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

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Abstract. We use a perturbative QCD based k_T-factorization approach, to calculate the amplitude for the diffractive $\gamma p \to Vp$ processes, where V is a J/ψ or Υ ground state or excited vector meson. Using these amplitudes, we evaluate the cross section for exclusive photoproduction of $J/\psi, \psi', \Upsilon$ mesons in proton-proton collisions. Calculations are performed for a variety of unintegrated gluon distributions, and we compare our results to LHCb data. Absorption effects are taken into account at the amplitude level. 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.

1 Introduction

Exclusive processes with large rapidity gaps of the type $pp \to pph$, where h is a hadron produced in the central rapidity region, are described by t-channel exchange mechanisms. If the rapidity gaps are required to be larger than $2 \div 3$ units, the exchange must have a "running spin" $J(t) \geq 1$. If we wish to study the production of vector mesons, the product of C-parities of the exchanges must be negative. All these rquirements are fulfilled for the photon-Pomeron fusion.

In this way, pp interactions allow us to study high-energy photoproduction of vector mesons at previously unaccessible energies [1]. 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]).

Differently from ep collision, in the pp case, due to the electromagnetic form factors (finite size) of the proton, virtualities of photons are strongly bounded (photons are quasireal) in the exclusive $pp \to Vpp$ 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].

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2 Exclusive photoproduction of $J/\psi, \psi(2S), \Upsilon$

The cross section of the $pp \to ppV$ reaction needs as an input the photoproduction amplitude for the $\gamma p \to Vp$ subprocess. For heavy quarkonia the Pomeron exchange can be modelled by a pQCD gluon ladder. We write the full amplitude at finite transverse momentum transfer $\Delta_\perp$ as:

$$\mathcal{M}(W, \Delta_\perp^2) = (i + \rho)\, \Im m \mathcal{M}(W, \Delta_\perp^2 = 0) \cdot f(-\Delta_\perp^2, W)\,. \tag{1}$$

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,

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

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

$$B(W) = b_0 + 2\alpha'_{eff} \log\Big(\frac{W^2}{W_0^2}\Big), \tag{2}$$

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

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

$$f(t, W) = \exp\Big(\frac{1}{2} B(W) t\Big). \tag{3}$$

For our purposes however an extension to larger $|t| \sim 1 \div 2\,\mathrm{GeV}^2$ is desirable. A comparison with ZEUS data [5] (see [4]) shows that a “stretched exponential” parametrization

$$f(t, W) = \exp(\mu^2 B(W)) \exp\Big(-\mu^2 B(W) \sqrt{1 - t/\mu^2}\Big)\,, \tag{4}$$

does a good job with only one new parameter. Different physical process can give rise to the stretched-exponential behaviour, such as a contamination of data by dissociative events, multiple scatterings, or – somewhat unlikely – “hard” scattering.

The exclusive photoproduction of J/ψ and $\psi'(2S)$ charmonia has first been observed by the CDF collaboration [6] and has recently been measured by the LHCb collaboration [7, 8]. In Fig. 1, we compare our calculations of the J/ψ rapidity distributions to the LHCb data, a similar picture is observed for $\psi(2S)$ production (see [4]).

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 Staśto [10] from the nonlinear evolution equation (rightmost panels). We stress that all the unintegrated gluon distributions reproduce the Tevatron data [6], see [4]. We wish to point out, that 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. 2). This would correspond to the exchange of a single Pomeron trajectory and casts some doubts on the necessity of saturation effects in the unintegrated glue. In the right panel of Fig. 2 we show a comparison of our results for Υ production compared to recent LHCb data [11]. The large error bars do not allow us to distinguish different choices for the diffractive slope.

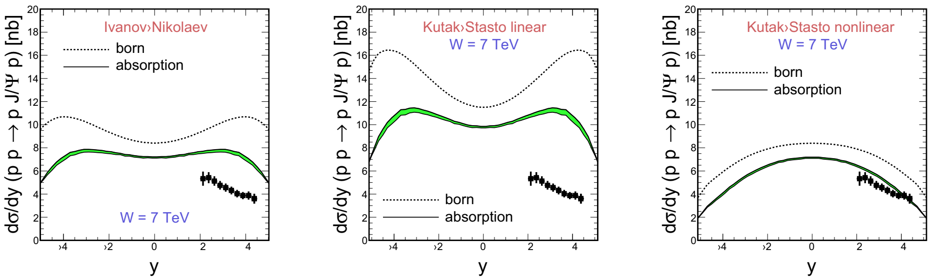

Figure 1. J/ψ rapidity distribution calculated with inclusion of absorption effects (solid lines), compared with the Born result (dashed line) for $\sqrt{s} = 7$ TeV. The LHCb data points [8] are shown for comparison.

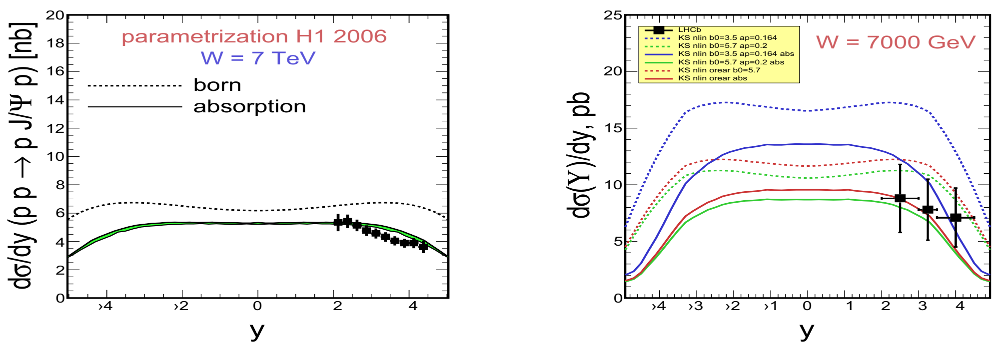

Figure 2. Left panel: J/ψ rapidity distribution calculated with a parametrization of the photoproduction amplitude previously used in [3]. Right panel: Rapidity distribution of exclusive Υ's. Data are taken from [11].

3 Diffractive photoproduction with electromagnetic dissociation

Proton dissociative events are of great practical importance as an often difficult background to exclusive events. 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 is:

$$\frac{d\sigma(pp \to XVp;s)}{dy d^2\mathbf{p}} = \int \frac{d^2\mathbf{q}}{\pi \mathbf{q}^2} \mathcal{F}^{(\mathrm{in})}_{\gamma/p}(z_+, \mathbf{q}^2) \frac{1}{\pi} \frac{d\sigma^{\gamma^* p \to Vp}}{dt}(z_+ s, t = -(\mathbf{q}-\mathbf{p})^2) + (z_+ \leftrightarrow z_-), \tag{5}$$

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, see [12]: Of special interest is the region of small invariant masses, $M_X < 2$ GeV, where resonance excitation is important. Our recent study (second ref. in [12]) showed, that here it is best to use a parametrization of F_2 given in [13]. In the left panel of Fig. 3 we show a distribution in invariant mass of the excited system for the $pp \to XJ/\psi p$ reaction. In the right panel of Fig. 3 we show the rapidity distribution of J/ψ for elastic and e.m. dissociative events. The e.m. dissociation can reach $10 \div 15\%$ of the exclusive cross section.

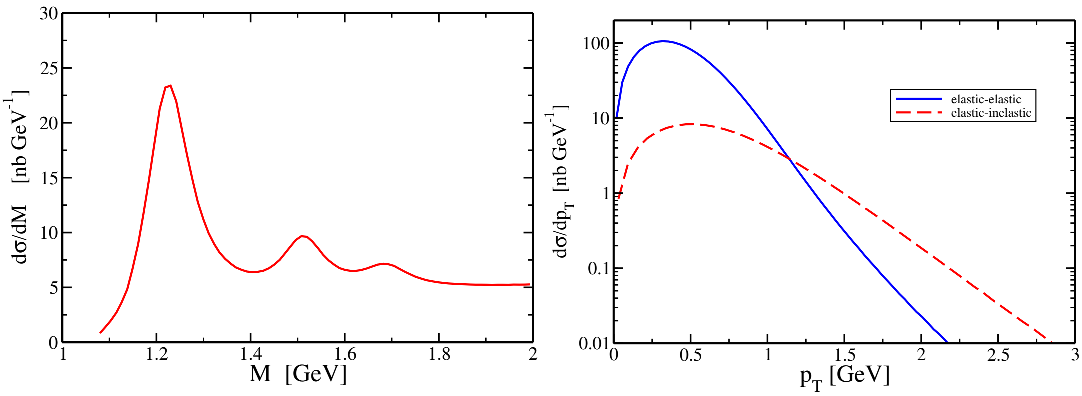

Figure 3. Left panel: distribution in the mass of the electromagnetically excited system, M_X for the $pp \to XJ/\psi p$ process. Right panel: Rapidity distribution of J/ψ for the same process (dashed line), for $M_X < 2$ GeV as well as for the exclusive diffractive production.

4 Conclusions

We have compared our $k_\perp$-factorization results with recent LHCb ($pp \longrightarrow p\ V\ p$) data, for $V = J/\psi, \psi(2S), \Upsilon$. The best description is obtained for a glue which does contain gluon saturation effects. Proton dissociation is a background to exclusive processes. Electromagnetic dissociation is calculable from F_2, excited states $M_X < 2\,\mathrm{GeV}$ make a contribution of $10 \div 15\%$ of the exclusive cross section for J/ψ production.

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