Exclusive photoproduction of quarkonium at the LHC energies within the color dipole approach

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Abstract. The exclusive photoproduction of $\psi(2S)$ meson was investigated and the coherent and the incoherent contributions were evaluated. The light-cone dipole formalism was considered in this analysis 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 with good agreement.

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INTRODUCTION

The exclusive vector meson photoproduction allows to test perturbative Quantum Chromodynamics and it is expected to probe the nuclear gluon-distribution. The perturbative scale is given by the large mass of quarkonium components and the scattering process is characterized by the color dipole cross section representing the interaction of those color dipoles with the target. 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 $2S$ excited vector mesons amplitude is suppressed compared with the $1S$ state due to the node effect [2]. The ratio $\sigma(\psi(2S))/\sigma(\psi(1S)) \simeq 0.2$ at DESY-HERA energies at $Q^2 = 0$ and the ratio is a Q^2-dependent quantity as the electroproduction cross sections are considered [3]. The node of the radial wavefunction of $2S$ states and the energy dependence of the dipole cross section, lead to an anomalous Q^2 and energy dependence of diffractive production of $2S$ vector mesons [4]. That appears also in the t-dependence of the differential cross section of radially excited $2S$ light vector mesons [5], which is in contradiction with the usual monotonical behavior of the corresponding $1S$ states.

This paper, focuses on the $\psi(2S)$ exclusive photoproduction in heavy ion relativistic collisions, $\gamma A \to \psi(2S)X$, 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. Corrections due to the gluon shadowing was considered, suppressing the rapidity distribution.

The ALICE Collaboration measures of the diffractive $\psi(1S)$ vector meson production [6, 7] opens the possibility to investigate small-x physics with heavy nuclei. 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 [8]. 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, investigate the photoproduction of $\psi(2S)$ in PbPb collisions at the LHC can give information about the pomeron and the supression of the 2S state in relation to the 1S state.

PHOTON-POMERON PROCESS IN RELATIVISTIC AA COLLISIONS

The nucleus-nucleus collisions are dominated by electromagnetic interaction at large impact parameter and at ultra relativistic energies. 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. Thus, the total cross section can

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be factorized in terms of the equivalent flux of photons ($\frac{dN_\gamma(\omega)}{d\omega}$) of the hadron projectile and the photon-photon or photon-target production cross section [9] excluding the hadronic interaction.

From the relationship 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 written 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. Thus, the rapidity distribution is a direct measure of the photoproduction cross section for a given energy.

In the light-cone dipole frame 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, 10]) $\mathscr{A}(x,Q^2,\Delta) = \sum_{h,\bar{h}}\int dz d^2r \Psi^{\gamma}_{h,\bar{h}}\mathscr{A}_{q\bar{q}}\Psi^{V*}_{h,\bar{h}}$, 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 corrections due to skewedness effect and real part of amplitude was considered [11]. The photon wavefunctions are relatively well known [10]. For the meson wave function the boosted gaussian wavefunction was considered [12]. 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. The coherent and incoherent cross sections are given by [13],

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

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

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 [3] for $\psi(1S)$ and $\psi(2S)$ at $W_{\gamma p} = 90$ GeV, i.e. $b^{\psi(1S)}_{el} = 4.99\pm0.41$ GeV^{-2} and $b^{\psi(2S)}_{el} = 4.31\pm0.73$ GeV^{-2}, respectively.

For the dipole cross section was considered the Color Glass Condensate model [14] 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. [15]. 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. [16]. We used the two models available for $R_G(x,Q^2)$ in [16], Models 1 and 2, which correspond to higher nuclear shadowing and lower nuclear shadowing, respectively.

RESULTS AND DISCUSSIONS

The left panel of Fig. 1 presents the rapidity distribution of coherent $\psi(1S)$ state within the color dipole formalism, using distinct scenarios for the nuclear gluon shadowing [17]. The dot-dashed curve represents the result using $R_G = 1$ and it is consistent with previous calculations using the same formalism [11]. The ALICE data is overestimated on the backward (forward) and mainly in central rapidities. The overestimation in the backward/forward rapidity case is due to the threshold factor for $x\to1$ was not included in the present calculation. In that kinematical region either a small-x photon scatters off a large-x gluon or vice-versa. For instance, for $y\simeq\pm3$ 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. For $R_G=1$ the ALICE data [7] is overestimated by a factor two, as already noticed in the recent study of Ref. [18]. Considering the ratio of the gluon density, $R_G(x,Q^2=m_V^2/4)$ [16], the situation is improved. The long-dashed (Fig.1) represents Model 1 which corresponds to a strong gluon shadowing and the solid line concerns to small nuclear shadowing. In this analysis, the small shadowing option is preferred . The theoretical uncertainty related to the choice of meson wavefunction is relatively large. The values $\frac{d\sigma}{dy}(y=0) = 4.95$, 1.68 and 2.27 mb were obtained for central rapidity for calculation using $R_G=1$, Model 1 and Model 2, respectively. R_G was considered as independent

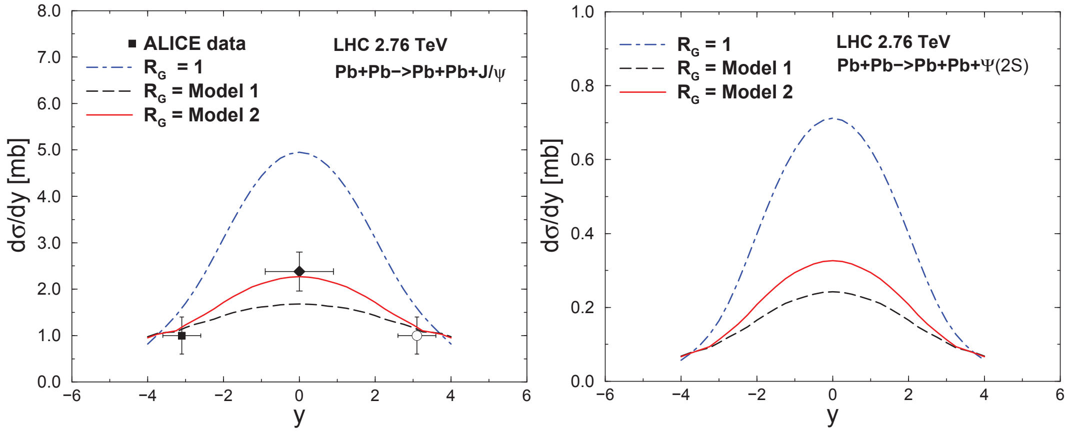

FIGURE 1. (Color online) The rapidity distribution of coherent $\psi(1S)$ meson photoproduction at $\sqrt{s} = 2.76$ TeV in PbPb collisions at the LHC [17]. The theoretical curves stand for color dipole formalism using $R_G = 1$ (dot-dashed curve) and two scenarios for the nuclear gluon distribution (solid and long-dashed curves, see text). Data from ALICE collaboration [6, 7].

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. [15] the suppression is of order 0.85 for the LHC energy and central rapidity.

The right panel of Fig. 1 shows the first estimate of $\psi(2S)$ coherent photoproduction in nucleus-nucleus collisions [17]. 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). For $R_G = 1$ one obtains $\frac{d\sigma}{dy}(y=0) = 0.71$ mb for central rapidity and $\frac{d\sigma}{dy}(y=\pm 3) = 0.16$ mb for the forward/backward region. When the nuclear shadowing suppression was considered in the dipole cross section, one gets $\frac{d\sigma}{dy}(y=0) = 0.24$ mb and 0.33 mb for Model 1 and Model 2, respectively. At central rapidities, the meson state ratio gives $R_{\psi}^{y=0} = \frac{\sigma_{\psi(2S)}}{dy} / \frac{d\sigma_{\psi(1S)}}{dy}(y=0) = 0.14$ 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 $p\bar{p}$ collisions [19]. A similar ratio is obtained using Model 1 and Model 2 at central rapidity as well. For the planned LHC run in PbPb mode at 5.5 TeV, the predictions are $\frac{d\sigma_{coh}}{dy}(y=0) = 1.27$ 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 incoherent contributions to the rapidity distribution for $\psi(1S)$ and $\psi(2S)$ are presented in the Fig. 2 [17], solid and dashed line, respectively. For the $\psi(1S)$ state, the present calculation can be directly compared with those studies presented in Ref. [18]. The incoherent cross section $\frac{d\sigma_{\text{inc}}}{dy}$ 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 [18]. Here, was obtained $\frac{d\sigma_{\text{inc}}}{dy}(y=0) = 1.1$ mb using a different expression for the incoherent amplitude, Eq. (2). The result of 1S state describes the recent ALICE data [7] for the incoherent cross section at mid-rapidity, $\frac{d\sigma_{inc}^{\text{ALICE}}}{dy}(-0.9 < y < 0.9) = 0.98 \pm 0.25$ mb. For the $\psi(2S)$ state, was found $\frac{d\sigma_{\text{inc}}}{dy} = 0.16$ 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.

CONCLUSIONS

The $\psi(2S)$ photoproduction was investigated in PbPb collisions at LHC energies using the light-cone dipole formalism. The suppression due to the gluon shadowing was also investigated and 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 two for the $\psi(1S)$ state photoproduction. The coherent exclusive photoproduction

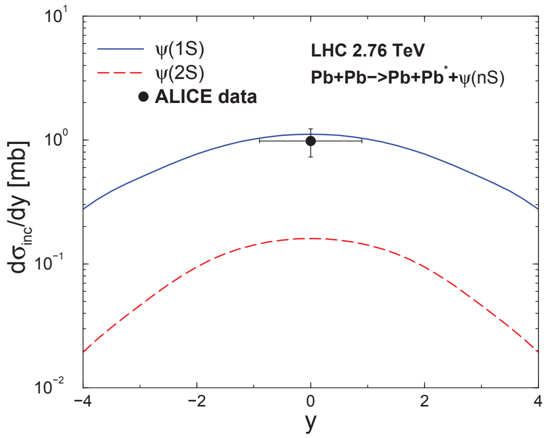

FIGURE 2. (Color online) The rapidity distribution of incoherent $\psi(1S)$ (solid line) and $\psi(2S)$ (dashed line) meson photoproduction at $\sqrt{s} = 2.76$ TeV in PbPb collisions at the LHC [17]. Data from ALICE collaboration [7].

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 is a factor 0.2 below the coherent one. For the incoherent cross section, the result 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 [20, 21]. Along these line, the authors of Ref. [22] 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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