

# Heavy quarkonium production in the Parton Reggeization Approach.

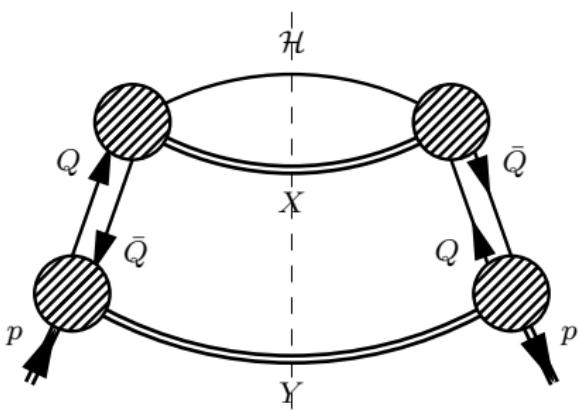
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# Outline.

- NRQCD-factorization.
- State of the art of NRQCD calculations.
- Introduction to the Parton Reggeization Approach.
- Charmonium production in PRA, from Tevatron to LHC.
- Bottomonium production in PRA vs. current experimental data.
- Charmonium and bottomonium polarization in PRA.

## NRQCD factorization.



Factorization of production amplitude:

$$\mathcal{A}[g + g \rightarrow \mathcal{H} + X] = \sum_n \mathcal{A}[g + g \rightarrow n] \langle n | \mathcal{H} + X \rangle$$

Where:  $n = Q\bar{Q} [{}^{2S+1}L_J^{(1,8)}]$ ,  $Q\bar{Q}g, \dots$ Inclusive production rate [G. T. Bodwin,  
E. Braaten, G. P. Lepage]:

$$|\mathcal{A}[g + g \rightarrow \mathcal{H} + X]|^2 = \sum_n |\mathcal{A}[g + g \rightarrow n]|^2 \times \langle 0 | \mathcal{O}^\mathcal{H} [n] | 0 \rangle$$

Operators  $\mathcal{O}^\mathcal{H} [n] = \mathcal{O}_n^\dagger (a_\mathcal{H}^\dagger a_\mathcal{H}) \mathcal{O}_n$ , where  $a_\mathcal{H}^\dagger a_\mathcal{H} = \sum_X |\mathcal{H} + X\rangle \langle \mathcal{H} + X|$ , and  $\mathcal{O}_n$ create the  $Q\bar{Q}$  state  $n$  from the vacuum.The  $\langle \mathcal{O}^\mathcal{H} [{}^3S_1^{(1)}] \rangle$  is LO in  $v$ . NMEs:

$$\langle \mathcal{O}^\mathcal{H} [{}^1S_0^{(8)}] \rangle \sim v^3 \langle \mathcal{O}^\mathcal{H} [{}^3S_1^{(1)}] \rangle, \quad \langle \mathcal{O}^\mathcal{H} [{}^3S_1^{(8)}] \rangle \sim v^4 \langle \mathcal{O}^\mathcal{H} [{}^3S_1^{(1)}] \rangle,$$

$$\langle \mathcal{O}^\mathcal{H} [{}^3P_J^{(8)}] \rangle \sim v^4 \langle \mathcal{O}^\mathcal{H} [{}^3S_1^{(1)}] \rangle$$

## NRQCD factorization.

Finally:  $|\mathcal{A}[gg \rightarrow \mathcal{H}(P) + X]|^2 =$

$$= \sum_n \frac{\langle \mathcal{O}^{\mathcal{H}}[n] \rangle}{N_{col} N_{pol}} \left| C_{ij}^{(1,8)} \Pi[n] \mathcal{A}_{ij} [gg \rightarrow Q(P/2+q) + \bar{Q}(P/2-q)] \right|_{q=0}^2$$

$Q\bar{Q}$ -Fock states (LO in  $v^2$ ):

$$n = {}^3S_1^{(1,8)}, {}^1S_0^{(1,8)}, {}^3P_J^{(1,8)},$$

$N_{pol} = 2J_{\mathcal{H}} + 1$ ,  $N_{col} = 2N_c$  for <sup>(1)</sup> and  $N_c^2 - 1$  for <sup>(8)</sup>. Color projectors:

$$C_{ij}^{(1)} = \frac{\delta_{ij}}{\sqrt{N_c}}, \quad C_{ij}^{(8)} = \sqrt{2} T_{ij}^a$$

Spin-orbital projectors:

$$\Pi_0 = (8m_Q^3)^{-1/2} \left( \hat{P}/2 - \hat{q} - m \right) \gamma_5 \left( \hat{P}/2 + \hat{q} + m \right)$$

$$\Pi_1^\alpha = (8m_Q^3)^{-1/2} \left( \hat{P}/2 - \hat{q} - m \right) \gamma^\alpha \left( \hat{P}/2 + \hat{q} + m \right)$$

$$\Pi [{}^1S_0] = \Pi_0, \quad \Pi [{}^3S_1] = \varepsilon_\alpha(P) \Pi_1^\alpha$$

$$\Pi [{}^1P_1] = \varepsilon^\beta(P) \frac{\partial}{\partial q^\beta} \Pi_0, \quad \Pi [{}^3P_J] = \varepsilon_{\alpha\beta}^{(J)}(P) \frac{\partial}{\partial q_\beta} \Pi_1^\alpha$$

# Long-distance matrix elements (LDMEs, NMEs, ...).

Color-singlet NMEs:

$$\begin{aligned}\left\langle \mathcal{O}^{\mathcal{H}_J} \left[ {}^3S_1^{(1)} \right] \right\rangle &= 2N_c(2J+1) \frac{1}{4\pi} |R(0)|^2, \\ \left\langle \mathcal{O}^{\mathcal{H}_J} \left[ {}^3P_J^{(1)} \right] \right\rangle &= 2N_c(2J+1) \frac{3}{4\pi} |R'(0)|^2.\end{aligned}$$

Radial wavefunction  $R(0)$  or it's derivative in the origin  $R'(0)$  is known from the potential models [E. J. Eichten and C. Quigg, Phys. Rev. D 52 (1995) 1726]. Multiplicative relations, proven in LO in  $v^2$ :

$$\begin{aligned}\langle \mathcal{O}^{\mathcal{H}} [{}^3P_J^{(1,8)}] \rangle &= (2J+1) \langle \mathcal{O}^{\mathcal{H}} [{}^3P_0^{(1,8)}] \rangle, \\ \langle \mathcal{O}^{\mathcal{H}_J} [{}^3S_1^{(8)}] \rangle &= (2J+1) \langle \mathcal{O}^{\mathcal{H}} [{}^3S_1^{(8)}] \rangle,\end{aligned}$$

Color-octet NMEs may be obtained using nonperturbative techniques or by a fit. So, the main task is to calculate the hard scattering matrix element:

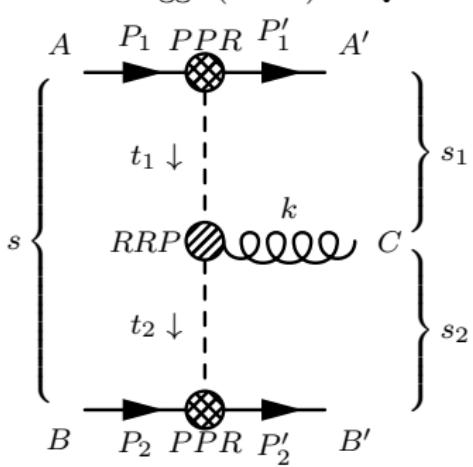
$$\mathcal{A} [pp \rightarrow Q\bar{Q} + X].$$

## State of the art of NRQCD calculations.

- **NLO, fixed order** in  $\alpha_s$  calculations of charmonium and bottomonium production in the Collinear Parton Model(CPM) are available [M. Butenschoen, B. A. Kniehl, Phys. Rev. D **84** (2011) 051501; Y. -Q. Ma, K. Wang, K. -T. Chao, Phys. Rev. Lett. **106** (2011) 042002]. But they are applicable only in the region of high  $p_T > M$ , because of appearance of large logs  $\alpha_s^m \log^{2m-1} (M^2/p_T^2)$ .
- **Resummation procedures**[P. Sun, C.-P. Yuan, F. Yuan, arXiv:hep-ph/1210.3432] usually works in the region  $\Lambda_{QCD} \ll p_T \ll M$ , and requires **matching** with high  $p_T$  region. So, the approach which describes low and high  $p_T$  regions on a same grounds is needed.
- **Non-complete NNLO\*** calculations in **Color-singlet model** [P. Artoisenet , J. Campbell , J.P. Lansberg , F. Maltoni , F. Tramontano, Phys. Rev. Lett. **101** (2008) 152001] show, that the NNLO corrections at high  $p_T$  can be large in CPM. So, the role of Color-octet production mechanism is disputable.

## Parton Reggeization Approach.

PRA is based on the Reggeization of amplitudes in gauge theories (QED, QCD, Gravity). The high energy asymptotic of the amplitude is dominated by the amplitude with  $t$ -channel exchange of the effective (Reggeized) particle and Multi-Regge (MRK) or Quasi-Multi-Regge Kinematics (QMRK) of final state.



In the limit  $s \rightarrow \infty, s_{1,2} \rightarrow \infty, t_1 \ll s_1, t_2 \ll s_2$  (Regge limit), 2  $\rightarrow$  3 amplitude has the form:

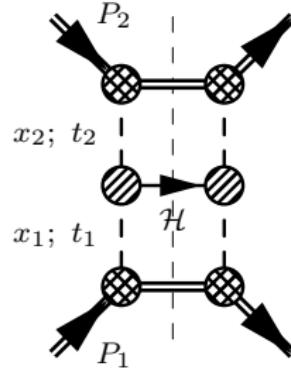
$$\mathcal{A}_{AB}^{A'B'C} = 2s \gamma_{A'A}^{R_1} \left( \frac{s_1}{s_0} \right)^{\omega(t_1)} \frac{1}{t_1} \times \\ \times \Gamma_{R_1 R_2}^C(q_1, q_2) \times \frac{1}{t_2} \left( \frac{s_2}{s_0} \right)^{\omega(t_2)} \gamma_{B'B}^{R_2} \\ \Gamma_{R_1 R_2}^C(q_1, q_2) - RRP \text{ effective production vertex,} \\ \gamma_{A'A}^{R_1} - PPR \text{ effective scattering vertex,} \\ \omega(t) - \text{Regge trajectory.}$$

Two approaches to obtain this asymptotics:

- BFKL-approach (Unitarity, Renormalizability and Gauge Invariance), see [B. Ioffe, V. S. Fadin, L. N. Lipatov, QCD – Perturbative and Nonperturbative aspects].
- Effective action approach [L. N. Lipatov, Nucl. Phys. B452 (1995) 369].

# PRA. Factorization, Feynman rules.

## Factorization:



Factorization formula:

$$d\sigma = \int \frac{d^2 \mathbf{q}_{T1}}{\pi} \int \frac{dx_1}{x_1} \Phi(x_1, t_1, \mu_F) \times \\ \times \int \frac{d^2 \mathbf{q}_{T2}}{\pi} \int \frac{dx_2}{x_2} \Phi(x_2, t_2, \mu_F) d\hat{\sigma}_{PRA}$$

Where  $\Phi$  - TMD (Unintegrated) PDFs.

Light-cone vectors:

$$n_-^\mu = \frac{2P_1^\mu}{\sqrt{S}}, \quad n_+^\mu = \frac{2P_2^\mu}{\sqrt{S}}, \quad (n_\pm)^2 = 0, \quad n_+ n_- = 2,$$

$$k^\mu = \frac{1}{2}(n_-^\mu k^+ + n_+^\mu k^-) + k_T, \quad k^\pm = n_\pm k$$

Feynman rules:

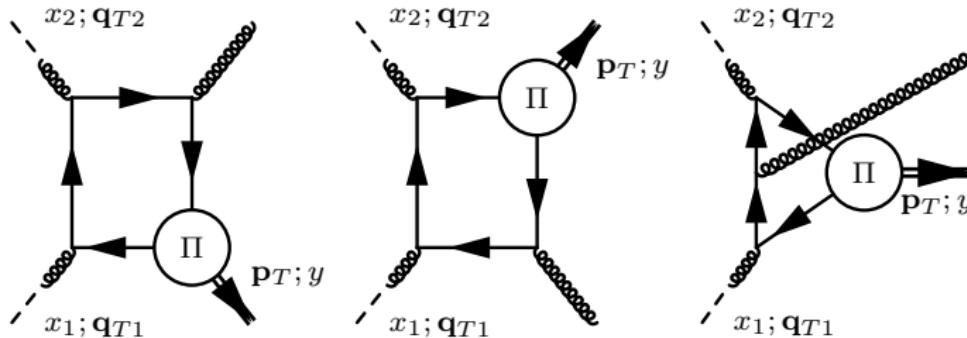
$$a \underset{n_-}{\text{---}} \xrightarrow{\text{wavy}} b; \mu \quad \Gamma_{ab}^{\pm\mu}(q) = i\delta^{ab} q^2 n_\pm^\mu$$

$$b; \mu \xleftarrow{\text{wavy}} \underset{n_+}{\text{---}} a \quad b; \nu$$

$$c \underset{\substack{\uparrow k_2 \\ \overbrace{q \text{ ---} n_-} \\ a; \mu}}{\text{---}} \xrightarrow{\text{wavy}} a; \mu \quad \Gamma_{acb}^{\mu\pm\nu}(k_1, q, k_2) = -g_s f^{abc} \frac{q^2}{k_1^\pm} n_\pm^\mu n_\pm^\nu$$

$$b; \nu \underset{\substack{\downarrow k_1 \\ \overbrace{q \text{ ---} n_+} \\ k_2}}{\text{---}} \xleftarrow{\text{wavy}}$$

$$R + R \rightarrow Q\bar{Q} \left[ {}^3S_1^{(1)} \right] + g \text{ Amplitude.}$$



Normalization factor ( $\mathbf{q}_{1T}^2 = t_1$ ,  $\mathbf{q}_{2T}^2 = t_2$ ):

$$\mathcal{N} = \frac{(x_1 x_2 S)^2}{16 t_1 t_2}$$

Collinear limit:

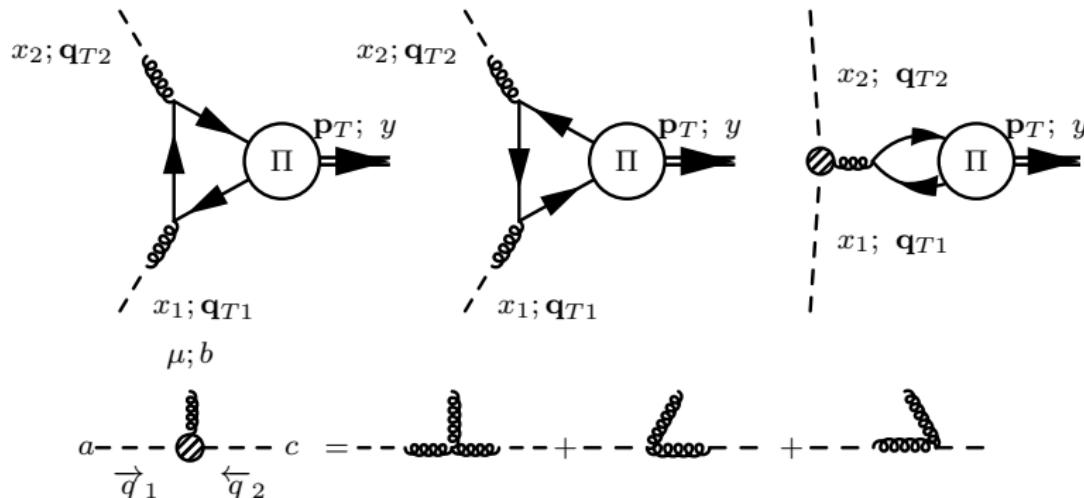
$$\lim_{t_{1,2} \rightarrow 0} \int_0^{2\pi} \frac{d\phi}{2\pi} |\mathcal{A}_{PRA}|^2 = \overline{|\mathcal{A}_{CPM}|^2}$$

**PRA result coincides with  $k_T$  factorization.** Due to gauge invariance:

$$q_{1,2T}^\mu = q_{1,2}^\mu - x_{1,2} P_{1,2}^\mu \rightarrow -x_{1,2} P_{1,2}^\mu$$

$2 \rightarrow 1$  Amplitudes.

Processes  $R + R \rightarrow Q\bar{Q}$   $\left[{}^3S_1^{(8)}, {}^1S_0^{(8)}, {}^3P_J^{(1,8)}\right]$



$$\Gamma_{abc}^{-\mu+}(q_1, q_2) = 2g_s f^{abc} \left[ n_-^\mu \left( q_1^+ + \frac{q_1^2}{q_2^-} \right) - n_+^\mu \left( q_2^- + \frac{q_2^2}{q_1^+} \right) + (q_2 - q_1)^\mu \right]$$

**PRA result coincides with  $k_T$  factorization.** Nontrivial point, not so e. g. for  $RR \rightarrow gg$ .

$2 \rightarrow 1$  processes.

Expressions for  $2 \rightarrow 1$  and  $2 \rightarrow 2$  subprocesses are derived in [B. A. Kniehl, V. A. Saleev, D. V. Vasin, Phys. Rev. D**73** (2006) 074022; Phys. Rev. D**74** (2006) 014024]

$$\begin{aligned} \overline{|\mathcal{M}(RR \rightarrow \mathcal{H}[{}^3S_1^{(8)}])|^2} &= \frac{\pi^2}{2} \alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[{}^3S_1^{(8)}] \rangle}{M^3} F[{}^3S_1](t_1, t_2, \varphi), \\ \overline{|\mathcal{M}(RR \rightarrow \mathcal{H}[{}^1S_0^{(8)}])|^2} &= \frac{5\pi^2}{12} \alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[{}^1S_0^{(8)}] \rangle}{M^3} F[{}^1S_0](t_1, t_2, \varphi), \\ \overline{|\mathcal{M}(RR \rightarrow \mathcal{H}[{}^3P_0^{(1)}])|^2} &= \frac{8\pi^2}{3} \alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[{}^3P_0^{(1)}] \rangle}{M^5} F[{}^3P_0](t_1, t_2, \varphi), \\ \overline{|\mathcal{M}(RR \rightarrow \mathcal{H}[{}^3P_1^{(1)}])|^2} &= \frac{16\pi^2}{3} \alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[{}^3P_1^{(1)}] \rangle}{M^5} F[{}^3P_1](t_1, t_2, \varphi), \\ \overline{|\mathcal{M}(RR \rightarrow \mathcal{H}[{}^3P_2^{(1)}])|^2} &= \frac{32\pi^2}{45} \alpha_s^2 \frac{\langle \mathcal{O}^{\mathcal{H}}[{}^3P_2^{(1)}] \rangle}{M^5} F[{}^3P_2](t_1, t_2, \varphi). \end{aligned}$$

$$\begin{aligned}
 F^{[{}^3S_1]}(t_1, t_2, \varphi) &= \frac{(M^2 + |\mathbf{p}_T|^2) (M^2(t_1 - 2\sqrt{t_1 t_2} \cos(\varphi) + t_2) + (t_1 + t_2)^2)}{(M^2 + t_1 + t_2)^2}, \\
 F^{[{}^1S_0]}(t_1, t_2, \varphi) &= \frac{2M^2}{(M^2 + t_1 + t_2)^2} (M^2 + |\mathbf{p}_T|^2) \sin^2(\varphi), \\
 F^{[{}^3P_0]}(t_1, t_2, \varphi) &= \frac{2}{9} \frac{M^2(M^2 + |\mathbf{p}_T|^2)^2 [(3M^2 + t_1 + t_2)\cos(\varphi) + 2\sqrt{t_1 t_2}]}{(M^2 + t_1 + t_2)^4}, \\
 F^{[{}^3P_1]}(t_1, t_2, \varphi) &= \frac{2}{9} \frac{M^2(M^2 + |\mathbf{p}_T|^2)^2}{(M^2 + t_1 + t_2)^4} [(t_1 + t_2)^2 \sin^2(\varphi) + \\
 &\quad + M^2(t_1 + t_2 - 2\sqrt{t_1 t_2} \cos(\varphi))], \\
 F^{[{}^3P_2]}(t_1, t_2, \varphi) &= \frac{1}{3} \frac{M^2(M^2 + |\mathbf{p}_T|^2)}{(M^2 + t_1 + t_2)^4} \{3M^4 + 3M^2(t_1 + t_2) + 4t_1 t_2 + \\
 &\quad + (t_1 + t_2)^2 \cos^2(\varphi) + 2\sqrt{t_1 t_2} [3M^2 + 2(t_1 + t_2)] \cos(\varphi)\}
 \end{aligned}$$

## Formulas for the cross-sections.

Partonic cross-section:

$$d\hat{\sigma} = \frac{(2\pi)^4}{2x_1x_2S} \overline{|\mathcal{A}(R + R \rightarrow b\bar{b}[^{2S+1}L_J^{(1,8)}])|^2} \delta(P_{initial} - P_{final}) \prod_{j=[final]} \frac{d^3 p_j}{(2\pi)^3 2p_j^0},$$

**2 → 1** subprocess:

$$\begin{aligned} \frac{d\sigma(p + p \rightarrow \mathcal{H} + X)}{dp_T dy} &= \frac{p_T}{(p_T^2 + M^2)^2} \int dt_1 \int d\varphi_1 \\ &\times \Phi_g^p(\xi_1, t_1, \mu^2) \Phi_g^p(\xi_2, t_2, \mu^2) \overline{|\mathcal{A}(R + R \rightarrow \mathcal{H})|^2}, \end{aligned}$$

where  $t_2 = t_1 + p_T^2 - 2p_T\sqrt{t_1} \cos(\phi_1)$ ,  $\xi_1 = (p^0 + p^3)/\sqrt{S}$ ,  $\xi_2 = (p^0 - p^3)/\sqrt{S}$ .

**2 → 2** subprocess:

$$\begin{aligned} \frac{d\sigma(p + p \rightarrow \mathcal{H} + X)}{dp_T dy} &= \frac{p_T}{(2\pi)^3} \int dt_1 \int d\varphi_1 \int dx_2 \int dt_2 \int d\varphi_2 \\ &\times \Phi_g^p(x_1, t_1, \mu^2) \Phi_g^p(x_2, t_2, \mu^2) \frac{\overline{|\mathcal{A}(R + R \rightarrow \mathcal{H} + g)|^2}}{(x_2 - \xi_2)(2x_1x_2S)^2}, \end{aligned}$$

where  $\phi_{1,2}$  are the angles enclosed between  $\vec{q}_{1,2T}$  and the transverse momentum  $\vec{p}_T$  of  $\mathcal{H}$ ,

$$x_1 = \frac{1}{(x_2 - \xi_2)S} [(q_{1T} + q_{2T} - p_T)^2 - M^2 - |p_T|^2 + x_2\xi_1 S].$$

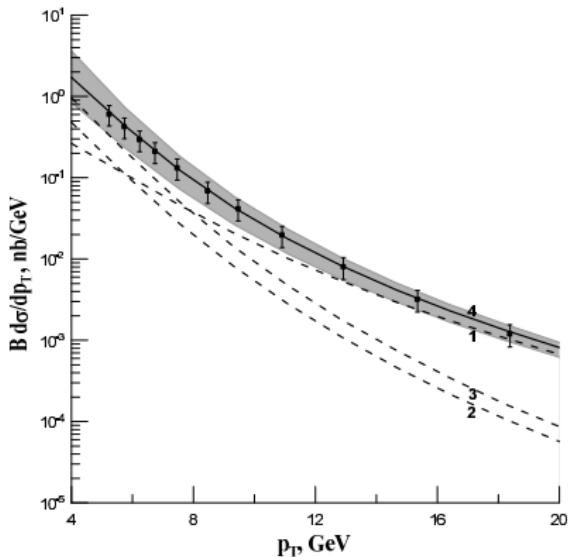
# Charmonium production. From Tevatron to LHC.

[V. A. Saleev, M. A. Nefedov, A. V. Shipilova, Phys. Rev. D85 (2012) 074013]

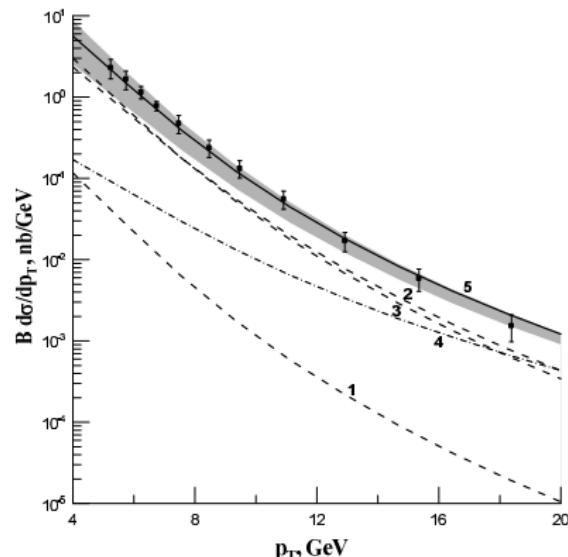
NMEs for  $J/\psi$ ,  $\psi'$ , and  $\chi_{cJ}$  mesons from fits of the CDF data in the NLO collinear parton model [B. A. Kniehl, M. Butenschoen] and in the parton Reggeization approach using the Blümlein, and KMR unintegrated gluon distribution functions.

NME	PM NLO	Fit B	Fit KMR
$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{(1)}] \rangle / \text{GeV}^3$	1.3	1.3	1.3
$\langle \mathcal{O}^{J/\psi}[{}^3S_1^{(8)}] \rangle / \text{GeV}^3$	$(1.68 \pm 0.46) \times 10^{-3}$	$(1.89 \pm 0.27) \times 10^{-3}$	$(2.23 \pm 0.27) \times 10^{-3}$
$\langle \mathcal{O}^{J/\psi}[{}^1S_0^{(8)}] \rangle / \text{GeV}^3$	$(3.04 \pm 0.35) \times 10^{-2}$	$(1.80 \pm 0.25) \times 10^{-2}$	$(1.84 \pm 0.19) \times 10^{-2}$
$\langle \mathcal{O}^{J/\psi}[{}^3P_0^{(8)}] \rangle / \text{GeV}^5$	$(-9.08 \pm 1.61) \times 10^{-3}$	0	0
$\chi^2/\text{d.o.f}$	—	1.0	1.0
$\langle \mathcal{O}^{\psi'}[{}^3S_1^{(1)}] \rangle / \text{GeV}^3$	$6.5 \times 10^{-1}$	$6.5 \times 10^{-1}$	$6.5 \times 10^{-1}$
$\langle \mathcal{O}^{\psi'}[{}^3S_1^{(8)}] \rangle / \text{GeV}^3$	$(1.88 \pm 0.62) \times 10^{-3}$	$(6.72 \pm 1.15) \times 10^{-4}$	$(9.33 \pm 1.62) \times 10^{-4}$
$\langle \mathcal{O}^{\psi'}[{}^1S_0^{(8)}] \rangle / \text{GeV}^3$	$(7.01 \pm 4.75) \times 10^{-3}$	$(3.63 \pm 1.40) \times 10^{-3}$	$(3.27 \pm 1.44) \times 10^{-3}$
$\langle \mathcal{O}^{\psi'}[{}^3P_0^{(8)}] \rangle / \text{GeV}^5$	$(-2.08 \pm 2.28) \times 10^{-3}$	0	0
$\chi^2/\text{d.o.f}$	—	0.033	0.051
$\langle \mathcal{O}^{\chi_{c0}}[{}^3P_0^{(1)}] \rangle / \text{GeV}^5$	$8.9 \times 10^{-2}$	$8.9 \times 10^{-2}$	$8.9 \times 10^{-2}$
$\langle \mathcal{O}^{\chi_{c0}}[{}^3S_1^{(8)}] \rangle / \text{GeV}^3$	—	$(2.14 \pm 0.67) \times 10^{-4}$	$(1.69 \pm 0.9) \times 10^{-4}$
$\chi^2/\text{d.o.f}$	—	0.89	0.41

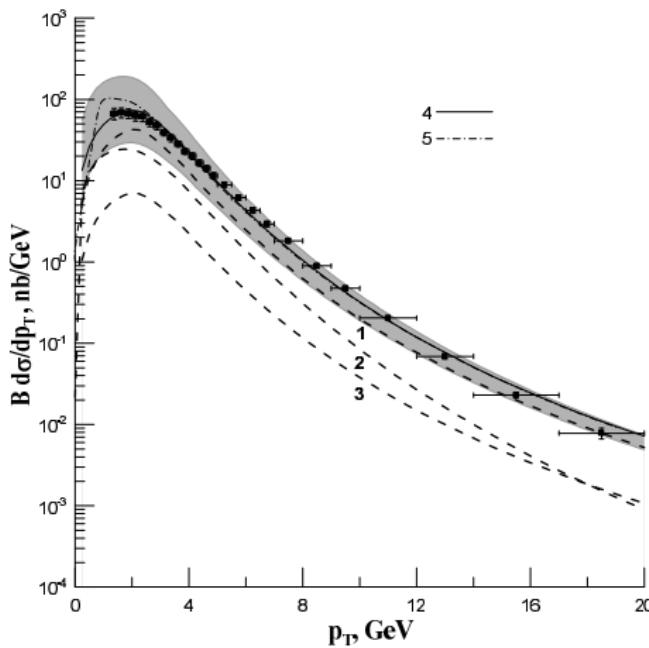
# $\psi'$ and $\chi_{cJ}$ production at the Tevatron.



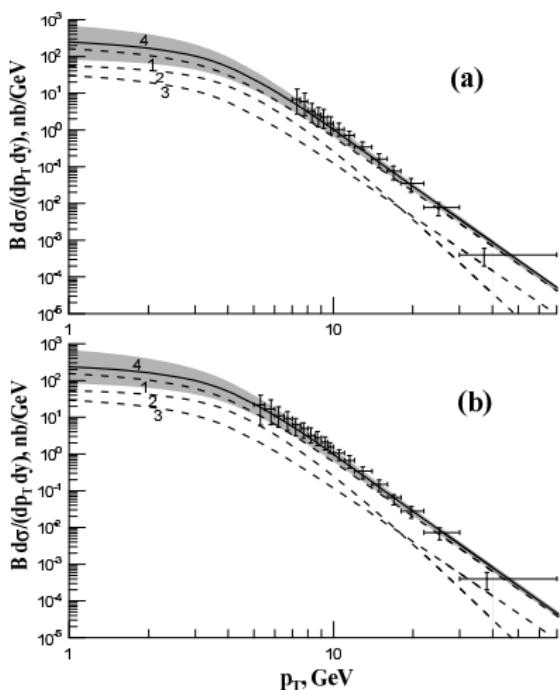
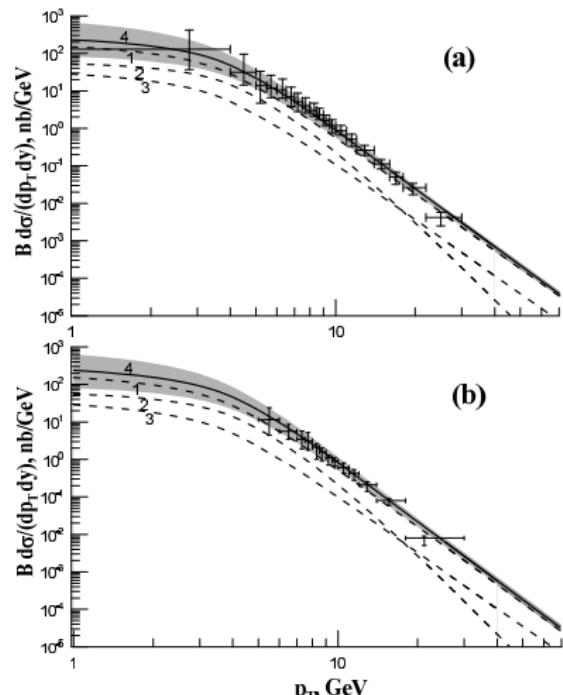
$J/\psi$  transverse-momentum spectrum from  $\psi'$  decays from CDF Collaboration,  $\sqrt{S} = 1.8$  TeV,  $|\eta| < 0.6$ , (1)  $-{}^3S_1^{(8)}$  contribution, (2)  $-{}^3S_1^{(1)}$ , (3)  $-{}^1S_0^{(8)}$ , (4) sum of all contributions.

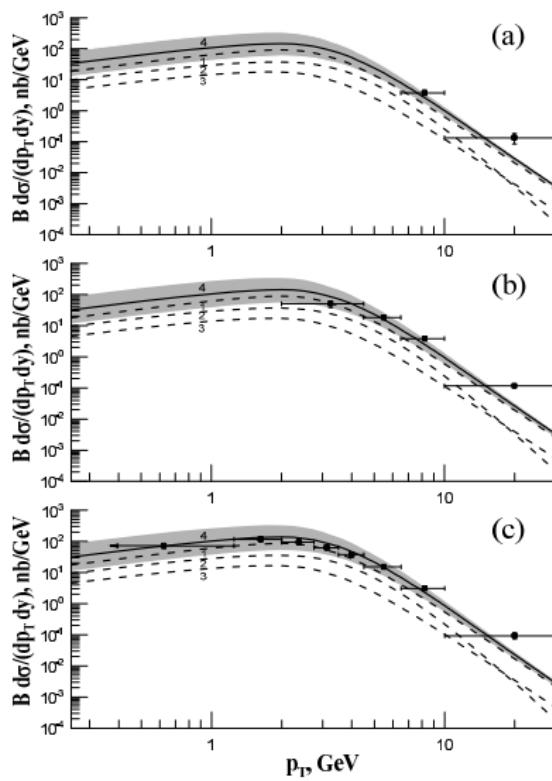


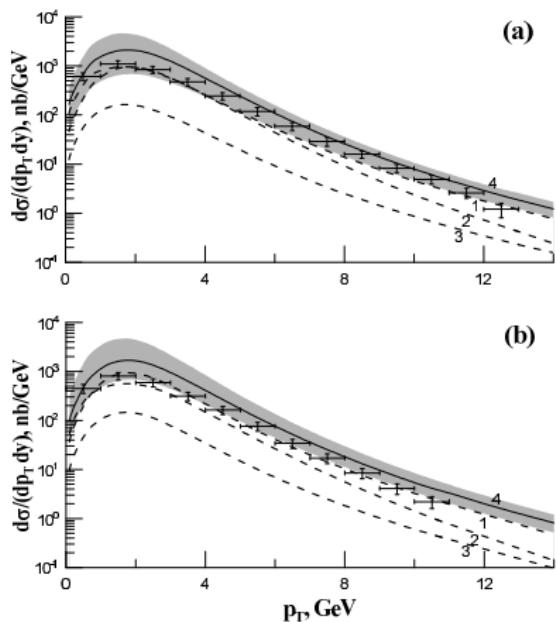
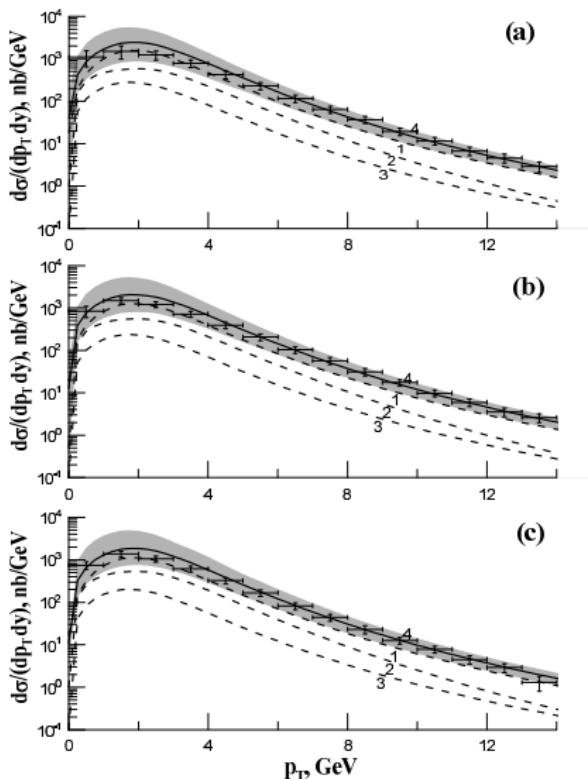
$J/\psi$  transverse-momentum spectrum from  $\chi_{cJ}$  decays from CDF Collaboration,  $\sqrt{S} = 1.8$  TeV,  $|\eta| < 0.6$ , (1)  $-{}^3P_0^{(1)}$ , (2)  $-{}^3P_1^{(1)}$ , (3)  $-{}^3P_2^{(1)}$ , (4)  $-{}^3S_1^{(8)}$ , (5) sum of all contributions.

Prompt  $J/\psi$  production at the Tevatron.

Prompt  $J/\psi$  transverse-momentum spectrum from CDF Collaboration,  $\sqrt{S} = 1.96$  TeV,  $|\eta| < 0.6$ , (1) is the direct production, (2) from  $\chi_{cJ}$  decays, (3) from  $\psi'$  decays, (4) sum of all contributions (KMR unPDF), (5) sum of all contributions (Blümlein unPDF).

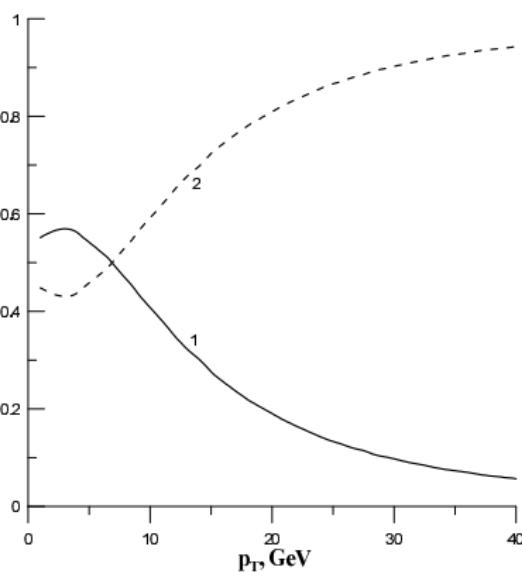
Prompt  $J/\psi$  production at the LHC (ATLAS).  $\sqrt{S} = 7$  TeV(a)  $|y| < 0.75$ , (b)  $0.75 < |y| < 1.5$ (a)  $1.5 < |y| < 2.0$ , (b)  $2.0 < |y| < 2.4$

Prompt  $J/\psi$  production at the LHC (CMS).  $\sqrt{S} = 7$  TeV

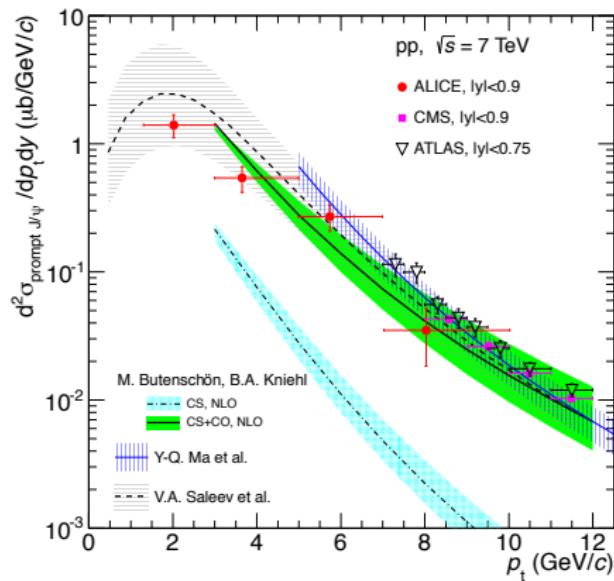
Prompt  $J/\psi$  production at the LHC (LHCb).  $\sqrt{S} = 7$  TeV

(a)  $3.5 < |y| < 4.0$ , (b)  $4.0 < |y| < 4.5$

# Realtive role of the CS and CO contributions. Comparation with NLO CPM.



The relative contributions of the color-singlet (curve 1) and color-octet (curve 2) production mechanisms to the prompt  $J/\psi$  transverse-momentum spectrum at the  $\sqrt{S} = 7$  TeV,  $1.5 < |y| < 2.0$ .



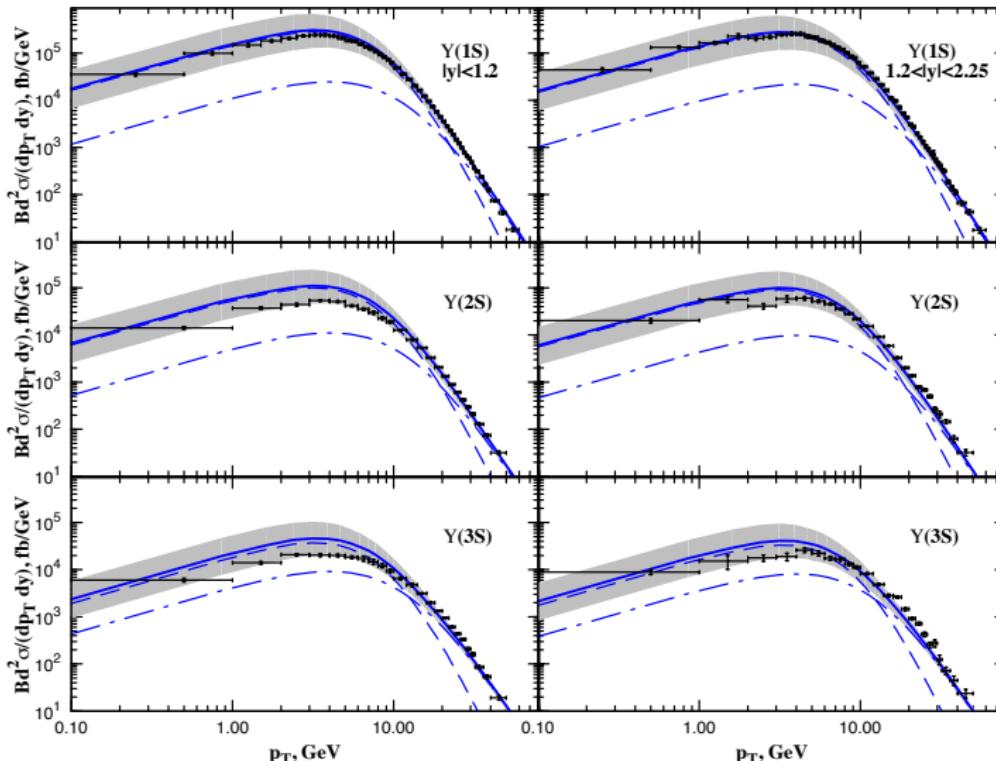
The plot is taken from  
[\[ArXiv:hep-ex/1205.5880, JHEP 1211 \(2012\) 065\]](https://arxiv.org/abs/1205.5880)

# Bottomonium production at the LHC and Tevatron.

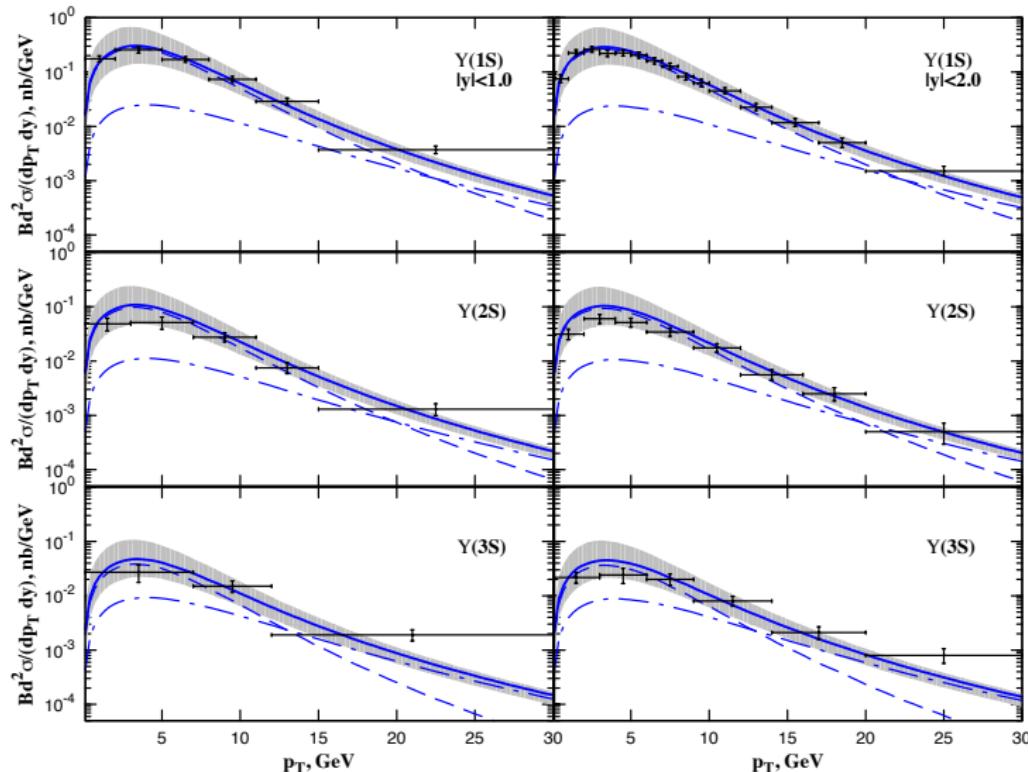
For the details see [M. A. Nefedov, V. A. Saleev, A. V. Shipilova, Phys. Rev. D88 (2013) 014003]

NME	Fit LO PRA
$\left\langle \mathcal{O}^{\Upsilon(1S)} \left[ 3S_1^{(1)} \right] \right\rangle \times \text{GeV}^{-3}$	9.28
$\left\langle \mathcal{O}^{\Upsilon(1S)} \left[ 3S_1^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-3}$	$2.31 \pm 0.25$
$\left\langle \mathcal{O}^{\Upsilon(1S)} \left[ 1S_0^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-3}$	$0.0 \pm 0.05$
$\left\langle \mathcal{O}^{\Upsilon(1S)} \left[ 3P_0^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-5}$	$0.0 \pm 0.38$
<hr/>	
$\left\langle \mathcal{O}^{\Upsilon(2S)} \left[ 3S_1^{(1)} \right] \right\rangle \times \text{GeV}^{-3}$	4.62
$\left\langle \mathcal{O}^{\Upsilon(2S)} \left[ 3S_1^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-3}$	$1.51 \pm 0.17$
$\left\langle \mathcal{O}^{\Upsilon(2S)} \left[ 1S_0^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-3}$	$0.0 \pm 0.01$
$\left\langle \mathcal{O}^{\Upsilon(2S)} \left[ 3P_0^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-5}$	$0.0 \pm 0.03$
<hr/>	
$\left\langle \mathcal{O}^{\Upsilon(3S)} \left[ 3S_1^{(1)} \right] \right\rangle \times \text{GeV}^{-3}$	3.54
$\left\langle \mathcal{O}^{\Upsilon(3S)} \left[ 3S_1^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-3}$	$1.24 \pm 0.13$
$\left\langle \mathcal{O}^{\Upsilon(3S)} \left[ 1S_0^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-3}$	$0.0 \pm 0.01$
$\left\langle \mathcal{O}^{\Upsilon(3S)} \left[ 3P_0^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-5}$	$0.0 \pm 0.02$
<hr/>	
$\left\langle \mathcal{O}^{\chi(1P)} \left[ 3P_0^{(1)} \right] \right\rangle \times \text{GeV}^{-5}$	2.03
$\left\langle \mathcal{O}^{\chi(1P)} \left[ 3S_1^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-3}$	0.0
<hr/>	
$\left\langle \mathcal{O}^{\chi(2P)} \left[ 3P_0^{(1)} \right] \right\rangle \times \text{GeV}^{-5}$	2.36
$\left\langle \mathcal{O}^{\chi(2P)} \left[ 3S_1^{(8)} \right] \right\rangle \times 10^2 \text{ GeV}^{-3}$	0.0

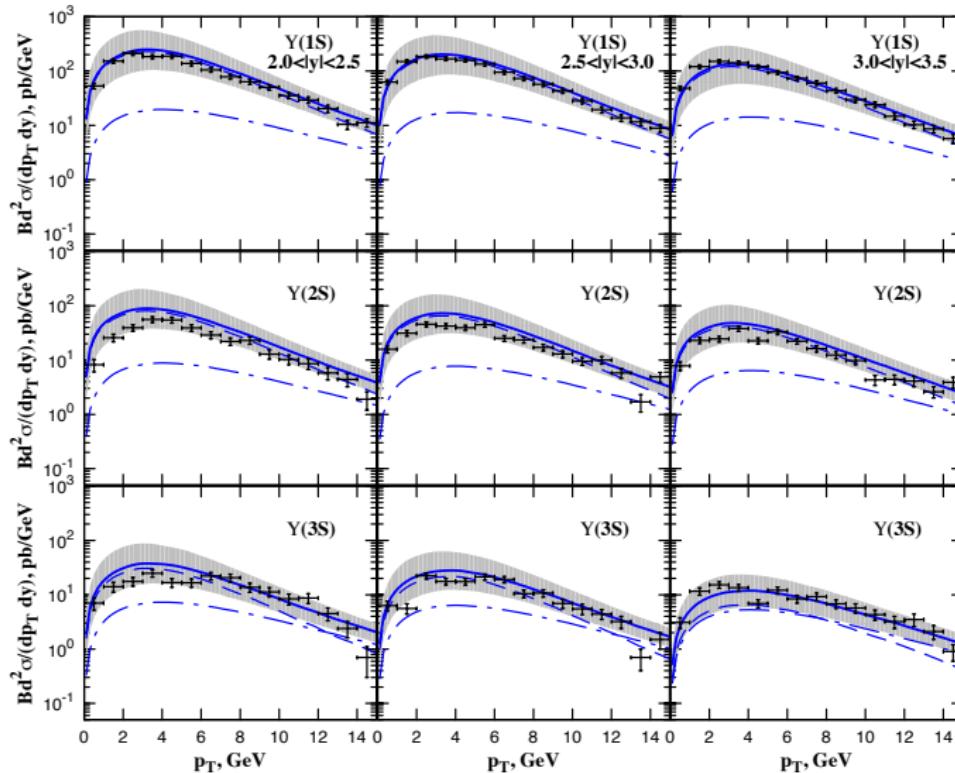
Inclusive  $\Upsilon(nS)$  production at the LHC (ATLAS).  $\sqrt{S} = 7$  TeV.

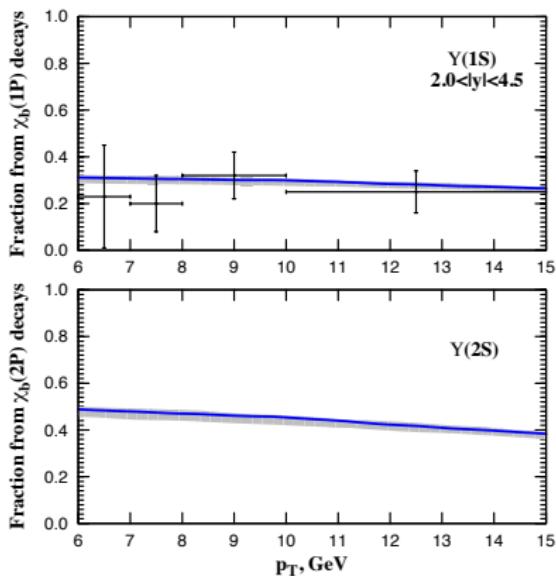
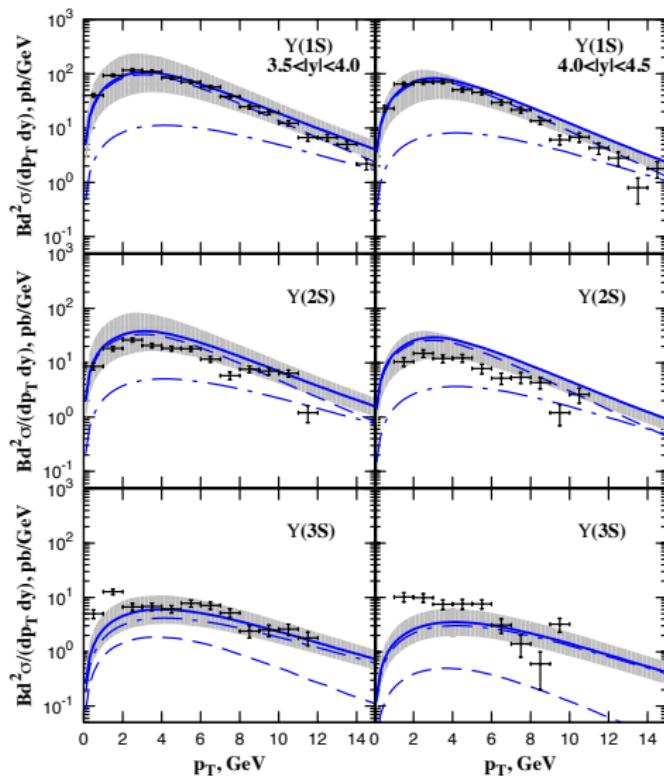


Dashed line – color-singlet contribution, dash-dotted line – color-octet contribution, solid line – sum of all contributions.

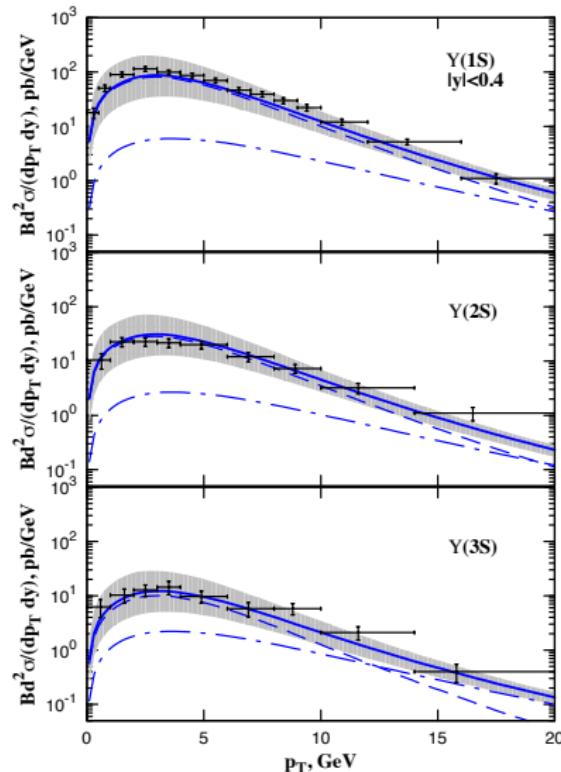
Inclusive  $\Upsilon(nS)$  production at the LHC (CMS).  $\sqrt{S} = 7$  TeV.

Inclusive  $\Upsilon(nS)$  production at the LHC (LHCb).  $\sqrt{S} = 7$  TeV.

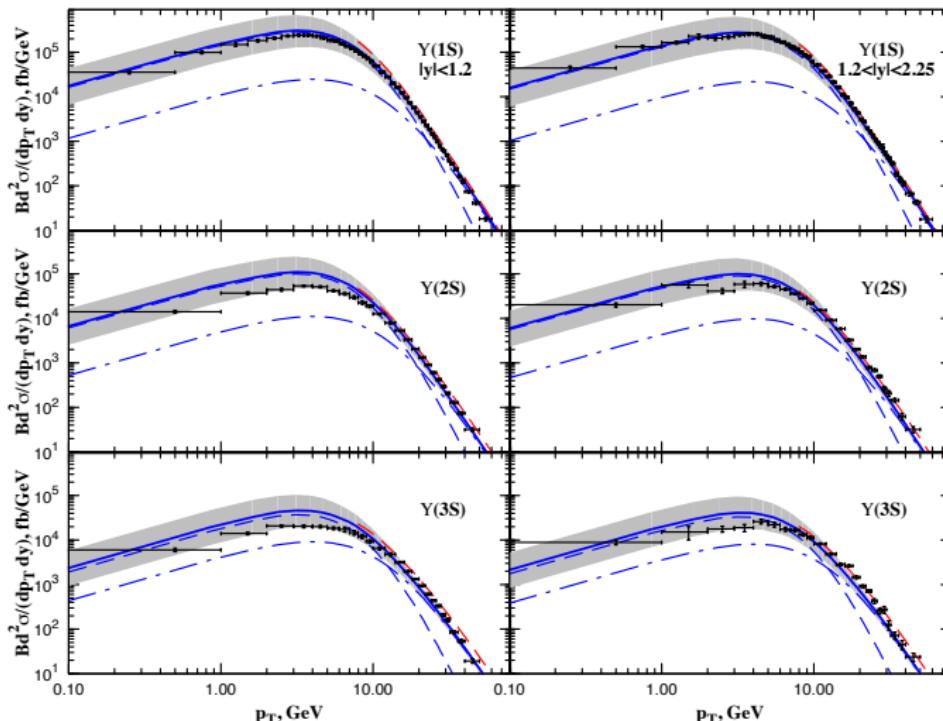


Inclusive  $\Upsilon(nS)$  production at the LHC (LHCb).  $\sqrt{S} = 7$  TeV.

Comparation with Tevatron data (CDF).  $\sqrt{S} = 1.8$  TeV.



# Comparation with NLO CPM.



Red line – LO PRA calculation with NMEs from [B. Gong et. al.,  
[arXiv:hep-ph/1305.0748](https://arxiv.org/abs/hep-ph/1305.0748)], the feeddown prescription for  $p_T$  spectrum is also included.

## Heavy quarkonium polarization.

Polarization parameters are defined through the angular distribution of muons in the quarkonium rest frame:

$$\frac{d\sigma}{d\Omega} \sim 1 + \lambda_\theta \cos^2(\theta) + \lambda_\varphi \sin^2(\theta) \cos(2\varphi) + \lambda_{\theta\varphi} \sin(2\theta) \cos(\varphi)$$

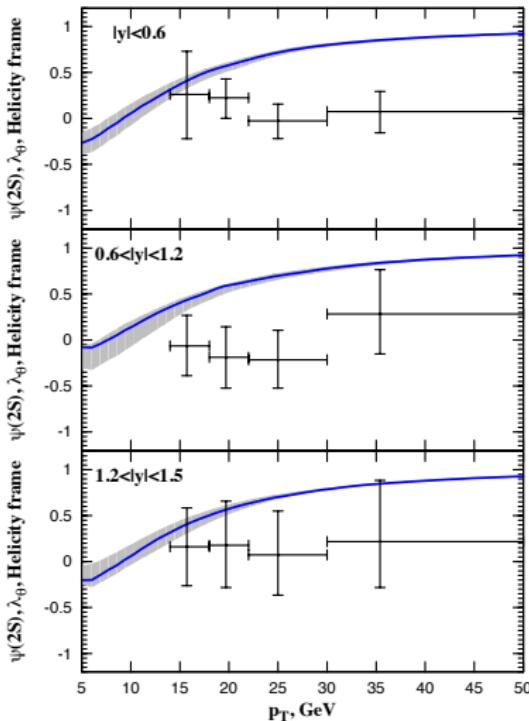
We study the polarization parameter  $\lambda_\theta$  for  $\psi(2S)$  and  $\Upsilon(3S)$  since these states are produced **directly** in our model and provide the cleanest test of production mechanism. Definition of  $\lambda_\theta$  through the density matrix elements:

$$\begin{aligned}\lambda_\theta &= \frac{\rho_{11} - \rho_{00}}{\rho_{11} + \rho_{00}} \\ \rho_{\lambda_1 \lambda_2} &= \mathcal{A}^\alpha (RR \rightarrow \mathcal{H}) \mathcal{A}^{*\alpha'} (RR \rightarrow \mathcal{H}) \varepsilon_\alpha^*(\lambda_1) \varepsilon_{\alpha'}(\lambda_2)\end{aligned}$$

$\lambda_\theta = 1$  – **transversal** polarization ( $\lambda_{1,2} = \pm 1$ ),  $\lambda_\theta = -1$  – **longitudinal** polarization ( $\lambda_{1,2} = 0$ ),  $\lambda_\theta = 0$  – **unpolarized** mixture.

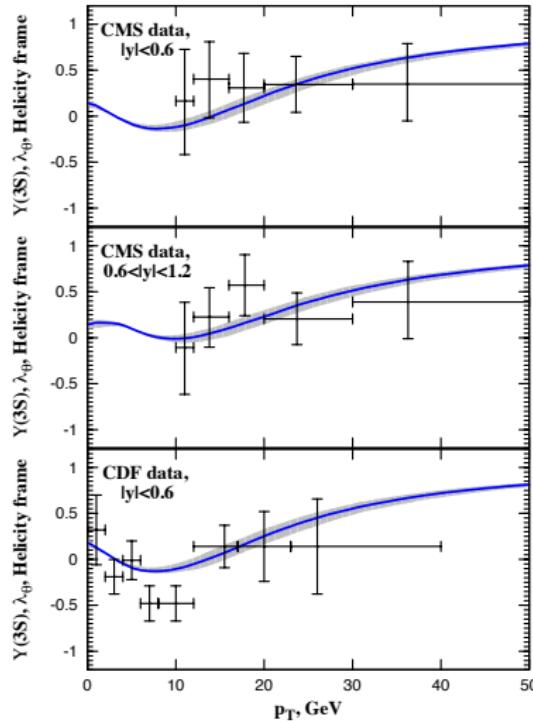
# $\psi(2S)$ and $\Upsilon(3S)$ polarization.

CMS data,  $\sqrt{S} = 7$  TeV.



Gray band – combined error from scale variation and CO NMEs.

CMS data,  $\sqrt{S} = 7$  TeV and CDF data  $\sqrt{S} = 1.96$  TeV.



## Conclusions.

- Tevatron and LHC data on cross-sections of heavy quarkonium production are in general well described in the LO PRA with small number of free parameters.
- The Color-Octet contributions are important at high  $p_T$  and  $|y|$ .
- Description of the polarization of the heaviest (directly produced) state in the model is the most difficult task. However, for  $\Upsilon(3S)$ , predictions agrees with existing data. *What is the depolarization mechanism for  $\psi(2S)$ ?*

# Heavy quarkonium production in $k_T$ -factorization approach.

## Color-singlet + Color-octet.

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- S. P. Baranov, Phys. Rev. D **66**, 114003 (2002)
- F. Yuan, K.-T. Chao, Phys. Rev. Lett. **87**, 022002; Phys. Rev. D **63**, 034006 (2001)
- B. A. Kniehl, D. V. Vasin, V. A. Saleev, Phys. Rev. D **73**, 074022; Phys. Rev. D **74**, 014024 (2006)
- V. A. Saleev, M. A. Nefedov, A. V. Shipilova, Phys. Rev. D **85**, 074013 (2012); Phys. Rev. D **88**, 014003 (2013)

## Color-singlet model.

- S. P. Baranov, N. P. Zotov, JETP Lett. **86**, 435 (2007)
- S. P. Baranov, A.V. Lipatov, N.P. Zotov, Phys. Rev. D **85**, 014034 (2012)
- S. P. Baranov, Phys. Rev. D **86**, 054015 (2012)