Physics Letters B 768 (2017) 299–304

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Investigating the impact of the gluon saturation effects on the momentum transfer distributions for the exclusive vector meson photoproduction in hadronic collisions

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ARTICLE INFO

Article history:
Received 4 January 2017
Received in revised form 22 February 2017
Accepted 6 March 2017
Available online 10 March 2017
Editor: A. Ringwald

ABSTRACT

The exclusive vector meson production cross section is one of the most promising observables to probe the high energy regime of the QCD dynamics. In particular, the squared momentum transfer (t) distributions are an important source of information about the spatial distribution of the gluons in the hadron and about fluctuations of the color fields. In this paper we complement previous studies on exclusive vector meson photoproduction in hadronic collisions presenting a comprehensive analysis of the t-spectrum measured in exclusive ρ, ϕ and J/Ψ photoproduction in pp and $PbPb$ collisions at the LHC. We compute the differential cross sections taking into account gluon saturation effects and compare the predictions with those obtained in the linear regime of the QCD dynamics. Our results show that gluon saturation suppresses the magnitude of the cross sections and shifts the position of the dips towards smaller values of t.

1. Introduction

Experimental results released in the last years have demonstrated that photon – induced interactions in hadronic collisions can be used to probe several aspects of the Standard Model (SM) as well as to test predictions of Beyond SM Physics. (For a recent review see Ref. [1].) In particular, the study of the exclusive vector meson photoproduction in hadronic collisions is an important source of information about the hadronic structure and also about QCD dynamics at high energies [2,3]. As exclusive processes are driven by the gluon content of the target, with the cross sections being proportional to the square of the scattering amplitude, they are strongly sensitive to the underlying QCD dynamics. Additionally, the squared momentum transfer (t) distributions give access to the spatial distribution of the gluons in the hadron and about fluctuations of the color fields (see e.g. Ref. [4]).

In the last years exclusive vector meson photoproduction in hadronic collisions has been discussed by several authors considering different assumptions and distinct approaches (see e.g. Refs. [5,7,8,10,9,6,11]). In particular, in Refs. [6,12] we demonstrated that the experimental LHC Run 1 data and the preliminary Run 2 data can be successfully described within the color dipole formalism if non-linear effects in the QCD dynamics are taken into account. The main advantage of this approach is that the main ingredients can be constrained by the very precise HERA data and hence the predictions for photon – induced interactions at the LHC are parameter free. In those previous works we presented our predictions for the t – integrated observables – rapidity distributions and total cross sections – which have been measured by the ALICE, CMS and LHCb Collaborations at the LHC in the Run 1. In principle, the t-distributions may be measured in Run 2 [1]. This encourages us to extend our previous studies and present the color dipole predictions for the t-spectrum measured in exclusive vector meson photoproduction in hadronic collisions. In particular, in this paper we will use the color dipole formalism to describe the photon-hadron interaction, with the scattering amplitude being expressed in terms of the impact parameter Color Glass Condensate (bCGC) model, which successfully describes the t-distributions for the exclusive vector meson production at HERA. We will compute the t-spectrum for the exclusive ρ, ϕ and J/Ψ photoproduction in pp and $PbPb$ collisions at the LHC energies probed in the Run 2. Moreover, in the case of $PbPb$ collisions, we will consider the coherent and incoherent contributions to exclusive production,

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http://dx.doi.org/10.1016/j.physletb.2017.03.009
0370-2693/

which are associated to processes where the nucleus target scatters elastically or breaks up, respectively. For a similar analysis considering alternative approaches see Ref. [13]. In order to investigate the impact of the gluon saturation effects, associated to non-linear contributions for the QCD dynamics at high energies, we will compare our predictions with those obtained disregarding these effects, i.e. using a linear model for the QCD dynamics. As the dipole formalism of exclusive processes has been discussed in detail in our previous works [6,12,14,15], in the next Section we will only review the main elements needed to study exclusive vector meson photoproduction in hadronic collisions. In Section 3 we will present our predictions for the rapidity and t-distributions and in Section 4 we will summarize our main conclusions.

2. Formalism

An ultra relativistic charged hadron (proton or nucleus) gives rise to strong electromagnetic fields. In a hadronic collision, 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) [16]. In the particular case of exclusive vector meson photoproduction in hadronic collisions, the differential cross section can be expressed as follows

$$\frac{d\sigma\;[h_1 + h_2 \rightarrow h_1 \otimes V \otimes h_2]}{dY\,dt} = \left[\omega \frac{dN}{d\omega}|_{h_1} \frac{d\sigma}{dt}(\gamma h_2 \rightarrow V \otimes h_2)\right]_{\omega_L} + \left[\omega \frac{dN}{d\omega}|_{h_2} \frac{d\sigma}{dt}(\gamma h_1 \rightarrow V \otimes h_1)\right]_{\omega_R} \;, \tag{1}$$

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 for the $\gamma h_i \rightarrow V \otimes h_i$ process, 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 photon energies from the h_1 and h_2 hadrons, respectively. Furthermore, $\frac{dN}{d\omega}$ 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 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 ω, decreasing exponentially at large ω. As in Refs. [6,12] we will assume that the photon flux associated to the proton and to the nucleus can be described by the Dress–Zeppenfeld [17] and the relativistic point – like charge [16] models, respectively.

In the color dipole formalism, the $\gamma h \rightarrow V h$ process 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 and the recombination into the vector meson V. The final state is characterized by the presence of a rapidity gap. The differential cross section for the exclusive vector meson photoproduction can be expressed as follows

$$\frac{d\sigma}{dt} = \frac{1}{16\pi}|\mathcal{A}^{\gamma h \rightarrow V h}(x, \Delta)|^2 \;, \tag{2}$$

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

$$\mathcal{A}^{\gamma h \rightarrow V h}(x, \Delta) = i \int dz\, d^2\boldsymbol{r}\, d^2\boldsymbol{b}_h\, e^{-i[\boldsymbol{b}_h - (1-z)\boldsymbol{r}].\boldsymbol{\Delta}} (\Psi^{V*}\Psi) \times 2\mathcal{N}^h(x, \boldsymbol{r}, \boldsymbol{b}_h) \;, \tag{3}$$

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 carries then $1 - z$), 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 non-linear 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 $x = M_V^2/W^2$. As in Refs. [6,12], in what follows we will consider the Boosted Gaussian model [18,19] for the overlap function and the impact parameter Color Glass Condensate (bCGC) model [19] for the dipole-proton scattering amplitude $\mathcal{N}^p$. In this model the dipole-proton scattering amplitude is given by [19]

$$\mathcal{N}^p(x, \boldsymbol{r}, \boldsymbol{b}_p) = \begin{cases} \mathcal{N}_0 \left(\frac{r\,Q_s(b_p)}{2}\right)^{2\left(\gamma_s + \frac{\ln(2/r\,Q_s(b_p))}{\kappa\,\lambda\,Y}\right)} & r Q_s(b_p) \leq 2 \\ 1 - e^{-A\,\ln^2(B\,r\,Q_s(b_p))} & r Q_s(b_p) > 2 \;, \end{cases} \tag{4}$$

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

$$Q_s(b_p) \equiv Q_s(x, b_p) = \left(\frac{x_0}{x}\right)^{\frac{\lambda}{2}} \left[\exp\left(-\frac{{b_p}^2}{2B_{\rm CGC}}\right)\right]^{\frac{1}{2\gamma_s}} \;, \tag{5}$$

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 $\lambda = 0.2063$. As demonstrated in Ref. [20], 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, the exclusive vector meson photoproduction can occur in coherent or incoherent interactions. If the nucleus scatters elastically, the process is called coherent production. On the other hand, if the nucleus scatters inelastically, i.e. breaks up, the process is denoted incoherent production. As discussed e.g. in Refs. [23,21,22], these different processes probe distinct properties of the gluon density of the nucleus. While coherent processes probe the average spatial distribution of gluons, the incoherent ones are determined by fluctuations and correlations in the gluon density. As demonstrated e.g. in Refs. [14,15], the incoherent processes dominate at large-t, with the coherent one being dominant when $t \rightarrow 0$. The coherent cross section is given by Eq. (2) in terms of the dipole-nucleus scattering amplitude $\mathcal{N}^A$. As in our previous works [6,12,14,15], we will assume that $\mathcal{N}^A$ can be expressed as follows

$$\mathcal{N}^A(x, \boldsymbol{r}, \boldsymbol{b}_A) = 1 - \exp\left[-\frac{1}{2}\sigma_{dp}(x, \boldsymbol{r}^2)\,A\,T_A(\boldsymbol{b}_A)\right] \;, \tag{6}$$

where $T_A(\boldsymbol{b}_A)$ is the nuclear profile function, which is obtained from a 3-parameter Fermi distribution form of the nuclear density normalized to 1, and σ_{dp} is the dipole-proton cross section that is expressed by