Study of gluon GPDs via vector meson production

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Based on arXiv: 2408.05800 and 2502.17743

Mar 23th, 2025

Outline

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

- Introduction to GPDs
- Theoretical frame of vector meson production using GPDs method
- Differential cross section of J/ψ in GPDs method
- Production of J/ψ at proton-proton UPCs
- Asymmetry in J/ψ production in ep scattering
- Summary

Introduction to GPDs

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

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

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]

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

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

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

$$\begin{aligned}
&\langle p'\nu'|\sum_{a,a'} A^{a\rho}(0)A^{a'\rho'}(\bar{z})|p\nu\rangle \\
=\;& \frac{1}{2}\sum_{\lambda=\pm1}\varepsilon^{\rho}(k_g,\lambda)\,\varepsilon^{*\rho'}(k_g,\lambda') \qquad (3)\\
\times\;& \int_0^1 \frac{dx}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)}\mathrm{e}^{-i(x-\xi)p\cdot\bar{z}} \\
\times\;& \left\{\frac{\bar{u}(p'\nu')\,\not{n}\,u(p\nu)}{2\bar{p}\cdot n}H^g(x,\xi,t)+\frac{\bar{u}(p'\nu')\,i\sigma^{\alpha\beta}n_\alpha\Delta_\beta\,u(p\nu)}{4m\,\bar{p}\cdot n}E^g(x,\xi,t)\right. \\
+\;& \left.\lambda\frac{\bar{u}(p'\nu')\,\not{n}\gamma_5\,u(p\nu)}{2\bar{p}\cdot n}\widetilde{H}^g(x,\xi,t)+\lambda\frac{\bar{u}(p'\nu')\,n\cdot\Delta\gamma_5\,u(p\nu)}{4m\,\bar{p}\cdot n}\widetilde{E}^g(x,\xi,t)\right\}.
\end{aligned}$$

Sum rules of GPDs

GPD connects parton distribution via $H(x,0,0) = xf(x)$. Hadron Form factor can be obtain from GPDs

$$\int dxH^q(x,\xi,t) = F_1^q(t), \qquad \int dxE_q(x,\xi,t) = F_2^q(t); \tag{4}$$

$$\int dx\tilde{H}^q(x,\xi,t) = G_A^q(t), \qquad \int dx\tilde{E}^q(x,\xi,t) = G_p^q(t). \tag{5}$$

Ji sum rules for the proton angular memonta

$$\int xdx(H^q(x,\xi,0) + E^q(x,\xi,0) = 2J^q. \tag{6}$$

$J_q = \frac{1}{2}\Delta q + L_q$. L_q is key quantity to solve the spin puzzle.

Heavy vector meson production diagram

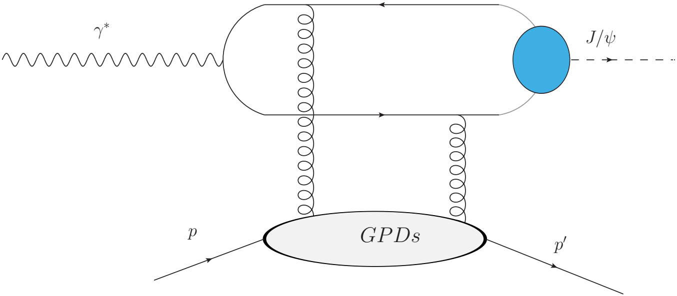


Figure 1: Typical diagram of heavy vector meson in photon-proton scattering.

Dipole model

Dipole model is employed to calculate vector mesons production in ep scattering. There are several models of the dipole amplitudes models, for example, IIM, IPsat, BGBK model. [PRD-74-074016 et al]

- Dipole model is valid in $x_B < 0.01$ region
- It didn't consider the the skewness of the ξ effect
- It can not calculate the asymmetries of the vector mesons production

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

$$\frac{d\sigma_T}{dt} = \frac{1}{16\pi W^2(W^2+Q^2)}\left[|\mathscr{M}_{++,++}|^2 + |\mathscr{M}_{+-,++}|^2\right], \quad (7)$$

$$\frac{d\sigma_L}{dt} = \frac{Q^2}{m_V^2}\frac{d\sigma_T}{dt}; \quad (8)$$

$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \varepsilon\frac{d\sigma_L}{dt}. \quad (9)$$

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

$$\begin{aligned}\mathscr{M}_{\mu'+,\mu+} &= \frac{e}{2}C_V\int_0^1\frac{dx}{(x+\xi)(x-\xi+i\varepsilon)} \\ &\times\left\{\mathscr{H}^{V+}_{\mu',\mu}H_g(x,\xi,t,\mu_F)+\mathscr{H}^{V-}_{\mu',\mu}\tilde{H}_g(x,\xi,t,\mu_F]\right\}. \quad (10)\end{aligned}$$

While the helicity flip amplitude can be written as

$$\begin{aligned}\mathscr{M}_{\mu'-,\mu+} &= -\frac{e}{2}C_V\frac{\sqrt{-t}}{2m}\int_0^1\frac{dx}{(x+\xi)(x-\xi+i\varepsilon)} \\ &\times\left\{\mathscr{H}^{V+}_{\mu',\mu}E_g(x,\xi,t,\mu_F)+\mathscr{H}^{V-}_{\mu',\mu}\tilde{E}_g(x,\xi,t,\mu_F)\right\}. \quad (11)\end{aligned}$$

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

$$\mathscr{H}^{V\pm}_{\mu',\mu}=\left[\mathscr{H}^{V}_{\mu'+,\mu+}\pm\mathscr{H}^{V}_{\mu'-,\mu-}\right], \quad (12)$$

and flavor factor $C_V = C_{J/\psi} = 2/3$.

Scattering amplitudes

There are 6 feynman diagrams of $\gamma + p \to V + p$. We must calculate the sum of feynman amplitudes of them

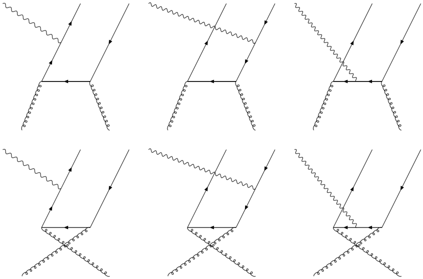


Figure 2: 6 Feynman diagrams of $\gamma + g \to V + g$

Scattering amplitudes

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

$$\mathscr{H}^{V\pm}_{\mu',\mu}(x,\xi) = 64\pi^2\alpha_s(\mu_R)\int_0^1 d\tau \int \frac{d^2\mathbf{k}_\perp}{16\pi^3}\psi(\tau,\mathbf{k}_\perp)\mathscr{F}^{\pm}_{\mu',\mu}(\tau,x,\xi,\mathbf{k}^2_\perp). \quad (13)$$

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

$$\psi(\tau,\mathbf{k}_\perp) = a_v^2 f_v \exp\left(-a_v^2\frac{\mathbf{k}^2_\perp}{\tau(1-\tau)}\right). \quad (14)$$

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

$$\mathscr{F}^{\pm}_{\mu',\mu} = \frac{f^{\pm}_{\mu',\mu}}{denominator} \tag{15}$$

$$\begin{aligned} denominator &= (2\mathbf{k}_\perp^2 + m_V^2 + Q^2)(4\xi\mathbf{k}_\perp^2 + (m_V^2 + Q^2) \\ &(\xi - x) + i\varepsilon)(4\xi\mathbf{k}_\perp^2 + (m_V^2 + Q^2)(\xi + x)) \end{aligned} \tag{16}$$

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

$$f^{+}_{00} = -64\sqrt{Q^2}(m_V^2 + Q^2)^2(x^2 - \xi^2), \tag{17}$$

$$f^{+}_{11} = 64 m_V (m_V^2 + Q^2)^2(x^2 - \xi^2). \tag{18}$$

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

$$f^{-}_{11} = -256(m_V^2 + Q^2)\mathbf{k}_\perp^2 m_V x \xi, \quad f^{-}_{00} = 0. \tag{19}$$

GPDs function definitions

The GPDs are constructed adopting the double distribution representation

$$F(x,\xi,t) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha \delta(\beta + \xi\alpha - x) f_g(\beta,\alpha,t), \tag{20}$$

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

$$f_g(\beta,\alpha,t) = e^{-b_V t} h_i(\beta,\mu_F) \frac{15}{16} \frac{[(1-|\beta|)^2 - \alpha^2]^2}{(1-|\beta|)^5}. \tag{21}$$

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

Ratio of the Re and Im of the amplitude

We can show the ratio of the Re and Im of the amplitudes.

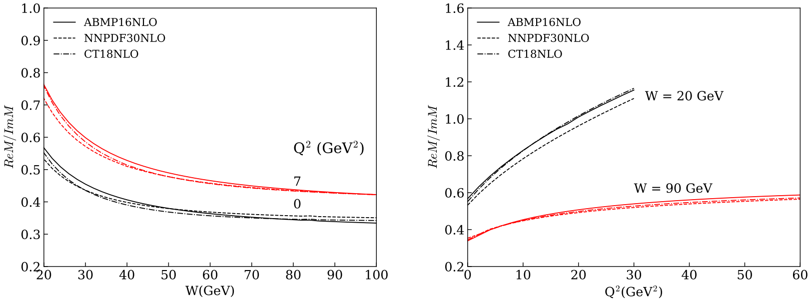
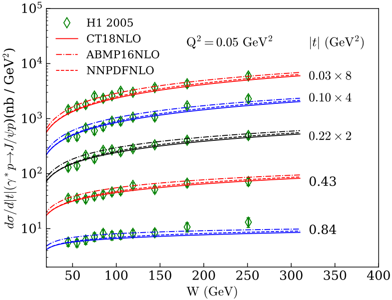


Figure 3: Ratio of ReM/ImM parts of J/ψ amplitudes at fixed W vs Q^2.

J/ψ production at different $|t|$



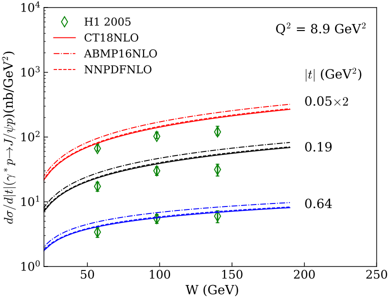


Figure 4: J/ψ differential cross section as a function of W at different $|t|$. The H1 experimental data are from EPJC-46-585.

J/ψ production at different $|t|$

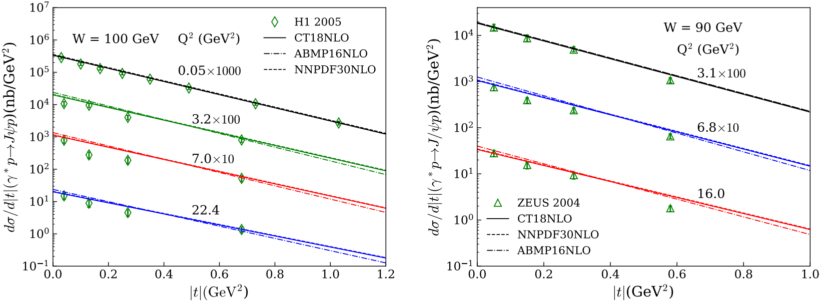


Figure 5: J/ψ differential cross section vs $|t|$ at fixed W and different Q^2. The HERA experimental data are from from NPB-695-3 and EPJC-46-585.Cross sections are scaled by the factor shown in the graph.

J/ψ production at different Q^2

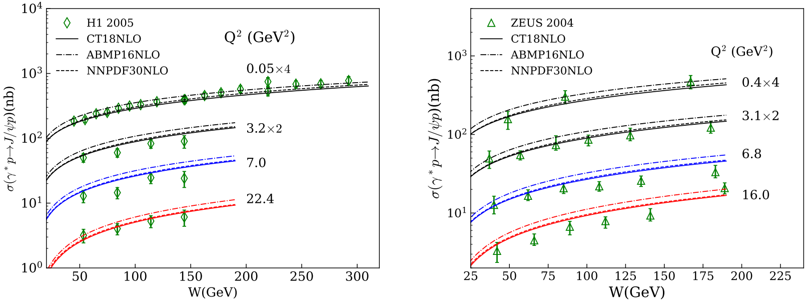
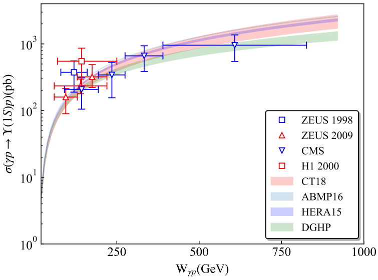


Figure 6: J/ψ total cross section vs W at different Q^2 comparing with the HERA experimental data are taken from NPB-695-3 and EPJC-46-585.

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



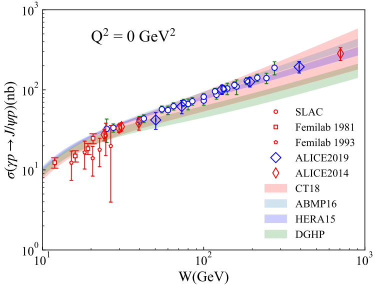


Figure 7: J/ψ and $\Upsilon(1S)$ total cross section and at $Q^2 = 0$ GeV^2 vs W from low to very high energy.

J/ψ production at proton-proton ultraperipheral collisions

In proton-proton ultraperipheral collisions, the vector meson production can be obtained as [JHEP-1311-085]

$$\frac{d\sigma^{th}(pp)}{dy} = S^2(W_+)\left(k_+\frac{dn}{dk_+}\right)\sigma_+^{th}(\gamma p) + S^2(W_-)\left(k_-\frac{dn}{dk_-}\right)\sigma_-^{th}(\gamma p). \quad (22)$$

$S(k)$ is the survival factors which have been studied in [JPG-44-03LT01]. The photon flux of the proton is given as

$$\frac{dn}{dk}(k) = \frac{\alpha_{em}}{2\pi k}\left[1+\left(1-\frac{2k}{\sqrt{s}}\right)^2\right]\left(\ln\Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3}\right). \quad (23)$$

J/ψ production at proton-proton ultraperipheral collisions

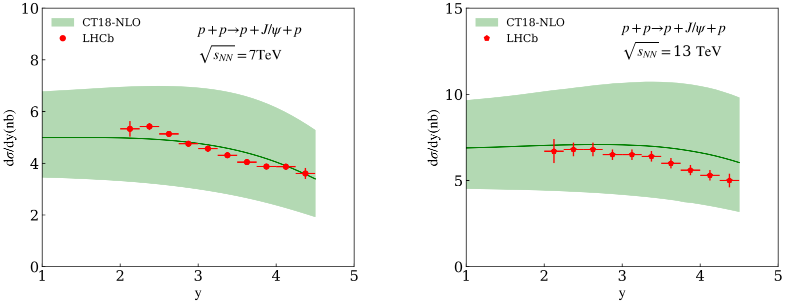


Figure 8: J/ψ production as a function of rapidity at pp UPC.

J/ψ production at proton-proton ultraperipheral collisions

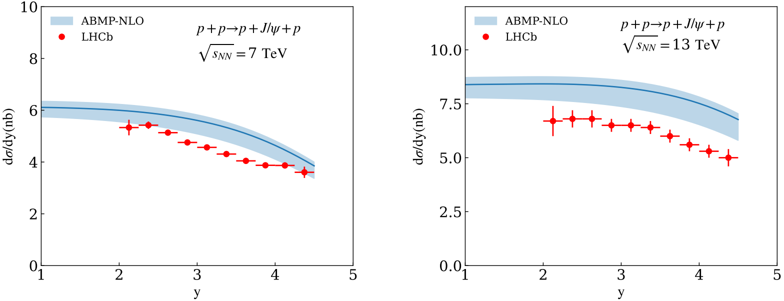


Figure 9: J/ψ production as a function of rapidity at pp UPC.

J/ψ production at proton-proton ultraperipheral collisions

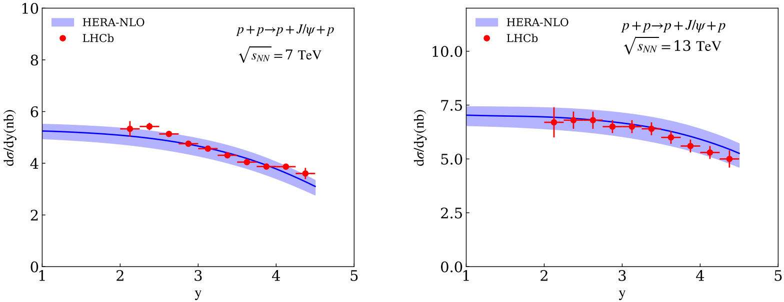


Figure 10: J/ψ production as a function of rapidity at pp UPC.

J/ψ and Υ production at p-Pb ultraperipheral collisions

In proton-proton ultraperipheral collisions, the vector meson production can be obtained as

$$\frac{d\sigma^{th}(pPb)}{dy} = n(\omega)\sigma^{th}(\gamma p) \tag{24}$$

The photon flux of the lead is given as

$$n(\omega) = \frac{2Z^2\alpha_{em}}{\pi}\left[\xi K_1(\xi)K_0(\xi) - \frac{\xi^2}{2}[K_1^2(\xi) - K_0^2(\xi)]\right], \tag{25}$$

where $\xi = 2\omega R_A/\gamma_L$, with R_A is the radius of the nucleus, $K_0(x)$ and $K_1(x)$ are the second kind of Bessel functions.

J/ψ production at p-Pb ultraperipheral collisions

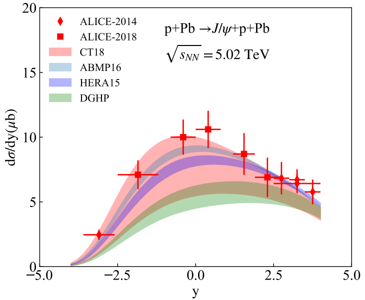


Figure 11: J/ψ production as a function of rapidity at p-Pb UPC.

$\Upsilon(1S)$ production at ultraperipheral collisions

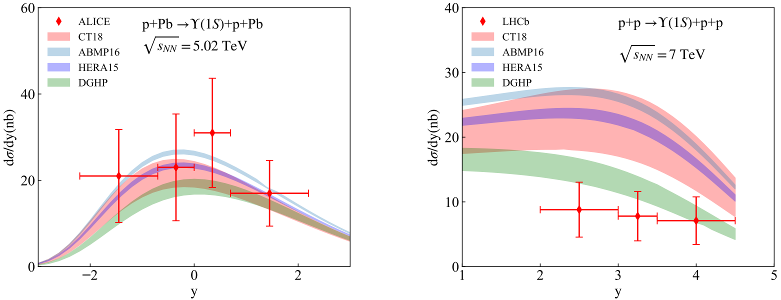


Figure 12: $\Upsilon(1S)$ production as a function of rapidity at UPC.

Summary

We can conclude following conclusions:

- 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.

Thanks for your attentions!