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Exclusive and semiexclusive production of vector mesons in proton-proton collisions with electromagnetic proton dissociation

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We calculate rapidity and transverse momentum distributions for different vector mesons in purely exclusive ($pp \to ppV$) and semiexclusive ($pp \to pXV$) processes with the electromagnetic dissociation of a proton. The cross section for exclusive production depends on the wave function of the vector mesons and unintegrated gluon distribution function. The cross section for the electromagnetic dissociation is expressed through electro-magnetic structure functions of the proton. We include the transverse momentum distribution of initial photons in the associated flux. Contributions of the exclusive and semiexclusive processes are compared for different vector mesons ($V = \phi, J/\psi, \Upsilon$). We show the ratio of semiexclusive to exclusive contributions and compare for different mesons as a function of different variables (y, p_t).

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1. Introducition

Exclusive production of vector mesons, especially of heavier quarkonia like J/ψ or Υ in $\gamma p \to Vp$ collisions is in principle subjected to pQCD methods. The energy dependence for the diffractive photoproduction of vector mesons was explored at the HERA accelerator. The results for exclusive production strongly depends on the model of the wave function and unintegrated gluon distribution function UGDF [1]. So far both (almost) exclusive J/ψ and Υ production [2, 3] was studied in proton-proton collisions at the LHC. The measurements are not fully exclusive because the outgoing protons were not measured, but only a veto on particle production in a large rapidity interval was imposed. For proton-proton collisions, two types of proton excitations are possible: diffractive and electromagnetic. In our earlier paper on J/ψ production [4] we developed a formalism how to calculate processes with rapdidity gaps, but including proton dissociation. To calculate electromagnetic dissociation, the method uses parametrizations of the proton structure functions. We have shown in [4] that the semi-exclusive mechanism cannot be completely removed by the rapidity veto on additionally produced particles. We were a bit surprised that the electromagnetic dissociation is more important than the diffractive dissociation [5].

2. Exclusive production of vector mesons

The amplitude for the exclusive production of vector meson is shown schematically in Fig.1.

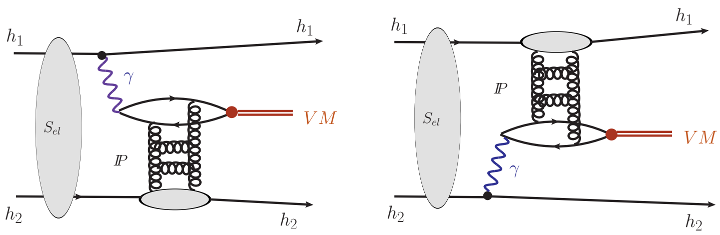

Figure 1: Diagrams representing the amplitude for the $pp \to pVp$ process.

2.1 Photoproduction of ϕ, J/ψ and Υ meson in γp collisions

The full amplitude for $\gamma p \to Vp$ process can be written as:

$$M(W, \Delta^2) = (i + \rho)\, \Im m M(W, \Delta^2 = 0, Q^2 = 0)\, \exp\left(\frac{-B(W)\Delta^2}{2}\right), \tag{1}$$

where ρ is the ratio of real to imaginary part of the amplitude and $B(W)$ is the slope parameter which depends on energy: $B(W) = B_0 + 2\alpha'_{eff} \log\left(\frac{W^2}{W_0^2}\right)$ [6]. The imaginary part of the amplitude depends on the unintegrated gluon distribution function (UGDF) $F(x_{eff}, \kappa^2)$ and on the wave function of the vector meson $\psi_V(z, k^2)$ and for $\Delta = 0$ and $Q^2 = 0$ is given by the formula [1]:

$$\Im m\, M(W, \Delta^2 = 0, Q^2 = 0) = W^2 \frac{c_V \sqrt{4\pi\alpha_{em}}}{4\pi^2}\, 2 \int_0^1 \frac{dz}{z(1-z)} \int_0^\infty \pi dk^2 \psi_V(z, k^2)$$
$$\int_0^\infty \frac{\pi d\kappa^2}{\kappa^4} \alpha_S(q^2) F(x, \kappa^2) \Big(A_0(z, k^2)\, W_0(k^2, \kappa^2) + A_1(z, k^2)\, W_1(k^2, \kappa^2) \Big). \tag{2}$$

Total cross section can be calculated as:

$$\sigma(\gamma p \to J/\psi p) = \frac{1+\rho^2}{16\pi B(W)} \left| \frac{\Im m M(W, \Delta^2 = 0, Q^2 = 0)}{W^2} \right|^2 . \quad (3)$$

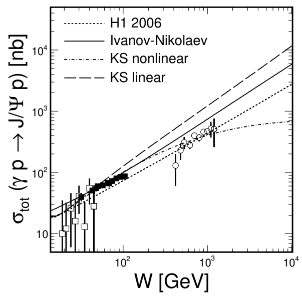

Figure 2: Total cross section for the J/ψ meson photoproduction as a function of collision energy.

In Fig. 2 we present the total cross section for $\gamma p \to J/\psi p$ process. It is shown as a function of collision energy for different models of UGDFs. We compared our results with HERA and LHCb experimental data.

2.2 Exclusive photoproduction of vector meson in pp collisions

The full amplitude for the $pp \longrightarrow pVp$ is calculated as:

$$M^{\lambda_1\lambda_2\to\lambda_1'\lambda_2'\lambda_V}_{h_1h_2\to h_1h_2V}(p_1,p_2) = M^{(0)\lambda_1\lambda_2\to\lambda_1'\lambda_2'\lambda_V}_{h_1h_2\to h_1h_2V}(s,s_1,s_2,t_1,t_2) - \delta M^{\lambda_1\lambda_2\to\lambda_1'\lambda_2'\lambda_V}_{h_1h_2\to h_1h_2V}(p_1,p_2)\,, \quad (4)$$

where $M^{(0)\lambda_1\lambda_2\to\lambda_1'\lambda_2'\lambda_V}_{h_1h_2\to h_1h_2V}(s,s_1,s_2,t_1,t_2)$ is the Born amplitude
and $\delta M^{\lambda_1\lambda_2\to\lambda_1'\lambda_2'\lambda_V}_{h_1h_2\to h_1h_2V}(p_1,p_2)$ is the absorptive correction to the amplitude [1].

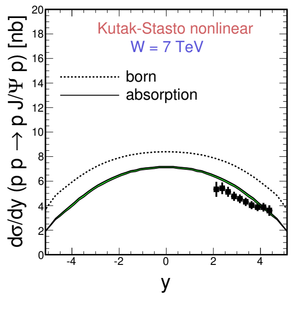

Figure 3: Differential cross section for the J/ψ meson production as a function of rapidity.

In Fig. 3 we shown rapidity distribution for J/ψ meson for the Kutak-Staśto nonlinear UGDF model for $\sqrt{s} = W = 7$ TeV. The results with the Kutak-Staśto nonlinear UGDF are almost consistent with the LHCb data [7].

3. Semiexclusive production of vector mesons with electromagnetic dissociation of protons

The semiexclusive production of vector mesons in proton-proton collisions with electromagnetic dissociation of protons is illustrated in Fig. 4.

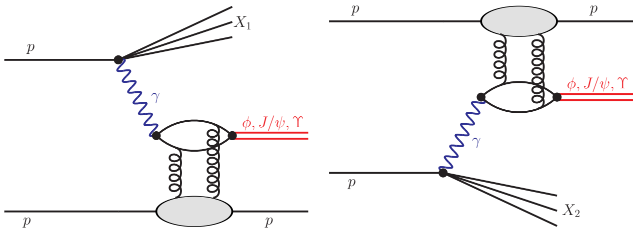

Figure 4: Schematic representation of the electromagnetic excitation of one (left panel) or second (right panel) proton.

The important property of these processes is that the $\gamma^\star p \to VX$ transition can be expressed by the electromagnetic structure functions of the proton. The cross section for such processes can be written as:

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

Photons carry a longitudinal momentum fraction $z_\pm = e^{\pm y}\sqrt{\boldsymbol{p}^2 + m_V^2}/\sqrt{s}$ and transverse momentum $\mathbf{q}$.

The effective photon flux in dissociative events can be expressed through the structure function F_2 as:

$$\mathcal{F}^{(\mathrm{inel})}_{\gamma/p}(z, \boldsymbol{q}^2, M_X^2) = \frac{\alpha_{\mathrm{em}}}{\pi}(1-z)\theta(M_X^2 - M_{\mathrm{thr}}^2)\frac{F_2(x_{Bj}, Q^2)}{M_X^2 + Q^2 - m_p^2}\left[\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z(M_X^2 - m_p^2) + z^2 m_p^2}\right]^2 , \quad (6)$$

with

$$Q^2 = \frac{1}{1-z}\left[\boldsymbol{q}^2 + z(M_X^2 - m_p^2) + z^2 m_p^2\right], x_{Bj} = \frac{Q^2}{Q^2 + M_X^2 - m_p^2} \ . \quad (7)$$

In practical calculation we used different parametrizations of electromagnetic structure functions of the proton [8–10].

In Fig. 5 we show the rapidity distribution for the semiexclusive production of vector mesons for the proton-proton collision energies of 7 TeV and 13 TeV. In the left panels we present our results for the ϕ meson, in the middle panels for the J/ψ meson and in the right panels for the Υ meson. We show the results for different parametrizations of the F_2 structure function. The blue solid lines are for Abramowicz-Levin-Levy-Maor (ALLM) [9], the red dash-dotted lines are for Fiore-Flachi-Jenkovszky-Lengyel-Magas (FFJLM) [8], the green dashed lines are for Szczurek-Uleshchenko (SU) [10] fits to F_2 and the dotted lines are for the VDM contribution alone.

In Fig. 6 we show the ratio $R^{EM/excl.}$ of EM dissociative and purely exlusive contributions as a function of rapidity for different upper limits on missing mass M_X. The ALLM type structure

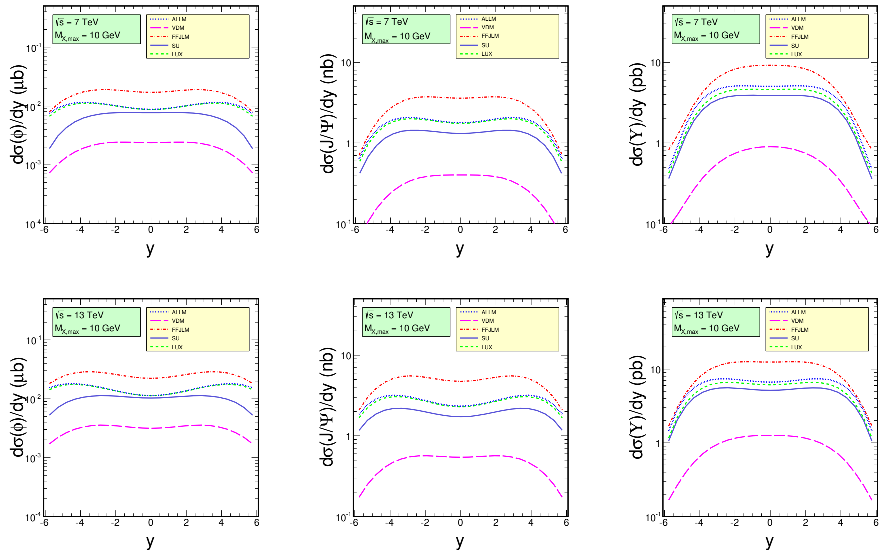

Figure 5: Rapidity distribution of vector mesons produced when one of the protons is excited due to photon exchange. Both contributions are added together.

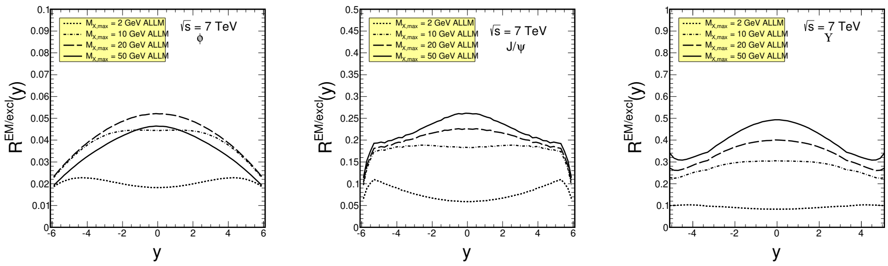

Figure 6: Ratio of inelastic diffractive to exclusive vector meson production as a function of rapidity for different upper limits on the mass M_X of the excited proton .

function of proton was used for these calculations. We show the results for: ϕ (left), J/ψ(middle) and Υ (right).

In Fig. 7 we show the ratio $R^{EM/excl.}$ as a function of transverse momentum for different upper limits on M_X, we see that as soon as high mass states are included, the inelastic contribution dominates at $p_t \gtrsim 1\,GeV$.

4. Conclusions

In this talk we have discussed exclusive and semiexclusive production of vector mesons in proton-proton collisions. These results were obtained in our recent papers [1, 4, 5]. It has been shown that results for exclusive production strongly depend on the model of the wave function and unintegrated gluon distribution function. Electromagnetic dissociation of protons was calculated using inelastic unintegrated photon flux based on modern parametrizations of deep-inelastic proton structure functions. Different parametrizations from the literature were used. The results depend

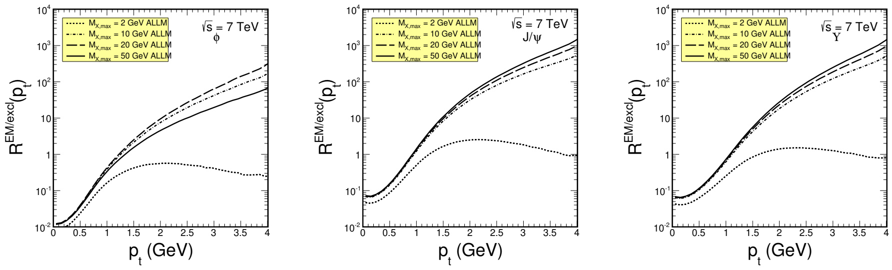

Figure 7: Ratio of inelastic diffractive to exclusive vector meson production as a function of of transverse momentum for different upper limits on the excited mass M_X.

strongly on the parametrization of the structure function used. In the γ-Pomeron fusion reactions in proton-proton scattering, the electromagnetic dissociation is of the same size as strong, diffractive dissociation. It even dominates in some regions of the phase space. The ratio of the semiexclusive to the purely exclusive contributions strongly depends on the vector meson transverse momentum and only mildly on its rapidity. In general, the bigger semiexclusive to exclusive ratio is obtained for heavier vector mesons.

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