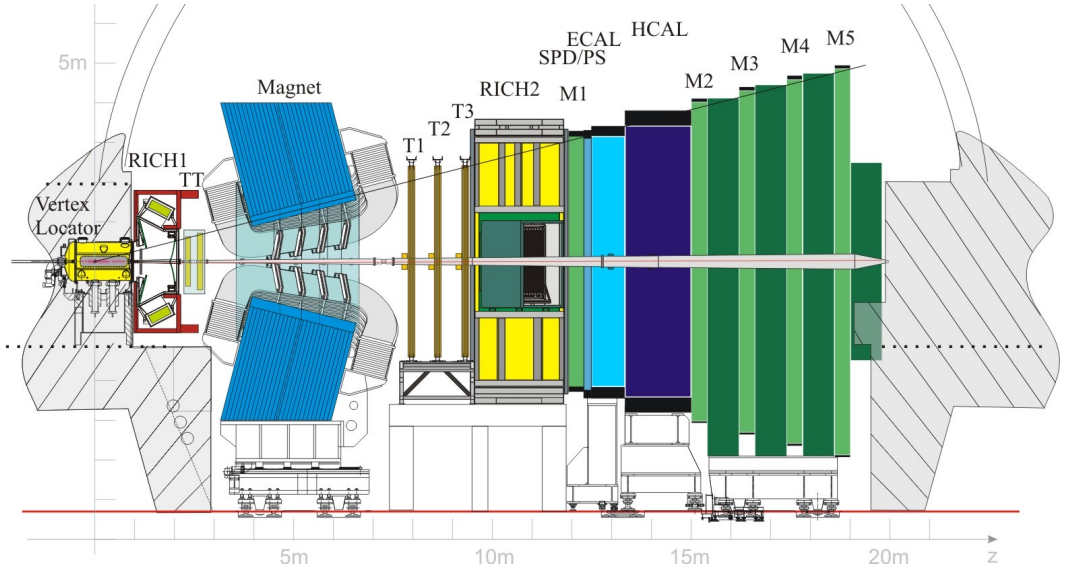
Charmonium(-like) state production in pp collisions at LHCb

Li XU, Tsinghua University
on behalf of the LHCb collaboration

July 28, 2021

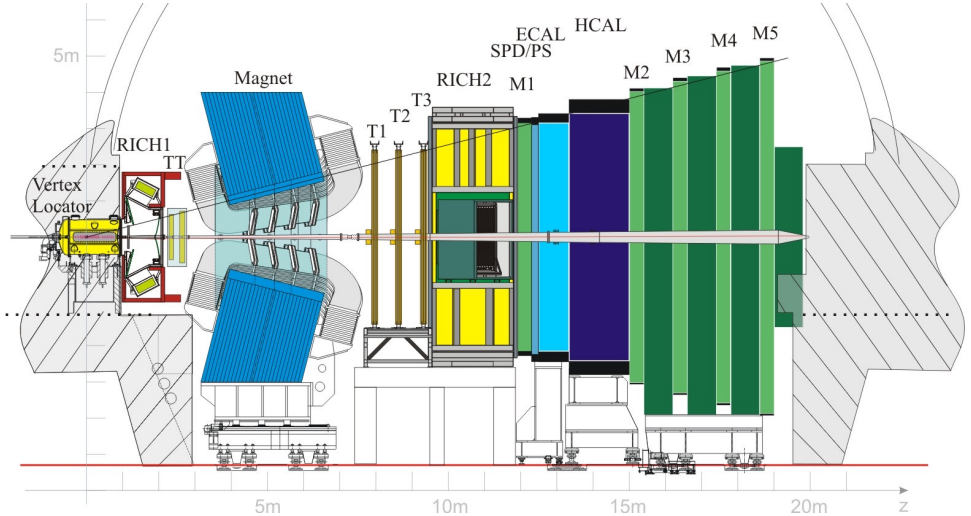
Outline

- LHCb detector
- Latest charmonium(-like) state production measurements
  - J/ψ production cross-sections at 5.02 TeV LHCb-PAPER-2021-020
  - $\chi_{c1}(3872)$ production cross-sections at 8 and 13 TeV LHCb-PAPER-2021-026

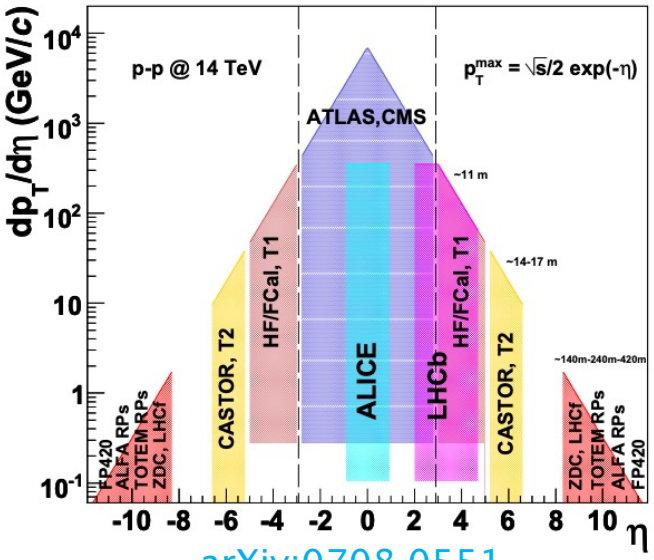


LHCb detector

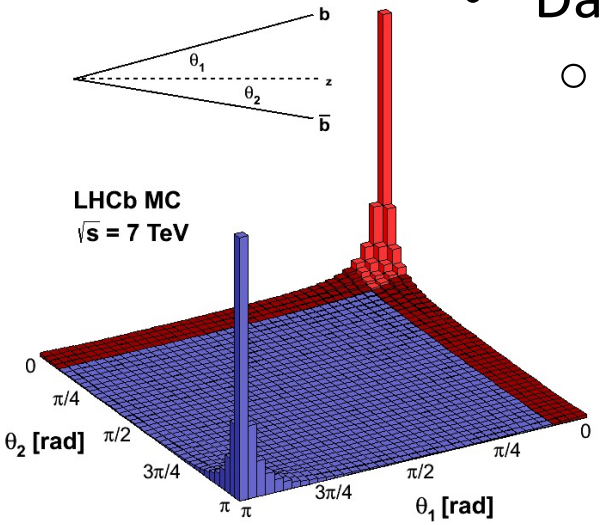
- Single-arm forward spectrometer
- Designed for the study of b and c physics
- Forward region $2 < \eta < 5$
  - $\sim 4\%$ of solid angle,
    but $\sim 25\%$ of $b\bar{b}$ quark pairs accepted



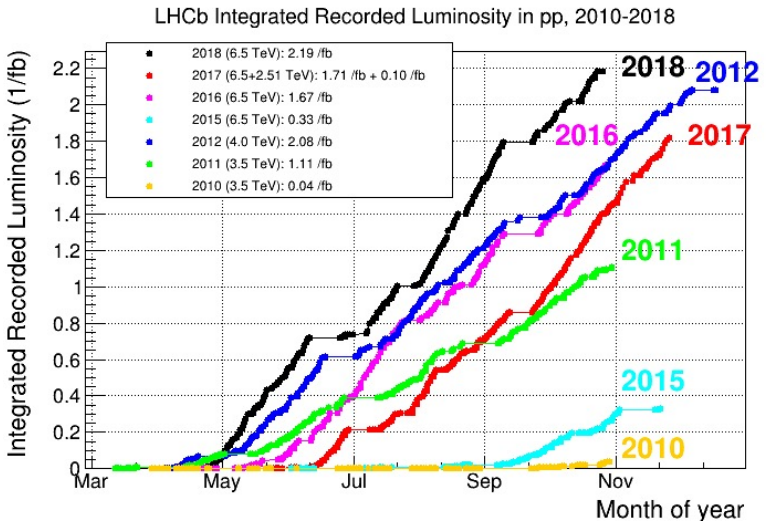
Int. J. Mod. Phys. A 30, 1530022 (2015)



arXiv:0708.0551

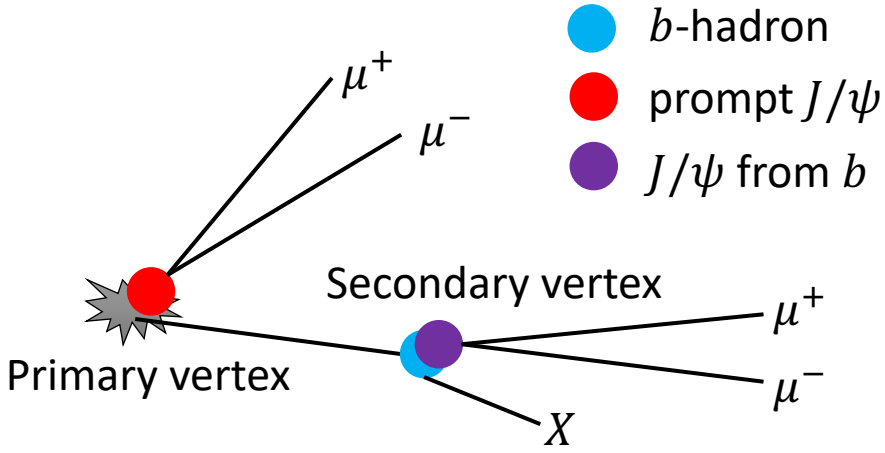


- Data collection
  - Totally ~ 9 fb^{-1} pp collision data at 5/7/8/13 TeV

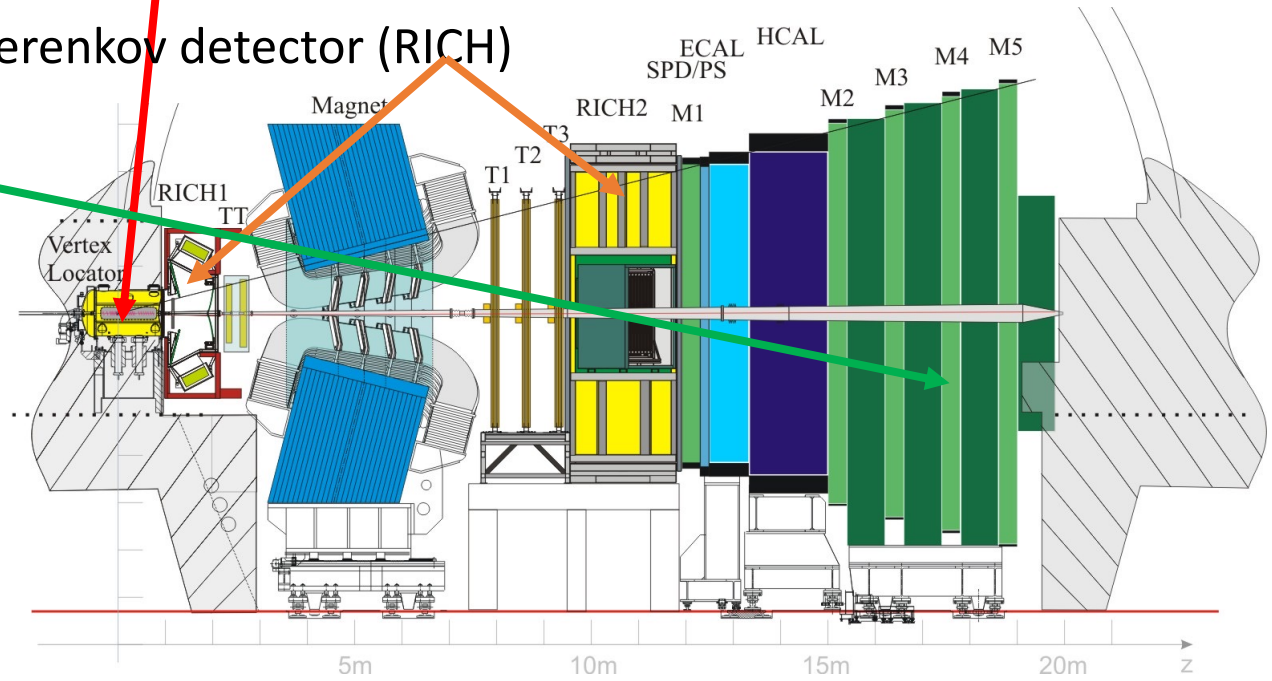


LHCb detector

- Key detector systems for charmonium(-like) state production
  - Vertex reconstruction with Vertex Locator (Velo)
    - Separate primary and secondary vertices
  - Particle identification
    - Charged hadron: ring-imaging Cherenkov detector (RICH)
    - μ: muon detector
- An ideal laboratory for charmonium(-like) state production studies



Example: J/ψ production



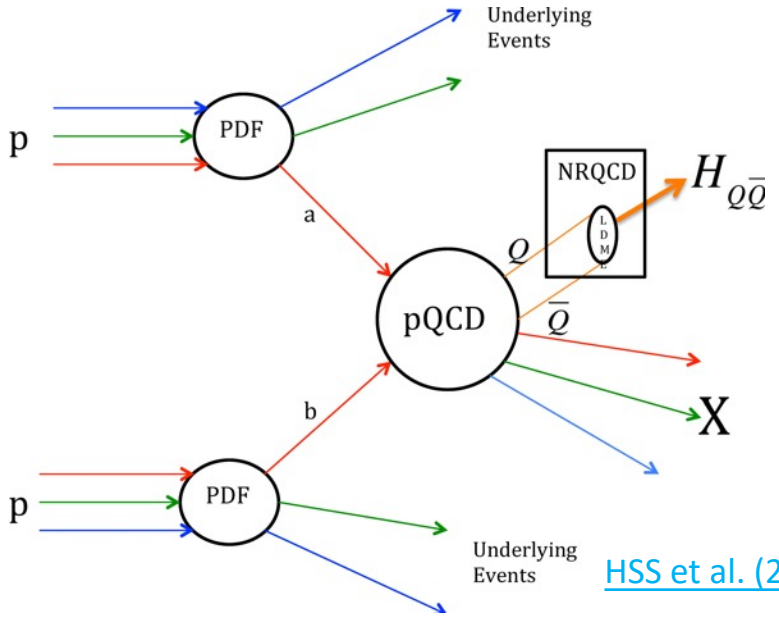
[Int. J. Mod. Phys. A 30, 1530022 (2015)]

J/ψ production at 5 TeV

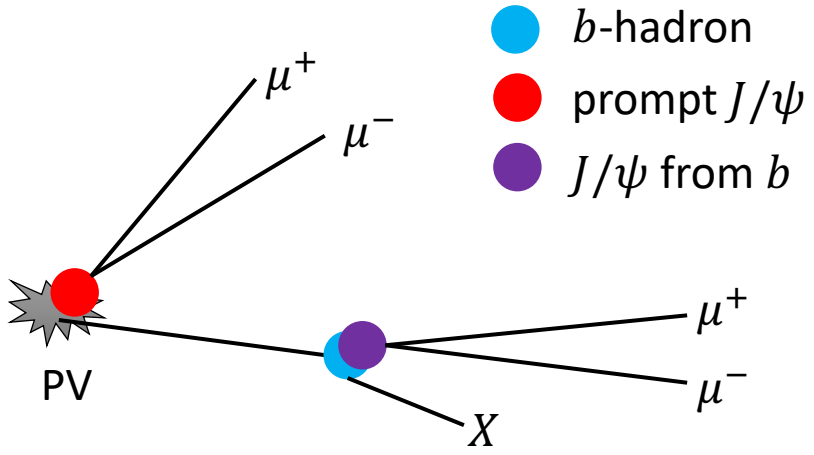
LHCb-PAPER-2021-020, in preparation

Motivation: probe QCD

- Prompt J/ψ: probe J/ψ production mechanism
  - The process involves:
    - $c\bar{c}$ pair production: perturbative QCD
    - Hadronisation: non-perturbative QCD
  - Theory model: Non-Relativistic QCD (NRQCD)
    - Color glass condensate (CGC) effects are combined with NRQCD at low p_{T}
- J/ψ from b: probe b-hadron production mechanism
  - Theory model: Fixed Order plus Next-to-Leading Logarithms (FONLL)
- Reference for cold/hot nuclear matter effect research in proton-lead and lead-lead collisions



HSS et al. (2015)

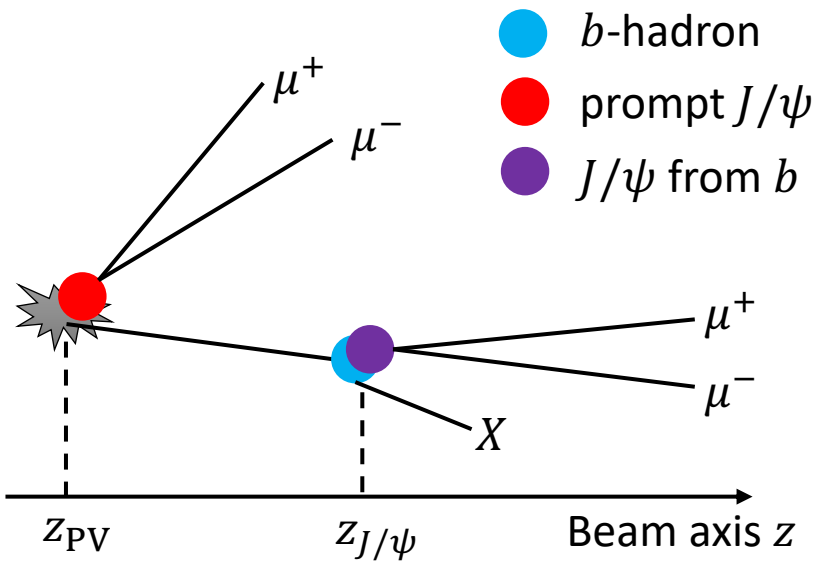


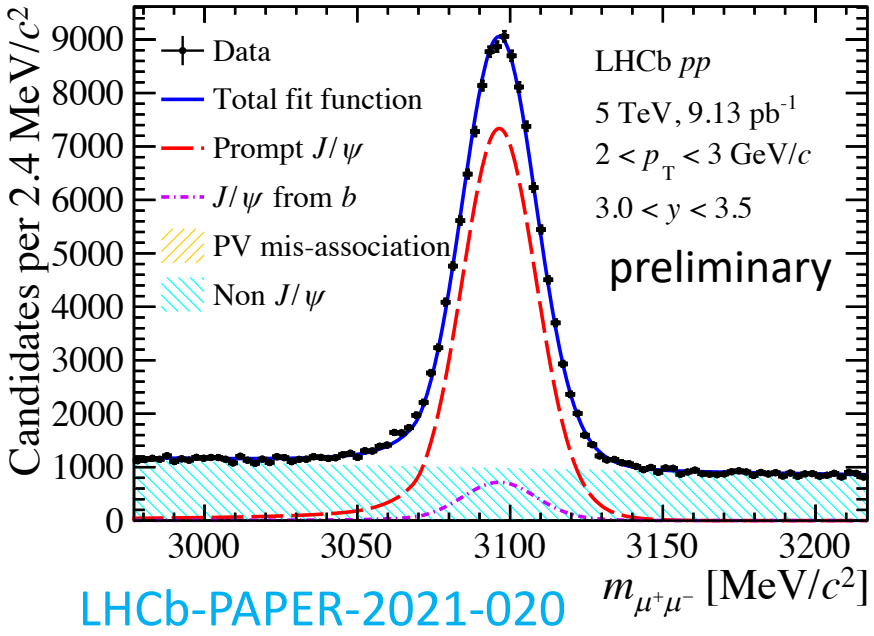
Analysis strategy

- Differential cross-section:

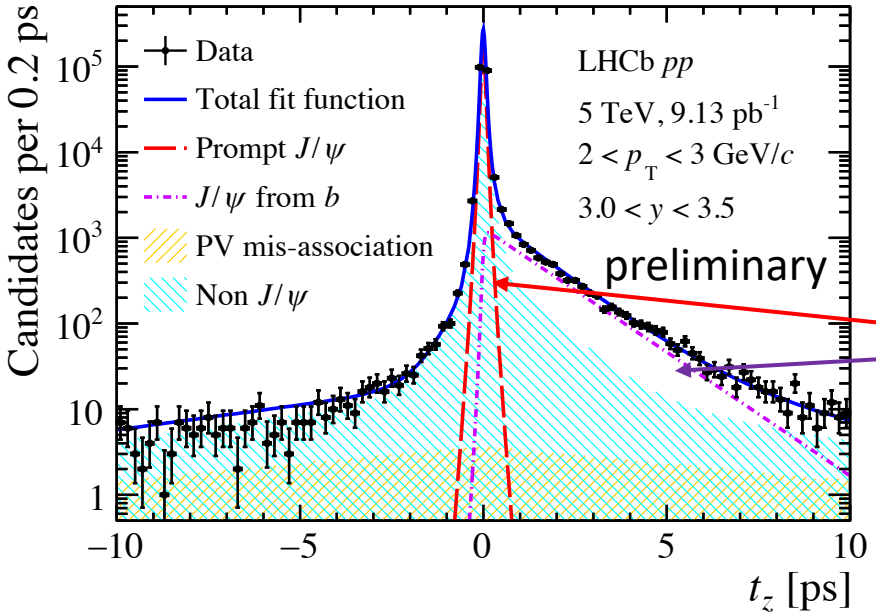
$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_\mathrm{T}} = \frac{N(J/\psi \to \mu^+\mu^-)}{\mathcal{L}\times\varepsilon_\mathrm{tot}\times\mathcal{B}(J/\psi \to \mu^+\mu^-)\times\Delta y\times\Delta p_\mathrm{T}}$$

- Kinematic range: $p_\mathrm{T} < 20\ \mathrm{GeV}/c,\ 2.0 < y < 4.5$
- Two-dimentional fit to **mass** and **pseudo decay time t_z**





LHCb-PAPER-2021-020



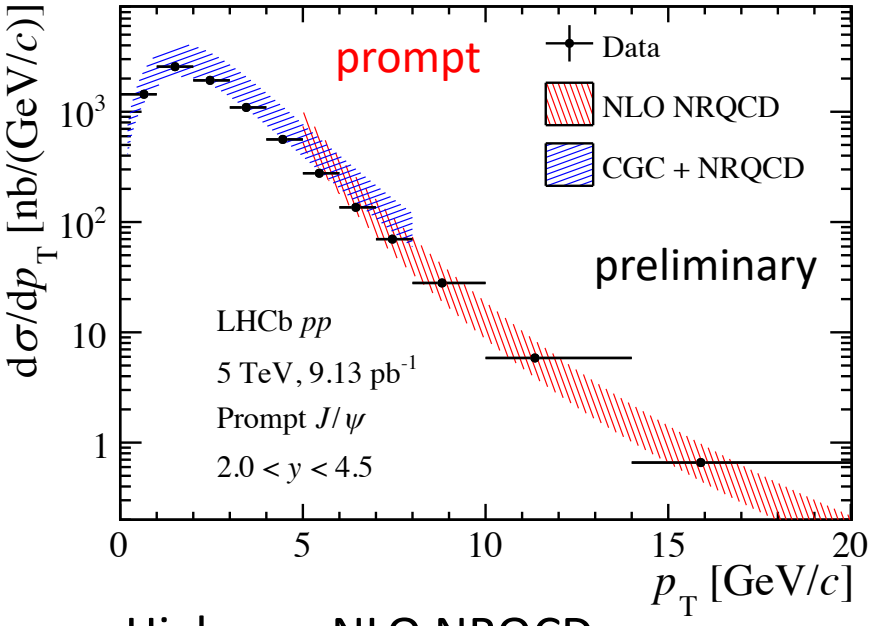
$$t_z = \frac{z_{J/\psi} - z_{\mathrm{PV}}}{p_z/m_{J/\psi}}$$

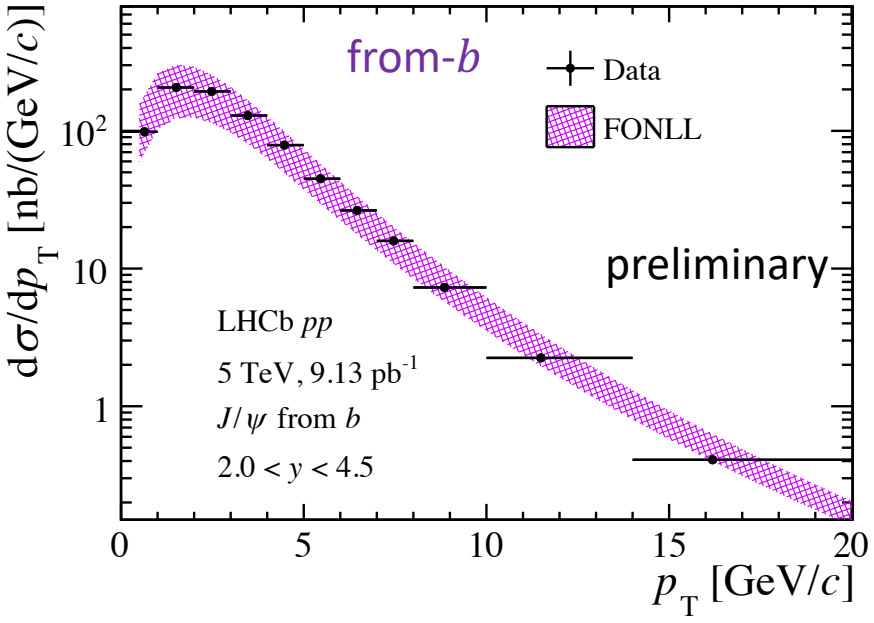
- Use t_z to separate prompt J/ψ and J/ψ from b
- Yields N are corrected by efficiency ε_tot in each (p_T, y) bin
- Assume zero polarisation

Cross-sections at 5 TeV

- Integrated cross-sections ($p_{\mathrm{T}} < 20\ \mathrm{GeV}/c,\ 2.0 < y < 4.5$)
  - $\sigma_{\mathrm{prompt}} = 8.154 \pm 0.010\,(\mathrm{stat.}) \pm 0.283\,(\mathrm{syst.})\ \mu\mathrm{b}$
  - $\sigma_{\mathrm{from}-b} = 0.820 \pm 0.002\,(\mathrm{stat.}) \pm 0.034\,(\mathrm{syst.})\ \mu\mathrm{b}$

LHCb-PAPER-2021-020





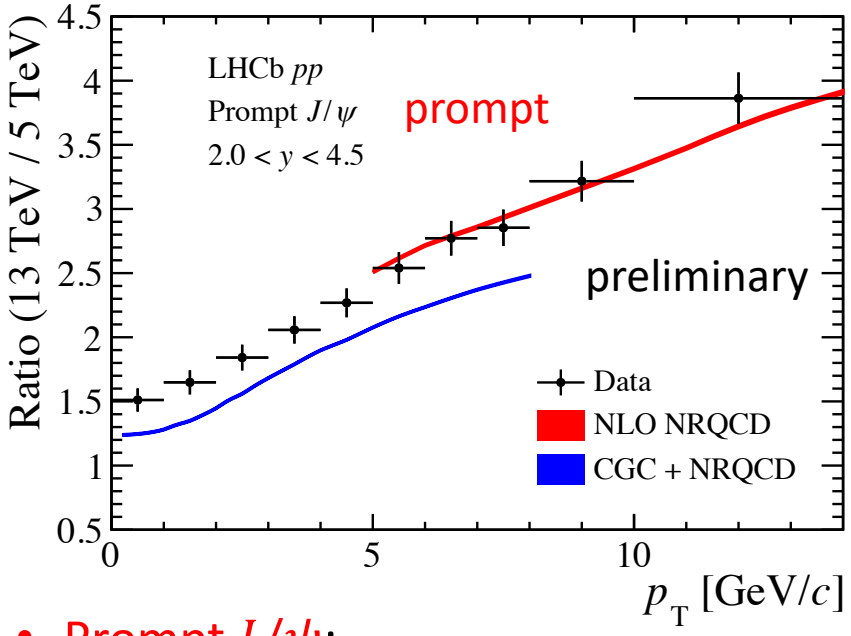
- High p_T : NLO NRQCD Phys. Rev. Lett. 106, 042002
- Low p_T : combine NRQCD with color glass condensate (CGC) effective theory Phys. Rev. Lett. 113, 192301
- FONLL JHEP 10 (2012) 137 Eur. Phys. J. C75 (2015) 610

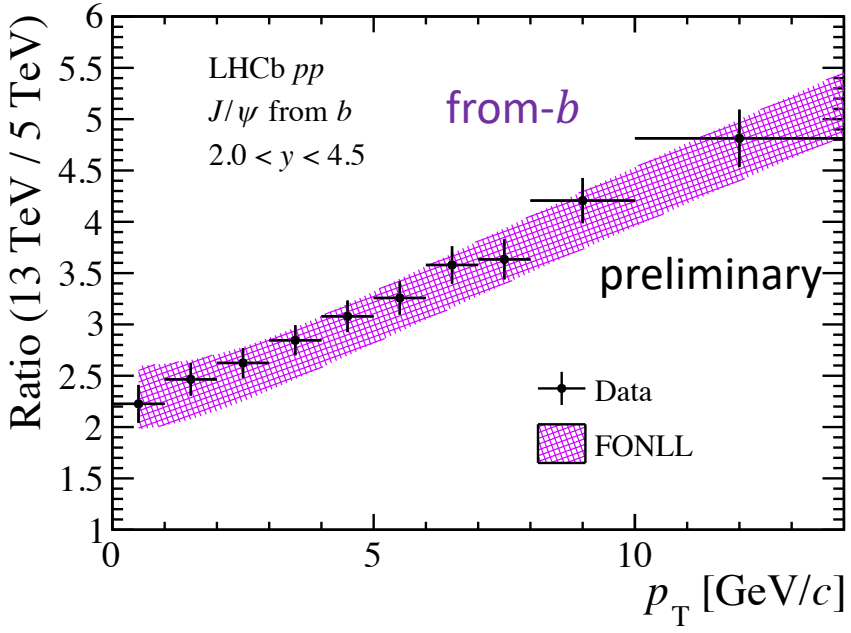
- The inclusion of CGC effects achieves a reasonable agreement between data and theory for prompt J/ψ at low p_{T}
- Good agreement with predictions both for prompt J/ψ and J/ψ from b

Cross-section ratio

- Ratio between 13 TeV and 5 TeV measurements (uncertainties cancel a lot in ratio)

LHCb-PAPER-2021-020



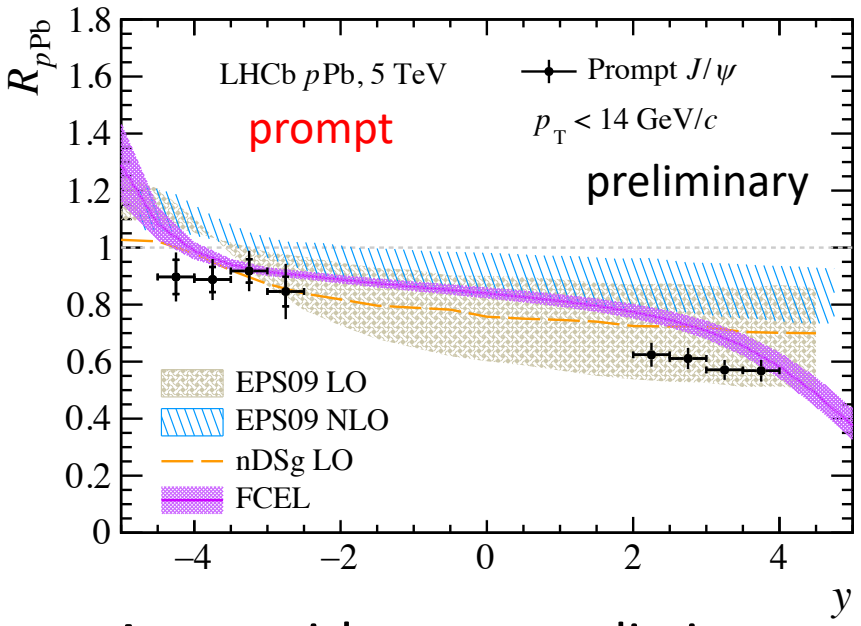


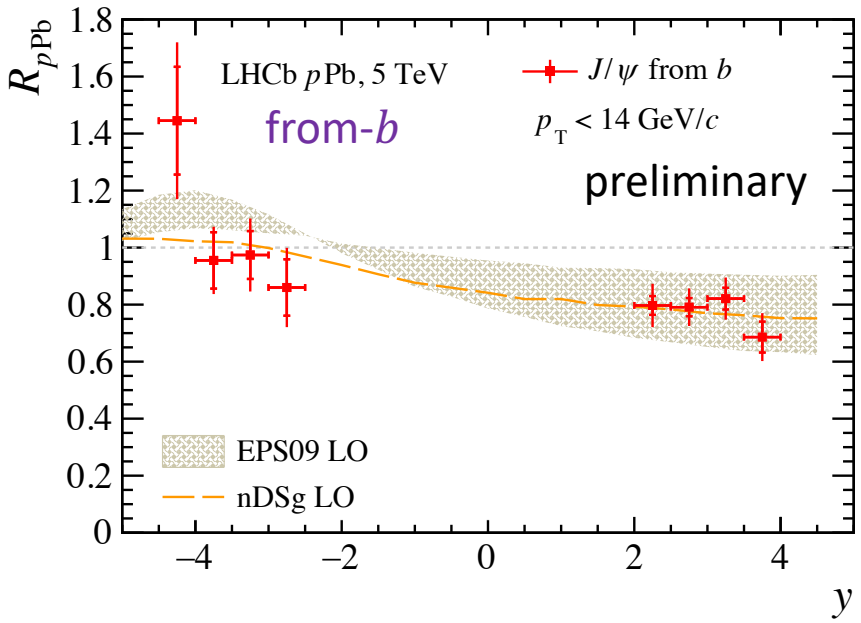
- Prompt J/ψ:
  - High p_T: good agreement between data and NLO NRQCD
  - Low p_T: a small tension between data and CGC + NRQCD
- J/ψ from b: good agreement between data and FONLL
- Same conclusion for the ratio between 8 TeV and 5 TeV measurements

Nuclear modification factor $R_{p\mathrm{Pb}}$

- $R_{p\mathrm{Pb}}$ at 5 TeV was calculated using interpolated pp collision cross-sections JHEP 02 (2014) 072
- $R_{p\mathrm{Pb}}$ is updated using direct measured pp collision cross-sections

LHCb-PAPER-2021-020





EPS09 LO
Phys. Rev. C88, 047901

EPS09 NLO
Int. J. Mod. Phys. E22, 1330007

nDSg LO
Phys. Rev. C88, 047901

FCEL
Phys. Rev. Lett. 109, 122301

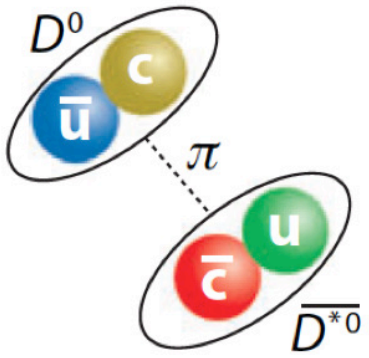
- Agree with most predictions
- EPS09 NLO provides a poorer description in the forward region for prompt J/ψ

$\chi_{c1}(3872)$ production at 8 and 13 TeV

LHCb-PAPER-2021-026, in preparation

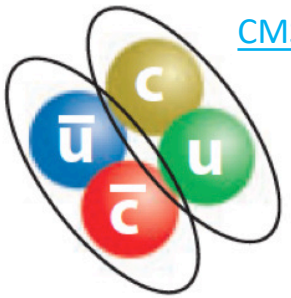
Introduction to $\chi_{c1}(3872)$ AKA $X(3872)$

- An exotic hadron discovered by Belle in 2003 Phys. Rev. Lett. 91, 262001
- $J^{PC} = 1^{++}$ determined by LHCb Phys. Rev. Lett. 110, 222001
- $\delta E|_{\mathrm{LHCb}} = m_{D^0} + m_{\overline{D}^{*0}} - m_{\chi_{c1}(3872)} = 70 \pm 120\ \mathrm{keV}$ Phys. Rev. D102, 092005 JHEP 08 (2020) 123
- Nonzero width $\sim 1\ \mathrm{MeV}$ is observed Phys. Rev. D102, 092005 JHEP 08 (2020) 123
- The nature of $\chi_{c1}(3872)$ is still unclear
  - Charmonium? disfavoured by measured mass and J^{PC}, and isospin breaking Phys. Rev. Lett. 110, 222001 Phys. Rev. B590, 209
  - Hadronic molecule? Phys. Rev. B590, 209
  - Compact tetraquark? Phys. Rev. D71, 014028
  - Mixture of states?
    - $\chi_{c1}(2P) + D^0\overline{D}^{*0}$? Phys. Rev. D96, 074014



D^0–$\overline{D^{*0}}$ "molecule"

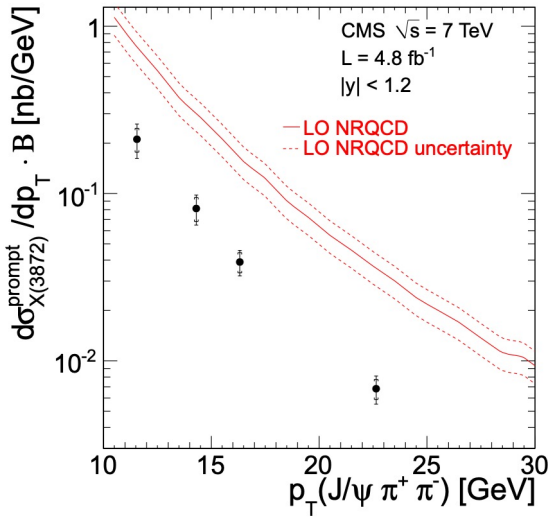
CMS website

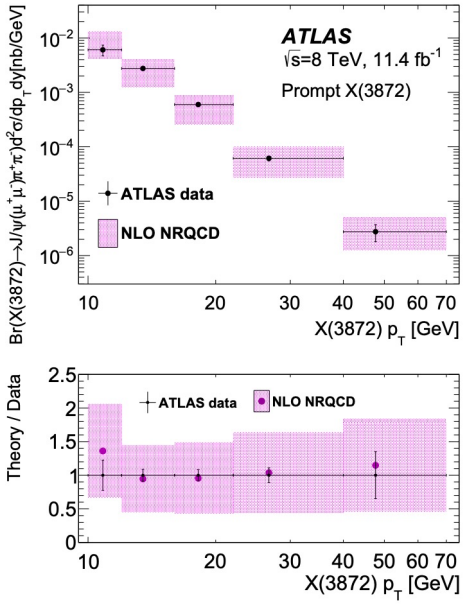


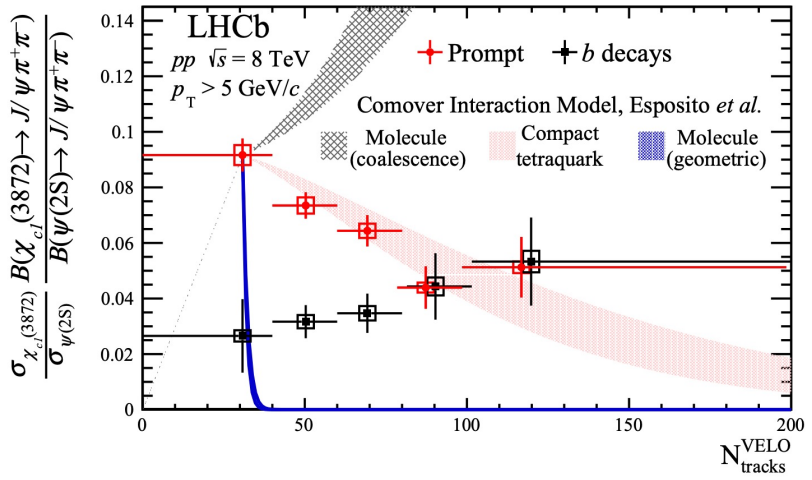
Diquark–diantiquark

Previous production measurements

- CMS results $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}} <$ LO NRQCD for $D^0\overline{D}^{*0}$ molecule [JHEP 04 (2013) 154]
- ATLAS results are consistent with NLO NRQCD prediction for a mixed $\chi_{c1}(2P)$-$D^0\overline{D}^{*0}$ state [JHEP 01 (2017) 117]
- LHCb: $\chi_{c1}(3872)/\psi(2S)$ vs multiplicity in pp collisions [Phys. Rev. Lett. 126, 092001]
  - Prompt: $\chi_{c1}(3872)$ suppressed relative to $\psi(2S)$ as multiplicity increases
    - Compact tetraquark?
  - b decays: no significant dependence on multiplicity is observed





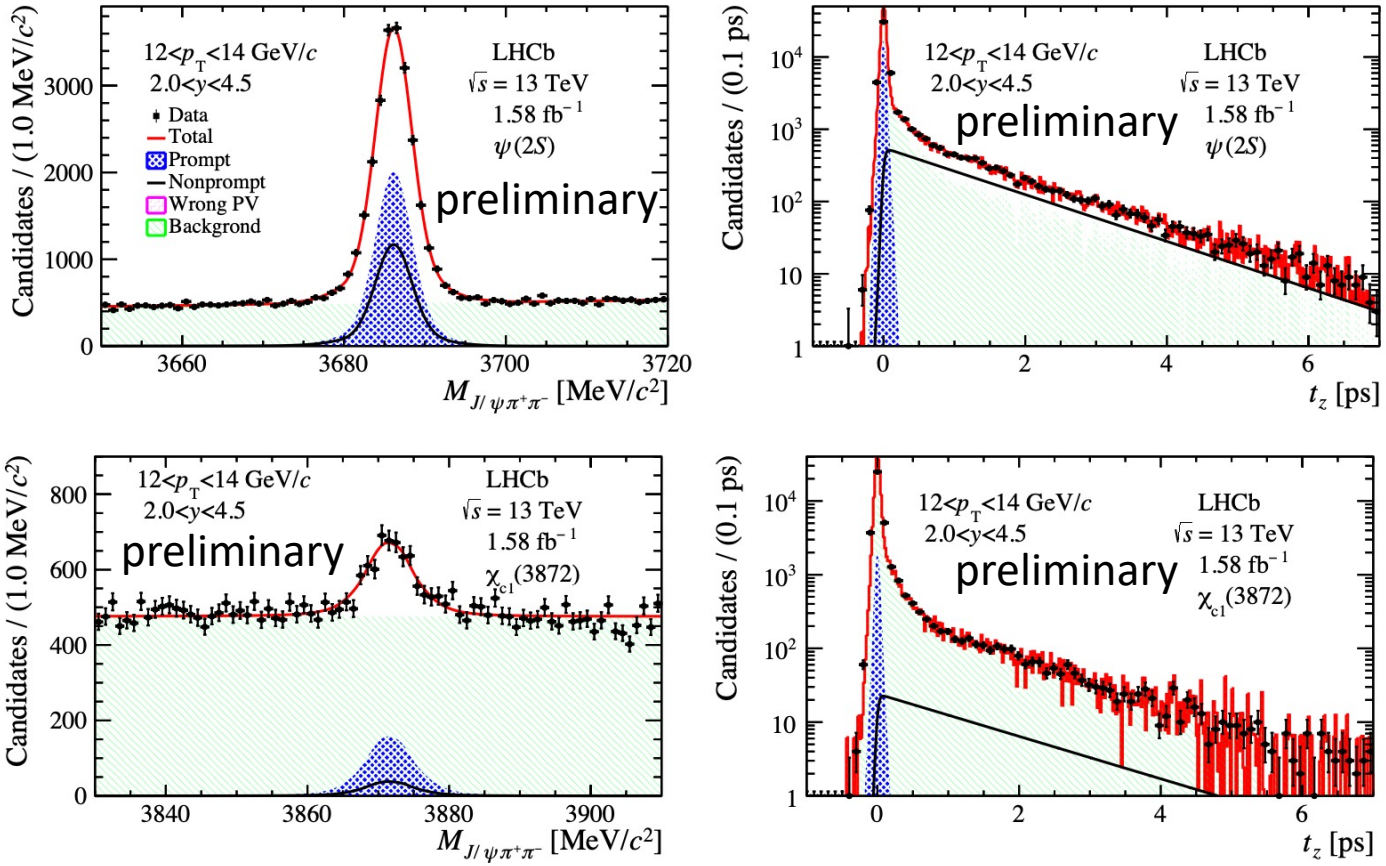


Analysis strategy

$$R = \frac{\sigma\left(\chi_{c1}(3872)\right)\times\mathcal{B}(\chi_{c1}(3872)\to J/\psi\pi^+\pi^-)}{\sigma(\psi(2S))\times\mathcal{B}(\psi(2S)\to J/\psi\pi^+\pi^-)} = \frac{N_{\chi_{c1}(3872)}/\varepsilon_{\chi_{c1}(3872)}}{N_{\psi(2S)}/\varepsilon_{\psi(2S)}}$$

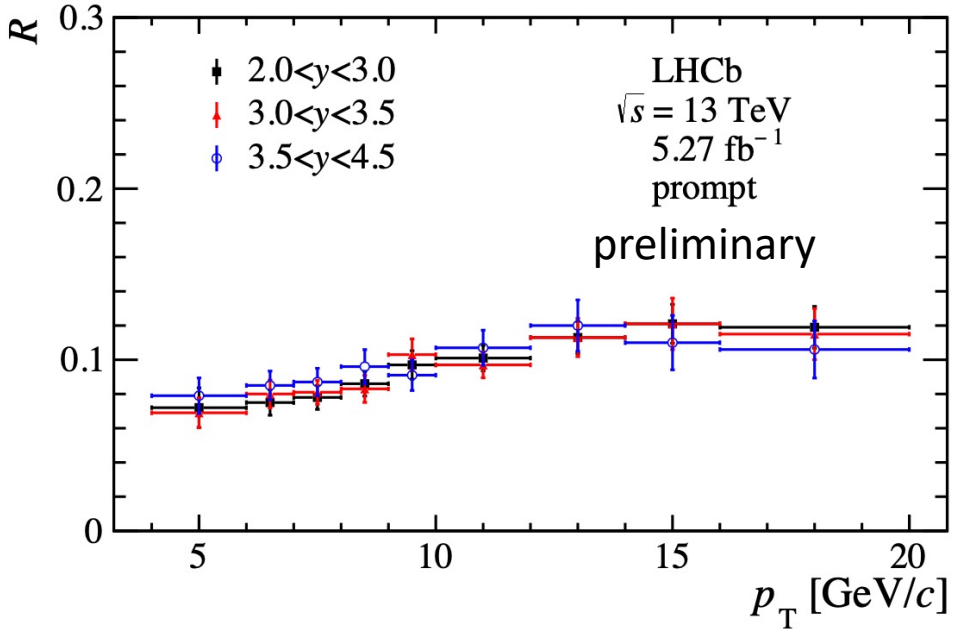
LHCb-PAPER-2021-026

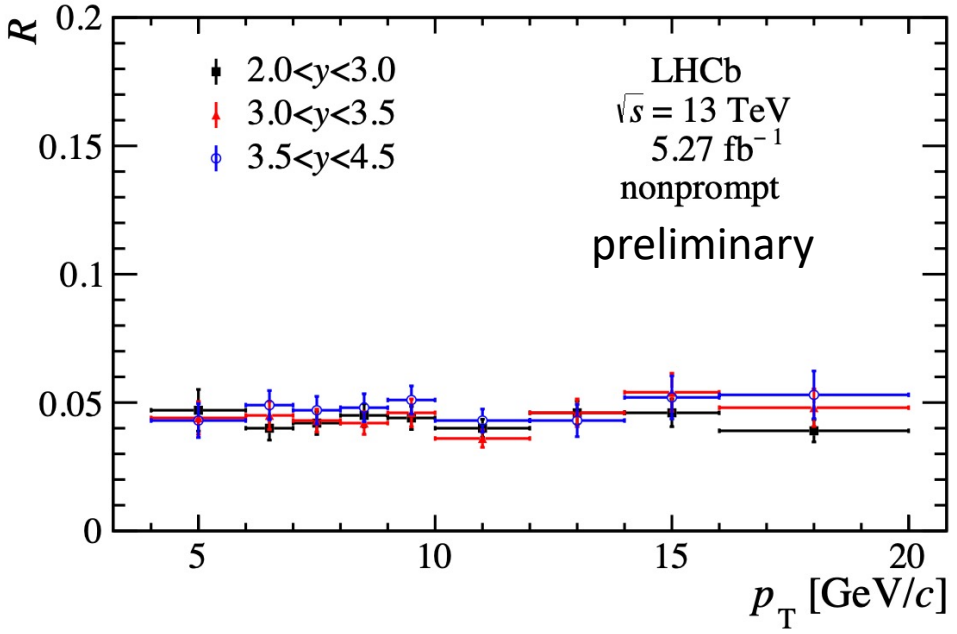
- Two-dimentional fit to **mass** and **pseudo decay time t_z**
  - $t_z = \frac{z-z_{\mathrm{PV}}}{p_z/m}$
- Yields N are corrected by efficiency ε
- Kinematic range
  - $4 < p_{\mathrm{T}} < 20\ \mathrm{GeV}/c$
  - $2.0 < y < 4.5$
- Assume zero polarisation



Cross-section ratio $\chi_{c1}(3872)/\psi(2S)$

LHCb-PAPER-2021-026



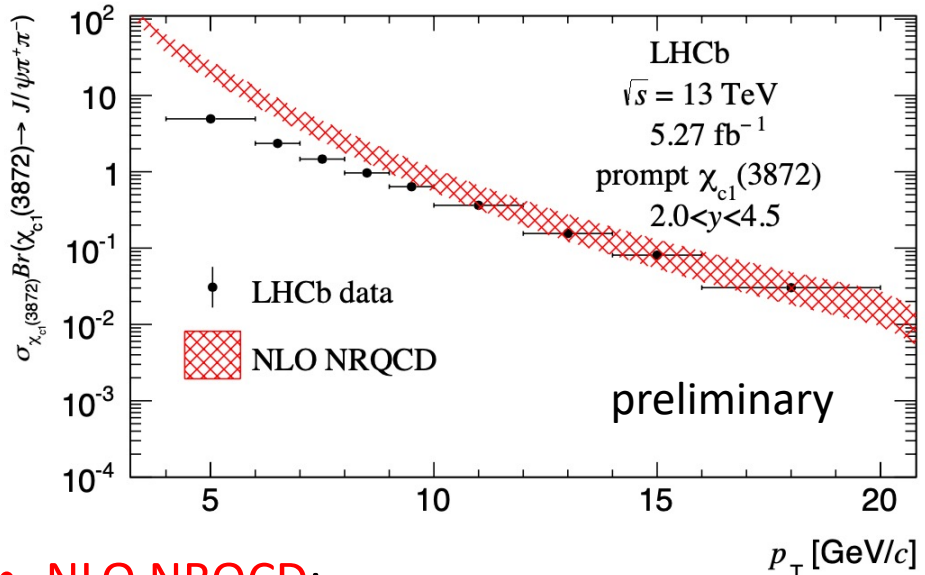


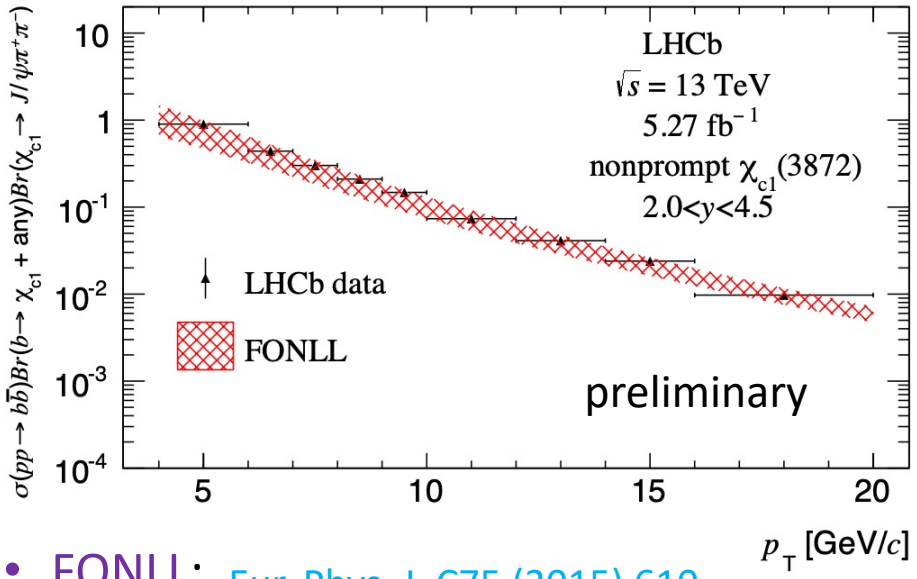
- Prompt: increase as a function of p_{T}
  - $\chi_{c1}(3872)$ production is enhanced relative to $\psi(2S)$ in the higher p_{T} region
  - Similar to prompt $\psi(2S)$ / J/ψ production ratio Eur. Phys. J. C80 (2020) 185
- Nonprompt (from b decays): consistent with a flat trend as a function of p_{T}
- Same conclusion for the ratio at 8 TeV

$\chi_{c1}(3872)$ cross-sections

- $\psi(2S)$ production cross-section is taken as an input [Eur. Phys. J. C80 (2020) 185]
- Prompt compared with NLO NRQCD, and nonprompt compared with FONLL

LHCb-PAPER-2021-026





- NLO NRQCD: [Phys. Rev. Lett. 126, 092001]
  - Assume $\chi_{c1}(2P)$-$D^0\overline{D}^{*0}$ mixing model
- Good agreement between data and NLO NRQCD for $p_{\mathrm{T}} > 10\ \mathrm{GeV}/c$
  - Imply that $\chi_{c1}(3872)$ is a mixed state?

- FONLL: [Eur. Phys. J. C75 (2015) 610]
  - Input: $\mathcal{B}(b \to \chi_{c1}(3872) + \text{any}) \times \mathcal{B}(\chi_{c1}(3872) \to J/\psi\pi^+\pi^-) = (4.3 \pm 0.5) \times 10^{-5}$
- Good agreement between data and FONLL

Summary

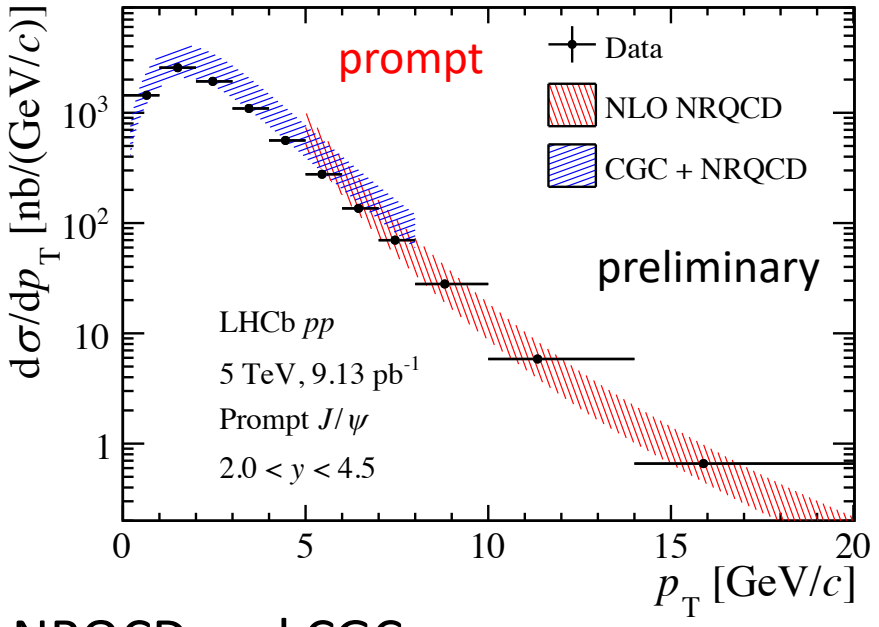
- Latest charmonium(-like) state production measurements in pp collisions are reported here
- J/ψ production cross-sections at 5.02 TeV
  - Results are consistent with theoretical predictions
  - A small tension between data and theory for prompt J/ψ in the low p_T region
- $\chi_{c1}(3872)$ production cross-sections at 8 and 13 TeV
  - Provide new input to probe the nature of $\chi_{c1}(3872)$

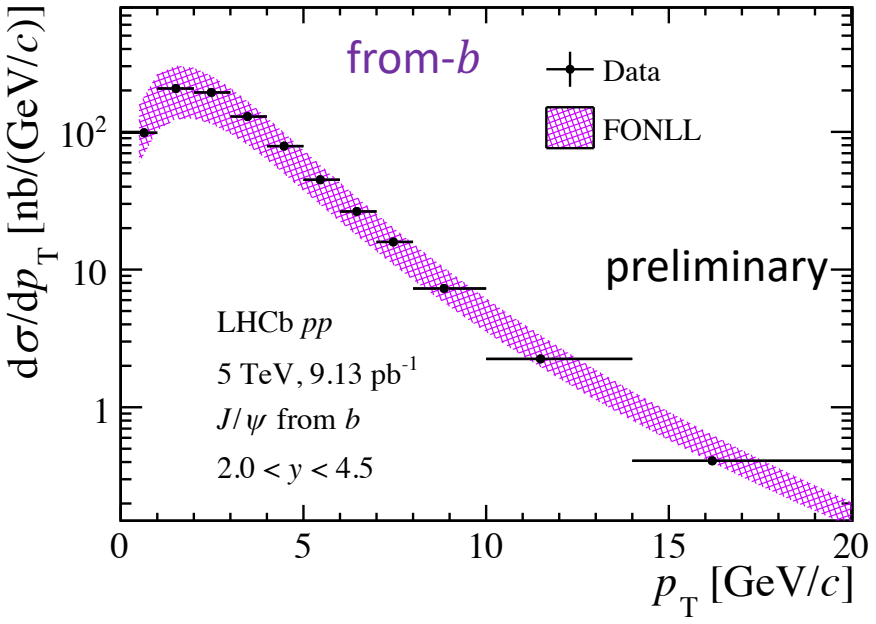
Thank you!

Backup Slides

J/ψ cross-sections at 5.02 TeV

LHCb-PAPER-2021-020



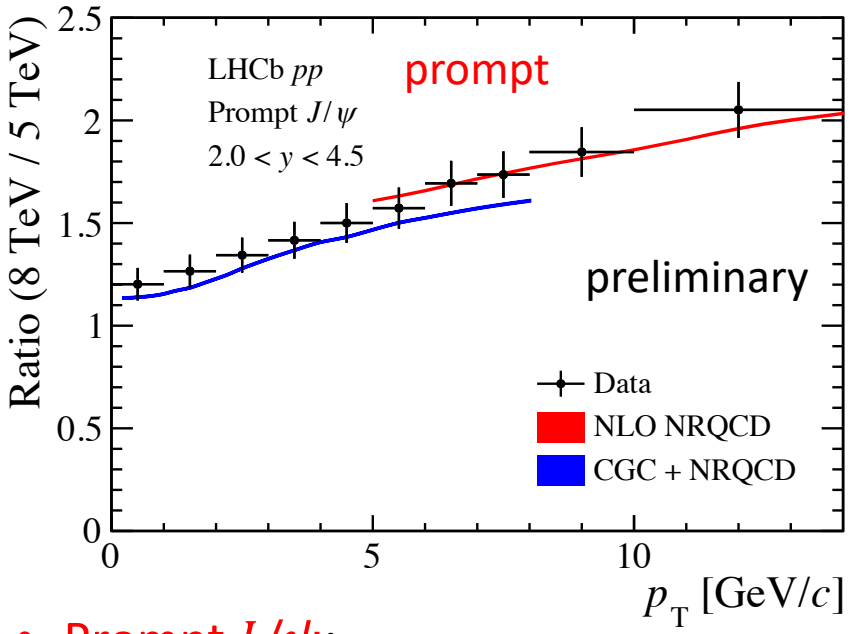


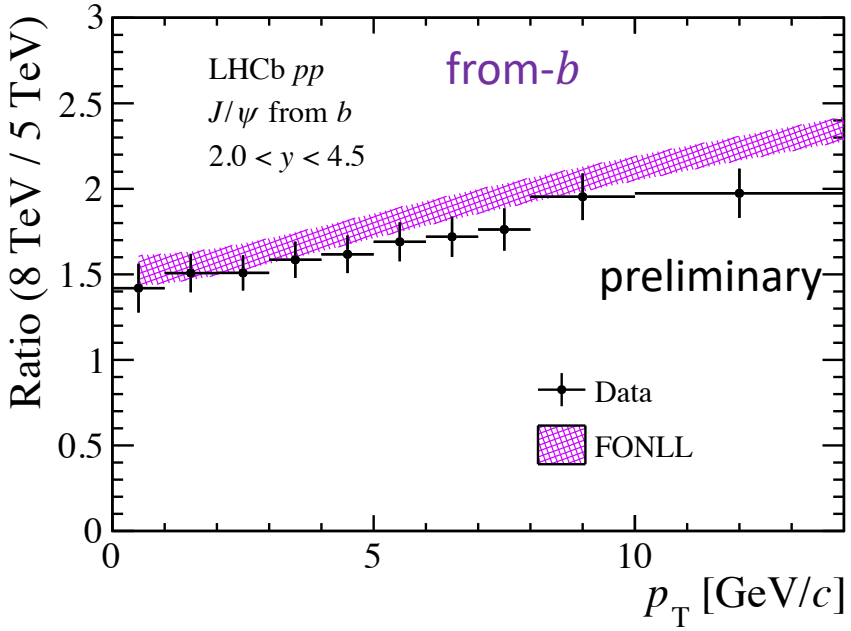
- NRQCD and CGC
  - Uncertainties due to LDMEs determination, renormalisation scales, and factorisation scales
  - Cancel most in ratios
- FONLL
  - PDFs uncertainties, the uncertainty due to the b-quark mass, and that due to the scales of renormalisation and factorisation

Cross-section ratio

- Ratio between 8 TeV and 5.02 TeV measurements

LHCb-PAPER-2021-020

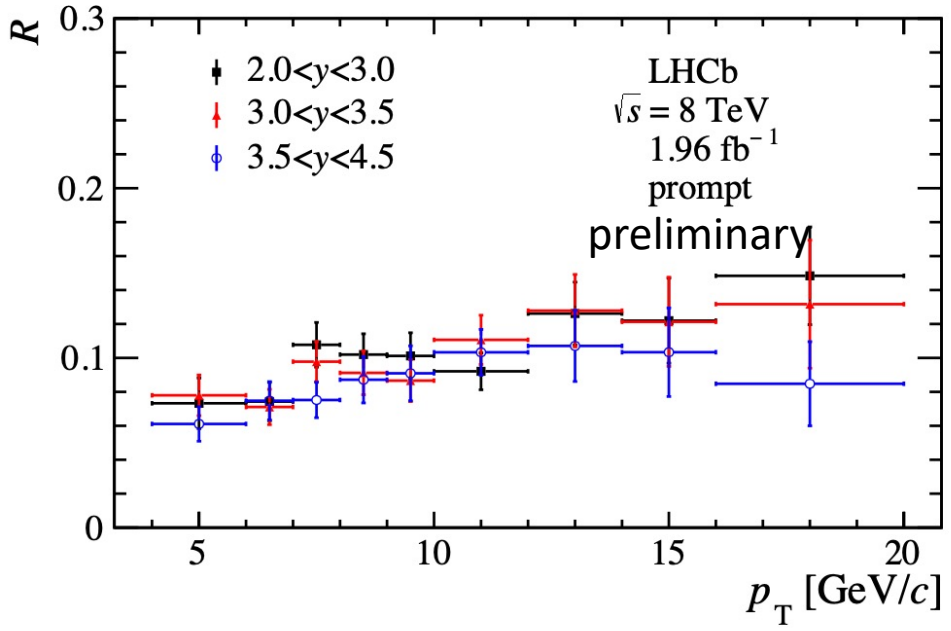


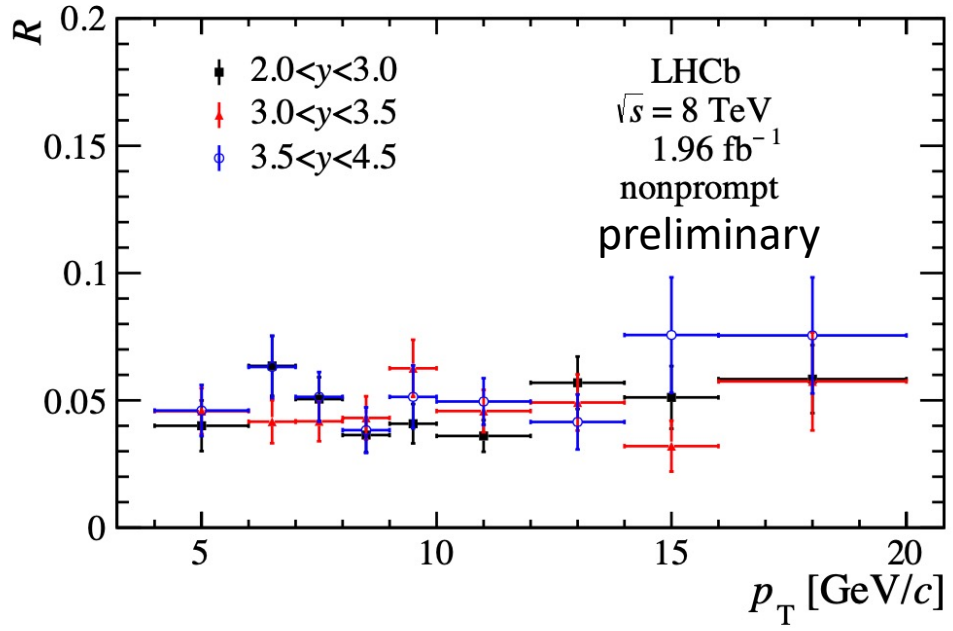


- Prompt J/ψ:
  - High p_T: good agreement between data and NLO NRQCD
  - Low p_T: a small tension between data and CGC + NRQCD
    - Need further corrections in the theory model?
- J/ψ from b: good agreement between data and FONLL

Cross-section ratio $\chi_{c1}(3872)/\psi(2S)$ at 8 TeV

LHCb-PAPER-2021-026





- Prompt: increase as a function of p_{T}
  - $\chi_{c1}(3872)$ production is enhanced relative to $\psi(2S)$ in the higher p_{T} region
- Nonprompt (from b decays): consistent with a flat trend as a function of p_{T}

Cross-section ratio $\psi(2S)$ / J/ψ

Eur. Phys. J. C80 (2020) 185