Odderon signatures at the EIC

Sanjin Benić (University of Zagreb)

SB, Horvatić, Kaushik, Vivoda, Phys. Rev. D 108 (2023) 7, 074005

SB, Dumitru, Kaushik, Motyka, Stebel, Phys. Rev. D 110 (2024) 1, 014025

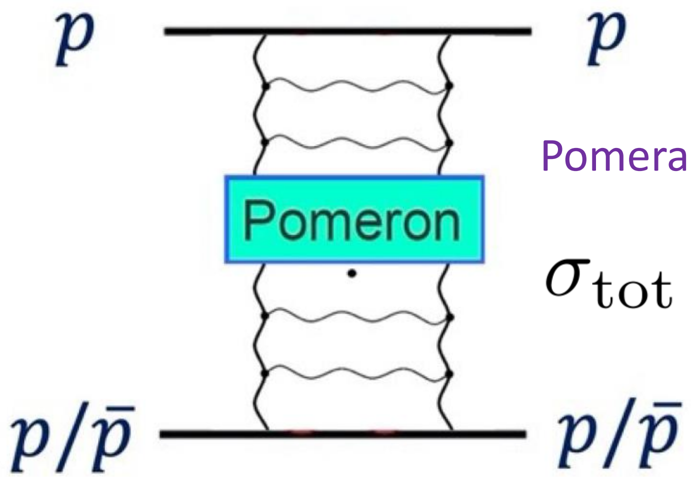
SB, Dumitru, Motyka, Stebel, 2407.04968

Exclusive, Diffraction & Tagging meeting @ BNL (online), October 21, 2024

Croatian Science Foundation

Pomeron brother: the elusive Odderon

. **colorless propagators** to govern the total cross section asymptotics



Pomeranchuk (1961)

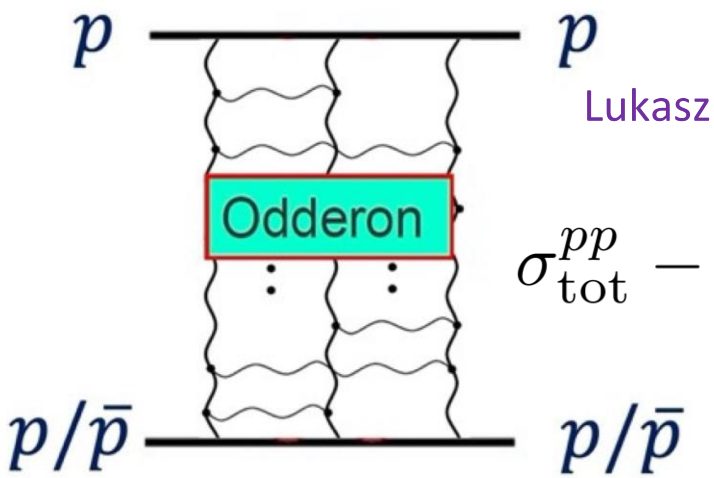
$$\sigma_{\text{tot}} \sim s^{\alpha_{\mathcal{P}}-1}$$

QCD: 2-gluon exchange

known for decades

pp: soft pomeron ✓

DIS: hard pomeron ✓



Lukaszuk, Nicolescu (1973)

$$\sigma_{\text{tot}}^{pp} - \sigma_{\text{tot}}^{p\bar{p}} \sim s^{\alpha_{\mathcal{O}}-1}$$

QCD: color symmetric 3-gluon exchange

elusive for decades

pp: soft odderon -> TOTEM/D0 (2021)

DIS: hard odderon -> **???**

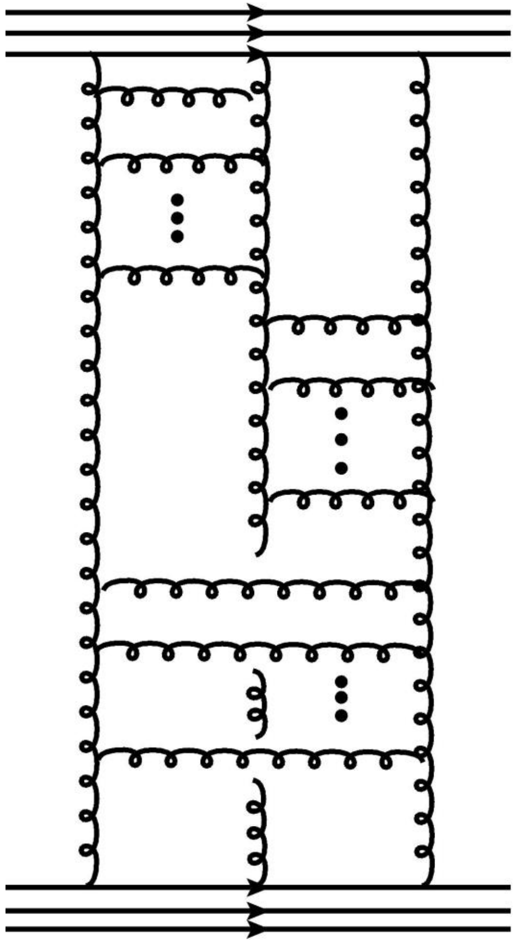
Odderon – so what?

. not just 3-gluon exchange

. probe of non-Gaussian structure in the proton at small-x

$$\mathcal{O}(\boldsymbol{q}_{1\perp}, \boldsymbol{q}_{2\perp}, \boldsymbol{q}_{3\perp}) \sim d^{abc} \langle J^{+a}(\boldsymbol{q}_{1\perp}) J^{+b}(\boldsymbol{q}_{2\perp}) J^{+c}(\boldsymbol{q}_{3\perp}) \rangle$$

Dumitru, Miller, Venugopalan (2018)



. small-x resummations: BJKP/BK equation

-> pairwise ladders between three (reggeized) gluons

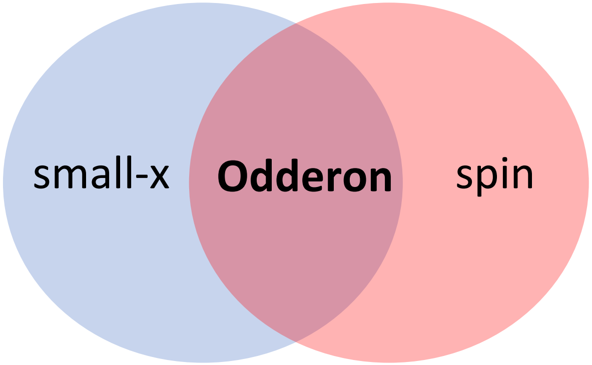
Bartels (1979)
Jaroszewicz (1980)
Kwiecinski, Praszalowicz (1980)

. connections to spin physics

Odderon at t->0 ⟷ Gluon Sivers function

$$(\boldsymbol{S}_\perp \times \boldsymbol{k}_\perp) f_{1T}^{\perp g}(x, \boldsymbol{k}_\perp)$$

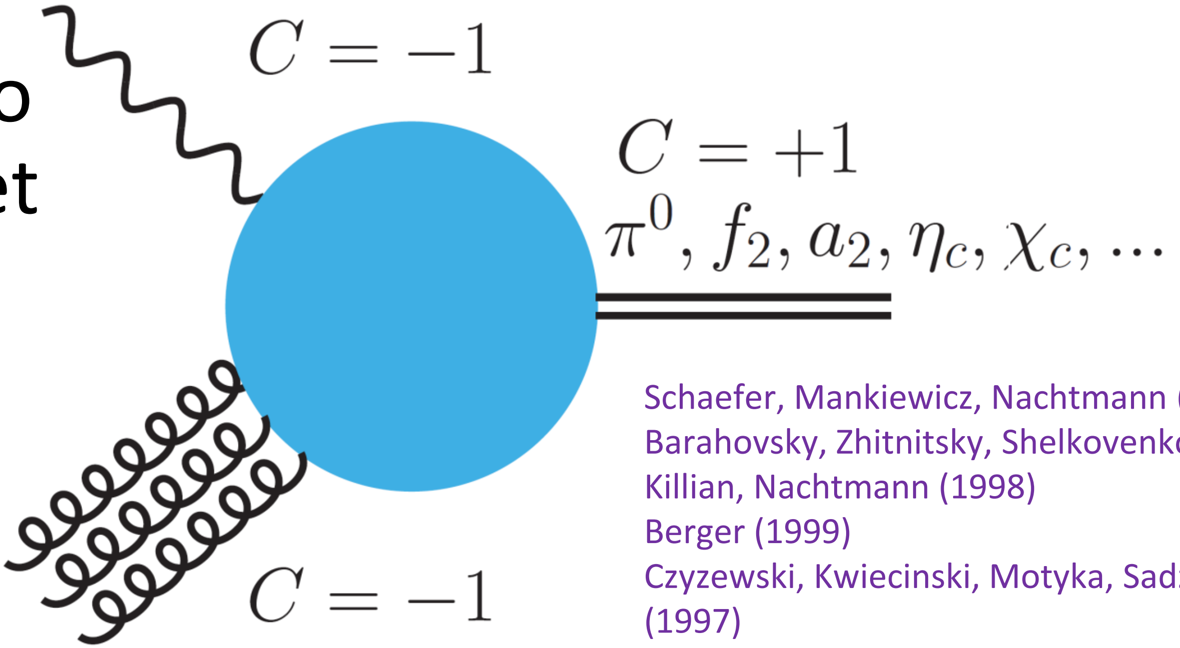
Zhou (2013)
Boer, Echevarria, Mulders, Zhou (2016)



Odderon searches in the DIS

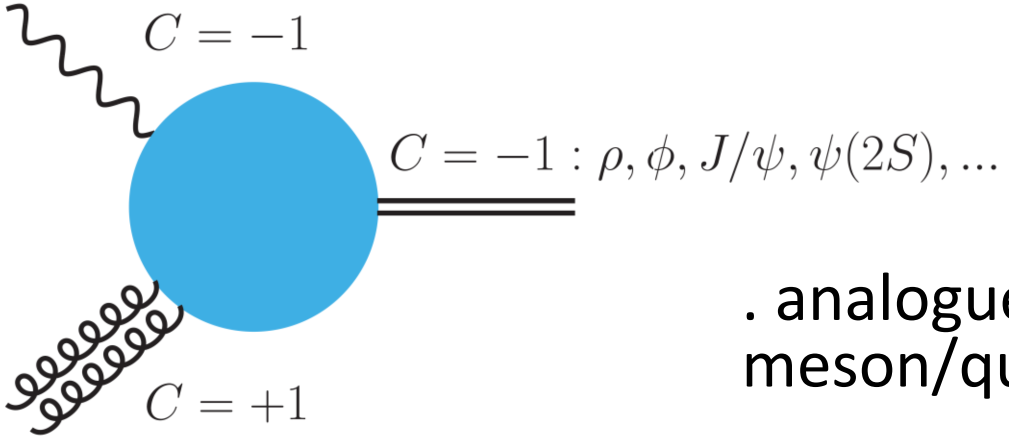
➡ perspective of discovering the **hard Odderon** in the DIS?

. exclusive reactions that tag onto the negative C-parity in the target



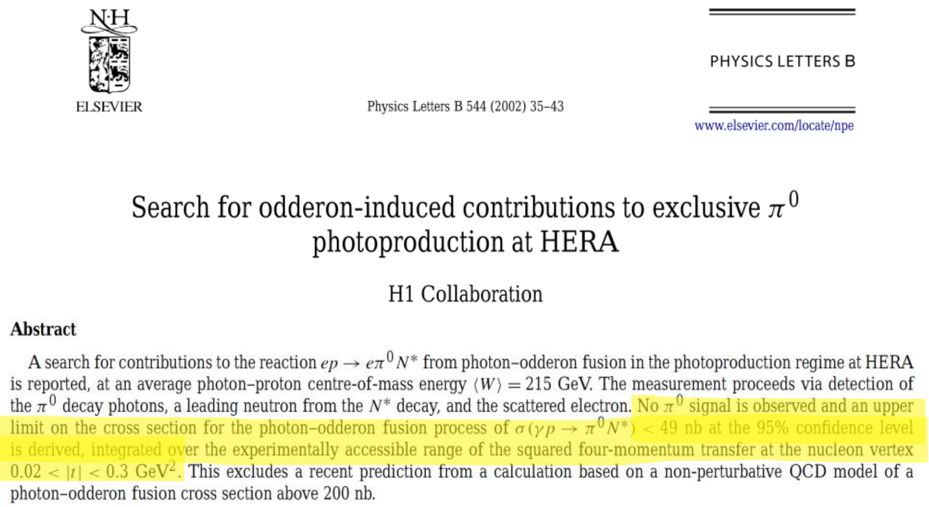
Schaefer, Mankiewicz, Nachtmann (1991)
Barahovsky, Zhitnitsky, Shelkovenko (1991)
Killian, Nachtmann (1998)
Berger (1999)
Czyzewski, Kwiecinski, Motyka, Sadzikowski (1997)
Bartels, Braun, Colferai, Vacca (2001)

. C=+1 meson/quarkonia in the final state



. analogue to exclusive C = -1 meson/quarkonia for hard Pomeron,...

HERA searches for the Odderon


Physics Letters B 544 (2002) 35–43

PHYSICS LETTERS B

www.elsevier.com/locate/npe

Search for odderon-induced contributions to exclusive π^0 photoproduction at HERA

H1 Collaboration

Abstract

A search for contributions to the reaction $ep \to e\pi^0 N^*$ from photon–odderon fusion in the photoproduction regime at HERA is reported, at an average photon–proton centre-of-mass energy $\langle W \rangle = 215$ GeV. The measurement proceeds via detection of the π^0 decay photons, a leading neutron from the N^* decay, and the scattered electron. No π^0 signal is observed and an upper limit on the cross section for the photon–odderon fusion process of $\sigma(\gamma p \to \pi^0 N^*) < 49$ nb at the 95% confidence level is derived, integrated over the experimentally accessible range of the squared four-momentum transfer at the nucleon vertex $0.02 < |t| < 0.3$ GeV^2. This excludes a recent prediction from a calculation based on a non-perturbative QCD model of a photon–odderon fusion cross section above 200 nb.

$\sigma(\gamma^* p \to \pi^0 N^*) < 39$ nb

nucleon excited to a P-wave to couple to the quasi-real transverse photon

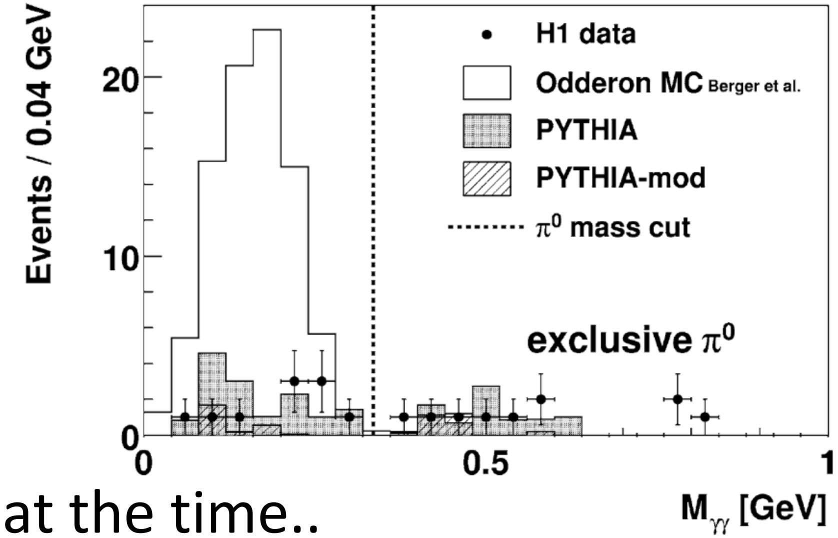
H1 (2002)

HERA kinematics:

$0.02 < |t| < 0.3$ GeV^2

$Q^2 < 0.01$ GeV^2

$\langle W \rangle \sim 200$ GeV



. about order of magnitude lower than the theory predictions at the time..

Berger (1999)

. **possible explanations**:

-> low-Q^2 -> cannot exclude non-perturbative contributions

-> energy dependence: $\sim(W^2)^{0.15}$ but in QCD Odderon is at most a constant with energy (modulo absorptive corrections)

-> strong suppression in the chiral limit $\sim (m_\pi/M_N)^4$ Ewerz, Nachtmann (2006)

Exclusive π^0 at low energy

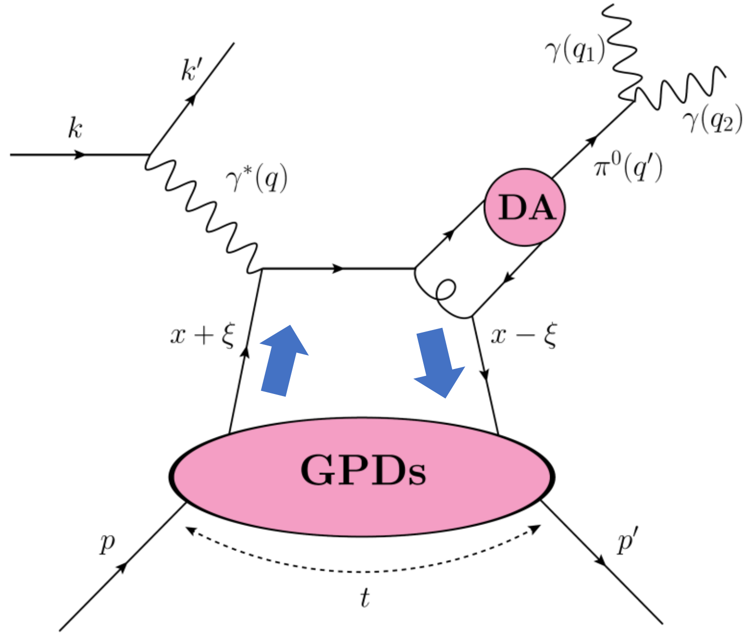
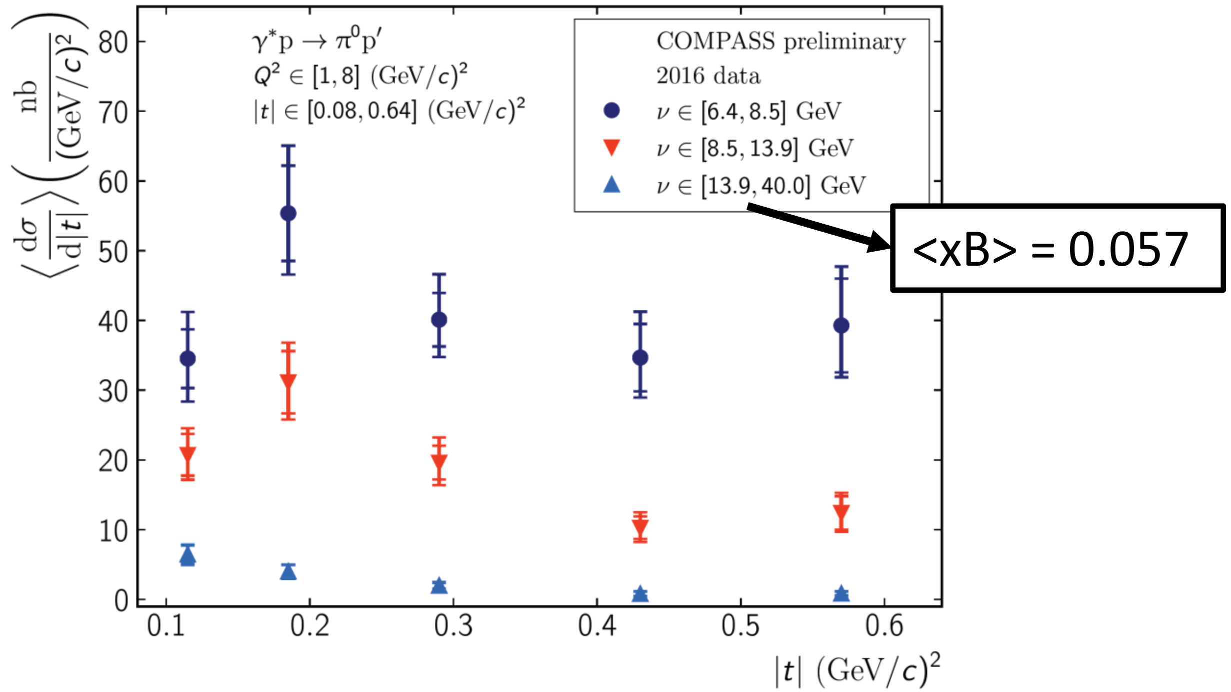


Fig. from Lavickova, Diff&Low-x 2024



sensitive to (parton) helicity-flip GPDs: H_T, E_T, $\tilde{H}_T$, $\tilde{E}_T$

forward limit: transversity PDF

Ahmad, Goldstein, Luiti (2009)
Goloskokov, Kroll (2011)
Duplancic, Kroll, Passek-Kumericki, Szymanowski (2024)

measured at COMPASS, JLab,..

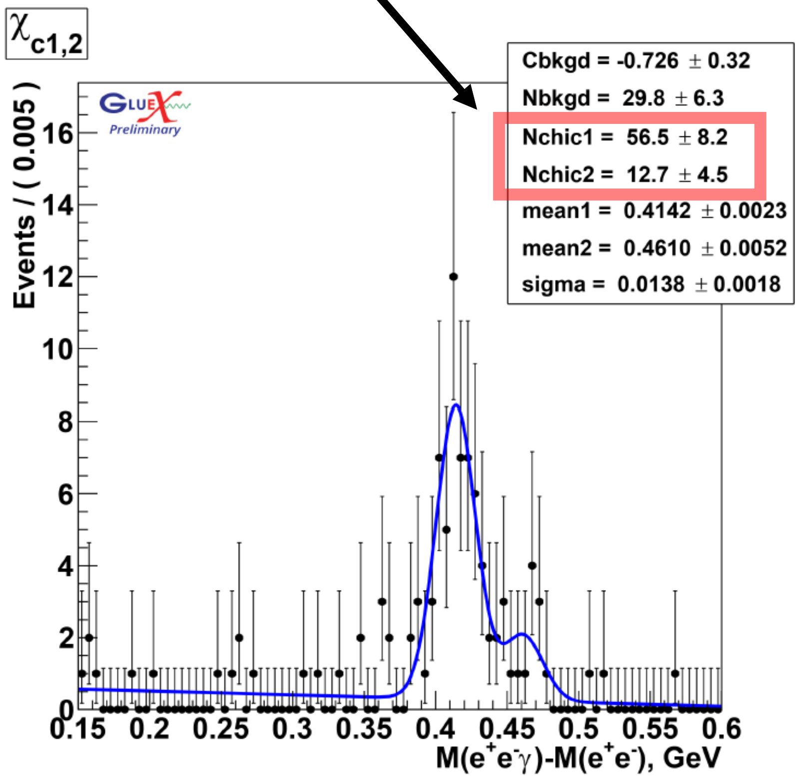
COMPASS, PLB 135454 (2020)
JLab, PRL 127 152301 (2021)

-> transition to odderon at high energy?

C-even quarkonia: χ_{cJ}

. χ_c are P-waves -> main decay mode χ_{cJ}->J/ψ + γ (BR ~ 34% for χ_{c1}!)

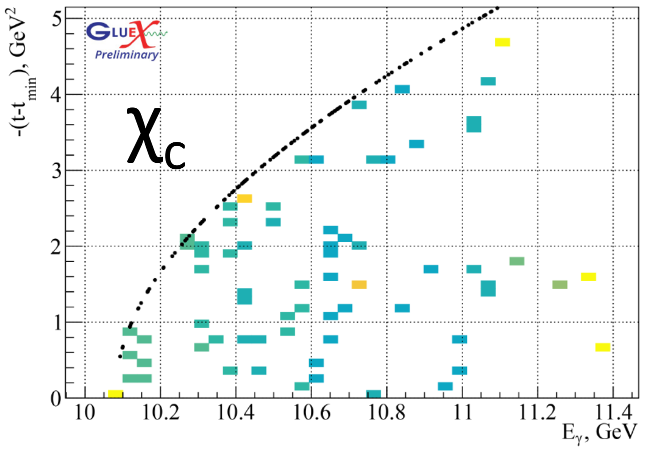
. first ever (?) detection of exclusive χ_c -> **near threshold** with GlueX

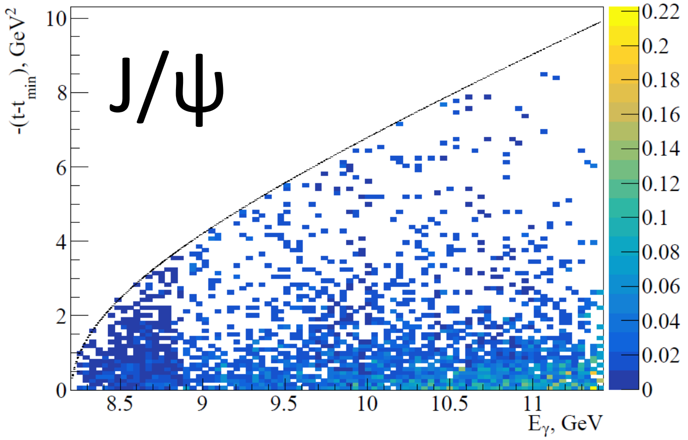


$\sim M_{\chi c} - M_{J/\psi}$

Pentchev, PoS(SPIN2023)152

t-distributions





"strikingly different" t-distributions for χ_c and J/ψ

can this be measured at the EIC?

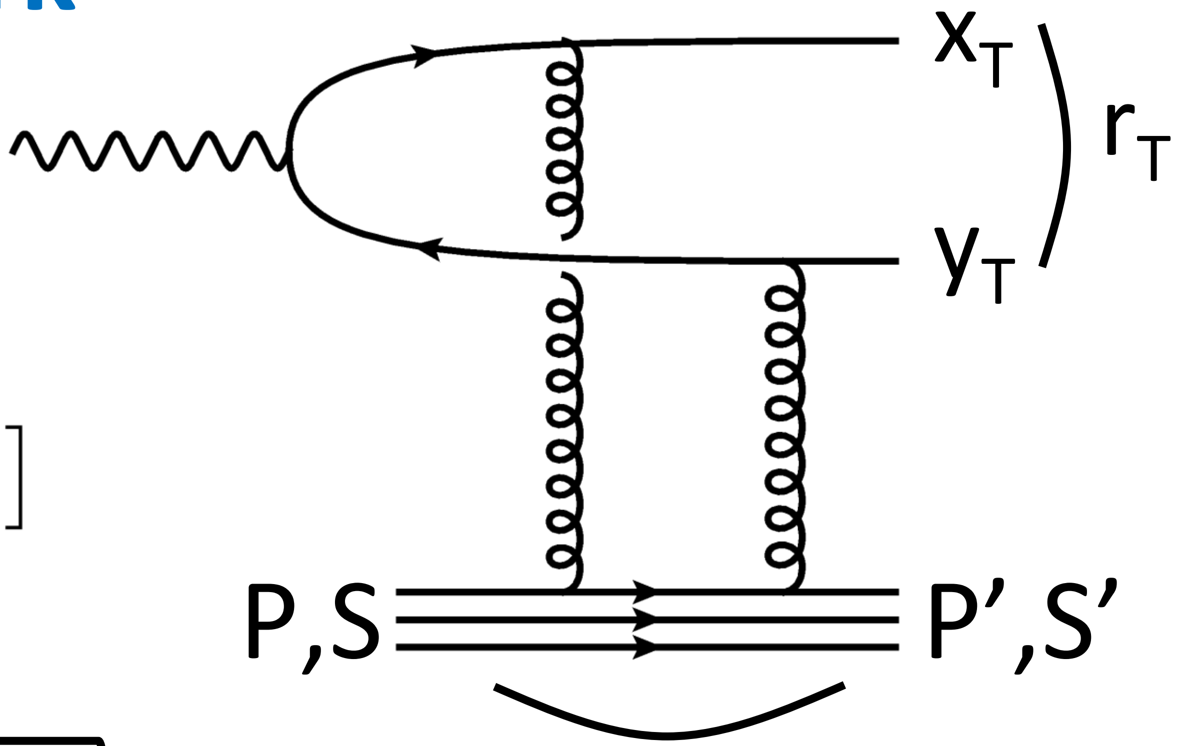
DIS in the dipole framework

. QCD at high energy

. off-forward dipole S-matrix

$$\mathcal{D}(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp)=\frac{1}{N_c}\mathrm{tr}\left[V(\boldsymbol{x}_\perp)V^\dagger(\boldsymbol{y}_\perp)\right]$$

$$V(\boldsymbol{x}_\perp)=\mathcal{P}\exp\left[-\mathrm{i}g\overbrace{\int \mathrm{d}y^- A^{+,a}(y^-,\boldsymbol{x}_\perp)}^{\alpha^a(\boldsymbol{x}_\perp)}t^a\right]$$



t=(P-P')^2

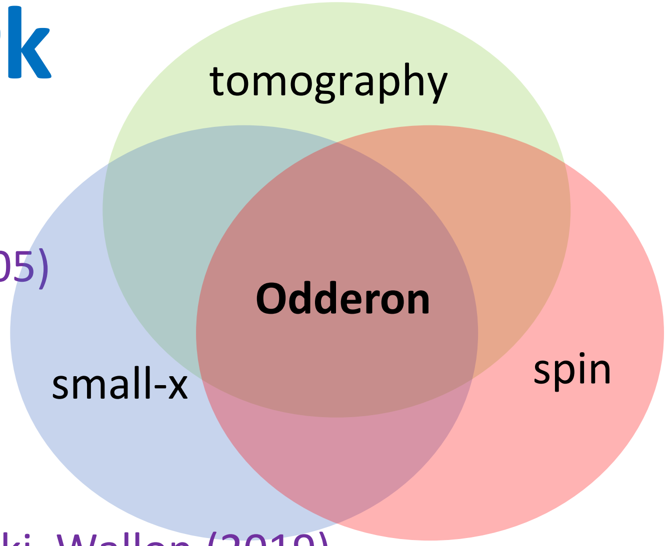
$$\boldsymbol{b}_\perp=\frac{1}{2}(\boldsymbol{x}_\perp+\boldsymbol{y}_\perp)$$

(impact parameter)

. in momentum space

$$\mathcal{D}_{SS'}(\boldsymbol{k}_\perp,\boldsymbol{\Delta}_\perp)=\frac{1}{\langle PS|PS\rangle}\int_{\boldsymbol{r}_\perp\boldsymbol{b}_\perp}\mathrm{e}^{-\mathrm{i}\boldsymbol{k}_\perp\cdot\boldsymbol{r}_\perp}\mathrm{e}^{-\mathrm{i}\boldsymbol{\Delta}_\perp\cdot\boldsymbol{b}_\perp}\langle P'S'|\mathcal{D}(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp)|PS\rangle$$

Odderon in the dipole/GTMD framework



. Odderon as the imaginary part

Kovchegov, Szymanowski, Wallon (2004)
Hatta, Iancu, Itakura, McLerran (2005)

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

. decomposition into GTMDs at small-x

Boussarie, Hatta, Szymanowski, Wallon (2019)

$$\mathcal{D}_{SS'}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp) \approx \frac{(2\pi)^3 g^2}{4M_p N_c}\frac{1}{\boldsymbol{k}_\perp^2 - \frac{\boldsymbol{\Delta}_\perp^2}{4}}\bar{u}(P', S')\left[F_{1,1} + \mathrm{i}\frac{\sigma^{i+}}{P^+}k_\perp^i F_{1,2} + \mathrm{i}\frac{\sigma^{i+}}{P^+}\Delta_\perp^i F_{1,3}\right]u(P, S)$$

$$f_{1,1}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp) + \mathrm{i}\frac{\boldsymbol{k}_\perp \cdot \boldsymbol{\Delta}_\perp}{M_p^2}g_{1,1}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp)$$

$$\frac{\boldsymbol{k}_\perp \cdot \boldsymbol{\Delta}_\perp}{M_p^2}f_{1,2}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp) + \mathrm{i}g_{1,2}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp)$$

spin-independent Odderon

tomography

spin

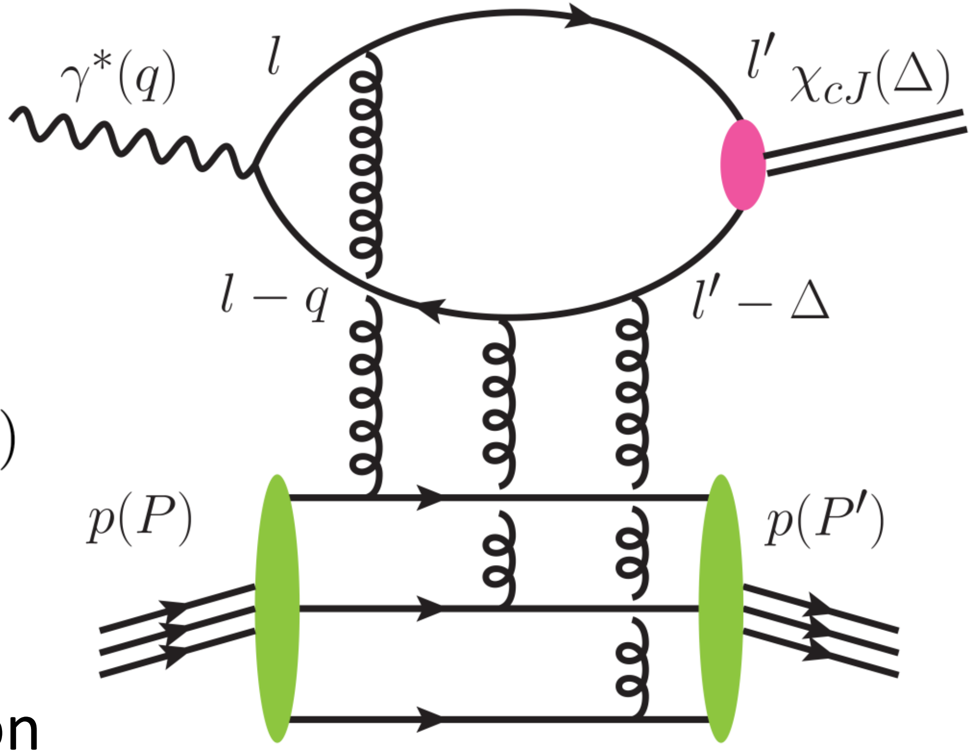
gluon Sivers at |t|->0

$$g_{1,2}(\boldsymbol{k}_\perp, 0) = -\frac{1}{2}x f_{1T}^{\perp g}(x, \boldsymbol{k}_\perp)$$

Zhou (2013)
Boer, Echevarria, Mulders, Zhou (2016)

Amplitude

$$\gamma^*(q)p(P) \to \mathcal{H}(\Delta)p(P')$$



$$\langle \mathcal{M}_{\lambda\bar{\lambda}} \rangle = 2q^- N_c \int_{\boldsymbol{r}_\perp \boldsymbol{b}_\perp} \mathrm{e}^{-\mathrm{i}\boldsymbol{\Delta}_\perp \cdot \boldsymbol{b}_\perp} \mathrm{i}\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) \mathcal{A}_{\lambda\bar{\lambda}}(\boldsymbol{r}_\perp, \boldsymbol{\Delta}_\perp)$$

(spin-independent) Odderon amplitude: three-quark model of the proton LCWF + small-x evolution

Kovchegov, Szymanowski, Wallon (2004)
Hatta, Iancu, Itakura, McLerran (2005)

Brodsky, Schlumpf (1994)
Dumitru, Miller, Venugopalan (2018)
SB, Horvatić, Kaushik, Vivoda (2023)

. reduced amplitude

$$\mathcal{A}_{\lambda\bar{\lambda}}(\boldsymbol{r}_\perp, \boldsymbol{\Delta}_\perp) = \int_z \int_{\boldsymbol{l}_\perp \boldsymbol{l}'_\perp} \sum_{h\bar{h}} \Psi^{\gamma}_{\lambda,h\bar{h}}(\boldsymbol{l}_\perp, z) \Psi^{\mathcal{H}*}_{\bar{\lambda},h\bar{h}}(\boldsymbol{l}'_\perp - z\boldsymbol{\Delta}_\perp, z) \mathrm{e}^{\mathrm{i}(\boldsymbol{l}_\perp - \boldsymbol{l}'_\perp + \frac{1}{2}\boldsymbol{\Delta}_\perp)\cdot \boldsymbol{r}_\perp}$$

photon LCWF (perturbative)

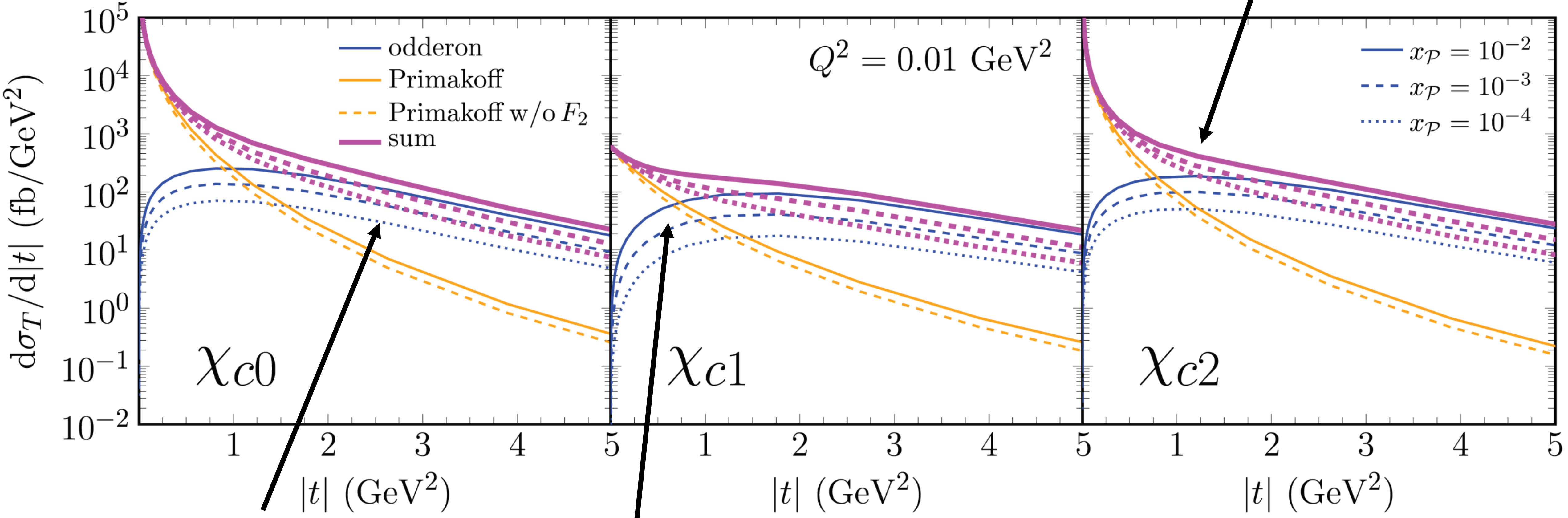
χ_{cJ} quarkonia LCWF (model)

SB, Dumitru, Kaushik, Motyka, Stebel (2024)

t-distributions

. Odderon important after |t|~ 1 GeV², low t-region dominated by Primakoff (photon exchange)

photon and Odderon interfere **constructively**

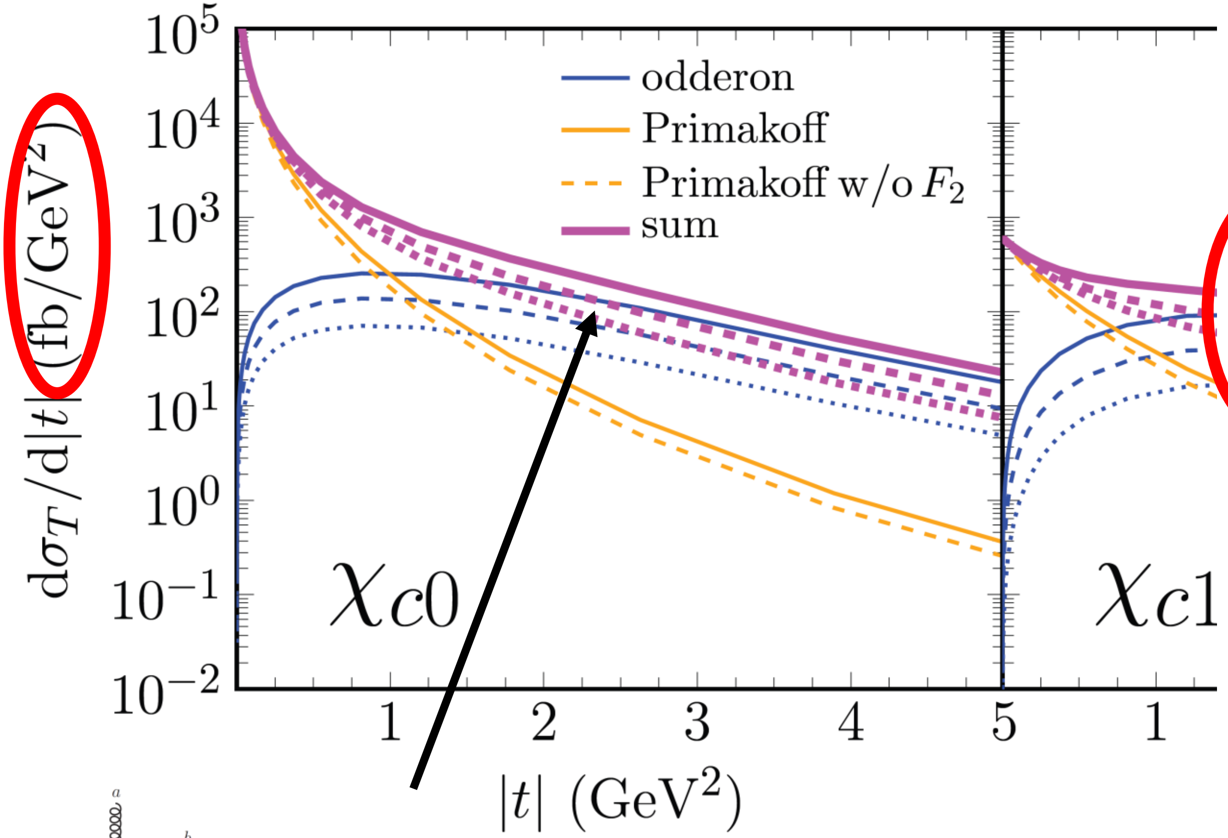


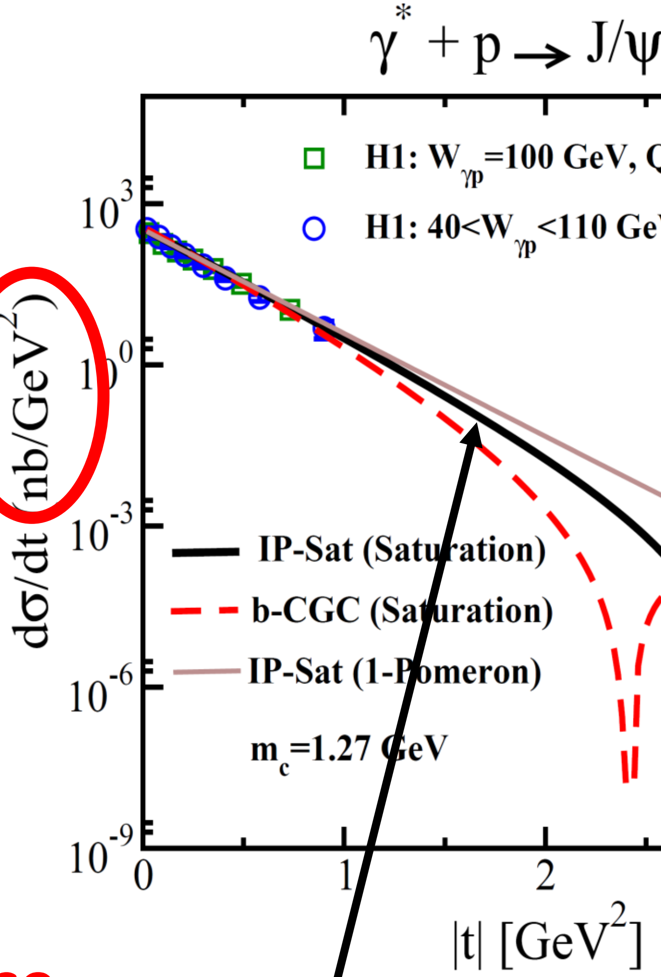
weak t-dependence

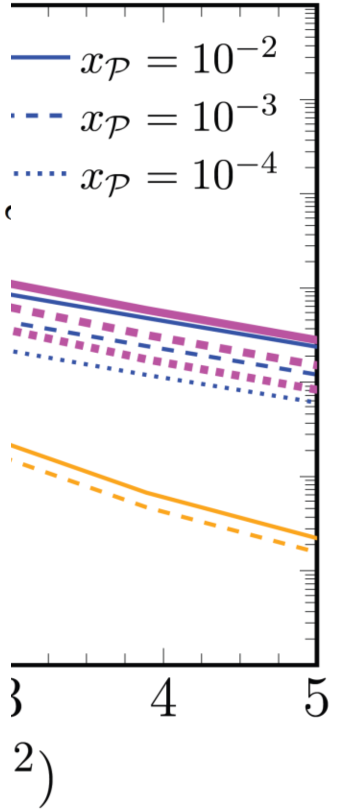
SB, Dumitru, Kaushik, Motyka, Stebel (2024)

Odderon drops with x->0 (saturation corrections in evolution eqn.)

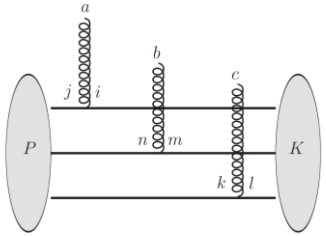
Contrast with J/ψ production





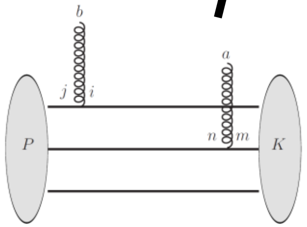


Armesto, Rezaeian (2014)



Odderon: **weak t-dependence**

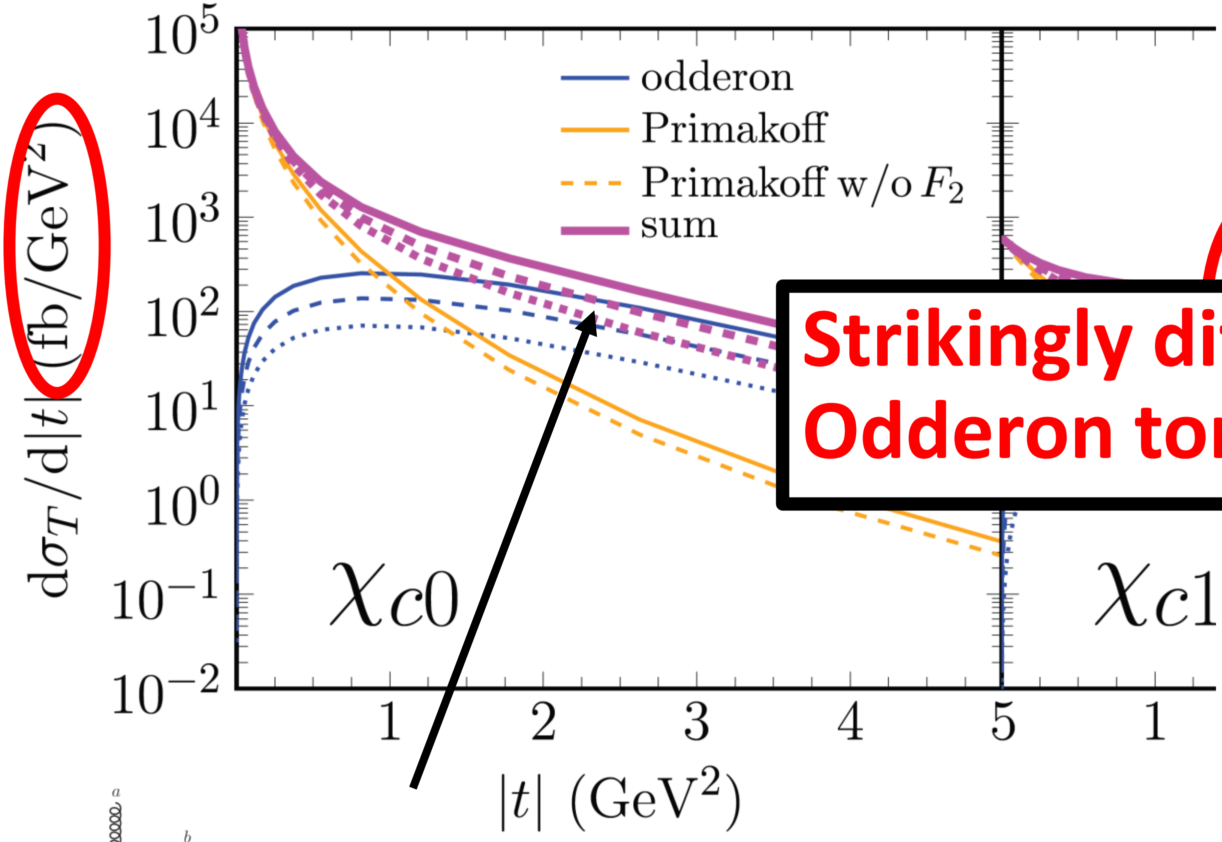
dσ/d|t|∝|t|*exp(-B|t|), B≈1 GeV^{-2}

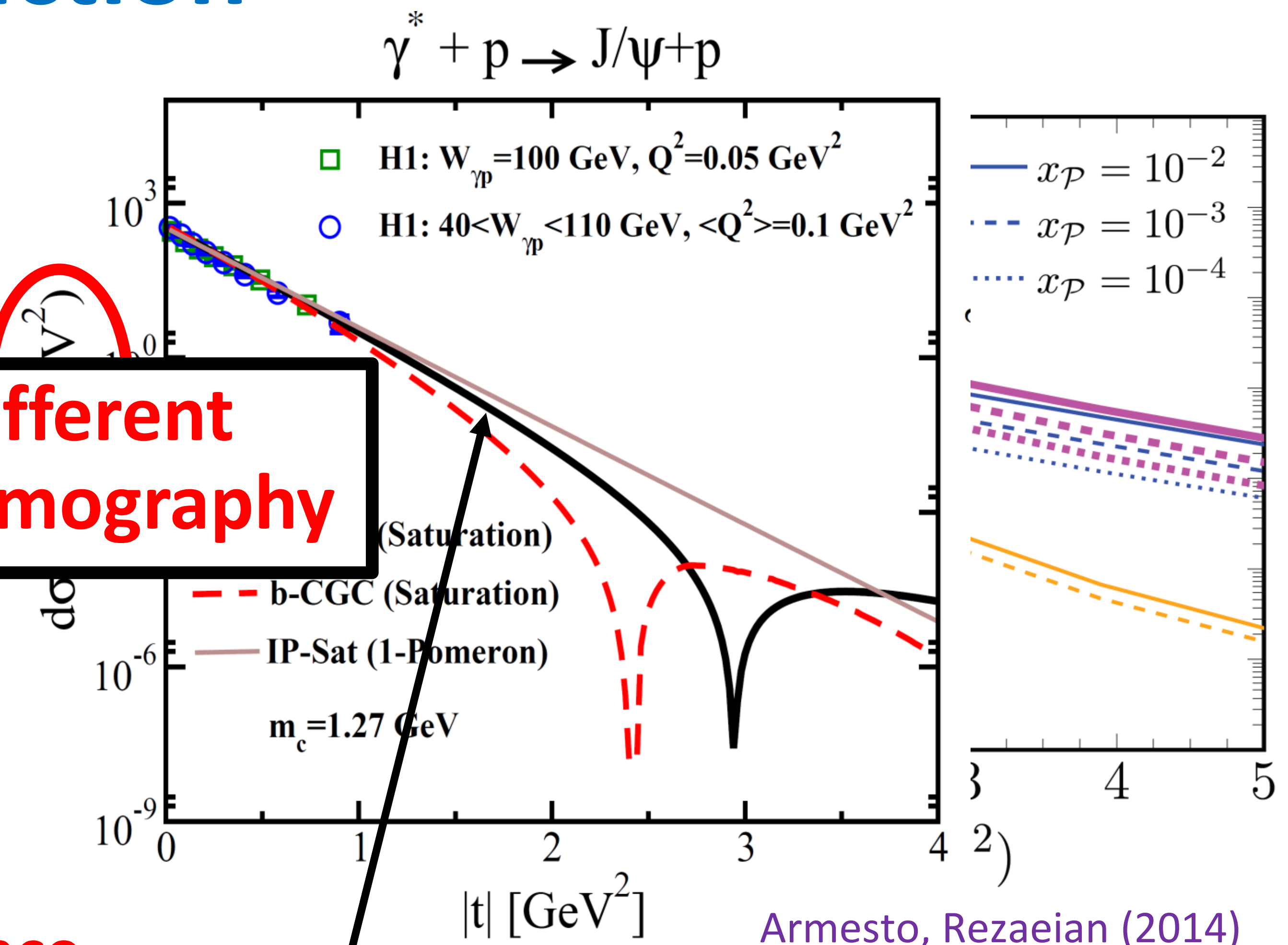


Pomeron: **strong t-dependence**

dσ/d|t|∝exp(-B|t|), B≈4 GeV^{-2}

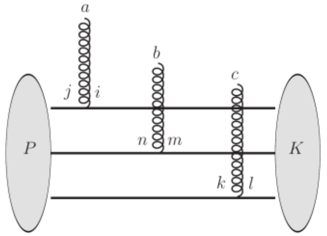
Contrast with J/ψ production





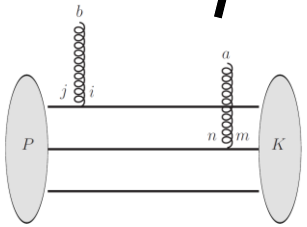
Strikingly different Odderon tomography

Armesto, Rezaeian (2014)



Odderon: **weak t-dependence**

$d\sigma/d|t| \propto |t| * \exp(-B|t|)$, $B \approx 1$ GeV^{-2}



Pomeron: **strong t-dependence**

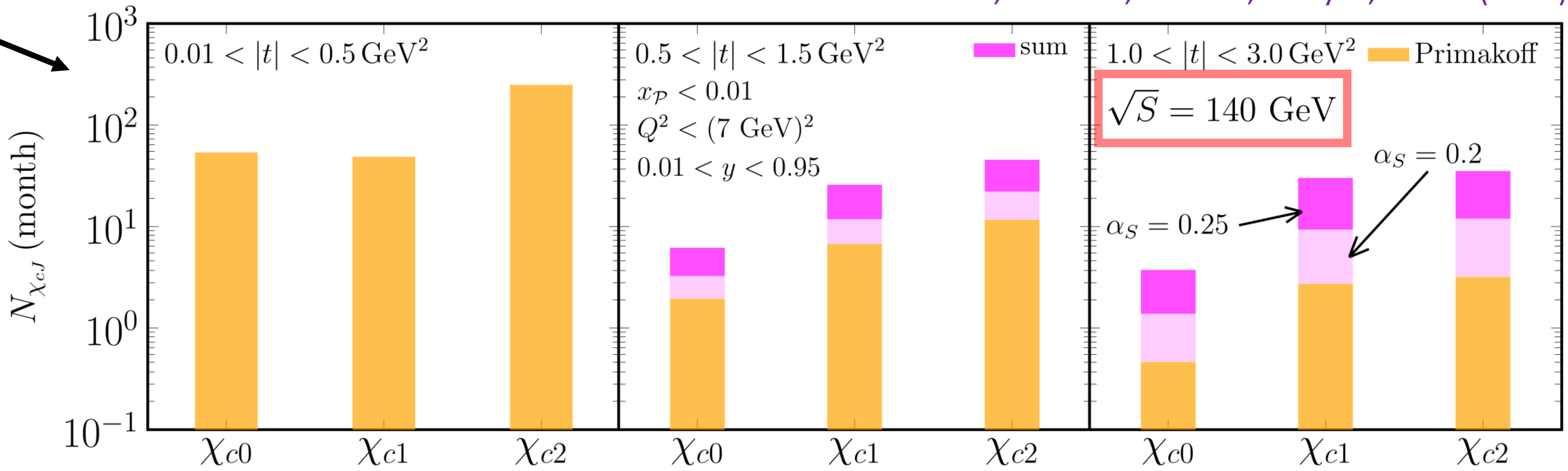
$d\sigma/d|t| \propto \exp(-B|t|)$, $B \approx 4$ GeV^{-2}

Expected number of events at the EIC

. detection channel: $\chi_{cJ} \to J/\psi\ \gamma$, $J/\psi \to l^+ l^-$

$$N_{\chi_{cJ}} = L \times \sigma_{ep}(ep \to \chi_{cJ} ep) \times \mathrm{BR}(\chi_{cJ} \to J/\psi\gamma) \times \mathrm{BR}(J/\psi \to \ell^+\ell^-)$$

SB, Dumitru, Kaushik, Motyka, Stebel (2024)

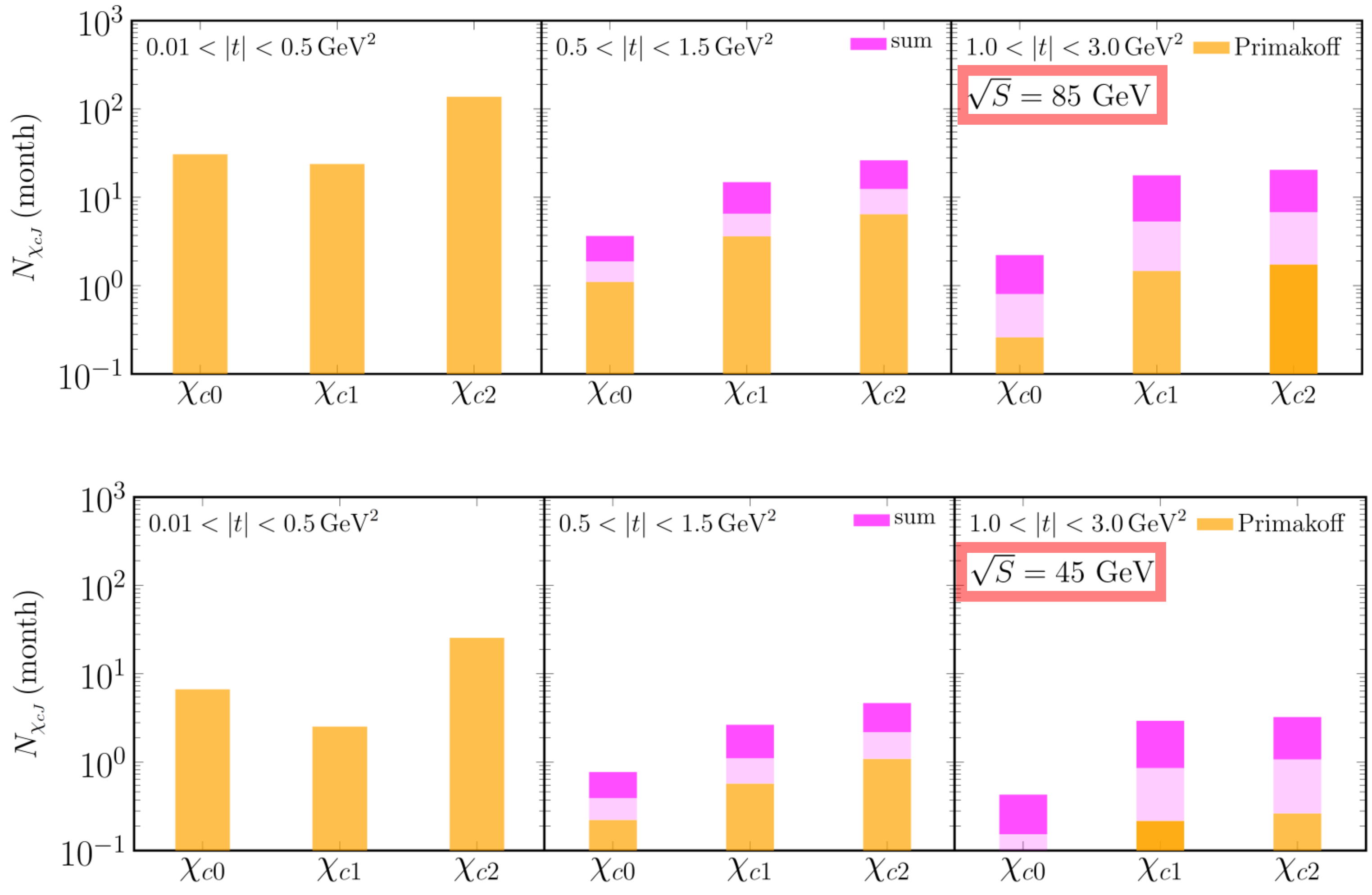


. we predict **excess** in odderon events over Primakoff background

. for χ_{c1} (34% BR to $J/\psi + \gamma$): with EIC luminosity $10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

expect ~20 events/month (only Primakoff~5 events/month)

Expected number of events at the EIC



. decent counts even at lower collision energy

SB, Dumitru, Kaushik, Motyka, Stebel (2024)

Forward limit: gluon Sivers

Ma (2003)
Boussarie, Hatta, Szymanowski, Wallon (2020)

transverse spin basis --> $\mathcal{O}_{\boldsymbol{S}_\perp \boldsymbol{S}_\perp}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp = 0) \propto (\boldsymbol{S}_\perp \times \boldsymbol{k}_\perp) f_{1T}^{\perp g}(x, \boldsymbol{k}_\perp)$

helicity basis --> $\mathcal{O}_{\lambda\lambda'}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp = 0) \propto \lambda \delta_{\lambda,-\lambda'} (\boldsymbol{\epsilon}_\perp^\lambda \times \boldsymbol{k}_\perp) f_{1T}^{\perp g}(x, \boldsymbol{k}_\perp)$

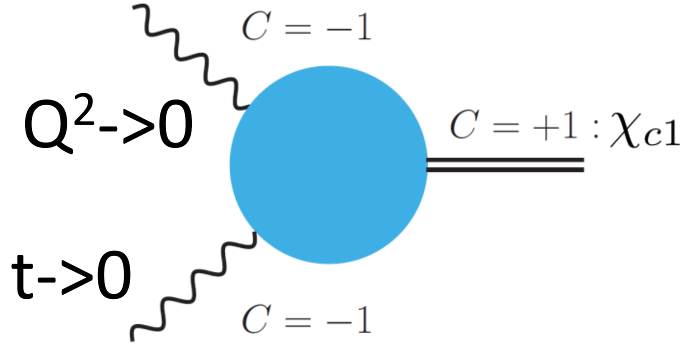
helicity flip! -> naturally contributes in *unpolarized* cross section

SB, Dumitru, Motyka, Stebel (2024)

$$\lim_{t\to 0} \frac{\mathrm{d}\sigma_{\mathrm{Siv}}}{\mathrm{d}|t|} = \frac{3\pi^3 q_c^2 \alpha \alpha_S^2 M_p^2 |R'(0)|^2 |x f_{1T}^{\perp(1)g}(x)|^2}{N_c m_c^{11}}$$

gluon Sivers squared!

. χ_{c1}: Coulomb tail screened thanks to Landau-Yang selection rule



$$\lim_{t\to 0} \frac{\mathrm{d}\sigma_{\mathrm{Prim}}}{\mathrm{d}|t|} = \frac{3\pi q_c^4 \alpha^3 N_c |R'(0)|^2 |F_1(0)|^2}{m_c^9}$$

finite!!

Jia, Mo, Pan, Zhang (2023)
SB, Dumitru, Motyka, Stebel (2024)

χ_{c1} polarization

SB, Dumitru, Motyka, Stebel (2024)

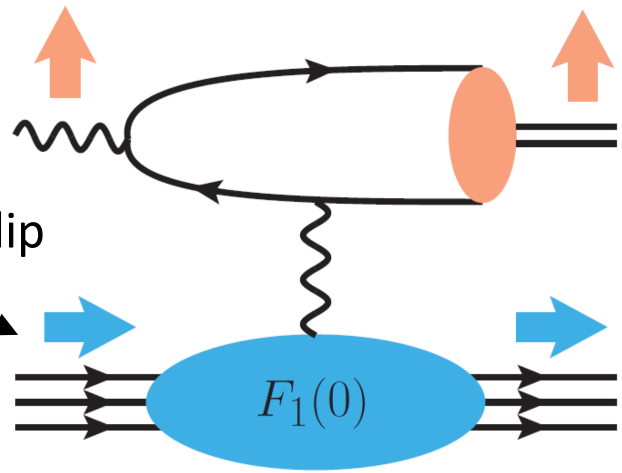
Primakoff

χ_{c1} transversely polarized

Q^2->0

no helicity flip

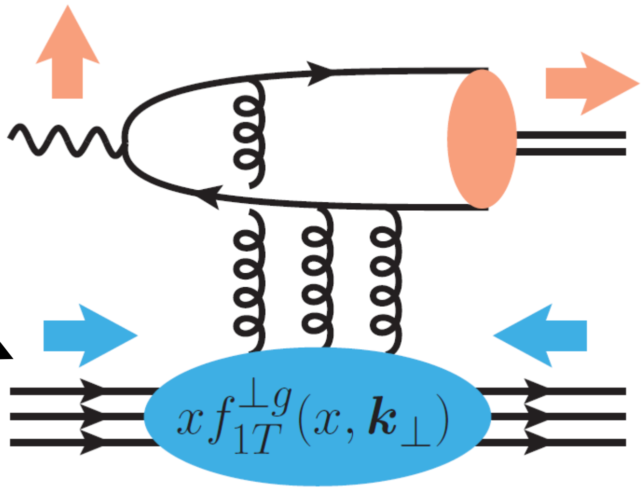
t->0



Sivers

χ_{c1} longitudinally polarized

helicity flip



-> distinct signature in angular distribution of the decay: χ_{c1}->J/ψ+γ

$$W(\theta,\phi) \propto \frac{N}{3+\lambda_\theta}\left(1+\lambda_\theta \cos^2\theta + \dots\right)$$

$$\lambda_\theta = \frac{2r-1}{2r+3}$$

r->0: $\lambda_\theta = -1/3$

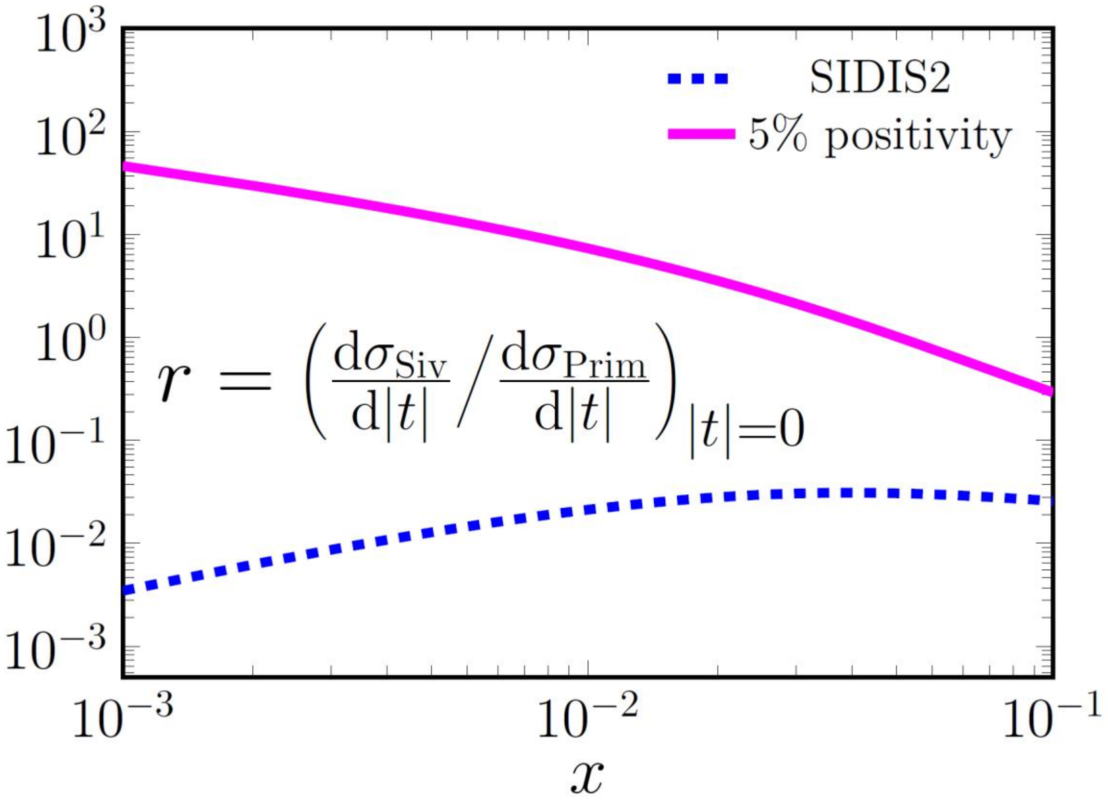
1/r->0: $\lambda_\theta = +1$

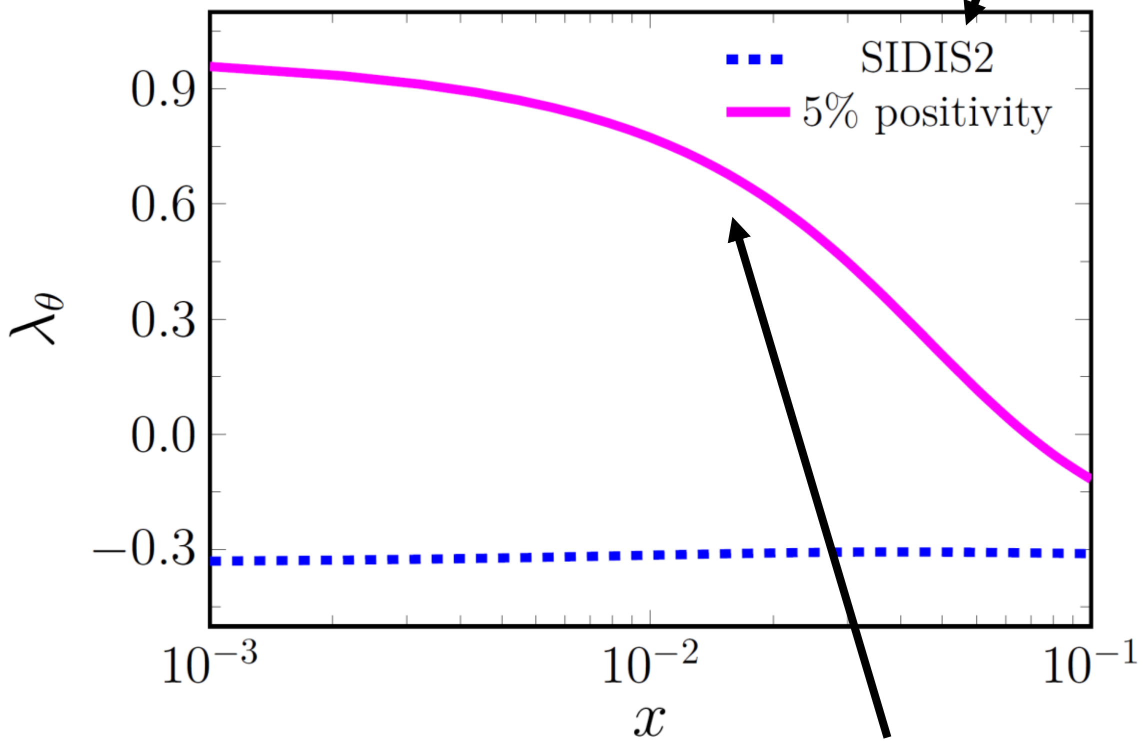
Polar anisotropy changes sign!

$$r = \left(\frac{\mathrm{d}\sigma_{\mathrm{Siv}}}{\mathrm{d}|t|} \Big/ \frac{\mathrm{d}\sigma_{\mathrm{Prim}}}{\mathrm{d}|t|}\right)_{t=0}$$

Model results

Anselmino, Boglione, D'Alesio, Leader, Murgia (2004)
D'Alesio, Murgia, Pisano (2015)





a positive polar anisotropy is a signature of spin-dependent Odderon (gluon Sivers)!

. large uncertainty in current models of gluon Sivers

. Sivers and Primakoff can be of similar magnitude

$$(d\sigma_{\rm Prim}/d|t|)_{t=0} \approx 0.69\,{\rm pb}/{\rm GeV}^2$$

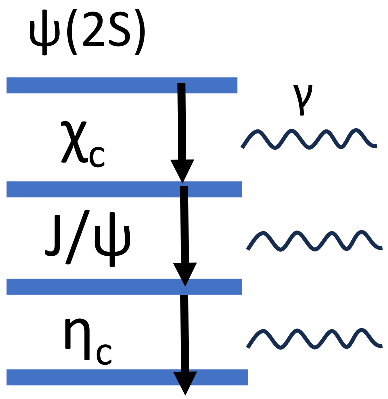
. unique opportunity for UPCs at the LHC

SB, Dumitru, Motyka, Stebel (2024)

Challenges and outlook

. **production**: a 10-100 fb cross section will be a **challenge** for the experimentalist -> high luminosity at the EIC

. **detection**: feed-down from $\psi(2S)$ -> $\chi_c + \gamma$



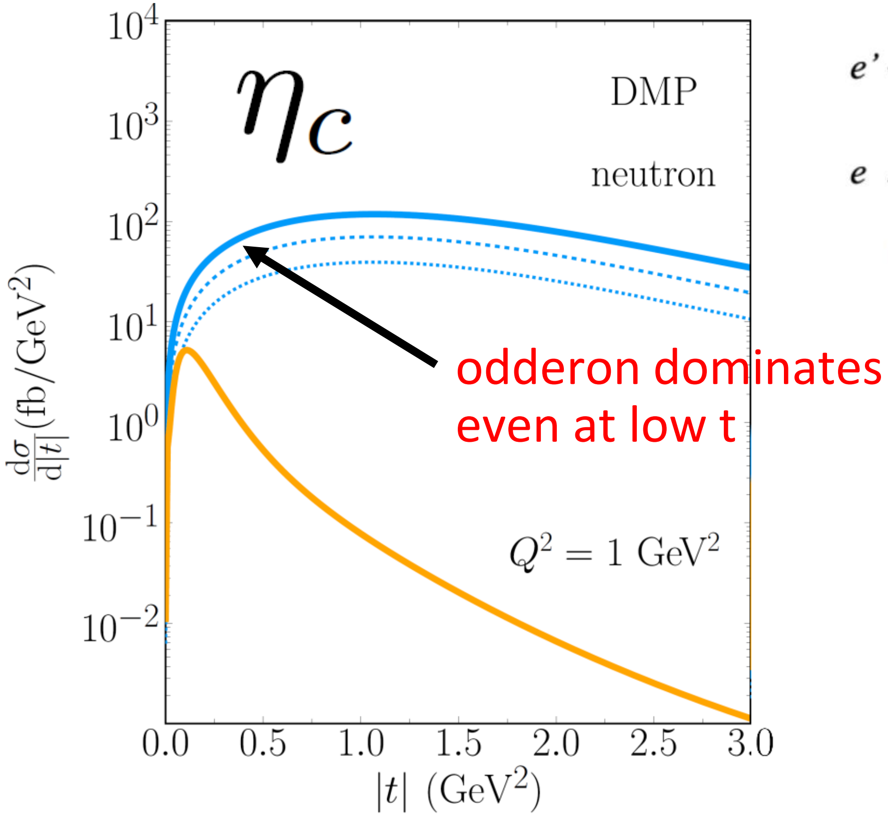
-> χ_c from feed-down expected with a sharper t-spectra

. exclusive π^0 deserves a theory update for the EIC kinematics, calculations underway (here, feed-down from ω -> $\pi^0 + \gamma$)

Uses of different targets

SB, Kaushik, Horvatić, Vivoda (2023)

-> “tagged DIS”: use neutron targets to suppress Primakoff background



Jentsch, Tu, Weiss (2021)
CLAS (2012)
Friscic et al (2021)

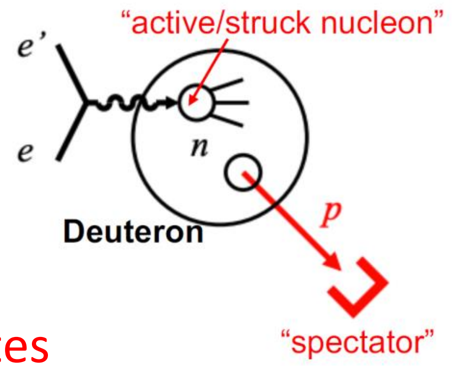
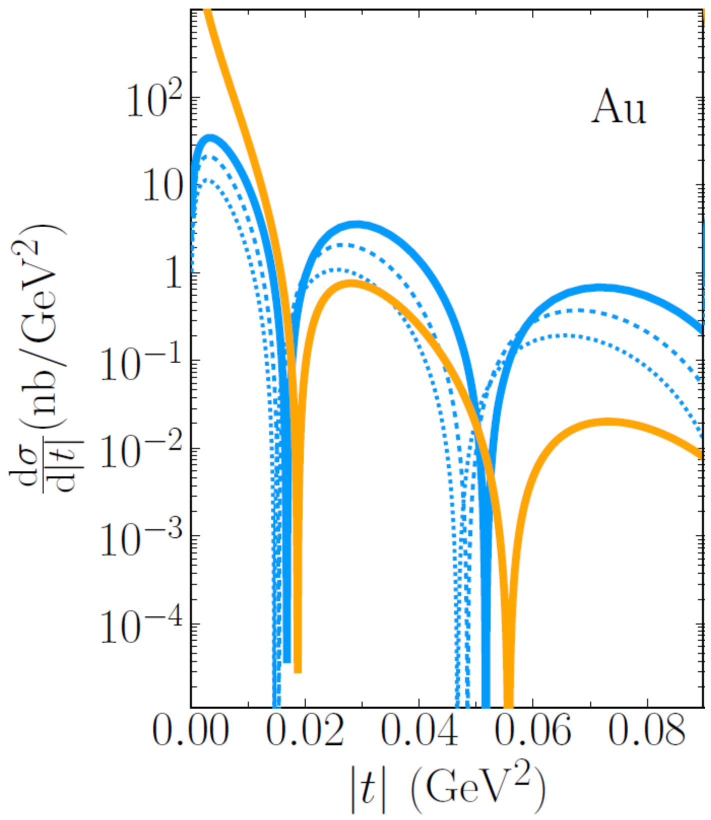


Fig. from Jentsch Diff&Low-x 2024



-> for nuclei, expect an enhancement factor (~Z^2 for Primakoff)

$$\frac{d\sigma}{dt} \sim A^2 \qquad \sigma \sim A^{4/3}$$

-> Odderon cross section moves into 10-100 pb range