Exclusive photoproduction of charmonia in hadronic collisions

Anna Cisek

University of Rzeszow

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

1. Introduction

2. Photoproduction in photon-proton collisions

3. Exclusive photoproduction in \(pp\) and \(p\bar{p}\) collisions
   - Formalism
   - Results

4. Conclusions

Anna Cisek, Wolfgang Schäfer and Antoni Szczurek
Introduction

- Exclusive production of $J/\Psi$ 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 $J/\Psi$ and $\Psi'$ mesons at $y = 0$.

- New experimental data in proton-proton collisions for $J/\Psi$ and $\Psi'$ 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
- Oderon-Pomeron fusion
- Radiative Decay of $\chi_c$

Photoproduction:

```
h_1 \quad t_1 \quad h_1
\gamma
s
h_2 \quad t_2 \quad h_2
```

Oderon-Pomeron fusion:

```
h_1 \quad t_1 \quad h_1
\phi
s_1
h_2 \quad t_2 \quad h_2
```

Radiative Decay of $\chi_c$:

```
h_1 \quad t_1 \quad h_1
\gamma
h_2 \quad t_2 \quad h_2
```

Khoze-Martin-Ryskin 2002
Klein-Nystrand 2004
Schäfer, Mankiewicz, Nachtmann 1991
Bzdak, Motyka, Szymanowski, Cudell 2007
Pasechnik, Szczurek, Teryaev 2008

- In our analysis we restrict only to photon-Pomeron fusion mechanism
Photoproduction in photon-proton collisions

Exclusive photoproduction in $pp$ and $p\bar{p}$ collisions

Conclusions

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

$F(x, \kappa) = \frac{\partial G(x, \kappa)}{\partial \log \kappa^2}$

- $\psi_V(z, k^2) \rightarrow$ wave function of the vector meson
- $F(x, \kappa^2) \rightarrow$ unintegrated gluon distribution function
- $x \sim \frac{(Q^2 + M_{J/\Psi}^2)}{W^2}$
The production amplitude for $\gamma p \to J/\Psi p$

The imaginary part of the amplitude can be written as:

\[
\Im m \mathcal{M}_T(W, \Delta^2 = 0, Q^2 = 0) = W^2 \frac{c_v \sqrt{4\pi \alpha_{em}}}{4\pi^2} \int_0^1 dz \frac{\psi_V(z, k^2)}{z(1-z)} \int_0^\infty \pi dk^2 \psi_V(z, k^2)
\]

\[
\int_0^\infty \frac{\pi d\kappa^2}{\kappa^4} \alpha_s(q^2) \mathcal{F}(x_{\text{eff}}, \kappa^2) \left( A_0(z, k^2) W_0(k^2, \kappa^2) + A_1(z, k^2) W_1(k^2, \kappa^2) \right)
\]

where

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

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

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

\[
W_1(k^2, \kappa^2) = 1 - \frac{k^2 + m_c^2}{2k^2} \left( 1 + \frac{k^2 - m_c^2 - \kappa^2}{\sqrt{(k^2 - m_c^2 - \kappa^2)^2 + 4m_c^2 k^2}} \right).
\]
Cross section for $\gamma p \rightarrow J/\Psi(\Psi') p$

The full amplitude:

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

where

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

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

Total cross section can be written as:

$$\sigma_T(\gamma p \rightarrow J/\Psi p) = \frac{1 + \rho_T^2}{16\pi B(W)} \left|\frac{\Im \mathcal{M}_T(W, \Delta^2 = 0, Q^2 = 0)}{W^2}\right|^2.$$
Total cross section for $\gamma p \rightarrow J/\Psi (\Psi') p$

HERA data and extracted LHCb data

Parameters of the vector meson wave functions

How to choose parameters of the wave function

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

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

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

Radial excitations

**Gauss:**
\[ \psi_{1S}(k^2) = C_1 \exp\left(-\frac{k^2a_1^2}{2}\right) \]
\[ \psi_{2S}(k^2) = C_2(\xi_0 - p^2a_2^2) \exp\left(-\frac{k^2a_2^2}{2}\right) \]

**Coulomb:**
\[ \psi_{1S}(k^2) = \frac{C_1}{\sqrt{M}} \frac{1}{(1 + a_1^2k^2)^2} \]
\[ \psi_{2S}(k^2) = \frac{C_2}{\sqrt{M}} \frac{\xi_0 - a_2^2k^2}{(1 + a_2^2k^2)^3} \]

- strong dependence on the wave function
Diagram for exclusive production of $J/\Psi(\Psi')$ meson in proton-proton collisions

**Formalism**

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

- **photon-Pomeron**
- **Pomeron-photon**
Diagram for $pp \rightarrow p J/\Psi(\Psi') p$ with absorptive corrections

photon-Pomeron  
Pomeron-photon
Amplitude for process $pp \rightarrow p J/\Psi(\Psi') p$

Amplitude without absorption:

$$M^{(0)}(p_1, p_2) = e_1 \frac{2}{z_1 t_1} \mathcal{F}_{\lambda_1' \lambda_1}(p_1, t_1) M_{\gamma h_2 \rightarrow vh_2}(s_2, t_2, Q_1^2) + e_2 \frac{2}{z_2 t_2} \mathcal{F}_{\lambda_2' \lambda_2}(p_2, t_2) M_{\gamma h_1 \rightarrow vh_1}(s_1, t_1, Q_2^2)$$

Full amplitude for $pp \rightarrow pVP$:

$$M(p_1, p_2) = \int \frac{d^2 k}{(2\pi)^2} Sel(k) M^{(0)}(p_1 - k, p_2 + k)$$

$$= M^{(0)}(p_1, p_2) - \delta M(p_1, p_2)$$

The absorptive corrections for amplitude:

$$\delta M(p_1, p_2) = \int \frac{d^2 k}{2(2\pi)^2} T(k) M^{(0)}(p_1 - k, p_2 + k)$$

where

$$T(k) = \sigma_{tot}^{pp}(s) \exp\left(-\frac{1}{2}B_{el}k^2\right)$$
Old results for Tevatron

- Old results
- Different UGDFs
- Gauss wave function
Helicity conserving and helicity flip amplitudes

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

$$
\mathcal{M}_{\lambda_1 \lambda_2 \rightarrow \lambda'_1 \lambda'_2 \lambda_V}^{h_1 h_2 \rightarrow h_1 h_2 V}(s, s_1, s_2, t_1, t_2) = \mathcal{M}_{\gamma P} + \mathcal{M}_{P \gamma}
$$

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

$$
+ \langle p'_2, \lambda'_2 | J_\mu | p_2, \lambda_2 \rangle \epsilon^*_\mu(q_2, \lambda_V) \frac{\sqrt{4\pi \alpha_{em}}}{t_2} \mathcal{M}_{\gamma^* h_1 \rightarrow V h_1}^{\lambda'_1 \lambda_1 \rightarrow \lambda_V \lambda_1}(s_1, t_1, Q_2^2)
$$

Simple structure:

$$
\langle p'_1, \lambda'_1 | J_\mu | p_1, \lambda_1 \rangle \epsilon^*_\mu(q_1, \lambda_V) = \frac{(\epsilon_2^{*(\lambda_V)} q_1)}{\sqrt{1 - z_1}} \frac{2}{z_1} .
$$

$$
\cdot \chi_{\lambda'}^\dagger \left\{ F_1(Q_1^2) - \frac{i \kappa_p F_2(Q_1^2)}{2m_p} (\sigma_1 \cdot [q_1, n]) \right\} \chi_{\lambda}
$$

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

**Dirac vs Pauli form factors (Born)**

- **Ivanov-Nikolaev**
  - Born amplitude
  - $W = 7$ TeV

- **Kutak-Stasto linear**
  - Born amplitude
  - $W = 7$ TeV

- **Kutak-Stasto nonlinear**
  - Born amplitude
  - $W = 7$ TeV

- $F_2$ - only small change of normalization
- $F_1$ and $F_2$ contributions do not interfere
- Absorption must be included

- R. Aaij et al. (LHCb collaboration), J. Phys. [G40](2013) 045001
- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
Results

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 $p_t$
Results

Absorption effect

- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
- Absorption may be bigger
Cross section for $\gamma p \to J/\psi p$ parametrized in the power-like form fitted to HERA data
Excited state $\Psi'$

- R. Aaij et al. (LHCb collaboration), arXiv:1401.3288 [hep-ex]
- Absorption may be bigger
Excited state $\Psi'$

![Graphs showing $\frac{d\sigma}{dp_t}(pp \rightarrow p\Psi'p)$ for different models and $W = 7$ TeV.](image)

- The same shape for $\Psi'$ and $J/\psi$
Absorption effect for $J/\Psi$ and $\Psi'$ at the Tevatron

Dirac and Pauli form factor (Born) for $J/\Psi$ and $\Psi'$ at the Tevatron
Conclusions

- We have compared our results with recent HERA $(\gamma p \rightarrow J/\Psi(\Psi') p)$ and LHCb $(pp \rightarrow p J/\Psi(\Psi') p)$ data.

- $d\sigma/dy = d\sigma^{\gamma P}/dy + d\sigma^{P\gamma}/dy$ only in the Born approximation.

- Sensitivity to the quarkonium wave function and testing UGDF.

- $d\sigma/d\phi$ is due to interference of $\gamma P$ and $P\gamma$ 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 $y$. 