EIC and the Odderon: exclusive productions of χ_{cJ} charmonia

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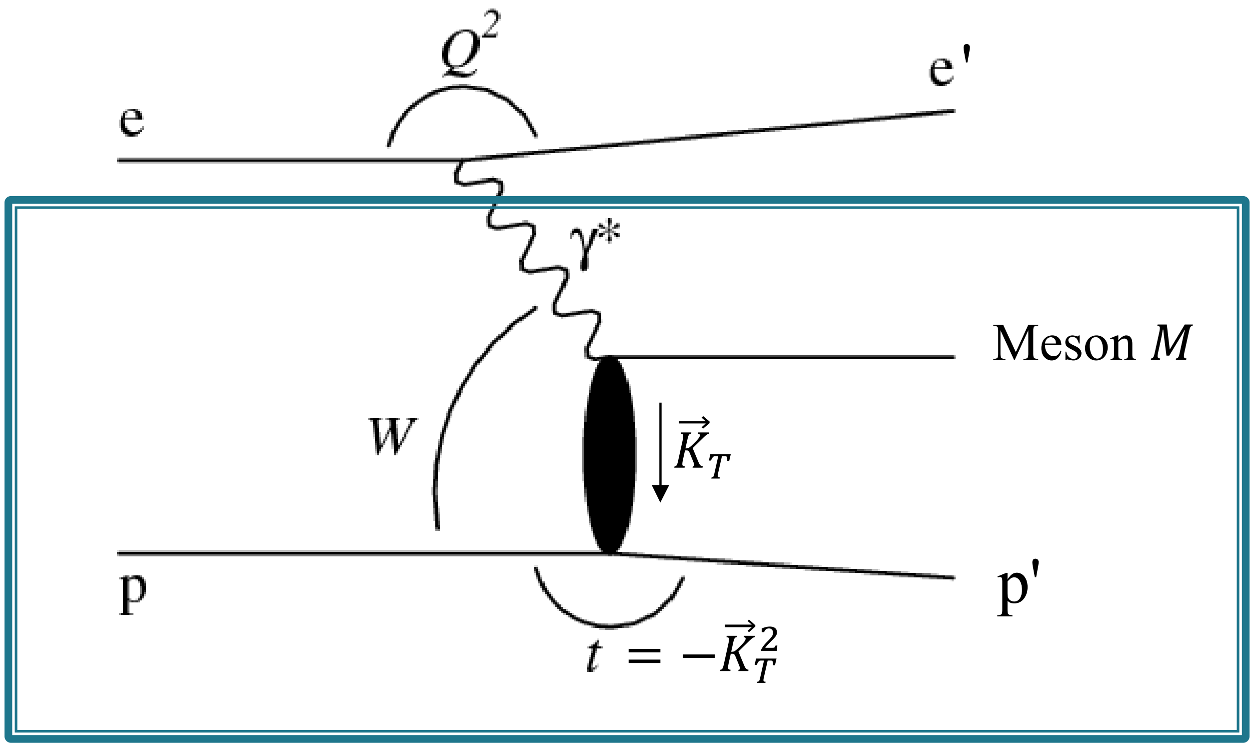
Exclusive meson electroproduction in ep scattering

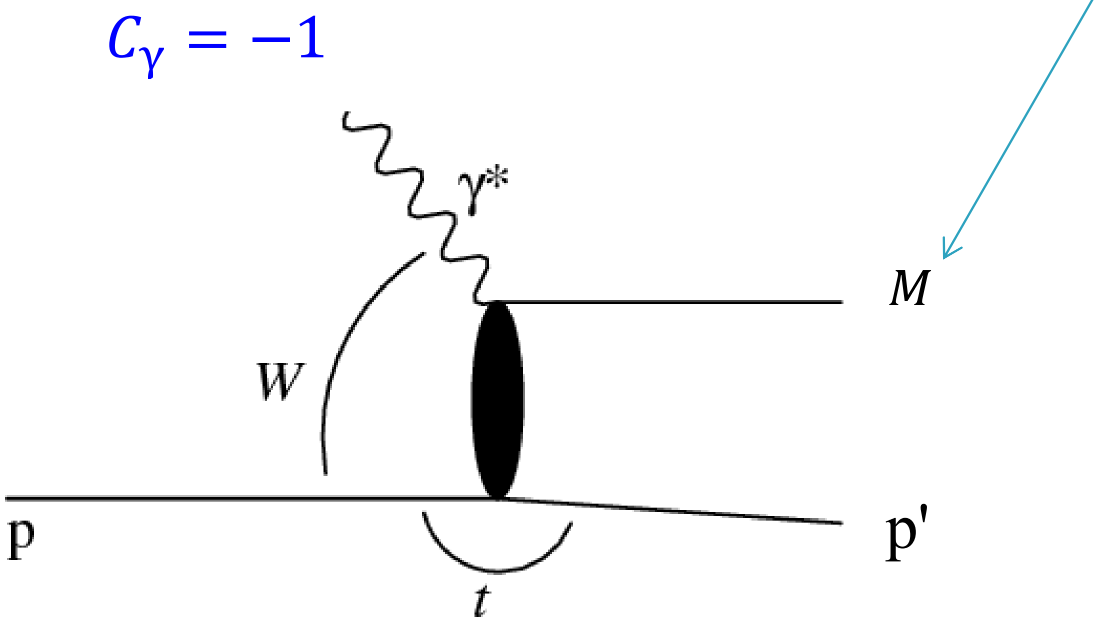
$$e + p \rightarrow e' + p' + M$$



$$\gamma^* + p \rightarrow p' + M$$

Exclusive meson production in $\gamma^* - p$ scattering

Consider C−parity of particles:



Meson with given C−parity:

$C_M = -1$, eg. ρ, ϕ, J/ψ …
(pomeron exchange)

or

$C_M = +1$, eg. π^0, η_c, χ_c …
(odderon exchange)

For small W other exchanges also possible.

L. Lukaszuk and B. Nicolescu, Lett. Nuovo Cim. 8, 405 (1973) J. Bartels, Nucl. Phys. B 175, 365 (1980) J. Kwiecinski and M. Praszalowicz, Phys. Lett. 94B, 413 (1980)

R. A. Janik and J. Wosiek, Phys. Rev. Lett. 82, 1092 (1999) J. Bartels, L. N. Lipatov and G. P. Vacca, Phys. Lett. B 477, 178 (2000)

Pomeron and Odderon

Regge theory: $\sigma_{tot} \sim s^{\alpha(0)-1}$

Intercept of Regge trajectory:
$\alpha(t) = \alpha(0) + \alpha' t$

POMERON

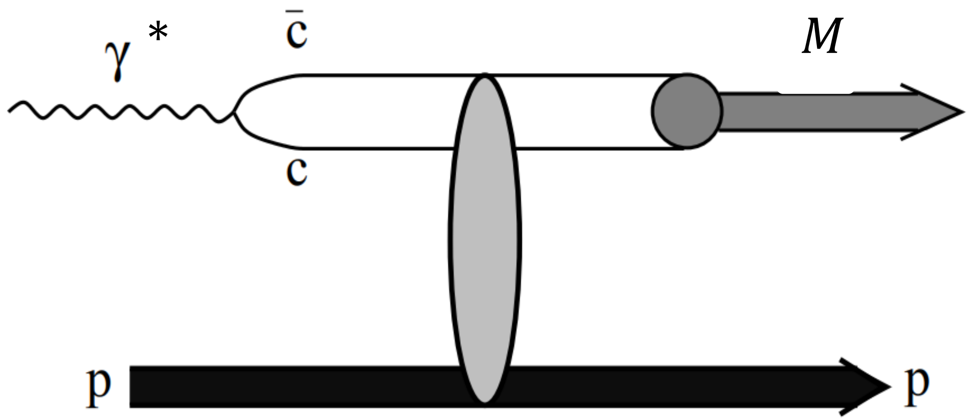
- $C = 1,\ P = 1$
- $\alpha_P(0) > 1$
- Leading logarithms $\alpha_S^n (\log s)^n$ resummed by Balitsky–Fadin–Kuraev–Lipatov (BFKL) equation
- Observed experimentally in many processes

ODDERON

- $C = -1,\ P = -1$
- $\alpha_O(0) \lesssim 1$
- Leading logarithms $\alpha_S^n (\log s)^n$ resummed by Bartels–Kwieciński–Praszałowicz (BKP) equation
- Evidence for existence (comparison pp vs. $p\bar{p}$) by TOTEM, G. Antchev et al. Eur.Phys.J.C 80 (2020) 2, 91)

Charmonia

- Charmonia $= c\bar{c}$ states



1) charm mass is a hard scale: $m_c \sim 1.3\ \text{GeV} \gg \Lambda_{QCD}$

2) relatively easy to measure

In this talk we consider :

χ_{cJ}: $J = 0$ scalar, $J = 1$ vector, $J = 2$ tensor
P–wave meson with $C_{\eta_c} = +1$

Odderon–type exchange

Why χ_{cJ}?

From late 90's theorists focus on exclusive η_c production as a evidence of odderon exchange.

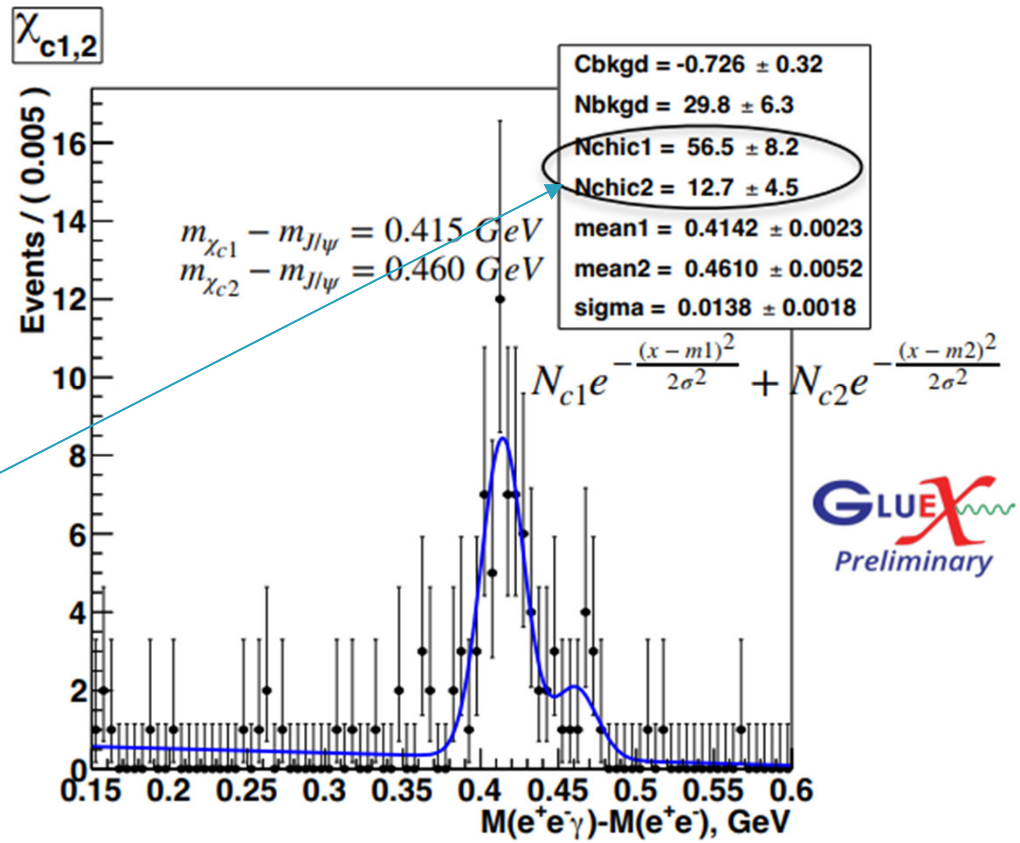
J. Czyzewski, J. Kwiecinski, L. Motyka, and M. Sadzikowski, Phys. Lett. B 398, 400 (1997),
R. Engel, D. Y. Ivanov, R. Kirschner, and L. Szymanowski, Eur. Phys. J. C 4, 93 (1998)

At HERA no evidence for exclusive η_c production was found. It is hard to measure:

small branching ratio $\mathrm{Br}(\eta_c \to \gamma\gamma) \sim 10^{-4}$ & feedown from J/ψ.

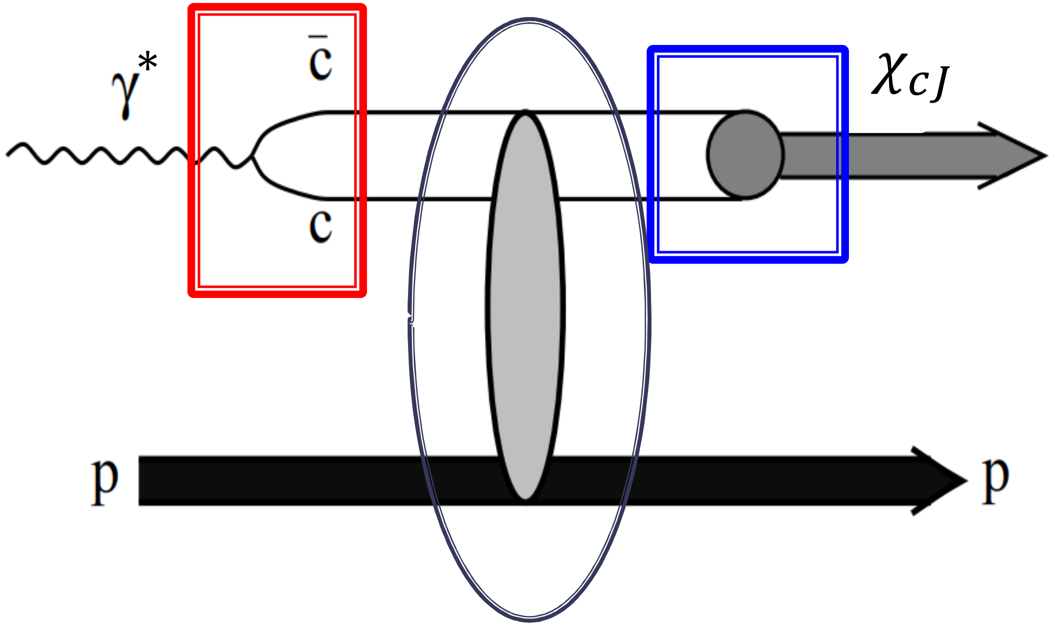
Last year results from GlueX

$$\gamma p \to \chi_c p \to (J/\psi\gamma)\, p \to (e^+e^-\gamma)\, p$$



L. Pentchev et al. (GlueX), Exclusive threshold J/ψ photoproduction with GlueX (2023), presented at DIS2023.

Amplitude for $\gamma^* + p \rightarrow p' + \chi_{cJ}$



Odderon exchange

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

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

Photon wave function

Meson wave function

Wave functions

Photon wave function: $$\Psi^{\gamma}_{\lambda,h\bar{h}}(\boldsymbol{k}_\perp, z) \equiv \sqrt{z\bar{z}}\,\frac{\bar{u}_h(k) e q_c \not{\epsilon}(\lambda, q) v_{\bar{h}}(q-k)}{\boldsymbol{k}_\perp^2 + \varepsilon^2}$$

Meson wave function (covariant): $$\Psi^{\mathcal{H}}_{\bar{\lambda},h\bar{h}}(\boldsymbol{k}_\perp, z) \equiv \frac{1}{\sqrt{z\bar{z}}}\bar{u}_h(k)\Gamma^{\mathcal{H}}_{\bar{\lambda}}(k, k')v_{\bar{h}}(k')\phi_{\mathcal{H}}(\boldsymbol{k}_\perp, z)$$

where:

$$\Gamma^{\mathcal{H}}_{\bar{\lambda}}(k, k') = \begin{cases} 1\ , & \mathcal{H} = \mathcal{S}\,, \\ \mathrm{i}\gamma_5 \not{E}(\bar{\lambda}, \Delta_0)\ , & \mathcal{H} = \mathcal{A}\,, \\ \frac{1}{2}\left(\gamma_\mu(k_\nu - k'_\nu) + \gamma_\nu(k_\mu - k'_\mu)\right) E^{\mu\nu}(\bar{\lambda}, \Delta_0)\ , & \mathcal{H} = \mathcal{T}\,. \end{cases}$$

Final results for amplitudes (scalar quarkonium χ_{c0}):

$$\mathcal{A}_L(r_\perp) \equiv -\frac{2}{\pi} m_c Q(z - \bar{z}) K_0(\varepsilon r_\perp)\phi_{\mathcal{S}}(r_\perp, z)\,,$$
$$\mathcal{A}_T(r_\perp) \equiv \frac{\mathrm{i}\sqrt{2}}{2\pi}\frac{m_c}{z\bar{z}}\left[(z-\bar{z})^2 \varepsilon K_1(\varepsilon r_\perp)\phi_{\mathcal{S}}(r_\perp, z) - K_0(\varepsilon r_\perp)\frac{\partial \phi_{\mathcal{S}}}{\partial r_\perp}\right]$$

Similar expressions for axial χ_{c1} and tensor χ_{c2}

H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D 74, 074016 (2006)

Boosted Gaussian

- Scalar part of meson w.f. needs to be modeled. We use:

$$\phi_{\mathcal{H},B}(r_\perp, z) = \mathcal{N}_{\mathcal{H},B}\, z\bar{z} \exp\left(-\frac{m_c^2 \mathcal{R}_{\mathcal{H}}^2}{8 z\bar{z}} - \frac{2 z\bar{z} r_\perp^2}{\mathcal{R}_{\mathcal{H}}^2} + \frac{1}{2} m_c^2 \mathcal{R}_{\mathcal{H}}^2 \right)$$

Free parameters, $\mathcal{R}_H$ and $\mathcal{N}_{\mathcal{H},B}$ we obtained from:

1) normalization condition:

$$1 = N_c \sum_{h\bar{h}} \int_z \int_{\boldsymbol{r}_\perp} \left| \Psi^{\mathcal{H}}_{\lambda, h\bar{h}}(\boldsymbol{r}_\perp, z) \right|^2$$

2) decay into $\gamma\gamma$:

$$\Gamma(\mathcal{S} \to \gamma\gamma) = \frac{\pi\alpha^2}{4} M_{\mathcal{S}}^3 F_{\mathcal{S}}^2 \,,$$

$$F_{\mathcal{S}} \equiv 4 q_c^2 m_c N_c \int_z \int_{\boldsymbol{k}_\perp} \frac{\boldsymbol{k}_\perp^2 + (z-\bar{z})^2 m_c^2}{(\boldsymbol{k}_\perp^2 + m_c^2)^2} \frac{\phi_{\mathcal{S}}(\boldsymbol{k}_\perp, z)}{z\bar{z}}$$

Exception: χ_{c1}

Landau–Yung theorem: massive particle with spin 1 cannot decay into two real photons.

We assume $\mathcal{R}_{\chi_{c1}} = \mathcal{R}_{\chi_{c2}}$

Dipole distribution evolution

Dipole distribution in terms of Wilson lines:

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

Small-x evolution is given by the Balitsky-Kovchegov (BK) equation:

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

We also have decomposition: $\mathcal{D}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) = 1 - \mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) + \mathrm{i}\mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)$

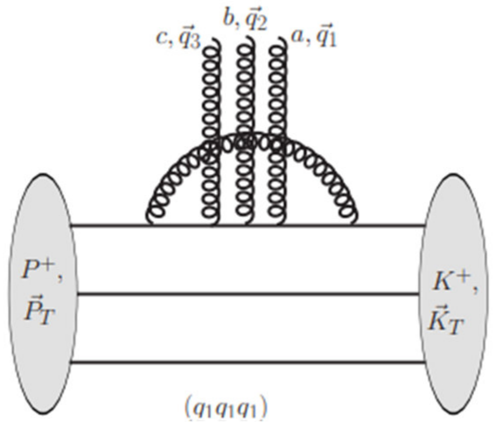
Pomeron Odderon

$$\frac{\partial \mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)}{\partial Y} = \int_{\boldsymbol{r}_{1\perp}} \mathcal{K}_{\mathrm{Bal}}(\boldsymbol{r}_\perp, \boldsymbol{r}_{1\perp}, \boldsymbol{r}_{2\perp}) \big[\mathcal{N}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp) + \mathcal{N}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) - \mathcal{N}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) + \mathcal{N}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp) \mathcal{N}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) - \mathcal{O}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp) \mathcal{O}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) \big]$$

$$\frac{\partial \mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp)}{\partial Y} = \int_{\boldsymbol{r}_{1\perp}} \mathcal{K}_{\mathrm{Bal}}(\boldsymbol{r}_\perp, \boldsymbol{r}_{1\perp}, \boldsymbol{r}_{2\perp}) \big[\mathcal{O}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp) + \mathcal{O}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) - \mathcal{O}(\boldsymbol{r}_\perp, \boldsymbol{b}_\perp) - \mathcal{N}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp) \mathcal{O}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) - \mathcal{O}(\boldsymbol{r}_{1\perp}, \boldsymbol{b}_\perp) \mathcal{N}(\boldsymbol{r}_{2\perp}, \boldsymbol{b}_\perp) \big]$$

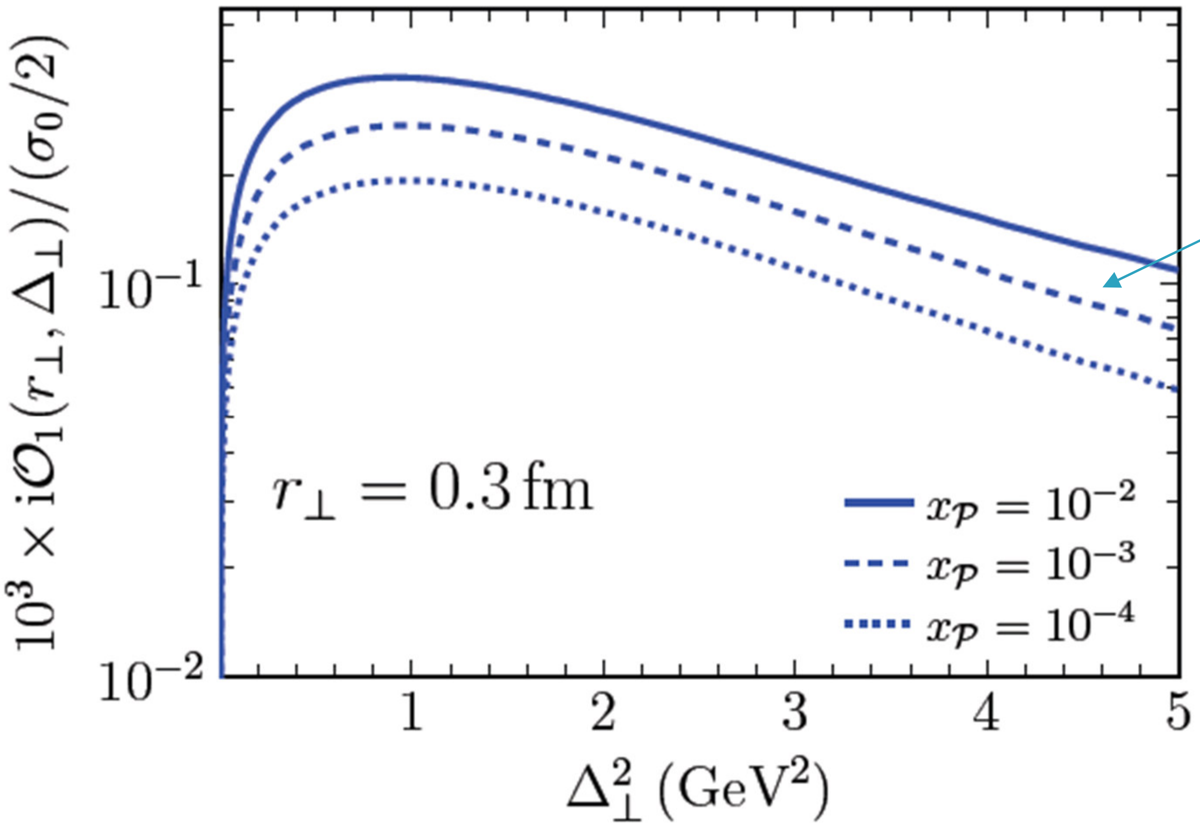
Benić, Horvatić, Kaushik, Vivoda, Phys. Rev. D 108, 074005 (2023),

Odderon evolution



Dumitru, H. Mantysaari, and R. Paatelainen, Phys. Rev. D 107, L011501 (2023),

At x=0.01 we use initial condition from 3-gluon exchange model & gluon emission.

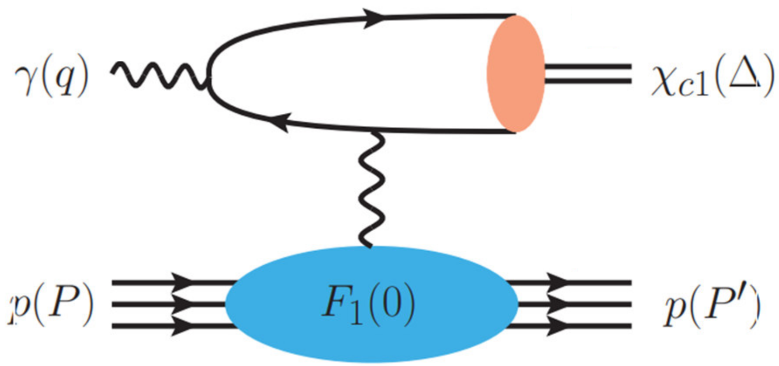


Decrease with energy

Backgroud

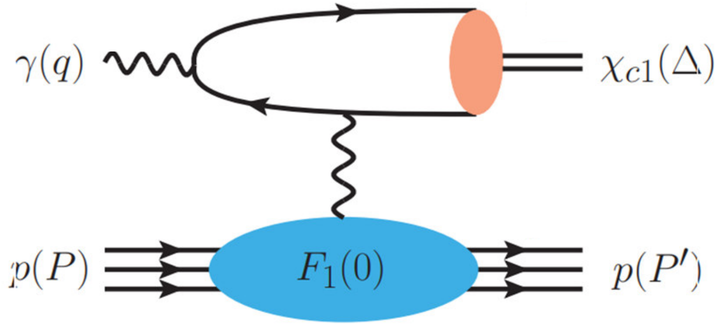
- We have two main sources of background for this process:

  - Primakoff process
    (photon exchange)



  - Feeddown from $\psi(2s) \to \chi_{cJ} + \gamma$ (this is not covered in this talk).

Primakoff process



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

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

Just replace:

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

Dirac form factor.

Adding Pauli form factor:

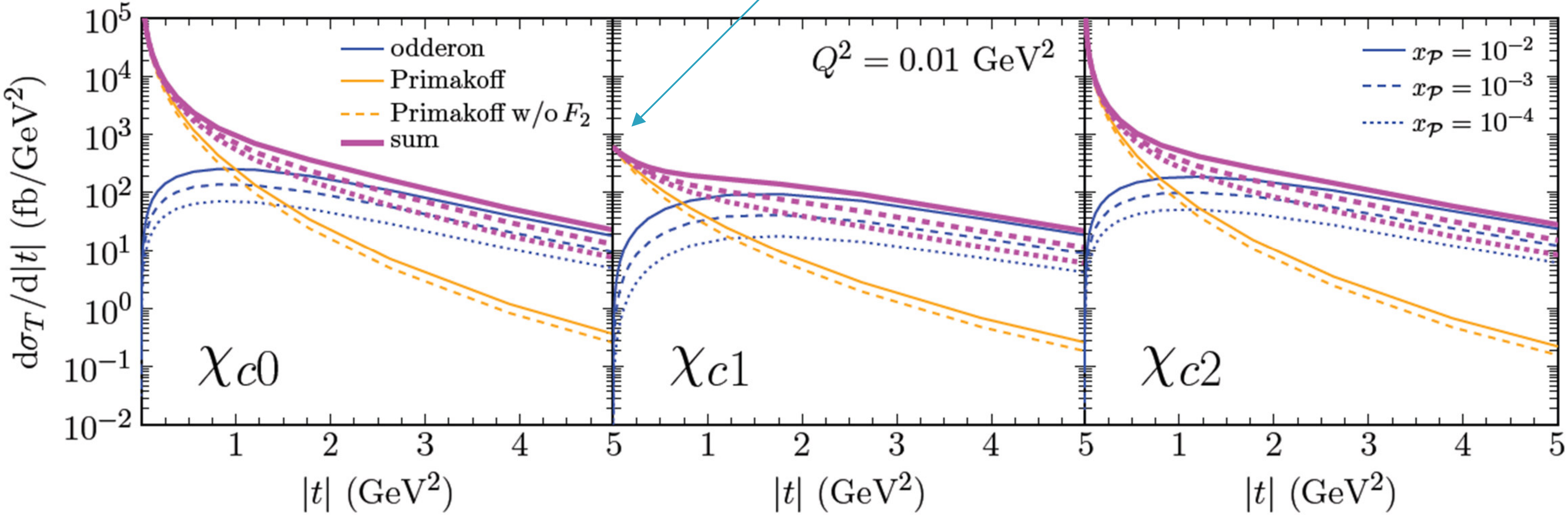
$$F_1^2(\ell_\perp) \to F_1^2(\ell_\perp) + \frac{\boldsymbol{\ell}_\perp^2}{4m_N^2} F_2^2(\ell_\perp)$$

Both form factors are very well constrained experimentally.

Numerical results for EIC

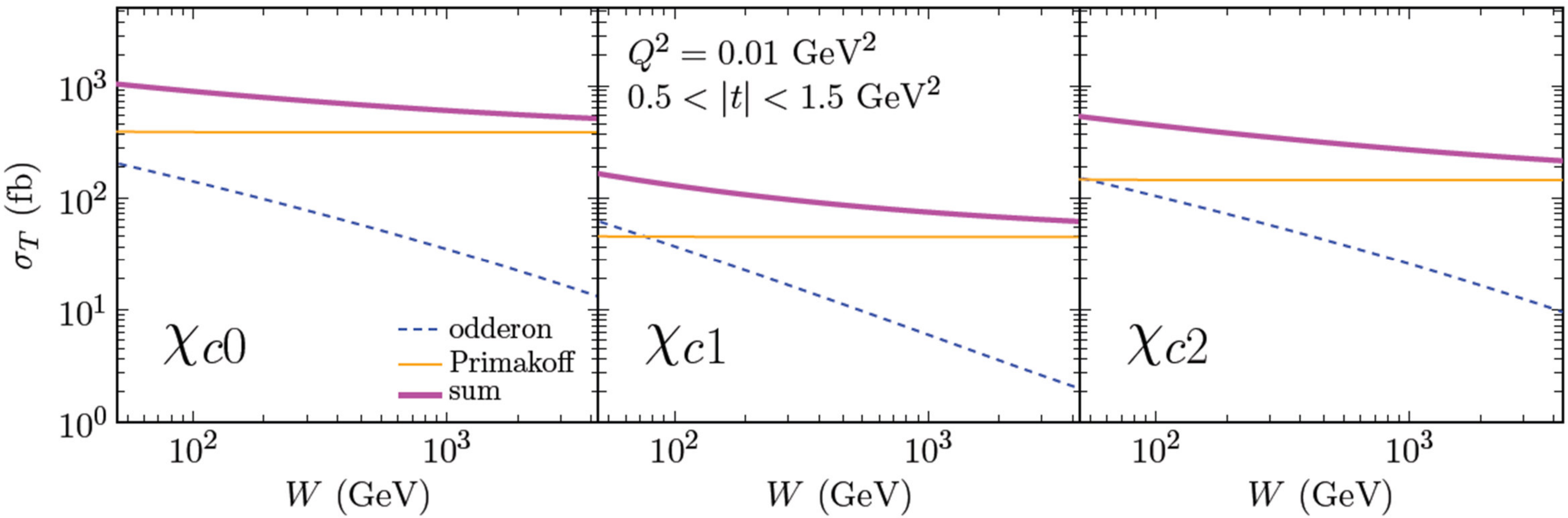
$\gamma^* + p \rightarrow p' + \chi_{cJ}$: momentum transfer dependence

Finite (Landau-Yung theorem)



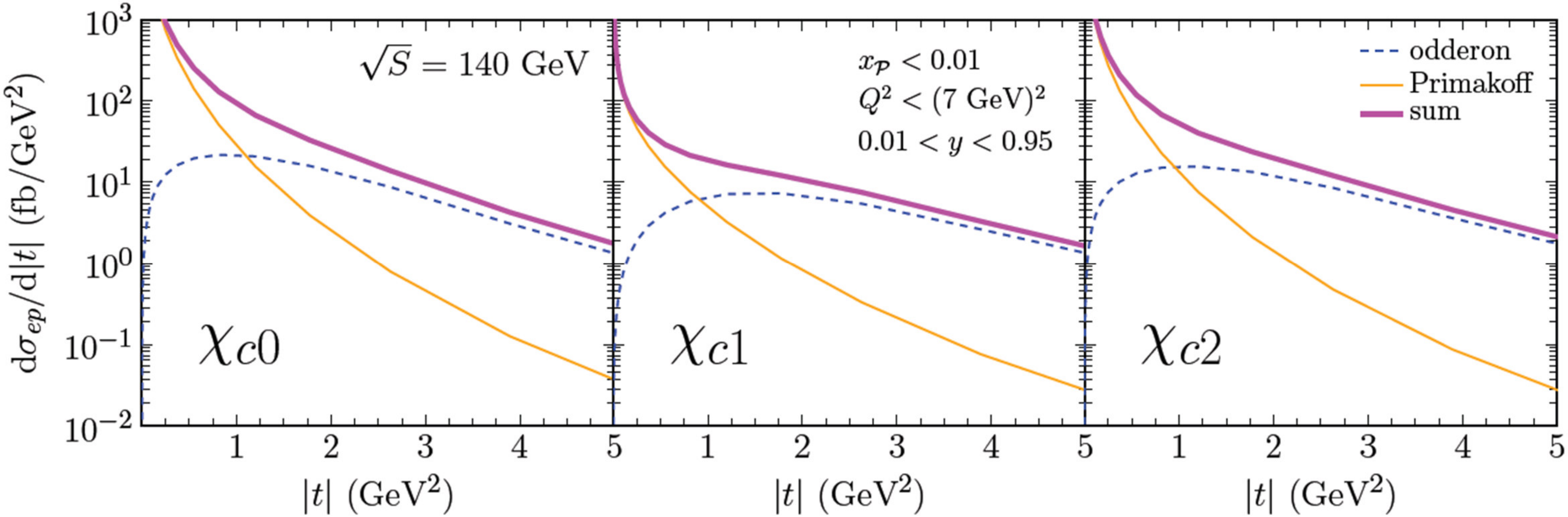
Positive interference between odderon and Primakoff.

$\gamma^* + p \to p' + \chi_{cJ}$: energy dependence

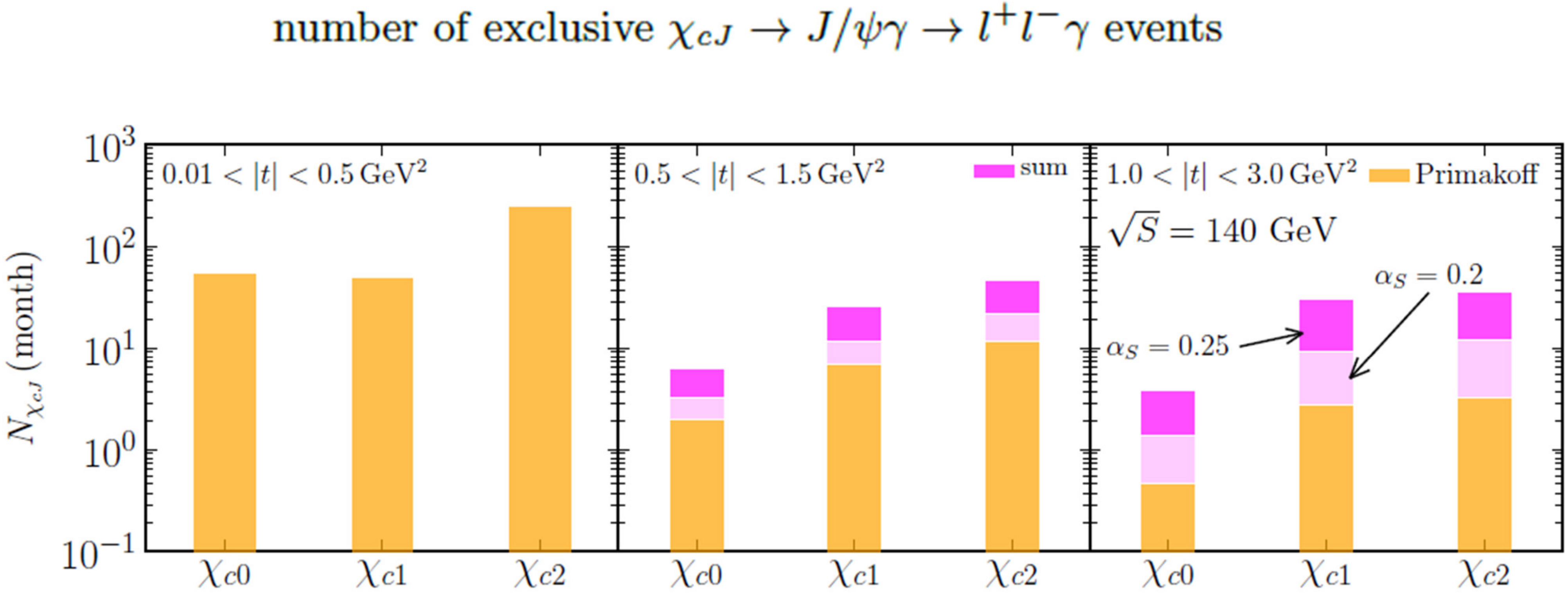


Electroproduction $ep \to \chi_{cJ}ep$

$$\frac{\mathrm{d}\sigma_{ep}}{\mathrm{d}x_{\mathcal{P}}\mathrm{d}Q^2\mathrm{d}|t|} = \frac{\alpha}{2\pi Q^2 x_{\mathcal{P}}}\left\{2(1-y)\frac{\mathrm{d}\sigma_L}{\mathrm{d}|t|} + \left(1+(1-y)^2 - 2(1-y)\frac{Q^2_{\mathrm{min}}}{Q^2}\right)\frac{\mathrm{d}\sigma_T}{\mathrm{d}|t|}\right\}$$



Electroproduction: number of events



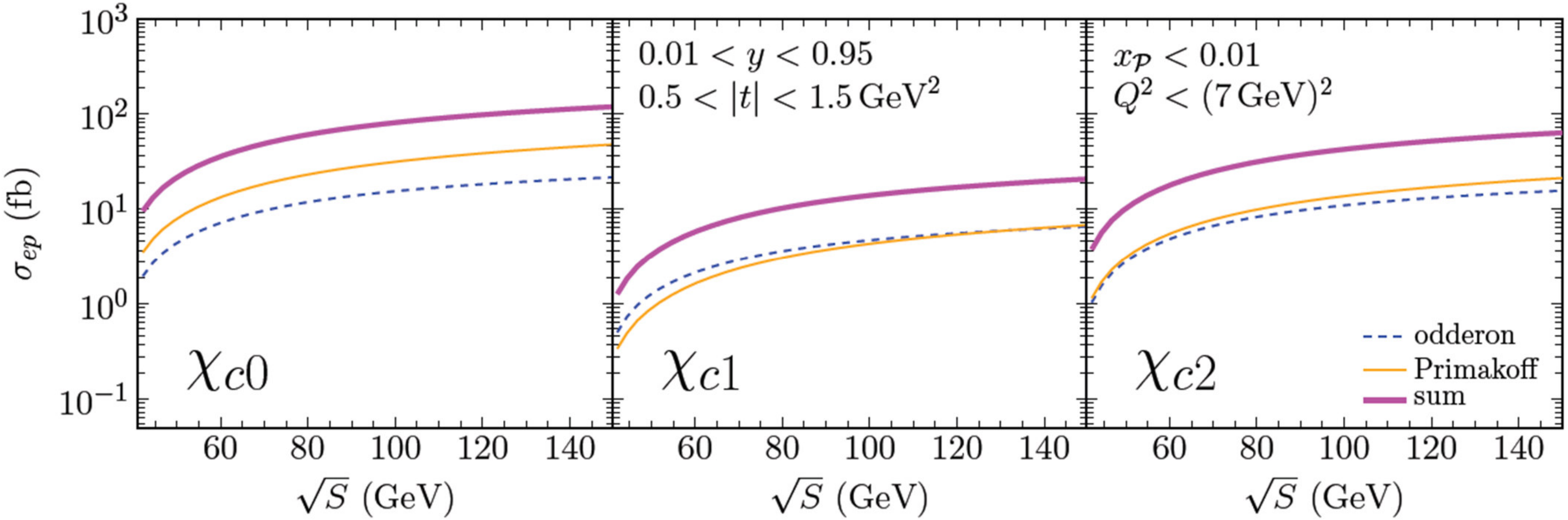
Branching ratios for decays included.
Top EIC luminosity is assumed.

Summary

- Searching for odderon is still interesting.
- We calculated exclusive production of χ_{cJ}.
- Interference between Primakoff and odderon is positive.
- Finding odderon may be possible at EIC.

Thank you!

Backup



σ_{ep} (fb)
10^3
10^2
10^1
10^0
10^{-1}
χ_{c0}
$0.01 < y < 0.95$
$0.5 < |t| < 1.5\,\mathrm{GeV}^2$
χ_{c1}
$x_{\mathcal{P}} < 0.01$
$Q^2 < (7\,\mathrm{GeV})^2$
χ_{c2}
odderon
Primakoff
sum
60 80 100 120 140
$\sqrt{S}$ (GeV)