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DIFFRACTIVE PHOTOPRODUCTION OF $\psi(2S)$ IN PHOTON-POMERON REACTIONS IN PbPb COLLISIONS AT THE CERN LHC

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ABSTRACT

This work investigates the exclusive photoproduction of $\psi(2S)$ meson off nuclei evaluating the coherent and the incoherent contributions. The theoretical framework used in the present analysis is the light-cone dipole formalism and predictions are done for PbPb collisions at the CERN-LHC energy of 2.76 TeV. A comparison is done to the recent ALICE Collaboration data for the $\psi(1S)$ state photoproduction.

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1 Introduction

The vector meson photoproduction is sensitive to the environment and yields new information about the dynamics of hard processes. This process provides crucial constraints on properties of the QCD Pomeron and the vector meson wave functions and is expected to probe the nuclear gluon-distribution. The sufficiently large mass of quarkonium states gives the perturbative scale. The scattering process is characterized by the color dipole cross section representing the interaction of those color dipoles with the target (protons or nuclei). The dipole cross section evolution at small Bjorken-x is given by the solution of a non-linear evolution equation. Dipole sizes of magnitude $r \sim 1/\sqrt{m_V^2 + Q^2}$ (m_V is the vector meson mass) are probed by the $1S$ vector meson production amplitude [1]. The production amplitude of radially excited vector mesons $2S$ is suppressed compared with the $1S$ state due to the node effect [2]. Which means a strong cancellation of the dipole size contributions to the production amplitude from the region above, and below the node position in the $2S$ radial wavefunction [3]. The ratio $\sigma(\psi')/\sigma(\psi) \simeq 0.2$ at DESY-HERA energies at $Q^2 = 0$ and the ratio is a Q^2-dependent quantity as the electroproduction cross sections are considered [4]. The combination of the energy dependence of the dipole cross section, and the node of the radial wavefunction of $2S$ states lead to an anomalous Q^2 and energy dependence of diffractive production of $2S$ vector mesons [6]. Such anomaly appears also in the t-dependence of the differential cross section of radially excited $2S$ light vector mesons [7], which is in contradiction with the usual monotonical behavior of the corresponding $1S$ states.
This paper, focuses on the photoproduction of radially excited vector mesons off nuclei in heavy ion relativistic collisions, analysing the exclusive photoproduction of ψ' off nuclei, $\gamma A \to \psi(2S)X$, where for the coherent scattering one has $X = A$, whereas for the incoherent case $X = A^*$ with A^* being an excited state of the A-nucleon system. The light-cone dipole formalism is considered. In such framework, the $c\bar{c}$ fluctuation of the incoming quasi-real photon interacts with the nucleus target through the dipole cross section and the result is projected on the wavefunction of the observed hadron. In the high energy regime, the dipole cross section depends on the gluon distribution in the target and nuclear shadowing of the gluon distribution is expected to reduce it compared to a proton target.

The ALICE Collaboration opens the possibility to investigate small-x physics with heavy nuclei through measures of the diffractive $\psi(1S)$ vector meson production at a relatively large rapidity $y \simeq 3$ [8] and central rapidities [9] as well in the $\sqrt{s} = 2.76$ TeV run. The incoherent $\psi(1S)$ cross section has been also measured [9]. For nuclear targets, the saturation is enhanced i.e. $Q_{\rm sat} \propto A^{1/3}$. The LHCb Collaboration has also measured the cross section in proton-proton collisions at $\sqrt{s} = 7$ TeV of exclusive dimuon final states, including the $\psi(2S)$ state [10]. The ratio at forward rapidity $2.0 \leq \eta_{\mu^\pm} \leq 4.5$ in that case is $\sigma(\psi(2S))/\sigma(\psi(1S)) = 0.19 \pm 0.04$, which is still consistent to the color dipole approach formalism. Therefore it is interesting to investigate the photoproduction of $\psi(2S)$ in PbPb collisions at the LHC.

2 Photon-pomeron process in relativistic AA collisions

At large impact parameter and at ultra relativistic energies nucleus-nucleus collisions are dominated by electromagnetic interaction. In heavy ion colliders, the heavy nuclei give rise to strong electromagnetic fields due to the coherent action of all protons in the nucleus, which can interact with each other. Consequently, the total cross section for a given process can be factorized in terms of the equivalent flux of photons of the hadron projectile and the photon-photon or photon-target production cross section [11]. For the photoproduction of radially excited vector mesons, photon-hadron processes are relevant. Considering that the photoproduction is not accompanied by hadronic interaction an analytic expression for the equivalent photon flux of a nuclei can be calculated [11] $\frac{dN_\gamma(\omega)}{d\omega} = \frac{2\,Z^2 \alpha_{em}}{\pi\,\omega}\,\left[\xi_R^{AA}\,K_0\,(\xi_R^{AA})\,K_1\,(\xi_R^{AA}) - \frac{(\xi_R^{AA})^2}{2}\,K_1^2\,(\xi_R^{AA}) - K_0^2\,(\xi_R^{AA})\right]$. where ω is the photon energy, γ_L is the Lorentz boost of a single beam and $K_0(\xi)$ and $K_1(\xi)$ are the modified Bessel functions. Considering symmetric nuclei having radius R_A, one has $\xi_R^{AA} = 2R_A\omega/\gamma_L$.

Using the relation with the photon energy ω, i.e. $y \propto \ln(2\omega/m_X)$, the rapidity distribution y for quarkonium photoproduction in nucleus-nucleus collisions can be also computed. Explicitly, the rapidity distribution is written down as, $\frac{d\sigma\,[AA \to A \otimes \psi(2S) \otimes X]}{dy} = \omega \frac{dN_\gamma(\omega)}{d\omega}\,\sigma_{\gamma A \to \psi(2S)X}\,(\omega)$, where $\otimes$ represents the presence of a rapidity gap. Consequently, given the photon flux, the rapidity distribution is thus a direct measure of the photoproduction cross section for a given energy.

In the light-cone dipole frame most of the energy is carried by the hadron, while the photon has just enough energy to dissociate into a quark-antiquark pair before the scattering. In this representation the probing projectile fluctuates into a quark-antiquark pair (a dipole) with transverse separation r long after the interaction, which then scatters off the hadron [1]. In this picture the amplitude for vector meson production off nucleons reads as (See e.g. Refs. [1, 12]) $\mathcal{A}\,(x, Q^2, \Delta) = \sum_{h,\bar{h}} \int dz\, d^2r\, \Psi^{\gamma}_{h,\bar{h}}\, \mathcal{A}_{q\bar{q}}\, \Psi^{V*}_{h,\bar{h}}$, where $\Psi^{\gamma}_{h,\bar{h}}(z,\, r, Q^2)$ and $\Psi^{V}_{h,\bar{h}}(z,\, r)$ are the light-cone wavefunctions of the photon and of the vector meson, respectively, h and $\bar{h}$ are the quark and antiquark helicities, r defines the relative transverse separation of the pair (dipole), z $(1-z)$ is the longitudinal momentum fractions of the quark (antiquark), Δ denotes the transverse momentum lost by the outgoing proton ($t = -\Delta^2$) and x is the Bjorken variable.

The predictions presented here take into account the corrections due to skewedness effect (off-diagonal gluon exchange) and real part of amplitude. Detail on the model dependence on these corrections can be found for instance in Ref. [13].

The photon wavefunctions are relatively well known [12]. For the meson wave function the boosted gaussian wavefunction was considered [14].

The boosted gaussian wavefunction considered here is a simplification of the NNPZ wavefunction presented in Refs. [1, 2]. It has been compared to recent analysis of DESY-HERA data for vector meson exclusive processes [14],[15]. The node effect plays an important role in the description of the measured ratio $\sigma(\psi')/\sigma(J/\psi)$ in the photoproduction case. Such a ratio is sensitive to the time-scale of the production process. In the dipole approach the interactions occur during the period where the color dipole is compact having a transverse size $r \simeq 1/m_q$ and the production cross section is proportional to the square of the quarkonium wavefunction at origin, $\sigma \propto |\phi(0)|^2$. On the other hand, further interactions depend on the wavefunction profile for transverse sizes larger than $r_B = \mathcal{O}(1/\alpha_s m_q)$, the Bohr radius. In exclusive charmonia electroproduction at relatively large Q^2 the dipole size is of order $1/Q^2 \ll r_B$ and the cross section is predicted to be proportional to $|\phi_n(0)|^2$. This leads the ratio to be of order $|\phi_{2S}(0)|^2/|\phi_{1S}(0)|^2 \simeq 0.6$ at large Q^2 whereas the measured value in photoproduction is around 0.16 [4]. The moderate value of charm mass and the dominant color transparency behavior of dipole cross section $\sigma_{dip} \propto r^2$ imply the amplitude to probe the meson wavefunction at a transverse size around r_B [1, 2]. So, the node effect reduces the $\psi(2S)$ contribution and the DESY-HERA ratio is correctly described. At $Q^2 \to 0$ the leading logarithmic approximation $rl_{\perp} \ll 1$, which gives the usual $\sigma_{dip} \propto r^2$, is not able to provide alone the correct value for the ratio ψ'/ψ [5]. Here, $l_{\perp}$ is the exchanged gluon transverse momentum in a two-gluon exchange model. Therefore, important contributions come from the overlap of the large-sized color dipole configurations and the $\psi(2S)$ wavefunction. Thus, despite the leading logarithmic approximation to be able to describe the J/ψ production cross section the same is not true for the excited states as the ψ'. For this reason it was used a dipole cross section model that takes into account the correct behavior for large dipole configurations (the transition hard-soft is given by the saturation scale).

The exclusive $\psi(2S)$ photoproduction off nuclei for coherent and incoherent processes can be simply computed in high energies where the large coherence length $l_c \gg R_A$ is fairly valid. In such case the transverse size of $c\bar{c}$ dipole is frozen by Lorentz effects. The expressions for the coherent and incoherent cross sections are given by [16],

$$\sigma^{\gamma A}_{coh} = \int d^2b\, |\langle \Psi^V| 1 - \exp\left[-\frac{1}{2}\sigma_{dip}(x,r) T_A(b)\right] |\Psi^{\gamma}\rangle|^2, \quad (1)$$

$$\sigma^{\gamma A}_{inc} = \frac{1}{16\pi\, B_V(s)} \int d^2b\, T_A(b) \times |\langle \Psi^V| \sigma_{dip}(x,r) \exp\left[-\frac{1}{2}\sigma_{dip}(x,r) T_A(b)\right] |\Psi^{\gamma}\rangle|^2. \quad (2)$$

where $T_A(b) = \int dz \rho_A(b,z)$ is the nuclear thickness function given by integration of nuclear density along the trajectory at a given impact parameter b. In addition, B_V is the diffractive slope parameter in the reaction $\gamma^* p \to \psi p$. Here, we consider the energy dependence of the slope using the Regge motivated expression $B_V(W_{\gamma p}) = b^V_{el} + 2\alpha' \log \frac{W^2_{\gamma p}}{W_0^2}$ with $\alpha' = 0.25$ GeV^{-2} and $W_0 = 95$ GeV. It is used the measured slopes [4] for $\psi(1S)$ and $\psi(2S)$ at $W_{\gamma p} = 90$ GeV, i.e. $b^{\psi(1S)}_{el} = 4.99 \pm 0.41$ GeV^{-2} and $b^{\psi(2S)}_{el} = 4.31 \pm 0.73$ GeV^{-2}, respectively.

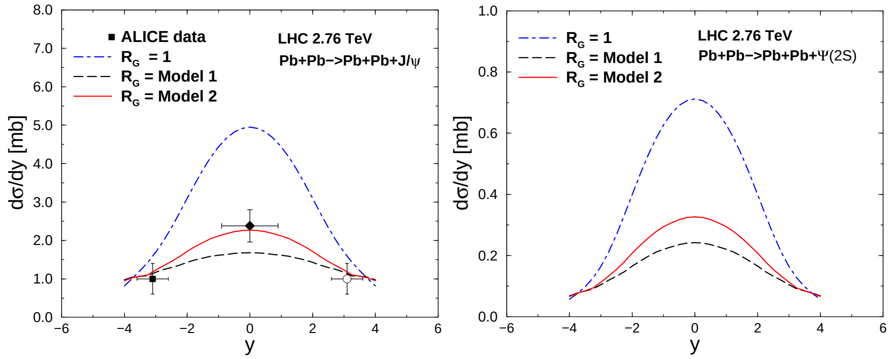

Figure 1: (Color online) *The rapidity distribution of coherent $\psi(1S)$ meson photoproduction at $\sqrt{s} = 2.76$ TeV in PbPb collisions at the LHC [20]. The theoretical curves stand for color dipole formalism using $R_G = 1$ (dot-dashed curve) and two scenarios for the nuclear gluon distribution (solid and long-dashed curves, see text). Data from ALICE collaboration [8, 9].*

For the dipole cross section was considered the Color Glass Condensate model [17] for $\sigma_{dip}(x,r)$. This model has been tested for a long period against DIS, diffractive DIS and exclusive production processes in *ep* collisions. Corrections due to gluons shadowing were also considered as the gluon density in nuclei at small-x region is known to be suppressed compared to a free nucleon. That is, we will take $\sigma_{dip} \to R_G(x, Q^2, b)\sigma_{dip}$ following studies in Ref. [18]. The factor R_G is the nuclear gluon density ratio. In the present investigation we will use the nuclear ratio from the leading twist theory of nuclear shadowing based on generalization of the Gribov-Glauber multiple scattering formalism as investigated in Ref. [19]. We used the two models available for $R_G(x, Q^2)$ in [19], Models 1 and 2, which correspond to higher nuclear shadowing and lower nuclear shadowing, respectively.

3 Results and discussions

The Fig. 1 (left) presents the numerical calculations for the rapidity distribution of coherent $\psi(1S)$ state within the color dipole formalism, Eqs. (2) and (1), using distinct scenarios for the nuclear gluon shadowing [20]. The dot-dashed curve represents the result using $R_G = 1$ and it is consistent with previous calculations using the same formalism [13]. The ALICE data is overestimated on the backward (forward) and mainly in central rapidities. The threshold factor for $x \to 1$ was not included in the present calculation, so the overestimation in the backward/forward rapidity case, is already expected. In that kinematical region either a small-x photon scatters off a large-x gluon or vice-versa. For instance, for $y \simeq \pm 3$ one gets x large as 0.02. On the other hand, for central rapidity $y = 0$ one can be obtained $x = M_V e^{\pm y}/\sqrt{s_{\rm NN}}$ smaller than 10^{-3} for the nuclear gluon distribution. The ALICE data [9] is overestimated by a factor 2 considering $R_G = 1$, as already noticed in the recent study of Ref. [21]. If we consider nuclear shadowing renormalizing the dipole cross section, the situation is improved due to the gluon density in nuclei at small Bjorken x is expected to be suppressed compared to a free nucleon due to interferences. For the ratio of the gluon density, $R_G(x, Q^2 = m_V^2/4)$, we have considered the theoretical evaluation of Ref. [19]. There, two scenarios for the gluon shadowing are investigated: Model 1 corresponds to a strong gluon shadowing and Model 2 concerns to small nuclear shadowing. The consequence of renormalizing the dipole cross section by gluon shadowing effects is represented by the long-dashed (Model 1) and solid (Model 2) lines, respectively. In the current analysis, the small shadowing option is preferred . The theoretical uncertainty related to the choice of meson wavefunction is relatively large. As a prediction at central rapidity, one obtains $\frac{d\sigma}{dy}(y = 0) = 4.95$, 1.68 and 2.27 mb for calculation using $R_G = 1$, Model 1 and Model 2, respectively. R_G was considered as independent on the impact parameter. It is known long time ago that a b-dependent ratio could give a smaller suppression compared to our calculation. For instance, in Ref. [18] the suppression is of order 0.85 for the LHC energy and central rapidity.

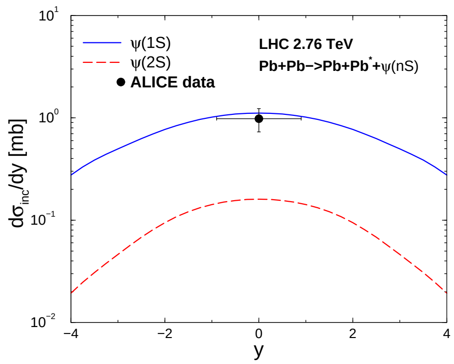

Figure 2: (Color online) *The rapidity distribution of incoherent $\psi(1S)$ (solid line) and $\psi(2S)$ (dashed line) meson photoproduction at $\sqrt{s} = 2.76$ TeV in PbPb collisions at the LHC [20]. Data from ALICE collaboration [9].*

The Fig. 2 (right) shows the first estimate in literature for the coherent photoproduction of $\psi(2S)$ state in nucleus-nucleus collisions [20]. The theoretical predictions follow the general trend as for the $1S$ state, where the notation for the curves are the same as used in Fig. 1 (left). In particular, for $R_G = 1$ one obtains for central rapidity $\frac{d\sigma}{dy}(y=0) = 0.71$ mb and the following in the forward/backward region $\frac{d\sigma}{dy}(y=\pm 3) = 0.16$ mb. When introducing the suppression in the dipole cross section due nuclear shadowing one gets instead $\frac{d\sigma}{dy}(y=0) = 0.24$ mb and 0.33 mb for Model 1 and Model 2, respectively. At central rapidities, the meson state ratio is evaluated to be $R_{\psi}^{y=0} = \frac{\sigma_{\psi(2S)}}{dy} / \frac{d\sigma_{\psi(1S)}}{dy}(y=0) = 0.14$ in case $R_G = 1$ which is consistent with the ratio measured in CDF, i.e. 0.14 ± 0.05, on the observation of exclusive charmonium production at 1.96 TeV in $p\overline{p}$ collisions [22]. A similar ratio is obtained using Model 1 and Model 2 at central rapidity as well. As a prediction for the planned LHC run in PbPb mode at 5.5 TeV, we obtain $\frac{d\sigma_{coh}}{dy}(y=0) = 1.27$ mb and $\frac{d\sigma_{inc}}{dy}(y=0) = 0.27$ mb for the coherent and incoherent $\psi(2S)$ cross sections (upper bound using $R_G = 1$), respectively.

The Fig. 3 presents the incoherent contribution to the rapidity distribution for both $\psi(1S)$ (solid line) and $\psi(2S)$ (dashed line) meson states [20]. For the $\psi(1S)$ state, the present calculation can be directly compared with those studies presented in Ref. [21]. The incoherent cross section $\frac{d\sigma_{\rm inc}}{dy}$ ranges between 0.5 to 0.7 mb (using IIM dipole cross section) or between 0.7 to 0.9 mb (using fIPsat dipole cross section) at central rapidities, with the uncertainty determined by the distinct meson wavefunction considered [21]. Here, was obtained $\frac{d\sigma_{\rm inc}}{dy}(y=0) = 1.1$ mb using a different expression for the incoherent amplitude, Eq. (2). This result describes the recent ALICE data [9] for the incoherent cross section at mid-rapidity, $\frac{d\sigma_{inc}^{\rm ALICE}}{dy}(-0.9 < y < 0.9) = 0.98 \pm 0.25$ mb. For the $\psi(2S)$ state, was found $\frac{d\sigma_{\rm inc}}{dy} = 0.16$ mb for central rapidities. In both cases was only computed the case for $R_G = 1$. Therefore, this gives an upper bound for the incoherent cross section compared to Model 1 and Model 2 calculation. For the incoherent case, the gluon shadowing is weaker than the coherent case and the reduction is around 20 % compared to the case $R_G = 1$. The incoherent piece is quite smaller compared to the main coherent contribution. As an example of order of magnitude, the ratio incoherent/coherent is a factor 0.22 for the $1S$ state and 0.23 for the $2S$ state at central rapidity.

4 Conclusions

The photoproduction of radially excited vector mesons was investigated in heavy ion relativistic collisions as the $\psi(2S)$ charmonium state using the light-cone dipole formalism. Predictions are done for PbPb collisions at the CERN-LHC energy of 2.76 TeV. The fact that the gluons shadowing suppresses the dipole cross section was studied and the results for $R_G = 1$ gives the larger cross sections. The coherent exclusive photoproduction of $\psi(2S)$ off nuclei has an upper bound of order 0.71 mb at $y = 0$ down to 0.10 mb for backward/forward rapidities $y = \pm 3$. The incoherent contribution was also computed and it is a factor 0.2 below the coherent one. A small nuclear shadowing $R_G(x, Q^2 = \frac{m_V^2}{4})$ is preferred in ALICE data description whereas the usual $R_G = 1$ value overestimates the central rapidity cross section by a factor 2 for the $\psi(1S)$ state photoproduction. For incoherent cross section, the present theoretical approach describes the ALICE data. Thus, the central rapidity data measured by ALICE Collaboration for the rapidity distribution of the $\psi(1S)$ state is crucial to constrain the nuclear gluon function. The cross section for exclusive quarkonium production is proportional to $[\alpha(Q^2)xg_A(x, Q^2)]^2$ in the leading-order pQCD calculations, evaluated at the relevant scale $Q^2 \approx m_V^2/4$ and at momentum fraction $x \simeq 10^{-3}$ in central rapidities. The theoretical uncertainty is large and it has been investigated in several studies [23, 24]. Along these line, the authors of Ref. [25] extract the nuclear suppression factor, $S(x \approx 10^{-3}) = 0.61 \pm 0.064$, using the ALICE data on coherent $\psi(1S)$ and considering the nuclear gluon shadowing predicted by nuclear pdf's and by leading twist nuclear shadowing.

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