Exclusive J/Ψ Production and Gluon GPDs Effects

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Исследование эксклюзивного фоторождение J/Ψ мезонов выполнено в факторизацонном подходе. Обобщенные партоные распределения (ОПР) глюонов, играющие здесь важную роль, построены с использованием представления двойного распределения. Полученные сечения J/Ψ рождения в широкой области знергий хорошо согласуются с экспериментом. Оценены спиновые асимметрии в J/Ψ рождении. Эти расчеты расширены на рождение J/Ψ мезонов в ультрапериферических pp столкновениях. Показано хорошее соответствие наших результатов с данными LHCb. Сделаны предсказания для энергий NICA. Результаты модели могут быть использованы при исследовании глюонных ОПР на будущих коллайдерах.

Study of exclusive photoproduction of J/Ψ mesons was carried out in a factorization approach. Generalized parton distributions (GPDs) for gluons, which play an important role here, are constructed using the double distribution representation. The obtained cross sections of J/Ψ production in a wide energy range are in good agreement with the experiment. The spin asymmetries in the J/Ψ production were estimated. These calculations were extended to the of J/Ψ mesons production in ultraperipherical pp collisions. It was shown a good agreement of our results with the LHCb data. Predictions have been made for the NICA energy range. The model results can be used to study the gluon GPDs in future colliders.

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Introduction

In this report, we analyze exclusive production of J/Ψ mesons which can be used to study gluon GPDs. GPDs are important objects that contain extensive information about the hadron structure. GPDs depend on three variables: longitudinal momentum fraction x, skewness ξ- longitudinal momentum transfer fraction, and momentum transfer, t. In the forward limit, GPDs are equal to parton distribution functions (PDFs). The GPDs moments are connected with hadron form factors and contain information on the parton angular momenta. This means that GPDs give information on the 3D structure of hadrons (see e.g. review [1–3] and references there).

An important processes to study GPDs are deeply virtual Compton scattering, light meson leptoproduction at high photon virtuality and some other reactions where the gluon and quark GPDs can be analyzed, see e.g. [4, 5]. The amplitudes of these reactions factorize into the hard subprocess and

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GPDs [4,6,7]. It is well known that heavy meson production gives information on gluon GPDs in proton [8,9].

This report is devoted to studying the production of heavy J/Ψ mesons in lepton-proton and proton-proton reactions. In section 2, we present the handbag approach where the exclusive J/Ψ meson photoproduction amplitudes can be presented as a convolution of hard subprocess and soft GPDs [10]. The gluon GPDs H_g are constructed using double distribution representation.

In section 3, we show a comparison of model results for the J/Ψ production cross section with experimental data from HERA to LHC energies [10] which described fine. We estimate J/Ψ spin asymmetries at the energies of future electron-ion colliders in USA and China [11,12] where information on E_g and $\tilde{H}_g$ GPDs can be obtained.

In section 4, we extend our model calculations to exclusive J/Ψ production in proton-proton collisions [13]. The survival factors and equivalent photon approximation are applied to predict the exclusive J/Ψ production in pp collisions. Obtained results are in a good agreement with the experimental data at LHCb. We predict the exclusive J/Ψ production cross section at NICA energies.

Our GPD approach predictions can be employed to estimate the exclusive J/Ψ production observables in future lepton–proton and proton–proton experiments to get essential information on gluon GPDs.

Handbag approach for heavy meson leptoproduction

The meson production amplitude $\mathcal{M}$ in Eq. (3) can be presented in the form [10,14]

$$\begin{aligned}\mathcal{M}_{\mu'+,\mu+} &= \frac{e}{2}C_V\int_0^1\frac{dx}{(x+\xi)(x-\xi+i\epsilon)}\mathcal{H}_{\mu',\mu}\,H_g(x,\xi,t), \qquad (1)\\ \mathcal{M}_{\mu'-,\mu+} &= -\frac{e}{2}C_V\frac{\sqrt{-t}}{2m}\int_0^1\frac{dx}{(x+\xi)(x-\xi+i\epsilon)}\mathcal{H}_{\mu',\mu}\,E_g(x,\xi,t).\end{aligned}$$

Here the proton non-flip and the helicity flip amplitudes contain the hard part $\mathcal{H}$ that is calculated perturbatively and soft gluon GPDs H_g and E_g, respectively.

We consider 6 gluon diagrams to calculate hard scattering amplitude [10, 14]. The hard amplitude $\mathcal{H}$ can be written as

$$\mathcal{H}_{\mu'+,\mu+} \simeq \alpha_s(\mu_R)\int_0^1 d\tau\int\frac{d^2k_\perp}{16\pi^3}\phi_V(\tau,k_\perp^2)\;f_{\mu',\mu}(x,\xi,\tau)\hat{D}(Q^2,k_\perp^2). \qquad (2)$$

In calculations we take into account the transverse part of quark momenta $k_\perp$ in the soft meson wave function ϕ and in quark propagators, which are collected in the D function

$$D=\frac{1}{(2\mathbf{k}_\perp^2+\mu_V^2)(4\xi\mathbf{k}_\perp^2+\mu_V^2(\xi-x)+i\epsilon)(4\xi\mathbf{k}_\perp^2+\mu_V^2(\xi+x))}. \qquad (3)$$

This form is valid for the case of the nonrelativistic wave function ϕ_V in Eq. (2) with the same quark and antiquark momenta ($\tau = 1/2$). The average value of $k_\perp^2$ in propagators Eq. (3) is determined by the wave function. We find that $< k_\perp^2 > \sim 1\text{GeV}^2$ describes experimental data well.

A typical variable (scale) in the hard propagators D is $\mu_V^2 = m_V^2 + Q^2$ which is large for J/Ψ production that provides the amplitude factorization even for $Q^2 = 0$. The hard amplitudes f in (2) for longitudinally and transversally polarized photon and vector meson have a form

$$f_{11} = 64\sqrt{Q^2}\mu_V^4(x^2 - \xi^2), \quad f_{00} = -\frac{\sqrt{Q^2}}{m_V} f_{11}. \tag{4}$$

This means that for the same form of wave function for the longitudinally and transversally polarized meson, we have a relation

$$\mathcal{M}_{0\nu',0\nu} = -\frac{\sqrt{Q^2}}{m_V}\mathcal{M}_{+\nu',+\nu}. \tag{5}$$

To construct GPDs, we use the double distribution representation [15] which connects GPDs with PDFs and determines the skewness ξ dependencies of GPDs

$$F_i(x,\xi,t) = \int_{-1}^{1} d\rho \int_{-1+|\rho|}^{1-|\rho|} d\lambda\, \delta(\rho + \xi\lambda - x) g_i(\rho,\lambda,t). \tag{6}$$

where $F_i = H,\ \tilde{H},\ E,\ \tilde{E}$ GPDs. The double distribution functions g_i for gluon contribution have a form

$$g_i(\rho,\lambda,t) = e^{B_V t}\, h_i(\rho,\mu_F)\frac{15}{16}\frac{[(1-|\rho|)^2 - \lambda^2]^2}{(1-|\rho|)^5}. \tag{7}$$

Here $h_i(\rho,\mu_F)$ is a corresponding h and e gluon PDFs at the scale $\mu_F \sim \mu_V$, B_V is a slope parameter. Its form can be found in [10]. We use in our calculations 3 different GPDs models based on PDFs (ABMP, NNPDF, CT). Note, that all references on gluon PDFs and experimental data on J/Ψ production can be found in [10, 13].

J/Ψ production in lepton-proton reactions

The differential cross sections and their transversal part of heavy vector meson in photon-proton scattering are calculated as

$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt}(1 + \frac{Q^2}{m_V^2}), \quad \frac{d\sigma_T}{dt} = \frac{1}{16\pi W^2(W^2+Q^2)}\sum_{\lambda=\pm}|\mathcal{M}_{+\lambda,++}|^2. \tag{8}$$

The total cross section σ is $\frac{d\sigma}{dt}$ integrated over t.

The model gives the possibility to calculate real and imaginary parts of the production amplitude. Our results for the $R = ReM/ImM$ ratio are

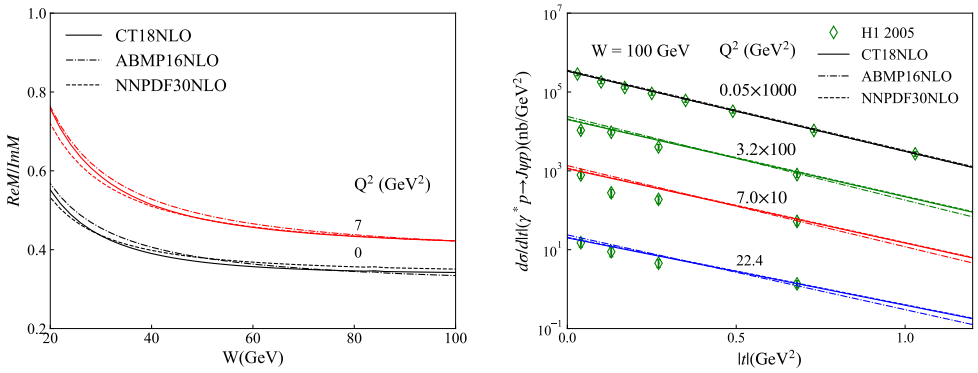


Fig. 1. Left:Ratio of ReM/ImM parts of J/Ψ production amplitudes. J/ψ differential cross section vs $|t|$ at different Q^2, right graph. Cross sections are scaled by the factor shown in the graph.

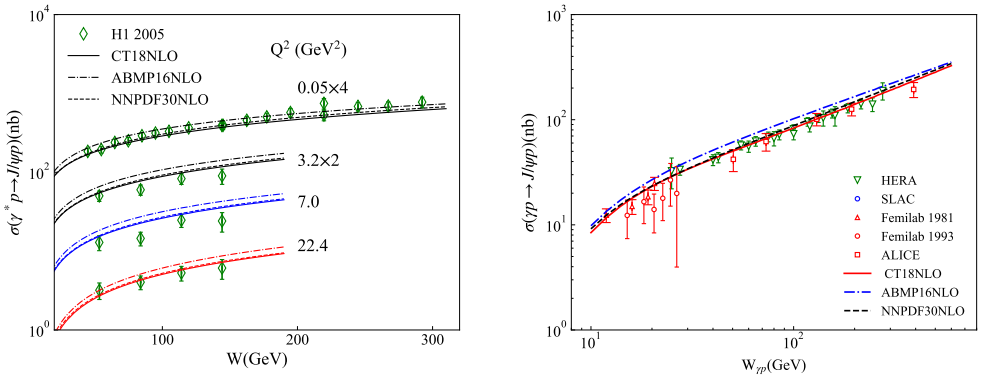


Fig. 2. Left: J/ψ total cross section at HERA for fixed Q^2 vs the energy W and at $Q^2 = 0$ from low to very high energies, right graph.

presented in Fig.1, left. R-ratio at fixed Q^2 decreases with energy, and at $W = 20$GeV (China EicC) $R(20GeV) \sim 1$, at $W = 100$GeV (USA EiC) $R(100GeV) \sim 0.5$.

We compare model results with available experimental data on the differential cross sections of J/ψ production for H1 at HERA. Our results for differential cross section are in good agreement with data and are shown in Fig. 1, right. Results for the total cross section at HERA energies are shown in Fig.2, left, and describe experimental data fine. In Fig 2, right the low energy photoproduction data are shown together with very high energies data from LHC ALICE experiment. It can be seen that all GPDs models give good descriptions of experimental data in a wide energy range. More comparison with experiment can be found in [10]

The single spin asymmetry A_N and double spin A_{LL} correlation can also be measured at heavy vector meson production. They are connected with

E_g and polarized $\tilde{H}_g$ GPDs for gluons correspondingly:

$$A_N = -\frac{2\mathrm{Im}[\mathcal{M}^{H}_{++,++}\mathcal{M}^{E*}_{+-,++}]}{|\mathcal{M}^{H}_{++,++}|^2 + |\mathcal{M}^{E}_{+-,++}|^2}, \quad A_{LL} = 2\frac{\mathrm{Re}[\mathcal{M}^{H}_{++,++}\mathcal{M}^{\tilde{H}*}_{++,++}]}{\epsilon|\mathcal{M}^{H}_{0+,0+}|^2 + |\mathcal{M}^{H}_{++,++}|^2} \quad (9)$$

The E_g GPDs are determine proton spin-flip amplitude Eq. (1). Previous analyses A_N asymmetry in J/Ψ production can be found in [16].

To estimate E_g we use parameterizations (2,3) from [17], that called here as (V1,V2). They are different mainly by the sign. Energy dependencies of this asymmetry is rather weak because the low -x dependencies of $e_g(x)$ and $h_g(x)$ PDFs are similar. Our results on A_N asymmetry for J/Ψ photoproduction are shown in Fig. 3, left. We find that $|A_N| \sim 0.05$.

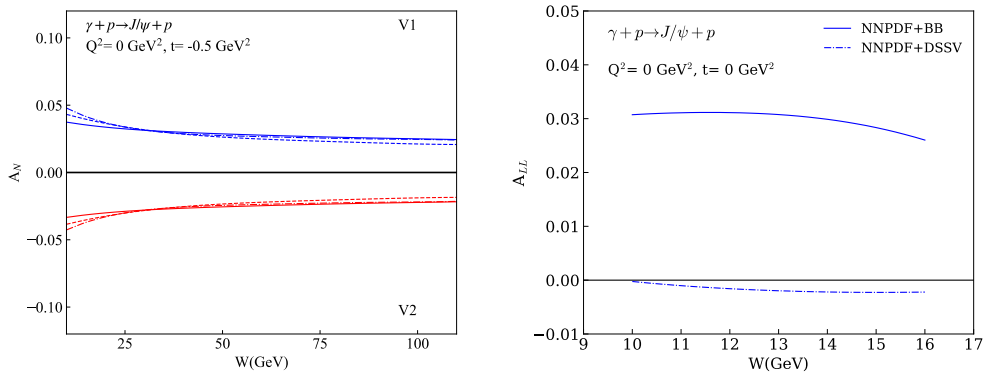


Fig. 3. Left: Single spin asymmetry A_N versus W at $Q^2 = 0$ GeV^2 and double spin correlation A_{LL}, right graph.

Effects of $\tilde{H}_g$ can be tested in A_{LL} asymmetry. Details of calculations can be found in [10]. To study A_{LL} asymmetry, we use BB and DSSV parameterizations of Δg PDFs which determine $\tilde{H}^g$ GPDs through DD representation (6). A_{LL} asymmetry decreases rapidly with energy, and at US Eic energies it is close to zero. We show in Fig.3, right, the W dependencies of J/Ψ A_{LL} correlation at energies typical for China EicC. We find that $A_{LL} \sim 0.03$ for BB case and $A_{LL} \sim 0.0$ for DSSV parameterizations. Thus, study of A_{LL} correlation at the future EicC can give an answer about the value of $\tilde{H}^g$.

J/Ψ production in proton-proton ultraperipheral collisions

We adopt our model for J/Ψ production in pp reactions. At the proton-proton ultraperipheral collisions, the vector mesons rapidity distributions can be written as follows [18]

$$\frac{d\sigma(pp)}{dy} = S^2(W_+)\Big(k_+\frac{dn}{dk_+}\Big)\sigma^{J/\Psi}_+(\gamma p) + S^2(W_-)\Big(k_-\frac{dn}{dk_-}\Big)\sigma^{J/\Psi}_-(\gamma p). \quad (10)$$

The photon momentum, $k_\pm = x^\pm_\gamma\sqrt{s_{NN}}/2 \approx (m_V/2)e^{\pm|y|}$. y is the rapidity of the vector meson, s_{NN} is the collision energy, and $W^2_\pm = M_V\sqrt{s_{NN}}e^{\pm|y|}$.

$S^2(W_\pm)$ is the survival factor that has been studied in [18]. dn/dk is the photon flux of the proton. We use the survival factors in LHCb proton-proton ultraperipheral collisions from [18]. At the NICA energies, we use the survival factors equal to unity in accordance with [18].

The exclusive J/ψ production was measured at LHCb in proton-proton ultraperipheral collisions. The model results for J/ψ cross section in proton-proton ultraperipheral collisions as a function of rapidity for GPDs based on the HERA gluon density are shown in Fig 4, left. Our results describe LHCb data well. The uncertainties in cross section are quite small because the gluon density uncertainties at small-x are small.

We predict the J/ψ cross section at NICA $\sqrt{s_{NN}} = 24$ GeV. Our results are presented in Fig. 4, right. The cross section at NICA is not very high because J/ψ meson production here is not far from the threshold. The model estimations for the J/ψ cross section at $\sqrt{s_{NN}} = 24$ GeV can help to simulate the detector system of NICA. Generally, the gluon density uncertainties are strongly correlated with J/ψ production cross section uncertainties. This means that the vector meson production in pp ultraperipheral collisions can be employed to obtain an additional constrain for the uncertainties of gluon density.

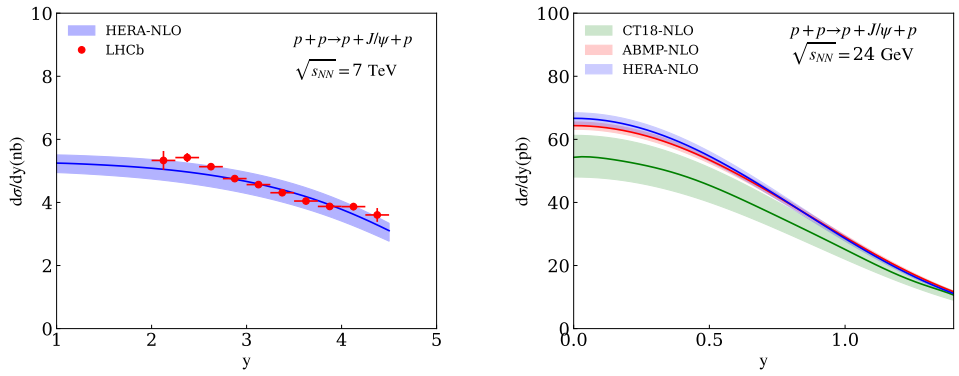


Fig. 4. Left: Exclusive J/ψ production in proton-proton ultraperipheral collisions as a function of rapidity at LHCb, and for NICA energy range, right graph.

To conclude, we can mention that we study the exclusive production of J/Ψ meson within a handback factorization approach. We analyze heavy meson production in lepton-proton and ultraperipheral pp collisions. The obtained cross sections of J/Ψ production in a wide energy range are in good agreement with the experiment. We perform prediction for spin asymmetries for the energy range of future colliders. Important information on gluon GPDs (especially E_g and $\tilde{H}_g$) can be obtained at US EIC, China EicC and NICA.

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All authors of this paper declare that they have no conflicts of interest.

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