

Photoproduction of J/ψ and Υ states in exclusive and proton-dissociative diffractive events

Wolfgang Schäfer^{*†}

Institute of Nuclear Physics, Krakow

E-mail: wolfgang.schafer@ifj.edu.pl

Antoni Szczurek

Institute of Nuclear Physics, Krakow

E-mail: Antoni.Szczurek@ifj.edu.pl

Anna Cisek

University of Rzeszów, Rzeszów

E-mail: acisek@ur.edu.pl

The amplitude for $\gamma p \rightarrow V p$, where V is a J/ψ or Υ ground state or excited vector meson, is calculated in a pQCD k_T -factorization approach. We use this amplitude to predict the cross section for exclusive photoproduction of J/ψ , ψ' , Υ mesons in proton-proton collisions. Calculations are performed for a variety of unintegrated gluon distributions, and we compare our results to LHCb data. Here we especially focus on the possibility of constraining saturation effects. Compared to earlier calculations we include both Dirac and Pauli electromagnetic form factors. We discuss the role of the $Q\bar{Q}$ light-cone wave functions for differential distributions for ratios such as $\sigma(\psi')/\sigma(J/\psi)$. Absorption effects are always taken into account.

We also discuss the related diffractive production in proton dissociative events. Here we concentrate on electromagnetic dissociation, which is calculable without additional free parameters. Besides being of interest in their own right, dissociative events constitute an important experimental background to exclusive production.

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^{*}Speaker.

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1. Introduction

The flux of Weizsäcker-Williams photons, which accompany high energy charged particles opens a possibility to study high-energy photon-hadron interactions at previously inaccessible energies in collisions at the LHC [1]. Of special interest is the exclusive photoproduction of vector mesons, $pp \rightarrow ppV$, and here in turn the heavy quarkonia play a special role. A rich body of experimental data from ep collisions taken at HERA, and a large amount of theoretical works, have convincingly established the diffractive vector meson production as a testing ground of the transition between soft and hard QCD Pomeron physics (for a review, see [2]).

There are a number of crucial differences between the ep and pp collisions. Firstly, due to the electromagnetic form factors (finite size) of the proton, virtualities of photons are strongly bounded (photons are quasireal) in the exclusive $pp \rightarrow Vpp$ processes. This means that photon virtuality Q^2 cannot serve as a hard scale. In order to study the perturbative QCD (pQCD) driven hard Pomeron, we have to restrict ourselves to heavy quarkonia. Secondly, both of the incoming protons can be a source of photons, so that two amplitudes have to be added coherently. Thirdly, protons are strongly interacting, and the many open inelastic channels require the evaluation of absorptive corrections to the naive γ -Pomeron fusion amplitude. For a discussion of these issues and explicit formulas, see e.g. [3, 4].

2. Exclusive photoproduction of J/ψ , $\psi(2S)$, Υ

The crucial input for the evaluation of the $pp \rightarrow ppV$ cross section is the photoproduction amplitude for the $\gamma p \rightarrow Vp$ subprocess. We concentrate on heavy quarkonia, so that the Pomeron exchange can be modelled by a pQCD gluon ladder. We write the full amplitude at finite transverse momentum transfer Δ_\perp as:

$$\mathcal{M}(W, \Delta_\perp^2) = (i + \rho) \Im m \mathcal{M}(W, \Delta_\perp^2 = 0) \cdot f(-\Delta_\perp^2, W). \quad (2.1)$$

Here, the imaginary amplitude of the forward amplitude can be calculated in terms of the unintegrated gluon distribution in the target proton and the light-cone wave function of the vector meson. For the formalism used, see [4].

The real part of the amplitude is restored from analyticity,

$$\rho = \frac{\Re e \mathcal{M}}{\Im m \mathcal{M}} = \tan \left(\frac{\pi}{2} \frac{\partial \log (\Im m \mathcal{M} / W^2)}{\partial \log W^2} \right).$$

The dependence on momentum transfer $t = -\Delta_\perp^2$ is parametrized by the function $f(t, W)$, which dependence on energy derives from the Regge slope

$$B(W) = b_0 + 2\alpha'_{eff} \log \left(\frac{W^2}{W_0^2} \right), \quad (2.2)$$

where we use: $b_0 = 4.88$, $\alpha'_{eff} = 0.164 \text{ GeV}^{-2}$ and $W_0 = 90 \text{ GeV}$.

Within the diffraction cone it is customary to use the exponential parametrization:

$$f(t, W) = \exp \left(\frac{1}{2} B(W) t \right). \quad (2.3)$$

For our purposes however an extension to larger $|t| \sim 1 \div 2 \text{ GeV}^2$ is desirable. A comparison with ZEUS data [5] (see Fig. 1) shows that a “stretched exponential” parametrization

$$f(t, W) = \exp(\mu^2 B(W)) \exp\left(-\mu^2 B(W) \sqrt{1 - t/\mu^2}\right), \quad (2.4)$$

does a good job with only one new parameter. What is the physics of the “hard tail” encoded in the stretched exponential? At this moment we cannot tell, it might as well be a contamination of data by dissociative events, an effect of multiple scatterings, or – somewhat unlikely – “hard” scattering.

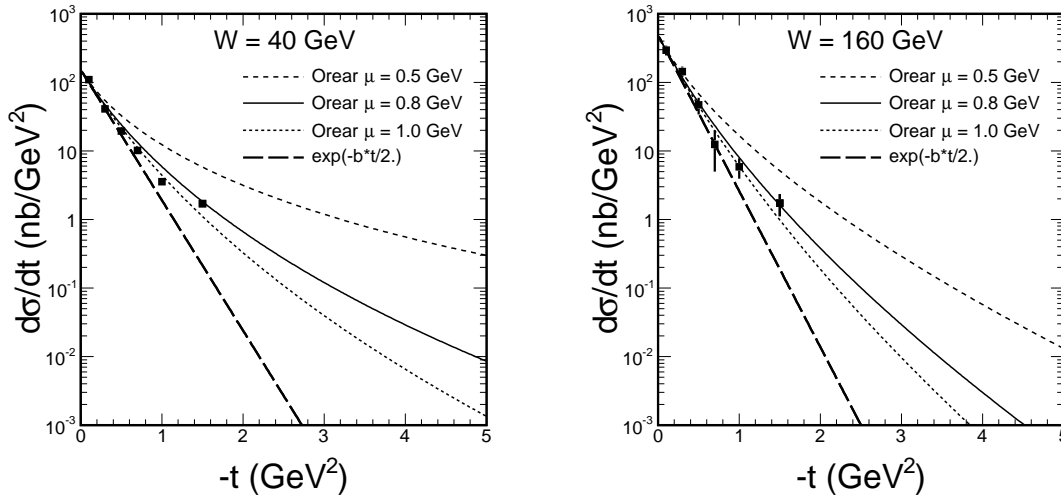


Figure 1: $d\sigma/dt$ for $\gamma p \rightarrow J/\psi p$ for different energies indicated in the figure caption. Data from [5]. “Orear” denotes the stretched-exponential parametrization.

The exclusive photoproduction of J/ψ and $\psi'(2S)$ charmonia has first been observed by the CDF collaboration at the Tevatron [6] and recently been measured by the LHCb collaboration [7, 8] at the LHC. In Fig. 2, we compare our calculations of the J/ψ rapidity distributions to the LHCb data, in Fig. 3 we show the comparison with data for the case of $\psi(2S)$ production.

In the leftmost panels we show the result using the Ivanov-Nikolaev glue [9]. While it gives a reasonable account of the shape of the rapidity distribution, it overestimates the cross section. A similar job is done by a gluon distribution of [10], which solves a BFKL-type linear evolution equation. A quite good agreement is found for the unintegrated glue of Kutak and Stašo [10] from the nonlinear evolution equation (rightmost panels). We stress that all the unintegrated gluon distributions reproduce the Tevatron data [6], see [4]. Somewhat ironically also a straight-line extrapolation of a H1-fit used previously in [3] gives a good fit of the cross section (see the left panel of Fig. 4). As it would correspond to the exchange of a single –effective– Pomeron trajectory, it casts a certain doubt on the necessity of saturation effects in the unintegrated glue. Finally, in the right panel of Fig. 4 we show a comparison of our results for Υ production compared to recent LHCb data [11].

3. Diffractive photoproduction with electromagnetic dissociation

Proton dissociative events are of great practical importance as an often difficult background to

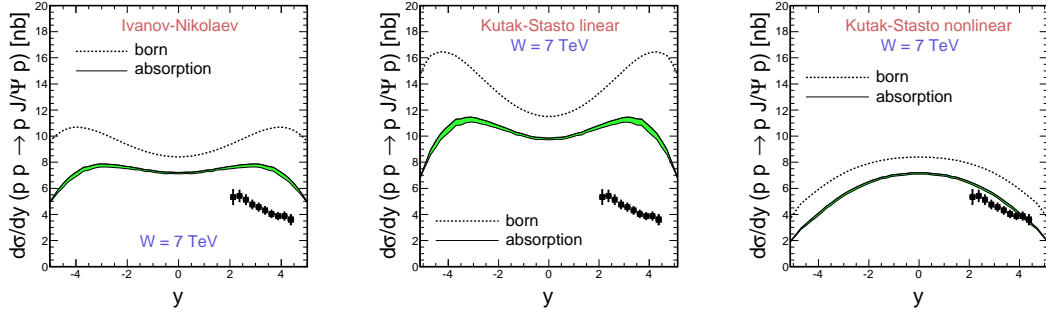


Figure 2: J/ψ rapidity distribution calculated with inclusion of absorption effects (solid lines), compared with the Born result (dashed line) for $\sqrt{s} = 7$ TeV. The LHCb data points [8] are shown for comparison.

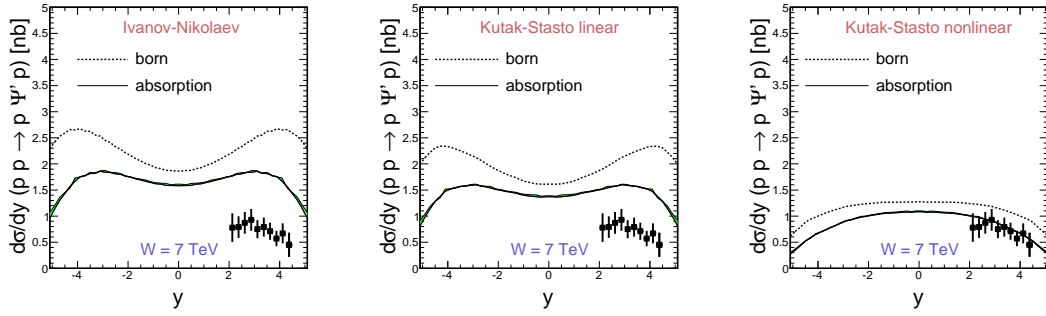


Figure 3: $\psi(2S)$ rapidity distribution calculated with inclusion of absorption effects (solid lines), compared with the Born result (dashed line) for $\sqrt{s} = 7$ TeV. The LHCb data points [8] are shown for comparison.

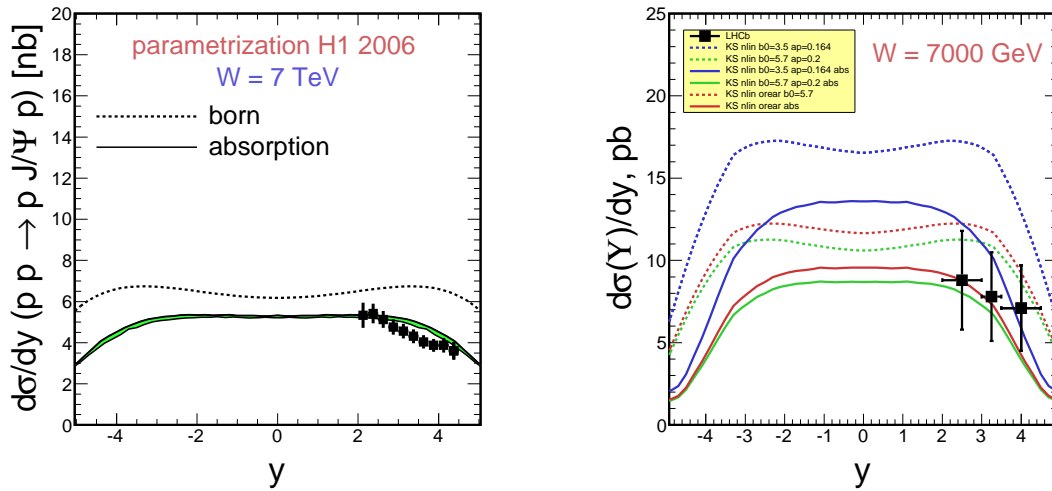


Figure 4: Left panel: J/ψ rapidity distribution calculated with a parametrization of the photoproduction amplitude previously used in [3]. Right panel: Rapidity distribution of exclusive Υ 's. Data are taken from [11].

exclusive events. They are also of general interest for our understanding of diffractive scattering and Pomeron physics. Here we concentrate on a simple example relevant to exclusive vector meson production: the events with electromagnetic dissociation of one of the protons. The cross section for such processes can be written as:

$$\frac{d\sigma(pp \rightarrow XVp; s)}{dyd^2\mathbf{p}} = \int \frac{d^2\mathbf{q}}{\pi\mathbf{q}^2} \mathcal{F}_{\gamma/p}^{(\text{in})}(z_+, \mathbf{q}^2) \frac{1}{\pi} \frac{d\sigma^{\gamma^* p \rightarrow Vp}}{dt}(z_+s, t = -(\mathbf{q} - \mathbf{p})^2) + (z_+ \leftrightarrow z_-), \quad (3.1)$$

where $z_{\pm} = e^{\pm y} \sqrt{(\mathbf{p}^2 + m_V^2)}/s$. Here the flux of photons associated with the breakup of the proton is calculable in terms of the structure function F_2 of a proton [12, 13]:

$$\mathcal{F}_{\gamma/p}^{(\text{inel})}(z, \mathbf{q}^2) = \frac{\alpha_{\text{em}}}{\pi} (1-z) \int_{M_X^2}^{\infty} \frac{dM_X^2 F_2(x_{Bj}, Q^2)}{M_X^2 + Q^2 - m_p^2} \left[\frac{\mathbf{q}^2}{\mathbf{q}^2 + z(M_X^2 - m_p^2) + z^2 m_p^2} \right]^2, \quad (3.2)$$

where

$$Q^2 = \frac{1}{1-z} \left[\mathbf{q}^2 + z(M_X^2 - m_p^2) + z^2 m_p^2 \right], x_{Bj} = \frac{Q^2}{Q^2 + M_X^2 - m_p^2}. \quad (3.3)$$

We are especially interested in the region of small invariant masses, $M_X < 2$ GeV, where resonance excitation is important. Our recent study [13] showed, that here it is best to use a parametrization of F_2 given in [14]. In the left panel of Fig. 5 we show a distribution in invariant mass of the excited system for the $pp \rightarrow XJ/\psi p$ reaction. In the right panel of Fig. 5 we show the rapidity distribution of J/ψ for elastic and e.m. dissociative events. The e.m. dissociation can reach 10 ÷ 15% of the exclusive cross section.

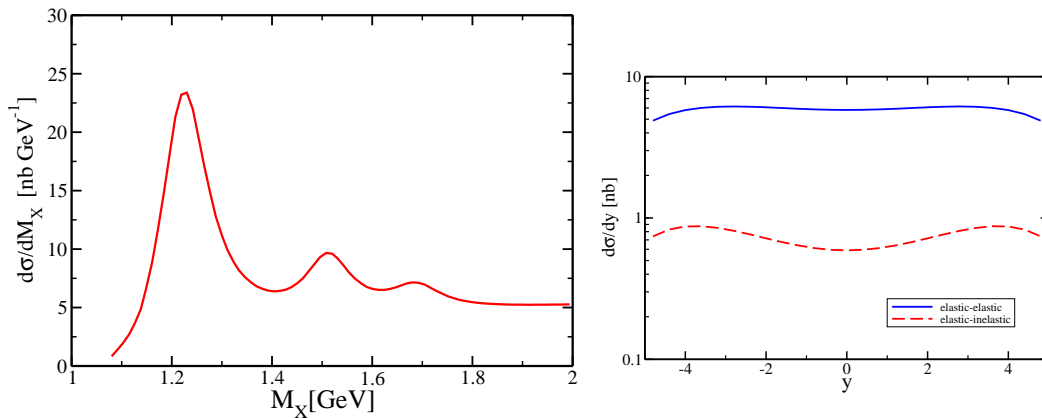


Figure 5: Left panel: distribution in the mass of the electromagnetically excite system, M_X for the $pp \rightarrow XJ/\psi p$ process. Right panel: Rapidity distribution of J/ψ for the same process, for $M_X < 2$ GeV.

4. Conclusions

- We have compared our k_{\perp} -factorization results with recent LHCb ($pp \rightarrow p V p$) data, for $V = J/\psi, \psi(2S), \Upsilon$. The best description is obtained for a glue which does contain saturation effects.

- Our calculations [4] also demonstrate, that absorptive corrections are a strong function of kinematics. At large p_T , relevant for Odderon searches, the Pauli coupling needs to be included. There is a sizeable uncertainty due to absorption in the p_T distribution.
- Proton dissociation is a background to exclusive processes. Electromagnetic dissociation is calculable from F_2 , excited states $M_X < 2\text{ GeV}$ make a contribution of $10 \div 15\%$ of the exclusive cross section for J/ψ .

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