Helicity Evolution at Small x

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with Daniel Pitonyak
and Yuri Kovchegov

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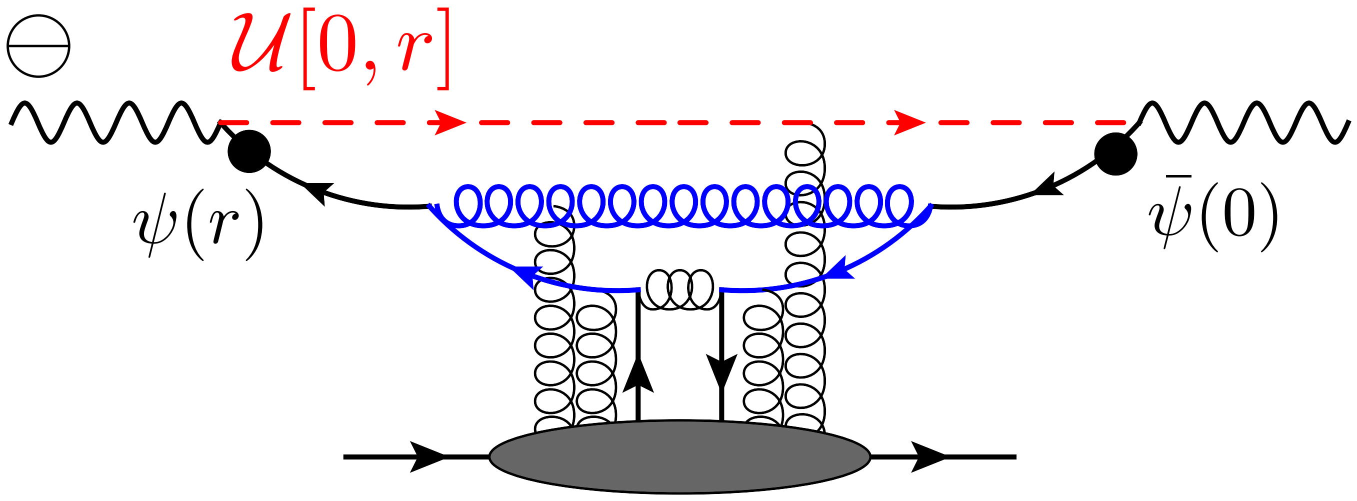
RBRC Workshop: Emerging Spin and Transverse Momentum Effects in pp / pA

Small-x Helicity Evolution



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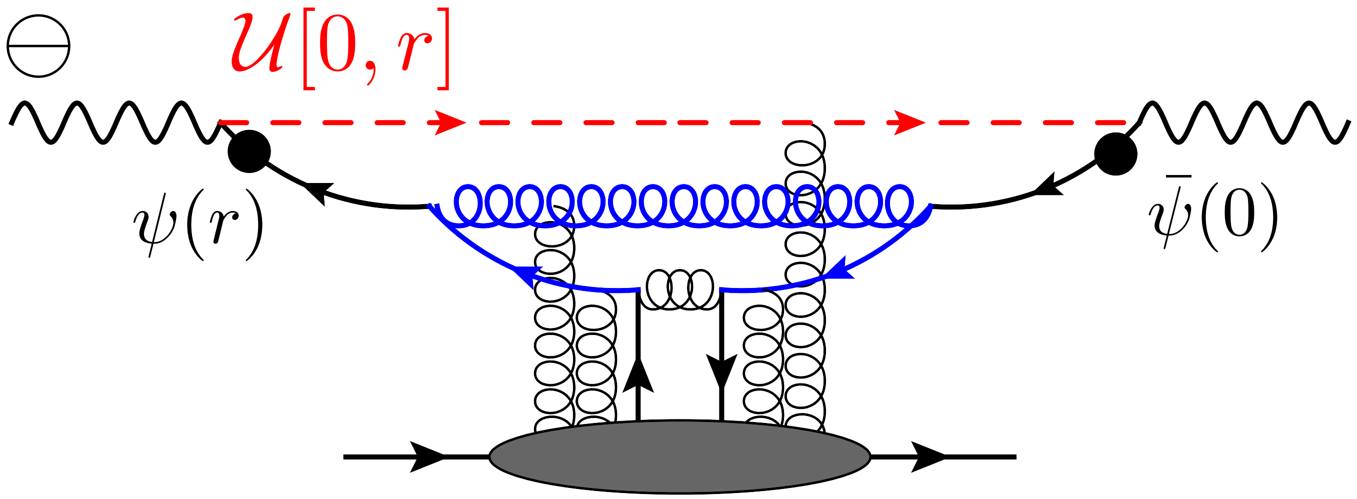

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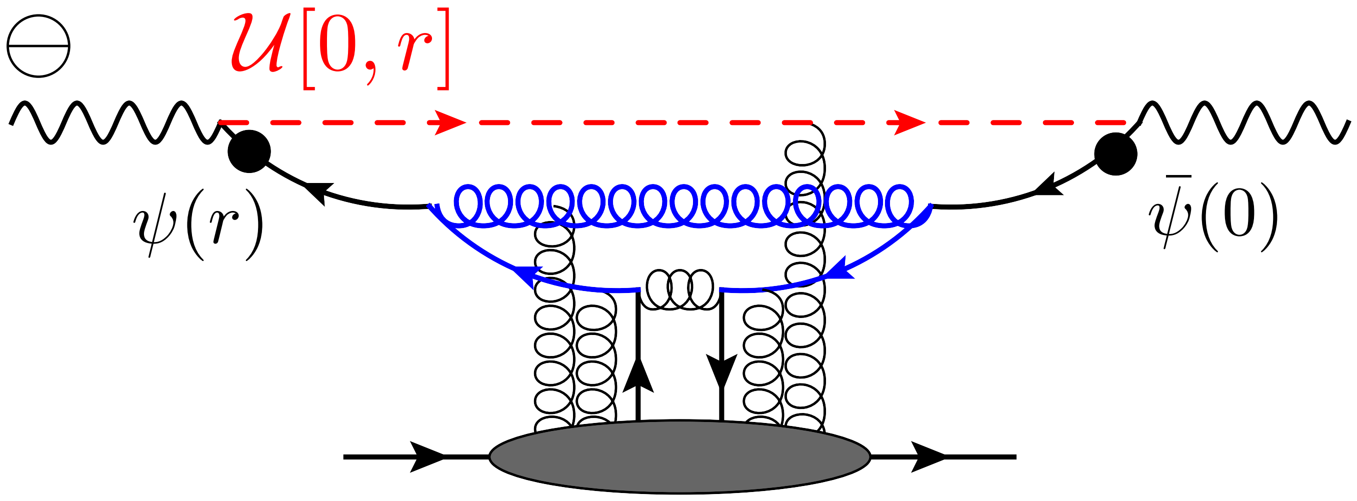

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- Quark helicity at very small x evolves by the radiation of soft polarized quarks and gluons.
- We can formulate a small-x evolution equation for the quark helicity, which appears to show rapid growth at small x.
- But helicity evolution is much more complex than unpolarized small-x evolution....

- The "Proton Spin Budget" is described by the Jaffe-Manohar Sum Rule.

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  ➡ Gluon spins from in polarized proton-proton collisions

DSSV ('09-'14) fits: data from

$$0.001 < x < 1$$

$$\boxed{\begin{aligned} \Delta\Sigma &\approx 0.25 \;\; (25\%) \\ \Delta G &\approx 0.2 \;\; (40\%) \end{aligned}}$$

Motivation: Proton Spin Puzzle

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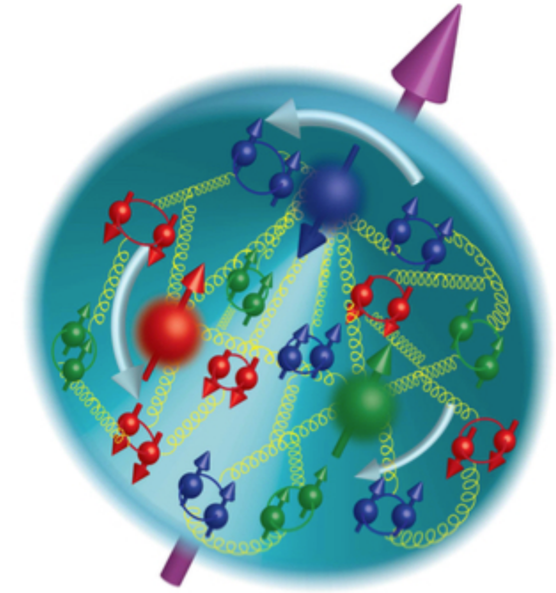
- Proton structure is much more complex than previously believed!
  - ➡ Orbital angular momentum?
  - $\boxed{\text{➡ Polarization at very small x?}}$



Definition: TMD Parton Distributions

$$\underline{\phi_{\alpha\beta}(x, \vec{k}_\perp)} = \int \frac{d^{2-}r}{(2\pi)^3} \, e^{ik\cdot r} \langle h(p,S)| \, \bar{\psi}_\beta(0) \, \mathcal{U}[0,r] \, \psi_\alpha(r) \, |h(p,S)\rangle$$

Transverse Momentum Dependent
Parton Distribution Functions

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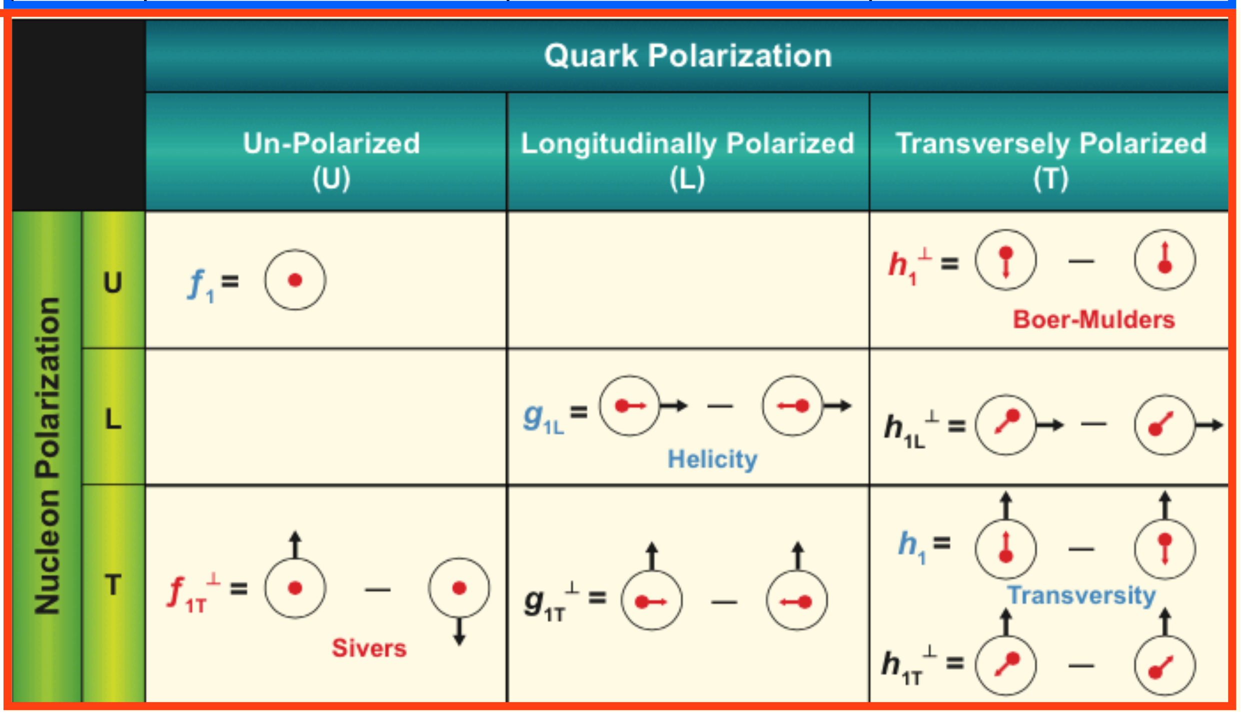

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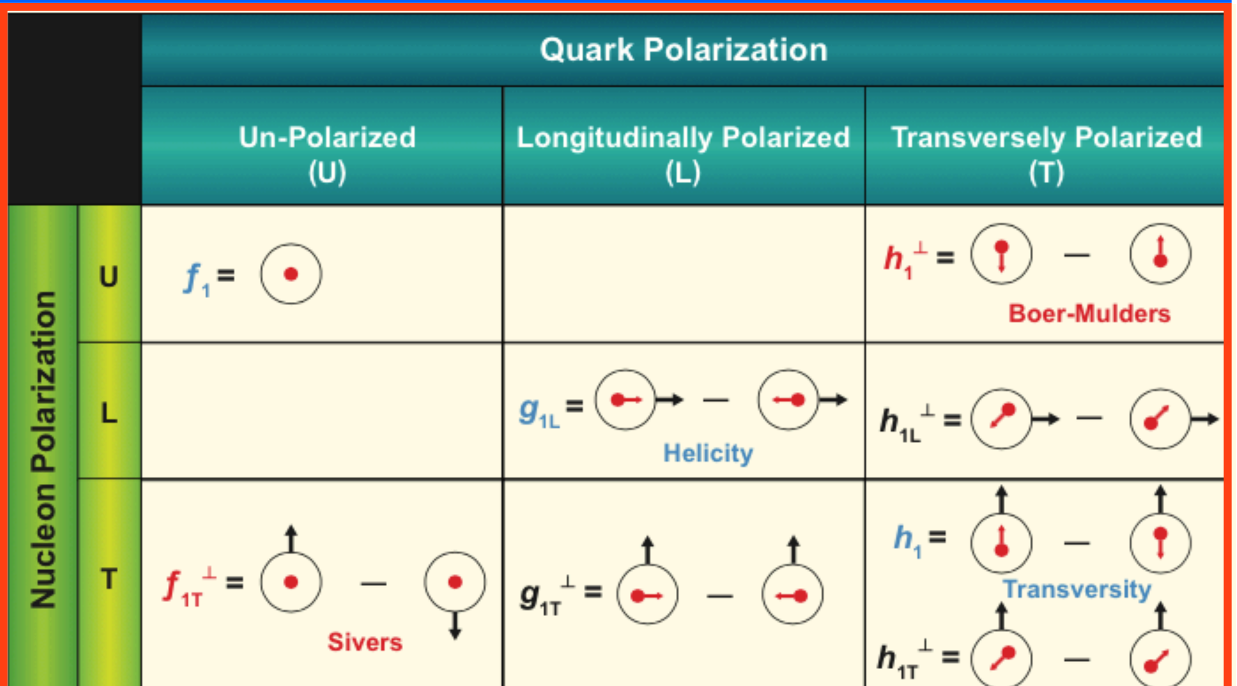
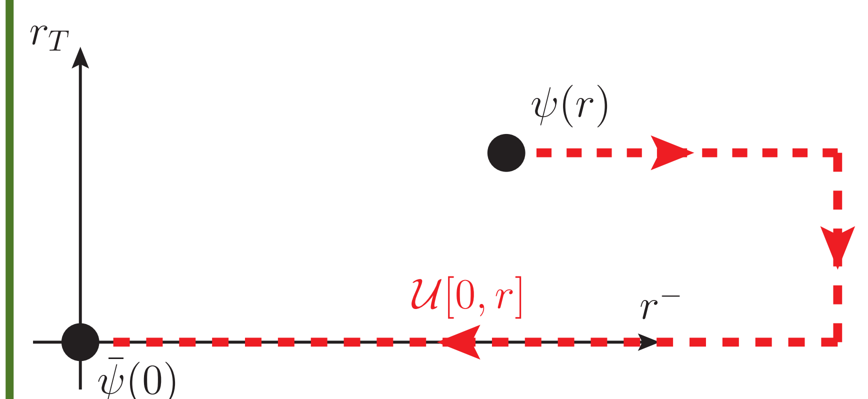


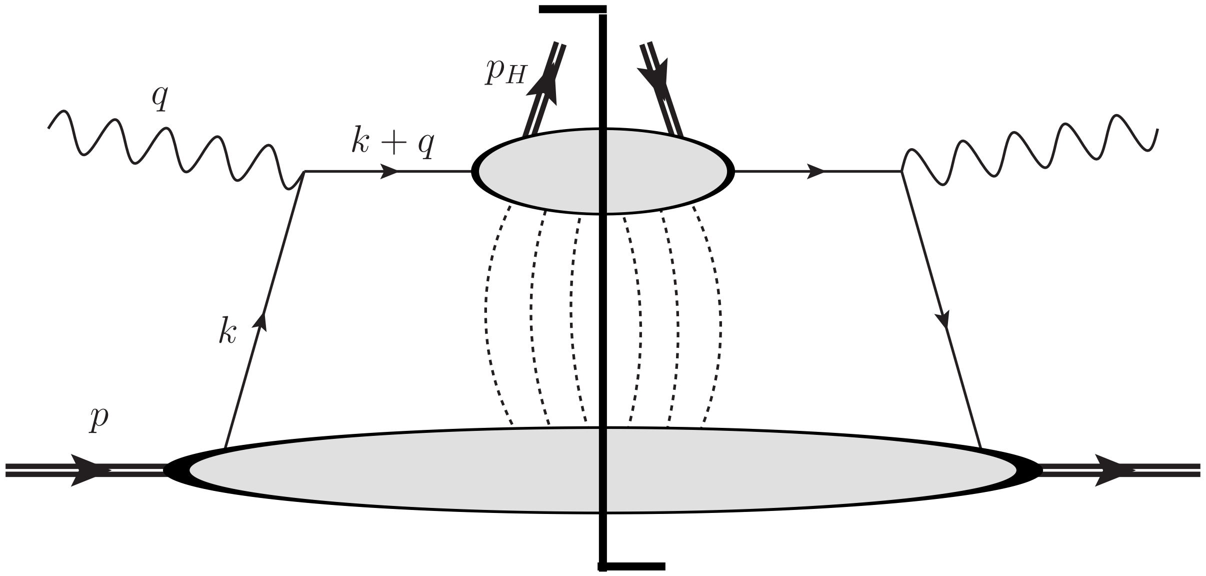


Staple-shaped Gauge Link

encodes final-state interactions

Semi-Inclusive
Deep Inelastic Scattering (SIDIS)

$$e + p \to e' + h + X$$



Large-x Kinematics:

$$\boxed{\begin{array}{c} \hat{s} \sim Q^2 \gg k_T^2 \\ x = \frac{Q^2}{\hat{s}+Q^2} \sim \mathcal{O}(1) \end{array}}$$

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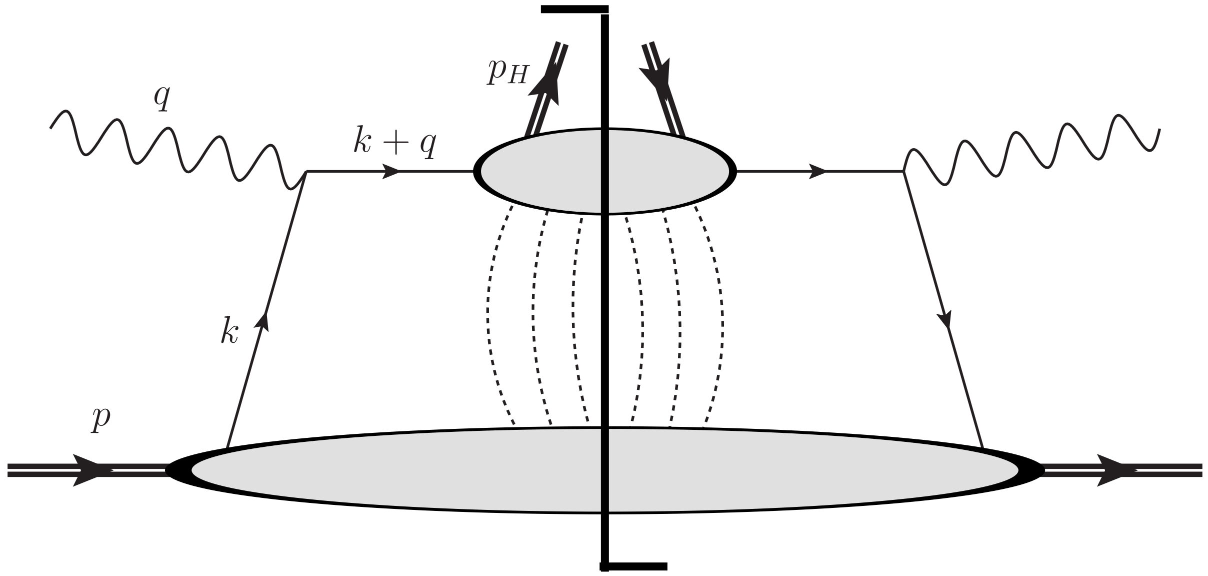

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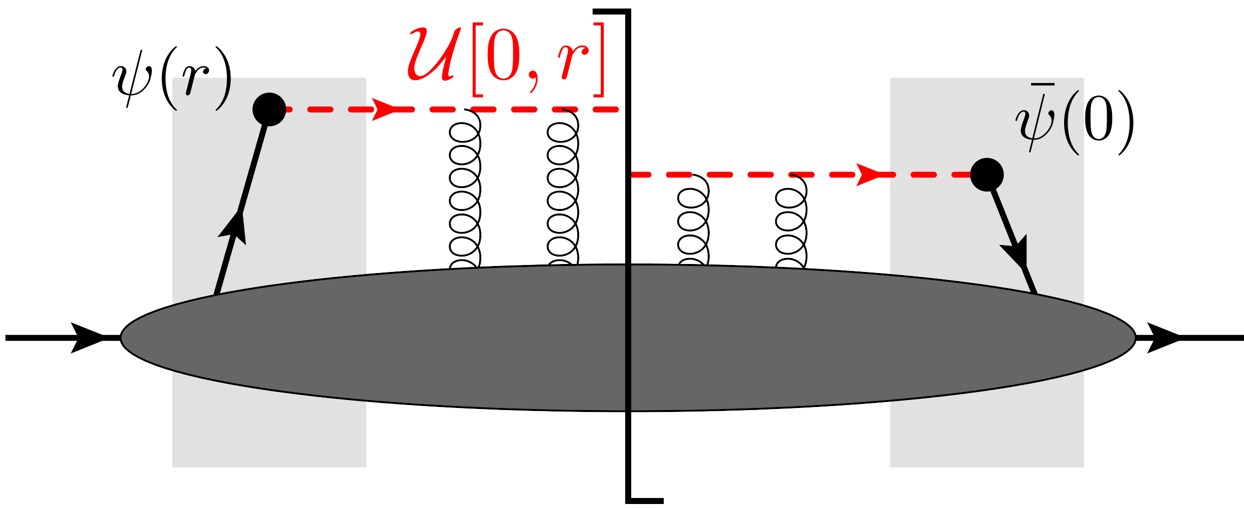

- Photon knocks out a quark from the proton.
- Propagates through the gauge field before escaping

TMD's at Large x

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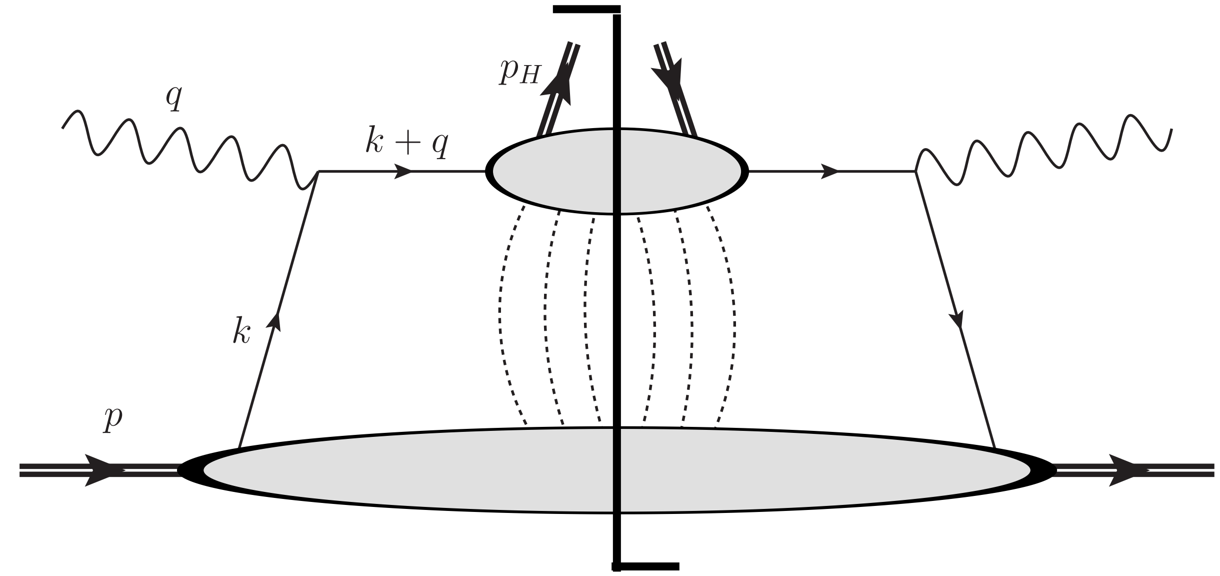

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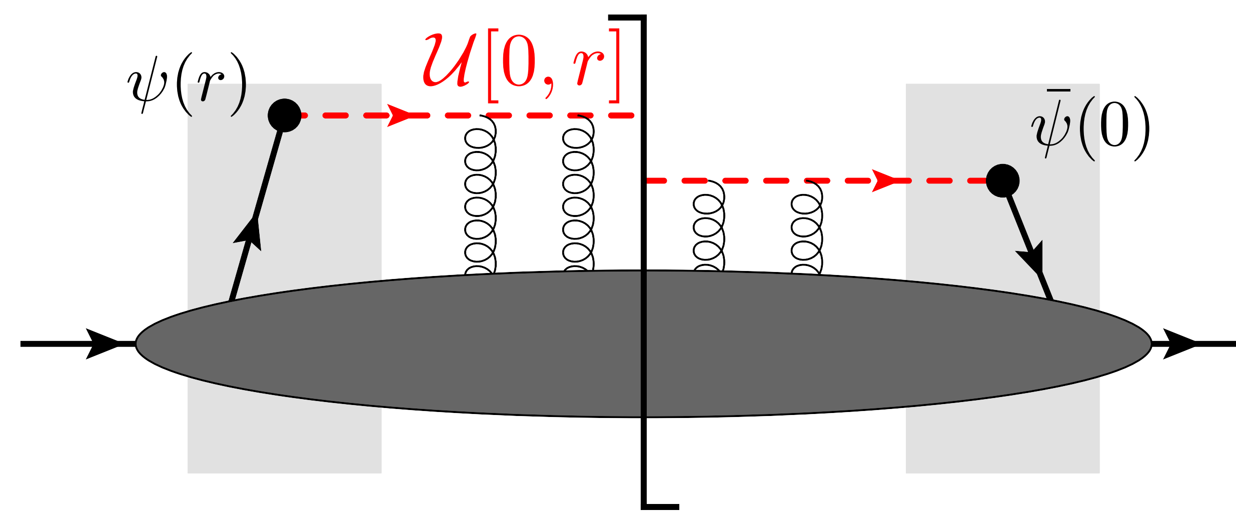

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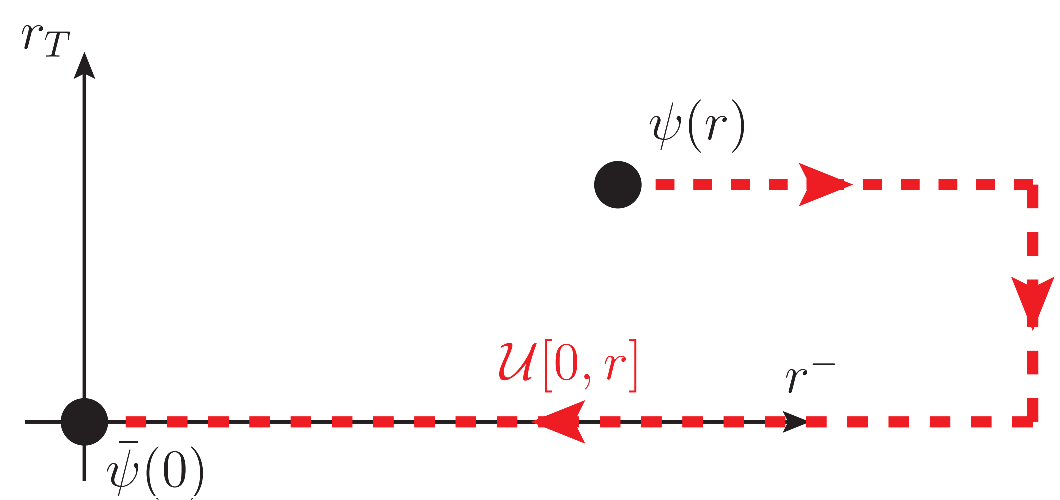
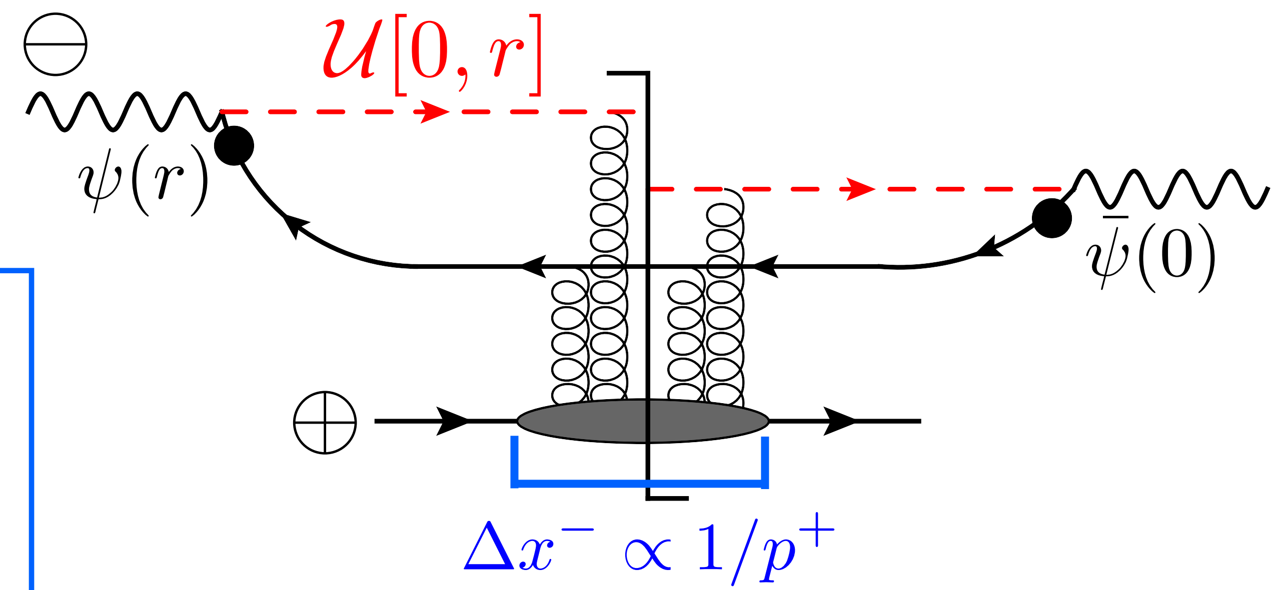


Small-x Kinematics: $\boxed{\begin{array}{l}\hat{s} \gg Q^2 \gg k_T^2 \\ x = \frac{Q^2}{\hat{s}} \ll 1\end{array}}$

$$\Delta t < \frac{1}{m_N x}$$



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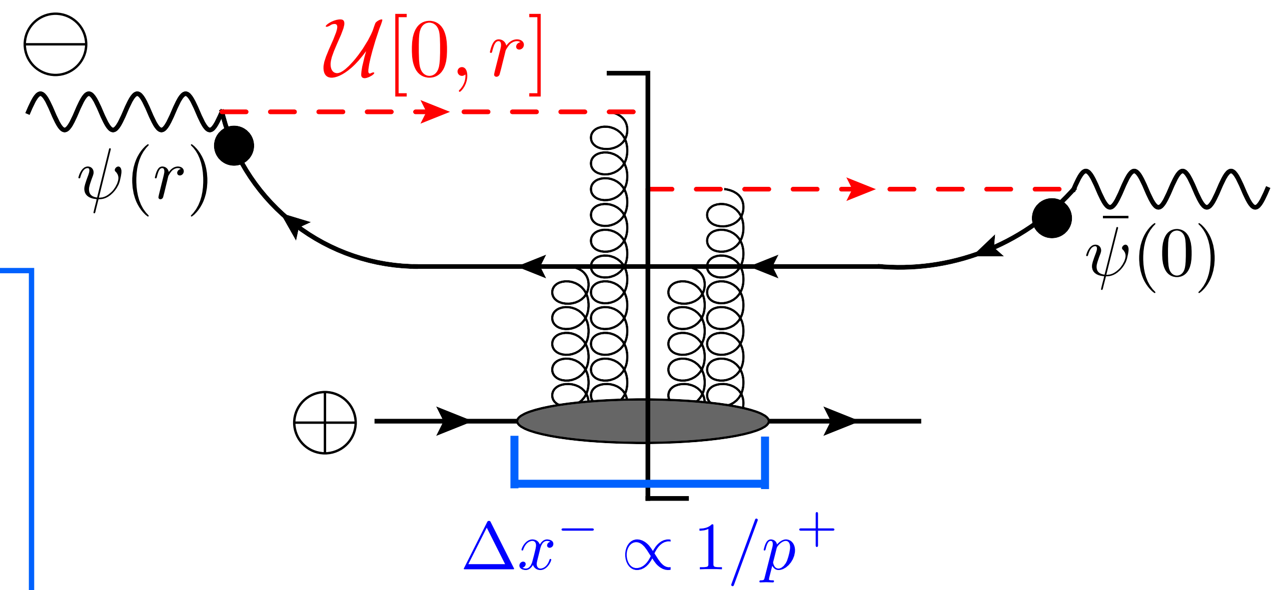

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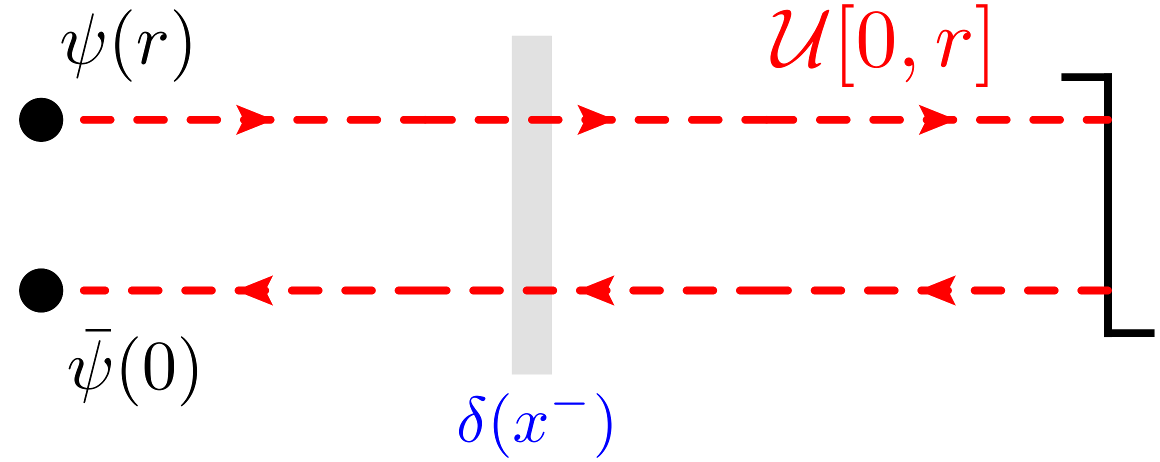

- Proton is Lorentz-contracted to a "shockwave".

➡ Gauge link covers the entire proton.

➡ Infinite dipole degrees of freedom at small x

$$S_{xy} = \frac{1}{N_c} \mathrm{Tr}\left[V_x V_y^\dagger\right]$$

- Long-lived projectile sees whole target coherently.

➡ High gluon density at small x enhances multiple scattering

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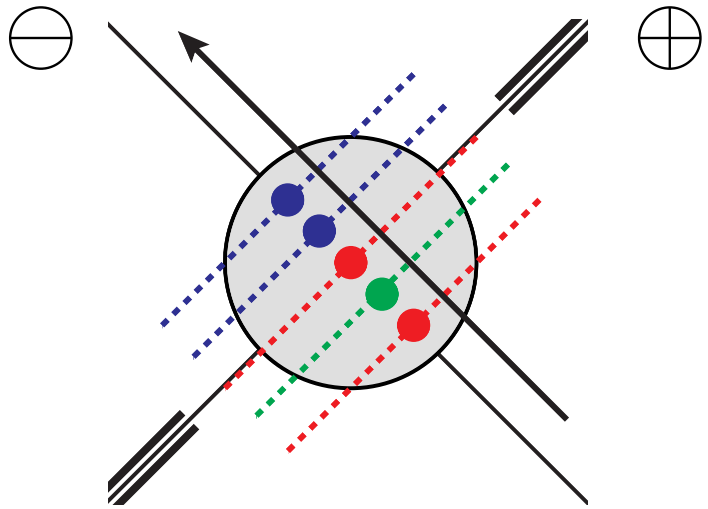
Y. Kovchegov
2:30 - 3:00



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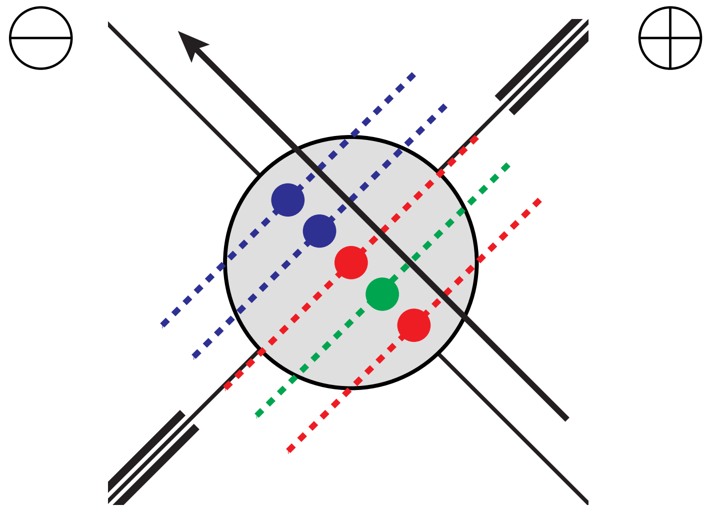

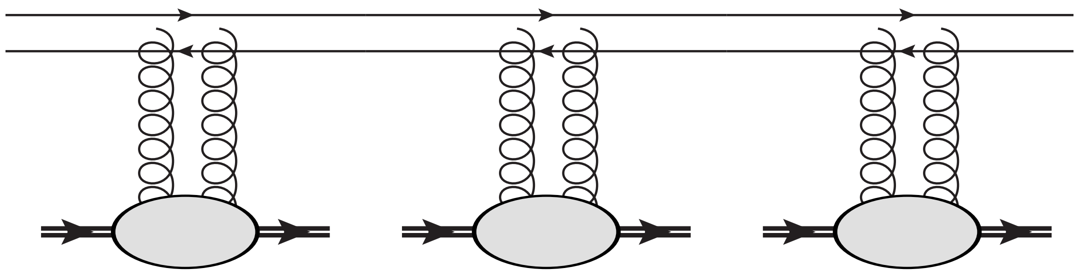

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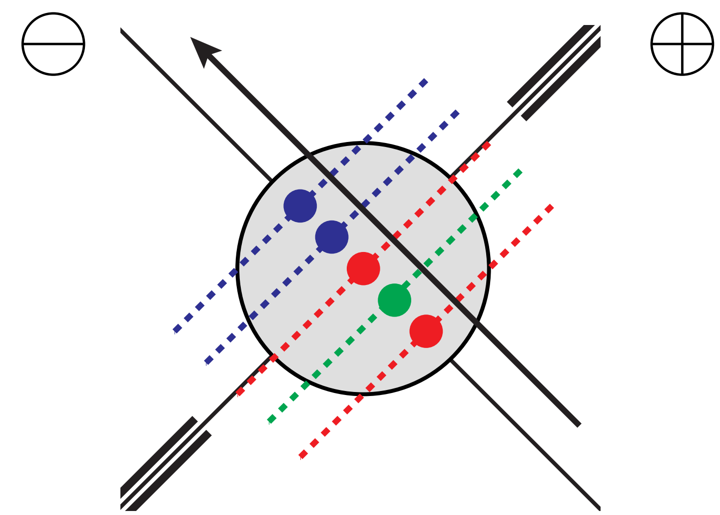

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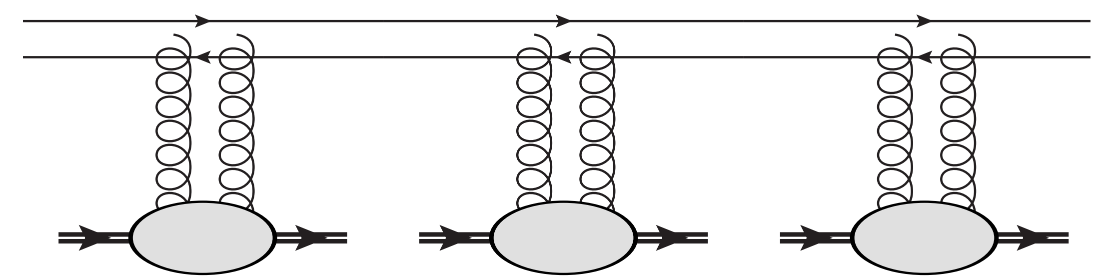
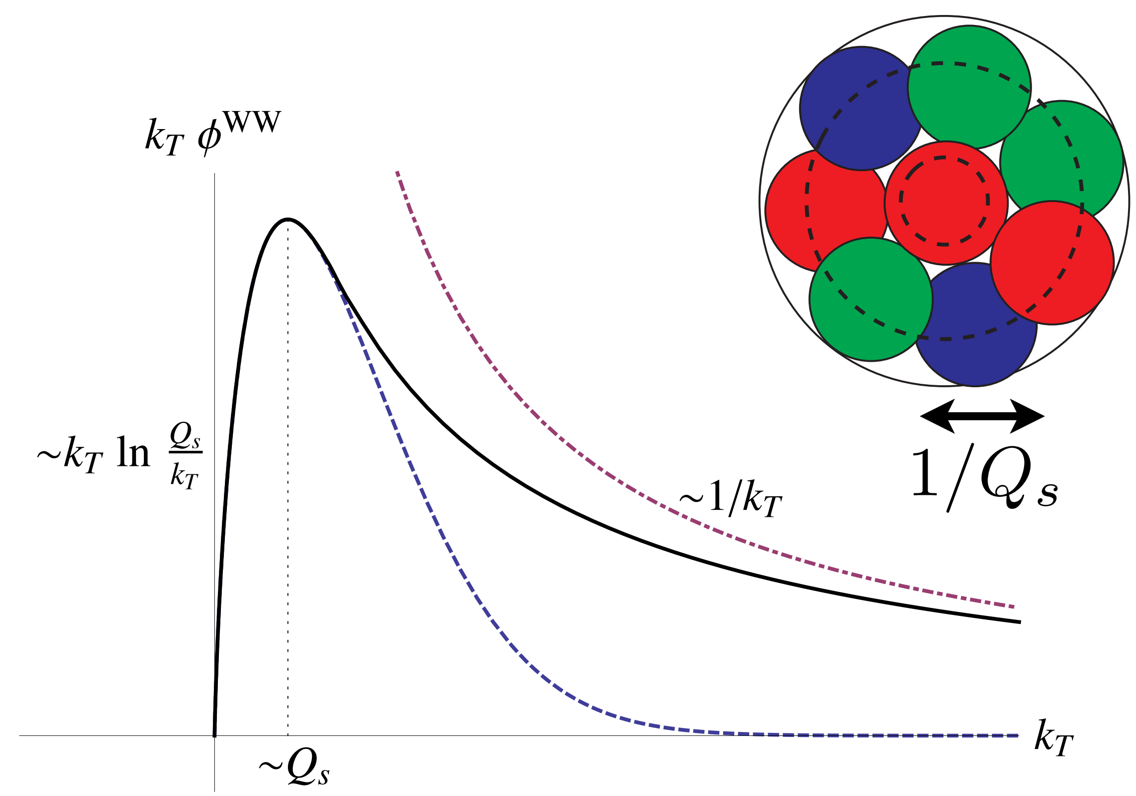


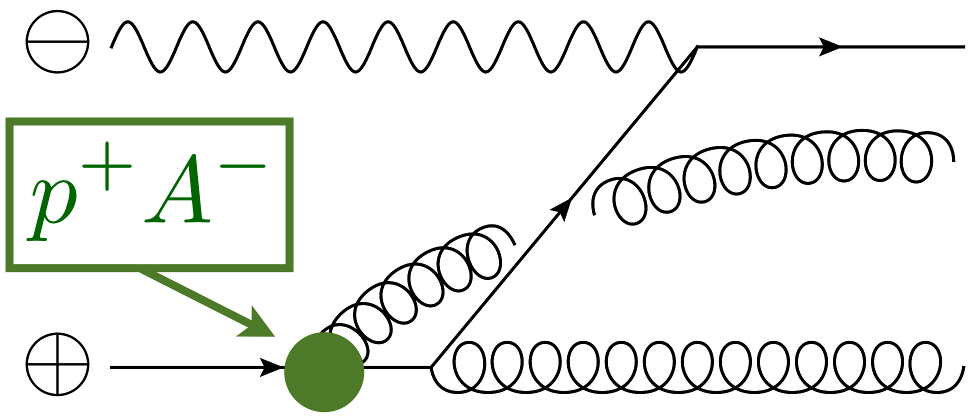
- Charge density defines a hard momentum scale which screens the IR gluon field.

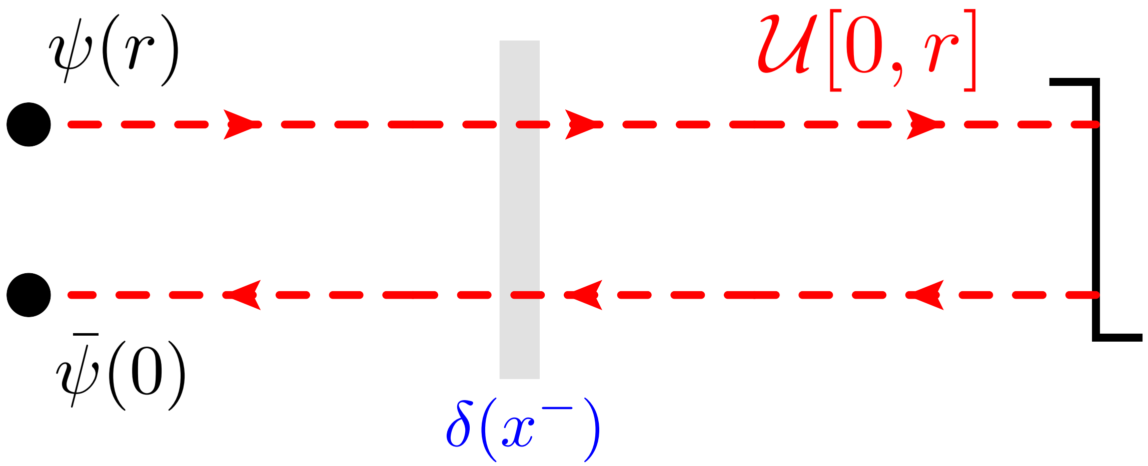
Both: $Q_s^2 \propto \alpha_s^2 A^{1/3} \propto \alpha_s \rho$

$Q_s^2 \gg \Lambda^2$



Quantum Evolution in the Light-Cone Gauge





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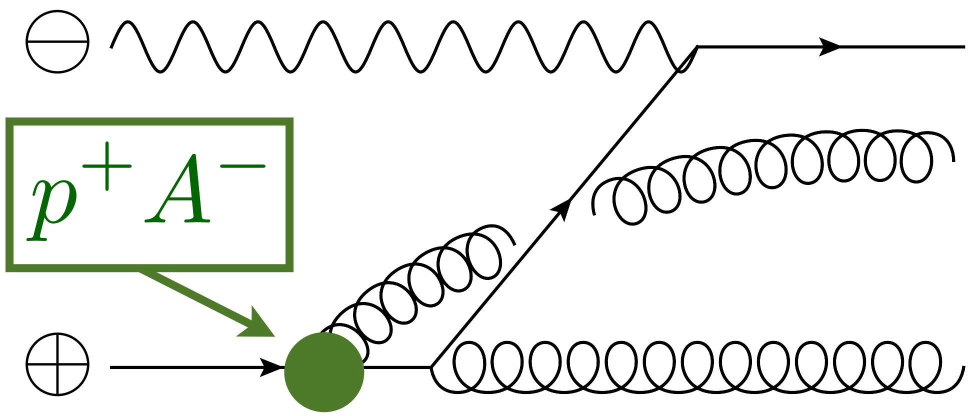

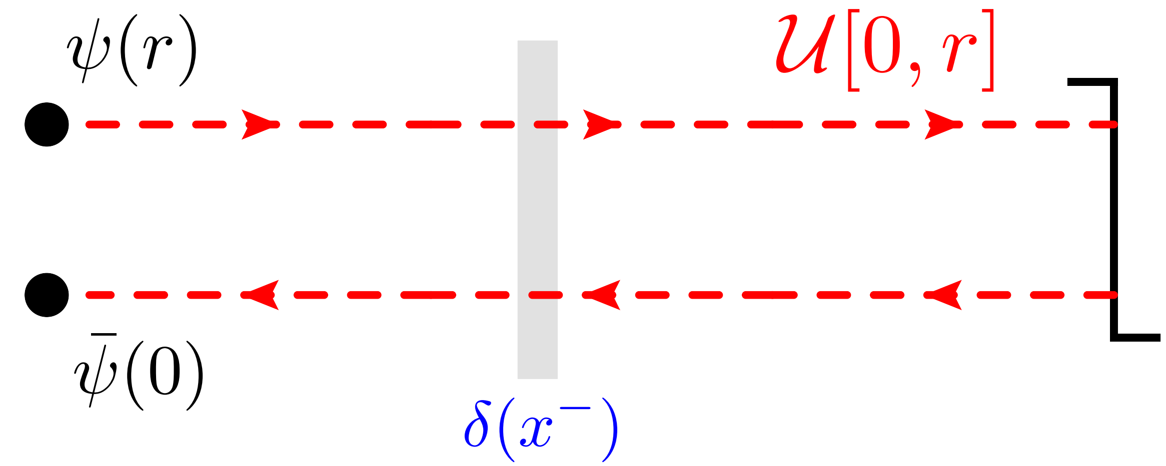

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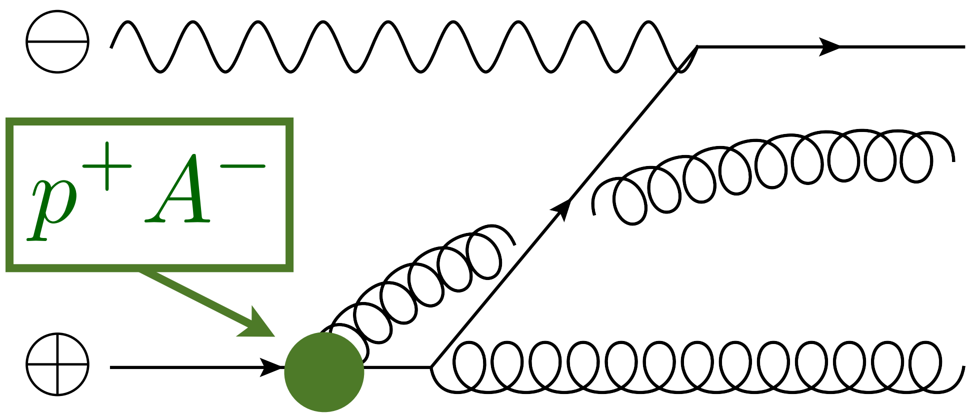

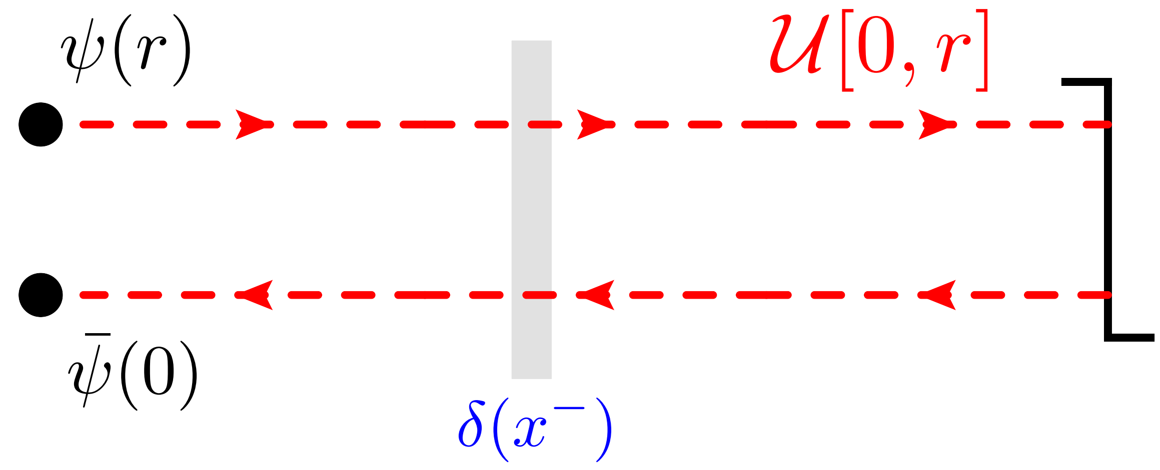

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- For classical fields and leading-log evolution, $A_\perp = 0$ as well.

➡ The transverse part of the gauge link does not contribute.

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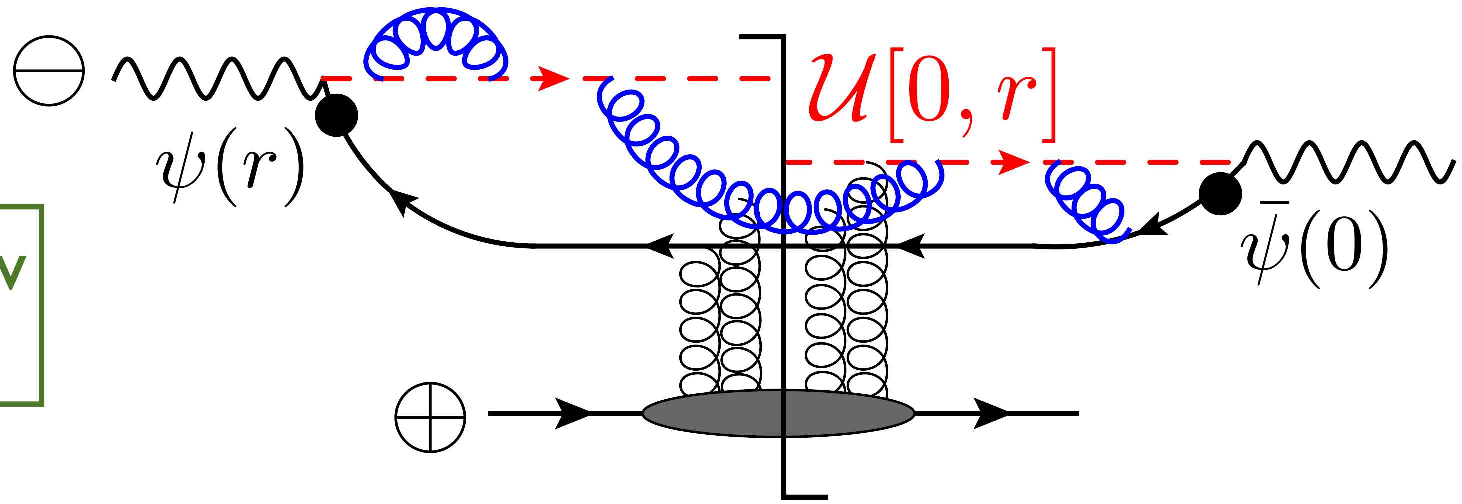

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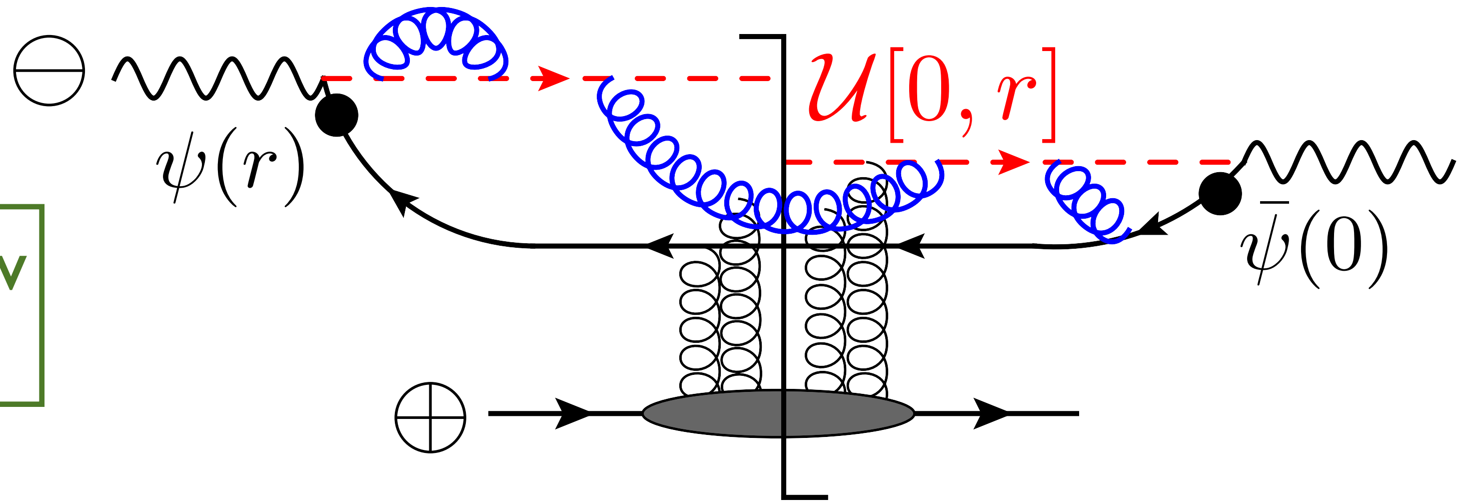
➡ Evolution of the dipole scattering amplitude

➡ Re-sums single logarithms of x

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

Unpolarized Small-x Evolution



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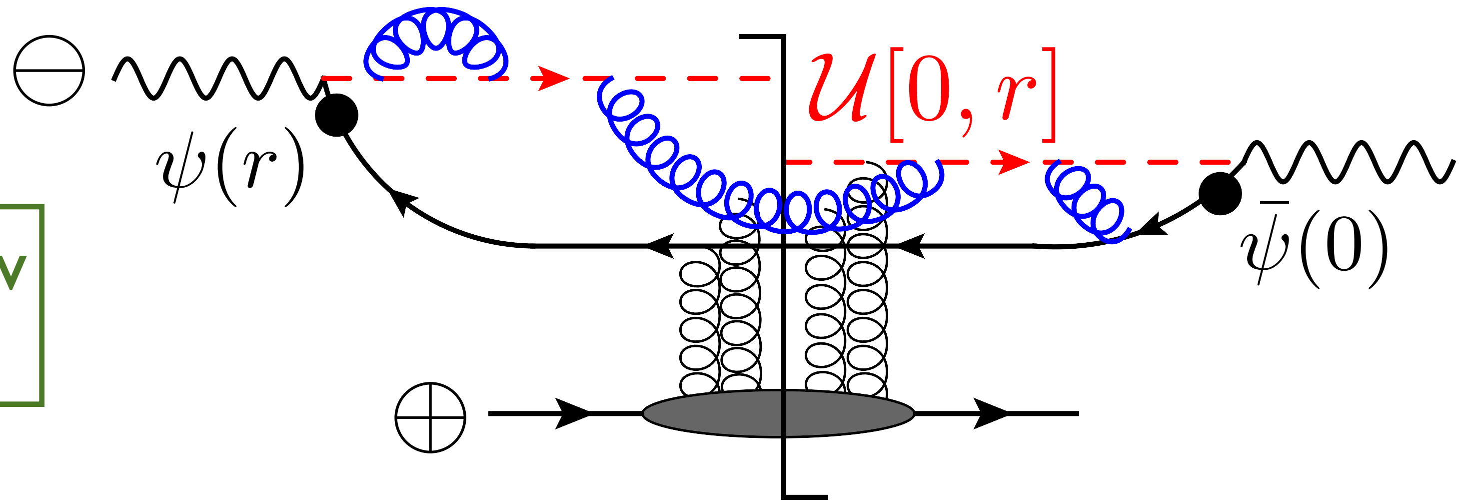

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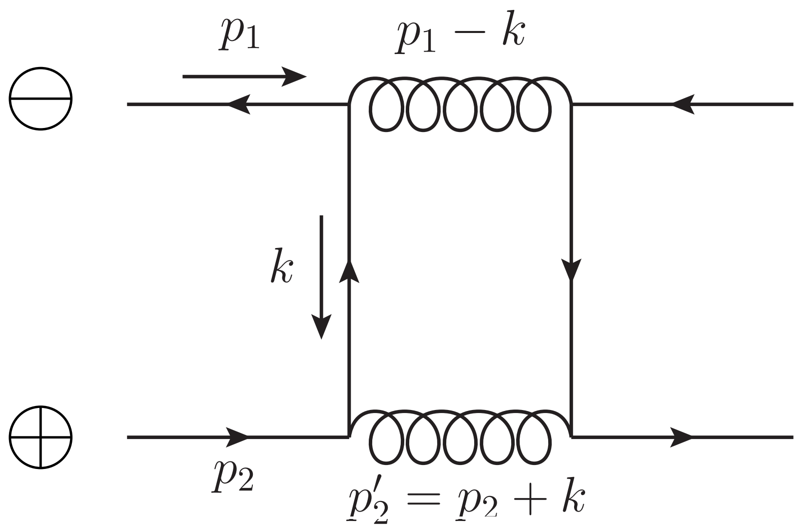
- Evolution closes in the large N_c limit (BK eqn.) $\quad Q_s^2(x) \sim \left(\frac{1}{x}\right)^{0.3}$

Leading-Order Spin Dependence

- High energy (small x) scattering is predominantly spin independent.

➡ BK evolution: total cross section, unpolarized quark distribution.



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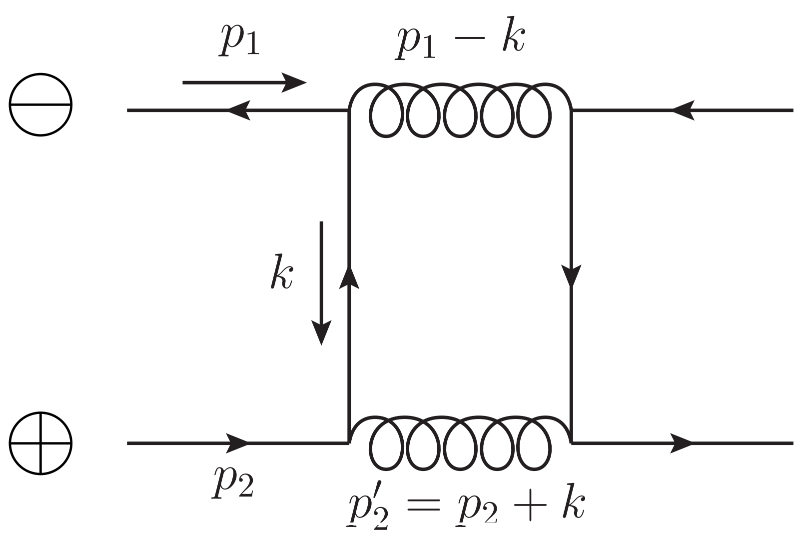

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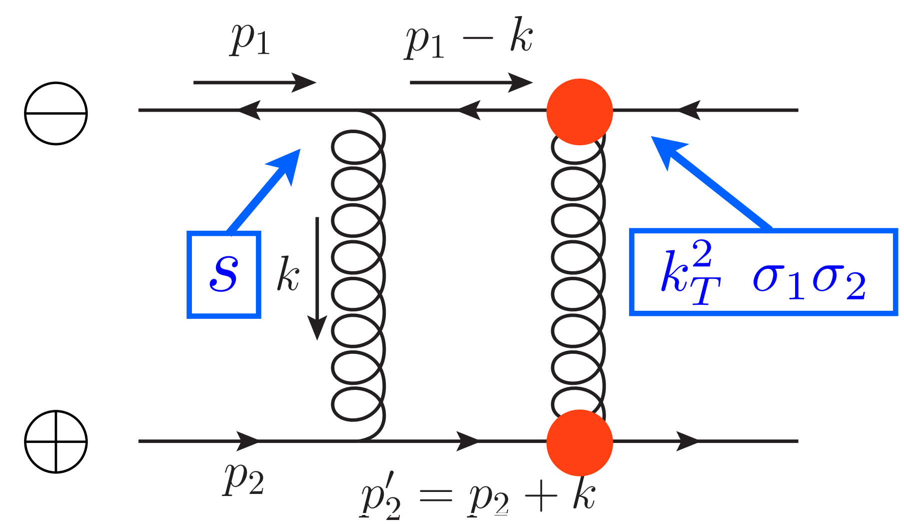

$$\frac{d\Delta\sigma_G}{d^2k} = +\frac{\alpha_s^2 C_F}{N_c}\,\frac{1}{s}\,\frac{1}{k_T^2}$$

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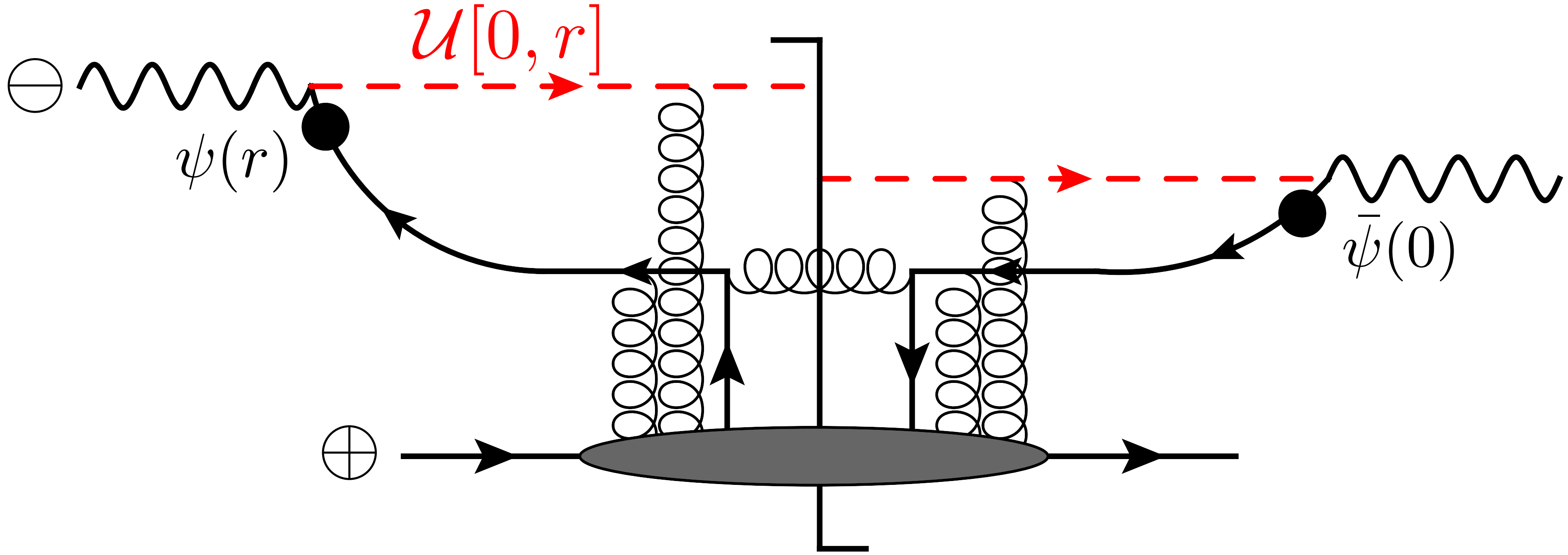
- Sub-leading gluon exchange can also transfer spin dependence.

➡Gluon exchange can mix with quark exchange.

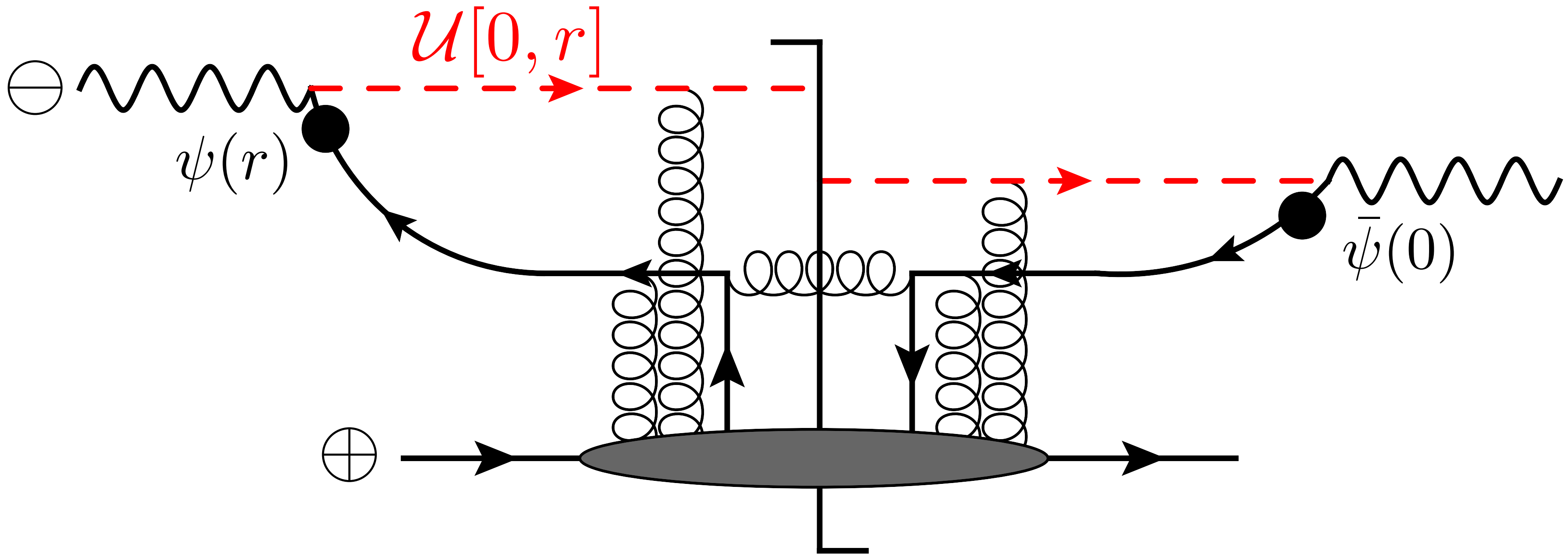
Spin-Dependent Initial Conditions



- "Polarized Wilson Line" - Coherent, spin-dependent scattering.

➡ One spin-dependent exchange (more are suppressed)

➡ Dressed by multiple unpolarized scattering



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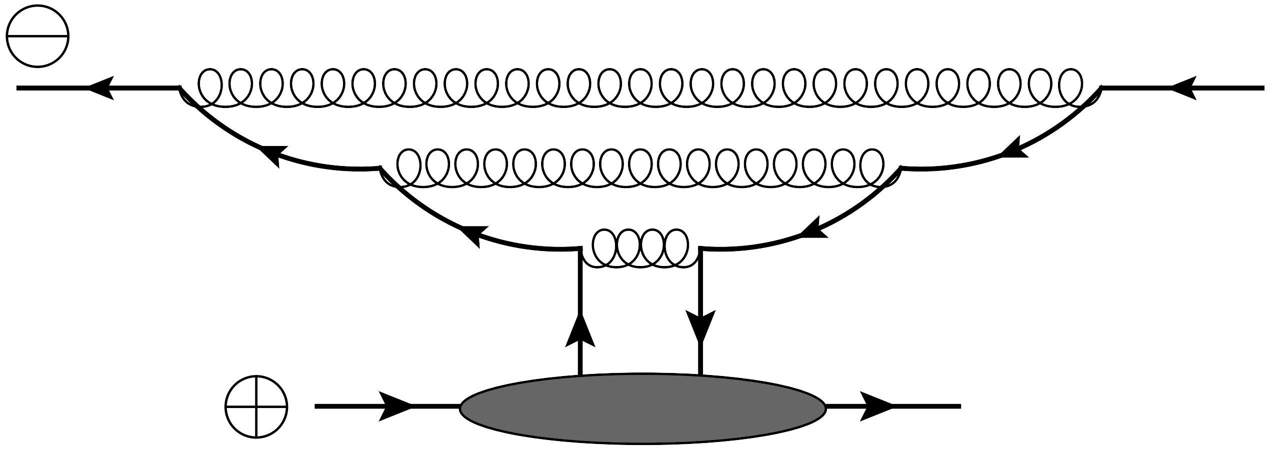
- "Polarized Dipole Amplitude":

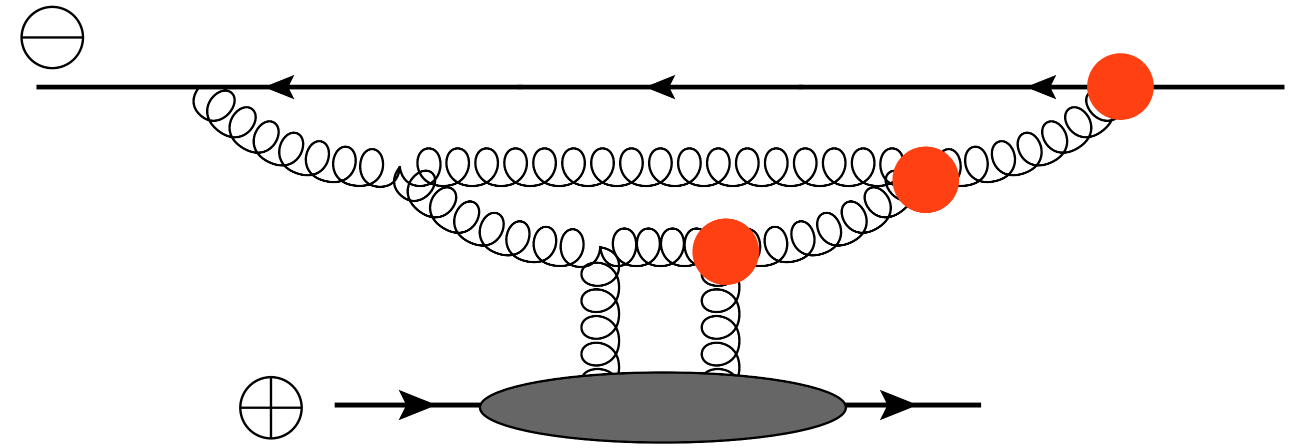
➡ Quark (gauge link) scatters by an unpolarized Wilson line.

➡ Fermion (antiquark) scatters by a polarized Wilson line.

$$G_{xy} \equiv \frac{1}{2N_c} \mathrm{Tr} \left[V_x V_y^\dagger(\sigma) + V_y(\sigma) V_x^\dagger \right]$$

Constructing Polarized Splitting Kernels

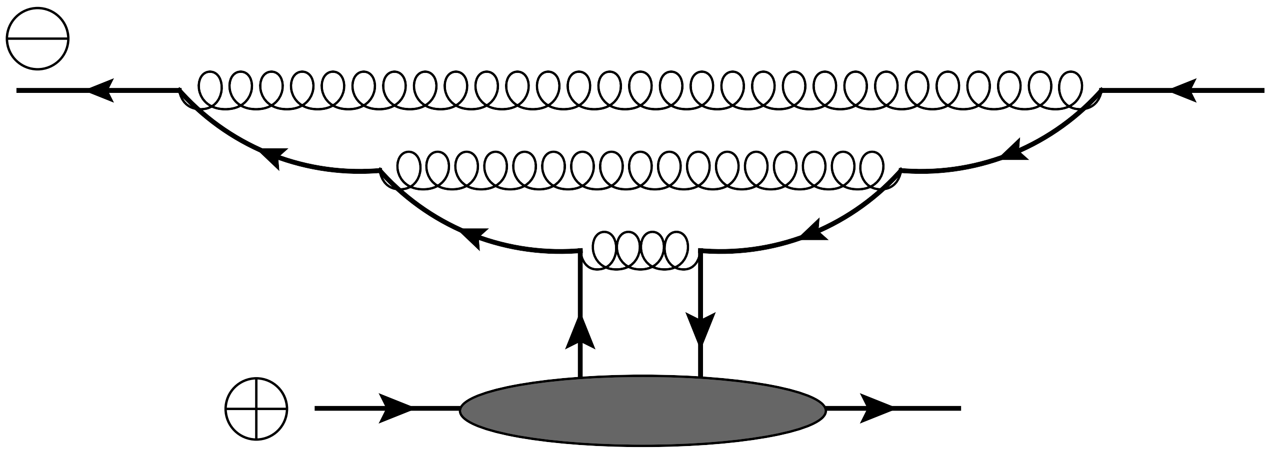


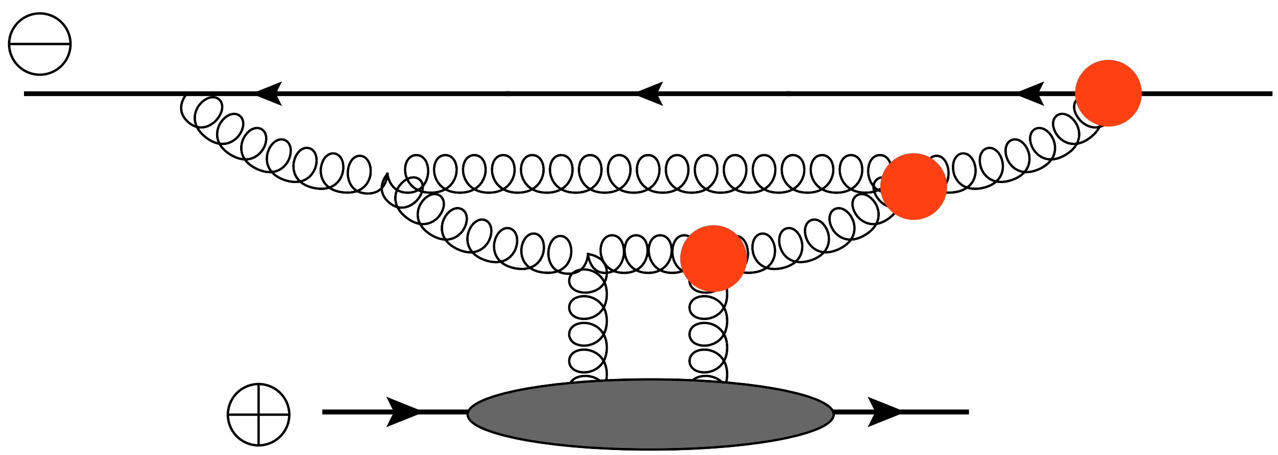


- Kernels: Spin-dependent quark / gluon wave functions

➡ Soft quarks and soft gluons can mix (same order)

Constructing Polarized Splitting Kernels





- Kernels: Spin-dependent quark / gluon wave functions

➡ Soft quarks and soft gluons can mix (same order)

- Requires longitudinal and transverse momentum ordering

$$1 \gg z_1 \gg z_2 \gg \cdots \gg \frac{Q^2}{s} \qquad\qquad Q^2 \ll \frac{k_{1T}^2}{z_1} \ll \frac{k_{2T}^2}{z_2} \ll \cdots$$

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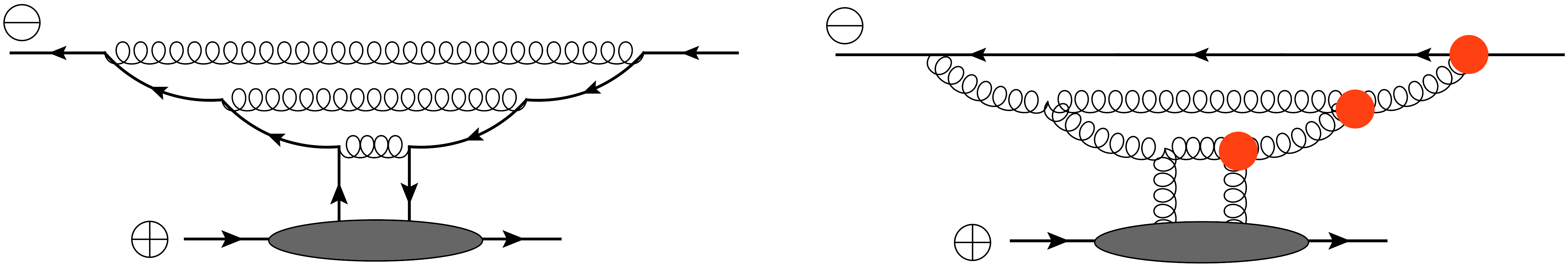

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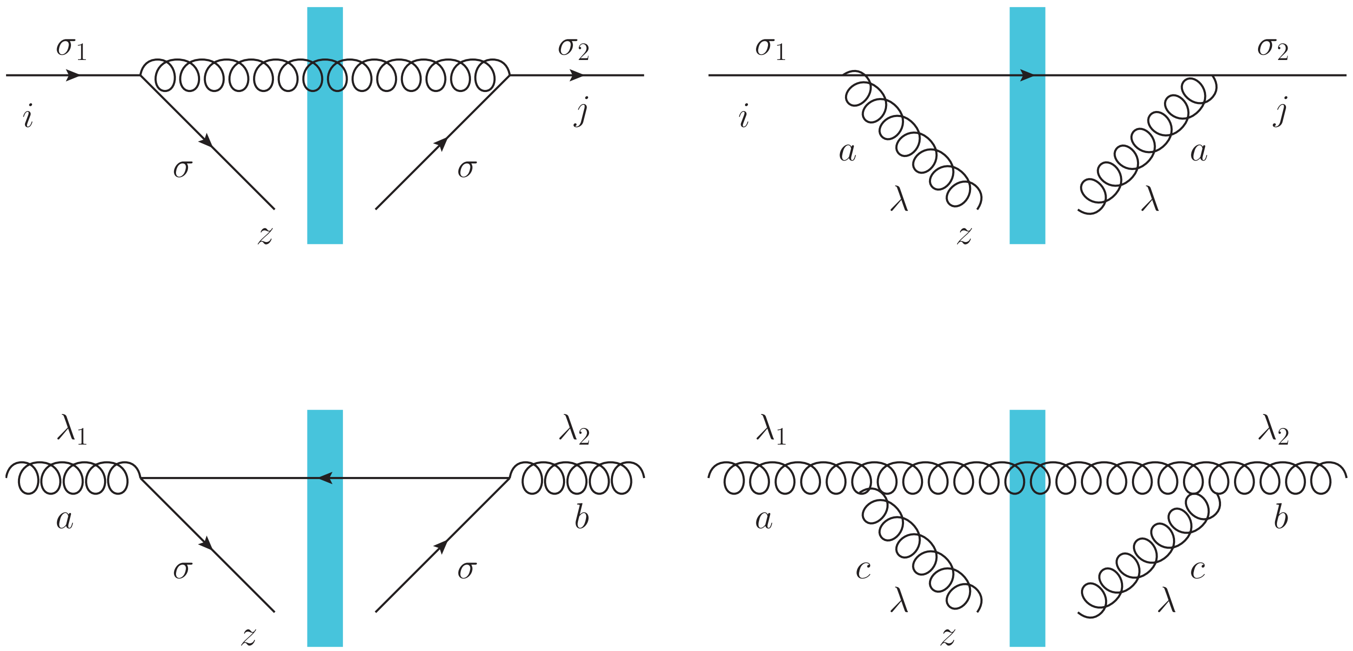
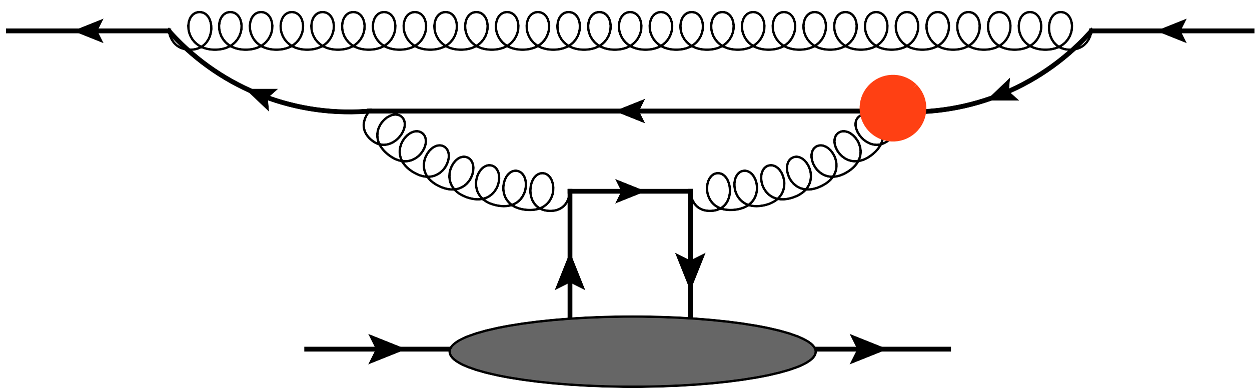
- Leads to double-log evolution.

➡ Faster evolution than unpolarized BK!

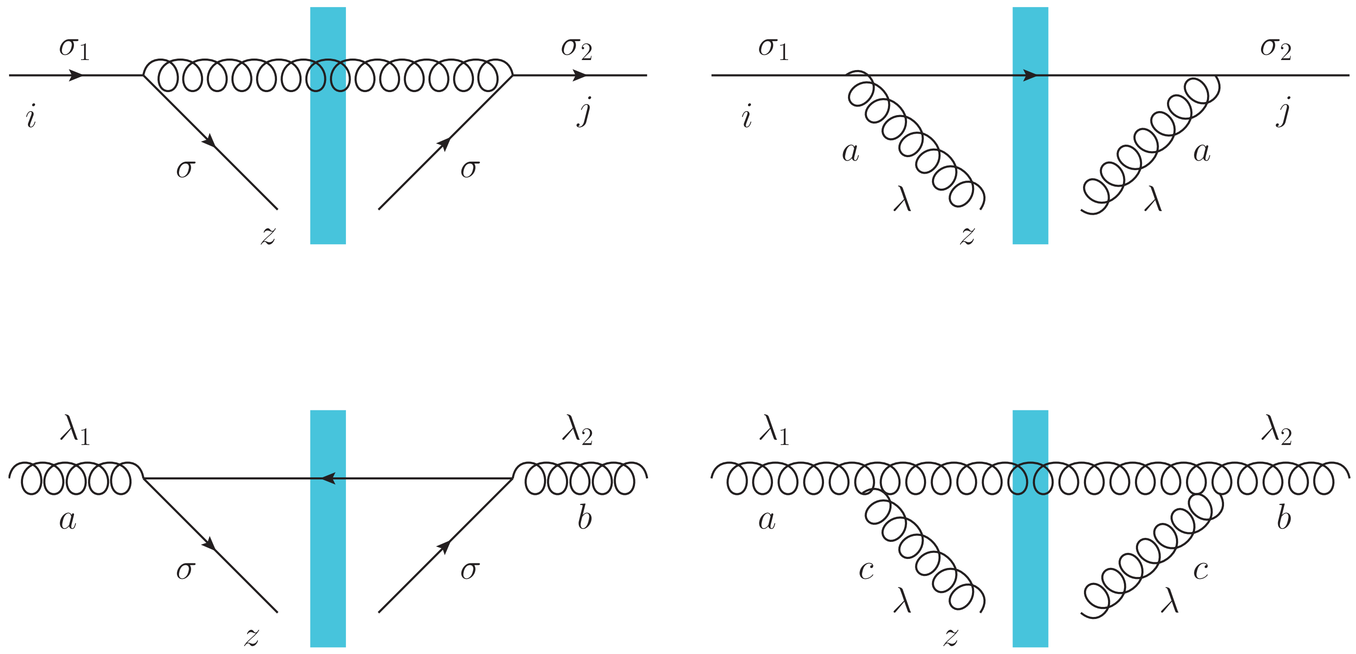
$$\alpha_s \ln^2 \frac{1}{x} \sim 1$$

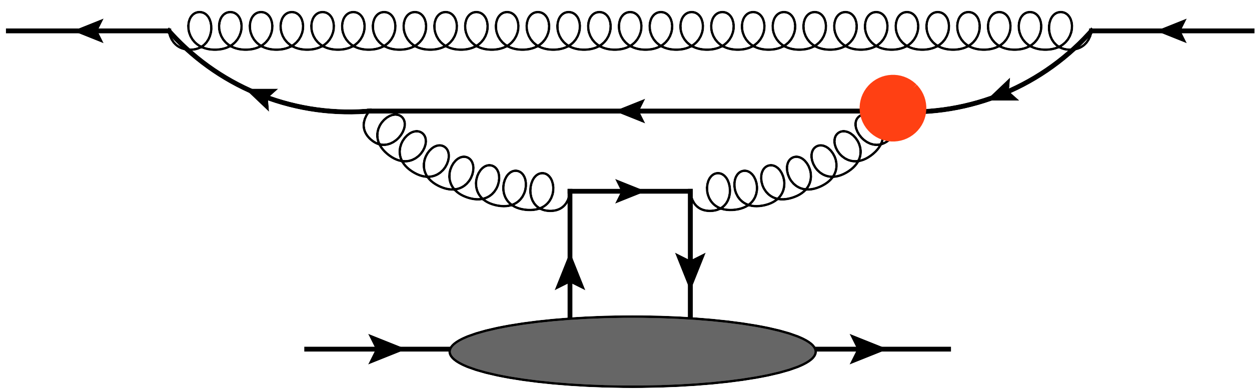




- To solve, first keep only the kernels without unpolarized rescattering.

$$\frac{\alpha_s}{2\pi}\int\frac{dz}{z}\int\frac{dk_T^2}{k_T^2}\begin{pmatrix} C_F & 2C_F \\ -N_f & 4N_c \end{pmatrix}$$





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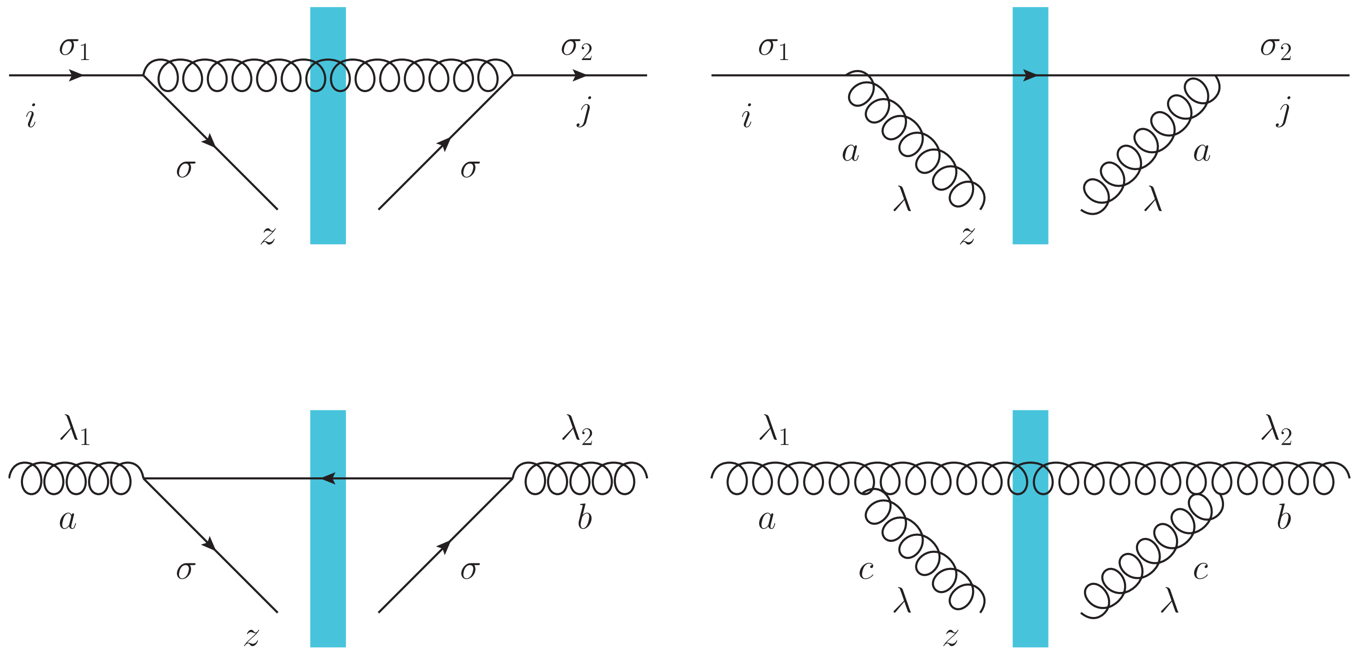
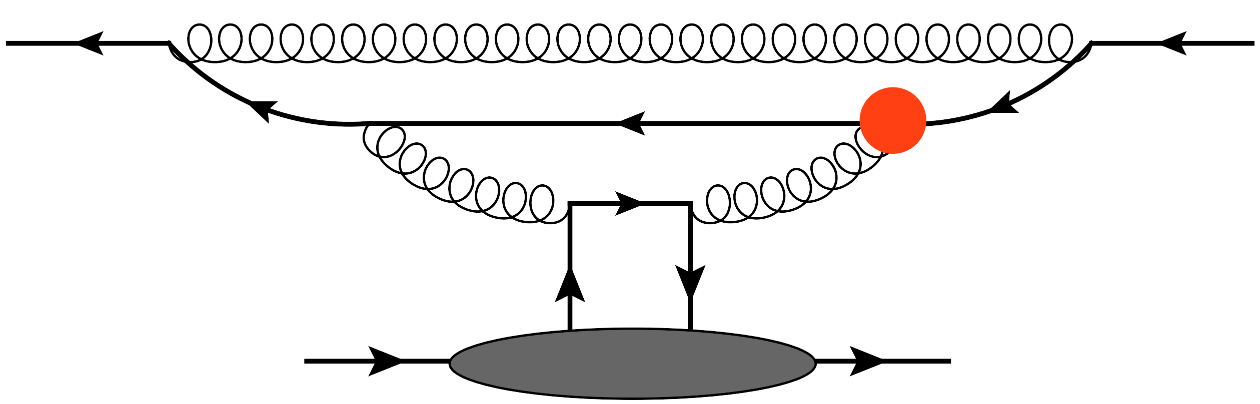
- Solve by Mellin transform and saddle point approximation.

$$\alpha_s = 0.3$$
$$N_c = N_f = 3$$

$$G_{xy}(s) \sim \left(\frac{s}{Q^2}\right)^{1.46}$$

Solution: Ladder Evolution





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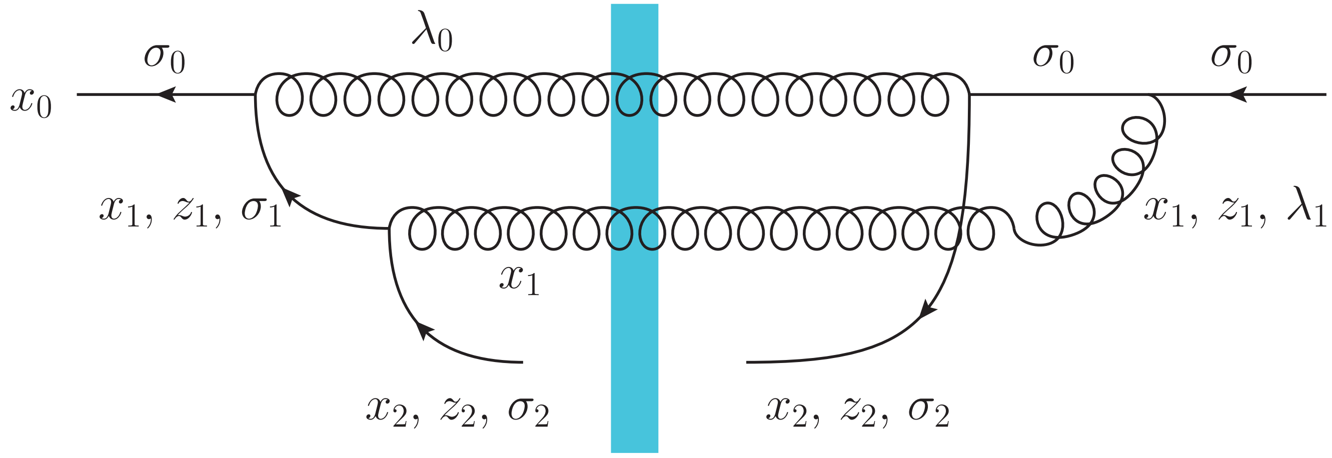
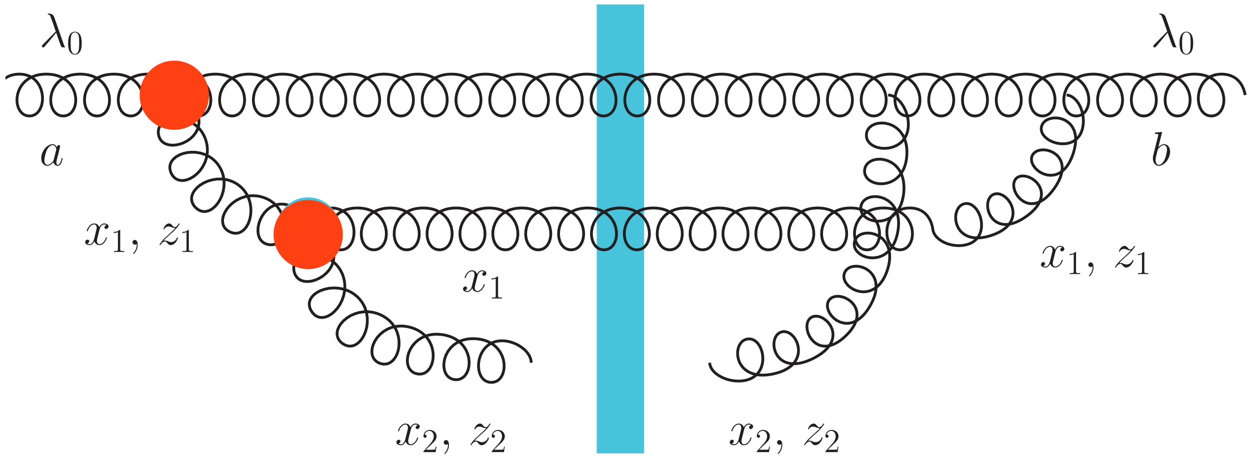
- Fast growth of quark polarization at small x!

➡ Large contribution to the proton spin?

$$S_{xy}(s) \sim \left(\frac{s}{Q^2}\right)^{0.3}$$

The Complication: Non-Ladder Graphs

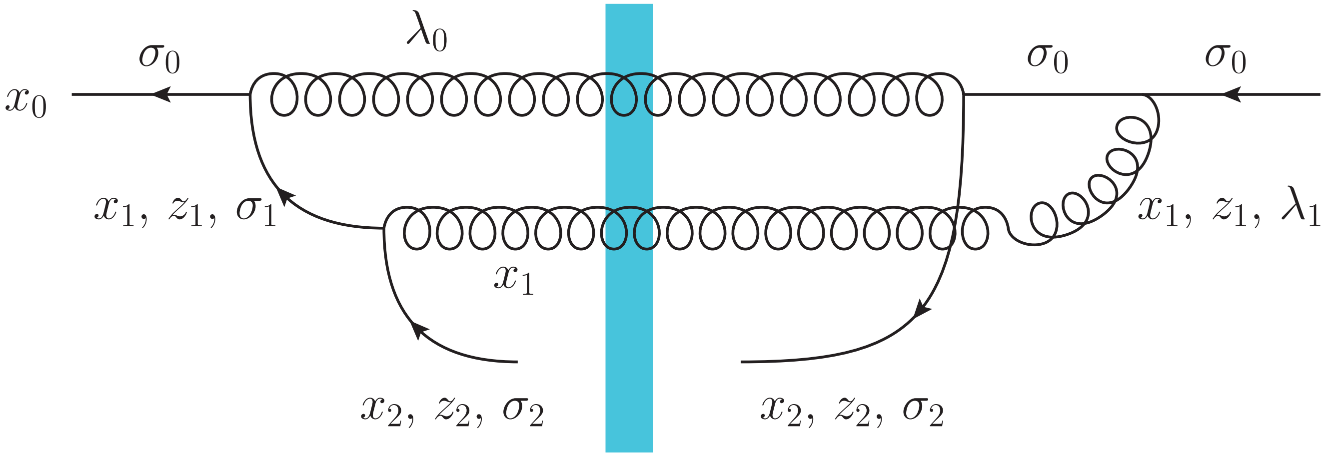


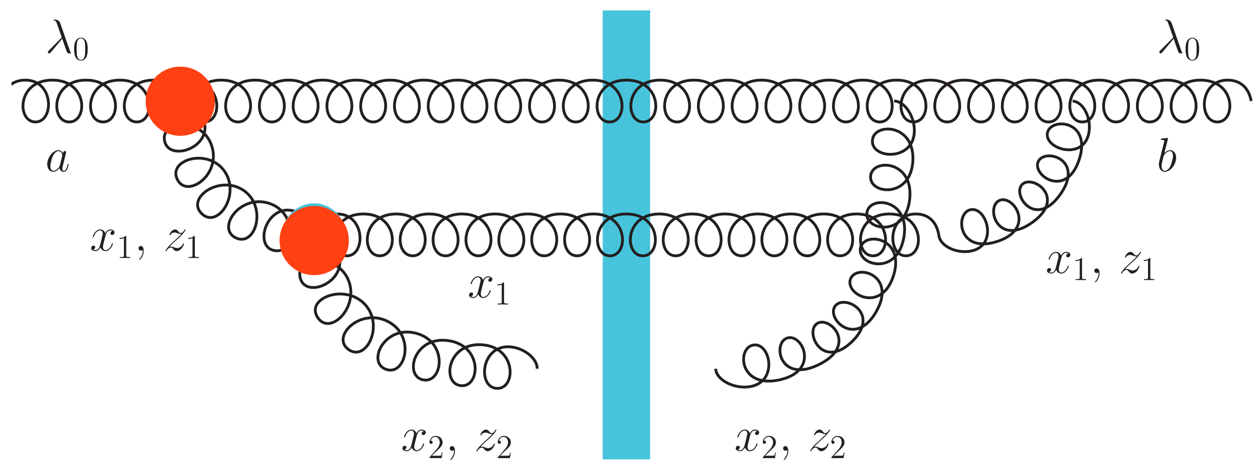


- Unlike BK or DGLAP, leading-log evolution is also generated by non-ladder graphs

➡ Arises uniquely from the IR sector.

$$k_{1T}^2 \gg k_{2T}^2 \gg k_{1T}^2 \frac{z_2}{z_1}$$





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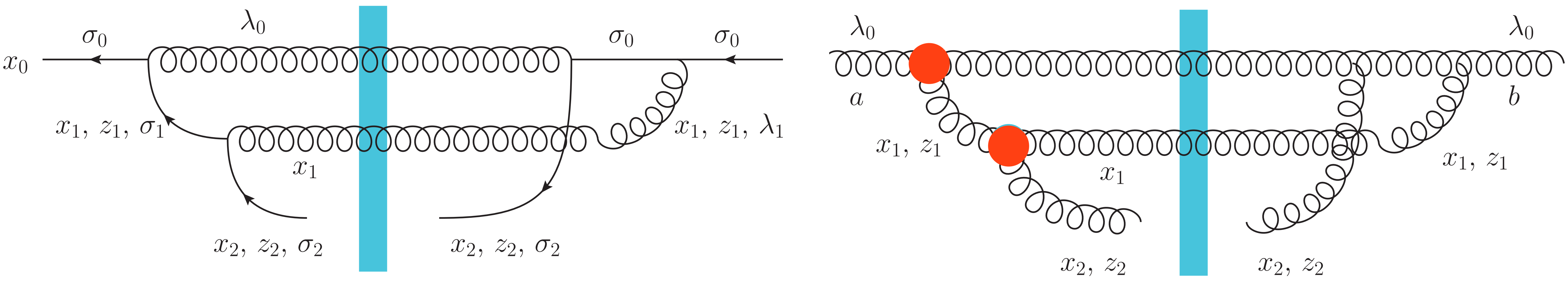

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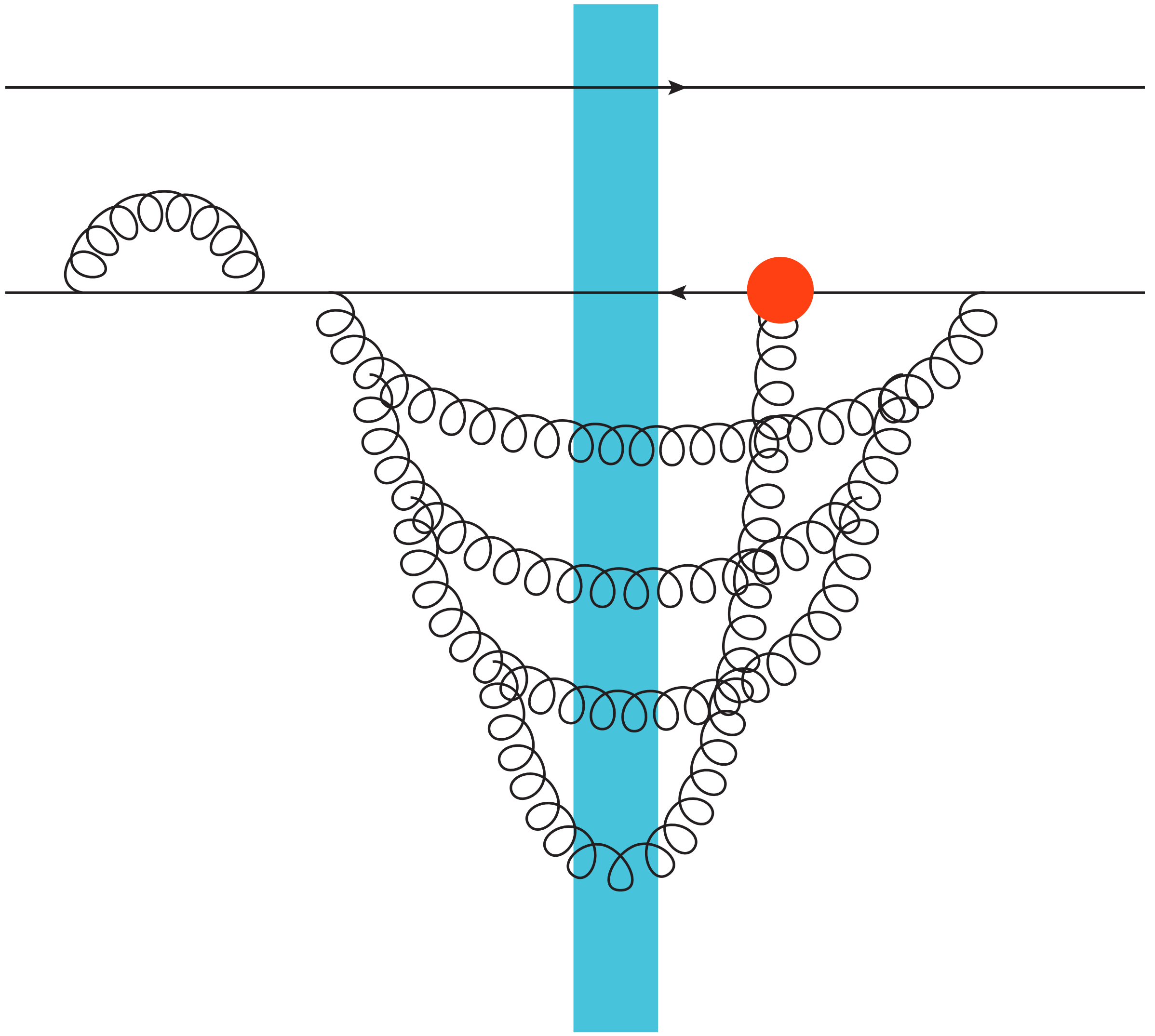
- Complication: Gluon non-ladder graphs do not cancel.

➡ Ladder evolution is an unjustified truncation

A Mess of Non-Ladder Gluons

- Non-ladder gluons can stack in complex ways which still generate leading logarithms.

➡ Polarized gluons can "jump a rung" of evolution



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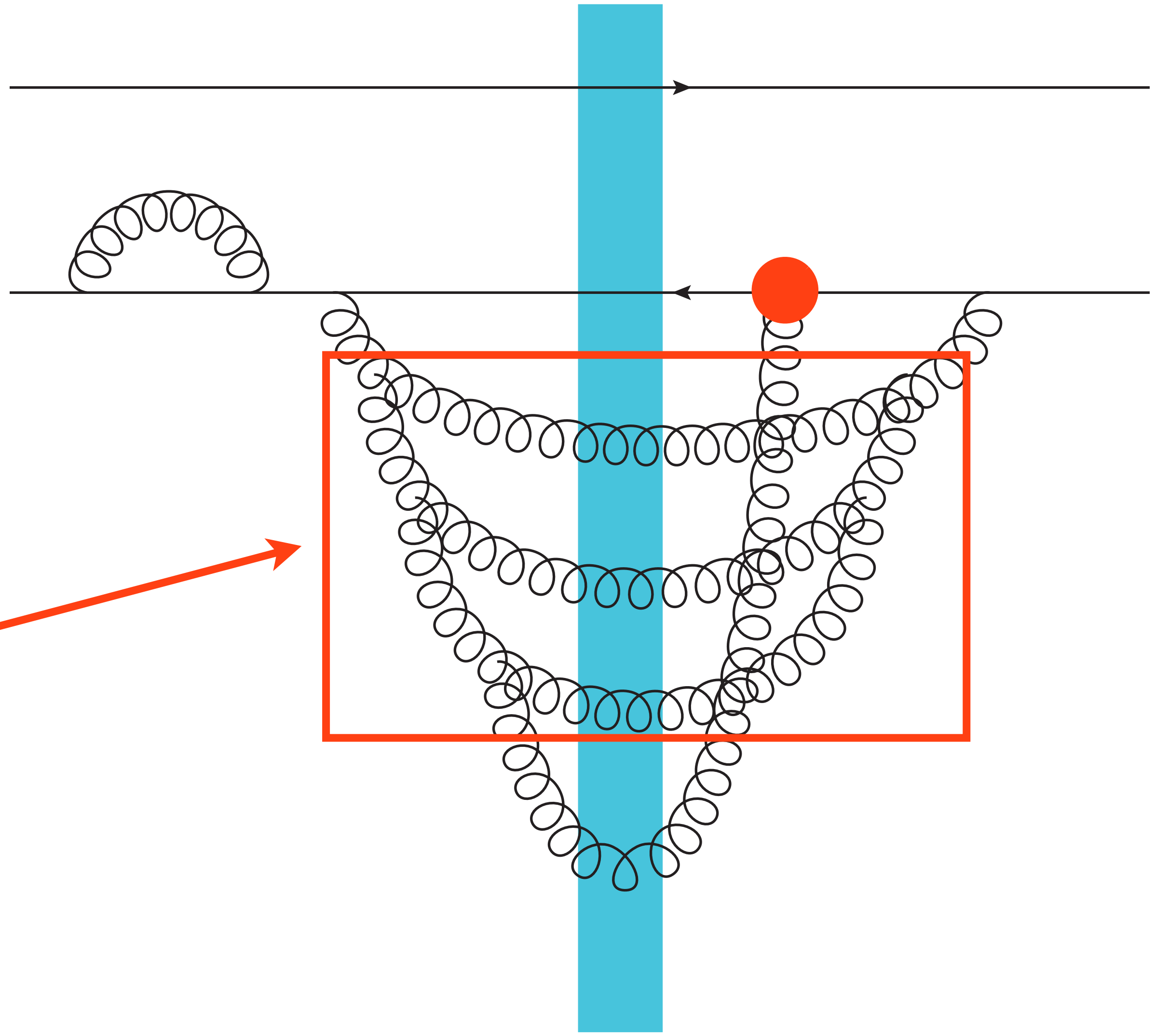

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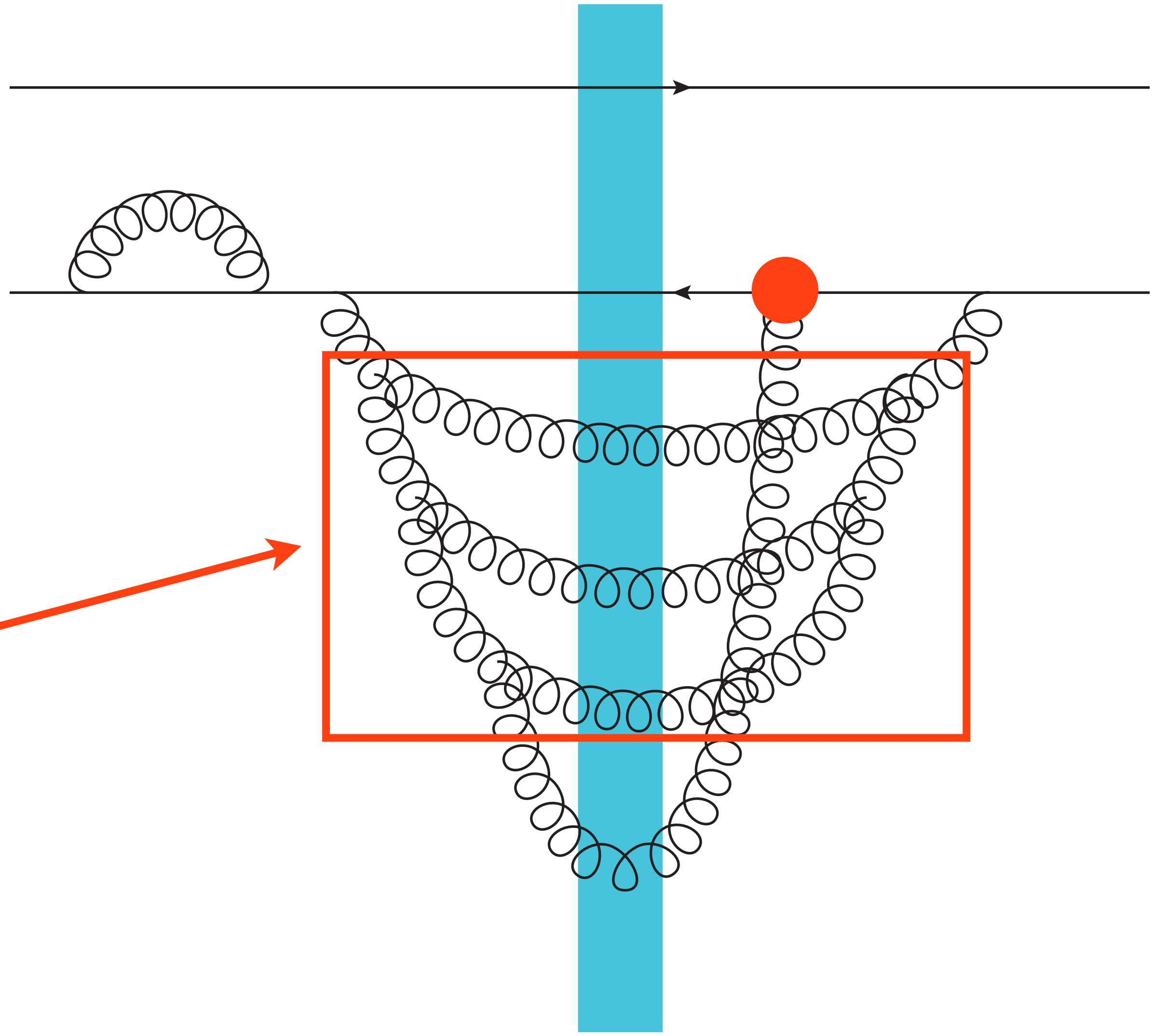
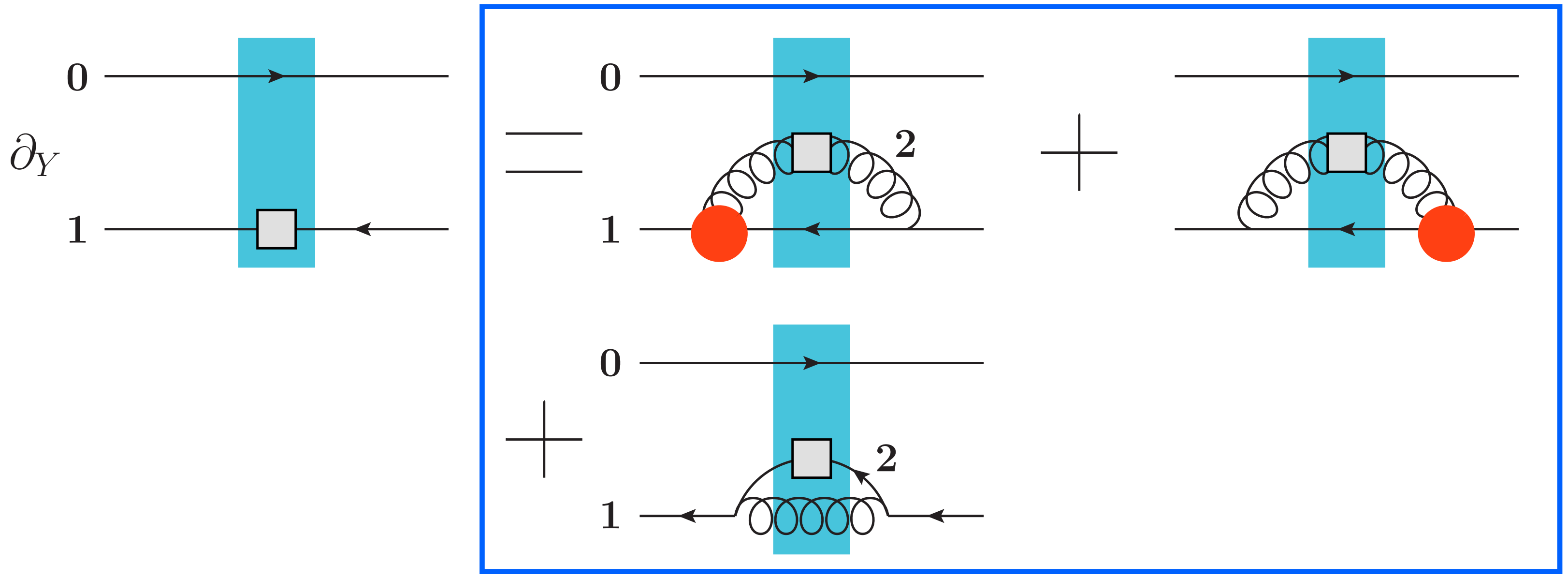
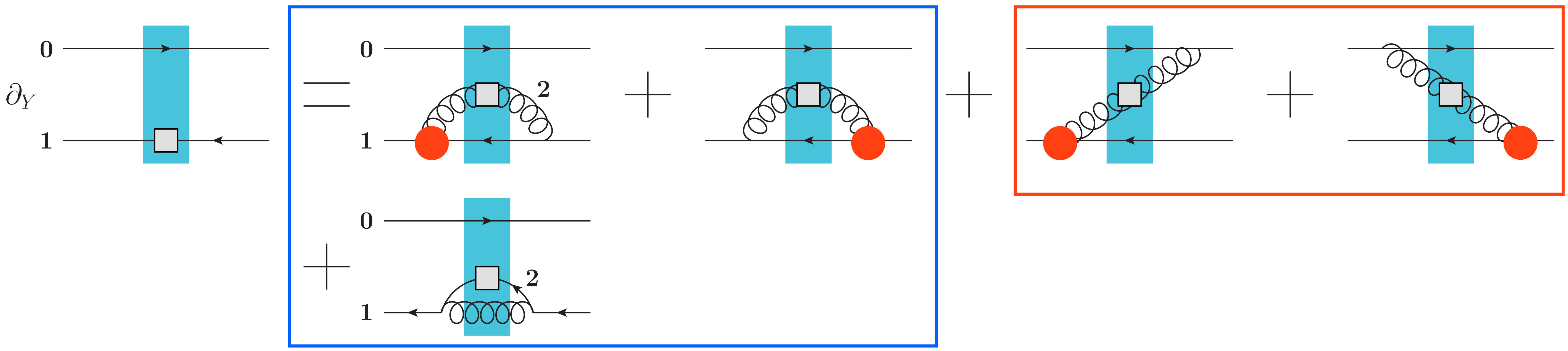
➡ Unpolarized evolution is in a color-octet state (unlike ordinary BK evolution)



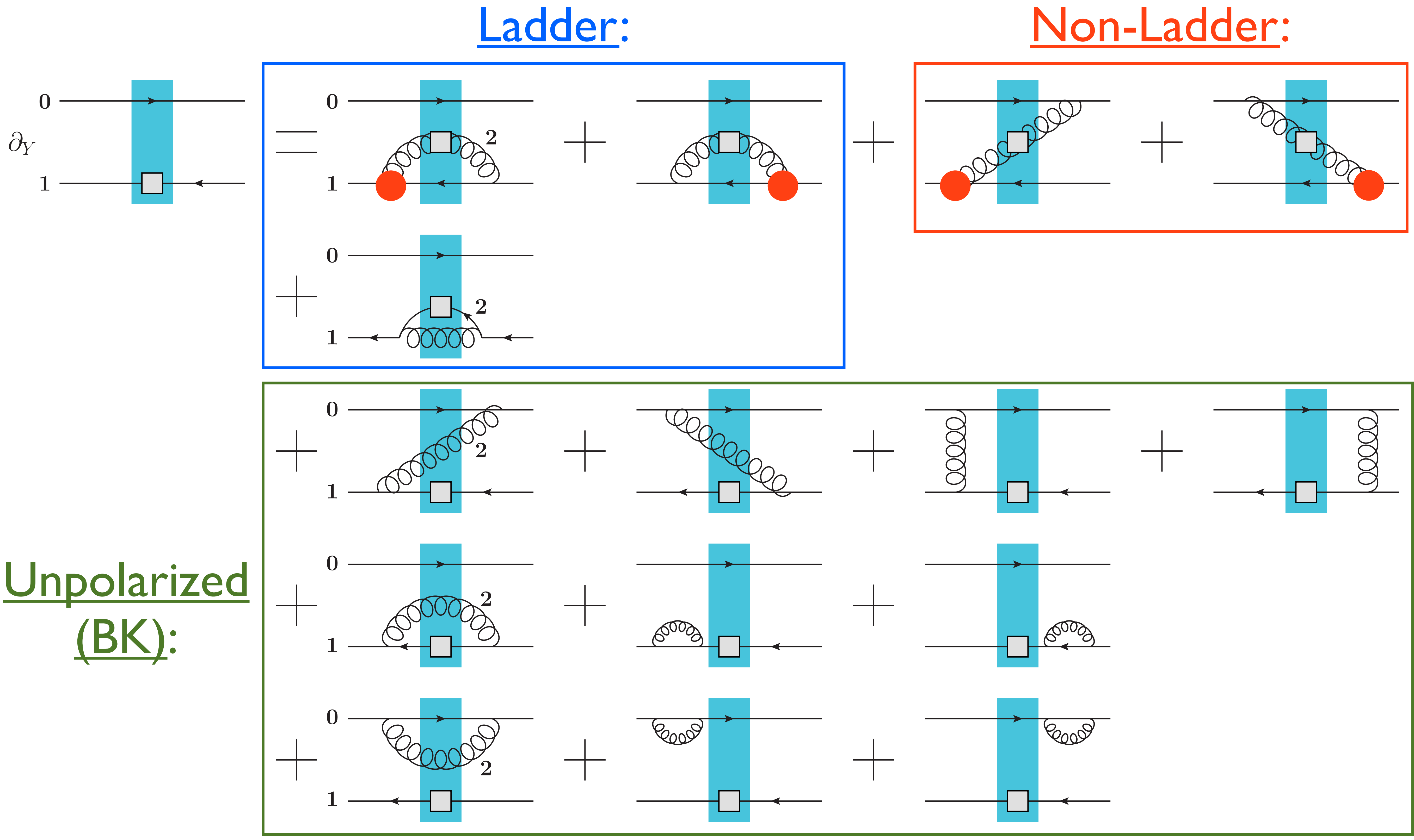
Ladder:



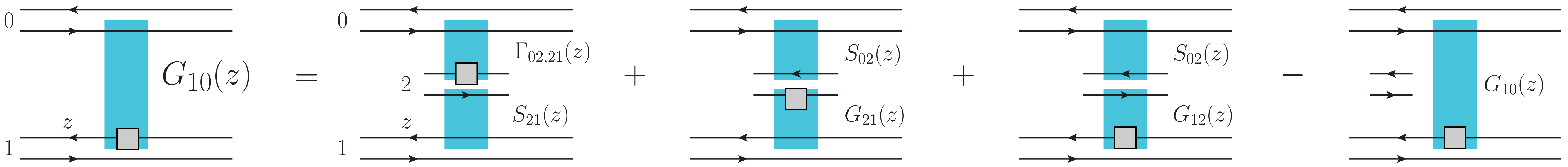
Ladder: Non-Ladder:



Helicity Evolution: Polarized Dipole Operator



Trying to Solve It: The Large N_c Approximation



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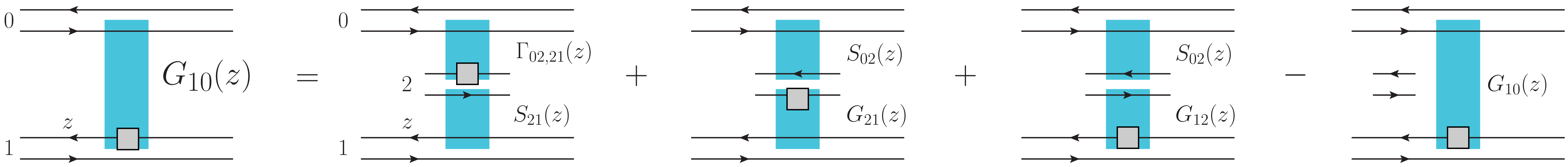

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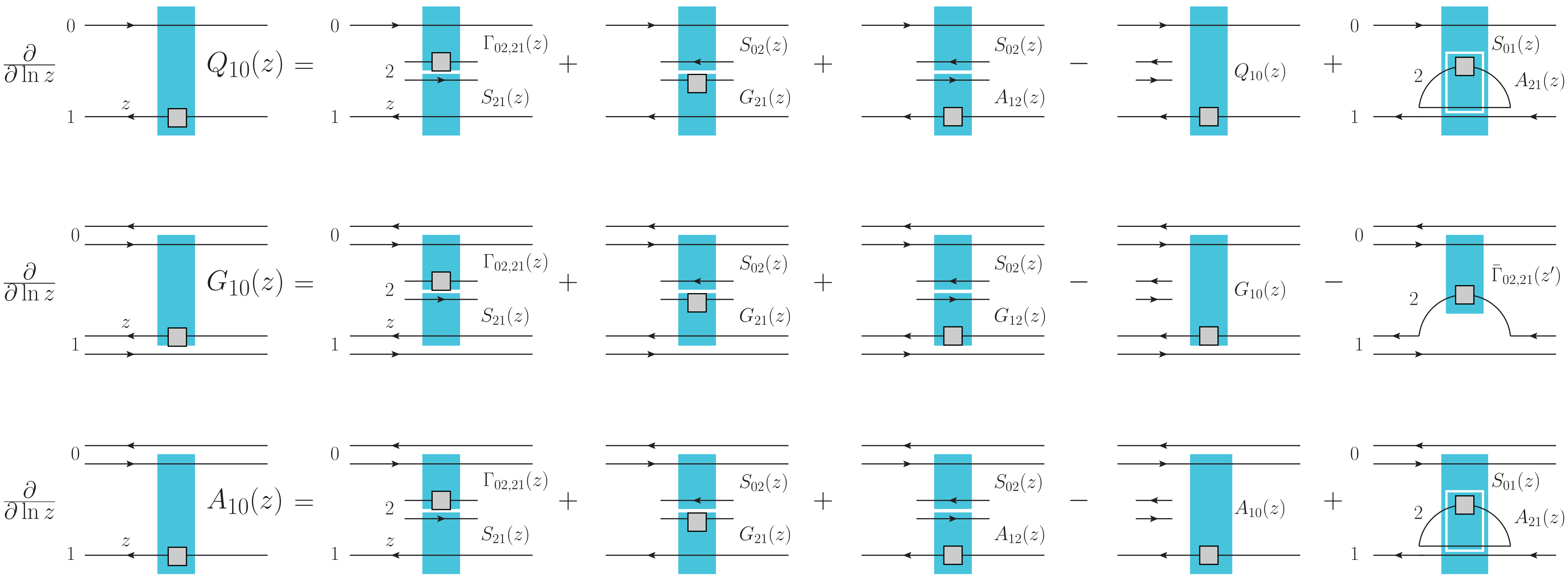
- The transverse ordering condition is not automatically satisfied.

$$Q^2 \ll \frac{k_{1T}^2}{z_1} \ll \frac{k_{2T}^2}{z_2} \ll \cdots$$

➡ Polarized dipoles can depend on their "neighbors"

➡ More complex than the large N_c BK equation.

A Better Approximation: Large N_c , N_f



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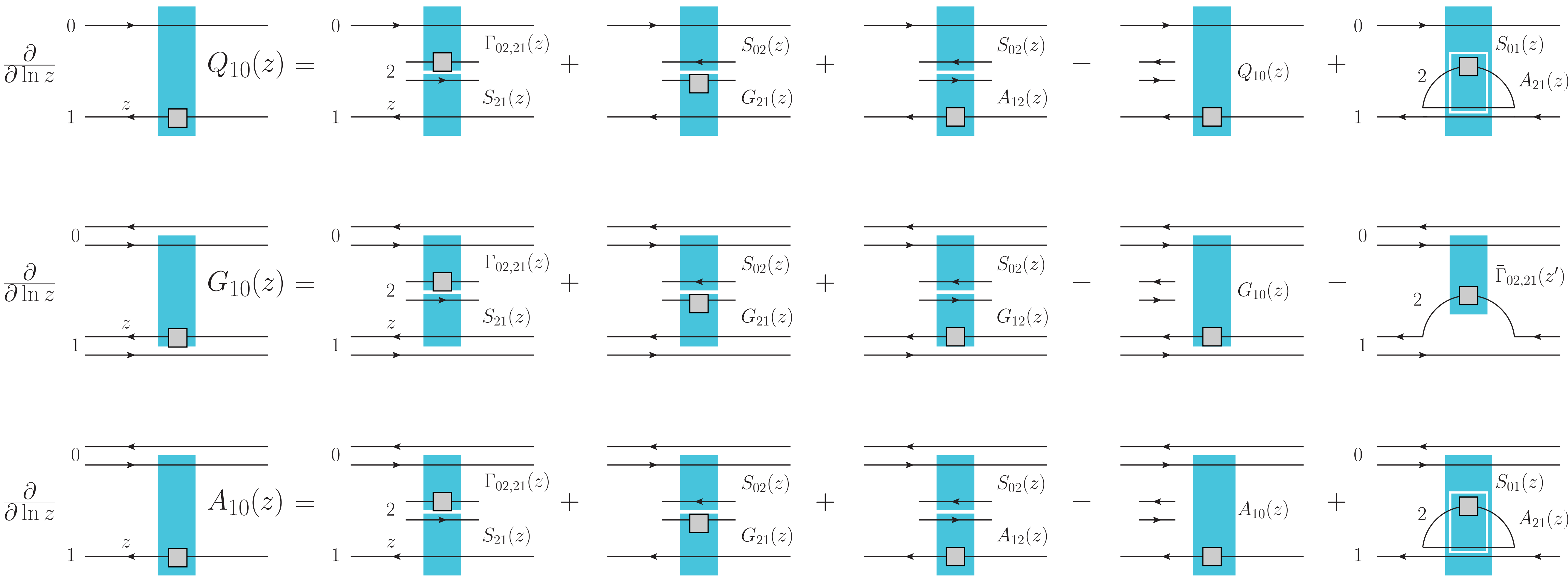

- To keep quark contributions, must also take N_f large.

➡ Must distinguish between dipoles made of actual quarks vs. large N_c gluons.

➡ Evolution equation closes, but even more complicated....

Outlook: The Truth Is Out There!

- Can we solve the helicity evolution in ANY systematic approximation?
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- What about other polarization observables like transversity?

Summary

- Up to 35% of the proton angular momentum is unaccounted for.
  - ➡ Is there significant polarization at small x?

$$0.001 < x < 1$$

$$\Delta\Sigma \approx 0.25 \;\; (25\%)$$
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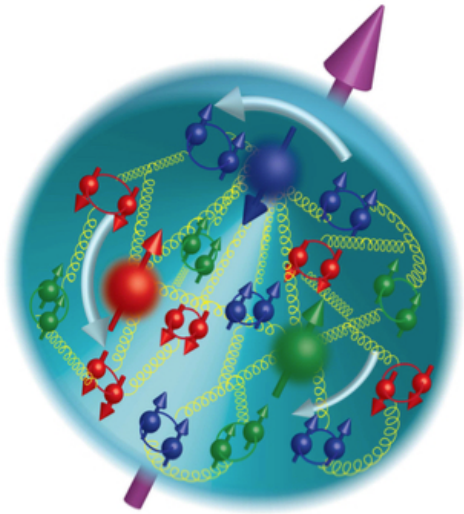

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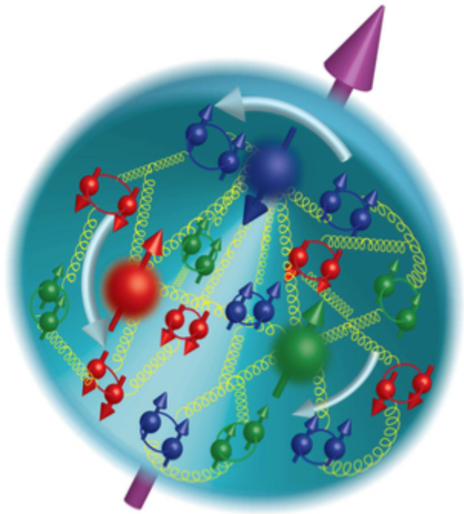

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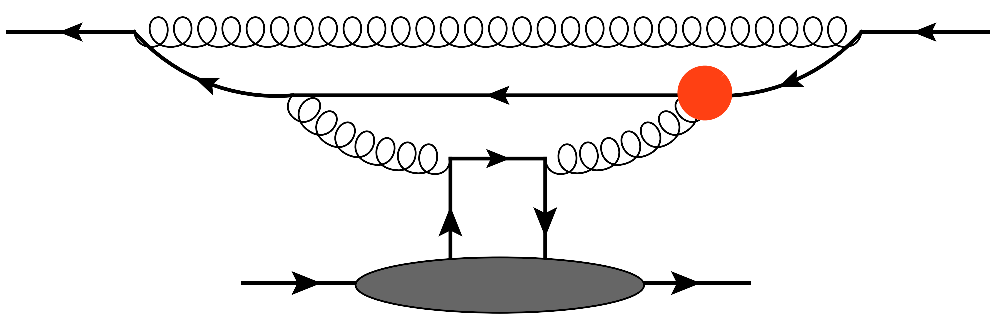

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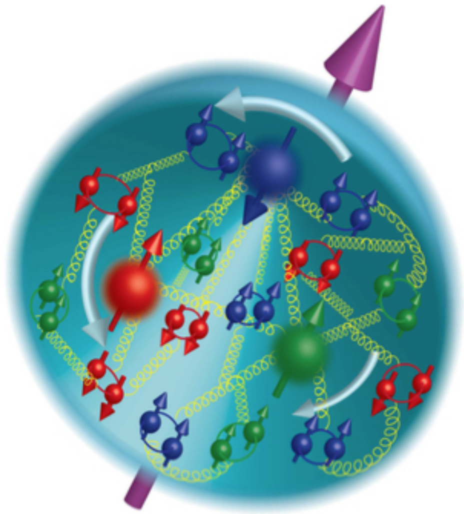

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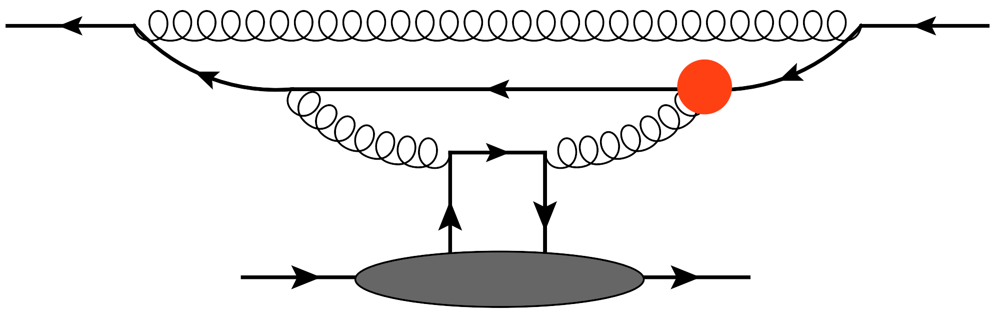

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- Massive complications due to non-ladder gluons and IR phase space.
  - ➡ Much more to discover just around the corner!