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Quarkonium photoproduction in pp and AA collisions at the LHC

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Abstract. In this contribution we report on the investigations of the exclusive production of quarkonium states in proton-proton and nucleus-nucleus reactions at the LHC using the theoretical framework of the light-cone dipole formalism. In particular, we discuss the rapidity distribution for J/ψ, $\psi(2S)$ and $\Upsilon(1S)$ states and the transverse momentum distribution for the J/ψ meson. The numerical calculations are compared to recent experimental results and prediction are done for future LHC runs in the ultraperipheral channel.

1 Introduction

The exclusive vector meson photoproduction has being investigated both experimentally and theoretically in recent years as it allows to test perturbative Quantum Chromodynamics. The quarkonium masses, m_V, give a perturbative scale for the problem even in the photoproduction limit. An important feature of these processes at the high energy regime is the possibility to investigate the Pomeron exchange. For this energy domain hadrons and photons can be considered as color dipoles in the mixed light cone representation, where their transverse size can be considered frozen during the interaction. Therefore, the scattering process is characterized by the color dipole cross section describing the interaction of those color dipoles with the nucleon/nucleus target. Here, we summarize the main results published in Refs. [1, 2] where the exclusive production of J/ψ and the radially excited $\psi(2S)$ mesons were studied in pp and AA collisions in the LHC energy range. In addition, in this contribution we address the case for $\Upsilon(1S)$ state and the transverse momentum distribution for the J/ψ meson. The theoretical framework considered is the light-cone dipole formalism, where the $Q\bar{Q}$ fluctuation (color dipole) of the incoming quasi-real photon interacts with the nucleon or nucleus target via the dipole cross section and the result is projected in the wavefunction of the observed hadron. At high energies, the transition of the regime described by the linear dynamics of emissions chain to a new regime where the physical process of recombination of partons becomes important is expected. It is characterized by the limitation on the maximum phase-space parton density that can be reached in the hadron wavefunction, the so-called parton saturation phenomenon. The transition is set by saturation scale $Q_{\mathrm{sat}} \propto x^{-\lambda}$ (with $\lambda \simeq 0.3$), which is enhanced in the nuclear case. The Bjorken-x variable is connected in the photoproduction case to the center-of-mass-energy of the photon-nucleon (or nucleus) system, W, by the relation $x = M_V^2/W^2$.

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2 Theoretical framework

The exclusive meson photoproduction in hadron-hadron collisions can be factorized in terms of the equivalent flux of photons of the hadron projectile and photon-target production cross section [3]. The photon energy spectrum, $dN_{\gamma}^{p}/d\omega$, which depends on the photon energy ω, is well known [3]. The rapidity distribution y for quarkonium photoproduction in pp collisions can be written down as,

$$\frac{d\sigma}{dy}(pp \to p \otimes V \otimes p) \;=\; S^2_{\mathrm{gap}}\left[\omega\frac{dN_{\gamma}^{p}}{d\omega}\sigma(\gamma p \to V + p) + (y \to -y)\right]. \tag{1}$$

The produced state with mass m_V has rapidity $y \simeq \ln(2\omega/m_V)$ and the square of the γp centre-of-mass energy is given by $W_{\gamma p}^2 \simeq 2\omega\sqrt{s}$. The symbol $\otimes$ denotes a large rapidity gap between the proton and the meson. The absorptive corrections due to spectator interactions between the two hadrons are represented by the factor S_{gap}. The photon-Pomeron interaction will be described within the light-cone dipole frame, where the probing projectile fluctuates into a quark-antiquark pair with transverse separation r (and momentum fraction z) long after the interaction, which then scatters off the hadron. The cross section for exclusive photoproduction of quarkonia off a nucleon target is given by,

$$\sigma(\gamma p \to V + p) = \frac{1}{16\pi B_V}\left|\sum_{h,\bar{h}}\int dz\, d^2r\, \Psi^{\gamma}_{h,\bar{h}}(z,r)\,\sigma_{dip}(x,r)\,\Psi^{V*}_{h,\bar{h}}(z,r,M_V)\right|^2, \tag{2}$$

where Ψ^{γ} and Ψ^{V} are the light-cone wavefunction of the photon and of the vector meson, respectively. In the photoproduction limit, only the transverse polarization contribution is relevant. The Bjorken variable is denoted by x, the dipole cross section by $\sigma_{dip}(x,r)$ and the diffractive slope parameter by B_V. Here, we consider the energy dependence of the slope using the Regge motivated expression (see Refs. [1, 2] for details). Similarly, the rapidity distribution y in nucleus-nucleus collisions has the same factorized form,

$$\frac{d\sigma}{dy}(AA \to A \otimes V \otimes Y) = \left[\omega\frac{dN_{\gamma}^{A}}{d\omega}\,\sigma(\gamma A \to V + Y) + (y \to -y)\right], \tag{3}$$

where the photon flux in nucleus is denoted by $dN_{\gamma}^{A}/d\omega$ and $Y = A$ (coherent case) or $Y = A^*$ (incoherent case). The exclusive 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 expressions for both cases are given by [4],

$$\frac{d^2\sigma_{coh}}{d^2b} \;=\; \left|\sum_{h,\bar{h}}\int dz\, d^2r\, \Psi^{V*}(z,r,M_V)\left[1-\exp\left(-\frac{1}{2}R_G\sigma_{dip}(x,r)T_A(b)\right)\right]\Psi^{\gamma}(z,r)\right|^2, \tag{4}$$

$$\frac{d^2\sigma_{incoh}}{d^2b} \;=\; \frac{T_A(b)}{16\pi\, B_V}\left|\sum_{h,\bar{h}}\int dz\, d^2r\, \Psi^{V*}\left[R_G\sigma_{dip}(x,r)\exp\left(-\frac{1}{2}R_G\sigma_{dip}(x,r)T_A(b)\right)\right]\Psi^{\gamma}\right|^2, \tag{5}$$

where $T_A(b) = \int dz\rho_A(b,z)$ is the nuclear thickness function. In the numerical evaluations, we have considered the boosted Gaussian (BG) wavefunction and the phenomenological saturation model proposed in Ref. [5] (IIM model) which encodes the main properties of the saturation approaches. For that model we used the fitted parameters from DESY-HERA data including the contribution of charm quark, with $m_c = 1.4$ GeV [6] (for the bottom mass we will use the fixed value $m_b = 4.5$ GeV). The nuclear ratio for the gluon density is denoted by $R_G(x, Q^2 = m_V^2/4)$. 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. [7]. We used the two models available for $R_G(x, Q^2)$ in [7], Models 1 and 2, which correspond to higher nuclear shadowing and lower nuclear shadowing, respectively. Such a choice is completely arbitrary and other nuclear gluon ratios available in literature could be considered.

In the numerical calculation shown in next section, the corrections due to skewedness effect (off-diagonal gluon exchange) and real part of amplitude are also taken into account. Detail on the model dependence on these corrections can be found for instance in Ref. [1, 2]. In order to give details on the meson wavefunction, the boosted Gaussian is given by the expression:

$$\psi^{nS}_{\lambda,h\bar{h}} = \sqrt{\frac{N_c}{4\pi}}\frac{\sqrt{2}}{z(1-z)}\left\{\delta_{h,\bar{h}}\delta_{\lambda,2h}m_c + i(2h)\delta_{h,-\bar{h}}e^{i\lambda\phi}\left[(1-z)\delta_{\lambda,-2h} + z\delta_{\lambda,2h}\right]\partial_r\right\}\phi_{nS}(z,r). \tag{6}$$

Here, $\phi(z,r)$ in the mixed (r,z) representation is obtained by boosting a Schrödinger Gaussian wavefunction in momentum representation, $\Psi(z,\mathbf{k})$. In this case, one obtains the following expression for the $1S$ state:

$$\phi_{1S}(r,z) = N_T^{(1S)}\left\{4z(1-z)\sqrt{2\pi R_{1S}^2}\exp\left[-\frac{m_q^2R_{1S}^2}{8z(1-z)}\right]\exp\left[-\frac{2z(1-z)r^2}{R_{1S}^2}\right]\exp\left[\frac{m_q^2R_{1S}^2}{2}\right]\right\}, \tag{7}$$

where for the $1S$ ground state vector mesons we determine the parameters R_{1S}^2 and N_T by considering the normalization property of wavefunctions and the predicted decay widths. The radial wavefunction of the $2S$ state is obtained by the following modification of the $1S$ state:

$$\begin{aligned}\phi_{2S}(r,z) &= N_T^{(2S)}\left\{4z(1-z)\sqrt{2\pi R_{2S}^2}\exp\left[-\frac{m_q^2R_{2S}^2}{8z(1-z)}\right]\exp\left[-\frac{2z(1-z)r^2}{R_{2S}^2}\right]\exp\left[\frac{m_q^2R_{2S}^2}{2}\right]\right.\\ &\times \left.\left[1-\alpha\left(1+m_q^2R_{2S}^2-\frac{m_q^2R_{2S}^2}{4z(1-z)}+\frac{4z(1-z)}{R_{2S}^2}r^2\right)\right]\right\},\end{aligned} \tag{8}$$

with the new parameter α controlling the position of the node. In addition, the two parameters α and R_{2S} are determined from the orthogonality conditions for the meson wavefunction.

Finally, as we mentioned above the phenomenological parton saturation model proposed in Ref. [5] (hereafter IIM-old or CGC model) was taken into account which encodes the main properties of the saturation approaches. Thus, the dipole cross section is parameterized as follows

$$\sigma_{dip}(x,r) = \sigma_0\left\{\begin{array}{ll} \mathcal{N}_0\left(\frac{\bar{\tau}^2}{4}\right)^{\gamma_{\rm eff}(x,r)}, & \text{for } \bar{\tau}\le 2\,,\\ 1-\exp\left[-a\,\ln^2(b\,\bar{\tau})\right], & \text{for } \bar{\tau}>2\,,\end{array}\right.$$

where $\bar{\tau} = rQ_{\rm sat}(x)$ and the expression for $\bar{\tau} > 2$ (saturation region) has the correct functional form, as obtained from the theory of the Color Glass Condensate (CGC). For the color transparency region near saturation border ($\bar{\tau} \le 2$), the behavior is driven by the effective anomalous dimension $\gamma_{\rm eff}(x, r) = \gamma_{\rm sat} + \frac{\ln(2/\bar{\tau})}{\kappa\lambda y}$, where $\gamma_{\rm sat} = 0.63$ is the LO BFKL anomalous dimension at saturation limit.

3 Numerical results and data comparison

Let us start by the proton-proton mode at the LHC. First, we compare our study to the data measured by LHCb Collaboration at 7 TeV in pp collisions at the forward region $2.0 < \eta_{\pm} < 4.5$ [8], which cover values of Bjorken-x variable down to $x \approx 5\times10^{-6}$. We assume for the absorption factor the

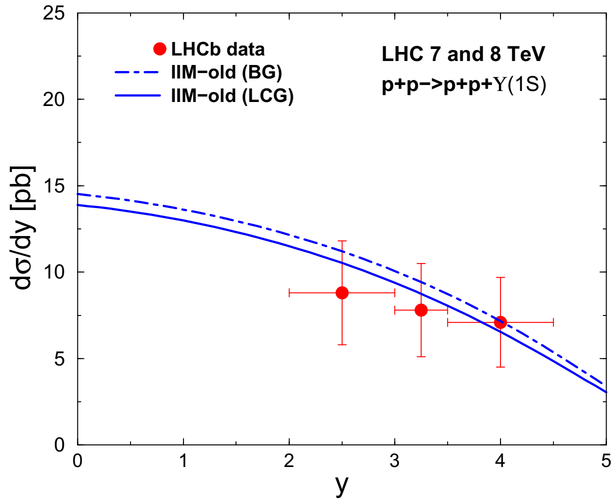

Figure 1. The rapidity distribution for $\Upsilon(1S)$ exclusive production in proton-proton collisions at 7 and 8 TeV. See discussion in text. Data from LHCb Collaboration [10].

average value $S^2_{\rm gap} = 0.8$. We obtain $\sigma(pp \to p + J/\psi + p) \times {\rm Br} = 698$ pb for rapidity between 2 and 4.5. In terms of muon pseudorapidities we get $\sigma_{pp\to J/\psi(\to\mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 298$ pb. This is in good agreement to the experimental result 307 ± 42 pb [8]. For the $\psi(2S)$ mesons it is obtained $\sigma(pp \to p + \psi(2S) + p) \times {\rm Br} = 18$ pb for rapidities $2.0 < y < 4.5$. Accordingly, we now predict $\sigma_{pp\to\psi(2S)(\to\mu^+\mu^-)}(2.0 < \eta_{\mu^\pm} < 4.5) = 7.7$ pb compared to 7.8 ± 1.6 pb measured value [8]. We performed predictions for the next LHC runs in pp mode. We have found $\frac{d\sigma_{J/\psi}}{dy} = 6.2$ nb and 7.9 nb for central rapidities at energies of 8 and 14 TeV, respectively. For the $\psi(2S)$ state the extrapolation gives $\frac{d\sigma_{\psi(2S)}}{dy} = 1.0$ nb and 1.4 nb for the same energies at central rapidity. In addition, the rapidity distributions for J/ψ and $\psi(2S)$ are completely consistent within the errors with the more precise LHCb data published in Ref. [9] (we quote Fig. 7 of that paper, where our predictions are compared to experimental results). Still in the proton-proton mode, we have predicted the rapidity distribution for the $\Upsilon(1S)$ state and compare the analysis to the recent measurement of exclusive Υ production at 7 and 8 TeV by LHCb Collaboration [10]. The results is presented in Fig. 1, where the uncertainty on the choice for the meson wavefunction is presented using the IIM model (labeled here as IIM-old) for the dipole cross section. The solid line corresponds to the results for the light cone Gaussian wavefunction (LCG) and the dot-dashed curve stands for the boosted Gaussian (BG) wavefunction. Both predictions are somewhat consistent with the present data accuracy.

For sake of completeness, in Fig. 2 we present the transverse momentum distribution for the J/ψ exclusive production in the fixed energies of 7 TeV(solid line), 8 TeV (dashed line) and 14 TeV (dot-dashed line). We consider the CGC model (IIM model) and BG wavefunction and central rapidity, $y = 0$. The p_T-distribution is directly connected to the t-dependence of the dipole cross section. In our case, we use the hypothesis of exponential behavior on t for the differential cross section. Distinct distributions will be obtained using more sophisticated models for the b-dependence on the dipole cross section.

In Fig. 3 (left panel) we present the calculations for the rapidity distribution of coherent J/ψ state, using distinct scenarios for the nuclear gluon shadowing. The dot-dashed curve represents the

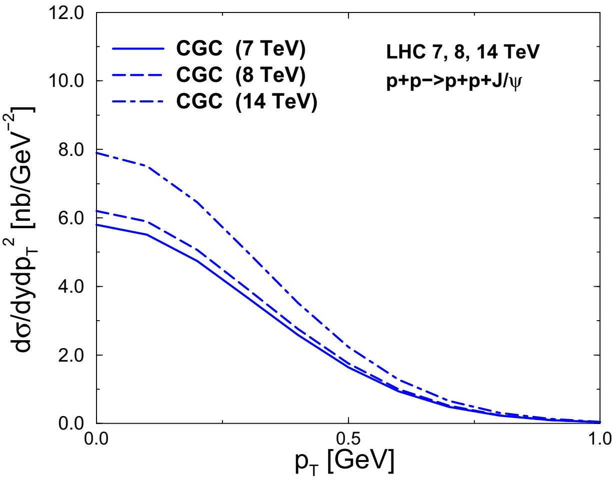

Figure 2. The transverse momentum distribution for J/ψ exclusive production in proton-proton collisions at 7, 8 and 14 TeV. See discussion in text.

result using $R_G = 1$. It overestimates the ALICE data [11, 12] on the backward (forward) and mainly in central rapidities. The situation is improved if we consider nuclear shadowing renormalising the dipole cross section. The reason is that the gluon density in nuclei at small Bjorken x is expected to be suppressed compared to a free nucleon due to interferences. For R_G, we have considered the theoretical evaluation of Ref. [7]. 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 (strong shadowing) and Model 2 (weak shadowing), respectively. In Fig. 3 (right panel) is presented the incoherent cross section for both J/ψ and $\psi(2S)$ states with $R_G = 1$. In this case, the data description is very good compared to the ALICE data. Here some comments are in order. It was recently shown [13] that the color dipole approach with $R_G = 1$ is not able to describe the ALICE data for coherent production of J/ψ at 2.76 GeV [11, 12] at midrapidity even including the theoretical uncertainties related to the meson wavefunction and models for the dipole cross section (and distinct choices for the charm quark mass). The mid-rapidity cross section is overestimated by a factor two in the case presented here. It is advocated in Ref. [14] the reason is that for $R_G = 1$ in the photon-nucleus cross section the nuclear effect included via eikonalization corresponds to lowest $Q\bar{Q}$ Fock component, $|Q\bar{Q}\rangle$. It does not include any correction for gluon shadowing, but rather correspond to shadowing of sea quarks in nuclei. Although σ_{dip} includes all possibles effects of gluon radiation, the eikonal assumes that none of radiated gluons take part in multiple interactions in the nucleus. The leading order correction corresponding to gluon shadowing comes from the eikonalization of the next Fock component $|Q\bar{Q}G\rangle$. Explicitly, in the large coherence length limit $\ell_c \to \infty$ the general formula for the γA cross section is given by,

$$\begin{aligned} \frac{d^2\sigma_{\gamma A}}{d^2b} &= 2\int dz \int d^2r \left|\psi_{q\bar{q}}\right|^2 \left[1 - \exp\left(-\frac{1}{2}\sigma_{q\bar{q}} T_A(b)\right)\right] \\ &+ 2\int dz \int \frac{dz_G}{z_G} \int d^2r_1 \int d^2r_2 \left|\psi_{q\bar{q}G}\right|^2 \left[1 - \exp\left(-\frac{1}{2}\sigma_{q\bar{q}G} T_A(b)\right)\right], \end{aligned} \quad (9)$$

where $\psi_{q\bar{q}G}$ is the wavefunction for the gluonic component and the cross section for the three body system $\sigma_{q\bar{q}G}$ can be expressed in terms of the dipole cross section, σ_{dip}. The complete calculation

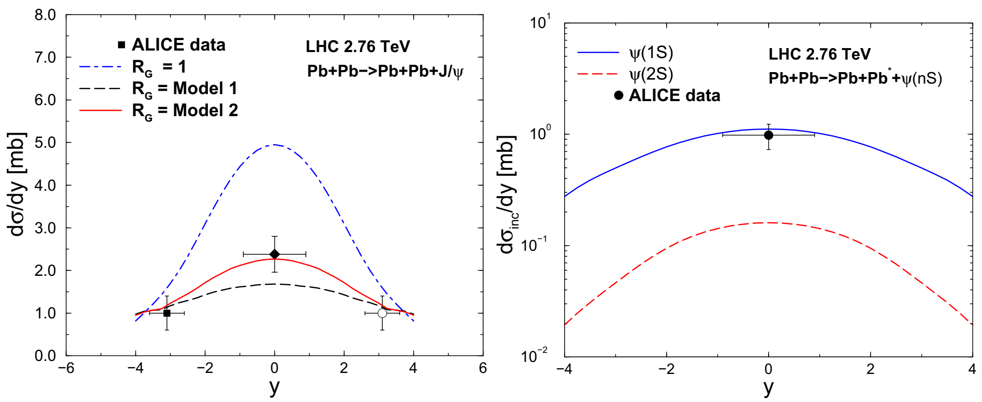

Figure 3. The rapidity distribution of coherent (left panel) J/ψ production and the incoherent (right panel) J/ψ and $\psi(2S)$ exclusive photoproduction at $\sqrt{s}$ = 2.76 TeV in PbPb collisions at the LHC (see text).

has been done in Ref. [14], and it was shown that the $|Q\bar{Q}G\rangle$ contribution can be absorbed in a factor $R_G(x, Q^2, b)$ multiplying the original dipole cross section.

As a summary, we calculate the results for the exclusive production of quarkonium states in proton-proton and nucleus-nucleus reactions at the LHC using the theoretical framework of light-cone dipole formalism. The exclusive production in proton-proton case is consistently described by our approach being in good agreement wit the rapidity distribution for J/ψ, $\psi(2S)$ and $\Upsilon(1S)$ states. In the nucleus-nucleus case, the approach fairly describes the incoherent cross section and we discuss the role played by the gluon nuclear shadowing in order to evaluate the coherent cross section at midrapidity.

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