Odderon at the EIC from exclusive χ_c productions at high energies

Sanjin Benić (University of Zagreb)

SB, Dumitru, Kaushik, Motyka, Stebel, 2402.19134

Diffraction and gluon saturation at the LHC and the EIC

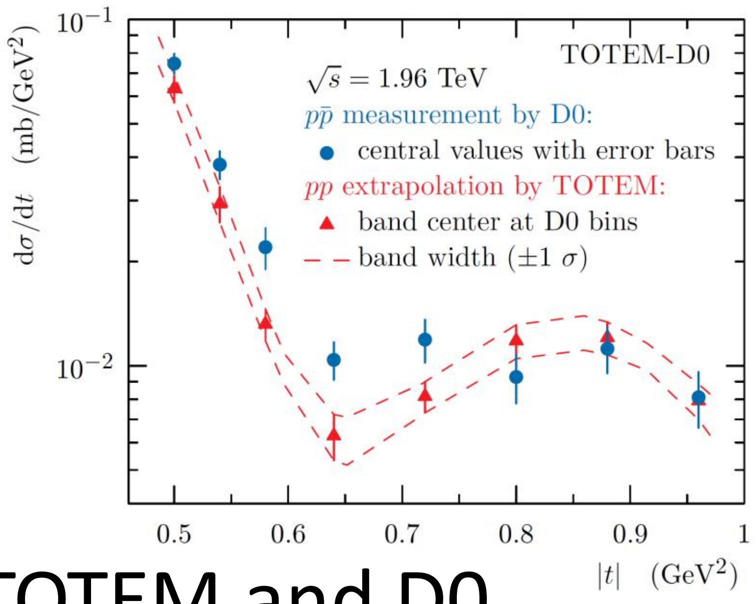
ECT* Trento, Italy, June 10-14, 2024

UNIVERSITAS STUDIORUM ZAGRABIENSIS MDCLXIX

HrZZ
Croatian Science Foundation

Odderon in hadronic collisions

TOTEM, D0 (2021)



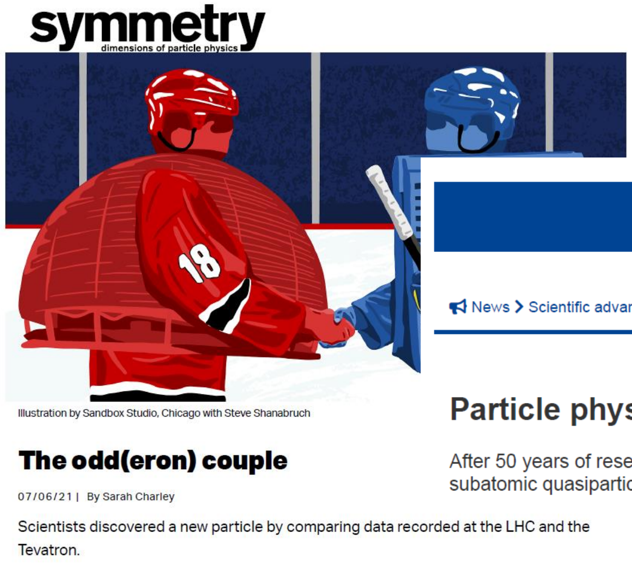
. suggested 50+ years ago – colorless **C-odd** exchange to govern the pp vs $p\bar{p}$ cross section difference

Lukaszuk, Nicolescu (1973)
Ewerz (2003)

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

talk by F. Nemes (Mon, 09:50)

-> the story was featured in media outlets



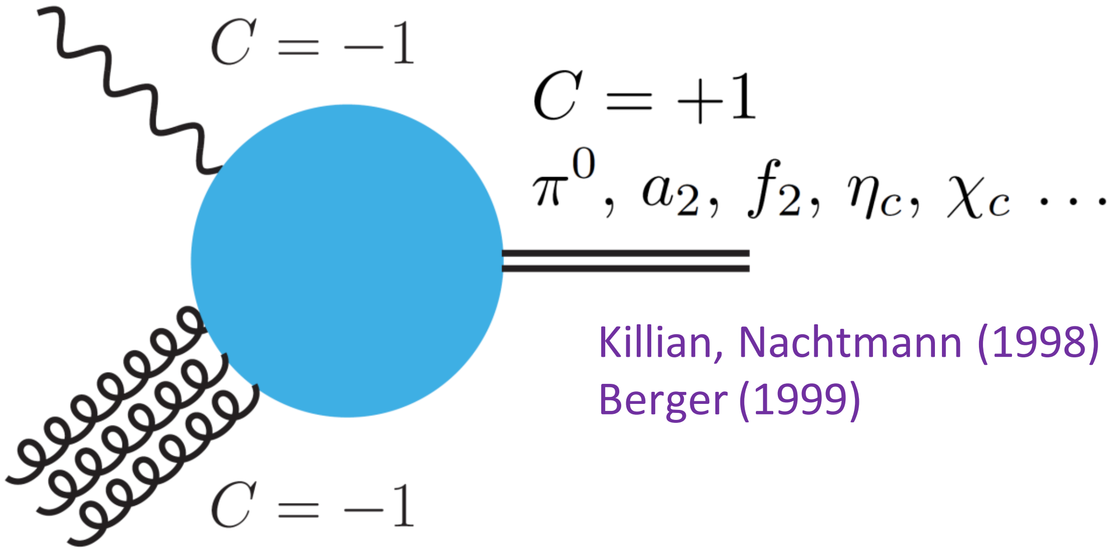
Odderon in DIS?

. for pp it is difficult to make perturbative QCD computation

. DIS offers more theoretical control

→ **desirable to verify/confirm/discover the (hard) odderon in DIS**

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

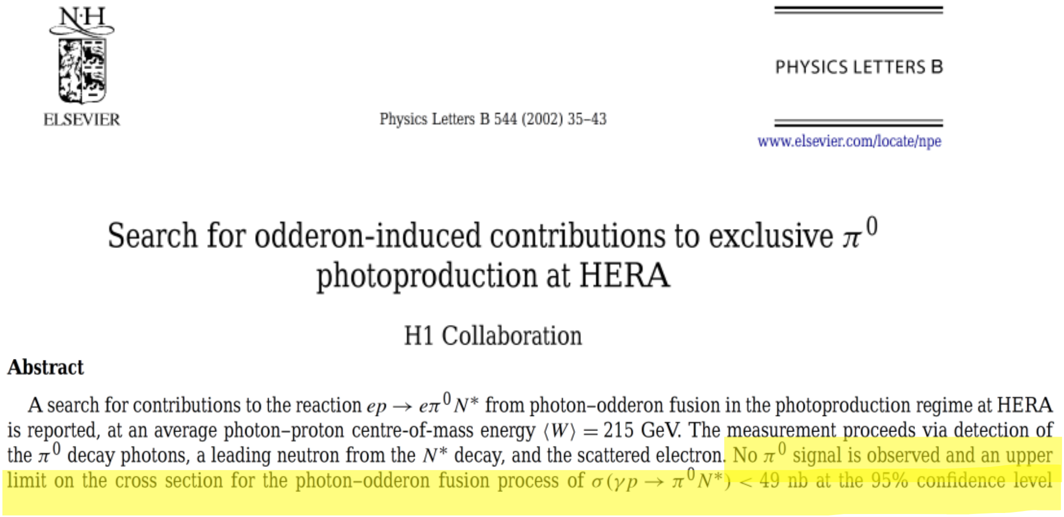


Killian, Nachtmann (1998)
Berger (1999)

. 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:



PHYSICS LETTERS B
Physics Letters B 544 (2002) 35–43
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

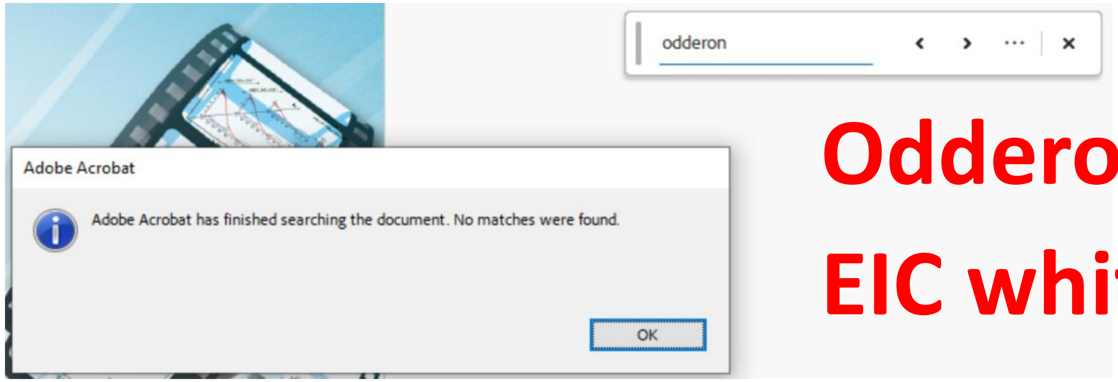
$\sigma(\gamma^* p \to \pi^0 N^*) < 39$ nb

$\sigma(\gamma^* p \to f_2 X) < 16$ nb

$\sigma(\gamma^* p \to a_2 X) < 96$ 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

. 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)

HERA kinematics:

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

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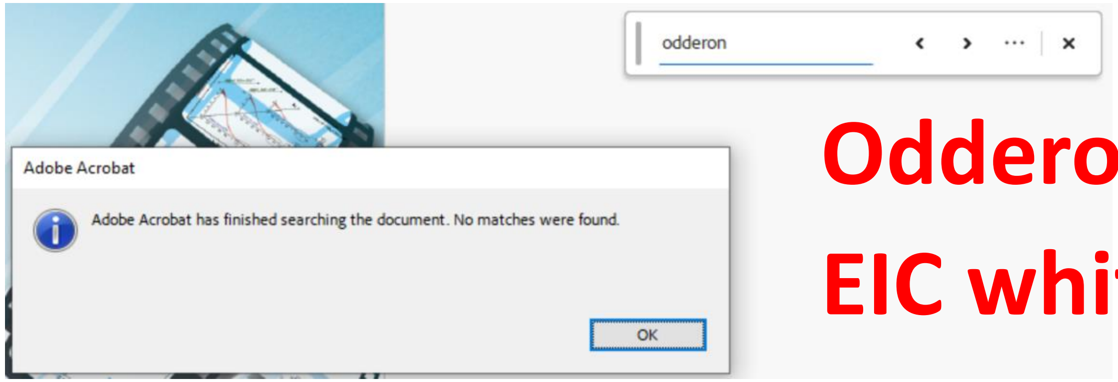


1212.1701 (EIC white paper)

Odderon not discussed in the EIC white paper

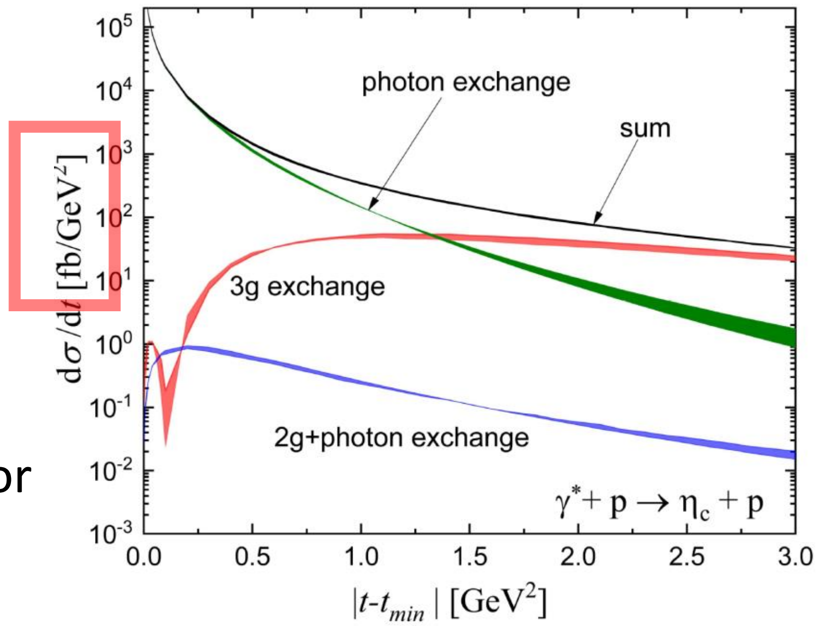
Odderon searches in DIS: quarkonia

. from late 90's theorists explore exclusive η_c

. **no experimental detection so far**

Czyzewski, Kwiecinski, Motyka, Sadzikowski (1997)
Bartels, Braun, Colferai, Vacca (2001)
Dumitru, Stebel (2019)
SB, Horvatić, Kaushik, Vivoda (2023)

recent computation within a quark model for the proton WF



. note: $d\sigma/d|t|$~10-100 fb/GeV^2 (at most)

-> much smaller than the HERA upper bound (which is also at low |t|)

-> explains why Odderon is not seen at HERA

-> at low |t| there is a background from photon exchange (Primakoff process)

. issues with η_c detection (small branching ratios to hadronic channels)

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

Odderon searches in DIS: quarkonia

-> we argue exclusive χ_{cJ} (J = 0, 1, 2) productions is a **golden channel** for 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/ψ γ (BR ~ 34% for χ_{c1}!)

. about 56 χ_{c1}'s and ~12 χ_{c2}'s (exclusive) detected (!) near threshold with GlueX

Pentchev, DIS2023, GHP 2023

. odderon cross sections expected to be small but keep in mind that 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

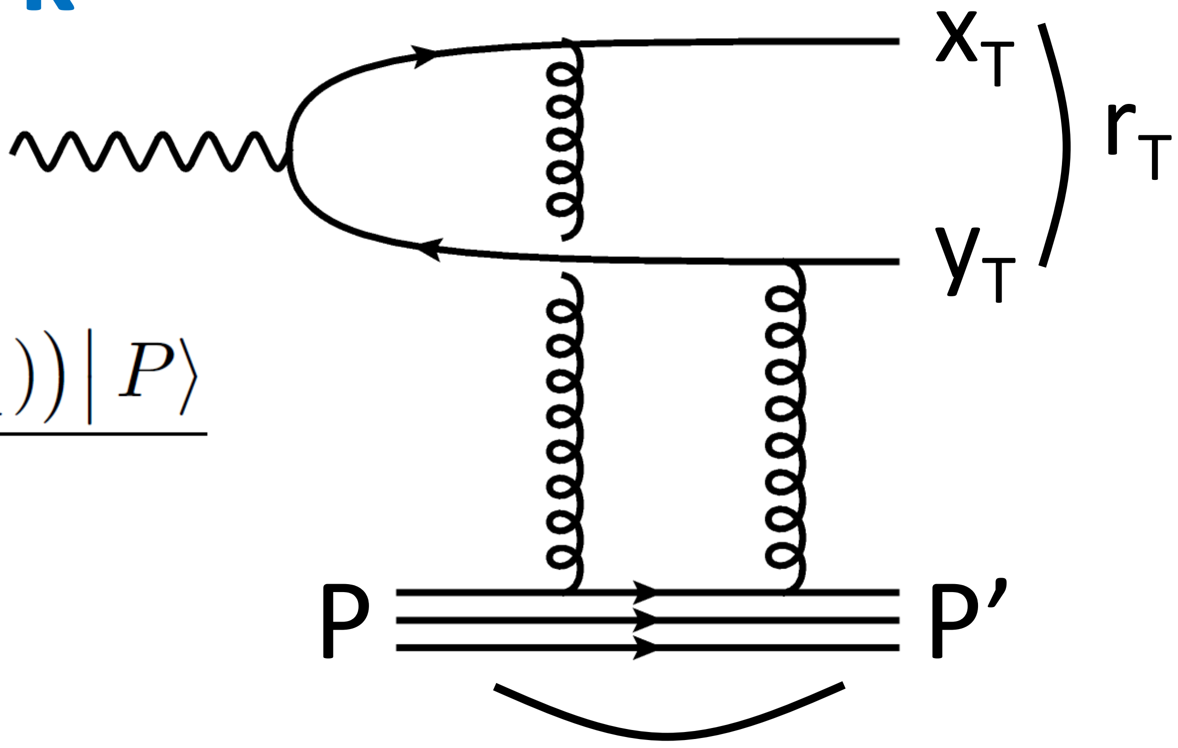
. QCD at high energy

. off-forward dipole S-matrix

$$\mathcal{D}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = \frac{1}{N_c} \frac{\langle P' | \mathrm{tr}\left(V(\boldsymbol{x}_\perp) V^\dagger(\boldsymbol{y}_\perp) \right) | P \rangle}{\langle P | P \rangle}$$

$$= \frac{1}{N_c} \mathrm{tr} \langle V(\boldsymbol{x}_\perp) V^\dagger(\boldsymbol{y}_\perp) \rangle$$

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



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

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

(impact parameter)

Odderon in the dipole framework

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

. odderon as the imaginary part

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

. expand the Wilson line

$$\mathcal{O}(\boldsymbol{x}_\perp, \boldsymbol{y}_\perp) = -\frac{g^3}{24N_c} d^{abc} (\alpha^a(\boldsymbol{x}_\perp) - \alpha^a(\boldsymbol{y}_\perp))(\alpha^b(\boldsymbol{x}_\perp) - \alpha^b(\boldsymbol{y}_\perp))(\alpha^c(\boldsymbol{x}_\perp) - \alpha^c(\boldsymbol{y}_\perp))$$

-> three-gluons with color tied in symmetric way

. charge conjugation $\boldsymbol{x}_\perp \leftrightarrow \boldsymbol{y}_\perp$ ➡ odderon flips sign (C-odd)

Odderon in the dipole framework

-> odderon linear in $\boldsymbol{r}_\perp$ -> need another vector: $\boldsymbol{r}_\perp \cdot \boldsymbol{b}_\perp$

-> odderon as an off-forward amplitude (generalized TMD - GTMD)

$$\mathcal{D}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - \mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) + i\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$$

Kovchegov, Szymanowski, Wallon (2004)
Hatta, Iancu, Itakura, McLerran (2005)
Motyka (2006)

. non-linear (Balitsky-Kovchegov) evolution equation (written here in local approx)

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

linear piece: equivalent to BJKP/BLV evolution -> constant odderon

saturation corrections: acts to suppress the odderon at high energy

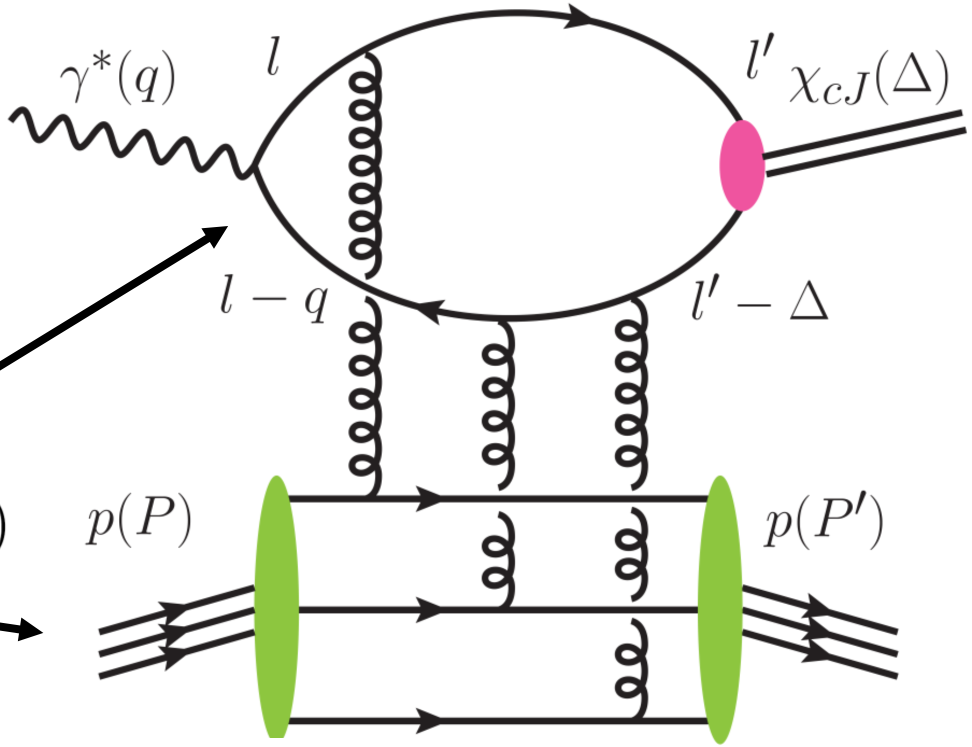
$$Y = \log(1/x)$$

Amplitude

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

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

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



. reduced amplitude

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

. perturbative photon wave function $\Psi^\gamma_{\lambda,h\bar{h}}(\boldsymbol{k}_\perp, z) \equiv \sqrt{z\bar{z}} \dfrac{\bar{u}_h(k) e q_c \not{\epsilon}(\lambda, q) v_{\bar{h}}(q-k)}{\boldsymbol{k}_\perp^2 + \varepsilon^2}$

$$\varepsilon \equiv \sqrt{m_c^2 + z\bar{z}Q^2} \qquad z = \frac{k^-}{q^-} \qquad \bar{z} \equiv 1 - z$$

C-even charmonia wave functions

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

scalar function: boosted Gaussian ansatz

$$\Psi^{\mathcal{H}}_{\bar{\lambda},h\bar{h}}(\boldsymbol{k}_\perp, z) \equiv \frac{1}{\sqrt{z\bar{z}}} \underbrace{\bar{u}_h(k)\Gamma^{\mathcal{H}}_{\bar{\lambda}}(k,k')v_{\bar{h}}(k')}_{\text{spin structure}} \phi_{\mathcal{H}}(\boldsymbol{k}_\perp, z)$$

Forshaw, Sandapen, Shaw (2004)
Kowalski, Motyka, Watt (2006)

. covariant ansatz

polarization vector for spin 1

$$\Gamma^{\mathcal{H}}_{\bar{\lambda}}(k,k') = \begin{cases} 1\ , & \mathcal{H} = \mathcal{S} \\ \mathrm{i}\gamma_5 \not{E}(\bar{\lambda},\Delta_0)\ , & \mathcal{H} = \mathcal{A} \\ \frac{1}{4}\left(\gamma_\mu(k_\nu - k'_\nu) + \gamma_\nu(k_\mu - k'_\mu)\right) E^{\mu\nu}(\bar{\lambda},\Delta_0)\ , & \mathcal{H} = \mathcal{T} \end{cases}$$

χ_{cJ}

spin 2 -> coupling to the energy momentum tensor

spin 2 polarization tensor: in terms of spin 1 via Clebsch-Gordans

Berger, Donnachie, Dosch, Nachtmann (2000)
Fiore, Zoller (2005)
Motyka, Watt (2008)
Babiarz, Pasechnik, Schaefer, Szczurek (2022)

. model parameters fit to the γγ widths

Odderon initial condition

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

operator for Weiszacker-Williams gluon field

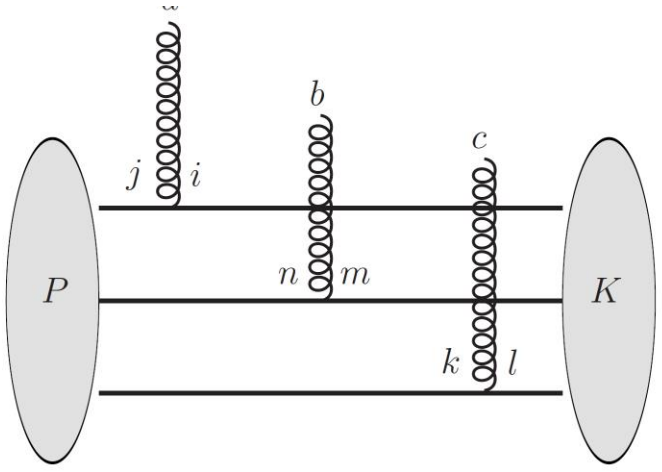
$$\mathcal{O}(\boldsymbol{r}_\perp,\boldsymbol{b}_\perp) = -\frac{1}{2iN_c}\mathrm{tr}\left\langle V\left(\boldsymbol{b}_\perp+\frac{\boldsymbol{r}_\perp}{2}\right)V^\dagger\left(\boldsymbol{b}_\perp-\frac{\boldsymbol{r}_\perp}{2}\right) - V\left(\boldsymbol{b}_\perp-\frac{\boldsymbol{r}_\perp}{2}\right)V^\dagger\left(\boldsymbol{b}_\perp+\frac{\boldsymbol{r}_\p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

quark density operators sandwiched between off-forward proton WF

. expand Wilson lines to cubic order

$$\mathcal{T}^{O(\rho^3)}(\vec{r},\vec{b}_\perp;\vec{K}_\perp) = -\frac{g^6}{8N_c}d^{abc}\int_{q_1}\int_{q_2}\int_{q_3}\frac{1}{q_1^2}\frac{1}{q_2^2}\frac{1}{q_3^2}\langle\tilde{\rho}^a(\vec{q}_1)\tilde{\rho}^b(\vec{q}_2)\tilde{\rho}^c(\vec{q}_3)\rangle_{K_\perp}e^{i\vec{b}_\perp\cdot(\vec{q}_1+\vec{q}_2+\vec{q}_3)}$$
$$\times\left[2\sin\left(\frac{\vec{r}}{2}\cdot(\vec{q}_1-\vec{q}_2-\vec{q}_3)\right)+\frac{2}{3}\sin\left(\frac{\vec{r}}{2}\cdot(\vec{q}_1+\vec{q}_2+\vec{q}_3)\right)\right].$$

Dumitru, Miller, Venugopalan (2018)



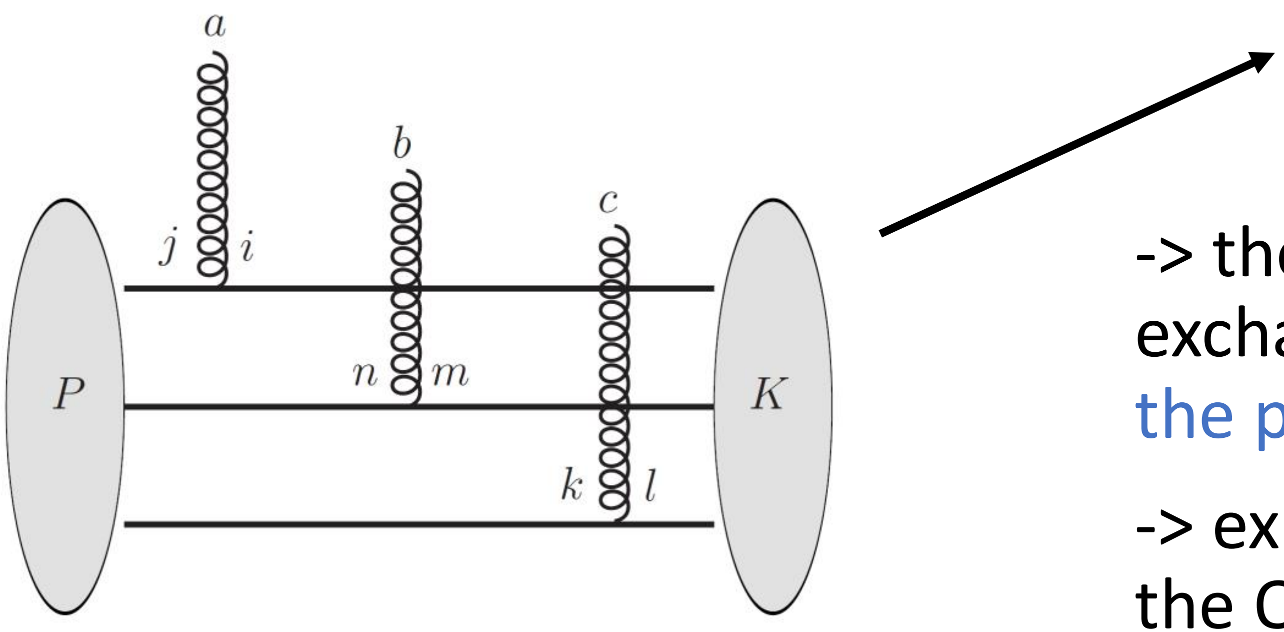
. uses earlier fits to nucleon radii, magnetic moments and coupling to weak currents (g_A)

Brodsky, Schlumpf (1994)

. this quark-based model of the proton WF does a decent job to describe the pomeron sector

Dumitru, Mantysaari, Paatelainen (2023)

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

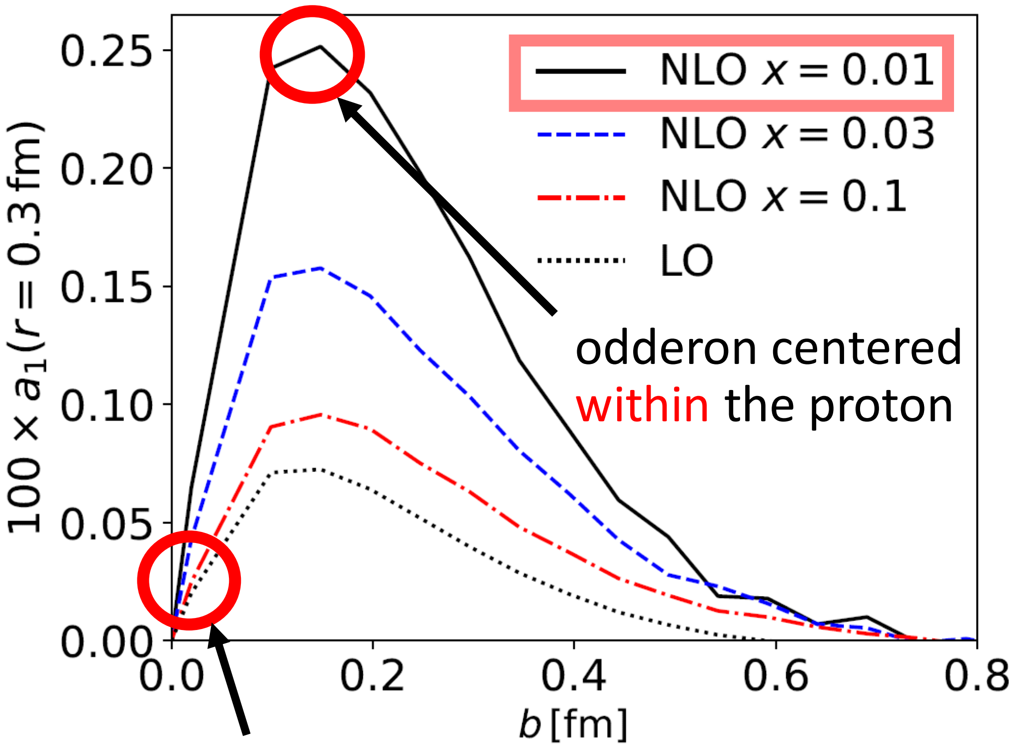
-> expect a weak t-dependence of the Odderon exchange amplitude

. model computation fixes the overall sign of the odderon

. numerically we find odderon sign not changed by evolution

Odderon evolved

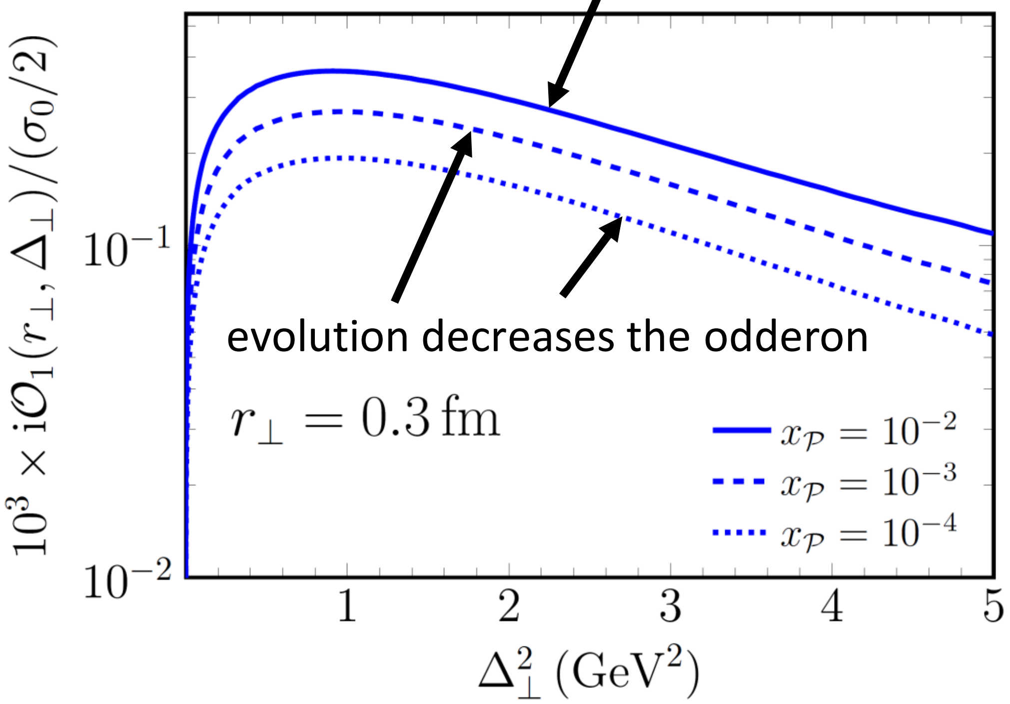
-> **solved on a 3D grid** in r_T, b_T and relative angle



Dumitru, Mantysaari, Paatelainen (2022)
Dumitru, Mantysaari, Paatelainen (2023)

Fourier transform

many diagrams in practice but intuitive picture of the weak t-dependence (at high t) seems to work



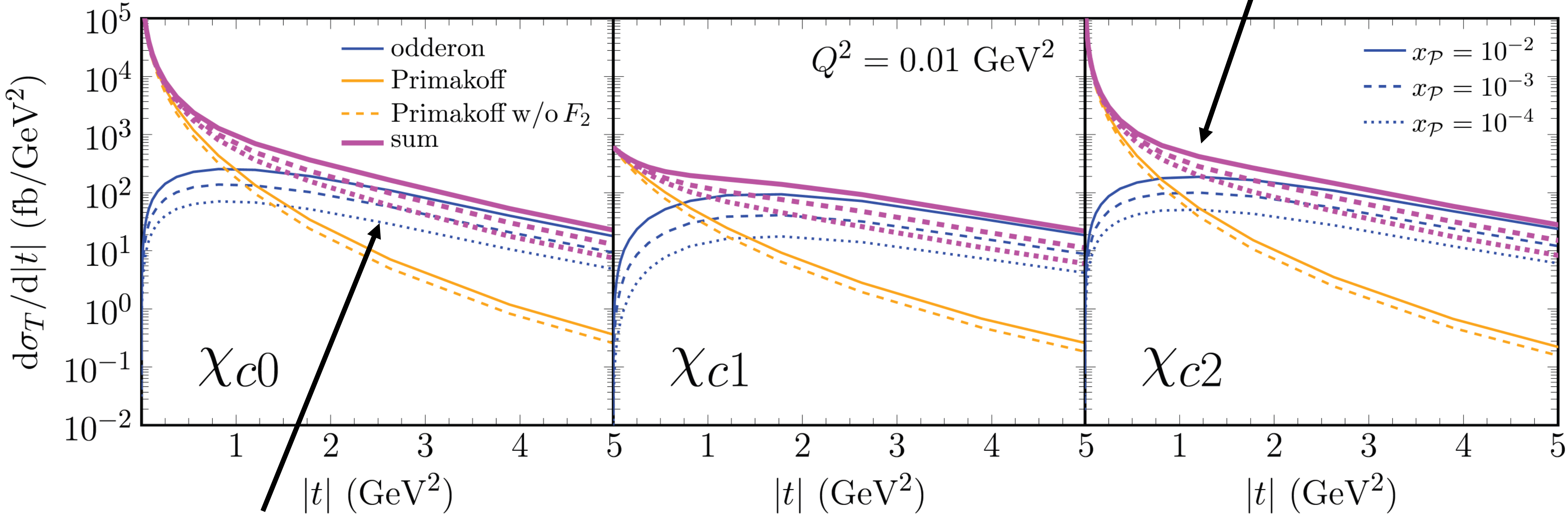
slope unaffected by small-x evolution

SB, Horvatic, Kaushik, Vivoda (2023)
SB, Dumitru, Kaushik, Motyka, Stebel (2024)

t-distributions

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

coherent sum of photon+odderon

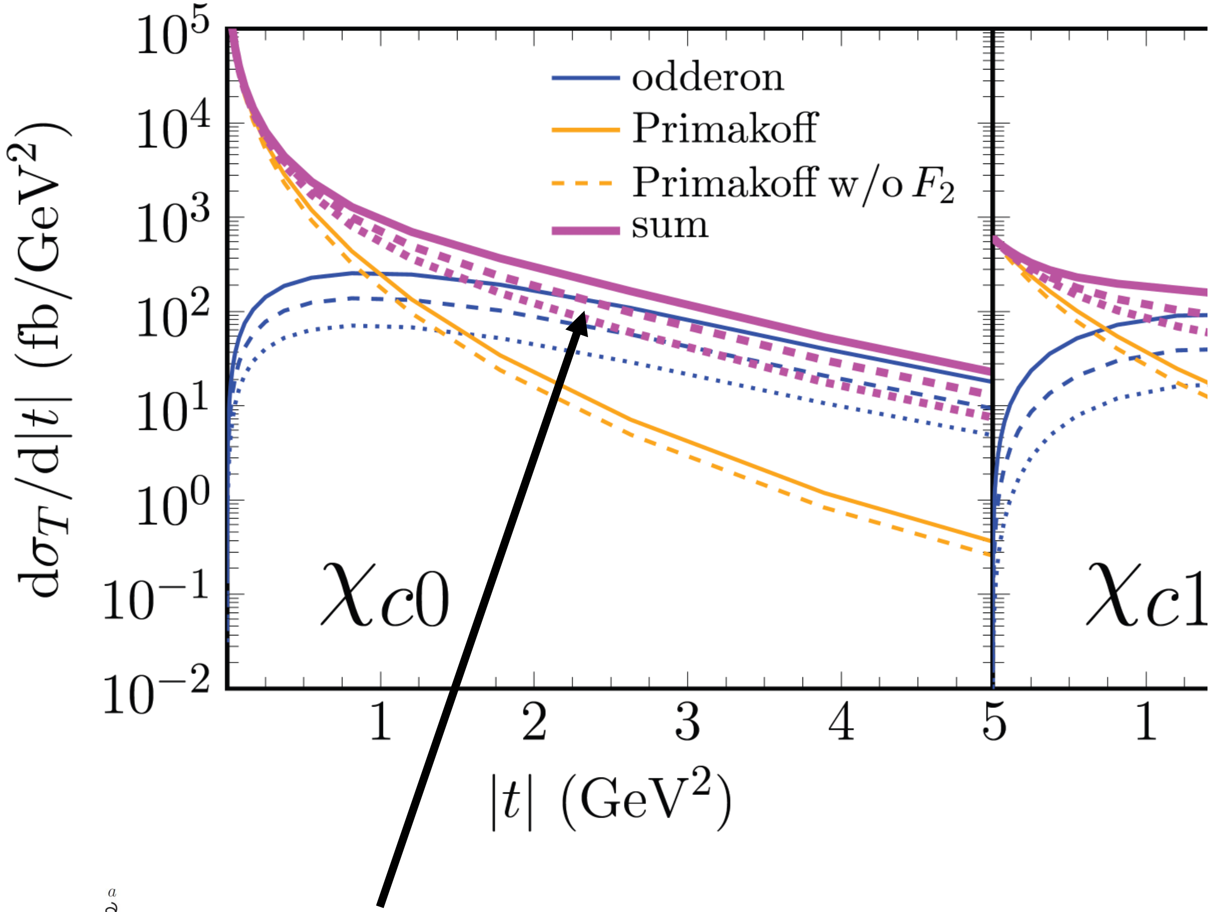


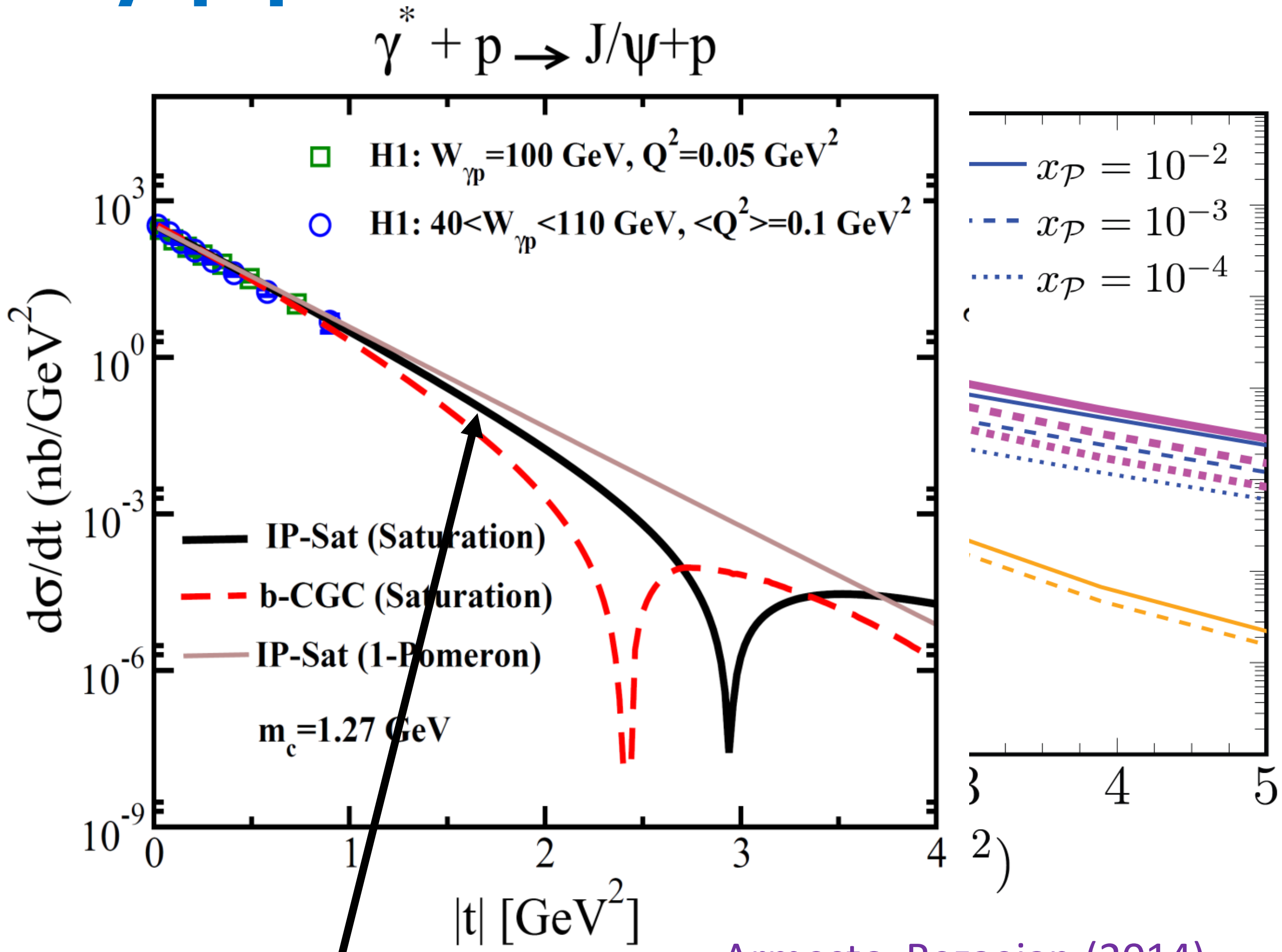
weak t-dependence

photon and odderon interfere **constructively**

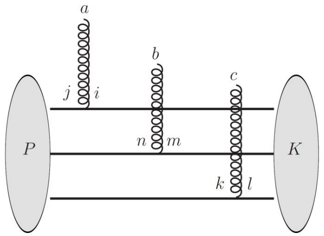
SB, Dumitru, Kaushik, Motyka, Stebel (2024)

Note the stark contrast with J/ψ production

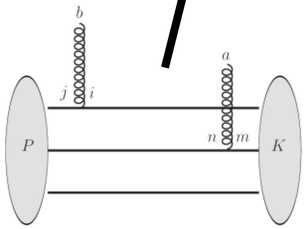




Armesto, Rezaeian (2014)

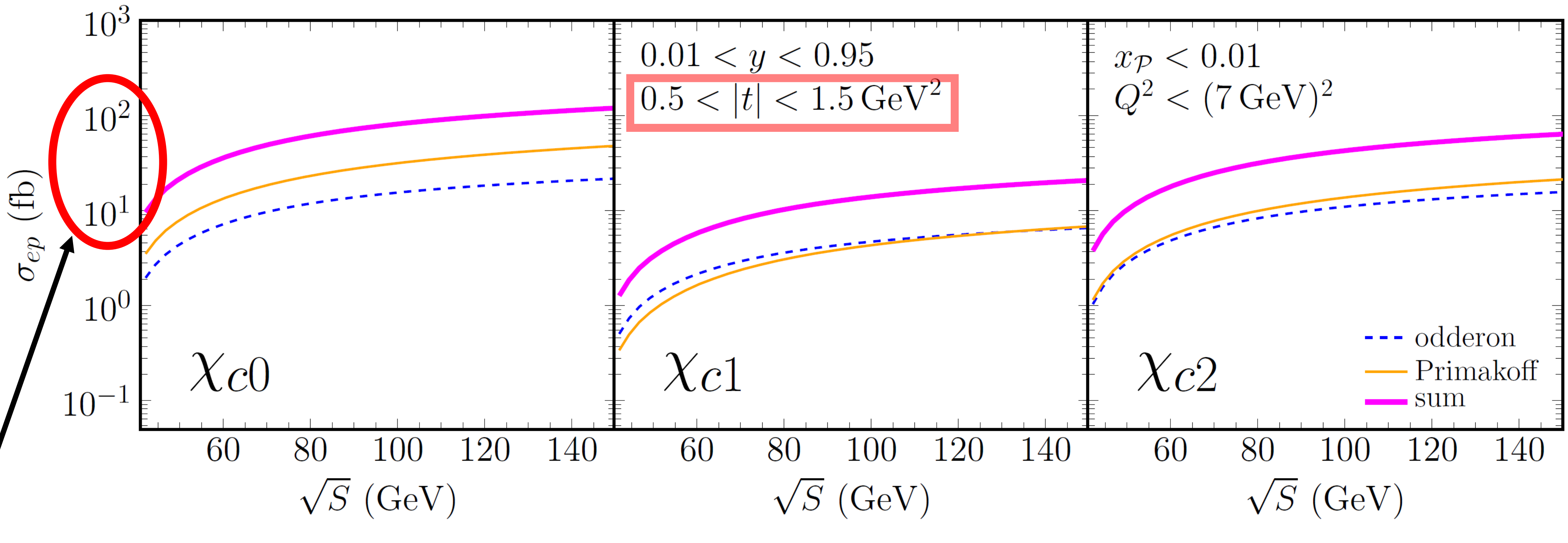


Odderon: **weak t-dependence**



Pomeron: **strong t-dependence** exp(-B|t|)

Total electroproduction cross section



Is this enough for the EIC?

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

. note: at the EIC proton detection seems to be up to p_T~1.3 GeV

EIC Yellow report

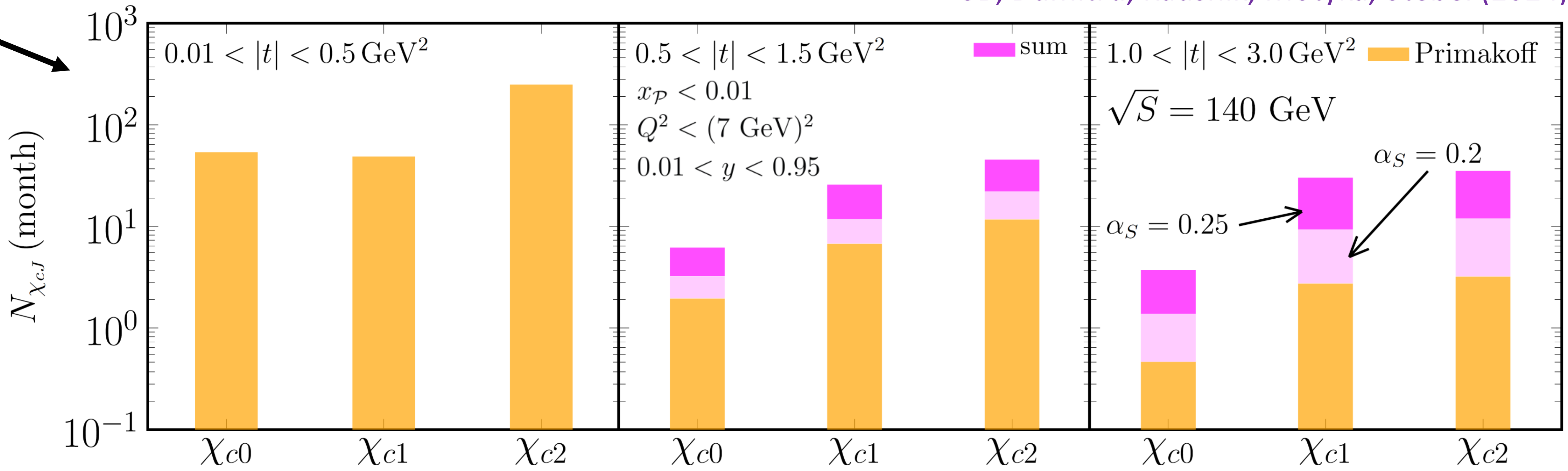
Expected number of events at the EIC

. detection channel: χ_{cJ} -> J/ψγ, 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/ψ + γ): with EIC luminosity 10^{34} cm^{-2} s^{-1}

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

Concluding remarks

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

. our suggestion: exclusive χ_c production

. odderon signal enhancement thanks to a constructive photon-odderon interference

-> event excess above the Primakoff background

. we predict about a few dozen events/month at the EIC (top energy, top luminosity)

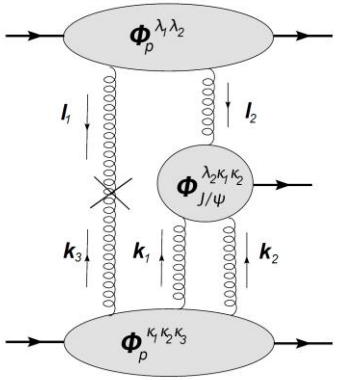
. was not possible at HERA.. (luminosity ~ 10^{32} cm^{-2} s^{-1}) but just might work at the EIC!

. high|t|and low Q^2 preferred (opposite from GPDs)

More odderon sensitive observables

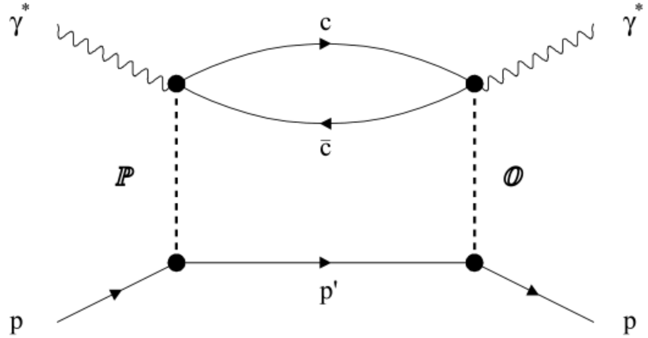
. exclusive J/ψ production in pp

Bzdak, Motyka, Szymanovski, Cudell (2007)



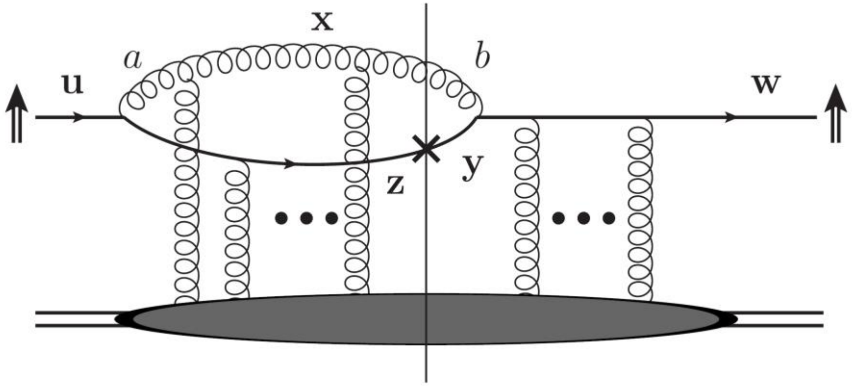
. diffractive dijet/heavy quark asymmetries in DIS

Brodsky, Rathsmann, Merino (1999)
Hagler, Pire, Szymanovski, Teryaev (2002)



. single transverse spin asymmetry (pp, inclusive)

Kovchegov, Sievert (2012)
SB, Horvatić, Kaushik, Vivoda (2023)
SB, Vivoda (in preparation)



-> pomeron-odderon interferences

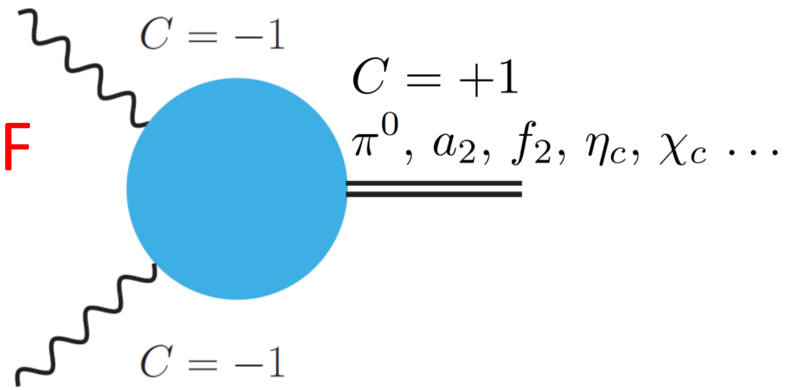
The Primakoff process

. usually we do not care about QED contributions to QCD process

. but in case of odderon QCD cross section is small (~α_S^6)

-> Primakoff process is a serious background to the odderon searches

. replace odderon with photon exchange



$$\gamma^*(q)\gamma^*(\ell) \to \mathcal{H}(\Delta)$$

QED charge FF

$$\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{\Delta}_\perp) \to 8\pi i q_c \alpha \sin\left(\frac{\boldsymbol{\Delta}_\perp \cdot \boldsymbol{r}_\perp}{2}\right) \frac{F_1(\Delta_\perp)}{\boldsymbol{\Delta}_\perp^2}$$

. In numerical computations we also take into account Pauli (spin-flip) FF (up to 50% correction at finite t)

$$\langle \mathcal{M}_{\lambda\bar{\lambda}}(\gamma^* p \to \mathcal{H}p) \rangle = -n_\mu \mathcal{M}^\mu_{\lambda\bar{\lambda}}(\gamma^*\gamma^* \to \mathcal{H}) \left[\frac{eF_1(\ell_\perp)}{\boldsymbol{\ell}_\perp^2} \delta_{hh'} + \frac{eF_2(\ell_\perp)}{\boldsymbol{\ell}_\perp^2} \frac{\ell_\perp}{2m_N} h e^{ih\phi_\ell} \delta_{h,-h'} \right]$$

Special case: axial quarkonia

. gauge invariant decomposition

$$\widetilde{\mathcal{M}}^{\gamma^*\gamma^*}_{\mu\nu\rho} = \left(q_\rho - \ell_\rho + \frac{-q^2+\ell^2}{(q+\ell)^2}(q_\rho+\ell_\rho)\right)\epsilon_{\mu\nu q\ell} M_A F_{TT}(q^2,\ell^2)$$
$$+ \left(\ell_\mu - \frac{q\cdot\ell}{q^2}q_\mu\right)\epsilon_{\nu\rho q\ell}\sqrt{-q^2}F_{LT}(q^2,\ell^2) + \left(q_\nu - \frac{q\cdot\ell}{\ell^2}\ell_\nu\right)\epsilon_{\mu\rho q\ell}\sqrt{-\ell^2}F_{TL}(q^2,\ell^2)$$

$$F_{TT}(0,0)=0$$

LY theorem: massive vector particle cannot decay into two real photons

Landau (1948)

Yang (1950)

Babiarz, Pasechnik, Schaefer, Szczurek (2022)

. form-factor scalings -> reproduced by our model computations

$$F_{TT}(q^2,\ell^2) \propto q^2 - \ell^2 \qquad F_{LT}(q^2,\ell^2) \propto \sqrt{-q^2} \qquad F_{TL}(q^2,\ell^2) \propto \sqrt{-\ell^2}$$

-> amplitude scalings

Aihara et al (TPC/Two Gamma collaboration) (1988)

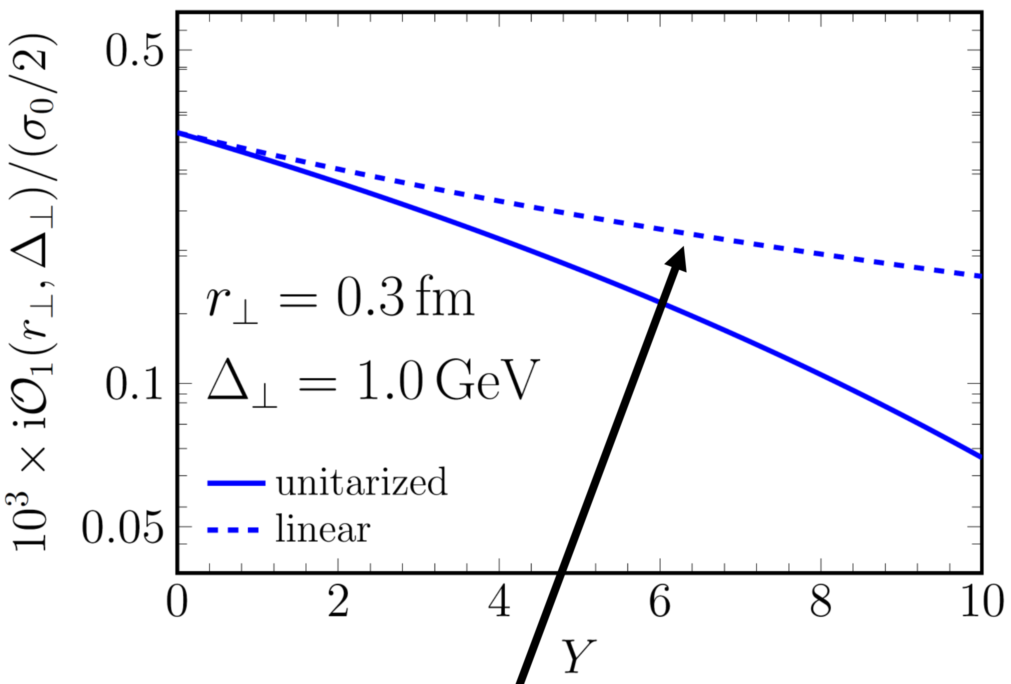
$$\widetilde{\mathcal{M}}_{\lambda=\pm1,\bar\lambda=0} \propto \frac{F_1(\Delta_\perp)}{\Delta_\perp^2} \times \Delta_\perp^2$$

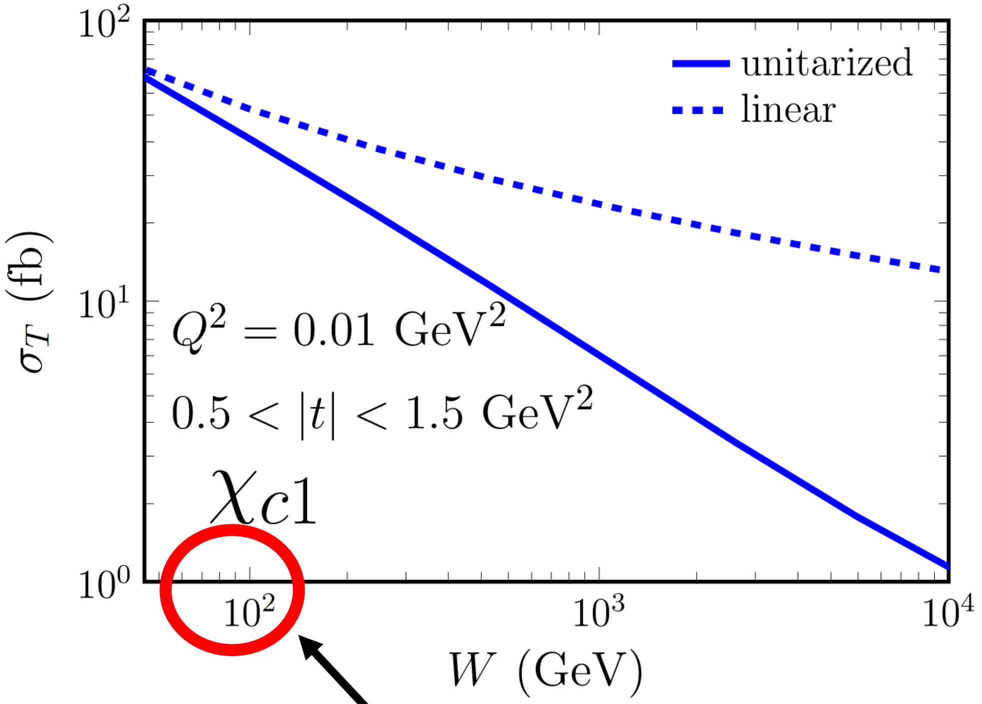
$$\widetilde{\mathcal{M}}_{\lambda=\pm1,\bar\lambda=\pm1} \propto \frac{F_1(\Delta_\perp)}{\Delta_\perp^2} \times \Delta_\perp^3$$

Coulomb tail is screened

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

W distributions: linear vs nonlinear evolution





Dropping the unitarity/saturation corrections Odderon evolution with Y much slower -> BLV asymptotics? (difficult to prove numerically..)

May not matter much at the EIC..

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