Vol. 12 (2019) *Acta Physica Polonica B Proceedings Supplement* No 4

VECTOR MESON ELECTRO-PRODUCTION WITHIN THE ENERGY-DEPENDENT HOT-SPOT MODEL*

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(Received March 5, 2019)

A model is presented in which the electro-production of light and heavy vector mesons is treated using the color dipole approach including the quantum fluctuations of the target structure. These fluctuations are generated by hot spots randomly placed in the transverse plane. The number of hot spots grows with decreasing Bjorken-x, which introduces an energy dependence of the target structure. This model successfully reproduces the exclusive and dissociative vector meson photo-production data from HERA and the LHC. Moreover, it predicts that, once the proton structure starts to resemble the gluon saturation picture, the dissociative cross section reaches a maximum and then decreases steeply with energy. This signal is present also in electro-production cross section and it has well-defined mass and scale dependence measurable at EIC/LHeC energies.

DOI:10.5506/APhysPolBSupp.12.787

1. Introduction

Perturbative QCD predicts that the gluon density in hadrons grows with energy or, equivalently, with decreasing Bjorken-x, up to a point where non-linear effects manifest to slow down this growth — a phenomenon known as gluon saturation; see *e.g.* [1]. A convenient tool for studying this phenomenon is the diffractive production of a vector meson.

In the Good–Walker formalism [2], exclusive diffractive processes are sensitive to the average over the different configurations of the target, while dissociative processes, where the target gets excited and dissociates into several particles, measure the variance over the configurations [3].

In this contribution, the report on studies [4–6] is presented, where the energy dependence of exclusive and dissociative $J/\Psi, \rho$ and Υ photo-production off protons is predicted, showing that it provides a clear signature

* Presented at the Diffraction and Low-x 2018 Workshop, August 26–September 1, 2018, Reggio Calabria, Italy.

of gluon saturation at the LHC. Our calculation reproduces correctly the rise of the exclusive and dissociative cross section with the c.m.s. energy W of the virtual photon and the incoming proton as measured at HERA and at the LHC, and predicts that the dissociative one reaches a maximum specific for each vector meson followed by a steep decrease of the cross section at higher energies. The data coming from future colliders EIC/LHeC will be crucial for testing the predicted phenomenon.

2. The amplitude of vector meson electro-production

The exclusive and dissociative production of vector mesons proceeds as follows. A photon with virtuality Q^2 interacts with the target proton with total energy W and forms a vector meson with mass M_{V} and Bjorken-$x = (M_{\mathrm{V}}^2 + Q^2)/(W^2 + Q^2)$. In the exclusive case, the target proton remains intact, while in the dissociative case the proton is resolved.

The amplitude of the process is treated within the color dipole model [7, 8] where the photon fluctuates into a coherent quark–antiquark pair with transverse size $\vec{r}$. This pair then interacts with the target at impact parameter $\vec{b}$ with the color dipole cross section σ_{dip} and, finally, the dipole forms a vector meson. In this approach, the amplitude can be written as follows (see *e.g.* [9]):

$$A^{\mathrm{T,L}}\left(x, Q^2, \vec{\Delta}\right) = i \int \mathrm{d}\vec{r} \int_0^1 \frac{\mathrm{d}z}{4\pi} (\Psi^* \Psi_{\mathrm{V}})_{\mathrm{T,L}} \int \mathrm{d}\vec{b}\, e^{-i\left(\vec{b}-(1-z)\vec{r}\right)\cdot\vec{\Delta}} \frac{\mathrm{d}\sigma_{\mathrm{dip}}}{\mathrm{d}\vec{b}}\,, \quad (1)$$

where Ψ_{V} and Ψ are the vector meson and the virtual photon wave functions, and z is the fraction of the longitudinal momenta of the dipole carried by the quark. The sub-indices 'T' and 'L' refer to the contribution of the transversal and longitudinal virtual photon, respectively. For Ψ the definitions and parameter values from [10] and for Ψ_{V} the boosted Gaussian model [11, 12] was used, with the numerical values of the parameters taken from [9].

The dipole–target cross section is related via the optical theorem to the imaginary part of the forward dipole–target amplitude $N(x, \vec{r}, \vec{b})$ as

$$\frac{\mathrm{d}\sigma_{\mathrm{dip}}}{\mathrm{d}\vec{b}} = 2N\left(x, \vec{r}, \vec{b}\right) = \sigma_0 N(x, r) T\left(\vec{b}\right)\,. \quad (2)$$

In order to use the impact parameter integrated dipole amplitude, the dipole scattering amplitude is factorized (see [4, 13]), where $\sigma_0 \equiv 4\pi B_p$ is a normalization constant and $T(\vec{b})$ describes the proton profile in the impact parameter plane. The form of $N(x, r)$ is given by the GBW model [10]. Following [4–6, 14, 15], the proton profile is defined as the sum of $N_{\mathrm{hs}}(x)$

regions of high-gluon density, called hot spots, with each of them having a Gaussian distribution

$$T\left(\vec{b}\right) = \frac{1}{N_{\rm hs}(x)} \sum_{i=1}^{N_{\rm hs}(x)} T_{\rm hs}\left(\vec{b}-\vec{b_i}\right), \qquad T_{\rm hs}\left(\vec{b}-\vec{b_i}\right) = \frac{1}{2\pi B_{\rm hs}} e^{-\frac{(\vec{b}-\vec{b_i})^2}{2B_{\rm hs}}}, \tag{3}$$

where each $\vec{b_i}$ is obtained from a 2-dimensional Gaussian distribution centered at $(0,0)$ and a width B_p. The key ingredient of our model is that it includes an indirect energy dependence of the proton profile $T(\vec{b}\,)$ by making the number of hot spots grow with decreasing x (see [6]).

Using amplitude (1), the cross section is

$$\frac{\mathrm{d}\sigma^{\gamma p\to Vp}_{\rm T,L}}{\mathrm{d}t} = \frac{1}{16\pi}\left|\left\langle A^{\rm T,L} R_g^{\rm T,L}\right\rangle\right|^2 \tag{4}$$

for the exclusive process, and

$$\frac{\mathrm{d}\sigma^{\gamma p\to VY}_{\rm T,L}}{\mathrm{d}t} = \frac{1}{16\pi}\left(\left\langle\left|A^{\rm T,L} R_g^{\rm T,L}\right|^2\right\rangle - \left|\left\langle A^{\rm T,L} R_g^{\rm T,L}\right\rangle\right|^2\right) \tag{5}$$

for the dissociative production, where R_g is the skewedness correction [16].

3. Results

Results shown here are based on [17]. The parameters of the model were fixed in [4, 6] using data for photo-production of J/Ψ from HERA. Although the model is relatively simple and has been developed to describe photo-production of J/Ψ, it has been shown in [6] that it describes also data for photo-production of other vector mesons. The key observation in [4, 6] is that the dissociative cross section for all mesons rises with W up to its maxima and it drops afterwards. This signature given by a process reminiscent of percolation of the hot-spot phase space has a clear dependence on the mass of the vector meson.

In Fig. 1, an extension of our model for J/Ψ, Υ and ρ for $Q^2>0$ is presented together with data from HERA [18–25] and from the LHC [26, 27] without introducing any additional parameter (see [17]). The model describes reasonably well available data for exclusive electro-production for all Q^2. The saturation signal seen in the photo-production of J/Ψ, Υ and ρ is also present in electro-production and the maximum of the cross section moves to higher W with increasing photon virtuality. The smaller the mass of the meson is, the faster the maximum moves with Q^2. Note that preliminary data from the H1 experiment for the dissociative ρ photo-production presented at ICHEP 2018 are well in line with our prediction as they show that the cross section decreases with energy.

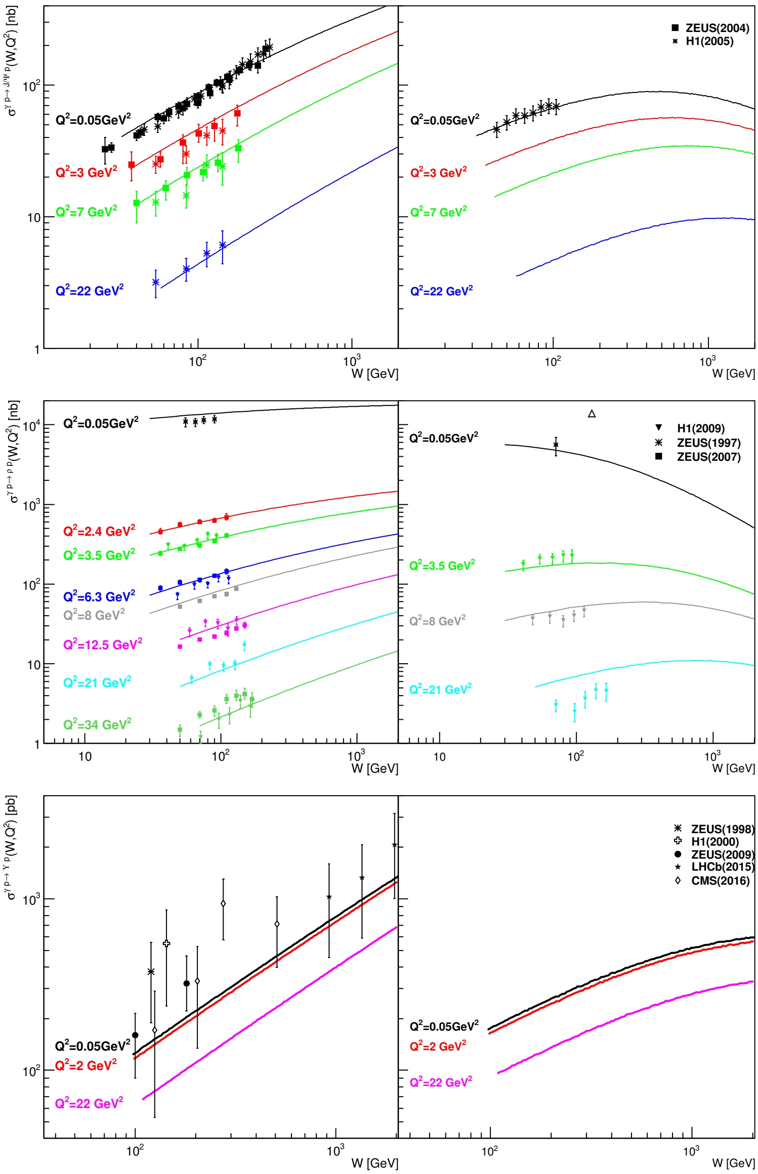

Fig. 1. The W dependence of the cross section for exclusive (left) and dissociative (right) production of J/Ψ (upper plots), Υ (middle plots) and ρ (lower plots) as measured by H1 [18, 19] and ZEUS [20–22]. Data from H1 [23], ZEUS [24, 25], LHCb [26], and CMS [27] for Υ are for photo-production only.

4. Summary and discussion

In this publication, a model for the exclusive and dissociative vector meson photo- and electro-production cross section that incorporates a fluctuating hot-spot structure of the proton in the impact parameter plane have been presented. The key ingredient of the model is that the number of hot spots grows with decreasing x. The model describes correctly the W dependence of the exclusive and dissociative J/Ψ, ρ and Υ production cross section as measured by HERA and LHC experiments.

The energy dependence of the dissociative cross section has a geometrical property reminiscent of percolation. At some point, the number of hot spots is so large that they overlap. When the overlap is large enough, different configurations look the same and the variance decreases. The model predicts that the energy dependence of the dissociative process increases from low energies up to a maximum and then steeply decreases. The position of the maxima depends on the mass of the vector meson considered and the scale of the process. This behavior happens within the energy range accessible at EIC for ρ and ϕ and at the LHeC for all vector mesons.

This work was supported by the grant 17-04505S of the Czech Science Foundation.

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