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Exclusive ρ and J/Ψ photoproduction in ultraperipheral pA collisions: Predictions of the gluon saturation models for the momentum transfer distributions

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ABSTRACT

In this letter we complement previous studies on exclusive vector meson photoproduction in hadronic collisions presenting a comprehensive analysis of the t-spectrum measured in exclusive ρ and J/Ψ photoproduction in pA collisions at the LHC. We compute the differential cross sections considering two phenomenological models for the gluon saturation effects and present predictions for pPb and pCa collisions. Moreover, we compare our predictions with the recent preliminary CMS data for the exclusive ρ photoproduction. We demonstrate that the gluon saturation models are able to describe the CMS data at small $-t$. On the other hand, the models underestimate the few data point at large $-t$. Our results indicate that future measurements of the large $-t$ region can be useful to probe the presence or absence of a dip in the t-spectrum and discriminate between the different approaches to the gluon saturation effects.

During the last years the study of photon – induced interactions at hadronic colliders has been strongly motivated by the possibility of constraining the dynamics of the strong interactions at large energies (for a recent review see Ref. [1]). One of most promising observables is the exclusive vector meson photoproduction cross section [2,3], which is driven by the gluon content of the target (proton or nucleus) and is strongly sensitive to non-linear effects (parton saturation). Such expectation has motivated the analysis of exclusive ρ, ϕ, J/Ψ, $\Psi(2S)$ and Υ photoproduction in pp, pA and AA collisions at RHIC and LHC energies considering different theoretical approaches for the treatment of the QCD dynamics and for the vector meson wave function (see, e.g., Refs. [4–11]). In particular, the recent study performed in Ref. [9] indicated that a global analysis of the experimental data for the rapidity distributions of all these different final states will be necessary to discriminate between the distinct theoretical approaches. On the other hand, the results presented in Refs. [10,12] indicate that the study of the squared momentum transfer (t) distributions is an important alternative to probe the QCD dynamics at high energies. These distributions are expected to provide information about the spatial distribution of the gluons in the hadron and about fluctuations of the color fields (see e.g. Ref. [13]). In Ref. [12] we have presented predictions for the t-spectrum measured in the exclusive vector meson photoproduction considering pp and $PbPb$ collisions at the LHC. Our goal is this letter is twofold. First, to complement that study and present, for the first time, predictions for the momentum transfer distributions measured in exclusive ρ and J/Ψ photoproduction in pPb collisions considering two phenomenological models for the treatment of the gluon saturation effects. Second, to present a comparison of gluon saturation predictions with the recent (preliminary) CMS data on exclusive ρ photoproduction in ultraperipheral pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [14]. Such comparison is also performed here for the first time. As we will demonstrate in what follows, our results indicate that the analysis of the t-spectrum can be useful to discriminate between the different approaches to gluon saturation effects. Moreover, we will show that these models are able to describe the CMS data at small $-t$ but underestimate the few data points at large $-t$.

Initially, let's present a brief review of the formalism used in our calculations. The exclusive vector meson photoproduction in pA collisions is dominated by photon - proton interactions, since the nuclear photon flux is enhanced by the square of the nuclear charge (Z) [15]. The process is represented in Fig. 1. The final state will be characterized by two intact hadrons (A and p) and two rapidity gaps, i.e. the outgoing particles (A, $V = \rho$, J/Ψ and p) are

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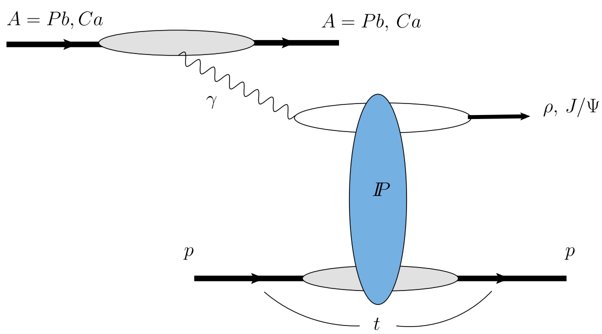

Fig. 1. Exclusive vector meson photoproduction in pA collisions.

separated by a large region in rapidity in which there is no additional hadronic activity observed in the detector. The differential cross section can be expressed as follows

$$\frac{d\sigma\ [A+p \rightarrow A \otimes V \otimes p]}{dY\, dt} = n_A(\omega) \cdot \frac{d\sigma}{dt}(\gamma p \rightarrow V \otimes p)\ , \quad (1)$$

where the rapidity (Y) of the vector meson in the final state is determined by the photon energy ω in the collider frame and by the mass M_V of the vector meson [$Y \propto \ln(\omega/M_V)$]. Moreover, $d\sigma/dt$ is the differential cross section of the $\gamma p \rightarrow V \otimes p$ process, with the symbol $\otimes$ representing the presence of a rapidity gap in the final state. Furthermore, $n_A(\omega)$ denotes the equivalent photon spectrum of the relativistic incident nucleus. As in our previous studies [9,12] we will assume a point – like form factor for the nucleus, which implies that [15]

$$n_A(\omega) = \frac{2Z^2\alpha_{em}}{\pi}\left[\xi K_0(\xi)K_1(\xi) - \frac{\xi^2}{2}\left(K_1^2(\xi) - K_0^2(\xi)\right)\right], \quad (2)$$

where $\xi = \omega\left(R_A + R_p\right)/\gamma_L$, with γ_L being the Lorentz factor. The differential cross section for the $\gamma p \rightarrow V \otimes p$ process is given by

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}|\mathcal{A}^{\gamma p \rightarrow Vp}(x,\Delta)|^2\ , \quad (3)$$

where $|t|$ is the squared transverse momentum of the vector meson in the final state and $\mathcal{A}$ is the amplitude for producing an exclusive vector meson diffractively. In the color dipole formalism [16], this amplitude can be factorized in terms of the fluctuation of the virtual photon into a $q\bar{q}$ color dipole, the dipole-hadron scattering by a color singlet exchange (denoted $I\!P$ in Fig. 1) and the recombination into the vector meson V. Consequently, the amplitude can be expressed as follows

$$\mathcal{A}^{\gamma p \rightarrow Vp}(x,\Delta) = i\int dz\, d^2\boldsymbol{r}\, d^2\boldsymbol{b}\, e^{-i[\boldsymbol{b}-(1-z)\boldsymbol{r}].\boldsymbol{\Delta}}\ (\Psi^{V*}\Psi)\ 2\mathcal{N}^p(x,\boldsymbol{r},\boldsymbol{b})\ , \quad (4)$$

where $(\Psi^{V*}\Psi)$ denotes the wave function overlap between the photon and vector meson wave functions, $\Delta = -\sqrt{t}$ is the momentum transfer and $\boldsymbol{b}$ is the impact parameter of the dipole relative to the proton target. Moreover, the variables $\boldsymbol{r}$ and z are the dipole transverse pair separation and the momentum fraction of the photon carried by a quark (an antiquark carries then $1-z$), respectively. As in Ref. [12], in what follows we will consider the Boosted Gaussian model [17,18] for the overlap function. However, the dependence of our results on this choice will also be discussed below. The function $\mathcal{N}^p(x,\boldsymbol{r},\boldsymbol{b})$ is the forward dipole-proton scattering amplitude (for a dipole at impact parameter $\boldsymbol{b}$) which encodes all the information about the hadronic scattering. It depends on the γh center-of-mass reaction energy, $W = [2\omega\sqrt{s_{NN}}]^{1/2}$, through the variable $x = M_V^2/W^2$. One of the main open questions in QCD is the treatment of its high energy regime, where non-linear (gluon saturation) effects are expected to contribute [19]. Currently, the bCGC and IP-Sat models, which are based on different assumptions for the treatment of the gluon saturation effects, describe with success the high precision HERA data for inclusive and exclusive processes. In the impact parameter Color Glass Condensate (bCGC) model [18] the dipole - proton scattering amplitude is given by

$$\mathcal{N}^p(x,\boldsymbol{r},\boldsymbol{b}) = \begin{cases} \mathcal{N}_0\left(\frac{r\,Q_s(b)}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/r\,Q_s(b))}{\kappa\,\lambda\,y}\right)} & r Q_s(b) \leq 2 \\ 1 - e^{-A\,\ln^2(B\,r\,Q_s(b))} & r Q_s(b) > 2\ , \end{cases} \quad (5)$$

with $\kappa = \chi''(\gamma_s)/\chi'(\gamma_s)$, where χ is the LO BFKL characteristic function and $y = \ln(1/x)$. The coefficients A and B are determined uniquely from the condition that $\mathcal{N}^p(x,\boldsymbol{r},\boldsymbol{b})$, and its derivative with respect to $r\,Q_s(b)$, are continuous at $r\,Q_s(b) = 2$. The impact parameter dependence of the proton saturation scale $Q_s(b)$ is given by:

$$Q_s(b) \equiv Q_s(x,b) = \left(\frac{x_0}{x}\right)^{\frac{\lambda}{2}}\left[\exp\left(-\frac{b^2}{2B_{\rm CGC}}\right)\right]^{\frac{1}{2\gamma_s}}\ , \quad (6)$$

with the parameter $B_{\rm CGC}$ being obtained by a fit of the t-dependence of exclusive J/ψ photoproduction. The factors $\mathcal{N}_0$ and γ_s were taken to be free. In what follows we consider the set of parameters obtained in Ref. [20] by fitting the recent HERA data on the reduced ep cross sections: $\gamma_s = 0.6599$, $\kappa = 9.9$, $B_{CGC} = 5.5$ GeV^{-2}, $\mathcal{N}_0 = 0.3358$, $x_0 = 0.00105$ and $\lambda = 0.2063$. In the bCGC model, the saturation regime, where $rQ_s(b) > 2$, is described by the Levin - Tuchin law [21] and the linear one by the BFKL dynamics near of the saturation line. On the other hand, in the IP-Sat model [22,23], $\mathcal{N}^p$ has an eikonalized form and depends on a gluon distribution evolved via DGLAP equation, being given by

$$\mathcal{N}^p(x,\boldsymbol{r},\boldsymbol{b}) = 1 - \exp\left[\frac{\pi^2 r^2}{N_c}\alpha_s(\mu^2)\ xg\left(x, \frac{4}{r^2}+\mu_0^2\right)\ T_G(b)\right], \quad (7)$$

with a Gaussian profile

$$T_G(b) = \frac{1}{2\pi B_G}\exp\left(-\frac{b^2}{2B_G}\right). \quad (8)$$

The initial gluon distribution evaluated at μ_0^2 is taken to be $xg(x,\mu_0^2) = A_g x^{-\lambda_g}(1-x)^{5.6}$. In this work we assume the parameters obtained in Ref. [24]. As in the bCGC model, the IP-Sat predicts the saturation of $\mathcal{N}^p$ at high energies and/or large dipoles, but the approach to this regime is not described by the Levin - Tuchin law. Moreover, in contrast to the bCGC model, the IP-Sat takes into account the effects associated to the DGLAP evolution, which are expected to be important in the description of the small dipoles. Consequently, both models are based on different assumptions for the linear and non-linear regimes. As pointed above, the current high precision HERA data are not able to discriminate between these models. In what follows we analyze the possibility of constraining the models of gluon saturation effects in exclusive vector meson photoproduction at pA collisions. As in Ref. [12], we also will present the predictions derived assuming that $\mathcal{N}^p(x,\boldsymbol{r},\boldsymbol{b})$ is given by the linear part of the bCGC model, which is

$$\mathcal{N}^p(x,\boldsymbol{r},\boldsymbol{b}) = \mathcal{N}_0\left(\frac{r\,Q_s(b)}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/r\,Q_s(b))}{\kappa\,\lambda\,y}\right)}\ , \quad (9)$$

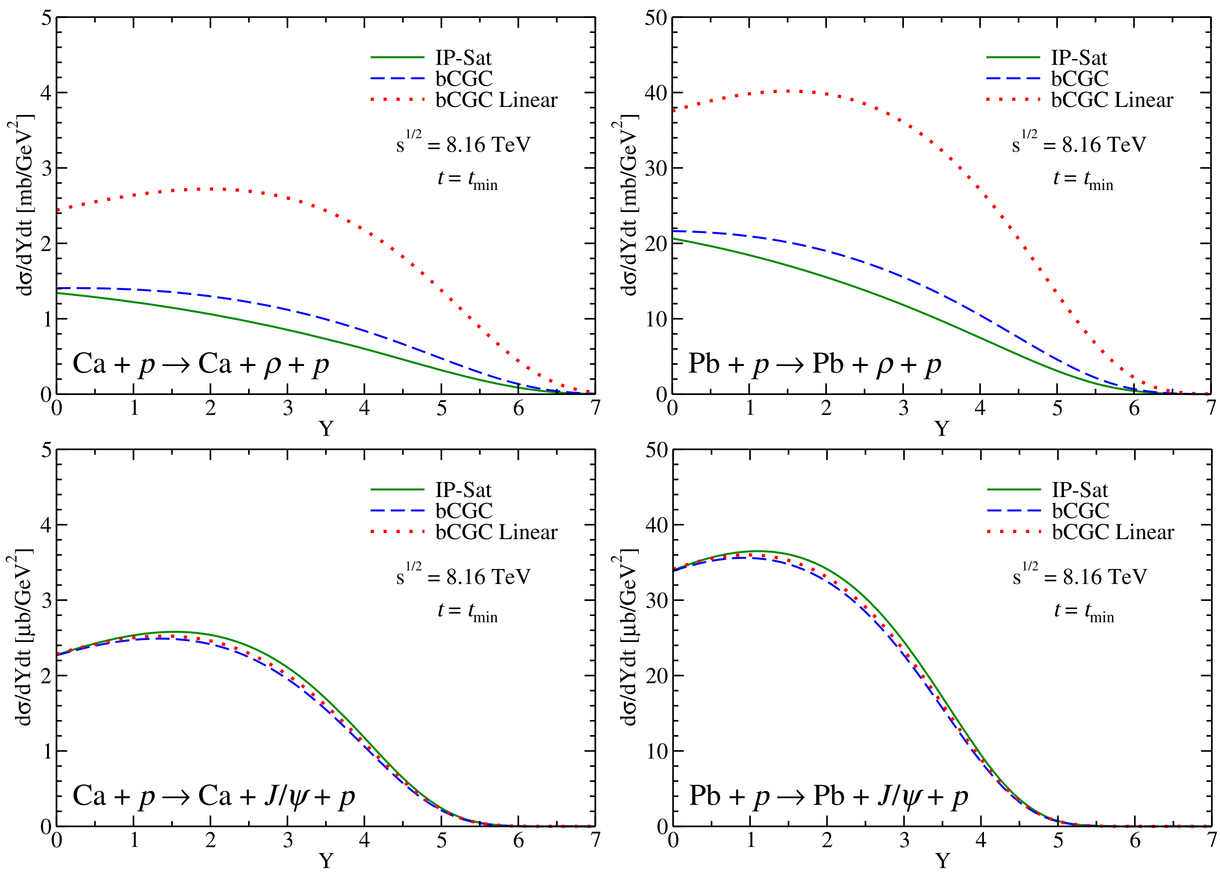

Fig. 2. Rapidity distribution for the exclusive ρ (upper panels) and J/Ψ (lower panels) photoproduction in pCa and pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV.

with the same parameters used before in Eq. (5).

Let's consider the exclusive ρ and J/Ψ photoproduction in pCa and pPb collisions at the LHC energies. Our main focus will be on the transverse momentum distributions, which are expected to be studied considering the higher statistics of Run 2 and 3 [1]. However, firstly let us analyse the impact of the gluon saturation effects on the rapidity distributions at a fixed value of the momentum transfer t. We will estimate Eq. (1) for $t = t_{min}$, with $t_{min} = -m_N^2 M_V^4/W^4$. In Fig. 2 we present our predictions for the rapidity distributions considering the exclusive ρ (upper panels) and J/Ψ (lower panels) photoproduction in pCa and pPb collisions. The rapidity Y is calculated in the center-of-mass of the pA system. We observe that the difference between the bCGC and IP-Sat is larger for ρ production, with the IP-Sat predictions being smaller than the bCGC ones. On the other hand, the IP-Sat model predicts larger values of the rapidity distribution when the J/Ψ production is considered. Finally, the bCGC linear model predicts larger (similar) values of the rapidity distributions for the ρ (J/Ψ) production. These results are expected, since the bCGC and IP-Sat models assume different behavior for the linear and non-linear regimes. In the ρ case, the process is dominated by the contribution of large dipole sizes, which are expected to be strongly suppressed by the gluon saturation effects. On the other hand, J/Ψ production is dominated by small dipoles, i.e. the cross section is expected to be mainly determined by the linear regime of the QCD dynamics. The main difference between the predictions for pCa and pPb collisions is the normalization of the distributions. This result is also expected, since the distribution is calculated by the product of the photon flux and the photon - proton cross section [See Eq. (1)], with n_A being proportional to Z^2. The rapidity and transverse momentum dependencies are determined by the $\gamma p \to Vp$ cross section, which is the same for pCa and pPb collisions. Consequently, in what follows, we will only present our predictions for the t-distributions in pPb collisions.

Let us now analyze the predictions of the different gluon saturation models for the distributions on the squared transverse momentum of the vector mesons considering pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV and assuming three different fixed values for the vector meson rapidity ($Y = 0$, 2 and 4). Our results for the exclusive ρ and J/Ψ photoproduction are presented in the upper and lower panels of Fig. 3, respectively. We observe that the bCGC and IP-Sat predictions are similar at small $-|t|$, but differ at larger values. The position of the dip is dependent on the description of the gluon saturation effects, with the bCGC model predicting the dip at smaller values of $|t|$, independently of the produced vector meson. Moreover, we see that the position of the dip is displaced at smaller $|t|$ with the growth of the rapidity and the number of dips predicted for the ρ production in the range $|t| \leq 4$ GeV^2 is larger than for the J/Ψ case. On the other hand, if the non-linear effects are disregarded in the bCGC model, the normalization is increased, with the increasing being larger for the ρ production. Such result is expected from the analysis of the Fig. 2. The bCGC linear model also predicts the presence of a dip, in a position that is almost independent of the rapidity, and that occurs at larger values of $|t|$ in comparison to the predictions that include the non-linear effects. These results indicate that the study of the t-distribution in the range $0.75 \leq |t| \leq 1.5$ GeV^2 ($2.0 \leq |t| \leq 3.0$ GeV^2) for the case of ρ (J/Ψ) production can be useful to constrain the description of the gluon saturation effects.

The exclusive ρ photoproduction in ultraperipheral pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV has been studied by the CMS Collaboration. In particular, they released, very recently, the first (prelim-

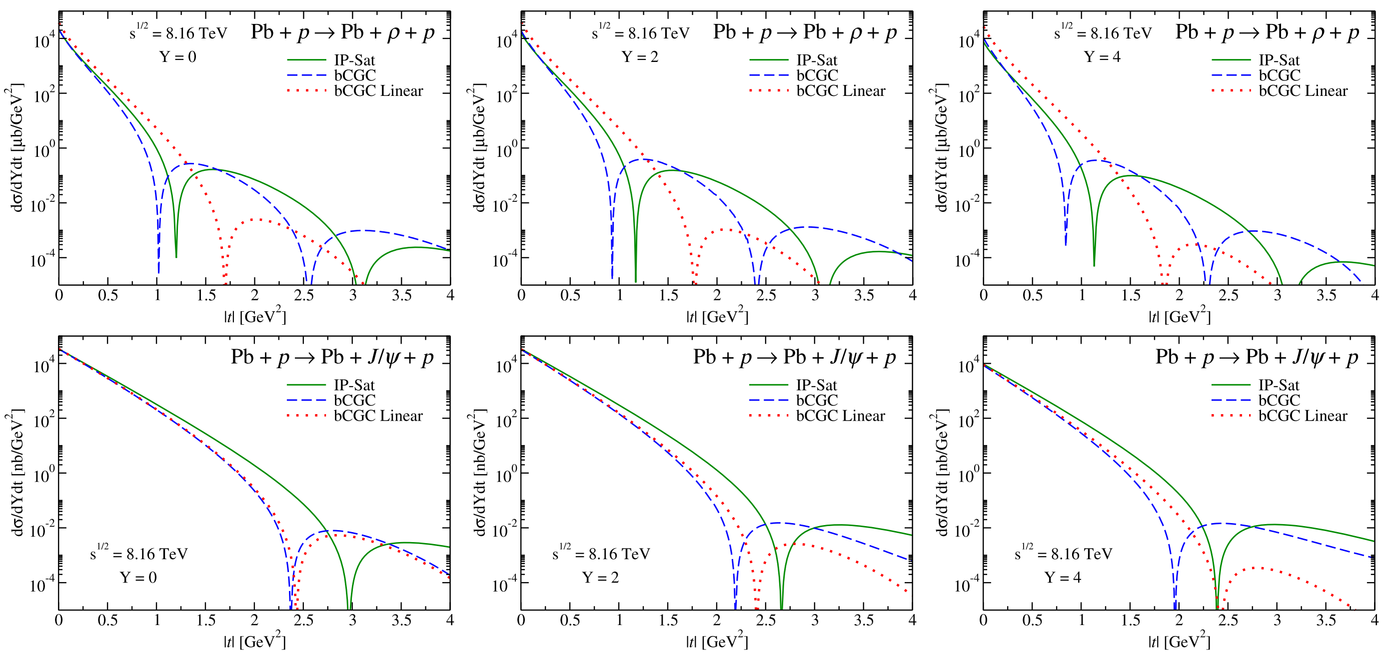

Fig. 3. The differential cross sections for the exclusive ρ (upper panels) and J/Ψ (lower panels) photoproduction as a function of $|t|$ assuming pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. Predictions have been calculated considering three different values for the vector meson rapidity.

inary) data [14] for the t-distributions of the $\gamma p \to \rho p$ process at different center-of-mass energies of the γp system. Assuming that the nuclear photon flux is well known and that there is a direct relation between the rapidity Y of the vector meson and the γp center-of-mass energy (W), they measured $d\sigma/dt$ for different rapidity bins and, consequently, for averaged values of W. A comparison between our predictions and these preliminary data is presented in Fig. 4. The bCGC and IP-Sat models describe quite well the distributions for $|t| \le 0.4$ GeV^2. On the other hand, at larger values of $|t|$, where the number of experimental points is smaller and the uncertainty is larger, the predictions of the gluon saturation models underestimate the data, with the IP-Sat predictions being closer to the data. In addition, the bCGC linear model overestimates the total cross sections and is not able to describe the data at low $|t|$, in particular for larger values of W. It is important to emphasize that the discrepancy between the non-linear predictions and the data starts to occur exactly in the region where the presence of dips becomes important and the t-distribution can no longer be described by an exponential with a fixed slope. Moreover, in this range of large values of $|t|$, the background associated to the contribution of dissociative processes (in which the proton dissociates in a low - mass hadronic system with the same quantum numbers) becomes non-negligible. The proton dissociation is expected to generate additional tracks in the final state. Consequently, the exclusive and dissociative events can be separated by tagging the proton and/or by imposing some special selection requirements in the final state, as in the case of the analysis performed in Ref. [14]. The CMS Collaboration has assumed that the dissociative contribution can be efficiently suppressed by rejecting events with activity in its detectors and that the preliminary data presented in Fig. 4 correspond to exclusive events, with a minimal contribution of dissociative processes. Such assumption can be checked with the tagging of proton in the final state in future measurements of exclusive processes in pA collisions at the LHC. If confirmed, these data can be a first indication that the model of the spatial distribution of gluons in the proton (present in the bCGC and IP-Sat models) should be improved in the study of gluon saturation effects. Certainly, more data on exclusive vector meson photoproduction will be very useful to improve our understanding of the QCD dynamics at high energies.

Finally, let's analyze the impact on our predictions of the model used to describe the vector meson wave function. As discussed e.g. in Refs. [9,18], the description of the vector meson wave function is still a theme of debate, with different models being able to describe the HERA data. Two popular models are the Boosted Gaussian, used in the calculations presented before, and the Gauss - LC model. In these models the vector meson is assumed to be predominantly a quark-antiquark state, with the spin and polarization structure being the same as in the photon. They differ in the description of the scalar part of the wave function and imply a different dipole size dependence of the overlap function (see Fig. 1 in Ref. [9]). In Fig. 5 we compare the predictions for the exclusive ρ (left panel) and J/Ψ (right panel) photoproduction in pPb collisions, derived using the Boosted Gaussian and the Gauss - LC models for the meson wave function. We are only presenting the predictions for $Y = 2$, but similar conclusions can be derived from the analysis of the results for other rapidities. We can see that all predictions are similar at small $- |t|$, but the position of the dip is sensitive to the model used to describe the vector meson. The impact on the predictions for the J/Ψ production is small, with the shape of the distributions being similar for a given saturation model, and the dip position being slightly displaced at smaller values of $|t|$ if the Gauss - LC model is used. Therefore, the analysis of the $|t|$-distribution for this meson can be useful to discriminate between the IP-Sat and bCGC predictions. On the other hand, for the ρ case, the Gauss - LC model implies that the dip is displaced to larger values of $|t|$. One important aspect is that if the Gauss - LC and the bCGC models are used to calculate the differential cross section, the prediction for the position of the first dip becomes similar to that derived using the Boosted - Gaussian and IP-Sat models. Such similarity is also present for other rapidities, with the position of the dip being dependent of the rapidity, in agreement with the results presented in Fig. 3. Consequently, if future experimental data for the exclusive ρ photoproduction at $Y = 2$ observe a dip in $|t| \approx 1.15$ GeV^2, we will not be able to discriminate between the models. In this case, the discrimination

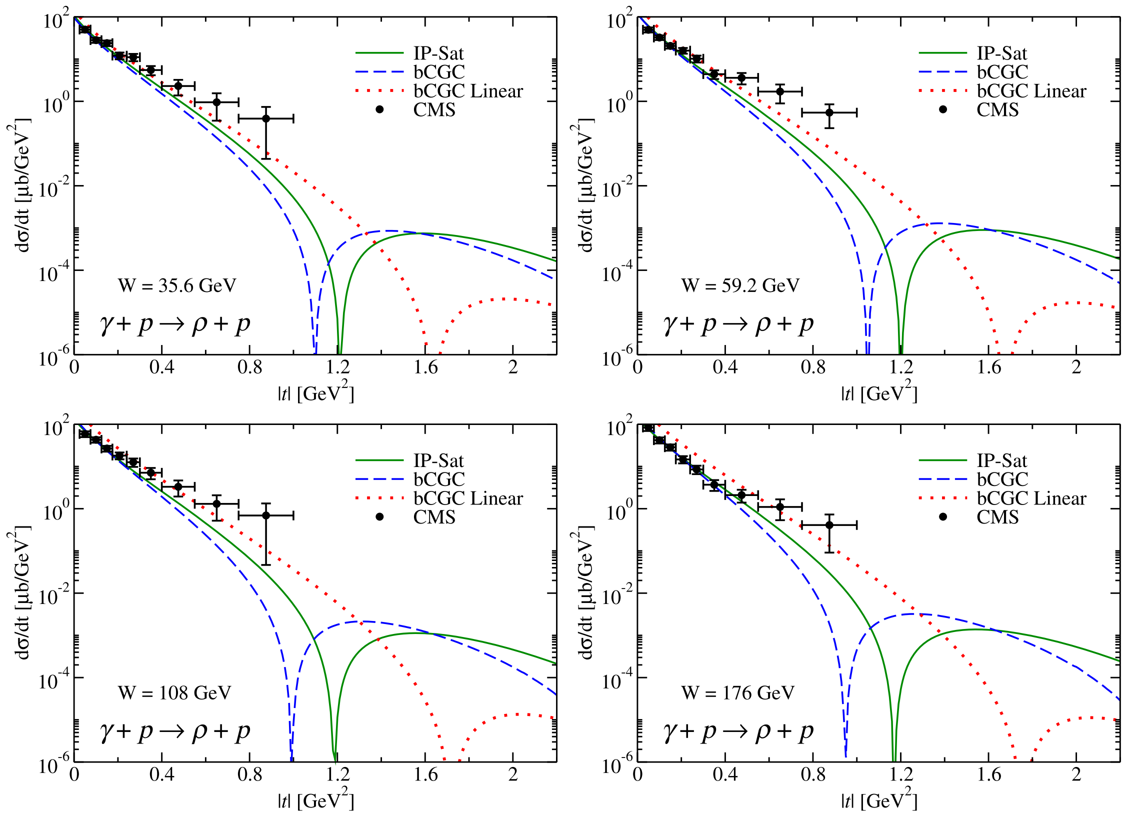

Fig. 4. The differential cross sections for the exclusive ρ photoproduction as a function of $|t|$ considering different center-of-mass energies of the γp system. Preliminary data from the CMS Collaboration [14].

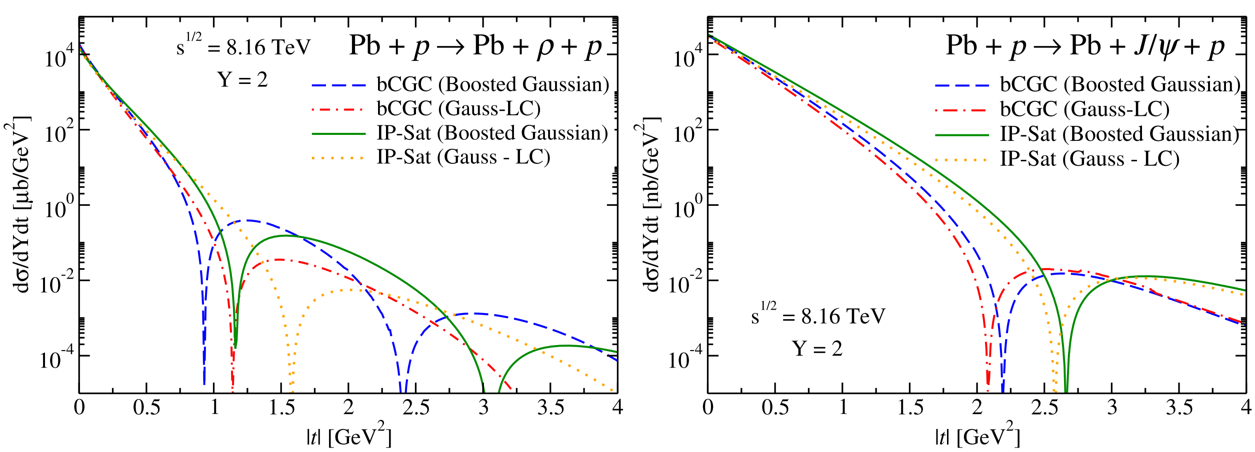

Fig. 5. The differential cross sections for the exclusive ρ (left panel) and J/Ψ (right panel) photoproduction as a function of $|t|$ assuming pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV. Predictions calculated considering different models for $\mathcal{N}^p(x, \boldsymbol{r}, \boldsymbol{b})$ and for the vector meson function.

will only be possible if a global analysis is performed considering the data for other vector mesons (as e.g. J/Ψ). A similar conclusion has been reached in Ref. [9]. In contrast, if the first dip occurs at smaller (larger) values of $|t|$, we will have an indication that the adequate representation of the process is given by the bCGC (IP-Sat) model to describe the non-linear effects and by Boosted Gaussian (Gauss - LC) model for the vector meson wave function. Such results indicate that a future experimental analysis of the $|t|$ - distributions in exclusive processes can be useful to discriminate between these different approaches.

As a summary, in this letter we have investigated the exclusive ρ and J/Ψ photoproduction in pA collisions at the LHC, motivated by the expectation that this process may allow us to constrain the description of the QCD dynamics at high energies. Differently from pp and AA collisions, in pA collisions the rapidity of the vector meson allows to unambiguously determine the γp center-of-mass energy and, consequently, to probe the QCD dynamics at the given value of the Bjorken – x variable. We have considered the exclusive ρ and J/Ψ production, which mainly probes the non-linear and linear QCD regimes, respectively, and presented the bCGC and IP-Sat predictions for the rapidity and transverse momentum distributions. These two models, even though describing the available HERA data, are based on different assumptions for the gluon saturation effects. We demonstrated that their predictions for the

t-spectra are similar at small values of $|t|$ but differ at large – $|t|$, with the position of the dip being model dependent. A comparison of our predictions with the very recent (preliminary) CMS data has been presented for the first time, with the data at small – $|t|$ being quite well described by both gluon saturation models. However, the large – $|t|$ data are underestimated by the models. This can be a first indication that the description of the spatial distribution of the gluons in the proton should be improved. These results indicate that the experimental analysis of the transverse momentum distribution is useful to discriminate between different approaches for the QCD dynamics as well to improve our descriptions of the gluon saturation effects and of the vector meson wave functions.

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