# Signatures of Odderon in DIS: exclusive productions of $\chi_c$

Sanjin Benić (University of Zagreb)

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

SB, Dumitru, Motyka, Stebel, 2407.04968

Diffraction and Low-x, Sep 8-14, 2024

Croatian Science Foundation

# Odderon

Royon/Ostenberg 9/9, 16:15
Luna 9/9, 17:15
Csorgo, 13/9, 11:20

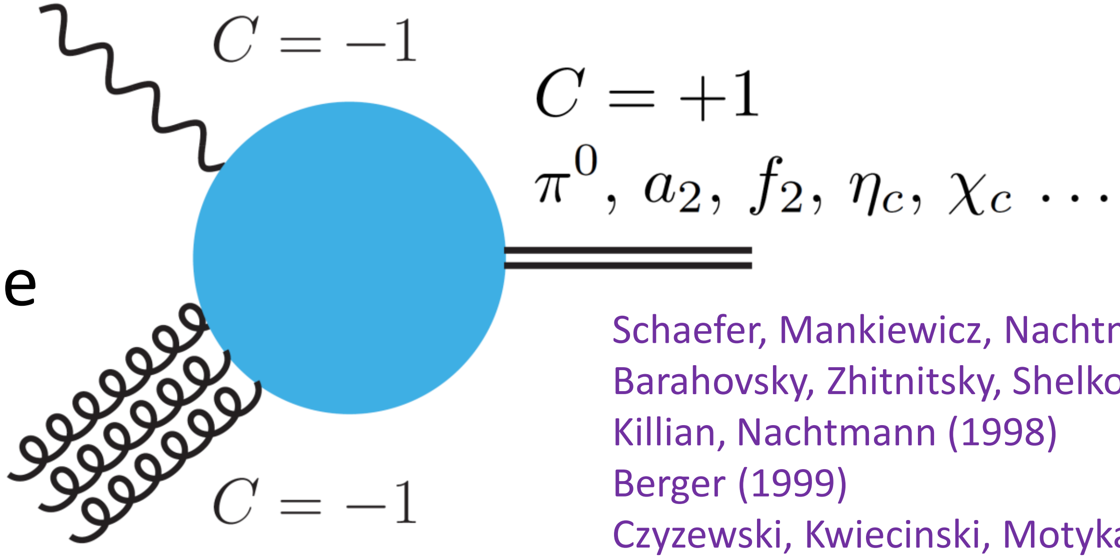
. C-odd partner to the Pomeron

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

TOTEM, D0 (2021)

. DIS -> theoretical control

## a **direct** discovery of the (hard) ggg odderon in DIS?




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

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

Schaefer, Mankiewicz, Nachtmann (1991)
Barahovsky, Zhitnitsky, Shelkovenko (1991)
Killian, Nachtmann (1998)
Berger (1999)
Czyzewski, Kwiecinski, Motyka, Sadzikowski (1997)
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ELSEVIER

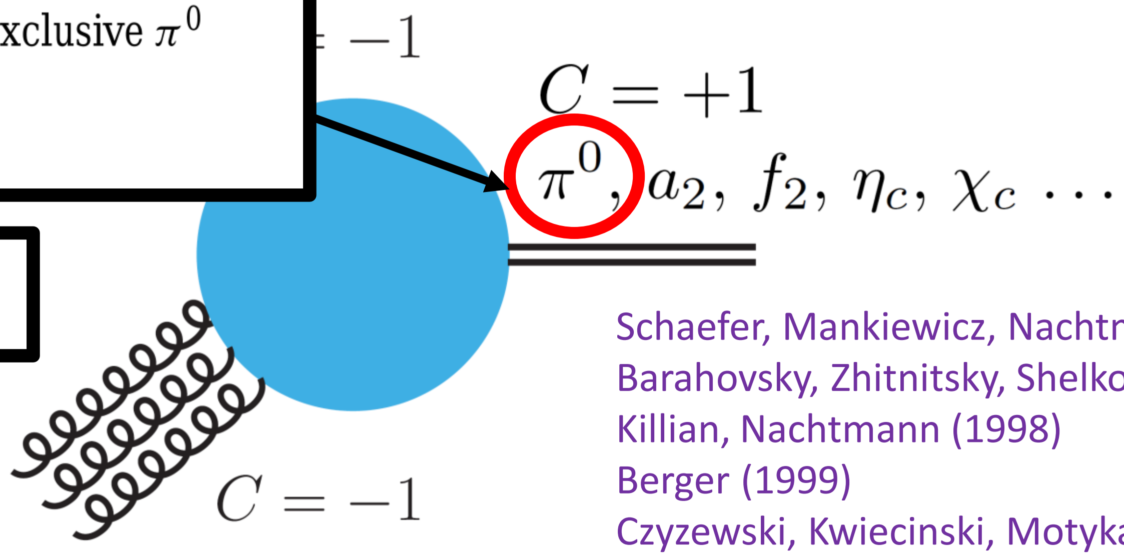
PHYSICS LETTERS B

Physics Letters B 544 (2002) 35–43

Search for odderon-induced contributions to exclusive $\pi^0$ photoproduction at HERA

H1 Collaboration

. Large-x: Lavickova 12/9, 16:25




. exclusive r

$\sigma(\gamma^* p \to \pi^0 N^*) < 49$ nb

negative C-

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. Large-x: Lavickov

**This work**: $\chi_{c0}$, $\chi_{c1}$, $\chi_{c2}$, **quarkonia**

$BR(\chi_{c0} \to J/\psi+\gamma) = 1.4\%$

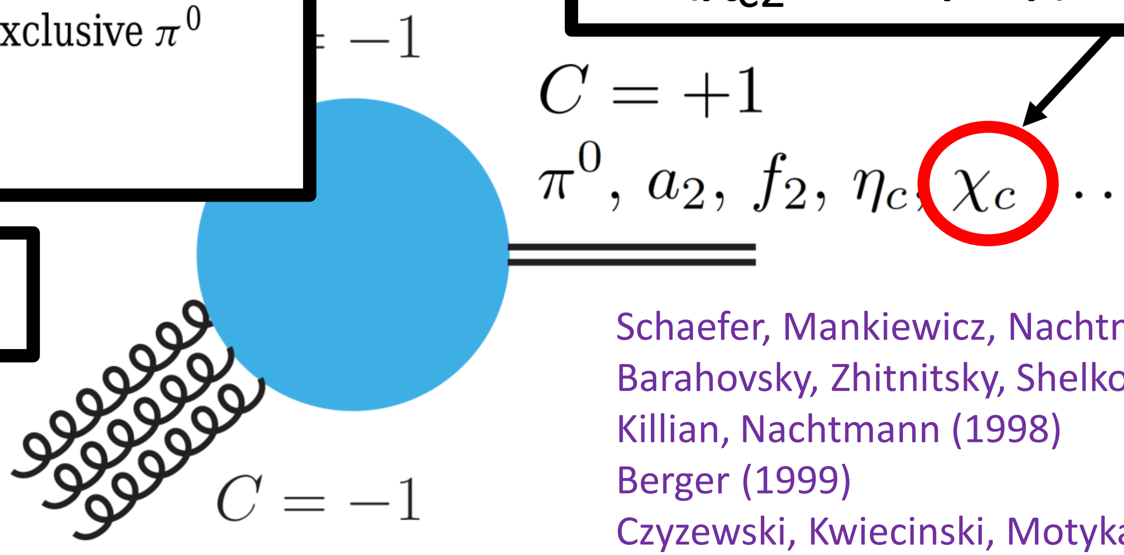
$BR(\chi_{c1} \to J/\psi+\gamma) = 34.3\%$

$BR(\chi_{c2} \to J/\psi+\gamma) = 19.5\%$

. exclusive r

$\sigma(\gamma^* p \to \pi^0 N^*) < 49$ nb

negative C-parity in the target

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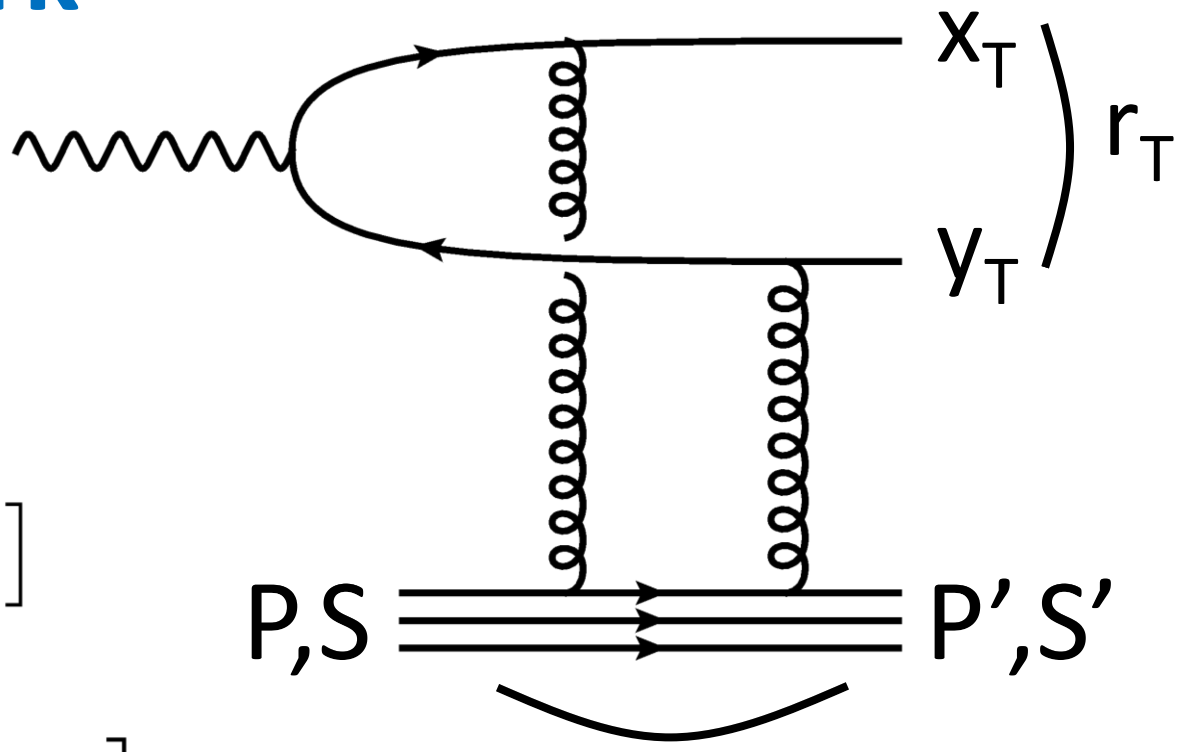
# DIS in the dipole framework




. QCD at high energy

. off-forward dipole S-matrix

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

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

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 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

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

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

Bartels, Lipatov, Vacca (2000)

saturation corrections: suppress the Odderon at high energy

Pomeron

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

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

$$f_{1,1}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp) + \underbrace{\boxed{\mathrm{i}\frac{\boldsymbol{k}_\perp \cdot \boldsymbol{\Delta}_\perp}{M_p^2} g_{1,1}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp)}}_{\text{spin-independent odderon ("directed-flow")}}$$

$$\frac{\boldsymbol{k}_\perp \cdot \boldsymbol{\Delta}_\perp}{M_p^2} f_{1,2}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp) + \underbrace{\boxed{\mathrm{i} g_{1,2}(\boldsymbol{k}_\perp, \boldsymbol{\Delta}_\perp)}}_{\text{spin-dependent Odderon}}$$

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

Zhou (2013)
Boer, Echevarria, Mulders, Zhou (2016)
Radici 12/9, 14:35

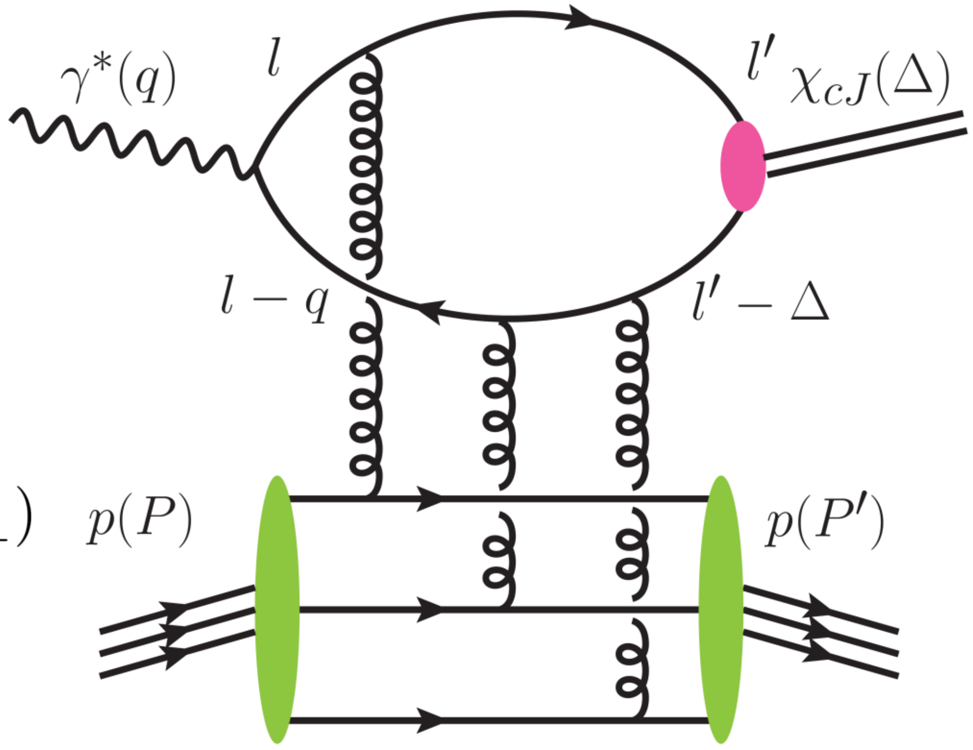
$$g_{1,2}(\boldsymbol{k}_\perp, 0) = -\frac{1}{2} x f_{1T}^{\perp g}(x, \boldsymbol{k}_\perp)$$

# Amplitude

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

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

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




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

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

. reduced amplitude

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

**$\chi_{cJ}$ quarkonia LCWF** (model)

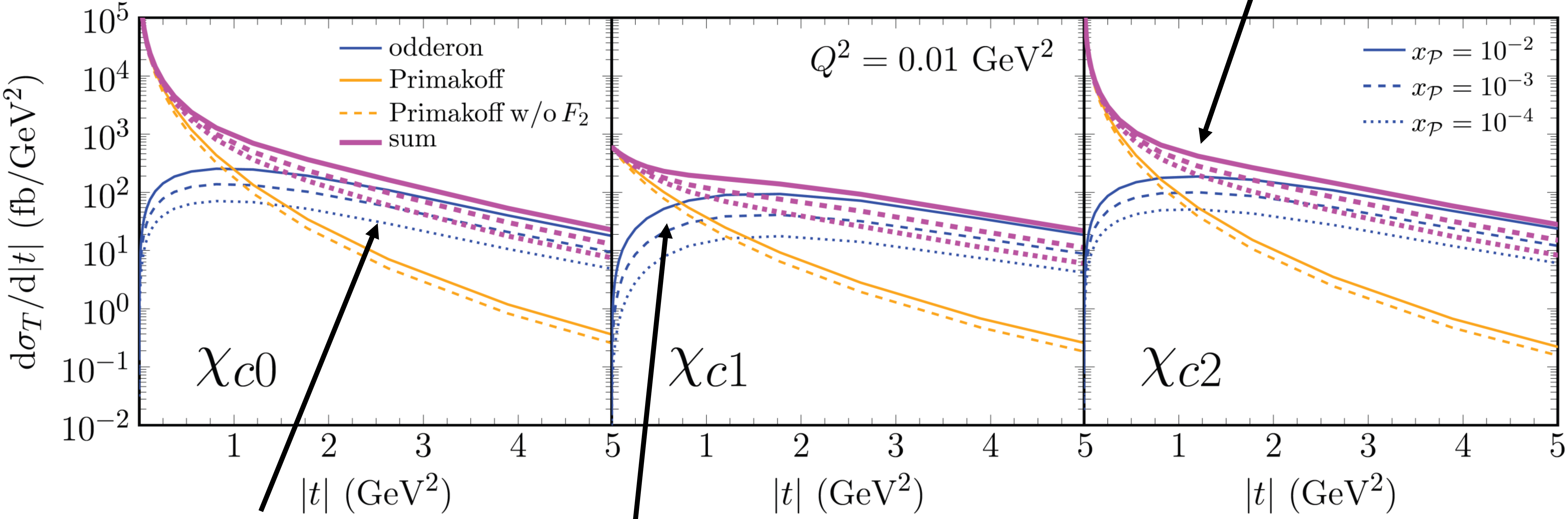
SB, Dumitru, Kaushik, Motyka, Stebel (2024)

**photon LCWF** (perturbative)

# t-distributions

photon and Odderon interfere **constructively**

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




**weak t-dependence**

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

Odderon drops with x->0 (saturation corrections)

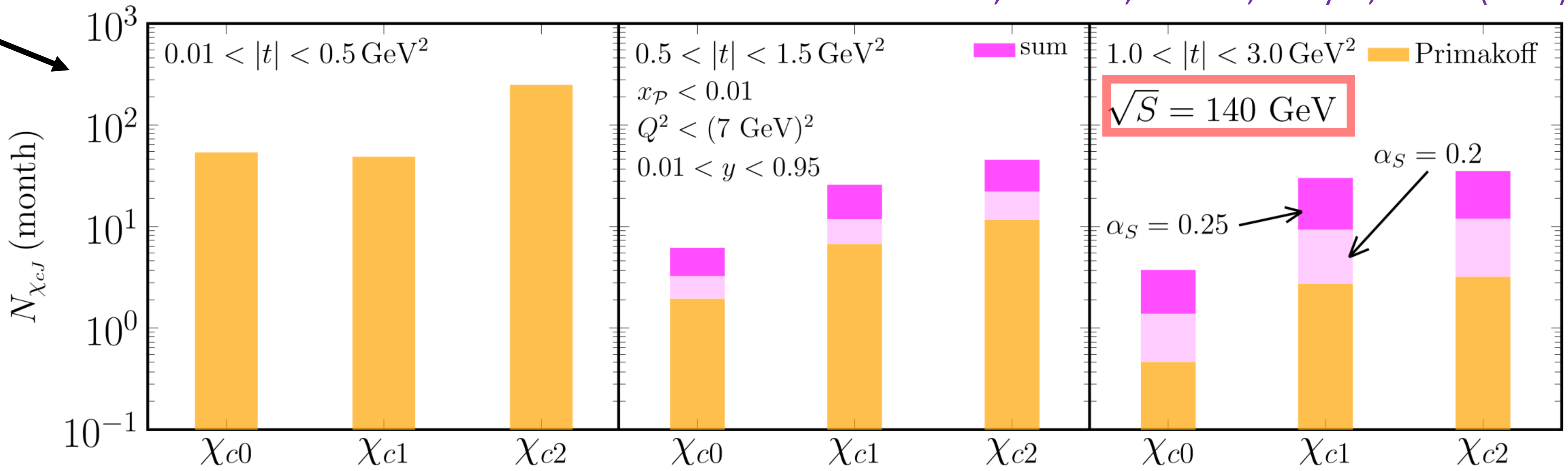
# Expected number of events at the EIC

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

. 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 $\chi_{c1}$ (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)

# Forward limit: Spin-dependent Odderon

gluon Sivers!

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

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

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

hallmark of single spin asymmetry

virtually unknown, one of the key TMDs to be explored at the EIC or the LHCSpin project

Zheng, Aschenauer, Lee, Xiao, Yin (2018)
Santimaria 12/09, 17:15

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

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

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 $\chi_{c1}$: Coulomb tail screened thanks to Landau-Yang selection rule

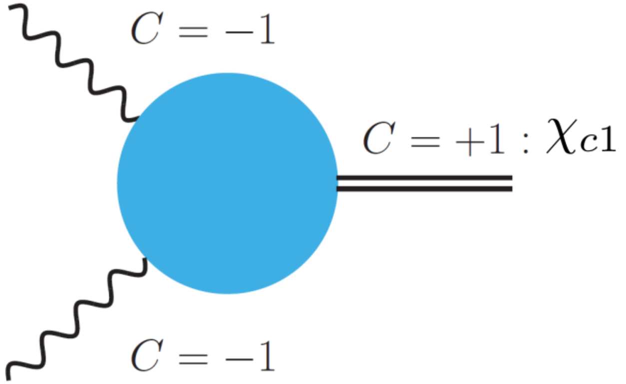
PHYSICAL REVIEW VOLUME 77, NUMBER 2 JANUARY 15, 1950

**Selection Rules for the Dematerialization of a Particle into Two Photons**

C. N. YANG*
*Institute for Nuclear Studies, University of Chicago, Chicago, Illinois*
(Received August 22, 1949)

IT has been pointed out[1] that a positronium in the $^3S$ state cannot decay through annihilation with the emission of two photons. Recent calculation[2] shows that also a vector or a pseudovector neutral meson cannot disintegrate into two photons. It is the purpose of the present paper to show that these facts are immediate consequences of certain selection rules which can be derived from the general principle of invariance under space rotation and inversion.

$Q^2$->0




t->0

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

Primakoff cross section finite as t->0!

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

# Forward limit: Spin-dependent Odderon

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

. proton flips helicity -> no interference with Primakoff

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

heavy quark limit: sensitive to the first moment of the gluon Sivers (analogue to the Ryskin formula for J/ψ)

. proportional to the square of gluon Sivers

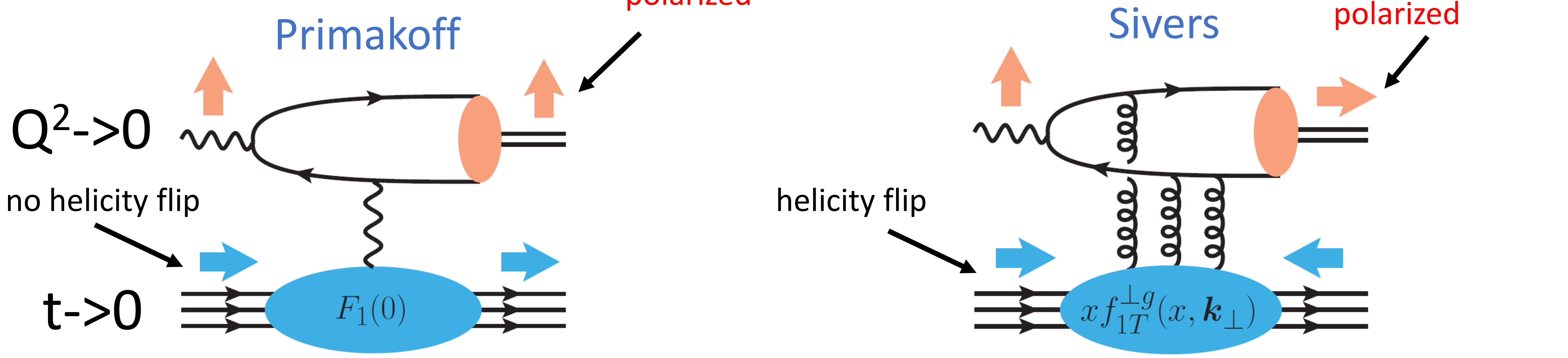
(transverse spin asymmetries linear in gluon Sivers)

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

$\chi_{c1}$ WF drops out!

SB, Dumitru, Motyka, Stebel (2024)

# $\chi_{c1}$ polarization




-> distinct signature in angular distribution of the decay: $\chi_{c1}$->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 $\lambda_\theta = -1/3$

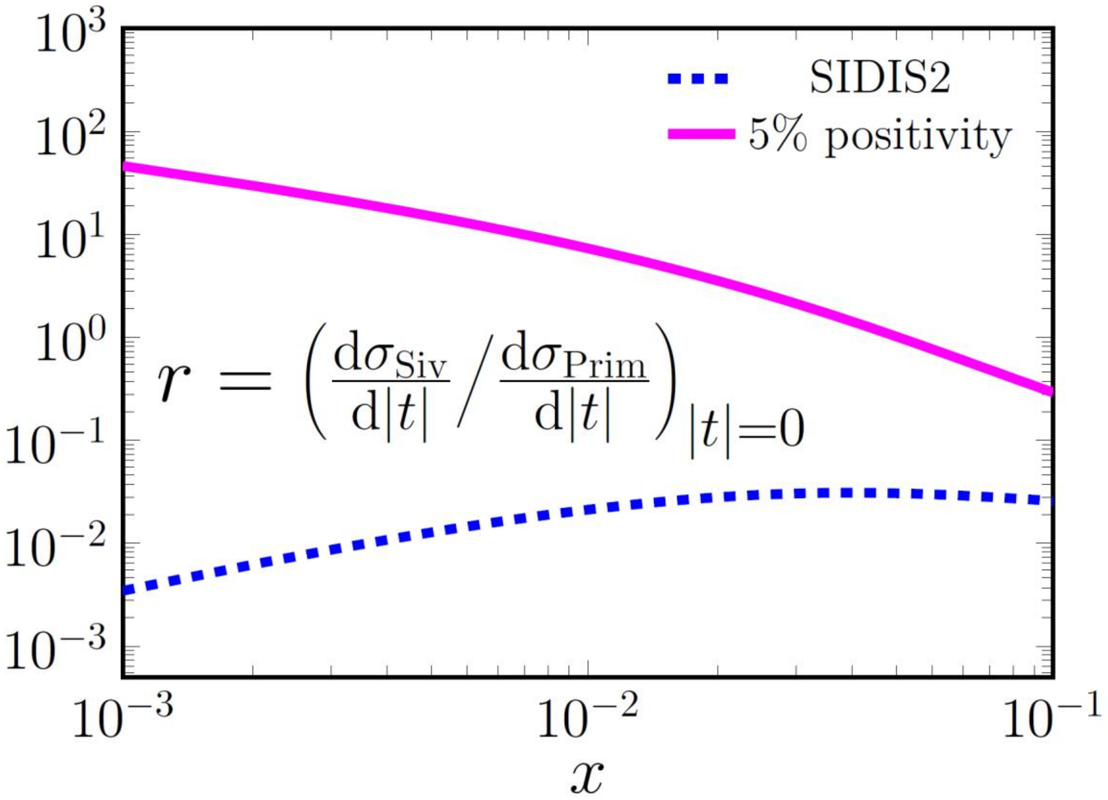
1/r->0 $\lambda_\theta = +1$

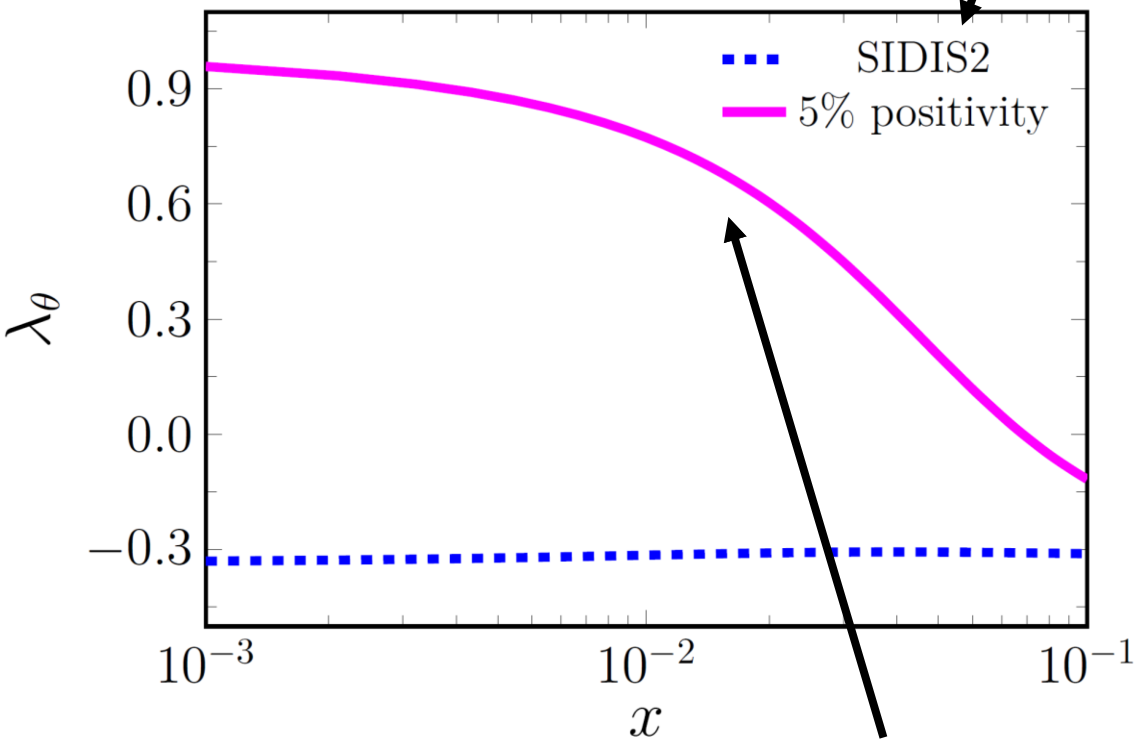
Polar anisotropy changes sign!

SB, Dumitru, Motyka, Stebel (2024)

# 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

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

. opportunity also with pA UPCs

SB, Dumitru, Motyka, Stebel (2024)

# Conclusions and challenges

. **signature at moderate t**: shape of t-distributions in exclusive $\chi_c$, event excess above the Primakoff background

. **signature at t->0**: x dependence in the cross section in exclusive $\chi_{c1}$, sign change of the decay angular coefficient

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

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

-> $\chi_c$ from feed-down expected with a sharper t-spectra