Exclusive pseudoscalar and heavy vector mesons production using GPD approach in EIC

Ya-Ping Xie

Institute of Modern Physics, CAS
Collaborated with S. V. Goloskokov and V. Goncalves
Based on arXiv: 2408.05800, 2502.17743 and 2507.20448

Apr 22, 2026

Outline

This slide focus on the gluon GPDs to study vector meson production. It contains follow sections:

- Introduction to GPDs
- Process in ep scattering to study GPDs
- Time like Compton Scattering using GPD in EIC
- Pseudoscalar meson production using GPD in EIC
- Vector meson production within GPD in EIC
- Summary

Introduction to GPDs

Generalized Parton Distributions (GPDs) can be extracted from Deep Virtual Compton Scattering (DVCS), Double Deep Virtual Compton Scattering(DDVCS) Time-like Compton Scattering (TCS) and Hard Exclusive Meson Production (HEMP) processes. GPDs can be employed to study

- Spin puzzle
- Energy Momentum tensor
- Gravitational form factor
- Mass radius, distributions and pressure

Sum rules of GPDs

There are several kinds of GPD function, H_q,E_q, $\tilde{H}_q$, $\tilde{E}_q$. There are similar for gluon GPDs.
GPD connects parton distribution via $H(x,0,0) = xf(x)$. Hadron Form factor can be obtain from GPDs

$$\int dx H^q(x,\xi,t) = F_1^q(t), \qquad \int dx E_q(x,\xi,t) = F_2^q(t); \tag{1}$$

$$\int dx \tilde{H}^q(x,\xi,t) = G_A^q(t), \qquad \int dx \tilde{E}^q(x,\xi,t) = G_p^q(t). \tag{2}$$

Ji sum rules for the proton angular memonta

$$\int x dx (H^q(x,\xi,0) + E^q(x,\xi,0) = 2J^q. \tag{3}$$

- GPDs H^q and E^q can be tested in ρ meson production
- $\tilde{H}^q$ and $\tilde{E}^q$ can be tested in π^0 production

Quark helicity conservation distributions

The quark helicity conservation distributions go with the Dirac matrix γ^+ and $\gamma^+\gamma_5$, where $i = 1,2$ is a transverse index, it is defined as[EPJC-19-485]

$$\frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p',\lambda'|\bar{\psi}(-\frac{1}{2}z)\gamma^+\psi(\frac{1}{2}z)|P,\lambda\rangle|_{z^+=0,z_T=0}$$
$$= \frac{1}{2P^+}\bar{u}(p',\lambda')\left[H^q\gamma^+ + E^q\frac{i\sigma^{+\alpha}\Delta_\alpha}{2m}\right]u(p,\lambda). \quad (4)$$

$$\frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p',\lambda'|\bar{\psi}(-\frac{1}{2}z)\gamma^+\gamma_5\psi(\frac{1}{2}z)|P,\lambda\rangle|_{z^+=0,z_T=0}$$
$$= \frac{1}{2P^+}\bar{u}(p',\lambda')\left[\widetilde{H}^q\gamma^+\gamma_5 + \widetilde{E}^q\frac{\gamma_5\Delta^+}{2m}\right]u(p,\lambda). \quad (5)$$

H^q, E^q, $\widetilde{H}^q$ and $\widetilde{E}^q$ are quark helicity conservation distributions.

Gluon GPD

The gluon GPD have four parts of GPDs

$$
\begin{aligned}
& \langle p'\nu'|\sum_{a,a'} A^{a\rho}(0)A^{a'\rho'}(\bar{z})|p\nu\rangle \\
= \quad & \frac{1}{2}\sum_{\lambda=\pm 1}\varepsilon^{\rho}(k_g,\lambda)\,\varepsilon^{*\rho'}(k_g,\lambda') \qquad (6) \\
\times \quad & \int_0^1 \frac{dx}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)} e^{-i(x-\xi)p\cdot\bar{z}} \\
\times \quad & \left\{ \frac{\bar{u}(p'\nu')\,\not{n}\,u(p\nu)}{2\bar{p}\cdot n} H^g(x,\xi,t) + \frac{\bar{u}(p'\nu')\,i\sigma^{\alpha\beta}\,n_\alpha\Delta_\beta\,u(p\nu)}{4m\,\bar{p}\cdot n} E^g(x,\xi,t) \right. \\
+ \quad & \left. \lambda\frac{\bar{u}(p'\nu')\,\not{n}\gamma_5\,u(p\nu)}{2\bar{p}\cdot n}\widetilde{H}^g(x,\xi,t) + \lambda\frac{\bar{u}(p'\nu')\,n\cdot\Delta\,\gamma_5\,u(p\nu)}{4m\,\bar{p}\cdot n}\widetilde{E}^g(x,\xi,t) \right\}.
\end{aligned}
$$

Quark helicity flip distributions

The quark helicity flip distributions go with the Dirac matrix σ^{+i}, where $i = 1,2$ is a transverse index, it is defined as[EPJC-19-485]

$$\begin{aligned}
&\frac{1}{2}\int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p',\lambda'|\bar{\psi}(-\frac{1}{2}z) i\sigma^{+i} \psi(\frac{1}{2}z)|P,\lambda\rangle|_{z^+=0,z_T=0} \\
&= \frac{1}{2P^+}\bar{u}(p',\lambda')\Big[H_T^q i\sigma^{+i} + \widetilde{H}_T^q \frac{P^+\Delta^i - \Delta^+ P^i}{m^2} \\
&+ E_T^q \frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2m} + \widetilde{E}_T^q \frac{\gamma^+ P^i - P^+\gamma^i}{m}\Big] u(p,\lambda). \qquad (7)
\end{aligned}$$

H_T^q, $\widetilde{H}_T^q$, E_T^q and $\widetilde{E}_T^q$ are quark helicity flip distributions.

Physical processes to study GPD

There are several processes can be studied GPDs in ep scattering

- Deep Virtual Compton Scattering (DVCS)
- Time-like Compton Scattering (TCS)
- Double Deep Virtual Compton Scattering (DDVCS)
- Deep Virtual Meson Production (DVMP)

Deep Virtual Compton Scattering

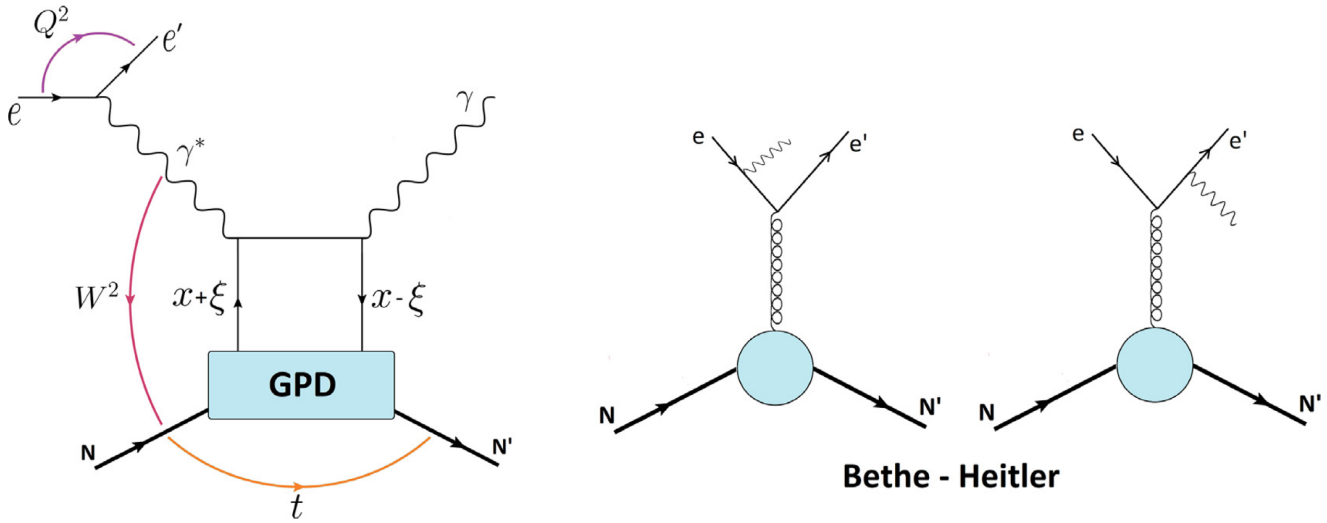

Figure 1: DVCS schematic diagram.

Double Deep Virtual Compton Scattering

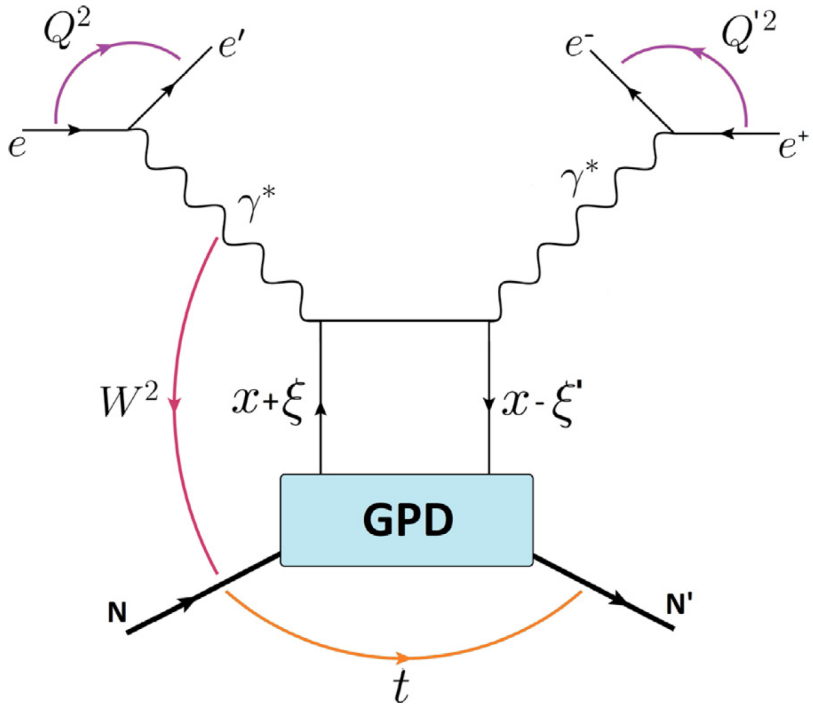

Figure 2: DDVCS schematic diagram.

Time Compton Scattering

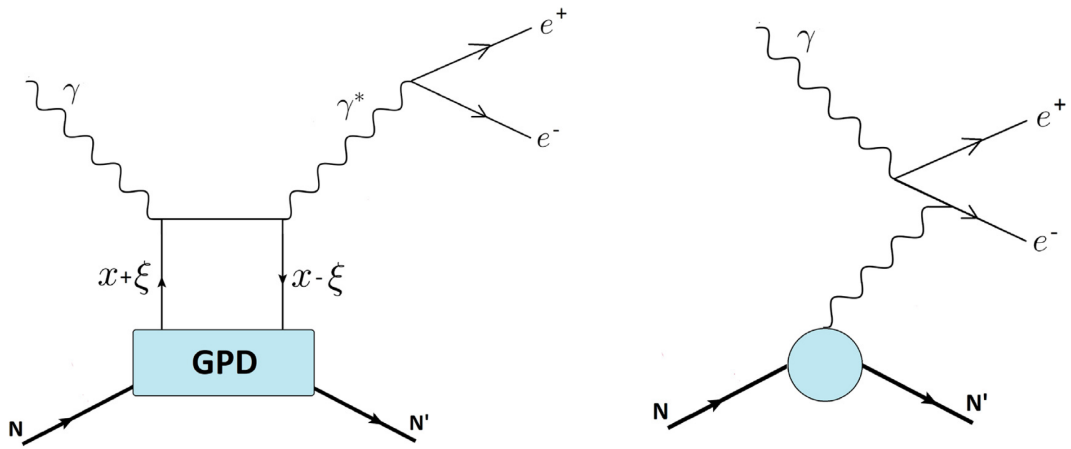

Figure 3: TCS schematic diagram.

TCS

In TCS, the differential cross section are given as [EPJC-23-675]

$$\frac{d\sigma^{TCS}_{\gamma p\to l^+l^- p}}{dQ^2dtd(\cos\theta)d\phi}=\frac{\alpha^3_{em}}{8\pi s^2_{\gamma p}}\frac{1}{Q^2}\frac{1+\cos^2\theta}{2}\left\{(1-\eta^2)(|\mathscr{H}_1|^2+|\widetilde{\mathscr{H}_1}|^2)\right.$$
$$\left.-2\eta^2 Re(\mathscr{H}_1^*\widetilde{\mathscr{E}_1})-\eta^2\frac{t}{4M_p^2}|\widetilde{\mathscr{E}_1}|^2\right\}, \quad (8)$$

$$\frac{d\sigma^{INT}_{\gamma p\to l^+l^- p}}{dQ^2dtd(\cos\theta)d\phi} = -\frac{\alpha^3_{em}}{4\pi s^2_{\gamma p}}\frac{\sqrt{t_0-t}}{-tQ}\frac{\sqrt{1-\eta}}{\eta}\left(\cos\phi\frac{1+\cos^2\theta}{\sin\theta}\right)$$
$$\times \quad Re\left[F_1(t)\mathscr{H}_1-\eta(F_1(t)+F_2(t))\widetilde{\mathscr{H}_1}-\frac{t}{4M_p^2}F_2(t)\mathscr{E}_1\right], \quad (9)$$

TCS cross section

The differential cross section of TCS at p-Pb UPC using GK model [arXiv.2212.07657].

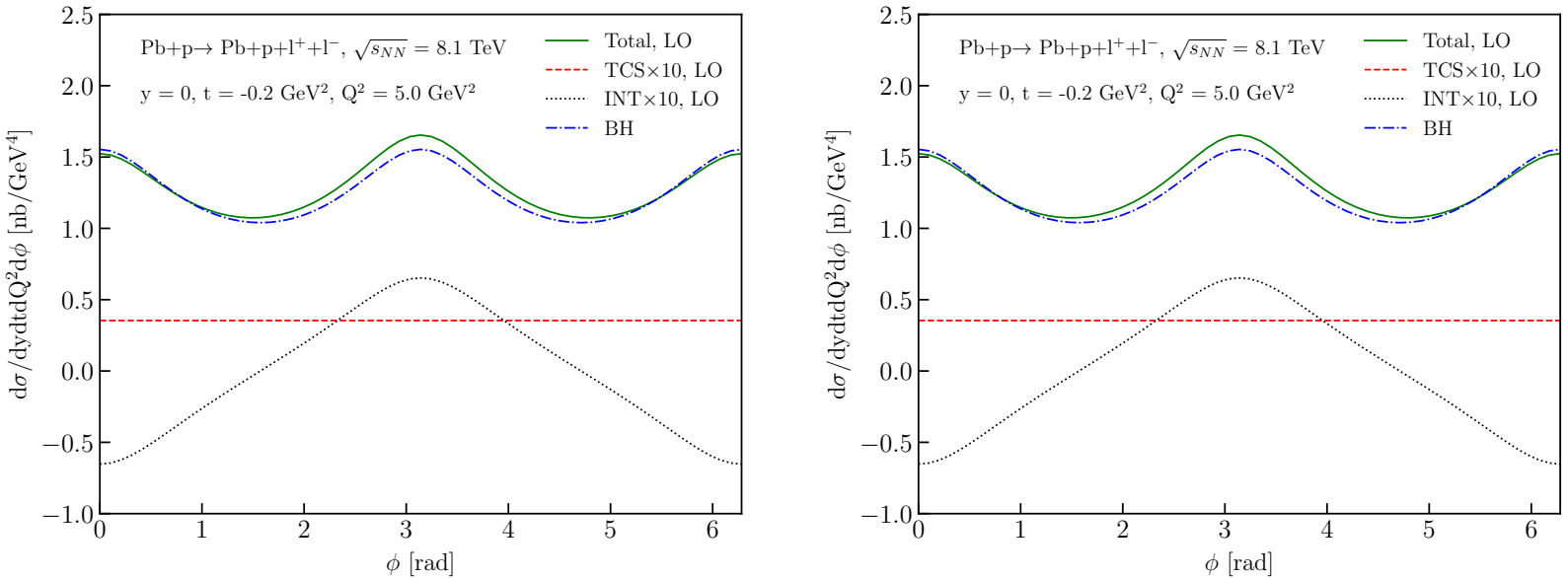

Figure 4: Azimuthal distributions of the lepton pair for fixed values of Q2 and t and two values of rapidity considering ultraperipheral pPb collisions at $\sqrt{s_N}N$ = 8.1 TeV..

Deep Virtual Meson Production

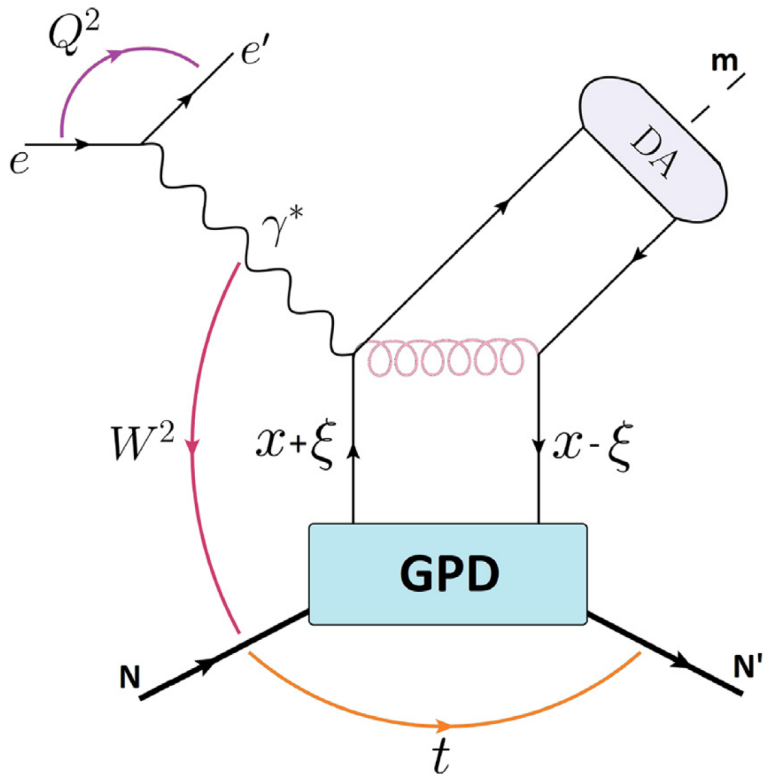

Figure 5: DVMP schematic diagram.

PM production

In the process $\gamma^* + p \to \pi + p$ [EPJC-65-137]

$$\frac{d^2\sigma}{dtd\phi} = \frac{1}{2\pi}\left(\frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt} + \varepsilon\cos 2\phi\,\frac{d\sigma_{TT}}{dt} + \sqrt{2\varepsilon(1+\varepsilon)}\cos\phi\,\frac{d\sigma_{LT}}{dt}\right), \quad (10)$$

For Pseudoscalar meson production. The cross section can be expressed as

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'Q^6}\left[(1-\xi^2)|\langle\tilde{H}\rangle|^2 - 2\xi^2 Re[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle] - \frac{t'}{4m^2}\xi^2|\langle\tilde{E}\rangle|^2\right], \quad (11)$$

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha\mu_\pi^2}{2k'Q^8}\left[(1-\xi^2)|\langle H_T\rangle|^2 - \frac{t'}{8m^2}|\langle\tilde{E}_T\rangle|^2\right], \quad (12)$$

$$\frac{d\sigma_{LT}}{dt} = \frac{4\pi\alpha\mu_\pi}{\sqrt{2}k'Q^7}\frac{\sqrt{t'}}{2m}\xi\sqrt{1-\xi^2}Re[\langle H_T\rangle^*\langle\tilde{E}\rangle], \quad (13)$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha\mu_\pi^2}{2k'Q^8}\frac{t'}{16m^2}|\langle\tilde{E}_T\rangle|^2. \quad (14)$$

PM scattering amplitude

For twist-2 convolution function is given as

$$\mathscr{H}^{twist-2}_{0\lambda,0\lambda} = 4\pi\alpha_s(\mu_R)\int dz d^2\mathbf{k}_\perp \Psi^{(2)}_\pi(z,\mathbf{k}_\perp)\mathscr{F}^{(2)}(z,x,\xi,\mathbf{k}_\perp). \tag{15}$$

The hard subprocess of twist-2 is written as

$$\mathscr{F}^{(2)}(z,x,\xi,\mathbf{k}_\perp) = C_F\sqrt{\frac{2}{N_c}}\frac{Q^2}{\xi}(T_s - T_u). \tag{16}$$

T_s and T_u are propagator which are defined as

$$T_s = \frac{1}{\bar{z}Q^2(x-\xi)/(2\xi) - \mathbf{k}^2_\perp + i\varepsilon}. \tag{17}$$

$$T_u = \frac{1}{-zQ^2(x+\xi)/(2\xi) - \mathbf{k}^2_\perp + i\varepsilon}. \tag{18}$$

PM scattering amplitude

The twist-3 convolution function is defined as

$$\mathscr{H}_{0^{-+}}^{twist-3} = \frac{2}{\pi^2}\frac{C_F}{\sqrt{2N_C}}\int dz d^2\mathbf{k}_\perp \Psi_{\pi P}^{(3)}(z,\mathbf{k}_\perp)\alpha_s(\mu_R) \times\left[\frac{1}{x-\xi+\varepsilon}\frac{1}{\bar{z}\frac{x-\xi}{2\xi}Q^2-\mathbf{k}_\perp^2+\varepsilon}-\frac{1}{x+\xi+\varepsilon}\frac{1}{-z\frac{x+\xi}{2\xi}Q^2-\mathbf{k}_\perp^2+\varepsilon}\right] \quad (19)$$

π^0 cross section

The π^0 cross section at CLAS are shown as [arXiv.2206.06547]

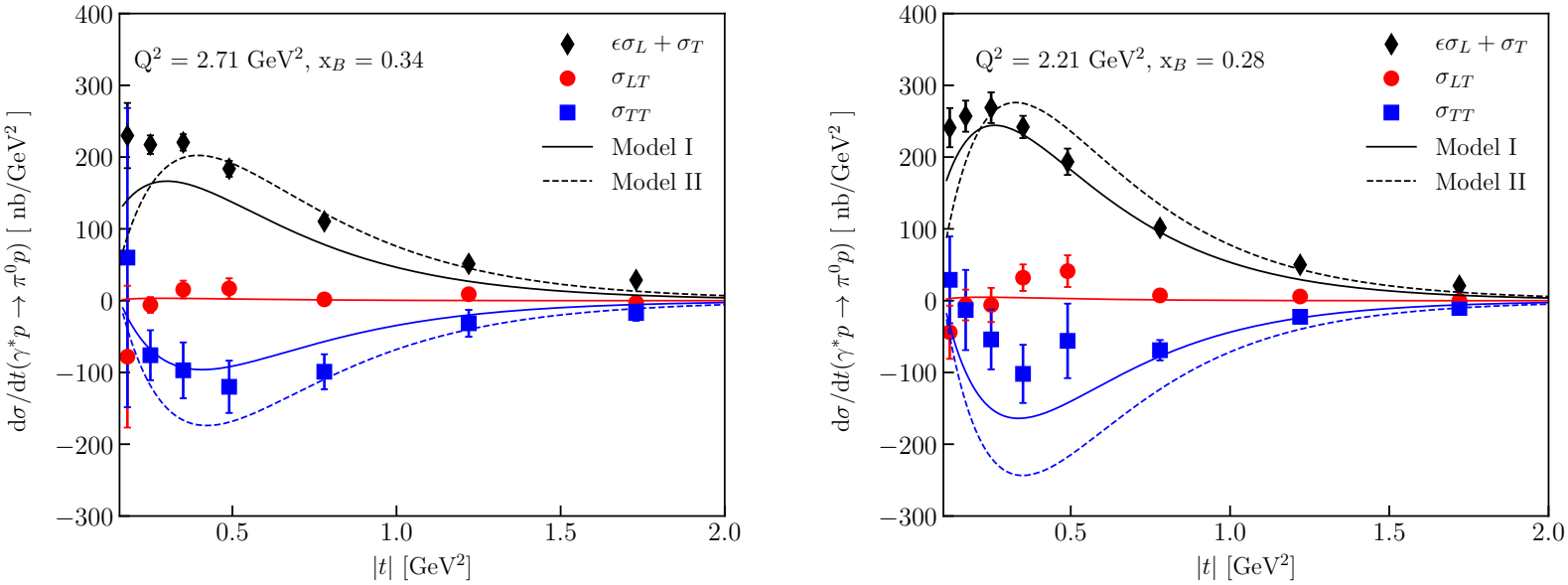

Figure 6: Cross section of π^0 production in the CLAS energy range together with the CLAS data. Black lines are $\sigma = \sigma_T + \varepsilon\sigma_L$, red lines label σ_{LT}, and blue lines present σ_{TT}.

π^0 cross section

The π^0 cross section at EicC are shown as [arXiv.2206.06547]

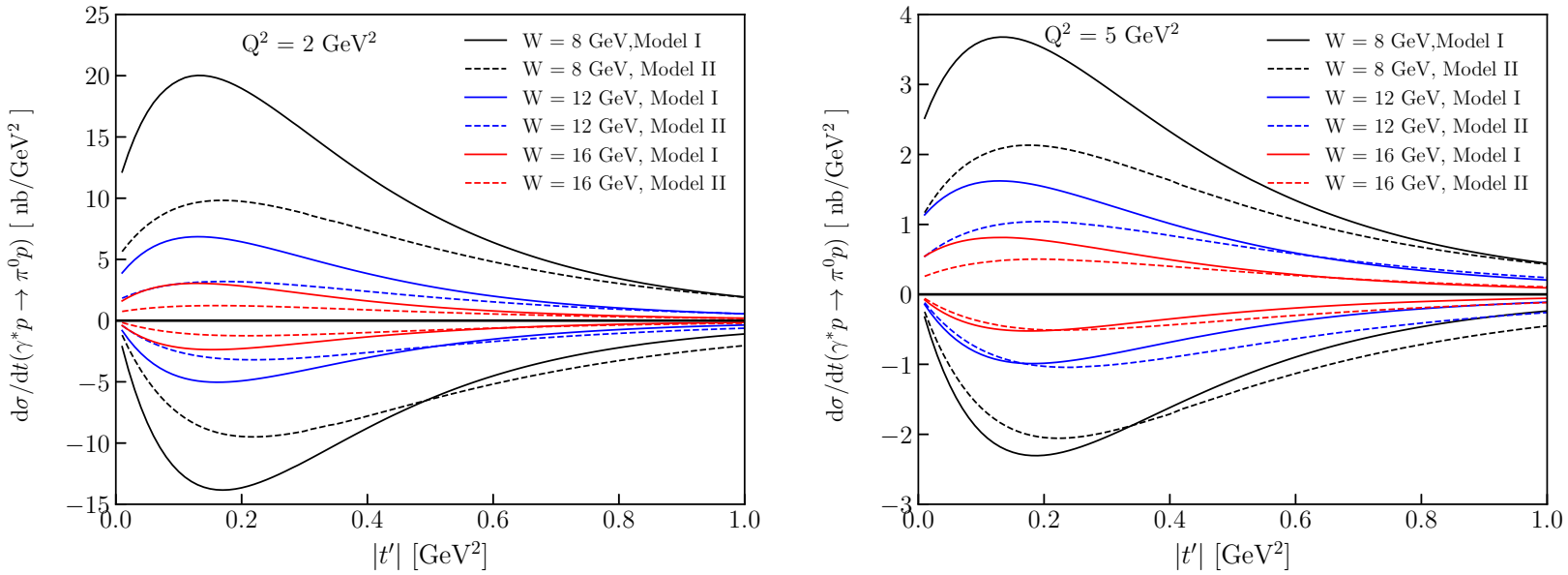

Figure 7: Models results for σ and σ_{TT} cross section at EicC kinematics. W dependencies at fixed Q^2 are shown

Vector meson production

GPDs can be employed to study meson production in several process.

- ρ production $(\frac{2}{3}H^u + \frac{1}{3}H^d)$
- ω production $(\frac{2}{3}H^u - \frac{1}{3}H^d)$
- ϕ production (H^s, H_g)
- J/ψ and Υ production (H_g)

Differential cross sections of vector mesons

The longitudinal and transversal differential cross sections as functions of $|t|$ and total cross sections of heavy vector meson in photon-proton scattering as function of W and Q^2 are calculated as [arXiv.2310.00980]

$$\frac{d\sigma_T}{dt} = \frac{1}{16\pi W^2(W^2+Q^2)}\left[|\mathscr{M}_{++,++}|^2 + |\mathscr{M}_{+-,++}|^2\right], \tag{20}$$

$$\frac{d\sigma_L}{dt} = \frac{Q^2}{m_V^2}\frac{d\sigma_T}{dt}; \tag{21}$$

$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt}. \tag{22}$$

Differential cross section of vector mesons

The gluon contribution to light vector meson electroproduction within GPD approach were calculated in [EPJC-42-281]. The helicity conservation amplitude of heavy vector meson production is given as

$$\begin{aligned}\mathcal{M}_{\mu'+,\mu+} &= \frac{e}{2}C_V\int_0^1\frac{dx}{(x+\xi)(x-\xi+i\varepsilon)}\\ &\times\left\{\mathcal{H}^{V+}_{\mu',\mu}H_g(x,\xi,t,\mu_F)+\mathcal{H}^{V-}_{\mu',\mu}\tilde{H}_g(x,\xi,t,\mu_F]\right\}. \quad (23)\end{aligned}$$

While the helicity flip amplitude can be written as

$$\begin{aligned}\mathcal{M}_{\mu'-,\mu+} &= -\frac{e}{2}C_V\frac{\sqrt{-t}}{2m}\int_0^1\frac{dx}{(x+\xi)(x-\xi+i\varepsilon)}\\ &\times\left\{\mathcal{H}^{V+}_{\mu',\mu}E_g(x,\xi,t,\mu_F)+\mathcal{H}^{V-}_{\mu',\mu}\tilde{E}_g(x,\xi,t,\mu_F)\right\}. \quad (24)\end{aligned}$$

Here the amplitudes $\mathcal{H}^{V\pm}_{\mu',\mu}$ are determined as a sum and differences of amplitudes with different gluon helicities.

$$\mathcal{H}^{V\pm}_{\mu',\mu}=\left[\mathcal{H}^{V}_{\mu'+,\mu+}\pm\mathcal{H}^{V}_{\mu'-,\mu-}\right], \quad (25)$$

Scattering amplitudes

To calculate hard scattering amplitude we consider six gluon Feynman diagrams. After a length calculations, the hard amplitude can be cast into

$$\mathscr{H}^{V\pm}_{\mu',\mu}(x,\xi) = 64\pi^2\alpha_s(\mu_R)\int_0^1 d\tau \int \frac{d^2\mathbf{k}_\perp}{16\pi^3}\psi(\tau,\mathbf{k}_\perp)\mathscr{F}^{\pm}_{\mu',\mu}(\tau,x,\xi,\mathbf{k}^2_\perp). \quad (26)$$

Here τ and $1-\tau$ are the fraction of longitudinal part of quark (antiquark) momenta incoming to the meson wave function, $\mathbf{k}_\perp$ is there transverse part. The k -dependent wave function of the vector meson is written as

$$\psi(\tau,\mathbf{k}_\perp) = a_v^2 f_v \exp\left(-a_v^2\frac{\mathbf{k}^2_\perp}{\tau(1-\tau)}\right). \quad (27)$$

Here f_v is a J/ψ decay constant, the parameter a_v is fixed from the best fit J/ψ cross section and determine the average value of $\langle\mathbf{k}\rangle^2_\perp$.

Hard part of scattering amplitude in J/ψ production

For $\tau = 1/2$, the hard part of the amplitude can be written as

$$\mathscr{F}^{\pm}_{\mu',\mu} = \frac{f^{\pm}_{\mu',\mu}}{denominator} \tag{28}$$

$$\begin{aligned} denominator = &(2\mathbf{k}_\perp^2 + m_V^2 + Q^2)(4\xi\mathbf{k}_\perp^2 + (m_V^2 + Q^2) \\ &(\xi - x) + i\varepsilon)(4\xi\mathbf{k}_\perp^2 + (m_V^2 + Q^2)(\xi + x)) \end{aligned} \tag{29}$$

For longitudinal and transverse helicity conservation amplitudes $f^{+}_{\mu,\mu}$ have a form

$$f^{+}_{00} = -64\sqrt{Q^2}(m_V^2 + Q^2)^2(x^2 - \xi^2), \tag{30}$$

$$f^{+}_{11} = 64 m_V (m_V^2 + Q^2)^2 (x^2 - \xi^2). \tag{31}$$

Here we omit k dependent terms. For the $f^{-}_{\mu,\mu}$ which contains $\tilde{H}$ contribution, we find that

$$f^{-}_{11} = -256(m_V^2 + Q^2)\mathbf{k}_\perp^2 m_V x \xi, \;\; f^{-}_{00} = 0. \tag{32}$$

GPDs function definitions

The GPDs are constructed adopting the double distribution representation

$$F(x,\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(\beta + \xi\,\alpha - x)\, f_g(\beta,\alpha,t), \tag{33}$$

F with PDFs h via the double distribution functions $f_i(\beta,\alpha,t)$. For gluon double distribution functions, it is

$$f_g(\beta,\alpha,t) = e^{-b_V t}\, h_i(\beta,\mu_F)\, \frac{15}{16}\, \frac{[(1-|\beta|)^2 - \alpha^2]^2}{(1-|\beta|)^5}. \tag{34}$$

The t- dependence in PDFs $h(\beta,\mu_F)$ is the fitted from conlinear PDF (CT18NLO, NNPDF, ABMP)

J/ψ production at different $|t|$

The J/psi differential cross section as a function of W using GK model [arXiv.2310.00980]

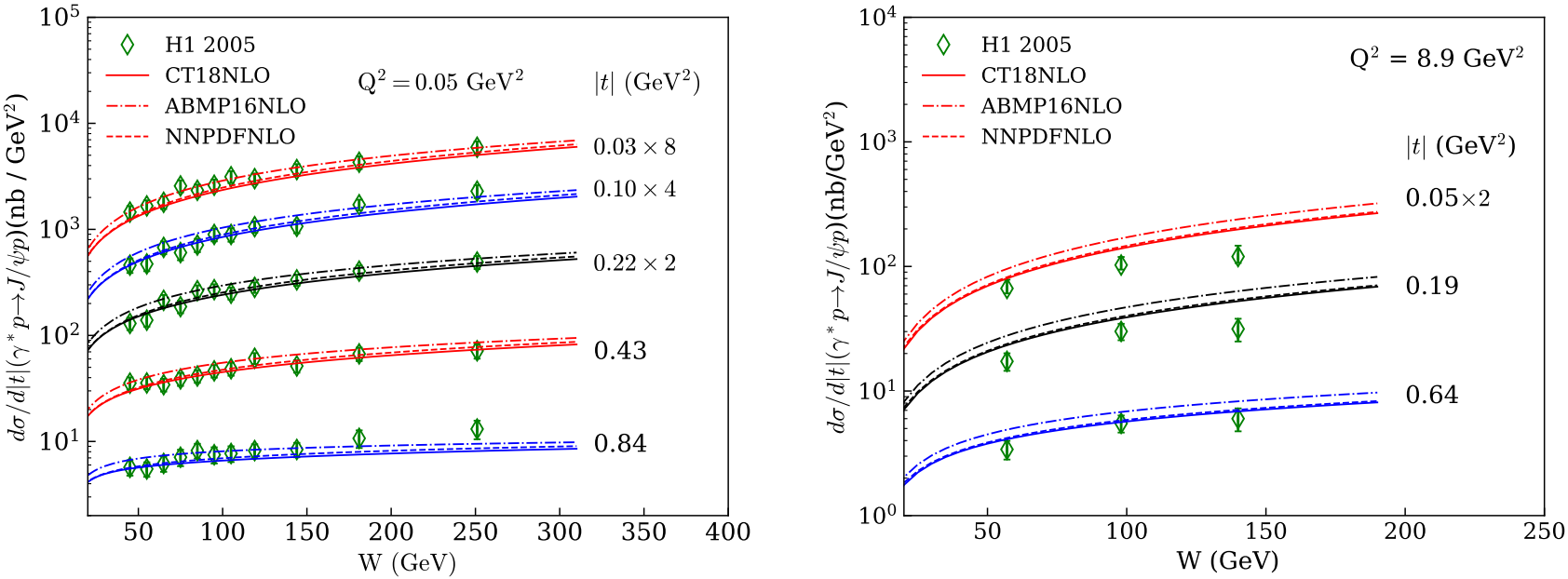

Figure 8: J/ψ differential cross section as a function of W at different $|t|$. The H1 experimental data are from EPJC-46-585.

- t-dependencies of cross section at fix W and Q^2 decrease well.
- The B-slope factor is good

J/ψ and $\Upsilon(1S)$ production in ep scattering

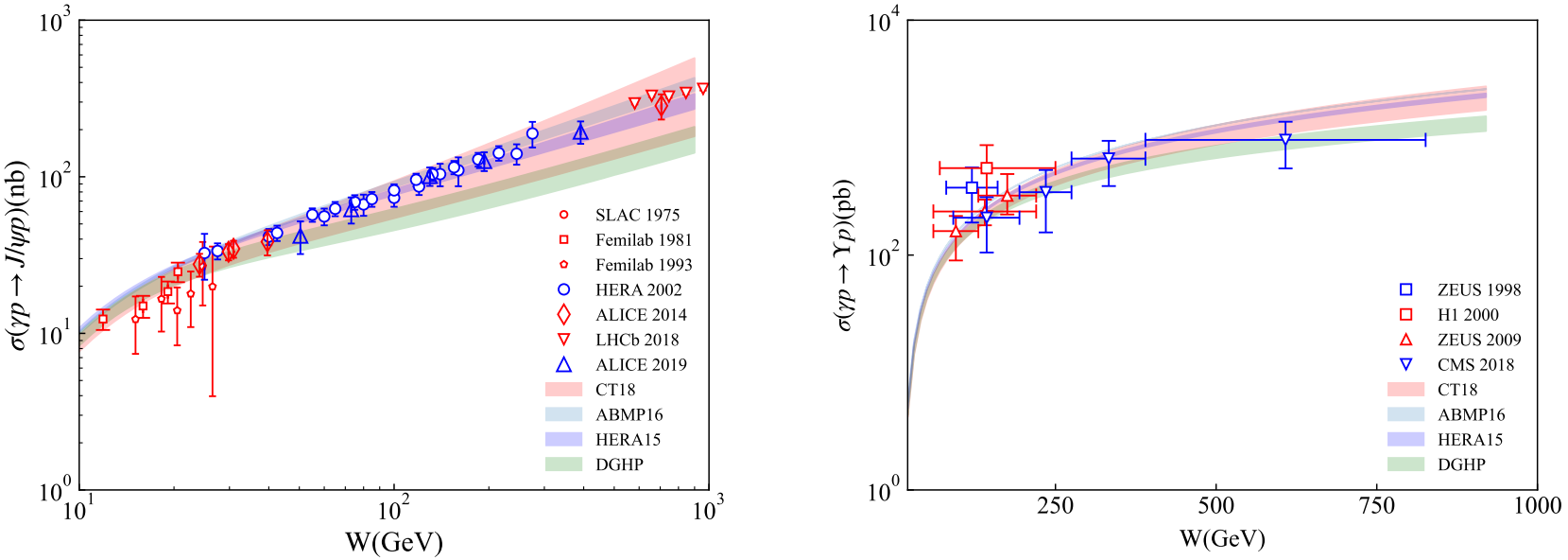

Figure 9: J/ψ and $\Upsilon(1S)$ total cross section and at Q^2 = 0 GeV^2 vs W from low to very high energy.

- The model can describe the J/ψ photoproduction cross section at a large W region.
- Our calculation agree with the Υ photoproduction cross sections.

J/ψ production at proton-proton collisions

The J/psi differential cross section at pp collision as a function of W using GK model [arXiv. 2502.17743]

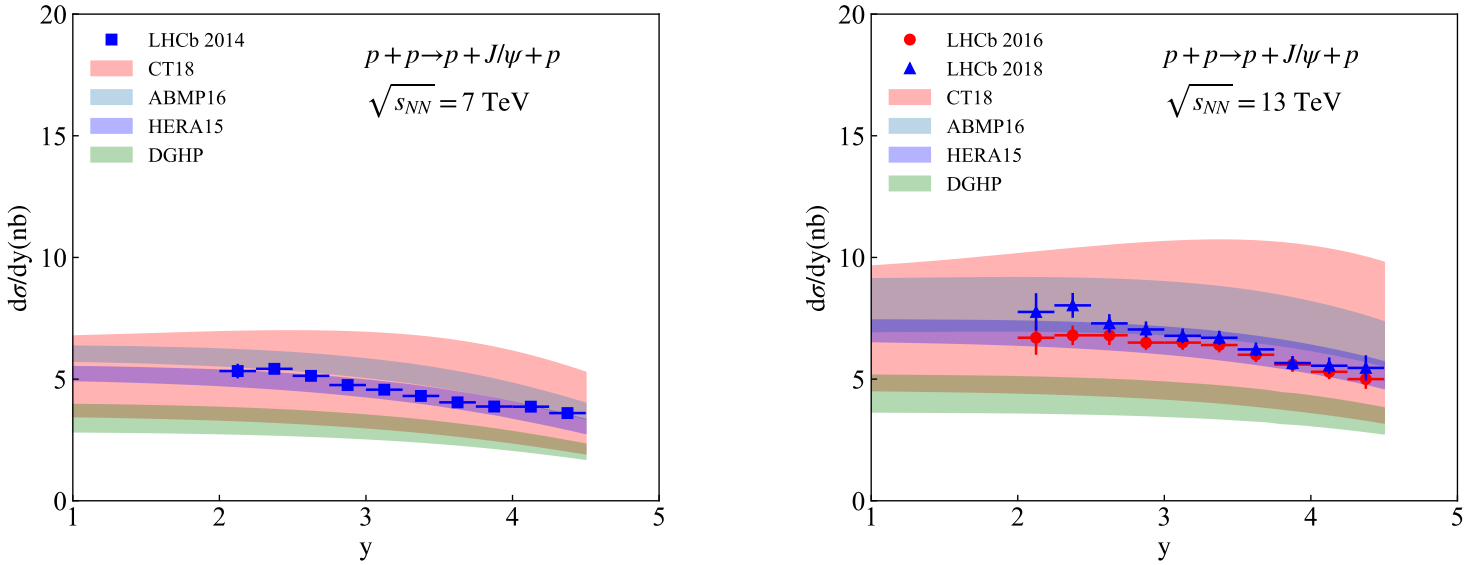

Figure 10: J/ψ production as a function of rapidity at pp UPC.

- The model can describe proton proton collision cross section at high energy.
- The cross section uncertainties of model is large since large

J/ψ production at p-Pb ultraperipheral collisions

The J/ψ rapidity distribution at p-Pb UPCs using GK model [arXiv.2507.20448]

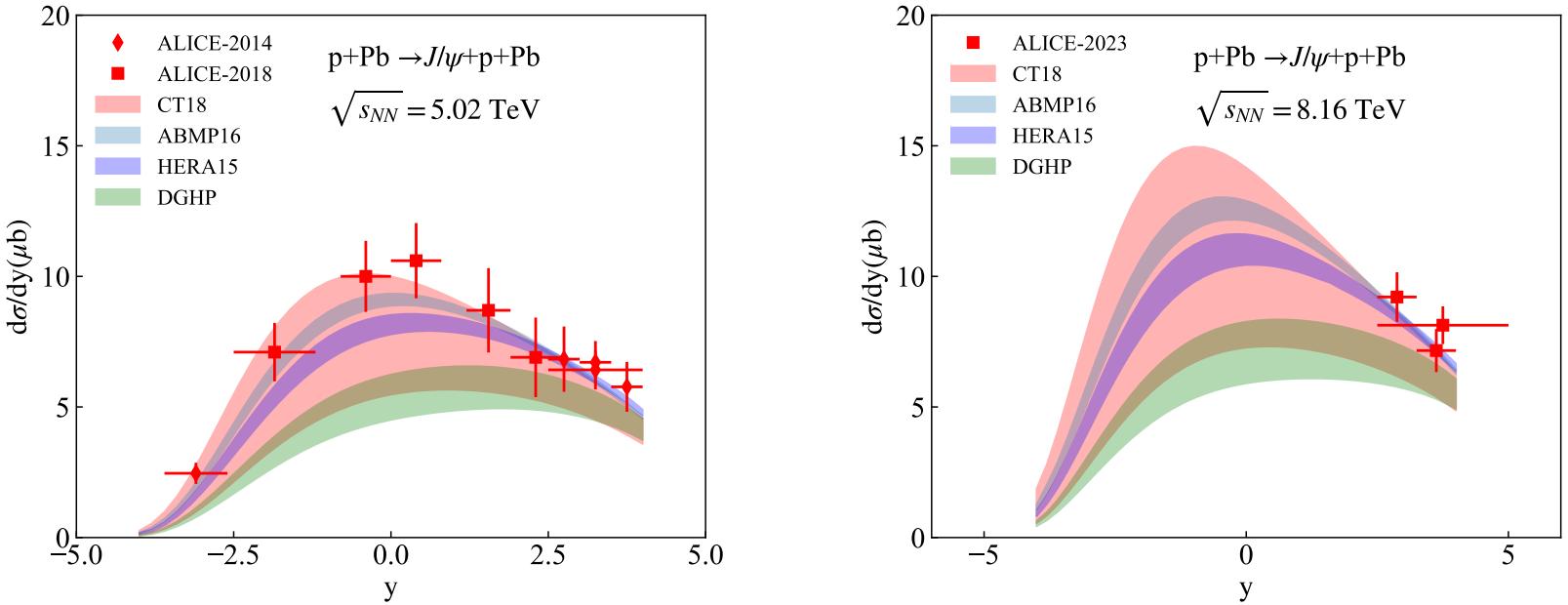

Figure 11: J/ψ production as a function of rapidity at p-Pb UPC.

- The model can describe J/ψ proton-lead collision cross section at high energy.

Summary

We can conclude following conclusions:

- GPDs can be studied in various processes (DVCS, DDVCS, TCS, DVMP).
- GPDs method can be employed to perform heavy vector mesons production in ep scattering and UPCs.
- Gluon density can be constrained via heavy vector meson cross sections in UPCs at high energy limit.
- Results of this work can be applied in future EicC experiments to give additional essential constraints on transversity GPDs at EicC energies range.
- Important information on gluon GPDs (especially E_g, H_g) can be obtained at US EIC, EicC and LHCb.

Thanks for your attentions!