Entanglement in Hard Scattering

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Frascati March 18

Types of QCD Factorization

- Parton Model:
  - Classical probability intuition
  - Unique universal PDFs -> clear hadron structure interpretation.

Strong Factorization

- Collinear Factorization in real pQCD:
  - Like parton model but with caveats.
    - Optimal choice of μ is hard scale dependent -> ***Evolution***

Caveats Needed

- TMD Factorization in DY, SIDIS in real pQCD:
  - Like Collinear but with even more caveats.
    - **Sivers sign flip** = non-universality from Wilson line geometry.
    - **Soft Evolution** = Strongly universality scaling violations.

More caveats

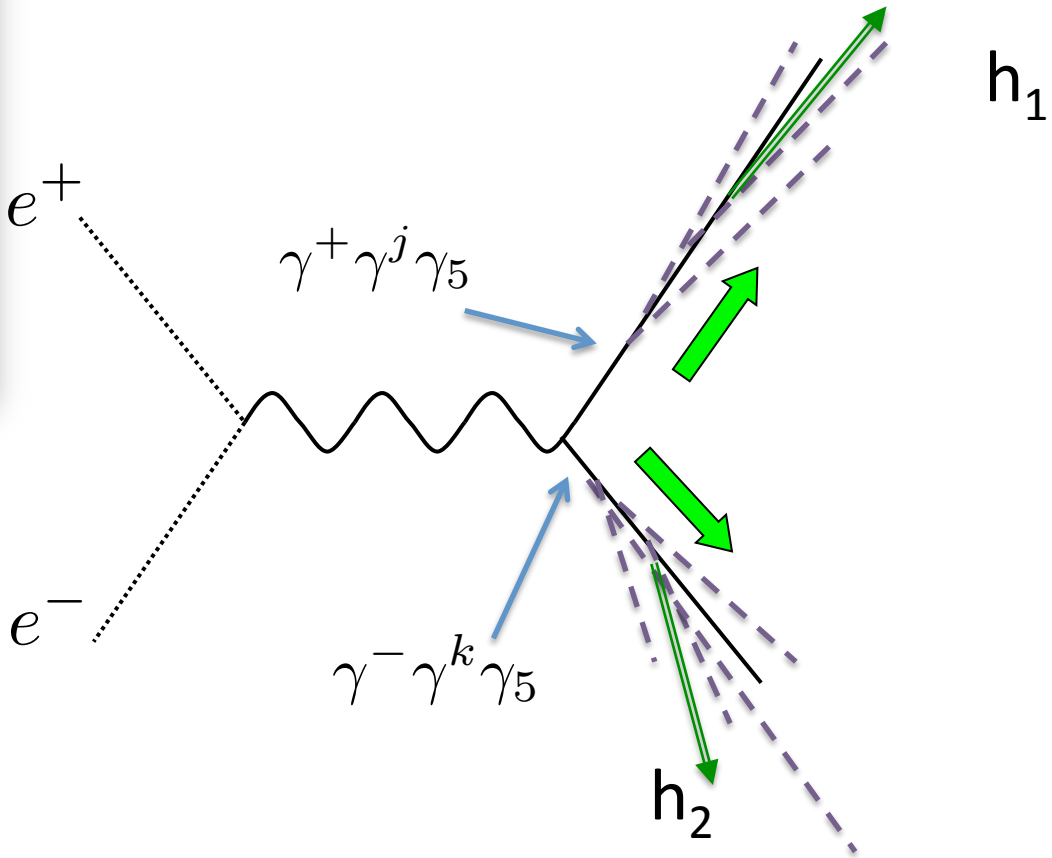
- TMD Factorization for back-to-back $H_1 + H_2 \rightarrow H_3 + H_4 + X$:
  - No disentangling… even through complex Wilson lines.
  - Ward identities incompatible with separate gauge invariant definitions.

Still more caveats?

Collins-Type Effects

"This implies that the quark and antiquark are individually unpolarized, but that their spins are correlated; the spin state is thus an entangled state."

- J. C. Collins, textbook (2011)

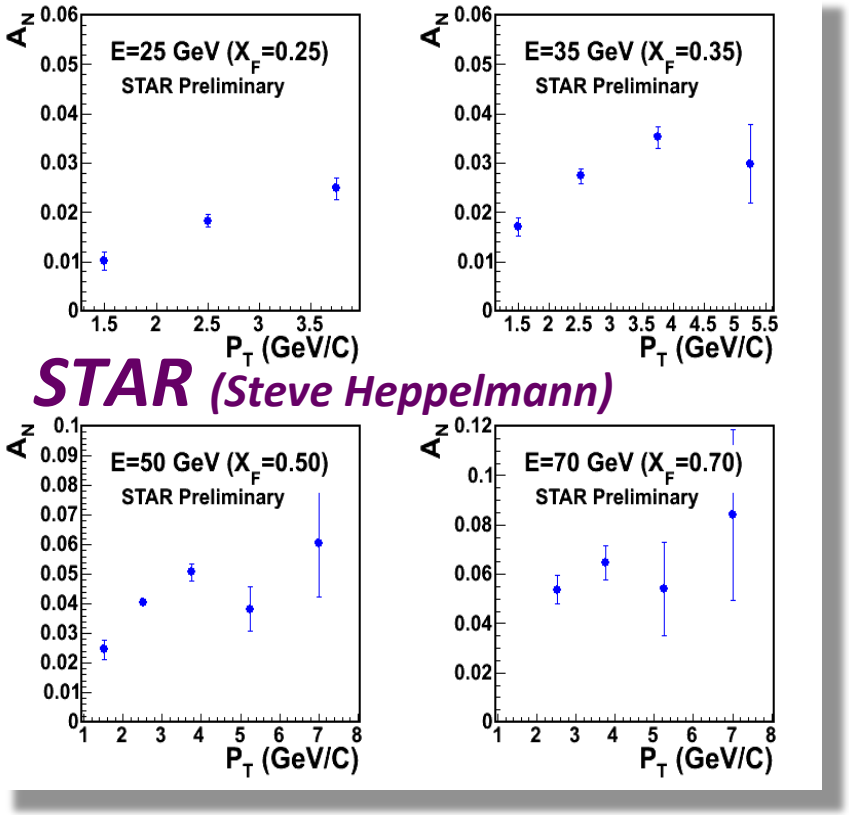


TMD in Inclusive Scattering

1) Transverse single spin asymmetries:

2) Hyperon transverse polarization (1976-) polarizing fragmentation function?

3) Prompt photon.



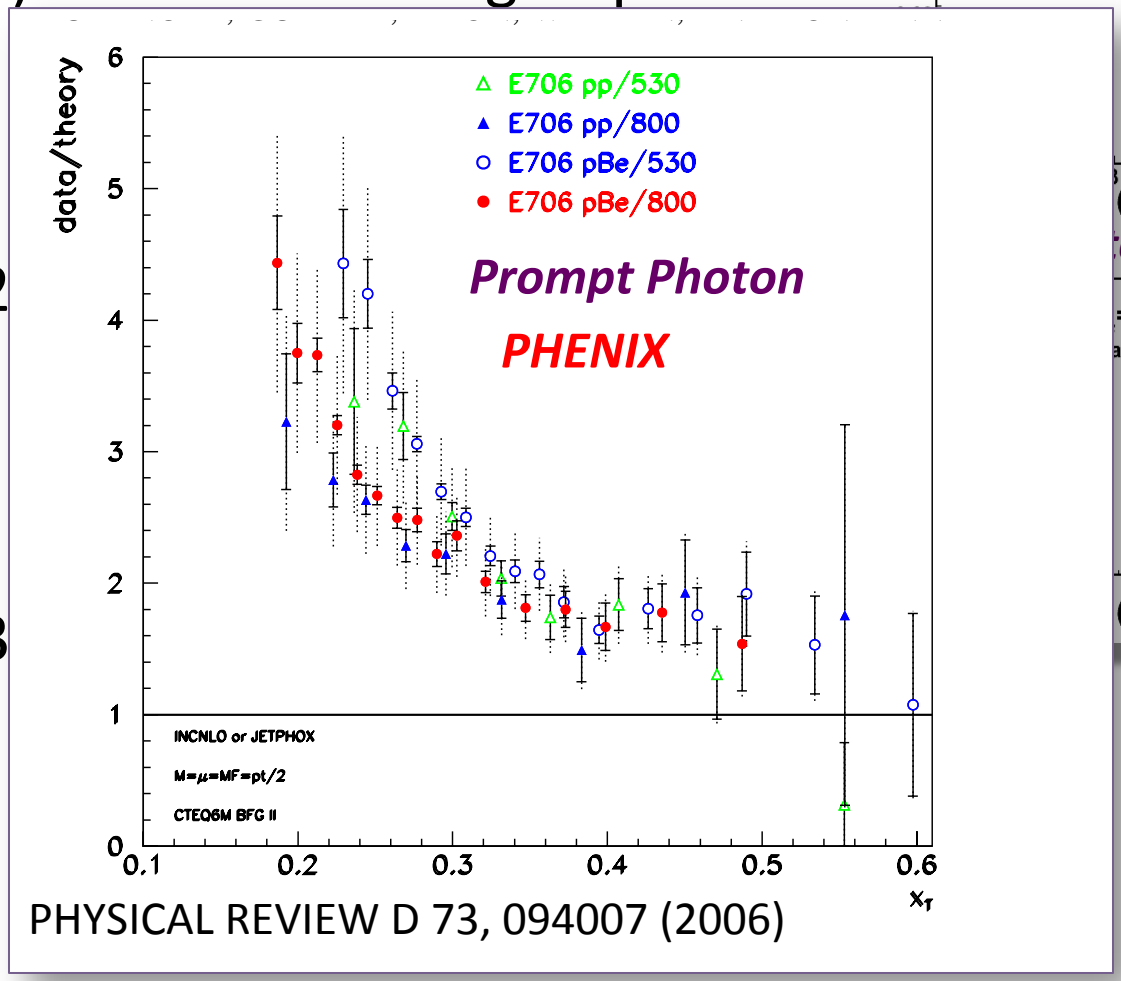
STAR ***(Steve Heppelmann)***

TMD in Inclusive Scattering

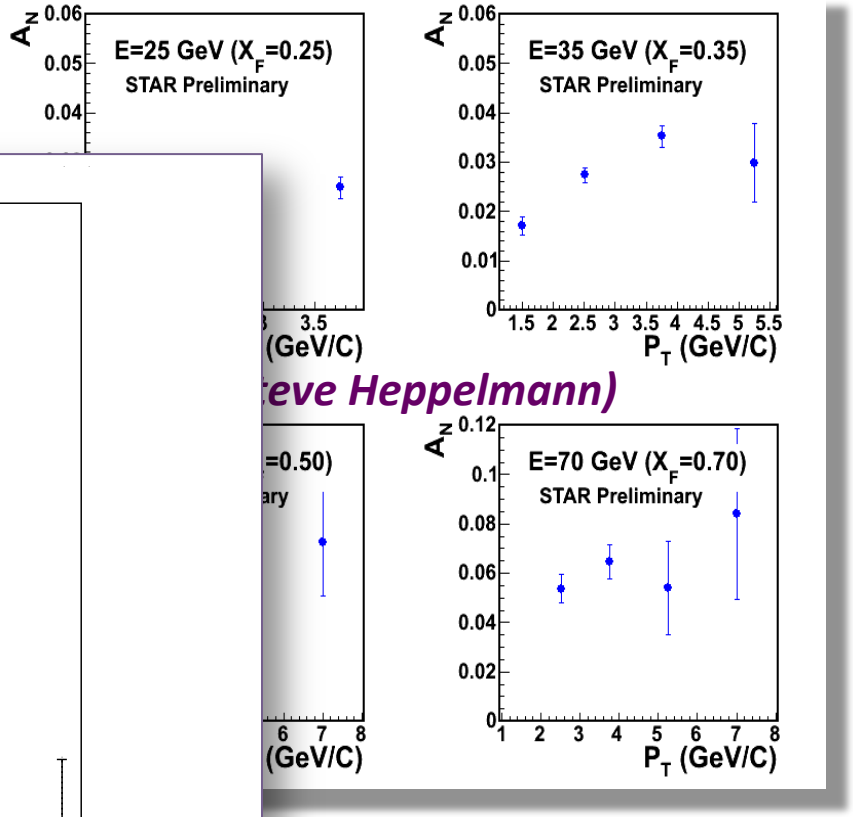
1) Transverse single spin

2

3



PHYSICAL REVIEW D 73, 094007 (2006)



(Steve Heppelmann)

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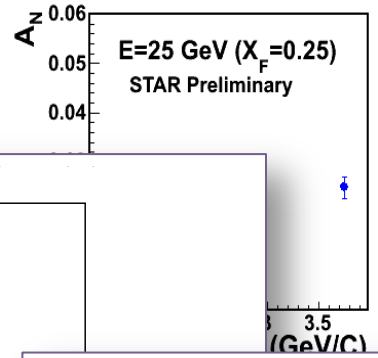

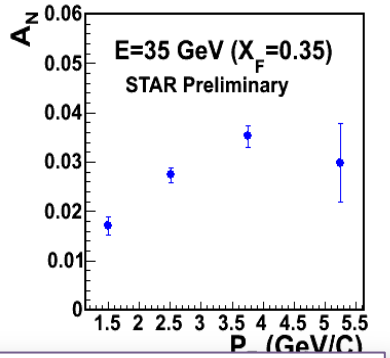

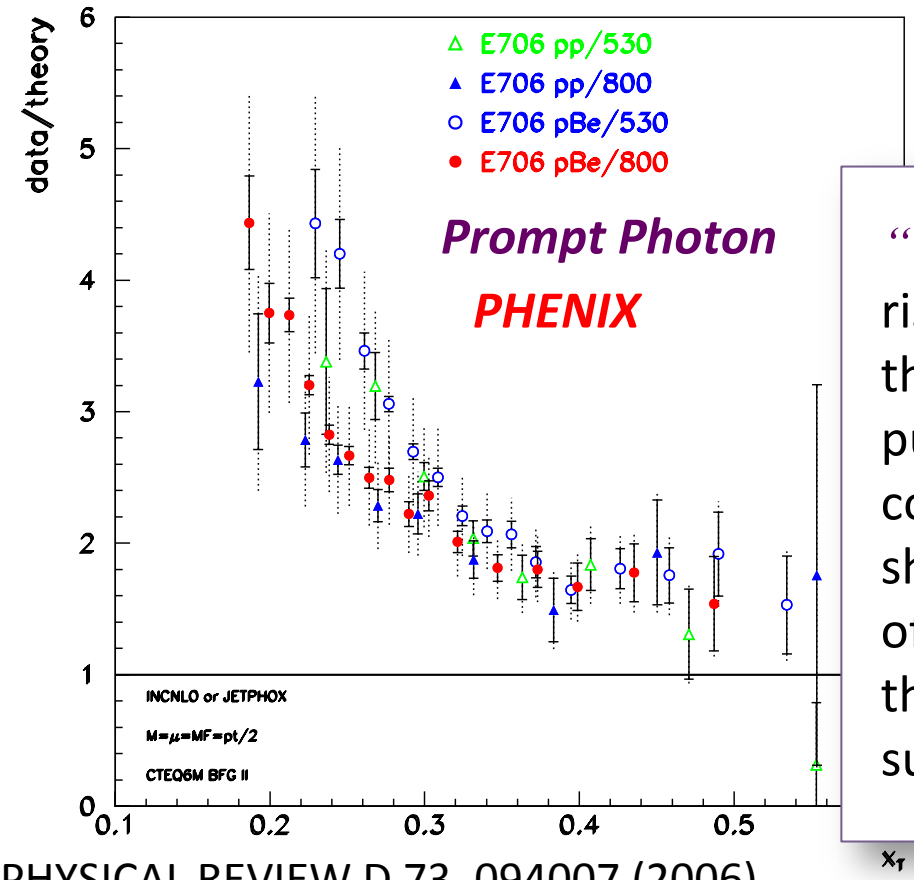

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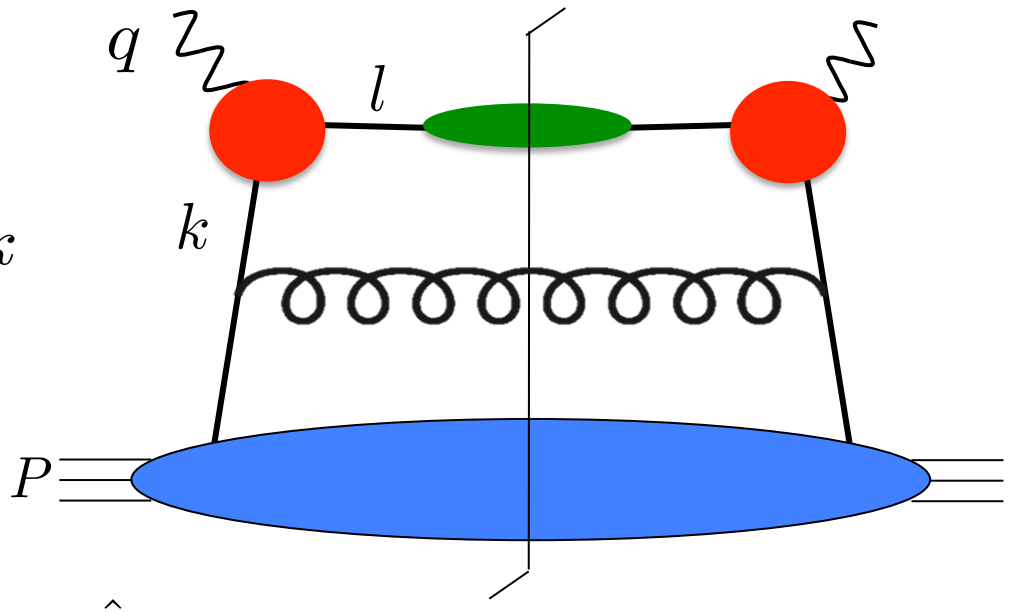
"NLO QCD cannot explain this rise and another mechanism, the $\mathbf{k_T}$-enhancement, has been put forward by the E706 collaboration to explain the shape and normalization of the cross sections. Let us note that no other experiment needs such an enhancement."

Transverse Momentum Dependent Functions at Large x?

$$\int d^4k$$



$$k^2_{T,\max} = \frac{\hat{s}}{4}$$

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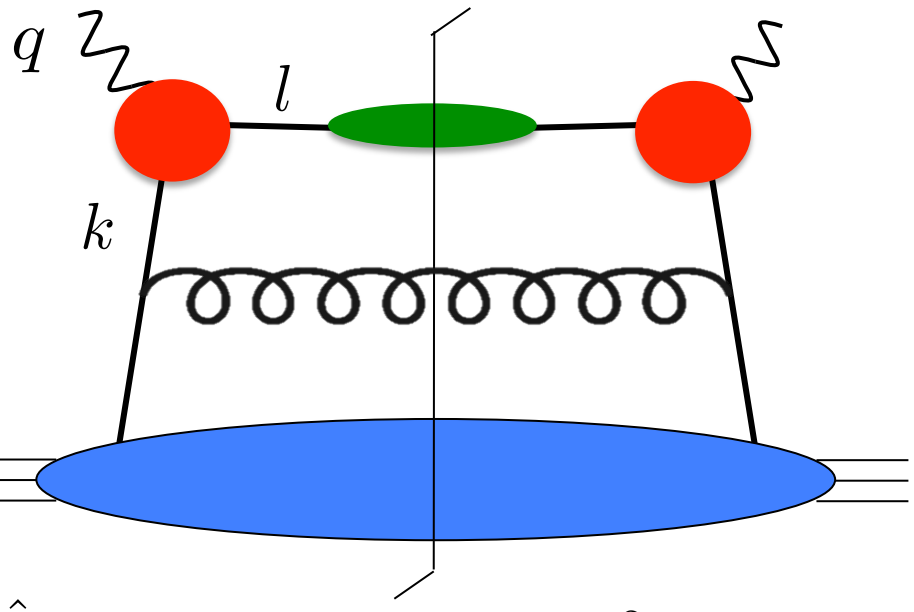

$$k^2_{T,\max} = \frac{\hat{s}}{4} \qquad \hat{s} = (q+\hat{k})^2 = \frac{Q^2(1-x/\xi)}{(x/\xi)} = \frac{Q^2(1-z)}{z}$$

$$x \to 1.0$$

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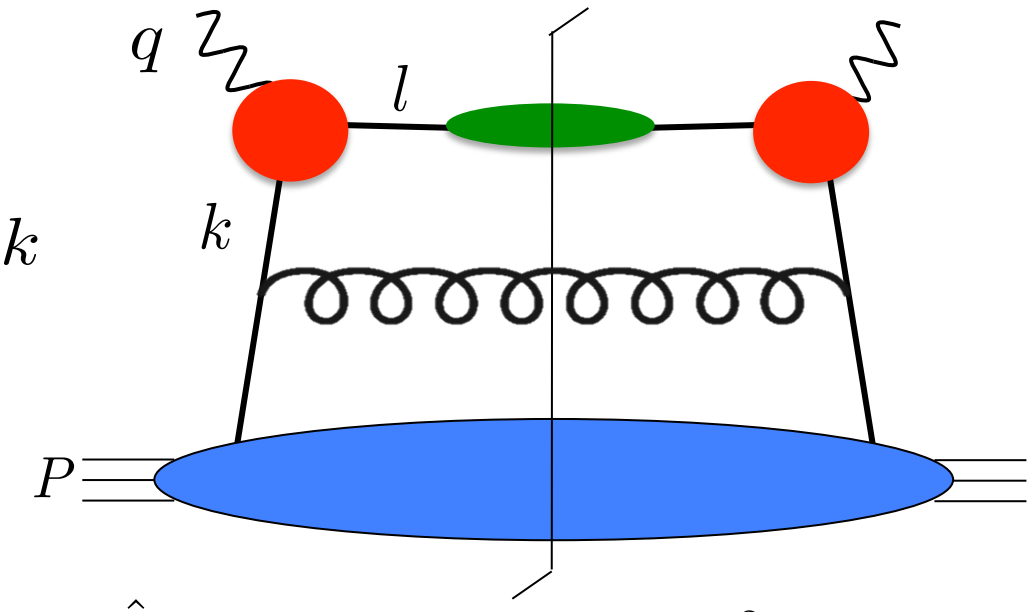

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$$H(x;\mu) \otimes f(x;\mu)$$

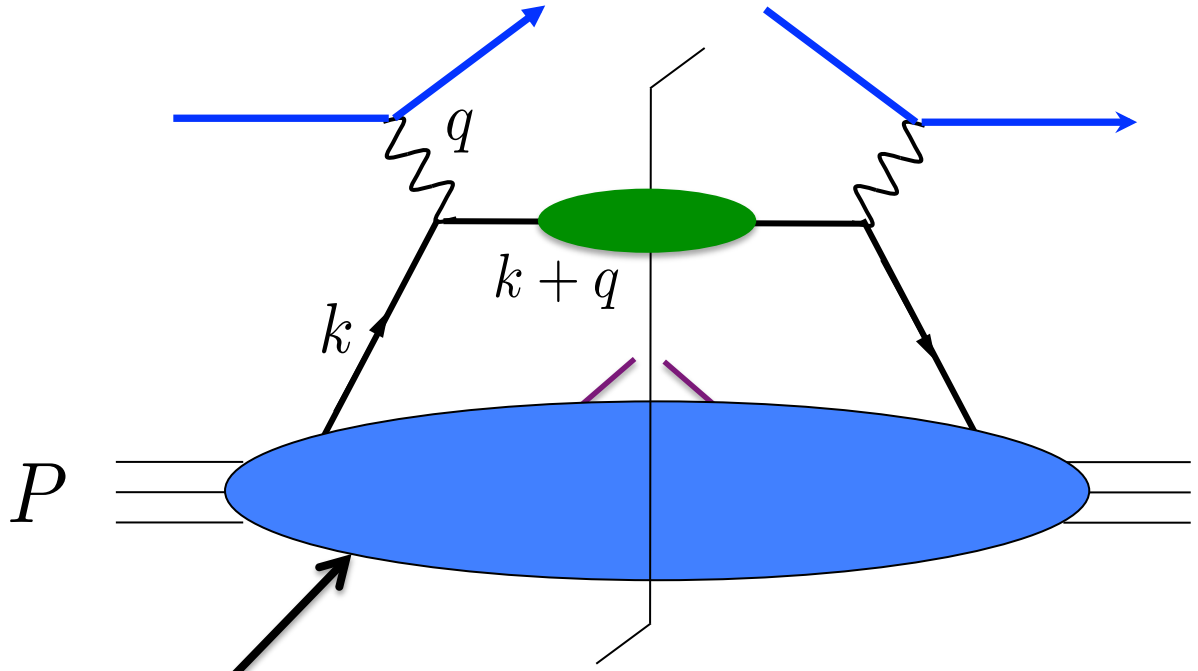
Collinear Factorization

Or?

$$\int^{k^2_{T,\max}} dk^2_T \underbrace{\frac{d\hat{\sigma}}{dx\, dk^2_T}}$$

TMD factorization

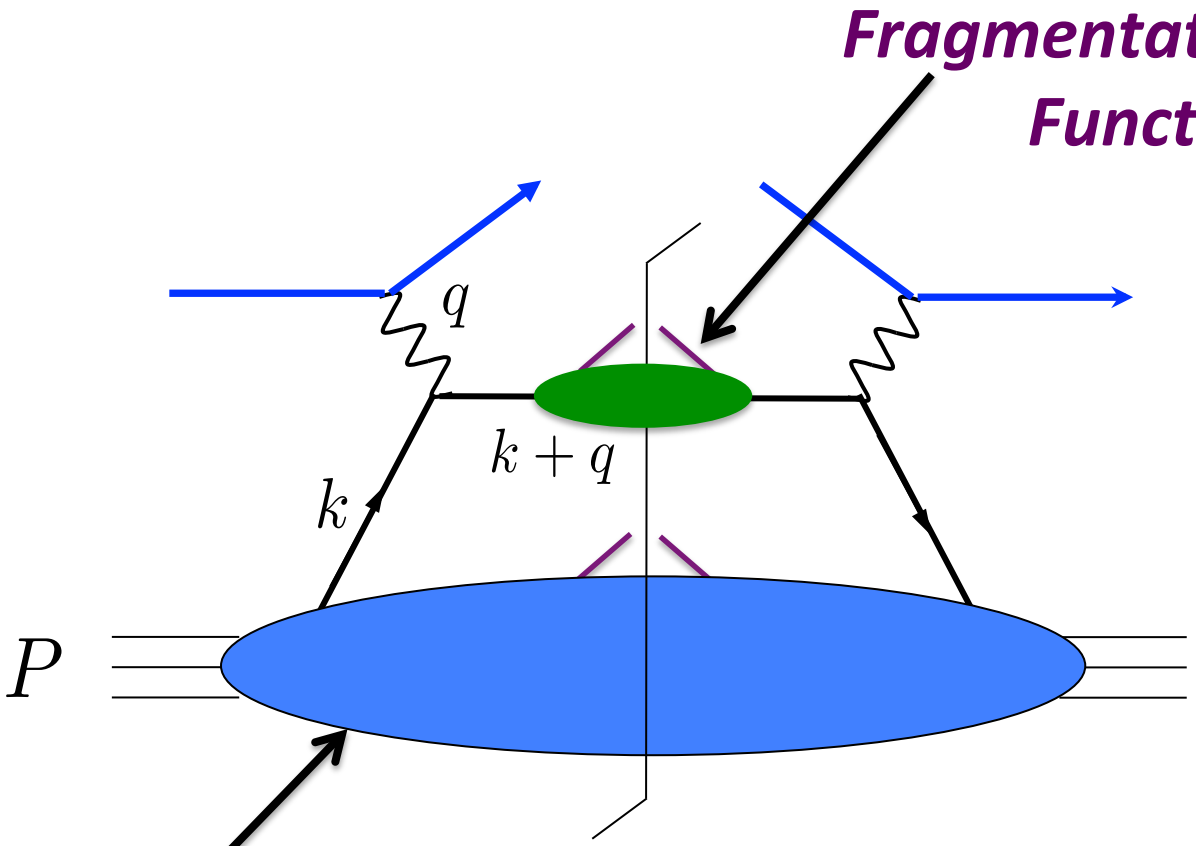
Transverse Momentum Dependent Fracture Functions



(M. Anselmino, V. Barone, A. Kotzinian, (2011))

Fracture Function

Transverse Momentum Dependent Fracture Functions



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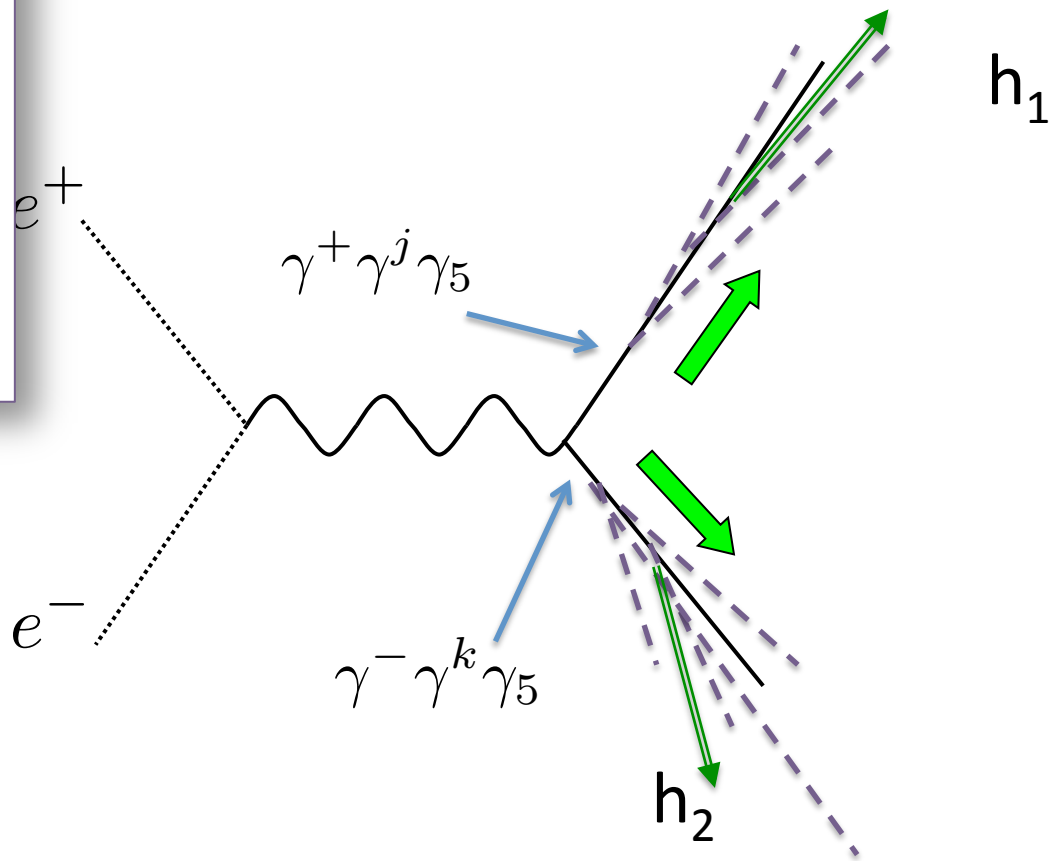

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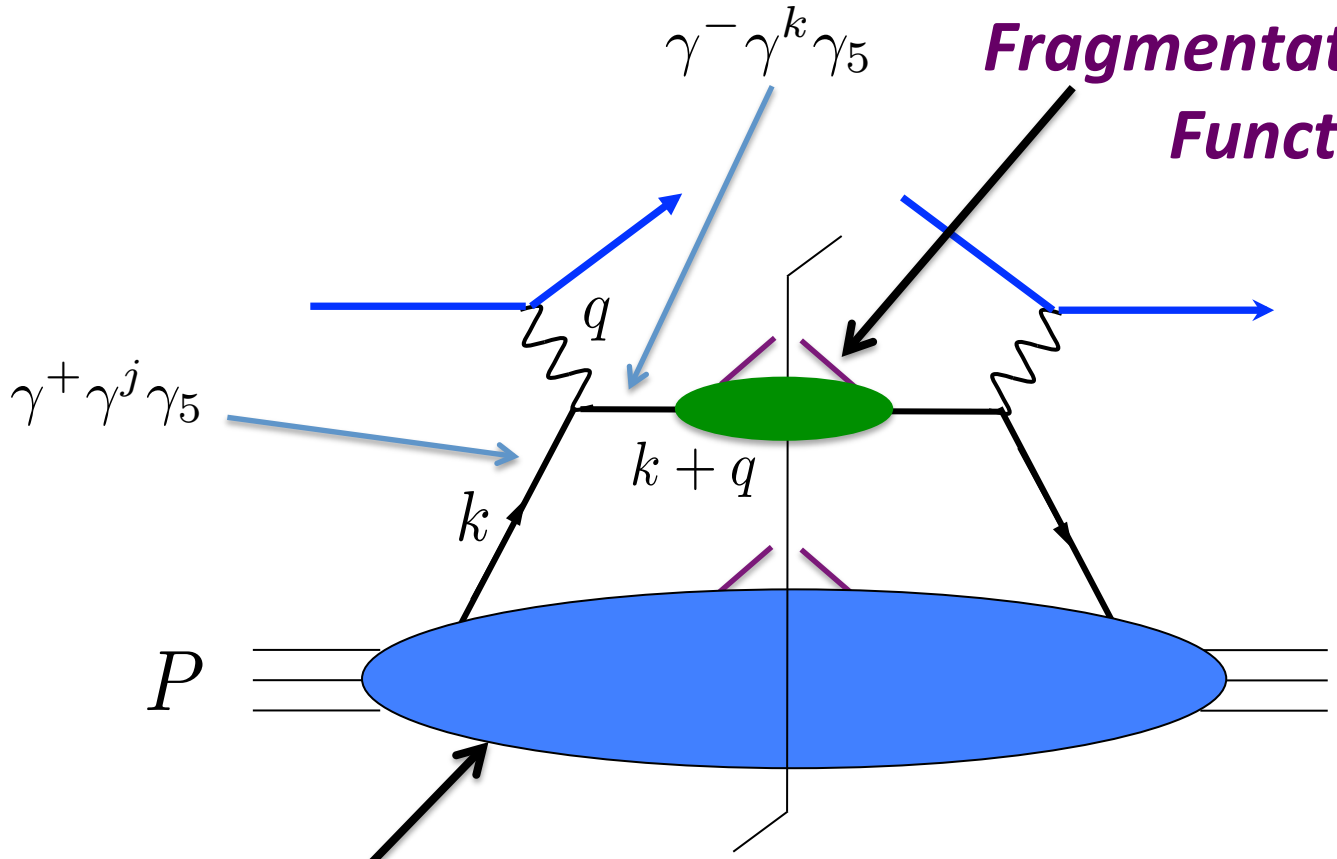

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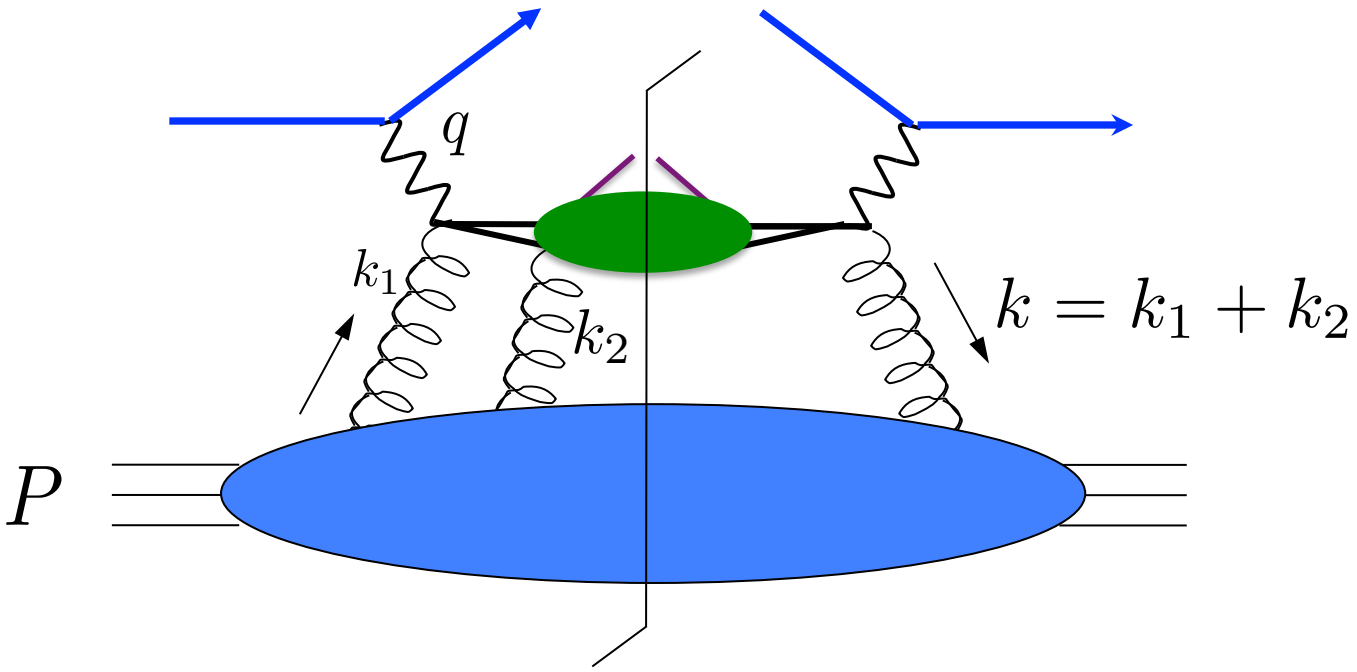
Transverse Momentum Dependence with Double Hadrons

- Additional structures accessible.
- Evolution (strongly universal).
- Details of fragmentation/hadronization process.

Gluon Effects

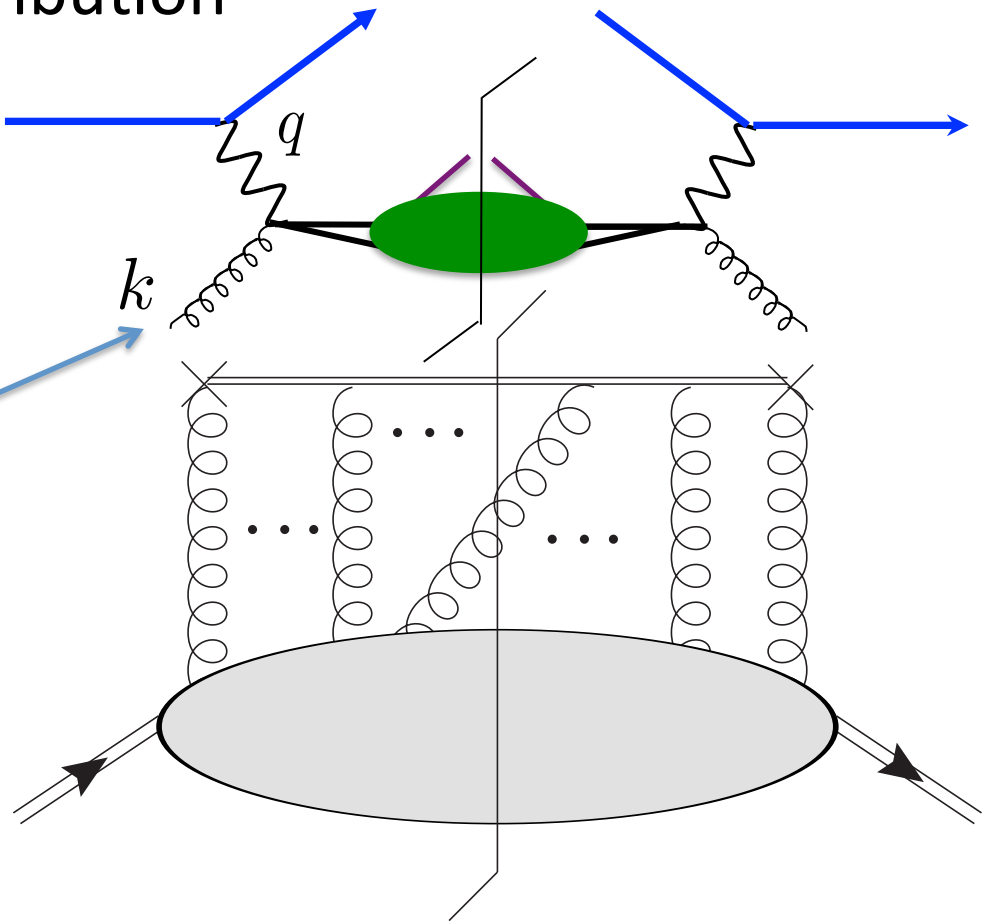
- Collinear Gluon Distribution -> TMD Gluon Distribution

Gluon Effects



Gluon Effects

- Gluon Distribution



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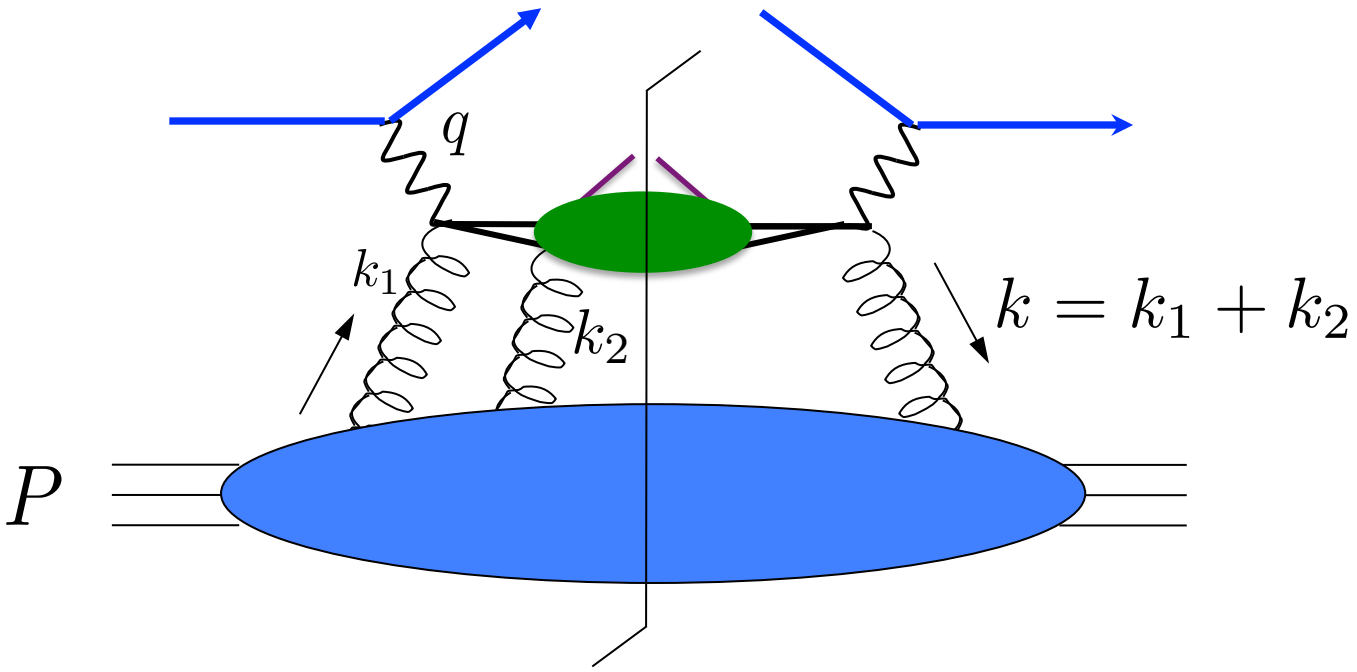
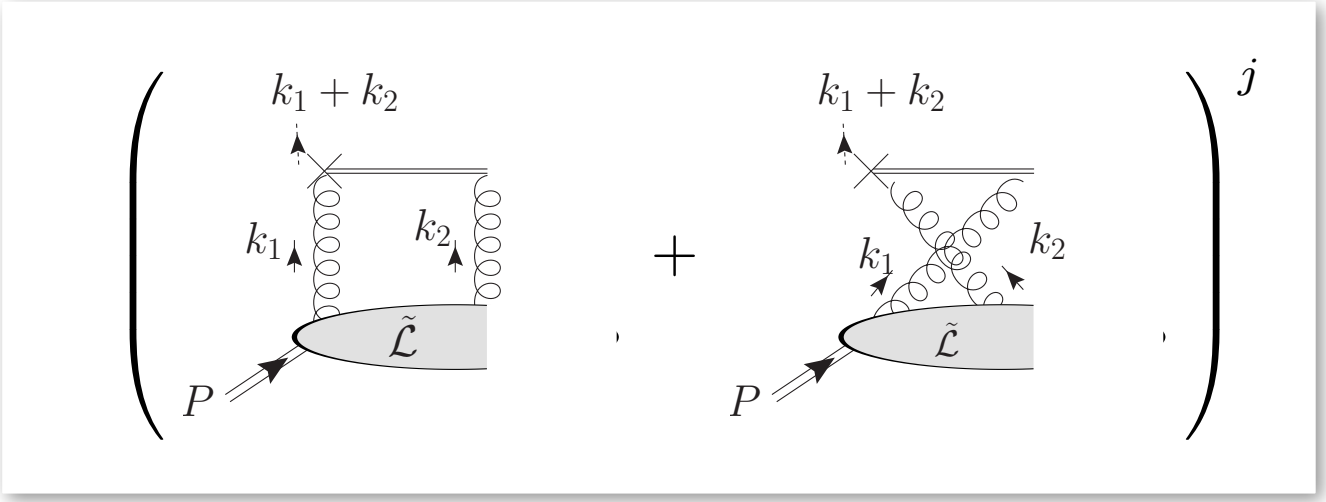


Superleading Contribution $\propto k_1^\mu k_2^\nu$

Gluon Effects

- Collinear Gluon Distribution: One Gluon



$$ig_s f_{\alpha\beta\kappa}\left[\frac{n_{\rm J}{}^{\mu_2}\mathcal{L}^{\alpha\beta}_{j\mu_2}}{k_2\cdot n_{\rm J}}-\frac{n_{\rm J}{}^{\mu_1}\mathcal{L}^{\alpha\beta}_{\mu_1 j}}{k_1\cdot n_{\rm J}}+\frac{n_{\rm J}{}^{\mu_1}n_{\rm J}{}^{\mu_2}}{(k_1+k_2)\cdot n_{\rm J}}\left(\frac{k_{2\,j}}{k_1\cdot n_{\rm J}}-\frac{k_{1\,j}}{k_2\cdot n_{\rm J}}\right)\mathcal{L}^{\alpha\beta}_{\mu_1\mu_2}\right]$$

(J. Collins ,TCR (2013))

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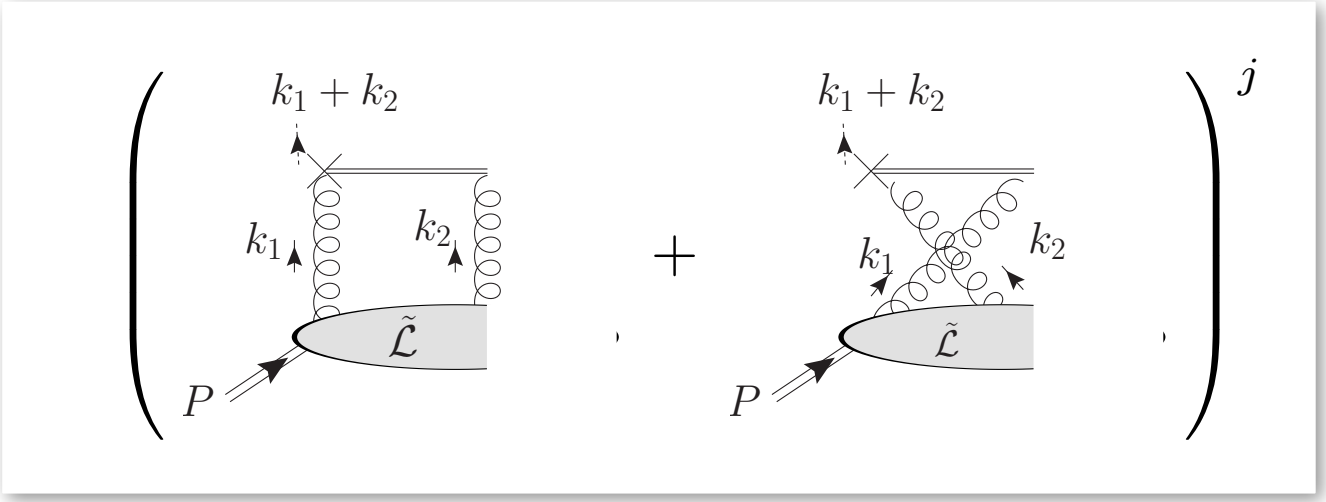

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Familiar Eikonal Lines

(J. Collins ,TCR (2013))

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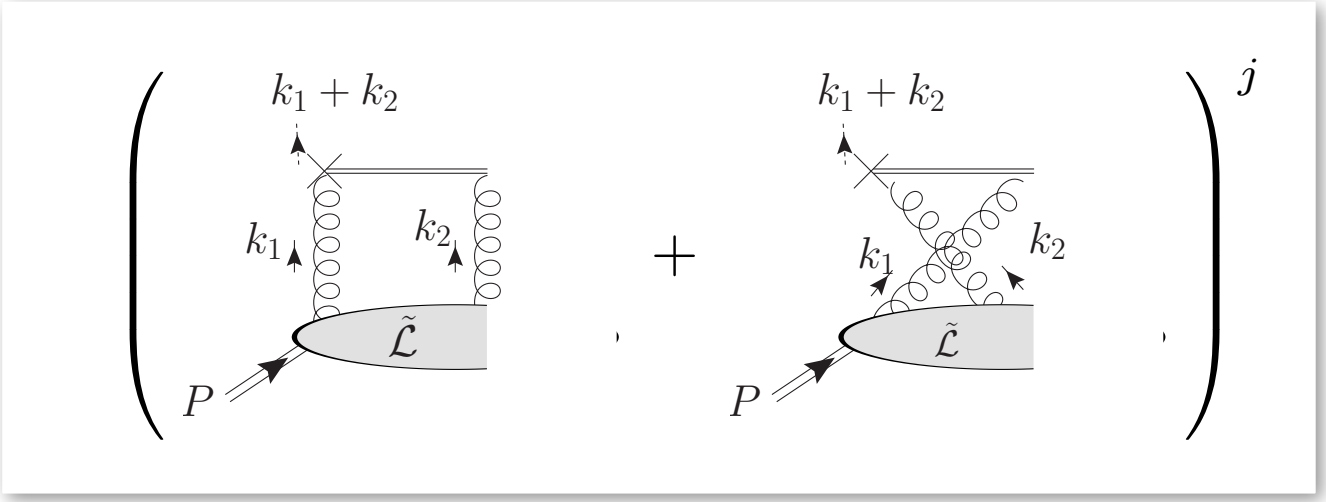

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Familiar Eikonal Lines

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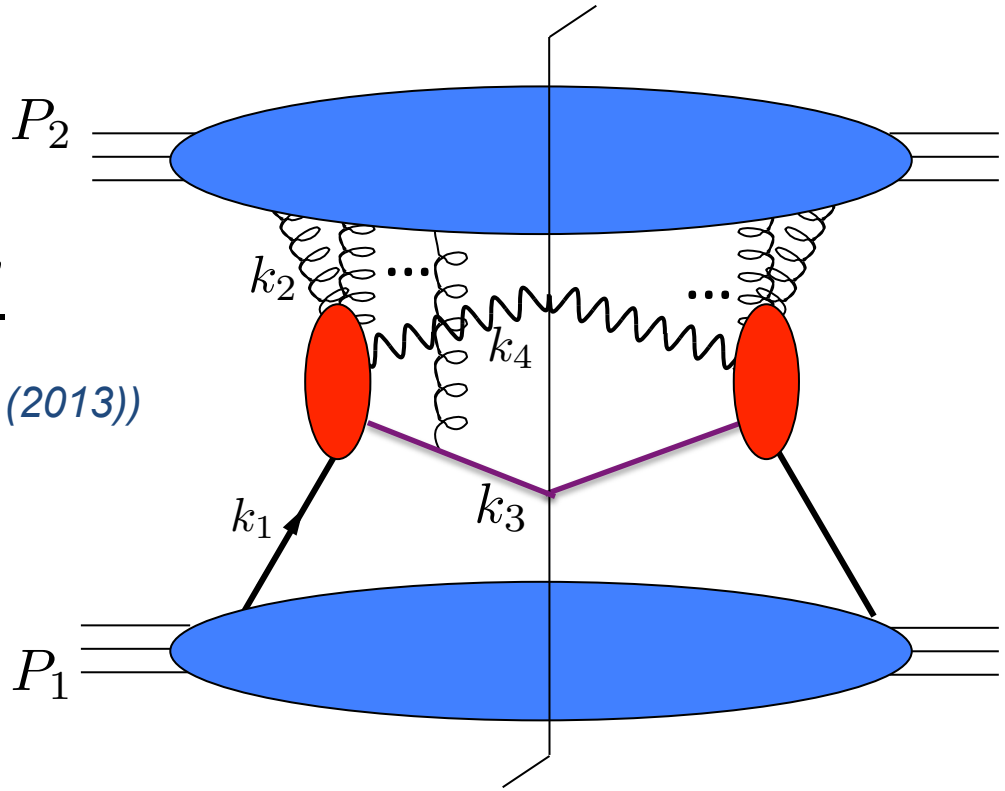
Extra Transverse Momentum Dependence

Gluon Effects

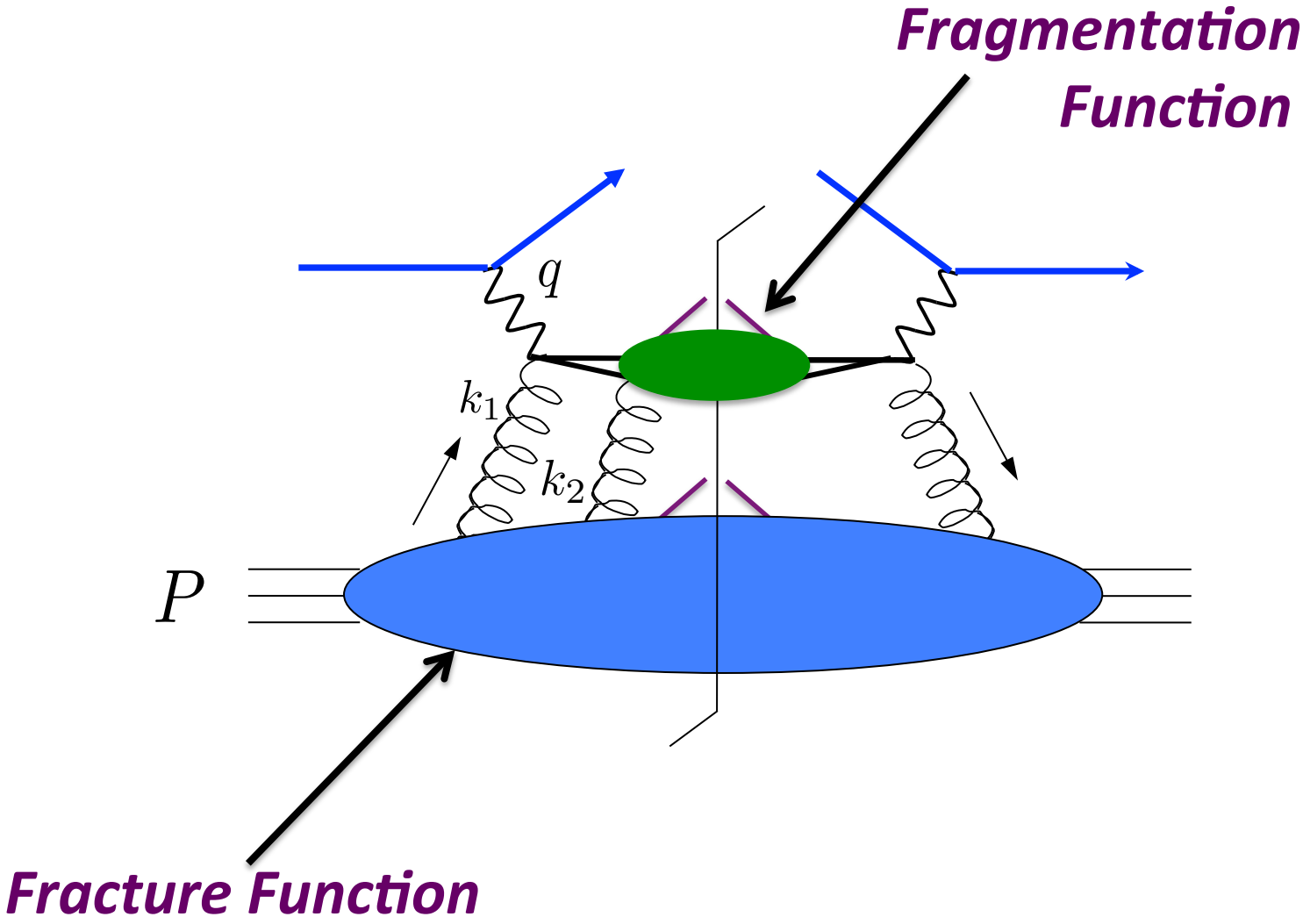
Example:

(TCR (2013))



$P_1 + P_2 \rightarrow \gamma$ + Hadron

Gluon Effects



Conclusions

- Interesting QCD effects beyond strong (parton model) factorization.

- Kinematics and transverse momentum in inclusive processes?

- Fracture functions and entanglement: new operators structures to probe.

  (See M. Anselmino, V. Barone, A. Kotzinian, (2011))

- Gluon target effects?