VECTOR MESON PRODUCTION IN ULTRAPERIPHERAL COLLISIONS AT THE LHC

© R. Fiore,∗ L. Jenkovszky,† V. Libov,‡ and M. V. T. Machado§

Using a Regge-pole model for vector meson production (VMP) that successfully describes the HERA data, we analyze the correlation between VMP cross sections in photon-induced reactions at HERA and those in ultraperipheral collisions at the large hadron collider. We obtain predictions for future experiments on the production of \( J/\psi \) and other vector mesons.

Keywords: vector meson, collider, HERA, large hadron collider, pomeron

1. Introduction

After the shutdown of the HERA collider at DESY (Germany), exclusive diffractive production of mesons in ultraperipheral collisions of protons and nuclei became among the priorities of present and future studies at the CERN large hadron collider (LHC) [1], [2], triggering a large number of theoretical investigations [3]–[7] (see, e.g., [8] for a relevant review). The first results for vector meson production (VMP), for \( J/\psi \) in particular, have already been published [1], [2].

In this study of VMP at the CERN LHC, we scrutinize possible changes in the energy dependence of the cross sections when moving from HERA to the LHC. In particular, we are interested in the change from “soft” (light vector mesons) to heavy mesons (\( \phi \), \( J/\psi \), \( \Upsilon \), etc.).

2. The VMP at HERA

The VMP was studied in detail at HERA by both the H1 and ZEUS collaborations. Most of the events were chosen in the kinematic region corresponding to diffractive scattering, which means that the processes can be described by a pomeron exchange (see Fig. 1). Pomeron dominance is especially clean in \( J/\Psi \) production, where any exchange of secondary trajectories made of quarks is forbidden by the Zweig (OZI) rule, thus leaving the uncontaminated pomeron exchange alone. This does not mean that the dynamics is simple, but we have the opportunity in this class of reactions to scrutinize the nature of the pomeron, a complicated and controversial object. The main problem is the twin nature of the pomeron: it seems to be “soft” or “hard” depending on the virtuality of the incident photon and/or the mass of the produced vector meson.

∗Dipartimento di Fisica, Università della Calabria, Calabria, Italy; Instituto Nazionale di Fisica Nucleare, Gruppo collegato di Cosenza, Cosenza, Italy, e-mail: fiore@fis.unical.it.
†Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine, e-mail: jenk@bitp.kiev.ua.
‡DESY, Hamburg, Germany, e-mail: vladyslav.libov@desy.de.
§HEP Phenomenology Group, CEP, Porto Alegre, RS, Brazil, e-mail: magnus@if.ufrgs.br.

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In most of the papers on the subject, the existence of two pomerons is assumed: a hard or QCD pomeron, resulting from perturbative quantum chromodynamic calculations, and a soft pomeron, somewhat misleadingly called a “nonperturbative” pomeron. We instead believe that there is only one pomeron in Nature, but it has two components, whose relative weight is regulated by relevant $Q^2$-dependent factors in front of them, where the measure of the “hardness” $\tilde{Q}^2 = Q^2 + M^2_V$ is the sum of the squared photon virtuality $Q^2$ and the mass $M^2_V$ of the produced vector meson.

A specific model realizing this idea was recently constructed and tested against the experimental data (see [9], [10] and the references therein). The relevant VMP amplitude is

$$A(s, t, Q^2, M^2_V) = \tilde{A}_s e^{-(i\pi/2)\alpha_s(t)} \left( \frac{s}{s_0} \right)^{\alpha_s(t)} e^{b_s t - n_s \log(1 + \tilde{Q}^2/\tilde{Q}_s^2)} + \tilde{A}_h e^{-(i\pi/2)\alpha_h(t)} \left( \frac{s}{s_0} \right)^{\alpha_h(t)} \times$$

$$\times \exp \left[ b_h t - (n_h + 1) \log \left( 1 + \frac{\tilde{Q}^2}{Q_h^2} \right) + \log \left( \frac{\tilde{Q}^2}{Q_h^2} \right) \right],$$

where $\alpha_s(t)$ and $\alpha_h(t)$ are the soft and hard pomeron trajectories. We stress that the pomeron is unique in all reactions, but its components (and parameters) vary. Examples with detailed fits can be found in [9], [10].

The integrated (also called total) VMP cross section can be calculated simply without integration for an exponential diffraction cone according to the formula

$$\sigma_{el}(s) = \frac{1}{B(s)} \left. \frac{d\sigma}{dt} \right|_{t=0}.$$

Because our primary goal is to compare the energy dependence of VMP at HERA and at the LHC, we start with very simple expressions for the cross section $\gamma p \rightarrow Vp$ and postpone using more complicated expressions (1) to a future study.

3. The VMP at the LHC

The VMP cross section (see Fig. 2) can be written in a factored form (see [4], [8], in particular, Eqs. (1) and (9) in the first paper in [4]). The distribution in the rapidity $Y$ of the production of a vector meson $V$ in the reaction $h_1 + h_2 \rightarrow h_1 V h_2$ (where $h$ can be a hadron, e.g., proton, or a nucleus, pPb, PbPb,
is calculated according to a standard prescription based on the factorization of the photon flux and photon–proton cross section (see below).

Generally speaking, the $\gamma p$ differential cross section depends on three variables: the total energy $W$ of the $\gamma p$ system, the squared momentum transfer $t$ at the proton vertex, and $Q^2 = Q^2 + M^2_V$, where $Q^2 = -q^2$ is the photon virtuality. Because $b \gg R_1 + R_2$ by definition in ultraperipheral collisions, where $b$ is the impact parameter, i.e., the closest distance between the centers of the colliding particles/nuclei and $R$ is their radii, photons are nearly real, $Q^2 = 0$, and $M^2_V$ remains the only measure of “hardness.” We note that this might not hold for the peripheral collisions $b \sim R_1 + R_2$ and if pomeron or Odderon exchange replaces the photon.

We use VMP cross sections integrated over $t$ or, equivalently, the relevant differential cross section divided by the slope of the forward cone. We start with a simple parameterization of the cross section $\sigma_{\gamma p \to Vp}(W)$,

$$
\sigma_{\gamma p \to Vp}(W) = \int_{t_{\text{thr}}}^{t_{\text{thr}}/s} dt \frac{d\sigma}{dt}, \quad t_{\text{min}} \approx -\frac{s}{2}, \quad t_{\text{thr}} \approx 0,
$$
suggested by Donnachie and Landshoff [11]: $\sigma(W) \sim W^\delta$ and $\delta \approx 0.8$ (more involved models [9], [10], [12] are used below).

The differential cross section as function of the rapidity is

$$
\frac{d\sigma_{h_1 h_2 \to h_1 V h_2}}{dY} = \omega_+ \frac{dN_{\gamma h_1}(\omega_+)}{d\omega} \sigma_{\gamma h_2 \to V h_2}(\omega_+) + \\
+ \omega_- \frac{dN_{\gamma h_2}(\omega_-)}{d\omega} \sigma_{\gamma h_1 \to V h_1}(\omega_-), \tag{2}
$$

where $dN_{\gamma/h}(\omega)/d\omega$ is the “equivalent” photon flux [8]

$$
\frac{dN_{\gamma/h}(\omega)}{d\omega} = \frac{\alpha_{em}}{2\pi\omega} \left[ 1 + \left( 1 - \frac{2\omega}{\sqrt{s}} \right)^2 \left( \log \Omega - \frac{11}{6} + \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3} \right) \right],
$$

$\sigma_{\gamma p \to Vp}(\omega)$ is the total cross section (integrated over $t$) of the vector meson photoproduction subprocess (the same as at HERA; see [12]), $\omega$ is the photon energy, $\omega = W_{\gamma p}^2/2\sqrt{s}$, and $\omega_{\text{min}} = M^2_V/4\gamma_L m_p$, where $\gamma_L = \sqrt{s}/2m_p$ is the Lorentz factor (Lorentz boost of a single beam). For example, for $pp$ at the LHC for $\sqrt{s} = 7$ TeV, we have $\gamma_L = 3731$. Further, $\Omega = 1 + Q_0^2/Q_{\text{min}}^2$, $Q_{\text{min}}^2 = \omega/\gamma_L^2$, $Q_0^2 = 0.71$ GeV, $x = M_V e^{-y}/\sqrt{s}$, and $Y \sim \log(2\omega/m_V)$ is the rapidity.
For definiteness, we fix the following: (a) the colliding particles are protons; (b) the produced vector meson $V$ is $J/\psi$, and the collision energy is $\sqrt{s} = 7$ TeV; (c) the constants are combined in $A = \alpha_{em}/2\pi$ with $c = Q^2_{0L}^2$ (we note that the shape of the distribution in $Y$ is sensitive to the value and sign of the constant $c$). The signs $i = \pm$ of $\omega$ correspond to the respective first or second term in (2), $\omega_{\pm} \sim e^{\pm Y}$.

3.1. Corrections for rapidity gap survival probabilities. The above results may be modified by initial and final state interactions, also called rescattering. Calculating these corrections is far from unambiguous, and the result depends on both the input and the unitarization procedure chosen. The better (more realistic) the input, the smaller the unitarity (rapidity gap survival probability) corrections. Because of the ambiguity of this complicated phenomenon deserving separate study beyond the scope of this paper, we here use only a generally accepted recipe [5], multiplying the scattering amplitude (cross section) by a number (less than one) that depends on the energy and possibly on other kinematic variables. For simplicity, we set the value of this constant equal to 0.8.

4. Results

We compare our theoretical predictions with the experimental data. For the calculations, we use two models for the exclusive photoproduction cross section $\sigma_{\gamma p \rightarrow J/\psi}$: a model with the power-law behavior $\sigma_{\gamma p \rightarrow J/\psi} \sim W^\delta$ with $\delta = 0.8$ and the so-called geometric model proposed and used for DVCS [11].

In addition to $W$ and $t$, the model also contains a dependence on the virtuality $Q^2$. The parameters were fitted to the HERA data on DVCS, but the model can also be successfully used to describe VMP. Here, we use two versions of the Reggeometric model [9], [10]. In [9], it describes the photoproduction cross section ($Q^2 = 0$) and also the integrated cross section (Eq. (11) in [9])

$$\sigma_{\gamma p \rightarrow J/\psi} = A_0^2 \frac{(W/W_0)^{4(\alpha_0-1)}}{(1 + Q^2/Q_0^2)^{2n}[4\alpha' \log(W/W_0) + 4(a/Q^2 + b/2m_N^2)],}$$

where $\bar{Q}^2 = Q^2 + m_N^2$, and the parameters fitted in [9] to $J/\psi$ photoproduction were presented in Table II in that work: $A_0 = 29.8 \pm 2.8$, $Q_0^2 = 2.1 \pm 0.4$ GeV, $n = 1.37 \pm 0.14$, $\alpha_0 = 1.20 \pm 0.02$ GeV$^{-2}$, $\alpha' = 0.17 \pm 0.05$ GeV$^{-2}$, $a = 1.01 \pm 0.11$, $b = 0.44 \pm 0.08$, and $W_0 = 1$ GeV. We note that in contrast to the original formula, we here replace $s$ with $W^2$ because $W$ in our case relates to the energy in center-of-mass system for the photon–proton system while $\sqrt{s}$ is the energy in the center-of-mass system for two protons.

In Fig. 3a, we show the predicted cross sections of $J/\Psi$ production at LHC with $\sqrt{s} = 7$ TeV as a function of the rapidity $Y$. Generally speaking, the power-law and geometric models yield similar distributions, although the latter is flatter. In Fig. 3b, we show the dependence of the $J/\psi$ photoproduction cross section on $W$. Here, the predictions of the two models are close.

The LHCb Collaboration [1], [2] at the LHC recently measured the $J/\Psi$ production cross section as a function of the rapidity. In Fig. 4a, we show a comparison of our calculations with these data. As can be seen in the figure, the experimental points go somewhat more steeply than both of the theoretical curves. The photoproduction cross section as a function of $W$ was also obtained by the LHCb Collaboration from the distribution over rapidity. The result obtained by the experimenters is compared with our predictions in Fig. 4b, where data from the ZEUS and H1 Collaborations are also shown.

4.1. Fitting the power-law dependence to the LHCb data. As noted above, the LHCb Collaboration rapidity distribution is steeper than our predictions. We discuss the role of the power $\delta$ in these distributions. In particular, we fit these data with a least squared deviation. The power $\delta$ and the normalization are the free parameters. Fitting gives $\delta = 0.37$, and the result is shown in Fig. 5. It can be seen from the figure that the predicted rapidity distribution with this parameter value turns out better. It
Fig. 3. Differential cross section of exclusive $J/\psi$ production at the LHC as a function of (a) the rapidity $Y$ and (b) the energy $W$ in the center-of-mass system for two photons: the solid curves correspond to the simple power-law parameterization of the scattering cross section of a photon on a proton, and the dotted curves correspond to the geometric model.

is instructive to compare with other parameterizations, in particular, with the logarithmic, which is less steep than than the power law (see Fig. 6). The description using the logarithm is also good. In Fig. 7, we show predictions from other groups together with rapidity distribution of the LHCb Collaboration. The description result can be considered reasonable.

Our predictions are also compared the data from the H1 and ZEUS Collaborations in Fig. 8. As can be seen from this figure, the better agreement is obtained with the geometric model. The power-law parameterization with the value $\delta = 0.8$ also gives a reasonable description. At the same time, with $\delta = 0.37$, this parameterization and also the logarithmic parameterization diverge from the experimental data.
5. Conclusions and outlook

We have presented predictions for the exclusive $J/\Psi$ meson production at the LHC and compared them with the experimental data from the LHCb Collaboration. For comparison, we also presented data from the H1 and ZEUS Collaborations at HERA. We used simple power-law parameterizations and also a more advanced geometric model to describe the photon–proton cross section. The rapidity distributions measured by LHCb turned out to be steeper than our predictions. A better description can be obtained by tuning the power, but this is inconsistent with the HERA data.

This study will be continued in the following directions:
Fig. 5. Differential cross section of $J/\psi$ production at the LHC as a function of the rapidity $Y$ and the LHCb data: the calculations use the simple power-law parameterization with $\delta = 0.8$ (solid curve) and $\delta = 0.37$ (dotted curve).

Fig. 6. Differential cross section of $J/\psi$ production at the LHC as a function of the rapidity $Y$ and the LHCb data with various parameterizations used for the photon–proton scattering cross section: power law with $\delta = 0.8$ and $\delta = 0.37$ (respective curves 1 and 2), logarithmic (curve 4), and the geometric model (curve 4).

1. inclusion of the dependence on $t$, purely exponential and also with deviations from it corresponding to nonlinear Regge trajectories;

2. accounting for the dependence of the $\sigma_{\gamma p \rightarrow Vp}$ cross section on $Q^2$, negligible in a photon exchange but important in an exchange with Reggeons (pomeron, Odderon, etc.);

3. studies of inelastic processes, i.e., those in which additional particles are produced as a result of gluon radiation and/or proton dissociation; and

4. more detailed studies of corrections due to the rapidity gap survival probability.
Data with uncorrelated indeterminacies
Full indeterminacy of the data
Model with saturation (M. B. Gay Ducati et al. [4])
Model with saturation (L. Motyka, G. Watt [6])

Fig. 7. Differential cross section of $J/\psi$ production at the LHC as a function of the rapidity $Y$ and the LHCb data [2].

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