Unintegrated Parton Densities

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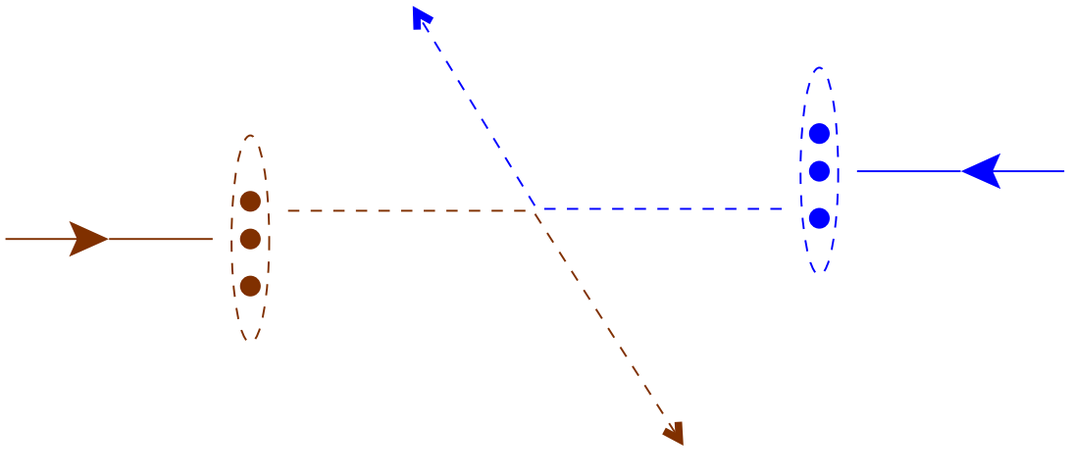
Summary

- Factorization; unintegrated pdfs: When & why?
- Eikonal propagation of fast partons
  - SSA etc
  - Evolution
- Factorization breaking

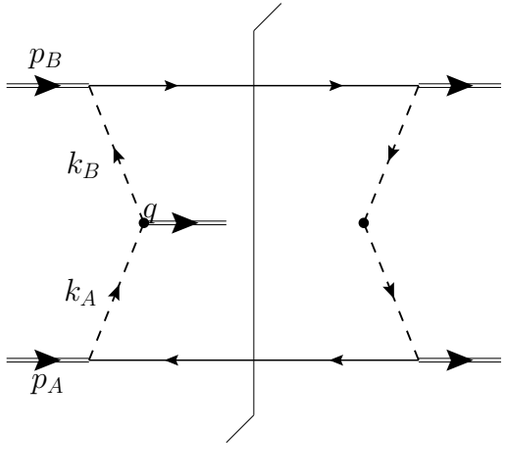
Basic idea of factorization



- Time dilated and Lorentz contracted beam particles
- Short-distance hard scattering
- Pdf $f_{i/p}(x)$ as probability density
  - Depends on longitudinal momentum fraction
  - Parton k_T and k^2 integrated over (neglected in hard scattering)
  - Fragmentation fn. similarly.
- Factorization formula for e.g., $H_1 + H_2 \to H_3 + H_4 + X$, high p_T
- Predictions: from universality of pdfs, perturbative calculations of hard scattering

Unintegrated parton densities

- E.g., Drell-Yan cross section with measured q_T (in model):
- In model:



- Can*not* neglect parton k_T in hard scattering
- $\dfrac{d\sigma}{d^4q} \propto \int d^2k_T\, P_{\bar{q}}(x_1, k_T)\, P_q(x_2, q_t - k_T)\, \hat{\sigma}_{q\bar{q}} \ldots$

Unintegrated parton densities

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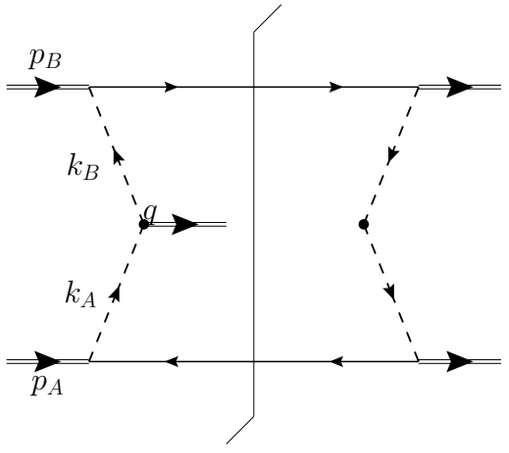

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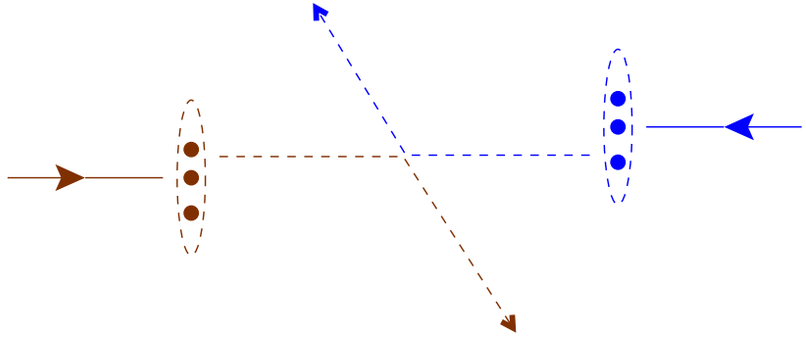
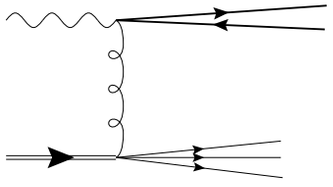
- Similarly for out-of-plane p_T in $H_1 + H_2 \to H_3 + H_4 + X$:



Where need for unintegrated pdfs etc shows up:

E.g.: γ-prod. of $c\bar{c}$:

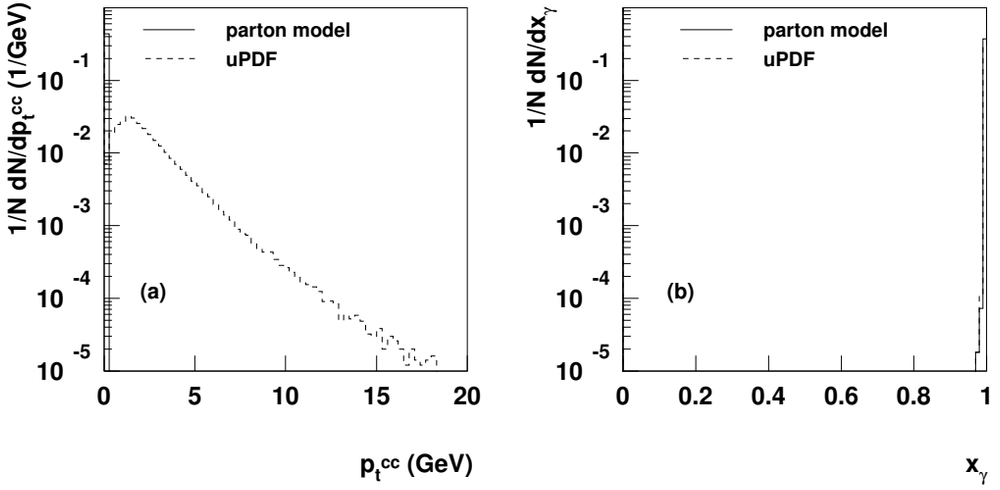


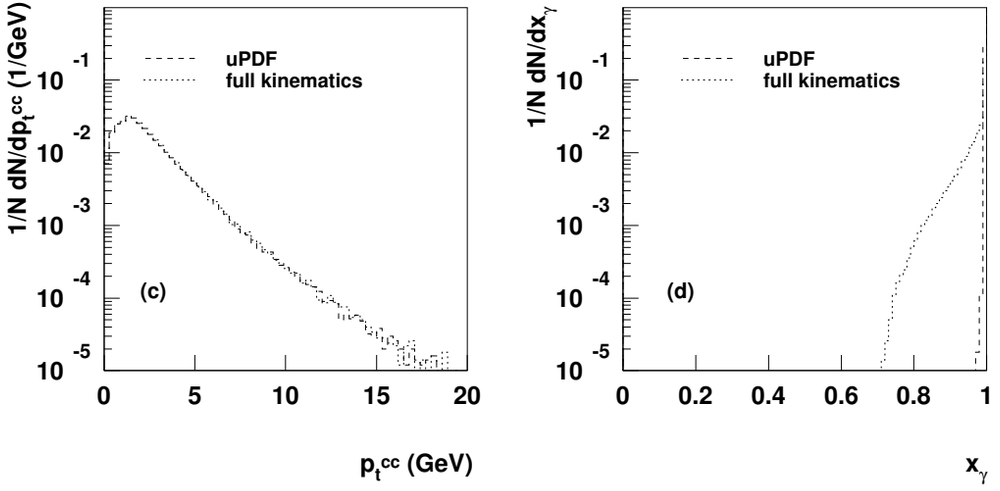
Differential cross section:

$p_T \Longrightarrow$ unint. pdf

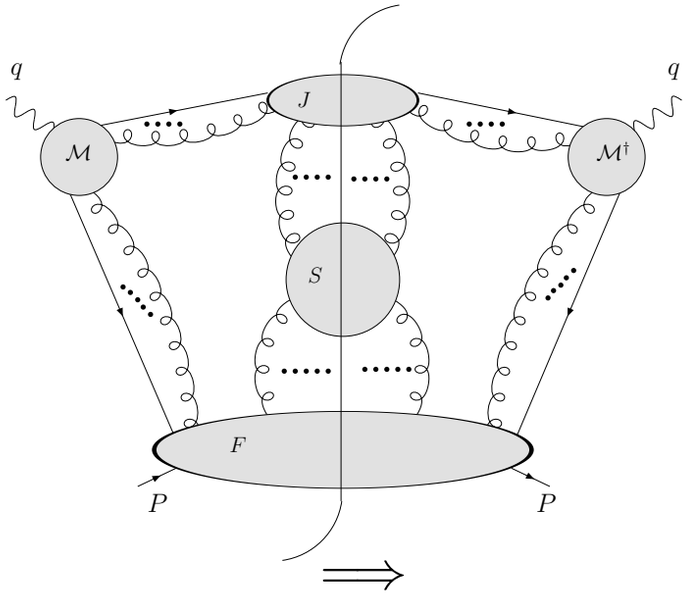
$x_\gamma \Longrightarrow$ parton correl. fn.

(Plots: JCC & Jung,
arXiv:hep-ph/0508280)

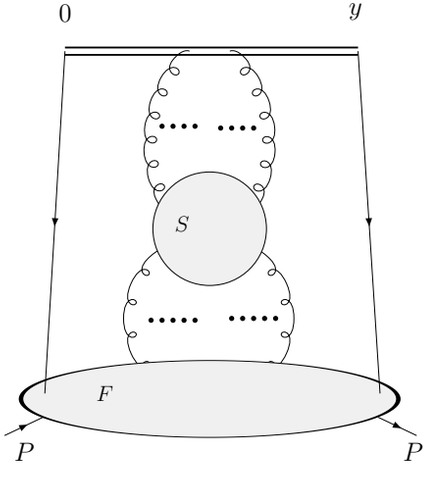




Propagation of quark; Wilson lines in definition of pdf



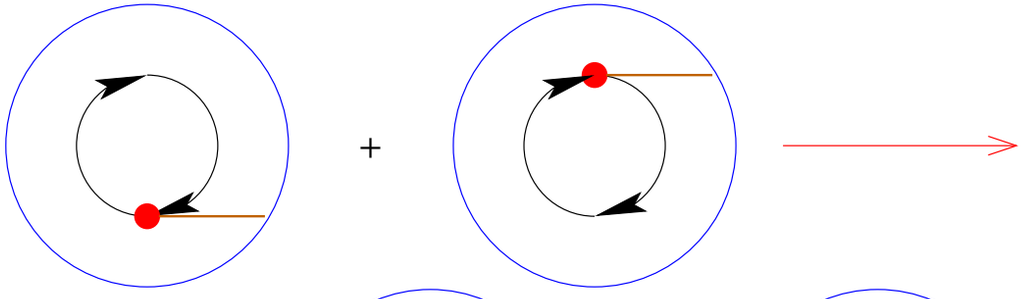
$\Longrightarrow$



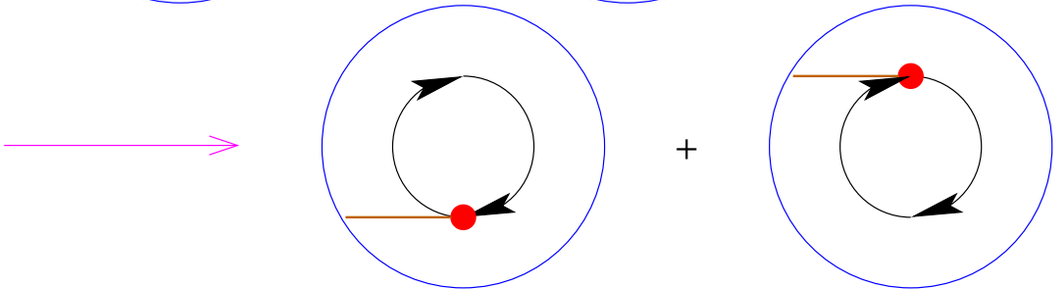
pdf $=$ $= \mathsf{FT\ of}\ \langle p,s|\ \overline{\psi}(y)\, W(y,\infty)^\dagger\ W(0,\infty)\,\psi(0)\ |p,s\rangle$

DIS v. DY; Sivers function; modified universality

SIDIS:



DY:



Future- v. past-pointing propagation

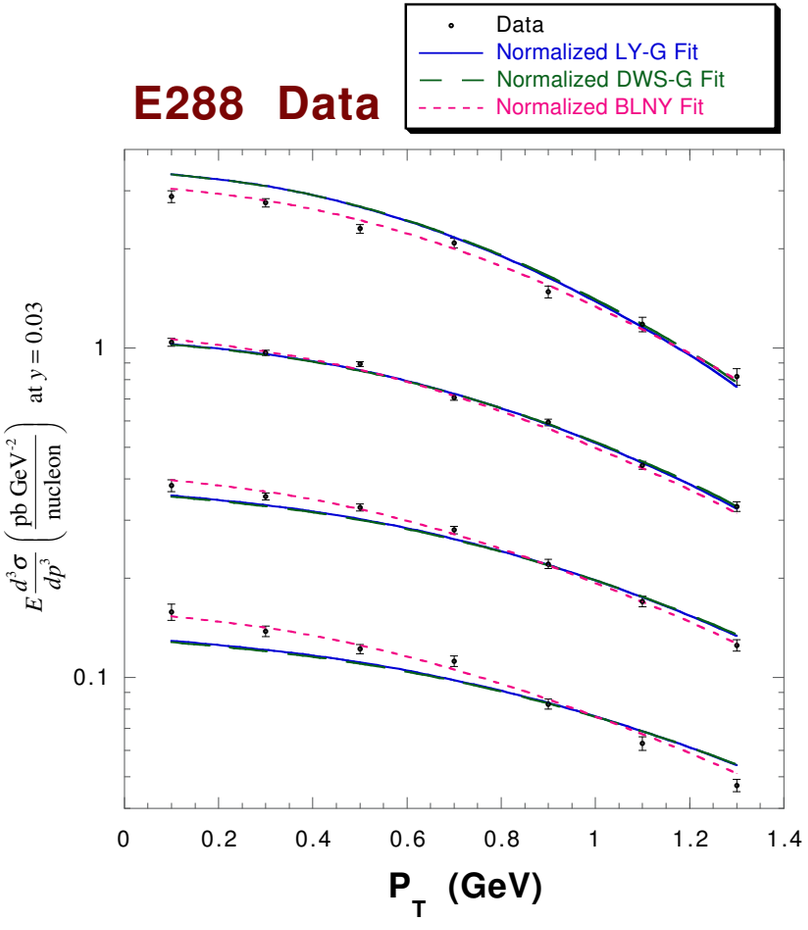
$$P(x, \mathbf{k}_T) \;=\; P_{\rm unpol}(x, |k_T|) \;+\; P_{\rm Sivers}(x, |k_T|) \sin(\phi - \phi_S)$$

Time-reversal

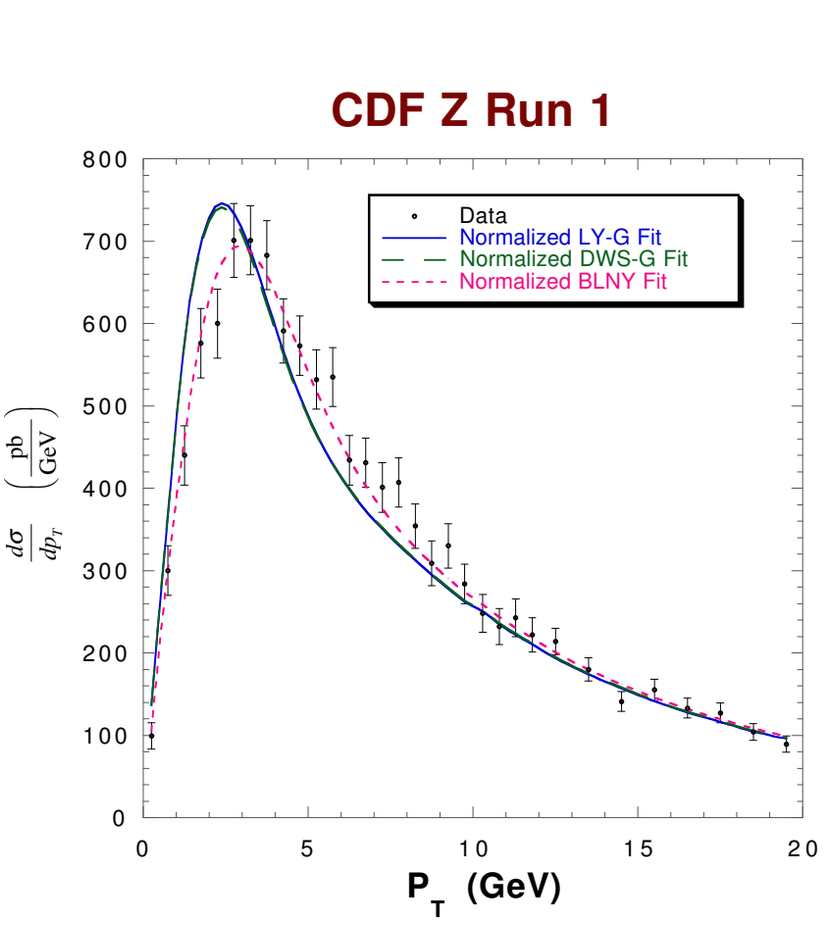
$\Longrightarrow$ Unpolarized density: same numerical value

$\Longrightarrow$ SSA: opposite

But CSS evolution



$\sqrt{s} = 27.4\,\text{GeV}$



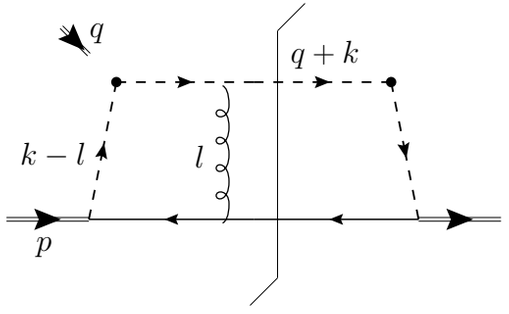
$\sqrt{s} \sim 900\,\text{GeV}$

[Landry et al., Phys. Rev. D67, 073016 (2003)]

Hadron production: Counterexample to factorization I

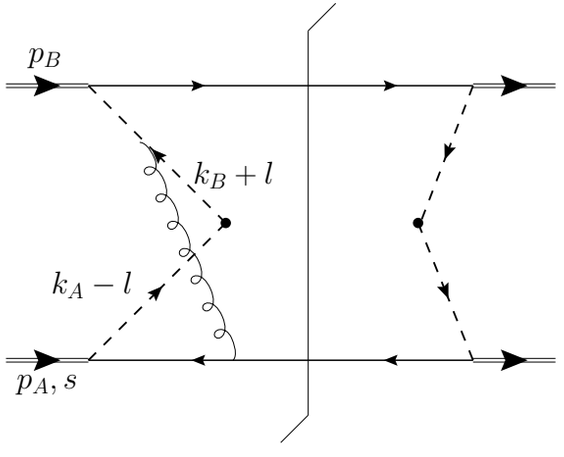
(JCC & Qiu, arXiv:0705.2141)

- Spectator model, with 1-extra-gluon exchange
- SSA starts with imaginary part (from on-shell intermediate state)
- In processes with factorization
  - SIDIS:



$$\Longrightarrow \frac{g \ \times \ 2q^-}{(q+k-l)^2-m^2+i\epsilon} \Longrightarrow g \times (-i\pi)$$

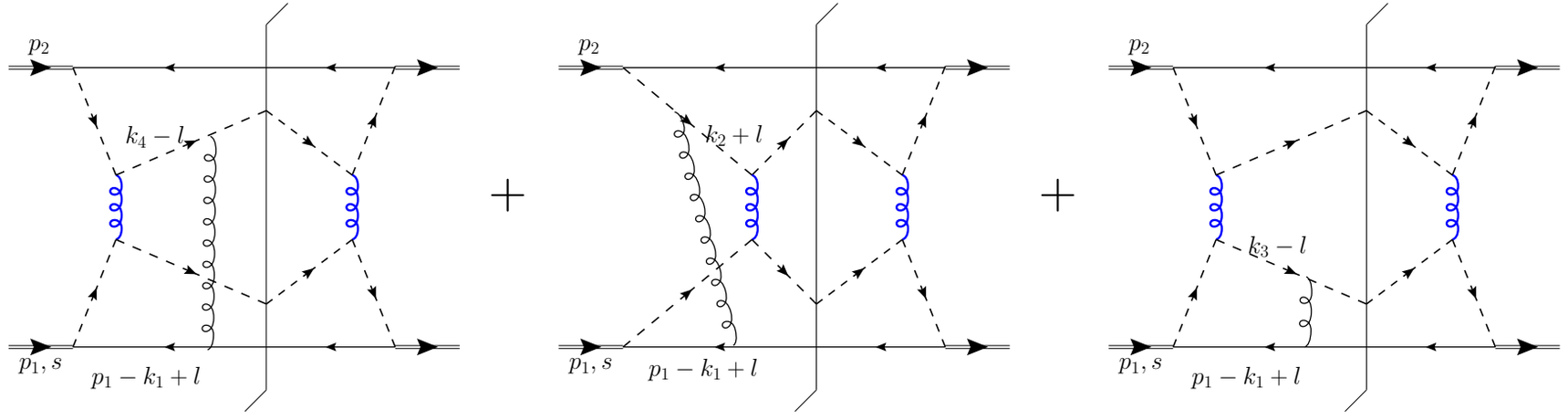
  - DY:



$$\Longrightarrow \frac{-g \ \times \ 2k_3^-}{(k_3+l)^2-m^2+i\epsilon} \Longrightarrow -g \times (-i\pi)$$

Hadron production: Counterexample to factorization II

- Simplified model with abelian gluons, different quark charges,
- Maximally simple calculation from:



$\Longrightarrow$ SSA from $\dfrac{g_2 \times 2k_4^-}{(k_4-l)^2 - m^2 + i\epsilon} + \dfrac{g_2 \times 2k_2^-}{(k_2-l)^2 - m^2 + i\epsilon} + \dfrac{g_1 \times 2k_3^-}{(k_3-l)^2 - m^2 + i\epsilon}$

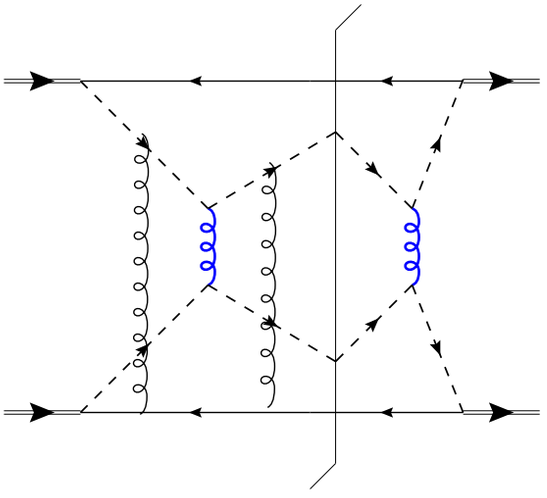
- Real part eikonalizes at leading power
- Imaginary part from $(2g_2 + g_1) \times (-i\pi)$

$\Longrightarrow$ Non-universality of pdfs or non-factorization

Non-factorization

- Correction of parton model by eikonal propagation of fast partons through glue
  - Factorization only by absorbing this in Wilson lines in definitions of pdfs, etc.
  - SSA with TMD especially sensitive
- Counter-example in model theory:
  - Spectator-related phenomenon: Pdf effect
  - Dependence on color of other parton: Cannot use Wilson line
- Kills proof of factorization with TMD in hadroproduction of hadrons
- Also for unpolarized cross section, resummation, etc, etc.

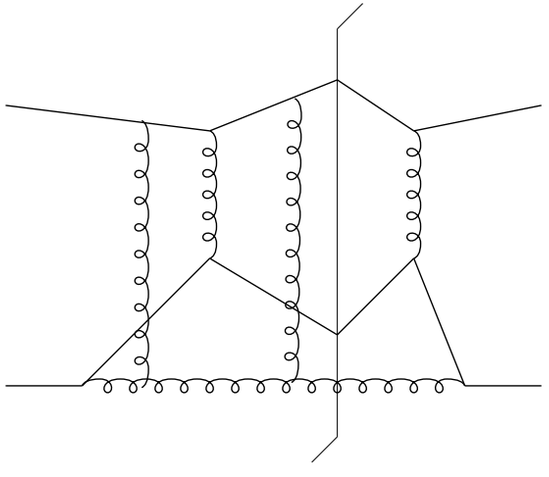
- Minimum factorization breaking graphs in unpolarized cross section:



etc. (Check!)

- Collinear factorization (without TMD sensitivity): Must check carefully!. (Derivations in literature quite inexplicit at the difficult points.)

- Ordinary unpolarized quark-gluon calculations only affected at NNLO:



etc

Conclusions

- TMD distributions natural and normal from parton model
- Needed in DY etc, where kinematics wrong at LO without parton k_T
- Give greater sensitivity to beyond-naive-parton-model effects
- Especially SSA
- Factorization breaking: Big opportunity
- SIDIS v. DY comparison vital