Vector meson production in ultra-peripheral collisions at hadronic colliders

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Abstract

By using a Regge-pole model for vector meson production (VMP), successfully describing the HERA data, we analyse the correlation between VMP cross sections in photon-induced reactions at HERA and those 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, 7, 8, 9, 10]. 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 this study of vector meson production at the LHC we scrutinize the 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;

2 VMP at HERA

At HERA VMP was studied in deatails both by the H1 and ZEUS collaboratons. Most of the events were chosen in the kinematical region corresponing to diffractive scattering, which means that the processes can be described by a Pomeron exchange, see Fig. **??**. Pomeron dominance is especially clean in J/Ψ production, where, by the Zweig (OZI) rule, any exchange of secondary trajectories made of quarks is forbidden, leaving and uncontaminated Pomeron exchange alone. This does not mean that the dynamics is simple, but we have the opportunigy to scrutinize in this class of reactions the nature of the Pomerone, 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 mass of the produced vector meson.

In most of the papers on the subject the existence of two Pomerons is assumed. One, hard or QCD pomeron, resulting from perturbetive quantum chromodynamic calculations, and a soft, somewhat misleadingly called "non-perturbetive". Instead, we believe that there is only one Pomoren in the Nature, but it has two components, whose relative weight is regulated by relevant $\tilde{Q}^2$-dependent factors in front of the two, where the measure of the "hardness" $\tilde{Q}^2 = Q^2 + M_V^2$ is the sum of the squared photon virtuality and the produced vector meson's mass.

A specific model realizing this idea was constructed and tested against the experimental data recently (see Ref. [6] and earlier references therein. The relevant VMP amplitude reads

$$A(s,t,Q^2,{M_v}^2) = \widetilde{A_s} e^{-i\frac{\pi}{2}\alpha_s(t)} \left(\frac{s}{s_0}\right)^{\alpha_s(t)} e^{b_s t - n_s \ln\left(1+\frac{\widetilde{Q^2}}{Q_s^2}\right)}$$

$$+\widetilde{A_h} e^{-i\frac{\pi}{2}\alpha_h(t)} \left(\frac{s}{s_0}\right)^{\alpha_h(t)} e^{b_h t - (n_h+1)\ln\left(1+\frac{\widetilde{Q^2}}{Q_h^2}\right) + \ln\left(\frac{\widetilde{Q^2}}{Q_h^2}\right)}, \tag{1}$$

where $\alpha_s(t)$ and and $\alpha_h(t)$ are the soft and hard Pomeron trajectories. Let us stress that the Pomeron is unique in all reactions, just its components (and perameters) change from one reaction to another. Examples with detailed fits can be found in recent papers [6].

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

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

Since our primary goal is the comparison between the energy dependence of VMP at HERA and the LHC, we start with a very simple ansätze for the $\gamma p \to Vp$ cross section, postponing the use of the advanced model Eq. (1) to a future study.

3 VMP at the LHC

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).

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 nearly 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.

To start with, we use VMP cross sections integrated in t equvalently, the relevant differential cross section at $t = 0$ divided by its foward slope B.

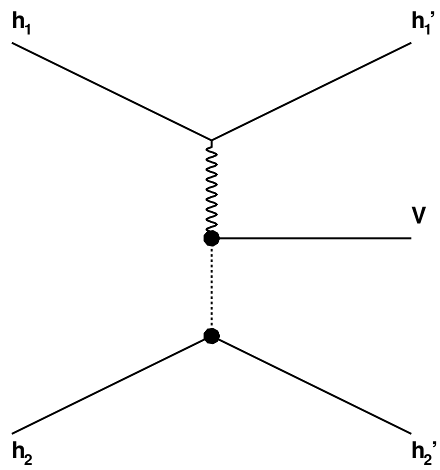


Figure 1: Feynman diagram of vector meson production in hadronic collision.

To start with, we use 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 [11]: $\sigma(W) \sim W^{\delta},\ \delta \approx 0.8$ (more involved models, e.g. of Ref. [13, ?] will be considered below).

The differential cross section as a function of rapidity reads:

$$\frac{d\sigma(h_1+h_2\to h_1+V+h_2)}{dY} = \omega_+\frac{dN_{\gamma/h_1}(\omega_+)}{d\omega}\sigma_{\gamma h_2\to Vh_2}(\omega_+) + \omega_-\frac{dN_{\gamma/h_2}(\omega_-)}{d\omega}\sigma_{\gamma h_1\to Vh_1}(\omega_-), \tag{2}$$

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 [13, ?]). Here ω is the photon energy, $\omega = W^2_{\gamma p}/2\sqrt{s}_{pp}$ 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, $\Omega = (\xi?!) = 1 + Q_0^2/Q^2_{min},\ Q^2_{min} = \omega/\gamma_L^2,\ Q_0^2 = 0.71 GeV^2,\ x = M_V e^{(-y)}/\sqrt{s},\ Y \sim \ln(2\omega/m_V)$ is rapidity, $y = Y(?)$. Furthermore we have: $\Omega = 1 + Q_0^2/Q^2_{min}$, where $Q_0^2 = 0.71,\quad Q^2_{min} = \omega/\gamma_L^2,\ \omega = m_V e^Y/2$, hence $\Omega_i = 1 + 0.71\gamma_L^2,\quad \gamma_L^2 = 7/(2m_p) \approx 3.57,\quad m_{V=J/\psi} = 3.1, \sqrt{s} = 7,\ \alpha_{em}/(2\pi) \approx 10^{-3}$, hence $Q^2_{min} \approx 5.54e^Y,\quad \Omega = 1 + 3.9e^{-Y}$. 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 $A = \alpha_{em}/(2\pi),\quad c = Q_0^2\gamma_L^2$. (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. (2), respectively, $\omega_\pm \sim e^{\pm Y}$.

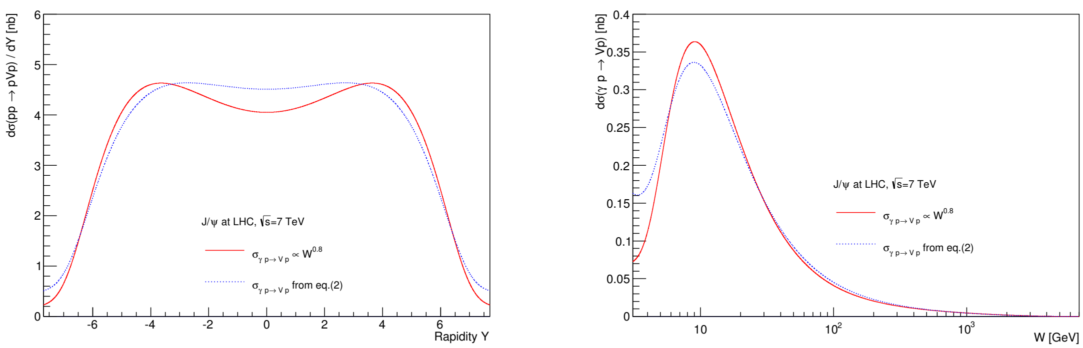
4 Results

4.1 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.[7] 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.**??**. **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.**

To fix the notation, to quote the basic parameters and to show the difference in the energy (W) dependence of the produced vector meson, we start with a simple 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)

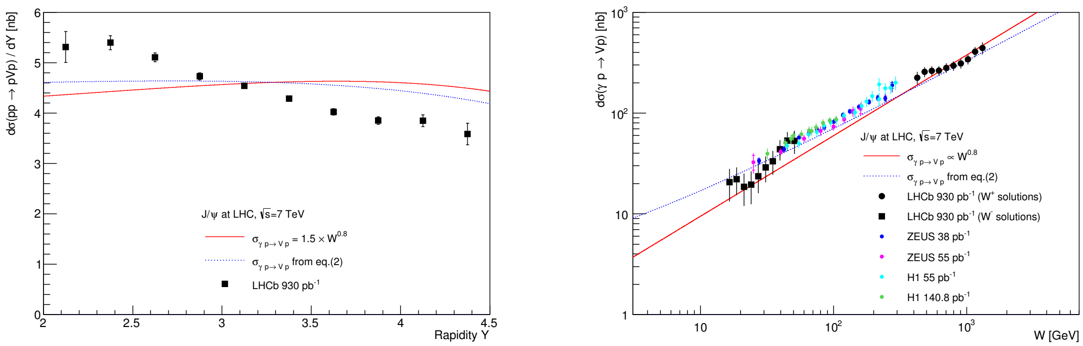
Figure 2: Differential cross section of J/ψ production at LHC as a function of rapidity Y (a) and of the photon-proton centre-of-mass energy W (b).

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).

The results are sensitive to the rate of increase of of the photoproduction cross section, *i.e.* the power δ in $\sigma(W) \sim W^{delta}$. Below we crutinize this phenomenon by fitting this parameter as well as the normaliztion to the data. For the sake of comparison, a logarithmic paremetrizaton of $\sigma(W)$ is also used.

4.1.1 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)



(a) (b)

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

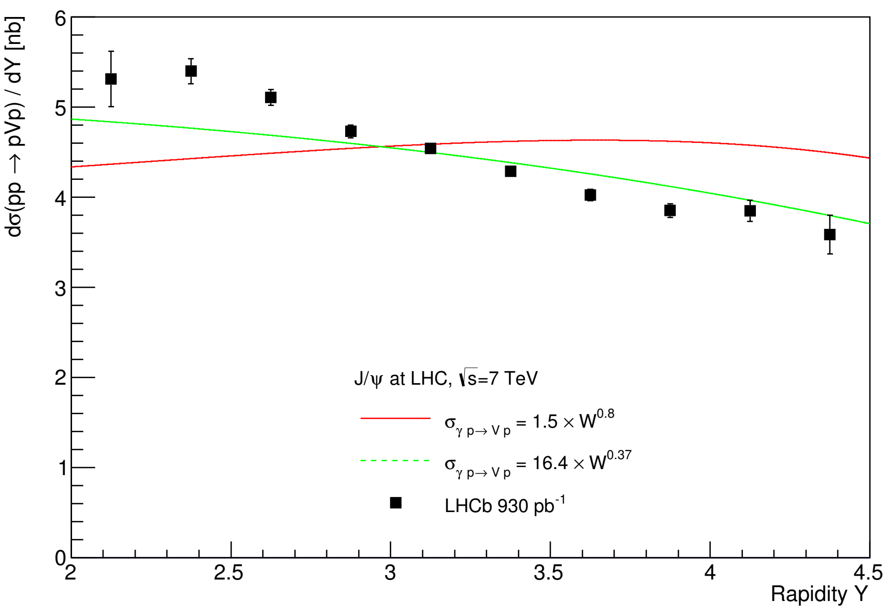


Figure 4: Power law (power+normalization) are fitted to LHCb rapidity data

4.1.2 Comparison of all available theory curves

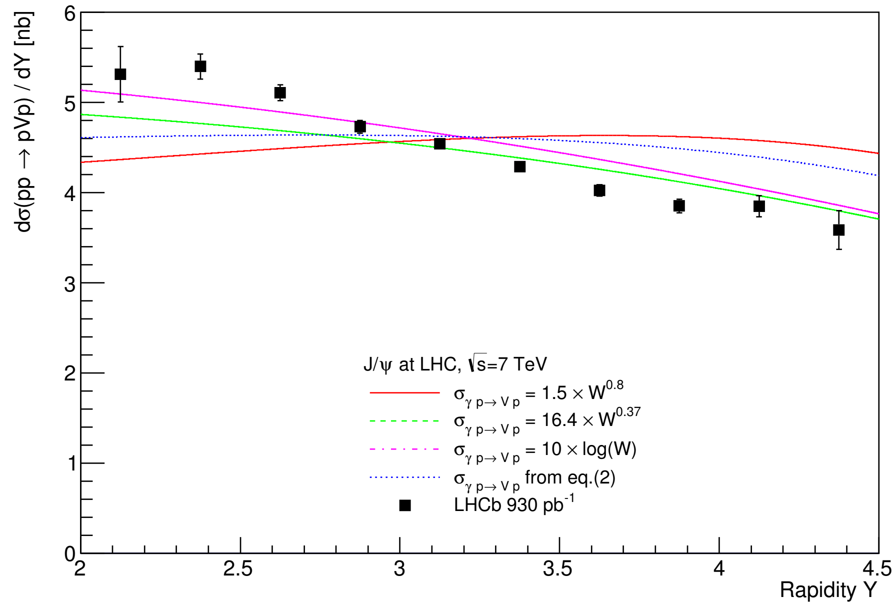


Figure 5: Power law (fitted and 0.8), logarithmic and geometric models compared to LHCb rapidity cross section

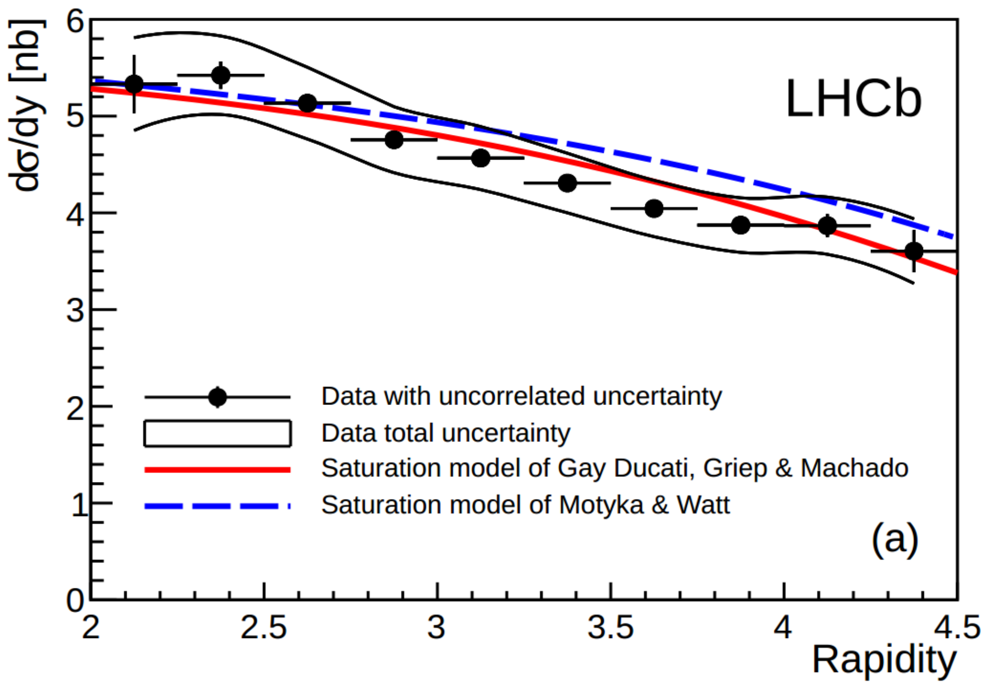


Figure 6: LHCb data compared with theoretical models

4.2 Comments on 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.

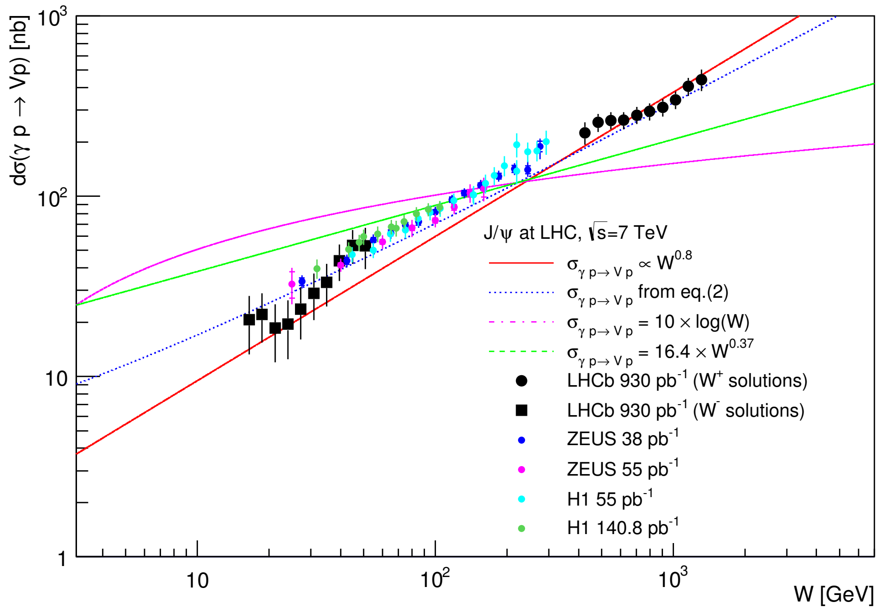


Figure 7: Power law (fitted and fixed to 0.8), logarithmic and geometric models compared to photon proton cross sections from LHCb and HERA.

5 Prospects

In subsequent sections (papers) 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.

Another simple and efficient model was suggested and applied to deeply virtual Compton scattering (DVCS) in Ref. [13]. 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. [**?**]a) and [**?**]b). Its first version [**?**] a) applies to photoproduction ($Q^2 = 0$), and the integrated photoproduction cross section, Eq. (11) in Ref. [**?**]a), is **(s was replaced by W^2)**

$$\sigma_{el} = A_0^2 \frac{(s/s_0)^{2(\alpha_0 - 1)}}{(1 + \tilde{Q}^2/Q_0^2)^{2n}[2\alpha' \ln(s/s_0) + 4\left(\frac{a}{\tilde{Q}^2} + \frac{b}{2m_N^2}\right)]}, \quad (3)$$

where $\tilde{Q}^2 = Q^2 + m_V^2$ and the parameters, fitted [?]a) to J/ψ photoproduction, quoted in Table II of Ref. [?]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. [?]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. [?]b) with the fitted parameters collected in Tables 2 to 4 of of the same paper.

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

5.2 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. 8.

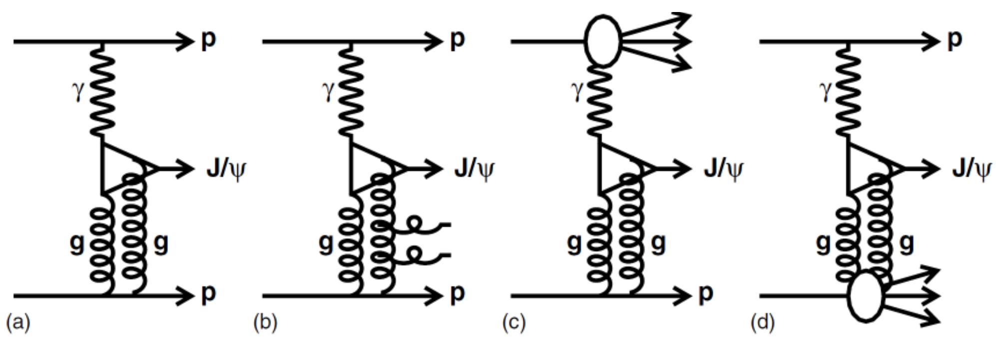


Figure 8: Feynman diagrams of non-exclusive $J\psi$ meson production.

6 Conclusions

Acknowledgements

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