Short-Range NN Correlations at an EIC

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Next Generation Nuclear Physics with JLab12 and EIC

Saturday, Feb. 13, 2016

Reference: 1512.03111

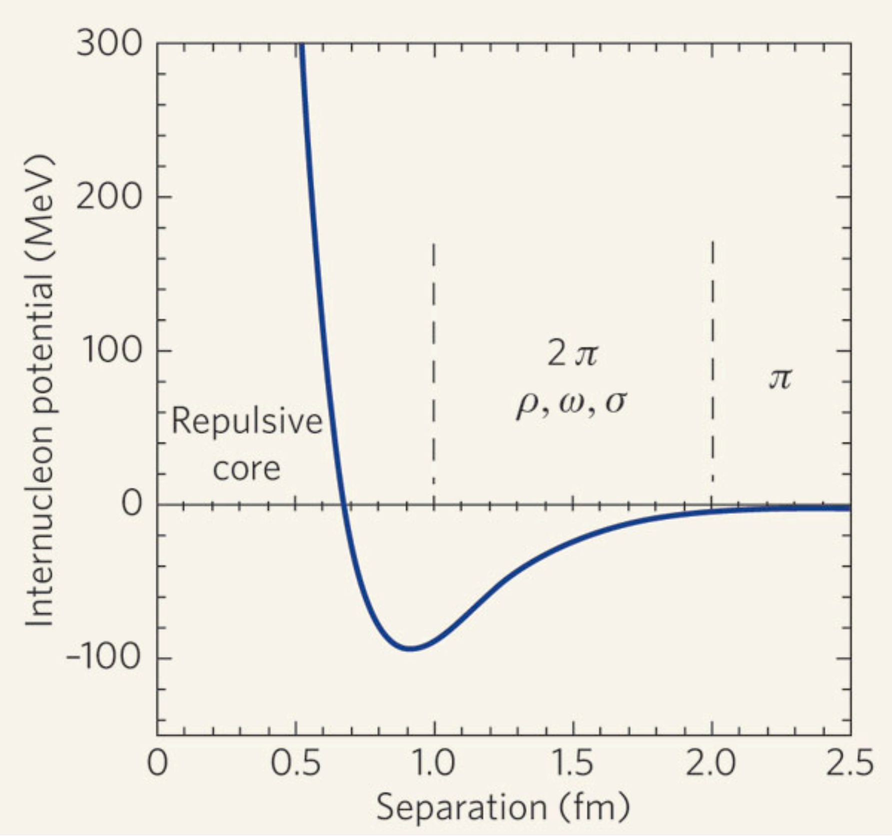
Outline

1. A New Way to Search for QCD in Short-Distance NN Scattering
2. Hard Exclusive Meson Production with Hard Deuteron Breakup
3. Calculations for the Quark Target Model
4. Realistic Nucleons at an EIC

Motivation: QCD in the NN Potential

- The inter-nucleon potential can constructed as an exchange of effective bosons.

➡ Exchanged particles (and their properties) vary for different distance scales...



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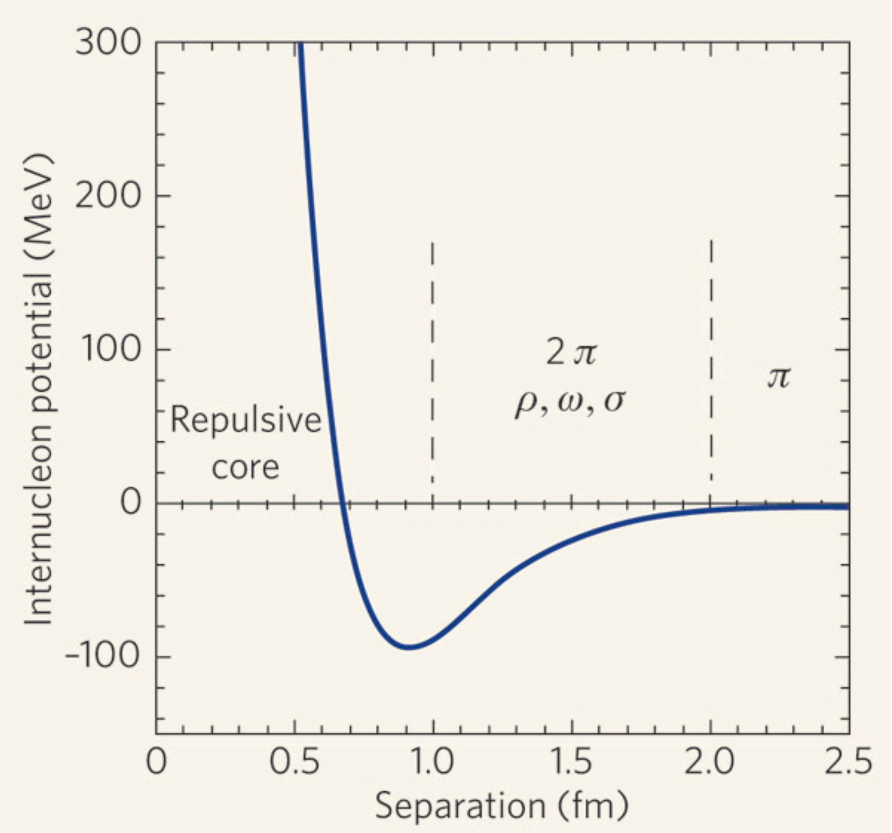

M. Sargsian 1403.0678

$r \geq 2\ fm$	Yukawa pion exchange
$2\ fm \geq r \geq 1.2\ fm$	2-pion exchange, etc. ; tensor force
$1.2\ fm \geq r \geq 0.7\ fm$	Vector boson exchange
$0.7\ fm \geq r$	Repulsive core ; highly virtual bosons...

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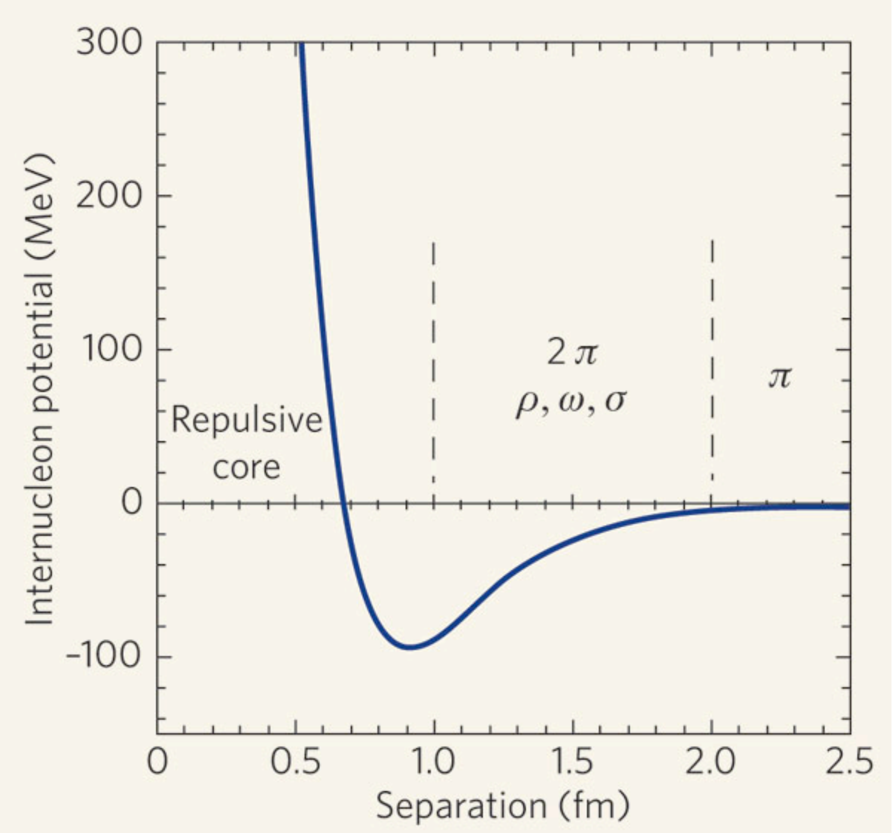

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"In fact a 'pion far off its mass shell' may be a meaningless - or at least highly complicated idea." - R. Feynman

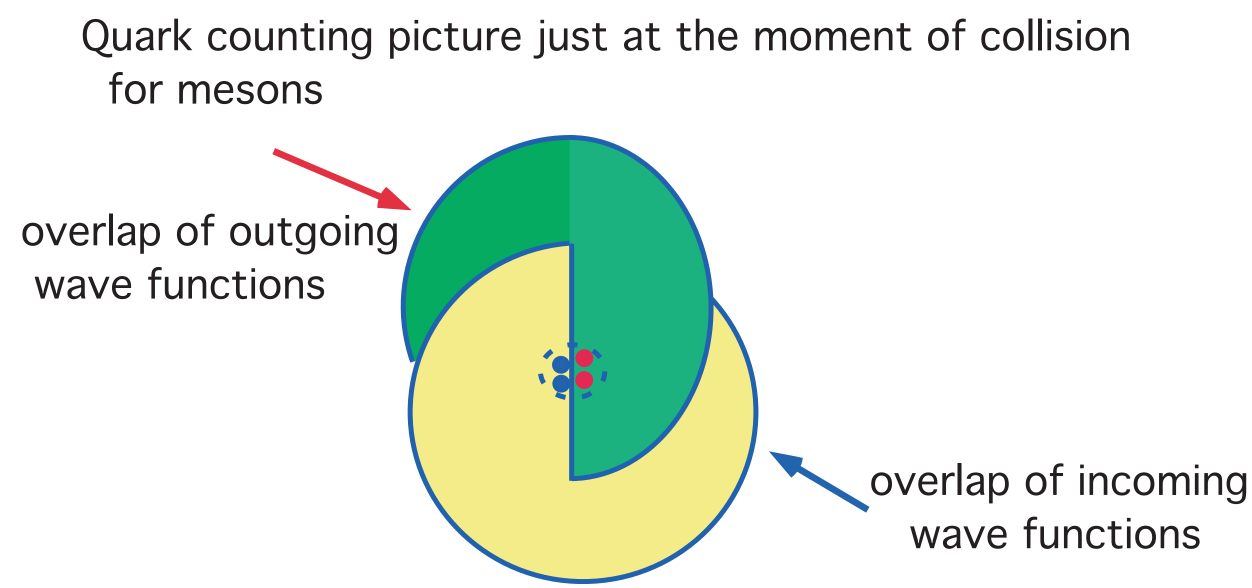
QCD degrees of freedom?

G. Sterman 1008.4122

$Q^2 \equiv -t \propto s$ for fixed θ_{cm}

- One hard reaction: all 3 valence quarks (per WF) are within $1/Q$

$$|\psi_1(x_\perp, x_\perp, x_\perp)|^2 |\psi_2(x_\perp, x_\perp, x_\perp)|^2 |\psi_3(x_\perp, x_\perp, x_\perp)|^2 |\psi_4(x_\perp, x_\perp, x_\perp)|^2$$



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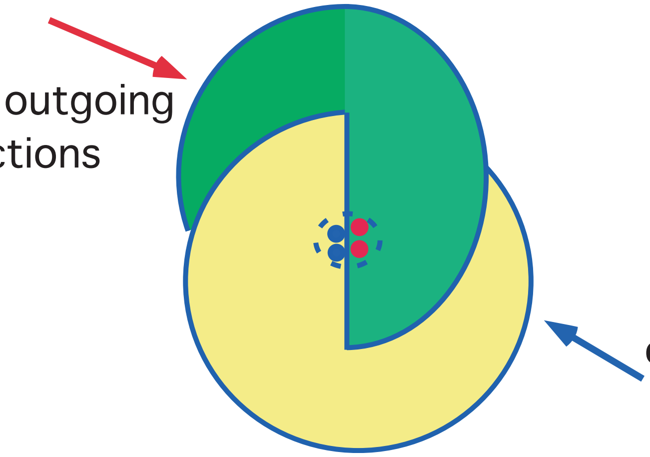
$$\frac{d\sigma}{dt} \propto \frac{1}{s^2} \left(\frac{m^2}{s} \right)^8 \propto \boxed{\frac{1}{s^{10}}}$$

- **Brodsky-Farrar quark counting rules**

Quark counting picture just at the moment of collision for mesons



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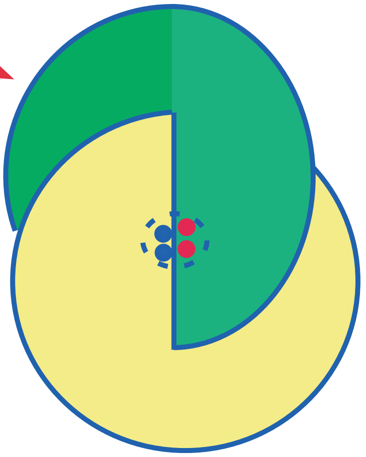

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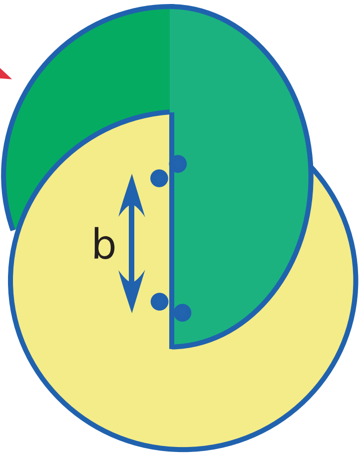
Two independent scatterings for meson-meson scattering



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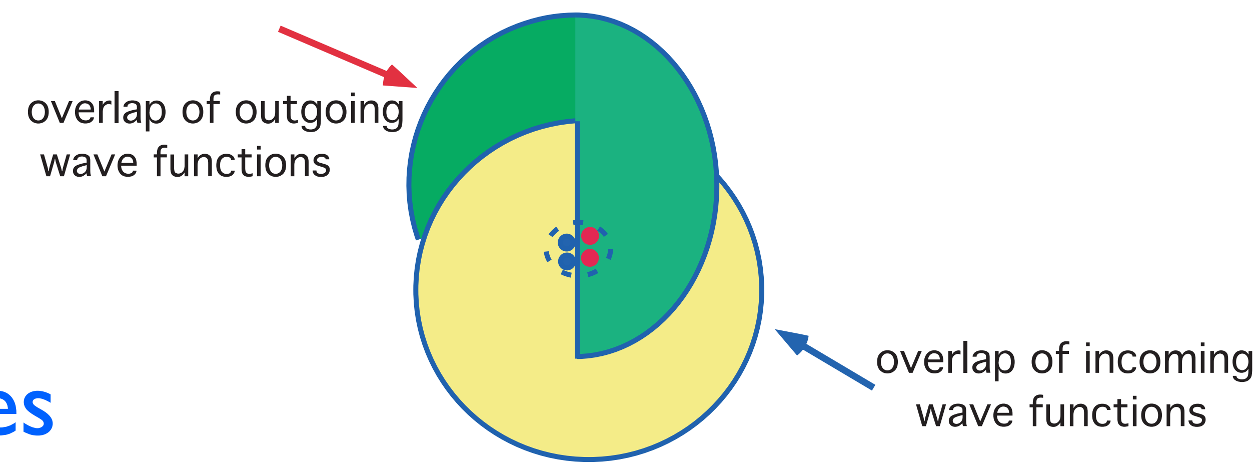

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- Landshoff mechanism

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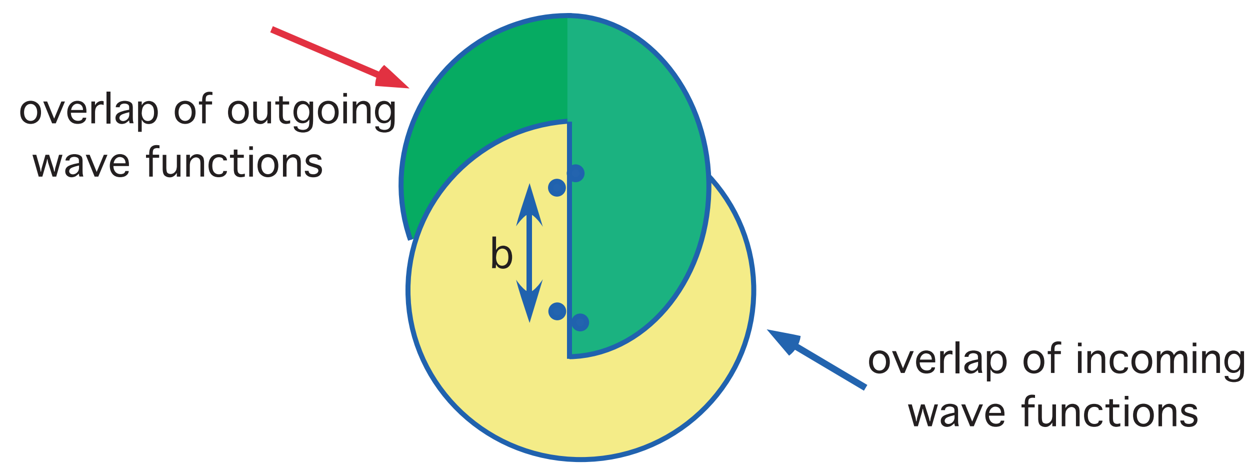
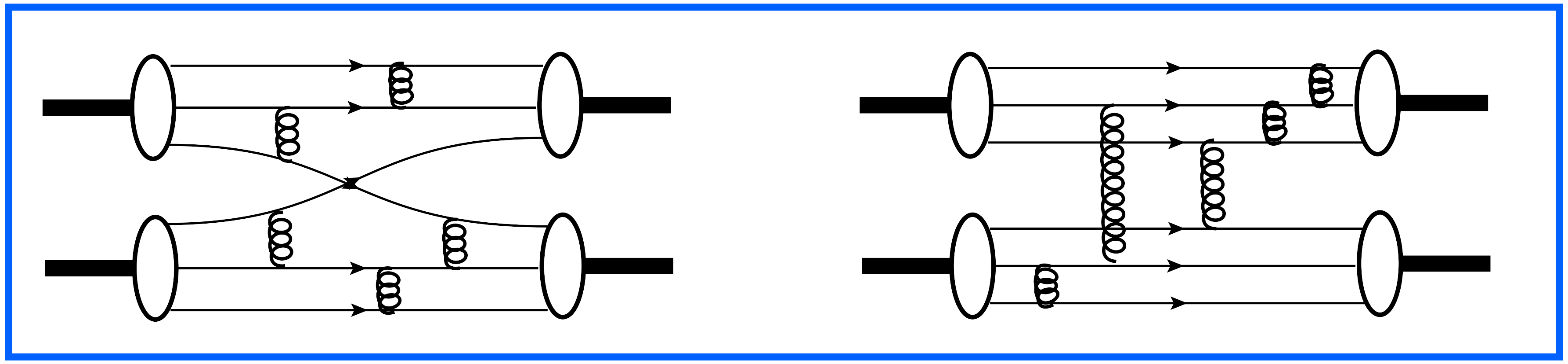


A Puzzle: Where Are the Gluons?

Brodsky-Farrar



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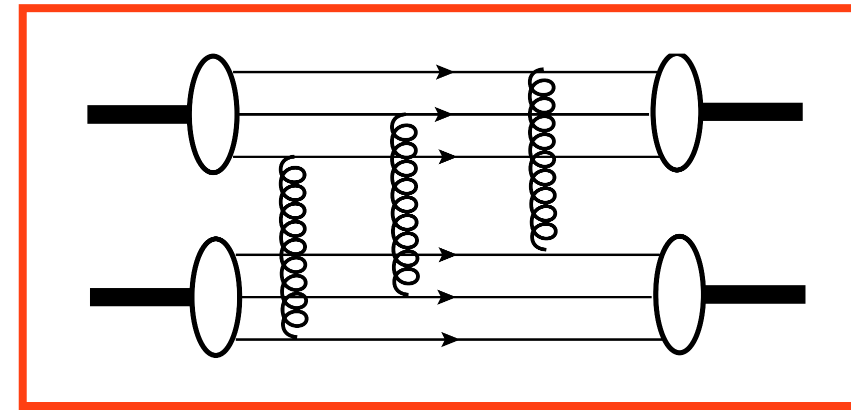

- Expect Landshoff mechanism to dominate at high energies

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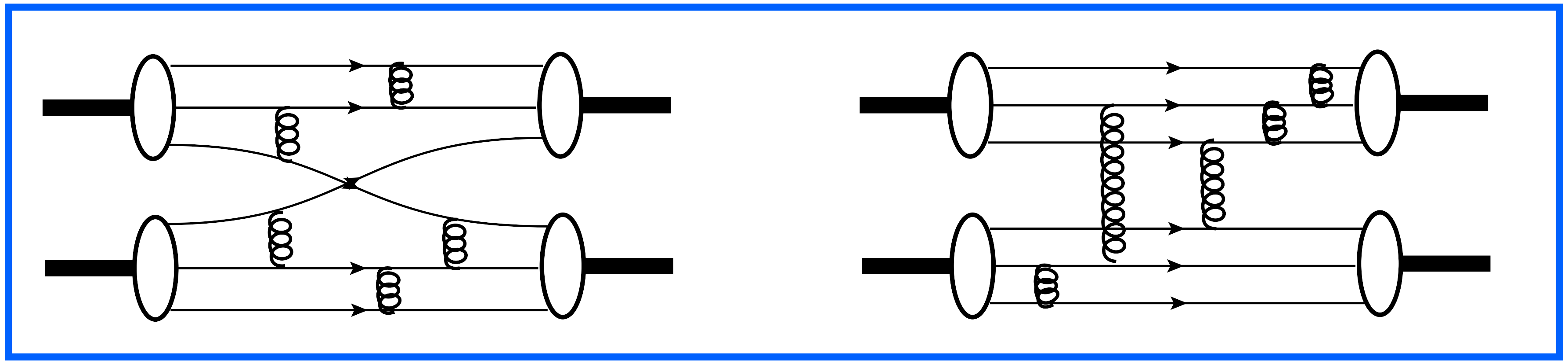

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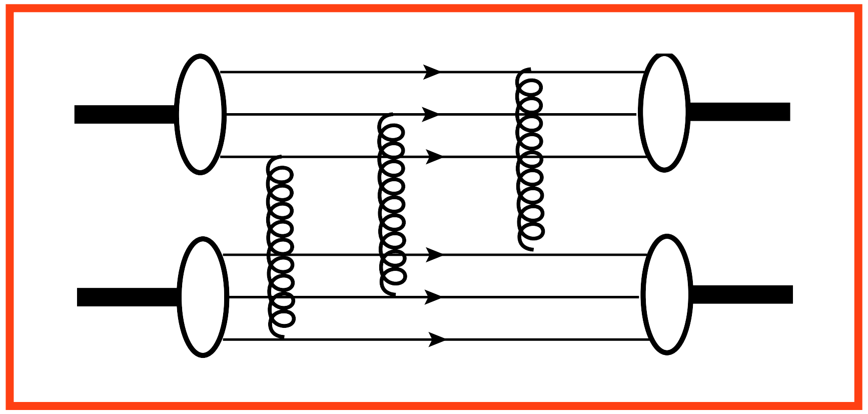

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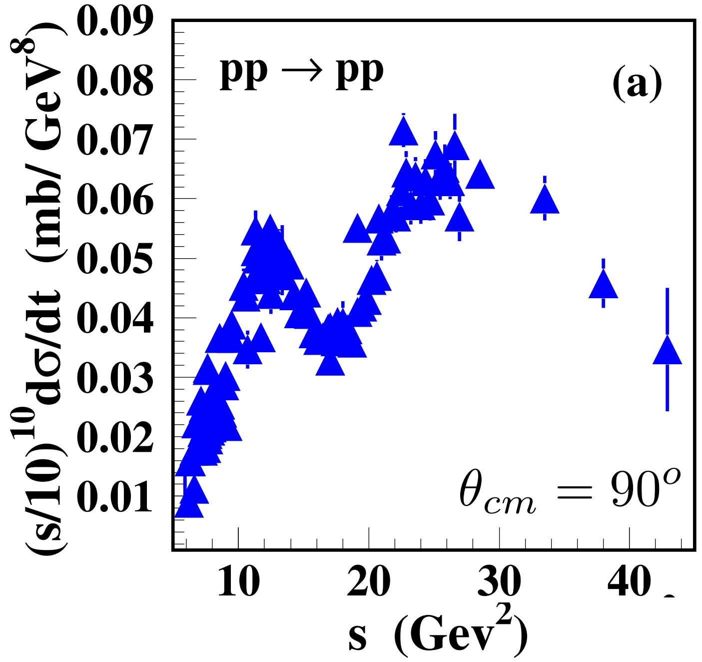
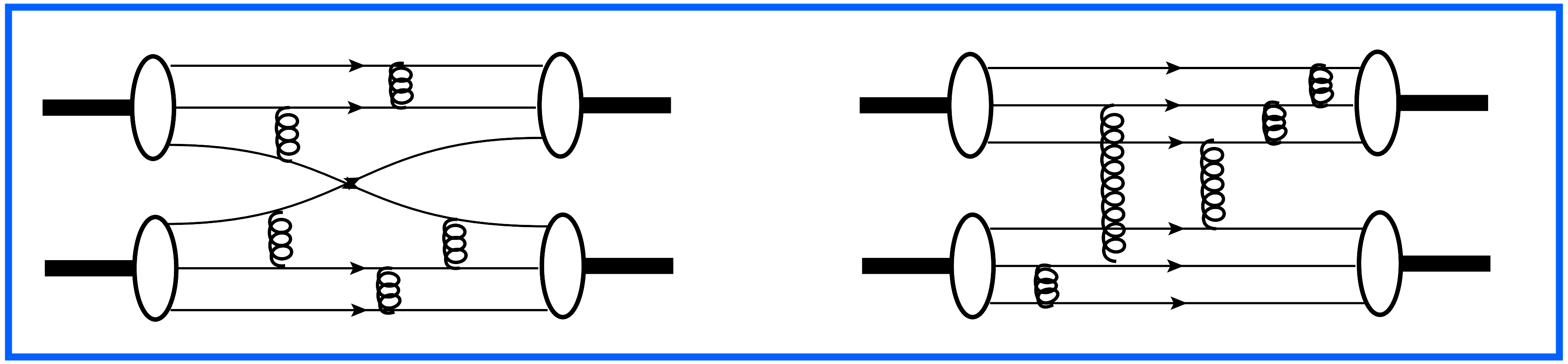


- But experimental energy scaling is consistent with Brodsky-Farrar: s^{-10} for $\theta_{cm} = 90^o$...
- ... and overwhelming dominance of flavor exchange.

Brodsky-Farrar



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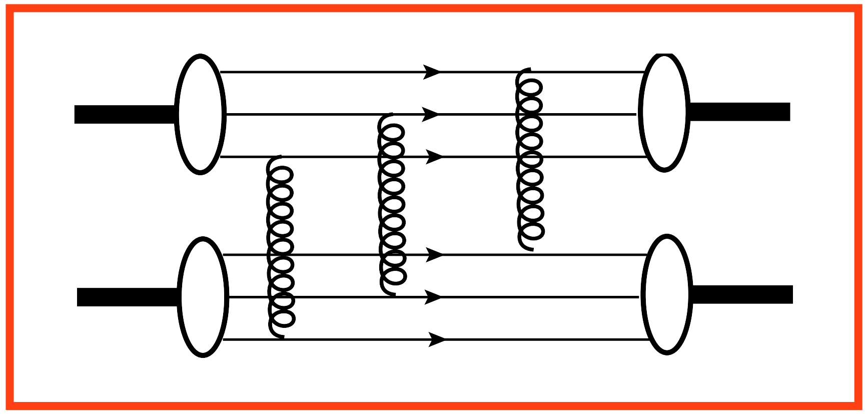

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➡ Quark interchange dominates.... Why??

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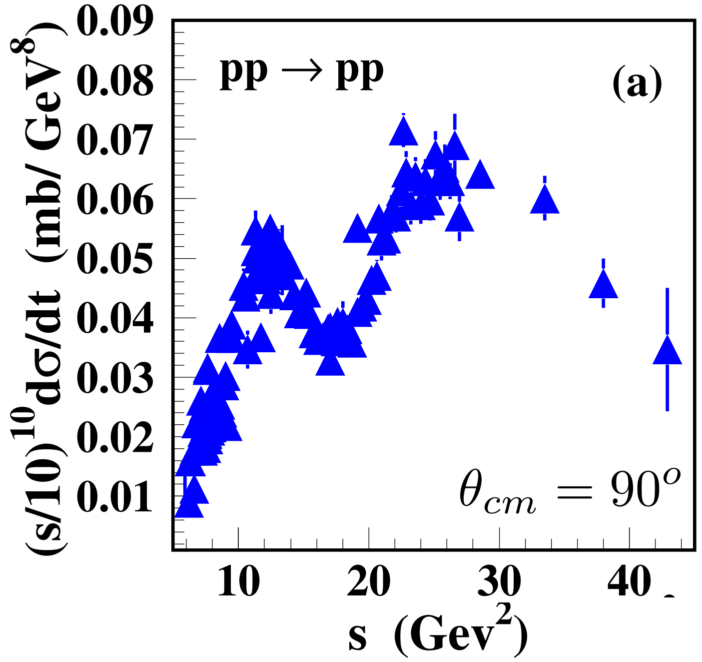
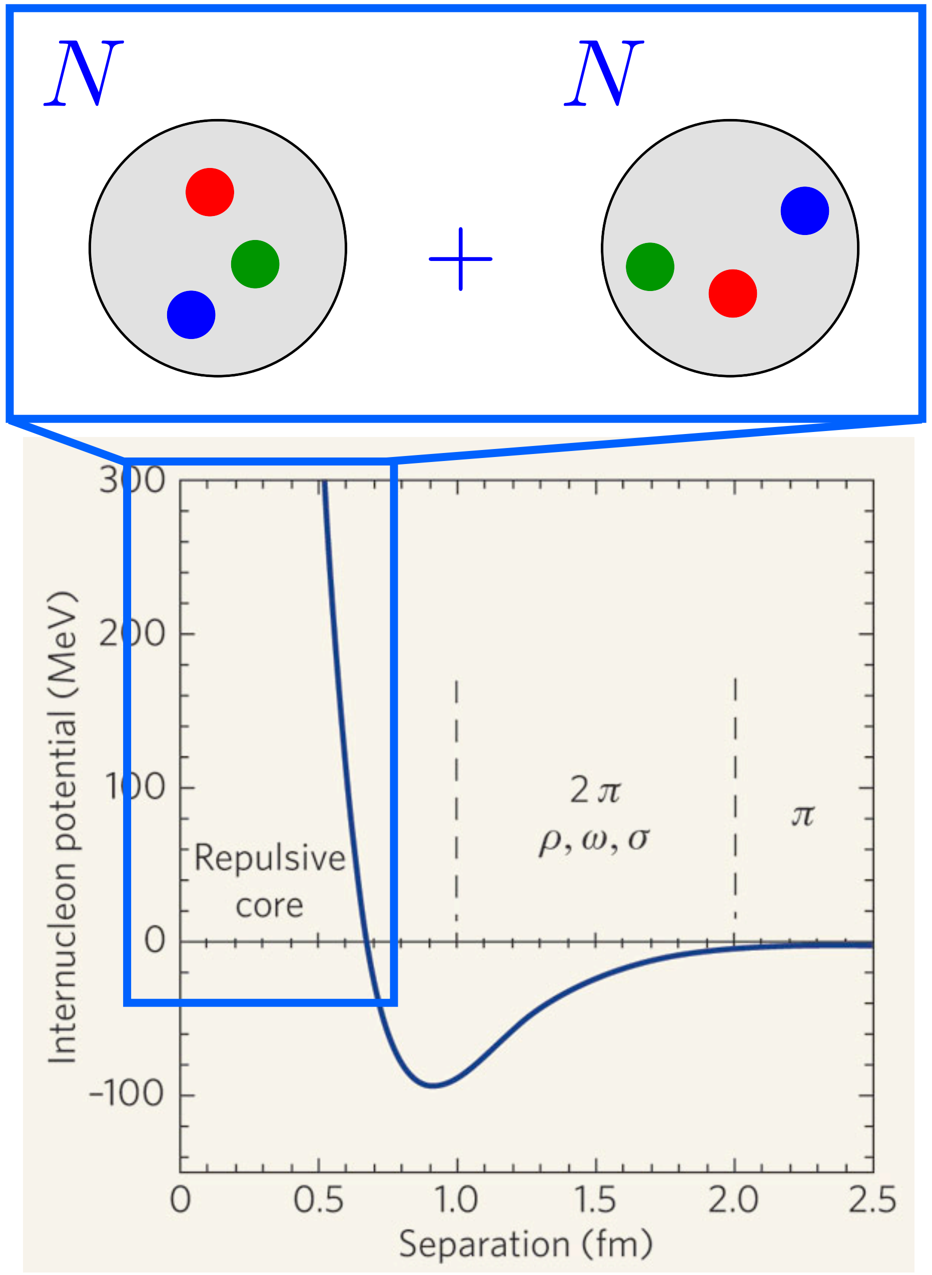


- At short distances, an NN system (6 quarks) doesn't need to assemble into color-singlet baryons.



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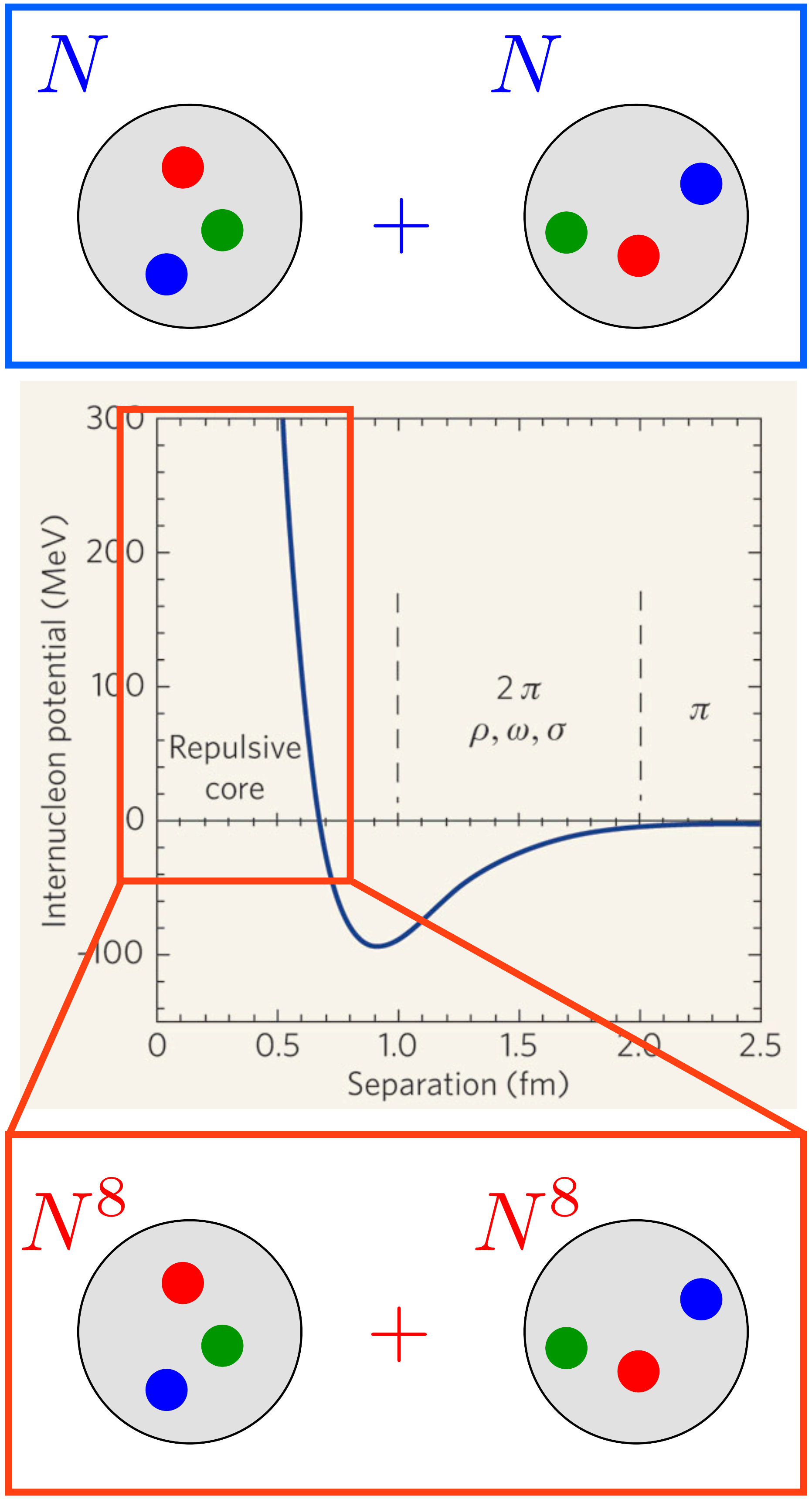

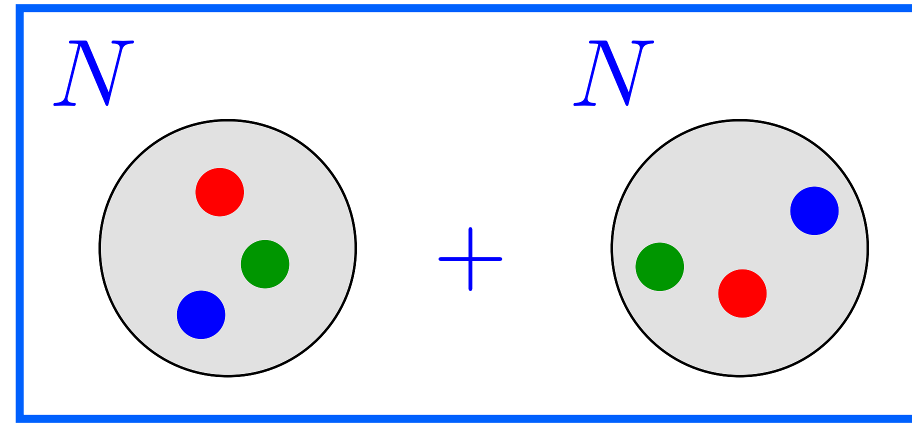

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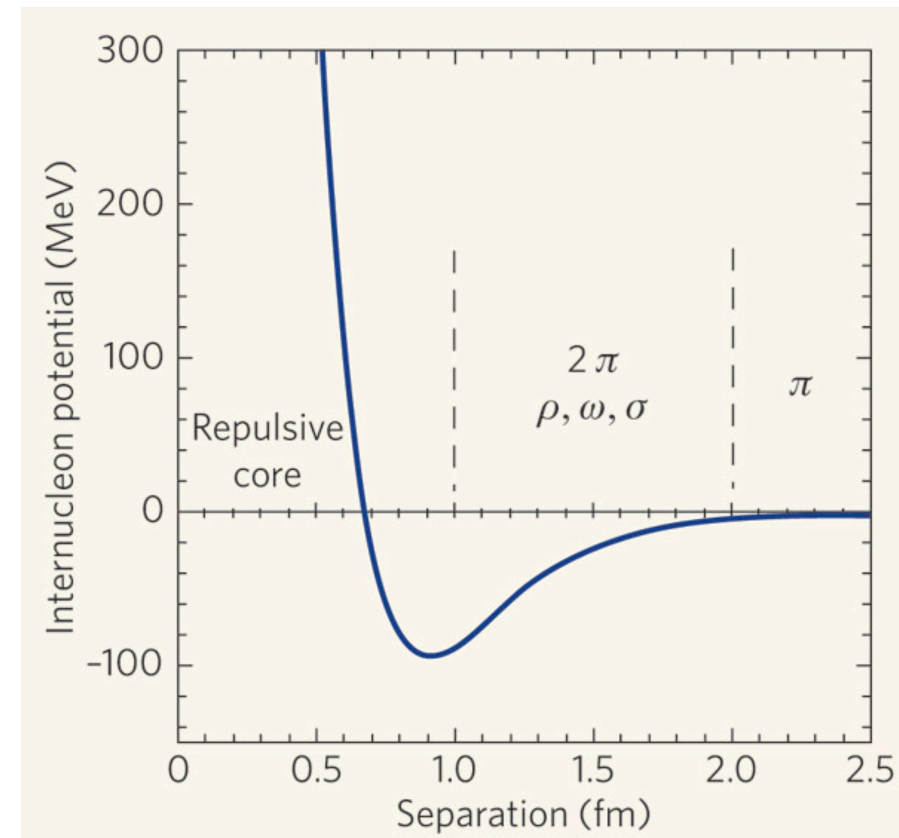
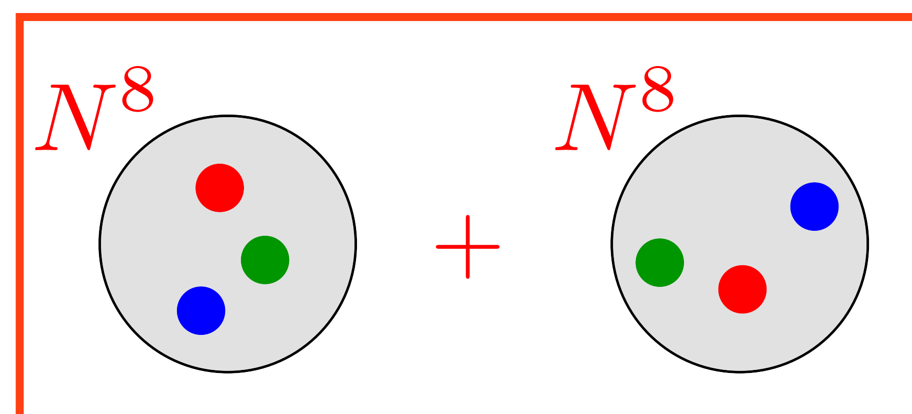


- From simple group theory, if 6 quarks are in the same orbital state, the hidden color component can be huge! 80%!

$$|6q\rangle = \sqrt{\frac{1}{9}}|NN\rangle + \sqrt{\frac{4}{45}}|\Delta\Delta\rangle + \sqrt{\frac{4}{5}}|N^8 N^8\rangle$$

M. Harvey, Nucl. Phys. A 352, 301 (1981)



Hidden Color: When Is a Nucleon Not a Nucleon?

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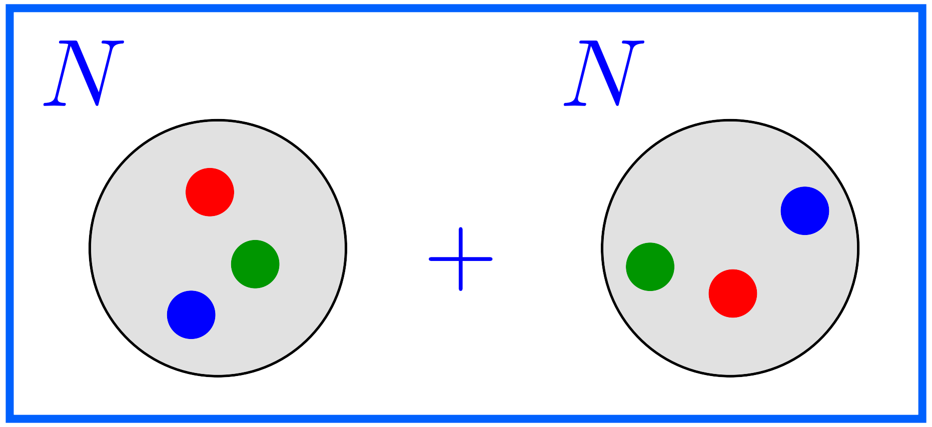

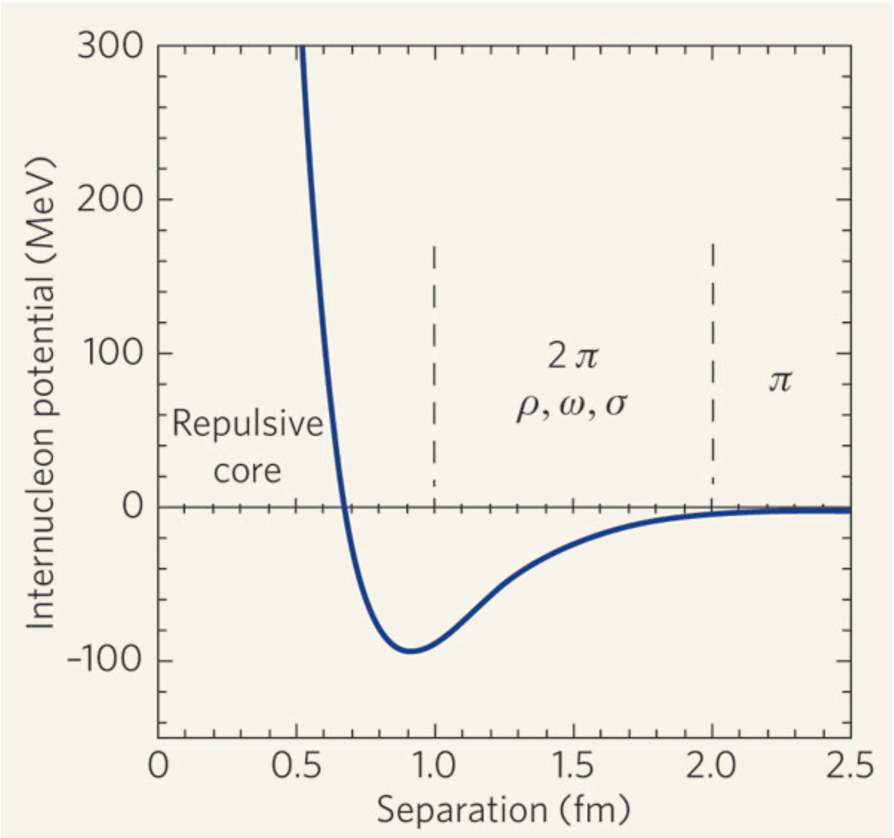

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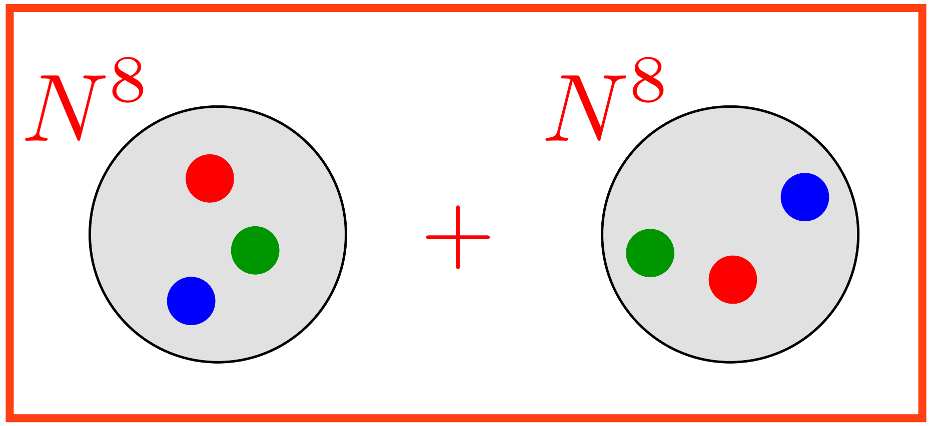
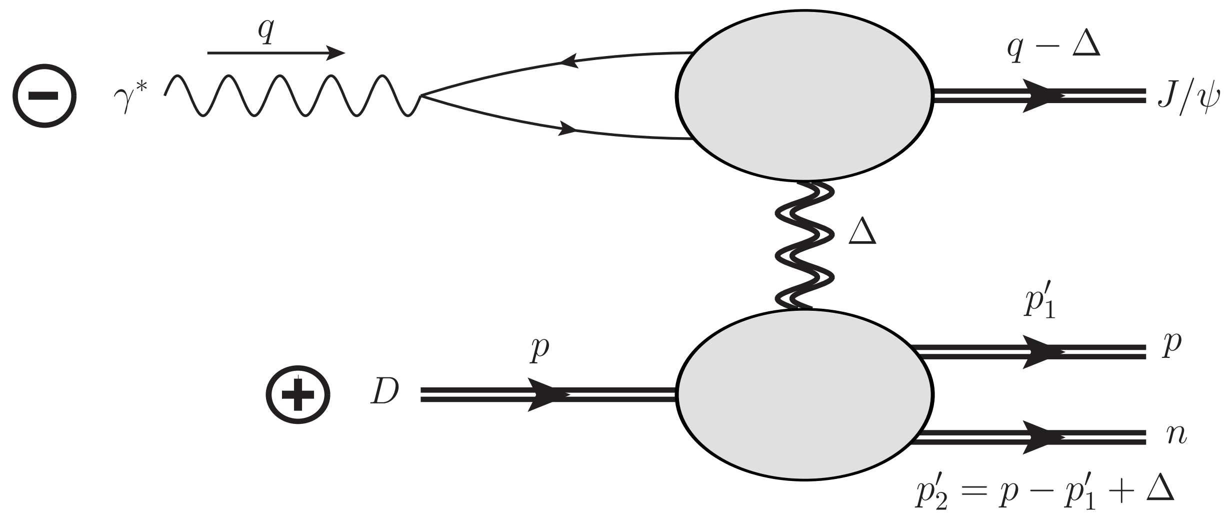
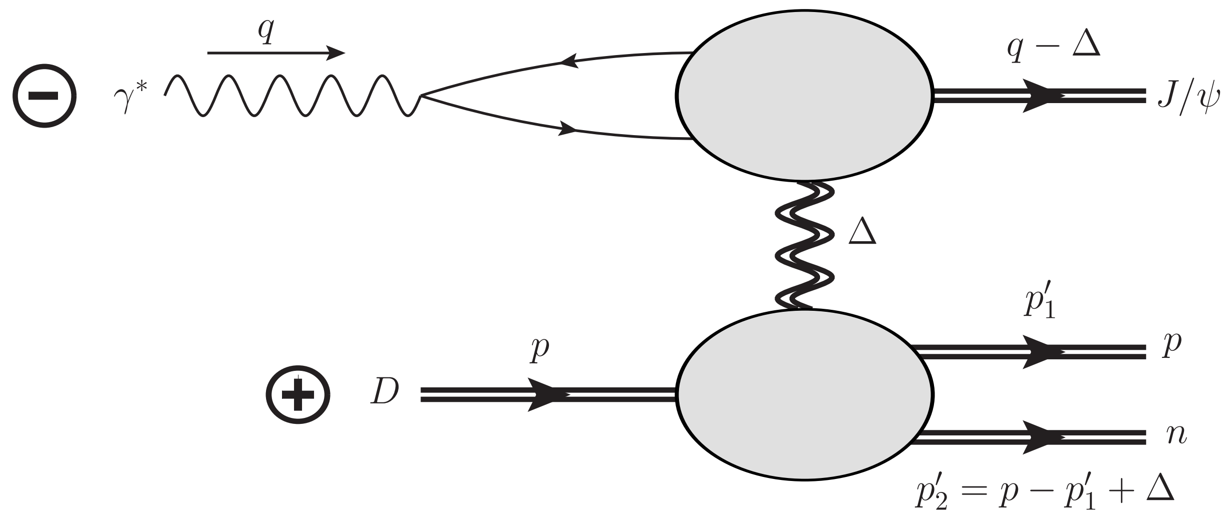
➡ But: Experimental upper bound of 1%!



Do hidden color states exist?
How can we learn about them?



- Our proposal: A different way to access high-energy NN scattering at an EIC.



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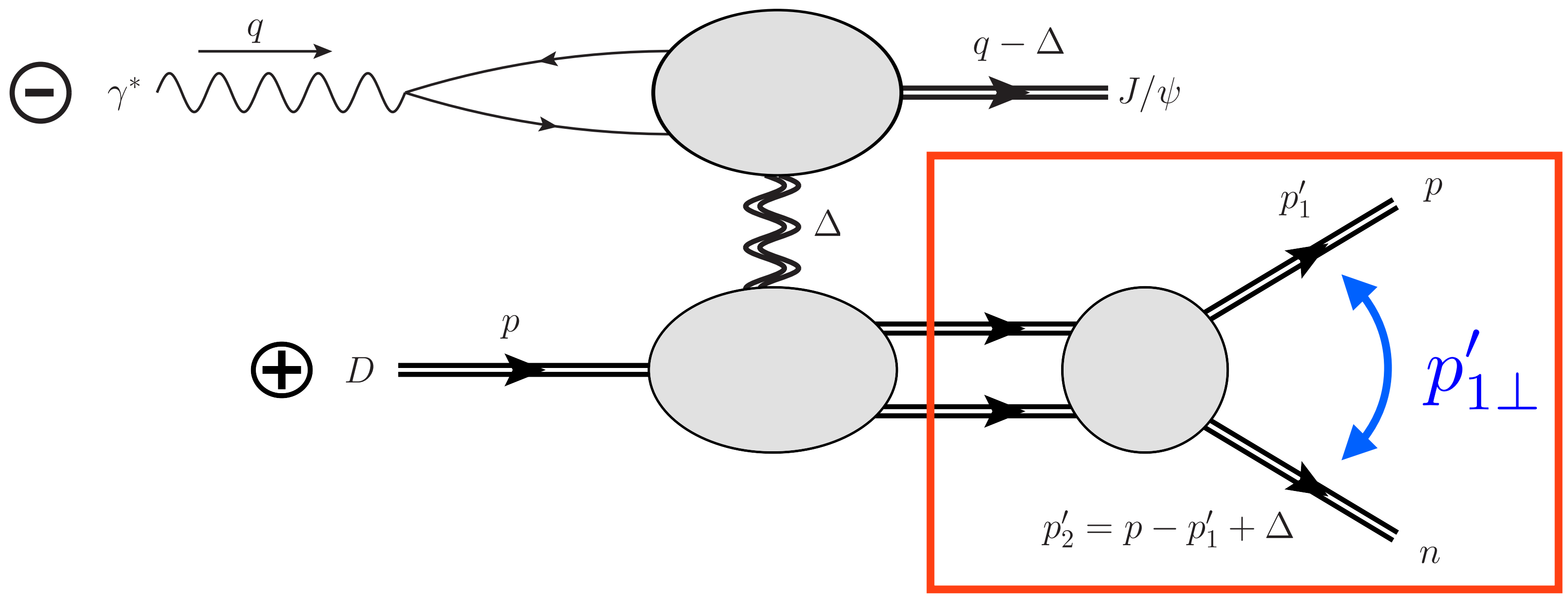
➡ Hard exclusive meson production off a deuteron target at small x

➡ Deuteron disintegrates into a proton / neutron pair



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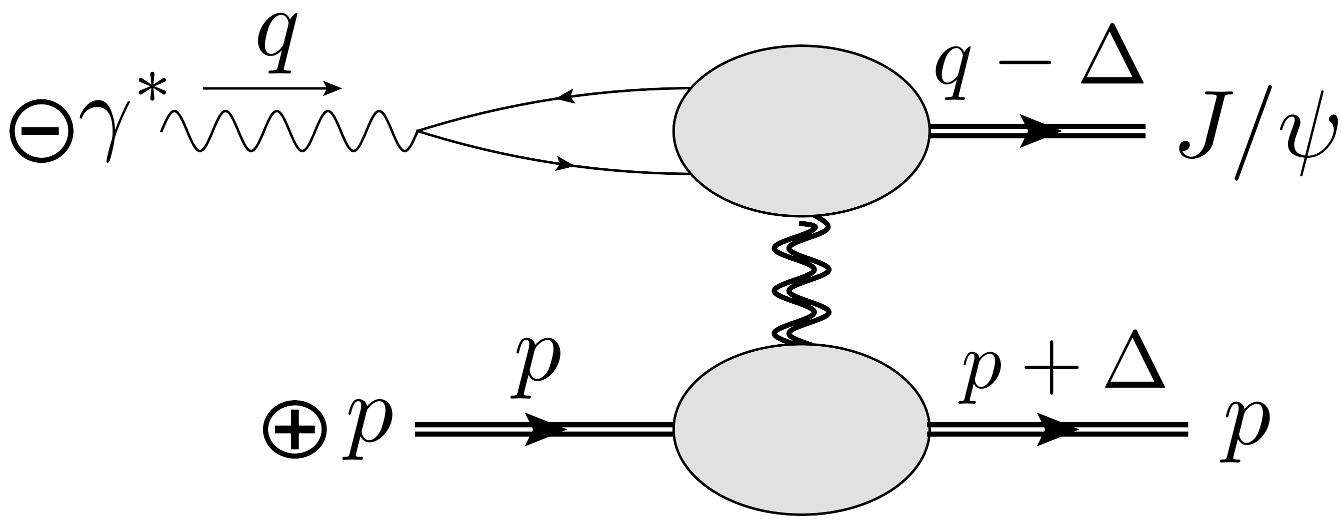
Key Concept: At high NN transverse momentum, can factorize a short-distance NN rescattering

2. Hard Exclusive Meson Production with Hard Deuteron Breakup

Hard Exclusive Meson Production on the Proton



$$s = W^2 = (p+q)^2$$

$$x_{eff} = \frac{Q^2 + M_J^2}{s} \ll 1$$

$$T \equiv \Delta^2 \approx -\Delta_T^2$$

- Exclusive vector meson production in DIS at small x:

➡ Virtual photon dissociates into a vector meson (ie, J/ψ)

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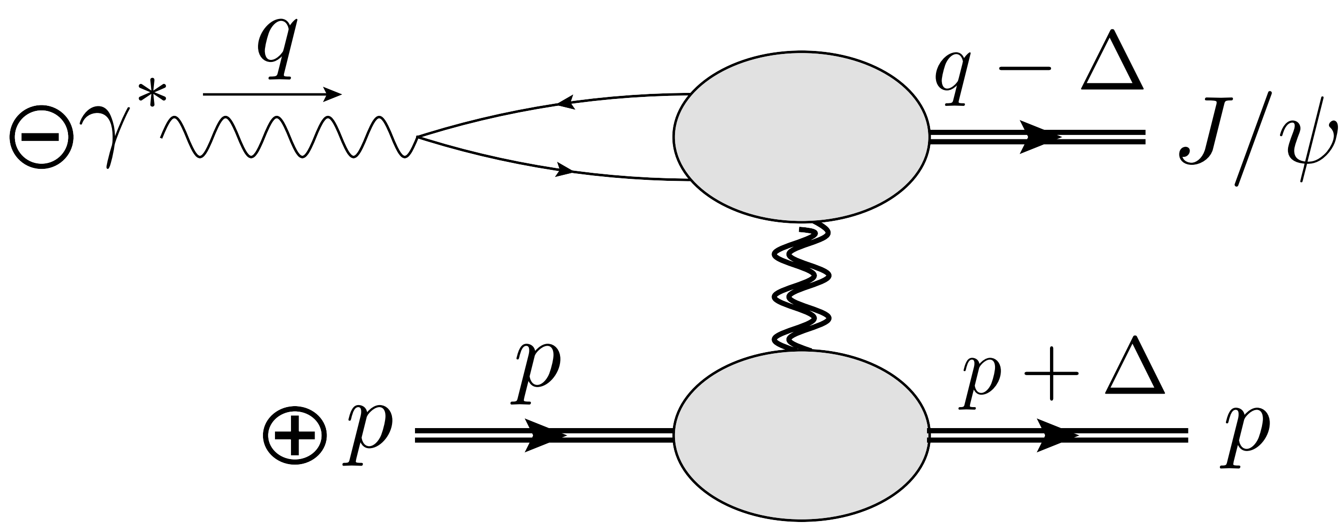

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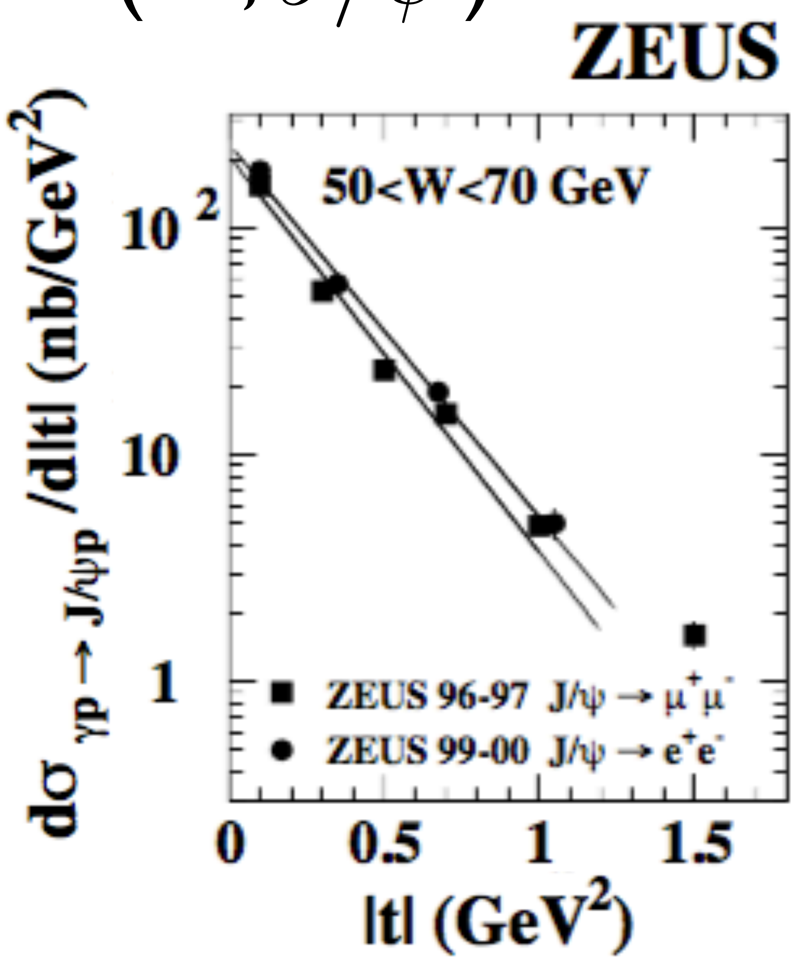
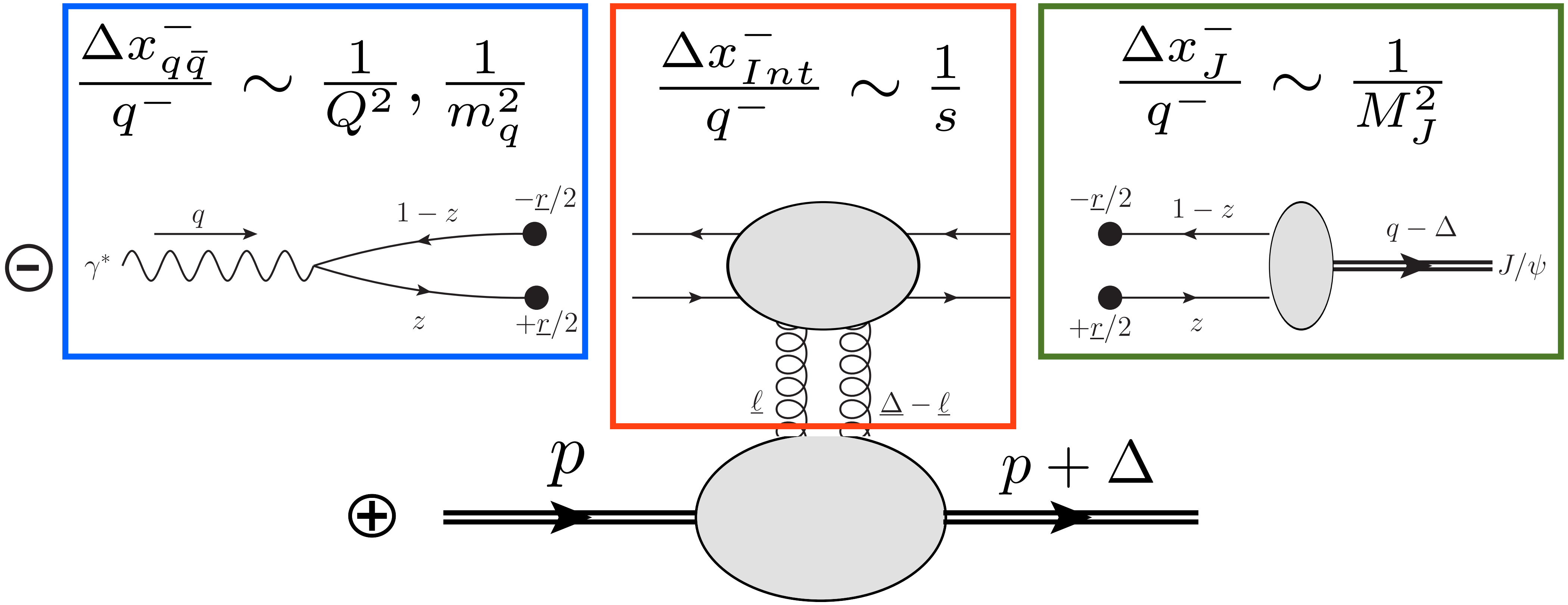
- Measured with high statistics at HERA
  - ➡ J/ψ decays to electrons, muons
  - ➡ Exponential falloff with T: $\frac{d\sigma}{d|T|} \propto e^{-b|T|}$
  - ➡ Muon dataset contains $38\ pb^{-1}$ of data



HEMP: Measuring the Gluon Field



- Separation of time scales: $\Delta x^-_{Int} \ll \Delta x^-_{q\bar{q}} \; , \; \Delta x^-_{J}$

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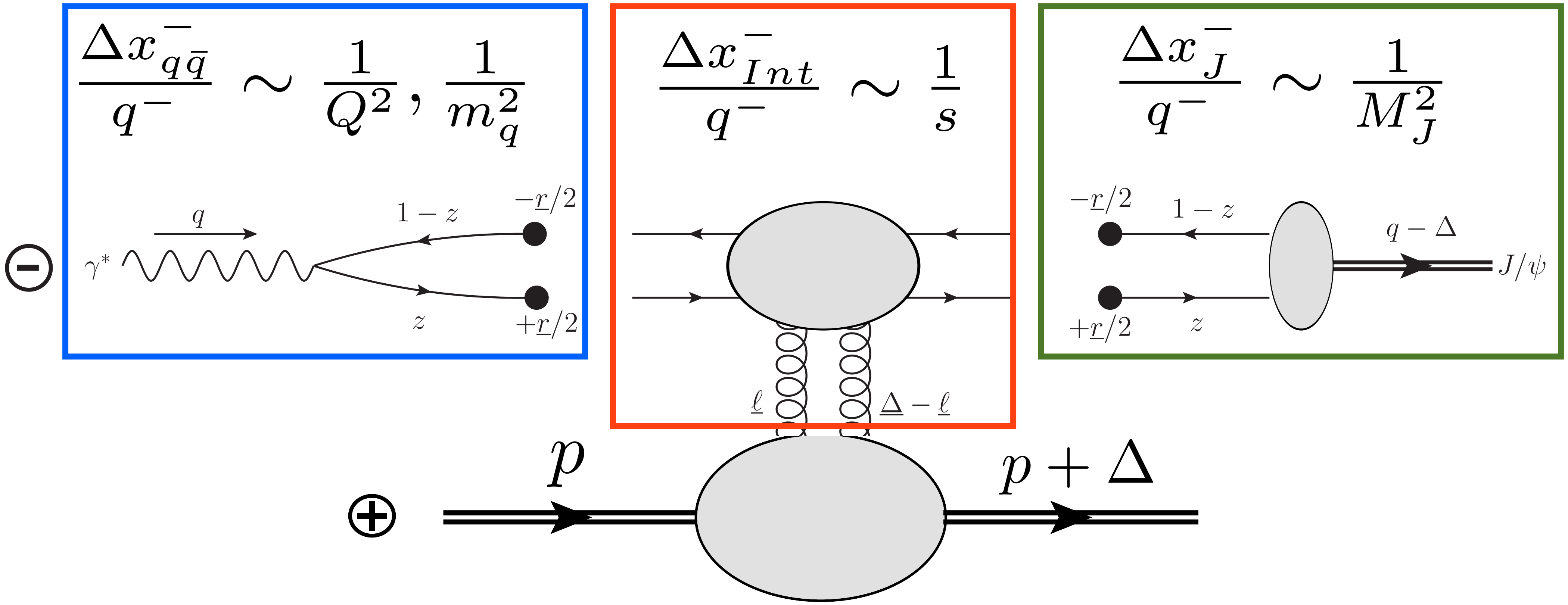

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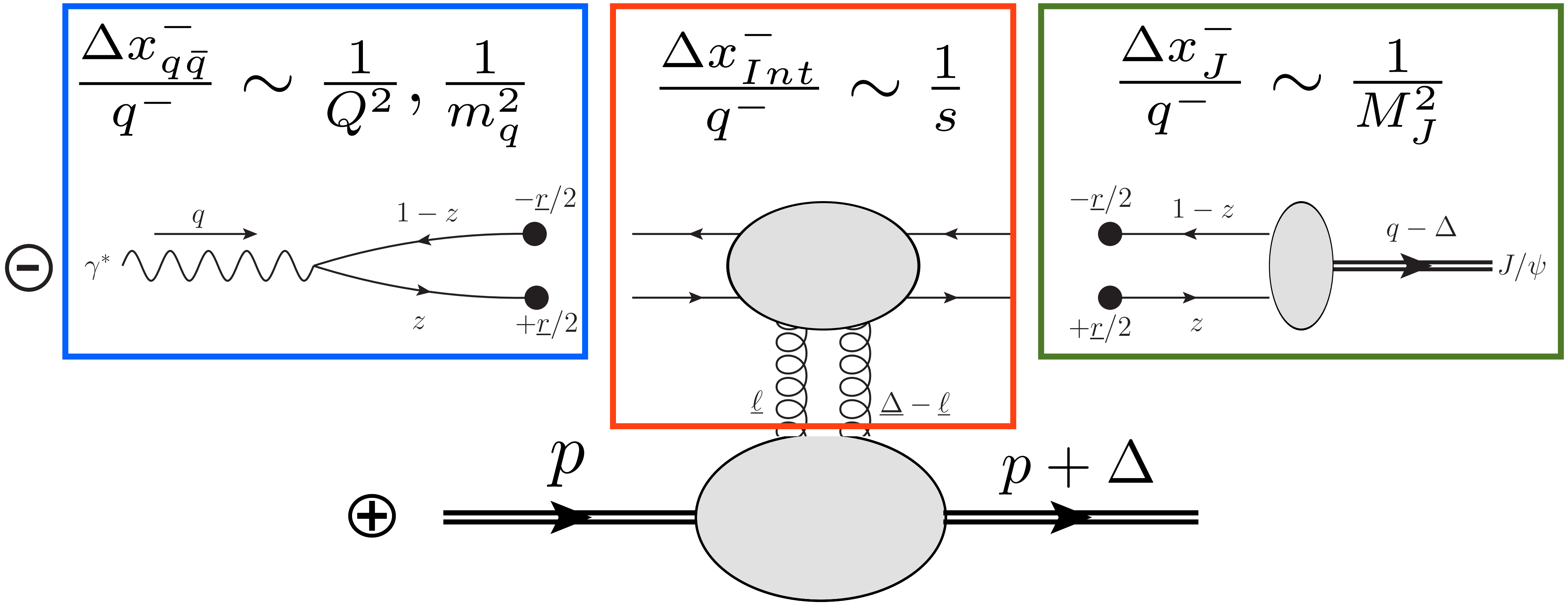

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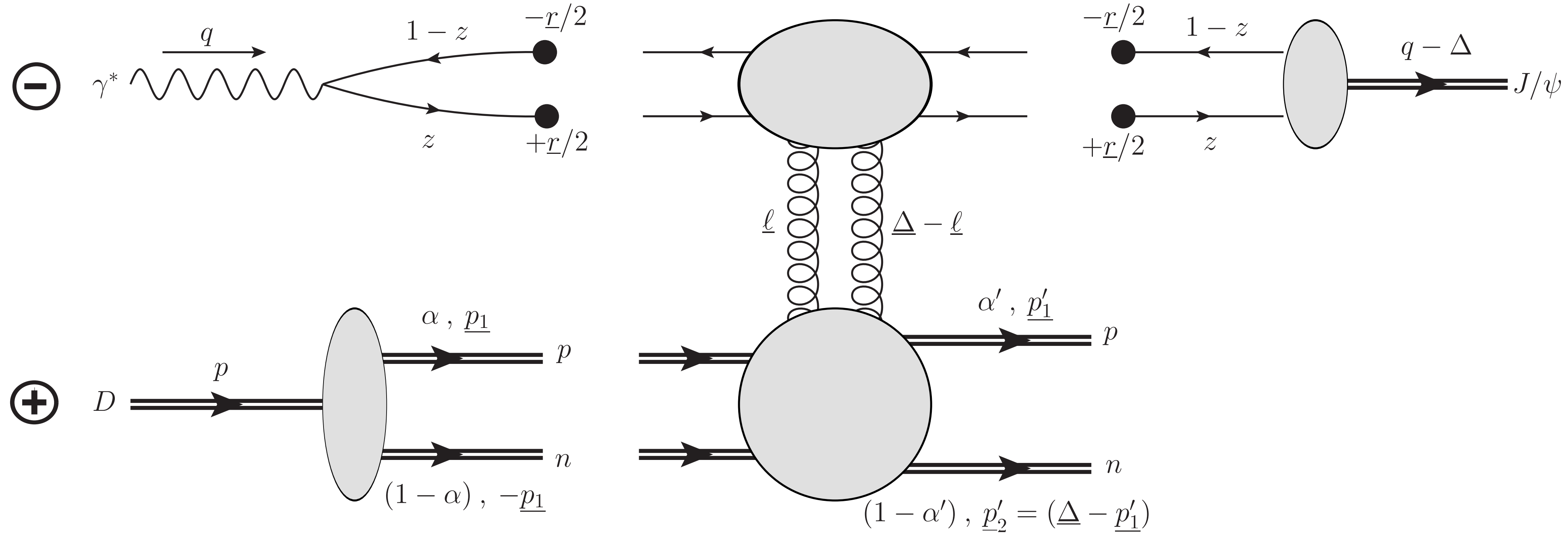
- Small dipole measures instantaneous snapshot of gluon field:

$$H^g(x,\xi,T) = \int \frac{dr^-}{2\pi p^+} e^{ixp^+r^-} \left\langle p + \tfrac{1}{2}\Delta \right| F^{+ia}(-\tfrac{1}{2}r) F^{+ia}(+\tfrac{1}{2}r) \left| p - \tfrac{1}{2}\Delta \right\rangle$$

$(A^+ = 0$ gauge)

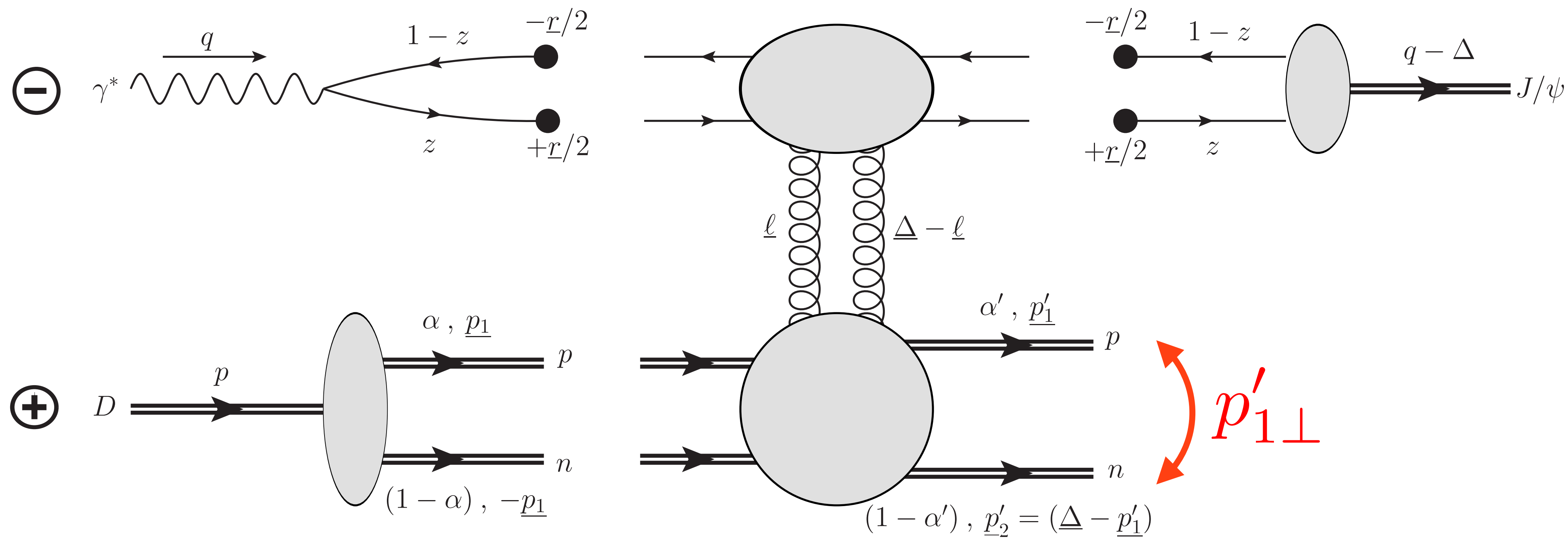
HEMP on the Deuteron



- Deuteron target: same formalism, but composite system.

➡ Loosely bound deuteron: predominantly NN wave function

➡ Gluon exchange essentially occurs on an NN target.



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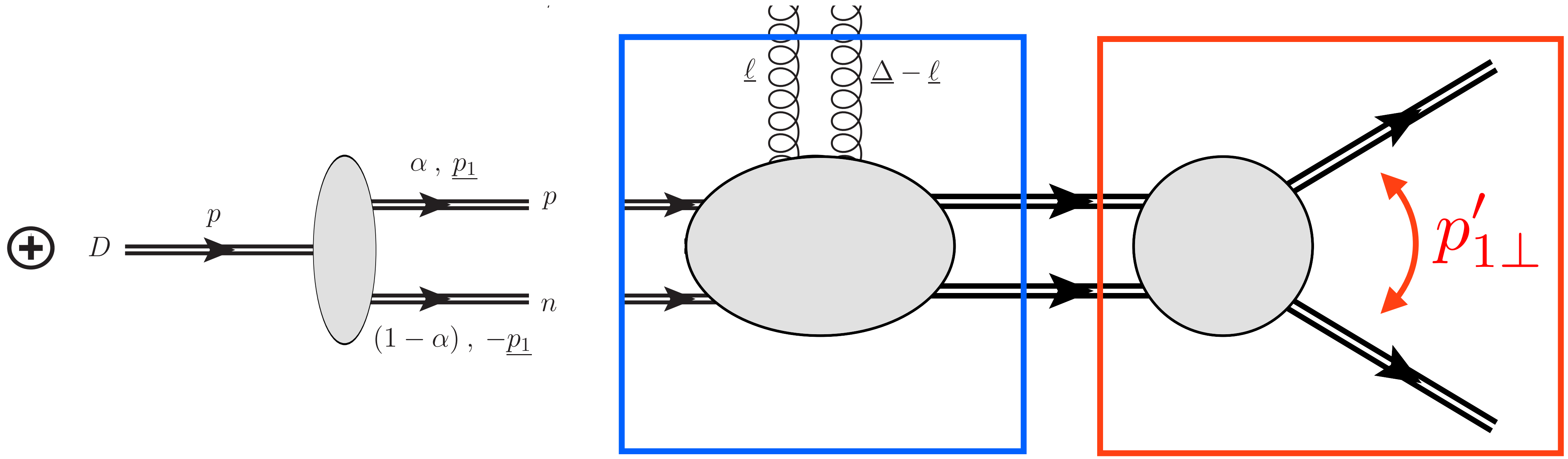
- Deuteron can dissociate into a p n final state

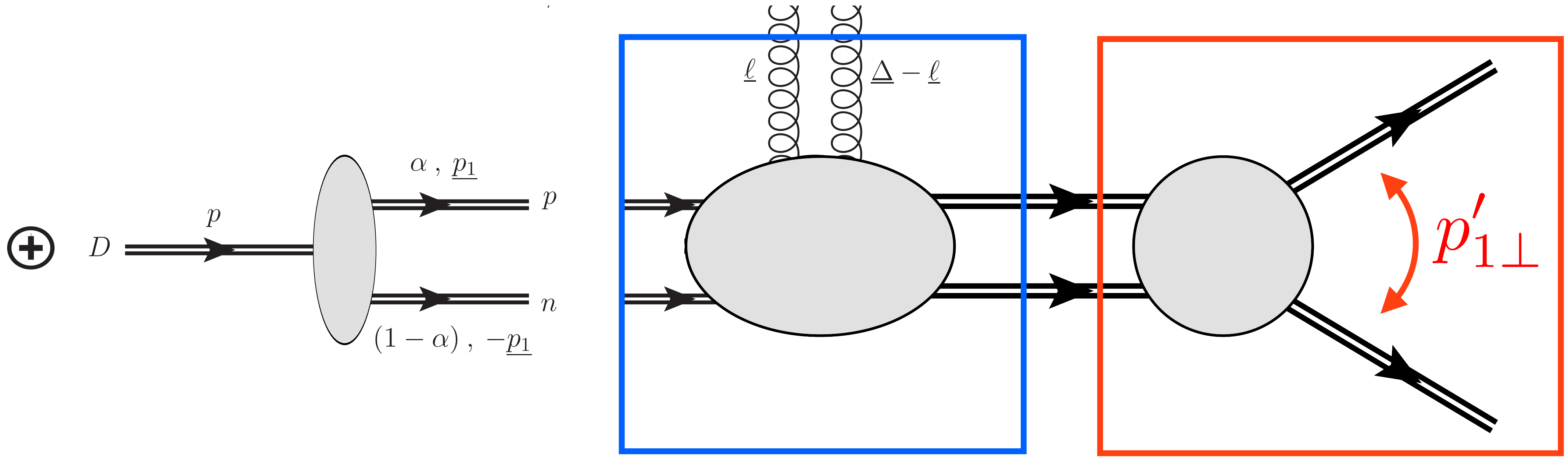
➡ Transition GPD: $\hat{H}^g_{(D)} = \int \frac{dr^-}{2\pi p^+} e^{ixp^+r^-} \langle p\, n\, (p'_{1\perp}) | F^{+ia}(-\tfrac{1}{2}r) F^{+ia}(+\tfrac{1}{2}r) | D \rangle$

➡ New internal momentum scale: $t \equiv (p'_1 - p)^2 \approx -2p'^2_{1T}$



$$\langle N'\ N'|F^{+ia}F^{+ia}|N\ N\rangle \otimes \langle p\, n\,(p'_{1\perp})|\ V\ |N'\ N'\rangle$$

- When $p'_{1\perp}$ becomes a hard scale, it should lead to a factorization of the T-GPD itself!



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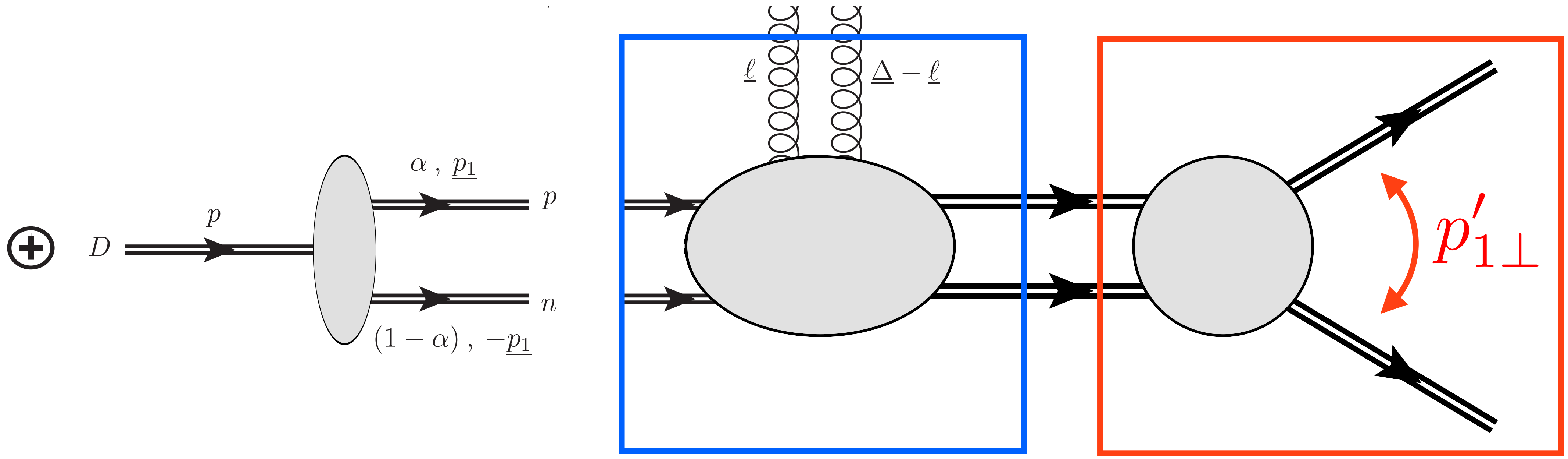
$$s_{NN} \approx 4 p'^2_{1T}$$

$$s \gg s_{NN} \gg \Lambda^2_{QCD}$$



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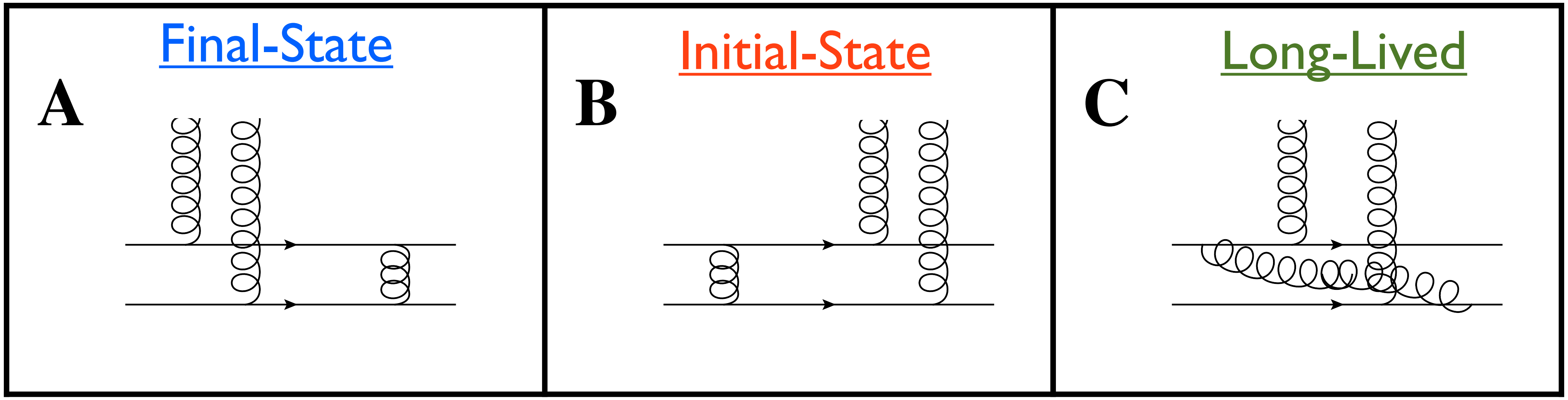
- How would such a factorization work?
- What are the signatures of possible NN scattering mechanisms?

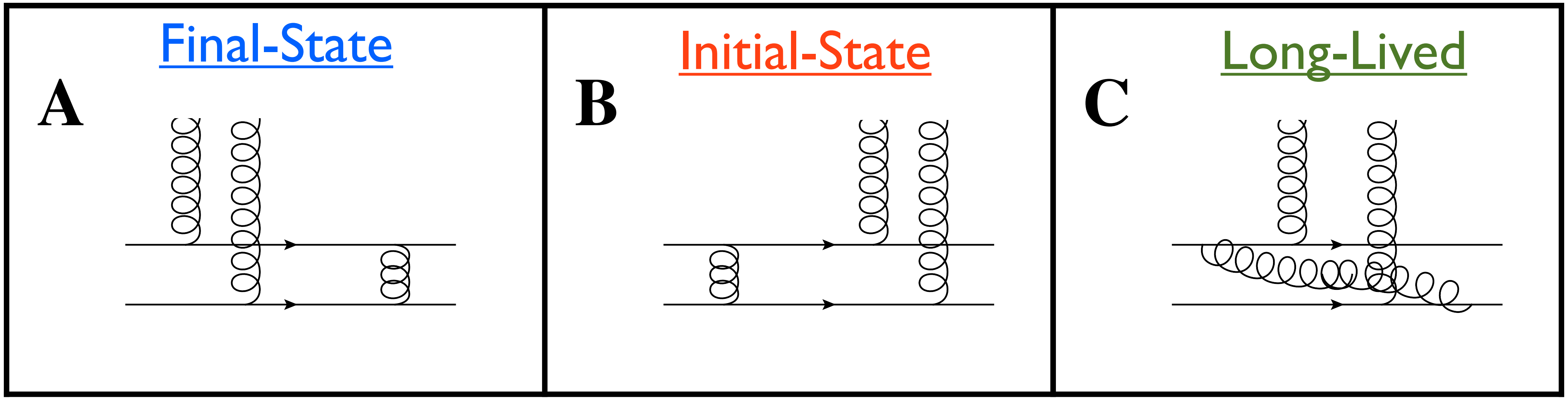
3. Calculations for the Quark Target Model

A First Approach: The Quark Target Model



- Quark Target Model: Treat the nucleons as single quarks in pQCD.

A First Approach: The Quark Target Model



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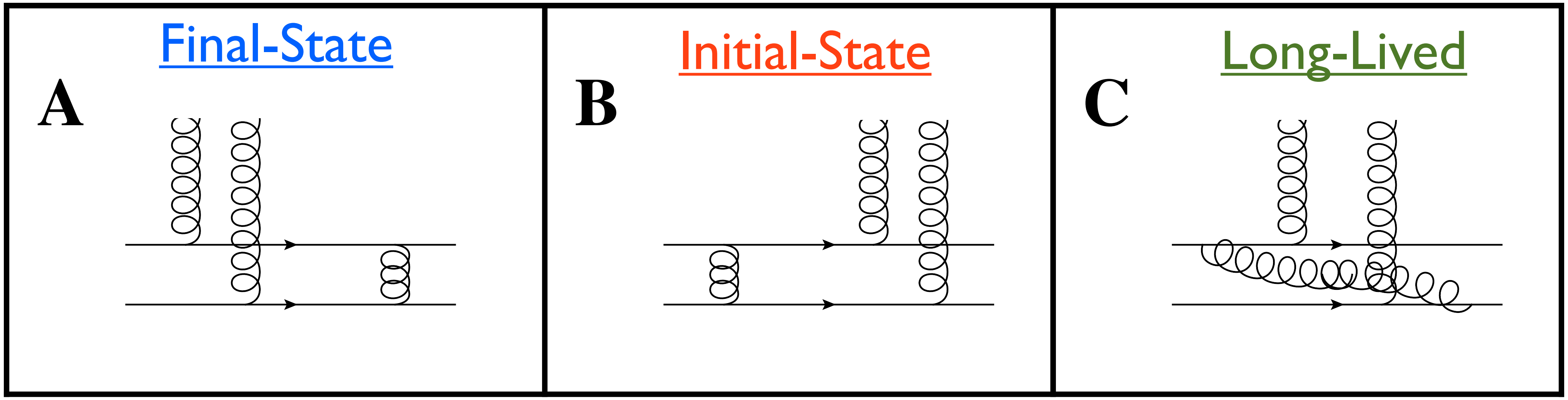

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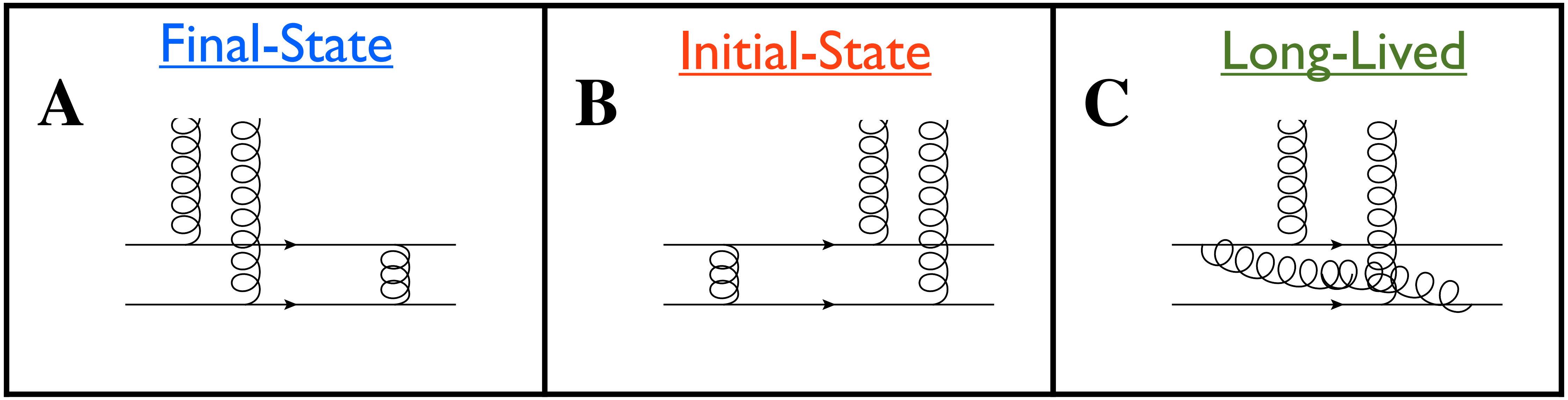

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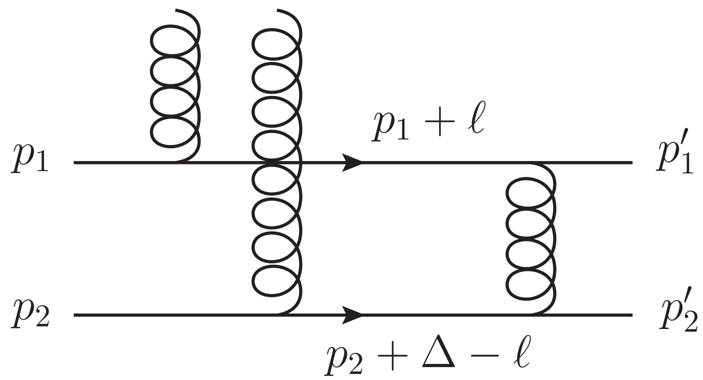
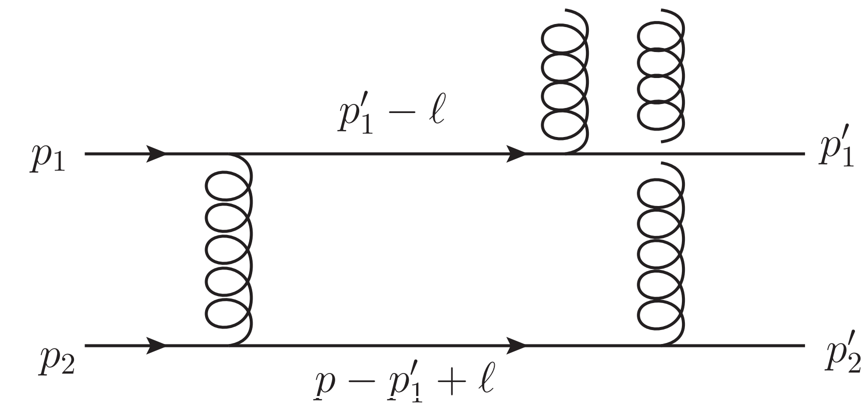
- 3 distinct topologies: FSI, ISI, and long-lived fluctuations.

Structure of the Quark Target Calculation

Final-State



Initial-State



Numerator Structure	$[\bar{U}_{\sigma'_p}(p'_1)\gamma_\perp^i \gamma^- \gamma^+ U_{\sigma_p}(p_1)]$ $[\bar{U}_{\sigma'_n}(p'_2)\gamma_\perp^i \gamma^- \gamma^+ U_{\sigma_p}(p_2)]$ $\sim p'^2_{1T}\, \delta_{\sigma_p, -\sigma_n}$ ➡ $(S_D)_z = 0$	
Pole Structure		

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	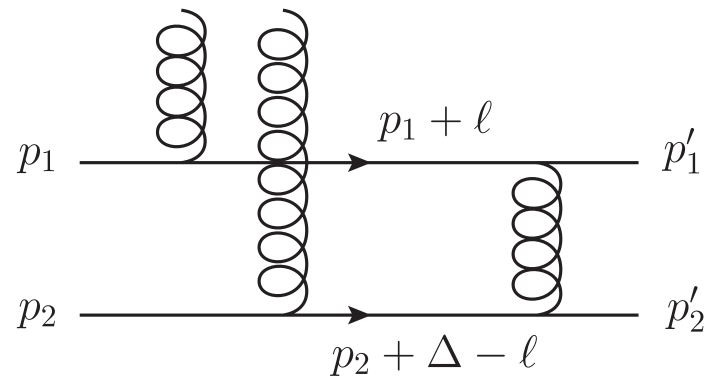	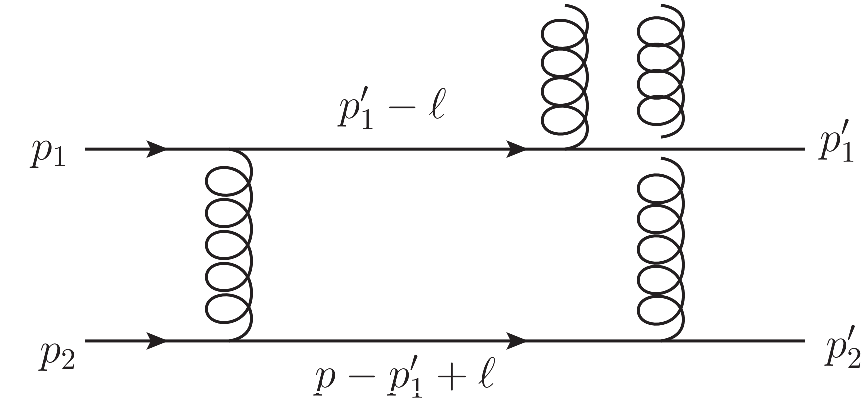
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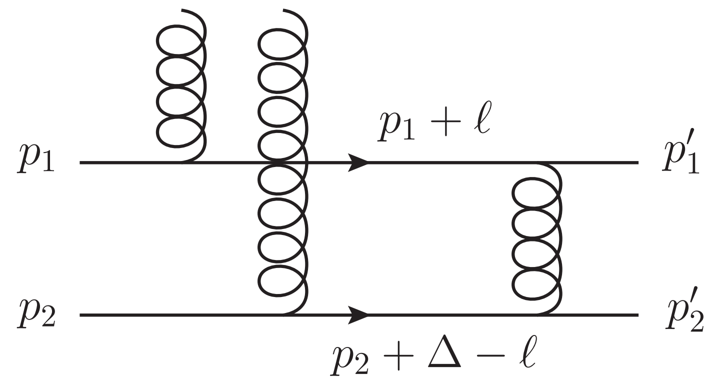	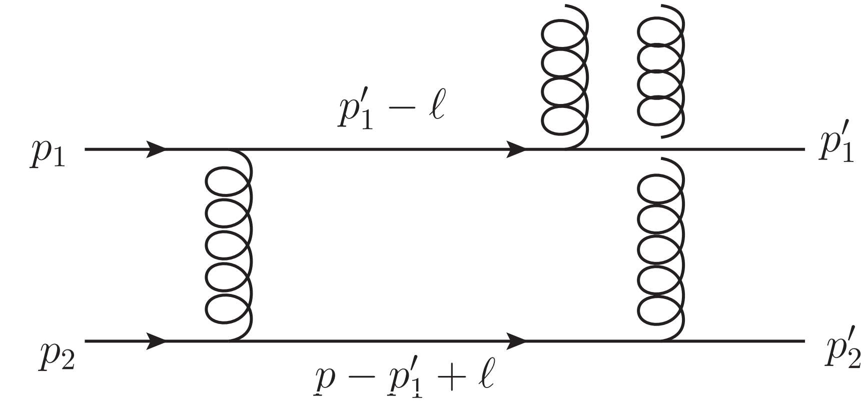

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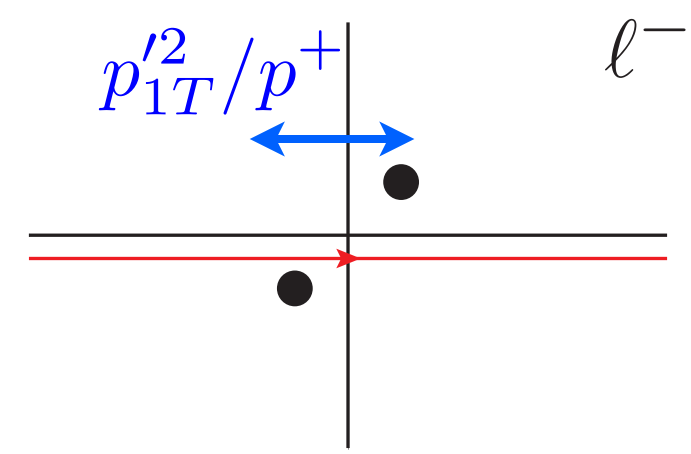
Pole Structure		

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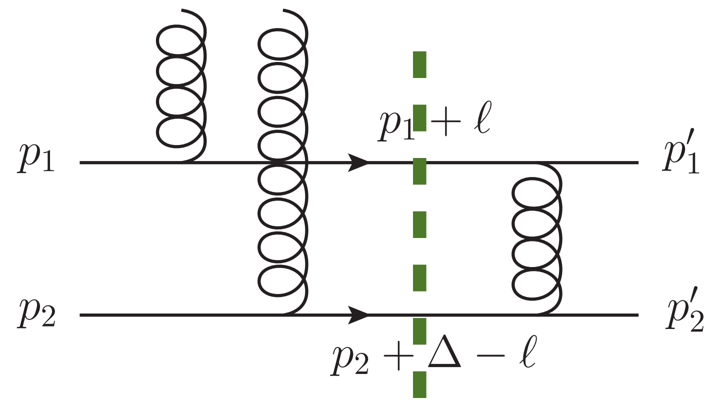

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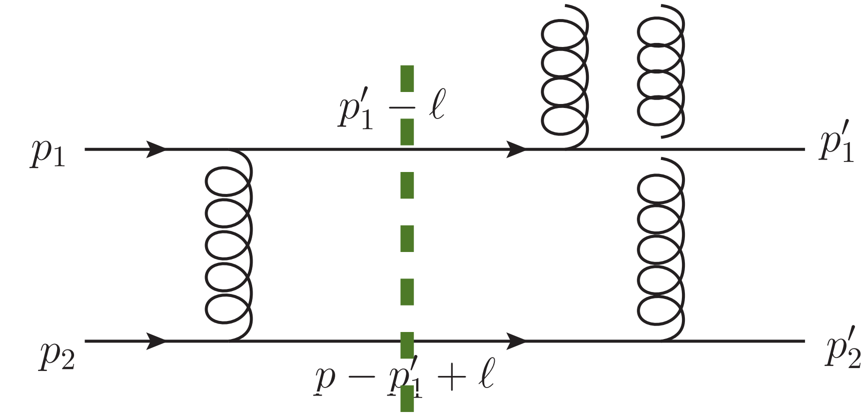

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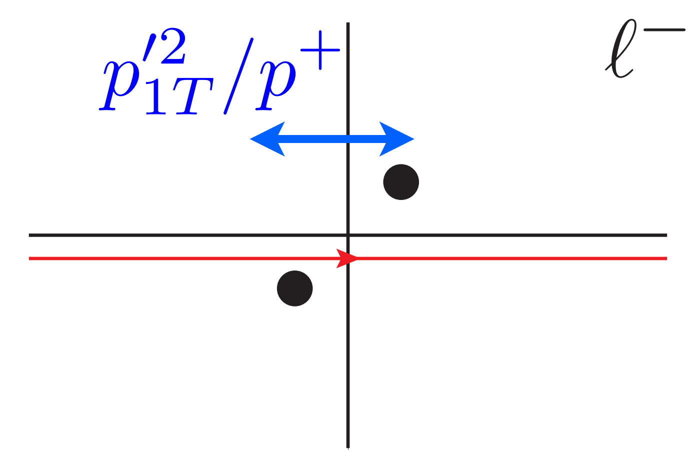
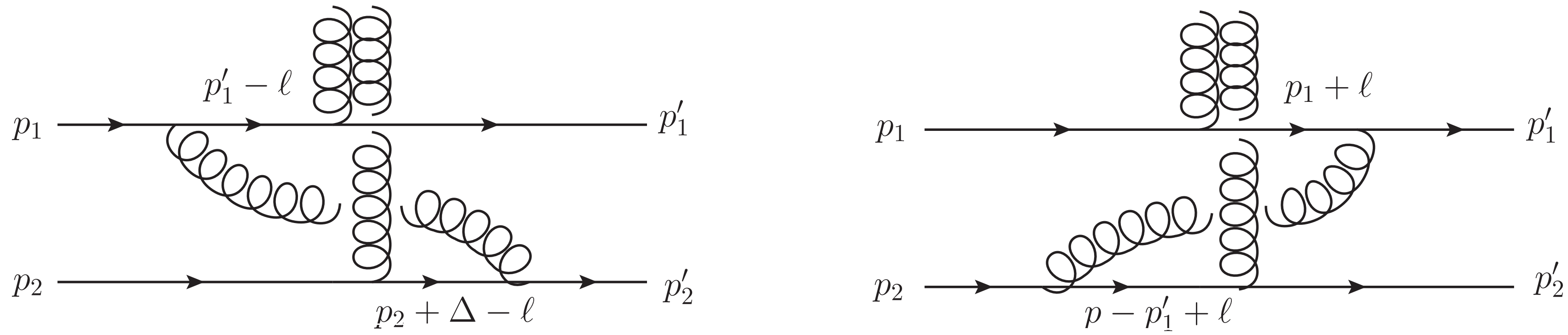
Pole Structure	➡ Virtuality $\sim p_{1T}'^2$ ➡ Lifetime $\sim 1/p_{1T}'$ ➡ Equivalent to light-front energy denominator	

"Long-Lived" Fluctuations



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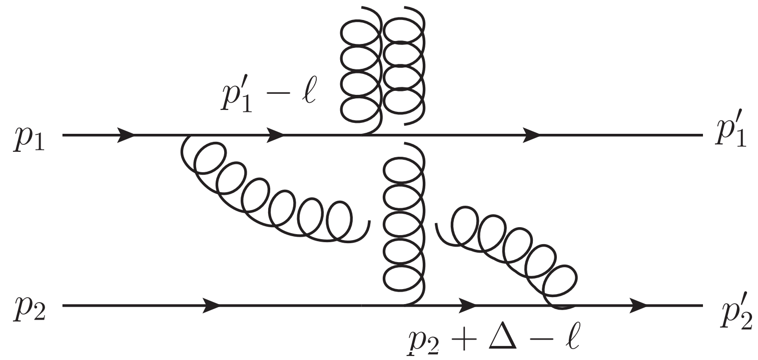
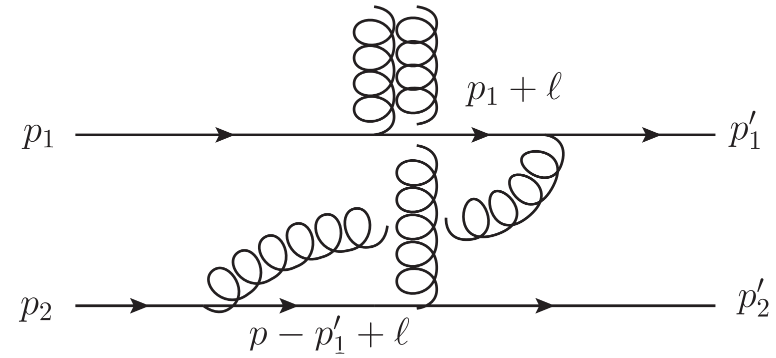
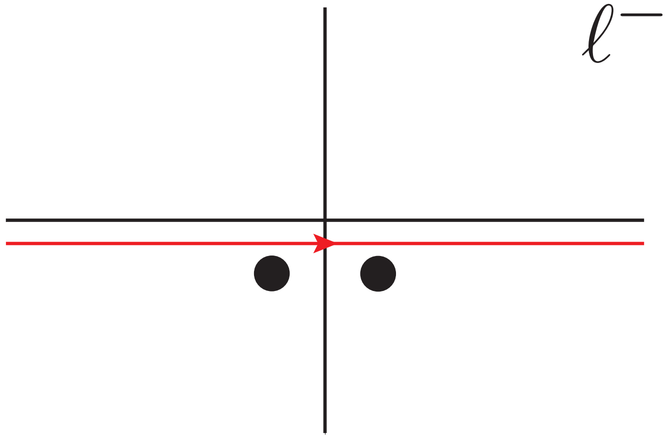
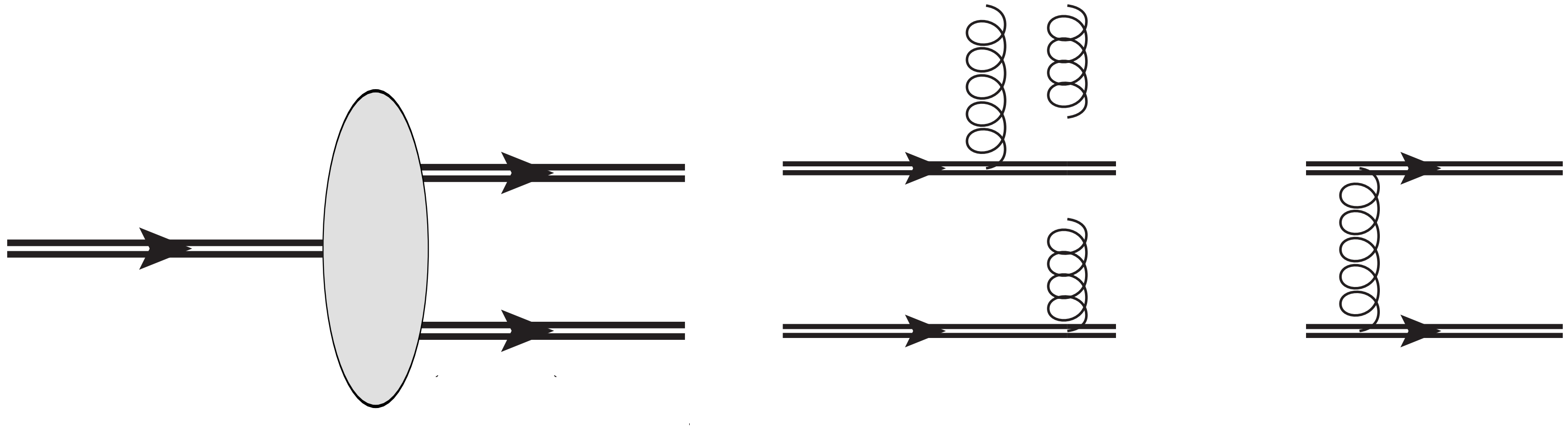


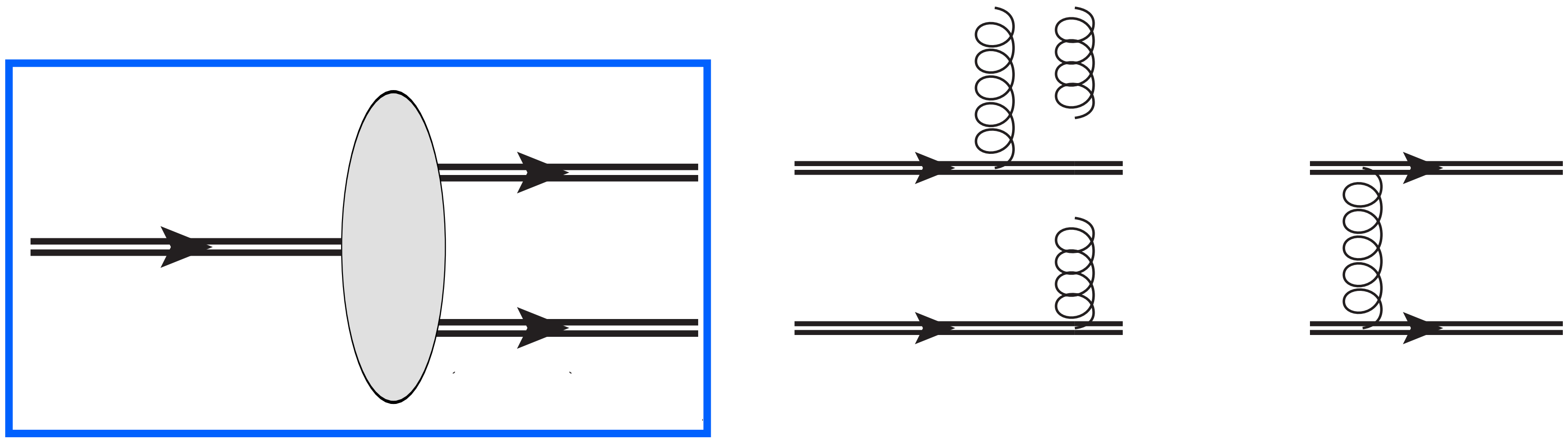


Color Structure	➡ Potentially dangerous "factorization breaking" terms. ➡ No analog (at this order) of "Meson Exchange Current" due to color structure.
Pole Structure	➡ Pinch is broken (same side of real axis) ➡ Interaction is zero in eikonal approximation 

Lessons of the Quark Target Model



$$\hat{H}^g_{(D)} \approx \psi_D(r_\perp = 0, x = \tfrac{1}{2}, S_z = 0)\, 2\frac{\alpha_s}{N_c} H^g_{(N)}\, \frac{1}{p'^2_{1T}}$$



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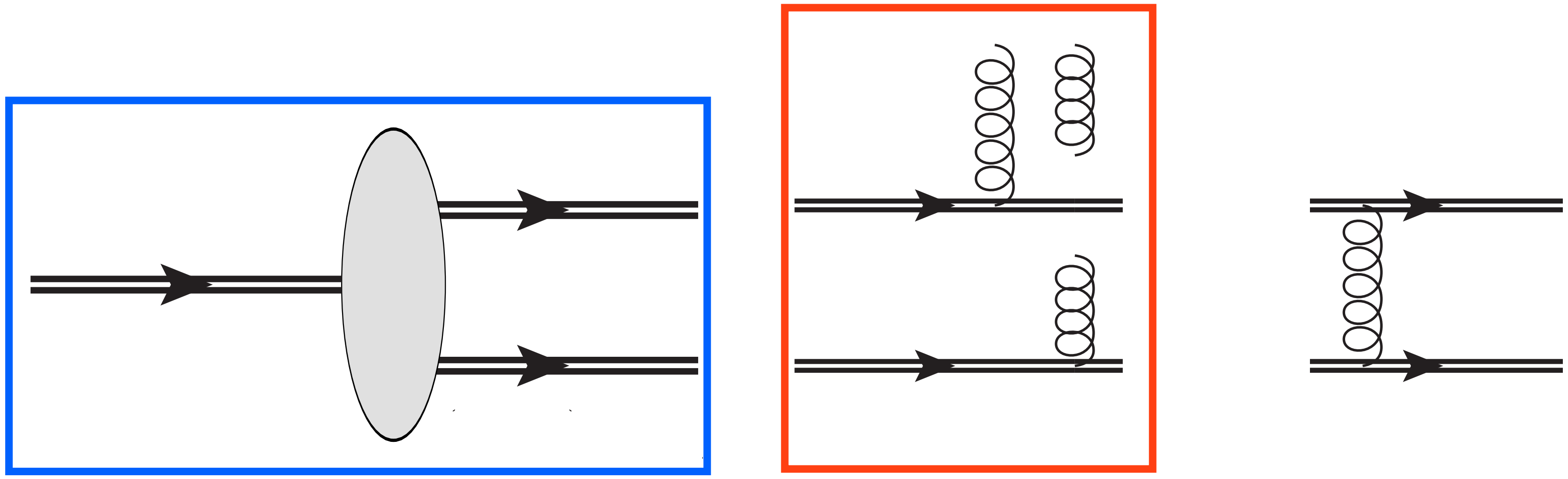

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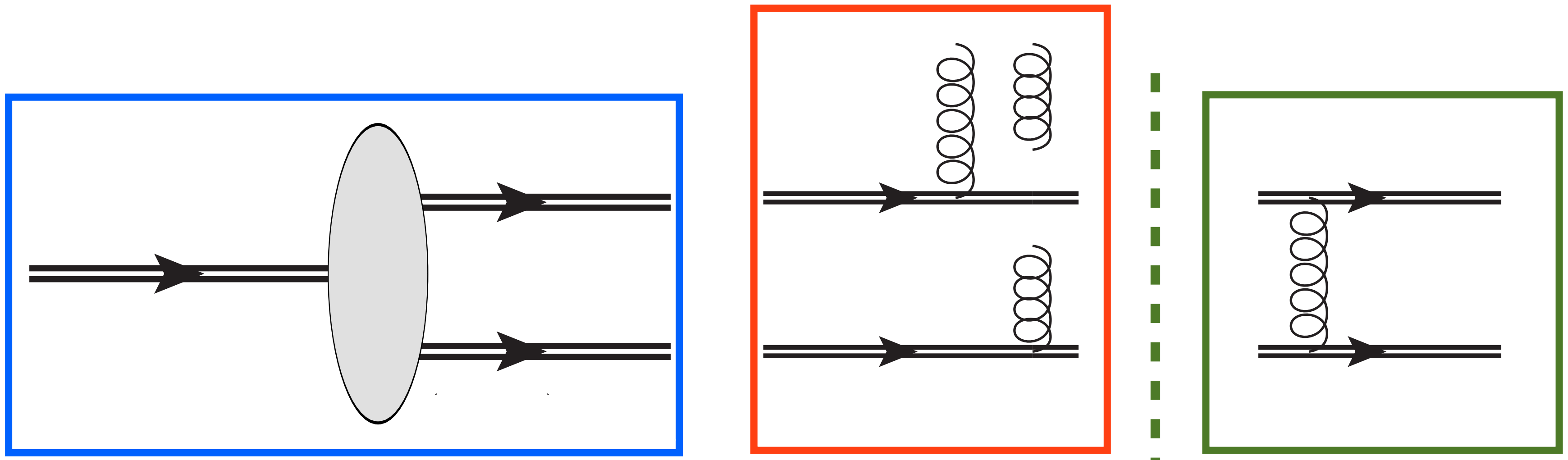

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- High transverse momentum couples to short transverse distances.
- Diffraction occurs on the NN system (model dependent).
- Robust pole structure: expect dominance of final-state rescattering.

➡ FSI are pinched: intermediate state energy denominator $\sim 1/p'_{1T}$

➡ ISI are suppressed: high-momentum tail of deuteron WF

➡ LLF are un-pinched: highly virtual, energy suppressed

Taking the Quark Target Model Seriously

$$\frac{d\sigma^{\gamma D \to V N N}}{dT\, dt\, dy} = \left[\frac{1}{12\pi} \frac{\alpha_s^2}{N_c^2} \frac{1}{p_{1T}'^4} \left| \psi_D(0_\perp, \tfrac{1}{2}) \right|^2 \right] \times \frac{d\sigma^{\gamma N \to V N}}{dT}$$

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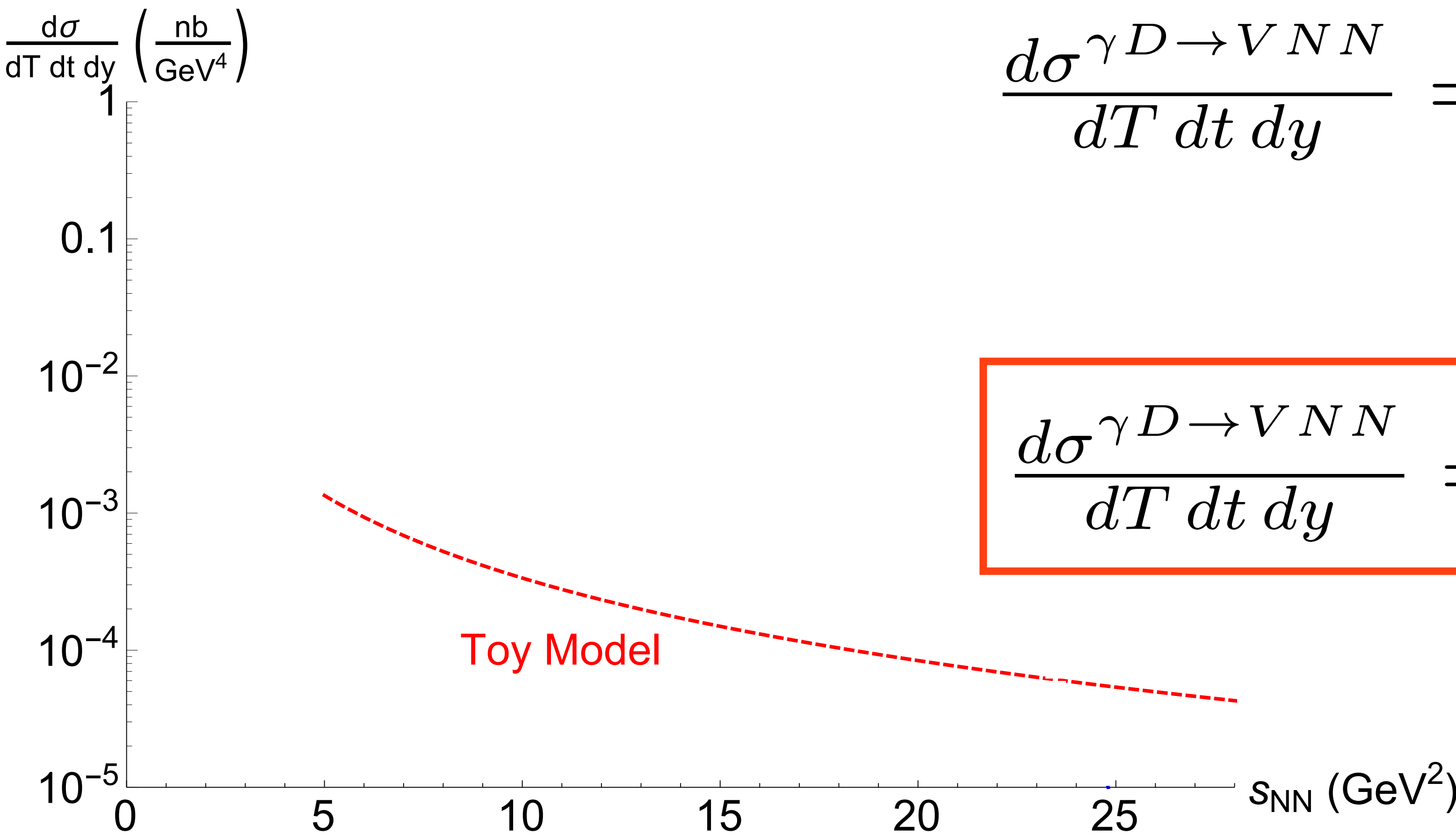

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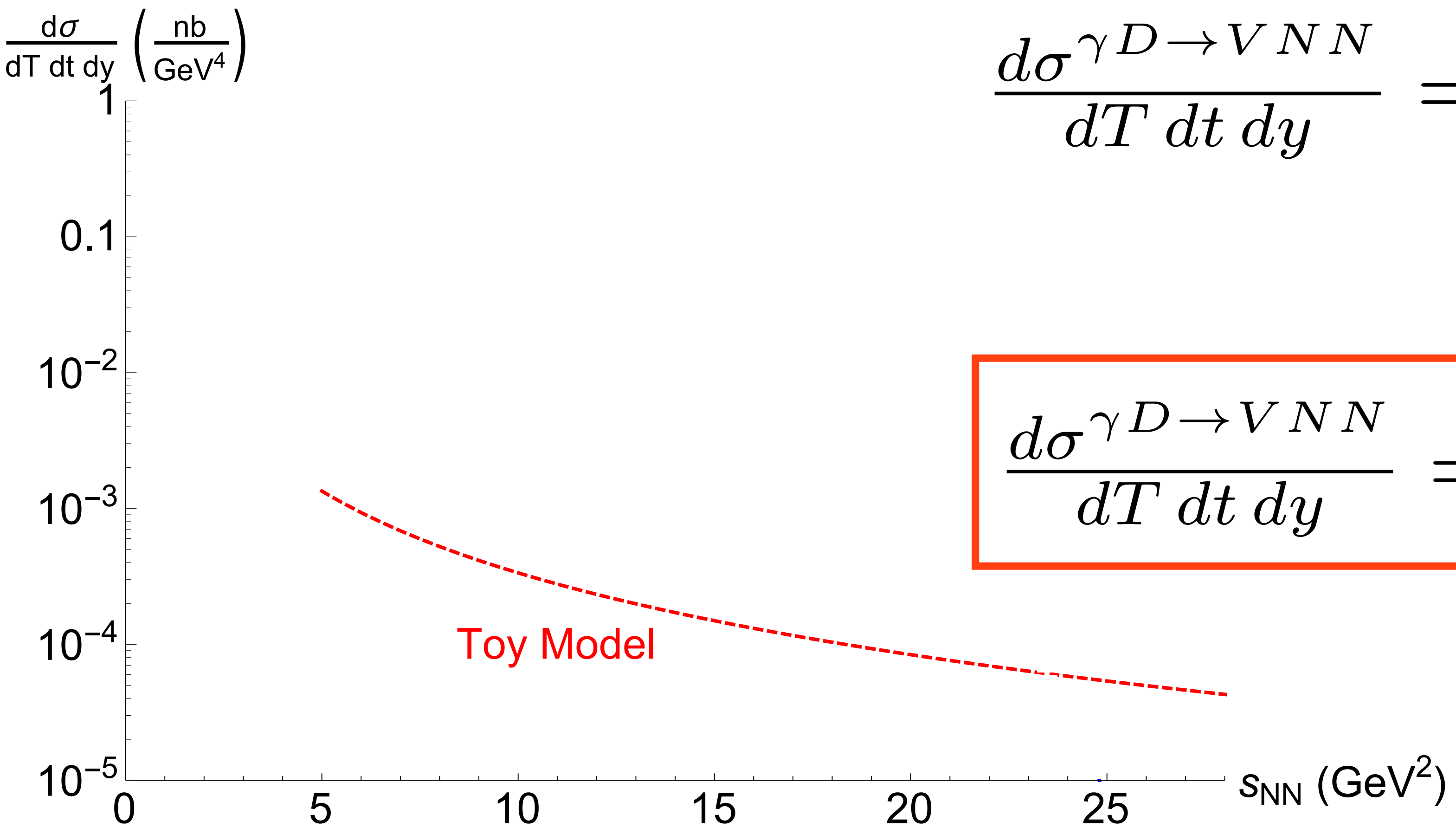

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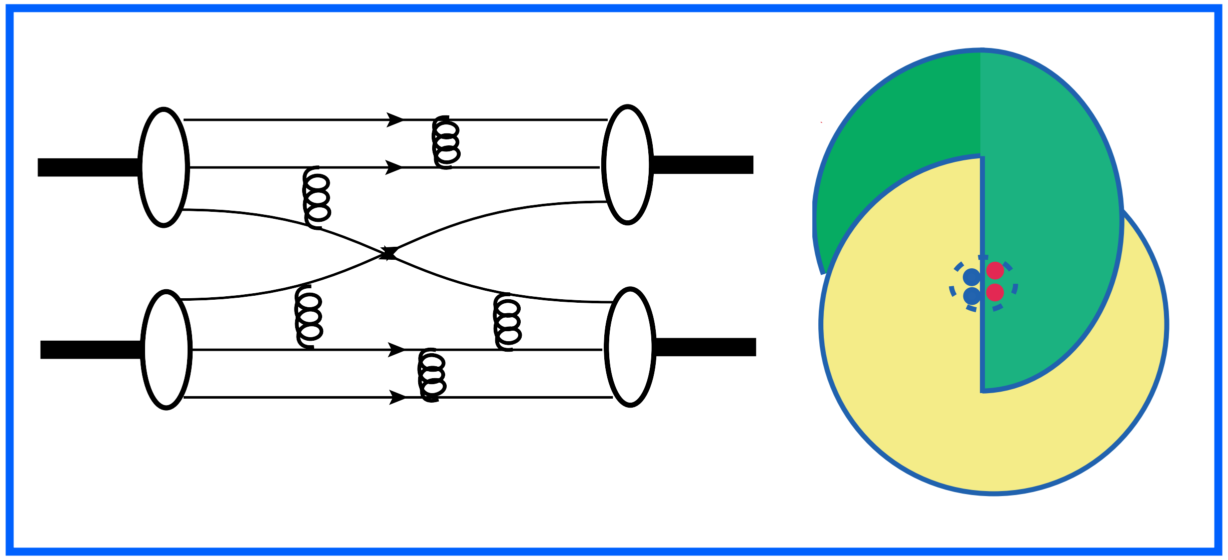
- pQCD rescattering: small magnitude, but slow falloff.
- Difficult, but within the reach of an EIC.

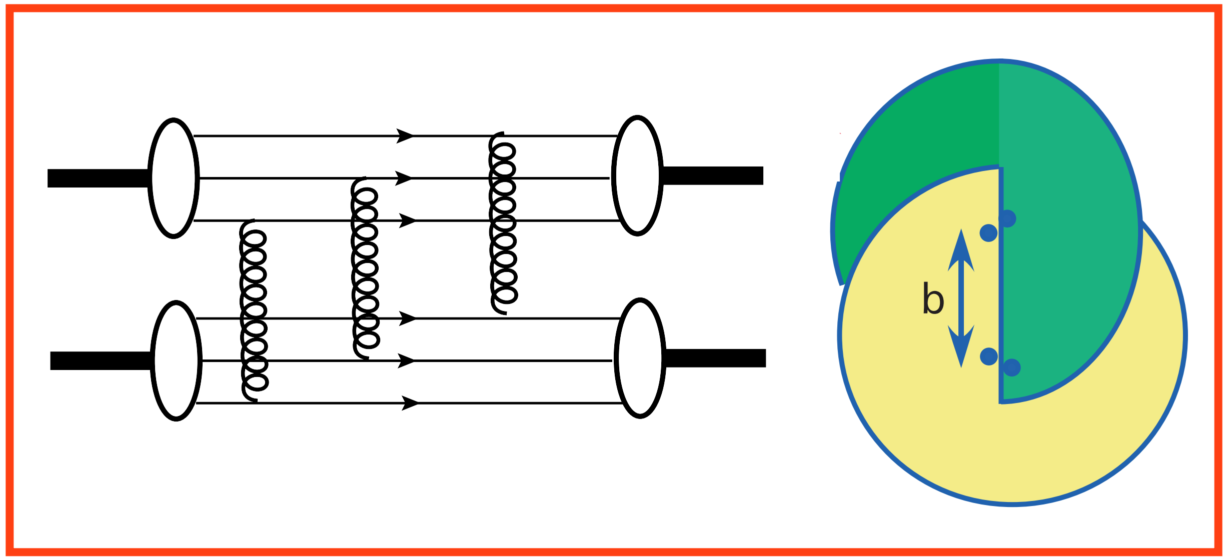
4. Realistic Nucleons at an EIC

Considerations for (More) Realistic Nucleons

Brodsky-Farrar



Landshoff



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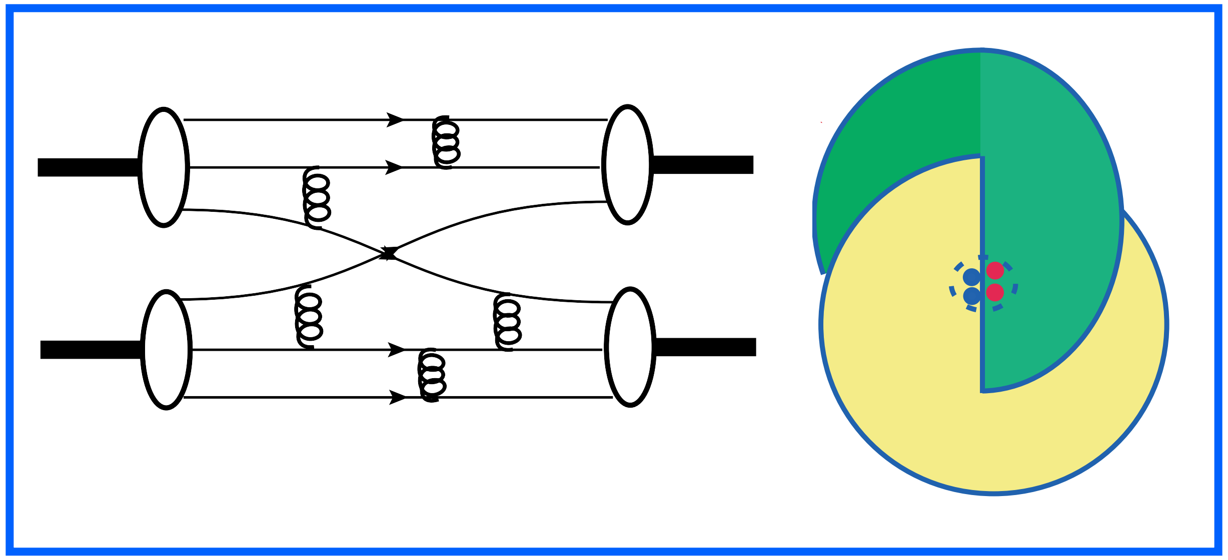

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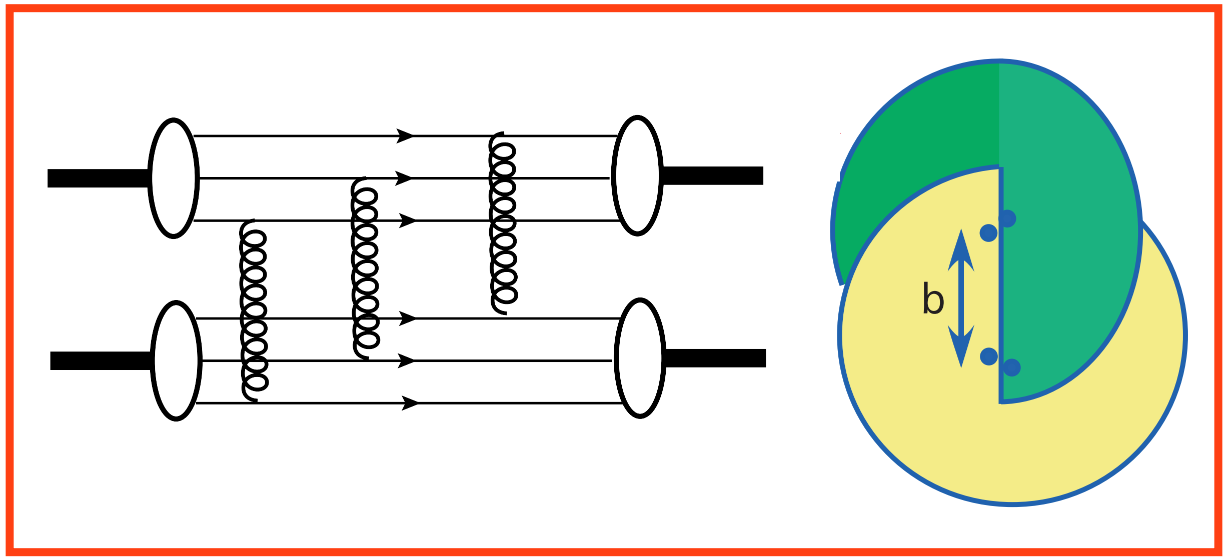

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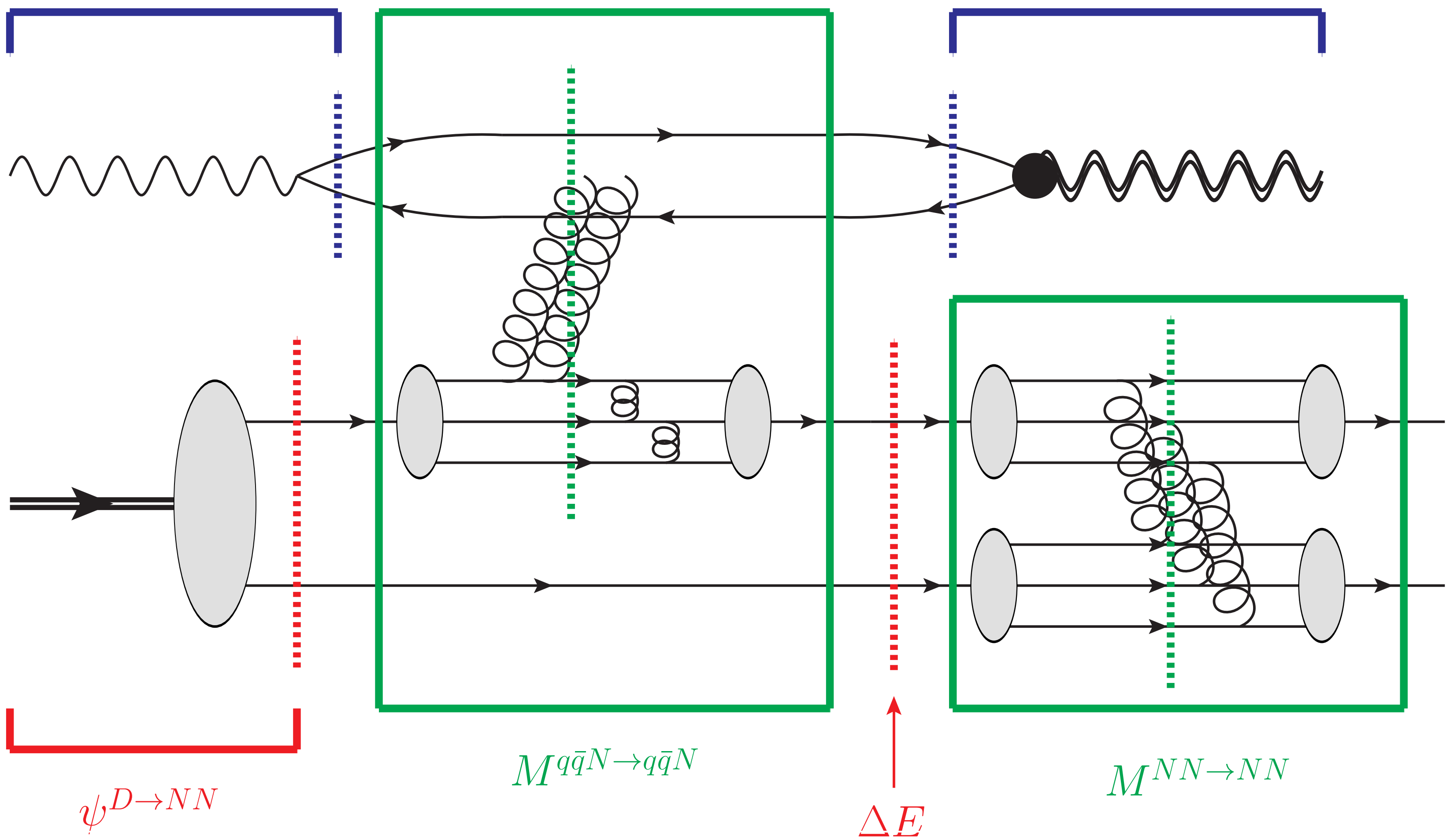
- General lessons of the Quark Target Model dictate the structure of the amplitude for nucleons.



$$\frac{d\sigma^{\gamma D \to V N N}}{dT\, dt\, dy} \propto \left|\psi_D(0_\perp, \tfrac{1}{2})\right|^2 \left|M^{\gamma N \to V N}\right|^2 \frac{1}{(p^+ \Delta E^-)^2} \left|M^{NN \to NN}\right|^2$$

- For color-singlet FSI, diffraction proceeds on one nucleon with the other nucleon a spectator.

➡ NN rescattering mechanism determines p'^2_{1T} dependence.

Typical Rates for (More) Realistic Nuclei

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J. Stone et al., Nucl. Phys. **B143**, 1 (1978)

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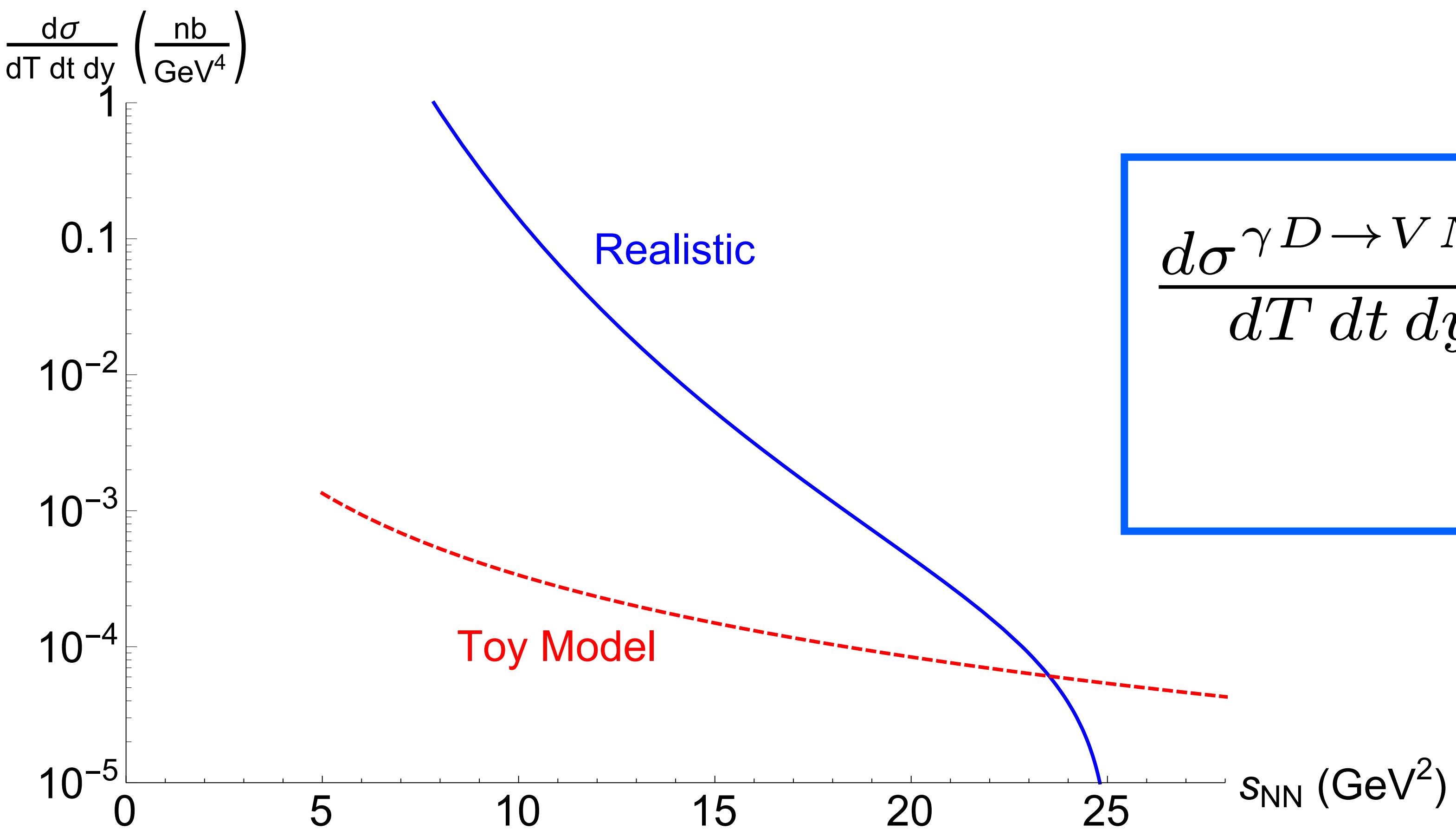

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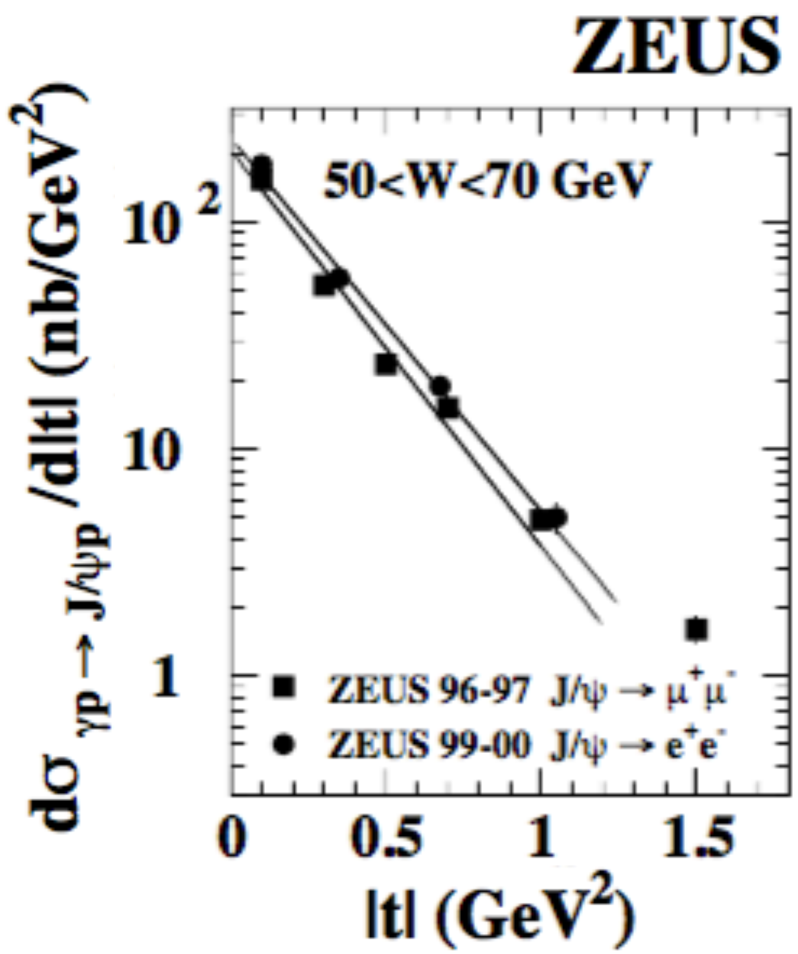
- NN rescattering: larger magnitude, but steeper falloff

Is It Measurable at an EIC?



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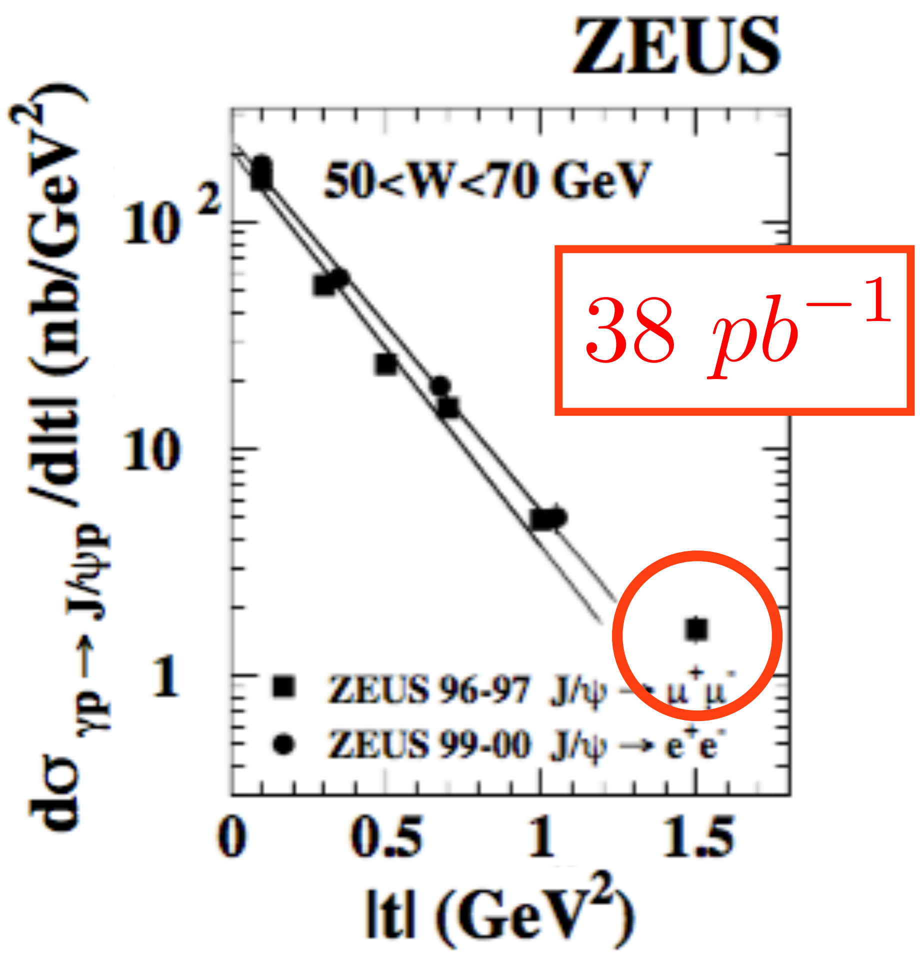

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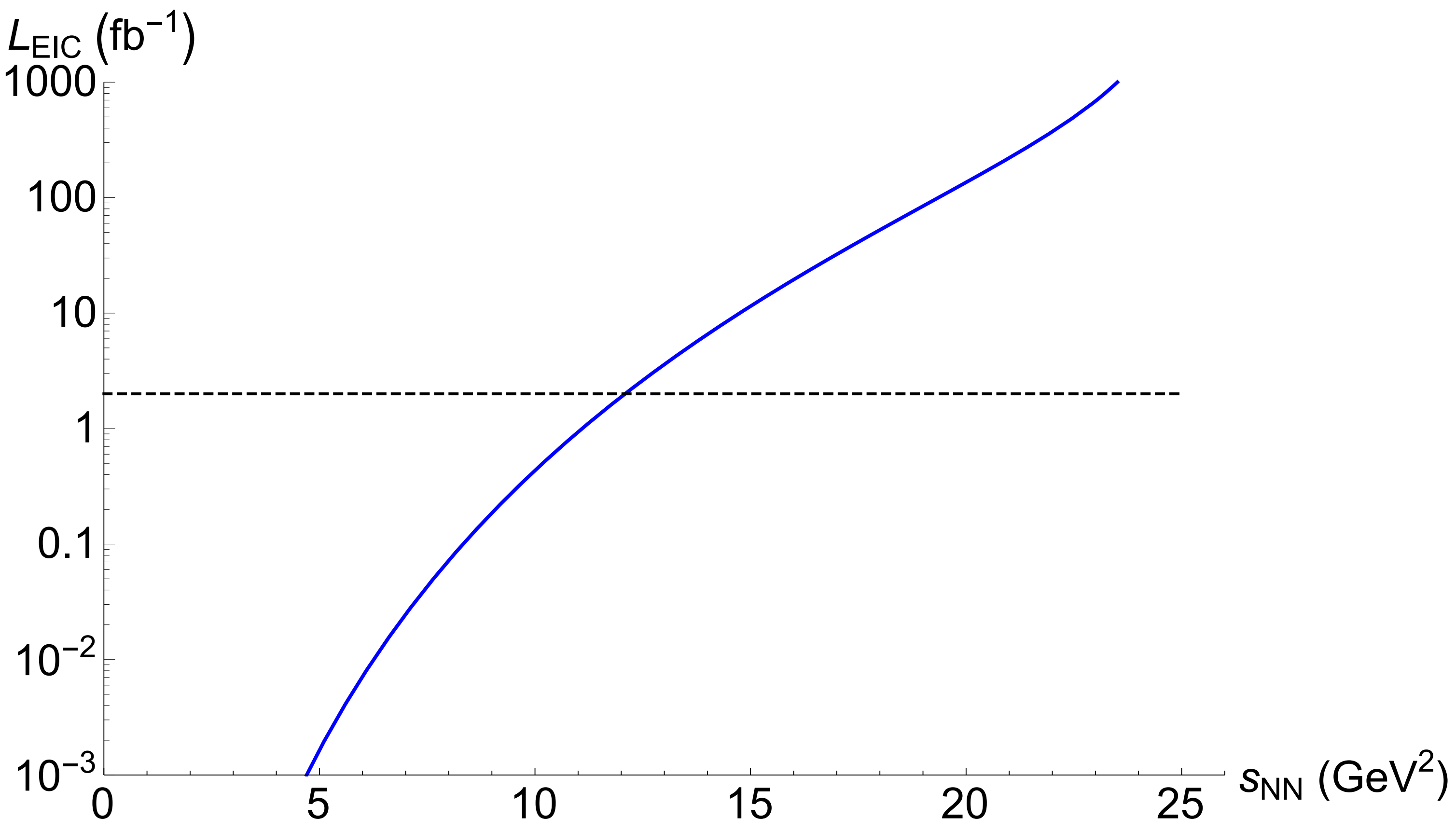

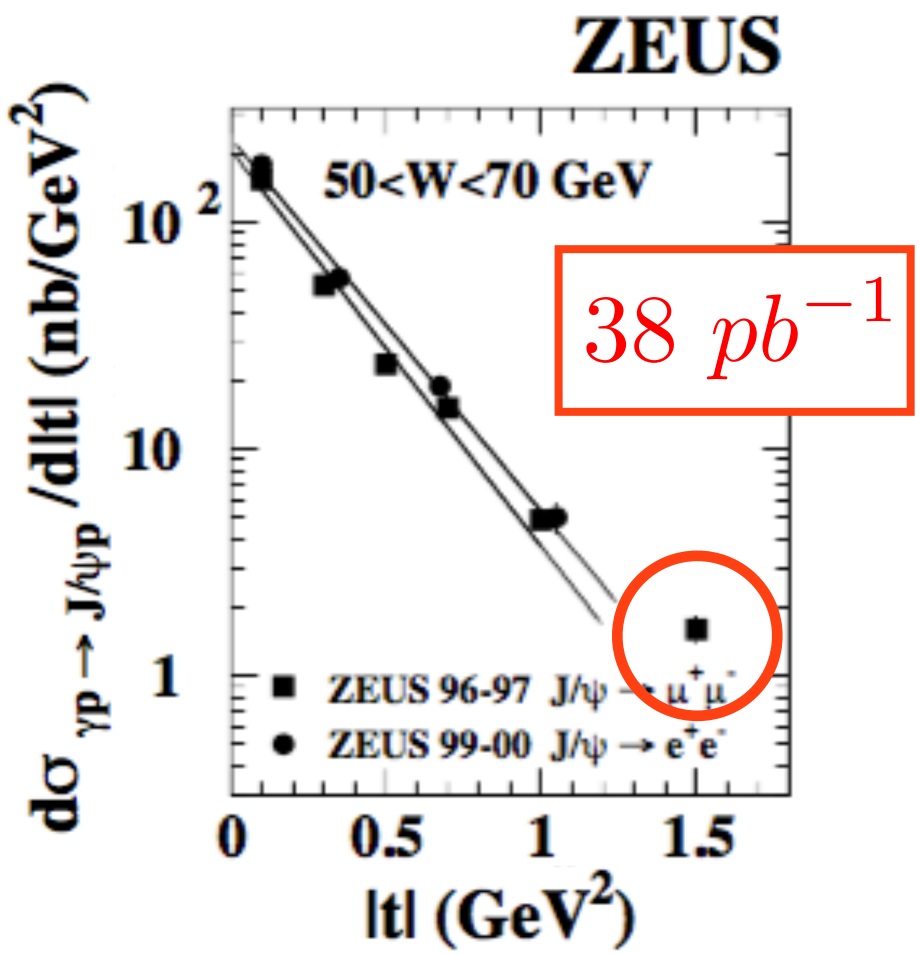

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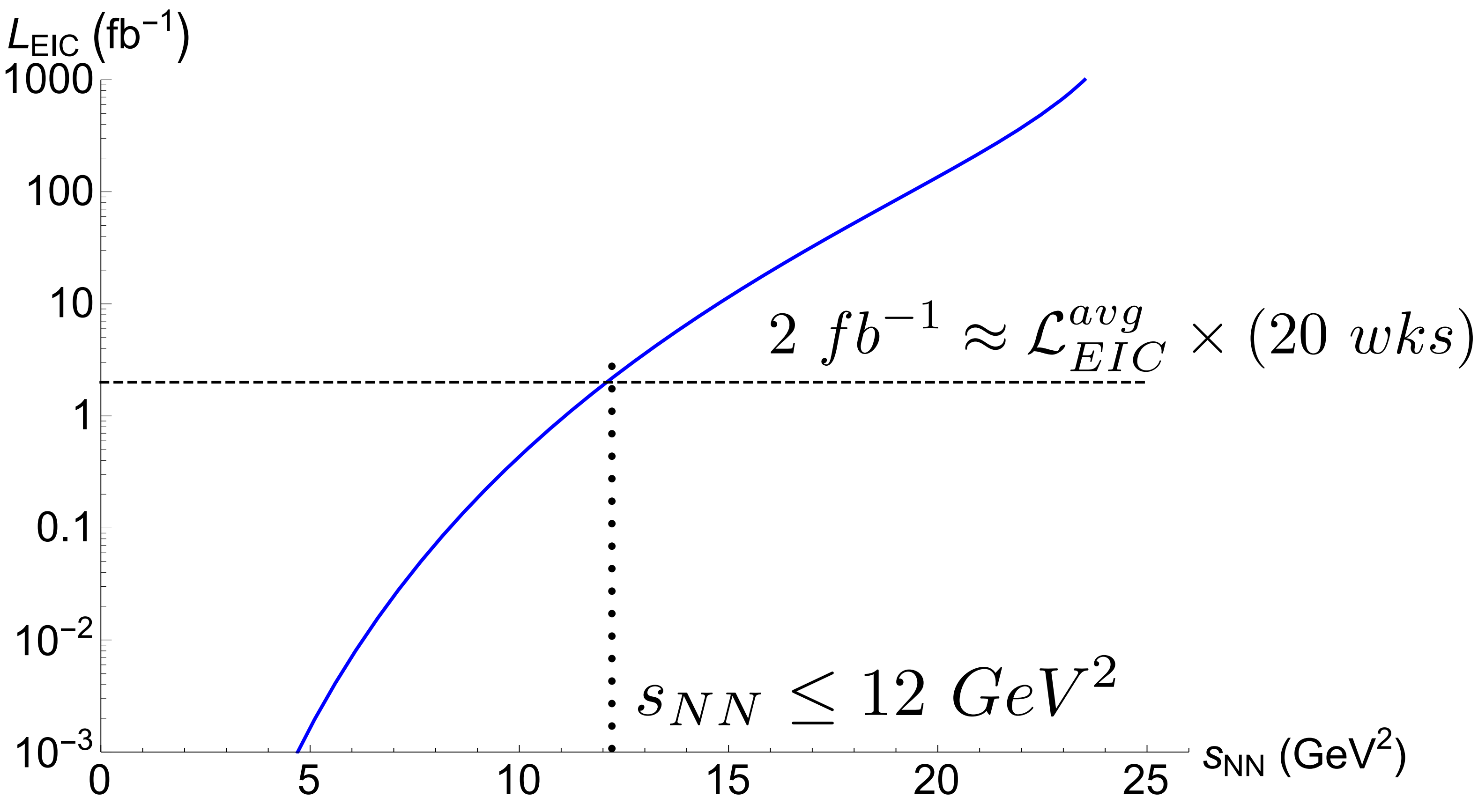

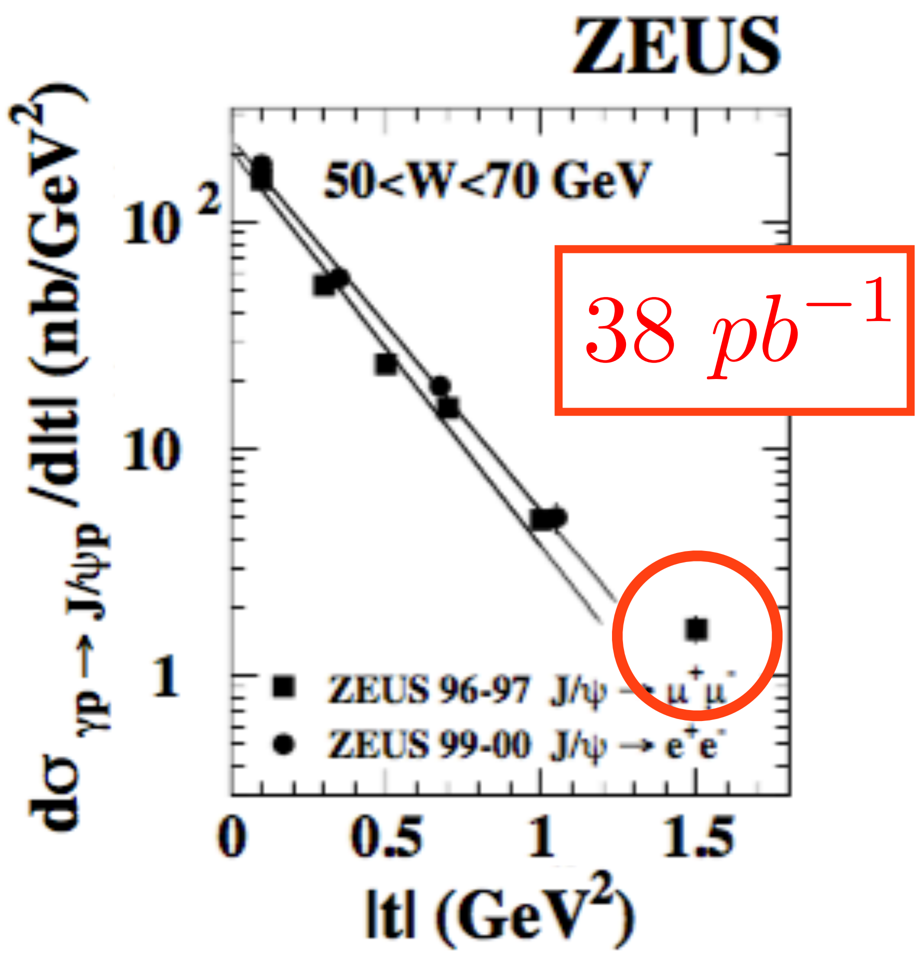

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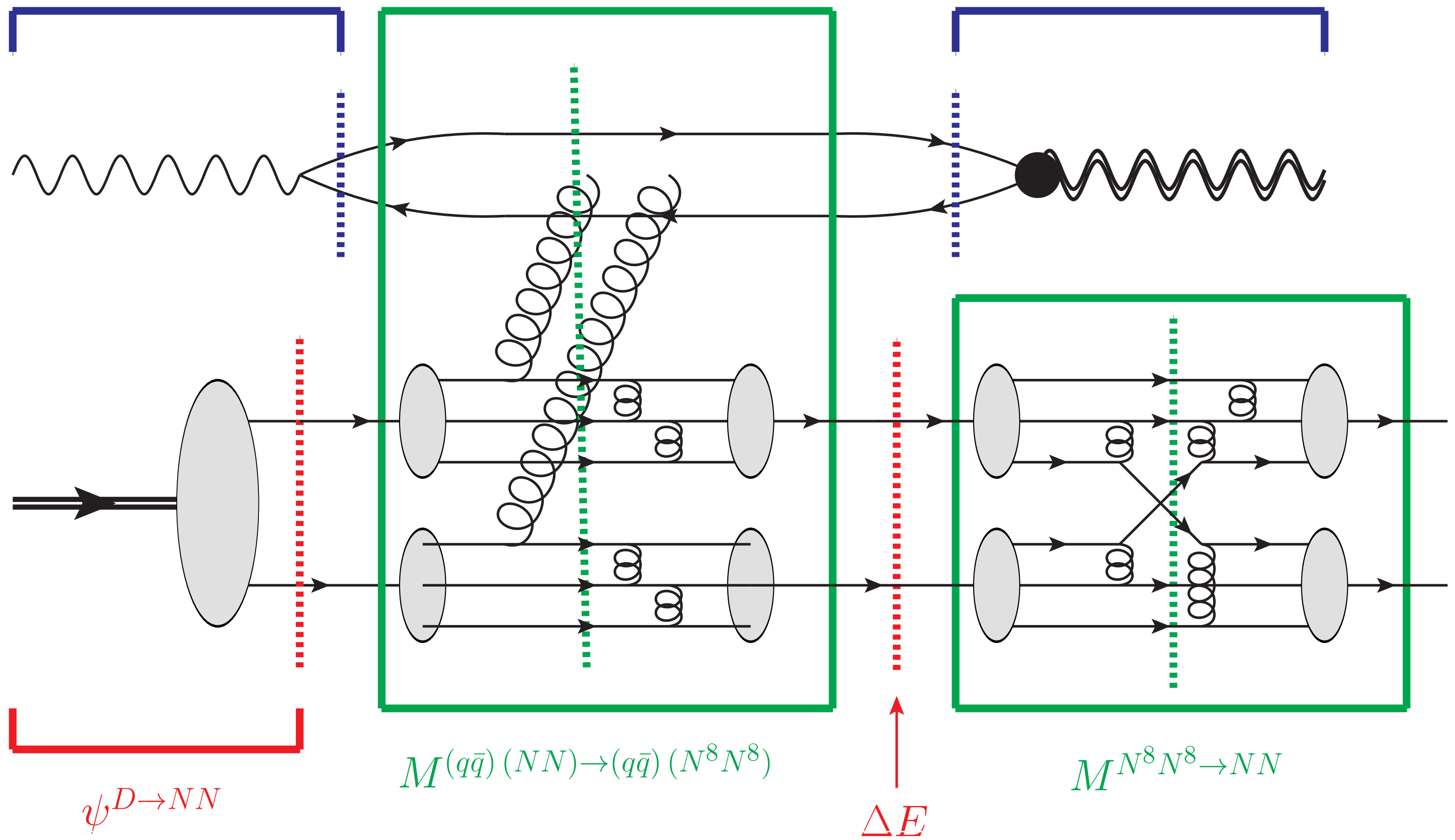
- EIC luminosity: $\mathcal{L}_{EIC}^{peak} \sim 10^{33} - 10^{34}\ cm^{-2} s^{-1}$

$$\mathcal{L}_{EIC}^{avg} \sim 1.6 \times 10^{32}\ cm^{-2} s^{-1}$$

A Unique Opportunity: Color Octet Scattering



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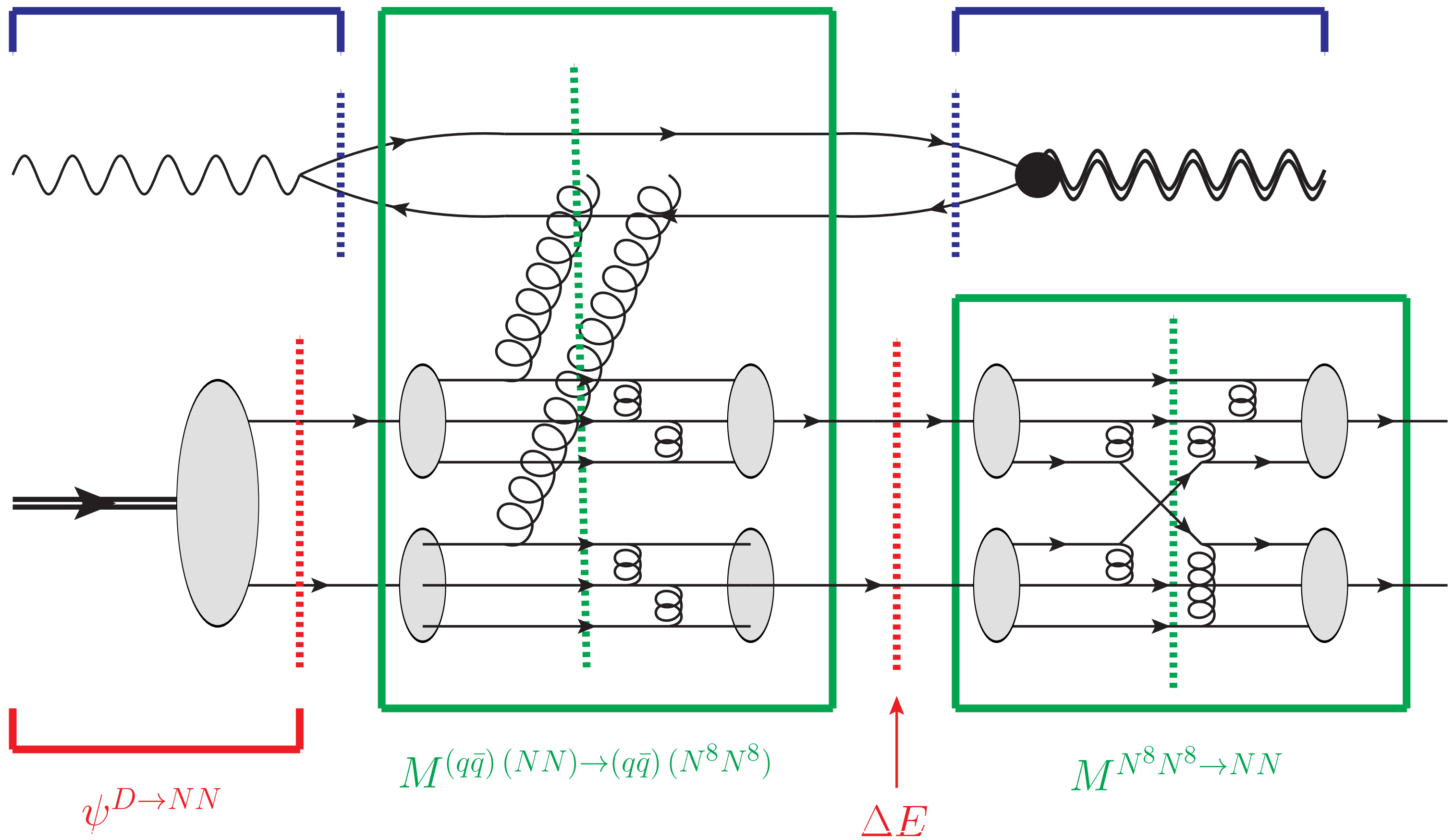

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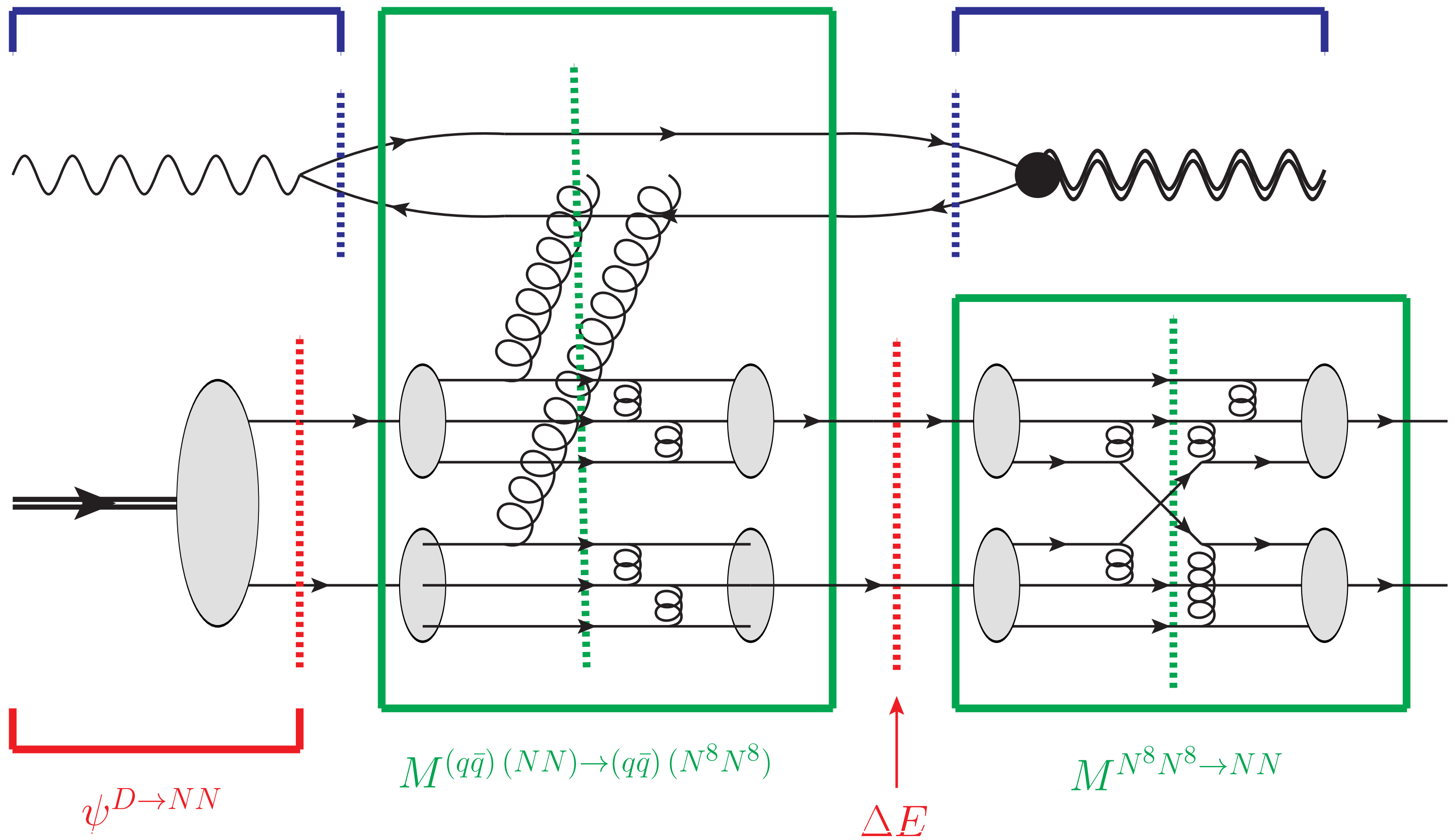

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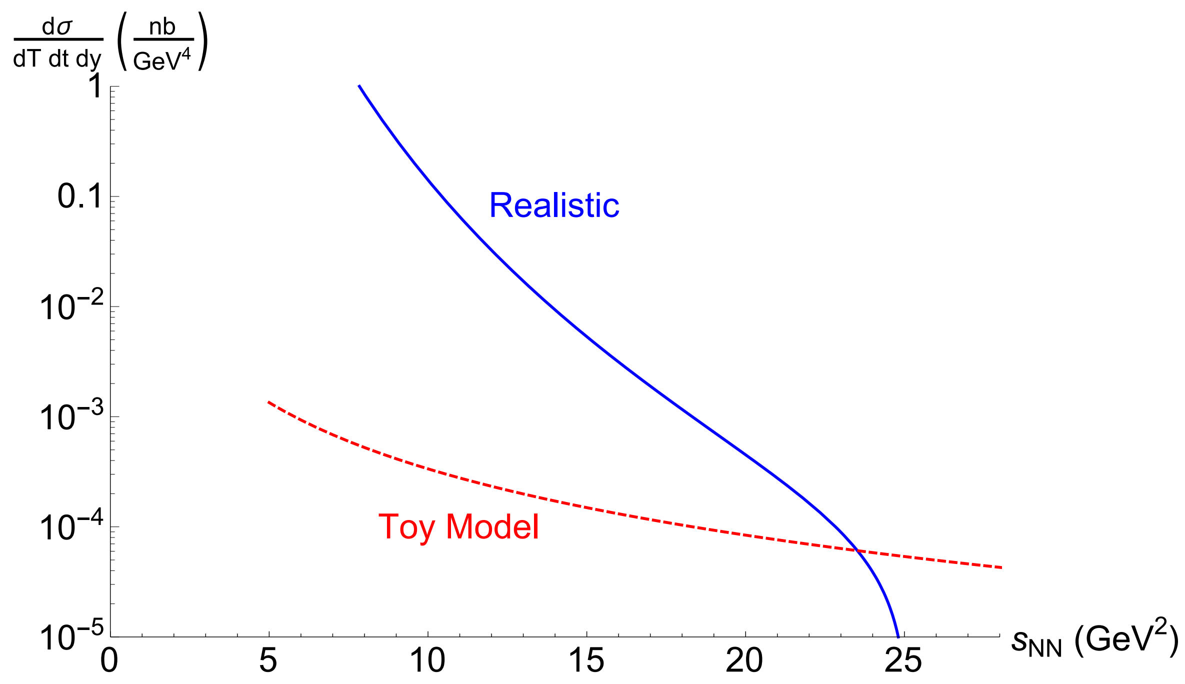
➡ Like in the Quark Target Model, color octet rescattering can couple to the diffractive gluon exchange.

➡ Information about the octet / singlet "hidden color potential"

➡ Even conventional mechanisms (ie, Landshoff) have nonzero projection onto color octet quantum numbers.

Outlook and Future Directions

- Quark Target Model and conventional NN scattering data provide useful upper / lower bounds for rates at an EIC.



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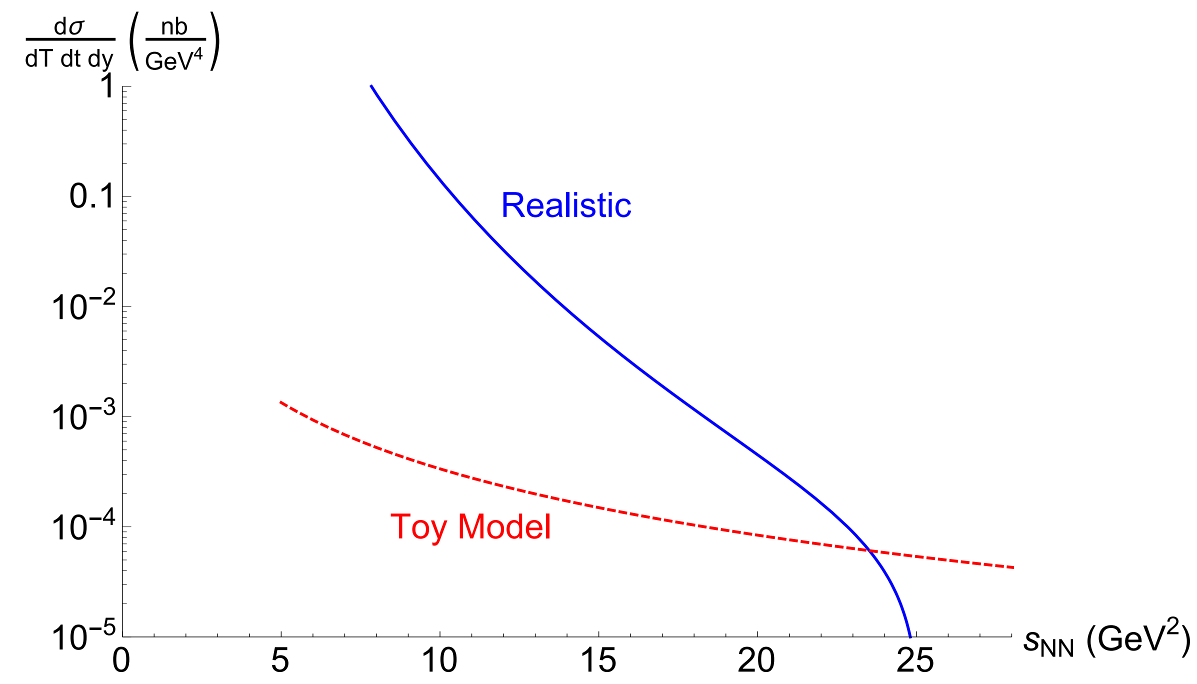

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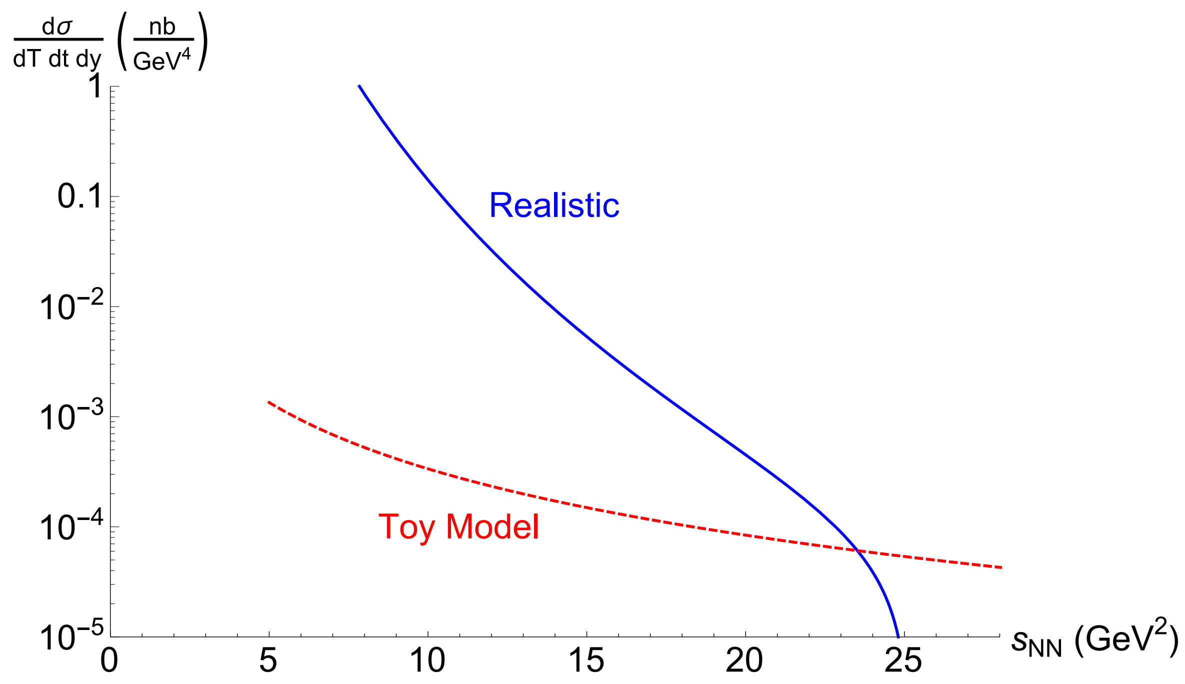

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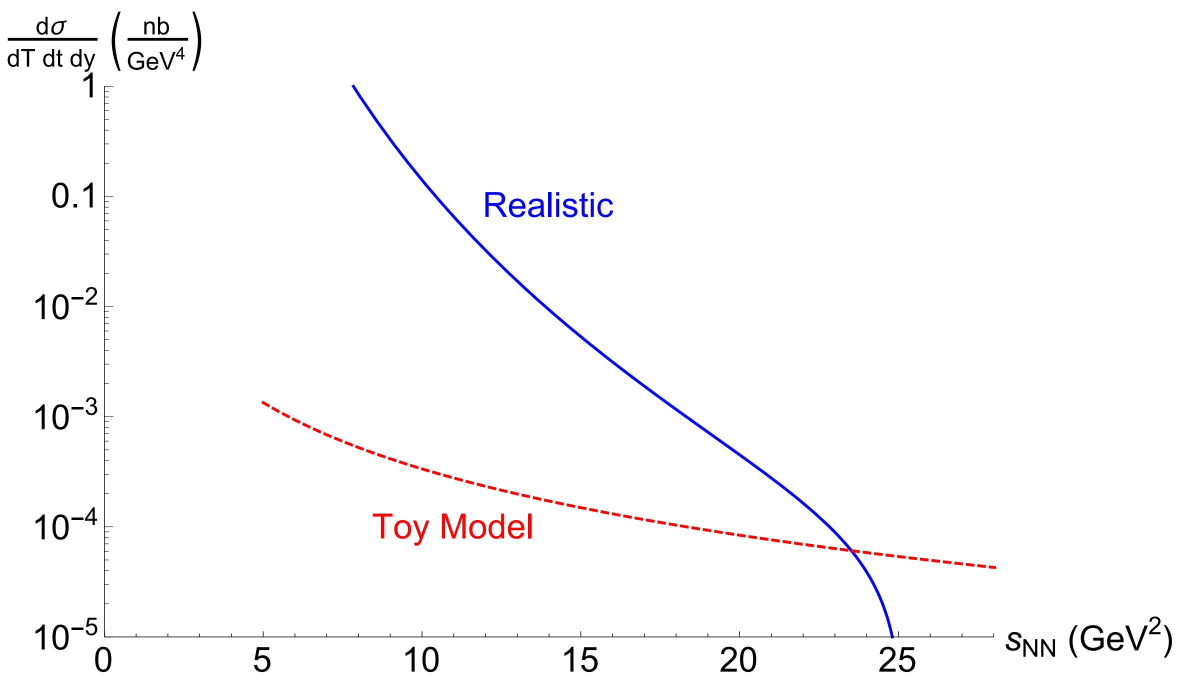

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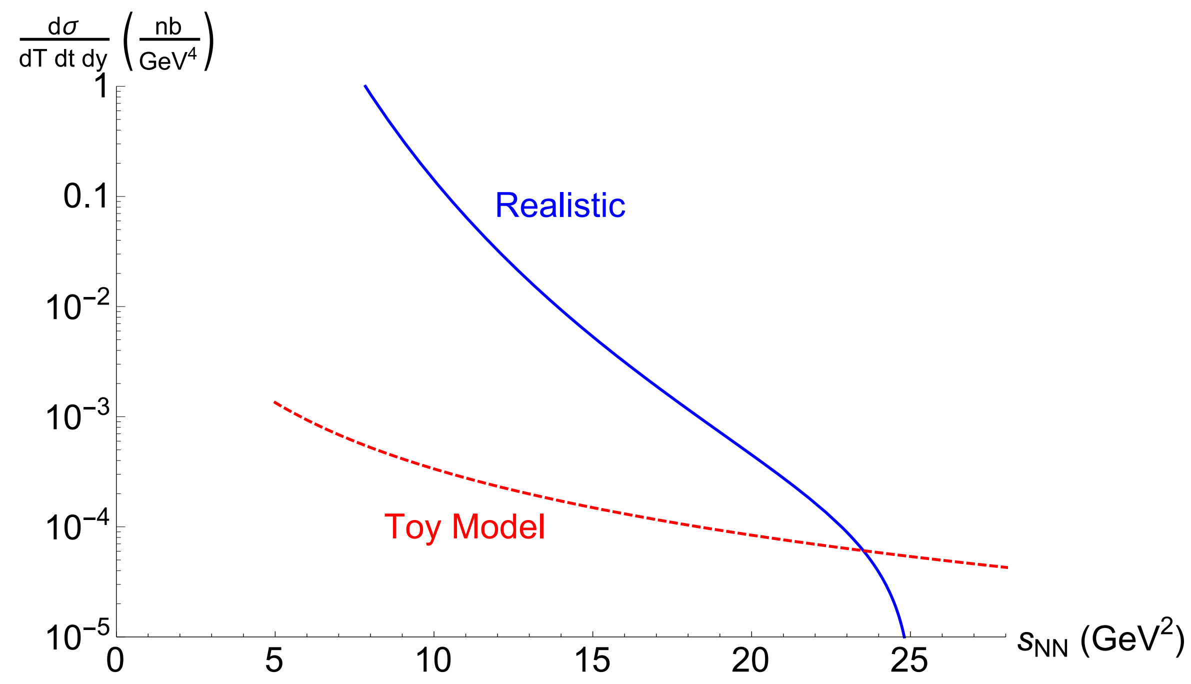

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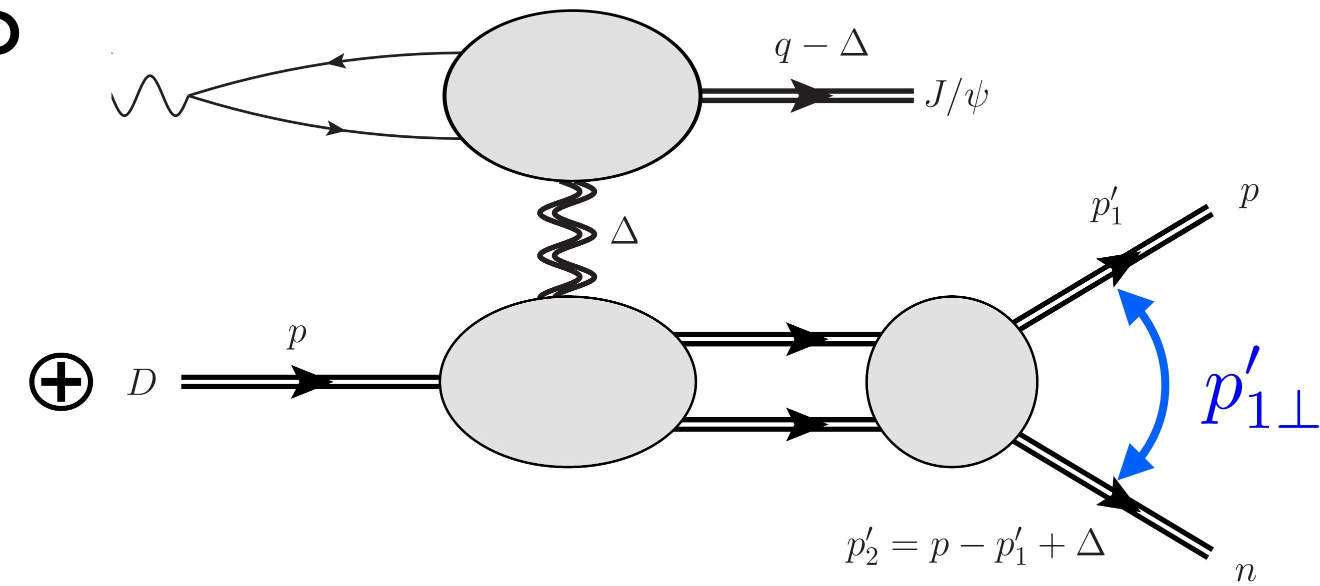
- Saturation corrections: multiple scattering at small x

➡ Could it drive up the cross-section?

- New reaction which is sensitive to short-distance NN scattering:

Hard exclusive meson production with hard deuteron breakup

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



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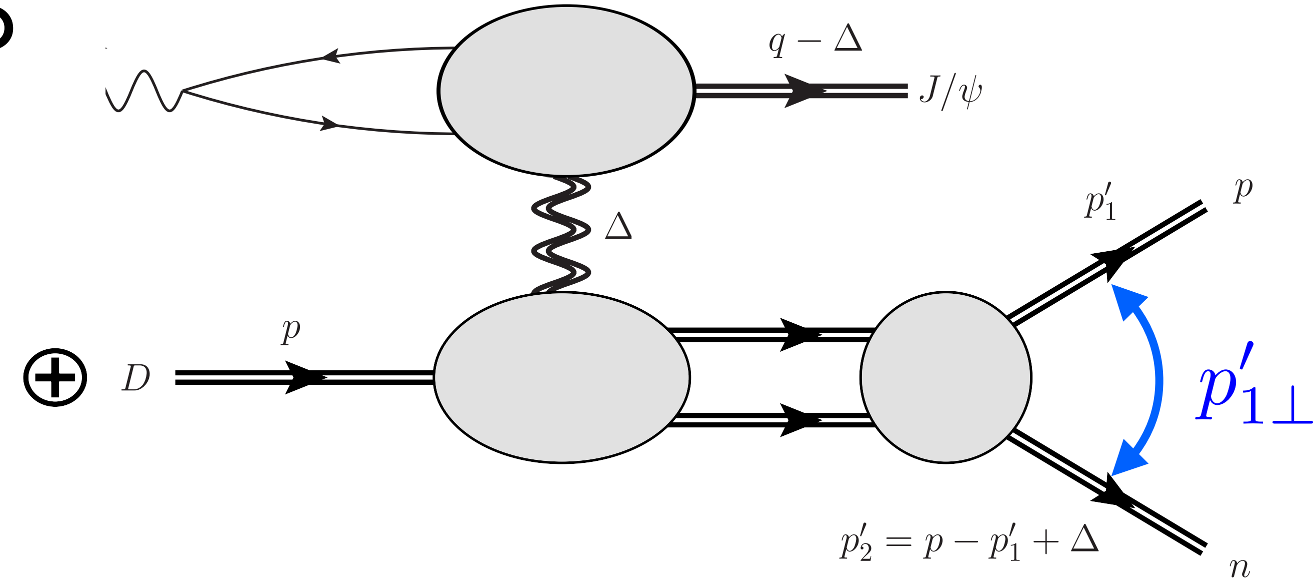
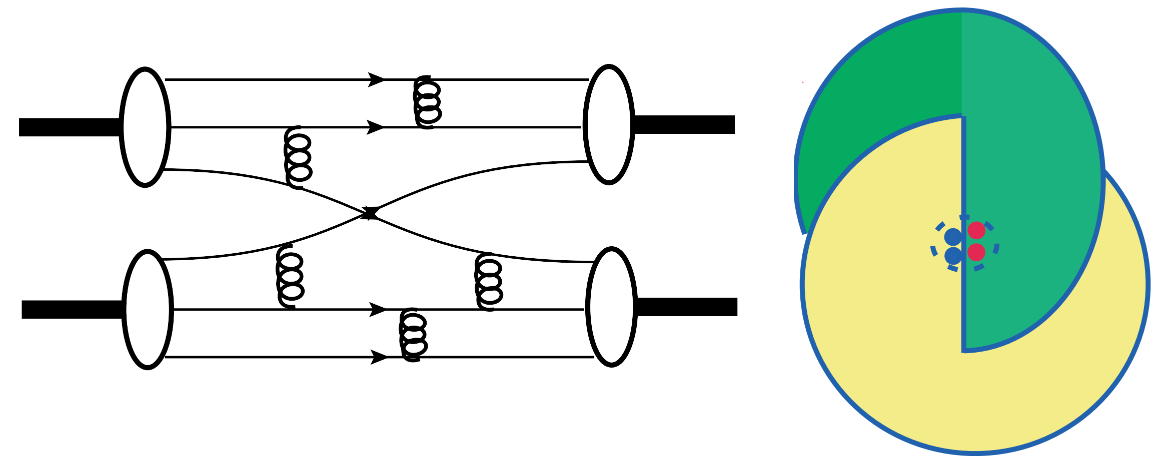
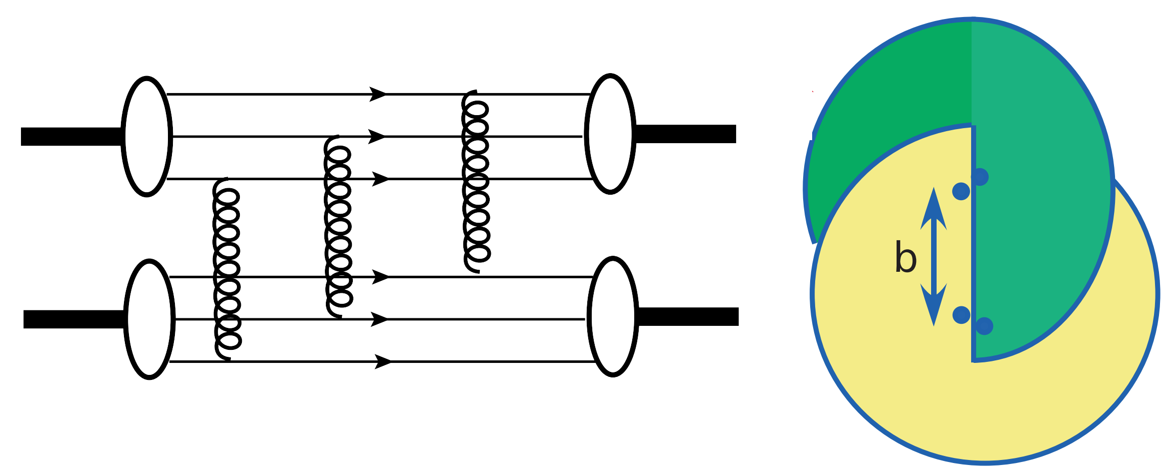


- Estimates show this process is measurable at an EIC, with a window in NN energies that can discriminate between scattering mechanisms.





Summary

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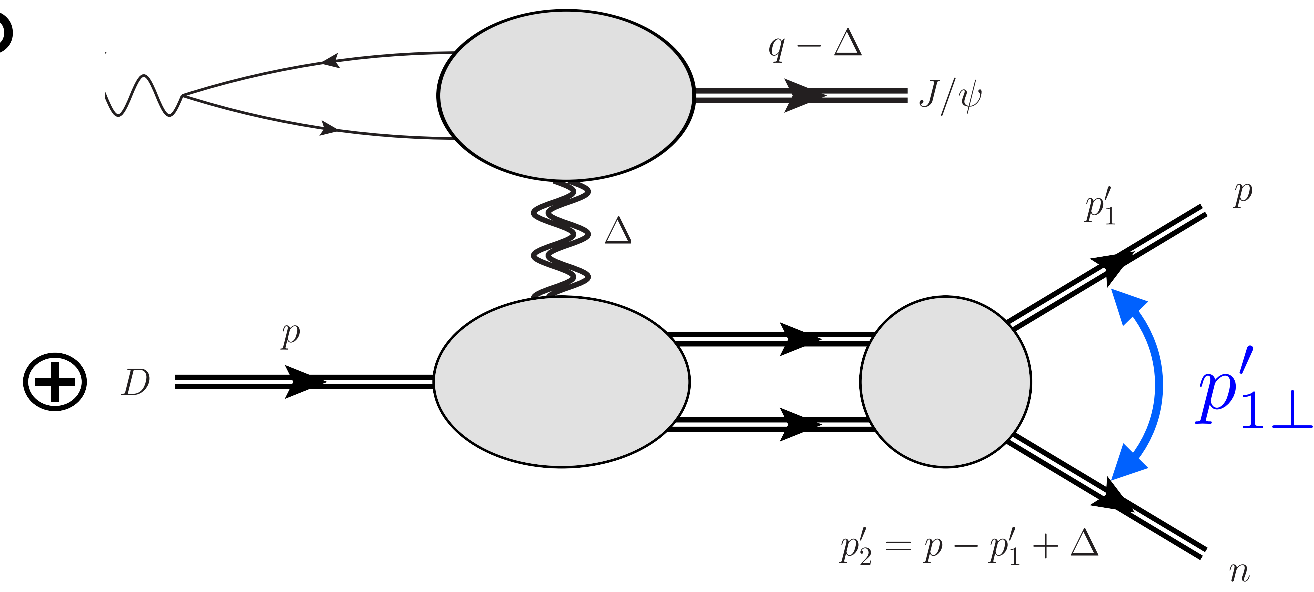

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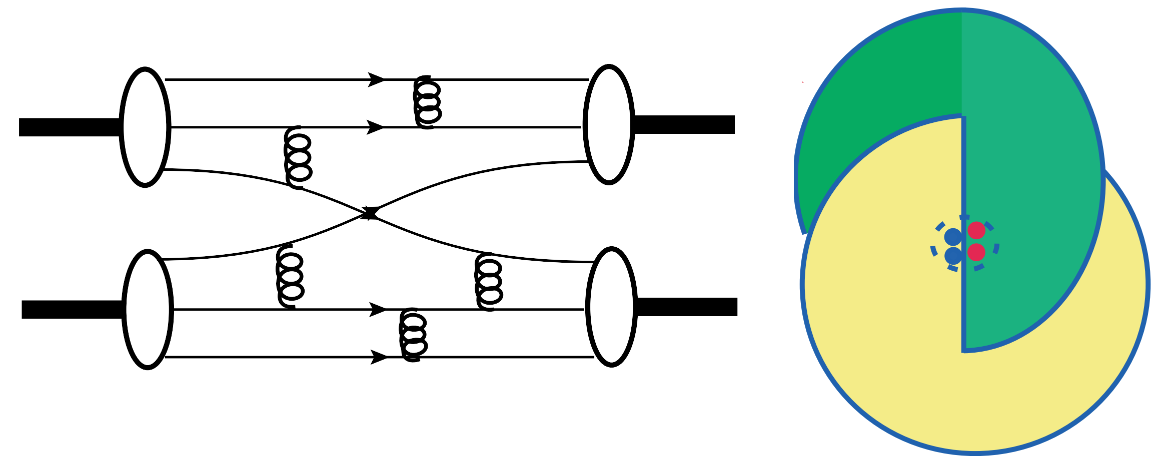

- This process is also sensitive to exotic "hidden color" scattering channels.