J/ψ production cross-sections in pp collisions at $\sqrt{s} = 5$ TeV

Li XU

Tsinghua University

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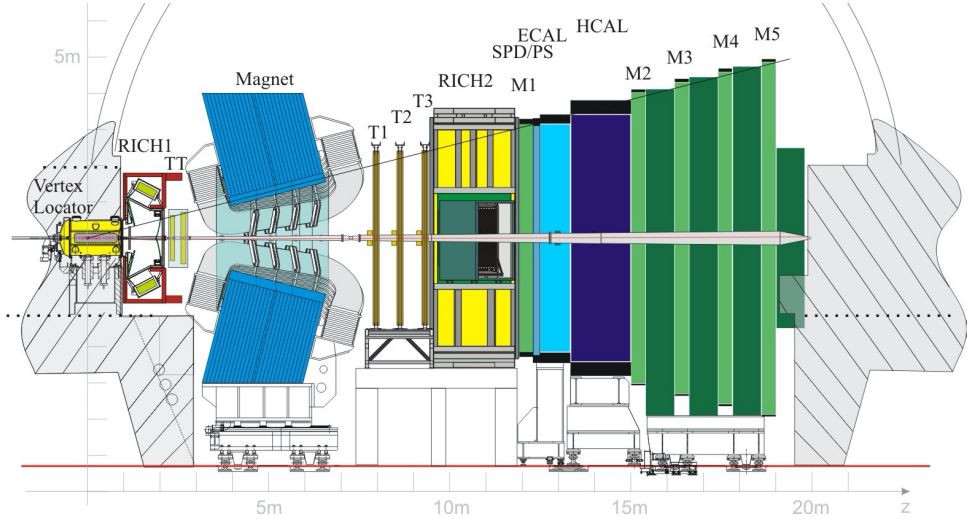
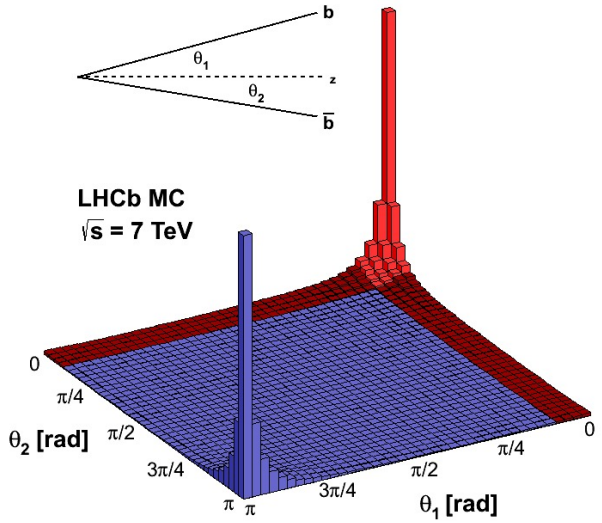
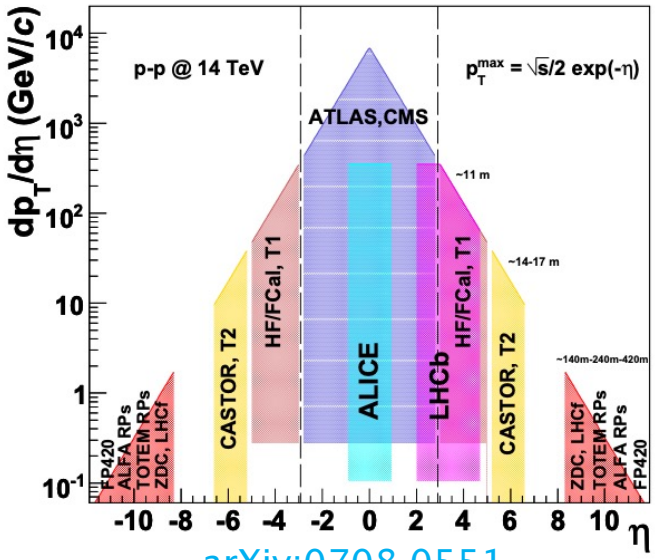
LHCb detector

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



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

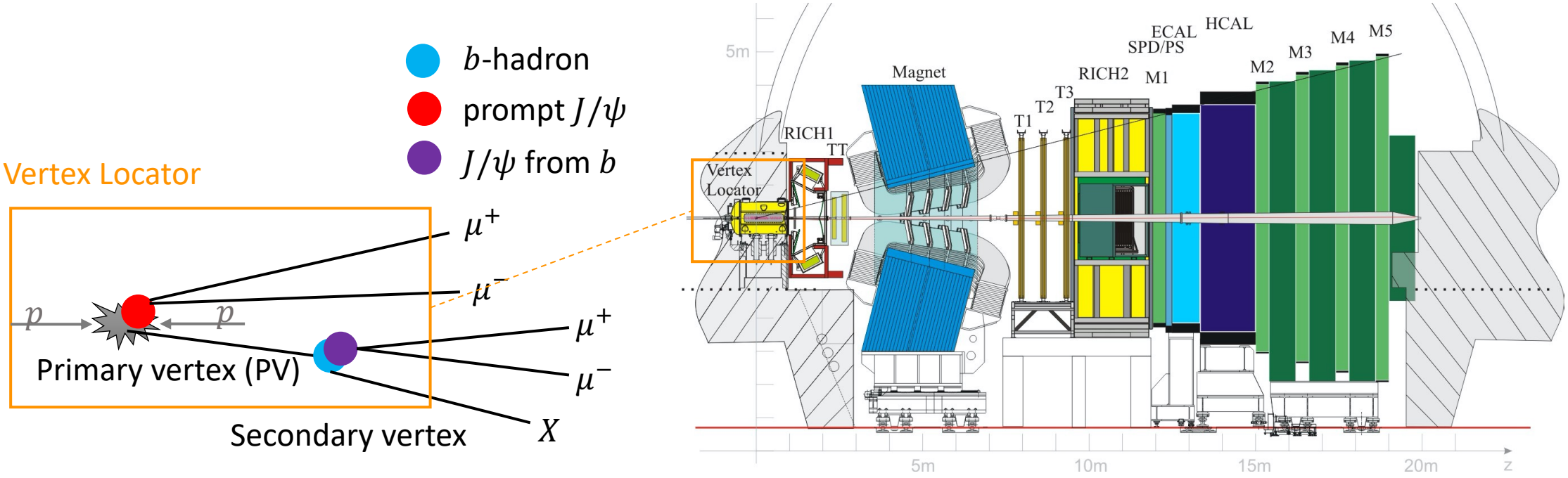




arXiv:0708.0551

J/ψ production at LHCb

- Prompt J/ψ:
  - originate from the primary pp collision vertex
- J/ψ from b:
  - originate from b-decay vertex (secondary vertex)
- Vertex Locator at LHCb can separate primary and secondary vertices



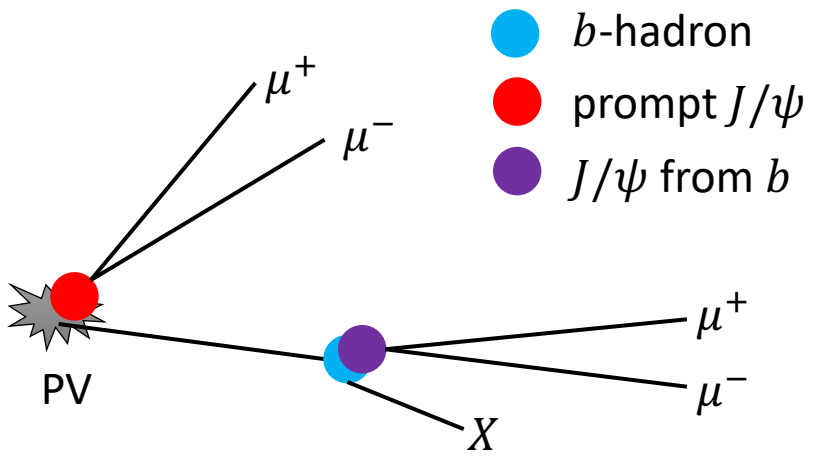
J/ψ production in pp collisions at 5 TeV

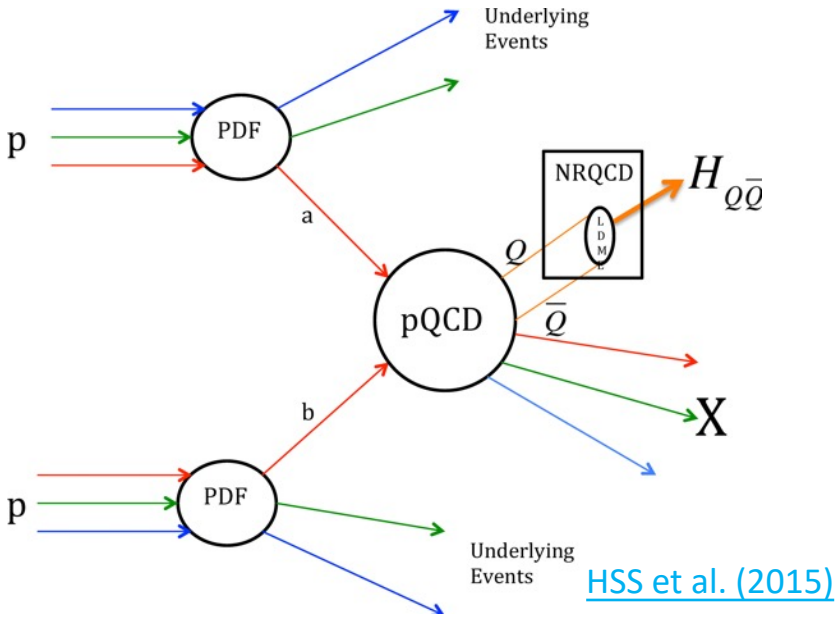
Accepted by JHEP, arXiv:2109.00220

- Motivation
- Analysis strategy
- Systematic uncertianty
- Cross-sections
- Nuclear modification factor $R_{p\mathrm{Pb}}$

Motivation: probe QCD

- Prompt J/ψ: probe J/ψ production mechanism
  - $c\bar{c}$ pair production: perturbative QCD
  - Hadronisation: non-perturbative QCD
    - Non-Relativistic QCD (NRQCD)
      - ➢ Long-distance matrix element (LDME)
        - ✓ Describe the transition probability that the $c\bar{c}$ pair evolves into a J/ψ
        - ✓ Determined from experimental data
      - ➢ NRQCD fails to describe the low $p_{\mathrm{T}} \lesssim M_{J/\psi}$ region
      - ➢ Color glass condensate (CGC) effects are combined with NRQCD at low p_{T}



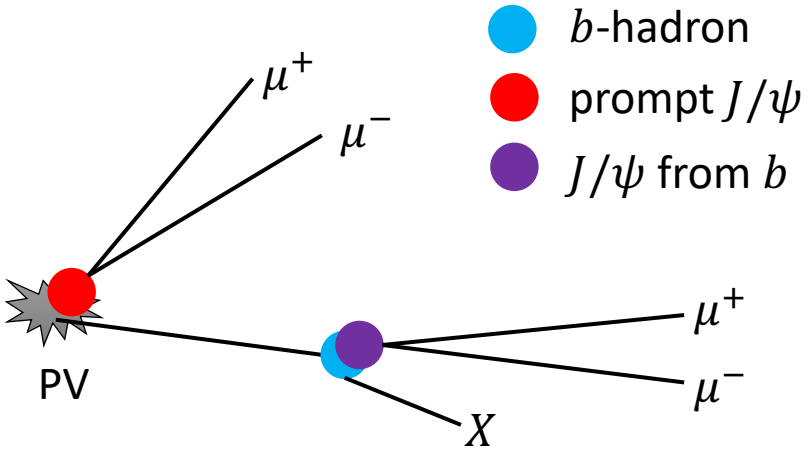


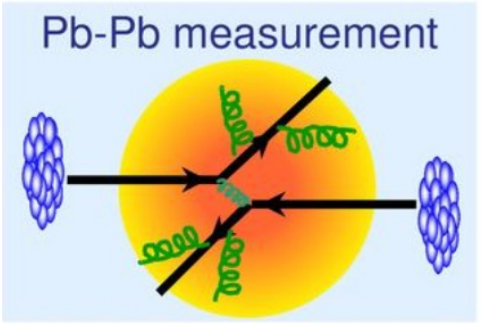
HSS et al. (2015)

Motivation: probe QCD

- J/ψ from b: probe b-quark production mechanism
  - $\sigma(J/\psi \text{ from } b) = \sigma(b\bar{b}) \times 2\mathcal{B}(b \to J/\psi X)$
  - Fixed Order plus Next-to-Leading Logarithms (FONLL)
- Reference for cold/hot nuclear matter effect studies in proton-lead and lead-lead collisions
  - Both for prompt J/ψ and J/ψ from b
  - Nuclear modification factor in pPb collisions

$$R_{p\mathrm{Pb}}(y) = \frac{1}{\mathrm{A}} \frac{\mathrm{d}\sigma_{p\mathrm{Pb}}/\mathrm{d}y}{\mathrm{d}\sigma_{pp}/\mathrm{d}y}, \text{where A} = 208$$



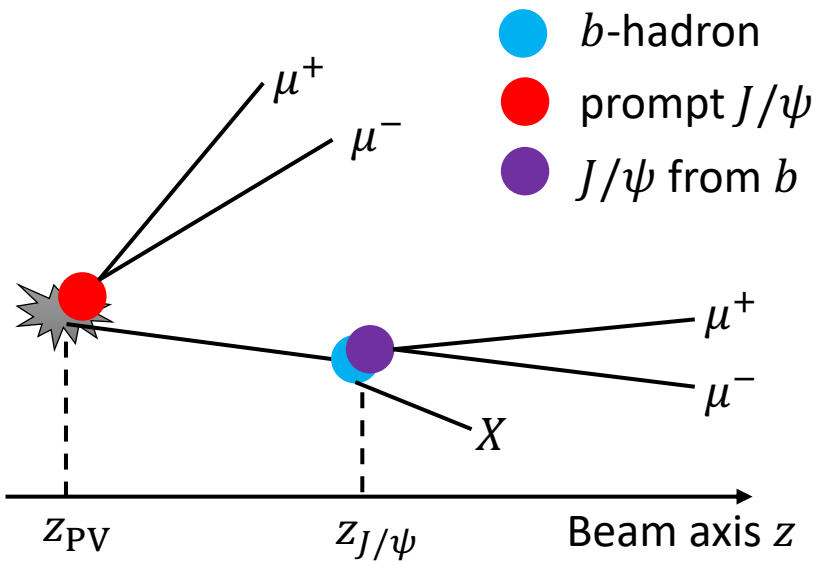


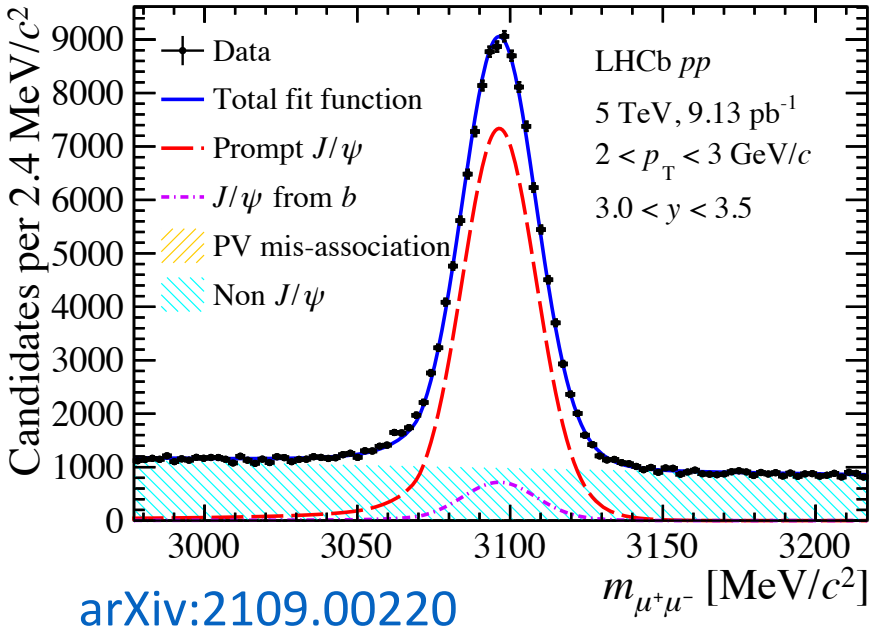
Analysis strategy

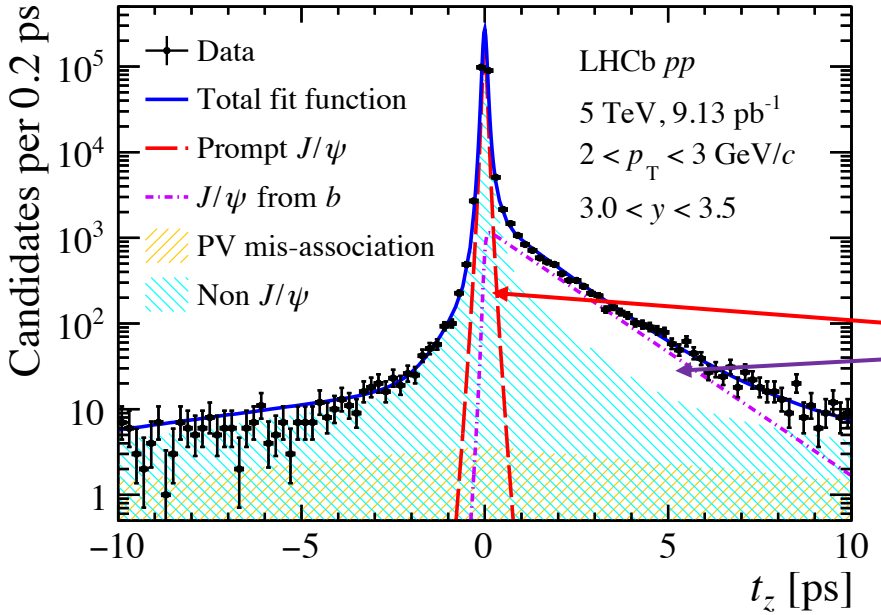
- Differential cross-section:

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

- Kinematic range: $0 < p_\mathrm{T} < 20\ \mathrm{GeV}/c,\ 2.0 < y < 4.5$
- Two-dimentional fit to **mass** and **pseudo decay time t_z**







arXiv:2109.00220

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

- Use t_z to separate **prompt J/ψ** and **J/ψ from b**
- Yields N are corrected by efficiency ε_tot obtained from simulation

Systematic uncertainty

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

Source	Relative uncertainty (%)	Source	Relative uncertainty (%)
Signal mass model	< 2.0	Tracking efficiency	$(< 3.7)\oplus 1.6$
Background mass model	< 0.7	PID efficiency	$(< 2.2)\oplus(< 1.5)$
Signal t_z model	prompt J/ψ: < 0.8 J/ψ from b: < 14.7	Trigger efficiency	$(< 1.9)\oplus 1.0$
		Radiative tail	1.0
Background t_z model	prompt J/ψ: < 1.2 J/ψ from b: < 4.0	Simulation sample size	prompt J/ψ: < 3.7 J/ψ from b: < 7.7
Luminosity	2.0	Branching fraction	0.6

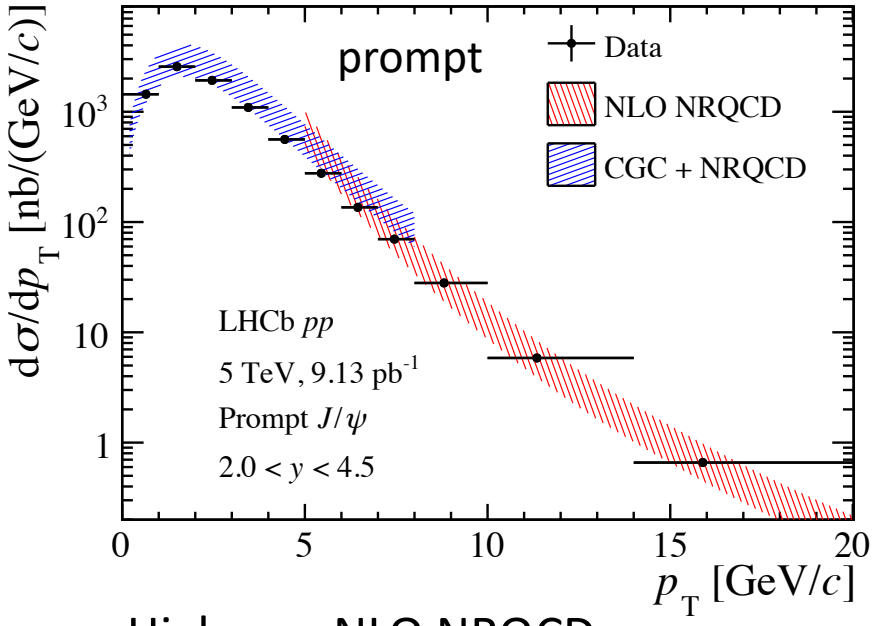
arXiv:2109.00220

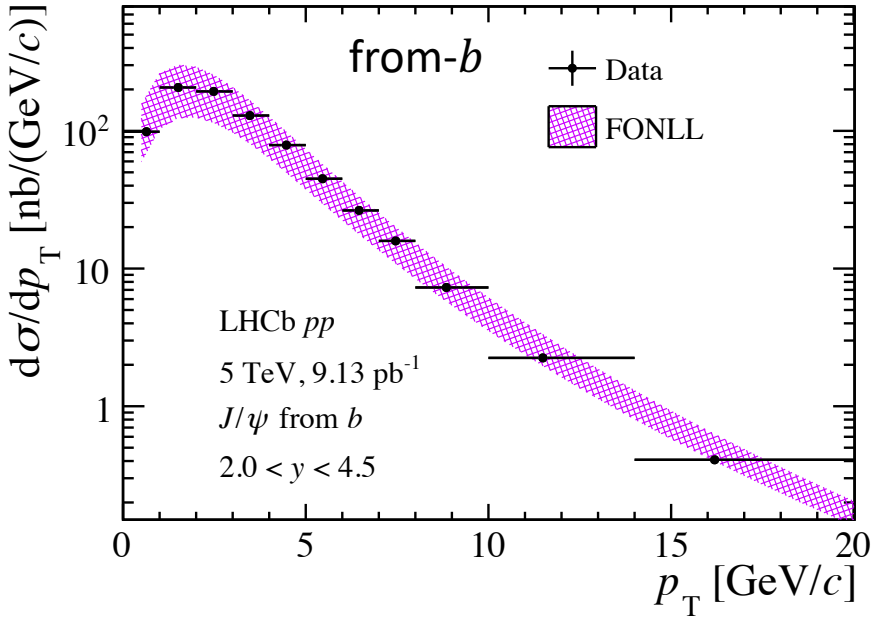
- Polarisation: assume unpolarised J/ψ
  - Only small longitudinal polarisations have been found ($\lambda_\theta \sim -0.2$, consistent with 0)
  - Assume $\lambda_\theta = -0.2$, integrated cross-sections decrease by 2.8%
  - Taken as the reference, rather than the uncertainty

Cross-sections at 5 TeV

- Integrated cross-sections $(0 < p_{\mathrm{T}} < 20\ \mathrm{GeV}/c,\ 2.0 < y < 4.5)$
  - $\sigma_{\mathrm{prompt}} = 8.154 \pm 0.010\ (\mathrm{stat.}) \pm 0.283\ (\mathrm{syst.})\ \mu\mathrm{b}$
  - $\sigma_{\mathrm{from}-b} = 0.820 \pm 0.002\ (\mathrm{stat.}) \pm 0.034\ (\mathrm{syst.})\ \mu\mathrm{b}$

arXiv:2109.00220





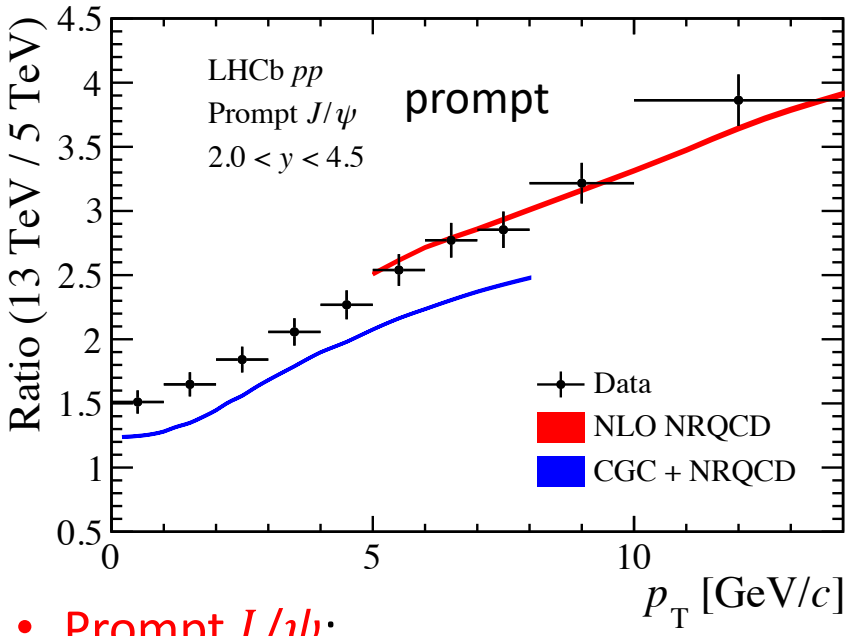
- High p_T : NLO NRQCD Phys. Rev. Lett. 106, 042002
- Low p_T : combine NRQCD with color glass condensate (CGC) effective theory Phys. Rev. Lett. 113, 192301
- FONLL JHEP 10 (2012) 137 Eur. Phys. J. C75 (2015) 610

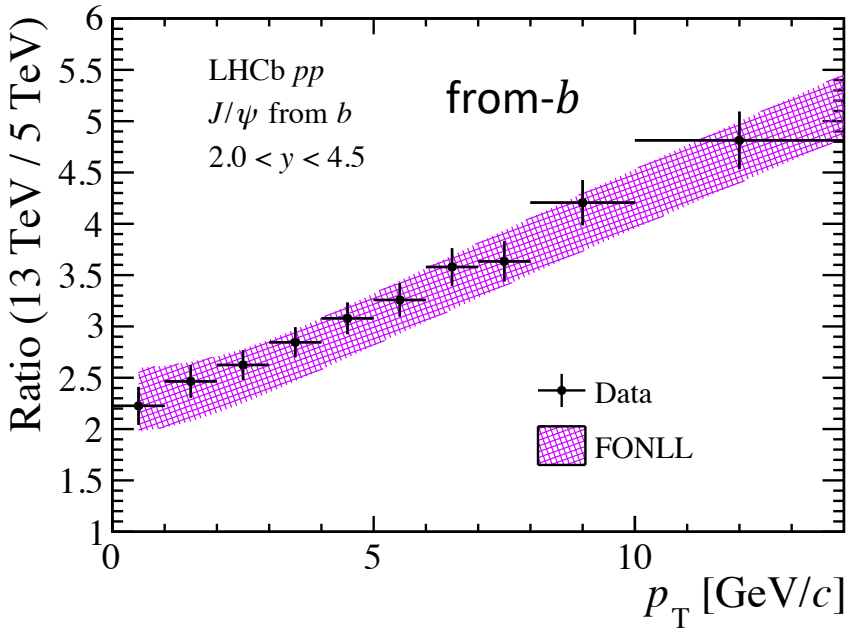
- The inclusion of CGC effects achieves a reasonable agreement between data and theory for prompt J/ψ at low p_{T}
- Good agreement with predictions both for prompt J/ψ and J/ψ from b

Cross-section ratio

- Ratio between 13 TeV and 5 TeV measurements
  - Experimental and theoretical uncertainties cancel a lot

arXiv:2109.00220



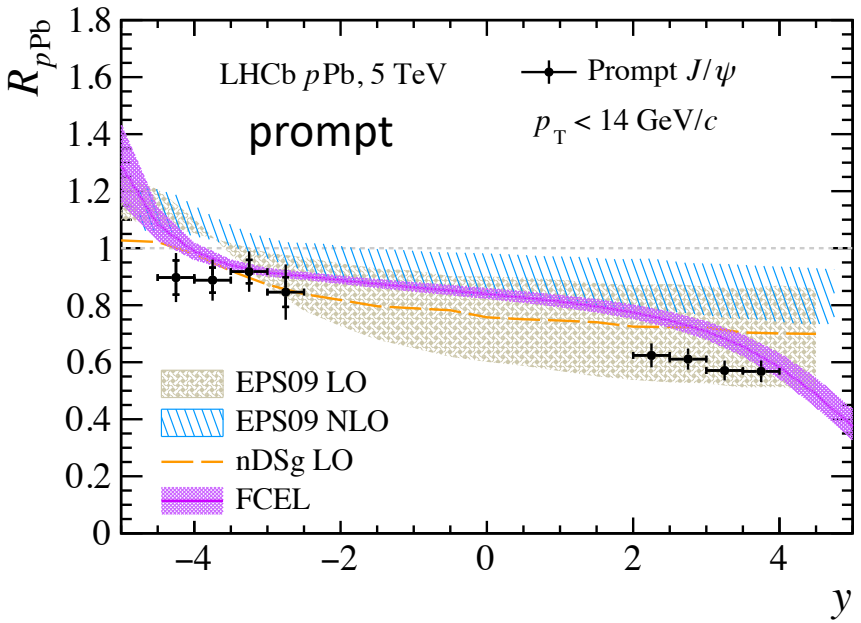


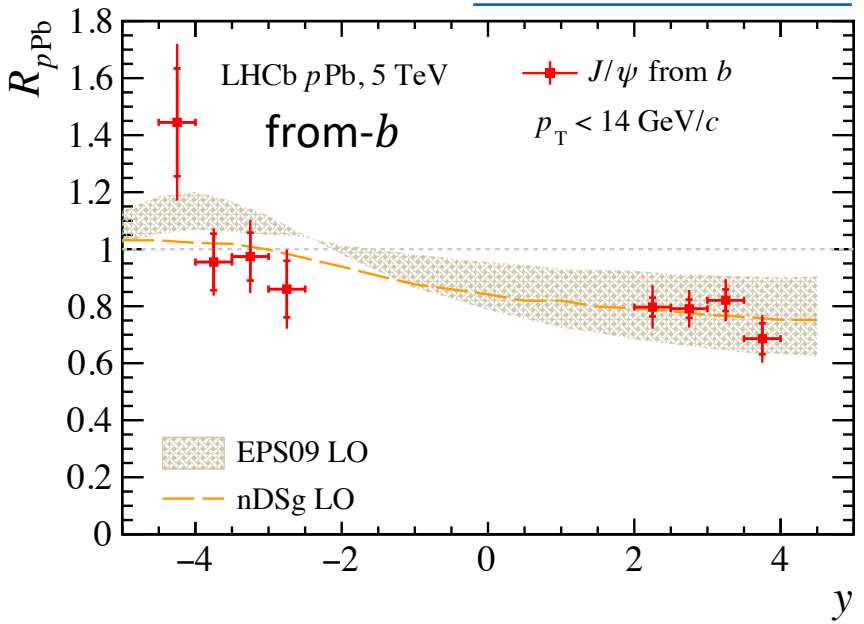
- Prompt J/ψ:
  - High p_{T}: good agreement between data and NLO NRQCD
  - Low p_{T}: a small discrepancy between data and CGC + NRQCD
- J/ψ from b: good agreement between data and FONLL
- Same conclusion for the ratio between 8 TeV and 5 TeV measurements

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
  - Consistent with previous results

arXiv:2109.00220





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

- A suppression is observed in the forward region, consistent with most predictions
- Much higher precision in the forward region than theoretical predictions, providing strong constraining power to improve nPDF modeling

Summary

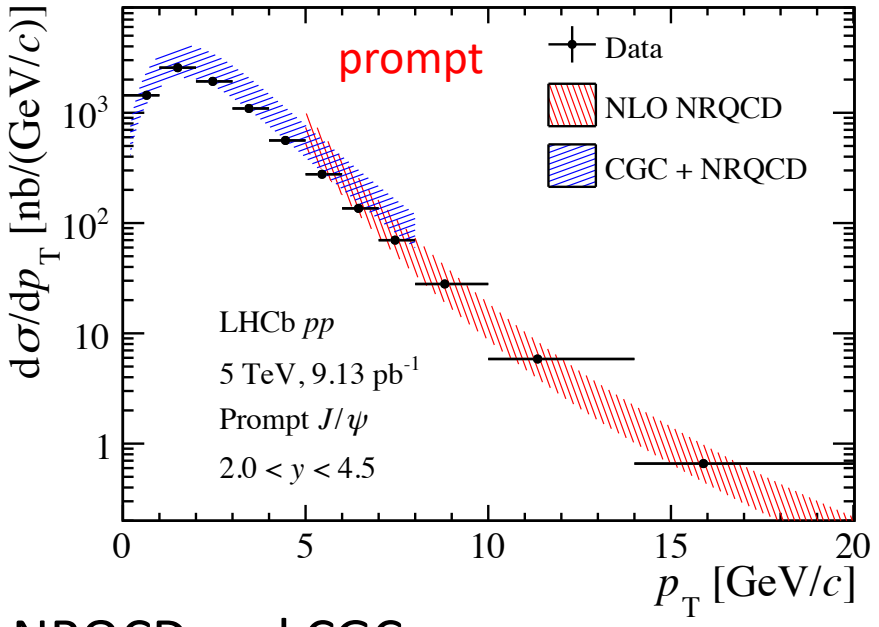
- J/ψ production cross-sections in pp collisions at 5 TeV
  - Prompt J/ψ
    - Good agreement with NLO NRQCD in the high p_{T} region
    - A small discrepancy between data and CGC+NRQCD in the low p_{T} region on the ratio $\sigma_{13\ \mathrm{TeV}}/\sigma_{5\ \mathrm{TeV}}$
  - J/ψ from b
    - Good agreement with FONLL
- Nuclear modification factor in pPb collisions
  - $R_{p\mathrm{Pb}}$ is updated
  - The results are consistent with most predictions

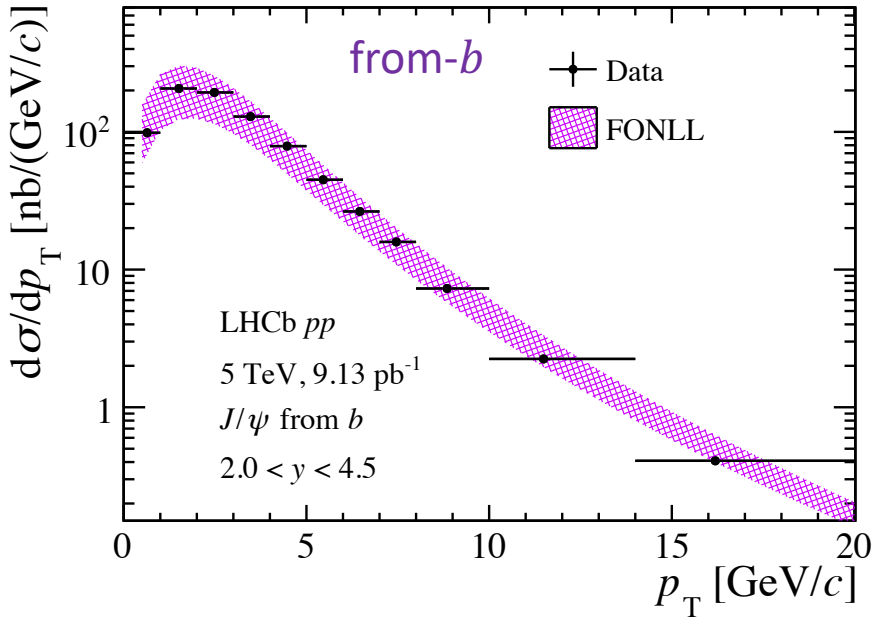
Thank you!

Backup Slides

Theroetical uncertainty

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

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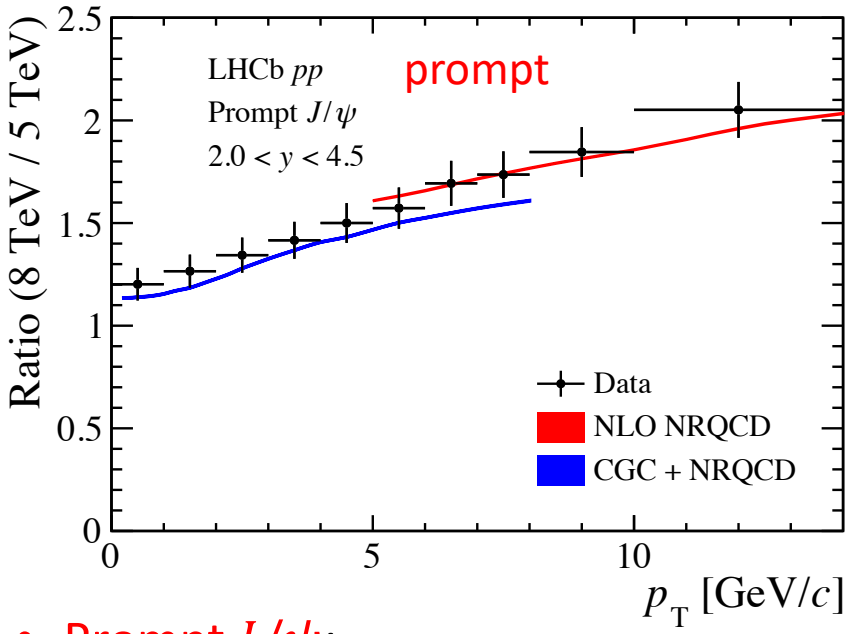

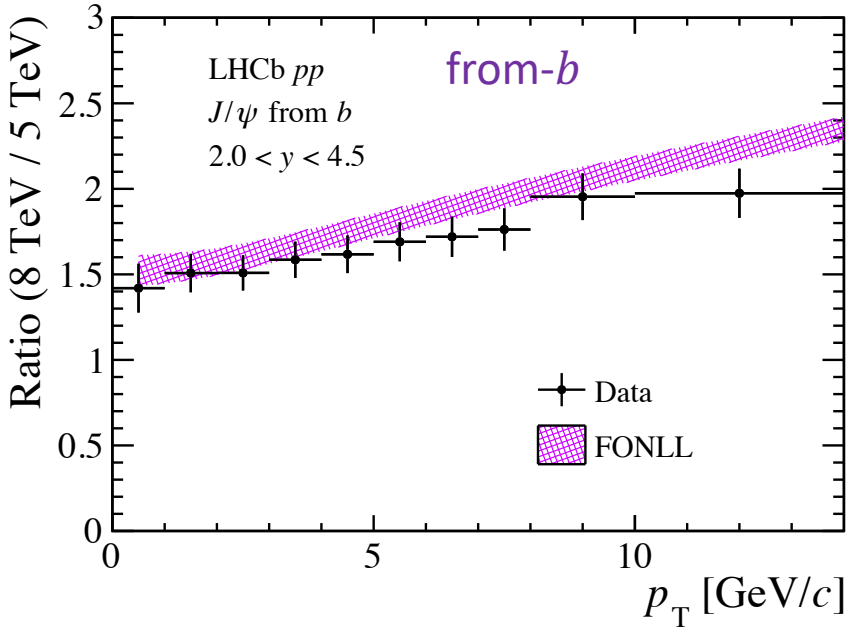

- Prompt J/ψ:
  - High p_T: good agreement between data and NLO NRQCD
  - Low p_T: a small tension between data and CGC + NRQCD
    - Need further corrections in the theory model?
- J/ψ from b: good agreement between data and FONLL