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Exclusive heavy vector meson photoproduction in hadronic collisions at the LHC: Predictions of the color glass condensate model for Run 2 energies

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In this paper, we update the predictions for exclusive J/Ψ, $\Psi(2S)$, and Υ photoproduction in proton-proton and nucleus-nucleus collisions at the Run 2 LHC energies obtained with the color dipole formalism and considering the impact-parameter color glass condensate model (bCGC) for the forward dipole-target scattering amplitude. The impact of the charm mass on the predictions is investigated, and a comparison with the LHCb data on rapidity distributions and photon-hadron cross sections is presented. Our results demonstrate that the current data can be quite well described by the bCGC model, which takes into account nonlinear effects in the QCD dynamics and reproduces the very precise HERA data, without introducing any additional effect or free parameter.

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I. INTRODUCTION

The study of photon-induced processes in hadronic collisions [1] has become a reality in the last several years [2–10], and new data associated with Run 2 of the LHC are expected to be released soon. Theoretically, we expect that these new data will allow us to get answers for several important open questions of the Standard Model (SM), as well as to shed some light on possible beyond-SM physics (For a recent review, see Ref. [11]). One of these questions is related to the treatment of the QCD dynamics at high energies and large nuclei [12], which is probed in exclusive vector meson photoproduction in hadronic collisions [13,14]. In the last several years, this process was studied by several theoretical groups considering different formalisms and underlying assumptions (See e.g. Refs. [15–19]). In particular, in Refs. [20,21] we estimated the exclusive J/Ψ and Υ photoproduction in hadronic collisions within the dipole formalism considering different models for the vector meson wave functions and/or for the forward dipole-hadron scattering amplitude. Moreover, we presented a comparison with the Run 1 LHC data and demonstrated that our predictions were able to describe those data if the nonlinear effects in the QCD dynamics are taken into account. Although in Refs. [20,21] we have presented some predictions for future runs of the LHC, they were calculated for center-of-mass energies different from those that are being considered for Run 2. One of the motivations for this paper is to present predictions that can be directly compared with the expected Run 2 data. Moreover, we present, for the first time, the bCGC predictions for the exclusive $\Psi(2S)$ photoproduction in hadronic collisions. Another motivation is to present for the first time a comparison between our predictions and the data on the energy dependence of the total $\gamma p \rightarrow V p$ $(V = J/\Psi, \Psi(2S), \Upsilon)$ cross section, which have been extracted from the data on rapidity distributions of the vector mesons photoproduced in hadronic collisions. Finally, as a byproduct, we also present a comparison of our prediction [21] for the exclusive Υ photoproduction in pp collisions at $\sqrt{s} =$ 7 TeV with the LHCb data [9] that have been released after the publication of our previous paper.

This paper is organized as follows: In the next section, we present a brief review of the formalism needed to describe the exclusive vector meson photoproduction in hadronic collisions. Moreover, we discuss the main assumptions and models used in our calculations. In Sec. III, we present our predictions for the total cross sections for the energies of Run 2 as well as for the rapidity distributions. A comparison with the Run 1 and preliminary Run 2 data also is presented. Finally, in Sec. IV, we summarize our main conclusions.

II. FORMALISM

Initially, let us present a brief review of the main concepts needed to describe the photon-induced interactions in hadronic collisions and the formalism used in our calculations. (For a detailed discussion, see Refs. [20,21]). The basic idea in photon-induced processes is that an ultra-relativistic charged hadron (proton or nucleus) gives rise to strong electromagnetic fields, such that the photon stemming from the electromagnetic field of one of the two colliding hadrons can interact with one photon of the other hadron (photon-photon process) or can interact directly with the other hadron (photon-hadron process) [1]. In these processes, the total cross section can be factorized in terms of the equivalent flux of photons into the hadron projectile and the photon-photon or photon-target cross section. In this paper, we focus on exclusive vector meson production in photon-hadron interactions in hadronic collisions. The differential cross section for the production of a vector meson V at rapidity Y can be expressed as follows:

$$\frac{d\sigma[h_1 + h_2 \to h_1 \otimes V \otimes h_2]}{dY} = \left[\omega \frac{dN}{d\omega}\bigg|_{h_1} \sigma_{\gamma h_2 \to V \otimes h_2}(\omega)\right]_{\omega_L} + \left[\omega \frac{dN}{d\omega}\bigg|_{h_2} \sigma_{\gamma h_1 \to V \otimes h_1}(\omega)\right]_{\omega_R}, \quad (1)$$

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, $\sigma_{\gamma h_i \to V \otimes h_i}$ is the total cross section of exclusive vector meson photoproduction, with the symbol $\otimes$ representing the presence of a rapidity gap in the final state and $\omega_L (\propto e^{-y})$ and $\omega_R (\propto e^{y})$ denoting photons from the h_1 and h_2 hadrons, respectively. Moreover, $\frac{dN}{d\omega}$ denotes the equivalent photon spectrum of the relativistic incident hadron, with the flux of a nucleus being enhanced by a factor Z^2 in comparison to the proton flux. Equation (1) takes into account the fact that both incident hadrons can be sources of the photons which will interact with the other hadron, with the first term on the right-hand side of Eq. (1) being dominant at positive rapidities, while the second term dominates at negative rapidities due to the fact that the photon flux has support at small values of ω, decreasing exponentially at large ω. As in Refs. [20,21], we will assume that the photon flux associated with the proton and nucleus can be described by the Dress-Zeppenfeld [22] and the relativistic pointlike charge [1] models, respectively. Additionally, in our calculations of exclusive vector meson photoproduction in hadronic collisions, we will assume that the rapidity gap survival probability S^2 (associated with the probability of the scattered proton not to dissociate due to secondary interactions) is equal to unity. The inclusion of these absorption effects in γh interactions is still a subject of intense debate [16,17,19].

The main input in Eq. (1) is the $\gamma h \to Vh$ cross section, which can be written as

$$\sigma(\gamma h \to Vh) = \int_{-\infty}^{0} \frac{d\sigma}{dt} dt = \frac{1}{16\pi} \int_{-\infty}^{0} |\mathcal{A}^{\gamma h \to Vh}(x, \Delta)|^2 dt, \quad (2)$$

with the amplitude for producing an exclusive vector meson diffractively being given in the color dipole formalism by

$$\mathcal{A}^{\gamma h \to Vh}(x, \Delta) = i \int dz d^2\boldsymbol{r} d^2\boldsymbol{b}_h (\Psi^{V*}\Psi) 2\mathcal{N}^h(x, \boldsymbol{r}, \boldsymbol{b}_h), \quad (3)$$

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 $\boldsymbol{b}_h$ is the impact parameter of the dipole relative to the hadron target. Moreover, the variables $\boldsymbol{r}$ and z are the dipole transverse radius and the momentum fraction of the photon carried by a quark (an antiquark, then, carries $1 - z$), respectively. $\mathcal{N}^h(x, \boldsymbol{r}, \boldsymbol{b}_h)$ is the forward dipole-target scattering amplitude (for a dipole at impact parameter $\boldsymbol{b}_h$), which encodes all the information about the hadronic scattering, and thus about the nonlinear and quantum effects in the hadron wave function. It depends on the γh center-of-mass reaction energy, $W = [2\omega\sqrt{s}]^{1/2}$, through the variable $x = m_V^2/W^2$. In the case of a nuclear target, we will assume that the forward dipole-nucleus amplitude can be expressed as follows:

$$\mathcal{N}^A(x, \boldsymbol{r}, \boldsymbol{b}_A) = 1 - \exp\left[-\frac{1}{2}\sigma_{dp}(x, \boldsymbol{r}^2) A T_A(\boldsymbol{b}_A)\right], \quad (4)$$

where $T_A(\boldsymbol{b}_A)$ is the nuclear profile function, which is obtained from a three-parameter Fermi distribution for the nuclear density normalized to 1, and σ_{dp} is the dipole-proton cross section expressed by

$$\sigma_{dp} = 2 \int d^2\boldsymbol{b}_p \mathcal{N}^p(x, \boldsymbol{r}, \boldsymbol{b}_p), \quad (5)$$

with $\mathcal{N}^p$ being the dipole-proton scattering amplitude.

We have that in order to estimate the γh cross sections and rapidity distributions in the color dipole formalism, we should specify the models for the vector meson wave functions and $\mathcal{N}^p$. In what follows, we will consider the boosted Gaussian model [23,24] for the overlap function and the impact-parameter color glass condensate (bCGC) model [24] for the dipole-proton scattering amplitude $\mathcal{N}^p$. As demonstrated in Ref. [25], these models allow us to successfully describe the high-precision combined HERA data on inclusive and exclusive processes. The impact on the predictions of different models for the vector meson wave function and dipole-proton scattering amplitude was investigated in Refs. [18,20,21,26]. These authors verified that the main effect of a different model for the vector meson wave function is the modification of the normalization of the cross sections, while distinct models for $\mathcal{N}^p$ predict different energy and rapidity dependencies for the observables. In this paper, we will complement these previous studies by the analysis of the impact of different values of the charm mass on the predictions. As demonstrated in Refs. [25,26], the high-precision combined HERA data can be described by two different sets of parameters for the bCGC and vector meson wave function, depending on the choice for the charm mass ($m_c = 1.27$ or 1.4 GeV). We will estimate the cross sections considering these two different sets of parameters, and the corresponding band will be denoted bCGC (13). For comparison, we also will present the predictions obtained using the parameters originally obtained in Ref. [24] for $m_c = 1.4$ GeV, which will be denoted bCGC(06) hereafter. Finally, as in Refs. [20,21], we also include in our calculations the corrections associated with the real part of the amplitude and the skewness factor, which is related to the fact that the gluons attached to the $q\bar{q}$ pair can carry different light-cone momentum fractions x, x' of the target.

III. RESULTS

In Fig. 1, we present our predictions for the rapidity distributions for exclusive J/Ψ, $\Psi(2S)$ and Υ photoproduction in pp (upper panels) and $PbPb$ (lower panels) collisions considering the center-of-mass energies of Run 2. One can see that the predictions calculated using the parameters for $m_c = 1.4(1.27)$ GeV define the lower (upper) bound of the band. In the particular case of the Υ production, we also have assumed $m_b = 4.5\ (4.2)$ GeV. The values of the corresponding cross sections are shown in Table I. Considering the results obtained assuming $m_c = 1.4$ GeV, we have that the bCGC(13) predictions for $Y = 0$ are smaller than the bCGC (06) one, with the difference increasing for heavier vector mesons. In comparison with our previous predictions [20,21] for the J/Ψ and Υ production, obtained for $m_c = 1.4$ GeV and $m_b = 4.2$ GeV, we observe that the values are smaller by $\approx$10%. In the case of $\Psi(2S)$ production, we have checked that our predictions for the Run 1 energies are smaller by $\approx$13% than the previous estimates [27], obtained using the Iancu-Itakura-Munier model [28] for the dipole-proton scattering amplitude. It is important to emphasize that the bCGC predictions for the Υ production in $PbPb$ collisions are being presented for the first time, since in our previous paper [21] this scenario was not considered.

In what follows, we will concentrate our analysis on exclusive vector meson photoproduction in pp collisions, which was studied by the LHCb Collaboration and allows us to do a more detailed comparison of our predictions with the experimental data. In particular, the LHCb Collaboration has recently released [10] the first (preliminary) data on exclusive J/Ψ and $\Psi(2S)$ production at $\sqrt{s} = 13$ TeV. In Fig. 2, we compare our predictions for the rapidity distributions measured in exclusive J/Ψ photoproduction in pp collisions at $\sqrt{s} = 7$ TeV (left panel) and 13 TeV (right panel) with the corresponding LHCb data [8,10]. The figure shows that the bCGC(13) predictions for $m_c = 1.4$ GeV are smaller than the bCGC(06) one for midrapidities, but larger for forward rapidities, which is directly associated with different energy dependence for the saturation scale predicted by these two versions of the bCGC model. Additionally, we observe that the bCGC(13) predictions for $m_c = 1.4$ GeV (lower curves of band) describe these data quite well, without the need of modifying the original parameters of the model or introducing any additional physical effect. Similar conclusions are derived from the analysis of Fig. 3, where we present our predictions for the exclusive $\Psi(2S)$ photoproduction.

In Fig. 4 (left panel), we present our predictions for exclusive Υ production and compare them with the LHCb data for $\sqrt{s} = 7$ TeV [9]. For this final state, the bCGC(13) predictions, obtained assuming $m_c = 1.4$ GeV and $m_b = 4.5$ GeV (lower curves of band), are smaller than the

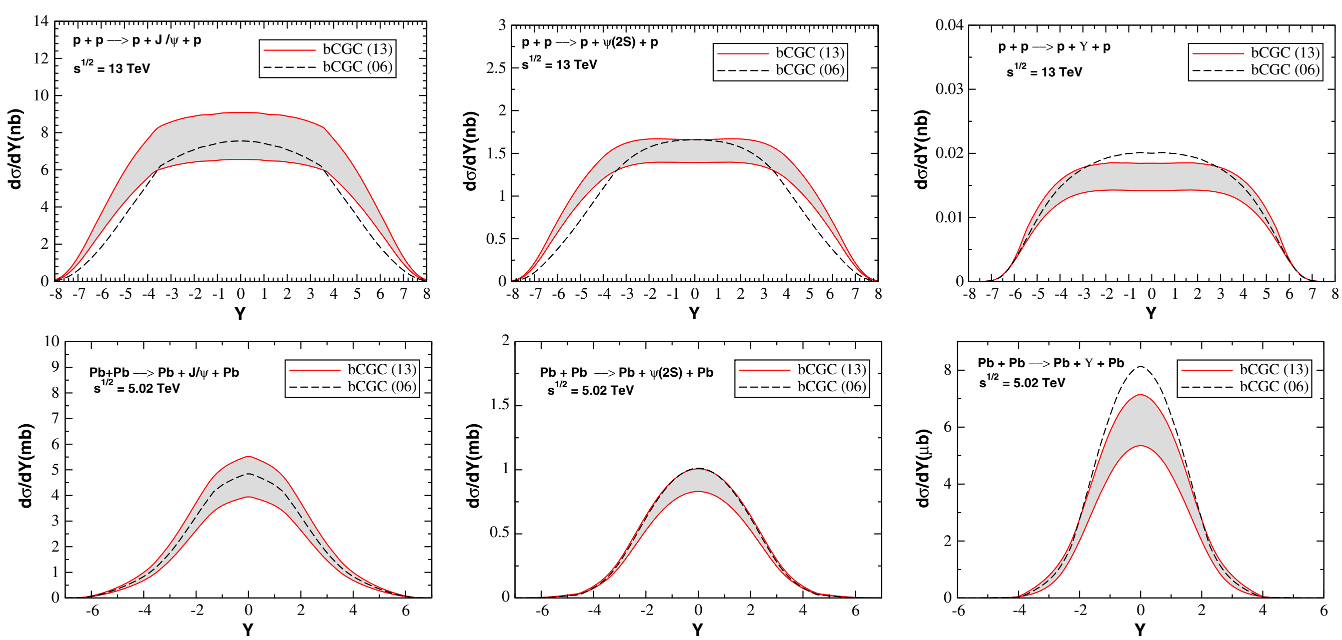

FIG. 1. Rapidity distributions for the exclusive J/Ψ, $\Psi(2S)$, and Υ photoproduction in pp (upper panels) and $PbPb$ (lower panels) collisions.

TABLE I. Total cross sections for the exclusive J/Ψ, $\Psi(2S)$ and Υ photoproduction in pp and $PbPb$ collisions at the Run 2 LHC energies considering the bCGC and vector meson parameters for $m_c = 1.4(1.27)$ GeV obtained in Refs. [25,26]. In the case of Υ production, we also have assumed $m_b = 4.5(4.2)$ GeV.

	J/Ψ	$\Psi(2S)$	Υ
pp ($\sqrt{s} = 13$ TeV)	72.4 (89.3) nb	15.5 (18.6) nb	150.6 (189.5) pb
$PbPb$ ($\sqrt{s} = 5.02$ TeV)	21.6 (28.7) mb	4.07 (4.93) mb	18.1 (26.02) μb

bCGC(06) in the full range of rapidities considered. Moreover, we can see that also for this final state, the bCGC(13) model prediction successfully describes the data. Our prediction for $\sqrt{s} = 13$ TeV, which is expected to be reached in Run 2, is also presented in the right panel of Fig. 4. The comparison of our predictions with future experimental data will be an important check of the bCGC model, since Υ production probes smaller dipole separations in comparison to J/Ψ production. While the J/Ψ photoproduction is expected to probe the nonlinear regime of the QCD dynamics, the Υ should be sensitive to the transition between the linear and nonlinear regimes. Therefore, we believe that a unified description of the exclusive J/Ψ, $\Psi(2S)$, and Υ photoproduction is one important test of the underlying dynamics.

One of the main motivations to study the rapidity distributions is that they allow us to access the energy dependence of the $\gamma h \to V h$ cross sections in a new

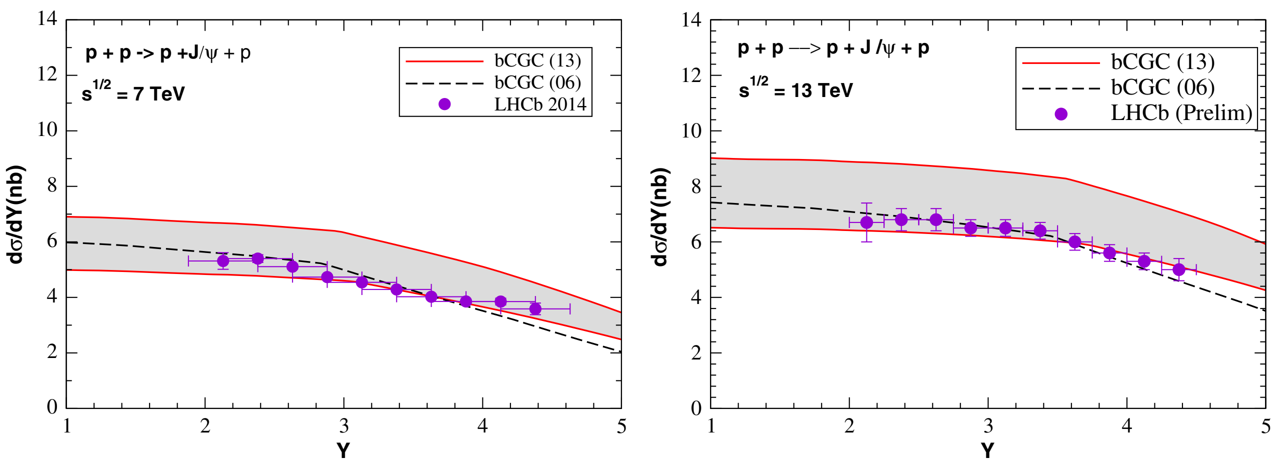

FIG. 2. Rapidity distributions for the exclusive J/Ψ photoproduction in pp collisions at $\sqrt{s} = 7$ TeV (left panel) and 13 TeV (right panel). Data from the LHCb Collaboration [8,10].

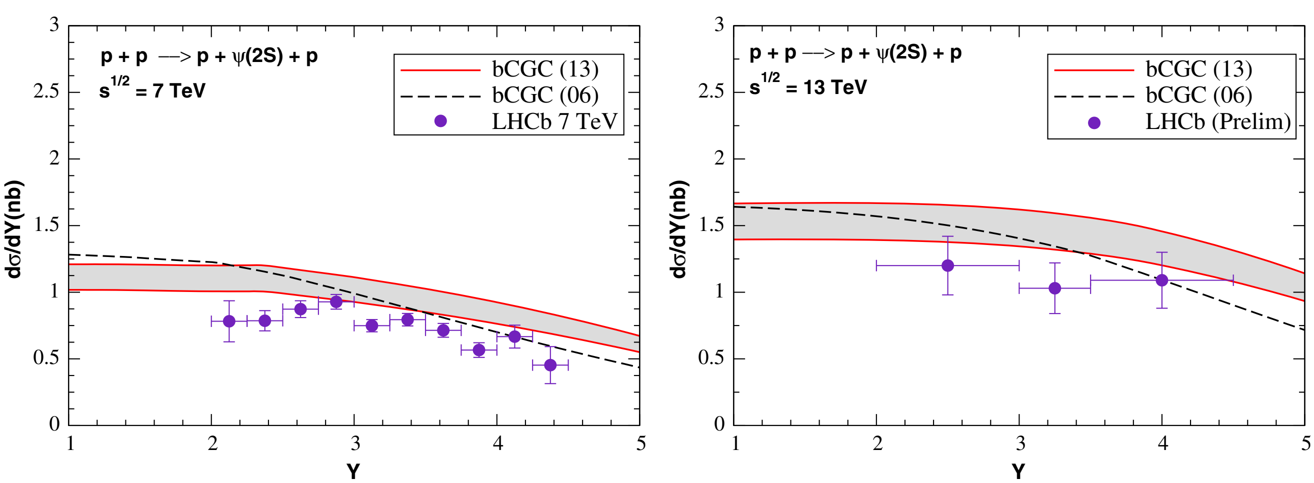

FIG. 3. Rapidity distributions for the exclusive $\Psi(2S)$ photoproduction in pp collisions at $\sqrt{s} = 7$ TeV (left panel) and 13 TeV (right panel). Data from the LHCb Collaboration [8,10].

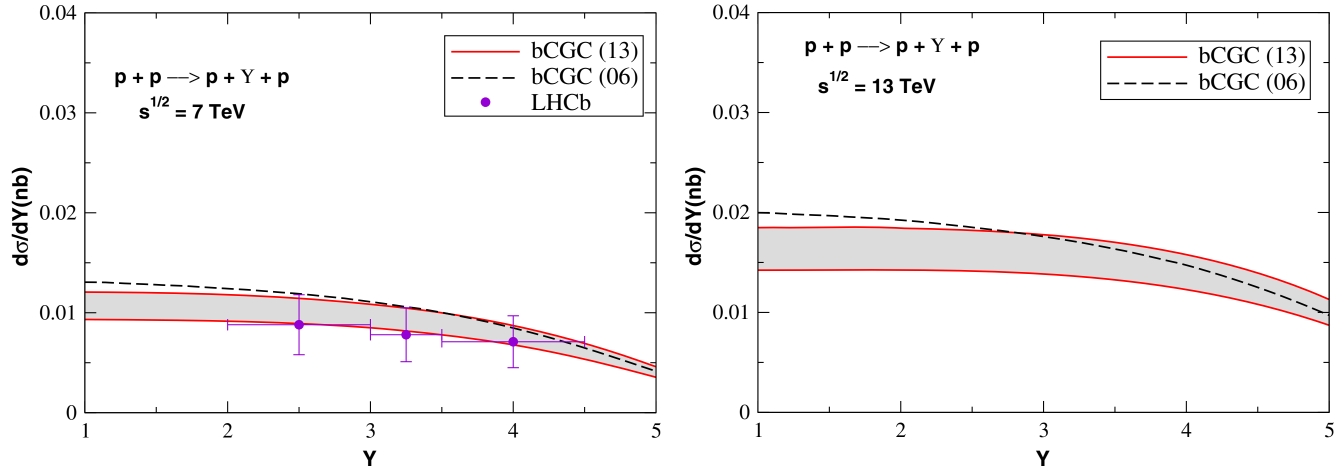

FIG. 4. Rapidity distributions for the exclusive Υ photoproduction in pp collisions at $\sqrt{s} = 7$ TeV (left panel) and 13 TeV (right panel). Data from the LHCb Collaboration [9].

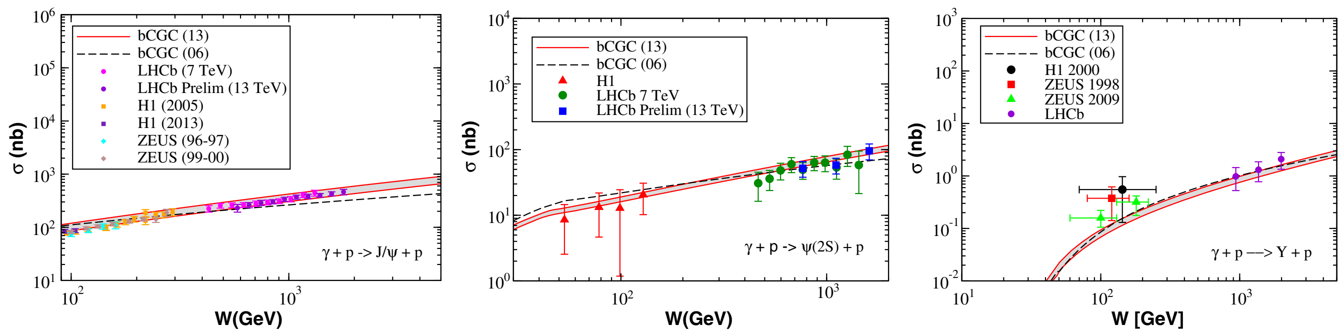

FIG. 5. Energy dependence of the exclusive J/Ψ, $\Psi(2S)$, and Υ photoproduction cross sections. Data from HERA [29,30] and LHCb [8–10].

kinematical range, which was not probed, e.g., in ep collisions at HERA. The presence of nonlinear effects in the QCD dynamics is predicted to modify the energy behavior of the cross sections, since the growth of the energy implies that smaller values of $x \approx M_V^2/W^2$ are probed in the forward dipole-target scattering amplitude. Moreover, due to the difference of masses between the J/Ψ and Υ, the studies of both mesons are complementary. Moreover, the study of the $\Psi(2S)$ provides complementary information about the description of the vector meson wave functions [26]. In Fig. 5, we compare our predictions with the LHCb data derived following the procedure presented in Refs. [9,10]. In particular, in the left panel we can see that our predictions describe quite well the preliminary LHCb data on the exclusive J/Ψ photoproduction in pp collisions at $\sqrt{s} = 13$ TeV, which cannot be described by a simple power-law fit of the HERA data [10]. Similar agreement is also observed in the case of the $\Psi(2S)$ and Υ production, shown in the central and right panels of Fig. 5, respectively. These conclusions are not unexpected, since the bCGC model describes the data for the rapidity distributions. We have that bCGC(06) predictions underestimate the J/Ψ data for high energies, which is directly associated with the behavior observed in Fig. 2 at large rapidities. For the $\Psi(2S)$ case, the bCGC(06) prediction for large energies also is smaller than the bCGC(13) one, as expected from Fig. 3. In contrast, in the case of Υ production, the bCGC(06) prediction is larger than the bCGC(13) one, but it also implies a satisfactory description of the current data. Finally, it is important to emphasize that our predictions for the $\gamma p \to Vp$ cross section, with $V = J/\Psi$ and $\Psi(2S)$, agree with those presented in Ref. [26]. In the case of Υ production, the bCGC(13) predictions are presented in this paper by the first time.

IV. SUMMARY

Recent experimental results have demonstrated that the study of hadronic physics using photon-induced interactions in $pp/pA/AA$ colliders is feasible. In particular, γh interactions at LHC probe a kinematical range unexplored by previous colliders. The outcoming data on exclusive J/Ψ, $\Psi(2S)$, and Υ photoproduction in hadronic collisions probe a kinematical range where nonlinear effects are expected to strongly affect the QCD dynamics. In our previous studies, we have shown that using the dipole framework and taking into account saturation effects (as in the bCGC model), we are able to describe the Run 1 LHC data. In this paper, we have updated our comparison with the Run 1 LHCb data, and we present our predictions for the energies considered in Run 2. The dependence of our predictions on the charm mass have been investigated. Our results demonstrated that the bCGC(13) model reproduces the Run 1 data as well as the preliminary data on pp collisions at $\sqrt{s} = 13$ TeV. Moreover, we have shown that the model also is able to describe the current data on the $\gamma p \rightarrow Vp$ cross section. Considering that the bCGC model is also able to describe the inclusive and exclusive HERA data, these results suggest that in order to understand γh interactions at high energies, we need to take into account QCD nonlinear effects. Although the Run 1 data can also be described by alternative models—as e.g. the model proposed in Ref. [19], which is based on different assumptions, a simplistic model for the vector meson wave functions, and that assumes an effective model for the gluon distribution adjusted to describe the data—we strongly believe that a comprehensive analysis of the experimental data on exclusive light and heavy vector meson photoproduction in hadronic collisions in Run 2 should demonstrate that only *a unified description of these different final states* will possibly take into account the nonlinear effects in QCD dynamics, allowing us to discriminate between the different approaches to the QCD dynamics.

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