1. Introduction - $B \to \pi K$ puzzle

- **Topological decomposition:** *Gronau, Hernandez, London, Rosner (94)*

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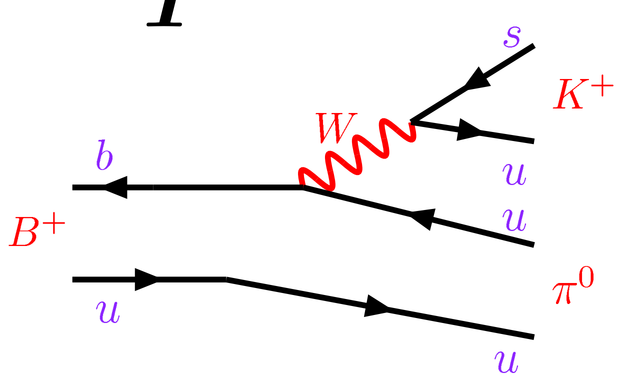
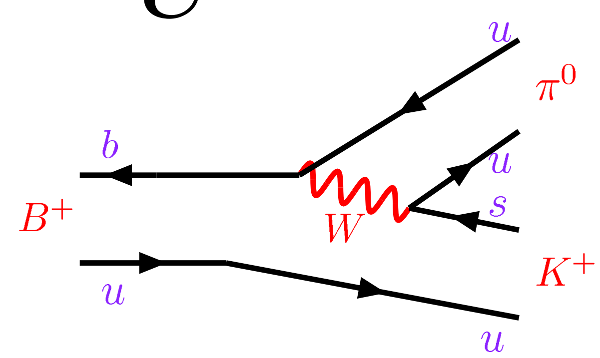


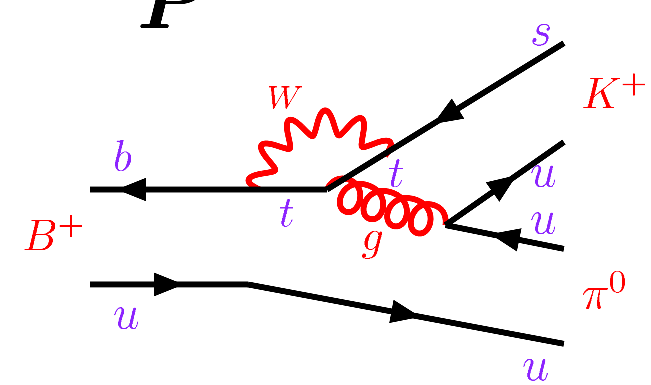
Tree

C



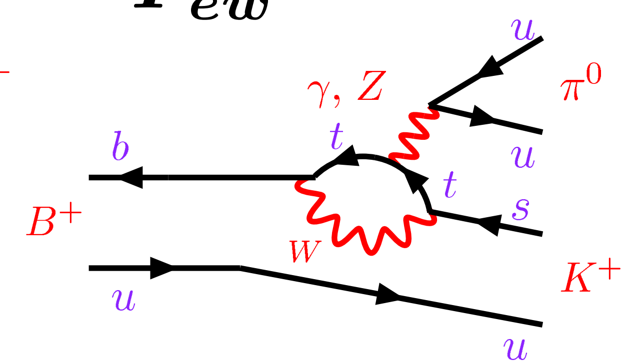
Color-suppressed Tree

P



Penguin

P_{ew}



EW Penguin

$$A(B^0 \to \pi^- K^+) = -P' - T' e^{i\phi_3}$$

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

- **Naive estimate:** $P' > T',\ P'_{ew} > C'$

  $1 : O(10^{-1}) : O(10^{-2})$

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

$B \to \pi K$ puzzle

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

- $P' > T',\ P'_{ew} > C'$ ⇨ $A_{\rm CP}(\pi^\mp K^\pm) \approx A_{\rm CP}(\pi^0 K^\pm)$
- Data: $A_{\rm CP}(\pi^\mp K^\pm) = (-9.8^{+1.2}_{-1.1})\ \%$
  $A_{\rm CP}(\pi^0 K^\pm) = (5.0 \pm 2.5)\ \%$

BaBar, PRL99,021603 (07)
PRD76, 091102 (07)
Belle, Nature 452 (08)
HFAG (10)

⇨ $A_{\rm CP}(\pi^\mp K^\pm) \not\approx A_{\rm CP}(\pi^0 K^\pm)$

Larger C' with a sizable strong phase
or larger Pew' with a NP CP phase *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

- A SM fit ⇨ $\dfrac{C'}{T'} \sim 0.58\, e^{-2.3\, i}$ *Baek, Chiang, London (09)*

$B \to \pi\pi$ puzzle

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

- Naive estimate: $T > C,\ P > P_{ew}$ $\quad 1 : O(10^{-1}) : O(10^{-2})$
- Prediction in naive factorization: *Ali, Kramer, Lu (98)*

$$B(\pi^+\pi^-) \gg B(\pi^0\pi^0) \approx (0.1 \sim 0.3) \times 10^{-6}$$

- Data: *HFAG (10)*

$$\begin{aligned} B(\pi^+\pi^-) &= (5.16 \pm 0.22) \times 10^{-6} \\ B(\pi^+\pi^0) &= (5.59^{+0.41}_{-0.40}) \times 10^{-6} \\ B(\pi^0\pi^0) &= (1.55 \pm 0.19) \times 10^{-6} \end{aligned}$$

⇨ Larger C seems to be favored.

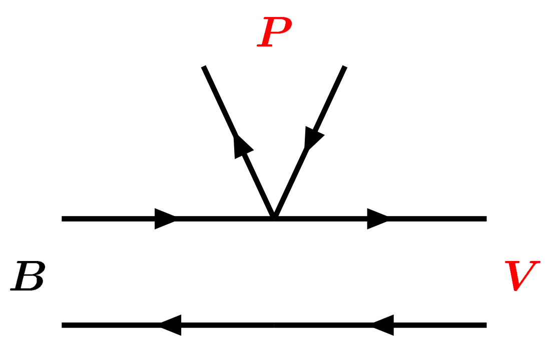
Large color-suppressed tree ?

- $B \to \rho^0\rho^0$ is similar to $B \to \pi^0\pi^0$ at the quark level, but its prediction is consistent with the data. *Li, S.M. (06)*
  - Prediction in naive factorization:

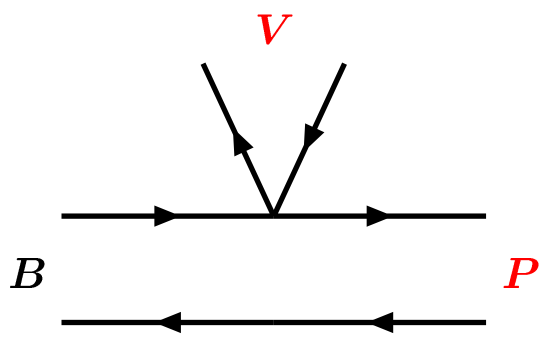
$$\mathcal{B}(\rho^0\rho^0) \approx 0.6 \times 10^{-6}$$ *Ali, Kramer, Lu (98)*

  - Data: $\mathcal{B}(\rho^0\rho^0) = (0.73^{+0.27}_{-0.28}) \times 10^{-6}$ *HFAG (10)*

- $B \to PV$ decays (not involving $\eta^{(\prime)}$, ϕ, ω): *Chiang, Zhou (09)*



$$\left|\frac{C_V}{T_V}\right| = 0.58 \pm 0.18$$



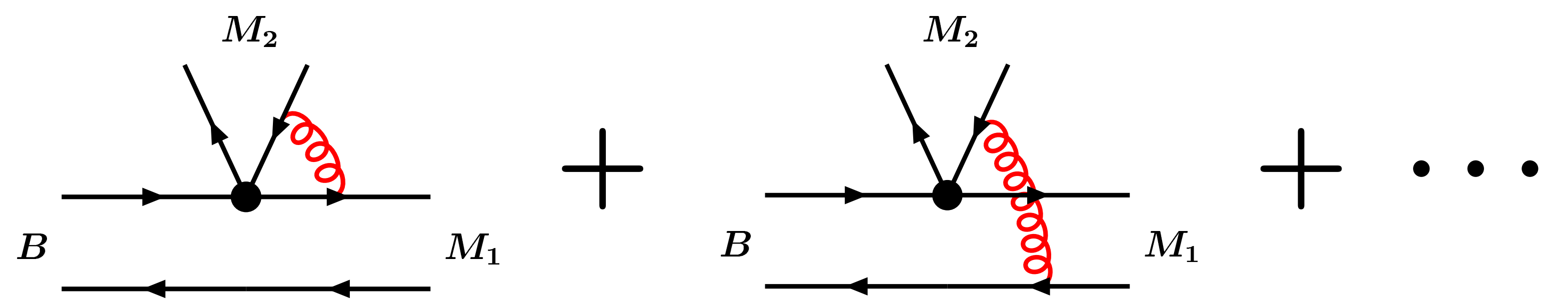
$$\left|\frac{C_P}{T_P}\right| = 0.25 \pm 0.31$$

2. Predictions in Factorization Approaches

QCDF, SCET, PQCD

Beyond naive estimate

- Color-suppressed tree is sensitive to subleading corrections.



- Need a reliable theoretical method to calculate B decay amplitudes, including higher order/power corrections beyond "naive factorization."

⇨ { Collinear factorization (QCDF, SCET)
  k_T factorization (PQCD)

factorize amplitudes even involving significant contribution from small x.

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Strong phase in QCDF, SCET and PQCD

	QCDF (BBNS-S4)	SCET (BPRS)	PQCD (KLS)
Annihilation	non-fact. large phase	factorizable real	factorizable large phase
Charm penguin	factorizable small phase	non-fact. large phase	factorizable small phase

BBNS = Beneke, Buchalla, Neubert, Sachrajda; BPRS = Bauer, Pirjol, Rothstein, Stewart; KLS = Keum, Li, Sanda

- Ann. in QCDF(BBNS) and Charm Pen. in SCET(BPRS) are regarded as phenomenological parameters.
- Ann. is factorizable and real in SCET w/ the zero-bin subtraction method. *Arnesen, Ligeti, Rothstein, Stewart (06)*
- Ann. appears always together with Charm Pen.

Charming penguin

See also Talk by Jaeger on 07/09

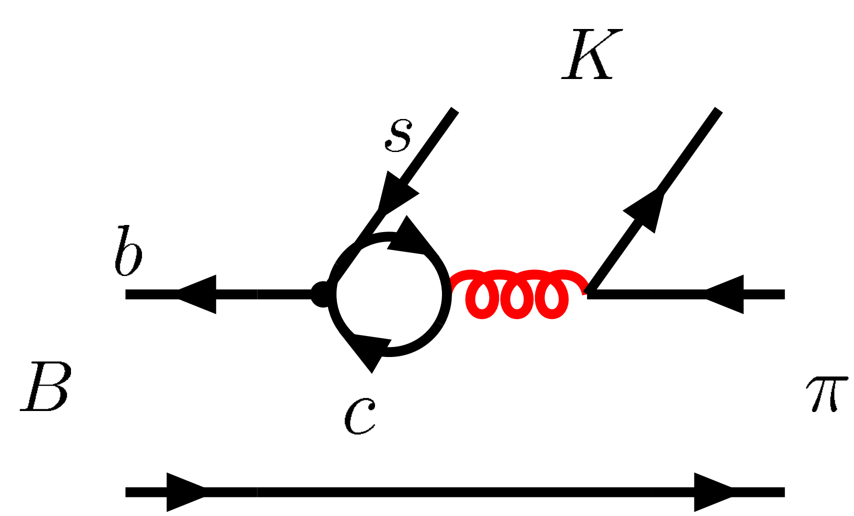
- Large and imaginary charming penguin from a fit to the data in SCET (BPRS).

No factorization due to the charm threshold contribution *Bauer, Pirjol, Rothstein, Stewart (04)*

- Recently, BBNS have showed non-perturbative effects are power suppressed.

$$\frac{A_{c\bar{c}}}{A_{\rm LO}} \sim \alpha_s(2m_c)\, f\left(\frac{2m_c}{m_b}\right) v \times \frac{4m_c^2 v^2}{m_b^2}$$

Beneke, Buchalla, Neubert, Sachrajda (09)



Predictions in QCDF and PQCD

- QCDF at NLO and PQCD at partial NLO

$[10^{-2}]$	Data	QCDF (S4)	PQCD
$A_{\rm CP}(\pi^\mp K^\pm)$	$-9.8^{+1.2}_{-1.1}$	$4.5^{+1.1+2.2+0.5+8.7}_{-1.1-2.5-0.6-9.5}\ (-4.1)$	-10^{+7}_{-8}
$A_{\rm CP}(\pi^0 K^\pm)$	5.0 ± 2.5	$7.1^{+1.7+2.0+0.8+9.0}_{-1.8-2.0-0.6-9.7}\ (-3.6)$	-1^{+3}_{-6}

HFAG (10)
Beneke, Neubert (03)
Cheng, Yang (08)
Li, S.M., Sanda (05)
Li, S.M. (06)

$[10^{-6}]$	Data	QCDF (S4)	PQCD
$B(\pi^0\pi^0)$	1.55 ± 0.19	$0.3^{+0.2+0.2+0.3+0.2}_{-0.2-0.1-0.1-0.1}\ (0.7)$	$0.29^{+0.50}_{-0.20}$
$B(\pi^0\rho^0)$	2.0 ± 0.5	$0.4^{+0.2+0.2+0.9+0.5}_{-0.2-0.1-0.3-0.3}\ (1.1)$	≈ 0.7
$B(\rho^0\rho^0)$	$0.73^{+0.27}_{-0.28}$	$0.9^{+1.5+1.1}_{-0.4-0.2}$	$0.92^{+1.10}_{-0.56}$

- QCDF: $\left|\dfrac{C^{(\prime)}}{T^{(\prime)}}\right| \sim 0.2\ (0.5)$ with small phase

  due to smaller λ_B, etc.

- PQCD: $\dfrac{C'}{T'} \sim 0.26\, e^{-1.4\, i}$ and $\dfrac{C}{T} \sim 0.19\, e^{-1.1\, i}$

In PQCD, NLO corrections yield large phase, but not desired magnitude.

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Recent progress in QCDF

- NNLO calculations have been completed for the trees.

  See Talk by Bell on 07/09 for detail

  - Cancellation between vertex and spectator-scattering.

    ⇨ NNLO predictions for the Br's are similar to the NLO ones.

    Bell (09); Bell, Pilipp (09); Beneke, Huber, Li (09)

  - Smaller λ_B $(\approx 200\,\mathrm{MeV})$ enhances C, but small phase.

- Subleading $1/m_b$ power corrections: *See Talk by Kagan on 08/09*

  - Significant corrections to C explain the data.

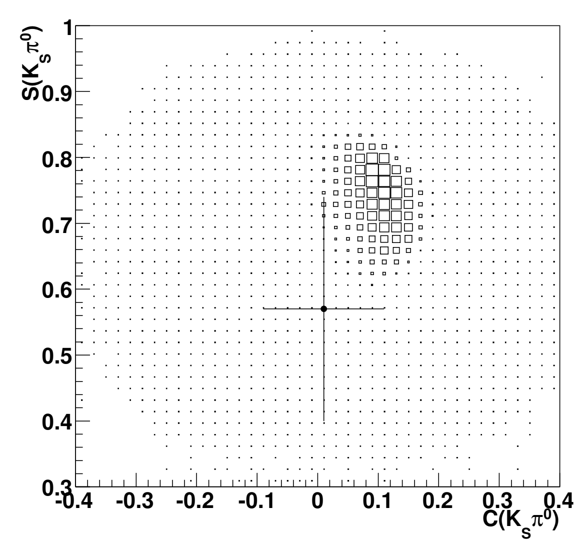
  - $C_{\pi^0 K_S}$ and $S_{\pi^0 K_S}$ are well determined.

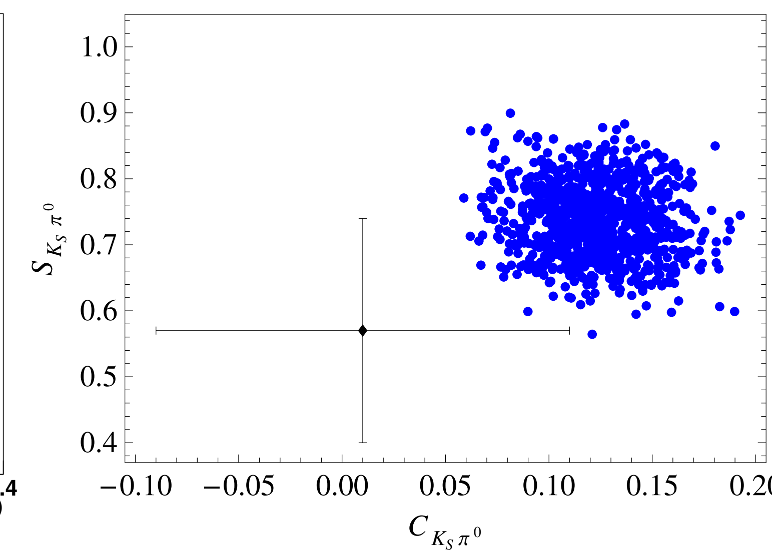
    ⇨ *Super B*

Ciuchini, Franco, Martinelli, Pierini, Silvestrini (08)

Duraisamy, Kagan (08)

Cheng, Chua (09)





3. Resolution in PQCD

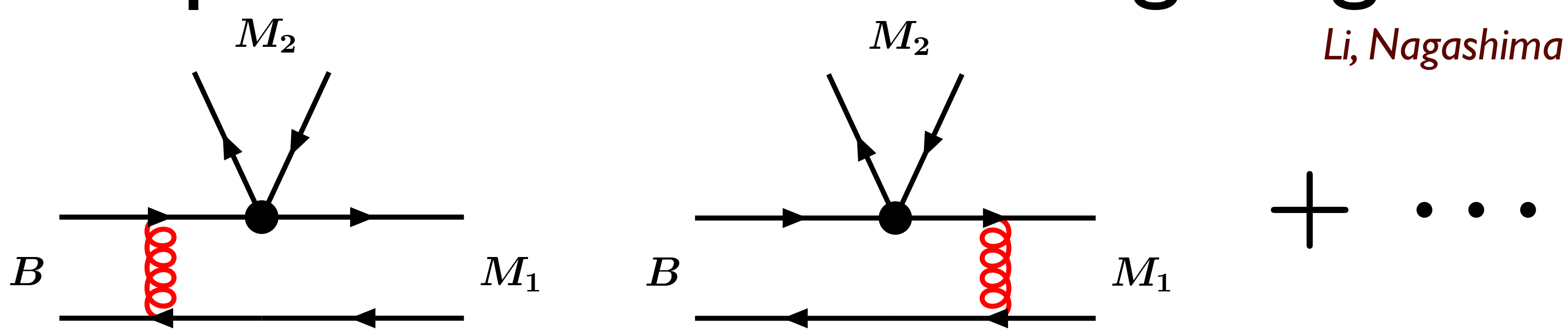
Hsiang-nan Li & S.M. (09)

Factorization for spectator diagrams

Key: Factorization for "spectator" diagrams

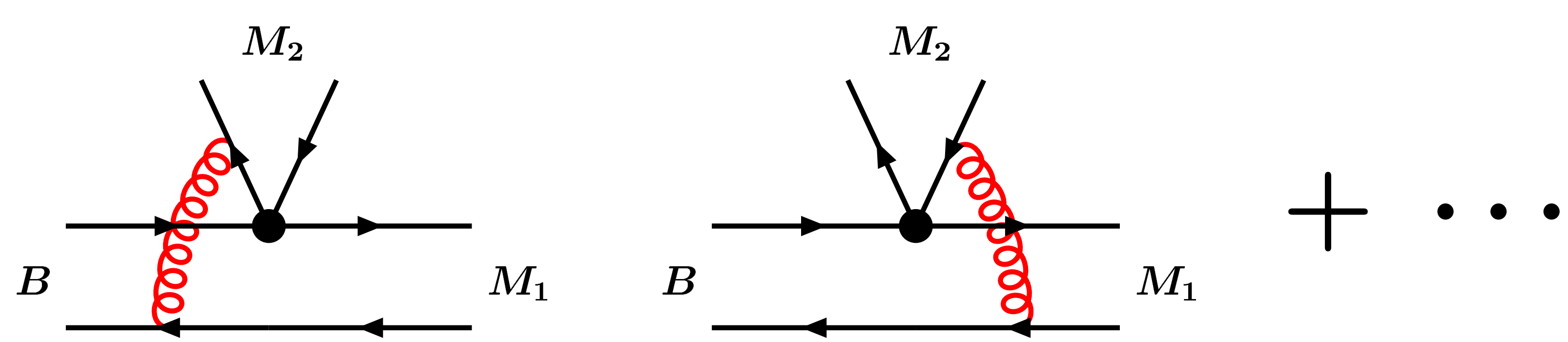
- In kT factorization (PQCD), the factorization has been proved in the following diagrams:

Li, Nagashima (03)



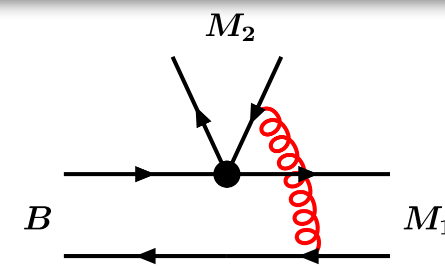
$$\textbf{Amp.} \sim \Phi_{M_1} \otimes \Phi_{M_2} \otimes H \otimes \Phi_B \otimes \textbf{(Sudakov)}$$

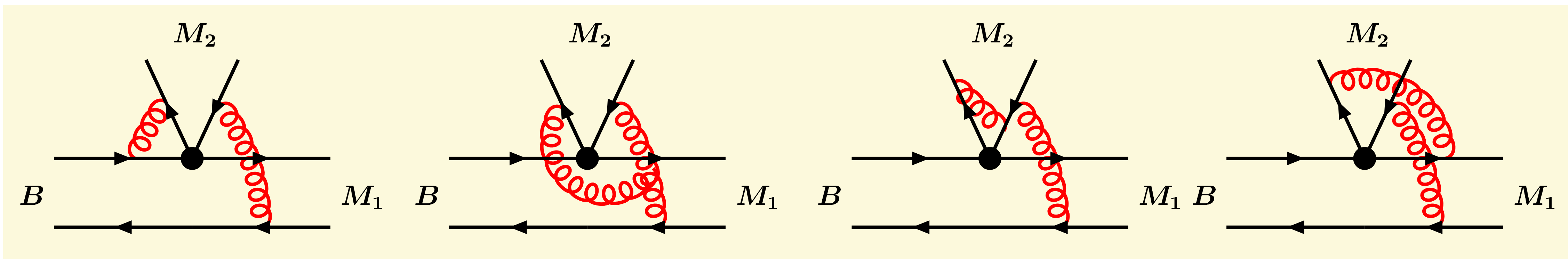
- However, the factorization for the spectator diagrams had been missing.



Glauber divergence

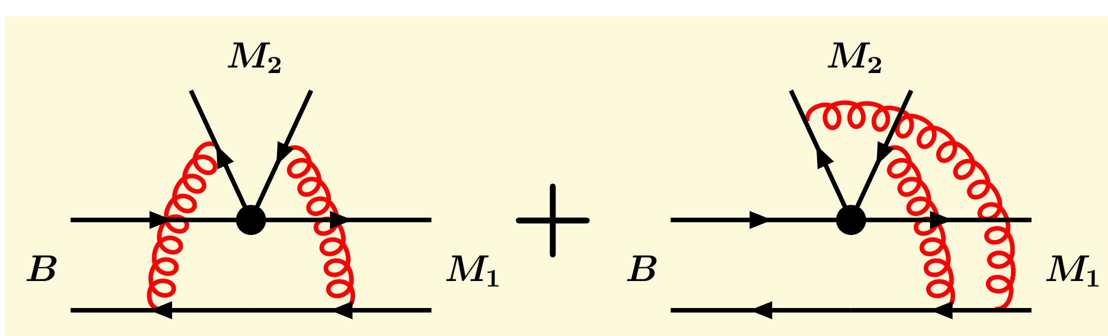
Li, S.M. (09)

- Radiative corrections to 



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

- The sum of remaining corrections gives a Glauber divergence at $\ell^2 \sim \Lambda^2$ with $\ell^+\ell^- \ll \ell_T^2$.



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

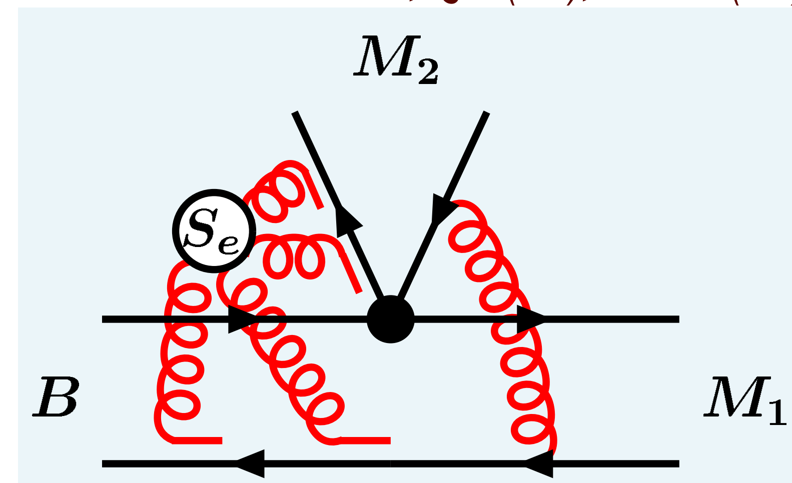
LO amplitude

Soft factor

Li, S.M. (09)

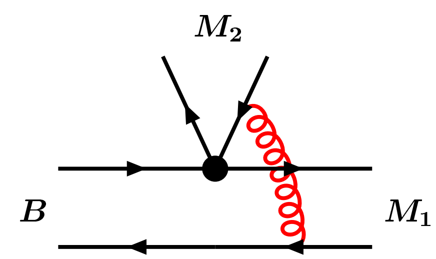
- A similar divergence was found in hadron-hadron collisions $H_1 + H_2 \to H_3 + H_4 + X$.

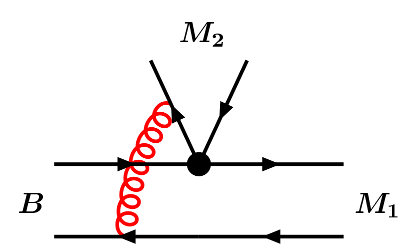
Collins, Qiu (07); Collins (07)



- The residual divergence can be factorized into a soft factor S_e using contour deformation and eikonal approximation.

Li, S.M. (09); Chang, Li (09)

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

- Similarly, corrections to  yield $e^{-iS_e}\mathcal{M}_b^{(\mathrm{LO})}$.

- $e^{iS_e(\mathrm{b})} = \langle 0|W_+(0,\mathrm{b};-\infty)W_+(0,\mathrm{b};\infty)^\dagger W_-(0,0_T;\infty)W_-(0,0_T;-\infty)^\dagger|0\rangle$

$$W_\pm(z^\pm, z_T;\infty) = P\exp\left[-ig\int_0^\infty d\lambda n_\pm \cdot A(z+\lambda n_\pm)\right]$$

depends on the transverse separation

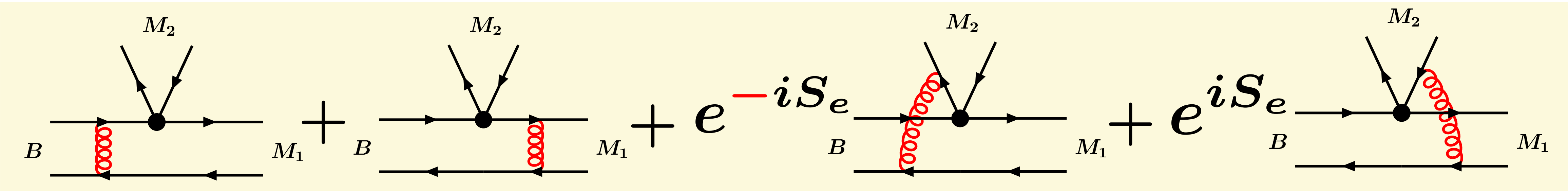
Soft contribution to C

Li, S.M. (09)

- "Modified" factorization formula:

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

- 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*

- The soft factor should be studied by nonpert. methods, but we treat it as a parameter.

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

Pion vs. Rho meson

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

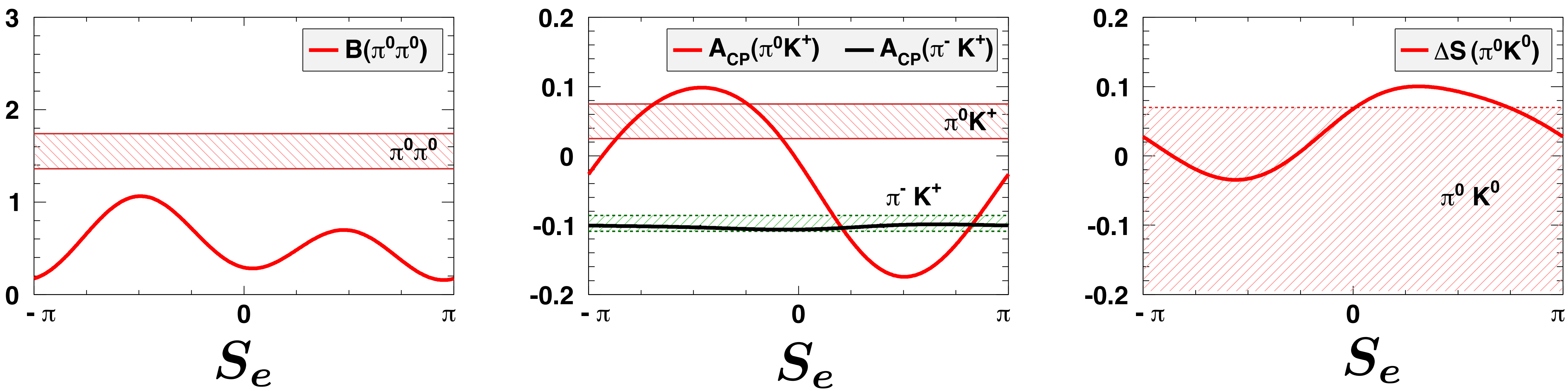
- Key: How to accommodate the simultaneous role of the pion as a $q\bar{q}$ state like ρ and an almost massless NG boson?
- The valence $q\bar{q}$ pair must be close enough to reduce the confinement effect: $r < O(1/m_\rho)$. If the pair is separated far apart, the linear potential will give the pion a high mass.
- $r = O(1/m_\rho)$ 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 decays with $\pi(\rho)$.

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

Li, S.M. (09)



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

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Glauber divergence in collinear factorization

- Since the Glauber divergence is purely imaginary, it does not affect cross sections at NLO in collinear factorization.

real

$$|\mathcal{M}|^2 \approx |\mathcal{M}^{(0)}|^2 + 2\,\mathrm{Re}[\mathcal{M}^{(0)}\mathcal{M}^{(1)*}]$$

- Moreover, Collins showed that the Glauber divergences cancel in the sum of diagrams, when integrating over kT's, in hadron-hadron collisions up to the two-loop level. *Collins (07)*

- The Glauber divergence may appears at the amplitude level in collinear factorization.

4. SM tests in $B \to \pi K$

SM tests in $B \to \pi K$

	Data *HFAG (10)*
$A_{\rm CP}(\pi^\pm K^0)$	0.009 ± 0.025
$A_{\rm CP}(\pi^0 K^\pm)$	0.050 ± 0.025
$A_{\rm CP}(\pi^\mp K^\pm)$	$-0.098^{+0.012}_{-0.011}$
$A_{\rm CP}(\pi^0 K^0)$	-0.01 ± 0.10

- A robust sum rule: *Gronau (05)*

$$A_{\rm CP}(\pi^\mp K^\pm) + A_{\rm CP}(\pi^\pm K^0)\,\frac{B(\pi^\pm K^0)}{B(\pi^\mp K^\pm)}\,\frac{\tau_0}{\tau_+} = A_{\rm CP}(\pi^0 K^\pm)\,\frac{2B(\pi^0 K^\pm)}{B(\pi^\mp K^\pm)}\,\frac{\tau_0}{\tau_+} + A_{\rm CP}(\pi^0 K^0)\,\frac{2B(\pi^0 K^0)}{B(\pi^\mp K^\pm)}$$

⇨ The current data predict $A_{\rm CP}(\pi^0 K^0) = -0.15 \pm 0.04$

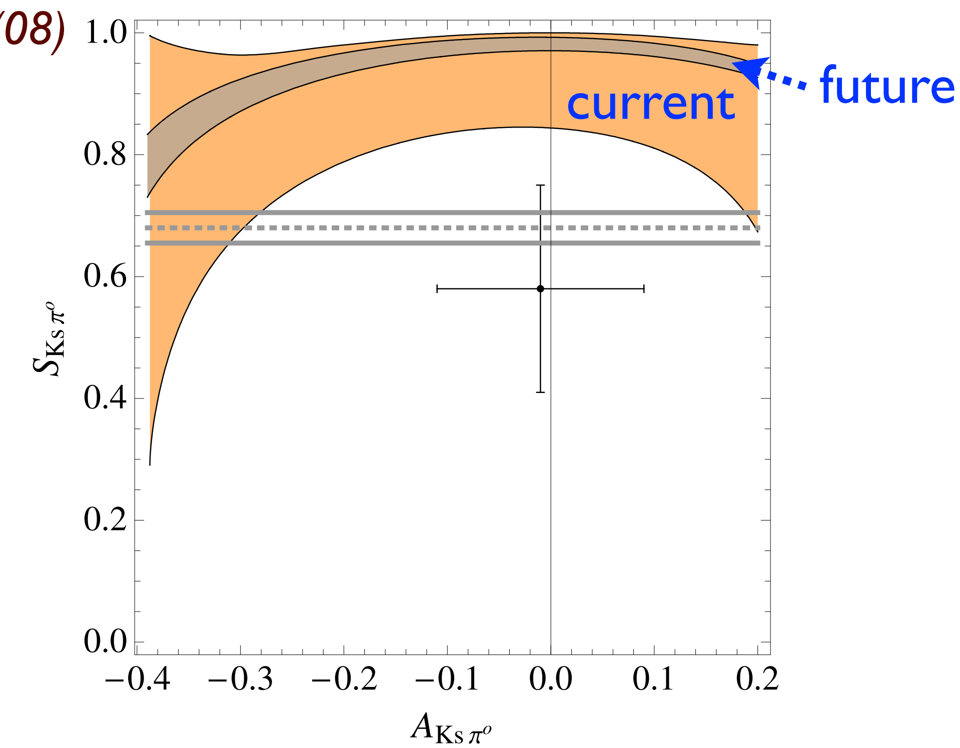
- Correlation between $A_{\rm CP}(\pi^0 K_S)$ and $S_{\pi^0 K_S}$

Fleischer, Jaeger, Pirjol, Zupan (08)
Gronau, Rosner (08)

Isospin relation:

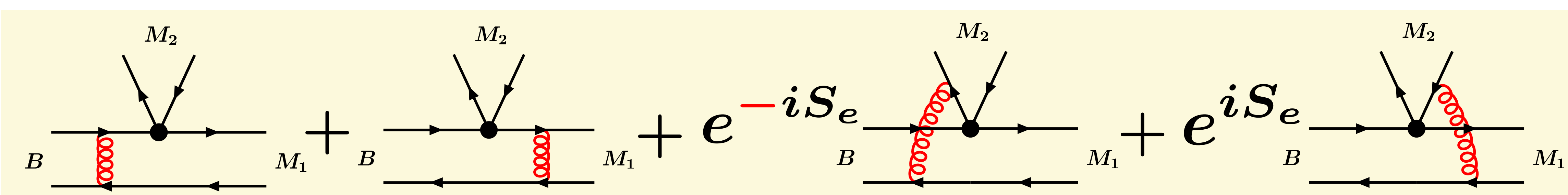
$$\sqrt{2}A(\pi^0 K^0) + A(\pi^- K^+) = -(\hat{T} + \hat{C})e^{i\gamma} - \hat{P}_{ew} \equiv 3A_{3/2}$$

fixed by $B(\pi^\pm \pi^0)$ with SU(3)



5. Summary

- The current data require a larger C with a sizable strong phase.
- In QCDF, significant power corrections may be a source of the large C.
- In PQCD, there exist uncanceled Glauber div's, which can be factorized into a soft factor.



⇨ C could be enhanced. $\frac{C}{T} \approx 0.5\, e^{-2.2i}$

- Future precise measurements of the CP asym's in $B \to \pi K$ will provide stringent tests of the SM.

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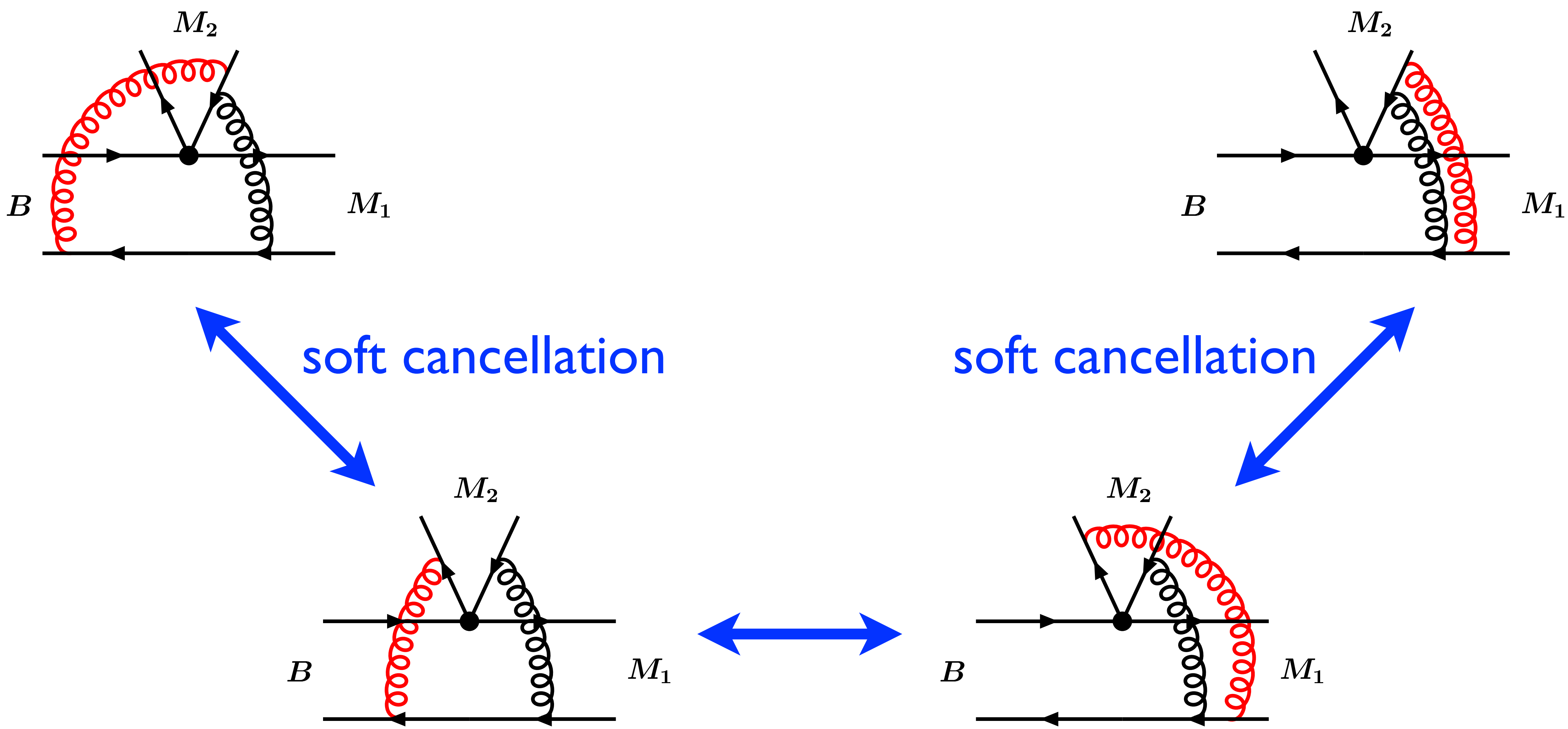
Backup Slides

Uncanceled Soft (Glauber) divergence

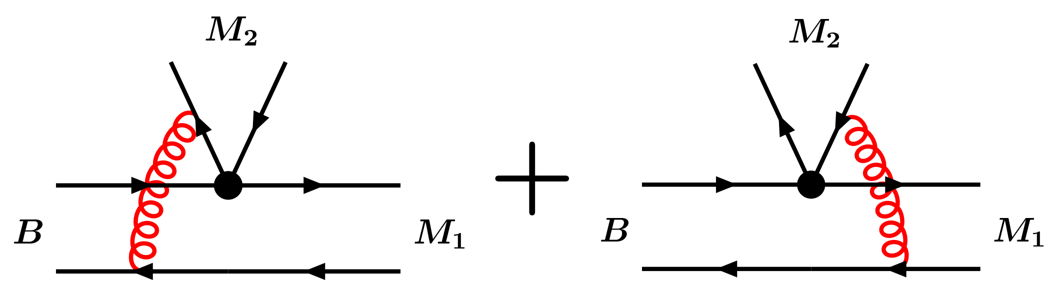


collinear cancellation

but Glauber divergence remains in the sum.

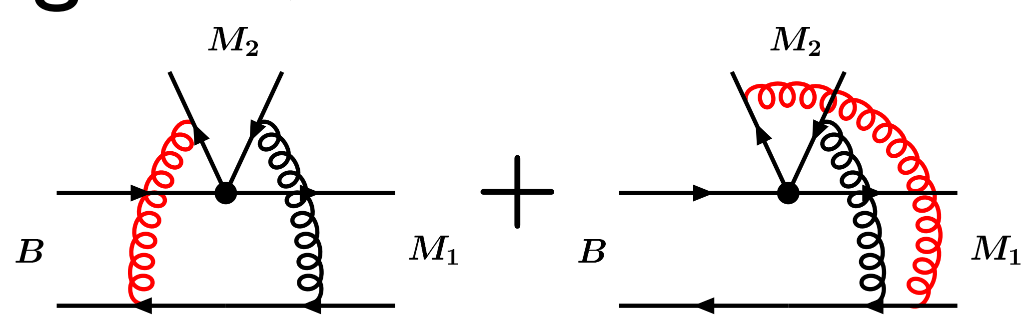
Glauber div. at the amplitude level in QCDF

- Only a single spin structure of the B meson wave function contributes to the sum of the spectator diagrams:



$$\longrightarrow \quad (\not{P}_B + m_B)\gamma_5 \not{n}_+ \phi_B^+(x)$$

- Applying the same spin structure to higher-order diagrams, no Glauber div. appears.



with $(\not{P}_B + m_B)\gamma_5 \not{n}_+ \phi_B^+(x)$

$$(\not{P}_B + m_B)\gamma_5 \not{n}_- \phi_B^-(x)$$

- We expect that the other structure yields Glauber div's at the amplitude level, (but they cancel in the sum after integrating over kT).