Exclusive production of η_C meson by exchange of small-x evolved odderon in ep and eA collisions

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Workshop: ACHT (2023) Non-Perturbative Aspects of Nuclear, Particle and Astroparticle Physics

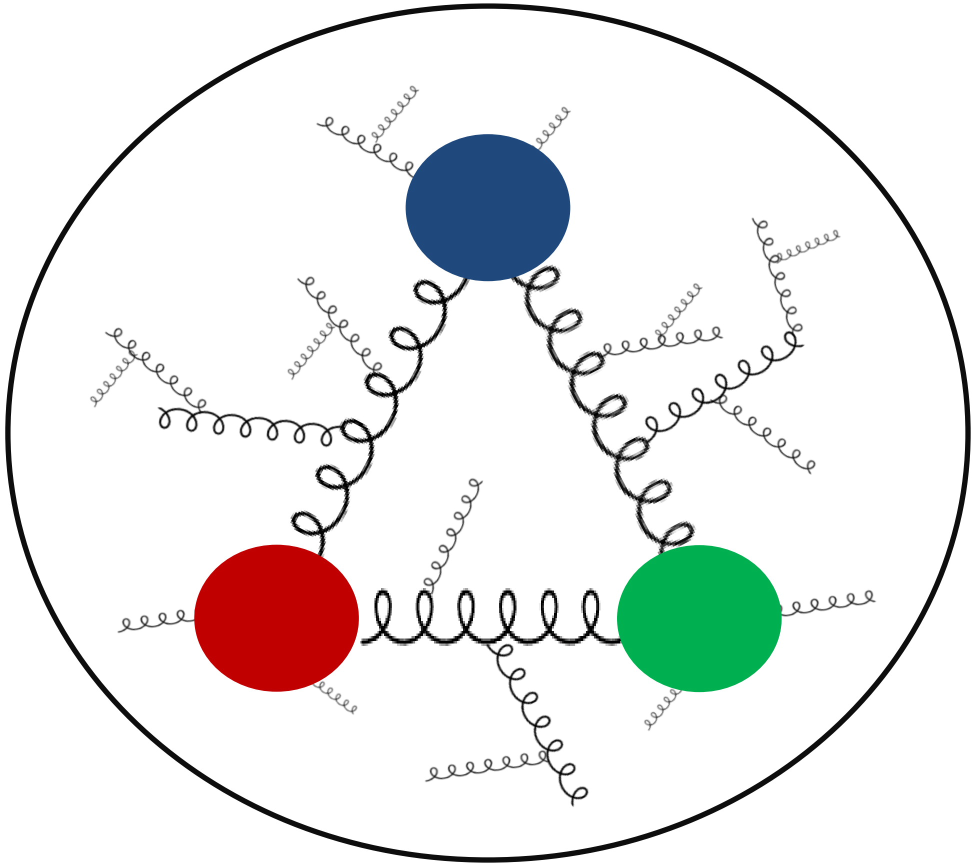
S. Benić, D. Horvatić, A. Kaushik and **E. A. Vivoda**, 2306.10626 (2023).

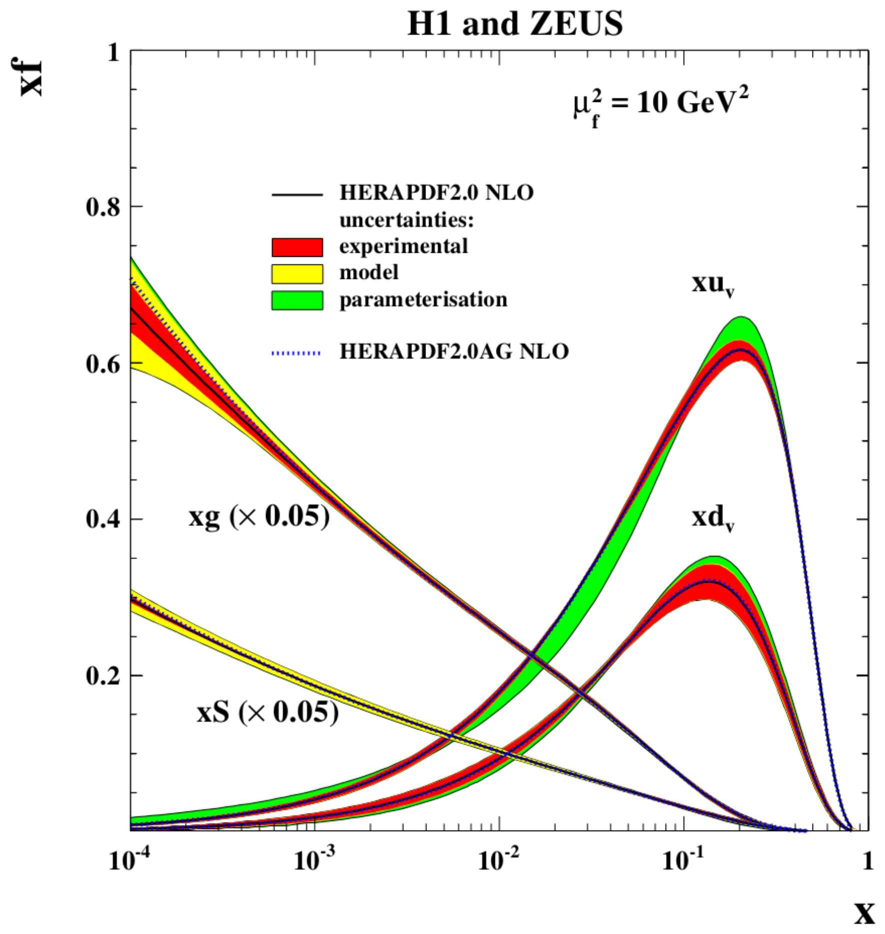
DER RETZHOF

29.9.2023.

How do we imagine proton?

- ➢It depends on the energy!





Momentum fraction $x \propto \frac{1}{\sqrt{s}}$

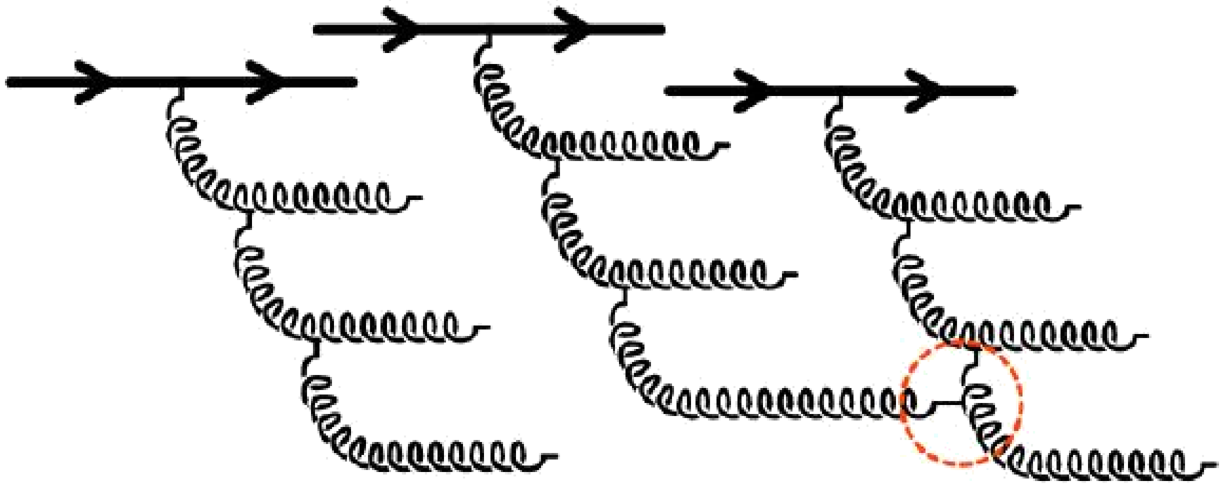
Color Glass Condensate:

- Small x in target (**Color Glass Condensate** (CGC) framework)

C SU(3) charge
G $\Delta x^+ \propto x$ (spin glass)
C Lot of gluons

Classicall YM equations!

➢Small x gluons dominate in hadrons/nuclei



F. Gelis, 1211.3327

$$\Gamma_{gg\to g} = \frac{\alpha_S N_C}{(N_C^2-1)Q^2} \frac{x f_g(x,Q^2)}{\pi R^2} \approx 1$$

$$(Q_s^A)^2 = A^{\frac{1}{3}}\left(Q_s^p\right)^2$$

Q_s- **Saturation scale**

***A* dependence!**

Color Glass Condensate:

C … SU(3) charge

… glass)

- Small x i…

➢ Small … equations!

- In ep or … ection):

$[D_\mu, F^{\mu\nu}]$ … $\frac{1}{\nabla_\perp^2}\rho_A(\boldsymbol{x}_\perp)$

- Quark p… → Wilson line

A. Perkov talk

Light-cone coordinates:

- $x^{\pm} = \frac{x^0 \pm x^3}{\sqrt{2}}$
- $\boldsymbol{x}_\perp = x_1\hat{e}_1 + x_2\hat{e}_2$

Color Glass Condensate:

C SU(3) charge

G $\Delta x^+ \propto x$ (spin glass)

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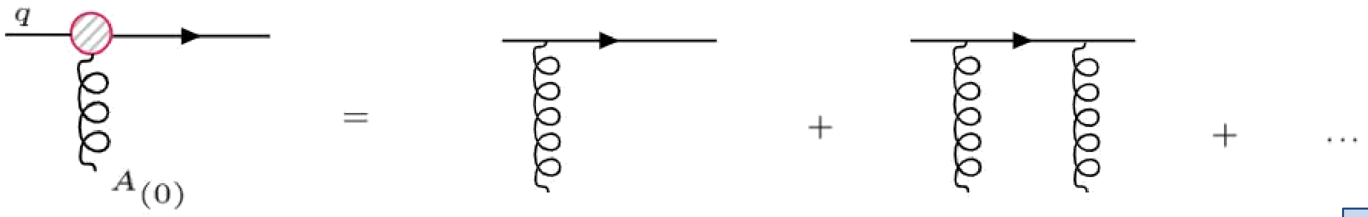
Classicall YM equations!

- Small x in target (**Color Glass Condensate** (CGC) framework)
  - ➢Small x gluons dominate in hadrons/nuclei

- In ep or eA collisions Yang-Mills equation is (p or A has momentum in + direction):

$$[D_\mu, F^{\mu\nu}] = J^\nu \qquad \text{With:} \qquad J^\nu = g\delta(x^-)\delta^{\nu+}\rho_{p/A}(\boldsymbol{x}_\perp) \longrightarrow A^\mu = -g\delta^{\mu+}\delta(x^-)\frac{1}{\boldsymbol{\nabla}_\perp^2}\rho_A(\boldsymbol{x}_\perp)$$

- Quark propagator:



$\propto (V(\boldsymbol{z}_\perp) - 1)$ Wilson line

$$V(\boldsymbol{z}_\perp) = \mathcal{P}\exp\left[ig\int_{-\infty}^{\infty} \mathrm{d}z^- A^+(z^-, \boldsymbol{z}_\perp)\right]$$

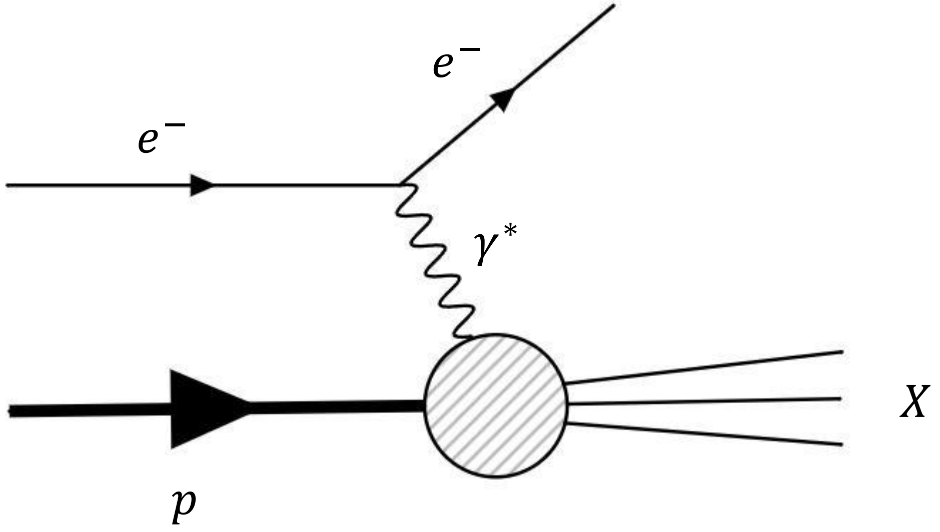
A. Perkov talk

Light-cone coordinates:

- $x^\pm = \frac{x^0 \pm x^3}{\sqrt{2}}$
- $\boldsymbol{x}_\perp = x_1\hat{e}_1 + x_2\hat{e}_2$

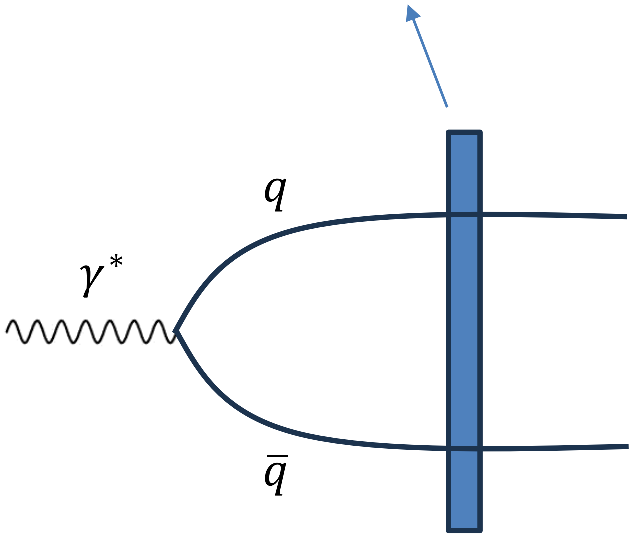
Probing quarks and gluons

- DIS, Drell-Yan, exclusive processes…



- How can photon interact with gluons inside proton?
- It can be split into $q\bar{q}$ pair

Interaction with gluons!

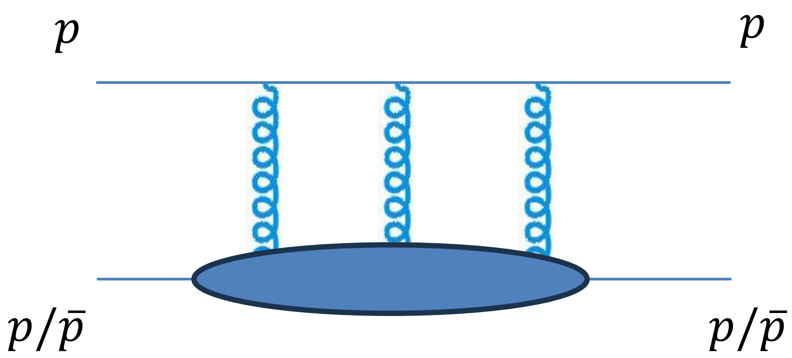


DIPOLE!

- What are possible interactions, what can represent?

Odderon

- In lowest order of QCD: C-odd t channel exchange of three gluons in color-singlet state ($8 \otimes 8 \otimes 8 = 1 \oplus \cdots$):



$$d^{abc} A_\mu^a A_\nu^b A_\rho^c$$

$$C A_\mu C^{-1} = -A_\mu^T$$

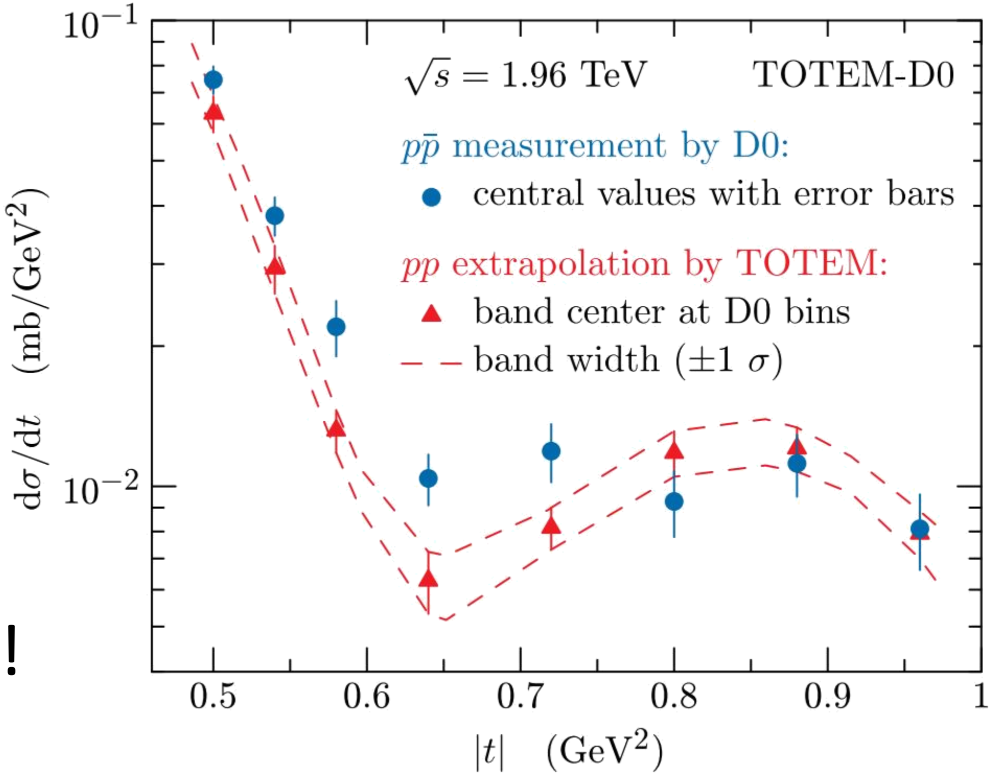
C-odd partner of Pomeron!

- First predicted in 1970s to explain difference in pp and $p\bar{p}$ elastic cross sections

L. Lukaszuk and B. Nicolescu, LNC **8** (1973).

- Recent experimental confirmation ($> 5\sigma$)!

TOTEM colaboration, PRL **127** (2021).



Odderon

- In lowest order of QCD: C-odd t-channel exchange of three gluons in color-singlet state (S

p

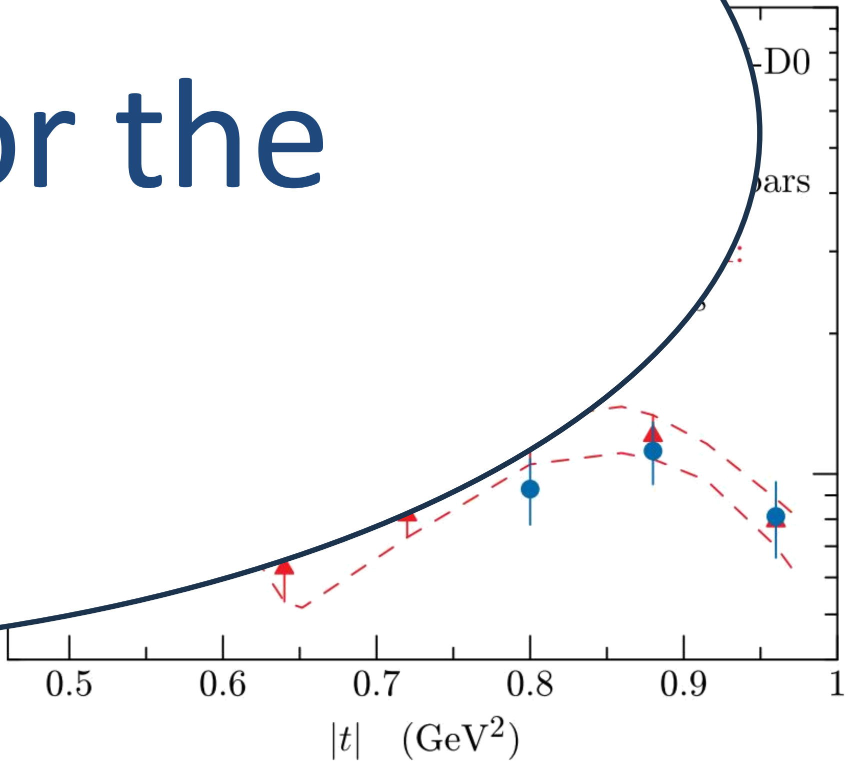
$= -A_\mu^T$

$p/\bar{p}$

Pomeron!

sect

L. Lukaszuk and



What could be a cleaner probe for the odderon?

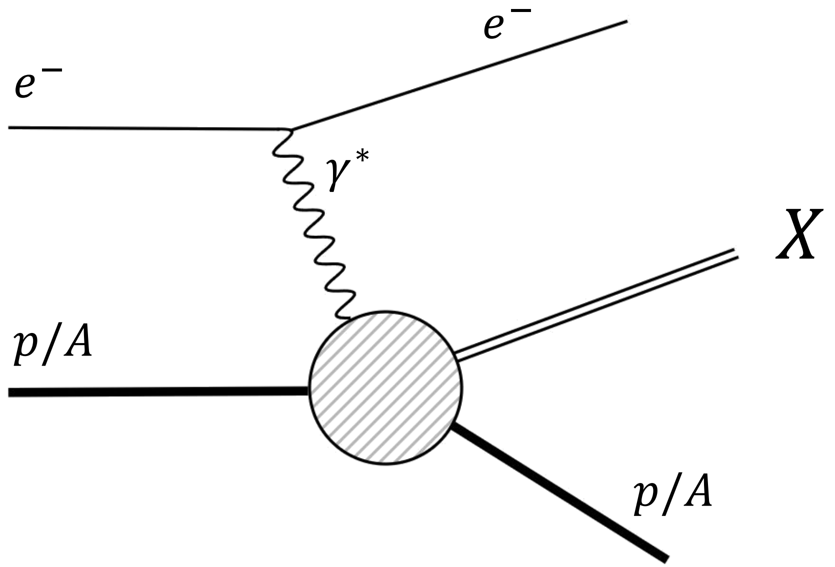
- Recent experimental confirmation

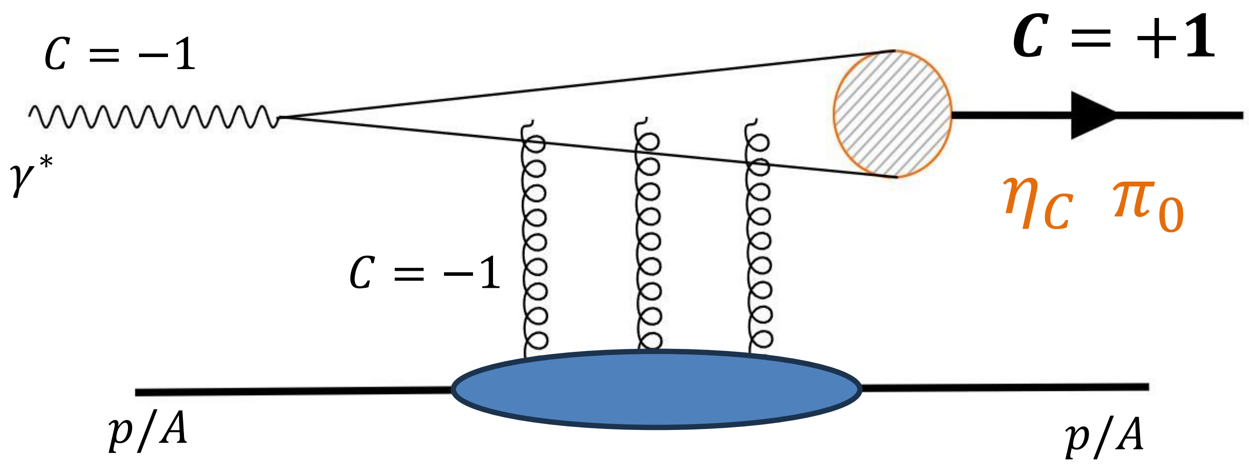
TOTEM colaboration, PRL **127** (2021).

Odderon in *ep* and *eA*

We need to look for exclusive production of C-even mesons!

- What should we look for? What should X be?





- Exclusive production of η_C meson: $e + p/A \to e + p/A + \eta_C$ $= c\bar{c}$

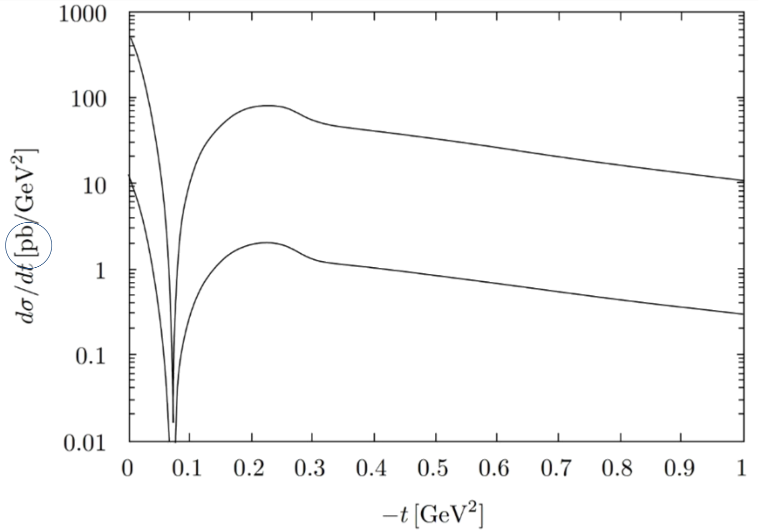
Probing the gluonic part of target!

- It is considered a golden probe for odderon

$e + p/A \rightarrow e + p/A + \eta_c$

R.Engel, D. Y. Ivanov, R. Kirschner and L. Szymanowski, EPJ. C **4**, 93 (1998).

- η_C production was not detected at HERA and JLab -> EIC has greater luminosity!
- Theoretical predictions were done for $x \approx 0.1$ -> dilute regime, no need for saturation effects

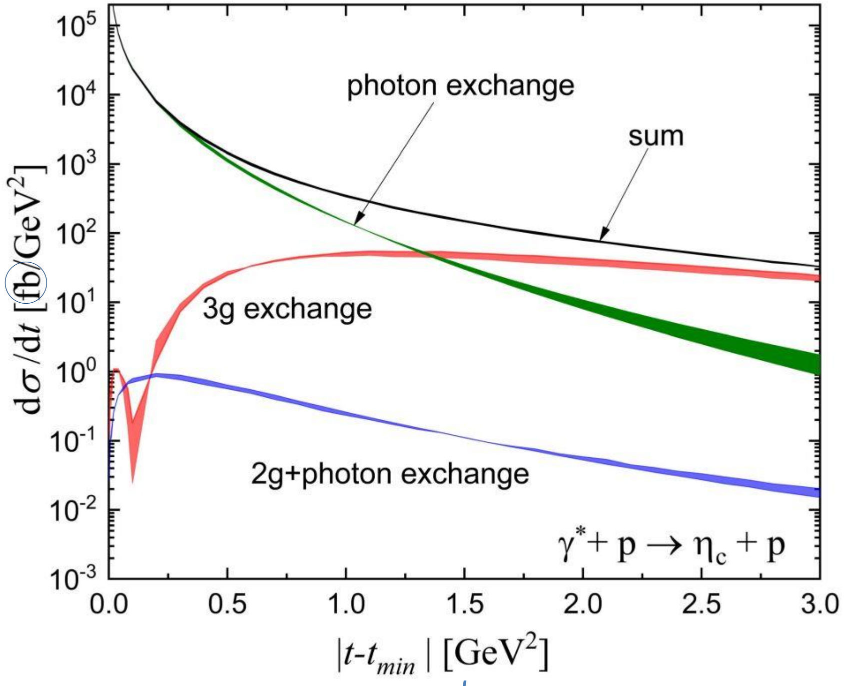


J. Bartels, M. A. Braun, D. Colferal and G. P. Vacca, EPJ C **20**, 323 (2001).

A. Dumitru and T. Stebel, PRD **99**, 094038 (2019).

Smaller cross section

J. Czyzewski, J. Kwiecinski, L. Motyka,and M. Sadzikowski, PLB **398**, 400 (1997).



Weak $|t|$ dependence!

- **This work**:
  - Evolution to smaller $x \in [10^{-4}, 10^{-2}]$ (EIC)
  - Dense regime -> Saturation physics -> Color Glass Condensate EFT
  - Nuclear targets are considered

Odderon in CGC framework:

Pomeron

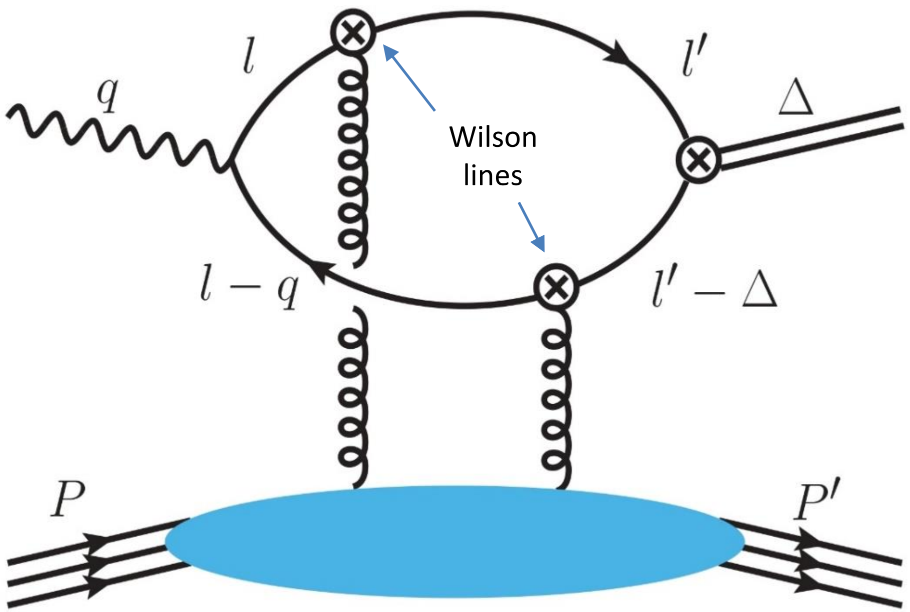
- **Odderon** = imaginary part of **dipole distribution function** (amplitude for $q\bar{q}$ pair to elastic scatter from the target)

$$\mathcal{S}(\boldsymbol{x}_\perp, \boldsymbol{x'}_\perp) \equiv \frac{1}{N_C}\mathrm{tr}\langle V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{x'}_\perp)\rangle \qquad \mathcal{S}(\boldsymbol{x}_\perp, \boldsymbol{x'}_\perp) \equiv \mathcal{P}(\boldsymbol{x}_\perp, \boldsymbol{x'}_\perp) + i\mathcal{O}(\boldsymbol{x}_\perp, \boldsymbol{x'}_\perp)$$

- Wilson lines come from the CGC vertex which is derived in eikonal approximation:

$$\tau(p,p') = 2\pi\delta(p^- - p'^-)\gamma^-\,\mathrm{sgn}(p^-)\int_{\boldsymbol{z}_\perp} e^{-i(\boldsymbol{p}_\perp - \boldsymbol{p'}_\perp)\cdot \boldsymbol{z}_\perp} V^{\mathrm{sgn}(p^-)}(\boldsymbol{z}_\perp)$$

Amplitude for η_C production:



$$S_\lambda = eq_C \int_{ll'} \mathrm{Tr}[S(l)\not{\epsilon}(\lambda,q)S(l-q)\tau(l-q,l'-\Delta)S(l'-\Delta)(i\gamma_5)S(l')\tau(l',l)]$$

$$\equiv -\mathcal{M}_\lambda (2\pi)\delta(q^- - \Delta^-)$$

A. Dumitru and T. Stebel,PRD **99**, 094038 (2019).

- $S(l)$ stands for Feynman propagator: $S(l) = i\dfrac{\not{l}+m_C}{l^2 - m_c^2 + i\epsilon}$

- Color averaged amplitude (in terms of CGC, A. Perkov talk):

$$\langle \mathcal{M}_\lambda \rangle = eq_C \int_{r_\perp} \int_{ll'} (2\pi)\delta(l^- - l'^-)\theta(l'^-)\theta(q^- - l^-)\mathrm{e}^{-i\left(l'_\perp - l_\perp - \frac{1}{2}\Delta_\perp\right)\cdot r_\perp} \times (-iN_C)\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{\Delta}_\perp)\mathrm{tr}[S(l)\not{\epsilon}(\lambda,q)S(l-q)\gamma^- S(l'-\Delta)(i\gamma_5)S(l')\gamma^-]$$

$$\equiv (2q^-)iN_C \int_{r_\perp} \mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{\Delta}_\perp)\mathcal{A}_\lambda(\boldsymbol{r}_\perp, \boldsymbol{\Delta}_\perp)$$

Here: $\boldsymbol{r}_\perp = \boldsymbol{x}_\perp - \boldsymbol{y}_\perp$ $\quad \boldsymbol{b}_\perp = \dfrac{\boldsymbol{x}_\perp + \boldsymbol{y}_\perp}{2}$

$\boldsymbol{\Delta}_\perp$ is conjugate to $\boldsymbol{b}_\perp$

Photoproduction cross section:

- After computing the Dirac trace and performing transverse integrations:

$$\int_z \equiv \int_0^1 \frac{\mathrm{d}z}{4\pi}$$

$$\mathcal{A}_\lambda(\boldsymbol{r}_\perp, \boldsymbol{\Delta}_\perp) = -e q_C \lambda \mathrm{e}^{i\lambda\phi_r} \int_z \mathrm{e}^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp} \frac{\sqrt{2} m_C}{2\pi} \frac{1}{z\bar{z}} \left[K_0(\xi r_\perp)\partial_{r_\perp}\phi_P(z, r_\perp) - \xi K_1(\xi r_\perp)\phi_P(z, r_\perp)\right]$$

$$\equiv e q_C \lambda \mathrm{e}^{i\lambda\phi_r} \int_z \mathrm{e}^{-i\boldsymbol{\delta}_\perp\cdot\boldsymbol{r}_\perp} \mathcal{A}(r_\perp)$$

$$\xi^2 = m_c^2 + z\bar{z}Q^2$$

$$\boldsymbol{\delta}_\perp = \frac{1}{2}(z - \bar{z})\boldsymbol{\Delta}_\perp$$

$$t = (P - P')^2$$

$$x = \frac{(P - P')\cdot q}{P\cdot q}$$

- Proportional to charm mass!
- Spin flip

Meson light cone wave function:

$$\phi_P(z, r_\perp) = N_P z\bar{z} \exp\left(-\frac{m_C^2 \mathcal{R}_P^2}{8z\bar{z}} - \frac{2z\bar{z}r_\perp^2}{\mathcal{R}_P^2} + \frac{1}{2}m_C^2\mathcal{R}_P^2\right)$$

- Longitudinal photon decouples, and we have polarization independent amplitude:

$$\langle\mathcal{M}\rangle = 8\pi i e q_C N_C \sum_{k=0}^{\infty}(-1)^k \int_z \int_0^\infty r_\perp dr_\perp \mathcal{O}_{2k+1}(r_\perp, \Delta_\perp)\mathcal{A}(r_\perp)\left[J_{2k}(r_\perp\delta_\perp) - \frac{2k+1}{r_\perp\delta_\perp}J_{2k+1}(r_\perp\delta_\perp)\right]$$

- Photoproduction cross section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}|t|} = \frac{1}{16\pi}|\langle\mathcal{M}\rangle|^2$$

A. Dumitru and T. Stebel, PRD **99**, 094038 (2019).

Odderon evolution (BK equation)

- If we know the odderon at some x, how can we evolve it on lower x?

Y. V. Kovchegov, PRD **60**,034008 (1999).

I. Balitsky, NPB **463**,99 (1996).

- Balitsky-Kovchegov (BK) equation:

$$\frac{\partial \mathcal{S}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp, Y)}{\partial Y} = \frac{\alpha_S N_C}{2\pi^2} \int_{r_{1\perp}} \frac{\boldsymbol{r}_\perp^2}{\boldsymbol{r}_{1\perp}^2 \boldsymbol{r}_{2\perp}^2} [\mathcal{S}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_{1\perp}, Y)\mathcal{S}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_{2\perp}, Y) - \mathcal{S}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp, Y)]$$

$$\boldsymbol{r}_\perp = \boldsymbol{x}_\perp - \boldsymbol{y}_\perp$$

$$\boldsymbol{r}_{1\perp} = \boldsymbol{x}_\perp - \boldsymbol{z}_\perp$$

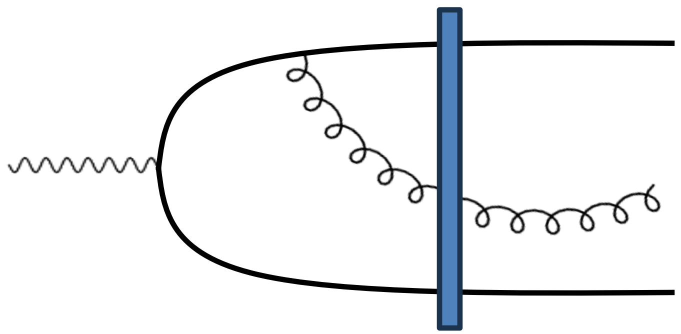
$$\boldsymbol{r}_{2\perp} = \boldsymbol{z}_\perp - \boldsymbol{y}_\perp$$

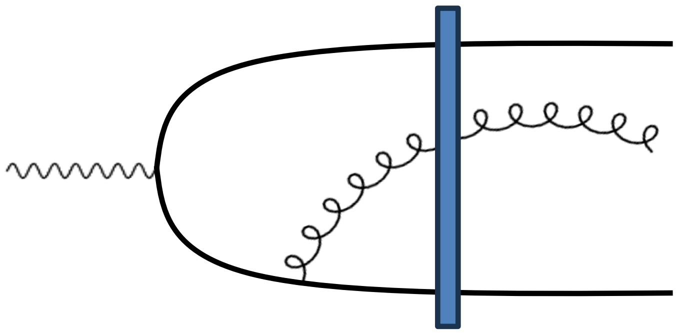
$$Y = \ln\left(\frac{1}{x}\right)$$

- A word on derivation:
  - Imagine that we have an increase in rapidity: $Y \to Y + \Delta Y$
  - Dipole can emit virtual gluon in rapidity range $[Y, Y + \Delta \mathrm{Y}]$

$$\boldsymbol{b}_{1\perp} = \boldsymbol{b}_\perp + \frac{(\boldsymbol{r}_\perp - \boldsymbol{r}_{1\perp})}{2}$$

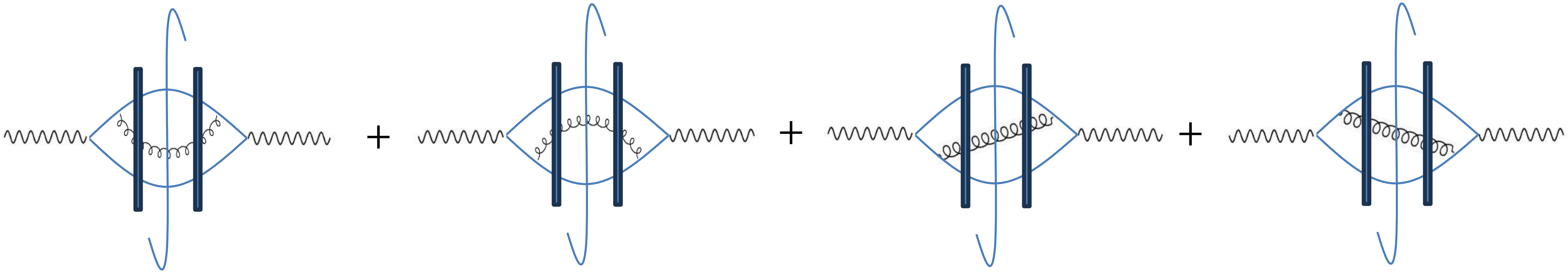
$$\boldsymbol{b}_{2\perp} = \boldsymbol{b}_\perp + \frac{(\boldsymbol{r}_\perp - \boldsymbol{r}_{2\perp})}{2}$$





- Gluon can be emitted from quark and antiquark
- To get probability of radiation we need to sum and square this two contributions

$$\left|\mathcal{M}_q + \mathcal{M}_{\bar{q}}\right|^2 =$$



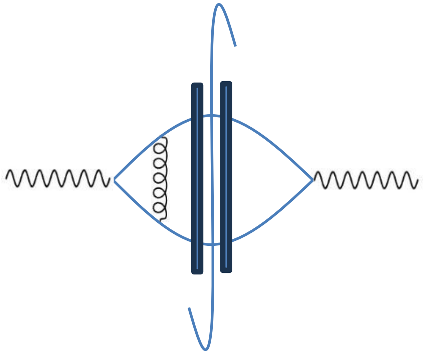
$$= \frac{\alpha_S N_C}{2\pi^2} \mathrm{d}^2 r_{1\perp} \mathrm{d}y \frac{\boldsymbol{r}_\perp^2}{\boldsymbol{r}_{1\perp}^2 \boldsymbol{r}_{2\perp}^2}$$

- Contribution to scattering amplitude: $= \frac{\alpha_S N_C \Delta Y}{2\pi^2} \int_{r_{1\perp}} \frac{\boldsymbol{r}_\perp^2}{\boldsymbol{r}_{1\perp}^2 \boldsymbol{r}_{2\perp}^2} \times \boxed{\mathcal{S}_{q\bar{q}g}(Y, \boldsymbol{r}_{1\perp}, \boldsymbol{r}_{2\perp})}$

- Amplitude for $q\bar{q}g$ system to scatter of the target
- In large N_C limit it is equal to: $\mathcal{S}(Y, \boldsymbol{r}_{1\perp}) \times \mathcal{S}(Y, \boldsymbol{r}_{2\perp})$

- We also need to consider a virtual gluon correction to the $q\bar{q}$ (it is the same order in α_S):

$$|\mathcal{M}_{LO} + \mathcal{M}_{NLO}|^2 =$$



$$+ h.c. + \cdots \quad = -\frac{\alpha_S N_C}{2\pi^2} \mathrm{d}^2 r_{1\perp} \mathrm{d}y \frac{\boldsymbol{r}_\perp^2}{\boldsymbol{r}_{1\perp}^2 \boldsymbol{r}_{2\perp}^2}$$

- Total contribution to up to NLO to the scattering amplitude therefore is:

$$\mathcal{S}(Y, \boldsymbol{r}_\perp) + \frac{\alpha_S N_C \Delta Y}{2\pi^2} \int_{r_{1\perp}} \frac{\boldsymbol{r}_\perp^2}{\boldsymbol{r}_{1\perp}^2 \boldsymbol{r}_{2\perp}^2} \left[\mathcal{S}(Y, \boldsymbol{r}_{1\perp}) \times \mathcal{S}(Y, \boldsymbol{r}_{2\perp}) - \mathcal{S}(Y, \boldsymbol{r}_\perp)\right]$$

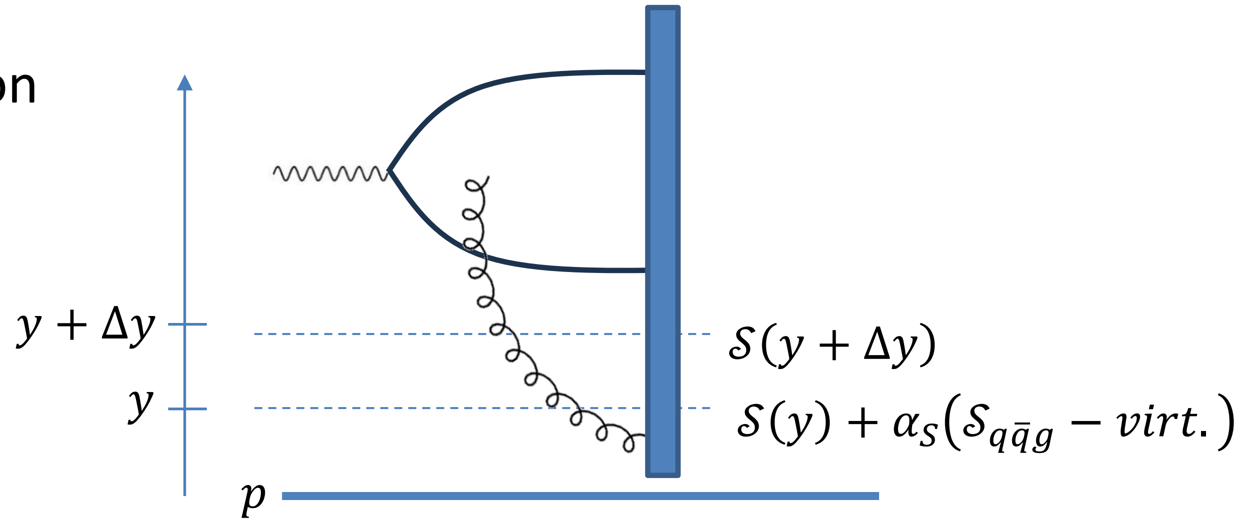
- So far, the gluon was treated as it originated from photon: $\gamma \to q\bar{q} \to q\bar{q}g$
- Gluon can also be seen as it originated from target:
  - In that case diople that interacts with target is on rapidity $Y + \Delta Y$

H. Mäntysaari, BK equation (2011).

- Physics must not depend on that choice:

$$\mathcal{S}(Y+\Delta Y, \boldsymbol{r}_\perp) = \mathcal{S}(Y, \boldsymbol{r}_\perp) + \frac{\alpha_S N_C \Delta Y}{2\pi^2}\int_{\boldsymbol{r}_{1\perp}} \frac{\boldsymbol{r}_\perp^2}{\boldsymbol{r}_{1\perp}^2 \boldsymbol{r}_{2\perp}^2}[\mathcal{S}(Y, \boldsymbol{r}_{1\perp}) \times \mathcal{S}(Y, \boldsymbol{r}_{2\perp}) - \mathcal{S}(Y, \boldsymbol{r}_\perp)]$$

- Taking the limit $\Delta Y \to 0$ we derive the equation
- Equation resums all powers of $\alpha_S Y$!



- Extracting the real and imaginary part of the equation ($\mathcal{N} = 1 - \mathcal{P}$):

$$\frac{\partial \mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)}{\partial Y} = \frac{\alpha_S N_C}{2\pi^2} \int_{r_{1\perp}} \frac{\boldsymbol{r}_\perp^2}{\boldsymbol{r}_{1\perp}^2 \boldsymbol{r}_{2\perp}^2} [\mathcal{N}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp) + \mathcal{N}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) - \mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$$
$$+\mathcal{N}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp)\mathcal{N}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) - \mathcal{O}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp)\mathcal{O}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp)$$

$$\frac{\partial \mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)}{\partial Y} = \frac{\alpha_S N_C}{2\pi^2} \int_{r_{1\perp}} \frac{\boldsymbol{r}_\perp^2}{\boldsymbol{r}_{1\perp}^2 \boldsymbol{r}_{2\perp}^2} [\mathcal{O}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp) + \mathcal{O}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) - \mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$$
$$-\mathcal{N}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp)\mathcal{O}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) - \mathcal{O}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp)\mathcal{N}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp)$$

Y.V. Kovchegov, L. Szymanowski and S. Wallon, PLB **586**, 267 (2004).

T. Lappi, A. Ramnath, K. Rummukainen and H. Weigert, PRD **94**, 054014 (2016).

Y. Hatta, E. Iancu, K. Itakura and L. McLerran, NPA **760**, 172 (2005).

- Pomeron-Odderon evolution is coupled!

Limiting solutions:

1. Big $r_\perp$ limit: $\mathcal{N} \to 1$

   $\mathcal{O} \propto \mathrm{e}^{-cY}$

2. Small $r_\perp$ limit: decoupling

   $\mathcal{O} \propto \mathrm{e}^{-cY}$

- To solve equations, we need initial conditions!
  - Pomeron: proton and nucleus
  - Odderon: proton and nucleus

Pomeron initial conditions:

T. Lappi and H. Mäntysaari, PRD **88**, 114020 (2013).

- Pomeron initial condition is given by fit to HERA data for F_2 proton structure function:

Proton:

$$\mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - \exp\left[-\frac{1}{4}\boldsymbol{r}_\perp^2 Q_{0,p}^2(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)\right]$$

$$Q_{0,p}^2(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \equiv T_p(\boldsymbol{b}_\perp)\frac{\sigma_0}{2}Q_{S,0}^2 \log\left(\frac{1}{r_\perp \Lambda_{QCD}} + e_c \mathrm{e}\right)$$

$$T_p(\boldsymbol{b}_\perp) = \frac{1}{\pi R_p^2} e^{-\frac{\boldsymbol{b}_\perp^2}{R_p^2}}$$

Nucleus:

$$\mathcal{N}(r_\perp, b_\perp) = 1 - \exp\left[-\frac{1}{4} r_\perp^2 Q_{0,A}^2(r_\perp, b_\perp)\right]$$

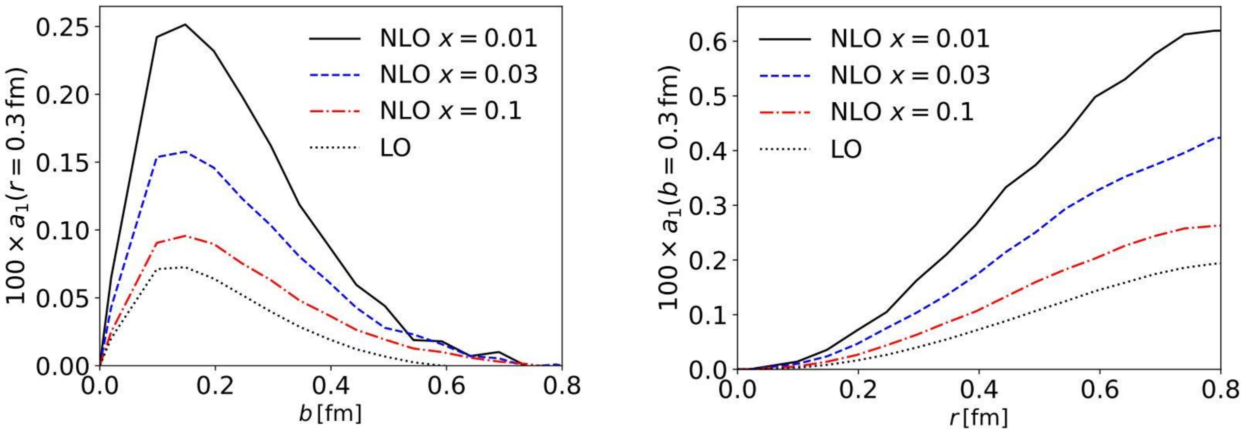
$$Q_{0,A}^2(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \equiv A T_A(\boldsymbol{b}_\perp)\frac{\sigma_0}{2}Q_{S,0}^2 \log\left(\frac{1}{r_\perp \Lambda_{QCD}} + e_c \mathrm{e}\right)$$

$$T_A(\boldsymbol{b}_\perp) = \int_{-\infty}^{\infty} \mathrm{d}z \frac{n_A}{1 + \exp\left[\frac{\sqrt{(\boldsymbol{b}_\perp^2 + z^2} - R_A}{d}\right]}$$

Odderon initial conditions:

Proton (DMP):

- We use recent Odderon model calculated from quark light-cone wavefunctions at NLO
  - DMP model!



- For initial condition we use $x = 0.01$
- Functional dependance obtained by interpolation on data

A. Dumitru, H. Mäntysaari and R. Paatelainen, PRD **107**, L011501 (2023).

Nuclei (JV):

- We use Jeon-Venugopalan (JV) model with the functional involving **cubic term**:

$$W[\rho] = \exp\left[-\int_{x_\perp}\left(\frac{\delta_{ab}\rho^a(\boldsymbol{x}_\perp)\rho^b(\boldsymbol{x}_\perp)}{2\mu^2}\right) - \frac{d_{abc}\rho^a(\boldsymbol{x}_\perp)\rho^b(\boldsymbol{x}_\perp)\rho^c(\boldsymbol{x}_\perp)}{\kappa}\right]$$

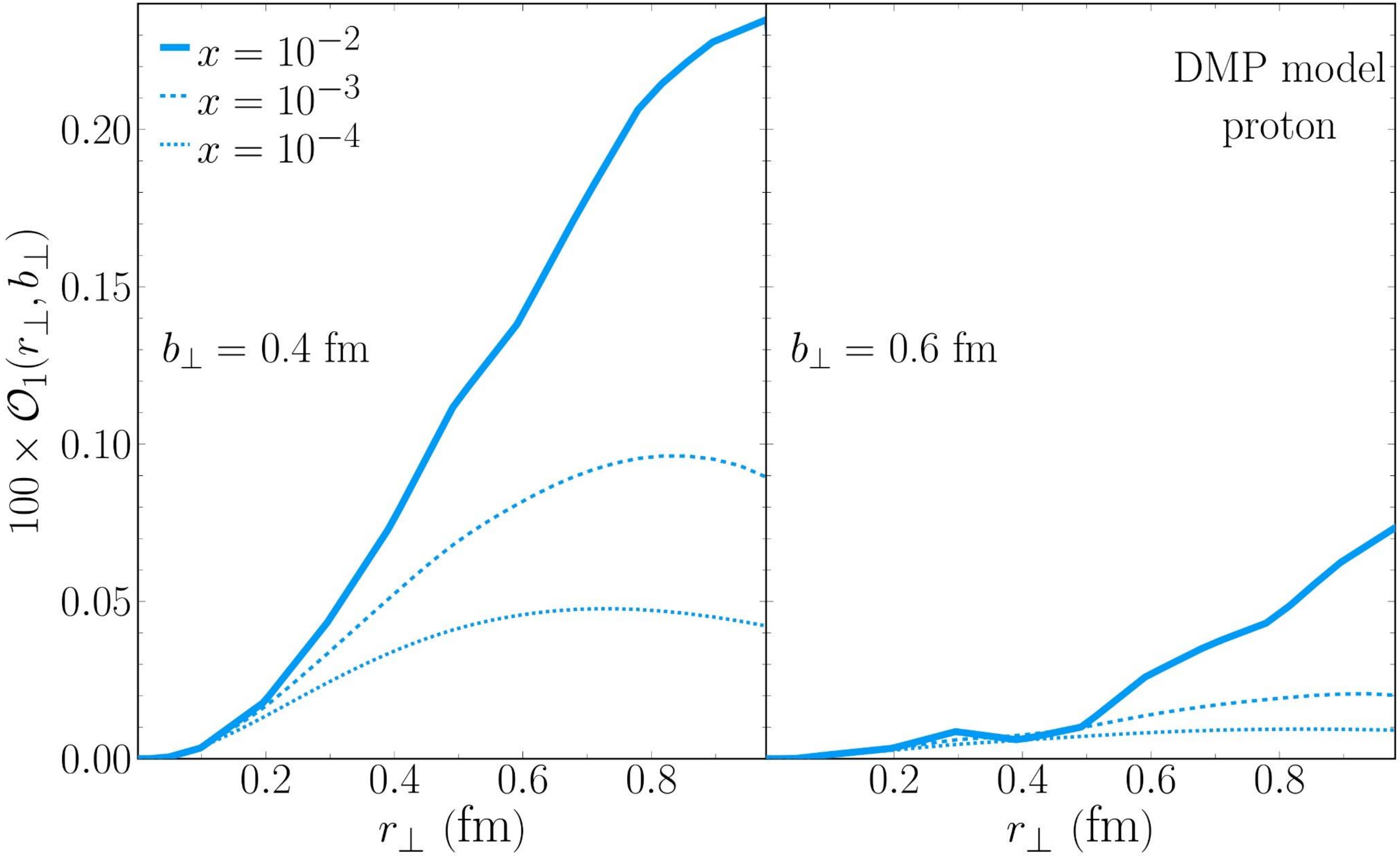
- Odderon initial condition is given by:

$$\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = \frac{\lambda_{JV}}{8}\left[R_A \frac{\mathrm{d}T_A(\boldsymbol{b}_\perp)}{\mathrm{d}b_\perp} A^{2/3}\frac{\sigma_0}{2}\right] Q_{S,0}^3 A^{1/2} r_\perp^3 (\hat{\boldsymbol{r}}_\perp \cdot \hat{\boldsymbol{b}}_\perp)$$
$$\times \log\left(\frac{1}{r_\perp \Lambda_{QCD}} + e_C \mathrm{e}\right) \exp\left[-\frac{1}{4}\boldsymbol{r}_\perp^2 Q_{0,A}^2(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)\right]$$

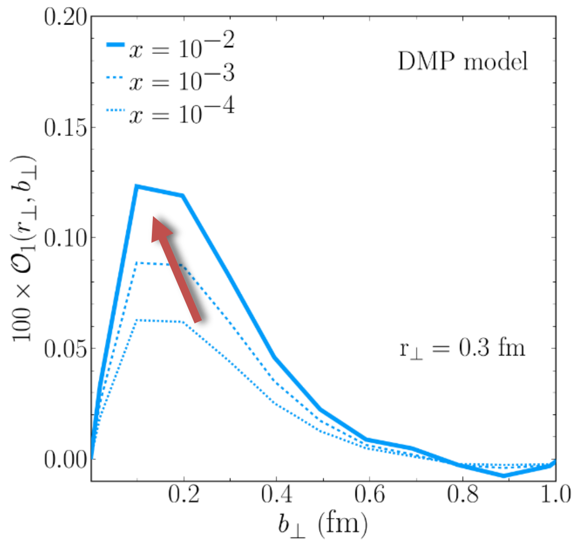
- With the coupling: $\lambda_{JV} = -\frac{3}{16}\frac{N_C^2-4}{(N_C^2-1)^2}\frac{Q_{S,0}^3 A^{\frac{1}{2}} R_A^3}{\alpha_S^3 A^2}$

S. Jeon and R. Venugopalan, PRD **71**, 125003 (2005).

Solution for proton:



- We considered $\mathcal{O}_1$ Fourier moment only (other moments are suppresed)
- Odderon is decreasing in size with evolution
- As a function of impact parameter peaks well inside the proton:



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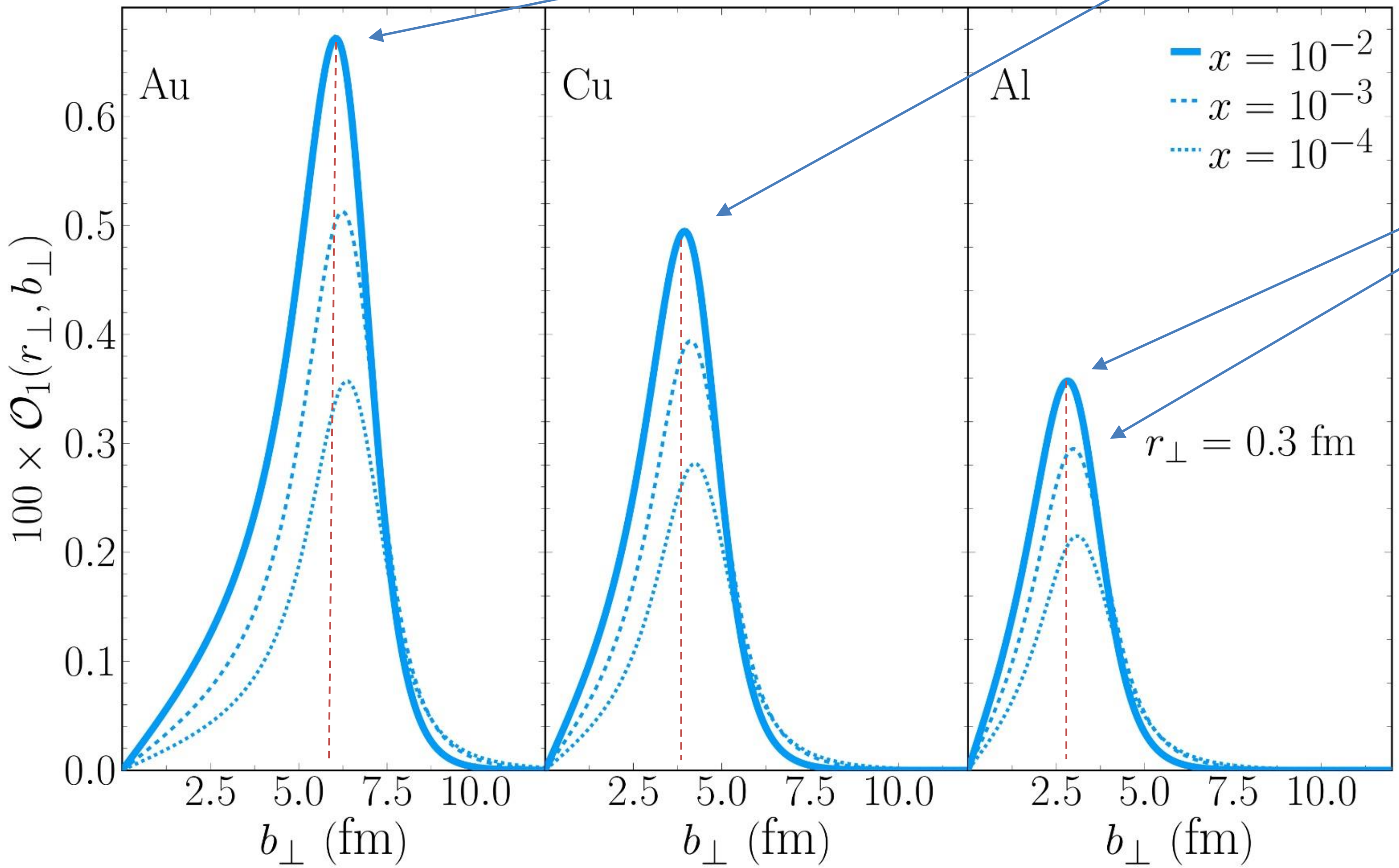
Solution for nuclei:



Nuclear effect:
Odderon peak moves to the right with increasing the atomic number A

Evolution effect:
Odderon peak slightly moves to the right with evolution

Odderon is decreasing in size with evolution

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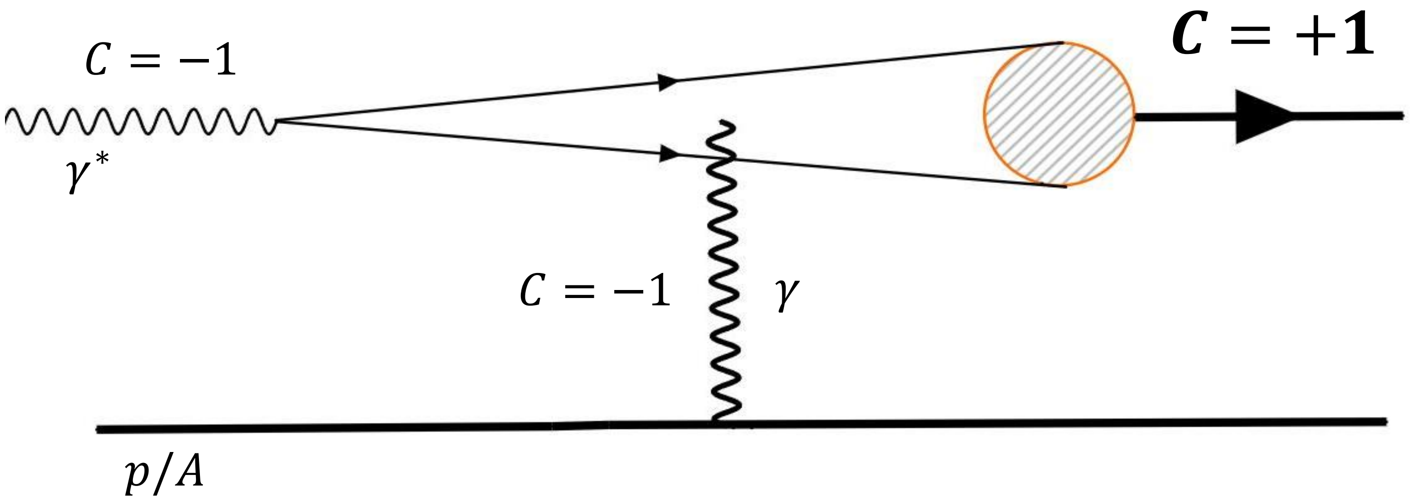
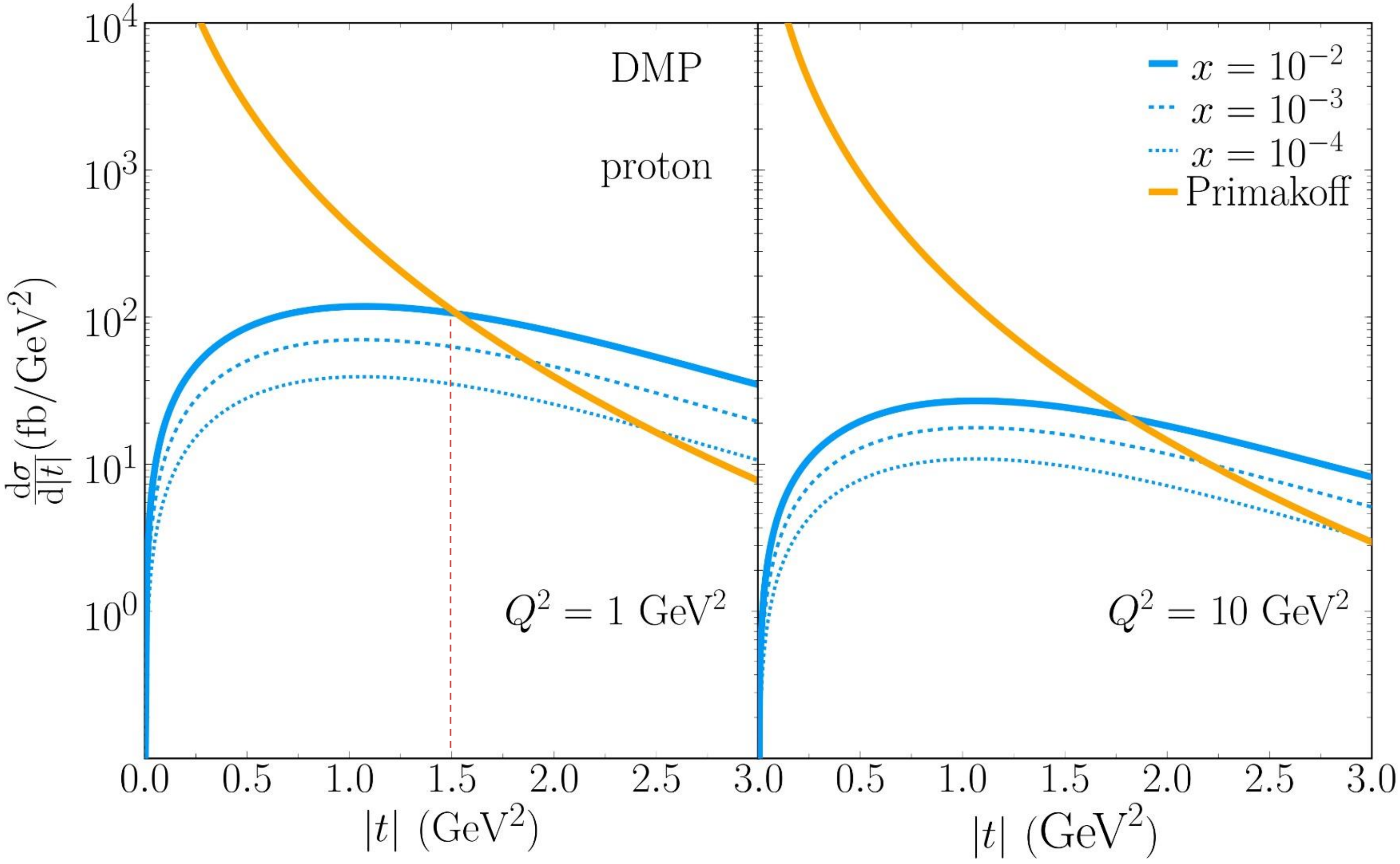
QED background:

- Since photon has negative charge parity, odd numbers of photons can also be exchanged to produce $C = +1$ meson
- More photons -> suppression with extra power of α_{QED}



- We considered exchange of one photon as an important background to odderon exchange
- In literature: Primakoff proces

Cross section results (proton):



- Small slope of odderon cross section; weak $|t|$ dependance
- Confirms previous results by Dumitru and Stebel for moderate $x \approx 0.1$
- Odderon is probed at higher $|t| \geq 1.5$ GeV^2

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- How can we suppress Primakoff contribution?
- Considering neutron targets instead of proton targets

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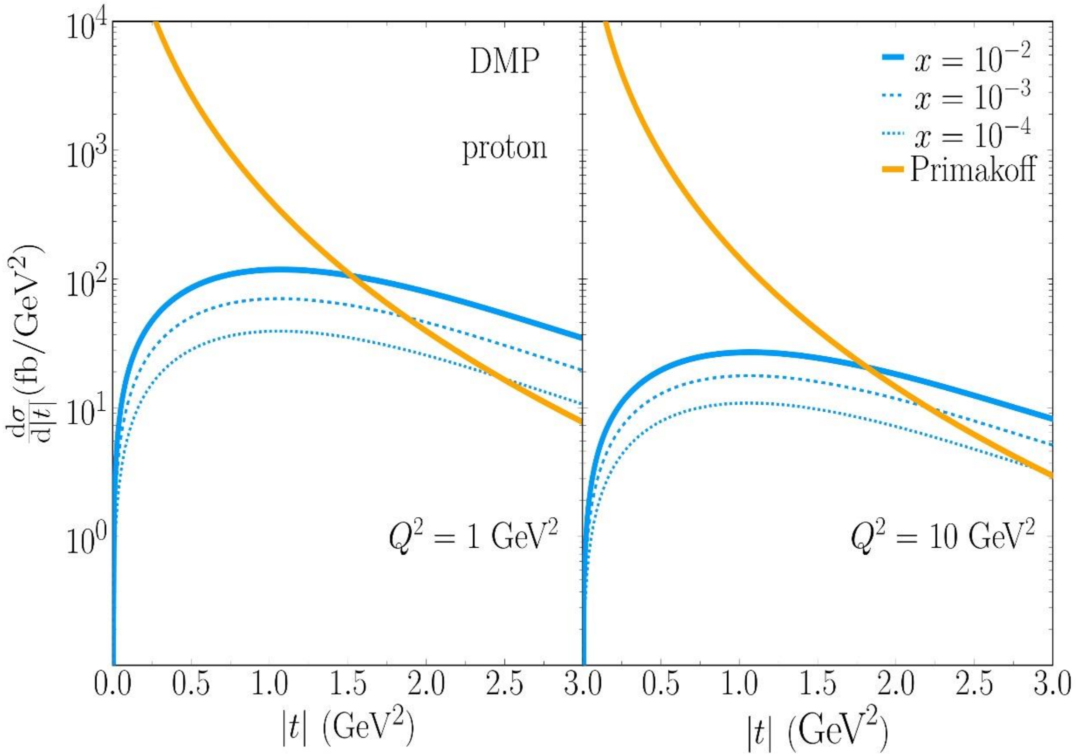

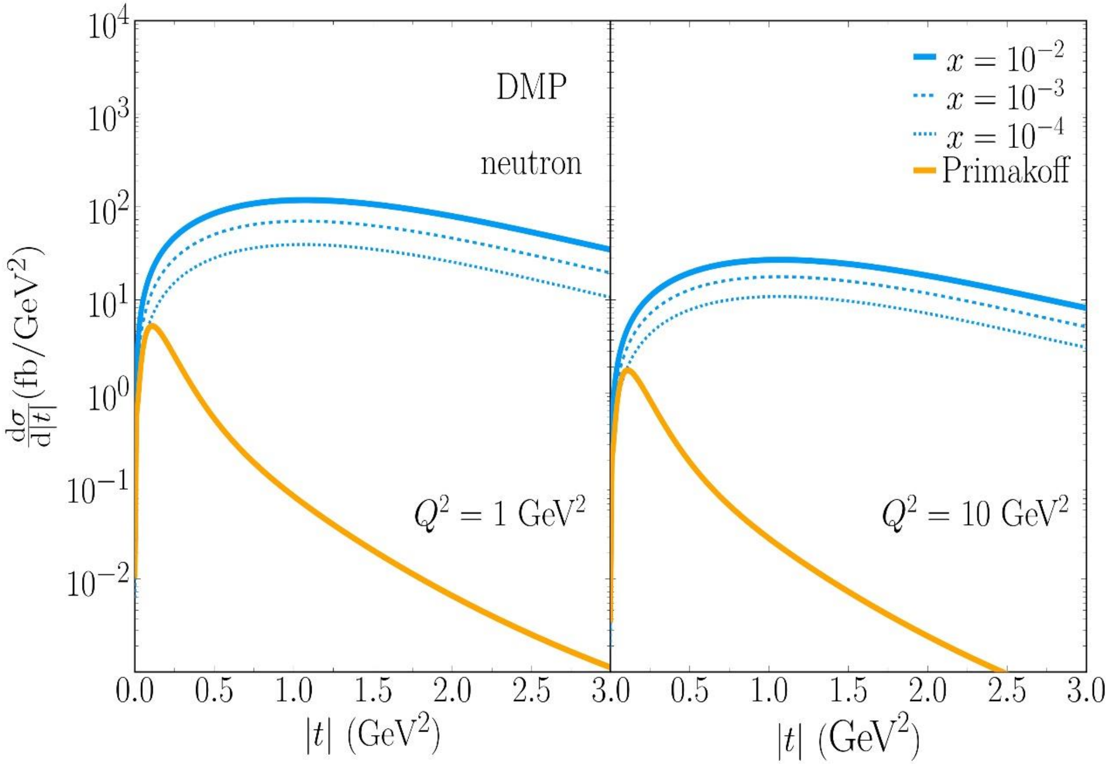

- Primakoff contribution is negligible in neutron case so we can probe the odderon even at small $|t|$
- Experimental possibilities: deuteron or He^3 (spectator proton tagging in near-forward direction)

Friščić et al., PLB **823**, 136726 (2021).

Landshoff mechanism:

A. Donnachie and P. V. Landshoff, NPB 267, 690 (1986).

A. Dumitru and T. Stebel,PRD **99**, 094038 (2019).

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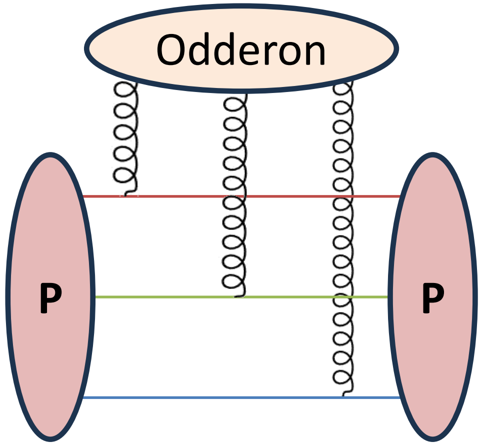
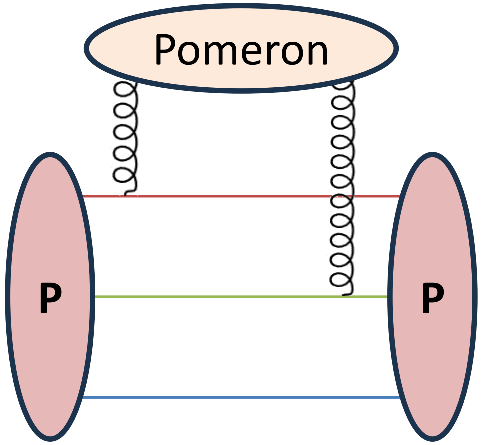
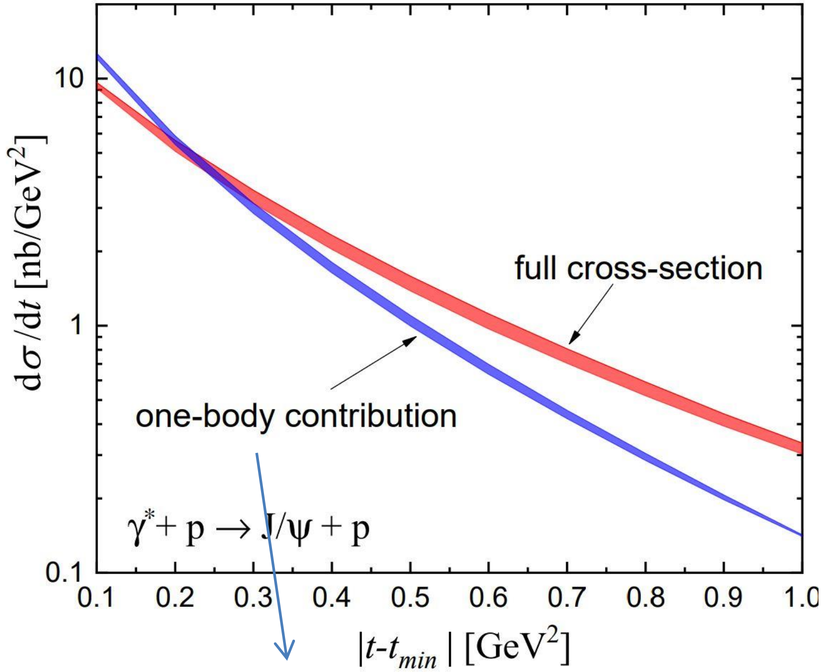
- To probe the Pomeron, we need to consider production of $\mathrm{C}=-1$ mesons
- Most work has been done on J/Ψ production
- Landshoff mechanism:

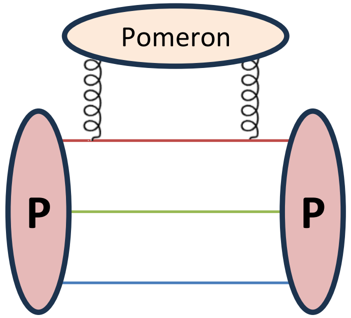


Weak $|t|$ dependence

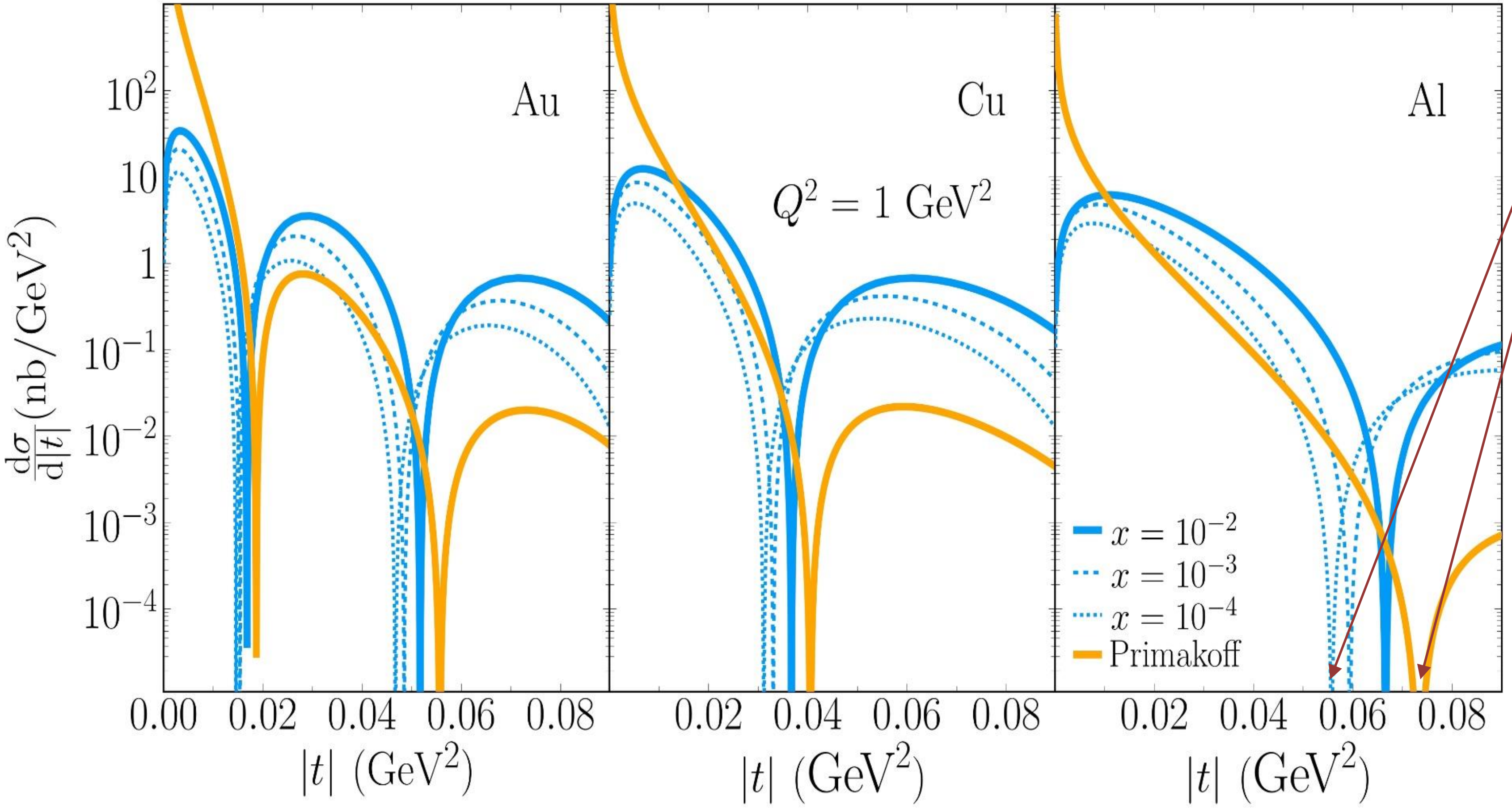


Stronger $|t|$ dependence





Cross section results (nuclei):



- Odderon cross section has shifted diffractive pattern in comparison to Primakoff
- Smaller x or larger $|t|$ means greater shift
- There is no diffractive shift at leading twist:

$$\frac{d\sigma}{d|t|_{\mathcal{O}}} \propto |t| T_A^2\left(\sqrt{|t|}\right) \qquad \frac{d\sigma}{d|t|_{\gamma}} \propto \frac{T_A^2\left(\sqrt{|t|}\right)}{|t|}$$

- Shifts are consequence of evolution and multiple scatterings in Odderon cross section

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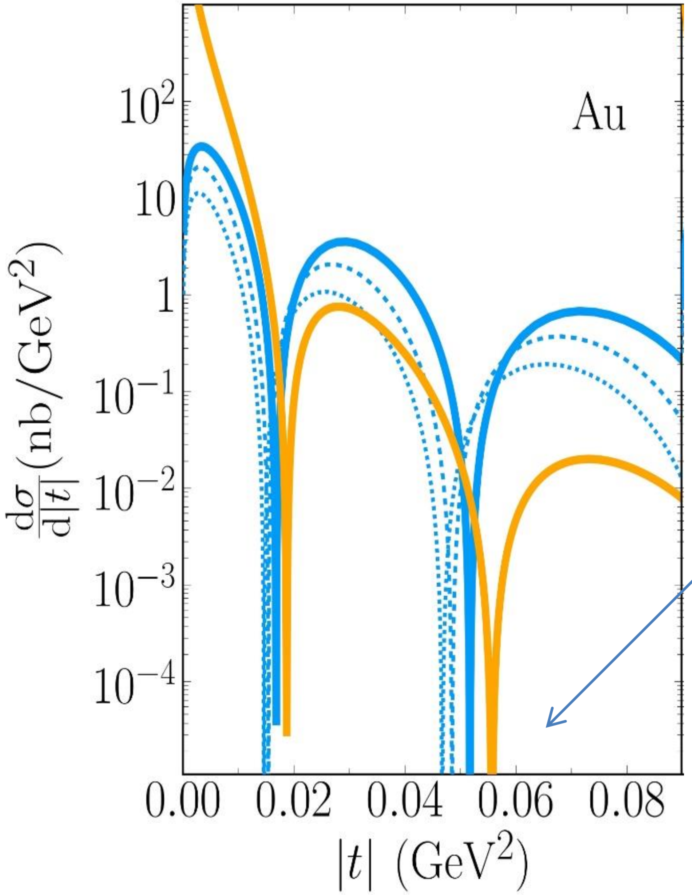
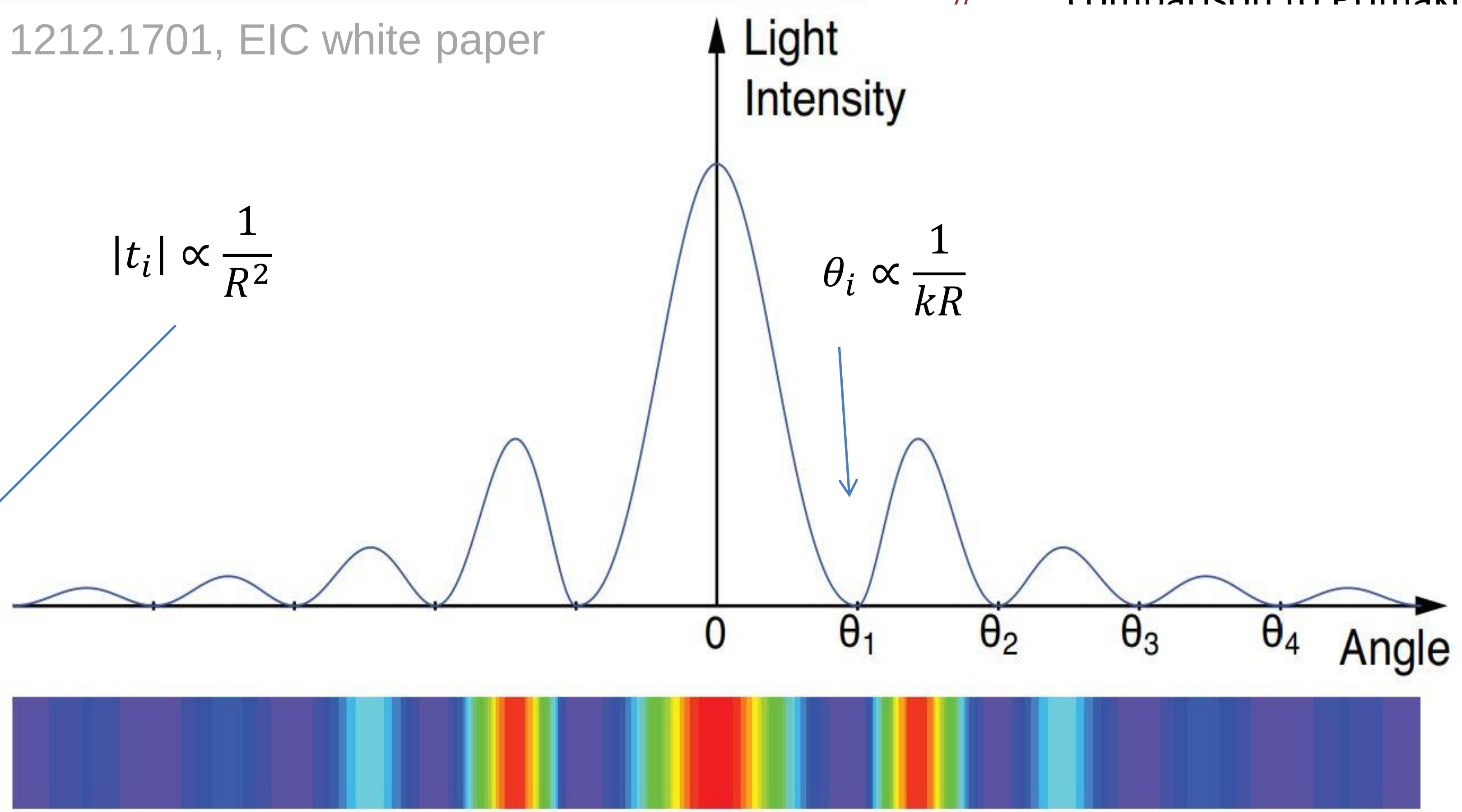


$|t_i| \propto \frac{1}{R^2}$



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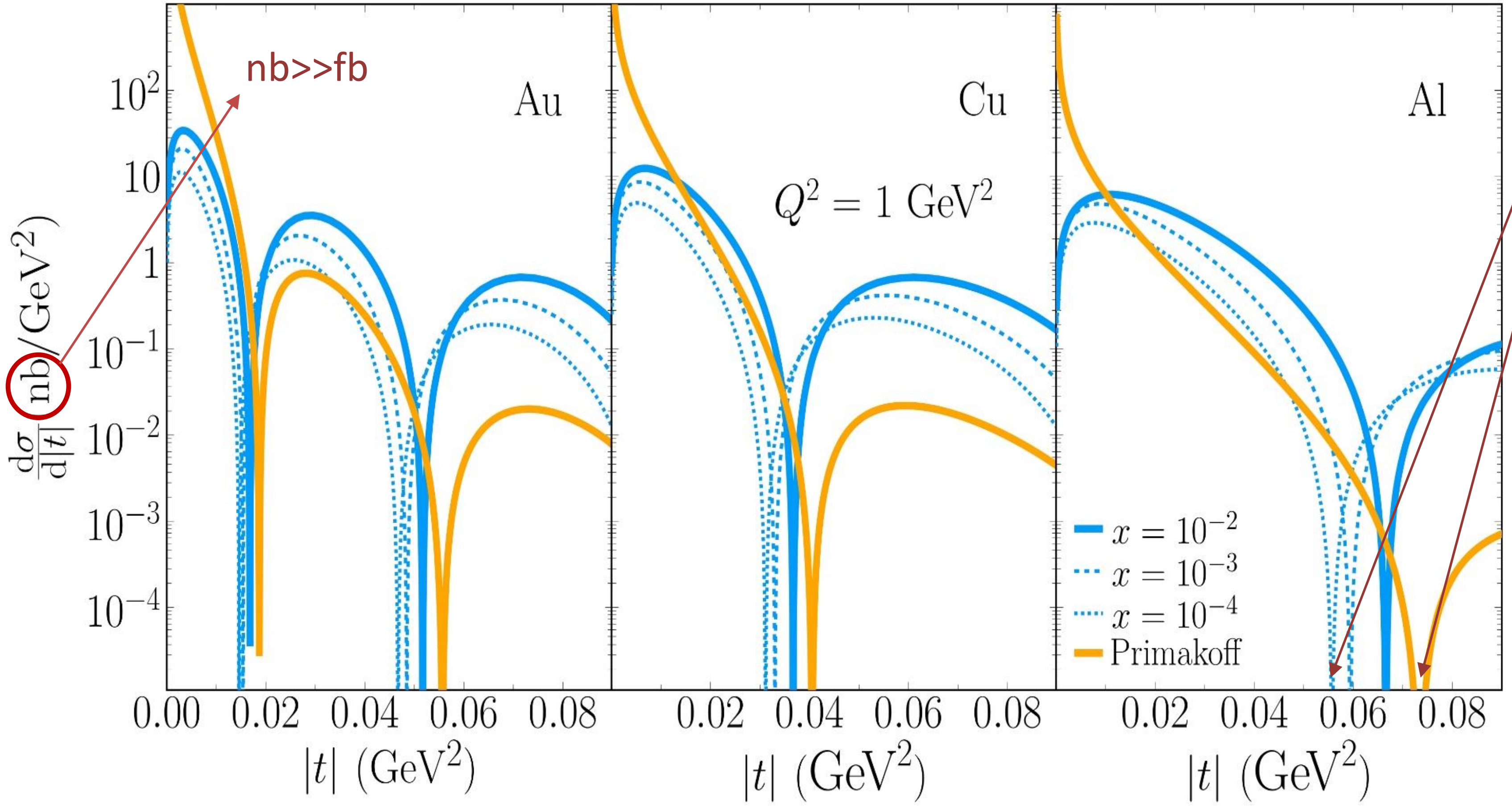

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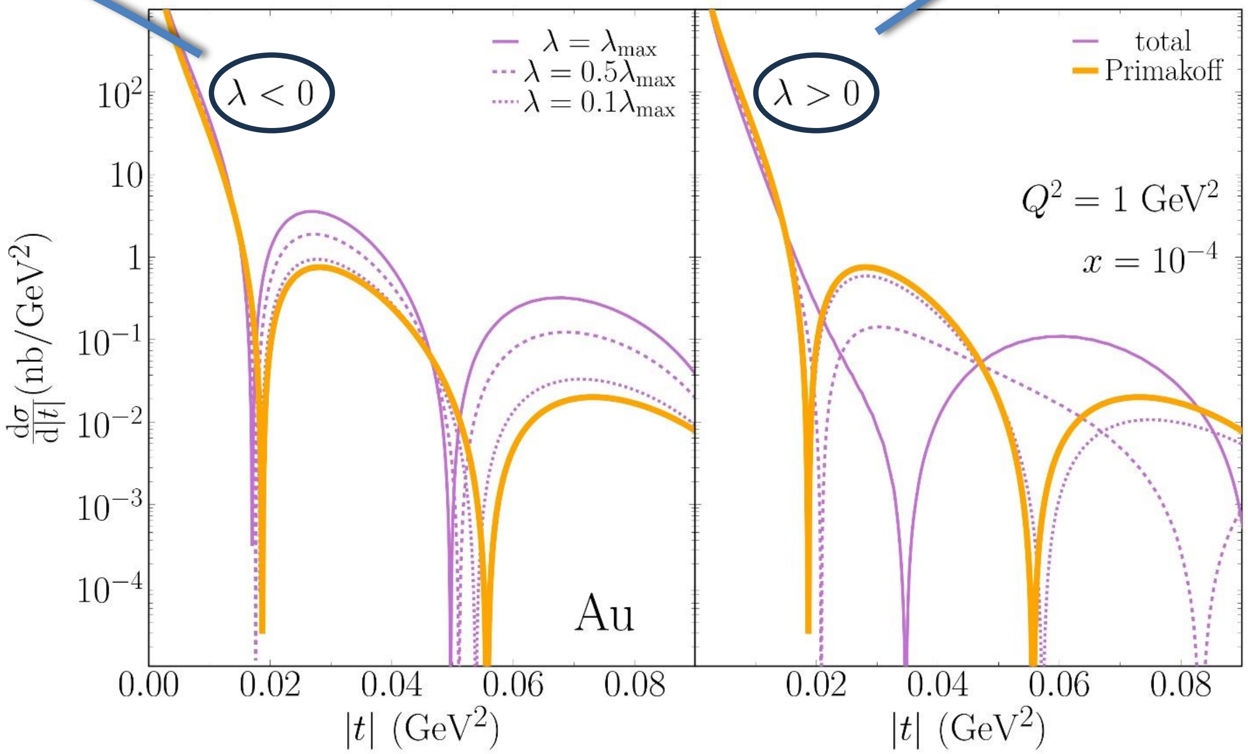
S. Benić, D. Horvatić, A. Kaushik and **E. A. Vivoda**, 2306.10626 (2023).

Odderon-Photon interference:

- Odderon and Photon amplitudes can interfere which can lead to constructive/destructive total cross section

- For $\lambda < 0$ we mostly observe constructive interference

- Altering the size of λ can slightly change diffractive pattern relative to Primakoff



- For $\lambda > 0$ we mostly observe destructive interference

- Total cross section can be severely lower then the Primakoff (depends on λ)

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Conclusions:

1. For proton target:
   - Odderon cross section becomes dominant in higher $|t|$ region (this behavior is not affected by evolution)
   - Odderon is decreased in size by evolution
   - Cross section has weak $|t|$ dependance
2. For neutron target:
   - Primakoff contribution is negligible
   - Problem with experimental implementation (possible He^3 or deuteron)
   - Useful to probe the odderon at low $|t|$
3. For nucleus targets:
   - Diffractive shifts that depend on x, $|t|$ and nuclear number A
   - Possible constructive/destructive interference with Primakoff
   - Greater cross section!

➢ **Can η_C be measured at the future EIC?!**

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Thank you!

➢ **Can η_C be measured at the future EIC?!**