Exclusive photoproduction of charmonia in hadronic collisions

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XXII International Workshop Deep-Inelastic Scattering
and Related Subjects DIS 2014, Warsaw, 28 April - 2 May 2014

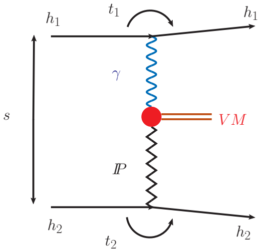
Outline

Introduction

- 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)
- This energy range is relevant for the exclusive photoproduction in proton-antiproton collisions at Tevatron energies for not too large rapidities of the meson
- For Tevatron we have only one experimental point for J/Ψ and Ψ' mesons at $y = 0$
- New experimental data in proton-proton collisions for J/Ψ and Ψ' mesons in the rapidity range $y \sim 2.0 - 4.5$ (LHCb)
- We include absorption effects in hadronic reaction

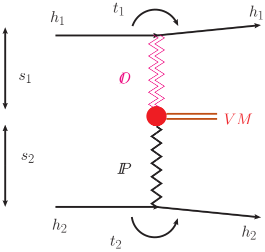
The possible mechanism to production of vector meson in hadronic collisions

Photoproduction



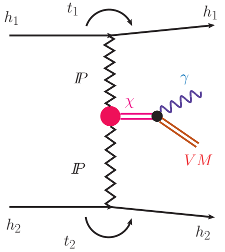
Khoze-Martin-Ryskin 2002
Klein-Nystrand 2004

Oderon-Pomeron fusion



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

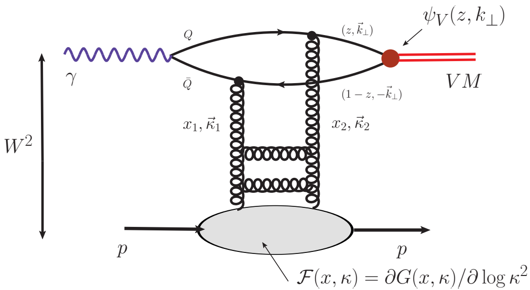
Radiative Decay of χ_c



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 imaginary part of the amplitude can be written as:

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

where

$$A_0(z,k^2) = m_c^2 + \frac{k^2 m_c}{M_{J/\Psi}+2m_c},$$

$$A_1(z,k^2) = \left[z^2+(1-z)^2-(2z-1)^2\frac{m_c}{M_{J/\Psi}+2m_c}\right]\frac{k^2}{k^2+m_c^2},$$

$$W_0(k^2,\kappa^2) = \frac{1}{k^2+m_c^2} - \frac{1}{\sqrt{(k^2-m_c^2-\kappa^2)^2+4m_c^2k^2}},$$

$$W_1(k^2,\kappa^2) = 1 - \frac{k^2+m_c^2}{2k^2}\left(1+\frac{k^2-m_c^2-\kappa^2}{\sqrt{(k^2-m_c^2-\kappa^2)^2+4m_c^2k^2}}\right).$$

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

The full amplitude:

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

where

$$\rho_T = \frac{\Re e \mathcal{M}_T}{\Im m \mathcal{M}_T} = \frac{\pi}{2}\, \frac{\partial \log\left(\Im m \mathcal{M}_T / W^2\right)}{\partial \log W^2} = \frac{\pi}{2}\, \Delta_{\mathbf{P}}\,,$$

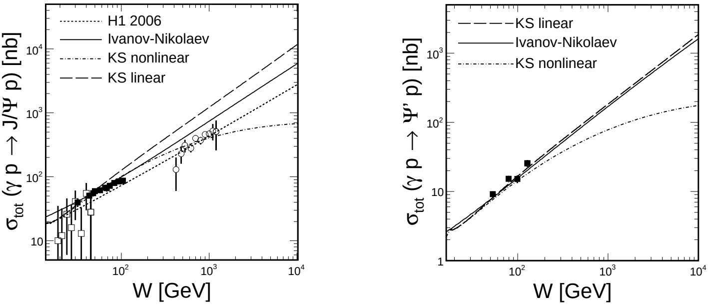
$$B(W) = B_0 + 2\alpha'_{eff} \log\left(\frac{W^2}{W_0^2}\right)\,.$$

Total cross section can be written as:

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

A.Rybarska, W.Schäfer, A.Szczurek: Phys. Lett. B668 (2008) 126

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



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

Parameters of the vector meson wave functions

How to choose parameters of the wave function

- $\Gamma(V \to e^+e^-) \Rightarrow g_V$
- $\psi_v(z,k) \Rightarrow g_V$
- normalization
- orthogonality

Decay electronic width: $\Gamma(V \to e^+e^-) = \dfrac{4\pi\alpha_{em}^2 c_v^2}{3M_V^3} \cdot g_V^2 \cdot K_{NLO}$

g_v -leptonic decay constant: $g_V = \dfrac{8N_c}{3} \int \dfrac{d^3\vec{p}}{(2\pi)^3} (M + m_q)\, \psi_v(z,k)$

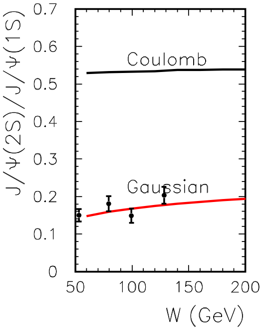
I.P.Ivanov, N.N.Nikolaev, A.A.Savin: Phys.Part.Nucl.37 (2006)

Radial excitations

Gauss:

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

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



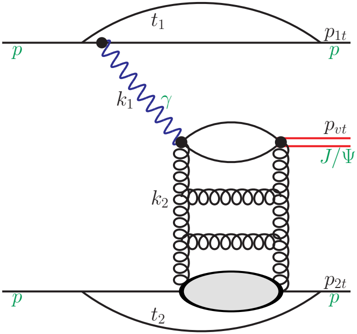
Coulomb:

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

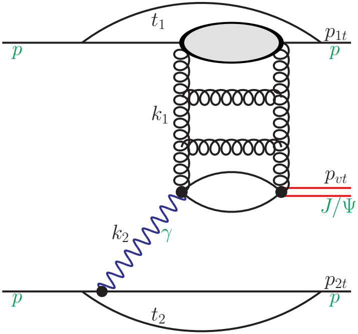
$$\psi_{2S}(k^2) = \frac{C_2}{\sqrt{M}} \frac{\xi_0 - a_2^2 k^2}{(1+a_2^2 k^2)^3}$$

- 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

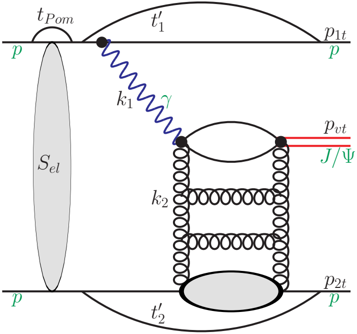


photon-Pomeron

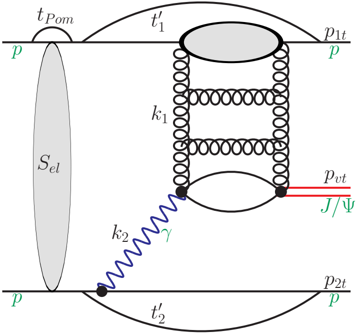


Pomeron-photon

Diagram for $pp \to p\ J/\Psi(\Psi')\ p$ with absorptive corrections



photon-Pomeron



Pomeron-photon

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

Amplitude without absorption:

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

Full apmlitude for $pp \longrightarrow pVp$:

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

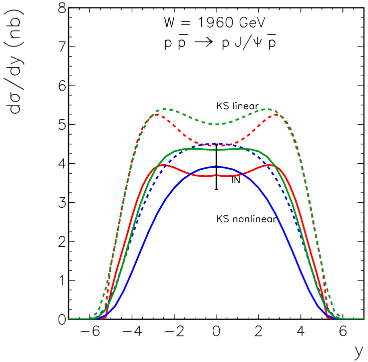
The absorptive corrections for amplitude:

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

where

$$T(\boldsymbol{k}) = \sigma_{tot}^{pp}(s)\, \exp\left(-\frac{1}{2}B_{el}\boldsymbol{k}^2\right)$$

Old results for Tevatron



- old results
- CDF Collaboration, T.Aaltonen et al. Phys. Rev. Lett. 102 (2009)
- A.Cisek PhD thesis (2012)
- different UGDFs
- Gauss wave function

Helicity conserving and helicity flip amplitudes

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

$$\mathcal{M}^{\lambda_1\lambda_2\to\lambda'_1\lambda'_2\lambda_V}_{h_1h_2\to h_1h_2V}(s,s_1,s_2,t_1,t_2) = \mathcal{M}_{\gamma\mathbf{P}} + \mathcal{M}_{\mathbf{P}\gamma}$$

$$= \langle p'_1,\lambda'_1|J_\mu|p_1,\lambda_1\rangle\epsilon^*_\mu(q_1,\lambda_V)\frac{\sqrt{4\pi\alpha_{em}}}{t_1}\mathcal{M}^{\lambda_{\gamma^*}\lambda_2\to\lambda_V\lambda_2}_{\gamma^*h_2\to Vh_2}(s_2,t_2,Q_1^2)$$

$$+\langle p'_2,\lambda'_2|J_\mu|p_2,\lambda_2\rangle\epsilon^*_\mu(q_2,\lambda_V)\frac{\sqrt{4\pi\alpha_{em}}}{t_2}\mathcal{M}^{\lambda_{\gamma^*}\lambda_1\to\lambda_V\lambda_1}_{\gamma^*h_1\to Vh_1}(s_1,t_1,Q_2^2)$$

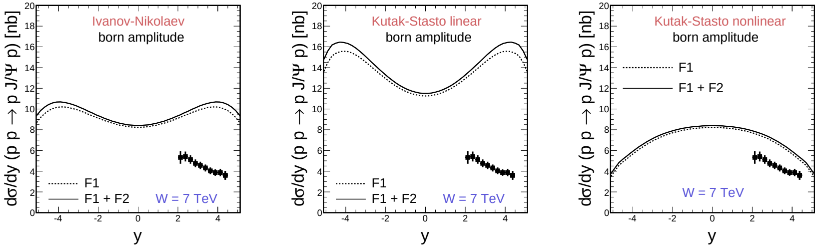
Simple structure:

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

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

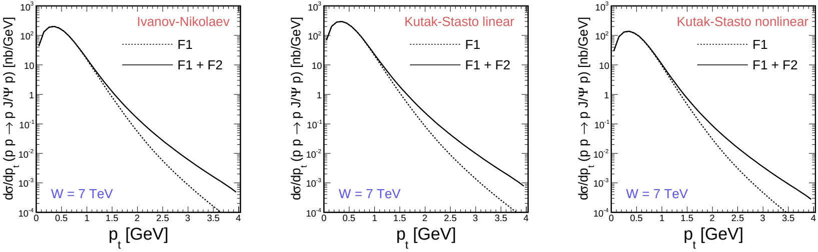
- The coupling with F_1 - proton helicity conserving, F_2 - proton helicity flip

Dirac vs Pauli form factors (Born)



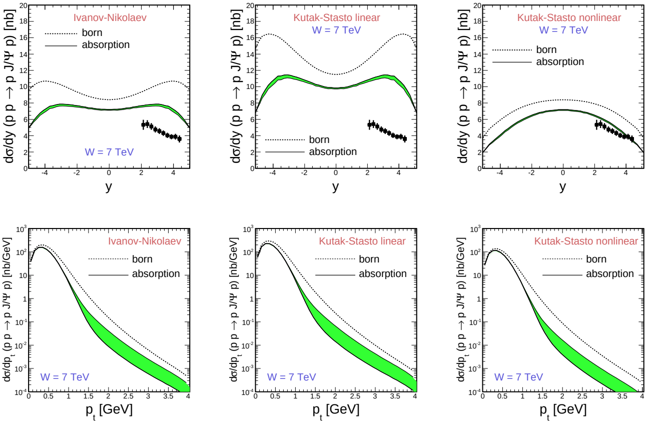
- R. Aaij et al. (LHCb collaboration), J. Phys. **G40** (2013) 045001
- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
- F_2 - only small change of normalization
- F_1 and F_2 contributions do not interfere
- Absorption must be included

Dirac vs Pauli form factors (Born)



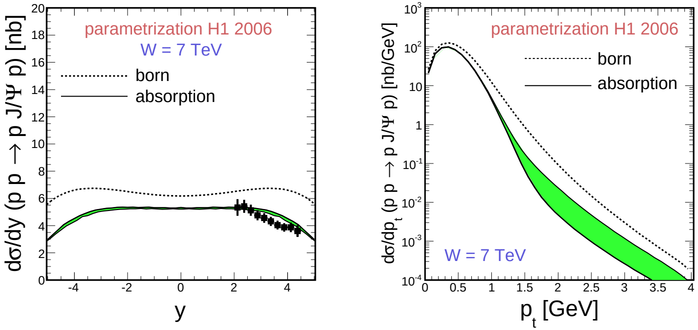
- At large p_t we get an enhancement factor of the cross section of order of 10
- Pauli form factor changes the p_t-shape of elastic contribution at larger p_t

Absorption effect



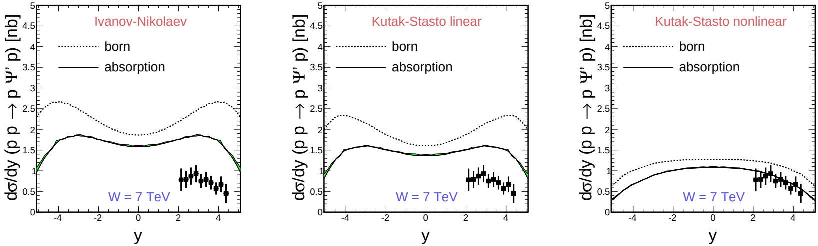
- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
- Absorption may be bigger

Extrapolation of the HERA data



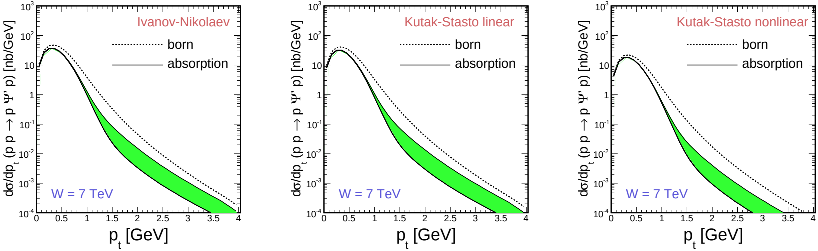
Cross section for $\gamma p \to J/\psi p$ parametrized in the power-like form fitted to HERA data

Excited state Ψ'



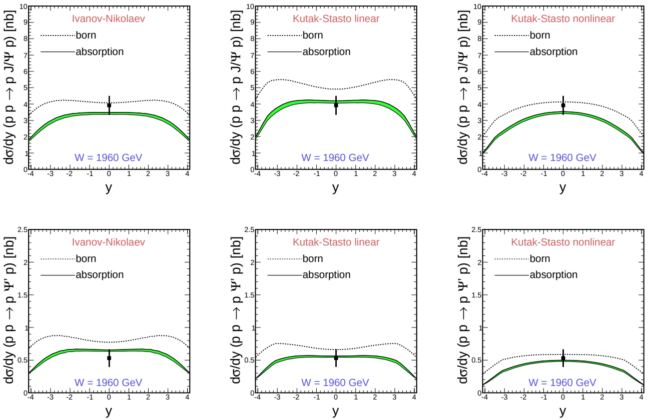
- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
- Absorption may be bigger

Excited state Ψ'



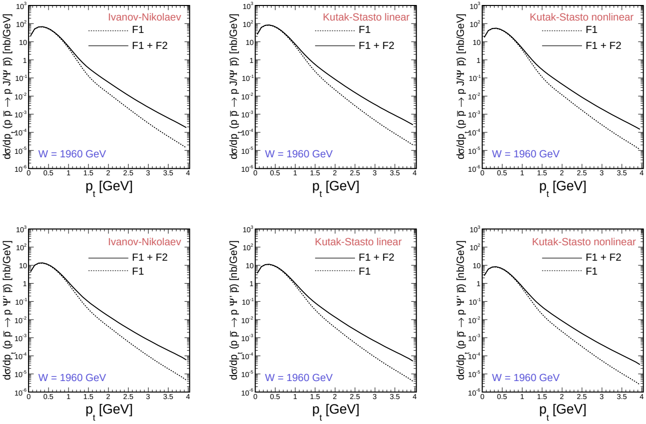
- The same shape for Ψ' and J/ψ

Absorption effect for J/Ψ and Ψ' at the Tevatron



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

Dirac and Pauli form factor (Born) for J/Ψ and Ψ' at the Tevatron



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.
- $d\sigma/dy = d\sigma^{\gamma \mathbb{P}}/dy + d\sigma^{\mathbb{P}\gamma}/dy$ only in the Born approximation.
- Sensitivity to the quarkonium wave function and testing UGDF.
- $d\sigma/d\phi$ is due to interference of $\gamma\mathbb{P}$ and $\mathbb{P}\gamma$ amplitudes.
- $d\sigma/dp_t$ is interesting (spin flip, Pomeron-Odderon fusion) but difficult to measure.
- Absorptive corrections have been included. Their effect depends on p_t and y.