Quarkonium Production at LHCb

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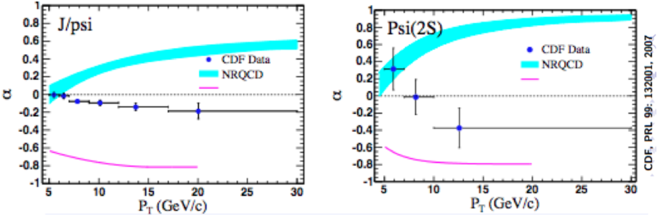
Outline

1. Introduction
2. J/ψ and $\Psi(2S)$
3. $\Upsilon(\mathrm{nS})$
4. Double charmonium and open charm production
5. Conclusions

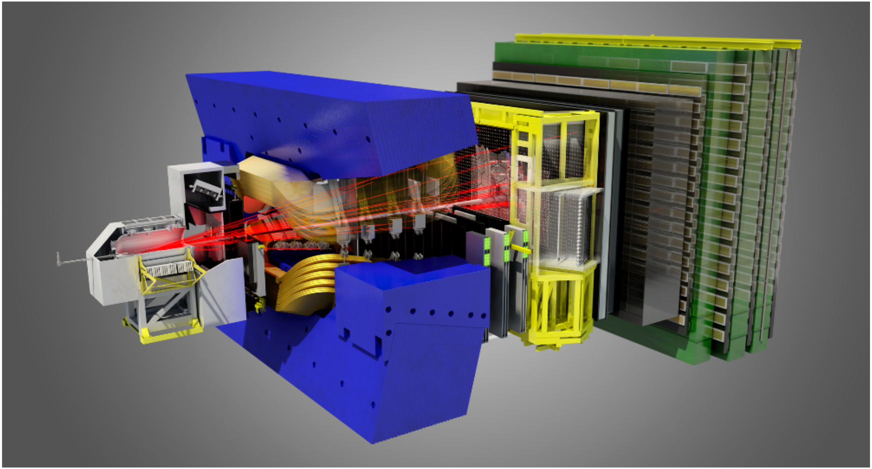
Why do we care about quarkonium?

- Since the first measurements at Tevatron the production of quarkonium states has proved a tough challenge.
- Various models have been proposed at different times and a combination of Color Octet and Color Singlet mechanisms appear to describe the p_{T} spectrum and cross-sections measured at Tevatron.
- However the a satisfactory description of polarization remains elusive.



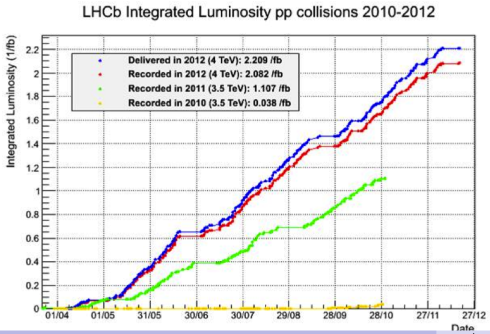
- Other observables, double-charm production, production in p-Pb interactions etc.. have been proposed to solve the puzzle.
- With its high luminosity the production cross-section and possibly the polarization of states such as χ_c, χ_b might also become available at the LHC.
- The interest in the study of heavy flavour production processes is not limited to its theoretical value but it also:
  - provides excellent test of p-QCD and MC generators at new energies;
  - improves the understanding of heavy flavour background in many searches;
  - is an important test of the understanding of the detector.

The LHCb Detector



The LHCb experiment in a nutshell

- Good separation of primary and secondary vertices.
- Good momentum resolution $\sim 0.5\%$ with J/ψ mass resolution of $\sim 13\,\mathrm{MeV}/c^2$.
- Good muon identification: pion $\to$ muon misidentification $\sim 0.7\%$.
- Low p_T triggers:
    - $1\ \mu : p_\mathrm{T} > 1.8\,\mathrm{GeV}/c$;
    - $2\ \mu : p_\mathrm{T} > 0.56\,\mathrm{GeV}/c$ and $p_\mathrm{T} > 0.48\,\mathrm{GeV}/c$.
- Rapidity region $2 < y < 4.5$ complementary to the GPD.



Unless metioned results presented in this talk are based on the 2010 and/or 2011 7 TeV datasets.

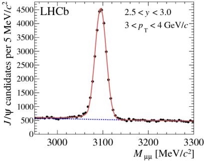
The Analysis Strategy

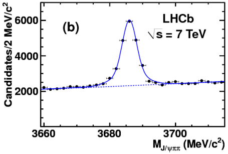
- Define a fiducial volume in the LHCb acceptance: $2.0 < y < 4.5$ and a maximum for p_{T} typically between $10\,\mathrm{GeV}/c$ and $20\,\mathrm{GeV}/c$ depending on the analysis.
- Reconstruct the quarkonium decay usually $\rightarrow \mu^{+}\mu^{-}$
- Remove background as much as possible with cuts on the usual kinematic and reconstruction variables.
- Require the decay products triggered the event.
- Subtract the remaining background.
- Apply per-event efficiency corrections, with efficiency determined as much as possible from data.
  - Geometric acceptance;
  - Reconstruction efficiency;
  - Muon identification efficiency.
  - Trigger efficiency;

Prompt J/ψ and $\Psi(2S)$

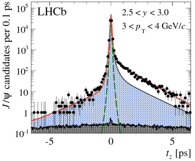
- EPJ C71(2011) 1645
- $J/\psi \to \mu^+\mu^-$
- 5.2 pb^{-1} from 2010 data

- EPJ C72(2012) 2100
- $\Psi(2S) \to \mu^+\mu^-$
- $\Psi(2S) \to J/\psi\,\pi^+\pi^-$
- 36 pb^{-1} from 2010 data

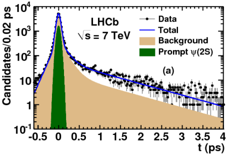




- J/ψ and $\Psi(2S)$ produced from primary vertex and in seconday decays.
- J/ψ also produced from feed-down from higher states.
- Secondary decays component removed exploiting pseudo propertime:

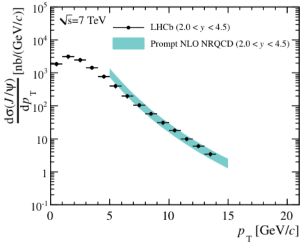


$$t_z = \frac{z_{J/\psi} - z_{PV} \times M_{J/\psi}}{p_z}$$

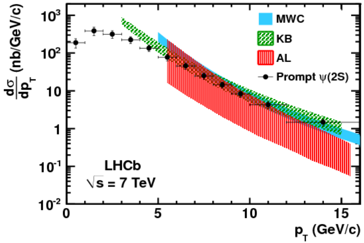


Prompt J/ψ and $\Psi(2S)$ 7 TeV results

- Dominant uncertainty is the unknown polarization affecting efficiency determination.
- Measurement performed in 3 cases assuming unpolarized, fully longitudinal and fully transversal polarization.
- $\sigma_{prompt}(J/\psi) = 10.52 \pm 0.04(stat) \pm 1.30(sys)^{+1.64}_{-2.20}(pol)$ μb EPJ C71(2011) 1645
- $\sigma_{prompt}(\Psi(2S)) = 1.44 \pm 0.01(stat) \pm 0.12(sys)^{+0.20}_{-0.40}(pol)$ μb EPJ C72(2012) 2100
- Models describe well the transverse momentum distribution.



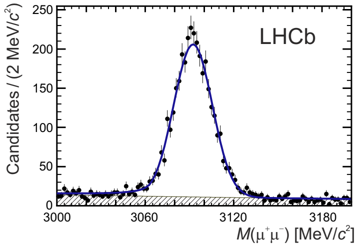
NNLO CS: PRL (2008) 152001

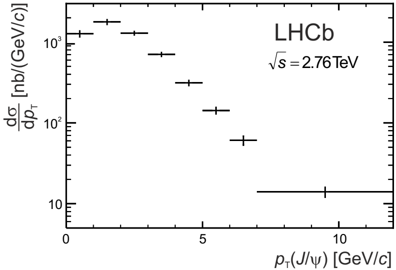


NNLO CS (AL): EPJ C61 (2009) 693
NNLO CS+CO (MWC): PRD 84 (2011) 114001
NNLO CS+CO (KB): PRL 106(2011) 022003

Prompt J/ψ 2.76 TeV results

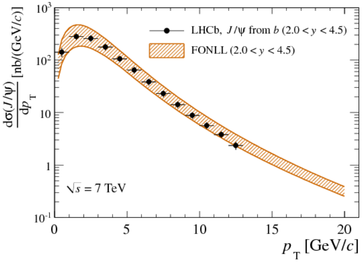
- A sample of 0.071 pb^{-1} collected in 2011 and used to measure the J/ψ cross-section JHEP 02 (2013) 041.
- Measurement carried out in the kinematic region $p_\mathrm{T} < 12\,\mathrm{GeV}/c$, $2 < y < 4.5$.
- $\sigma_{inclusive}(J/\psi) = 5.6 \pm 0.1(stat) \pm 0.4(sys)\,\mu\mathrm{b}$
- Uncertainty from unknown polarization estimated to be as large as an extra 20%.



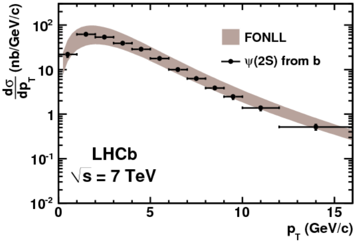


Non-prompt J/ψ and $\Psi(2S)$

- The 7 TeV data analysis provides a measument of the cross-section of J/ψ and $\Psi(2S)$ from B hadrons.
- Transverse momentum distributions in good agreement with FONLL predictions.



FONLL: JHEP 05 (1998) 007



FONLL: CERN-PH-TH/2011-227

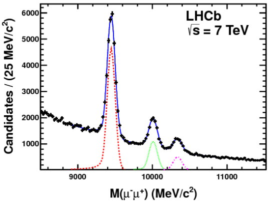
- J/ψ from B hadrons cross-section is measured at 2.76 TeV:

$$\sigma_{secondary}(J/\psi) = 400 \pm 35(stat) \pm 49(sys) nb$$

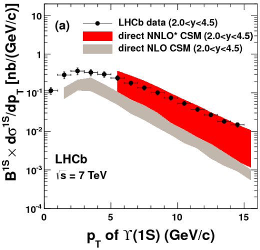
- Good agreement with theoretical prediction: 370^{+120}_{-110} nb JHEP 05 (2021) 137.

Υ(nS) at 7 TeV

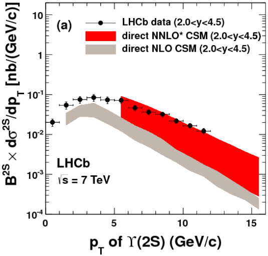
- $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ reconstructed in the $\mu^+\mu^-$ channel from a 25 pb^{-1} sample EPJC 72 (2012) 2025.
- Cross-sections measured in the range: $p_{\mathrm{T}} < 15\,\mathrm{GeV}/c$, $2 < y < 4.5$.
- Good agreement with theory predictions PRL 101 (2008) 152001.



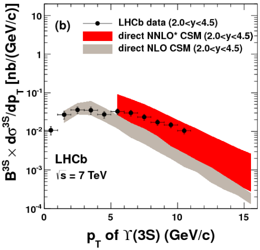
$\Upsilon(1S)$



$\Upsilon(2S)$

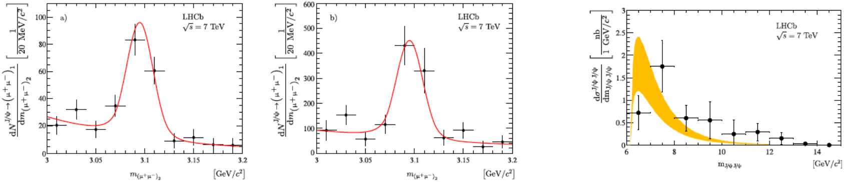


$\Upsilon(3S)$



Double J/ψ

- Analysis carried out on the $36\,\text{pb}^{-1}$ collected in 2010 PLB 707 (2012) 52-59.
- Cross section measured in the region $p_\text{T} < 10\,\text{GeV}/c$, $2 < y < 4.5$.
- First observation of double J/ψ production at hadronic collider.

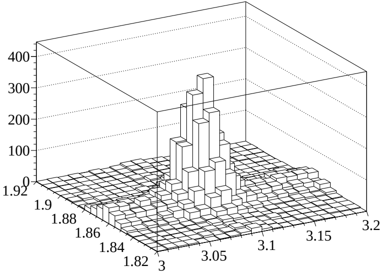


- Cross-section measured to be $\sigma = 5.1 \pm 1.0 \pm 1.1$ nb.
- In agreement with theoretical prediction of $\sigma = 4$ nb PRD 84 (2011) 094023.

Double J/ψ + open charm

J/ψ + one of: D^0, D^+, D_s^+, or Λ_c reconstructed in 355 pb^{-1} collected in 2011 JHEP 02 (2012) 141.

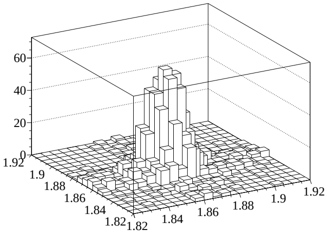
	Mode	Yield
a)	J/ψ D^0	4875 ± 86
b)	J/ψ D^+	3323 ± 71
c)	J/ψ D_s^+	328 ± 22
d)	J/ψ Λ_c^+	116 ± 14



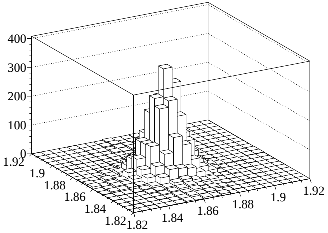
J/ψ + D^0.

Open charm + open charm

- Any pair of D^0, D^+, D_s^+, Λ_c reconstructed in 355 pb^{-1} collected in 2011 JHEP 02 (2012) 141.
- Both same sign and opposite sign considered.
- Opposite sign yields between $\sim 10^4$ and $\sim$ 200 events.
- Same sign yields between $\sim 10^3$ and $\sim$ 50 events.



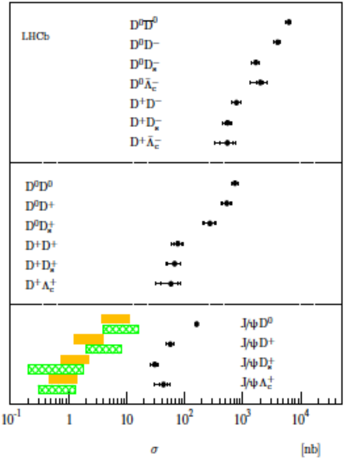
$D^0 + D^0$



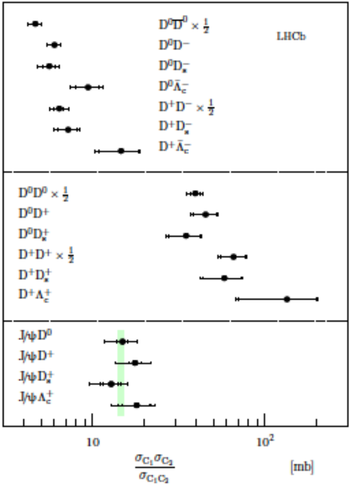
$D^0 + \bar{D}^0$

Cross-section

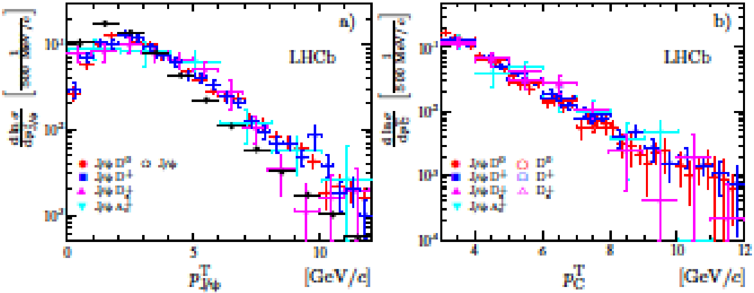
Cross-sections compared to $gg \to J/\psi\, c\bar{c}$ calculations PRD 57 (1998) 4385, PRD 73 (2006) 074021 and EPJC 62 (2009).



Cross-section ratios compared to Double Parton Scattering expectations based on Tevatron results.

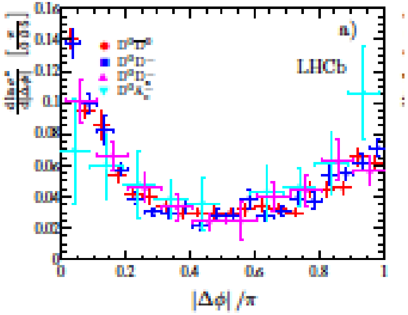


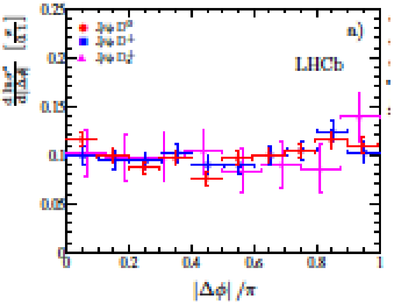
Transverse momentum spectrum



- The J/ψ p_{T} spectrum appears to be harder when accompanied by another charm.
- On the contrary the single open charm spectrum is harder than the double open charm one.

Azimuthal Angle Correlation





- The azimuthal angle difference between the J/ψ and the open charm or between two same sign open charm does not show a correlation.
- On the contrary the distribution for opposite sign OC+OC shows a peak at $\Delta\Phi \to 0$ suggesting a $g \to c\bar{c}$ splitting contribution.

Conclusions

- LHCb has successfully run during the first data taking collecting a wealth of $c\bar{c}$ and $b\bar{b}$ candidates.
- Many interesting results have already been produced including:
  - Cross-section measurements;
  - First observations;
  - First suggestions of the relevance of DPS.
- Work is currently ongoing to provide measurement of
  - Production cross-sections of other states;
  - Quarkonium polarization;
  - Differential cross-sections of double J/ψ states.
- So don't miss this workshop in 2014!