Opportunities at the Intersection of Spin and Saturation at RHIC

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BROOKHAVEN NATIONAL LABORATORY

2016 RHIC / AGS Annual Users' Meeting

Tuesday June 7, 2016

Outline

I. Spin and Saturation on a (pA) Collision Course

II. The Collinear Framework

III. The “Hybrid” Framework

IV. The TMD Framework

V. Some Selected Developments

I. Spin and Saturation on a (p A) Collision Course

What's So Special About Small x?

- Small x corresponds to high-energy kinematics and longitudinal coherence

$$x_B \sim \frac{Q^2}{s} \ll 1$$

$$\ell_{coh} \sim \frac{1}{mx} \gg \frac{1}{m}$$

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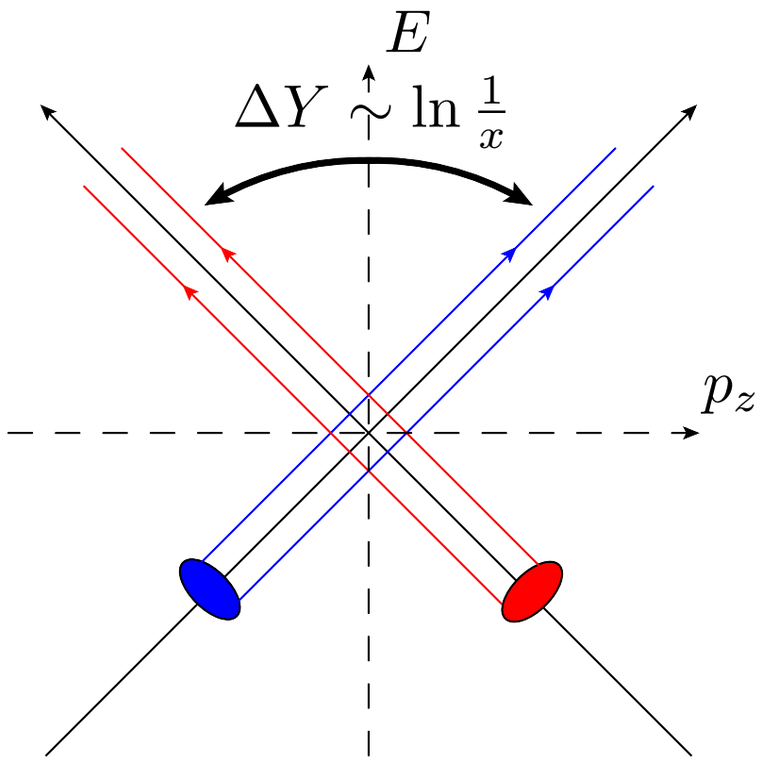
- Boosting the collision to even higher energies opens up additional phase space for soft gluon radiation



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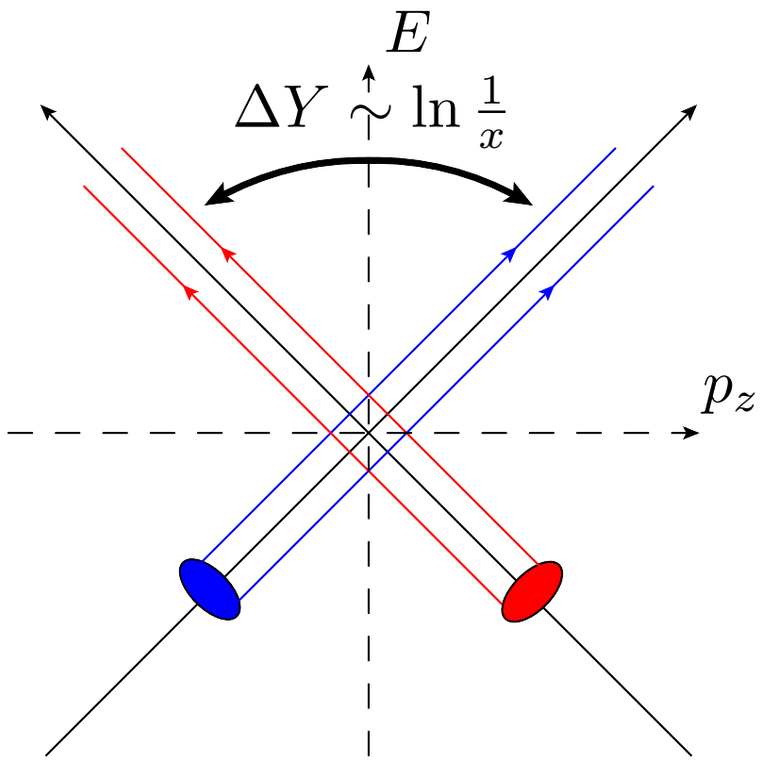


- Enhancement of radiation space drives the small-x quantum evolution (BFKL)

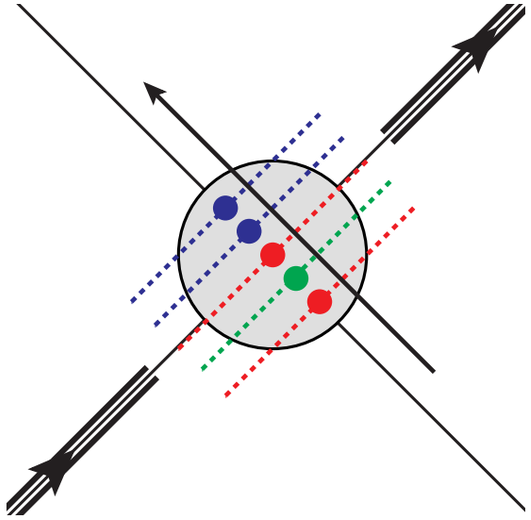
- Exponential gluon bremsstrahlung drives up the gluon density:

$$\alpha_s \ln \frac{1}{x} \sim 1$$

Small-x Limit = High-Density Limit

Saturation and Heavy Nuclei

- High densities enhance nonlinear multiple scattering on random color charges
  - ➡ Nonlinear small-x evolution (BK)
  - ➡ Characteristic scale of the color-charge fluctuations: $Q_s^2 \sim \alpha_s \rho$



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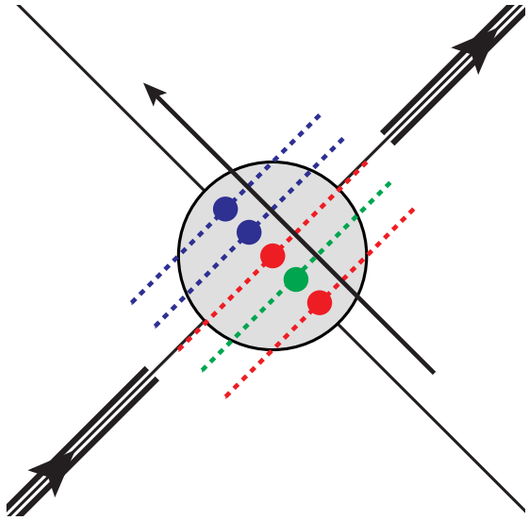
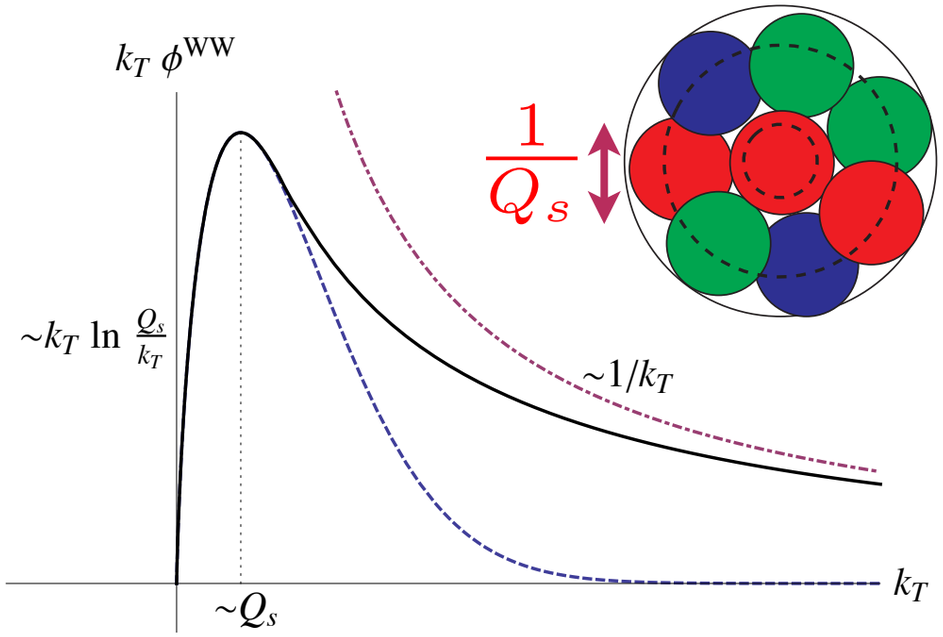


- Color fluctuations dynamically screen the IR gluon field
  - ➡ Saturates the gluon density



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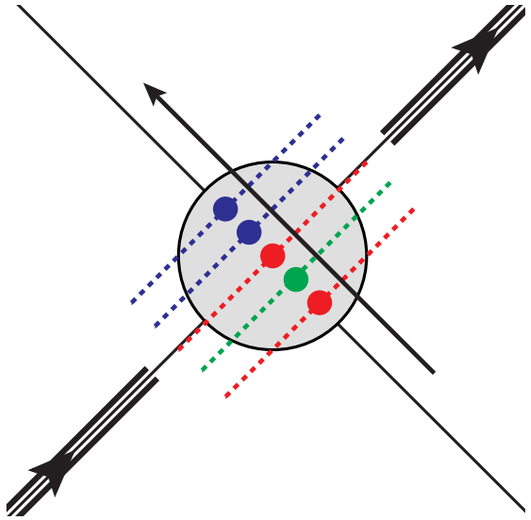

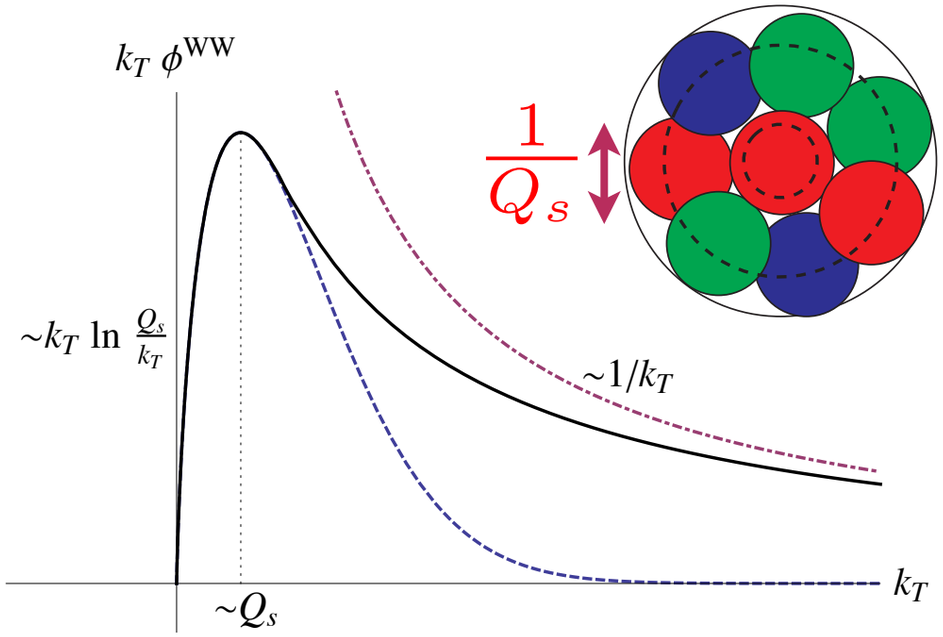

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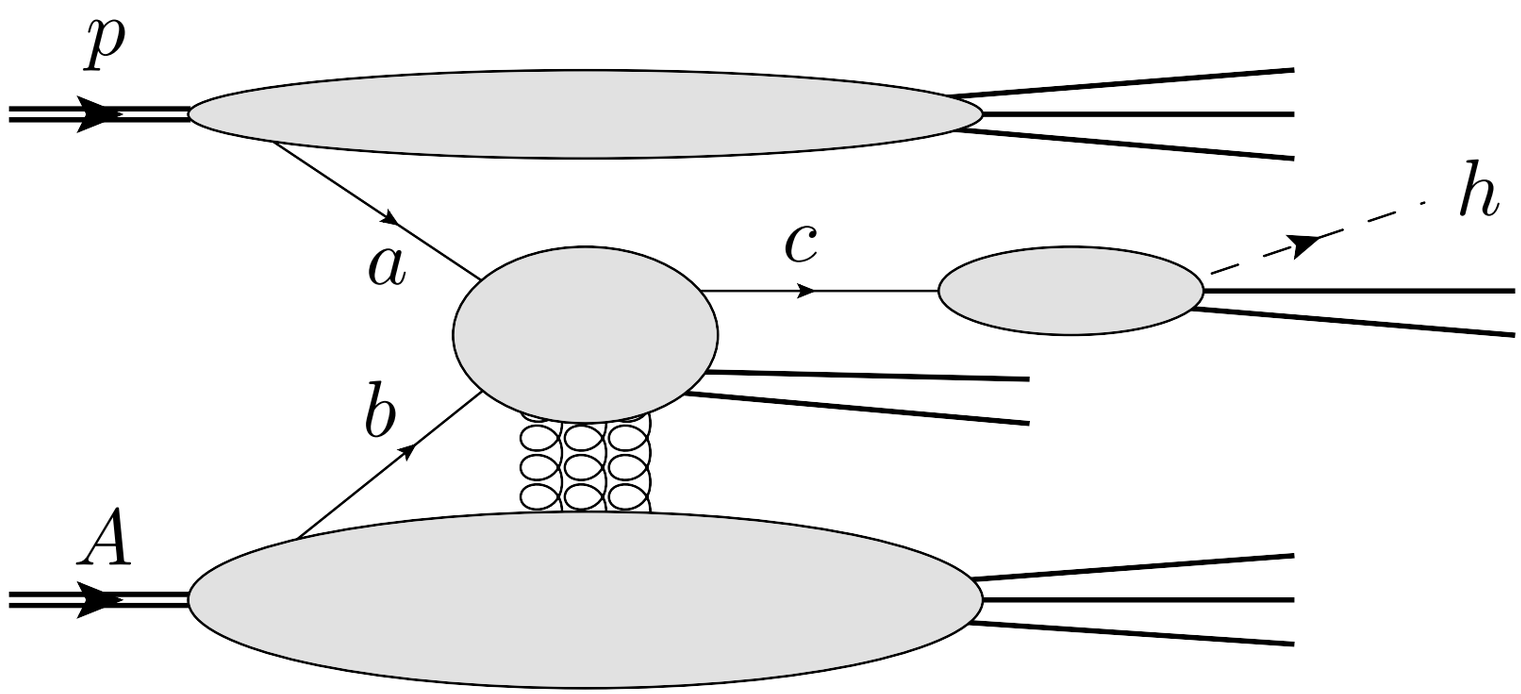
- Nuclei further enhance the density by $A^{1/3}$
  - ➡ Universal phase of gluonic matter at high energies / densities
  - ➡ "Color Glass Condensate" (CGC) effective theory

The Many Roles of Spin in pA Collisions



- (Polarized) pA collisions at RHIC bring together both spin and high gluon densities in novel ways.
- Within some factorization framework (collinear, hybrid, TMD), spin effects can occur in many places:

➡ The proton side, the nucleus side, and the fragmentation side.

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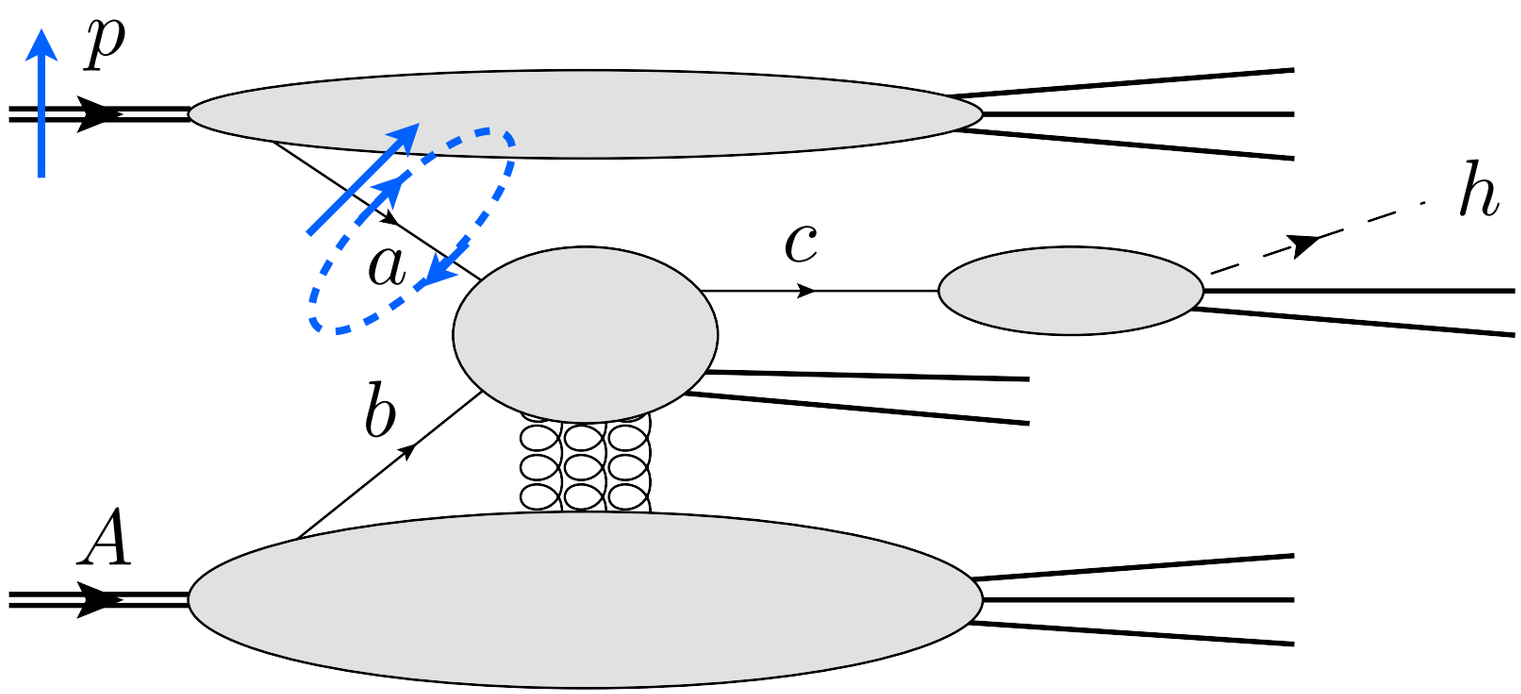

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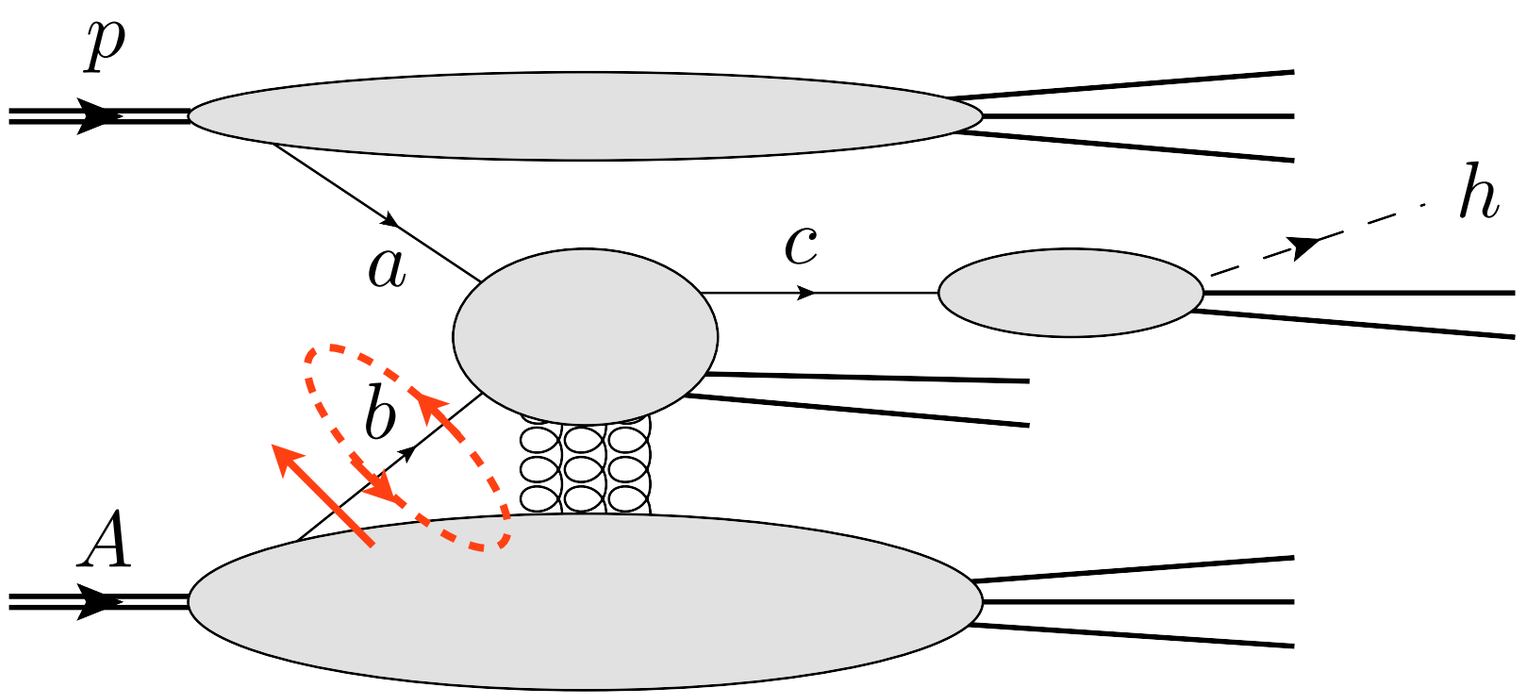

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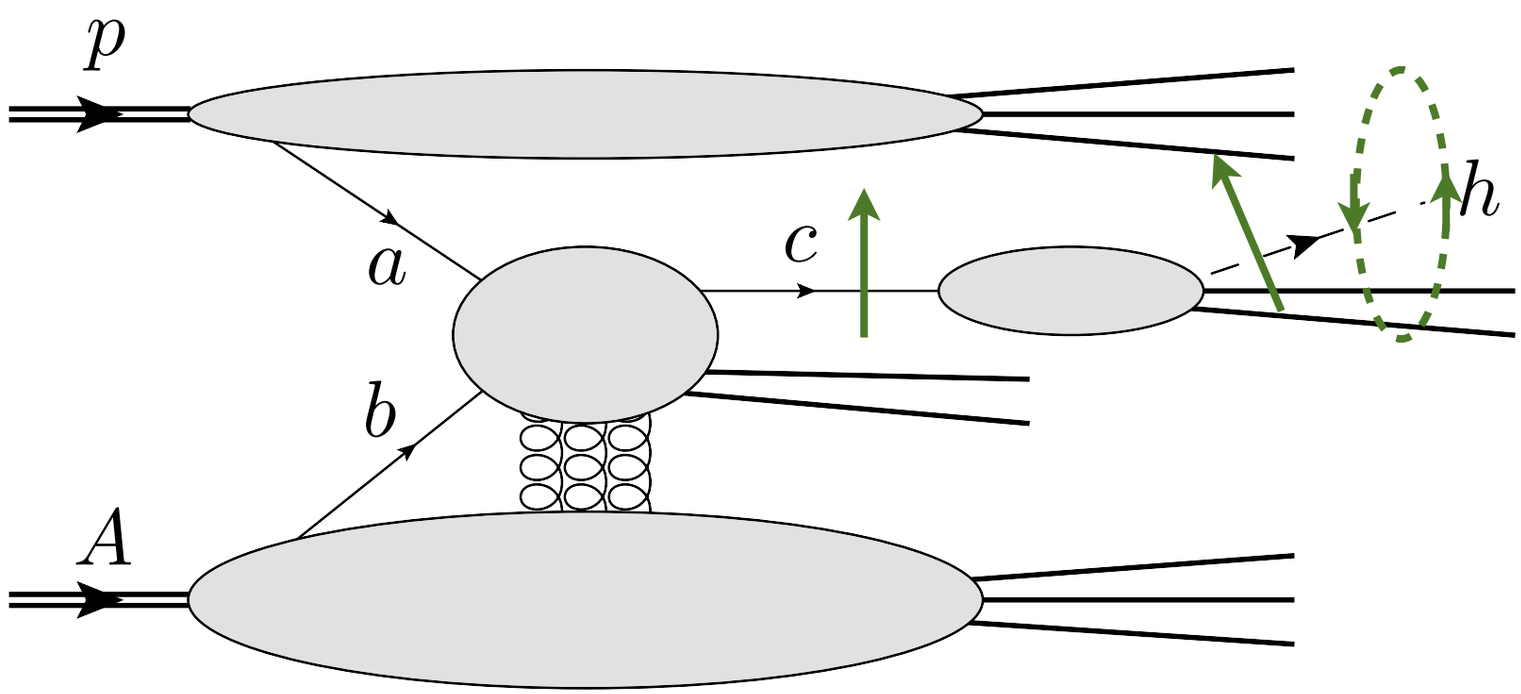

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A Wealth of Interconnected Observables

- Single inclusive hadronic final states:

➡ Single spin asymmetries

$$p^{\uparrow} + A \to h + X$$

$$p^{\uparrow} + A \to jet + X$$

$$p + A \to h^{\uparrow} + X$$

➡ Azimuthal modulations

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- Non-hadronic final states:

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TSSAs

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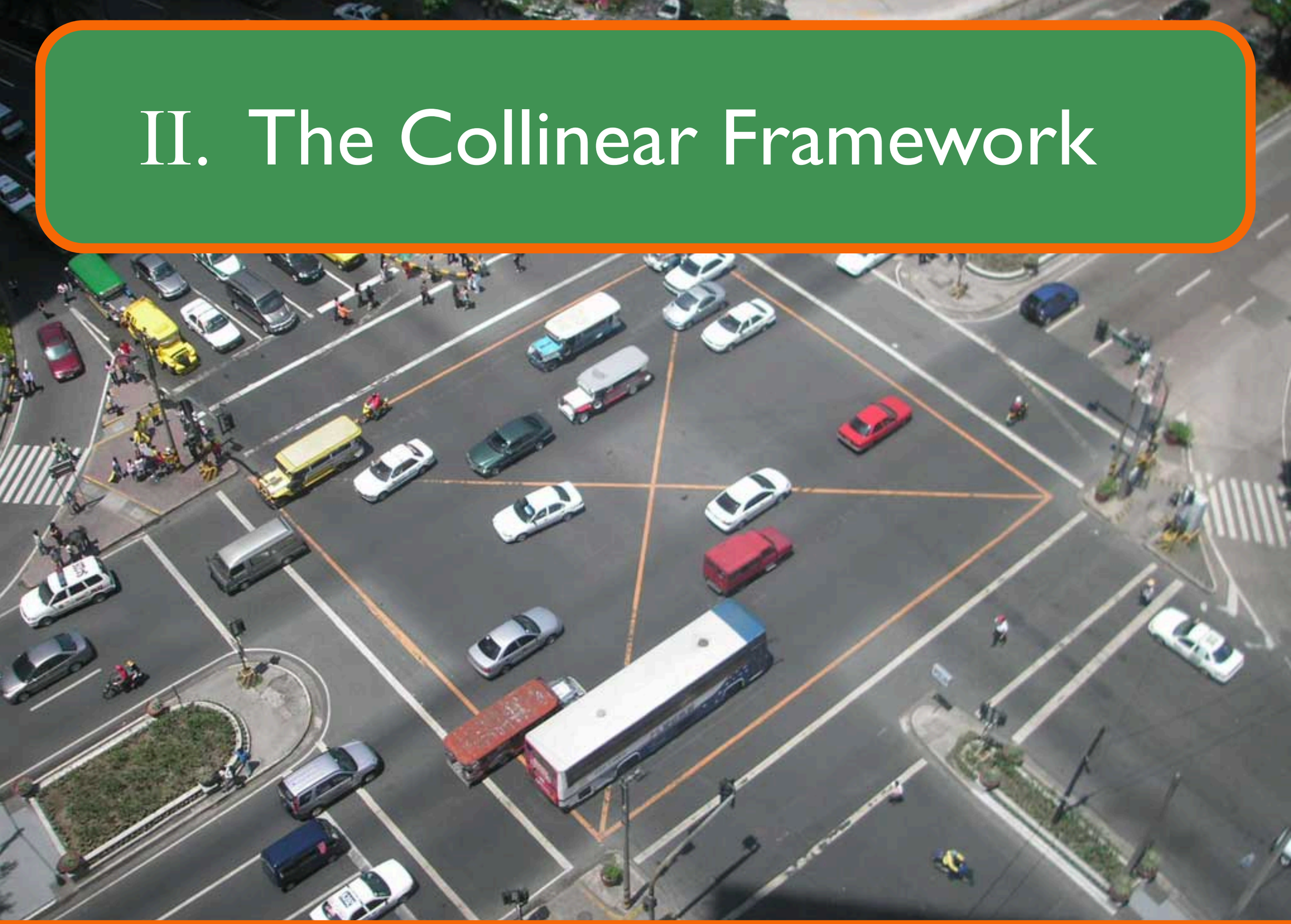
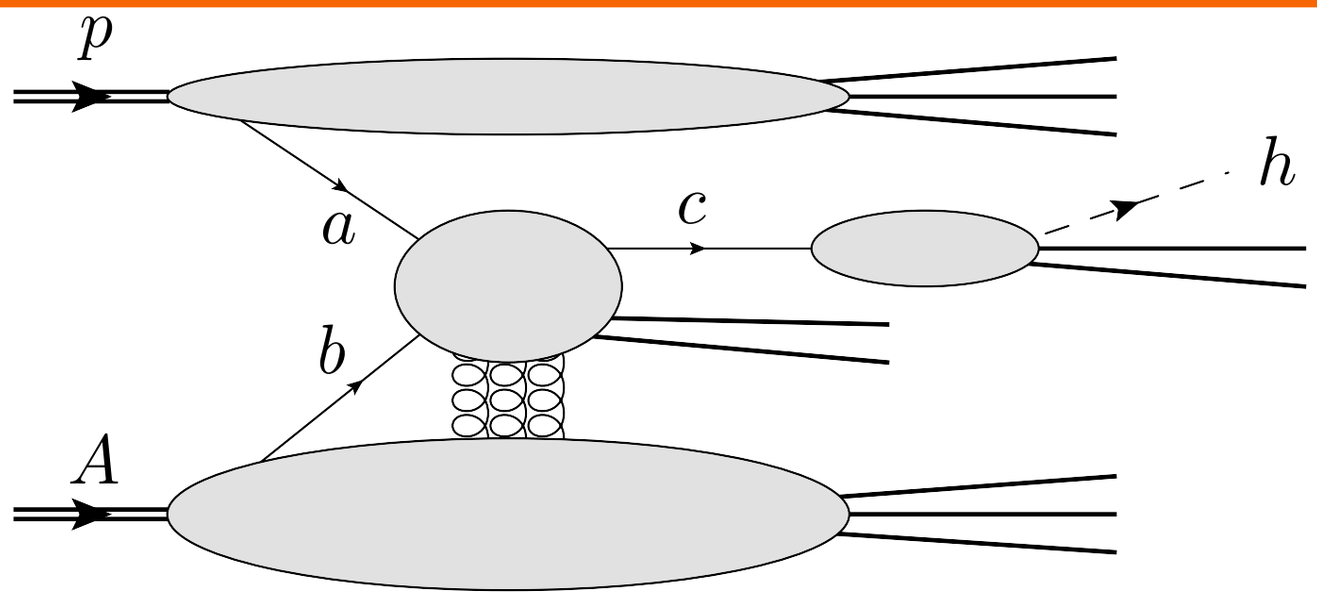
II. The Collinear Framework



Collinear Factorization



$$d\sigma \sim f_{a/p}(x_p) \otimes f_{b/A}(x_A) \otimes H_{a+b\to c+X}(p_T^2) \otimes D_{h/c}(z)$$

- Describes a process with one hard scale $p + A(Q_s) \to h(p_T) + X$

  ➡ "Twist" expansion in powers of p_T^2 $\qquad p_T \gg Q_s^2, \Lambda_{QCD}^2$

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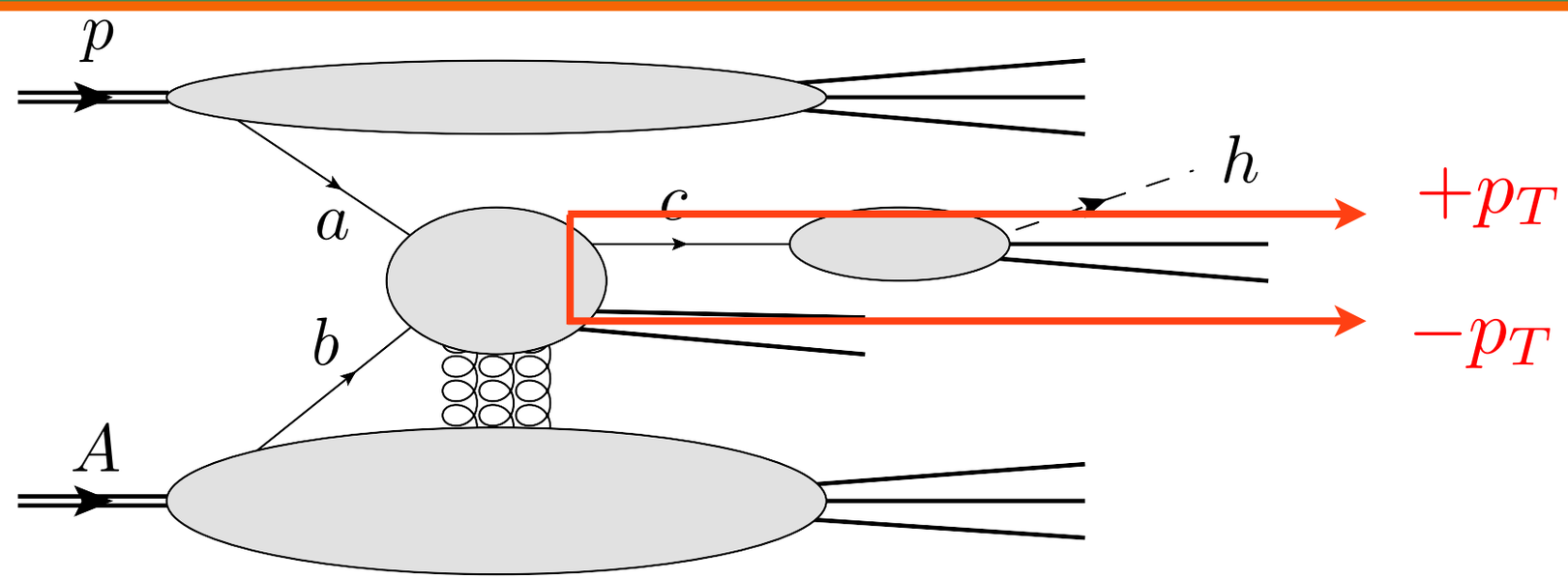

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  - ➡ "Twist" expansion in powers of p_T^2 $\qquad p_T \gg Q_s^2, \Lambda_{QCD}^2$
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  - ➡ $1\mathrm{D}$ parton distributions and fragmentation functions

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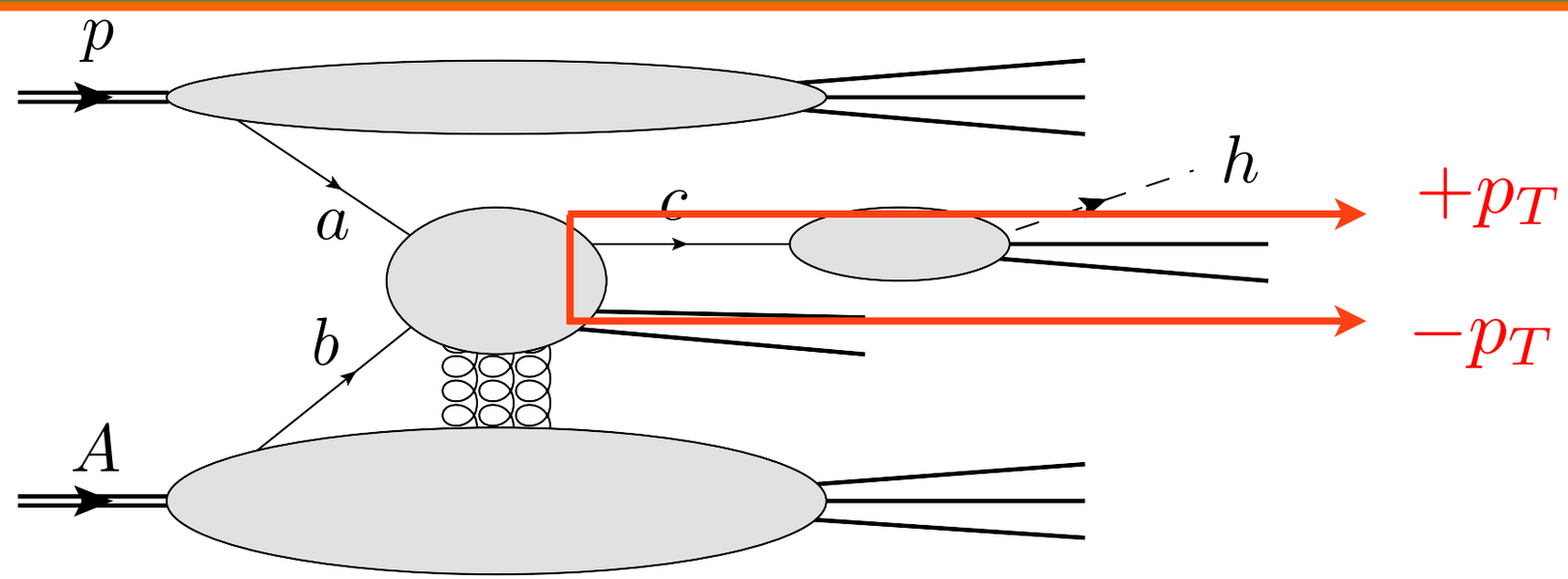

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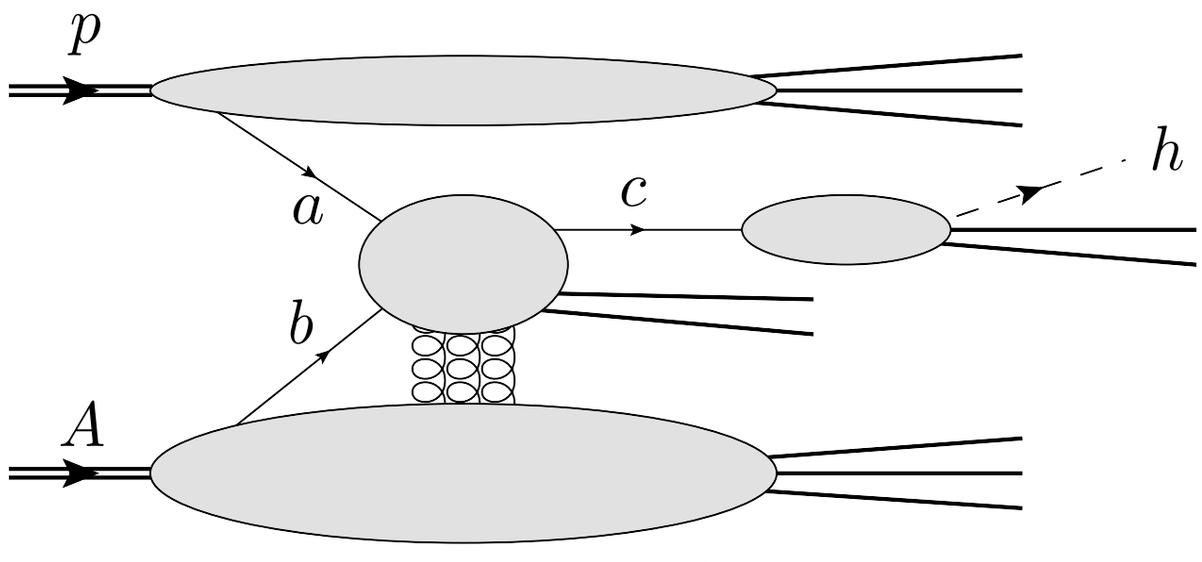
- Transverse momentum only flows through the hard subprocess
  - ➡ $1\mathrm{D}$ parton distributions and fragmentation functions
- Based on a factorization theorem derived at all orders in pQCD

Spin in the Collinear Framework



Qiu & Sterman, PRL **67**, 2264 (1991)

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At leading power: $\left(1/p_T^2\right)^0$ (Twist-2)

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- TSSAs prohibited by time reversal symmetry

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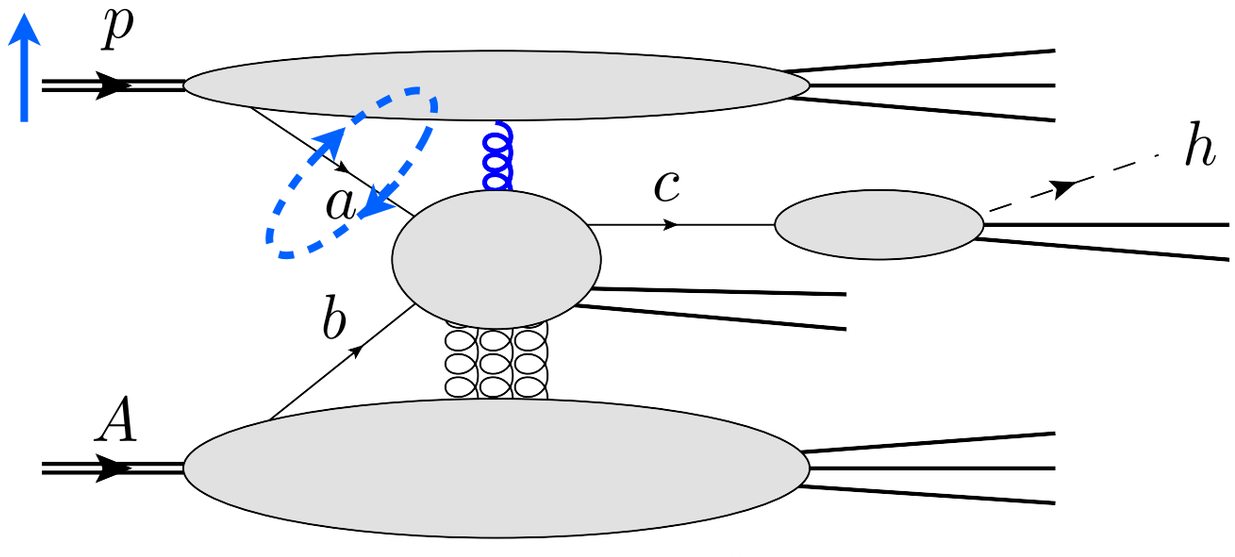

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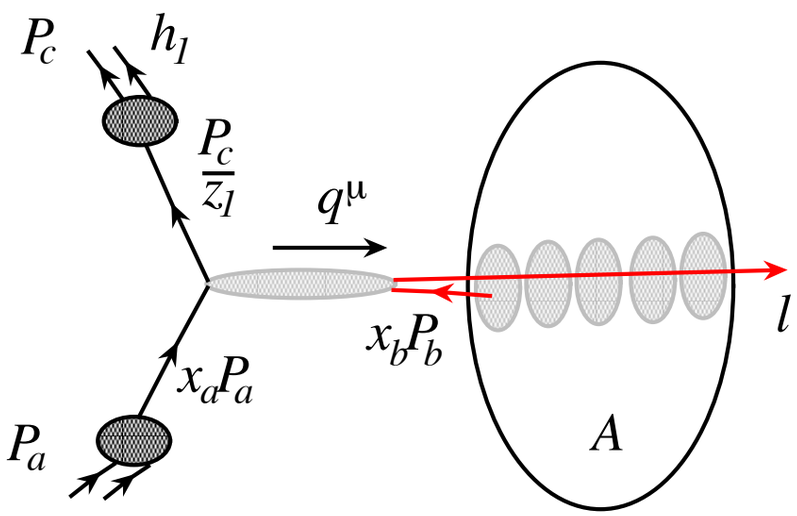
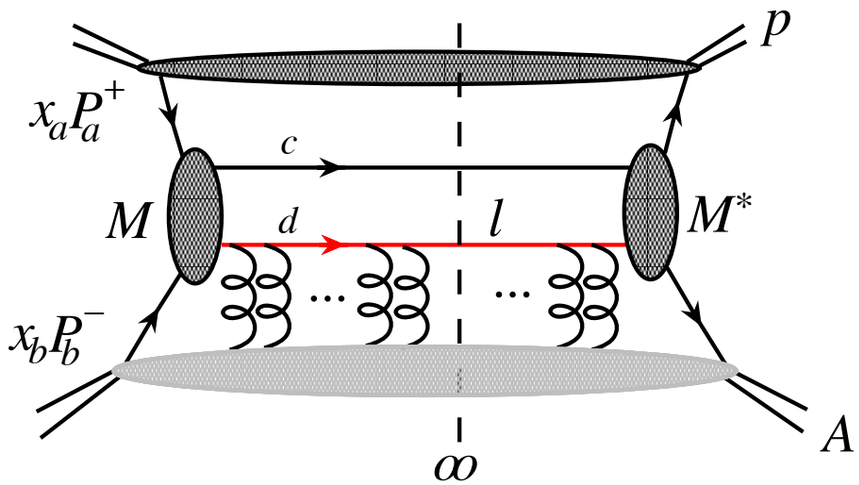
At next-to-leading power: $\left(1/p_T^2\right)$ (Twist-3)

- 3-parton correlations generate TSSAs (e.g., Qiu-Sterman function)
- Used to study TSSAs in $p^\uparrow + p$ collisions

Nuclear Effects in the Collinear Framework





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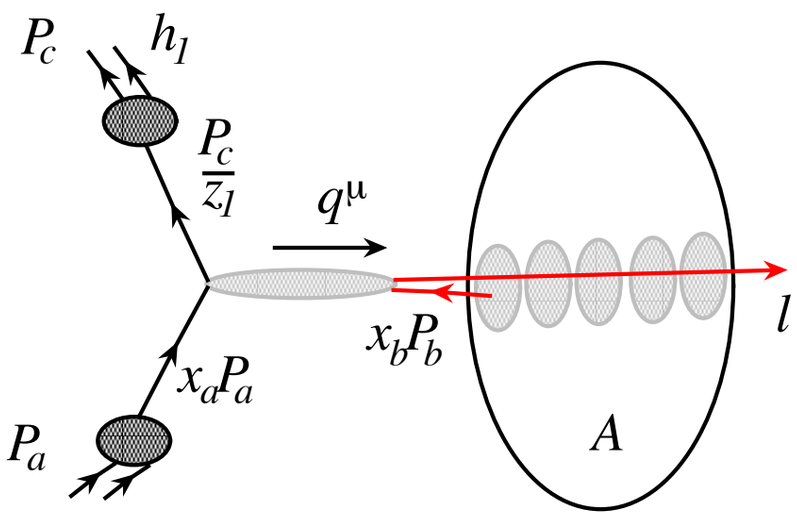

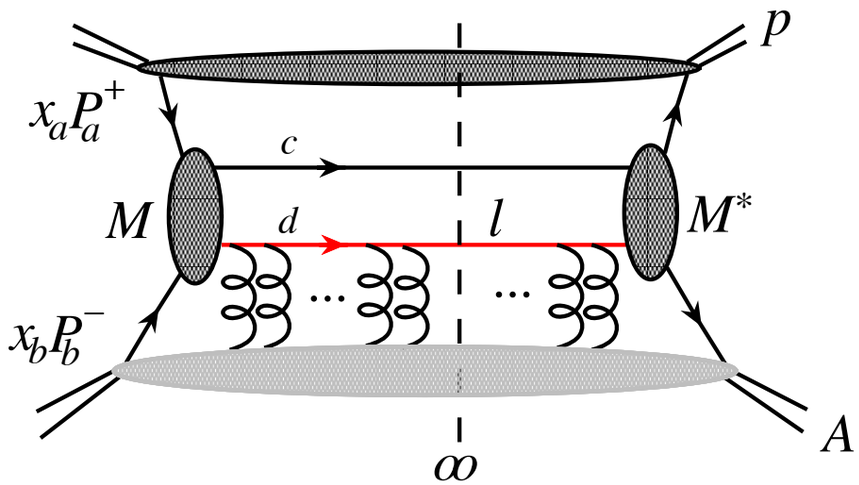

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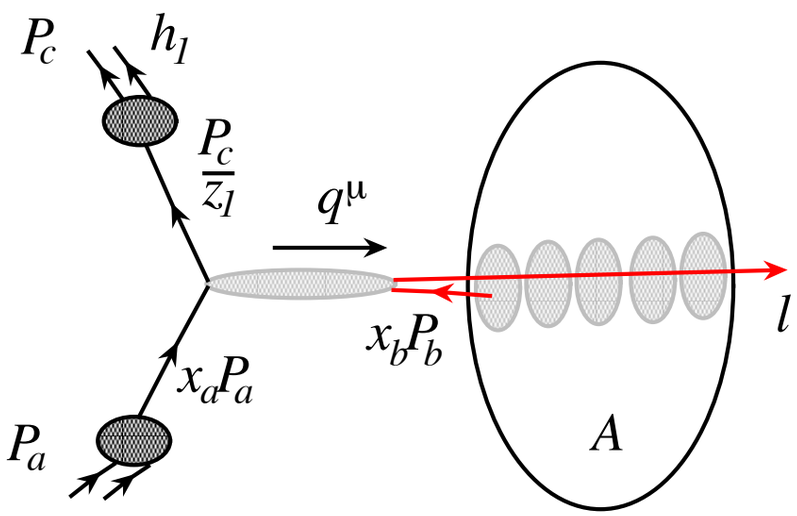
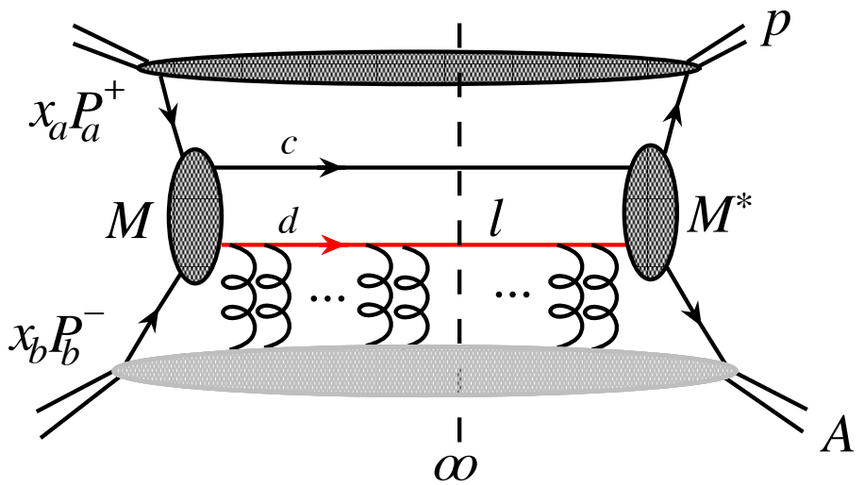
Nuclear Effects in the Collinear Framework





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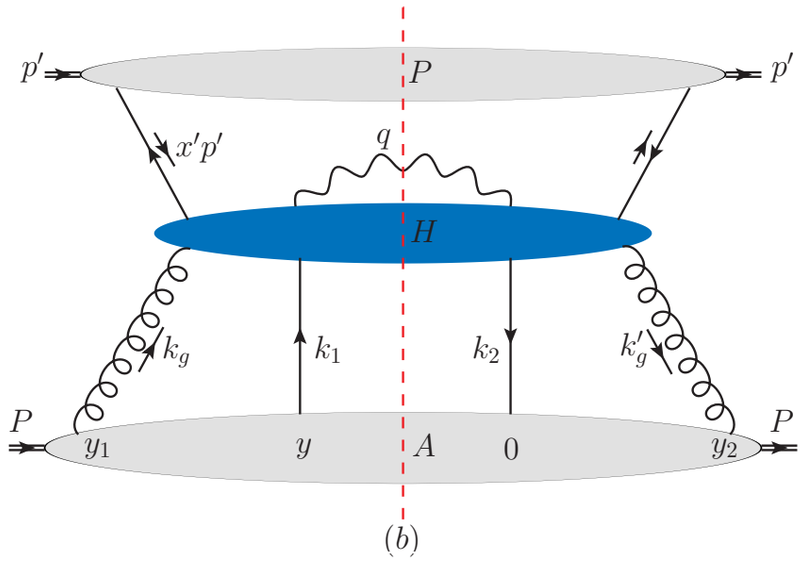
Opportunity: How does this shift in x affect the complete twist-3 picture of TSSAs?

Momentum Broadening in the Collinear Formalism



Kang et al., PRL **112**, 102001 (2014)
Kang et al., arXiv: 1605.07175

$$p + A(Q_s) \to (\ell^+\ell^-)(Q^2, p_T) + X$$

$$Q^2 \gg Q_s^2\,,\ \Lambda_{QCD}^2$$

- Multiple rescattering on the nucleus builds up transverse momentum

$$\langle p_T^2 \rangle \equiv \int dp_T^2\, p_T^2\, \frac{\frac{d\sigma}{dQ^2\, dp_T^2}}{\frac{d\sigma}{dQ^2}}$$

➡ $\langle p_T^2 \rangle$ is a Twist-4 collinear observable

➡ Twist-4 factorization holds through NLO.

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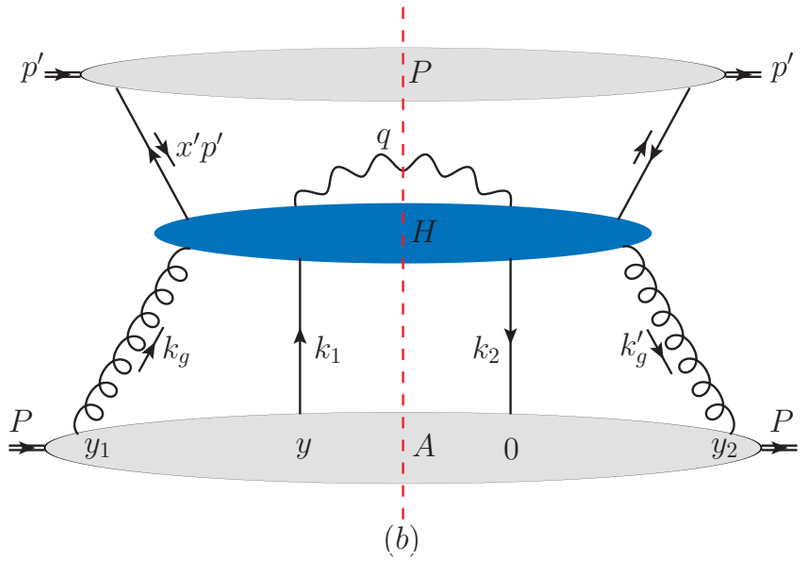

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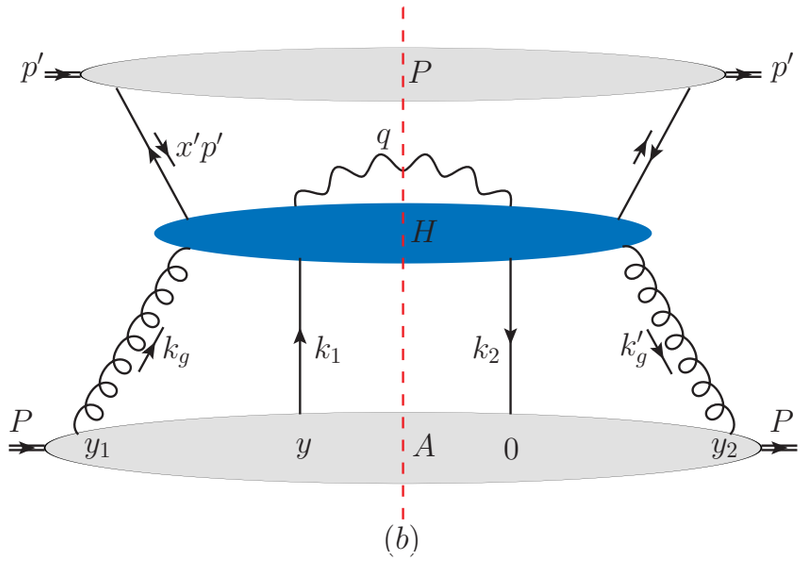

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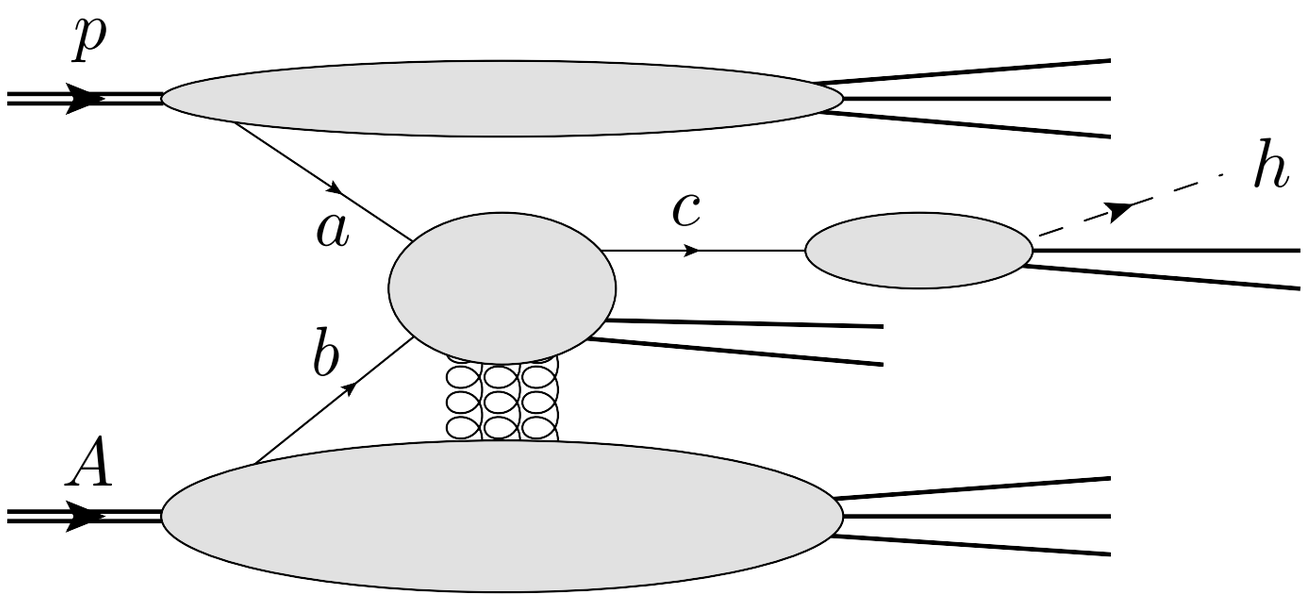
Opportunity: What spin-related azimuthal modulations are possible within this approach?

III. The “Hybrid” Framework

A Hybrid Factorization: Collinear + CGC



Dumitru & Jalilian-Marian, PRL **89**, 022301 (2002)
Gelis & Jalilian-Marian, PR **D66**, 014021 (2002)
Dumitru et al., NPA **765**, 464 (2006)
Chirilli et al., PR **D86**, 054005 (2012)

$$p + A(Q_s) \to h(p_T) + X$$

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$$d\sigma \sim f_{a/p}(x_p) \otimes F.T. \left[\left(S^{(2)}(r_\perp Q_s) + \ldots \right) \times H_{a+b\to c}(r_\perp) \right] \otimes D_{h/c}(z)$$

- Collinear proton PDF and FF couple to transverse momentum in CGC quark / gluon scattering amplitudes in coordinate space

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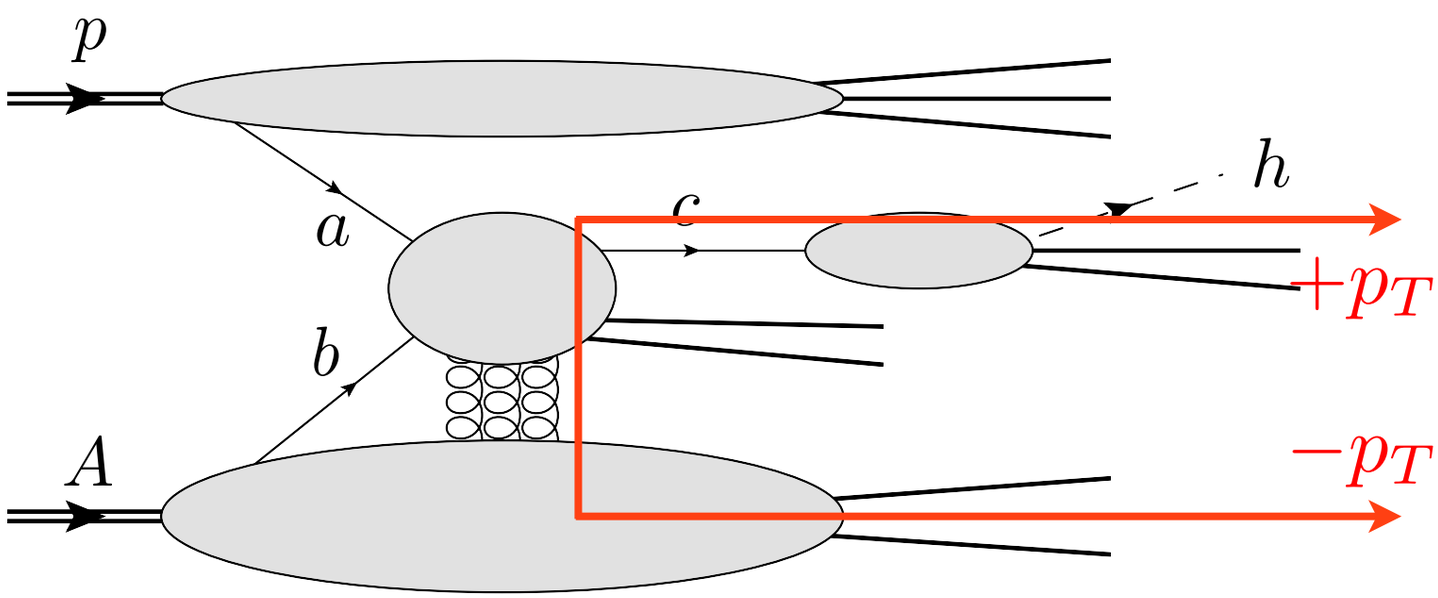

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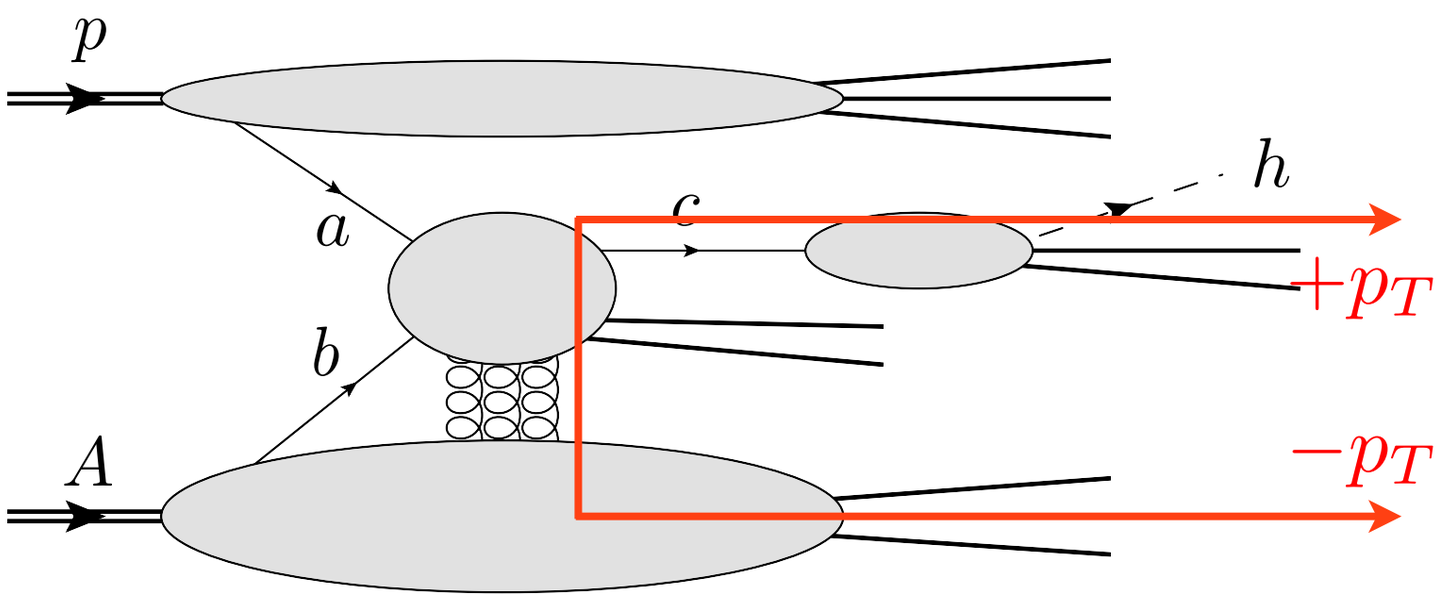
- Collinear proton PDF and FF couple to transverse momentum in CGC quark / gluon scattering amplitudes in coordinate space
- Transverse momenta of order Q_s from the dense nucleus dominate particle production.

$$p_T = \frac{k_T}{z} \sim \frac{Q_s}{z}$$

A Hybrid Factorization: Collinear + CGC



Dumitru & Jalilian-Marian, PRL **89**, 022301 (2002)
Gelis & Jalilian-Marian, PR **D66**, 014021 (2002)
Dumitru et al., NPA **765**, 464 (2006)
Chirilli et al., PR **D86**, 054005 (2012)

$$p + A(Q_s) \to h(p_T) + X$$

$$p_T^2, Q_s^2 \gg \Lambda_{QCD}^2$$

$$d\sigma \sim f_{a/p}(x_p) \otimes F.T. \left[\left(S^{(2)}(r_\perp Q_s) + \ldots \right) \times H_{a+b\to c}(r_\perp) \right] \otimes D_{h/c}(z)$$

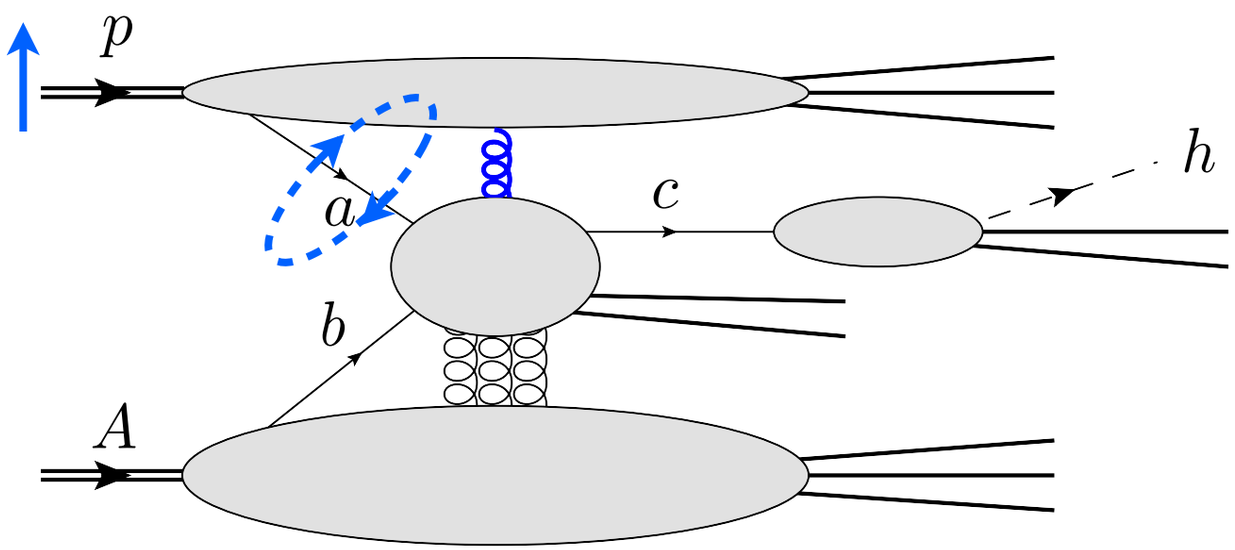
- Collinear proton PDF and FF couple to transverse momentum in CGC quark / gluon scattering amplitudes in coordinate space
- Transverse momenta of order Q_s from the dense nucleus dominate particle production.

$$p_T = \frac{k_T}{z} \sim \frac{Q_s}{z}$$

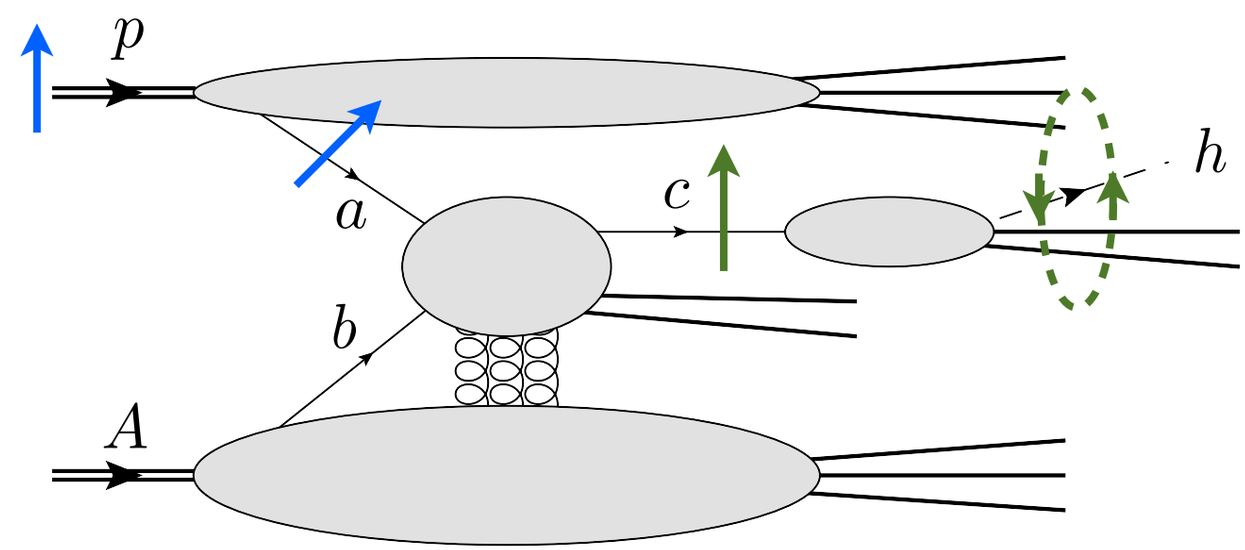
➡ Collinear divergences at NLO generate DGLAP evolution
➡ Rapidity divergences at NLO generate BK evolution
➡ Maps onto collinear factorization at large p_T

Some Early Hybrid Descriptions of TSSAs

Boer et al., PR **D74**, 074018 (2006)



Kang & Yuan, PR **D84**, 034019 (2011)



- Early attempts combined the idea of spin / momentum correlations (Sivers / Collins effects) with CGC amplitudes
  - ➡ Incorporated generic CGC features, like $f\left(\frac{p_T^2}{Q_s^2}\right)$ scaling
  - ➡ Need a full systematic treatment of transverse momentum

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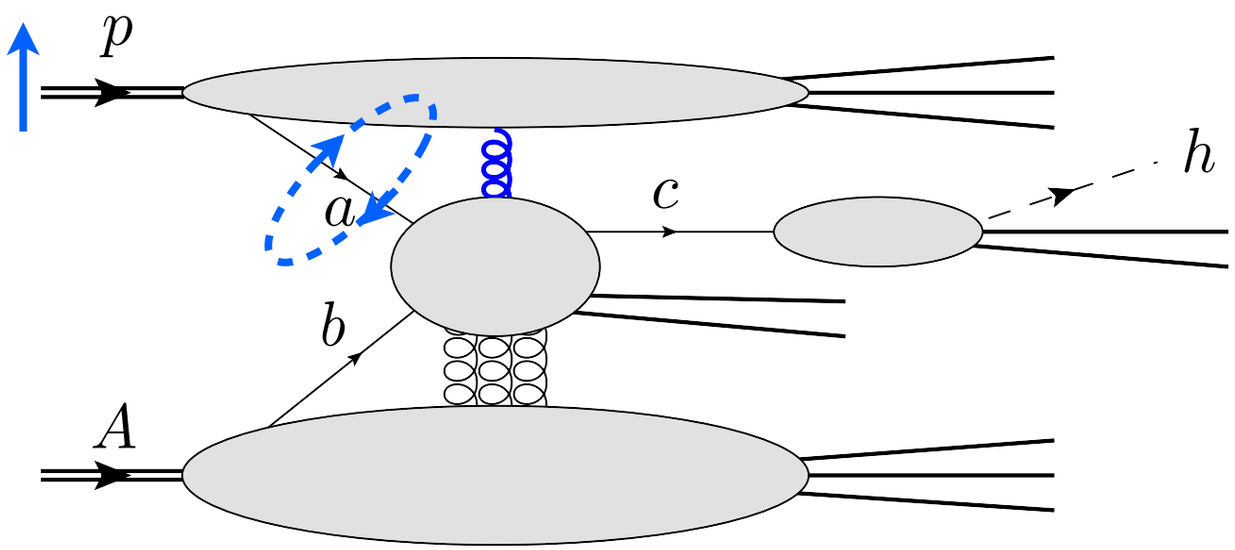

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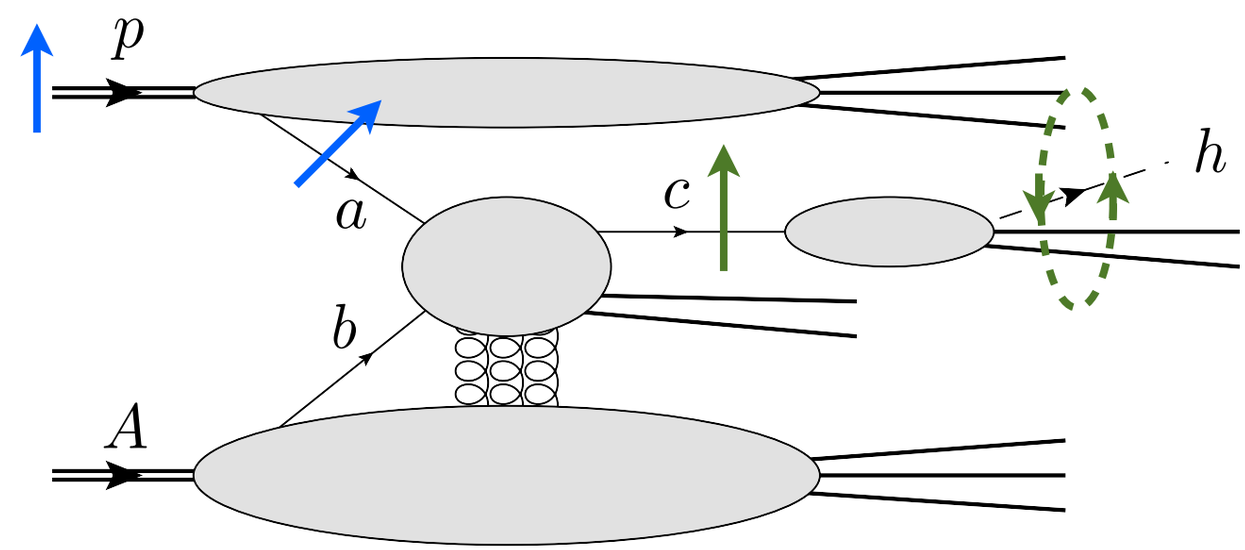

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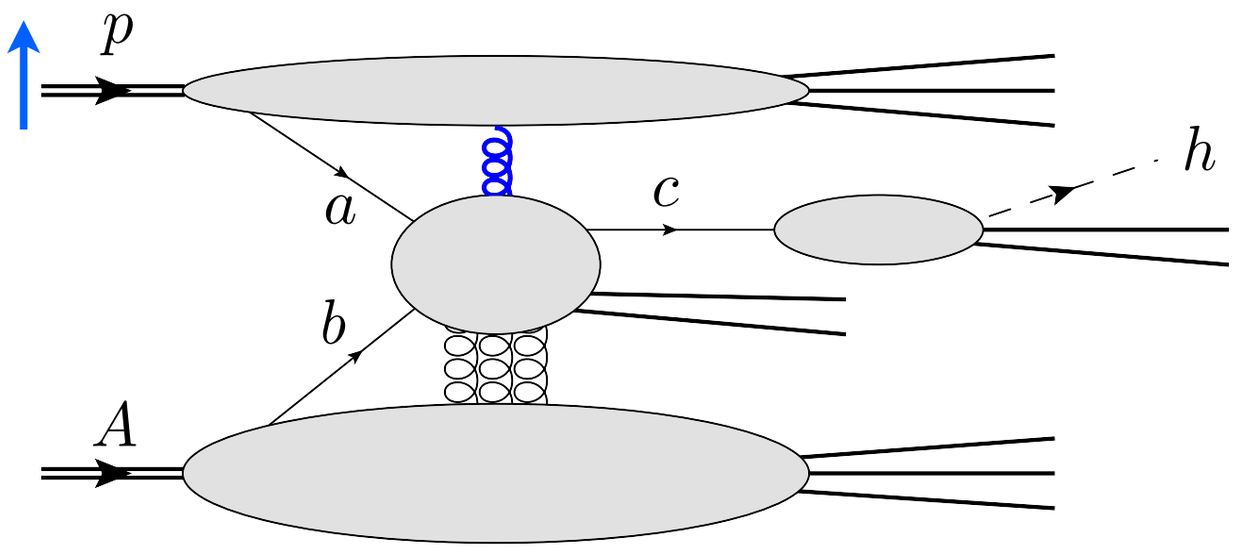
  - ➡ Incorporated generic CGC features, like $f\left(\frac{p_T^2}{Q_s^2}\right)$ scaling
  - ➡ Need a full systematic treatment of transverse momentum

- CGC rescattering tends to dilute the TSSA

$$\left.\frac{(A_N)^{pA}}{(A_N)^{pp}}\right|_{p_T^2 \ll Q_s^2} \sim \frac{(Q_s^2)_p}{(Q_s^2)_A} \qquad \left.\frac{(A_N)^{pA}}{(A_N)^{pp}}\right|_{p_T^2 \gg Q_s^2} \sim 1$$

A Modern Hybrid Calculation of a TSSA



Schäfer & Zhou, PR **D90**, 034016 (2014)

$$p^{\uparrow} + A(Q_s) \to \gamma(p_T) + X$$

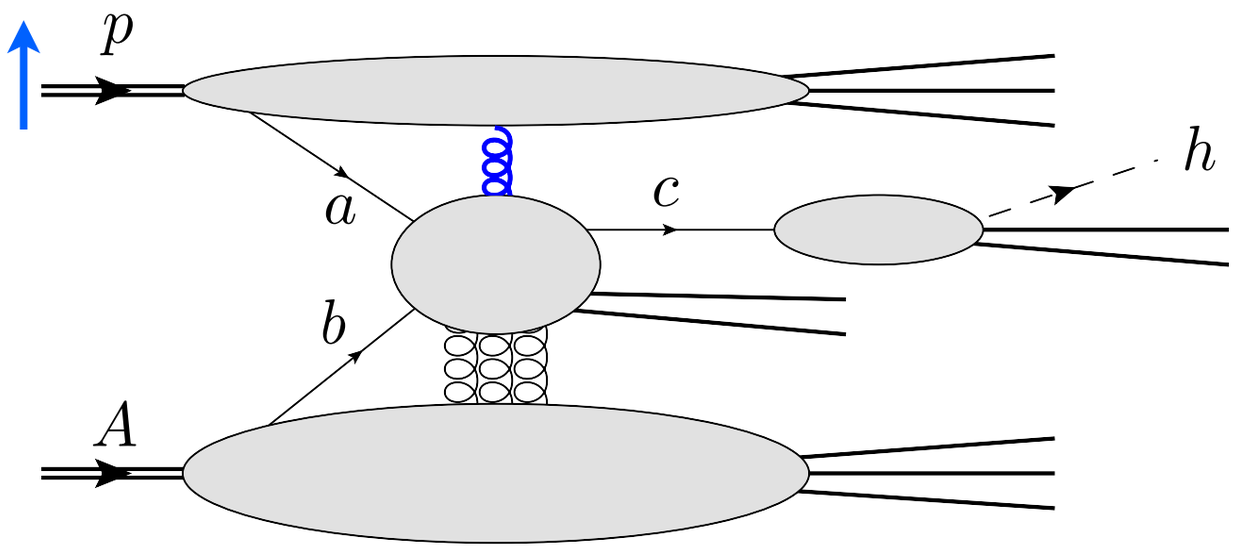
$$p_T^2, Q_s^2 \gg \Lambda_{QCD}^2$$

$$A_N \sim \frac{f(\phi) \otimes S^{(2)}(p_T) \otimes T_F(x_p)}{S^{(2)}(p_T) \otimes f(x_p)}$$

- Twist-3 Qiu-Sterman function in the proton generates the TSSA, which is dressed with CGC multiple rescattering.

➡ The nucleus still plays a passive role, diluting a pre-existing TSSA

A Modern Hybrid Calculation of a TSSA



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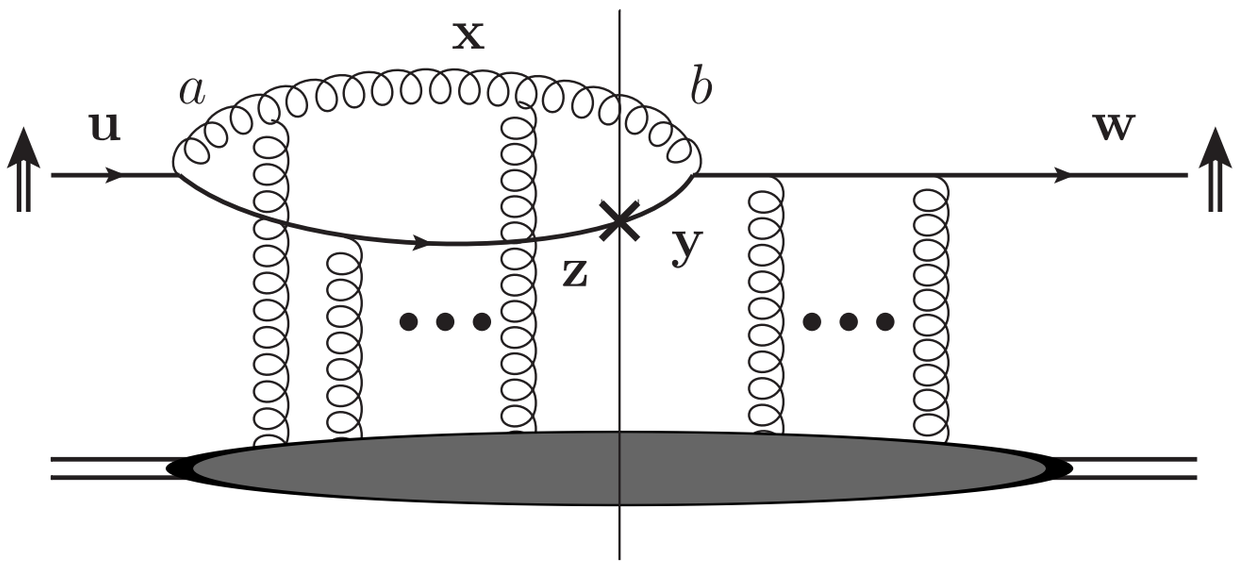
Opportunity: What is the TSSA in a full Twist-3 + CGC computation? How does it compare with the x shift from the collinear formalism?

The Odderon: TSSA Generated by Saturation Physics



Kovchegov & MS, PR **D86** 034028 (2012)

$$p^{\uparrow} + A(Q_s) \to h(p_T) + X$$

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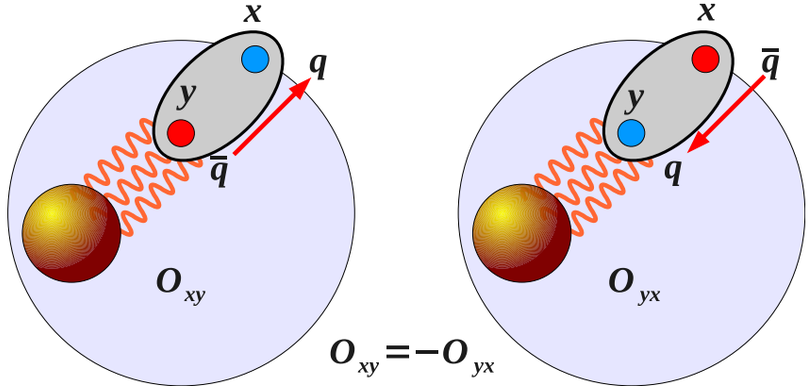
$$O_{xy} \sim \underset{x}{\mathrm{Tr}}[V_x V_y^\dagger - V_y V_x^\dagger]$$



- There is an exotic "odderon" component of the CGC gluon fields which has the right quantum numbers to generate TSSAs.

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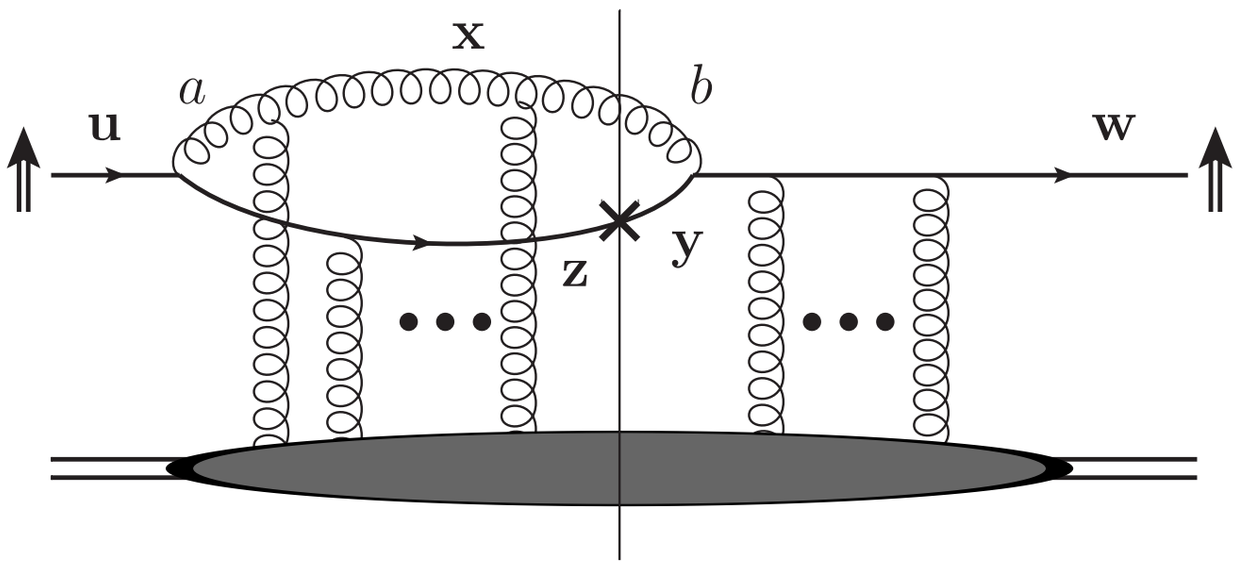

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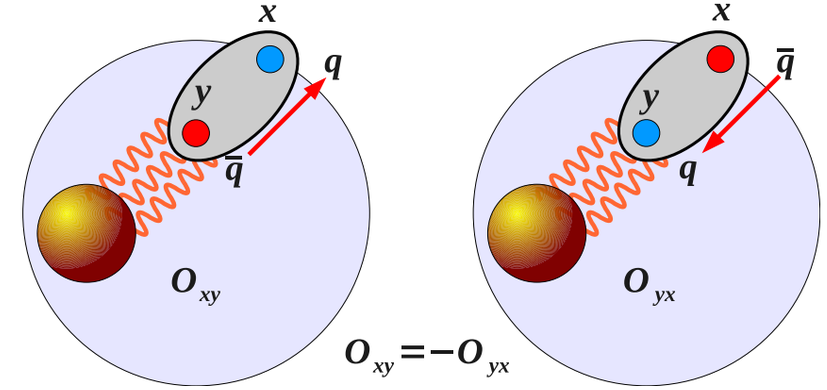


- There is an exotic "odderon" component of the CGC gluon fields which has the right quantum numbers to generate TSSAs.

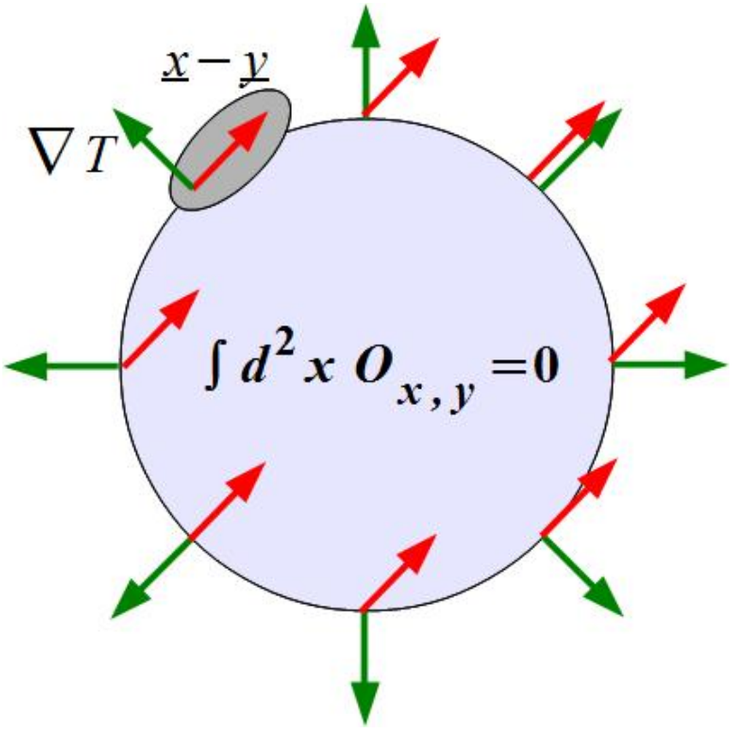
➡ TSSAs in the forward direction are sensitive to the odderon interaction with the unpolarized nucleus.

➡ Can generate TSSAs by coupling to proton transversity

➡ Effect is very small: quark mass and 5+ gluon exchange

Odderon-Mediated TSSAs in the Backward Direction

Gockeler et al., PRL **98** 222001 (2007)
Zhou, PR **D89** 074050 (2014)



- The odderon itself averages to zero over the unpolarized nucleus.

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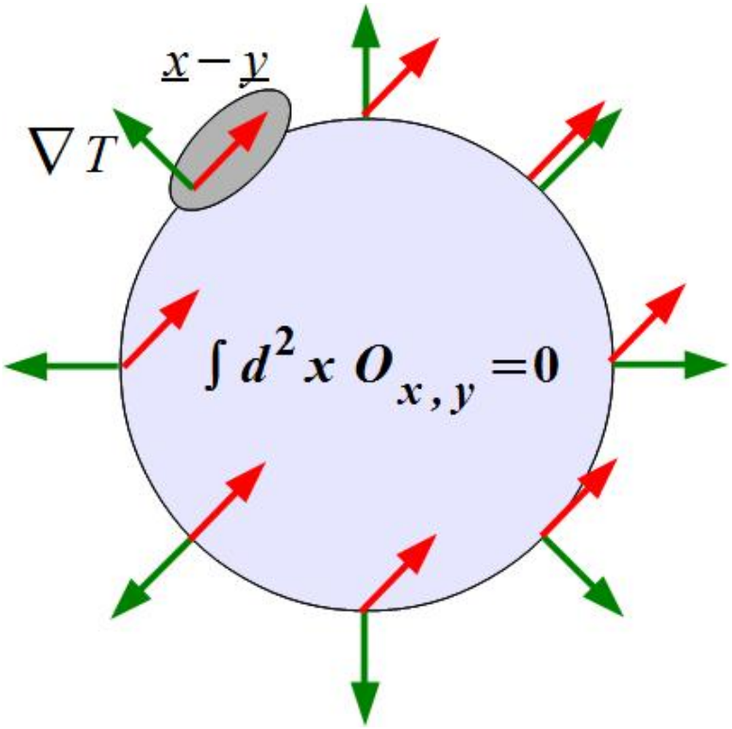

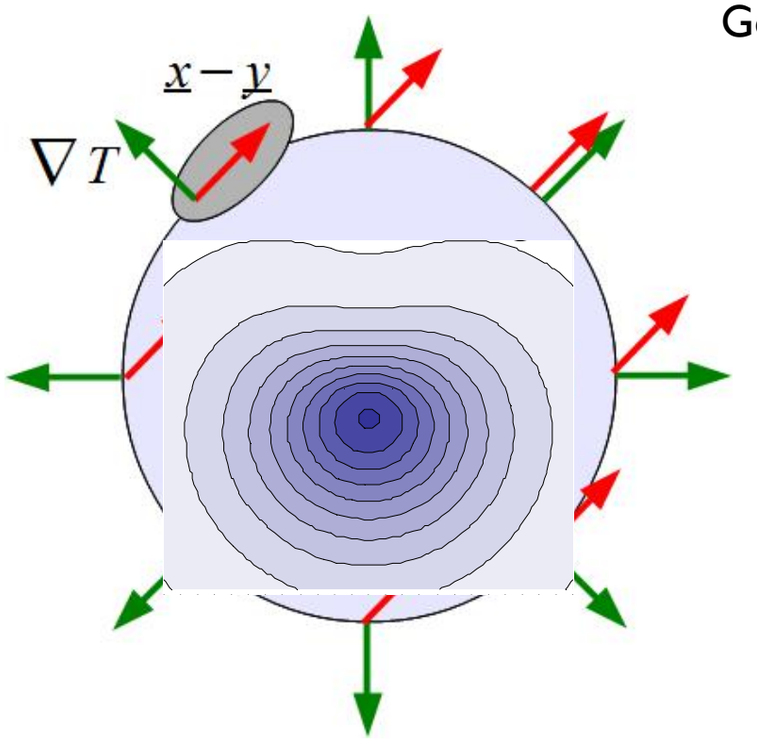

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➡ But may be nonzero due to the distortion in a transversely polarized target (GPD E)

➡ TSSAs in the backward direction are sensitive to the small-x odderon field of the polarized proton

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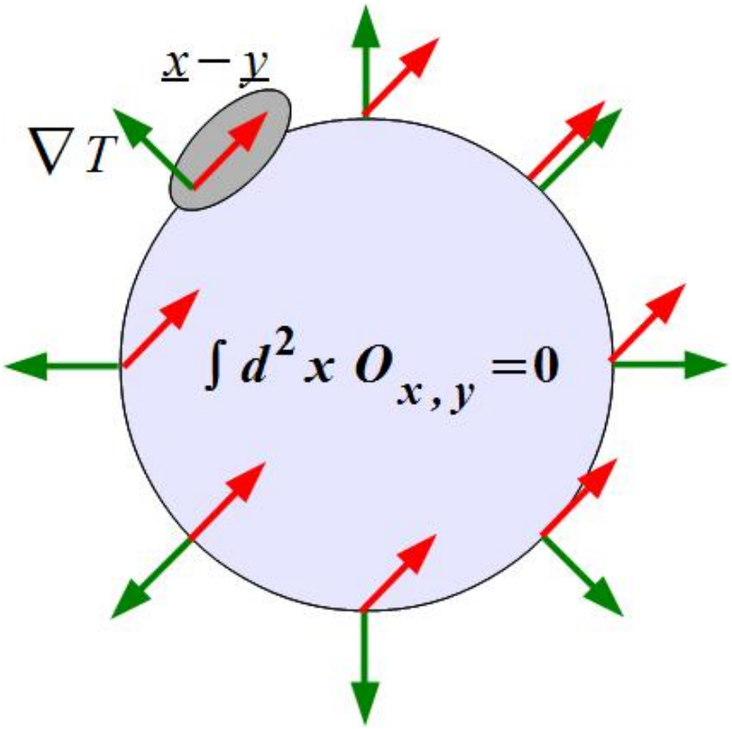

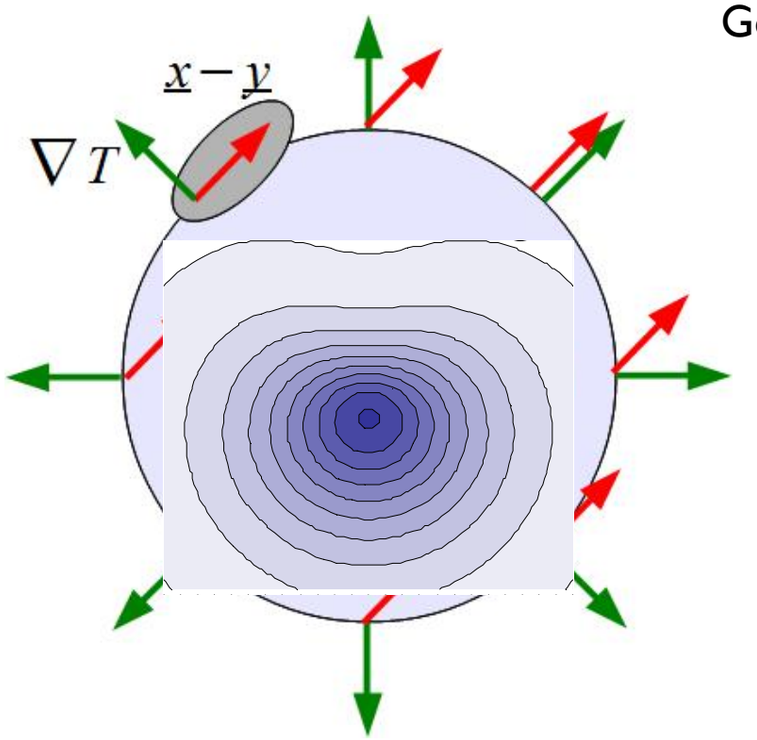

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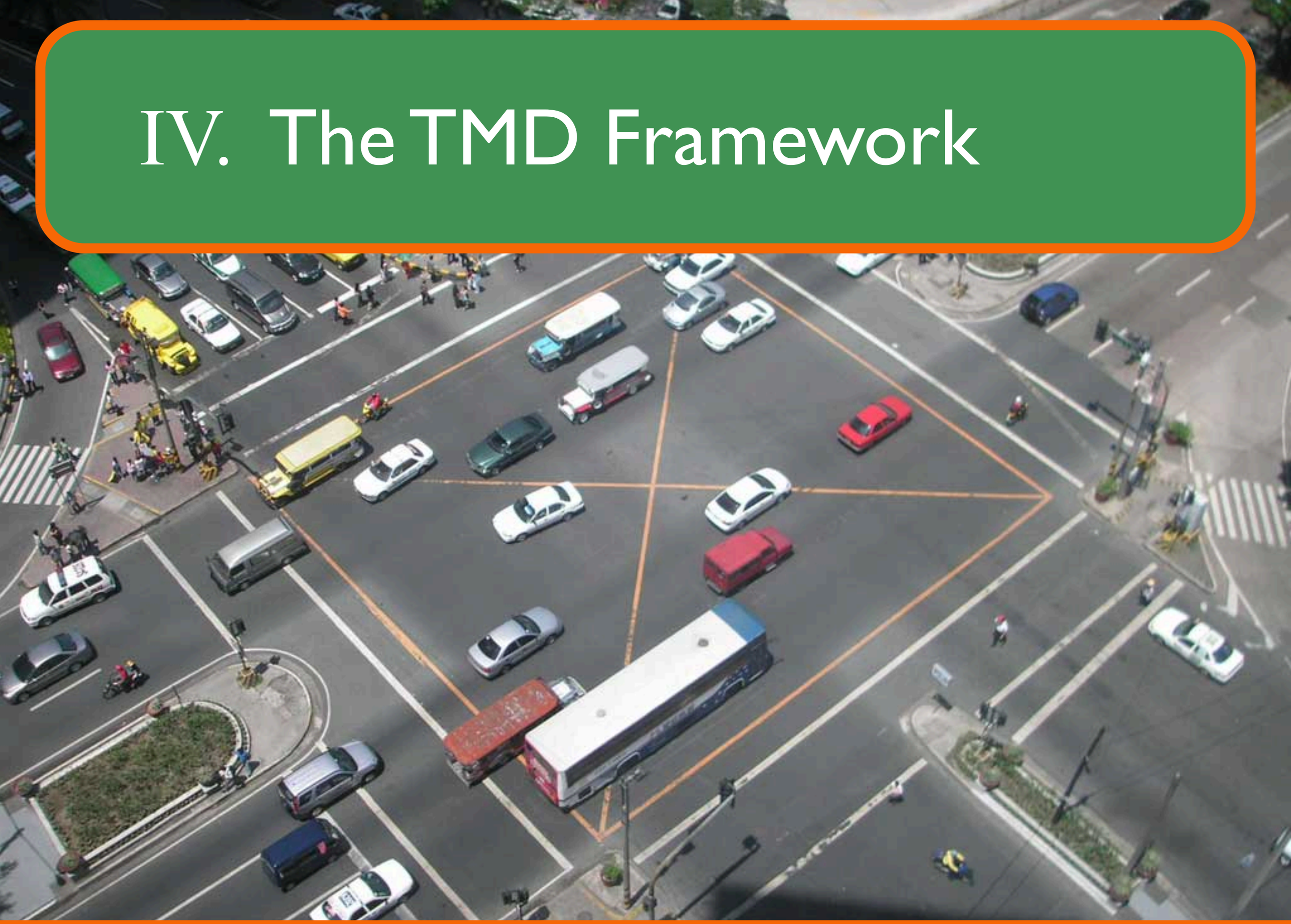
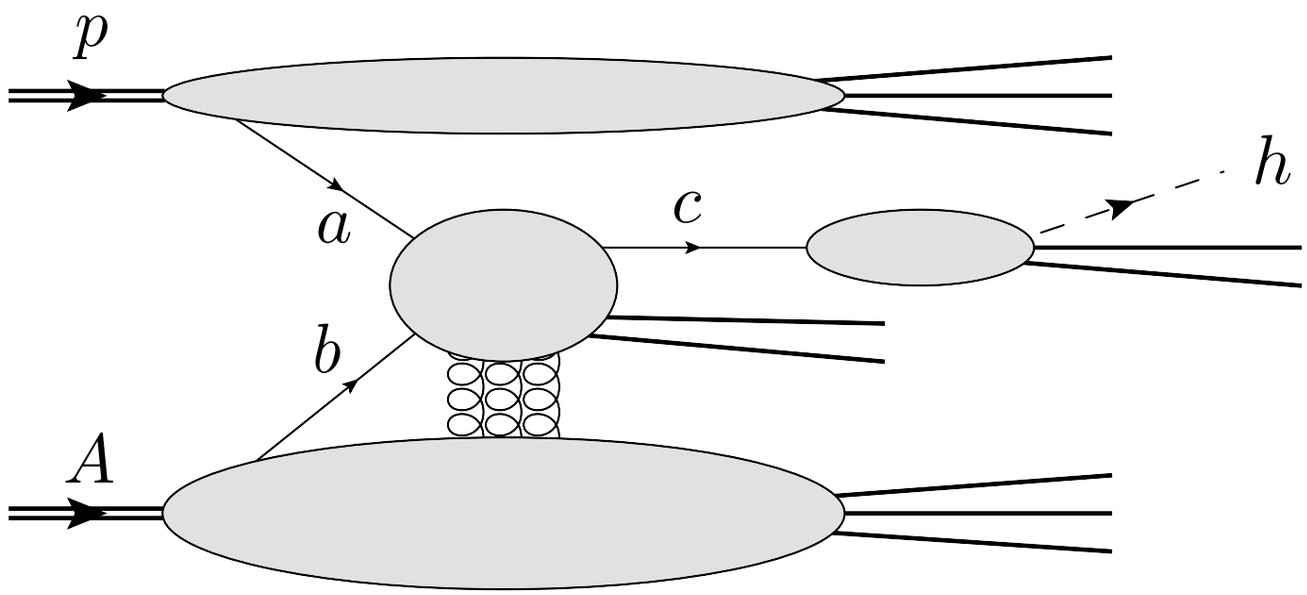
Opportunity: Does the C-odd odderon contribute to the TSSAs of protons vs antiprotons at FNAL?

IV. The TMD Framework



Transverse-Momentum-Dependent Factorization



$$d\sigma \sim f_{a/p}(x_p, k_{pT}) \otimes f_{b/A}(x_A, k_{AT}) \otimes H_{a+b\to c+X}(Q^2) \otimes D_{h/c}(z, k_{hT})$$

- Describes a process with a hard scale and a secondary scale:

$$p + A(Q_s) \to h(M^2 = Q^2, p_T) + X \qquad Q^2 \gg p_T^2\,,\ \Lambda_{QCD}^2$$

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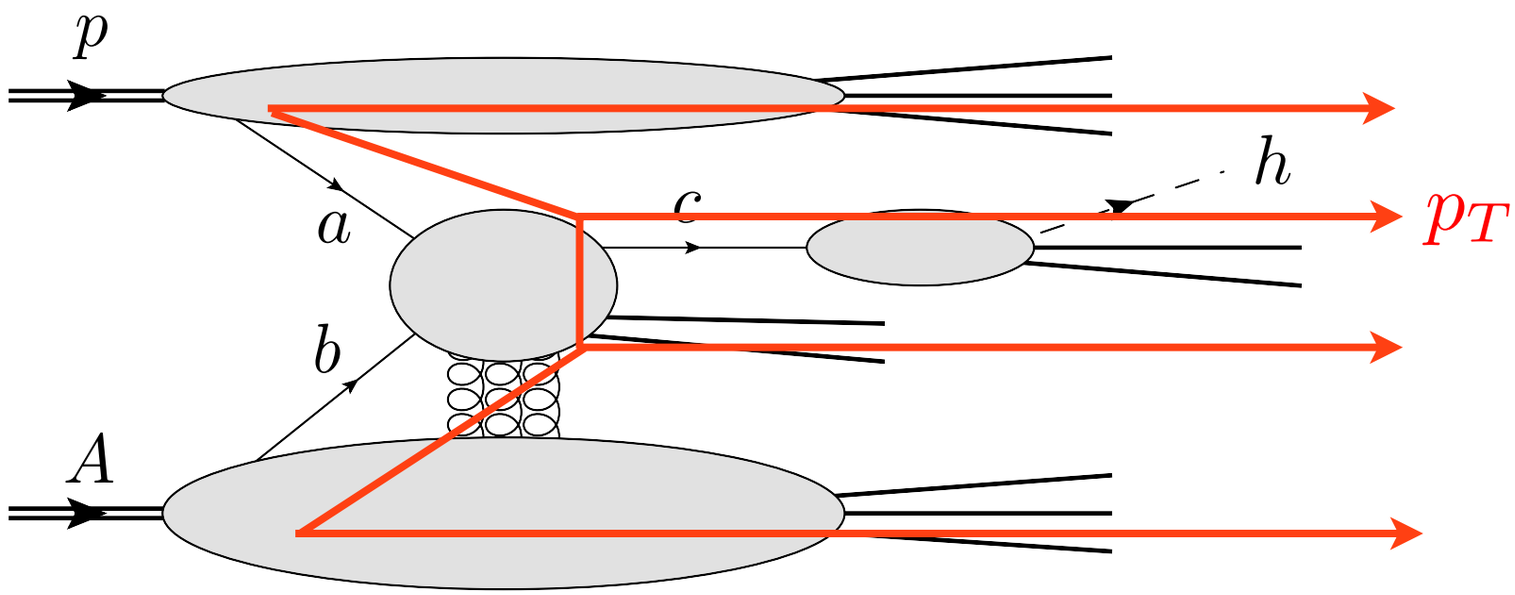

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➡ 3D parton distributions and fragmentation functions

➡ Multiple scattering may not be suppressed: $\left(\frac{1}{p_T^2}\right)^n$ vs $\left(\frac{1}{Q^2}\right)^n$

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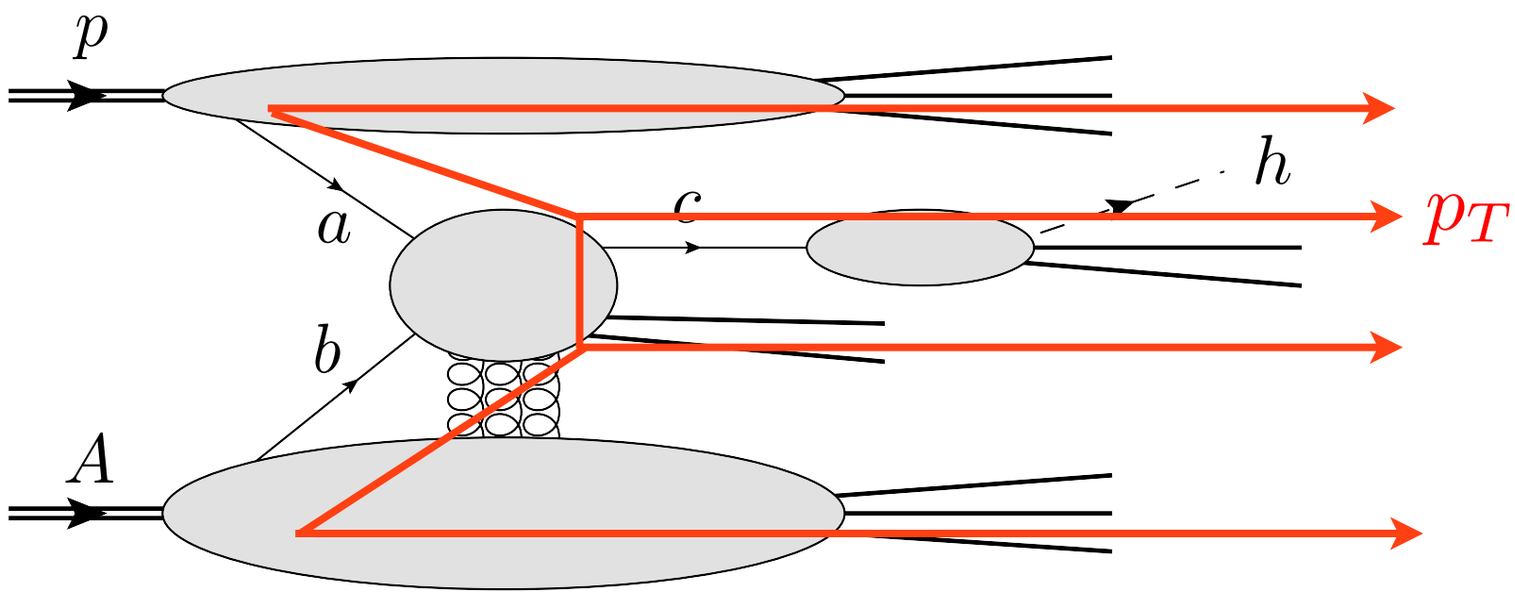

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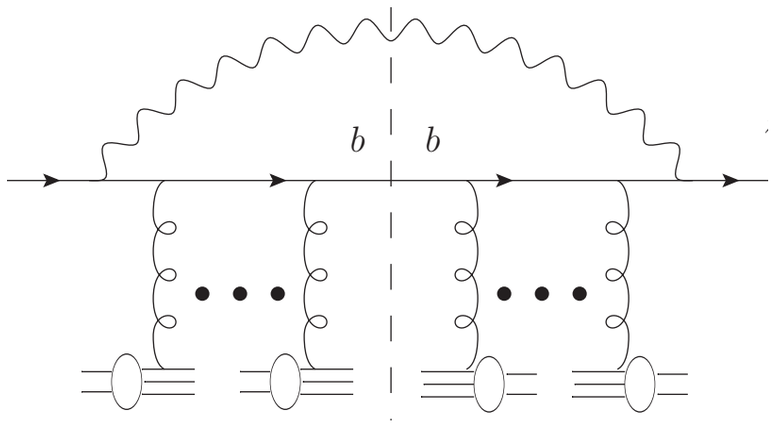
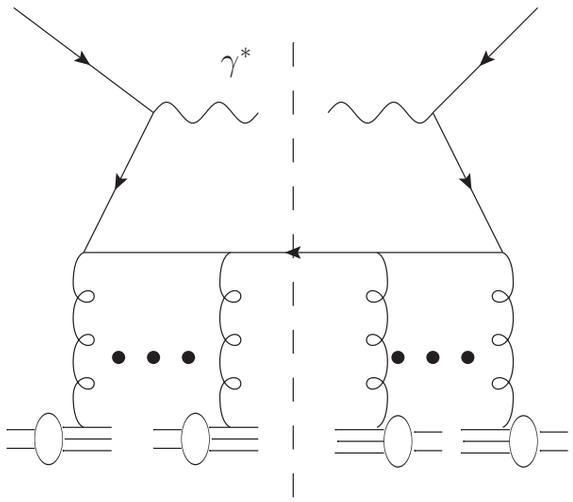
- Based on a factorization theorem derived at all orders in pQCD

TSSAs from Drell-Yan in pA

Kang & Xiao, PR **D87** 034038 (2013)





$$p + A(Q_s) \to (\ell^+\ell^-)(Q^2, p_T) + X$$

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- The Drell-Yan process is a clean application of TMD factorization

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➡ TSSA is generated by the proton TMD and dressed by CGC rescattering

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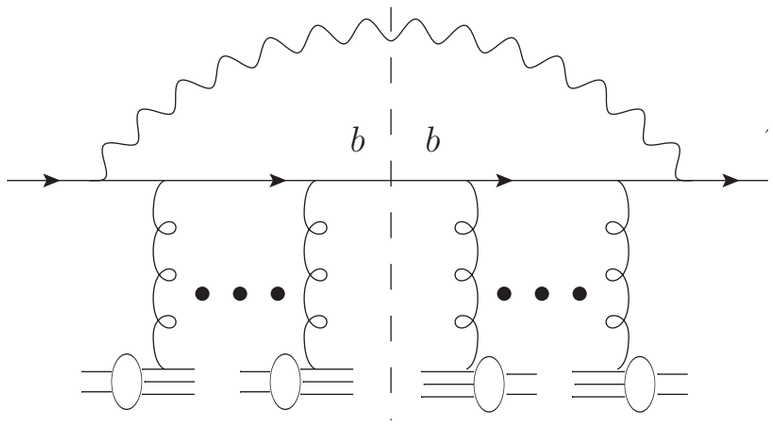

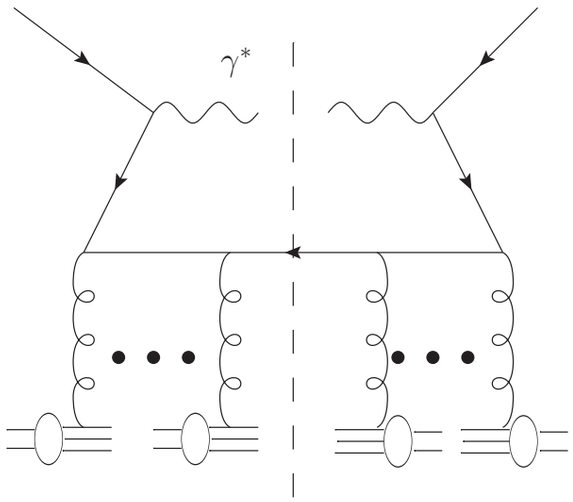

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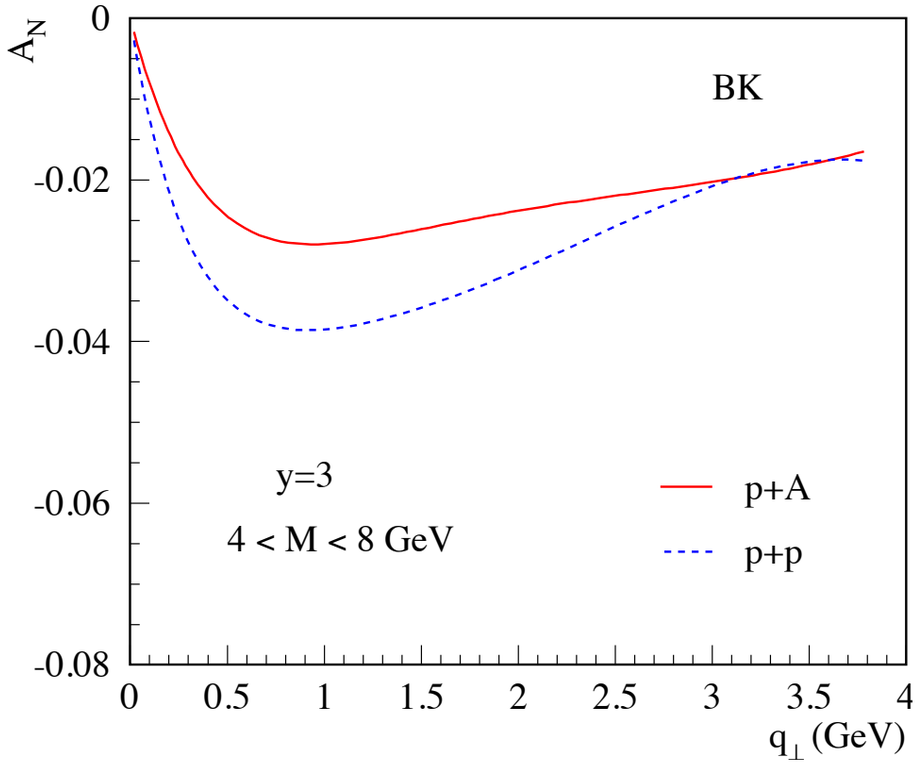
- Momentum broadening dilutes the TSSA compared to pp



Gluon TSSAs at Small x: Return of the Odderon

Boer et al., PRL **116** 122001 (2016)

$$\Gamma^{\mu\nu}_{T-odd} = \frac{k_\perp^\mu k_\perp^\nu}{g^2 V x p^+} \int \frac{d^2y}{(2\pi)^3} e^{ik_\perp \cdot y_\perp} \langle p, S | \mathrm{Tr}[U^{[\Box]}(y) - U^{[\Box]\dagger}(y)] | p, S \rangle$$

- The T-odd part of TMDs is a source of TSSAs
- Small-x gluon TMDs are relevant for hadron production in the backward direction in pA collisions.

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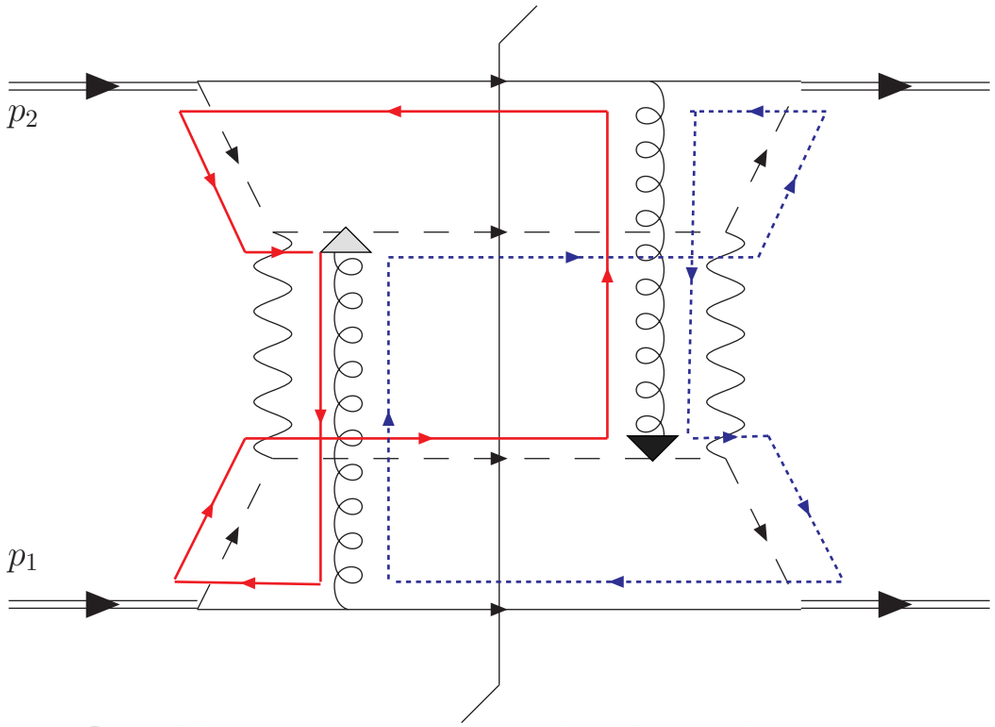
- The T-odd part of TMDs is a source of TSSAs
- Small-x gluon TMDs are relevant for hadron production in the backward direction in pA collisions.
- In the small-x limit, the T-odd gluon TMD is generated by the (spin dependent matrix element of) the odderon!

$$x f_{1T}^{\perp g} = x h_{1T}^{g} = x h_{1T}^{\perp g} = -\frac{k_T^2 N_c}{4\pi^2 \alpha_s} O(x, k_T^2)$$

➡ Agrees with the hybrid framework calculation

Factorization Breaking in pA



Mulders & Rogers, PR **D81** 094006 (2010)

Mulders & Rogers, arXiv: 1102.4569

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$$p + A(Q_s) \to (h_1 + h_2)(M^2 = Q^2, p_T) + X$$

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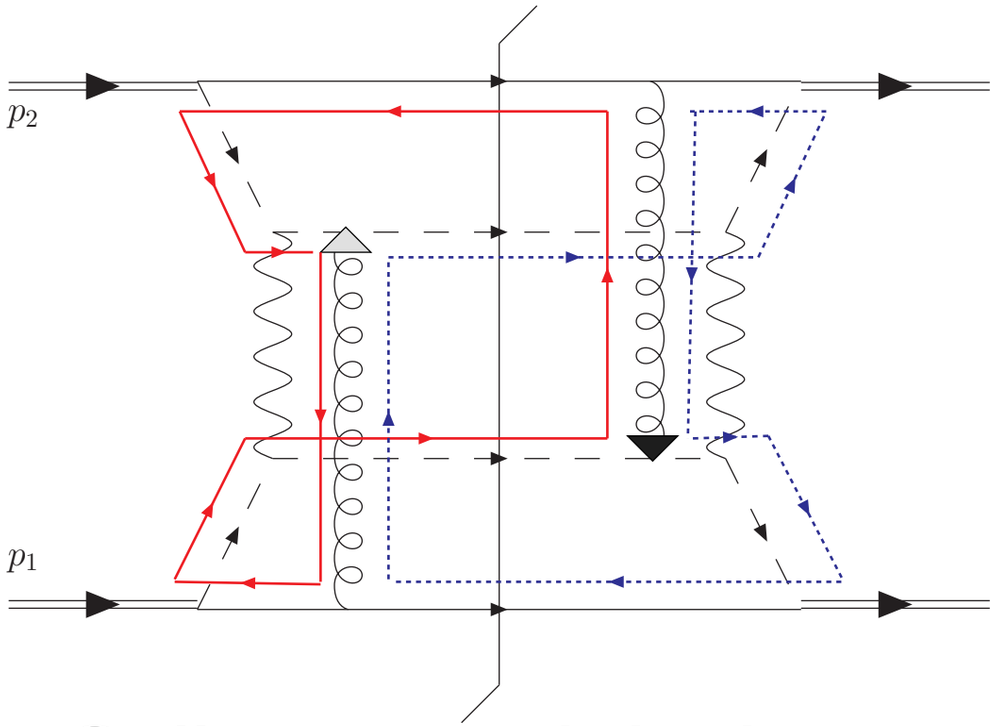
Factorization Breaking in pA



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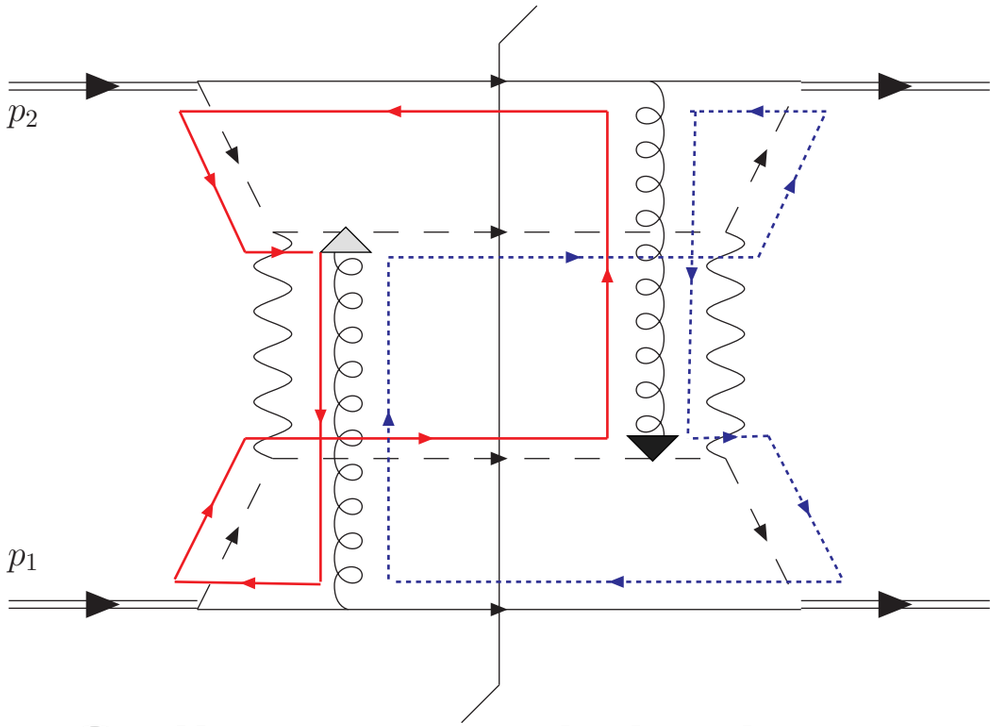
➡ Can elevate power-suppressed asymmetries to leading order

$p + A \to h + \gamma + X$: $(h\gamma)$ Longitudinal Double Spin Asymmetry

Factorization Breaking in pA



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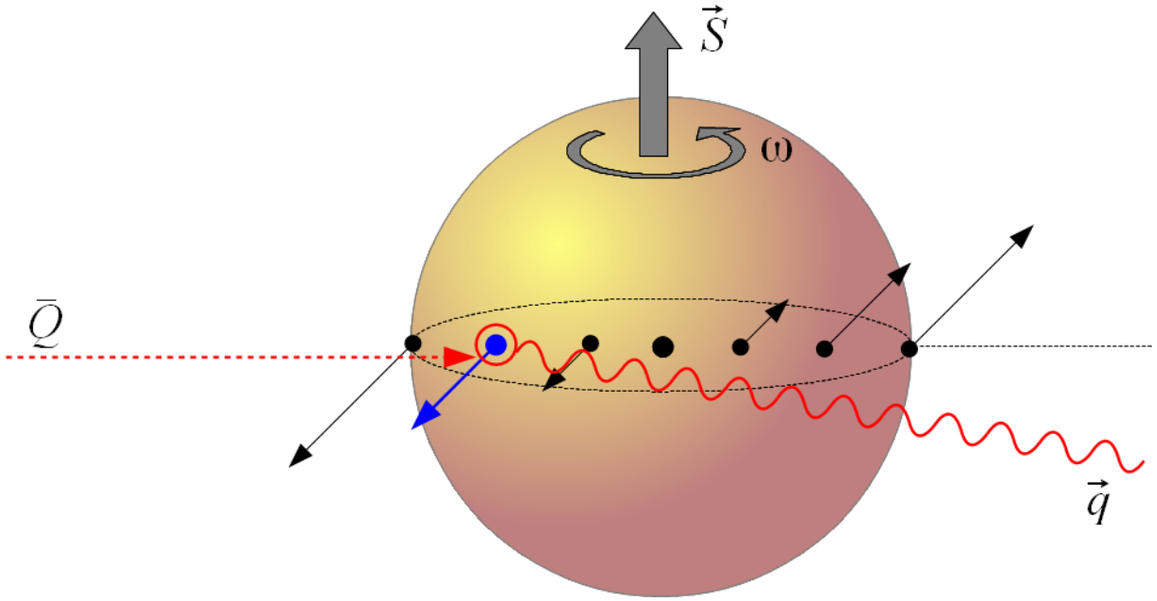
Gamberg & Kang, Phys. Lett. **B696** 109 (2011)

Opportunity: Need a full profile assuming TMD factorization holds in order to extract the factorization-breaking effects.

V. Some Selected Developments

Nuclear TMDs and TMD Mixing



Kovchegov & MS, PR **D89** 054035 (2014)

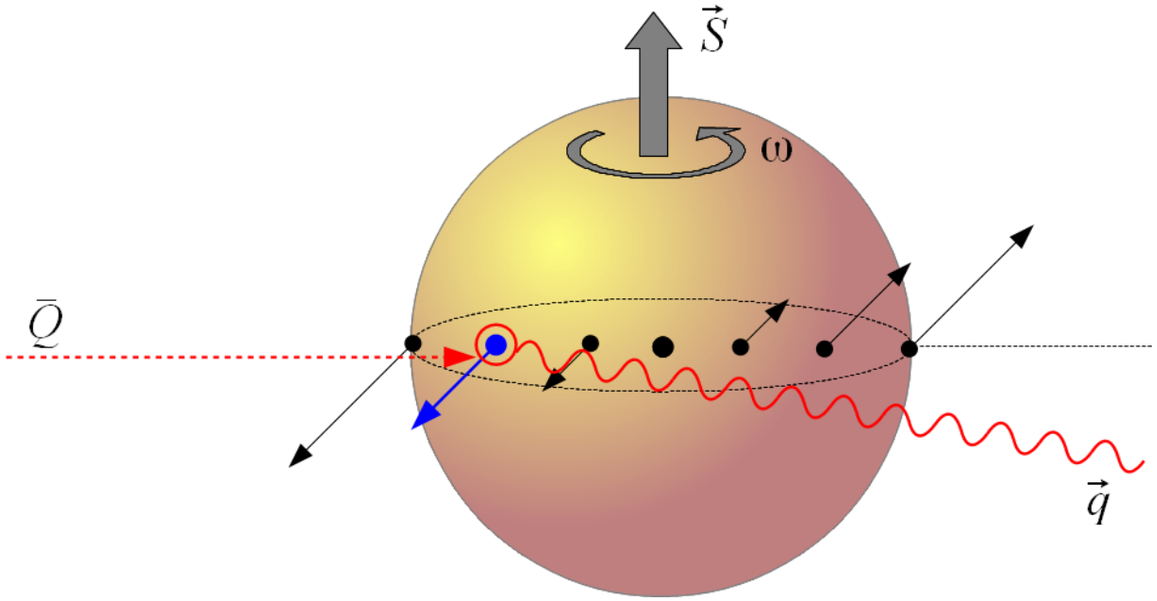
Kovchegov & MS, NP **B903** 164 (2016)

$$p + A(Q_s) \to (\ell^+\ell^-)(Q^2, p_T) + X$$

$$Q^2 \gg p_T^2 \,,\, Q_s^2$$

- TMDs of a heavy nucleus can be decomposed in terms of the TMDs of its nucleons

Nuclear TMDs and TMD Mixing



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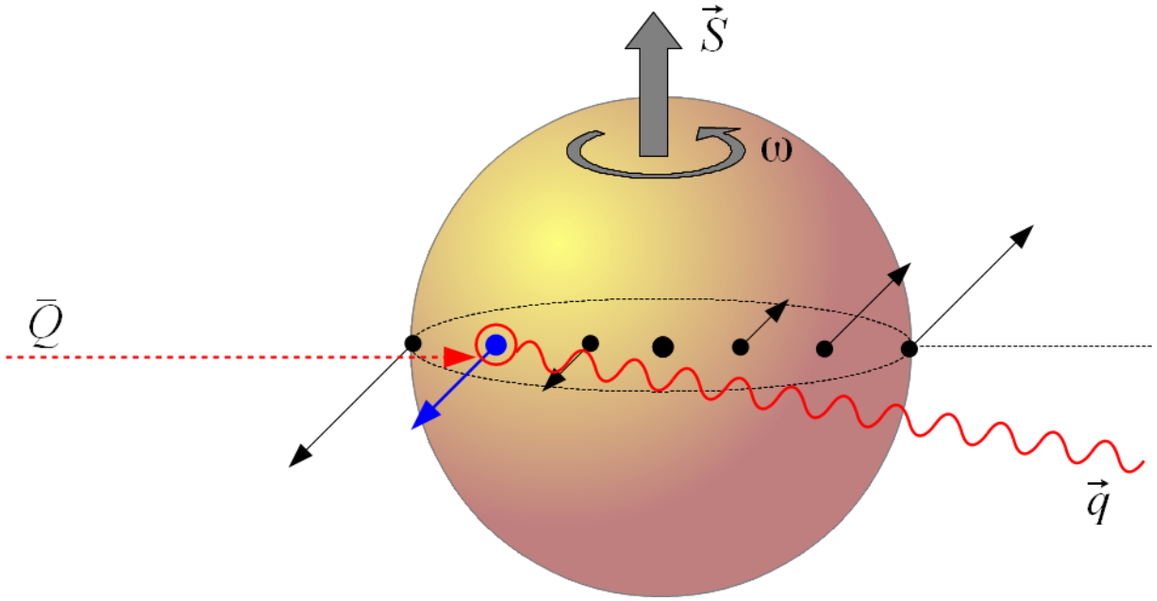
- TMDs of a heavy nucleus can be decomposed in terms of the TMDs of its nucleons

➡ Nuclear $(\vec{L}\cdot\vec{S})$ coupling and CGC rescattering can generate TMD mixing between the nucleons and the nucleus

➡ Multiple simultaneous mixings allows extraction of the $(\vec{L}\cdot\vec{S})$ coupling and predictive power for other channels.

Nuclear TMDs and TMD Mixing



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Kovchegov & MS, NP **B903** 164 (2016)

$$p + A(Q_s) \to (\ell^+\ell^-)(Q^2, p_T) + X$$

$$Q^2 \gg p_T^2\,,\; Q_s^2$$

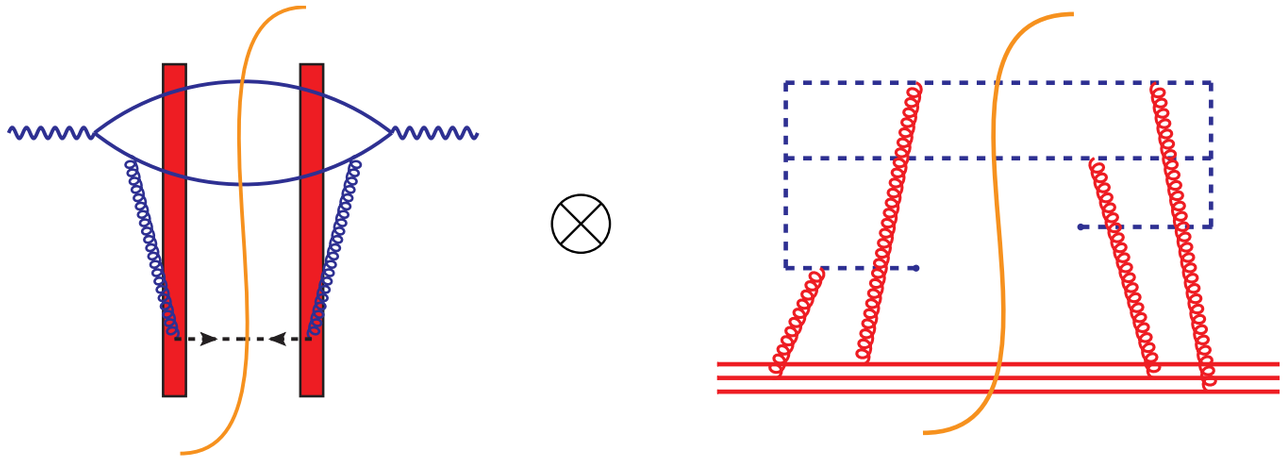
- TMDs of a heavy nucleus can be decomposed in terms of the TMDs of its nucleons

➡ Nuclear $(\vec{L}\cdot\vec{S})$ coupling and CGC rescattering can generate TMD mixing between the nucleons and the nucleus

➡ Multiple simultaneous mixings allows extraction of the $(\vec{L}\cdot\vec{S})$ coupling and predictive power for other channels.

Opportunity: Spectator neutron tagging at an EIC. Signatures of OAM in the proton?

A Unifying Paradigm for Evolution



Balitsky & Tarasov, JHEP **1510** 017 (2015)

Balitsky & Tarasov, arXiv: 1603.06548

- High energy "rapidity factorization" with a rapidity cutoff.
- Combines OPE and background field methods to evaluate the gluon TMD in a variety of kinematic regimes.

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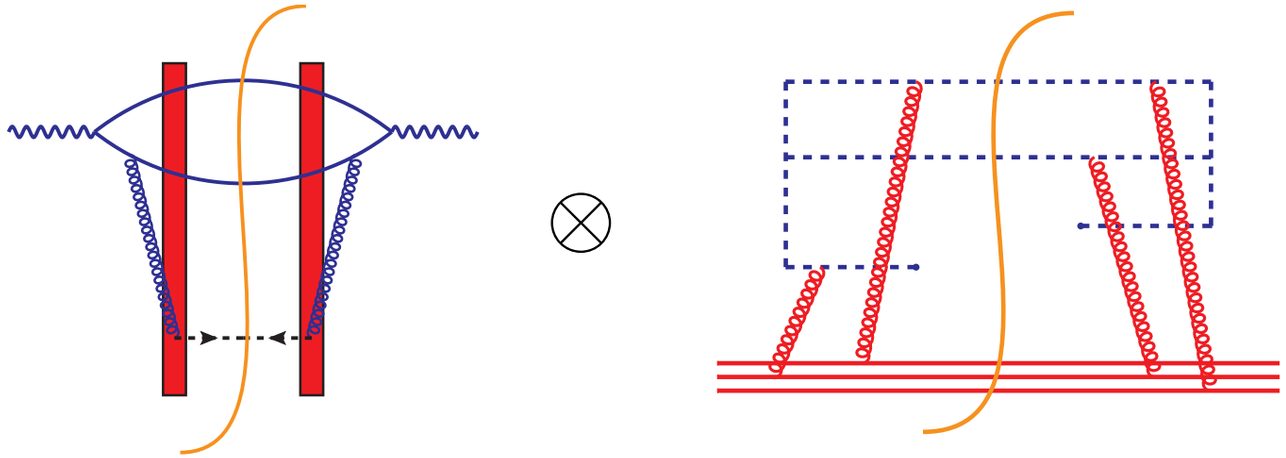

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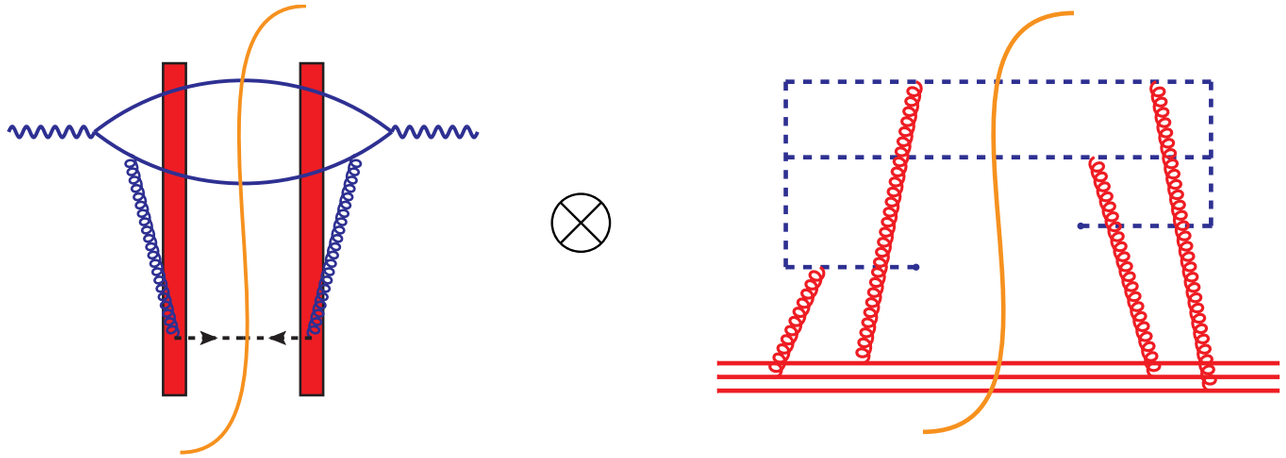

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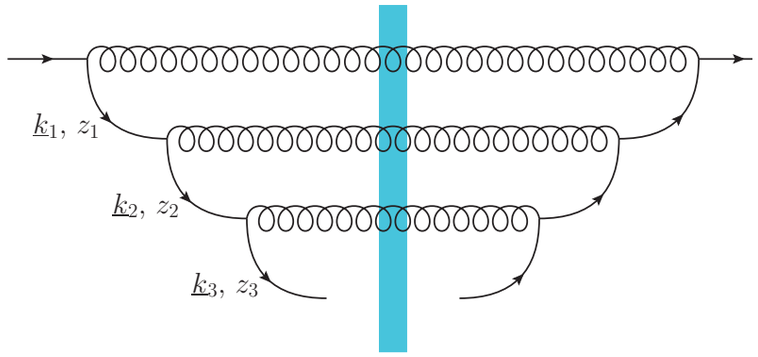
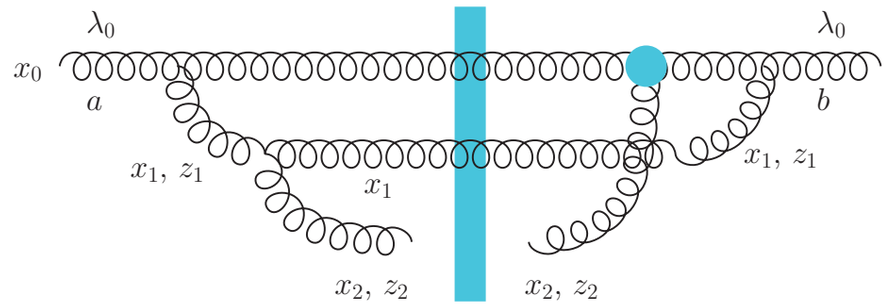
Opportunity: Is this a basis for a universal evolution formalism? Does it still work beyond leading log?

Helicity Evolution at Small x





Kirschner & Lipatov, NP **B213** 122 (1983)
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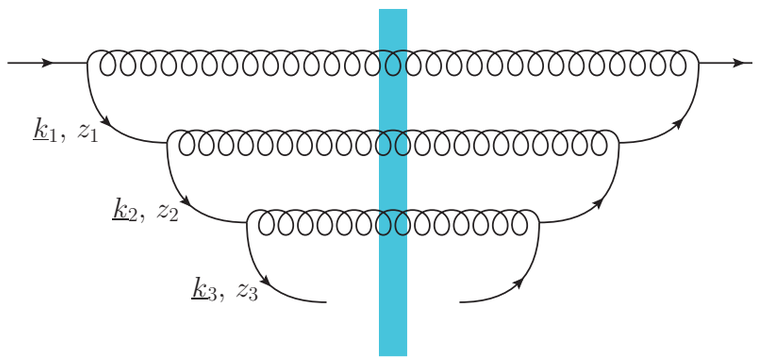

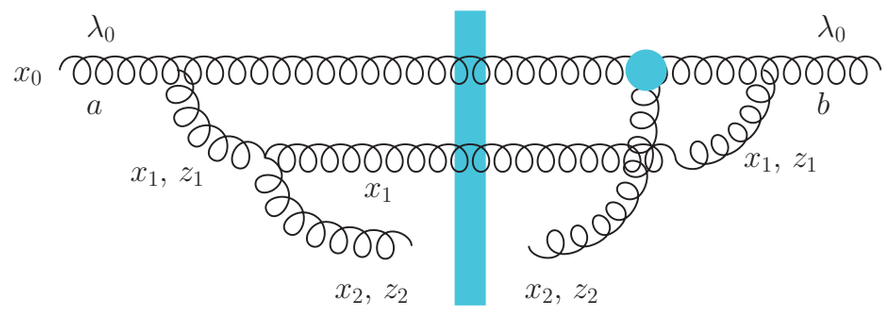

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➡ Complex non-ladder structure needs to be evaluated numerically...

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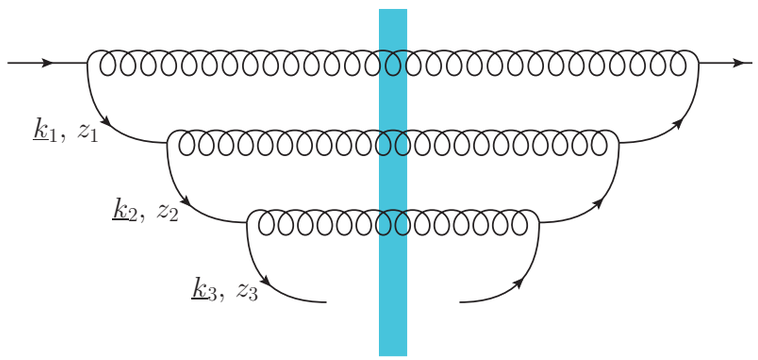

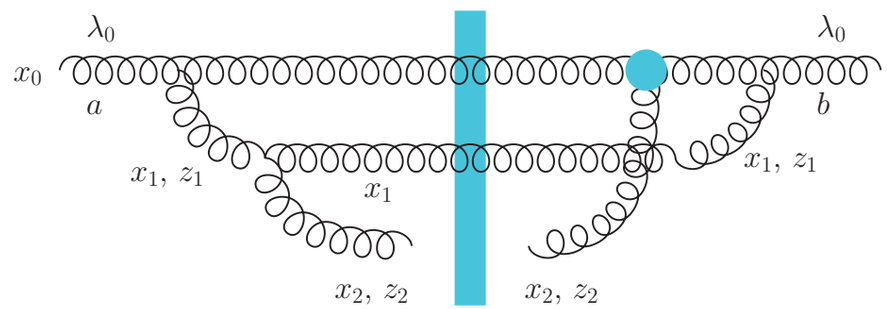

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Opportunity: Could there be polarization at small x? Estimates are borderline so far.

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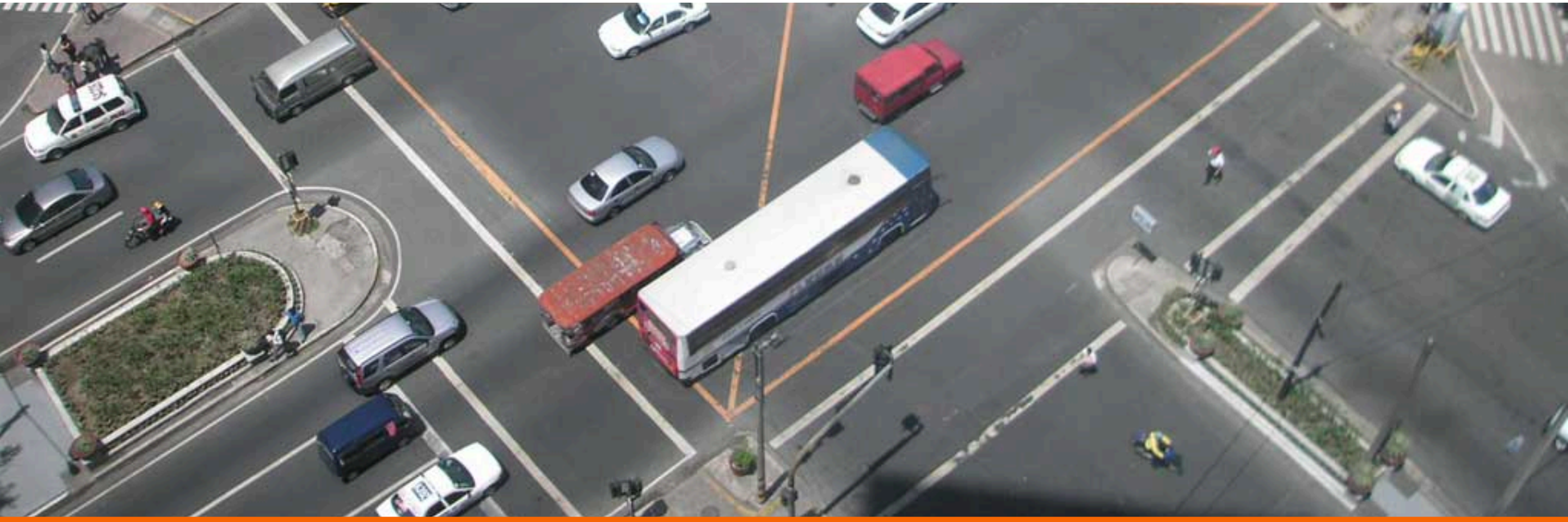

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- The RHIC spin and pA programs will usher in the coming EIC era.