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Exclusive Charmonium Photo-Production at HERA and LHC with Color Glass Condensate *

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We calculate the exclusive charmonium photo-production in the framework of color glass condensate. To obtain a good description of the vector meson production experimental data at HERA, we introduce a vector meson mass dependent skewness factor into the skewness effect. Then we extend the skewness improved model to the LHC energies. The numerical results of our model are in good agreement with the J/ψ and $\psi(2S)$ data in ultra-peripheral proton–proton collisions at LHC, which show the significance of the vector meson mass-dependent skewness factor. A prediction of the exclusive charmonium photo-production in ultra-peripheral nucleus–nucleus collisions is performed since it can provide a good way to test the effectiveness of the color glass condensate.

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The exclusive vector meson production has attracted great interests experimentally and theoretically as it provides a rich testing ground for quantum chromodynamics (QCD). In particular, the vector mesons through photo-production processes provide a valuable way to probe the generalized (or skewed) gluon density at small x,[1−3] and to unveil the mechanism of quarkonium production.[4] Experimentally, the H1 and ZEUS collaborations at HERA have carried out several measurements of the charmonium photo-production in γ-proton (γp) deep inelastic scattering.[5−7] The first measurement of the vector meson production in proton–proton (pp) collisions at LHC was made by the LHCb collaboration at $\sqrt{s} = 7\,\text{TeV}$.[8] Recently, the LHCb collaboration released the preliminary charmonium production data in pp collisions at $\sqrt{s} = 13\,\text{TeV}$.[9] The abundant data provide a golden opportunity to test the theoretical predictions. Theoretically, there are several approaches based on different mechanisms towards the charmonium photo-production proposed, such as the nonrelativistic QCD (NRQCD) factorization,[10] perturbative-QCD (pQCD) fragmentation function factorization,[11] k_{t} factorization[4,12,13] and color glass condensate (CGC) combined with Dokshitzer–Gribov–Lipatov–Altarelli–Parisi (DGLAP) equations.[14] It seems that all these theoretical models can describe the experimental data of vector meson production under some uncertainties. It is difficult to diagnose which mechanism is virtually dominant for the photo-production of the vector meson in γp and pp collisions at HERA and LHC energies. This study is focusing on the theory of CGC to establish a model for the vector meson photo-production, which can provide an effective way to distinguish the mechanism of charmonium production. Furthermore, this study can be used to test the effectiveness of the CGC theory.

The studies in Refs. [15,16] have shown that the exclusive vector meson production at HERA can be described with the CGC dipole model under some uncertainties. The basic idea of vector meson production in the CGC framework is that a photon emitted from the electron dissociates into a quark–antiquark dipole, and then interacts directly with the target proton, which can be described by dipole-target scattering amplitude. It seems that the models set up in Refs. [15,16] can reproduce the HERA data within relatively large uncertainties. However, the models proposed in Refs. [15,16] only confront with HERA data, which have relatively low statistics and precision at the time of works released. Therefore, these studies cannot take charge of distinguishing the above-mentioned mechanisms, which could be dominant in the vector meson production. Although Refs. [17,18] extended the CGC vector meson production approach to the LHC energies, and described J/ψ and $\psi(2S)$ with the CGC method, there is a tension when they reproduced the $\psi(2S)$ data measured by LHCb collaboration. We find that the deviation may come from the skewness correction. We devise a mass-dependent skewness correction which accounts for the mass change from J/ψ to $\psi(2S)$.

To fix the parameters in skewness correction, we first investigate the exclusive J/ψ and $\psi(2S)$ photo-production at HERA based on the impact parameter-dependent color glass condensate (bCGC) dipole model. Then we extend the formalism to the ultra-peripheral collisions (UPCs) of hadron–hadron at LHC energies. In the UPC processes, one of the hadrons can emit a photon in the high energy limit, which then interacts with another hadron. We find that the CGC formalism can well describe the J/ψ and $\psi(2S)$ data at LHC energies.

The dipole picture is a factorization scheme for

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DIS, which is valid at small x.[19,20] Specifically, the scattering between a virtual photon γ^* and a proton is seen as the dissociation of γ^* into a quark–antiquark dipole with transverse size $\boldsymbol{r}$ followed by the interaction of this dipole with the proton via gluon exchanges.[21,22] For the vector meson production processes, the outgoing $q\bar{q}$ pair finally recombines into a vector meson, while the proton keeps intact. The differential cross section of $\gamma^* p \to Vp$ is given by[15]

$$\frac{d\sigma_{\rm T,L}^{\gamma^* p\to Vp}}{dt} = \frac{1}{16\pi} \mid \mathcal{A}_{\rm T,L}^{\gamma^* p\to Vp} \mid^2, \tag{1}$$

where the subscripts T and L denote the longitudinal and transverse polarizations, respectively. The imaginary part of the scattering amplitude $\mathcal{A}_{\rm T,L}$ in Eq. (1) is given in the color dipole formalism by

$$\mathcal{A}_{\rm T,L}^{\gamma^* p\to Vp}(x,Q,\Delta) = i\int \frac{dz}{4\pi} d^2\boldsymbol{r} d^2\boldsymbol{b} (\Psi_{\rm V}^*\Psi)_{\rm T,L} \times e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}]\cdot\Delta} 2\mathcal{N}(x,\boldsymbol{r},\boldsymbol{b}), \tag{2}$$

where $(\Psi_{\rm V}^*\Psi)$ denotes the overlap of wave functions between the photon and the vector meson, and $\Delta = \sqrt{-t}$ is the momentum transfer. The variables z and x are the momentum fraction of the photon carried by quark (an antiquark carries $1-z$) and the momentum fraction of the proton carried by gluon, respectively. Here $\boldsymbol{b}$ is the impact parameter which describes the transverse distance from the center of the target to the dipole, and $\mathcal{N}(x,\boldsymbol{r},\boldsymbol{b})$ is the amplitude for the scattering between dipole and target, which will be discussed in detail later.

The overlap function $(\Psi_{\rm V}^*\Psi)$ in Eq. (2) contains the light-cone wavefunctions of the photon and the vector meson and reads[15]

$$(\Psi_{\rm V}^*\Psi)_{\rm T} = \hat{e}_{\rm f} e \frac{N_{\rm c}}{\pi z(1-z)} \{ m_{\rm f}^2 K_0(\epsilon r)\phi_{\rm T}(r,z) - [z^2+(1-z)^2]\epsilon K_1(\epsilon r)\partial_r\phi_{\rm T}(r,z)\}, \tag{3}$$

$$(\Psi_{\rm V}^*\Psi)_{\rm L} = \hat{e}_{\rm f} e \frac{N_{\rm c}}{\pi} 2Qz(1-z)K_0(\epsilon r) \times \Big[M_{\rm V}\phi_{\rm L}(r,z) + \delta \frac{m_{\rm f}^2 - \nabla_r^2}{M_V z(1-z)}\phi_{\rm L}(r,z)\Big], \tag{4}$$

where $m_{\rm f}$ is the quark mass, $N_{\rm c}=3$, $\hat{e}_{\rm f}=2/3$, $e=\sqrt{4\pi\alpha_{\rm em}}$, $\epsilon^2 = z(1-z)Q^2 + m_{\rm f}^2$ and $\phi_{\rm T,L}(r,z)$ are the scalar functions whose parameterized expressions are available in the literature. Currently, there are several parameterized forms of $\phi_{\rm T,L}(r,z)$,[15] like 'Gauss-LC' and 'boosted Gaussian'. In this study, we shall use the boosted Gaussian expression, which works well for the vector mesons production at both HERA and LHC energies.[23,24] For the charmonium ground state vector meson J/ψ and its first excited state $\psi(2S)$, the scalar functions $\phi_{\rm T,L}(r,z)$, have the following general form[25,26]

$$\phi_{\rm T,L}^{J/\psi}(r,z) = \mathcal{N}_{\rm T,L} z(1-z) \exp\Big(-\frac{m_{\rm f}^2\mathcal{R}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}^2} + \frac{m_{\rm f}^2\mathcal{R}^2}{2}\Big), \tag{5}$$

$$\phi_{\rm T,L}^{\psi(2S)}(r,z) = \mathcal{N}_{\rm T,L} z(1-z) \exp\Big(-\frac{m_{\rm f}^2\mathcal{R}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}^2} + \frac{m_{\rm f}^2\mathcal{R}^2}{2}\Big)\Big[1+\alpha_{2S}\Big(2 + \frac{m_{\rm f}^2\mathcal{R}^2}{4z(1-z)} - \frac{4z(1-z)r^2}{\mathcal{R}^2} - m_{\rm f}^2\mathcal{R}^2\Big)\Big]. \tag{6}$$

The parameters in the above two equations are listed in Table 1.

Table 1. Parameters of the boosted Gaussian scalar functions for J/ψ[15] and $\psi(2S)$.[25] The model parameters $\mathcal{N}_{\rm T}$, $\mathcal{N}_{\rm L}$ and $\mathcal{R}$ are determined by the normalization condition and the decay width.[25] The model parameter α_{2S} is fixed by requiring that the wavefunctions of the ground state and the first excited state can be orthogonal to each other.[26]

Meson	$m_{\rm f}$ (GeV)	$\mathcal{N}_{\rm L}$	$\mathcal{N}_{\rm T}$	$\mathcal{R}^2$ (GeV^2)	α_{2S}
J/ψ	$m_{\rm c}=1.4$	0.575	0.578	2.3	0
$\psi(2S)$	$m_{\rm c}=1.4$	0.67	0.67	3.72	−0.61

We would like to note that the last term in Eq. (2) is the dipole amplitude, which encodes all the information about the dipole–proton scattering. In what follows, we use the bCGC model as the dipole amplitude[15,16]

$$\mathcal{N}(x,\boldsymbol{r},\boldsymbol{b}) = \begin{cases} \mathcal{N}_0 (\frac{rQ_{\rm s}}{2})^{2(\gamma_{\rm s}+\frac{1}{\kappa\lambda Y}\ln\frac{2}{rQ_{\rm s}})}, & rQ_{\rm s}\le 2, \\ 1-e^{-A\ln^2(BrQ_{\rm s})}, & rQ_{\rm s}>2, \end{cases} \tag{7}$$

with

$$Q_{\rm s} = \Big(\frac{x_0}{x}\Big)^{\frac{\lambda}{2}} \Big[\exp\Big(-\frac{b^2}{2B_{\rm CGC}}\Big)\Big]^{\frac{1}{2\gamma_{\rm s}}}, \tag{8}$$

where $Y=\ln(1/x)$ and $\kappa = 9.9$. The coefficients A and B in Eq. (7) are determined uniquely by matching of the two parts of dipole amplitude and their logarithmic derivatives at $rQ_{\rm s}=2$. The value of $B_{\rm CGC}=5.5\,{\rm GeV}^{-2}$ is derived by the t distribution of the exclusive diffractive processes at HERA.[16] There are four free parameters $\mathcal{N}_0$, $\gamma_{\rm s}$, x_0, and λ, whose values can be determined by the fit to the F_2 data.[16]

As we know, the differential cross section given in Eq. (1) is a simplified version, which works well in light vector meson productions, like ρ.[27] In this study, for heavy meson production, the disregarded corrections need to be included in the differential amplitude.[26,28] The first correction comes from the real part of the scattering amplitude $\mathcal{A}_{\rm T,L}$, which is included in the amplitude via a factor $(1+\beta^2)$.[26] The second correction is the skewness effect which is equivalent to multiply Eq. (1) by a factor $R_{\rm g}^2$.[26] After including the above two corrections, the differential cross section becomes

$$\frac{d\sigma_{\rm T,L}^{\gamma^* p\to Vp}}{dt} = \frac{(1+\beta^2)R_{\rm g}^2}{16\pi} \mid \mathcal{A}_{\rm T,L}^{\gamma^* p\to Vp} \mid^2, \tag{9}$$

with

$$\beta = \tan\Big(\frac{\pi\delta}{2}\Big),\ R_{\rm g}(\delta) = \frac{2^{2\delta+3}}{\sqrt{\pi}}\frac{\Gamma(\delta+5/2)}{\Gamma(\delta+4)}, \tag{10}$$

where δ is defined as[16]

$$\delta \equiv \frac{\partial \ln(\mathcal{A}_{\mathrm{T,L}}^{\gamma^* p \to Vp})}{\partial \ln(1/x)}. \tag{11}$$

As we know, the calculation of the factor R_{g} is still an open problem.[16] One should take into account the skewness effect due to the fact that the two gluons carry different fractions of the proton's momentum. Unfortunately, the exact analytical expression of R_{g} is not available in the literature, which is generally regarded as a phenomenological estimation.[29] Therefore, there can be some possible mismatch between the precise and phenomenological values of R_{g}, which leads to some uncertainties in computing the vector meson productions, especially in heavy vector meson productions. As we can see, there are some deviations when one reproduces the $\psi(2S)$ data measured by LHCb collaboration using the above-mentioned skewness correction.[17] Based on these facts, in what follows, we devise a mass-dependent skewness correction which accounts for the mass variation of different vector mesons, for example, J/ψ and $\psi(2S)$. Inspired by the modification of $R_{\mathrm{g}}^2 \to R_{\mathrm{g}}^{2\gamma_{\mathrm{eff}}}$ in Ref. [16], we assume that the mass-dependent skewness correction has the form of $\gamma'_{\mathrm{eff}}(m_{\mathrm{V}})R_{\mathrm{g}}^2$ with

$$\gamma'_{\mathrm{eff}}(m_{\mathrm{V}}) = \frac{\beta'}{\ln(m_{\mathrm{V}}^2)}, \tag{12}$$

where β' can be determined by matching with J/ψ production data at HERA. Note that once the value of β' is fixed at HERA, we will keep the value of β' unchanged when we extend this formulism to describe the J/ψ and $\psi(2S)$ data at LHC.

In the high-energy pp collisions, there are possible events which happen at large impact parameters $b > 2R$ (R is the radius of the proton), usually called UPCs.[30] In UPCs, the total cross section can be factorized into the equivalent photon flux and the photon-target production cross section.[31] Therefore, the cross section for exclusive charmonium photoproduction in a pp collision can be written as[32]

$$\begin{aligned}&\sigma(p_1 + p_2 \to p_1 \otimes V \otimes p_2)\\ &= \int d\omega \frac{dN_{\gamma/p_1}(\omega)}{d\omega}\sigma_{\gamma p_2 \to Vp_2}(W_{\gamma p_2})\\ &\quad + \int d\omega \frac{dN_{\gamma/p_2}(\omega)}{d\omega}\sigma_{\gamma p_1 \to Vp_1}(W_{\gamma p_1}).\end{aligned} \tag{13}$$

Note that the rapidity y of the vector meson is related to the photon energy ω via $y = \ln(2\omega/M_{\mathrm{V}})$. Therefore, the rapidity distribution of the vector meson can be directly computed from Eq. (13) and can be written as

$$\begin{aligned}&\frac{d\sigma[p_1 + p_2 \to p_1 \otimes V \otimes p_2]}{dy}\\ &= \left[\omega \frac{dN_{\gamma/p_1}(\omega)}{d\omega}\sigma_{\gamma p_2 \to Vp_2}(\omega)\right]_{\omega_{\mathrm{L}}}\\ &\quad + \left[\omega \frac{dN_{\gamma/p_2}(\omega)}{d\omega}\sigma_{\gamma p_1 \to Vp_1}(\omega)\right]_{\omega_{\mathrm{R}}},\end{aligned} \tag{14}$$

where the subscripts L and R denote the photon emitting either from projectile proton (left) or from target proton (right), then the photon interacts with the rest proton. This is why we have two terms in Eq. (14). Here $\sigma_{\gamma p_1 \to Vp_1}$ and $\sigma_{\gamma p_2 \to Vp_2}$ are the total photon–proton cross sections. They can be obtained by integrating over t in Eq. (9). The photon–hadron center-of-mass energy squared and the photon energy are given by

$$W^2 = M_{\mathrm{V}}\sqrt{s}\exp(\pm|y|), \quad \omega = \frac{M_{\mathrm{V}}}{2}\exp(\pm|y|), \tag{15}$$

with $\sqrt{s}$ to be the center-of-mass energy of the pp collision system. In Eq. (14), the photon spectrum of a relativistic proton is given by[33]

$$\begin{aligned}\frac{dN_{\gamma/p}(\omega)}{d\omega} &= \frac{\alpha_{\mathrm{em}}}{2\pi\omega}\left[1 + \left(1 - \frac{2\omega}{\sqrt{s}}\right)^2\right]\\ &\quad \times \left(\ln A - \frac{11}{6} + \frac{3}{A} - \frac{3}{2A^2} + \frac{1}{3A^3}\right),\end{aligned} \tag{16}$$

where $A = 1 + [(0.71\,\mathrm{GeV}^2)/Q_{\mathrm{min}}^2]$, and Q_{min}^2 is equal to $(\omega/\gamma_{\mathrm{L}})^2$ at high energy limit.

Now we turn to the case of nucleus–nucleus scattering, it has similar formalism as the pp collisions. However, the dipole–nucleus amplitude is written as[34]

$$\mathcal{N}^A(x, \boldsymbol{r}, \boldsymbol{b}_{\mathrm{A}}) = 1 - \exp\left[-\frac{1}{2}\sigma_{\mathrm{dp}}(x, r)T_{\mathrm{A}}(\boldsymbol{b}_{\mathrm{A}})\right], \tag{17}$$

where the dipole–proton cross section σ_{dp} takes the form

$$\sigma_{\mathrm{dp}} = 2\int d^2\boldsymbol{b}_p \mathcal{N}^p(x, \boldsymbol{r}, \boldsymbol{b}_p), \tag{18}$$

with $\mathcal{N}^p$ given in Eq. (7). The thickness function in Eq. (17) is given by the Glauber model

$$T_{\mathrm{A}}(\boldsymbol{b}) = \int_{-\infty}^{+\infty} dz \rho_{\mathrm{A}}(\sqrt{\boldsymbol{b}^2 + z^2}), \tag{19}$$

where the nucleon distribution in a nucleus $\rho_{\mathrm{A}}(\vec{r})$ is parameterized according to the Woods–Saxon distribution[35]

$$\rho_{\mathrm{A}}(\vec{r}) = \frac{N}{\exp(\frac{(r-R_{\mathrm{A}})}{\delta}) + 1}, \tag{20}$$

with A denoting the number of nucleons in a nucleus, $\delta = 0.54\,\mathrm{fm}$, $R_{\mathrm{A}} = (1.12\,\mathrm{fm})A^{1/3} - (0.86\,\mathrm{fm})A^{-1/3}$ and N adjusting to normalize the distribution to A. For Pb-Pb collisions, $R_{\mathrm{A}} = 6.49\,\mathrm{fm}$ and $N = 0.17\,\mathrm{fm}^{-3}$.

In nucleus–nucleus scattering, the equivalent photon flux becomes[36]

$$\begin{aligned}\frac{dN_{\gamma/A}(\omega)}{d\omega} &= \frac{2Z^2\alpha_{\mathrm{em}}}{\pi\omega}\left[\xi K_0(\xi)K_1(\xi)\right.\\ &\quad \left. - \frac{\xi^2}{2}K_1^2(\xi) - K_0^2(\xi)\right],\end{aligned} \tag{21}$$

with K_0 and K_1 to be the modified Bessel functions of the second kind, and $\xi = 2R_{\mathrm{A}}\omega/\gamma_{\mathrm{L}}$.

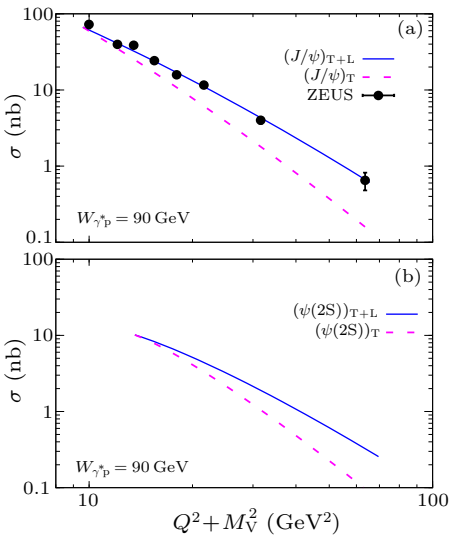

Fig. 1. Total cross section σ for J/ψ and $\psi(2S)$ as a function of $Q^2 + M_V^2$ calculated by the skewness improved CGC model. The solid and the dashed lines represent with and without the longitudinal overlap function, respectively. The J/ψ data are taken from ZEUS.[37]

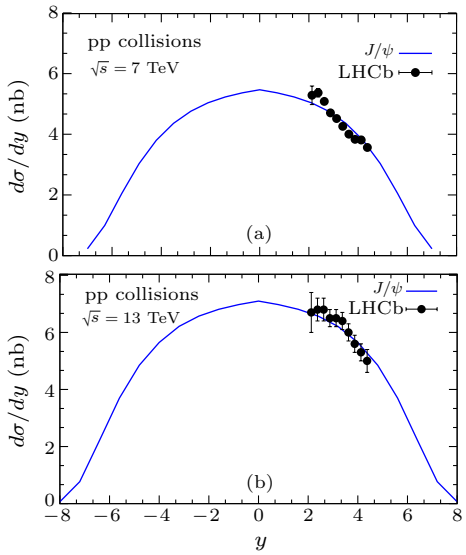

Fig. 2. Rapidity distribution of exclusive J/ψ photo-production in pp collisions at $\sqrt{s} = 7$ TeV (a) and $\sqrt{s} = 13$ TeV (b). The data are taken from LHCb.[9,38]

To fix the parameter in Eq. (12), we let our model confront the J/ψ production data at HERA. In the left panel of Fig. 1, we show the $Q^2 + M_V^2$ dependence of the total J/ψ cross section calculated by our modified bCGC model at a fixed value of $W_{\gamma p} = 90$ GeV. As one can see, our theoretical results are in good agreement with the experimental data by setting $\beta' = 1.93$. The longitudinal contribution is studied for the first time. As can be seen by comparing the curves with and without the longitudinal overlap function, the longitudinal overlap function has a significant effect on vector meson production, especially in the region of larger Q^2, see Fig. 1. In the right panel of Fig. 1, we present the numerical predictions of the total $\psi(2S)$ cross section at the same value of $W_{\gamma p} = 90$ GeV at HERA. One can see that the cross section of $\psi(2S)$ production is smaller than the J/ψ's since its mass is larger than the mass of J/ψ.

We extend the skewness improved CGC model to the UPCs of pp at LHC energies. In these processes, one of the protons can be considered as the source of photon, then the photon interacts with the other proton. Figure 2 gives the theoretical results of the rapidity distribution of the exclusive J/ψ photon-production at $\sqrt{s} = 7$ TeV (a) and $\sqrt{s} = 13$ TeV (b). By comparing the theoretical results with the experimental data from LHCb,[9,38] one can easily see that our results are in good agreement with the experimental data, which indicates that the skewness effect needs to be modified by a vector meson mass-dependent factor.

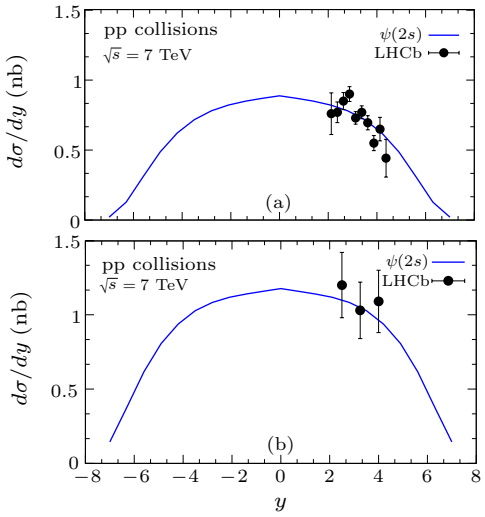

Fig. 3. Rapidity distribution of exclusive $\psi(2S)$ photo-production in pp collisions at $\sqrt{s} = 7$ TeV (a) and $\sqrt{s} = 13$ TeV (b). The data are taken from LHCb.[9,38]

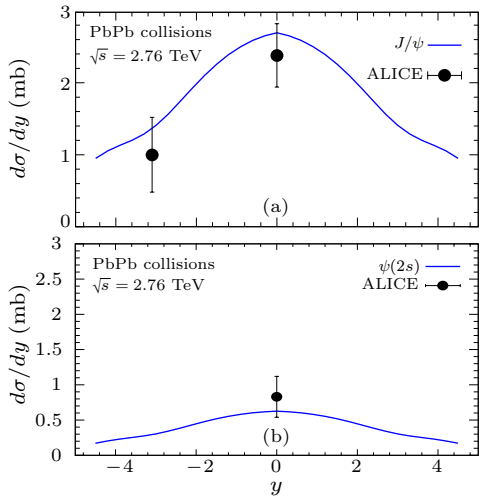

Fig. 4. Rapidity distribution of exclusive J/ψ (a) and $\psi(2S)$ (b) in Pb-Pb collisions at $\sqrt{s} = 2.76$ TeV. The data are taken from ALICE.[39,40]

We use the skewness improved CGC model to compute the rapidity distribution of the exclusive $\psi(2S)$ photo-production in pp collisions at $\sqrt{s} = 7$ TeV (a) and $\sqrt{s} = 13$ TeV (b) in Fig. 3. From Fig. 3, we can see that our results can well describe the LHCb preliminary experimental data.[9] We would like to point out

that the right panel of Fig. 3 gives the CGC vector meson production formulism to confront with pp data at $\sqrt{s} = 13\,\text{TeV}$ for the first time. Note that if the skewness effect is not modified by including vector meson's mass, there is a deviation between the theoretical calculations and the experimental data, see Ref. [17].

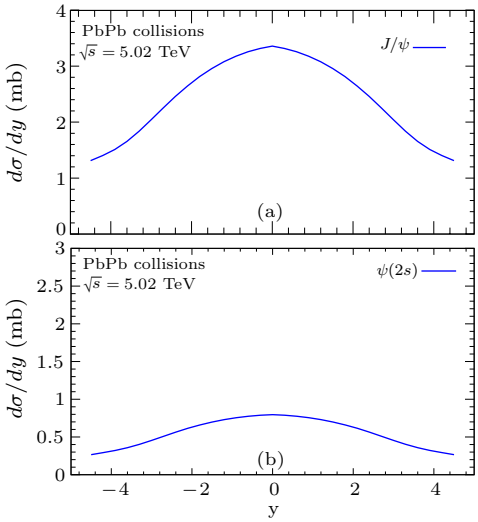

Fig. 5. Predictions of rapidity distribution of exclusive J/ψ (a) and $\psi(2S)$ (b) in Pb-Pb collisions at $\sqrt{s} = 5.02\,\text{TeV}$.

It is known that the ultra-peripheral nucleus–nucleus collisions have attracted growing interest recently due to some compelling topics, such as nuclear structure functions and gluon shadowing. The ultra-peripheral nucleus–nucleus collisions offer an effective way to understand the vector meson production, and to test effectiveness of the CGC theory. Therefore, we give the theoretical results of the rapidity distribution of the exclusive J/ψ (a) and $\psi(2S)$ (b) photo-production in ultra-peripheral Pb-Pb collisions at $\sqrt{s} = 2.76\,\text{TeV}$ in Fig. 4. The significance of the vector meson mass modified skewness factor can be seen from the matchings of the theoretical results computed by our model with the vector meson production experimental data in Figs. 1–4 at both HERA and LHC energies. To see the agreement between our theoretical model and experimental data, we calculate χ^2, the relevant results are listed in Table 2. Note that there are 36 data points in Figs. 2–4 and the corresponding χ^2/d.o.f. is 0.94, which indicates that our model gives a good description for vector-meson production. Furthermore, we give the predictions of the rapidity distribution of the exclusive J/ψ (a) and $\psi(2S)$ (b) in ultra-peripheral Pb-Pb collisions at $\sqrt{s} = 5.02\,\text{TeV}$ in Fig. 5.

Table 2. The parameters β' and χ^2/d.o.f. of the exclusive charmonium photo-production.

β'	Total points	χ^2/d.o.f.
1.93	36	0.94

In summary, we have investigated the exclusive charmonium photo-production at HERA and LHC with the CGC dipole picture by including a vector meson mass dependent factor into the skewness effect. We have computed the $Q^2 + M_{\text{V}}^2$ dependence of the total cross section for γp scattering at HERA and the rapidity distribution of the pp and Pb-Pb collisions at LHC. All of the theoretical results seem to match with the experimental data, which indicate that the vector meson mass modified skewness factor is significant. In this study we give a prediction of the exclusive J/ψ and $\psi(2S)$ in ultra-peripheral Pb-Pb collisions at $\sqrt{s} = 5.02\,\text{TeV}$, which would be measured in the near future at LHC. Throughout this work the dipole amplitude is within the leading order approximation, the next-to-leading order effect can dramatically affect the dipole amplitude,[41–46] and we will include the next-to-leading order effect into the charmonium photo-production at HERA and LHC energies in our next work.

References

[1] Ryskin M G 1993 *Z. Phys.* C **57** 89
[2] Rezaeian A H et al 2013 *Phys. Rev.* D **87** 034002
[3] Motyka L and Watt G 2008 *Phys. Rev.* D **78** 014023
[4] Cisek A et al 2009 *J. High Energy Phys.* **0904** 159
[5] Aktas A et al (H1 Collaboration) 2006 *Eur. Phys. J.* C **46** 585
[6] Adloff C et al (H1 Collaboration) 2002 *Phys. Lett.* B **541** 251
[7] Chekanov S et al (ZEUS Collaboration) 2002 *Eur. Phys. J.* C **24** 345
[8] Aaij R et al (LHCb collaboration) 2013 *J. Phys.* G **40** 045001
[9] Aaij R et al (LHCb collaboration) 2016 *LHCb reports* LHCb-CONF-2016-007
[10] Bodwin G T et al 1995 *Phys. Rev.* D **51** 1125
[11] Nayak G C et al 2005 *Phys. Lett.* B **613** 45
[12] Hagler P et al 2001 *Phys. Rev. Lett.* **86** 1446
[13] Baranov S P and Szczurek A 2008 *Phys. Rev.* D **77** 054016
[14] Fu Q and Chen X R 2016 arXiv:1612.01679[hep-ph]
[15] Kowalski H et al 2006 *Phys. Rev.* D **74** 074016
[16] Rezaeian A H and Schmidt I 2013 *Phys. Rev.* D **88** 074016
[17] Goncalve V P et al 2016 *Eur. Phys. J.* C **76** 97
[18] Goncalve V P et al 2008 *Phys. Rev.* D **77** 054011
[19] Xiang W C et al 2017 *Phys. Rev.* D **95** 116009
[20] Wu Q D et al 2016 *Chin. Phys. Lett.* **33** 012502
[21] Xiang W C et al 2009 *Chin. Phys.* C **32** 98
[22] Hu Y Y et al 2015 *Eur. Phys. J.* A **51** 159
[23] Forshaw J R et al 2006 *J. High Energy Phys.* **0611** 025
[24] Forshaw J R et al 2004 *Phys. Rev.* D **69** 094013
[25] Armesto N and Rezaeian A H 2014 *Phys. Rev.* D **90** 054003
[26] Cox B E et al 2009 *J. High Energy Phys.* **0906** 034
[27] Munier S et al 2001 *Nucl. Phys.* B **603** 427
[28] Shuvaev A G et al 1999 *Phys. Rev.* D **60** 014015
[29] Rezaeian A H et al 2013 arXiv:1307.0165[hep-ph]
[30] Bertulani C A et al 2005 *Rev. Nucl. Part. Sci.* B **55** 271
[31] Goncalves V P et al 2015 *Phys. Lett.* B **742** 172
[32] Klein S R and Nystrand J 2004 *Phys. Rev. Lett.* **92** 142003
[33] Drees M and Zeppenfeld D 1989 *Phys. Rev.* D **39** 2536
[34] Goncalves V P and Machado M V T 2003 *Eur. Phys. J.* C **30** 387
[35] Kowalski H and Teaney D 2003 *Phys. Rev.* D **68** 114005
[36] Papageorgiu E 1990 *Phys. Lett.* B **250** 155
[37] Chekanov S et al (ZEUS collaboration) 2004 *Nucl. Phys.* B **695** 3
[38] Aaij R et al (LHCb collaboration) 2014 *J. Phys.* G **41** 055002
[39] Abbas E et al (ALICE collaboration) 2013 *Eur. Phys. J.* C **73** 2617
[40] Abelev B et al (ALICE collaboration) 2013 *Phys. Lett.* B **718** 1273
[41] Xiang W C 2009 *Phys. Rev.* D **79** 014012
[42] Xiang W C 2010 *Phys. Rev.* D **81** 094004
[43] Ducloue B et al 2016 *Phys. Rev.* D **94** 074031
[44] Mantysaari H and Lappi T 2016 *Phys. Rev.* D **93** 094004
[45] Xiang W C et al 2013 *Chin. Phys. Lett.* **30** 082501
[46] Xiang W C et al 2016 *Chin. Phys. Lett.* **33** 082501