Inclusive production of vector quarkonia at the LHC

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QCD challenges in pp, pA and AA collisions at high energies
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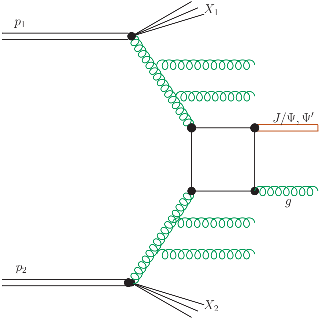
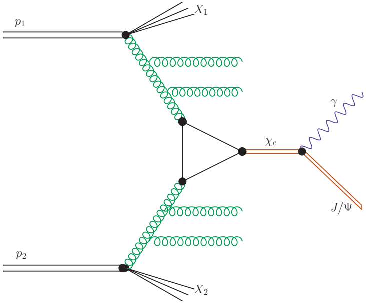
Outline

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**
- The **color-octet contribution** cannot be calculated from first principle and **is rather fitted to the experimental data**
- **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 KMR (Durham group) and KS (Kutak-Staśto)

Differential cross section for J/Ψ (Ψ')

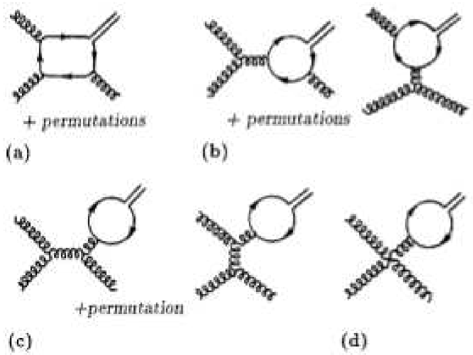
- In the differential cross section in the k_t factorization can be writen as:

$$\frac{d\sigma(pp \to J/\psi g X)}{dy_{J/\psi} dy_g d^2p_{J/\psi,t} d^2p_{g,t}} = \frac{1}{16\pi^2 \hat{s}^2} \int \frac{d^2q_{1t}}{\pi} \frac{d^2q_{2t}}{\pi} \overline{|\mathcal{M}_{\mathbf{g^* g^* \to Vg}}|^2} \times$$
$$\times \delta^2 \left(\mathbf{q_{1t}} + \mathbf{q_{2t}} - \mathbf{p_{V,t}} - \mathbf{p_{g,t}}\right) \mathcal{F}_{\mathbf{g}}(\mathbf{x_1}, \mathbf{q^2_{1t}}, \mu^2_{\mathbf{F}}) \mathcal{F}_{\mathbf{g}}(\mathbf{x_2}, \mathbf{q^2_{2t}}, \mu^2_{\mathbf{F}})$$

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

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

Matrix elements for J/Ψ (Ψ')



$$\mathcal{M}_{\mathbf{a}}(\mathbf{gg} \to \mathbf{J}/\psi\mathbf{g}) = tr\{\epsilon_{\mathbf{1}}(\mathbf{p_c} - \mathbf{k_1} + m_c)\epsilon_{\mathbf{2}} \times (-\mathbf{p_c} - \mathbf{k_3} + m_c)\epsilon_{\mathbf{3}} J(S, L)\} C_\Psi$$
$$\times tr\{T^a T^b T^c T^d\}[k_1^2 - 2(p_c k_1)]^{-1} \times [k_3^2 - 2(p_{\bar{c}} k_3)]^{-1} + 5\ permutations$$

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

Matrix elements for J/Ψ (Ψ')

$$\mathcal{M}_{\mathbf{b}}(\mathbf{gg} \to \mathbf{J}/\psi\mathbf{g}) = tr\{\gamma_\mu(p_{\bar{c}} - k_3 + m_c)\epsilon_{\mathbf{3}} J(S,L)\} \\ \times G^3(k_1, \epsilon_{\mathbf{1}}, k_2, \epsilon_{\mathbf{2}}, -k, \mu) C_\Psi f^{abe} \\ \times tr\{T^e T^c T^d\}[k^2]^{-1} \\ \times [k_3^2 - 2(p_{\bar{c}} k_3)]^{-1} + 5\ permutations$$

$$\mathcal{M}_{\mathbf{c}}(\mathbf{gg} \to \mathbf{J}/\psi\mathbf{g}) = tr\{\gamma_\mu J(S,L)\} G^3(k_1, \epsilon_{\mathbf{1}}, k_2, \epsilon_{\mathbf{2}}, -k, \mu) \\ \times G^3(-k_3, -\epsilon_{\mathbf{3}}, -p_\Psi, -\epsilon^{-}, -k, \nu) C_\Psi f^{abe} f^{cfe} \\ \times tr\{T^f T^d\}[k^2]^{-1} \times [m_\Psi^2]^{-1} + 2\ permutations$$

$$\mathcal{M}_{\mathbf{d}}(\mathbf{gg} \to \mathbf{J}/\psi\mathbf{g}) = tr\{\gamma_\nu J(S,L)\} G^{(4)A,B,C}(\epsilon_{\mathbf{1}}, \epsilon_{\mathbf{2}}, \epsilon_{\mathbf{3}}, \nu) C_\Psi \\ \times tr\{T^f T^d\}[k^2]^{-1}[m_\Psi^2]^{-1}$$

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:

$$\sigma_{\mathbf{pp}\to\chi_c} = \int \frac{dx_1}{x_1}\frac{dx_2}{x_2}\frac{d^2q_{1t}}{\pi}\frac{d^2q_{2t}}{\pi}\,\delta\left((q_1+q_2)^2 - M_{\chi_c}^2\right)\sigma_{gg\to\chi_c}(x_1,x_2,q_1,q_2)$$
$$\times\mathcal{F}_{\mathbf{g}}(\mathbf{x_1},\mathbf{q_{1t}^2},\mu_{\mathbf{F}}^2)\mathcal{F}_{\mathbf{g}}(\mathbf{x_2},\mathbf{q_{2t}^2},\mu_{\mathbf{F}}^2)$$

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

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

* For running coupling constants we choose:

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

where $\mu_1^2 = \mathbf{max}(\mathbf{q_{1t}^2},\mathbf{m_t^2})$ and $\mu_2^2 = \mathbf{max}(\mathbf{q_{2t}^2},\mathbf{m_t^2})$

Cross section for χ_c

- After some manipulation:

$$\sigma_{pp\to\chi_c} = \int dy d^2p_t d^2q_t \frac{1}{s\mathbf{x_1}\mathbf{x_2}} \frac{1}{m^2_{t,\chi_c}} \overline{|\mathcal{M}_{g^*g^*\to\chi_c}|^2} \mathcal{F}_g(\mathbf{x_1}, \mathbf{q^2_{1t}}, \mu^2_F) \mathcal{F}_g(\mathbf{x_2}, \mathbf{q^2_{2t}}, \mu^2_F)/4$$

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

$$\mathbf{p_t} = \mathbf{q_{1t}} + \mathbf{q_{2t}} \qquad \mathbf{q_t} = \mathbf{q_{1t}} - \mathbf{q_{2t}}$$

$$\mathbf{x_1} = \frac{\mathbf{m_{t,\chi_c}}}{\sqrt{\mathbf{s}}} \exp(\mathbf{y}) \qquad \mathbf{x_2} = \frac{\mathbf{m_{t,\chi_c}}}{\sqrt{\mathbf{s}}} \exp(-\mathbf{y})$$

- 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

$$\overline{|\mathcal{A}(g^\star + g^\star \to \mathcal{H}[^3P_0^{(1)}]|^2} = \frac{8}{3}\pi^2\alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[^3\mathbf{P}_\mathbf{0}^{(1)}]\rangle}{M^5} \mathbf{F}^{[^3\mathbf{P}_0]}(\mathbf{t_1}, \mathbf{t_2}, \varphi)$$

$$\overline{|\mathcal{A}(g^\star + g^\star \to \mathcal{H}[^3P_1^{(1)}]|^2} = \frac{16}{3}\pi^2\alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[^3\mathbf{P}_\mathbf{1}^{(1)}]\rangle}{M^5} \mathbf{F}^{[^3\mathbf{P}_1]}(\mathbf{t_1}, \mathbf{t_2}, \varphi)$$

$$\overline{|\mathcal{A}(g^\star + g^\star \to \mathcal{H}[^3P_2^{(1)}]|^2} = \frac{32}{45}\pi^2\alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[^3\mathbf{P}_\mathbf{2}^{(1)}]\rangle}{M^5} \mathbf{F}^{[^3\mathbf{P}_2]}(\mathbf{t_1}, \mathbf{t_2}, \varphi)$$

where

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

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

Matrix elements for χ_c

$$\mathbf{F}^{[^3\mathbf{P}_0]}(\mathbf{t_1},\mathbf{t_2},\varphi) = \frac{2}{9}\frac{M^2\left(M^2+|\mathbf{p}_t|^2\right)^2\left[(3M^2+t_1+t_2)\cos\varphi+2\sqrt{t_1t_2}\right]^2}{(M^2+t_1+t_2)^4}$$

$$\mathbf{F}^{[^3\mathbf{P}_1]}(\mathbf{t_1},\mathbf{t_2},\varphi) = \frac{2}{9}\frac{M^2\left(M^2+|\mathbf{p}_t|^2\right)^2\left[(t_1+t_2)^2\sin^2\varphi+M^2\left(t_1+t_2-2\sqrt{t_1t_2}\cos\varphi\right)\right]}{(M^2+t_1+t_2)^4}$$

$$\mathbf{F}^{[^3\mathbf{P}_2]}(\mathbf{t_1},\mathbf{t_2},\varphi) = \frac{1}{3}\frac{M^2}{(M^2+t_1+t_2)^4}(M^2+|\mathbf{p}_t|^2)^2\{3M^4+3M^2(t_1+t_2)+4t_1t_2 \\ +(t_1+t_2)^2\cos^2\varphi+2\sqrt{t_1t_2}[3M^2+2(t_1+t_2)]\cos\varphi\}$$

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

$$|\mathbf{p}_t|^2 = t_1+t_2+2\sqrt{t_1t_2}\cos\varphi$$

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

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

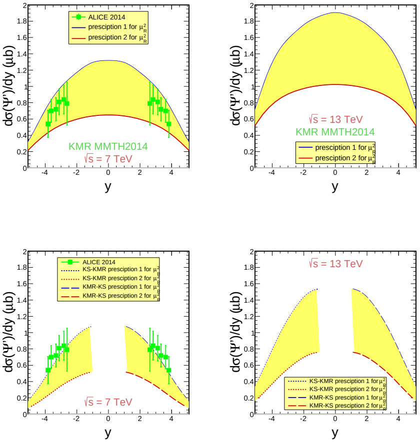
1. prescription 1
   - $\mu_1^2 = \mathbf{q_{1t}^2}$
   - $\mu_2^2 = \mathbf{q_{2t}^2}$
2. prescription 2
   - $\mu_1^2 = \mathbf{max}(\mathbf{q_{1t}^2}, \mathbf{m_t^2})$
   - $\mu_2^2 = \mathbf{max}(\mathbf{q_{2t}^2}, \mathbf{m_t^2})$

- 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
   - $\mu_1^2 = \mathbf{max}(\mathbf{q_{1t}^2}, \mathbf{m_t^2})$
   - $\mu_2^2 = \mathbf{max}(\mathbf{q_{2t}^2}, \mathbf{m_t^2})$
   - $\mu_3^2 = \mathbf{m_t^2}$

rapidity distribution for Ψ' meson



- **7 TeV** - B. Abelev et al.; Eur.Phys. J. C. **74** (2014) 2974
- the best solution is to take KMR distribution for large x and KS for small x

$$\mathcal{F}_{KMR}(x_1, q_{1t}^2, \mu_F^2)\mathcal{F}_{KMR}(x_2, q_{2t}^2, \mu_F^2)$$

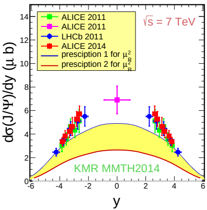
At large rapidities we propose

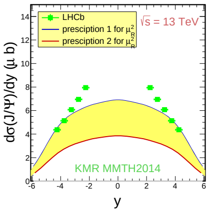
$$\mathcal{F}_{KMR}(x_1, q_{1t}^2, \mu_F^2)\mathcal{F}_{KS}(x_2, q_{2t}^2)$$

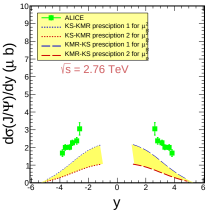
$$\mathcal{F}_{KS}(x_1, q_{1t}^2)\mathcal{F}_{KMR}(x_2, q_{2t}^2, \mu_F^2)$$

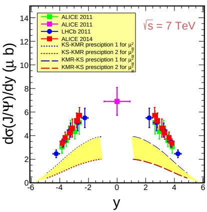
rapidity dependence for J/Ψ meson (direct)

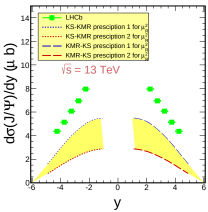
- **2,76 TeV** - B. Abelev et al.; Phys. Let. B. **718** (2012) 295-306
- **7 TeV** - B. Abelev et al.; Eur.Phys. J. C. **74** (2014) 2974
  7 TeV - K. Aamodt et al.; Phys. Let. B. **704** (2011) 442
  7 TeV - R. Aaij et al.; Eur.Phys. J. C. **71** (2011) 1645
- **13 TeV** - R. Aaij et al.; JHEP 1510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



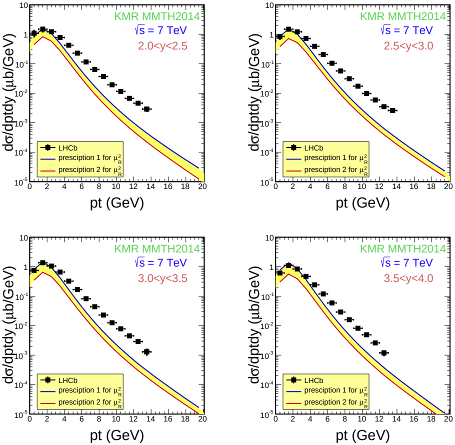








p_t distribution for J/Ψ meson (direct contributions)



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

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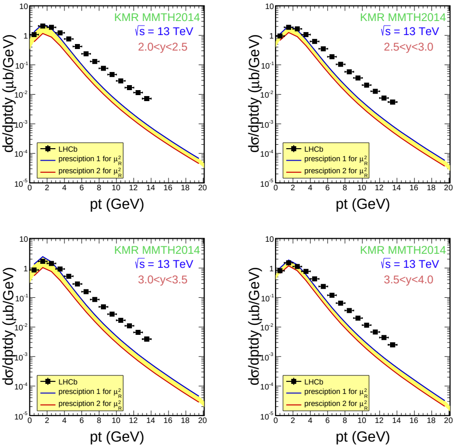
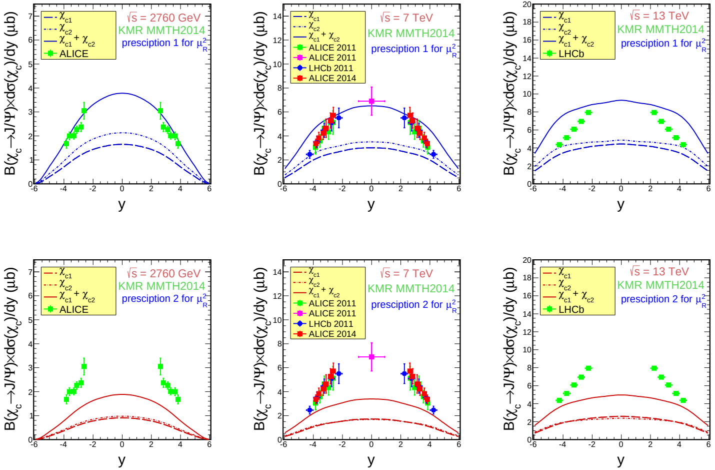
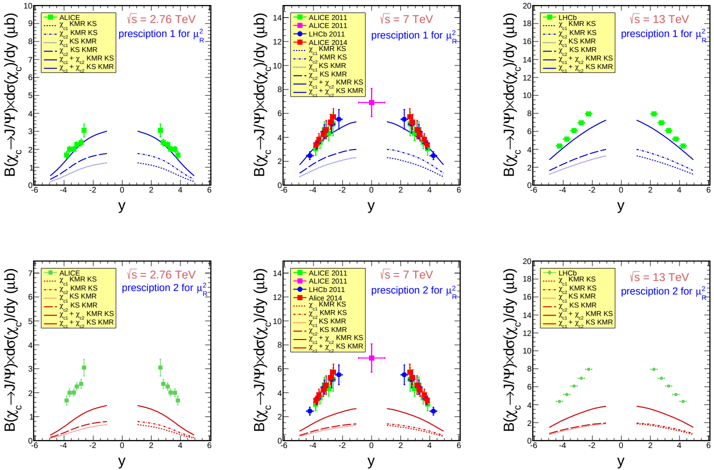


- **13 TeV** - R. Aaij et al.; JHEP **1510** (2015) 172

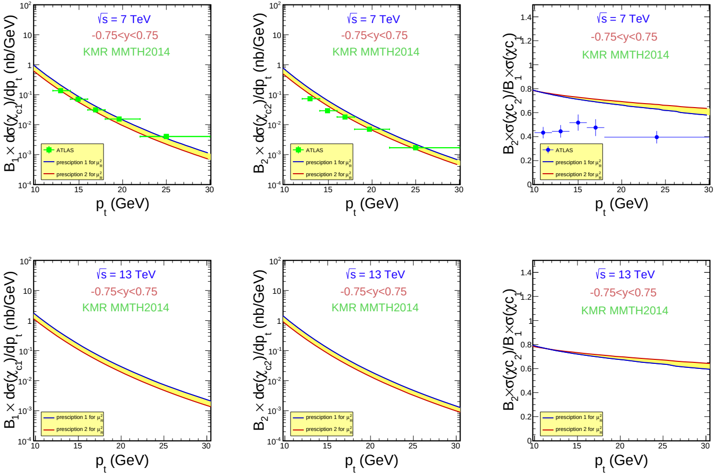
rapidity distribution J/Ψ from χ_c decays



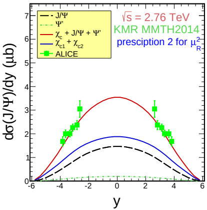
rapidity distribution J/Ψ from χ_c decays

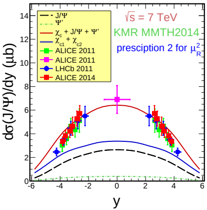


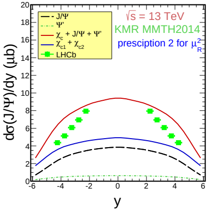
p_t distribution for χ_c meson



rapidity dependence







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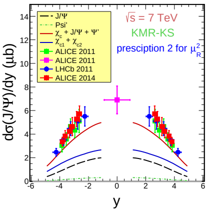

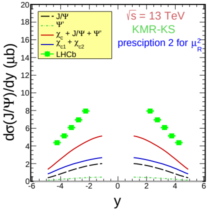

Conclusions

- **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