Exclusive heavy vector meson photoproduction in hadronic collisions at the LHC: predictions of the Color Glass Condensate model for Run 2 energies

V. P. Gonçalves 1, B. D. Moreira 2 and F. S. Navarra 2

1 High and Medium Energy Group, Instituto de Física e Matemática, Universidade Federal de Pelotas
Caixa Postal 354, CEP 96010-900, Pelotas, RS, Brazil
2 Instituto de Física, Universidade de São Paulo, C.P. 66318, 05315-970 São Paulo, SP, Brazil

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In this letter we update our predictions for exclusive J/Ψ 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. 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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The study of photon - induced processes in hadronic collisions [1] became a reality in the last years [2–11] and new data associated to the Run 2 of the LHC are expected to be released soon. Theoretically, we expect that these new data 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 [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 years, this process was studied by several theoretical groups considering different formalisms and underlying assumptions (See e.g. [15, 16]). In particular, in Refs. [15, 16] 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 have 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. [15, 16] 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 the Run 2. One of the motivations for this letter, is to present predictions that can be directly compared with the expected Run 2 data. Another one is to present for the first time a comparison between our predictions and the data on the energy dependence of the total γp → Vp (V = J/Ψ, Υ) cross section, which have been extracted from the data on rapidity distributions of the vector mesons photoproduced in hadronic collisions. Finally, as a by product, we also present a comparison of our prediction [16] for the exclusive Υ photoproduction in pp collisions at √s = 7 TeV with the LHCb data [3] that have been released after the publication of our previous paper.

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. [15, 16]). 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 letter 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:

\[
\frac{dσ}{dY}[h_1 + h_2 \rightarrow h_1 \otimes V \otimes h_2] = \left[ \frac{dN}{d\omega} \mid h_1, \sigma_{h_1 \rightarrow V \otimes h_2} (\omega) \right]_{\omega_{L}} + \left[ \frac{dN}{d\omega} \mid h_2, \sigma_{h_2 \rightarrow V \otimes h_1} (\omega) \right]_{\omega_{R}}
\]  

(1)
where the rapidity ($Y$) of the vector meson in the final state is determined by the photon energy $\omega$ in the collision frame and by the mass $M_V$ of the vector meson [$y \propto \ln(\omega/M_V)$]. Moreover, $\sigma_{\gamma h \rightarrow V \odot h}$ is the total cross section of exclusive vector meson photoproduction, with the symbol $\odot$ 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, $\frac{\Delta}{\sqrt{s}}$ 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 one. Eq. (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 the Eq. (1) being dominant at positive rapidities while the second term dominating at negative rapidities due to the fact that the photon flux has support at small values of $\omega$, decreasing exponentially at large $\omega$. As in Refs. [15,16] we will assume that the photon flux associated to the proton and nucleus can be described by the Dress - Zeppenfeld [21] and the relativistic point - like 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 to probability of the scattered proton not to dissociate due to secondary interactions) is equal to the unity. The inclusion of these absorption effects in $\gamma h$ interactions is still a subject of intense debate [18,20].

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

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

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

$$A^{\gamma h \rightarrow V h}(x,\Delta) = i \int dz d^2r d^2b_h (\Psi^{V*} \Psi) 2N^h(x,r,b_h)/(3)$$

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 $b_h$ is the impact parameter of the dipole relative to the hadron target. Moreover, the variables $r$ and $z$ are the dipole transverse radius and the momentum fraction of the photon carried by a quark (an antiquark carries then $1 - z$), respectively. $N^h(x,r,b_h)$ is the forward dipole-target scattering amplitude (for a dipole at impact parameter $b_h$) 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 $\gamma h$ center-of-mass reaction energy, $W = 2m_{\gamma}/W^2$. As in Refs. [15,16], in what follows we will consider the Boosted Gaussian model [22,23] for the overlap function and the impact parameter Color Glass Condensate (bCGC) model [23] for the dipole – proton scattering amplitude $N^p$. As demonstrated in Ref. [24], these models allow us to successfully describe the high precision combined HERA data on inclusive and exclusive processes. In the case of a nuclear target, we will assume that the forward dipole-nucleus amplitude can be expressed as follows

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

where $T_A(b_A)$ is the nuclear profile function, which is obtained from a 3-parameter Fermi distribution for the nuclear density normalized to 1, and the $\sigma_{dp}$ is the dipole-proton cross section is expressed by

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

with $N^p$ given by the bCGC model. Finally, as in Refs. [15,16], we also include in our calculations the corrections associated to 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.

In Fig. 1 we present our predictions for the rapidity distributions for exclusive $J/\Psi$ and $\Upsilon$ photoproduction in $pp$ (upper panel) and $PbPb$ (lower panel) collisions considering the center of mass energies of the Run 2. The values of the corresponding cross sections are show in Table I. In comparison with our previous predictions [15,16] we observe that the values are smaller by $\approx 10\%$. It is important to emphasize that the bCGC predictions for the $\Upsilon$ production in $PbPb$ collisions are being presented for the first time, since in our previous paper [16] 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 $J/\Psi$ production at $\sqrt{s} = 13$ TeV. In Fig. 2 we compare our predictions for the rapidity distributions measured in exclusive $J/\Psi$ photoproduction in $pp$ collisions at $\sqrt{s} = 7$ (upper panel) and 13 TeV (lower panel) with the corresponding LHCb data [8,10]. We observe that the bCGC predictions describe these data quite well, without the need of modifying the original

| $pp$ ($\sqrt{s} = 13$ TeV) | $pp$ ($\sqrt{s} = 5.02$ TeV) |
|--------------------------|--------------------------|
| 72.4 nb                  | 21.6 mb                  |
| 189.5 pb                 | 26.02 pb                 |

**TABLE I**: Total cross sections for the exclusive $J/\Psi$ and $\Upsilon$ photoproduction in $pp$ and $PbPb$ collisions at the Run 2 LHC energies.
parameters of the model or introducing any additional physical effect. In Fig. 3 (upper panel) we present our predictions for exclusive Υ production and compare them with the LHCb data for √s = 7 TeV [9]. We can see that also for this final state, the bCGC model successfully describes the data. Our prediction for √s = 13 TeV, which is expected to be reached in the Run 2, is also presented (lower panel). The comparison of our prediction 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.

One of the main motivations to study the rapidity distributions is that they allow us to access the energy dependence of the γh → Vh cross sections in a new 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. In Fig. 4 we compare our predictions with the LHCb data derived following the procedure presented in Refs. [9, 10]. In particular, in the upper panel we can see that our predictions describe quite well the preliminary LHCb data on the exclusive J/Ψ photoproduction in pp collisions at √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 Υ production, shown in the lower panel of Fig. 4. These conclusions are not unexpected, since the bCGC model describes the data for the rapidity distributions.

Finally, let us summarize our main conclusions. 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 outcome data on exclusive J/Ψ
FIG. 3: Rapidity distributions for the exclusive $\Upsilon$ photoproduction in $pp$ collisions at $\sqrt{s} = 7$ (upper panel) and 13 TeV (lower panel). Data from LHCb Collaboration [9].

and $\Upsilon$ 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 letter we have updated our comparison with the Run 1 LHCb data and we present our predictions for the energies considered in the Run 2. Our results demonstrated that the bCGC 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 $\gamma p \rightarrow J/\Psi + p$ 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 $\gamma h$ interactions at high energies we need to take into account QCD nonlinear effects. We strongly believe that a comprehensive analysis of the experimental data on exclusive light and heavy vector meson photoproduction in hadronic collisions at the Run 2 will allow to discriminate between the different approaches to the QCD dynamics.

FIG. 4: Energy dependence of the exclusive $J/\Psi$ (upper panel) and $\Upsilon$ (lower panel) $\gamma p$ cross sections. Data from HERA [25, 26] and LHCb [8–10].

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[1] G. Baur, K. Hencken, D. Trautmann, S. Sadovsky, Y. Kharlov, Phys. Rep. 364, 359 (2002); V. P. Goncalves and M. V. T. Machado, Mod. Phys. Lett. A 19, 2525 (2004); C. A. Bertulani, S. R. Klein and J. Nystrand, Ann. Rev. Nucl. Part. Sci. 55, 271 (2005); K. Hencken et al., Phys. Rept. 458, 1 (2008).
[2] T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 102, 242001 (2009)
[3] C. Adler et al. [STAR Collaboration], Phys. Rev. Lett. 89, 272302 (2002)
[4] S. Afanasiev et al. [PHENIX Collaboration], Phys. Lett. B 679, 321 (2009)
[5] B. Abelev et al. [ALICE Collaboration], Phys. Lett. B 718, 1273 (2013)
[6] E. Abbas et al. [ALICE Collaboration], Eur. Phys. J. C 73, 2617 (2013)
[7] R. Aaij et al. [LHCb Collaboration], J. Phys. G 40, 045001 (2013)
[8] R. Aaij et al. [LHCb Collaboration], J. Phys. G 41, 055002 (2014)
[9] R. Aaij et al. [LHCb Collaboration], JHEP 1509, 084 (2015)
[10] R. Aaij et al. [LHCb Collaboration], LHCb-CONF-2016-007.
[11] K. Akiba et al. [LHC Forward Physics Working Group Collaboration], J. Phys. G 43, 110201 (2016)
[12] F. Gelis, E. Iancu, J. Jalilian-Marian and R. Venugopalan, Ann. Rev. Nucl. Part. Sci. 60, 463 (2010); E. Iancu and R. Venugopalan, arXiv:hep-ph/0303204; H. Weigert, Prog. Part. Nucl. Phys. 55, 461 (2005); J. Jalilian-Marian and Y. V. Kovchegov, Prog. Part. Nucl. Phys. 56, 104 (2006); J. L. Albacete and C. Marquet, Prog. Part. Nucl. Phys. 76, 1 (2014).
[13] V. P. Goncalves and C. A. Bertulani, Phys. Rev. C 65, 054905 (2002).
[14] V. P. Goncalves and M. V. T. Machado, Eur. Phys. J. C 40, 519 (2005).
[15] V. P. Goncalves, B. D. Moreira and F. S. Navarra, Phys. Rev. C 90, 015203 (2014).
[16] V. P. Goncalves, B. D. Moreira and F. S. Navarra, Phys. Lett. B 742, 172 (2015).
[17] V. P. Goncalves and M. V. T. Machado, Phys. Rev. C 73, 044902 (2006); Phys. Rev. D 77, 014037 (2008); Phys. Rev. C 84, 011902 (2011).
[18] L. Frankfurt, V. Guzey, M. Strikman and M. Zhalov, JHEP 0308, 043 (2003); V. Guzey and M. Zhalov, JHEP 1310, 207 (2013); JHEP 1402, 046 (2014).
[19] W. Schafer and A. Szczurek, Phys. Rev. D 76, 094014 (2007); A. Rybarska, W. Schafer and A. Szczurek, Phys. Lett. B 668, 126 (2008); A. Cisek, W. Schafer and A. Szczurek, Phys. Rev. C 86, 014905 (2012).
[20] S. P. Jones, A. D. Martin, M. G. Ryskin and T. Teubner, JHEP 1311, 085 (2013); Eur. Phys. J. C 76, no. 11, 633 (2016).
[21] M. Drees and D. Zeppenfeld, Phys. Rev. D 39, 2536 (1989).
[22] H. Kowalski and D. Teaney, Phys. Rev. D 68, 114005 (2003).
[23] H. Kowalski, L. Motyka and G. Watt, Phys. Rev. D 74, 074016 (2006).
[24] A. Rezaeian and I. Schmidt, Phys. Rev. D 88, 074016 (2013).
[25] J. Breitweg et al. [ZEUS Collaboration], Phys. Lett. B 437, 432 (1998); C. Adloff et al. [H1 Collaboration], Phys. Lett. B 483, 23 (2000); S. Chekanov et al. [ZEUS Collaboration], Eur. Phys. J. C 24, 345 (2002); Phys. Lett. B 680, 4 (2009); A. Aktas et al. [H1 Collaboration], Eur. Phys. J. C 46, 585 (2006).
[26] J. Breitweg et al. [ZEUS Collaboration], Phys. Lett. B437, 432 (1998); C. Adloff et al. [H1 Collaboration], Phys. Lett. B483, 23 (2000); S. Chekanov et al. [ZEUS Collaboration], Phys. Lett. B680, 4 (2009).