# Charmonia Production at LHC

A.K. Likhoded, A.V. Luchinsky, S.V. Poslavsky

Institute for High Energy Physics, Protino, Russia

Sep 17, 2014

# Outline

# Heavy Quarkonia

$$\mathcal{Q} = (Q\bar{Q}), \qquad m_Q \gg \Lambda_{QCD}$$

- $\alpha_s(m_Q) \ll 1 \Rightarrow$ Perturbative QCD
- $(Q\bar{Q}) \to \mathcal{Q} \Rightarrow$ Nonpertubative QCD

Color Single Model *[Kartvelishvili et al, SJNP 28 (1978) 678]*

$$|\chi_{cJ}\rangle \sim |R'(0)||c\bar{c}[^3P_J^{[1]}]\rangle$$

Color Octet Model (NRQCD *[Bodwin et al, PRD51 (1995) 1125]*)

$$|\chi_{cJ}\rangle \sim |R'(0)||c\bar{c}[^3P_J^{[1]}]\rangle + \langle\mathcal{O}_S\rangle\,|c\bar{c}[^3S_1^{[8]}]g\rangle + \langle\mathcal{O}_P\rangle\,|c\bar{c}[^1P_0^{[8]}]g\rangle + \dots$$

- Higher terms are suppressed by $v$
- Model parameters $|R'(0)|^2$, $\langle\mathcal{O}_S\rangle$, $\langle\mathcal{O}_P\rangle$ are determined from experiment (decays, production)

## Decays

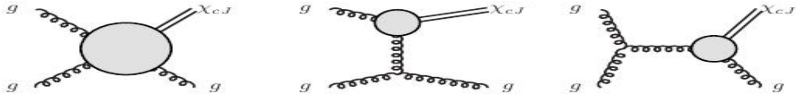
$$\Gamma^{tot}_{\chi_{Q2}} \approx \Gamma(\chi_{Q2} \to gg) = \frac{128}{5}\alpha_s^2 \frac{|R'(0)|^2}{M^4} \Rightarrow |R'(0)|^2 \approx 0.075\text{GeV}^5$$

## Hadronic Production

$$\sigma \sim f_1 \otimes f_2 \otimes \hat{\sigma}$$

- Collinear LO: $gg \to \mathcal{Q}$, $f = f(x)$
  - Only C=+1 states
  - $\chi_{c1}$ production is forbidden (L-Y theorem)
  - No information about $p_T$ distibutions
- $k_T$ factorization: $f = f(x, k_T)$
  - Poor knowledge of distribution functions
- Collinear NLO: $gg \to \mathcal{Q}g$, $f = f(x)$
  - All states can be produced
  - $p_T$ distribution can be predicted

# $pp \to \chi_{cJ} + X$, NLO




$$\frac{d\sigma}{dp_T} = \sum_{\mathcal{Q}} \int_0^1 f_g(x_1) f_g(x_2) \frac{d\hat{\sigma}(gg \to \mathcal{Q}g)}{dp_T}$$

| $\mathcal{Q}$ | $c\bar{c}[^3P_1^{[1]}]$ | $c\bar{c}[^3P_{0,2}^{[1]}]$ | $c\bar{c}[^1P_1^{[8]}]g$ | $c\bar{c}[^3S_0^{[8]}]g$ |
|---|---|---|---|---|
| $p_T \ll M_\chi$ | $\sim p_T$ | $\sim 1/p_T$ | $\sim 1/p_T$ | $\sim p_T$ |
| $p_T \gg M_\chi$ | $\sim 1/p_T^5$ | $\sim 1/p_T^5$ | $\sim 1/p_T^5$ | $\sim 1/p_T^3$ |

So, in higt $p_T$ region

- $S$ wave CO should dominate
- It is hard to separate CS and $P$-wave CO from $d\sigma(J/\psi)/dp_T$
- some other observable is needed

# $\chi_{c2}/\chi_{c1}$

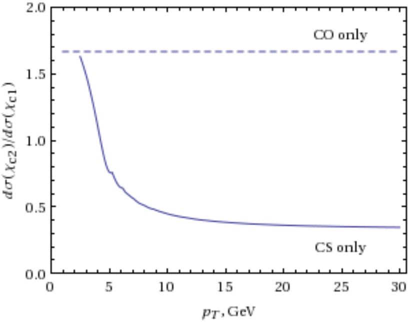
$$r_{J_1 J_2} = \frac{d\sigma(\chi_{cJ1})/dp_T}{d\sigma(\chi_{cJ2})/dp_T}$$

- No CS or nonzero $S$-wave CO

$$r_{J_1 J_2} \approx \frac{2J_1+1}{2J_2+1}$$

- CS, No $S$-wave CO

$$r_{21} \approx \frac{1}{3} + \frac{\langle \mathcal{O}_P \rangle}{0.75|R'(0)|^2 + 0.64 \langle \mathcal{O}_P \rangle}$$

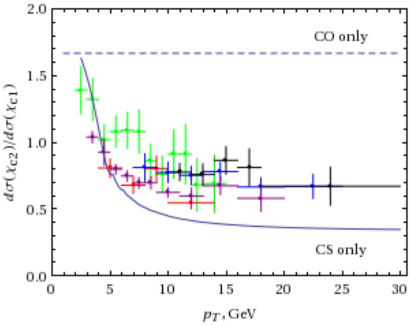


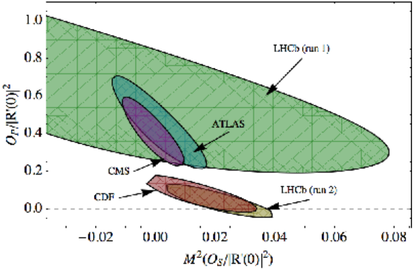
# $\chi_{c2}/\chi_{c1}$

## Experimental information

- A.Abulencia *et al.* [CDF Collaboration], Phys. Rev. Lett. **98**, 232001 (2007)
- R.Aaij *et al.* [LHCb Collaboration], Phys. Lett. B **714**, 215 (2012)
- S. Chatrchyan *et al.* [CMS Collaboration], Eur. Phys. J. C **72**, 2251 (2012),
- R. Aaij *et al.* [LHCb Collaboration], arXiv:1307.4285 [hep-ex]
- ATLAS collaboration, ATLAS-CONF-2013-095 (2013).

# $\chi_{c2}/\chi_{c1}$




Two groups

- LHCb2012, CMS, ATLAS
- CDF, LHCb2013

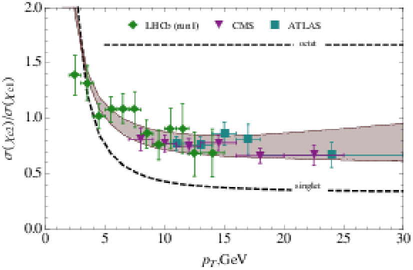
Will be analyzed separetely

# $\chi_{c2}/\chi_{c1}$: LHCb2012, CMS, ATLAS

$$\chi^2/DOF = 1.31$$

$$\frac{M^2 \langle \mathcal{O}_S \rangle}{|R'(0)|^2} = (0 \pm 0.46) \times 10^{-2}$$

$$\frac{\langle \mathcal{O}_P \rangle}{|R'(0)|^2} = 0.42 \pm 0.07$$

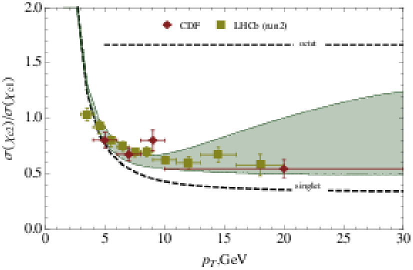


# $\chi_{c2}/\chi_{c1}$: CDF, LHCb2013

$$\chi^2/DOF = 4.45$$

$$\frac{M^2\langle\mathcal{O}_S\rangle}{|R'(0)|^2} = (1.88 \pm 1.13) \times 10^{-2}$$

$$\frac{\langle\mathcal{O}_P\rangle}{|R'(0)|^2} = 0.048 \pm 0.006$$

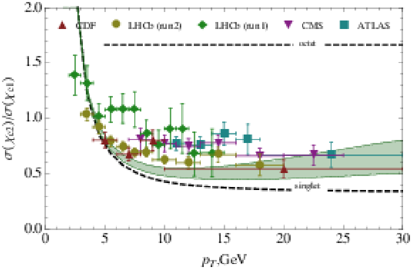


# $\chi_{c2}/\chi_{c1}$: Combined fit

$$\chi^2/DOF = 3.86$$

$$\frac{M^2 \langle \mathcal{O}_S \rangle}{|R'(0)|^2} = (1.41 \pm 0.6) \times 10^{-2}$$

$$\frac{\langle \mathcal{O}_P \rangle}{|R'(0)|^2} = 0.123 \pm 0.004$$



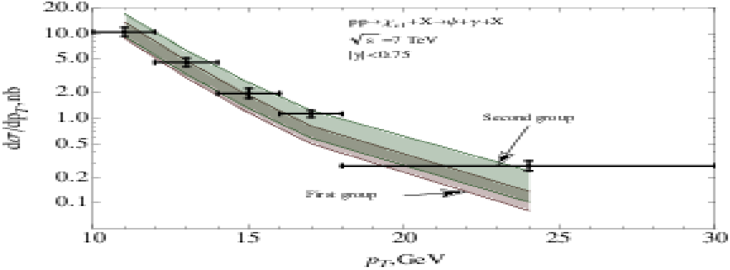
# $\chi_c$, Spectrum

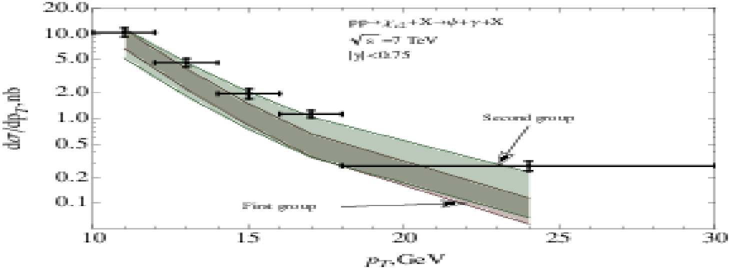
To obtain overall normalization one should use some cross section distributions

- F.Abe *et al.* [CDF Collaboration], Phys. Rev. Lett. **79**, 578 (1997).
- ATLAS collaboration, ATLAS-CONF-2013-095 (2013).

| | ATLAS, CMS | CDF, LHCb | all |
|---|---|---|---|
| $\chi^2/DOF$ | 1.24 | 2.64 | 3.14 |
| $\|R'(0)\|^2$, GeV$^5$ | $0.27 \pm 0.03$ | $0.38 \pm 0.05$ | $0.35 \pm 0.05$ |
| $\langle \mathcal{O}_S \rangle$, $10^{-3}$ GeV$^3$ | $0. \pm 0.1$ | $0.66 \pm 0.27$ | $0.44 \pm 0.16$ |
| $\langle \mathcal{O}_P \rangle$, $10^{-1}$ GeV$^5$ | $1.14 \pm 0.16$ | $0.14 \pm 0.15$ | $0.41 \pm 0.14$ |

# $\chi_c$, comparison with experiments



# $\chi_c$, Discussion

- CS gives main contributions,
- $|R'(0)|^2$ is about 4 times larger than phenomenological value $|R'(0)|^2 = 0.075\text{GeV}^5$
- $S$ wave CO are neglible
- These values are strongly correlated

$|R'(0)|^2$ is a result of Bohr-Oppenheimer approximation

$$\begin{aligned}\int A_{hard}(q)\psi(q)d^3q &\approx A_{hard}(0)\int \psi(q)d^3q + \nabla A_{hard}(0)\int \mathbf{q}\psi(q)d^3q = \\ &= A_{hard}(0)\psi(0) + A'_{hard}(0)\psi'(0)\end{aligned}$$

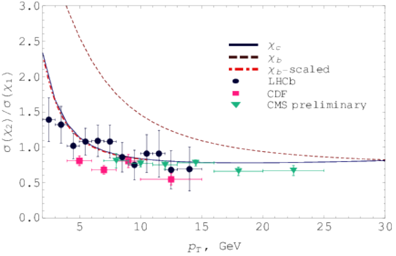
For $J/\psi$, $\eta_c$: $v^2 \approx 0.21$
For $\chi_c$: $v^2 \approx 0.3$

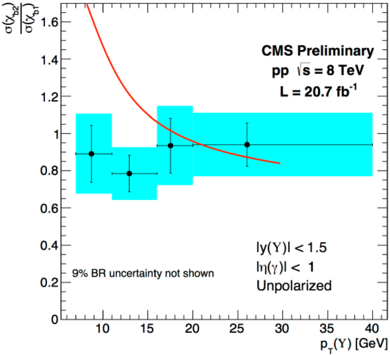
$q \sim m_c/2 \Rightarrow$ BO approximation ?
($e^+e^-$ annihilation at Belle)

# $\chi_b$, Scaling

$$\frac{d\sigma(\chi_{b2})/dp_T}{d\sigma(\chi_{b1})/dp_T}(zp_T; s) \approx \frac{d\sigma(\chi_{c2})/dp_T}{d\sigma(\chi_{c1})/dp_T}(p_T; s)$$

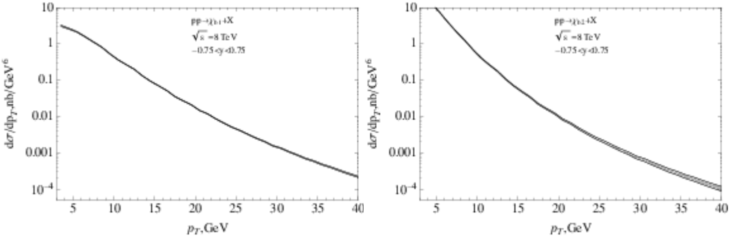
where $z = M_b/M_c$



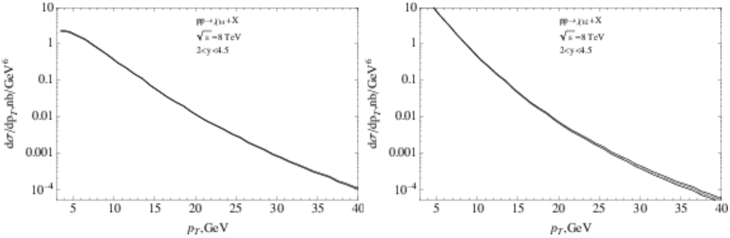



# $\chi_b$, spectrum

ATLAS




LHCb



# Conclusion

- Heavy quarkonia production can give information on strong interaction at different scales,
- Inclusuve $\chi_c$ production can be explained using NLO partonic reactions
- Two groups of experiments. In both cases
  - CS components give main contributions
  - $\chi_{c2}/\chi_{c1} \Rightarrow$ CO components are necessary
- $\chi_b$ production can be explained via scaling

Published in:


- A.K. Likhoded, A.V. Luchinsky, S.V. Poslavsky, Phys.Rev. D86 (2012) 074027;
- A.K. Likhoded, A.V. Luchinsky, S.V. Poslavsky, Yad.Fiz. 77 (2014) 966-973
- A.K. Likhoded, A.V. Luchinsky, S.V. Poslavsky,arXiv:1409.0693 [hep-ph], submitted to PRD


Thank you for your attention