Vector meson production in ultra-peripheral collisions at hadronic colliders

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Abstract

By using a two-component Pomeron model, successfully describing the HERA data on exclusive diffractive vector meson production (VMP) and deeply virtual Compton scattering (DVCS), we analyse the data on VMP in ultra-peripheral collisions at the LHC. Predictions for future experiments on production of J/ψ and other vector mesons are presented.

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1 Introduction

After the shutdown of HERA, exclusive diffractive production of mesons in ultra-peripheral collisions of protons and nuclei became among the priorities of the present and future studies at the LHC [1, 2], triggering a large number of theoretical investigations [3, 5, 6, 7, 8]. For relevant review papers see, e.g. [4]. First results on vector meson production, in particular of J/ψ, are already published [1, 2].

In our studies of vector meson production production at the LHC we concentrate on the following issues:

- we investigate possible changes in the energy dependence of the cross sections when moving from HERA to the LHC, in particular we are interested the change from "soft" (light vector mesons) to those heavy (ϕ, J/ψ, Υ *etc.*) mesons;
- apart from the "standard" (familiar) photon and Pomeron exchanges, we study the contribution from the Odderon and secondary trajectories;
- we study possible deviation from the exponential behaviour of the t-dependence (the forward cone);
- because of the long range of the electromagnetic interactions, ultra-peripheral collisions imply real photon exchange, which is not neccesarily true for the exchange of the Pomeron and other strongly interacting (short range) reggeons; therefore, differently from the papers of our predecessors [3, 5, 6, 7, 8], we consider also electroproduction ($Q^2 \neq 0$).

2 Simple parametrizations of $\sigma_{\gamma p \to Vp}(\omega)$; The photon flux

The vector meson production (VMP) cross section, Fig. 1, can be written in a factorized form, see [5, 4] (e.g. Eqs. (1) and (9) in [5]a)). The distribution in rapidity Y of the production of a vector meson V in the reaction $h_1+h_2 \to h_1 V h_2$, (where h may be a hadron, e.g. proton, or a nucleus, pPb, PbPb,...) is calculated according to a standard prescripion based on the factorization of the photon flux and photon-proton cross section (see below).

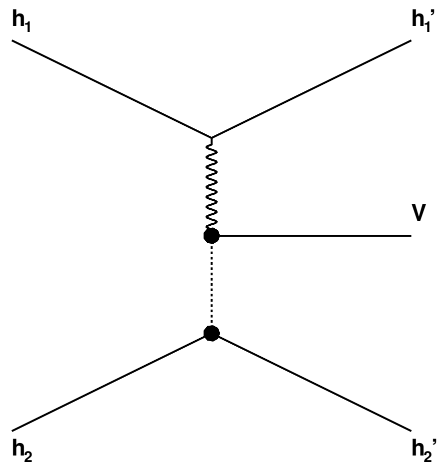


Figure 1: Feynman diagram of vector meson production in hadronic collision.

Generally speaking, the γp cross section depends on three variables: the total energy of the γp system, W, the squared momentum transfer at the proton vertex, t, and virtuality $\tilde{Q}^2 = Q^2 + M_V^2$, where $Q^2 = -q^2$ is the photon virtuality. Since, by definition, in ultraperipheral, $b >> R_1 + R_2$, collisions, where b is the impact parameter, i.e. the closest distance between the centres of the colliding particles/nuclei and R is their radii, photons are nearly real, $Q^2 = 0$, and M_V^2 remains the only measure of "hardness" (NB: this might not be true for the peripheral $b \sim R_1 + R_2$ collisions and in Pomeron or Odderon exchange instead of the photon). Finally, the t-dependence (shape of the diffraction cone) is known to be exponential. It can be either integrated, or kept explicit. Extending this parametrization to include a $t-$dependent exponential is easy (see below). In any case, $\sigma_{\gamma p \to Vp}(\tilde{Q}^2, t, W)$, is well known from HERA. **(I added Q^2, t as arguments since at this point we haven't yet said explicitely that we consider t integration.)**

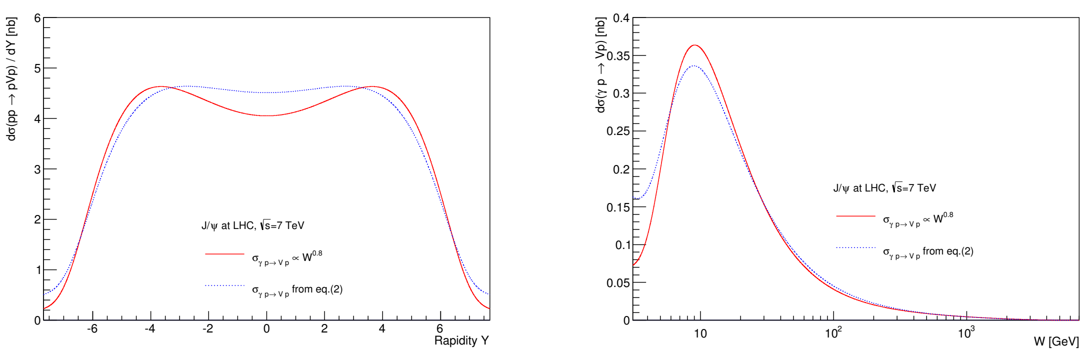
We start with a simple parametrization of the $\sigma_{\gamma p \to Vp}(W)$ cross section, $\sigma_{\gamma p \to Vp}(W) = \int_{t_m}^{t_{thr}} \frac{d\sigma}{dt}$, suggested by Donnachie and Landshoff [9]: $\sigma(W) \sim W^{\delta}$, $\delta \approx 0.8$ (more involved models, e.g. of Ref. [11, 12] will be considered below).

The differential cross section as a function of rapidity reads:

$$\frac{d\sigma(h_1 + h_2 \to h_1 + V + h_2)}{dY} = \omega_+ \frac{dN_{\gamma/h_1}(\omega_+)}{d\omega} \sigma_{\gamma h_2 \to V h_2}(\omega_+) + \omega_- \frac{dN_{\gamma/h_2}(\omega_-)}{d\omega} \sigma_{\gamma h_1 \to V h_1}(\omega_-), \tag{1}$$

where $\frac{dN_{\gamma/h}(\omega)}{d\omega}$ is the "equivalent" photon flux [4] $\frac{dN_{\gamma/h}(\omega)}{d\omega} = \frac{\alpha_{em}}{2\pi\omega}[1 + (1 - \frac{2\omega}{\sqrt{s}})^2](\ln \Omega - \frac{11}{6} + \frac{3}{\Omega} - \frac{3}{2\Omega^2} + \frac{1}{3\Omega^3})$ and $\sigma_{\gamma p \to Vp}(\omega)$ is the total (integrated over t) cross section of the vector meson photoproduction subprocess (same as e.g. at HERA, see [11, 12]). Here ω is the photon energy, $\omega = W_{\gamma p}^2/2\sqrt{s}_{pp}$ with $\omega_{min} = M_V^2/(4\gamma_L m_p)$, where $\gamma_L = \sqrt{s}/(2m_p)$ is the Lorentz factor (Lorentz boost of a single beam), e.g., for pp at the LHC for $\sqrt{s} = 7$ TeV, $\gamma_L = 3731$. Furthermore, $\Omega = (\xi?!) = 1 + Q_0^2/Q_{min}^2$, $Q_{min}^2 = \omega/\gamma_L^2$, $Q_0^2 = 0.71 GeV^2$, $x = M_V e^{(-y)}/\sqrt{s}$, $Y \sim \ln(2\omega/m_V)$ is rapidity, $y = Y(?)$. The subscripts $\pm$ should be respected following Eq. (1). Furthermore we have: $\Omega = 1 + Q_0^2/Q_{min}^2$, where $Q_0^2 = 0.71$, $Q_{min}^2 = \omega/\gamma_L^2$, $\omega = m_V e^Y/2$, hence $\Omega_i = 1 + 0.71\gamma_L^2$, $\gamma_L^2 = 7/(2m_p) \approx 3.57$, $m_{V=J/\psi} = 3.1, \sqrt{s} = 7$, $\alpha_{em}/(2\pi) \approx 10^{-3}$, hence $Q_{min}^2 \approx 5.54e^Y$, $\Omega = 1 + 3.9e^{-Y}$. For definiteness we fix: a) the colliding particles are protons; b) the produced vector meson V is J/ψ, and 3) the collision energy $\sqrt{s} = 7$ TeV. We comprise the constants in $A = \alpha_{em}/(2\pi)$, $c = Q_0^2\gamma_L^2$. (Notice that the shape of the distribution in Y is very sensitive to the value (and the sign) of the constant c!). The $i = \pm$ signs of ω correspond to the first or second term in Eq. (1), respectively, $\omega_\pm \sim e^{\pm Y}$.

To fix the notation, basic parameters and show the difference in the energy (W) dependence of the produced vector meson, we start with a "pedagogical" example containing the standard photon flux and the simplest model for $\sigma(W) \sim W^{0.8}$, without any t or Q^2 dependence (*i.e.* photoproduction for $t = 0$) **(it is integrated over t, not $t = 0$, right?)**. Fig. 2(a) shows the distribution in rapidity Y. Fig. 2(b) shows the energy dependence of J/ψ photoproduction cross section at the LHC ($\sqrt{s} = 7$ TeV).



(a) (b)

Figure 2: Differential cross section of J/ψ production at LHC as a function of rapidity Y (a) and of the photon-proton centre-of-mass energy W (b).

In subsequent sections we extend the simple model of the previous section, namely:

- We include t dependence - both exponential (corresopong to linear Regge trajectories) and with deviations from the exponential (from linar Regge trajectories);
- In the $\sigma_{\gamma p \to Vp}$ cross section we include, apart from W and t dependence, also Q dependence, negligible in $\gamma-$ but important in Reggeon (Pomeron, Odderon,...) exchanges.
- We include corrections due to rapidity gap survival probability.

3 Realistic model of $\gamma p \to V$ cross section

A simple model for J/ψ photoproduction ("testing field for diffraction"), based on a dipole Pomeron exchange was proposed in paper [10]. The model, Eqs. (5)-(7) of Ref. [10], with a limited number (five) of adjustable parameters, fits the data on J/ψ photoproduction, and it can be used for our purposes.

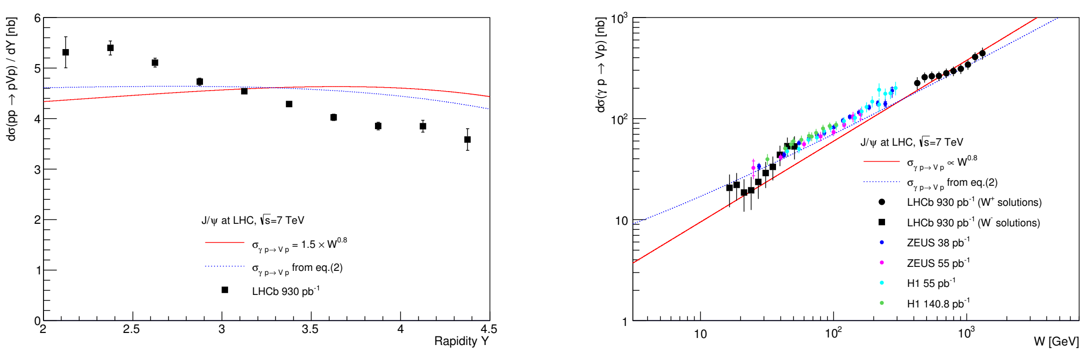
Another simple and efficient model was suggested and applied to deeply virtual Compton scattering (DVCS) in Ref. [11]. Apart from W and t, it contains alwo dependence on virtuality Q^2. The model was fitted to the HERA data on DVCS, but it can be applied also to vector meson production (VMP) by refitting its parametes. Instead, below we shall use two versions of the so-called Reggeometric model of VMP and DVCS, suggested in Refs. [12]a) and [12]b). Its first version [12] a) applies to photoproduction ($Q^2 = 0$), and the integrated photoproduction cross section, Eq. (11) in Ref. [12]a), is **(s was replaced by W^2)**

$$\sigma_{el} = A_0^2 \frac{(s/s_0)^{2(\alpha_0-1)}}{(1+\tilde{Q}^2/Q_0^2)^{2n}[2\alpha' \ln(s/s_0) + 4\left(\frac{a}{\tilde{Q}^2} + \frac{b}{2m_N^2}\right)]}, \tag{2}$$

where $\tilde{Q}^2 = Q^2 + m_V^2$ and the parameters, fitted [12]a) to J/ψ photoproduction, quoted in Table II of Ref. [12]a), are: $A_0 = 29.8 \pm 2.8$, $Q_0^2 = 2.1 \pm 0.4$, $n = 1.37 \pm 0.14$, $\alpha_0 = 1.20 \pm 0.02$, $\alpha' = 0.17 \pm 0.05, a = 1.01 \pm 0.11$, $b = 0.44 \pm 0.08$, $s_0 = 1$ and relevant dimensions here again are implied. Fig. 2(a) shows the calculated rapidity distributions for J/ψ production at the LHC while Fig. 2(b) shows the W dependence of the produced J/ψ.

A more advanced version of the Reggeometric model, Ref. [12]b) includes also Q^2- dependence (electroproduction), the universal "Reggeometric" Pomeron containing two terms, a "hard" and a "soft" one, their relative weight depending on $\tilde{Q}^2$. Te relevant scattering amplitude is quoted in Eq. (13) of Ref. [12]b) with the fitted parameters collected in Tables 2 to 4 of of the same paper.

The calculated cross sections as a function of rapidity together with the new data from LHC [1, 2] are shown in Fig. 3(a). The photoproduction cross section as a function of W is shown in Fig. 3(b).



(a) (b)

Figure 3: Differential cross section of J/ψ production at LHC as a function of rapidity Y (a). J/ψ photoproduction ($\gamma p \to J/\psi p$) cross section as a function photon-proton centre-of-mass energy (b).

4 Corrections for rapidity gap survival probabilities

The above results may be modified by initial and final state interactions, alternatively called as rescattering corrections. The calculation of these corrections is by far not unambiguous, the result depending both on the input and on the unitarization procedure chosen. The better (more realistic) the input, the smaller the unitarity (rapidity gap survival probability) corrections. Since this is a complicated and controversial issue *per se* deserving special studies beyond the scope of the present paper, to be coherent with the "common trend", here we use only familiar results from the literature. The standard prescription is to multiply the scattering amplitude (cross section) by a factor (smaller than one), depending on energy and eventually other kinematical variables. We borrow the values of these correction factors from Ref.[6] b), calculated accorging to Eq.(18) and collected in Table 2, both in that paper.

The obtained (corrected) results are shown in Fig... and are compared with the results of our calulations in Sec.3. **note, the correction of 0.8 was already included in all plots. If it's a constant, I think there is not much sense to reproduce both sets of plots (with and without the correctoin). But we could also try to use a rapidity dependent correction. then it would be interesting to compare.**

5 Pomeron, Odderon and other($\omega, f, ...$) Reggeon exchanges

6 Inelastic photoproduction

In this section we study inelastic VMP, where a small number of additional particles are produced due to either gluon radiation and/or (c,d) proton dissociation, see Fig. 4.

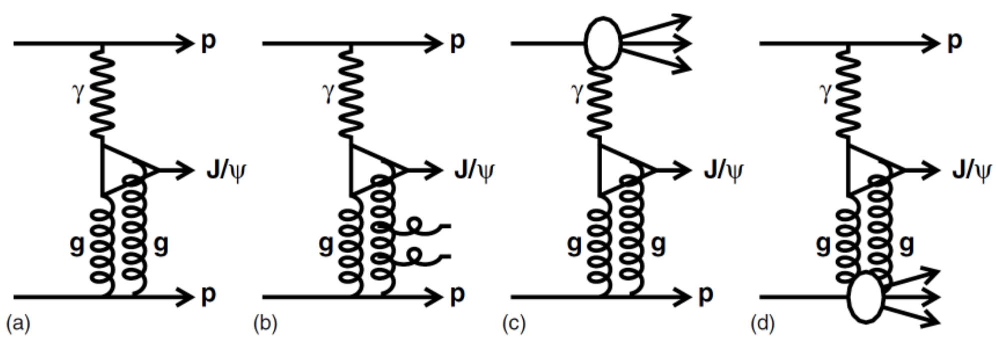


Figure 4: Feynman diagrams of non-exclusive $J\psi$ meson production.

7 Conclusions

Acknowledgements

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8 Appendices

Here some additional plots and comments are placed.

8.1 Comments to rapidity cross section

8.1.1 Fitting the power law to LHCb data

By fitting the power (and normalization) a much better description of data can be obtained (green curve) However, power tends to be very small (δ=0.37)

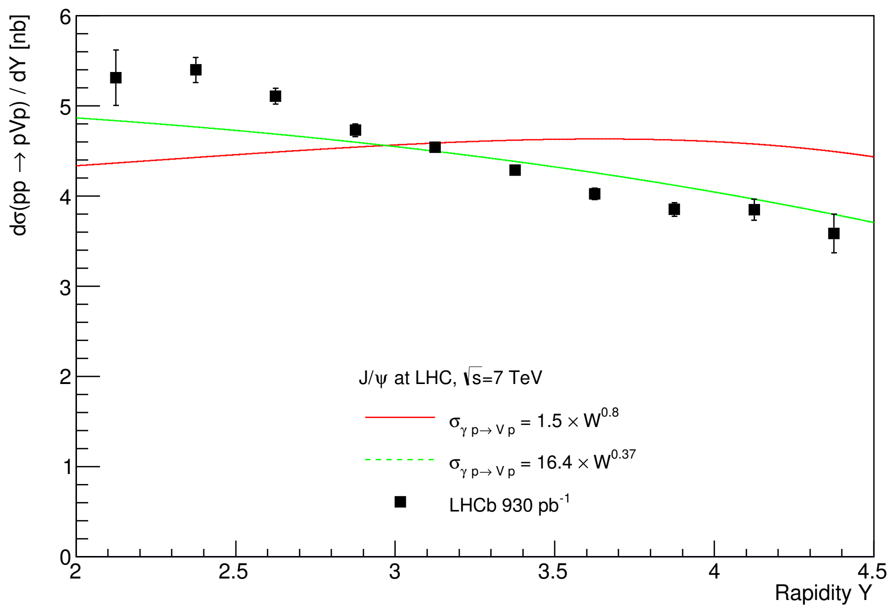

Figure 5: Power law (power+normalization) are fitted to LHCb rapidity data

8.1.2 Comparison of all available theory curves

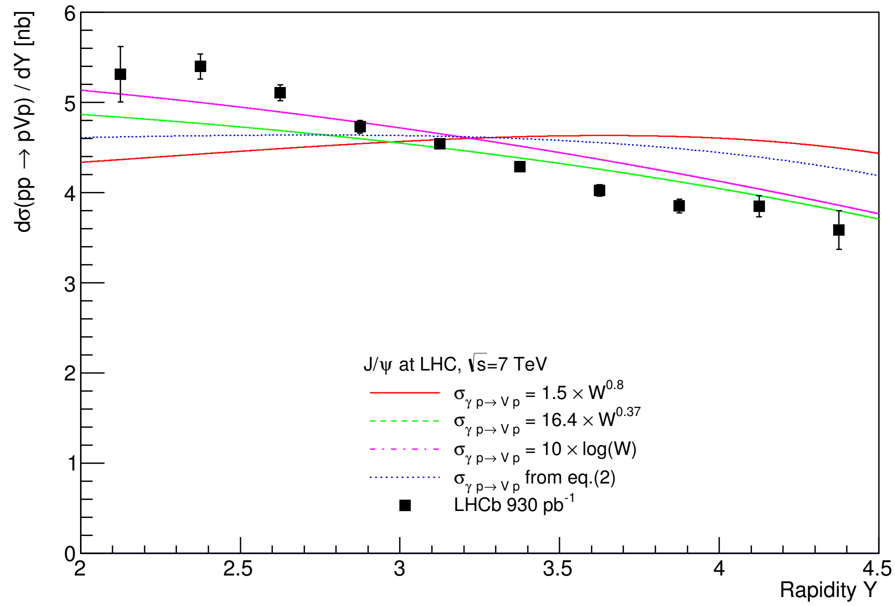

Figure 6: Power law (fitted and 0.8), logarithmic and geometric models compared to LHCb rapidity cross section

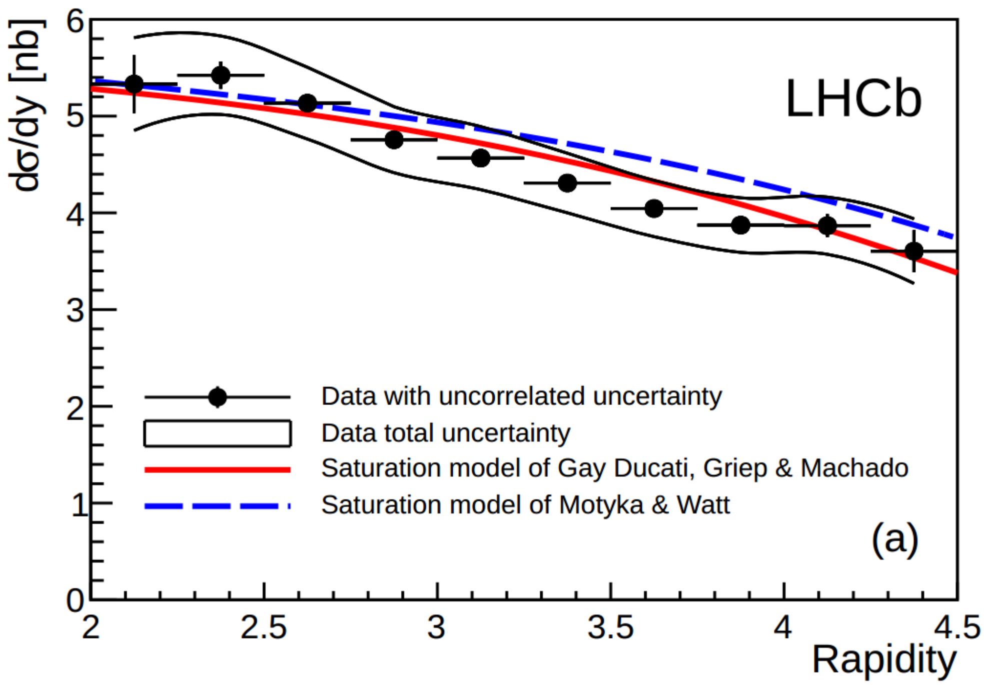

Figure 7: Figure from LHCb publication showing other models

8.2 Comments to photon proton cross section

Although by going to lower power it is possible to improve LHCb rapidity data, the photon proton cross section becomes clearly not consistent with data.

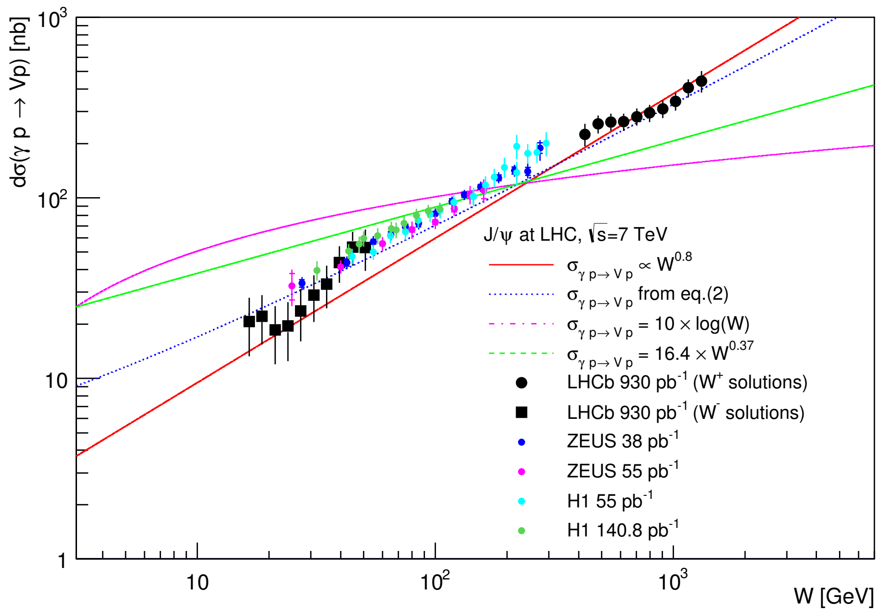

Figure 8: Power law (fitted and 0.8), logarithmic and geometric models compared to photon proton cross section from LHCb and HERA.