

Inclusive production of vector quarkonia at the LHC

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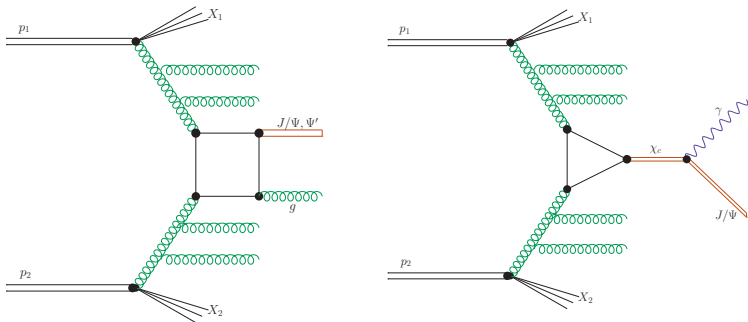
Outline

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- 2 Formalism
 - J/Ψ and Ψ' mesons production
 - J/Ψ production from radiative decay of χ_c mesons
- 3 Results
 - Ψ'
 - J/Ψ
 - χ_c
- 4 Conclusions

Introduction

- There is a long-standing lack of convergence in understanding production of J/ψ quarkonia in proton-proton or proton-antiproton collisions
- Some authors believe that the corresponding cross sections **are dominated by the so-called color-octet contribution**
- Some other authors expect that the **color-singlet contribution dominates**
- **We calculate the color-singlet contribution** in the NRQCD k_T -factorization
- We concentrate rather on small transverse momenta of J/ψ or ψ' relevant for ALICE and LHCb data

The main color-singlet mechanism of production of J/Ψ and Ψ' mesons



- We restrict to gluon-gluon fusion mechanism (high energy)
- We use unintegrated gluon distribution from the KMR (Durham group) and KS (Kutak-Staśto)

Differential cross section for J/Ψ (Ψ')

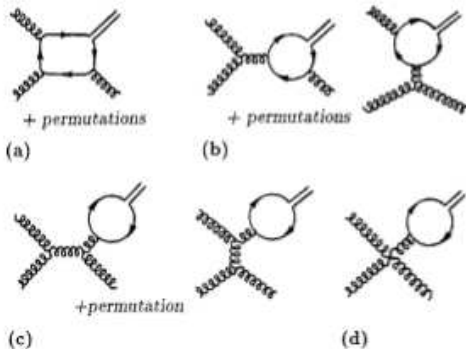
- The differential cross section in the k_t factorization can be written as:

$$\frac{d\sigma(pp \rightarrow J/\psi g X)}{dy_{J/\psi} dy_g d^2p_{J/\psi,t} d^2p_{g,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2q_{1t}}{\pi} \frac{d^2q_{2t}}{\pi} |\mathcal{M}_{g^*g^* \rightarrow Vg}|^2 \times \\ \times \delta^2(\mathbf{q}_{1t} + \mathbf{q}_{2t} - \mathbf{p}_{V,t} - \mathbf{p}_{g,t}) \mathcal{F}_g(\mathbf{x}_1, \mathbf{q}_{1t}^2, \mu_F^2) \mathcal{F}_g(\mathbf{x}_2, \mathbf{q}_{2t}^2, \mu_F^2)$$

- We calculate the dominant color-single $gg \rightarrow Vg$ contribution taking into account transverse momenta of initial gluons**
- The corresponding matrix element squared for the $gg \rightarrow Vg$ is

$$|\mathcal{M}_{gg \rightarrow Vg}|^2 \propto \alpha_s^3 |\mathbf{R}(\mathbf{0})|^2$$

Matrix elements for J/Ψ (Ψ')



$$\mathcal{M}_a(gg \rightarrow J/\psi g) = \text{tr}\{\epsilon_1(\mathbf{p}_c - \mathbf{k}_1 + m_c)\epsilon_2 \times (-\mathbf{p}_c - \mathbf{k}_3 + m_c)\epsilon_3 J(S, L)\} C_\Psi \\ \times \text{tr}\{T^a T^b T^c T^d\} [k_1^2 - 2(p_c k_1)]^{-1} \times [k_3^2 - 2(p_{\bar{c}} k_3)]^{-1} + 5 \text{ permutations}$$

S. P. Baranov, Phys. Rev. D **66** (2002) 114003

Matrix elements for J/Ψ (Ψ')

$$\begin{aligned} \mathcal{M}_b(\mathbf{gg} \rightarrow \mathbf{J}/\psi\mathbf{g}) &= \text{tr}\{\gamma_\mu(p_{\bar{c}} - k_3 + m_c)\epsilon_3 J(S, L)\} \\ &\quad \times G^3(k_1, \epsilon_1, k_2, \epsilon_2, -k, \mu) C_{\Psi f}^{fabe} \\ &\quad \times \text{tr}\{T^e T^c T^d\} [k^2]^{-1} \\ &\quad \times [k_3^2 - 2(p_{\bar{c}} k_3)]^{-1} + 5 \text{ permutations} \end{aligned}$$

$$\begin{aligned} \mathcal{M}_c(\mathbf{gg} \rightarrow \mathbf{J}/\psi\mathbf{g}) &= \text{tr}\{\gamma_\mu J(S, L)\} G^3(k_1, \epsilon_1, k_2, \epsilon_2, -k, \mu) \\ &\quad \times G^3(-k_3, -\epsilon_3, -p_\Psi, -\epsilon, -k, \nu) C_{\Psi f}^{fabe fcf^e} \\ &\quad \times \text{tr}\{T^f T^d\} [k^2]^{-1} \times [m_\Psi^2]^{-1} + 2 \text{ permutations} \end{aligned}$$

$$\begin{aligned} \mathcal{M}_d(\mathbf{gg} \rightarrow \mathbf{J}/\psi\mathbf{g}) &= \text{tr}\{\gamma_\nu J(S, L)\} G^{(4)A,B,C}(\epsilon_1, \epsilon_2, \epsilon_3, \nu) C_\Psi \\ &\quad \times \text{tr}\{T^f T^d\} [k^2]^{-1} [m_\Psi^2]^{-1} \end{aligned}$$

S. P. Baranov, Phys. Rev. D **66** (2002) 114003

χ_c production

- * In the k_t -factorization approach the leading-order **cross section for the χ_c meson production** can be written as:

$$\sigma_{\text{pp} \rightarrow \chi_c} = \int \frac{dx_1}{x_1} \frac{dx_2}{x_2} \frac{d^2 q_{1t}}{\pi} \frac{d^2 q_{2t}}{\pi} \delta((q_1 + q_2)^2 - M_{\chi_c}^2) \sigma_{gg \rightarrow \chi_c}(x_1, x_2, q_1, q_2) \\ \times \mathcal{F}_g(\mathbf{x}_1, \mathbf{q}_{1t}^2, \mu_F^2) \mathcal{F}_g(\mathbf{x}_2, \mathbf{q}_{2t}^2, \mu_F^2)$$

- * The matrix element squared for the $gg \rightarrow \chi_c$ subprocess is

$$|\mathcal{M}_{gg \rightarrow \chi_c}|^2 \propto \alpha_s^2 |\mathbf{R}'(\mathbf{0})|^2$$

- * For running coupling constants we choose:

$$\alpha_s^2 \rightarrow \alpha_s(\mu_1^2) \alpha_s(\mu_2^2)$$

where $\mu_1^2 = \max(\mathbf{q}_{1t}^2, \mathbf{m}_t^2)$ and $\mu_2^2 = \max(\mathbf{q}_{2t}^2, \mathbf{m}_t^2)$

Cross section for χ_c

- After some manipulation:

$$\sigma_{pp \rightarrow \chi_c} = \int dy d^2 p_t d^2 q_t \frac{1}{s \mathbf{x}_1 \mathbf{x}_2} \frac{1}{m_{t, \chi_c}^2} \overline{|\mathcal{M}_{g^* g^* \rightarrow \chi_c}|^2} \mathcal{F}_g(\mathbf{x}_1, \mathbf{q}_{1t}^2, \mu_F^2) \mathcal{F}_g(\mathbf{x}_2, \mathbf{q}_{2t}^2, \mu_F^2) / 4$$

- Which can be also used to calculate rapidity and transverse momentum distribution of the χ_c mesons
- In the last equation:

$$\mathbf{p}_t = \mathbf{q}_{1t} + \mathbf{q}_{2t} \quad \mathbf{q}_t = \mathbf{q}_{1t} - \mathbf{q}_{2t}$$

$$\mathbf{x}_1 = \frac{\mathbf{m}_{t, \chi_c}}{\sqrt{s}} \exp(\mathbf{y}) \quad \mathbf{x}_2 = \frac{\mathbf{m}_{t, \chi_c}}{\sqrt{s}} \exp(-\mathbf{y})$$

- The factor $\frac{1}{4}$ is the jacobian of transformation from $(\mathbf{q}_{1t}, \mathbf{q}_{2t})$ to $(\mathbf{p}_t, \mathbf{q}_t)$ variables

Matrix elements for χ_c

$$\begin{aligned} \overline{|\mathcal{A}(g^* + g^* \rightarrow \mathcal{H}[{}^3P_0^{(1)}])|^2} &= \frac{8}{3}\pi^2\alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[{}^3P_0^{(1)}] \rangle}{M^5} \mathbf{F}^{[{}^3P_0]}(\mathbf{t}_1, \mathbf{t}_2, \varphi) \\ \overline{|\mathcal{A}(g^* + g^* \rightarrow \mathcal{H}[{}^3P_1^{(1)}])|^2} &= \frac{16}{3}\pi^2\alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[{}^3P_1^{(1)}] \rangle}{M^5} \mathbf{F}^{[{}^3P_1]}(\mathbf{t}_1, \mathbf{t}_2, \varphi) \\ \overline{|\mathcal{A}(g^* + g^* \rightarrow \mathcal{H}[{}^3P_2^{(1)}])|^2} &= \frac{32}{45}\pi^2\alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[{}^3P_2^{(1)}] \rangle}{M^5} \mathbf{F}^{[{}^3P_2]}(\mathbf{t}_1, \mathbf{t}_2, \varphi) \end{aligned}$$

where

$$\langle \mathcal{O}^{\chi_{cJ}}[{}^3P_J^{(1)}] \rangle = 2N_c(2J+1)|\mathbf{R}'(\mathbf{0})|^2$$

B. A. Kniehl, D. V. Vasin, V. A. Saleev; Phys. Rev. D **73** (2006) 074022

Matrix elements for χ_c

$$\mathbf{F}^{[{}^3\mathbf{P}_0]}(\mathbf{t}_1, \mathbf{t}_2, \varphi) = \frac{2}{9} \frac{M^2 (M^2 + |\mathbf{p}_t|^2)^2 [(3M^2 + t_1 + t_2) \cos \varphi + 2\sqrt{t_1 t_2}]^2}{(M^2 + t_1 + t_2)^4}$$

$$\mathbf{F}^{[{}^3\mathbf{P}_1]}(\mathbf{t}_1, \mathbf{t}_2, \varphi) = \frac{2}{9} \frac{M^2 (M^2 + |\mathbf{p}_t|^2)^2 [(t_1 + t_2)^2 \sin^2 \varphi + M^2 (t_1 + t_2 - 2\sqrt{t_1 t_2} \cos \varphi)]}{(M^2 + t_1 + t_2)^4}$$

$$\begin{aligned} \mathbf{F}^{[{}^3\mathbf{P}_2]}(\mathbf{t}_1, \mathbf{t}_2, \varphi) = & \frac{1}{3} \frac{M^2}{(M^2 + t_1 + t_2)^4} (M^2 + |\mathbf{p}_t|^2)^2 \{3M^4 + 3M^2(t_1 + t_2) + 4t_1 t_2 \\ & + (t_1 + t_2)^2 \cos^2 \varphi + 2\sqrt{t_1 t_2} [3M^2 + 2(t_1 + t_2)] \cos \varphi\} \end{aligned}$$

where $\mathbf{p}_t = \mathbf{q}_{1t} + \mathbf{q}_{2t}$

and $\varphi = \varphi_1 - \varphi_2$ is the angle between \mathbf{q}_{1t} and \mathbf{q}_{2t} so

$$|\mathbf{p}_t|^2 = t_1 + t_2 + 2\sqrt{t_1 t_2} \cos \varphi$$

B. A. Kniehl, D. V. Vasin, V. A. Saleev; Phys. Rev. D **73** (2006) 074022

α_s - scale

For running coupling constants we choose different scale:

- χ_c

$$\alpha_s^2 \rightarrow \alpha_s(\mu_1^2) \alpha_s(\mu_2^2)$$

- ① prescription 1

- $\mu_1^2 = \mathbf{q}_{1t}^2$
- $\mu_2^2 = \mathbf{q}_{2t}^2$

- ② prescription 2

- $\mu_1^2 = \max(\mathbf{q}_{1t}^2, \mathbf{m}_t^2)$
- $\mu_2^2 = \max(\mathbf{q}_{2t}^2, \mathbf{m}_t^2)$

- J/Ψ

$$\alpha_s^3 \rightarrow \alpha_s(\mu_1^2) \alpha_s(\mu_2^2) \alpha_s(\mu_3^2)$$

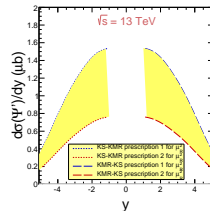
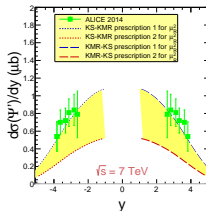
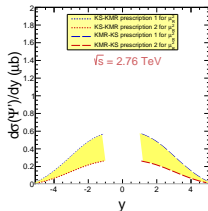
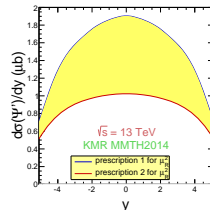
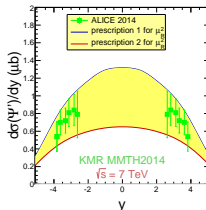
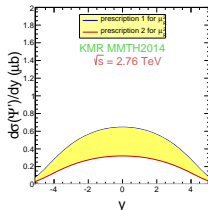
- ① prescription 1

- $\mu_1^2 = \mathbf{q}_{1t}^2$
- $\mu_2^2 = \mathbf{q}_{2t}^2$
- $\mu_3^2 = \mathbf{m}_t^2$

- ② prescription 2

- $\mu_1^2 = \max(\mathbf{q}_{1t}^2, \mathbf{m}_t^2)$
- $\mu_2^2 = \max(\mathbf{q}_{2t}^2, \mathbf{m}_t^2)$
- $\mu_3^2 = \mathbf{m}_t^2$

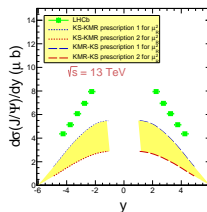
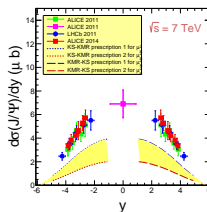
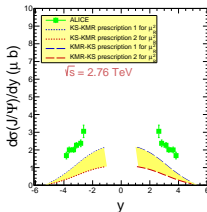
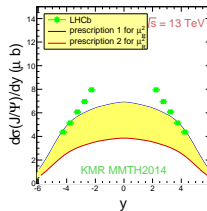
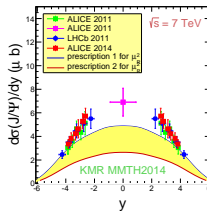
rapidity distribution for Ψ' meson



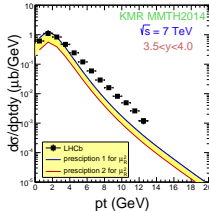
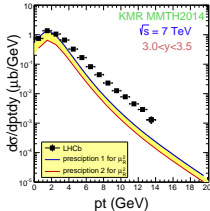
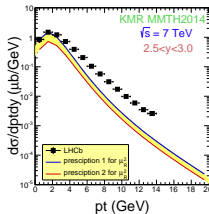
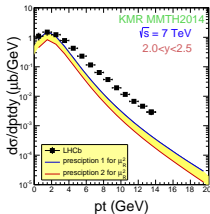
- **7 TeV** - B. Abelev et al.; Eur.Phys. J. C. **74** (2014) 2974

rapidity dependence for J/Ψ meson (direct)

- **2,76 TeV** - B. Abelev et al.;
Phys. Let. B. **718** (2012) 295-306
- **7 TeV** - B. Abelev et al.;
Eur.Phys. J. C. **74** (2014) 2974
- **7 TeV** - K. Aamodt et al.;
Phys. Let. B. **704** (2011) 442
- **7 TeV** - R. Aaij et al.;
Eur.Phys. J. C. **71** (2011) 1645
- **13 TeV** - R. Aaij et al.;
JHEP 1510 (2015) 172

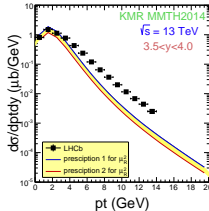
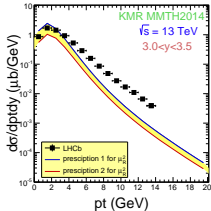
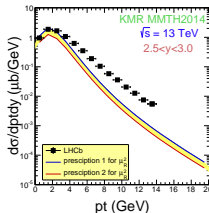
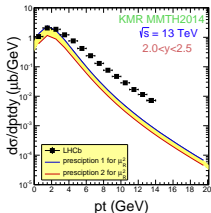


p_t distribution for J/Ψ meson (direct contributions)



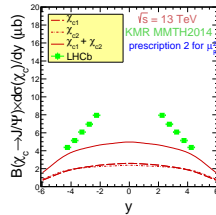
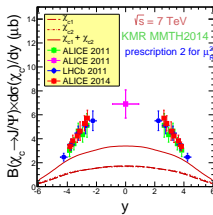
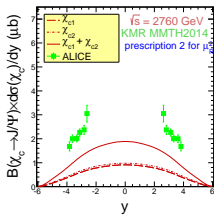
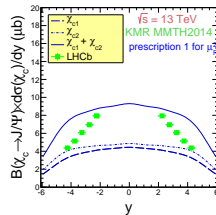
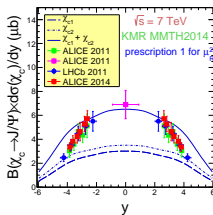
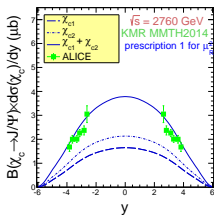
- **7 TeV** - R. Aaij et al.; Eur.Phys. J. C. **71** (2011) 1645

p_t distribution for J/Ψ meson (direct contributions)

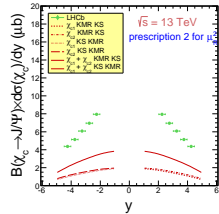
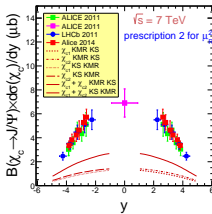
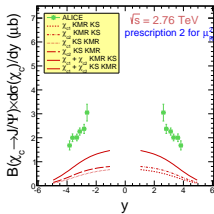
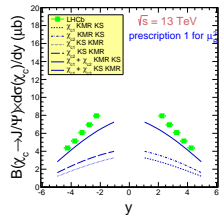
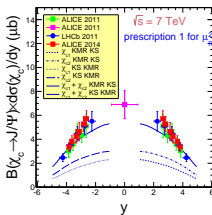
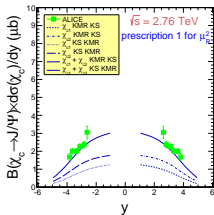


- **13 TeV** - R. Aaij et al.; JHEP **1510** (2015) 172

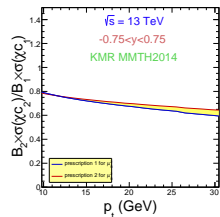
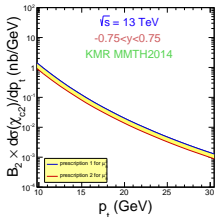
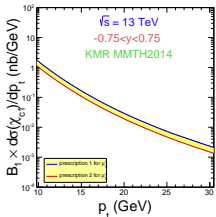
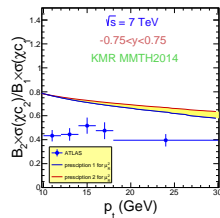
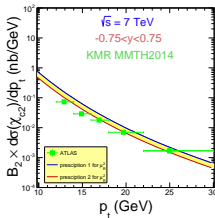
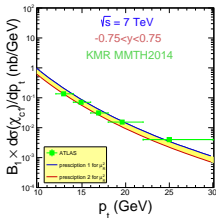
rapidity distribution J/Ψ from χ_c decays



rapidity distribution J/Ψ from χ_c decays

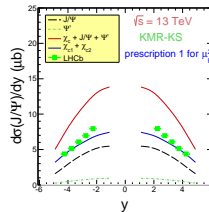
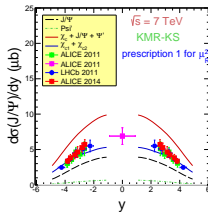
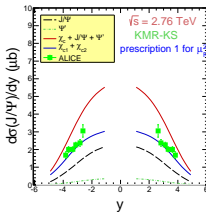
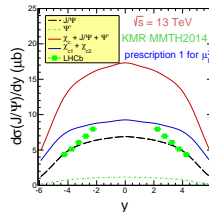
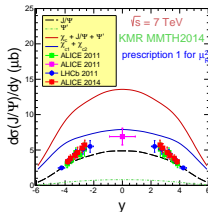
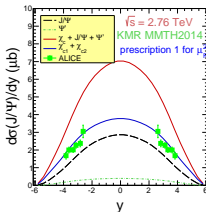


p_t distribution for χ_c meson

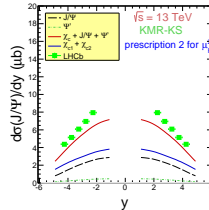
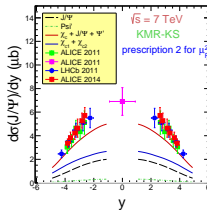
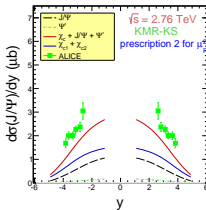
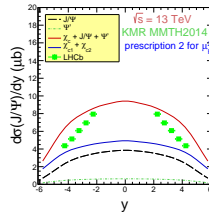
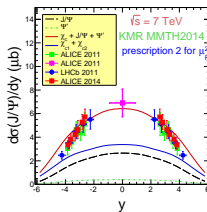
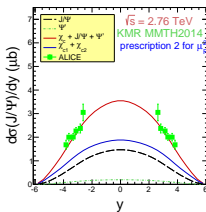


- inclusive $\chi_c(1)$ production in collinear NLO: Khoze et al.

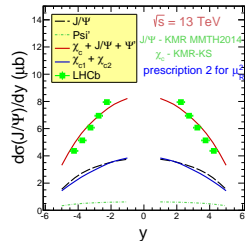
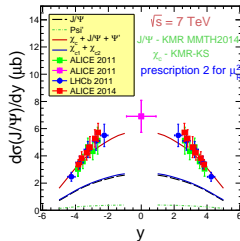
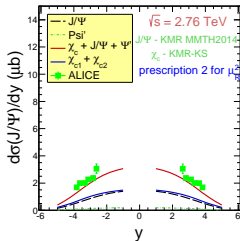
rapidity dependence - prescription 1



rapidity dependence - prescription 2



rapidity dependence



- Better solution is to take prescription 2 for α_s scale
- The best solution is to take KMR UGDF for J/ψ and ψ' mesons and mixed UGDFs for χ_c mesons

Conclusions

- **We have calculated the color-singlet contribution** in the NRQCD k_t -factorization
- **We have compared our results with ALICE and LHCb data for J/Ψ and ATLAS for χ_{c1} and χ_{c2}**
- Our results in rapidity are consistent with experimental data for KMR UGDF and better when nonlinear effects are included
- **Data at 13 TeV may require saturation effects in the small- x gluon**
- Not much room is left for color-octet contribution