Photoproduction of J/ψ in exclusive and semiexclusive proton-proton collisions

Anna Cisek

University of Rzeszow

EMMI Challenges in Photon Induced Interactions
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Outline

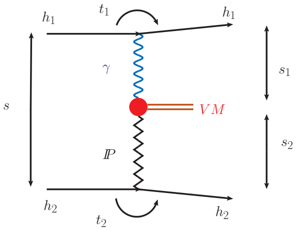
- **Anna Cisek, Wolfgang Schäfer, Antoni Szczurek**

Introduction

1. Exclusive production of J/Ψ meson in photon-proton collisions has been studied in the energy range $W \sim 20 - 300\ GeV$ (recently at HERA, LHCb)
2. This energy range is relevant for the exclusive photoproduction in proton-antiproton collisions at Tevatron energies for not too large rapidities of the meson
3. For Tevatron we have only one experimental point for J/Ψ and Ψ' mesons at $y = 0$
4. For LHCb experimental data in proton-proton collisions for J/Ψ and Ψ' mesons in the rapidity range $y \sim 2.0 - 4.5$

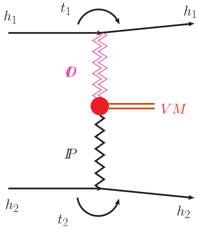
The possible mechanism to exclusive production of vector meson in hadronic collisions

Photoproduction



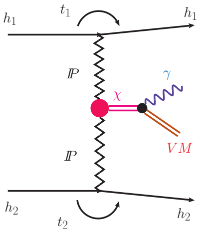
Khoze-Martin-Ryskin 2002
Klein-Nystrand 2004

Oderon-Pomeron fusion



Schäfer, Mankiewicz, Nachtmann 1991
Bzdak, Motyka, Szymanowski, Cudell 2007

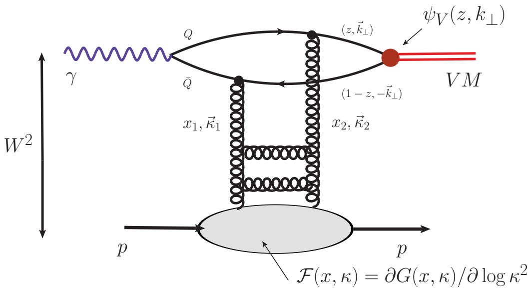
Radiative Decay of χ_c



Pasechnik, Szczurek, Teryaev 2008

- In our analysis we restrict only to photon-Pomeron fusion mechanism

Diagram for exclusive photoproduction $\gamma p \to J/\Psi p$



- $\psi_v(z, k^2) \to$ wave function of the vector meson
- $\mathcal{F}(x, \kappa^2) \to$ unintegrated gluon distribution function
- $x \sim (Q^2 + M^2_{J/\Psi})/W^2$

The production amplitude for $\gamma p \to J/\Psi p$

The full amplitude:

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

The imaginary part of the amplitude can be written as:

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

Real part

$$\rho_T = \frac{\Re e\mathcal{M}_T}{\Im m\mathcal{M}_T} = \frac{\pi}{2}\,\Delta_{\mathbf{P}}$$

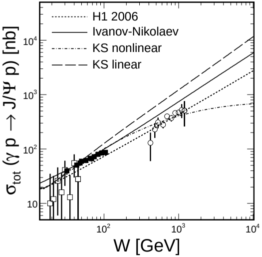
Slope parameter

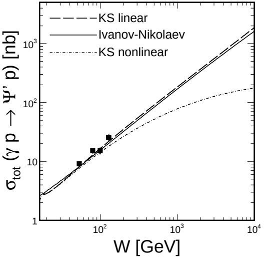
$$B(W) = B_0 + 2\alpha'_{eff}\log\left(\frac{W^2}{W_0^2}\right)$$

Total cross section for $\gamma p \to J/\Psi(\Psi')\, p$

Total cross section can be written as:

$$\sigma_T(\gamma p \to J/\Psi p) = \frac{1+\rho_T{}^2}{16\pi B(W)} \left| \frac{\Im m \mathcal{M}_T(W, \Delta^2 = 0, Q^2 = 0)}{W^2} \right|^2$$





HERA data and extracted LHCb data

- H1 Collaboration, Phys. Lett. B541 (2002) 251
- H1 Collaboration, Eur. Phys. J. C46 (2006) 585
- H1 Collaboration, Eur. Phys. J. C73 (2013) 2466

Radial excitations

Gauss wave function

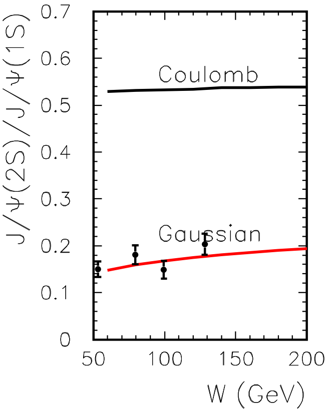
$$\psi_{1S}(k^2) = C_1 \exp(-\frac{k^2 a_1^2}{2})$$

$$\psi_{2S}(k^2) = C_2(\xi_0 - p^2 a_2^2) \exp(-\frac{k^2 a_2^2}{2})$$

Coulomb wave function

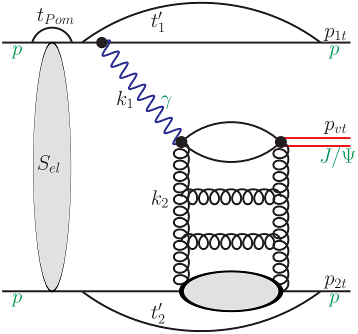
$$\psi_{1S}(k^2) = \frac{C_1}{\sqrt{M}} \frac{1}{(1 + a_1^2 k^2)^2}$$

$$\psi_{2S}(k^2) = \frac{C_2}{\sqrt{M}} \frac{\xi_0 - a_2^2 k^2}{(1 + a_2^2 k^2)^3}$$

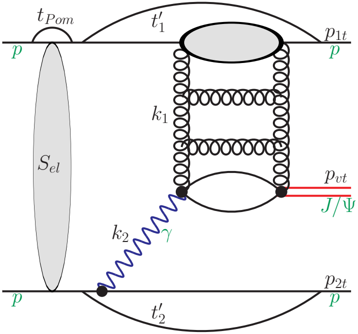


- strong dependence on the wave function
- H1 Collaboration, Phys. Lett. B541 (2002) 251

Diagram for exclusive production of $J/\Psi(\Psi')$ meson in proton-proton collisions



photon-Pomeron



Pomeron-photon

Amplitude for process $pp \to p\ J/\Psi(\Psi')\ p$

Full apmlitude for $pp \longrightarrow pVp$

$$\begin{aligned} \boldsymbol{M}(\boldsymbol{p}_1,\boldsymbol{p}_2) &= \int \frac{d^2\boldsymbol{k}}{(2\pi)^2}\, S_{el}(\boldsymbol{k})\, \boldsymbol{M}^{(0)}(\boldsymbol{p}_1-\boldsymbol{k},\boldsymbol{p}_2+\boldsymbol{k}) \\ &= \boldsymbol{M}^{(0)}(\boldsymbol{p}_1,\boldsymbol{p}_2) - \delta\boldsymbol{M}(\boldsymbol{p}_1,\boldsymbol{p}_2) \end{aligned}$$

Amplitude without absorption

$$\begin{aligned} \boldsymbol{M}^{(0)}(\boldsymbol{p}_1,\boldsymbol{p}_2) &= e_1 \frac{2}{z_1}\frac{\boldsymbol{p}_1}{t_1}\mathcal{F}_{\lambda_1'\lambda_1}(\boldsymbol{p}_1,t_1)\mathcal{M}_{\gamma h_2\to V h_2}(s_2,t_2,Q_1^2) \\ &+ e_2 \frac{2}{z_2}\frac{\boldsymbol{p}_2}{t_2}\mathcal{F}_{\lambda_2'\lambda_2}(\boldsymbol{p}_2,t_2)\mathcal{M}_{\gamma h_1\to V h_1}(s_1,t_1,Q_2^2) \end{aligned}$$

Absorptive corrections for the amplitude

$$\delta\boldsymbol{M}(\boldsymbol{p}_1,\boldsymbol{p}_2) = \int \frac{d^2\boldsymbol{k}}{2(2\pi)^2}\, T(\boldsymbol{k})\, \boldsymbol{M}^{(0)}(\boldsymbol{p}_1-\boldsymbol{k},\boldsymbol{p}_2+\boldsymbol{k})$$

Helicity conserving and helicity flip amplitudes

The full amplitude for the $pp \to pVp$ process can be written as

$$\mathcal{M}^{\lambda_1\lambda_2\to\lambda_1'\lambda_2'\lambda_V}_{h_1h_2\to h_1h_2V}(s,s_1,s_2,t_1,t_2) = \mathcal{M}_{\gamma\mathbf{P}} + \mathcal{M}_{\mathbf{P}\gamma}$$

$$= \langle p_1',\lambda_1'|J_\mu|p_1,\lambda_1\rangle\epsilon^*_\mu(q_1,\lambda_V)\frac{\sqrt{4\pi\alpha_{em}}}{t_1}\mathcal{M}^{\lambda_{\gamma^*}\lambda_2\to\lambda_V\lambda_2}_{\gamma^*h_2\to Vh_2}(s_2,t_2,Q_1^2)$$

$$+\langle p_2',\lambda_2'|J_\mu|p_2,\lambda_2\rangle\epsilon^*_\mu(q_2,\lambda_V)\frac{\sqrt{4\pi\alpha_{em}}}{t_2}\mathcal{M}^{\lambda_{\gamma^*}\lambda_1\to\lambda_V\lambda_1}_{\gamma^*h_1\to Vh_1}(s_1,t_1,Q_2^2)$$

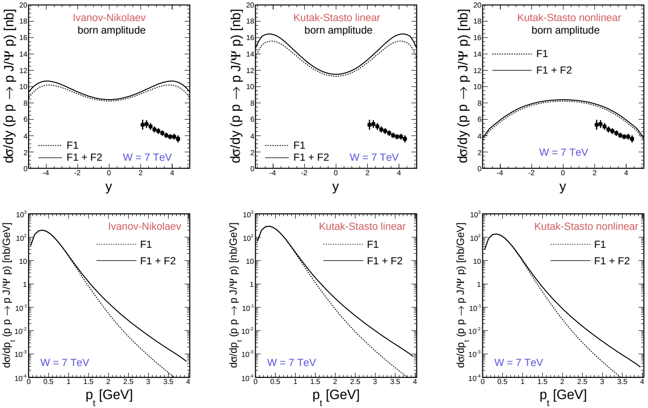
Simple structure:

$$\langle p_1',\lambda_1'|J_\mu|p_1,\lambda_1\rangle\epsilon^*_\mu(q_1,\lambda_V) = \frac{(\boldsymbol{e}^{*(\lambda_V)}\boldsymbol{q}_1)}{\sqrt{1-z_1}}\,\frac{2}{z_1}\,\cdot$$

$$\cdot\chi^\dagger_{\lambda'}\Big\{F_1(Q_1^2) - \frac{i\kappa_p F_2(Q_1^2)}{2m_p}(\boldsymbol{\sigma}_1\cdot[\boldsymbol{q}_1,\boldsymbol{n}])\Big\}\chi_\lambda$$

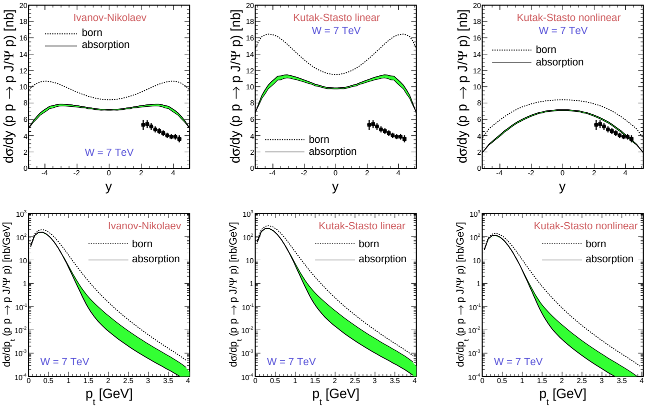
- The coupling with F_1 - proton helicity conserving, F_2 - proton helicity flip

Dirac vs Pauli form factors (Born)



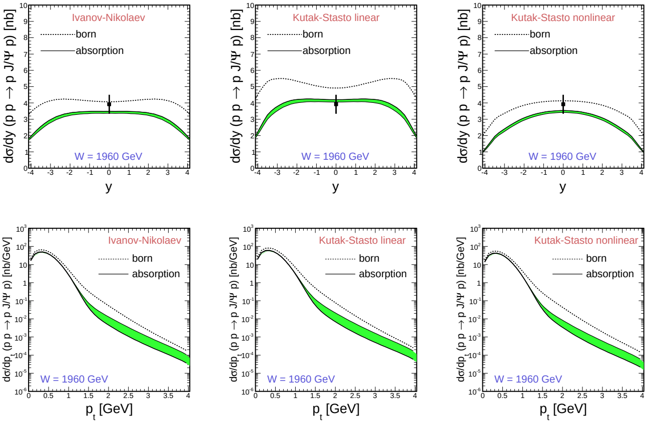
- R. Aaij et al. (LHCb collaboration), J. Phys. **G40** (2013) 045001
- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
- At large p_t we get an enhancement factor of the cross section of order of 10
- Absorption must be included

Absorption effect



- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
- Absorption may be bigger

Absorption effect for J/Ψ at the Tevatron

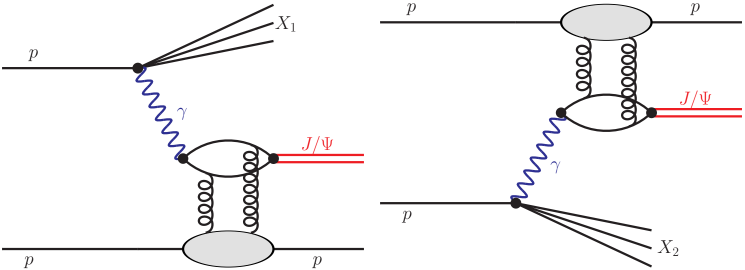


- CDF Collaboration, T.Aaltonen et al., Phys. Rev. Lett. 102 (2009)

Introduction

- We often have to deal with diffractive reactions which include excitation of incoming protons. Instead of fully inclusive final states: gap cross sections, or even only vetos on additional tracks(!) from a production vertex.
- In proton-proton collisions two different types of excitation are possible: diffractive as for $\gamma p \to VX$ and electromagnetic in $p \to X$ transitions in the vertex with photon exchange.
- A model for the diffractive excitation of low mass states was considered by Jenkovszky et al. Phys. Rev. **D83** (2011) 056014. In this approach the resonant contributions dominate.
- Inelastic state of mass M_X populates a rapidity interval $\Delta y \sim \log(M_X^2/m_q p^2)$.
- A background for exclusive production – or a possible signal when looking for large p_T vector mesons with a gap.

Diagrams representation of the electromagnetic excitation



- The schematic diagrams representation of the electromagnetic excitation of one (left panel) or second (right panel) photon
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Diffractive production with electromagnetic dissociation

The cross section for such proces can be written as:

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

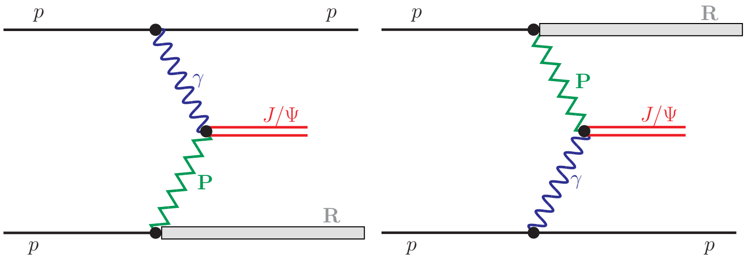
$$z_\pm = e^{\pm y} \sqrt{\boldsymbol{p}^2 + m_V^2} / \sqrt{s}$$

Structure function of proton

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

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

Difractive resonance with strong disociation



- low $p_T \rightarrow$ Dissociation into nucleon resonances/low mass continuum states. Dominated by $N^*(1680)$, $J^P = \frac{5}{2}^+$, $N^*(2220)$, $J^P = \frac{9}{2}^+$, $N^*(2700)$, $J^P = \frac{13}{2}^+$.
  A model by L.L. Jenkovszky, O.E. Kuprash, J.W. Lämsa, V.K. Magas and R. Orava (2011).
- large $p_T \rightarrow$ Incoherent diffractive photoproduction of J/ψ off partons. Large diffractive masses are possible here.

Difractive resonance with strong disociation

The large gap is proided by te Pomeron exchange, and we write the cross secion in such way:

$$\frac{d\sigma(\gamma p \to VX)}{dt dM_X^2} = \left(\frac{s_{\gamma p}}{M_X^2}\right)^{2\alpha_{\mathbf{P}}^{\rm eff}(t)-2} \cdot A_0 f_{\gamma\to V}^2(t) \cdot F(M_X^2, t)$$

The function $f_{\gamma\to V}(t) = \exp[B_{\gamma\to V} t/2]$ is a formfactor of the $\gamma \to V$ transition, while $F(M_X^2, t)$ contains the information on the dynamics of the diffractive dissociation.

$$F(M_X^2, t) = \frac{x(1-x)^2}{(M_X^2 - m_p^2)(1+\tau)^{3/2}}\left(\Im m A(M_X^2, t) + A_{\rm Roper}(M_X^2, t)\right)$$

$$x = \frac{|t|}{M_X^2 + |t|}, \; \tau = \frac{4m_p^2 x^2}{|t|}$$

Difractive resonance with strong disociation

Explicitly, they contribute to the $p\mathbb{P} \to X$ amplitude as:

$$\Im m A(M_X^2, t) = \sum_{n=1,3} [f(t)]^{2(n+1)} \cdot \frac{\Im m\, \alpha(M_X^2)}{(J_n - \Re e\, \alpha(M_X^2))^2 + (\Im m\, \alpha(M_X^2))^2}$$

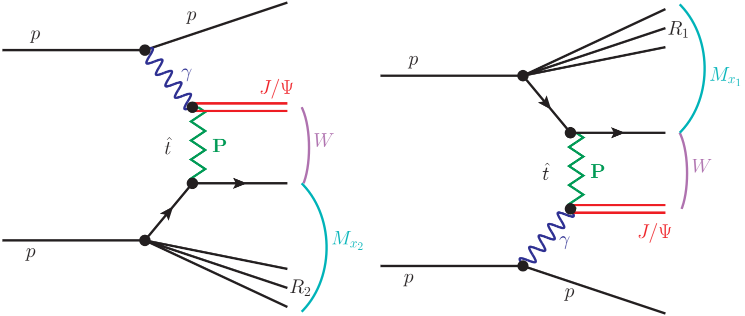
We can now compute the contribution from diffractive excitation of small masses from the formula

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

$$\mathcal{F}^{(\mathrm{el})}_{\gamma/p}(z, \boldsymbol{q}^2) = \frac{\alpha_{\mathrm{em}}}{\pi}(1-z)\left[\frac{\boldsymbol{q}^2}{\boldsymbol{q}^2 + z^2 m_p^2}\right]^2 \frac{4m_p^2 G_E^2(Q^2) + Q^2 G_M^2(Q^2)}{4m_p^2 + Q^2}$$

$$Q^2 = \frac{\boldsymbol{q}^2 + z^2 m_p^2}{1-z}$$

Difractive partonic with strong disociation



- dissociative production of vector mesons at large p_T probes the perturbative QCD Pomeron. (Ryskin, Forshaw et al.). An alternative to the "jet - gap - jet" type of processes.

Difractive partonic with strong disociation

Cross section

$$\frac{d\sigma^{diff,partonic}_{pp\to Vj}}{dy_V dy_j d^2p_t} = \frac{1}{\pi} x_1 q_{\rm eff}(x_1,\mu_F^2) x_2 \gamma_{el}(x_2) \frac{d\sigma(\gamma q \to Vq)}{d\hat{t}} + (x_1 \leftrightarrow x_2)$$

$$q_{\rm eff}(x,\mu_F^2) = \frac{81}{16} g(x,\mu_F^2) + \sum_f \left[q_f(x,\mu_F^2) + \bar{q}_f(x,\mu_F^2)\right]$$

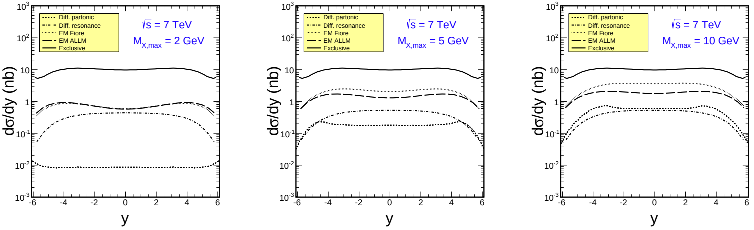
Factorization scale: $\mu_F^2 = m_V^2 + |\hat{t}|$

Simple formula for Pomeron-exchange

$$\frac{d\sigma_{\gamma q\to Vq}}{d\hat{t}} \propto \alpha_s^2(\bar{Q}_t^2)\alpha_s^2(|\hat{t}|) \frac{m_V^3 \Gamma(V\to l^+ l^-)}{(\bar{Q}_t^2)^4}$$

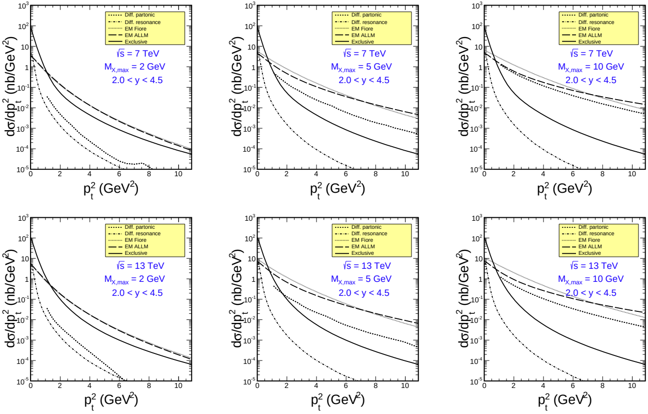
$\bar{Q}_t^2 = m_V^2 + |\hat{t}|$

Rapidity distribution



- Rapidity distribution of J/ψ mesons produced when one of the protons is excited due to photon or Pomeron exchange. We also show a reference distribution for the $pp \to ppJ/\psi$ exclusive process with parameters taken from A. Cisek, W. Schäfer and A. Szczurek (2015).

Transverse momentum distribution



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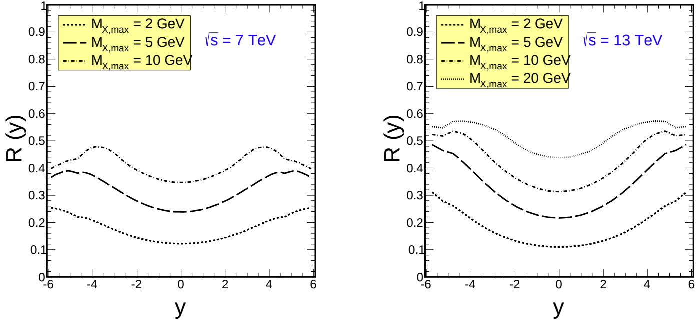
Ratio of dissociative to exclusive cross section



- $$R(y) = \frac{d\sigma_{pp\to pJ/\psi X}(M_X < M_{X,\max})/dy}{d\sigma_{pp\to pJ/\psi p}/dy} .$$

  $R(y)$ as a function of J/ψ rapidity for different ranges of M_X.
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Conclusions

- We have compared our results with recent HERA ($\gamma p \longrightarrow J/\Psi(\Psi')\ p$) and LHCb ($pp \longrightarrow p\ J/\Psi(\Psi')\ p$) data.
- $d\sigma/dp_t$ is interesting (spin flip, Pomeron-Odderon fusion) but difficult to measure.
- Absorptive corrections have been included. Their effect depends on p_t and y.
- In γ-Pomeron fusion reactions in proton-proton scattering, electromagnetic dissociation is of the same size as strong, diffractive dissociation. It even dominates in some regions of the phase space.
- Electromagnetic dissociation is calculable from F_2 data. Resonance excitation is important at low excited masses .
- Diffractive dissociation requires modelling, there is only little data to constrain it. The resonance contribution is concentrated at very small t, similar to the coherent elastic contribution