Signatures of Odderon in DIS: exclusive productions of χ_c

Sanjin Benić (University of Zagreb)

SB, Dumitru, Kaushik, Motyka, Stebel, 2402.19134 (PRD in press)

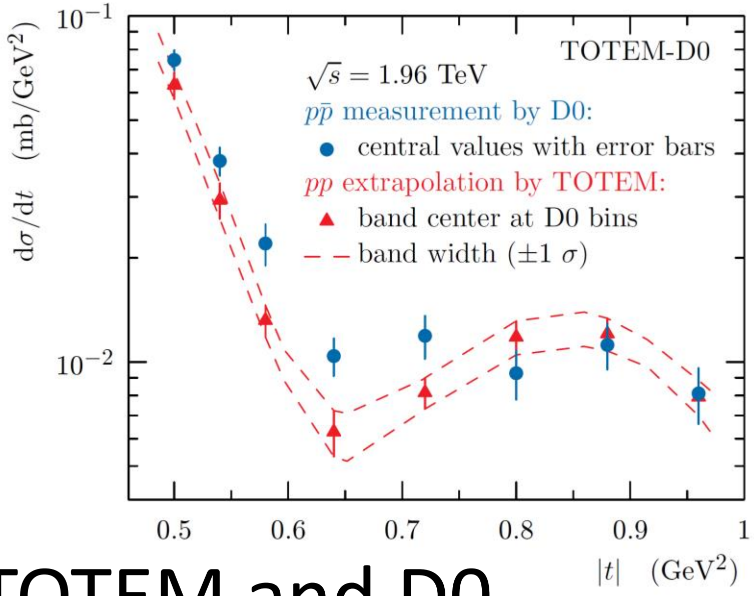
SB, Dumitru, Motyka, Stebel, 2407.04968

EICUG Theory WG meeting on Odderon Production at the EIC, July 18

HRZZ
Croatian Science Foundation

Odderon in hadronic collisions

TOTEM, D0 (2021)



. suggested 50+ years ago – colorless **C-odd** exchange to govern the pp vs $p\bar{p}$ cross section difference

Lukaszuk, Nicolescu (1973)
Ewerz (2003)

-> elusive for decades, discovered at last by the TOTEM and D0

-> the story featured in media outlets


After 48-year search, physicists discover ultra-rare 'triple glueball' particle

News By Rafi Letzter published April 13, 2021

This event was predicted in 1973 but had never been seen in the real world.

The particle physics lab CERN, home to the ATLAS experiment at the Large Hadron Collider shown here, celebrated its 60th anniversary on Sept. 29, 2014. (Image credit: CERN)

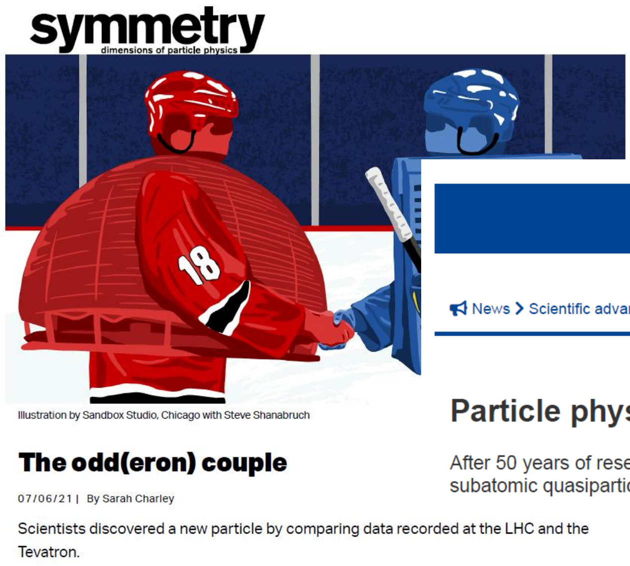


Illustration by Sandbox Studio, Chicago with Steve Shanabruch

The odd(eron) couple

07/06/21 | By Sarah Charley

Scientists discovered a new particle by comparing data recorded at the LHC and the Tevatron.

Particle physics milestone achieved at CERN

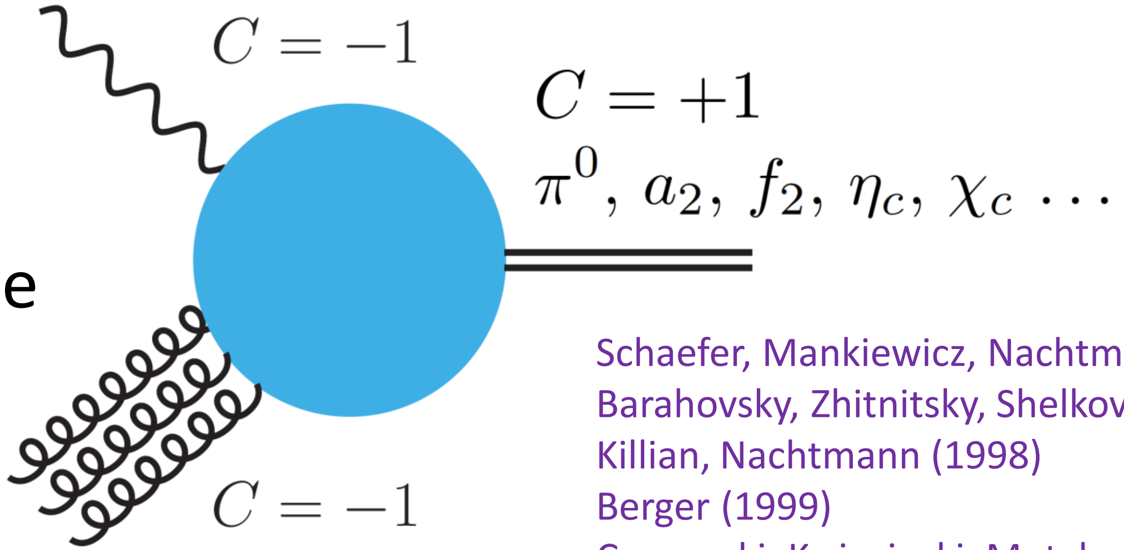
After 50 years of research, physicists have found evidence that the elusive subatomic quasiparticle called odderon actually exists.

Odderon in the DIS?

. for pp it is difficult to make perturbative QCD computation

. DIS offers more theoretical control

➡ a **direct** discovery of the (hard) odderon in 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)

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

Odderon searches in DIS: light mesons

. First searches conducted at HERA for light mesons:

ELSEVIER
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

H1 collaboration (2001,2002)

HERA kinematics:

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

$Q^2 < 0.01$ GeV^2

$\langle W \rangle \sim 200$ GeV

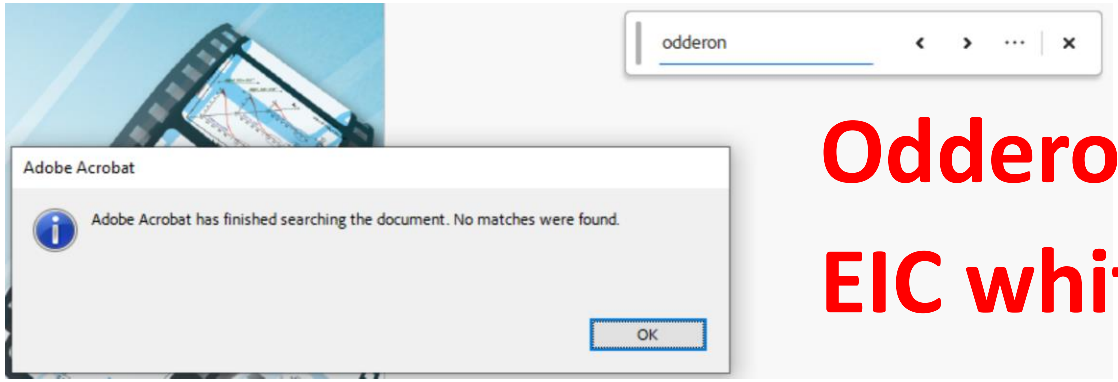
$\sigma(\gamma^* p \text{->} \pi^0 N^*)<49$ nb

$\sigma(\gamma^* p \text{->} f_2 X)<16$ nb

$\sigma(\gamma^* p \text{->} a_2 X)<96$ nb

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

Berger (1999)



1212.1701 (EIC white paper)

Odderon not discussed in the EIC white paper

Odderon searches in DIS: light mesons

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. First searches conducted at HERA for light mesons:

Vol. 33 (2002) *ACTA PHYSICA POLONICA B* No 11

INVESTIGATION OF POMERON- AND ODDERON INDUCED PHOTOPRODUCTION OF MESONS DECAYING TO PURE MULTIPHOTON FINAL STATES AT HERA* **

THOMAS BERNDT

For the H1 Collaboration

In this contribution the first search at HERA for Odderon induced reactions is presented and contrasted with cross section measurements for Pomeron induced processes. The searches are performed in the channels $\gamma p \to \pi^0 N^*$, $\gamma p \to f_2(1270)X$ and $\gamma p \to a_2 X$, where N^* denotes an excited nucleon state. The rates found are compatible with the background alone, and the upper limits derived therefrom are confronted with the ex-

H1 collaboration (2001,2002)

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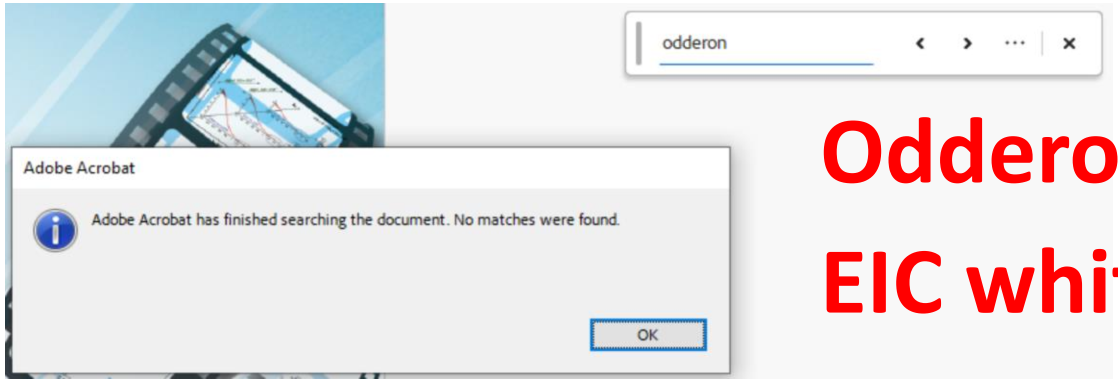


1212.1701 (EIC white paper)

Odderon not discussed in the EIC white paper

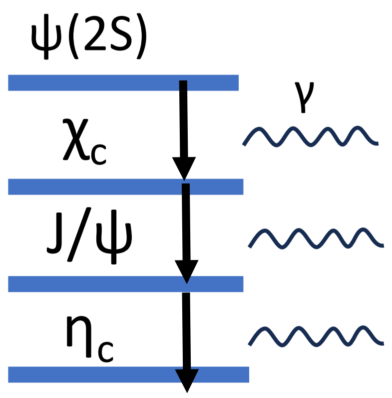
Odderon searches in DIS: quarkonia

. from late 90’s theorists focus on exclusive η_c

. issues with η_c detection (small branching ratios to hadronic channels & feed-down from J/ψ)

Harland-Lang, Khoze, Martin, Ryskin (2018)

-> we argue exclusive χ_{cJ} (J = 0, 1, 2) productions is a **golden channel** for direct Odderon discovery in DIS



. χ_c are C=+1 states. They are P-waves so they lie above J/ψ

-> main decay mode χ_{cJ}->J/ψγ (BR ~ 34% for χ_{c1}!)

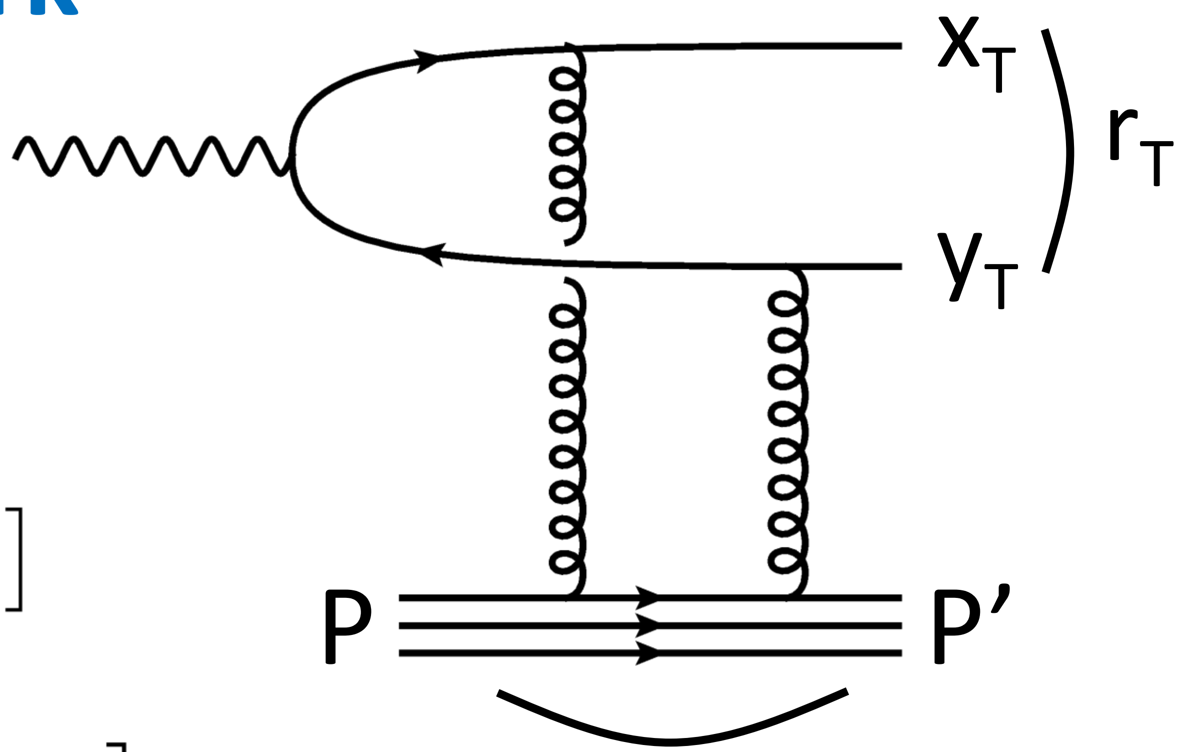
-> there will be a feed-down from ψ(2S)..

. Odderon cross sections expected to be small but EIC luminosity is two orders of magnitude higher than at HERA

-> a second chance for the odderon at the EIC?

DIS in the dipole framework

. QCD at high energy



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

. off-forward dipole S-matrix

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

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

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

(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 framework

. odderon as the imaginary part

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

. $\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$ satisfies a high-energy evolution (BK-type) equation

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

$$- \mathcal{N}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp)\mathcal{O}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) - \mathcal{O}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp)\mathcal{N}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) \Big]$$

BLV Odderon: $\mathcal{O} \sim \frac{1}{x^0}$

Bartels, Lipatov, Vacca (2000)

saturation corrections: suppress the Odderon at high energy

$$Y = \log(1/x)$$

Kovchegov, Szymanowski, Wallon (2004)
Hatta, Iancu, Itakura, McLerran (2005)
Motyka (2006)
Jeon, Venugopalan (2005)
Lappi, Ramnath, Rummukainen, Weigert (2016)

Odderon <-> GTMD connection

. dipole decomposition into GTMDs at small-x

Boussarie, Hatta, Szymanowski, Wallon (2019)

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

. Odderons as imaginary part of GTMDs

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

spin-independent odderon (“directed-flow”)

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

spin-dependent odderon

Zhou (2013)

. In the forward (t->0) limit connection to the gluon Sivers function

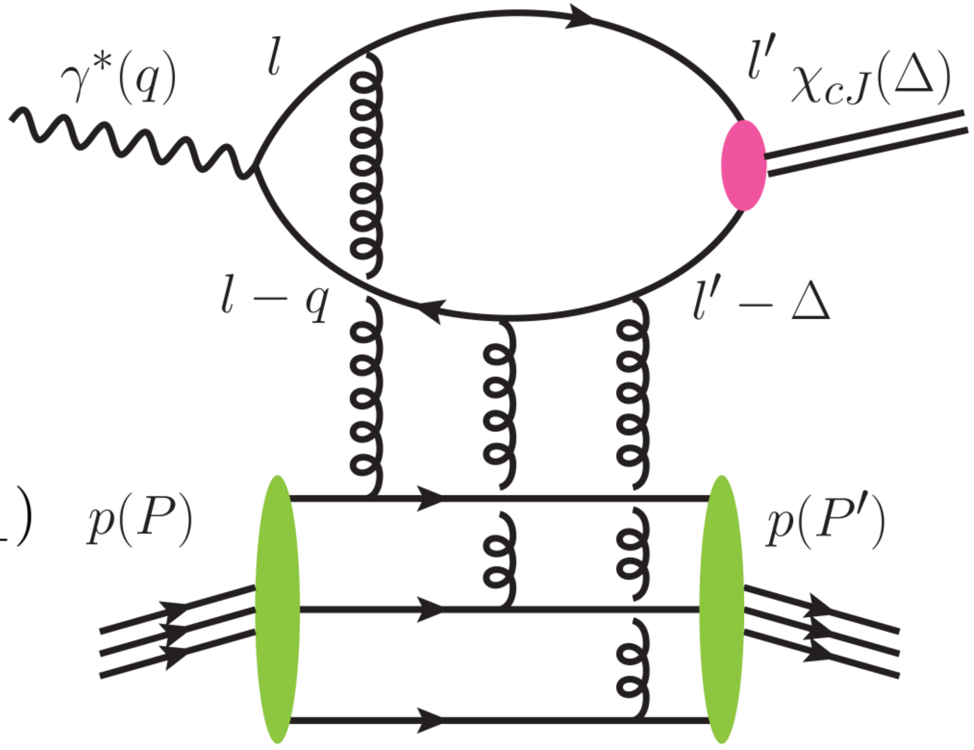
$$g_{1,2}(\boldsymbol{k}_\perp, 0) = -\frac{1}{2} x f_{1T}^{\perp g}(x, \boldsymbol{k}_\perp)$$

Amplitude

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

$$q^\mu = (-Q^2/2q^-, q^-, 0, 0) \qquad P^\mu = (P^+, M^2/2P^+, 0, 0)$$

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



(spin-independent) Odderon amplitude: three-quark model of the proton LCWF a la Brodsky-Schlumpf as initial condition + small-x evolution

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

. reduced amplitude

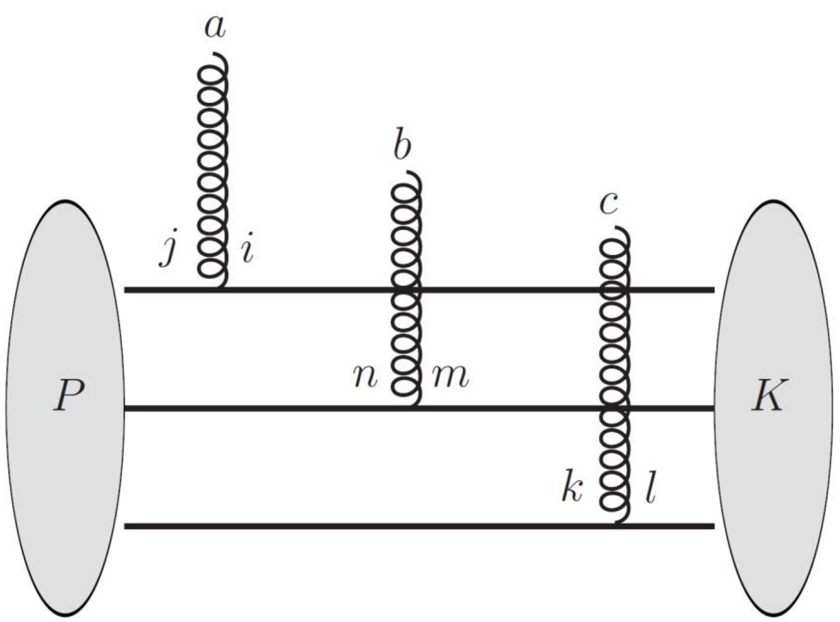
$$\mathcal{A}_{\lambda\bar{\lambda}}(\boldsymbol{r}_\perp, \boldsymbol{\Delta}_\perp) = \int_z \int_{\boldsymbol{l}_\perp \boldsymbol{l}'_\perp} \sum_{h\bar{h}} \Psi^{\gamma}_{\lambda,h\bar{h}}(\boldsymbol{l}_\perp, z) \Psi^{\mathcal{H}*}_{\bar{\lambda},h\bar{h}}(\boldsymbol{l}'_\perp - z\boldsymbol{\Delta}_\perp,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

χ_{cJ} quarkonia LCWF (model)

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

photon LCWF (perturbative)

Odderon initial condition



an example of a 3-body contribution that becomes relevant at high-t

-> the three gluons from odderon exchange can give a high-t kick to the proton without breaking it

-> expect a weak t-dependence of the Odderon exchange amplitude

. model computation fixes the overall sign of the odderon

. numerically we find odderon sign not changed by small-x evolution

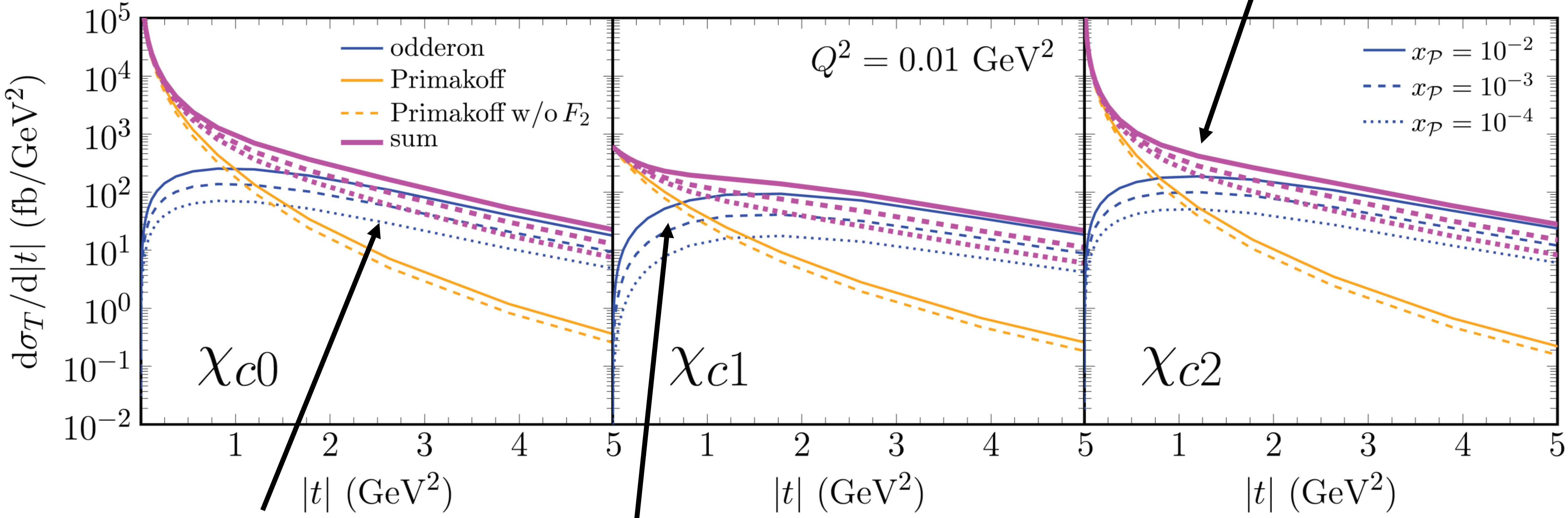
. same model does a decent job to describe the pomeron sector

Dumitru, Mantysaari, Paatelainen (2023)

t-distributions

. Odderon important after |t|~ 1 GeV^2 , low t-region dominated by Primakoff (photon exchange)

photon and Odderon interfere **constructively**

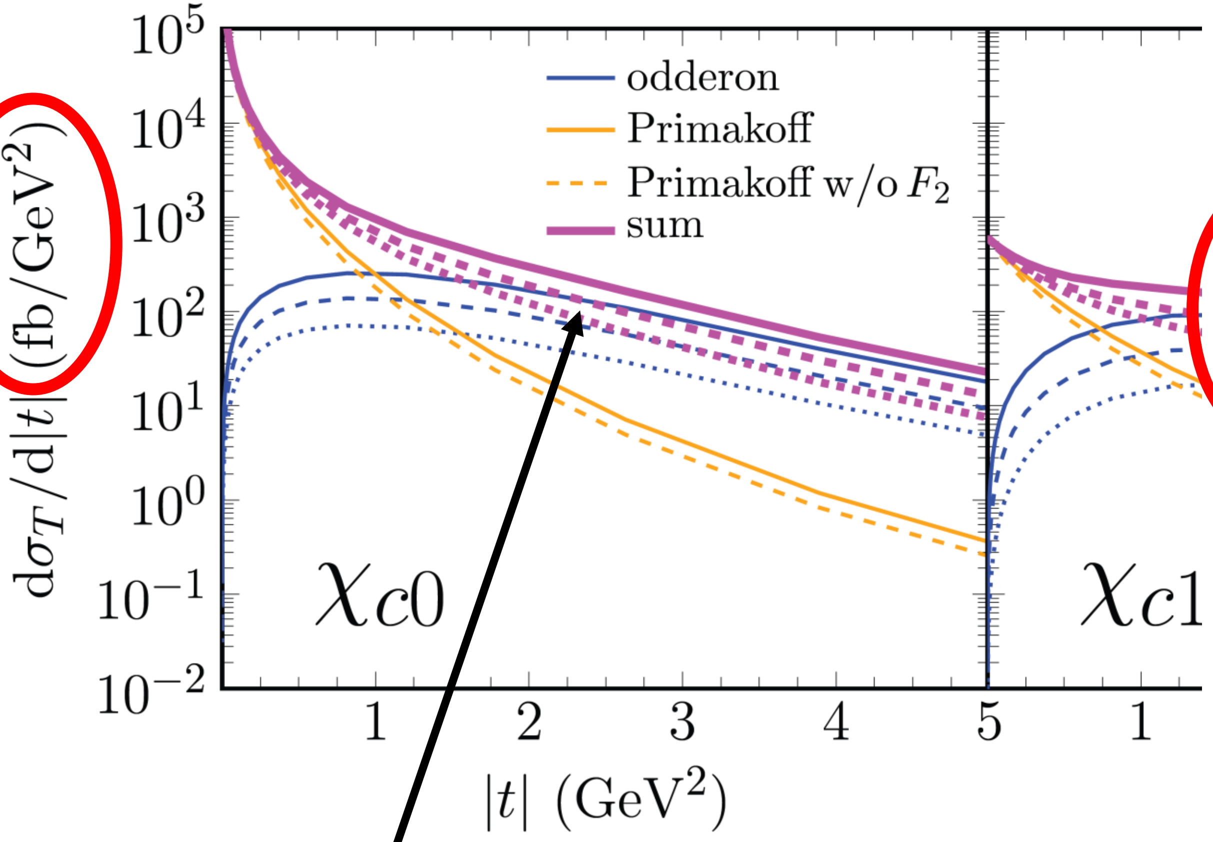


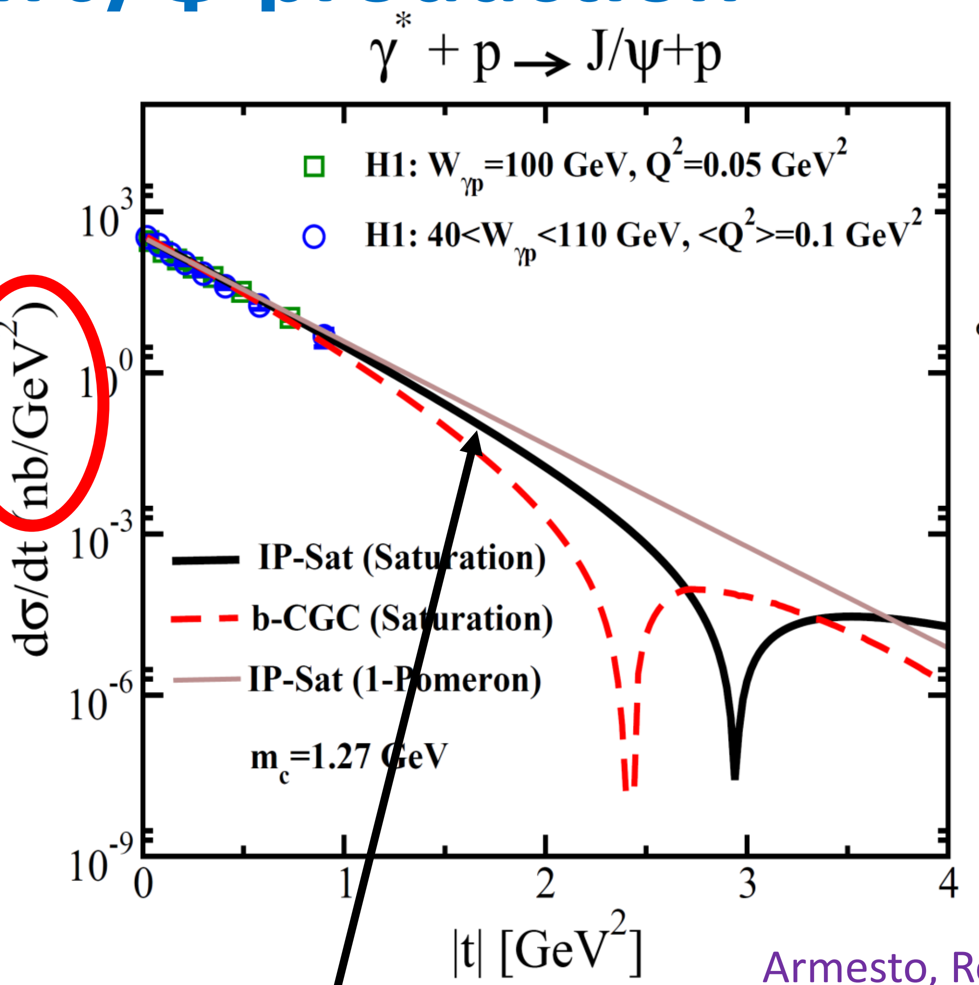
weak t-dependence

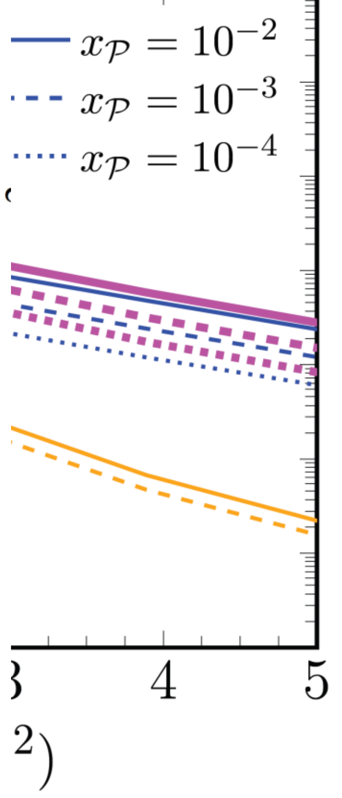
SB, Dumitru, Kaushik, Motyka, Stebel (2024)

Odderon drops with x->0 (saturation corrections)

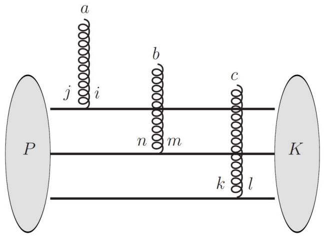
Note the stark contrast with J/ψ production





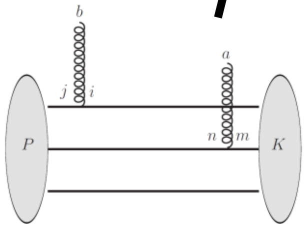


Armesto, Rezaeian (2014)



Odderon: **weak t-dependence**

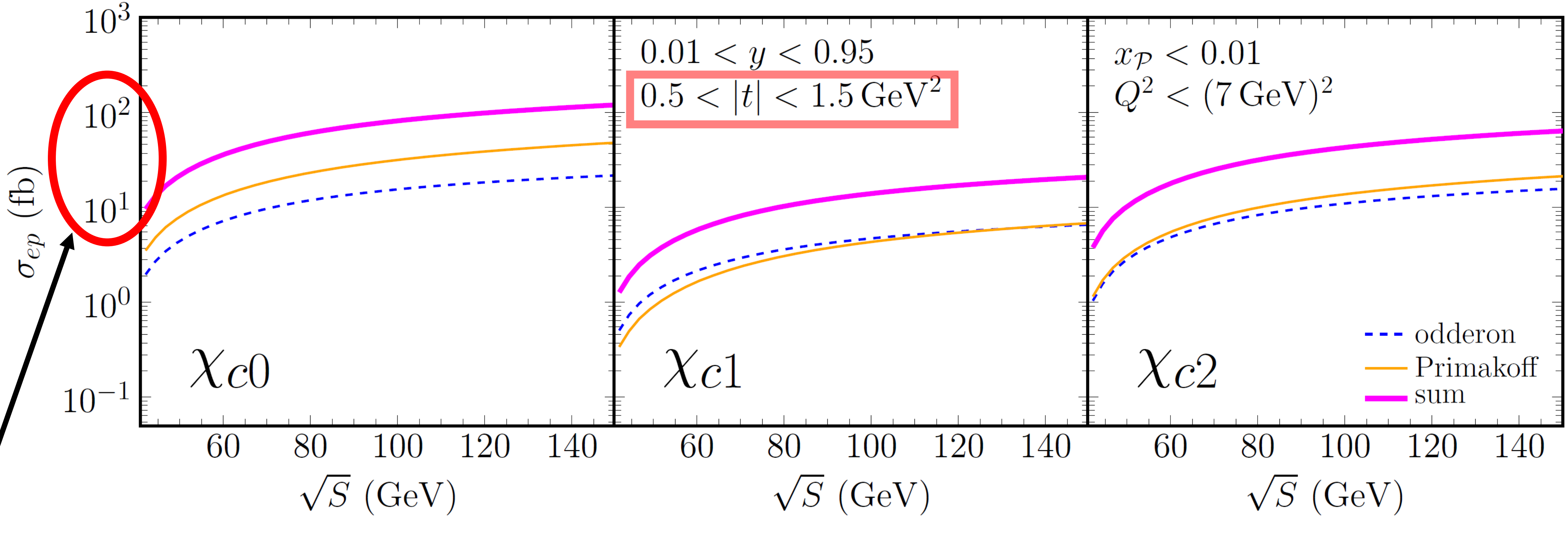
dσ/d|t|∝|t|*exp(-B|t|), $B \approx 1\ \mathrm{GeV}^{-2}$



Pomeron: **strong t-dependence**

dσ/d|t|∝exp(-B|t|), $B \approx 4\ \mathrm{GeV}^{-2}$

Total electroproduction cross section



Is this enough for the EIC?

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

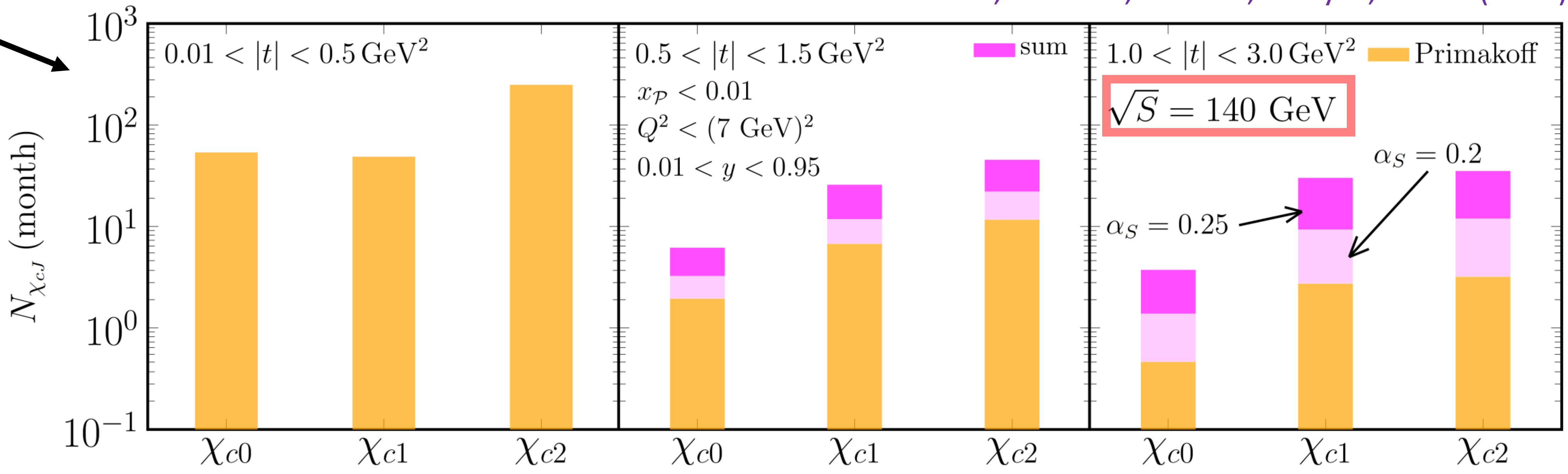
Expected number of events at the EIC

. detection channel: χ_{cJ} -> $J/\psi\gamma$, J/ψ->l^+l^-

. detector efficiency not taken into account!

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

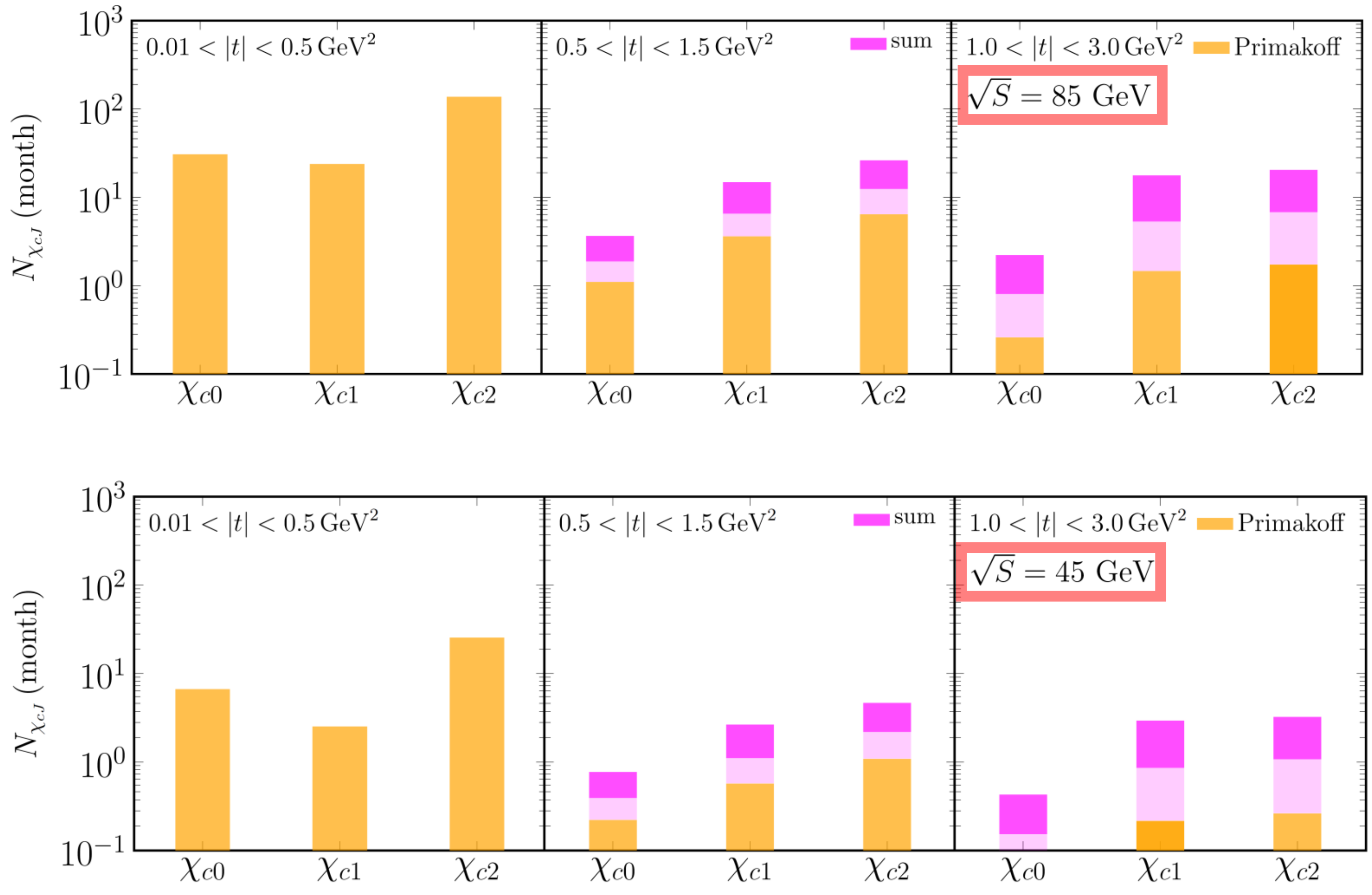
SB, Dumitru, Kaushik, Motyka, Stebel (2024)



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

. for χ_{c1} (34% BR to $J/\psi + \gamma$): with the EIC design luminosity 10^{34} cm^{-2} 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: Spin-dependent Odderon

gluon Sivers!

$$\mathcal{O}_{SS'}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp = 0) \propto k_\perp^i \bar{u}(P', S') \frac{\sigma^{i+}}{P^+} u(P, S) f_{1T}^{\perp g}(x, \boldsymbol{k}_\perp)$$

. gluon Sivers usually accessed by **transverse polarizations**

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

hallmark of single spin asymmetry

virtually unknown, one of the key TMDs to be measured at the EIC

Zheng, Aschenauer, Lee, Xiao, Yin (2018)

. alternatively, gluon Sivers from **helicity-flip** **with unpolarized targets**

$$\mathcal{O}_{\lambda\lambda'}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp = 0) \propto \lambda \delta_{\lambda, -\lambda'} (\boldsymbol{\epsilon}_\perp^\lambda \times \boldsymbol{k}_\perp) f_{1T}^{\perp g}(x, \boldsymbol{k}_\perp) \qquad \boldsymbol{\epsilon}_\perp^\lambda = \frac{1}{\sqrt{2}}(-\lambda, -\mathrm{i})$$

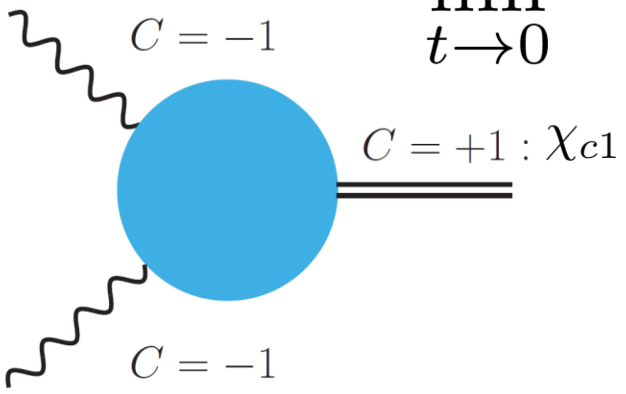
Ma (2003)
Boussarie, Hatta, Szymanowski, Wallon (2020)

Forward limit: Spin-dependent Odderon

. generic problem: at low-t extractions of gluon Sivers suffer from a large background from Primakoff process (~1/|t| Coulomb tail)

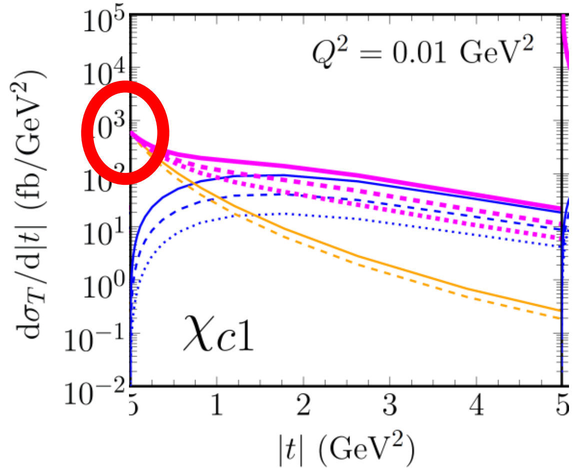
. exception is χ_{c1}: Coulomb tail screened thanks to Landau-Yang theorem

Q^2->0



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

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



t->0

Primakoff cross section finite as t->0!

Forward limit: Spin-dependent Odderon

. cross section from spin-dependent Odderon (gluon Sivers)

. proton flips helicity -> no interference with Primakoff

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

heavy quark limit: sensitive to the first moment of the gluon Sivers

. proportional to the square of gluon Sivers

(transverse spin asymmetries linear in gluon Sivers)

$$r = \left(\frac{\mathrm{d}\sigma_{\mathrm{Siv}}}{\mathrm{d}|t|}\Big/\frac{\mathrm{d}\sigma_{\mathrm{Prim}}}{\mathrm{d}|t|}\right)_{t=0} = \frac{4\pi^2}{q_c^2 N_c^2}\frac{\alpha_S^2}{\alpha^2}\frac{M_p^2}{M_\chi^2}|x f_{1T}^{\perp(1)g}(x)|^2$$

χ_{c1} WF drops out!

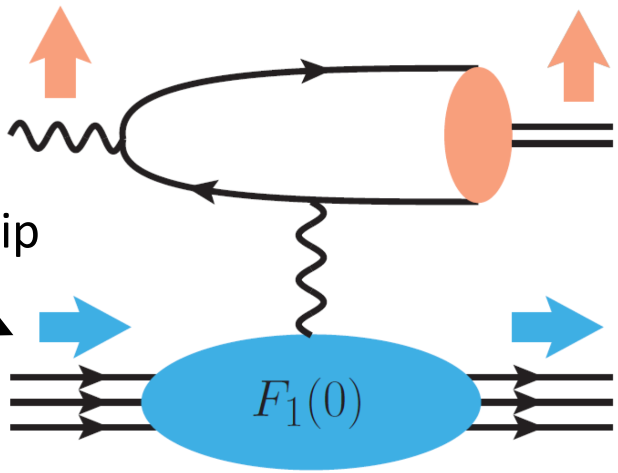
SB, Dumitru, Motyka, Stebel (2024)

χ_{c1} polarization

χ_{c1} transversely polarized

Primakoff

Q^2->0

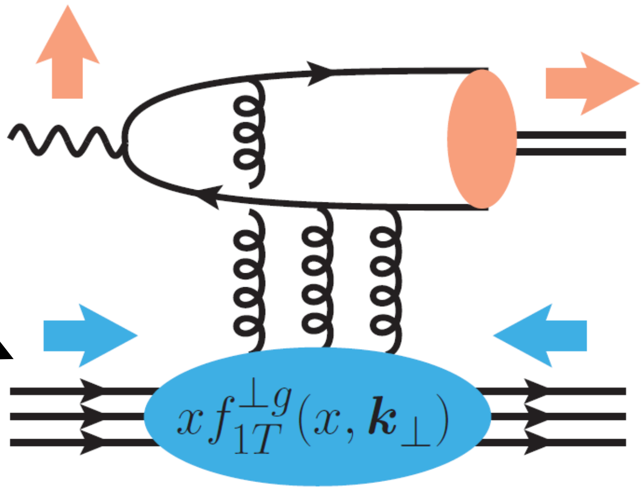


no helicity flip

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 $\lambda_\theta = -1/3$

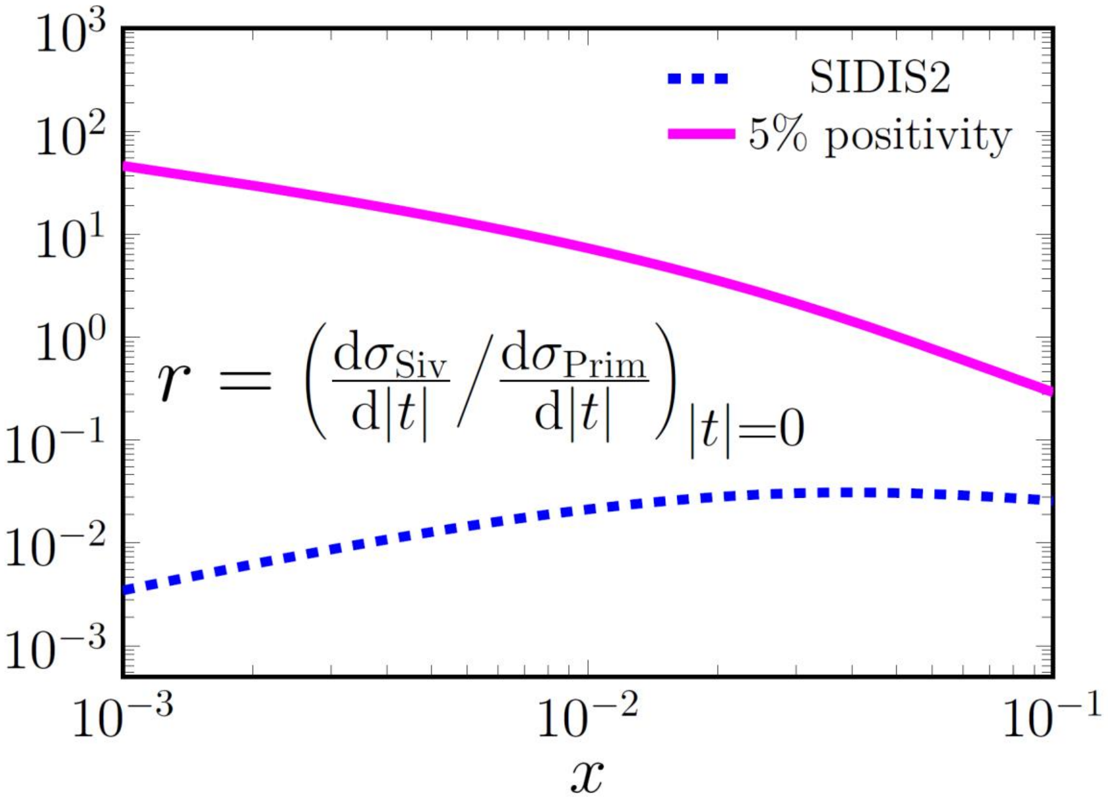
1/r->0 $\lambda_\theta = +1$

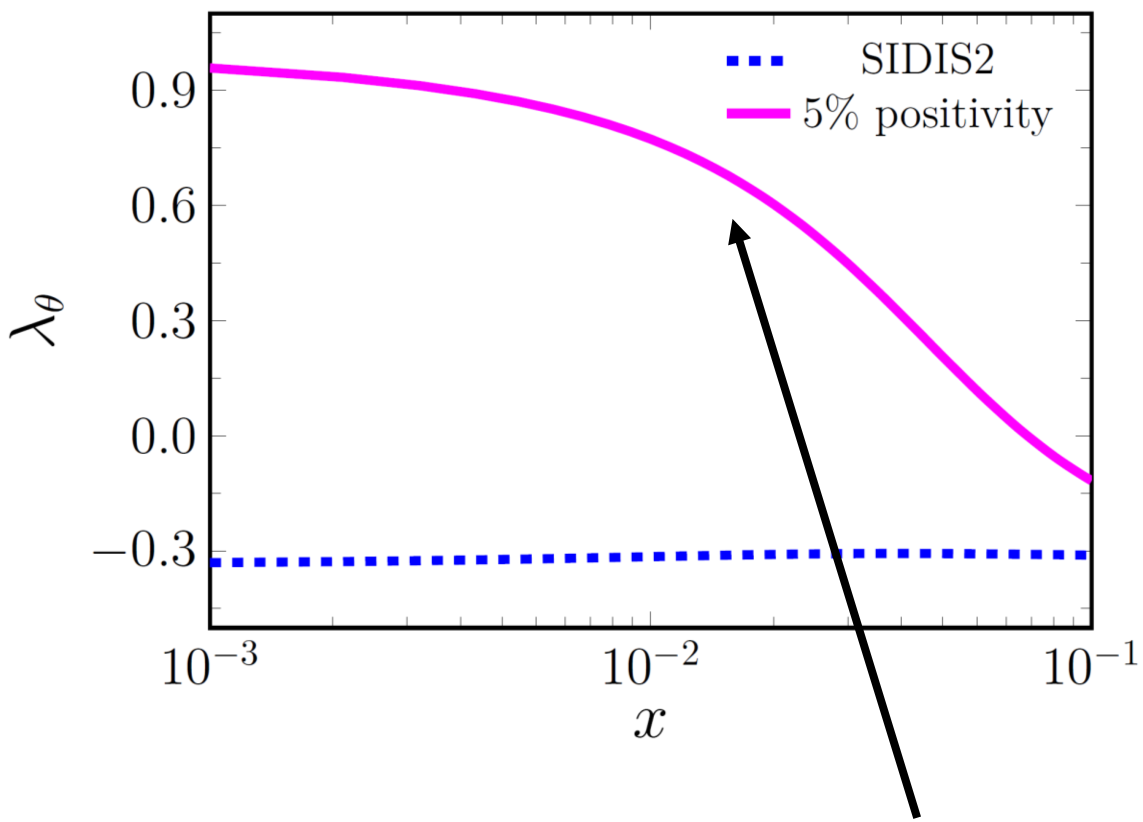
sign change!

SB, Dumitru, Motyka, Stebel (2024)

Model results

SB, Dumitru, Motyka, Stebel (2024)





. large uncertainty in current models of gluon Sivers

. Sivers and Primakoff can be of similar magnitude

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

. opportunity also with pA UPCs

a positive angular coefficient is a signature of spin-dependent Odderon (gluon Sivers)!

Concluding remarks

. can the **'hard' odderon (ggg exchange) be discovered** at the EIC?

. our suggestion: exclusive χ_c production

. **moderate to high-t**: constructive photon-Odderon interference
-> **signature**: event excess above the Primakoff background
. about a few dozen events/month at the EIC (top energy, top luminosity)

. **t->0**: quadratically sensitive to the spin dependent Odderon (gluon Sivers) -> Primakoff finite for χ_{c1}
-> **signature**: x dependence in the cross section and/or sign change of the decay angular coefficient