Quarkonia production at LHCb

Marco Adinolfi

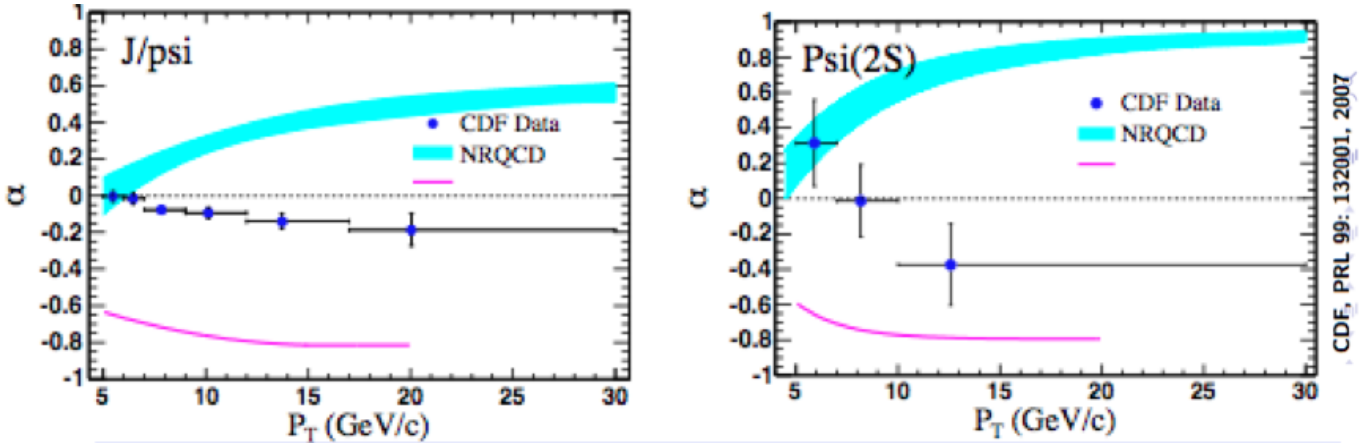
University of Bristol

29 April 2014

Outline

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.

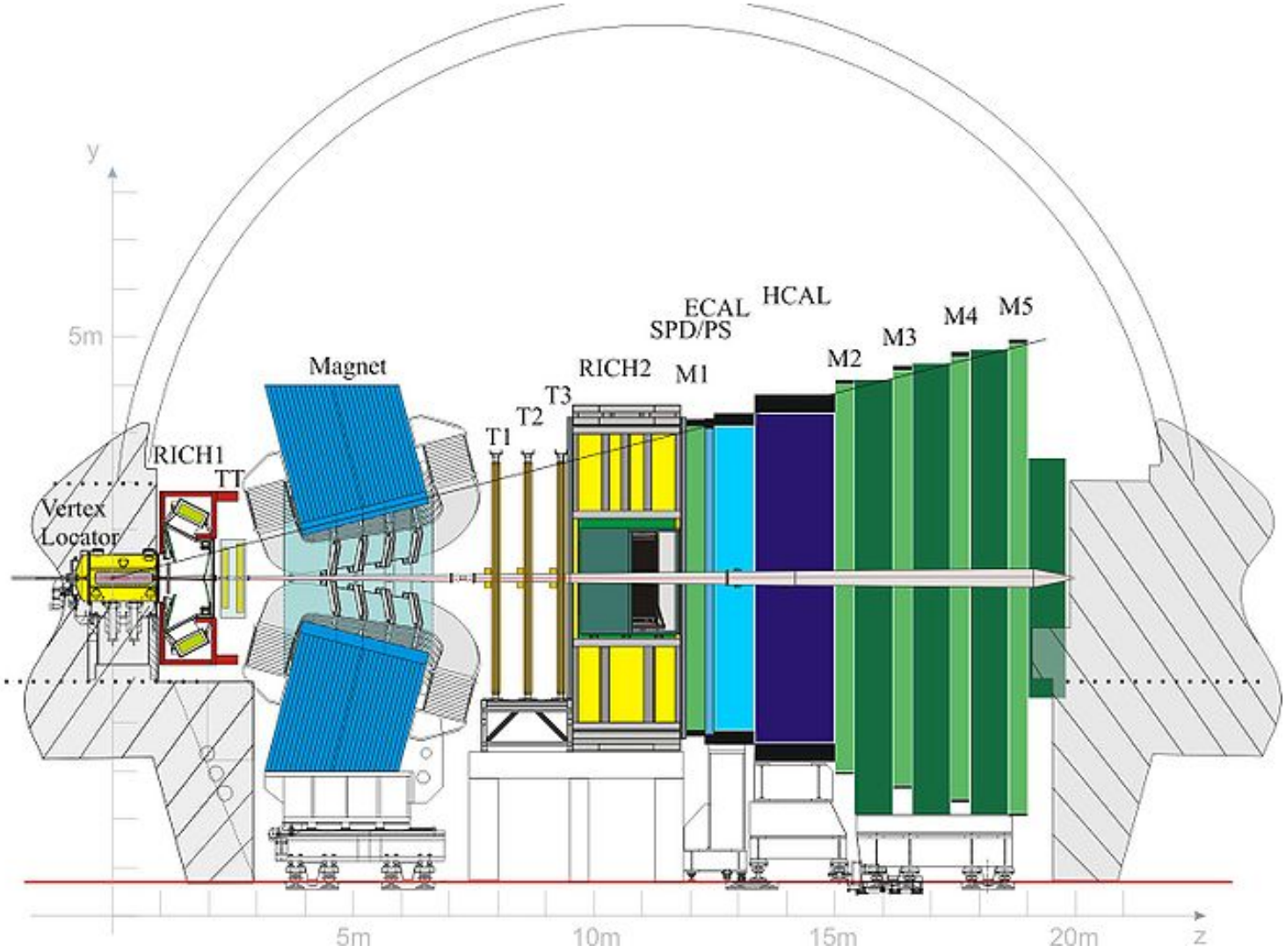


- Other observables, double-charm production, production in p-Pb interactions etc.. have been proposed to solve the puzzle.
- With its high luminosity the production cross-section and possibly the polarization of states such as χ_c, χ_b might also become available at the LHC.
- The interest in the study 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.

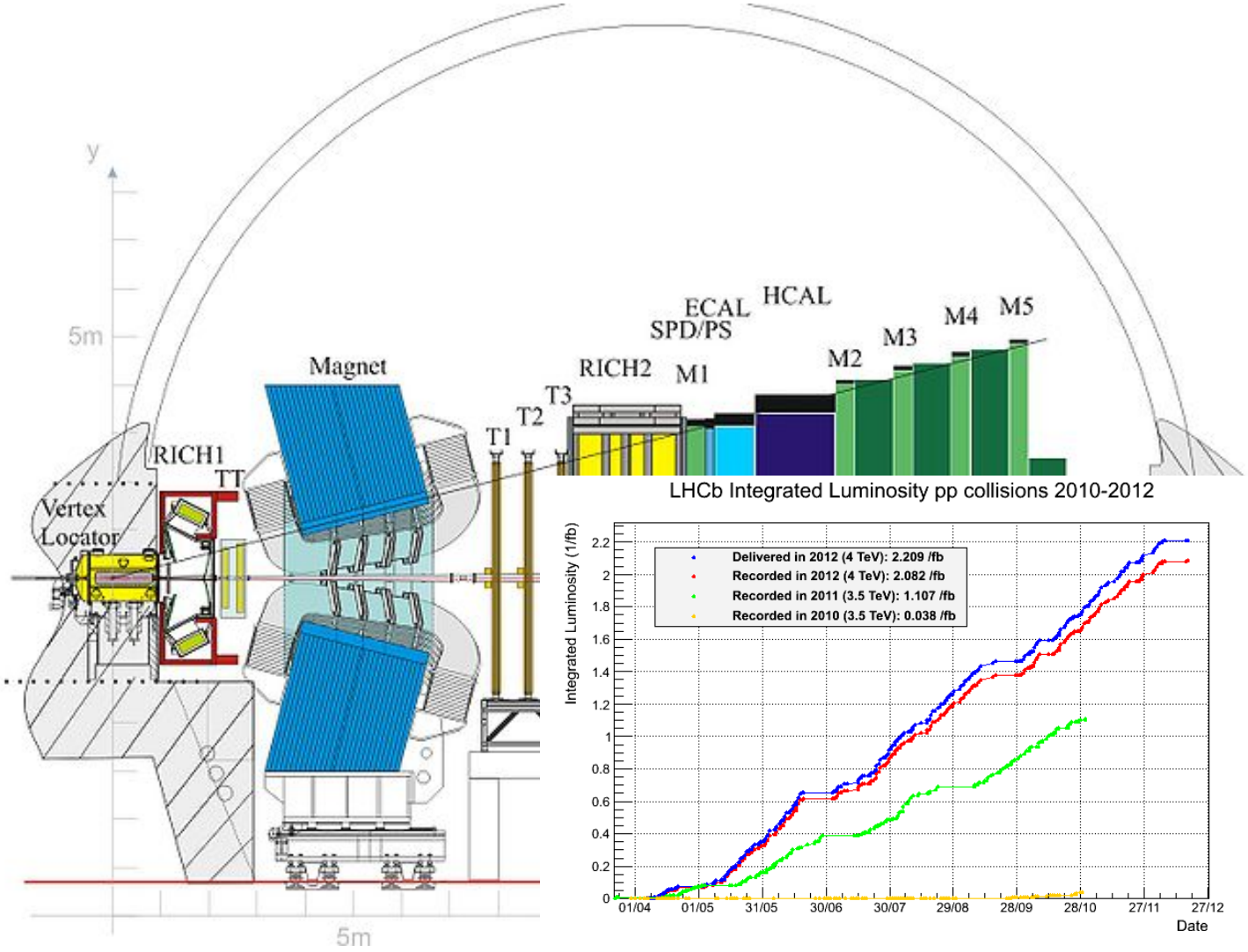
I will not cover

- Several other talks on quarkonia, so I will not cover:
  - Quarkonia and quarkonia-like spectroscopy at LHCb
  - Exclusive J/ψ and $\psi(2S)$ vector meson production
  - Study of J/ψ production and cold nuclear matter effects in pPb collisions

The LHCb Detector



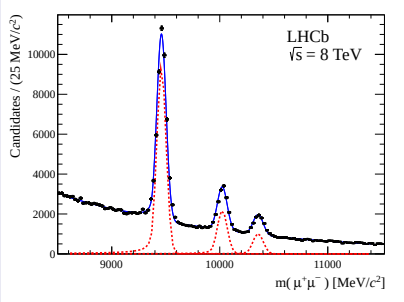
The LHCb Detector



A few numbers on LHCb

TRACKING

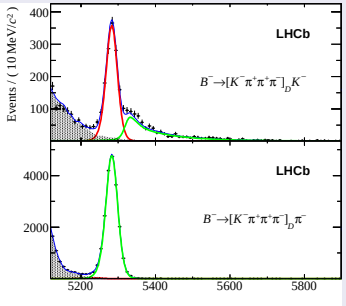
$\Delta p/p = 0.4 - 0.6\%$ at 5-100 GeV



J. High Energy Phys. 06 (2013) 064

PID

$\epsilon(K \to K) \sim 95\%$ $\epsilon(\pi \to K) \sim 5\%$

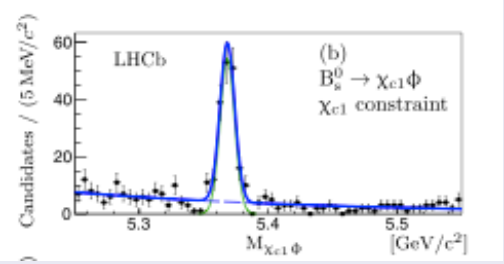


Phys. Lett. B723 (2013) 44-53

CALO

$\sigma_E/E \sim 10\%/\sqrt{E} \oplus 1\% - ECAL$

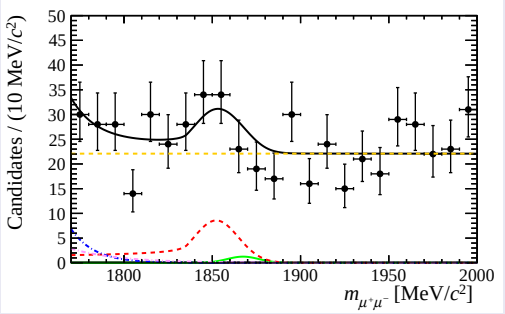
$\sigma_E/E \sim 70\%/\sqrt{E} \oplus 10\% - HCAL$



Nucl. Phys. B 874 (2013) 663-678

MUON

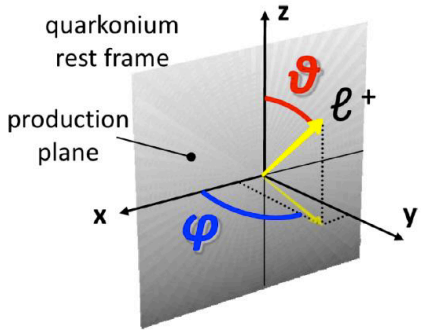
$\epsilon(\mu \to \mu) \sim 97\%$ $\epsilon(\pi \to \mu) \sim 1 - 3\%$



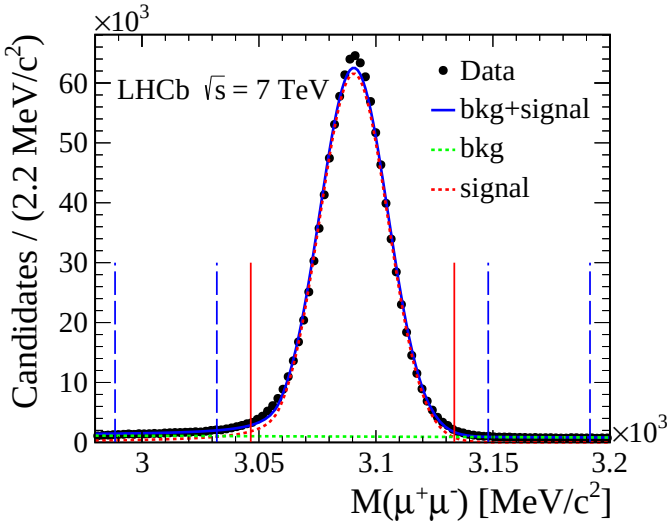
Phys. Lett. B 725 (2013) 15-24

J/ψ polarization strategy

- 371 pb^{-1} 7 TeV data from 2011, divided in bins of p_T and rapidity.
- Extract polarization from angular distribution of $J/\psi \to \mu^+\mu^-$ (feed down included).
- Full angular analysis to determine the polarization parameters $(\lambda_\theta, \lambda_{\theta\phi}, \lambda_\phi)$



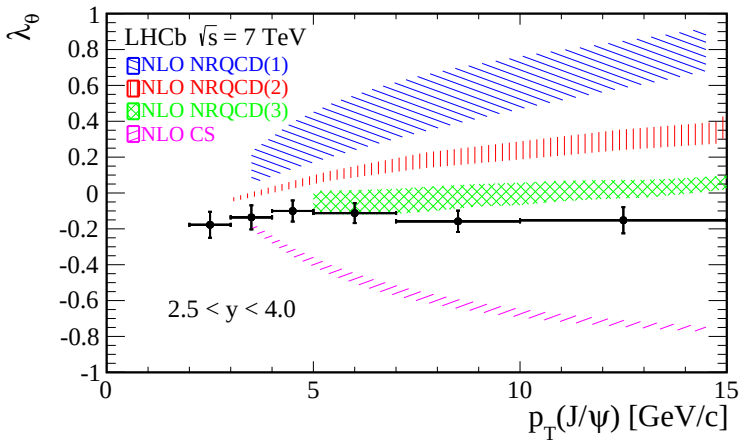
$$\frac{dN^2}{d\cos\theta d\phi} \propto 1 + \cos^2\theta + \lambda_{\theta\phi}\sin 2\theta\phi + \lambda_\phi \sin^2\theta\cos 2\phi$$



5 GeV/c $< p_T <$ 7 GeV/c and 3.0 $< y <$ 3.5

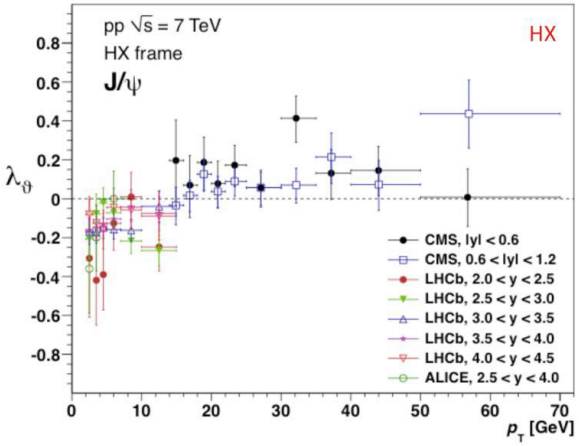
- Data presented in both Helicity frame (HX) and Collins-Soper frame (CS)
- Prompt J/ψ and J/ψ from b separated using pseudo propertime
- $\lambda_{inv} = (\lambda_\theta + 3\lambda_\phi)/(1 - \lambda_\phi)$ also measured (independent of the frame)
- Eur. Phys. J. C (2013) 73:2631

J/ψ polarization results



HX frame

- CSM no feed down: Nucl. Phys. Proc. Suppl. B222-224 (2012) 151
- NRQCD: no feed-down: Nucl. Phys. Proc. Suppl. B222-224 (2012) 151
- NRQCD: feed-down from $\chi_c(^3P_J^1, ^3S_J^8)$ and $\psi(2S)$ Phys. Rev. Lett. 110 (2013) 042002
- NRQCD: feed-down from $^3P^{[8]}$ Phys.Rev. Lett. 108 (2012) 242004



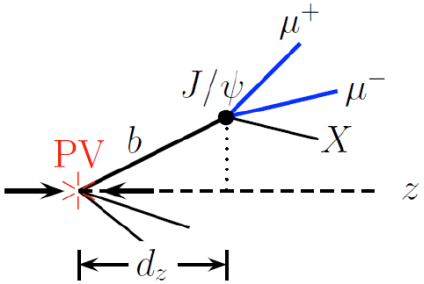
HX frame

- ALICE: PRL108(2012)082001
- CMS: arXiv:1307.6070
- LHCb: arXiv:1307.6379
- (P. Faccioli, QCD at LHC 2013, DESY, Hamburg)

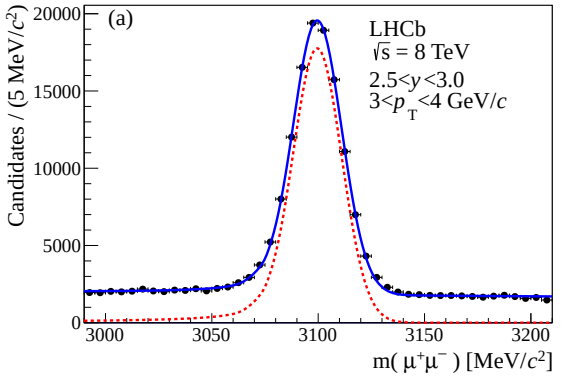
- $\lambda_{\theta\phi}$ and λ_ϕ consistent with 0 $\Rightarrow \lambda_\theta = \lambda_{inv}$
- Small longitudinal polarization observed $\lambda_\theta = -0.145 \pm 0.027$
- Results in HX and CS frame consistent.
- LHCb results are compatible with NLO NRQCD calculations that include feed-down contributions.
- Good agreement with ALICE.

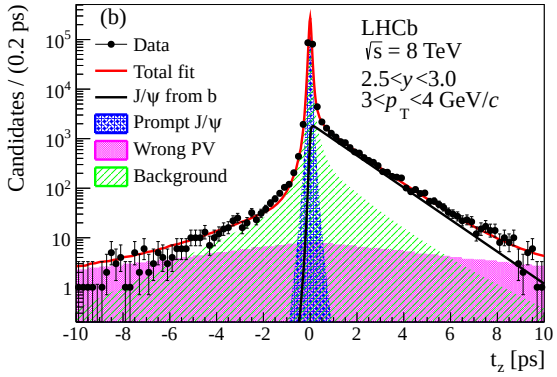
J/ψ production

- Select decays of J/ψ into muon pairs
  - Opposite charged tracks from the same vertex
  - Good track quality and muon id.
  - Require minimum muon p_T.
- Measure the double differential cross section in bins of p_T and y.
  - $p_T < 14\ \mathrm{GeV}/c$
  - $2.0 < y < 4.5$
- Measure the cross section separately for prompt J/ψ (includind feed-down) and J/ψ from b-decays.
- Two sample separated using pseudo propertime: $t_z = \left(z_{J/\psi} - z_{PV}\right) \times \frac{M_{J/\psi}}{p_z}$



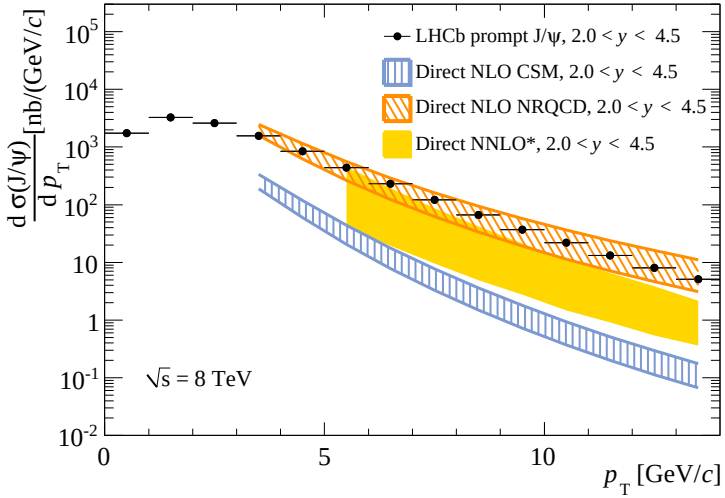
- Yields extracted from simultaneous fit of mass and t_z.





JHEP 06 (2013) 064

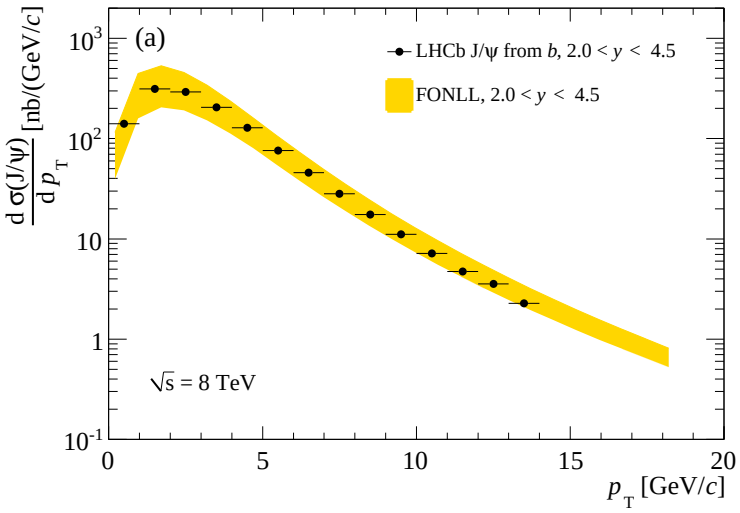
Prompt J/ψ

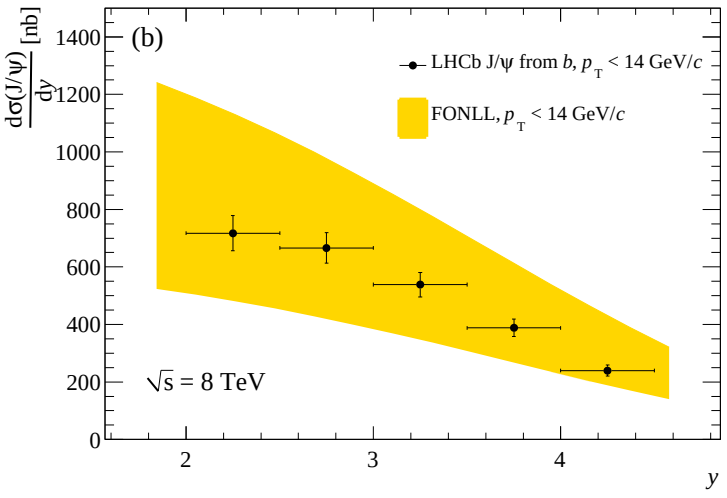


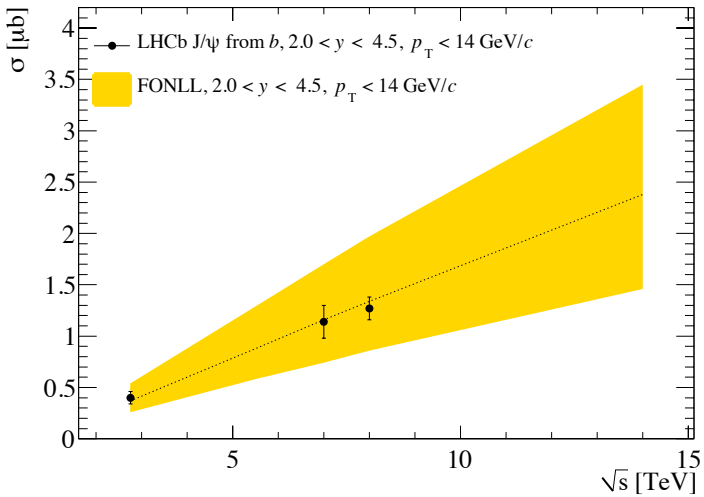
- NLO CSM model:
  - Phys. Rev. Lett. 98 (2007)
- NLO NRQCD model:
  - Phys. Rev. D84 (2011) 051501
  - Phys. Rev. Lett. 106 (2011) 022003
- NNLO* model:
  - Phys. Rev. Lett. 101 (2008) 152001
  - Eur. Phy. J. C 61 (2008) 693

- 8 TeV measurement using 18 pb^{-1} 2012 data.
- Prompt J/ψ assumed unpolarized.
- $\sigma_{prompt}(J/\psi) = 10.94 \pm 0.02(stat) \pm 0.79(sys)\ \mu\text{b}$
- $\sigma_{from\ b}(J/\psi) = 1.28 \pm 0.01(stat) \pm 0.11(sys)\ \mu\text{b}$
- Systematic uncertainty $\sim$7% mainly from luminosity and trigger efficiency.
- Experimental data include feed down $\sim$20% from χ_c and $\sim$8% from $\psi(2S)$.
- Data in good agreement with NLOQCD.

J/ψ from b

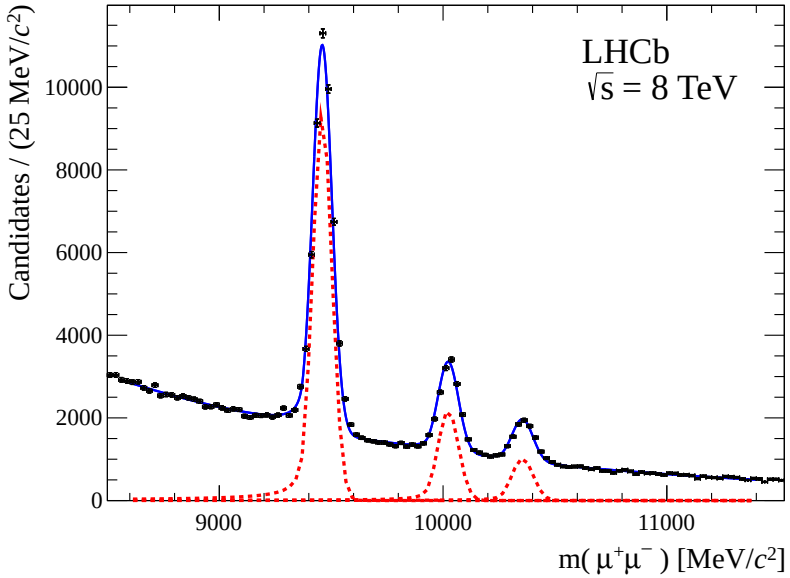


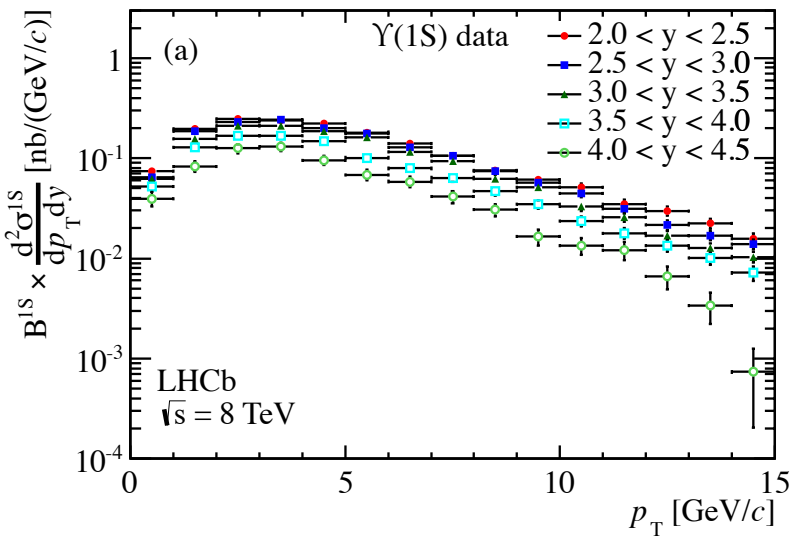




- Excellent agreement with theory
- 8 TeV: JHEP 06 (2013) 064
- 7 TeV: Eur. Phys. J. C71 (2011) 1645
- 2.76 TeV: JHEP 02 (2013) 041

$\Upsilon(nS)$ production





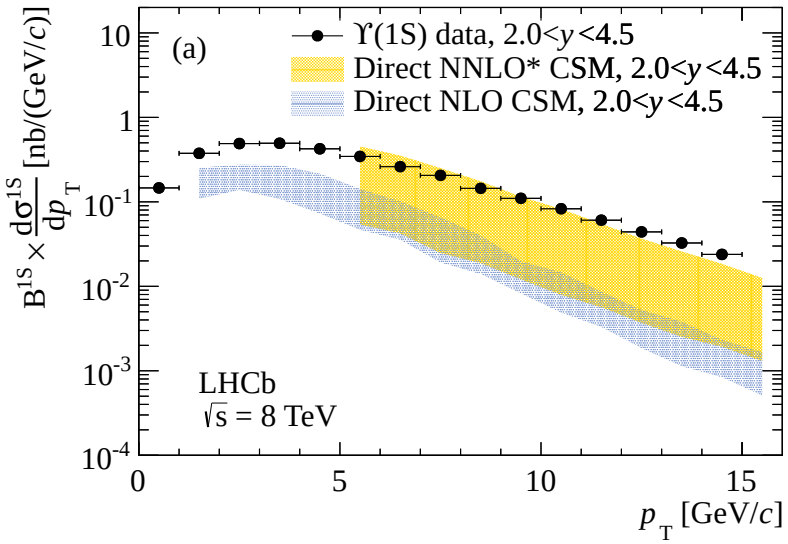
- 25 pb^{-1} 7 TeV 2010 data
- 51 pb^{-1} 8 TeV 2012 data
- Same procedure as for J/ψ
- $p_T < 15$ GeV/c
- $2.0 < y < 4.5$

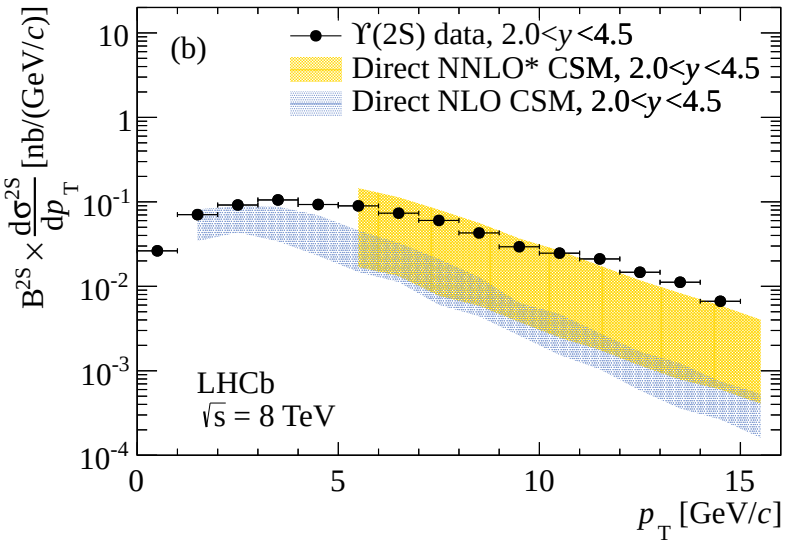
$$\sigma\,(pp \to \Upsilon(1S)X) \times B^{1S} = 3.241 \pm 0.018(stat) \pm 0.231(sys)\ nb$$

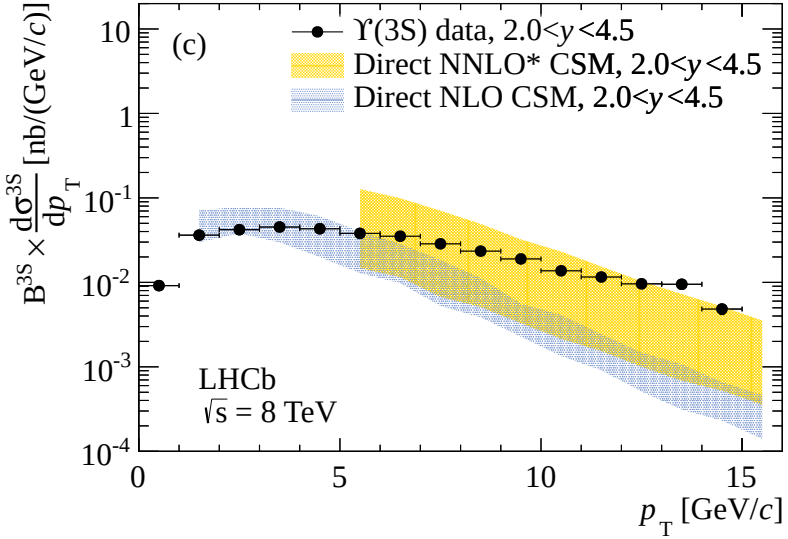
$$\sigma\,(pp \to \Upsilon(2S)X) \times B^{2S} = 0.761 \pm 0.008(stat) \pm 0.055(sys)\ nb$$

$$\sigma\,(pp \to \Upsilon(3S)X) \times B^{3S} = 0.369 \pm 0.005(stat) \pm 0.027(sys)\ nb$$

$\Upsilon(nS)$ comparison with theory



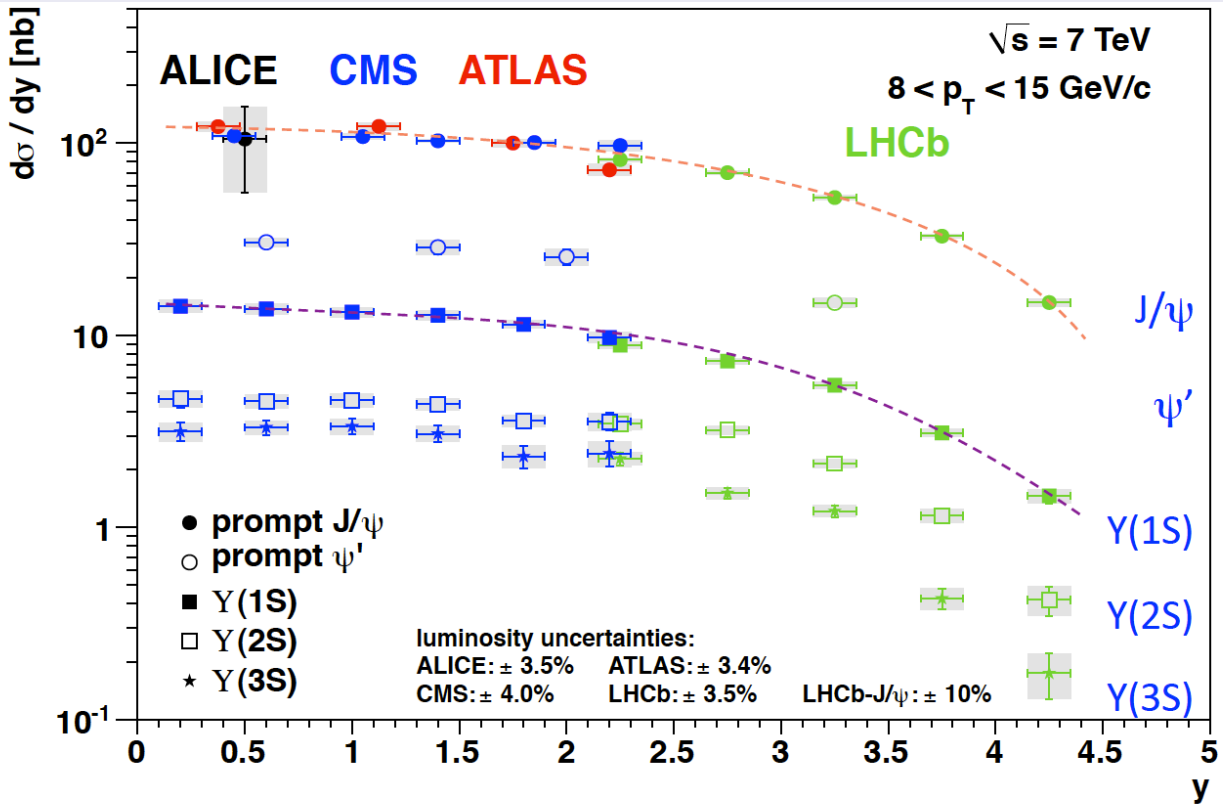




- Reasonable agreement with predictions
- No feed down included in theory
- NLO CSM: PRL 98 (2007) 252002
- NNLO* CSM: PRL 101 (2008) 152001

Production cross sections at LHC at 7 TeV

Presented by H.K. Woehri at LHCP 2013, Barcelona, 13-18 May 2013



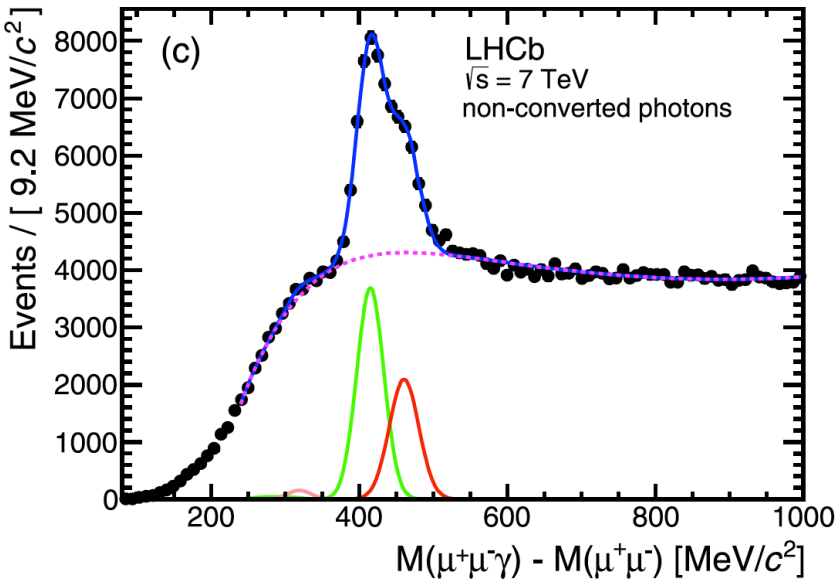
ALICE : 5.6 nb^{-1}
ATLAS : 2.2 pb^{-1}
CMS : 37, 36 pb^{-1}
LHCb : 5.2, 36, 25 pb^{-1}

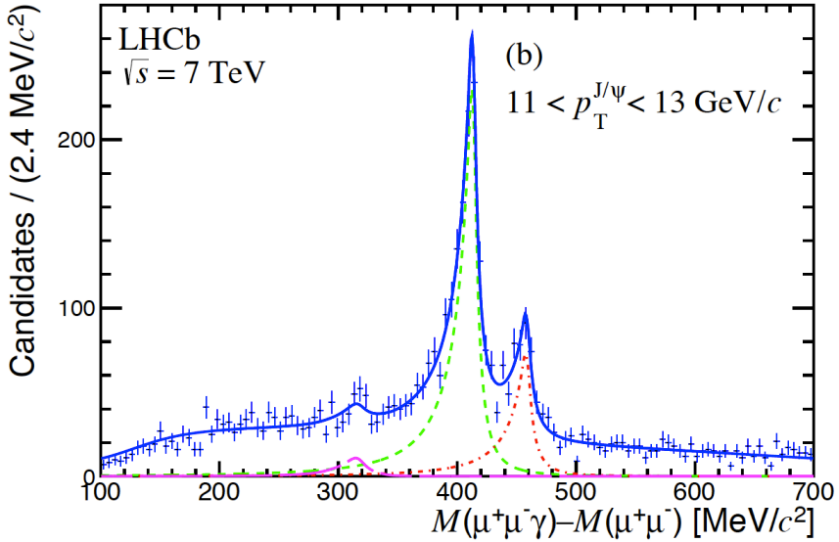
Note: the lines do not represent any theoretical model; they are added to help guiding the eye through the points

ALICE: arXiv:1205.5880
ATLAS: NPB850 (2011) 387
CMS: JHEP02 (2012) 011
LHCb: EPJC71 (2011) 1645
LHCb: arXiv:1204.1258
CMS: BPH-11-001
LHCb: EPJC72 (2012) 2025

χ_c production at 7 TeV

- Studies of χ_c production provide importat test of the understanding of quarkonium production
  - Large ($\sim$20%) feed down contribution to J/ψ from χ_c states affects J/ψ measurements.
  - $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ sensiive to CS and CO models.
- Select prompt $\chi_c \to (J/\psi \to \mu^+\mu^-)\gamma$
- Photons observed in ECAL
  - high statistics
  - poor resolution χ_{c1} and χ_{c2} not well separated
- Photons converted to e^+e^- in material
  - improved energy resolution using tracker χ_{c1} and χ_{c2} well separated
  - low statistics



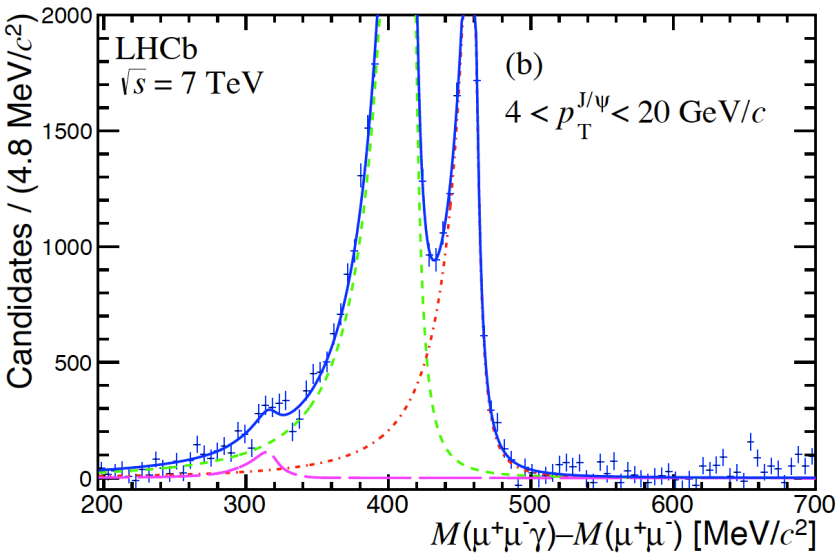


χ_c production analysis strategy

- JHEP 10 (2013) 115
- Used 1 fb^{-1} 7 TeV 2011 data.
- Measurement in bins of p_T, integrated over rapidity, $2.0 < y < 4.5$, using converted photons

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N(\chi_{c2})}{N(\chi_{c1})} \times \frac{\epsilon(\chi_{c2})}{\epsilon(\chi_{c1})} \times \frac{\mathcal{B}(\chi_{c2} \to J/\psi\gamma)}{\mathcal{B}(\chi_{c1} \to J/\psi\gamma)}$$

- First evidence of χ_{c0} at hadron collider (4.3σ)
- Efficiency from simulation
- BR from PDG



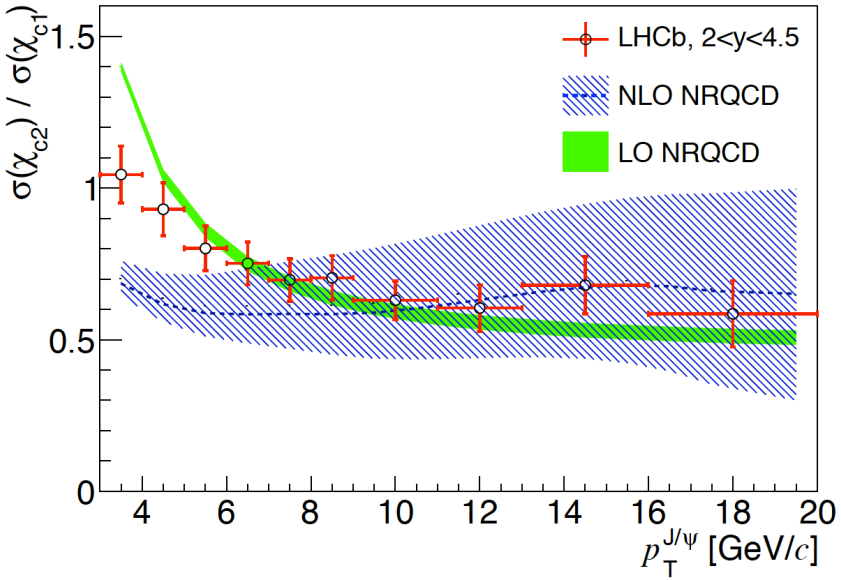
χ_c production results

χ_{c0}, χ_{c1} and χ_{c2} yields obtained fitting the ΔM spectrum

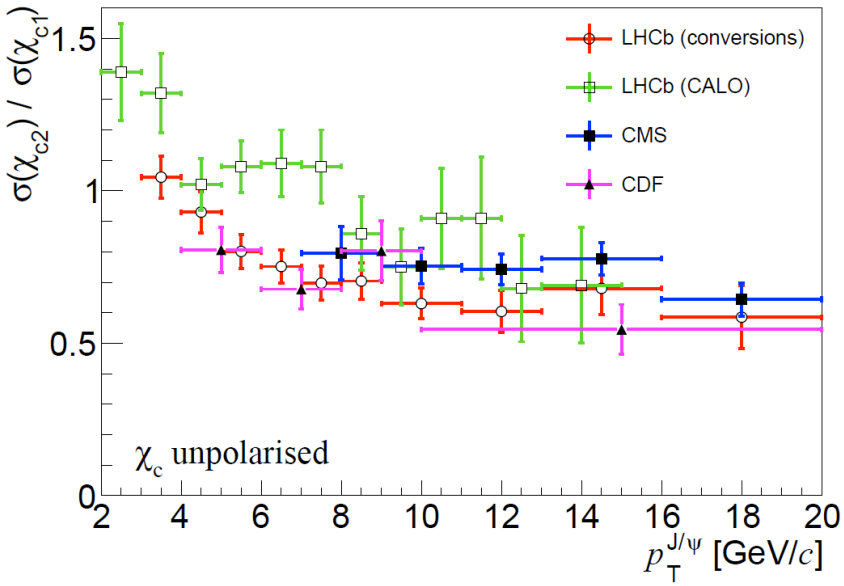
$$\Delta M = M(\chi_{cj}) - M(J/\psi)$$

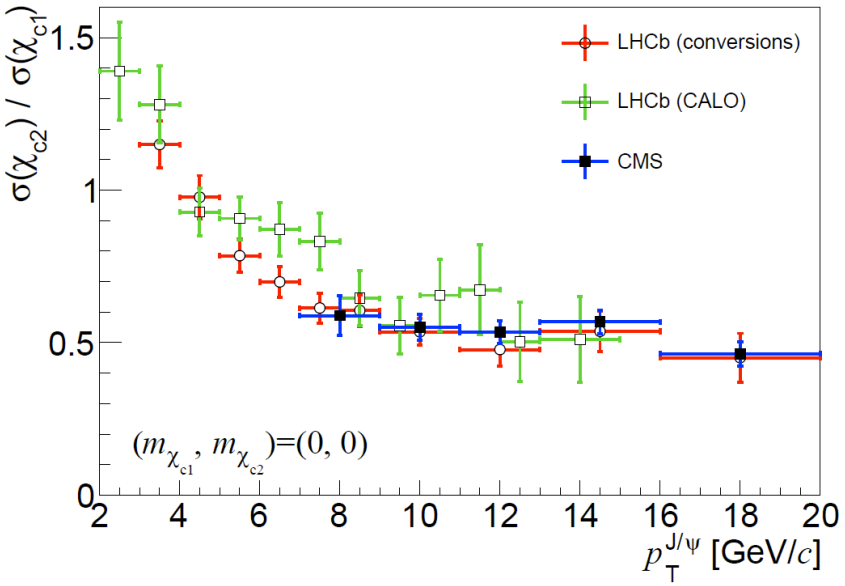
$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27(stat) \pm 0.29(sys) \pm 0.16(p_T model) \pm 0.09(\mathcal{B})$$
$$\sigma(\chi_{c2})/\sigma(\chi_{c1}) = 0.787 \pm 0.014(stat) \pm 0.034(sys) \pm 0.051(p_T model) \pm 0.047(\mathcal{B})$$

- $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ in reasonable agreement with NLO NRQCD for $p_T > 4\,\mathrm{GeV}/c$
- Large uncertainty, not inclued, due to the unknown polarization of the χ_c states
- Systematic uncertainty dominated by photon efficiency ($\sim$6%).



χ_c comparison with other experiments





- Comparible with CMS and CDF results.
- Agreement is better if the χ_c is polarized
  - Simulated events are unpolarized.
  - Efficiences corrected to the angular distribution under the polarization hypothesis

Conclusions

- During Run I LHCb has collected a wealth of $c\bar{c}$ and $b\bar{b}$ candidates.
- Many interesting results have already been produced including:
  - Production cross-section measurements
  - First observations
  - Evidence of small longitudinal polarization in the production of prompt J/ψ
- Work currently ongoing to provide measurements of:
  - More states production cross sections
  - More states production polarization
  - Differential cross sections of double J/ψ states
  - χ_b production ratios