Imaging the Odderon from exclusive η_c production at the EIC

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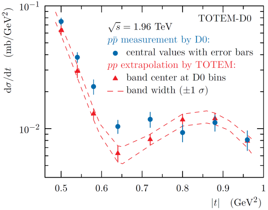
SB, Horvatić, Kaushik, Vivoda, 2306.10626

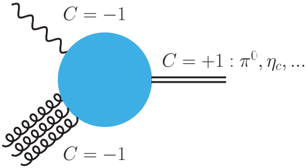
Low-x, Leros, Greece, September 4, 2023

HRZZ Croatian Science Foundation

Odderon

- 50 years ago Lukaszuk, Nicolescu: odderon is a $C = -1$ exchange
  Lukaszuk, Nicolescu, LNC 8 (1973) 405
  Joynson, Leader, Nicolescu, Lopez, NCA 30 (1975) 345
  Ewerz, 0306137
- QCD: three gluons $\mathrm{tr}_c\,[\{A^\mu, A^\nu\}A^\rho] \sim d_{abc}$





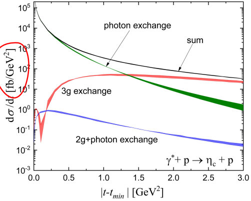
- elastic pp vs $p\bar{p}$
- Odderon found → QCD?
  TOTEM, D0, PRL 127 (2021) 6, 062003
  Royon, Monday, Sep. 4, 14:00
- ep collisions
- exclusive productions of C-even mesons
  Czyzewski, Kwiecinski, Motyka, Sadzikowski, PLB 398 400 (1997)
  Bartels, Braun, Colferai, Vacca, EPJC 20 323 (2001)

Odderon in $ep \to ep\eta_c$

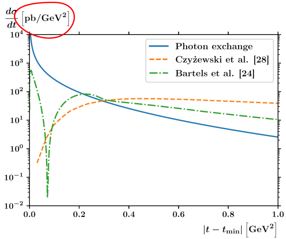
- no experimental confirmation so far
  $\to$ EIC, LHC UPCs?

  (null result from H1 at HERA: $\sigma(\gamma^* p \to \pi^0 N^*) < 49\text{nb}$)
  H1, PLB 544 (2002) 35-43

- more recent computations at moderate $x \sim 0.1$ lead to somewhat lower cross sections than the original estimates



Dumitru, Stebel, PRD 99 (2019) 9, 094038



Jia, Mo, Pan, Zhang, PRD 108 (2023) 1, 016015

- this work: take into account evolution effects and consider nuclear targets

Odderon in the CGC

- high energy collisions $\rightarrow$ Wilson lines

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

- Color Glass Condensate (CGC): emergence of a saturation scale $Q_S^2 \sim A^{1/3}$

  $\rightarrow$ better theoretical control for a large nuclei $Q_S^2 \gg \Lambda^2_{\mathrm{QCD}}$

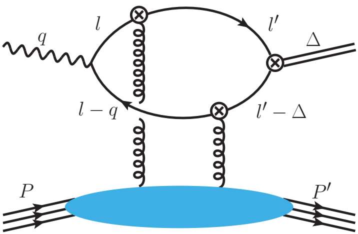
- odderon as imaginary part of the dipole

$$\mathcal{O}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) \equiv -\frac{1}{2iN_c} \mathrm{tr} \left\langle V(\boldsymbol{x}_\perp) V^\dagger(\boldsymbol{y}_\perp) - V(\boldsymbol{y}_\perp) V^\dagger(\boldsymbol{x}_\perp) \right\rangle$$

- C-odd: $\boldsymbol{x}_\perp \leftrightarrow \boldsymbol{y}_\perp$ $\mathcal{O}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) \rightarrow -\mathcal{O}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp)$

  Kovchegov, Szymanowski, Wallon, PLB 586, 267 (2004)
  Hatta, Iancu, Itakura, McLerran, Nucl.Phys.A 760 (2005) 172-207

Amplitude



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

$$\boldsymbol{b}_\perp \equiv \frac{\boldsymbol{x}_\perp + \boldsymbol{y}_\perp}{2}$$

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

- CGC vertex

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

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

Amplitude

- only transverse photon polarizations $\lambda = \pm 1$ survive in the eikonal approximation

$$\langle \mathcal{M}_\lambda \rangle = q^- \lambda e^{i\lambda\phi_\Delta} \langle \mathcal{M} \rangle \qquad \frac{d\sigma}{d|t|} = \frac{1}{16\pi} |\langle \mathcal{M} \rangle|^2$$

- polarization independent part of the amplitude

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

- result proportional to m_c

$$\mathcal{A}(\boldsymbol{r}_\perp) = (-1) \frac{\sqrt{2} m_c}{2\pi} \frac{1}{z\bar{z}} \left[K_0(\varepsilon r_\perp) \partial_{r_\perp} \phi_{\mathcal{P}}(z, r_\perp) - \varepsilon K_1(\varepsilon r_\perp) \phi_{\mathcal{P}}(z, r_\perp) \right]$$

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SB, Horvatić, Kaushik, Vivoda, 2306.10626

BK equation

- odderon $\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$ is explicitly $b_\perp$-dependent

  $\rightarrow$ in principle need to solve the fully impact parameter dependent Balitsky-Kovchegov (BK) equation

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

$$\boldsymbol{r}_{2\perp} = \boldsymbol{r}_\perp - \boldsymbol{r}_{1\perp} \quad \boldsymbol{b}_{1\perp} = \boldsymbol{b}_\perp + \frac{1}{2}(\boldsymbol{r}_\perp - \boldsymbol{r}_{1\perp}) \quad \boldsymbol{b}_{2\perp} = \boldsymbol{b}_\perp - \frac{1}{2}\boldsymbol{r}_{1\perp} \quad Y = \ln(1/x)$$

$$\mathcal{D}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = \frac{1}{N_c} \mathrm{tr} \left\langle V\left(\boldsymbol{b}_\perp + \frac{\boldsymbol{r}_\perp}{2}\right) V^\dagger\left(\boldsymbol{b}_\perp - \frac{\boldsymbol{r}_\perp}{2}\right)\right\rangle$$
$$= 1 - \mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) + i\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$$

- in general non-local in $\boldsymbol{b}_\perp$

- this work: local approximation $\rightarrow$ $b_\perp$ becomes an external parameter

  Kowalski, Lappi, Marquet, Venugopalan, PRC 78 (2008) 045201
  Lappi, Mäntysaari, PRD 88 (2013) 114020

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$$\boldsymbol{r}_{2\perp} = \boldsymbol{r}_\perp - \boldsymbol{r}_{1\perp} \quad \boldsymbol{b}_{1\perp} = \boldsymbol{b}_\perp \qquad \boldsymbol{b}_{2\perp} = \boldsymbol{b}_\perp \qquad Y = \ln(1/x)$$

$$\mathcal{D}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = \frac{1}{N_c} \mathrm{tr} \left\langle V\left(\boldsymbol{b}_\perp + \frac{\boldsymbol{r}_\perp}{2}\right) V^\dagger\left(\boldsymbol{b}_\perp - \frac{\boldsymbol{r}_\perp}{2}\right)\right\rangle$$
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  Kowalski, Lappi, Marquet, Venugopalan, PRC 78 (2008) 045201
  Lappi, Mäntysaari, PRD 88 (2013) 114020

BK equation

- non-linear terms couple the Pomeron-Odderon system

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

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

Kovchegov, Szymanowski, Wallon, PLB 586, 267 (2004)
Hatta, Iancu, Itakura, McLerran, NPA 760 (2005) 172-207
Motyka, PLB 637, 185 (2006)
Lappi, Ramnath, Rummukainen, Weigert, PRD 94, 054014 (2016)
Yao, Hagiwara, Hatta, PLB 790 (2019) 361-366

- small $r_\perp$ limit: $\mathcal{N} \to 0$ (linear) $\to \mathcal{O} \sim e^{-\# Y}$
- large $r_\perp$ limit: $\mathcal{N} \to 1$ (saturation) $\to \mathcal{O} \sim e^{-\# Y}$
- in numerical computations we are replacing $\frac{\alpha_S N_c}{2\pi^2}\frac{\boldsymbol{r}_\perp^2}{\boldsymbol{r}_{1\perp}^2 \boldsymbol{r}_{2\perp}^2}$ by a running coupling kernel with Balitsky's prescription

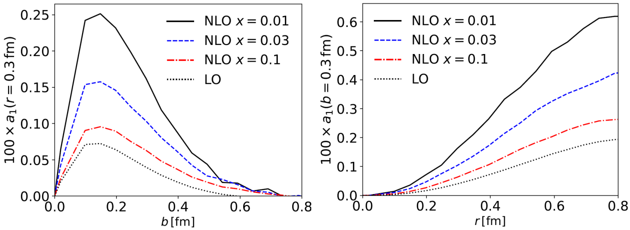
Initial condition for proton

- $\mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$: HERA fit

$$\mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - \exp\left[-\frac{1}{4}\boldsymbol{r}_\perp^2\, T_p(\boldsymbol{b}_\perp)\frac{\sigma_0}{2}\, Q_{S,0}^2 \log\left(\frac{1}{r_\perp \Lambda_{\rm QCD}} + e_c e\right)\right]$$

Lappi, Mäntysaari, PRD 88 (2013) 114020

- $\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$: recent computation starting from quark light-cone wavefunctions at NLO by Dumitru, Mäntysaari, Paatelainen (DMP)



Dumitru, Mäntysaari, Paatelainen, PRD 105 (2022) 3, 036007
Dumitru, Mäntysaari, Paatelainen, PRD 107 (2023) 1, L011501

Initial conditions for nuclei

- $\mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$ same HERA fit + optical Glauber

$$\mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - \exp\left[-\frac{1}{4}\boldsymbol{r}_\perp^2 A T_A(\boldsymbol{b}_\perp)\frac{\sigma_0}{2} Q_{S,0}^2 \log\left(\frac{1}{r_\perp \Lambda_{\rm QCD}} + e_c e\right)\right]$$

Lappi, Mäntysaari, PRD 88 (2013) 114020

- for $\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$ we use the Jeon-Venugopalan (JV) model

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

Jeon, Venugopalan, PRD 71 (2005) 125003

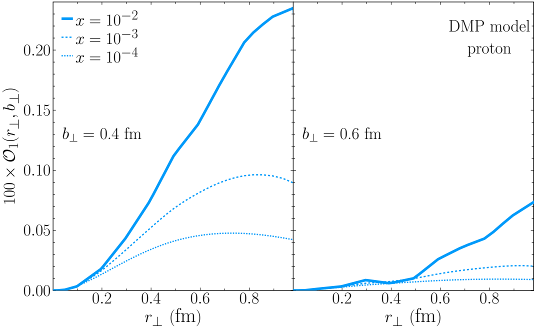
$$\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = \frac{\lambda}{8}\left[A^{2/3}\frac{dT_A(\boldsymbol{b}_\perp)}{db_\perp} R_A \frac{\sigma_0}{2}\right] A^{1/2}(Q_{S,0} r_\perp)^3 (\hat{\boldsymbol{r}}_\perp \cdot \hat{\boldsymbol{b}}_\perp)$$
$$\times \log\left(\frac{1}{r_\perp \Lambda_{QCD}}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

- in the JV model $\lambda_{\rm JV} = -\frac{3}{16}\frac{N_c^2-4}{(N_c^2-1)^2}\frac{(Q_{S,0}R_A)^3}{\alpha_S^3 A^{3/2}}$

Kovchegov, Sievert, PRD 86 (2012) 034028
Boer, Van Daal, Mulders, Petreska, JHEP 07, 140 (2018)
SB, Horvatić, Kaushik, Vivoda, 2306.10626

Numerical solutions: proton

- rapid drop of the odderon with evolution
- does not obey geometric scaling

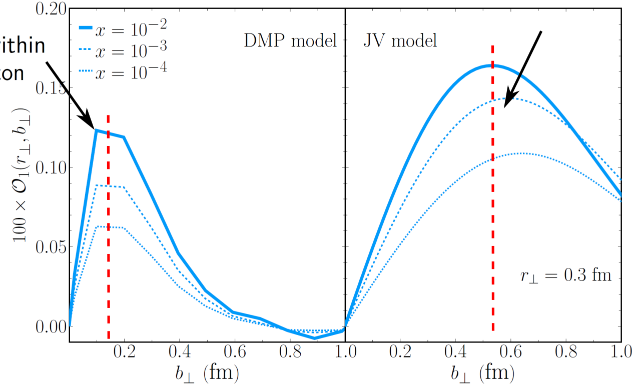


Motyka, PLB 637, 185 (2006)
Lappi, Ramnath, Rummukainen, Weigert, PRD 94, 054014 (2016)
Yao, Hagiwara, Hatta, PLB 790 (2019) 361-366
SB, Horvatić, Kaushik, Vivoda, 2306.10626

DMP vs JV for proton

peaks at the edge of the proton $\sim \frac{dT_p}{db_\perp}$

peaks within the proton



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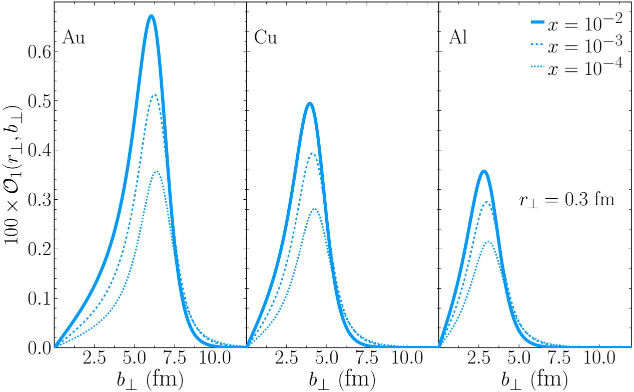
Odderon in case of nuclei

- for nuclei $T_A(\boldsymbol{b}_\perp)$ is given as a Woods-Saxon profile



- slight shift of the peak position with evolution to small-x

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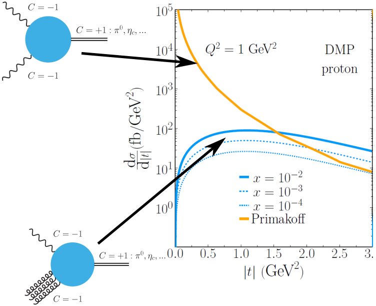
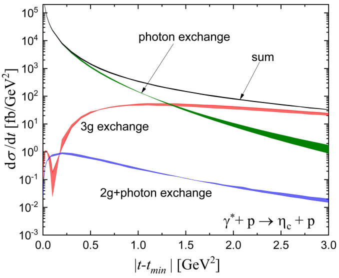
Results: proton target





$x \sim 10^{-2} - 10^{-4}$

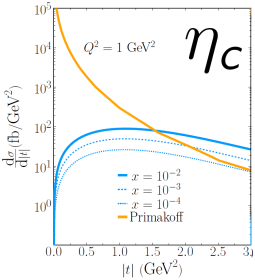
$x \sim 0.1$

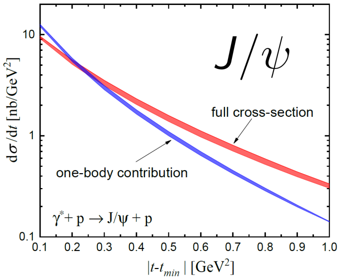
- weak $|t|$-dependence: not changed by evolution to small-x

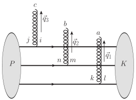
  $\rightarrow$ probes the odderon in the high $|t| > 1.5$ GeV^2 region
- confirming the general conclusions by Dumitru and Stebel

  Dumitru, Stebel, PRD 99 (2019) 9, 094038
  SB, Horvatić, Kaushik, Vivoda, 2306.10626

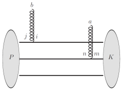
Contrast with J/Ψ







weak $|t|$ dependence



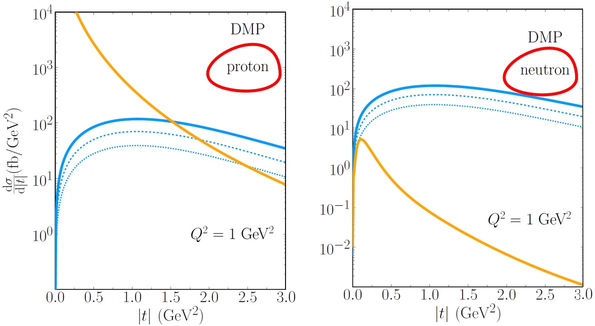
strong $|t|$ dependence

- Landshoff mechanism

Donnachie, Landshoff, Z. Phys. C 2 (1979) 55
Czyzewski, Kwiecinski, Motyka, Sadzikowski, PLB 398 400 (1997)
Dumitru, Stebel, PRD 99 (2019) 9, 094038
SB, Horvatić, Kaushik, Vivoda, 2306.10626

Results: neutron target

→ a way to suppress the Primakoff background!



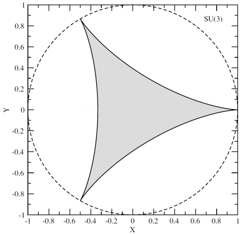
→ odderon dominance for all $|t|$!

- measurement prospect: d or ^{3}He with spectator proton forward tagging

SB, Horvatić, Kaushik, Vivoda, 2306.10626
CLAS, PRL 108, 142001 (2012)
Friščić et. al. PLB 823, 136726 (2021)

Nuclear targets: preliminary comments

- assumption: JV model captures the A-dependence, but odderon coupling has some uncertainty



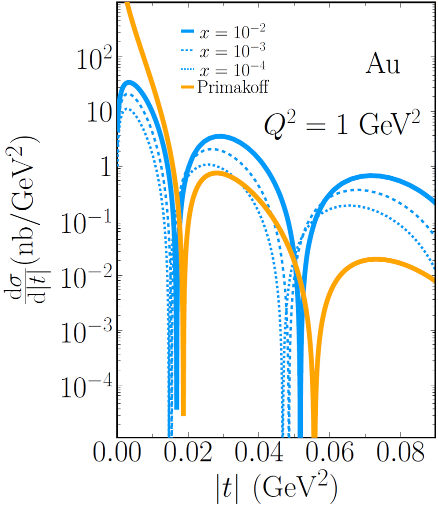
- upper bound by group theory constraint

Kaiser, JPA, 39, 15287 (2006)

Lappi, Ramnath, Rummukainen, Weigert, PRD 94, 054014 (2016)

- ultimately to be determined experimentally
- consider the odderon coupling as a free parameter

Results for nuclear targets



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- result for maximal coupling allowed by group theory
- cross section in nb/GeV^2!
- odderon contribution has a shifted diffractive pattern with respect to the Primakoff cross section
- mismatch becomes more pronounced at small-x/large $|t|$

Origin of the mismatch?

- the odderon cross section at leading twist

$$\frac{d\sigma}{d|t|} \simeq \frac{9\pi q_c^2 \alpha \alpha_S^6 A^2 C_{3F}^2 \mathcal{R}_{\mathcal{P}}^2(0)}{N_c m_c^5} \frac{|t|\, T_A^{\text{strong}}(\sqrt{|t|})^2}{m_c^4}$$

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- contrast with the Primakoff cross section

$$\frac{d\sigma}{d|t|} \simeq \frac{\pi q_c^4 \alpha^3 Z^2 N_c \mathcal{R}_{\mathcal{P}}^2(0)}{m_c^5} \frac{T_A^{\text{charge}}(\sqrt{|t|})^2}{|t|}$$

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- in our Woods-Saxon parametrizations

$$R_A^{\text{strong}} = R_A^{\text{charge}} \qquad d_A^{\text{strong}} = d_A^{\text{charge}}$$

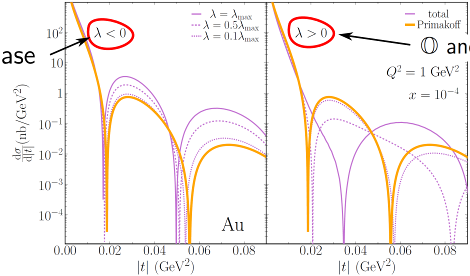
$\rightarrow$ shift is not seen at leading twist

$\rightarrow$ origin is the multiple scatterings+small-x evolution in the odderon distribution

Mismatch as odderon signature

- basic premise: locations of the Primakoff diffractive minima "known" from nuclear physics

  (any plans to measure nuclear charge FFs at the EIC?)



$\rightarrow$ odderon signature: a mismatch in the diffractive minima of the cross section w.r.t the Primakoff reference

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- large odderon coupling (λ): Primakoff diffractive dip gets washed away
- sensitivity to the sign of λ

Mismatch as odderon signature

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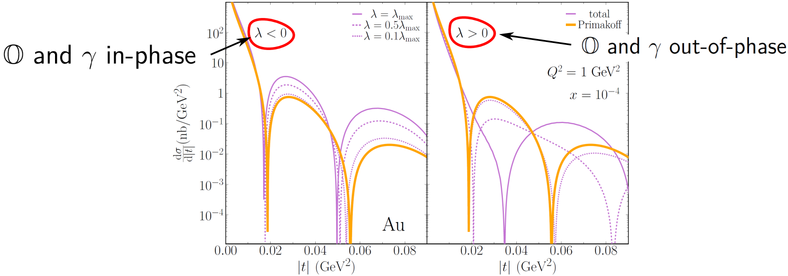
  (any plans to measure nuclear charge FFs at the EIC?)



→ odderon signature: a mismatch in the diffractive minima of the cross section w.r.t the Primakoff reference

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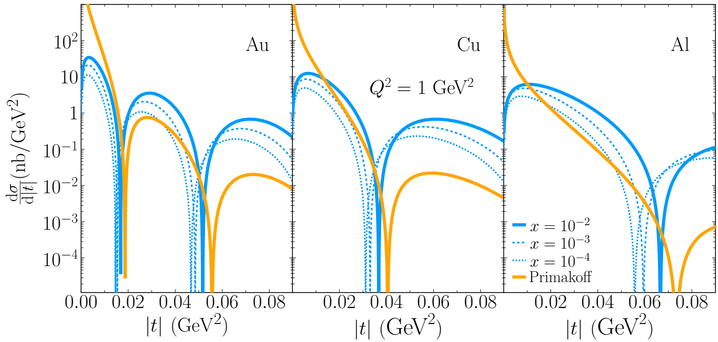
- can this be measured?
- need fine t-binning + control over incoherent contribution

Mismatch for different nuclei species



- diffractive pattern modified across nuclear species as a consequence of the geometry
- somewhat more pronounced in case of lighter nuclei
- another handle: nuclei with neutron skins

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Comments

- can η_c be measured at the EIC (or LHC)?
  $\rightarrow$ proof-of-concept results, should translate to light mesons $(\pi^0, \eta)/C$-even quarkonia states

- need to fix the odderon coupling
  $\rightarrow$ can elastic pp vs $p\bar{p}$ help?

- forward limit $|t| \rightarrow 0$ cross section vanishes
  $\rightarrow$ consider the spin-flip contribution from the gluon Sivers function
  Boussarie, Hatta, Szymanowski, Wallon, PRL 124 (2020) 17, 172501