Exclusive vs semi-exclusive production of vector mesons in proton-proton collisions with electromagnetic dissociation of protons

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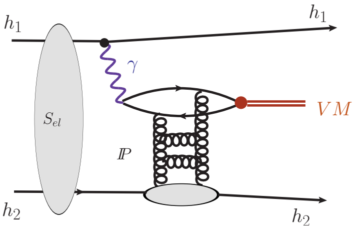
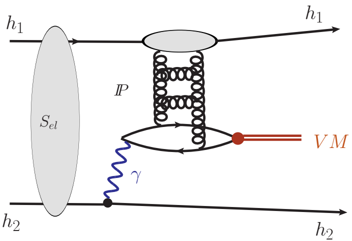
Introduction

- Exclusive production of heavy vector mesons in proton-proton collisions has been studied in rapidity range $y \sim 2.0 - 4.5$
- In the k_t - factorization approach the cross section strongly depends on unintegrated gluon distribution and quark-antiqark wave function.
- Large rapidity gaps: no exchange of charge or color. t-channel exchanges with the Regge intercept $\alpha(0)$ or spin $J \geq 1$.
- 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.
- A background for exclusive production – or a possible signal when looking for large p_T vector mesons with a gap.

Diagram for exclusive production of vector mesons in proton-proton collisions



photon-Pomeron



Pomeron-photon

The production amplitude for $\gamma p \to Vp$

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

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

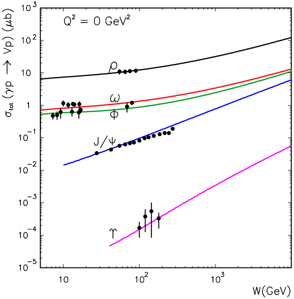
Slope parameter

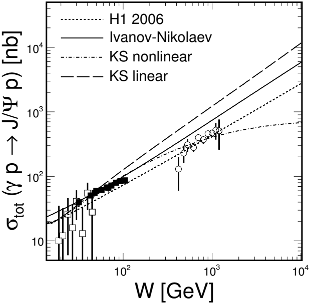
$$B(W) = B_0 + 2\alpha'_{eff}\log\left(\frac{W^2}{W_0^2}\right)$$

Total cross section for $\gamma p \to Vp$

Total cross section can be written as:

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





Amplitude for process $pp \to pV\,p$

Full apmlitude for $pp \longrightarrow pVp$

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

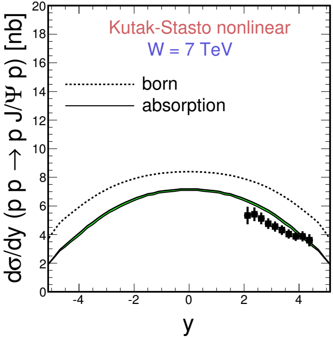
Amplitude without absorption

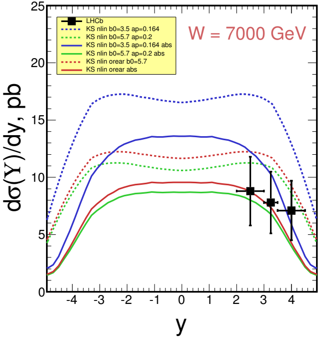
$$\begin{aligned} \boldsymbol{M}^{(0)}(\boldsymbol{p}_1,\boldsymbol{p}_2) &= e_1 \frac{2}{z_1}\frac{\boldsymbol{p}_1}{t_1}\mathcal{F}_{\lambda_1'\lambda_1}(\boldsymbol{p}_1,t_1)\mathcal{M}_{\gamma h_2\to V h_2}(s_2,t_2,Q_1^2) \\ &+ e_2 \frac{2}{z_2}\frac{\boldsymbol{p}_2}{t_2}\mathcal{F}_{\lambda_2'\lambda_2}(\boldsymbol{p}_2,t_2)\mathcal{M}_{\gamma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

Absorptive corrections for the amplitude

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

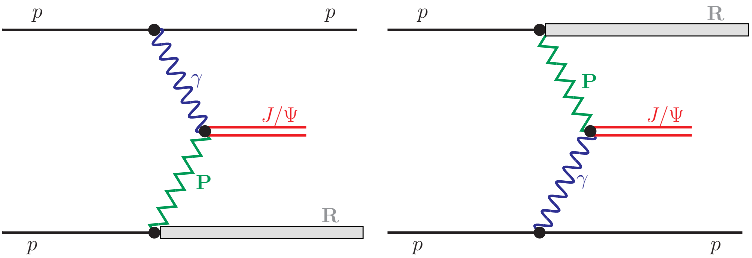
Rapidity distributions





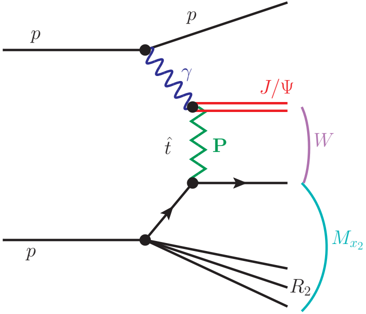
- R. Aaij et al. (LHCb collaboration), J. Phys. **G40** (2013) 045001
- Absorption must be included

Diffractive resonance production



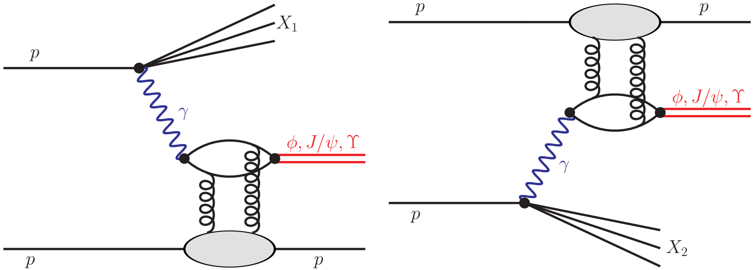
- low $p_T \rightarrow$ Dissociation into nucleon resonances/low mass continuum states. Dominated by $N^*(1680)$, $J^P = \frac{5}{2}^+$, $N^*(2220)$, $J^P = \frac{9}{2}^+$, $N^*(2700)$, $J^P = \frac{13}{2}^+$.
  A model by L.L. Jenkovszky, O.E. Kuprash, J.W. Lämsa, V.K. Magas and R. Orava (2011).
- large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

Diffractive partonic excitation



- 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.

Diagrams representation of the electromagnetic excitation



- The schematic diagrams representation of the electromagnetic excitation of one (left panel) or second (right panel) photon
- Anna Cisek, Wolfgang Schäfer, Antoni Szczurek
  Phys. Let. **B769** (2017) 176

Diffractive production of vector mesons with electromagnetic dissociation

- The importent property of these processes is that the $p\gamma^\star \to X$ transition is given by the electromagnetic structure function of protons

The cross section for such proces can be written as:

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

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

- Generalization of the Weizsäcker-Williams flux to dissociative processes.
- One must, in principle, add contributions of longitudinal photons. Negligible for heavy mesons as long as $Q^2 \ll m_V^2$

Diffractive production of vector mesons with electromagnetic dissociation

The flux of photons associated with the breakup of protons is calculable in terms of the structure function of protons

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

where

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

$$x_{Bj} = \frac{Q^2}{Q^2+M_X^2-m_p^2}$$

Structure function of protons

Useful fits to F2

- H. Abramowicz, E. M. Levin, A. Levy and U. Maor Phys. Lett. **B269**, (1991) 465

$$F_2(x, Q^2) = \frac{Q^2}{Q^2 + m_0^2} \left(F_2^{\mathcal{P}}(x, Q^2) + F_2^{\mathcal{R}}(x, Q^2) \right)$$

Useful fits to F2

- R. Fiore, A. Flachi, L. L. Jenkovszky, A. I. Lengyel and V. K. Magas - Phys. Rev. **D70**, 054003 (2004)

$$\mathcal{I}m\alpha(s) = s^{\delta} \sum_n c_n \left(\frac{s - s_n}{s} \right)^{\mathcal{R}e\alpha(s_n)} \cdot \theta(s - s_n)$$

$$\mathcal{R}e\,\alpha(s) = \alpha(0) + \frac{s}{\pi} PV \int_0^{\infty} ds' \frac{\mathcal{I}m\alpha(s')}{s'(s' - s)}$$

Structure function of protons

Useful fits to F2

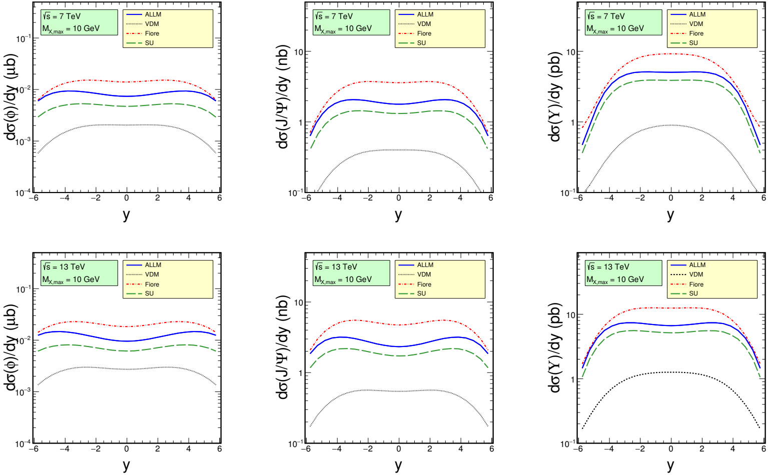
- A. Szczurek, V. Uleshchenko
  Eur. Phys. J. **C12** (200) 663-671

$$F_2^N(x, Q^2) = F_2^{N,VDM}(x, Q^2) + F_2^{N,part}(x, Q^2)$$

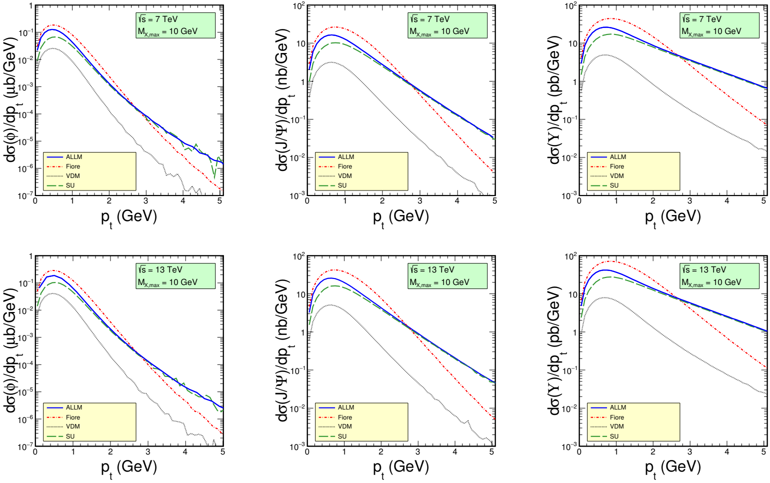
$$F_2^{N,VDM}(x, Q^2) = \frac{Q^2}{\pi} \sum_V \frac{M_V^4 \cdot \sigma_{VN}^{tot}(s^{1/2})}{\gamma_V^2 (Q^2 + M_V^2)^2} \cdot \Omega_V(x, Q^2)$$

$$F_2^{N,part}(x, Q^2) = \frac{Q^2}{Q^2 + Q_0^2} \cdot F_2^{asymp}(\bar{x}, \bar{Q}^2)$$

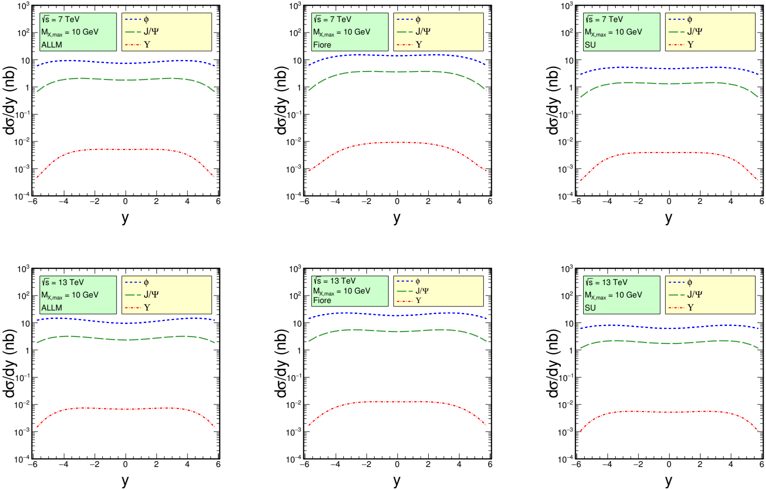
Rapidity distributions - different structure function of proton



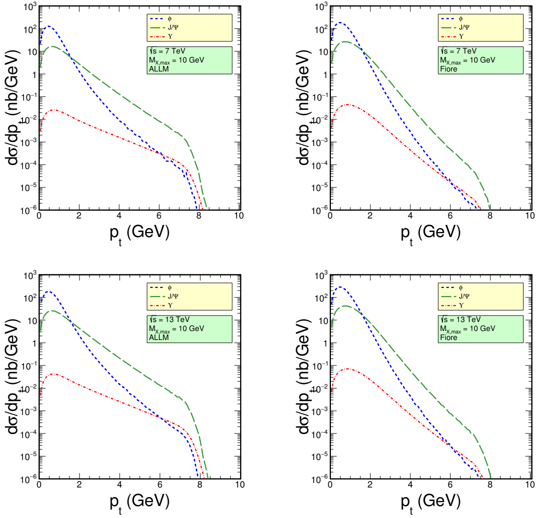
Transverse momentum distributions - different structure function of proton



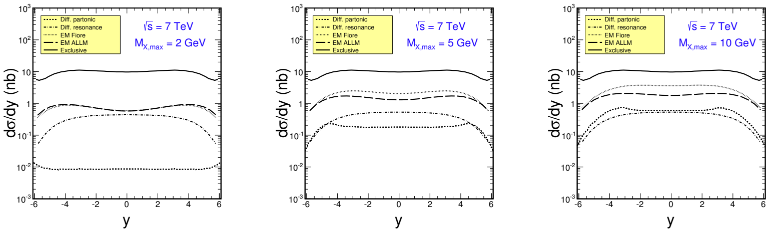
Rapidity distributions of mesons, comparison



Transverse momentum distributions

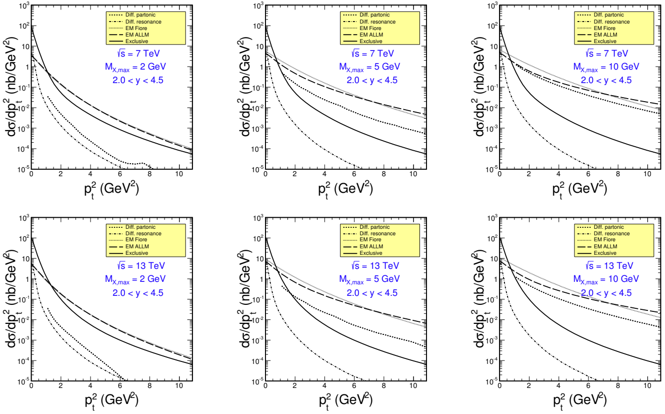


Rapidity distributions, $\sqrt{s}$ = 7 TeV - different mechanisms, comparisons



- Rapidity distribution of J/ψ mesons produced when one of the protons is excited due to photon or Pomeron exchange. Both contributions (one or second proton excitation) are added together. We also show a reference distribution for the $pp \to ppJ/\psi$ exclusive process with parameters taken from Anna Cisek, Wolfgang Schäfer, Antoni Szczurek: JHEP 1504 (2015) 159.
- Anna Cisek, Wolfgang Schäfer, Antoni Szczurek
  Phys. Let. **B769** (2017) 176

Transverse momentum - mechanism comparision



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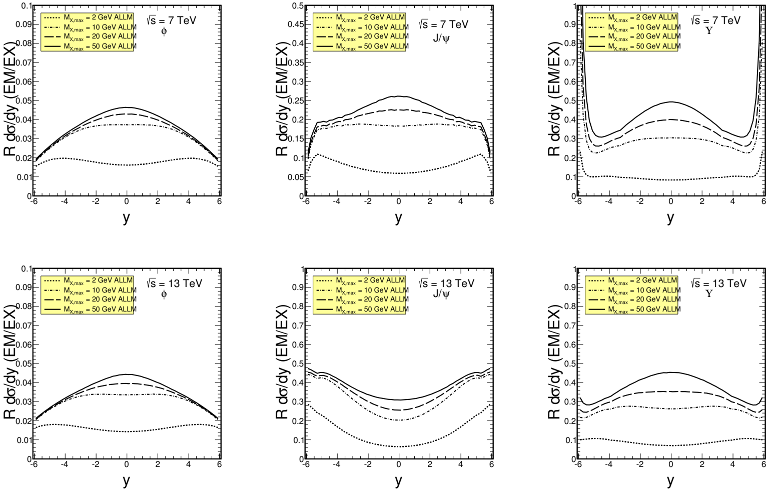
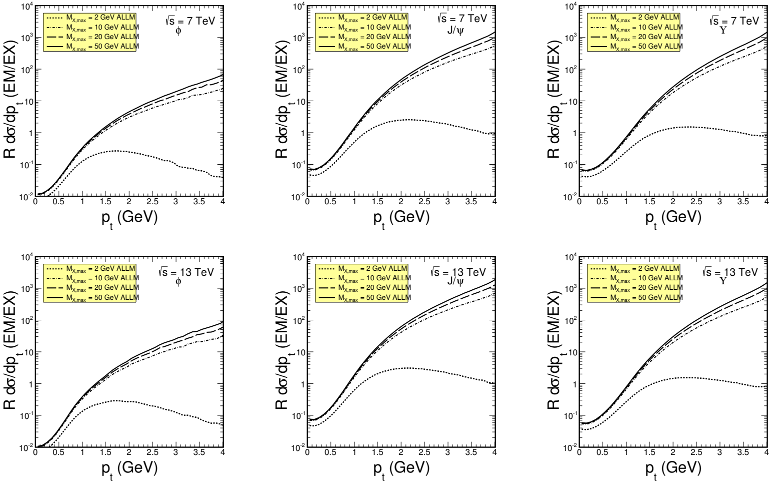
Rapidity distributions - ratio semiexclusive to exclusive



Transverse momentum distributions - ratio semiexclusive to exclusive



Conclusions

- 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 for low excited masses. Large cross sections have been obtained from the calculations.
- The electromagnetic dissociation gives dominant contribution at large transverse momenta of vector mesons. Therefore the ratio of the semiesclusive to exclusive contributions depends strongly on p_t.
- 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