Gluon Content of the Nucleon Potential from Disintegration of the Deuteron

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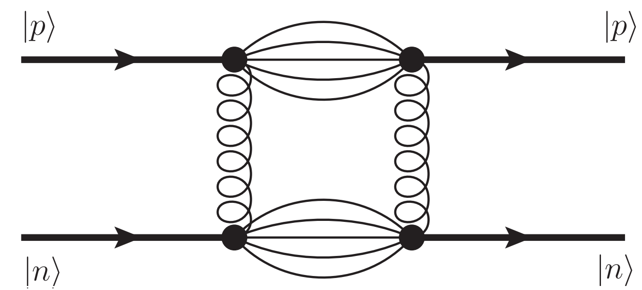
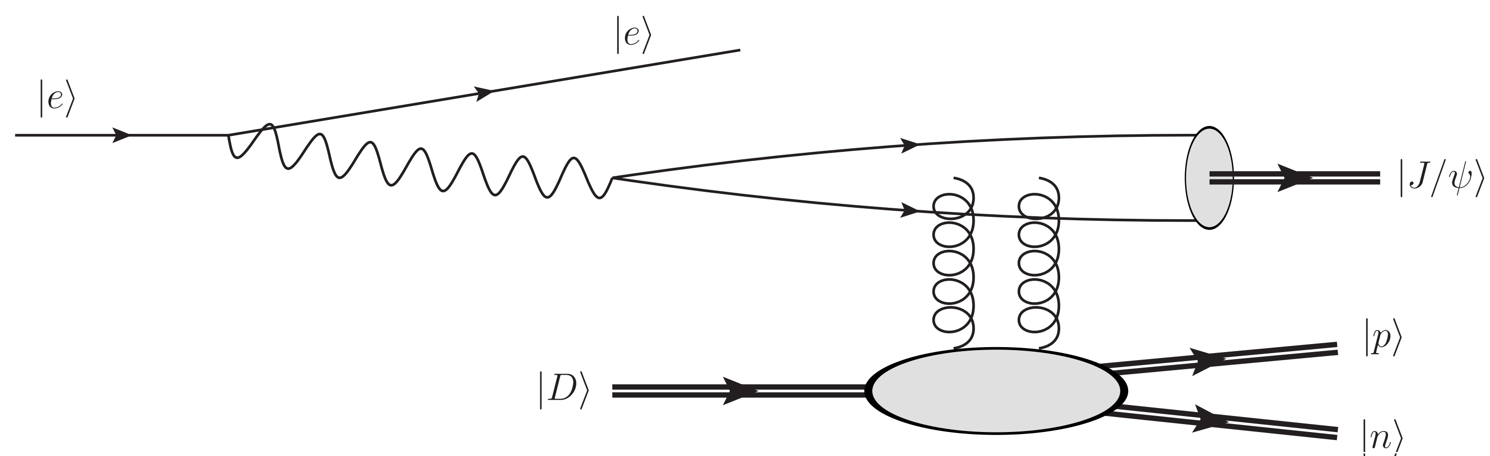
I. Motivation

What is the QCD contribution to the nucleon potential?



II. The Process

$$e + D \rightarrow e + J/\psi + p + n$$



III. The Calculation

IV. Outlook

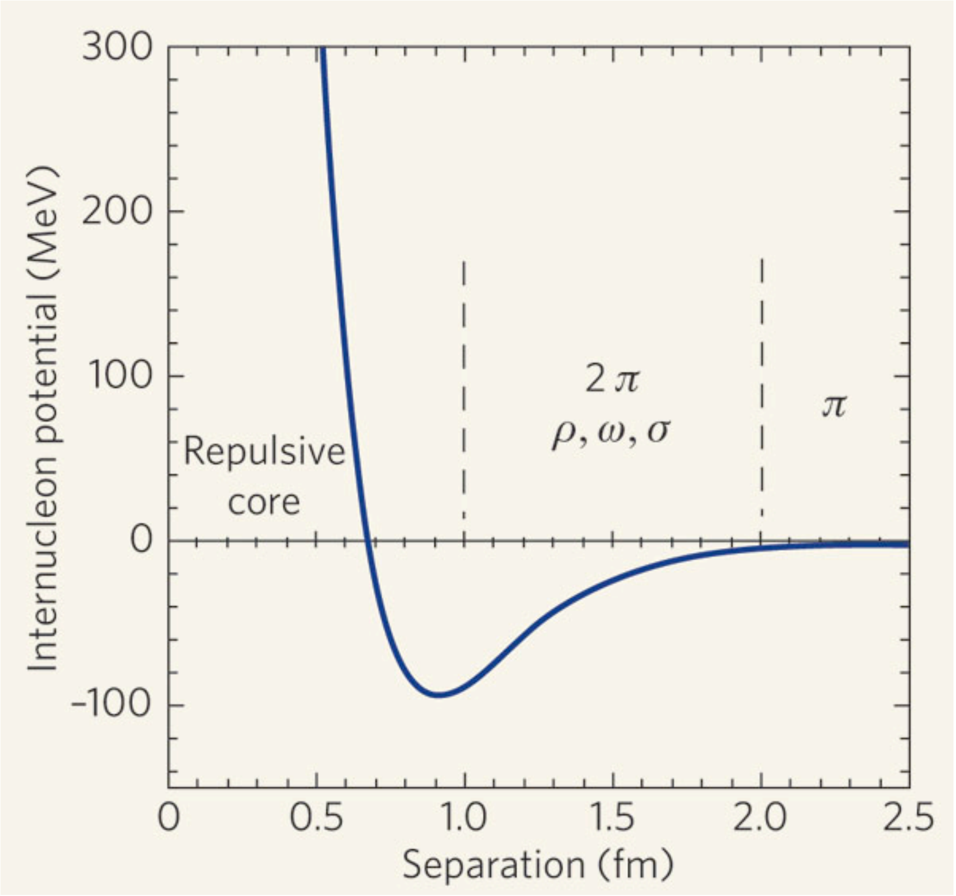
Is it measurable at a future EIC?

The Nucleon Potential:

- At long distances, the nucleon potential consists of meson exchange: $\pi, \rho, \omega, \sigma, \ldots$

- At short distances, the perturbative QCD degrees of freedom (ie, gluons) should contribute to the repulsive core.

- Even modern potentials (Nijmegen ESC08) model this as a simple Gaussian repulsion, e.g. :



Frank Wilczek, *Nature* **445**, 156-157

$$V_P(k^2) = \frac{g_p^2}{M^2} \exp[-k^2/4m_p^2]$$

de Swart, et. al, *Nuov. Cim.* **102 A**, 203

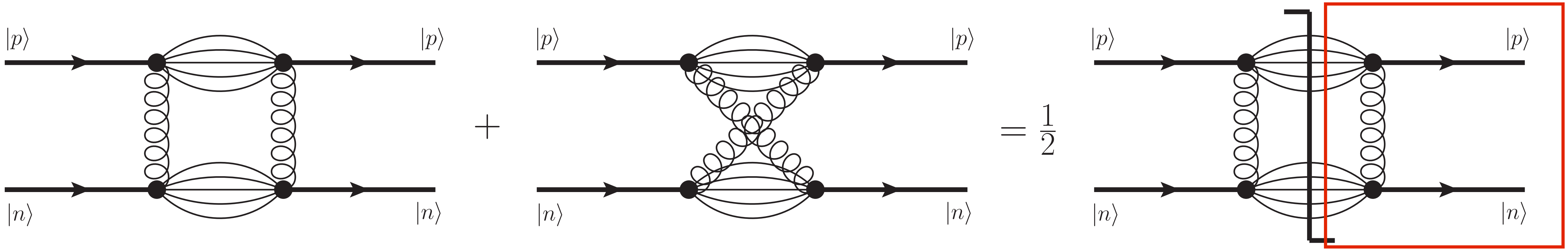
$$V_P(k^2) = \frac{g_P^2}{k^2 + M^2} \exp[-k^2/4m_p^2]$$

Nagels, et. al, arXiv: *1408.4825*

Gluonic Content of the Nucleon Potential:

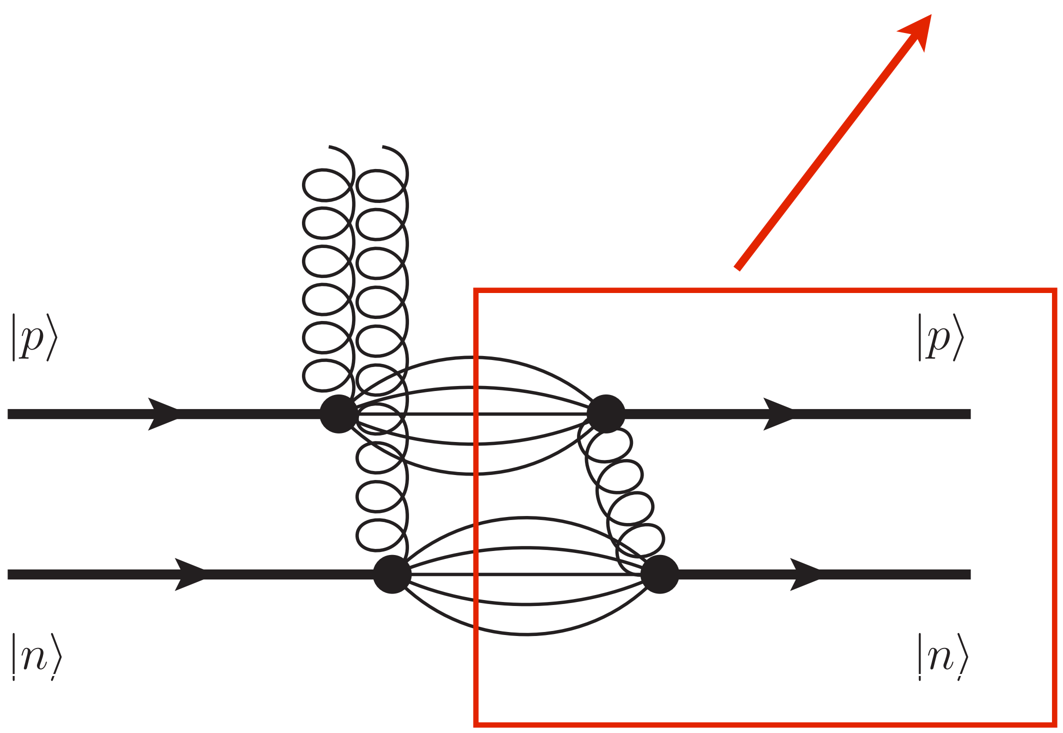
• The lowest-order gluon contribution is the "perturbative pomeron": a color-singlet two-gluon exchange leading to a repulsive potential.

➡ The building block is the one-gluon amplitude $p + n \to X$



•If a projectile excites the nucleons into color-octet states, but they remain intact, then they must have exchanged a gluon to neutralize the color.

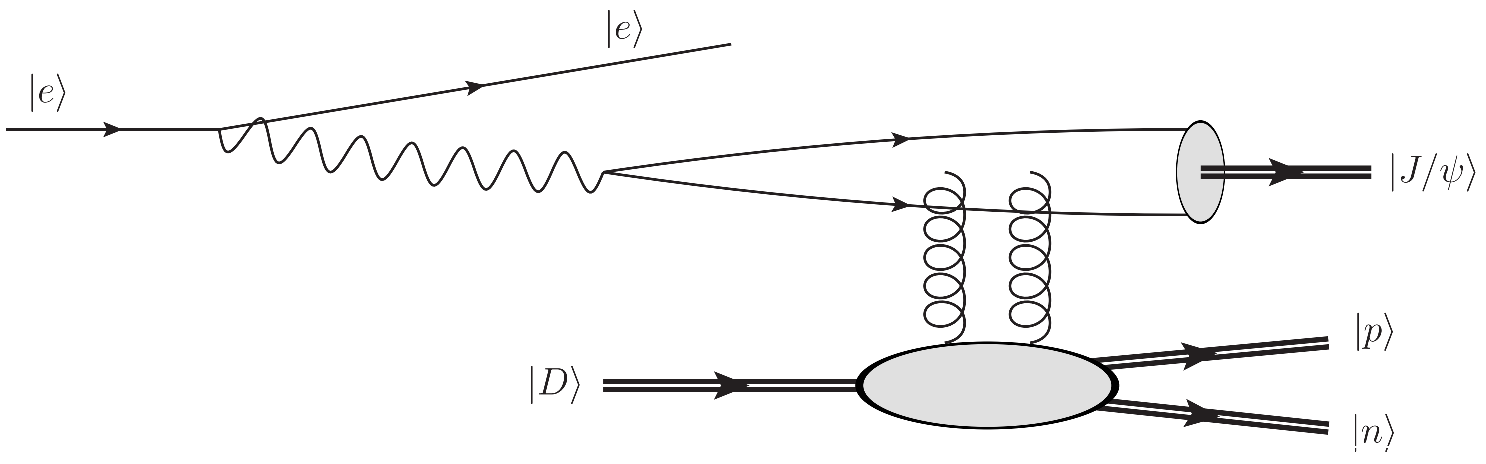
➡ If the excitation is perturbative, we could use this process to measure the gluonic contribution to the nucleon potential.



The Process:

Electroproduction of J/ψ with Diffractive Disintegration of the Deuteron

$$e + D \to e + J/\psi + p + n$$



- Deep inelastic scattering on a deuteron target in Regge kinematics

  ➡ Time dilation: virtual photon fluctuates into a quark dipole and exchanges gluons with the deuteron.

$$s \gg Q^2$$

$$x_B \ll 1$$

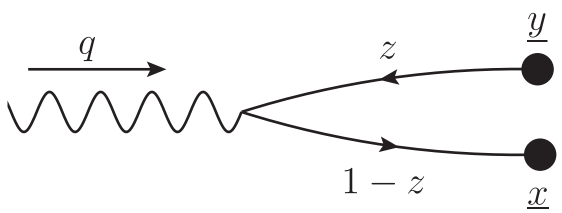
- The J/ψ mass provides a hard scale which ensures that the scattering is perturbative.

- Diffractive scattering with an exclusive final state makes it possible to "color-lock" the nucleon quantum numbers.

Separation of time scales:

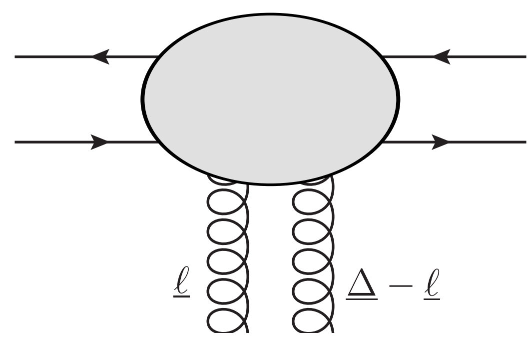
$$s \gg Q^2, M_J^2$$

$$\frac{\Delta\tau_{q\bar{q}}}{E} \sim \frac{1}{Q^2}$$



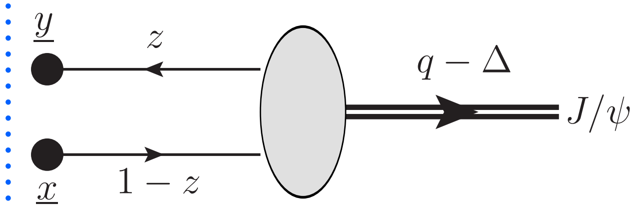
Long-lived dipole

$$\frac{\Delta\tau_{Int}}{E} \sim \frac{1}{s}$$



Instantaneous scattering

$$\frac{\Delta\tau_J}{E} \sim \frac{1}{M_J^2}$$



Long J/ψ formation time

$$\Delta\tau_{q\bar{q}}\,,\ \Delta\tau_J \gg \Delta\tau_{Int}$$

- In Regge kinematics, the high-energy scattering occurs almost instantaneously, while the lifetime of the quark dipole and the formation of the J/ψ take place over much longer times.

  ➡ Leads to a natural factorization of the long-time dynamics (wave functions of photon, deuteron, J/ψ) from the scattering dynamics.

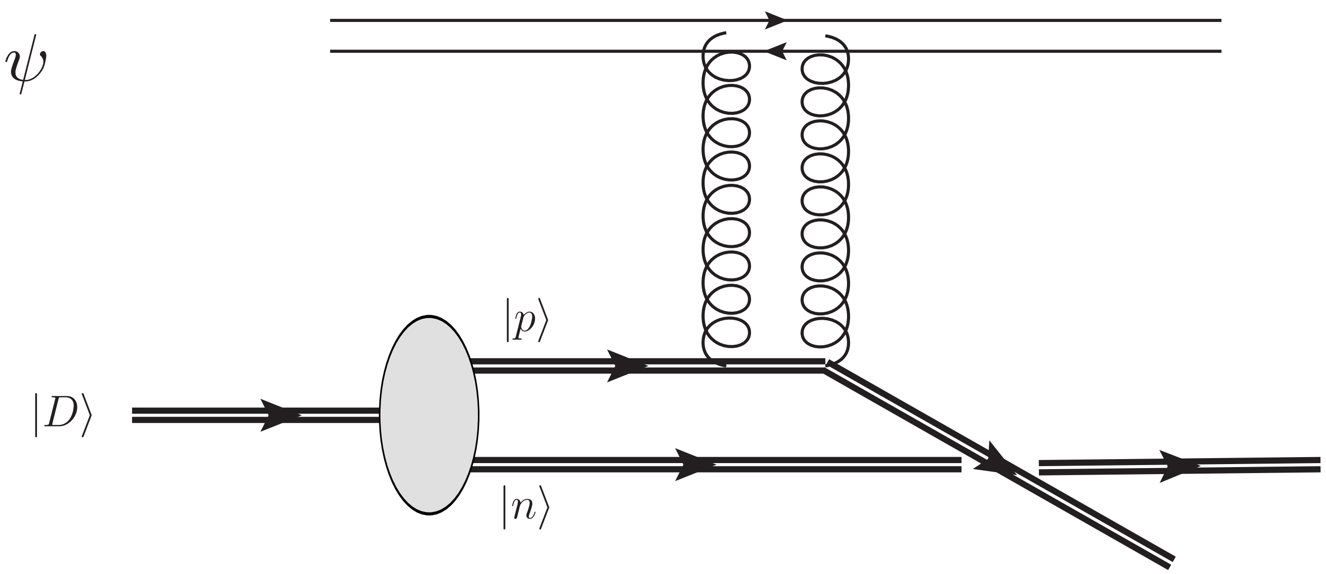
Collins, et. al, *Phys. Rev*. **D56** (1997)
Frankfurt, et. al, *Phys. Rev*. **D57** (1998)

- Simple picture: fixed transverse coordinates, longitudinal path ordering.

The Leading-Order Process:

•Because of the hard scales in the photon and J/ψ wave functions, the dipole is perturbatively small:

$$r_T \sim \min\left(\frac{1}{Q}, \frac{1}{M_J}\right)$$



• The small dipole probes the gluon distribution of either the proton or the neutron.

$$\frac{d\sigma}{dT} \propto \frac{\alpha_{EM} f_J^2}{Q^6} [\alpha_s \, xG(x, Q^2)]^2$$

Brodsky, et. al, *Phys. Rev*. **D50** (1994)

Frankfurt, et. al, *Phys. Rev*. **D54** (1996)

• The struck nucleon recoils with the momentum exchanged through the T-channel.

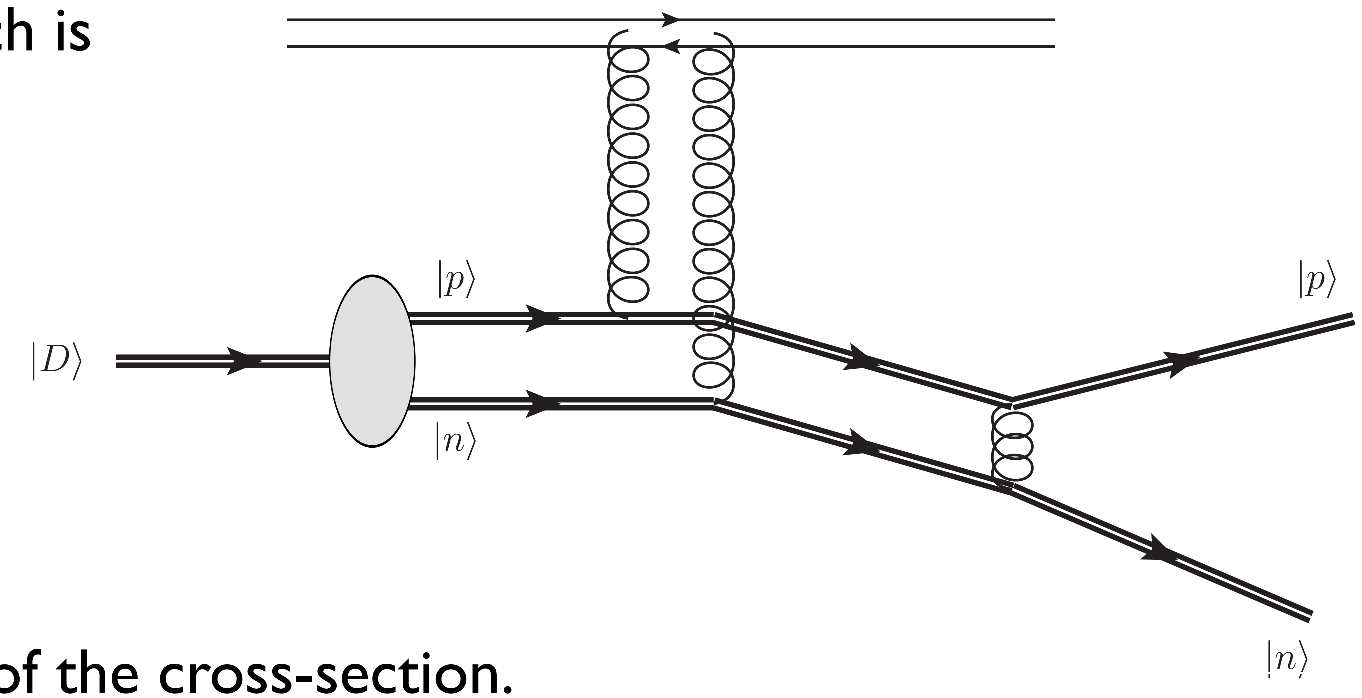
$$p_T^2 = |T|$$

➡ The other nucleon is a spectator

Our Process:

•If the nucleon is observed with a hard p_T which is greater than what was delivered through the T-channel, then a short-distance rescattering must have occurred.

$$p_T^2 \gg |T| \gg \Lambda_{QCD}^2$$



• Higher-order in the coupling: α_s^2 at the level of the cross-section.

•Each nucleon absorbs a gluon and is excited into a color octet state, and they must exchange an additional gluon to neutralize the color.

➡ Diffractive scattering and exclusive final state "color locks" the nucleon interaction to be gluonic.

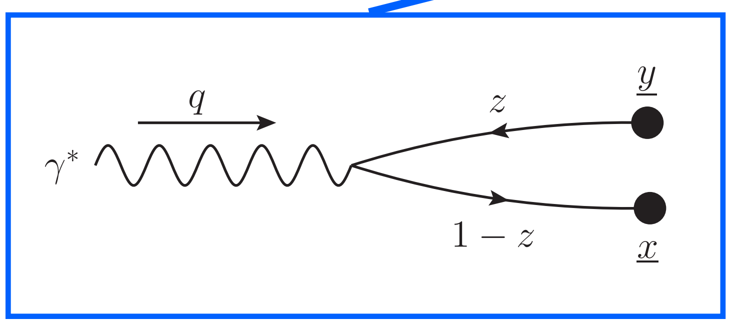
$$\psi^D \left(\Delta x_\perp < \frac{1}{\Lambda_{QCD}} \right)$$

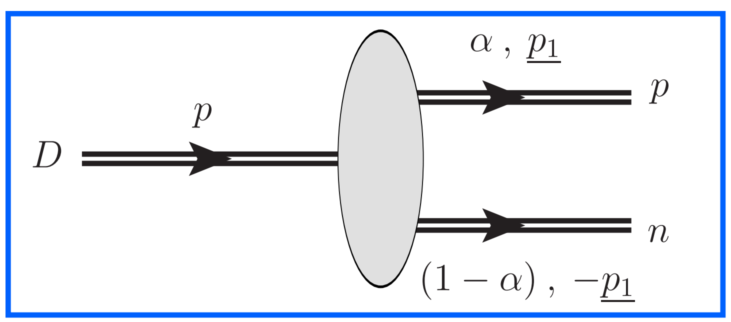
➡ Sensitive to the short-distance components of the deuteron wave function

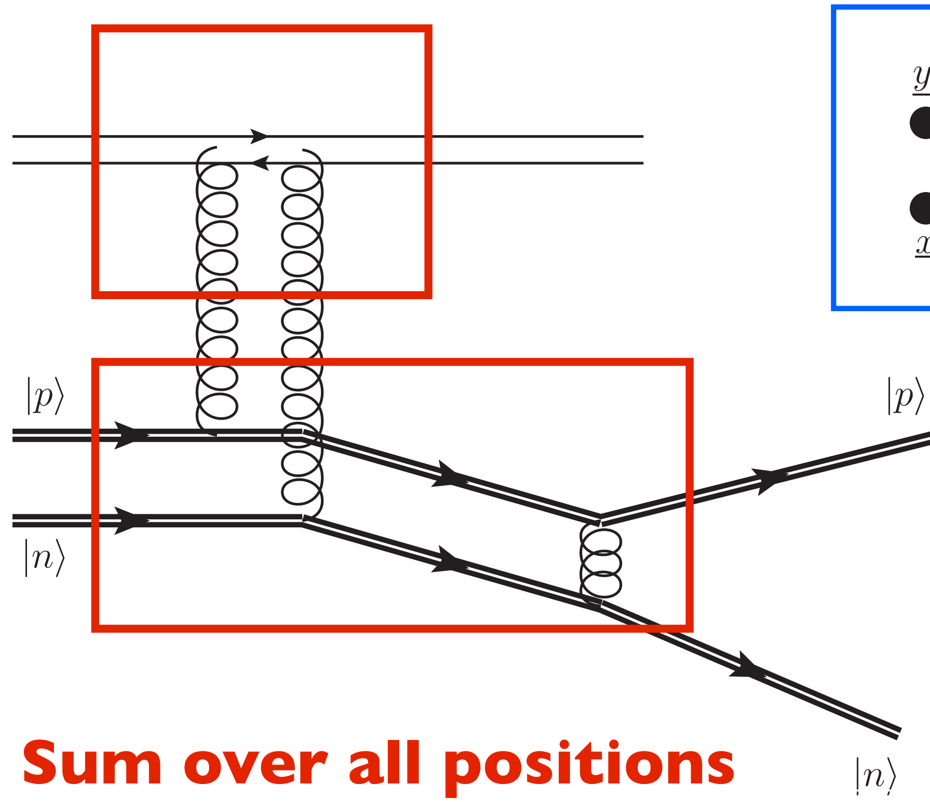
Anatomy of the Calculation:

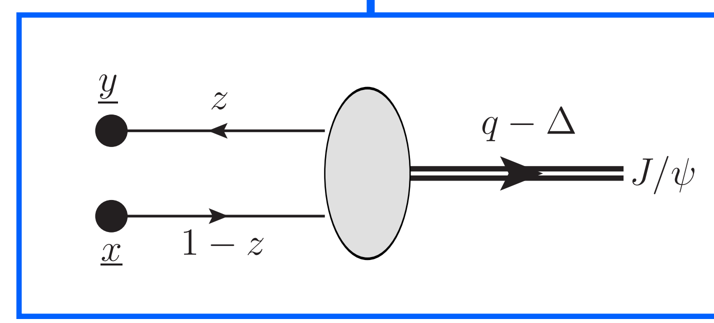
Convolute with wave functions

Sum over all gluon connections to dipole



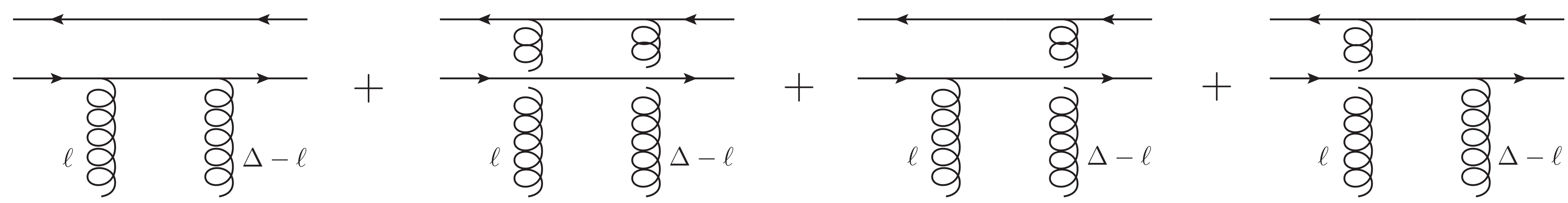






Sum over all positions of the rescattering

Dipole Interaction:



$$\int d^2b \frac{d^2\ell}{(2\pi)^2} \frac{d^2\ell'}{(2\pi)^2} \frac{1}{\ell_T^2 \ell_T'^2} \Big[e^{-i(\ell_\perp + \ell'_\perp)\cdot x_\perp} + e^{-i(\ell_\perp + \ell'_\perp)\cdot y_\perp} - e^{-i\ell_\perp \cdot x_\perp} e^{-i\ell'_\perp \cdot y_\perp} - e^{-i\ell_\perp \cdot y_\perp} e^{-i\ell'_\perp \cdot x_\perp} \Big]$$

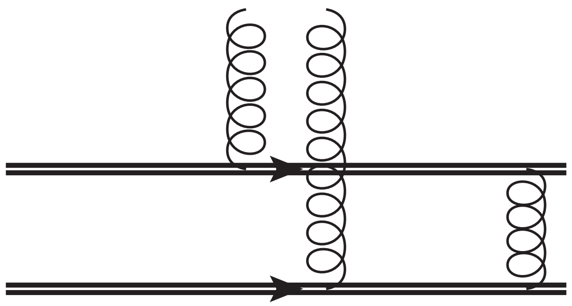
- High-energy dipole couples to Glauber (Coulomb) gluons' transverse momentum
- Relative signs account for charge of quark vs. antiquark
- Small dipole approximation: $|x_\perp - y_\perp| \sim 1/Q$

$$\sim |x_\perp - y_\perp|^2 \, xG(x, Q^2)$$

Dipole couples to the gluon distribution

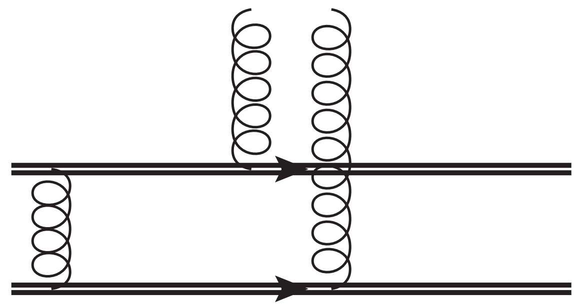
Nucleon-Nucleon Rescattering:

- From the numerator algebra, final-state rescattering dominates over the other diagrams



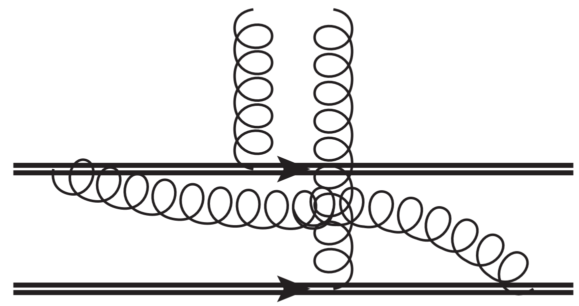
Final-State Interaction

$\mathrm{Num} \propto p_T^2$



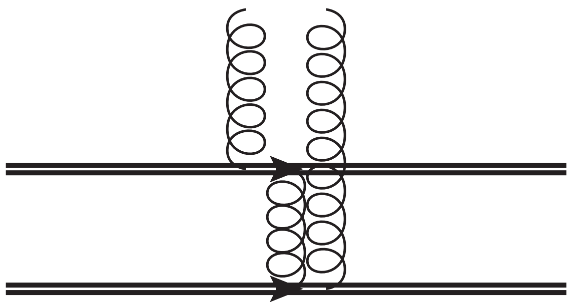
Initial-State Interaction

$\mathrm{Num} \propto m^2$



Long-Lived Gluon

$\mathrm{Num} \propto m \times p_T$



Intermediate Interaction

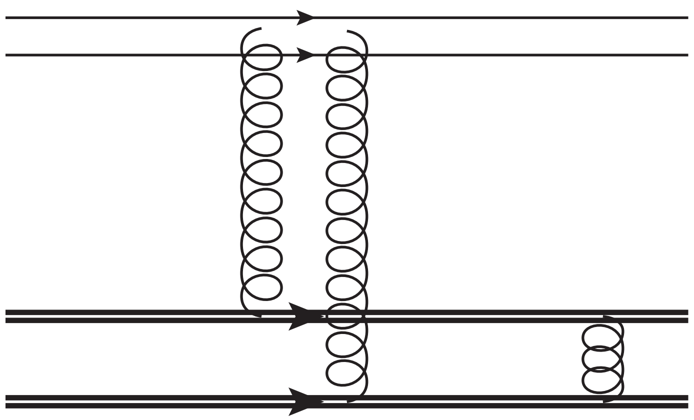
Suppressed by $1/s$

$m^2 \ll p_T^2$

(Scattering is instantaneous)

The pQCD Result:

$$\frac{d\sigma}{dT\,dp_T^2} \propto \frac{\alpha_{EM} f_J^2}{Q^6} [\alpha_s \, xG(x,Q^2)]^2 \times \left(\frac{\alpha_s^2}{p_T^4} \, |\psi^D(0_\perp)|^2 \right)$$



- Proportional to the leading-order result, with a multiplicative factor related to the rescattering

  ➡ Higher order in the coupling
  ➡ Transverse momentum from the extra gluon propagator
  ➡ Probability of finding the nucleons close enough in the transverse plane to exchange gluons

- Integrate p_T over a finite range of detector acceptance:

$$\int \frac{dp_T^2}{p_T^4} = \frac{1}{p_{T,min}^2} \left(1 - \frac{p_{T,min}^2}{p_{T,max}^2} \right)$$

Estimates - Is it Measurable at an EIC?

- Define the ratio to the leading-order cross-section:

$$\mathcal{R} \equiv \frac{1}{(L.O.)} \frac{d\sigma}{dT} \sim \frac{\alpha_s^2}{p_{T,min}^2} \left(1 - \frac{p_{T,min}^2}{p_{T,max}^2} \right) \left| \psi^D (0_\perp) \right|^2$$

- Take $\alpha_s \approx 0.3$

- For "Roman pot" detectors, $p_{T,min} \approx 0.4\ GeV$ and $p_{T,max} \approx 1.5\ GeV$

- The overlap area in which the nucleons can exchange gluons is approximately given by the "gluonic radius" of the proton:

$$\left| \psi^D (0_\perp) \right|^2 \approx \frac{1}{\pi R_G^2} \quad \text{with} \quad R_G \approx 0.5\ fm$$

- Altogether, this gives the estimate $\boxed{\mathcal{R} \approx 3\%}$

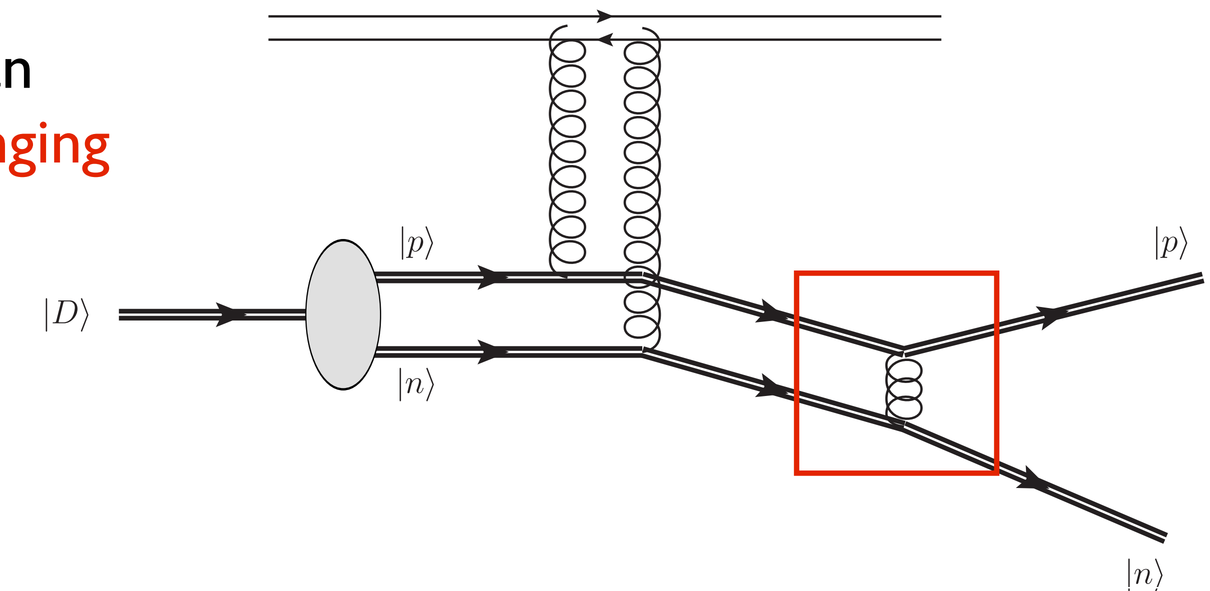
- If an EIC has 100x the luminosity of HERA, then we could see these events with the same statistics that HERA saw J/ψ production on the proton!

Outlook:

• By producing a carefully constructed final state, we can isolate cases where the nucleons rescattered by exchanging a gluon.

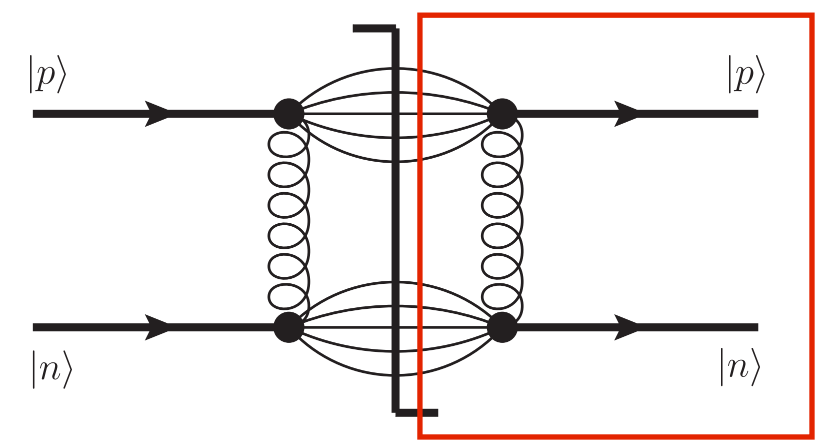
$$e + D \to e + J/\psi + p + n$$

$$p_T^2 \gg |T| \gg \Lambda_{QCD}^2$$



• By "color locking" the nucleon rescattering, we can learn something about the short-distance nucleon-nucleon potential.

$$\frac{d\sigma}{dT\,dp_T^2} \propto \frac{\alpha_{EM} f_J^2}{Q^6} [\alpha_s\, xG(x,Q^2)]^2 \times \left(\frac{\alpha_s^2}{p_T^4} |\psi^D(0_\perp)|^2 \right)$$



• With the enhanced luminosity of an EIC, this process could be measurable with statistics comparable to J/ψ production at HERA.

$$\mathcal{R} \approx 3\% \; \left(\times 100 \text{ relative luminosity}\right)$$

• Finalization of details is in progress.
Look for the paper soon!