Quarkonia production at LHCb

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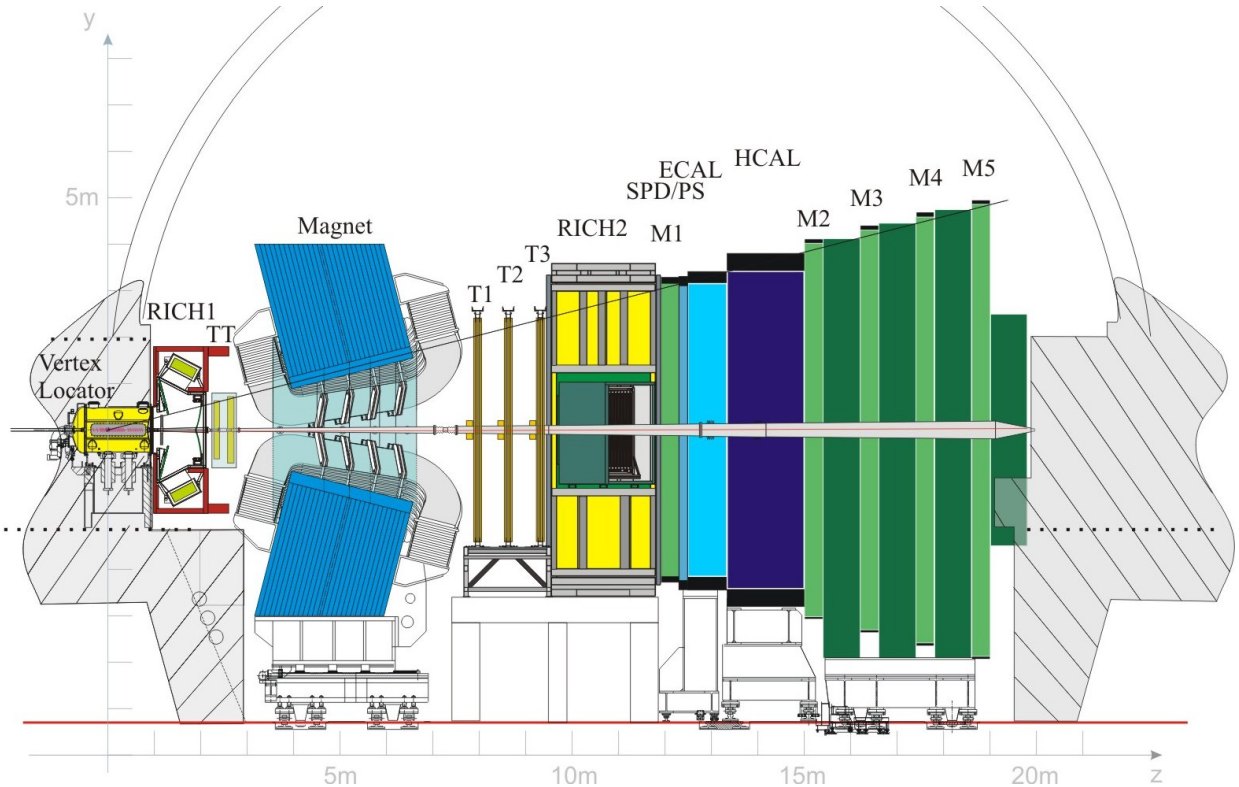
Outline

- View of the LHCb experiment.
- Charmonium:
  - J/ψ and $\psi(2S)$ polarization (**NEW!**) $\rightarrow$ needed together with cross section measurements to distinguish among different production models;
  - χ_{c2}/χ_{c1} production ratio: sensitive to Colour Singlet vs Colour Octet prediction:
  - First observation at hadron collider of χ_{c0} state.
- Bottomonium: Υ production cross section at 2.76 TeV (**NEW!**)
  - first time in the forward region $2.0 < y < 4.5$;
  - essential reference for pA ongoing studies.
- Conclusion.

The LHCb experiment

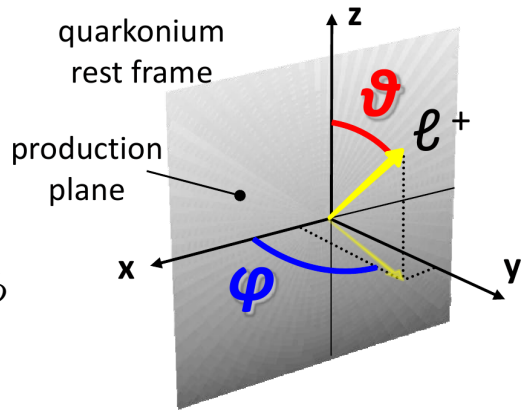
- Single-arm forward spectrometer. Pseudorapidity range: $2 < \eta < 5$.
- Characteristics and performances:
  - Vertexing: proper time resolution 30-50 fs
  - MuonId: $\epsilon(\mu \to \mu) = 97\%$ $\epsilon(\pi \to \mu) = 2\%$
  - Charged tracks $\Delta p/p < 0.4\% - 0.6\%$



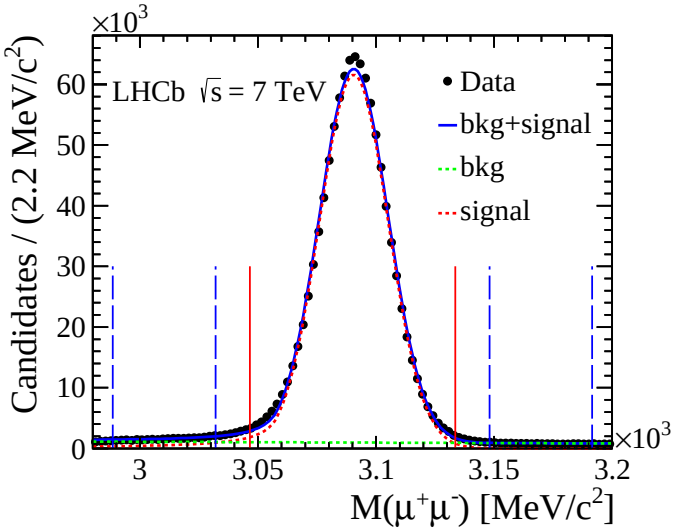
J/ψ and $\psi(2S)$ polarization EPJ C 73 (2013), 11 arXiv:1403.1339

- Mandatory to disentangle among different theoretical prediction (CSM, NRQCD...)
- Reconstruct di-muon decay and fit angular distribution in the **Helicity frame** (use **Collins-Soper** as cross check)

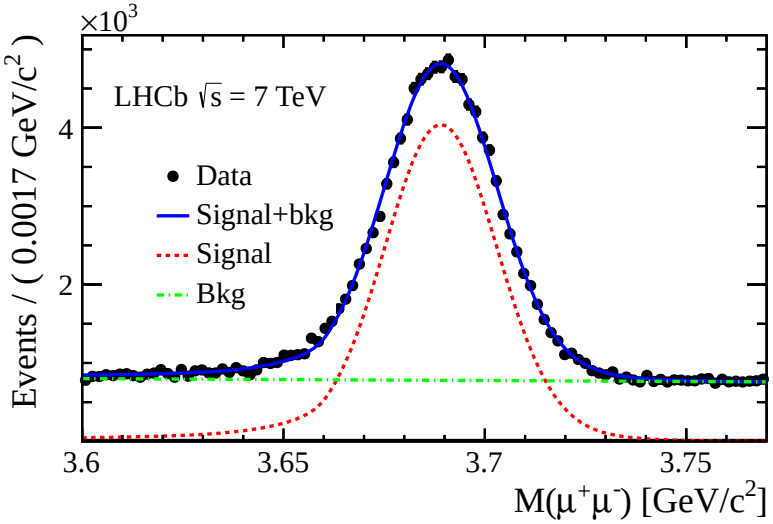
$$\frac{d^2N}{d\cos\theta d\phi} = 1+\lambda_\theta \cos^2\theta+\lambda_{\theta\phi}\sin 2\theta\cos\phi+\lambda_\phi \sin^2\theta\cos 2\phi$$



$J/\psi \to \mu^+\mu^-$



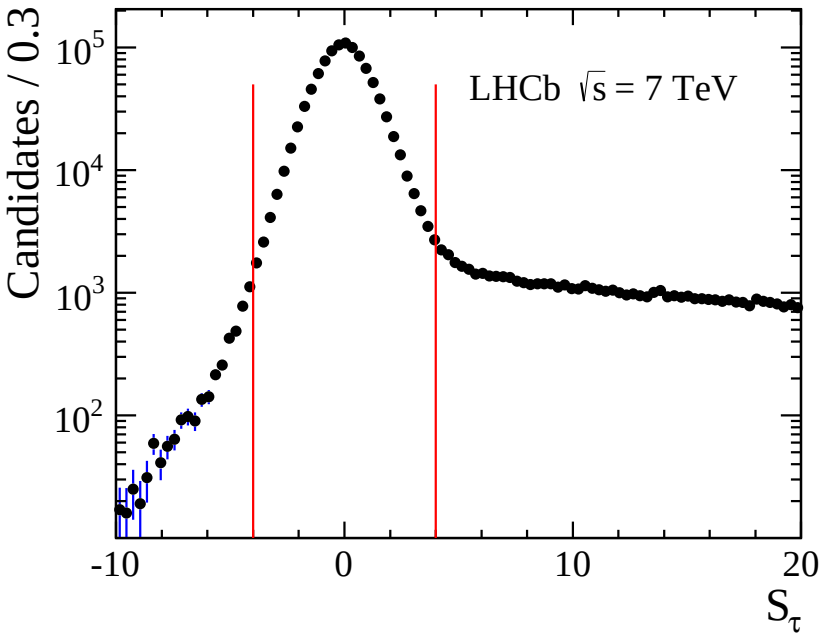
$\psi(2S) \to \mu^+\mu^-$



Analysis strategy

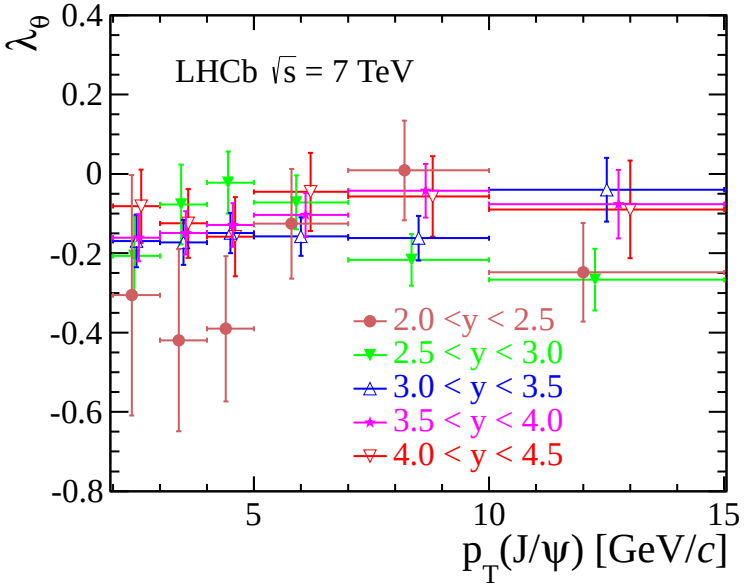
- Analysis range: charmonium $p_T < 15$ GeV/c and $2.0 < y < 4.5$.
- Require good vertex reconstruction and muon track quality.
- Select **prompt** component:
  - directly produced in pp collisions;
  - decay of higher charmonium states;

  $\rightarrow$ cut on pseudo proper time significance S_τ.



- Background subtracted with s-Weight method.
- Determine the angular detector acceptance from unpolarized Monte Carlo sample and correct the di-muon distribution to disentangle the polarization distortion.

Results on J/ψ EPJ C 73 (2013), 11

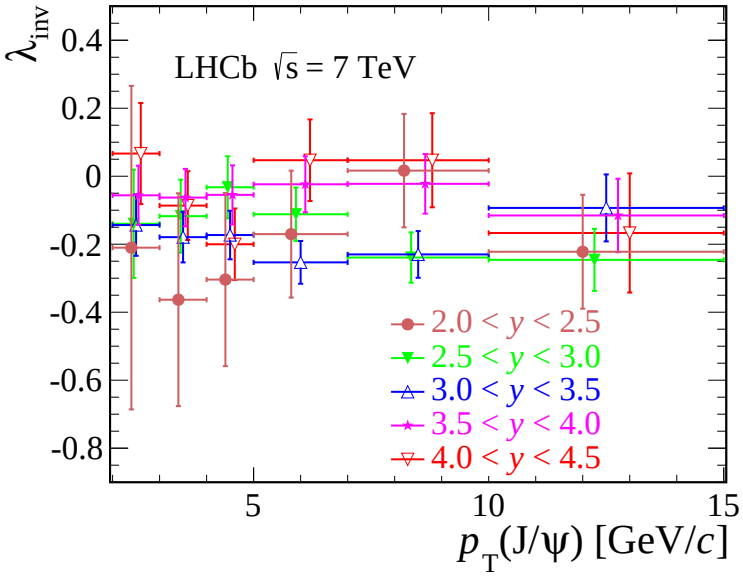


- λ_ϕ, $\lambda_{\theta\phi}$ consistent with 0.

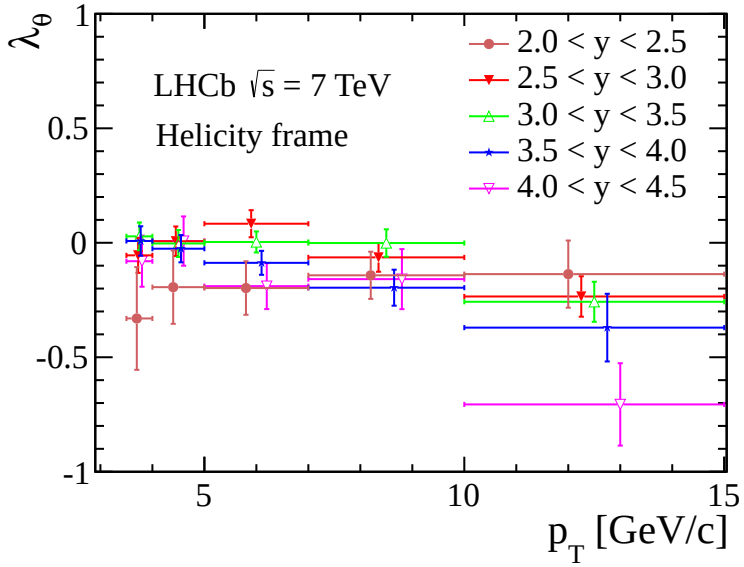
- Check invariant parameter

$$\lambda_{inv} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

not changing with respect to the different polarization frames (**Helicity** vs **Collins-Soper**).

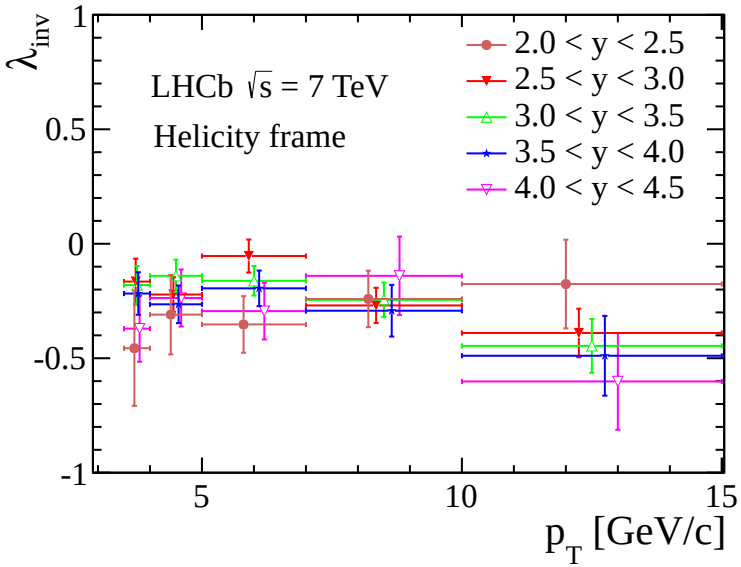


Results on $\psi(2S)$ arXiv:1403.1339



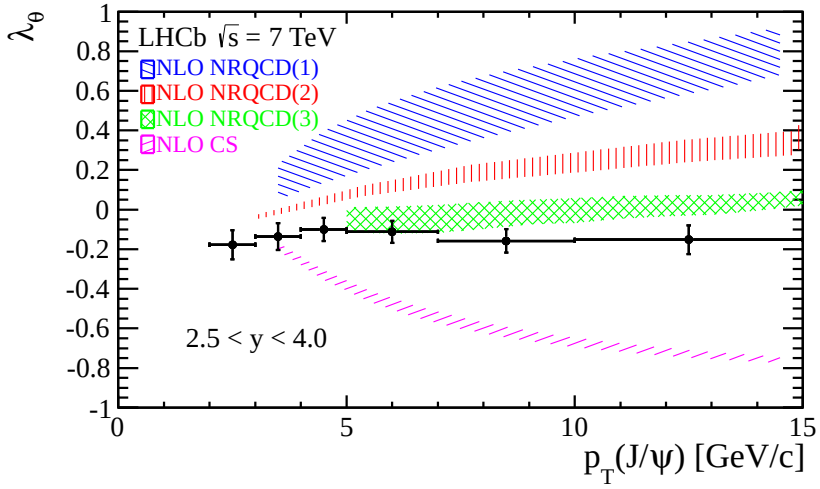
- λ_θ show a small longitudinal polarization.
- λ_ϕ, $\lambda_{\theta\phi}$ consistent with 0.

- λ_{inv} consistent in **Helicity** and **Collins-Soper** frames.



Comparison with theoretical models

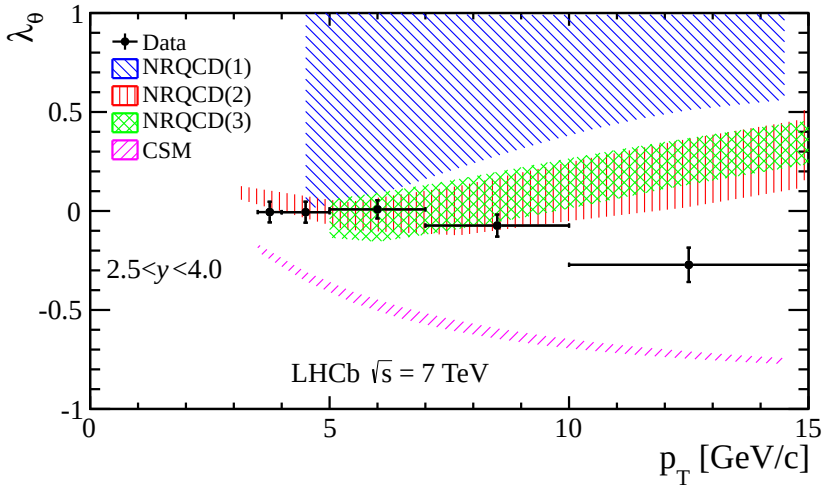
$J/\psi \to \mu^+\mu^-$



- NLO CS and NLO NRQCD (1) **PRL 108 (2012) 172002**.
- NLO NRQCD (2) **PRL 110 (2013) 042002**.
- NLO NRQCD (3) **PRL 108 (2012) 242004**.

- Both J/ψ and $\psi(2S)$ measured polarization disfavour CSM.
- Best agreement given by NLO NRQCD (3) calculation but in high p_T region predict a more transverse polarization for $\psi(2S)$ than what found in data.

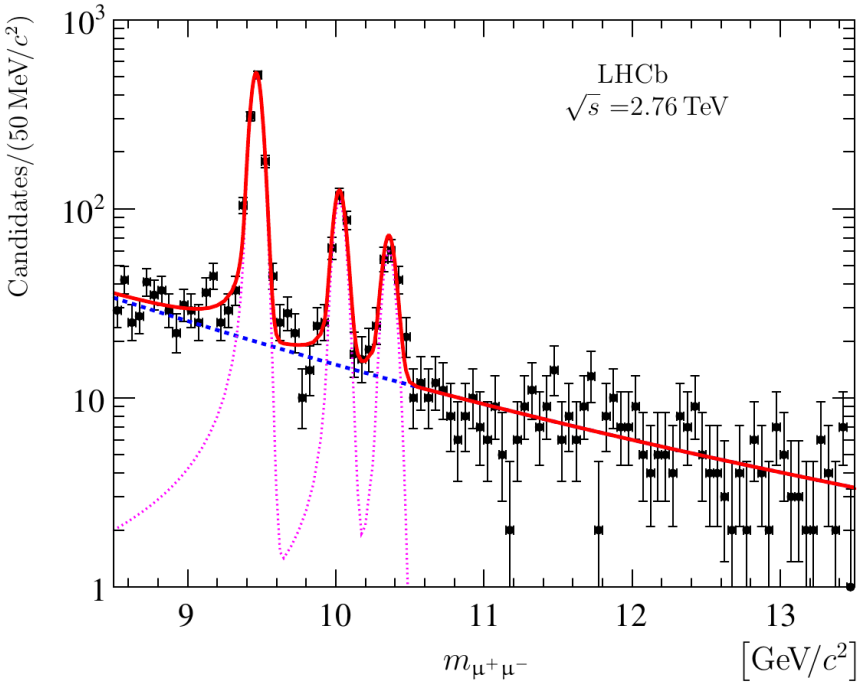
$\psi(2S) \to \mu^+\mu^-$



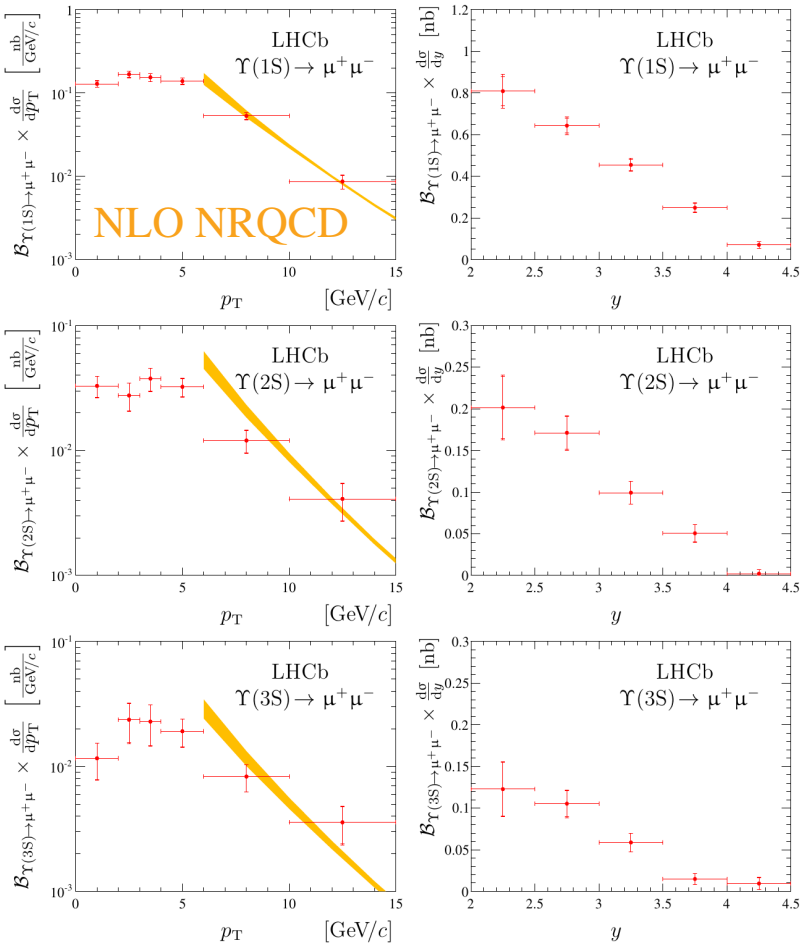
Υ at $\sqrt{s} = 2.76$ TeV arXiv:1402.2539

- Production at $\sqrt{s} = 2.76$ TeV on 3.3 pb^{-1} data sample: first measurement of Υ cross section at 2.76 TeV in the forward region.
- Complementary to $\sqrt{s} = 7$ and 8 TeV JHEP 06 (2013) 064 .

- Reconstruct the $\Upsilon \to \mu^+\mu^-$ channel.
- Analysed kinematic range: $p_T < 15$ GeV/c, $2.0 < y < 4.5$.
- Measurement of differential production cross section as function of p_T and y for $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ states.
- Measurement of ratios $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$.



Production cross section for $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$



- Integrated cross section in $2.0 < y < 4.5$

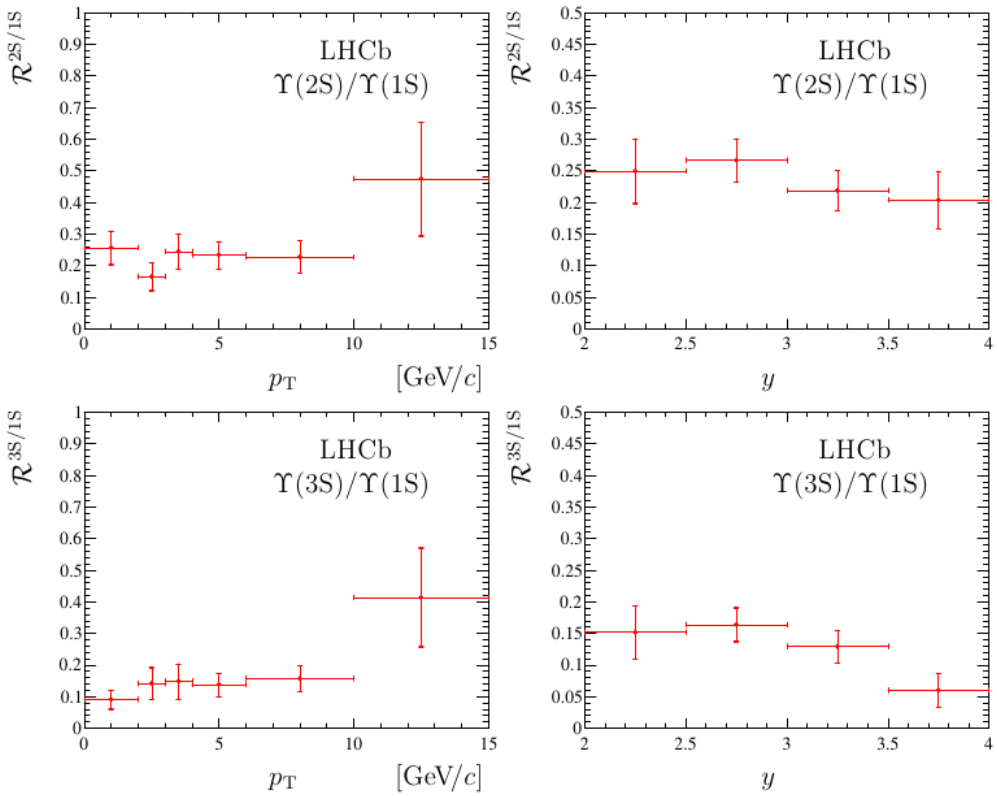
$$\sigma(pp \to \Upsilon(1S)X)\mathcal{B}_{\Upsilon(1S)\to\mu^+\mu^-} = 1.111 \pm 0.043 \pm 0.044\text{nb}$$
$$\sigma(pp \to \Upsilon(2S)X)\mathcal{B}_{\Upsilon(2S)\to\mu^+\mu^-} = 0.264 \pm 0.023 \pm 0.011\text{nb}$$
$$\sigma(pp \to \Upsilon(3S)X)\mathcal{B}_{\Upsilon(3S)\to\mu^+\mu^-} = 0.159 \pm 0.020 \pm 0.007\text{nb}$$

- Integrated cross section in $2.5 < y < 4.0$ $\to$ provide references for the pPb cross section at 5 TeV,

$$\sigma(pp \to \Upsilon(1S)X)\mathcal{B}_{\Upsilon(1S)\to\mu^+\mu^-} = 0.670 \pm 0.025 \pm 0.026\text{nb}$$
$$\sigma(pp \to \Upsilon(2S)X)\mathcal{B}_{\Upsilon(2S)\to\mu^+\mu^-} = 0.159 \pm 0.013 \pm 0.007\text{nb}$$
$$\sigma(pp \to \Upsilon(3S)X)\mathcal{B}_{\Upsilon(3S)\to\mu^+\mu^-} = 0.089 \pm 0.010 \pm 0.004\text{nb}$$

- Experimental data compared with NLO NRQCD prediction (yellow band) **Phys. Rev. Lett. 112, 032001 (2014)**.

Cross section ratios



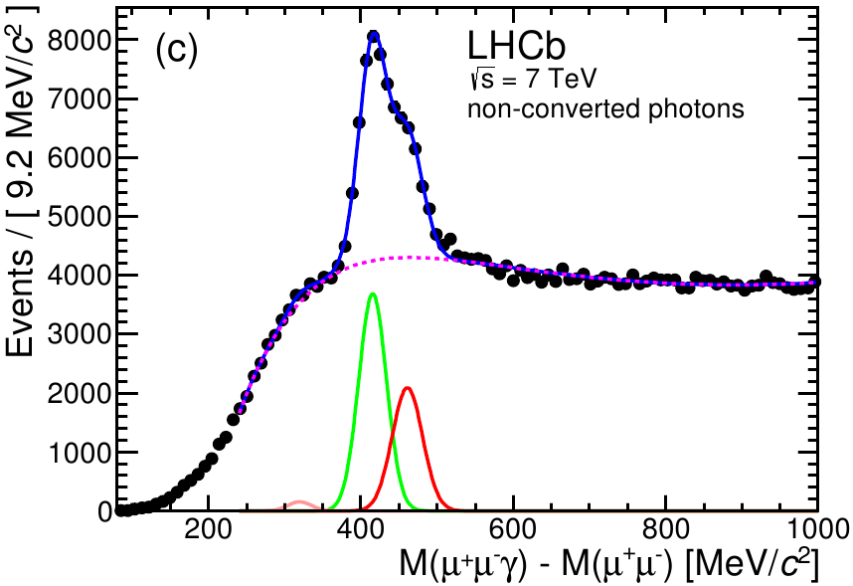
- Measured $\Upsilon(3S)/\Upsilon(1S)$ and $\Upsilon(2S)/\Upsilon(1S)$ ratio in agreement with previous results at $\sqrt{s} = 7$ and 8 TeV.
- Agree with mixed heavy quark hybrid theory (**Mod. P.L.A 28, 16 (2013) 1350067**): 50% standard $b\bar{b}$ + 50% $b\bar{b}g$

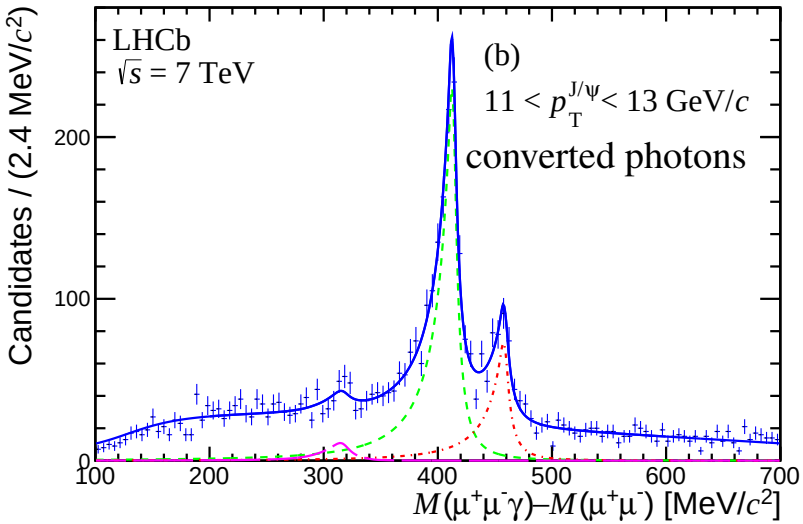
$$\Upsilon(2S)/\Upsilon(1S)_{mixed} \simeq 0.27$$
$$\Upsilon(3S)/\Upsilon(1S)_{mixed} \simeq 0.1$$

- $\Upsilon(3S)/\Upsilon(1S)$ disfavours Standard Model predictions $\Upsilon(3S)/\Upsilon(1S)_{SM} \simeq 0.04$

χ_{c2} and χ_{c1} signal yields

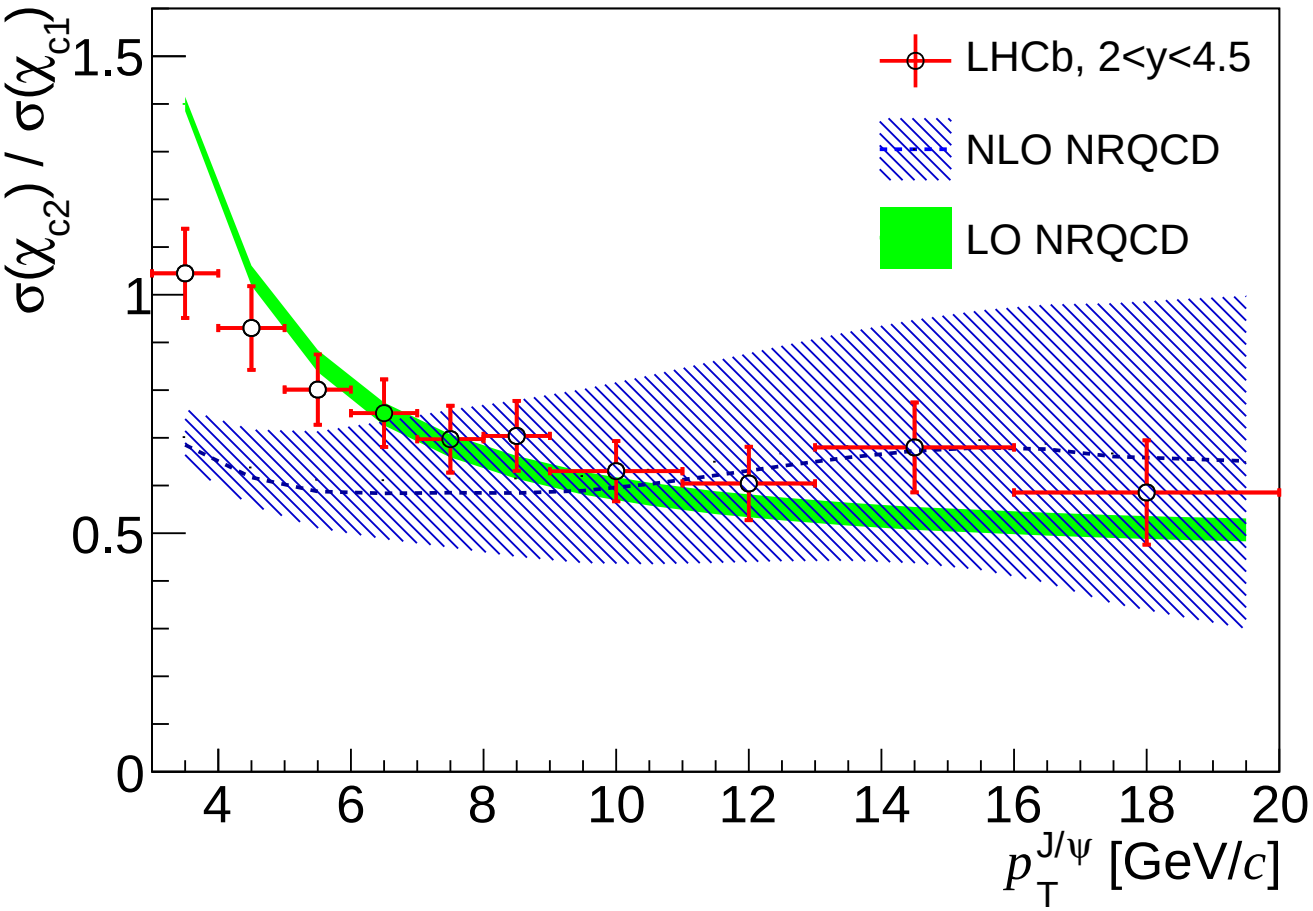
- Important test for understanding quarkonium production: χ_{c2}/χ_{c1} sensitive to Color Singlet and Color Octet approach.
- Use χ_c radiative decay to J/ψ with $J/\psi \to \mu^+\mu^-$:
  - PLB 714 (2012), 215) with photon reconstructed in the calorimeter system: high statistics but not enough resolution to separate the χ_{cJ} states;
  - JHEP 10 (2013) 115) with photons converted in detector material before magnet: excellent tracker resolution allow to resolve the individual states.





- More studies: χ_c to J/ψ cross section ratio (PLB 718 (2012), 431).

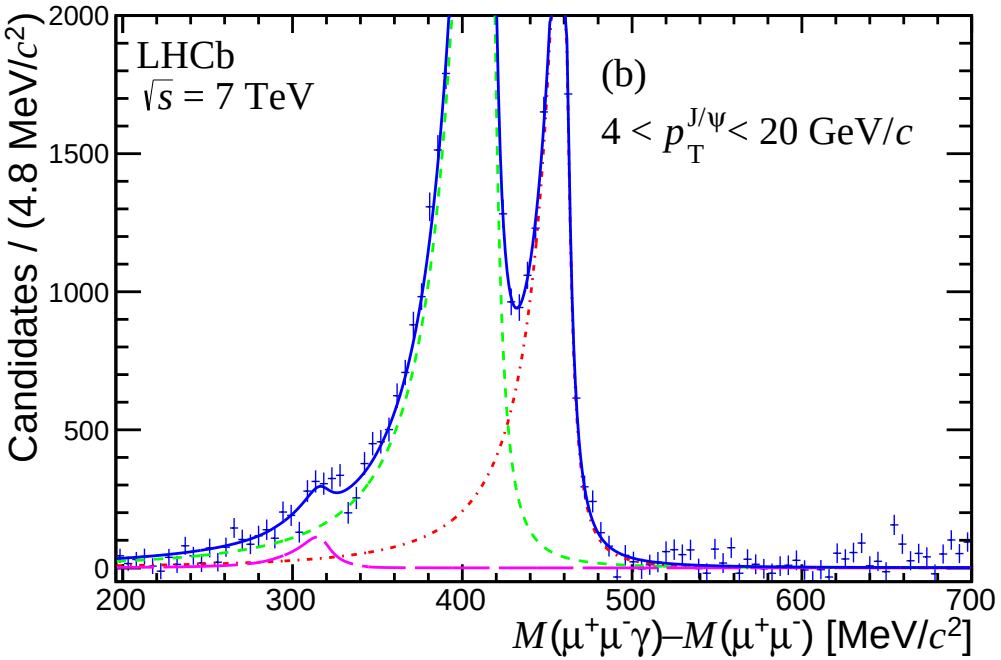
Results on χ_{c2}/χ_{c1} JHEP 10 (2013) 115



- LO NRQCD calculations **arXiv:1305.2389**.
- NLO NRQCD calculations **PRD 83 (2011) 111503**.

Evidence of χ_{c0}

- First evidence of χ_{c0} state at hadron collider.



- χ_{c0} signal evidence in $4 < p_T^{J/\psi} < 20\,\mathrm{GeV}/c$.
- Number of signal events all p_T bins $N_{\chi_{c0}} = 705 \pm 163$ with 4.3σ statistical significance.

Relative cross section for $4 < p_T^{J/\psi} < 20\mathrm{GeV}/c$:

$$\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 1.19 \pm 0.27(\mathrm{stat}) \pm 0.29(\mathrm{syst}) \pm 0.16(p_T\ \mathrm{model}) \pm 0.09(\mathcal{B})$$

Theoretical expectations:

- $\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 0.62 \pm 0.10$ at NLO NRQCD **arXiv:1305.2389**
- $\sigma(\chi_{c0})/\sigma(\chi_{c2}) = 0.53 \pm 0.02$ at LO NRQCD **PRD 83 (2011) 111503**

Conclusion

- Lots of contributions in quarkonium sector from LHCb.
- Prompt J/ψ and $\psi(2S)$ polarization: measurement indicates a small longitudinal polarization.
  - CSM prediction disfavoured, best agreement with NLO NRQCD calculation;
  - J/ψ polarization used to correct and reduce the uncertainty on the production cross section.
- Υ production cross section measured for the fist time at $\sqrt{s} = 2.76$ TeV in the forward region:
  - provide important reference for the *pPb* cross section at 5 TeV.
- Measurement of χ_{c2} to χ_{c1} production cross section and first evidence of χ_{c0} state at an hadron collider.
- More results on the track: Υ production in *pPb*, $\chi_b(nP)$ production...