



Heavy flavour production in pp collision at LHCb

Jialu Wang (Peking University) on behalf of LHCb collaboration

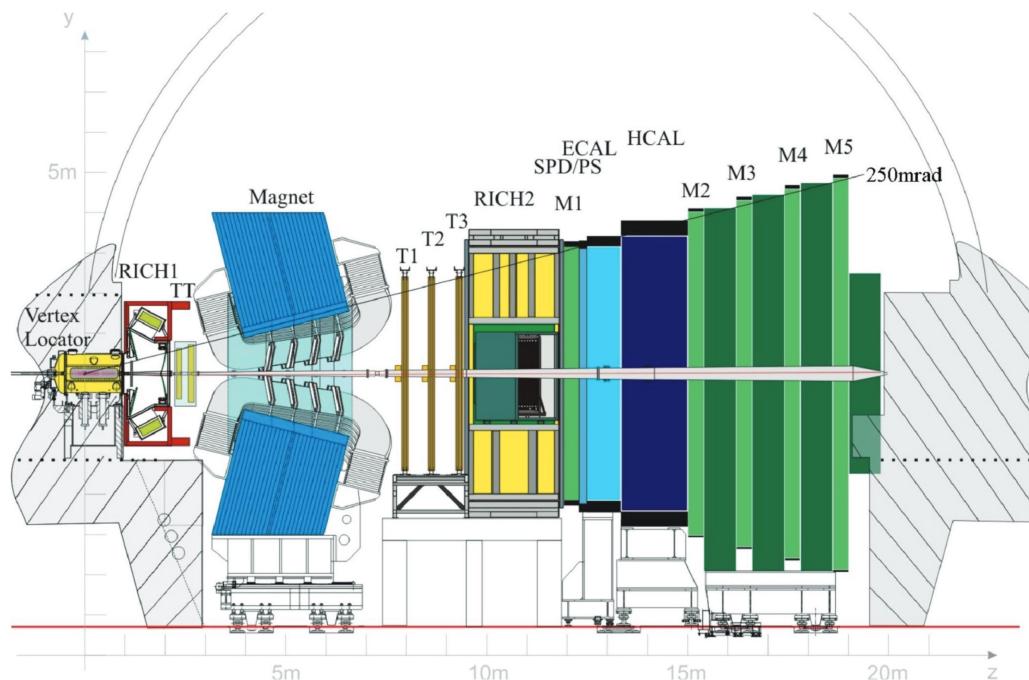
Date: May 30, 2023

21th Conference on Flavor Physics and CP Violation

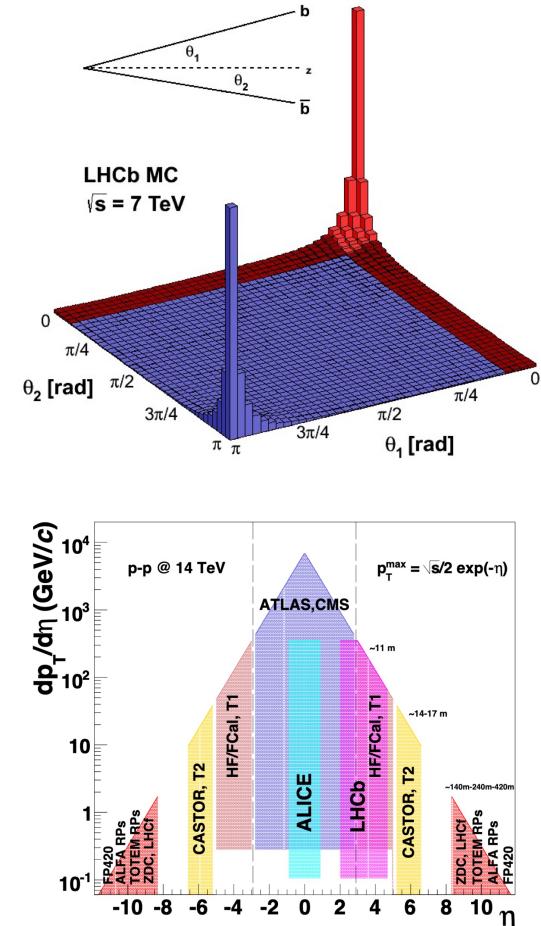
- ★ LHCb detector
- ★ Heavy flavour production measurement at LHCb
 - ★ $\gamma(nS)$ production cross-sections at $\sqrt{s} = 5$ TeV
 - ★ J/ψ production cross-sections at $\sqrt{s} = 5$ TeV
 - ★ $\chi_{c1}(3872)$ production cross-sections at $\sqrt{s} = 8$ TeV and 13 TeV
- ★ Summary and outlook

LHCb detector

- ★ Designed for the studies of b and c physics
- ★ Single-arm forward detector, forward region: $2 < \eta < 5$
 - ★ ~4% of solid angle, but ~25% of $b\bar{b}$ quark pairs accepted
 - ★ Complementary to other LHC experiments



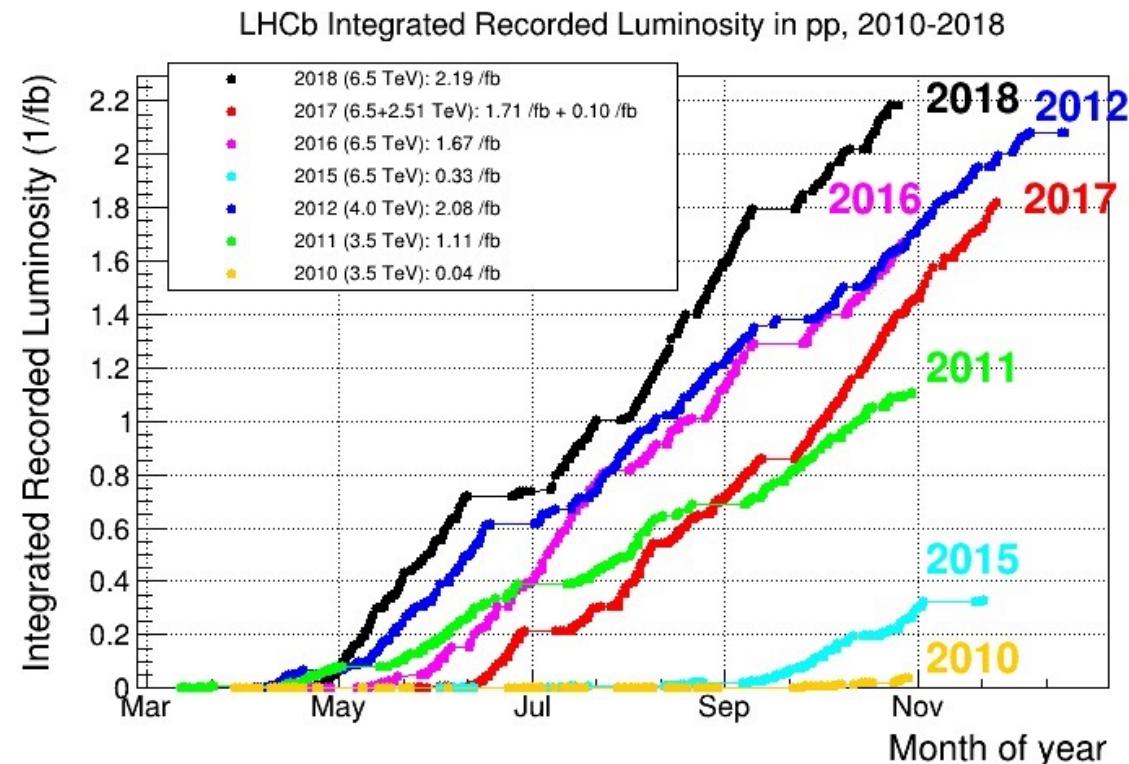
[JINST 3 \(2008\) S08005, IJMPA 30 \(2015\) 1530022](#)



$p_T - \eta$ coverage of current detectors at the LHC. [[arXiv:0708.0551](#)]

- ★ Data collection (Run1+Run2)

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

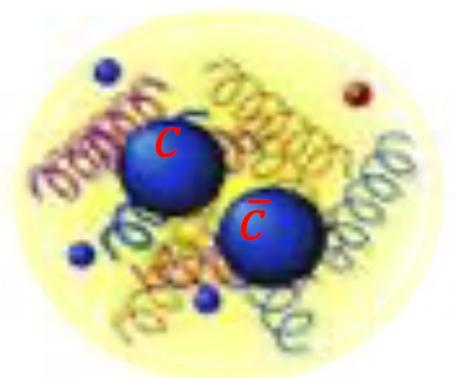
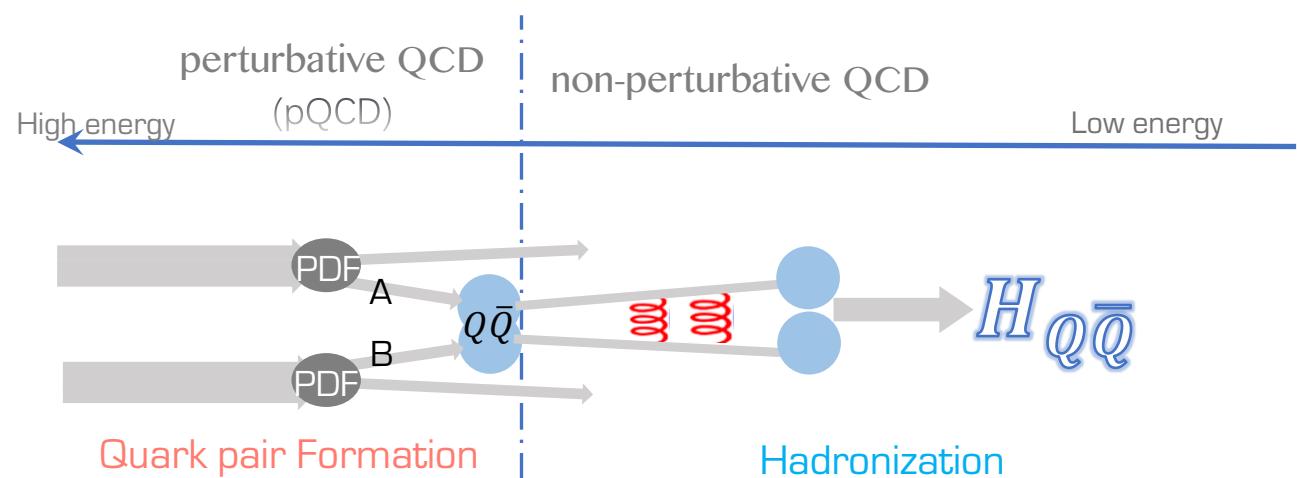


$\gamma(nS)$ production cross-sections at $\sqrt{s} = 5$ TeV

[arXiv:2212.12664 \[hep-ex\]](https://arxiv.org/abs/2212.12664)

Motivation

- ★ Heavy quarkonium ($c\bar{c}, b\bar{b}$) production at high energy hadronic collisions is important to probe QCD
- ★ The heavy quarkonium production can be factorized into two processes
 - ★ **Quark pair formation**: perturbative QCD
 - ★ **Hadronization**: non-perturbative

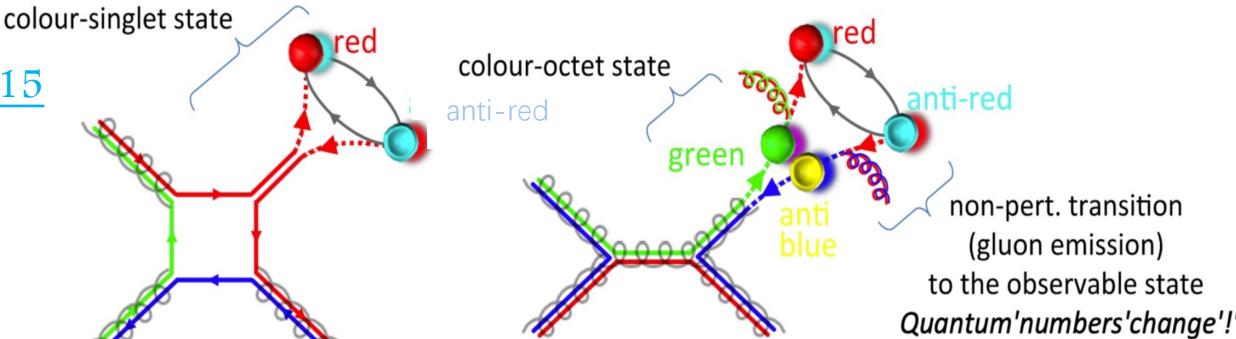


- ★ Different treatments of the nonperturbative hadronization process lead to different theoretical models for quarkonium production

Theoretical models

Color Singlet Model (CSM) : [Phys. Rev. D14 \(1976\) 3115](#)

- ★ Colourless intermediate $Q\bar{Q}$
- ★ Same spin-parity quantum number with final state
- ★ Underestimate production cross-section

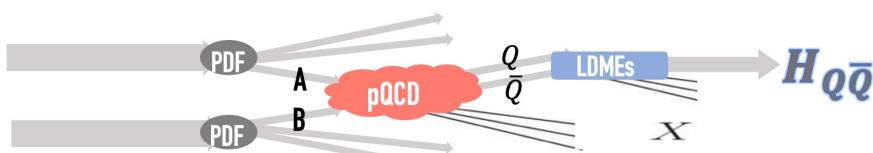


Non-Relativistic QCD (NRQCD): [Phys. Rev. D51 \(1995\) 1125](#)

- ★ Consider all possible colour-spin-parity quantum numbers
- ★ Polarization puzzle

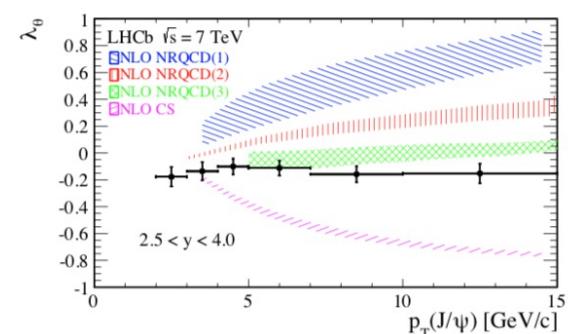
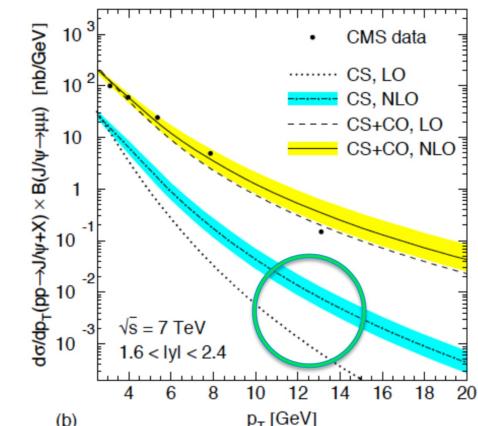
$$d\sigma_{[p_1 p_2 \rightarrow H + X]} = \sum_n \int F_1(A) F_2(B) dA dB \frac{d\hat{\sigma}_{[A+B \rightarrow Q\bar{Q}(n)+X]}}{d\hat{\sigma}_{[A+B \rightarrow Q\bar{Q}(n)+X]}} \times \langle O^H(n) \rangle$$

Parton distribution function
Production of heavy-quark pair
Long distance matrix elements (LDMEs)



LDMEs:

- * The transition probability that the quark pair evolves into a heavy quarkonium.
- * Determined from experimental results.



Analysis strategy

[arXiv:2212.12664 \[hep-ex\]](https://arxiv.org/abs/2212.12664)

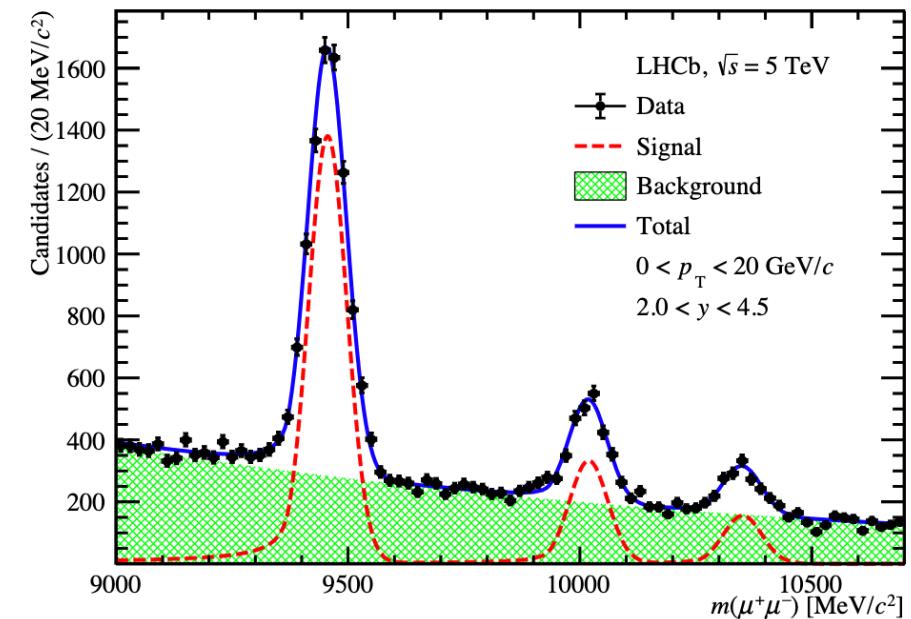
- ★ Dataset: LHCb 2015 pp collision at $\sqrt{s} = 5 \text{ TeV}$
- ★ Integrated Luminosity: $9.13 \pm 0.18 \text{ pb}^{-1}$

- ★ Channel: $\Upsilon(nS) \rightarrow \mu^+ \mu^-$
- ★ Double-differential cross-section:

$$\mathcal{B}(\Upsilon(nS) \rightarrow \mu^+ \mu^-) \times \frac{d^2\sigma}{dy dp_T} = \frac{N_{\text{observed}}(\Upsilon(nS) \rightarrow \mu^+ \mu^-) / \varepsilon_{\text{tot}}}{\Delta y \times \Delta p_T \times \mathcal{L}}$$

Kinematic range: $0 < p_T < 20 \text{ GeV}/c$, $2.0 < y < 4.5$

- ★ Fit to invariant-mass ($\mu^+ \mu^-$) distribution to obtain **yield N**



Cross-sections

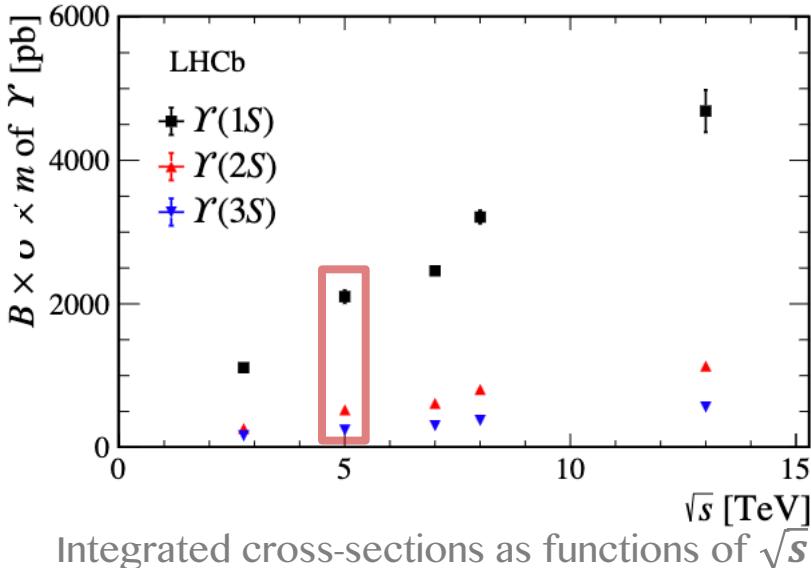
[arXiv:2212.12664 \[hep-ex\]](https://arxiv.org/abs/2212.12664)

LHCb
THCP

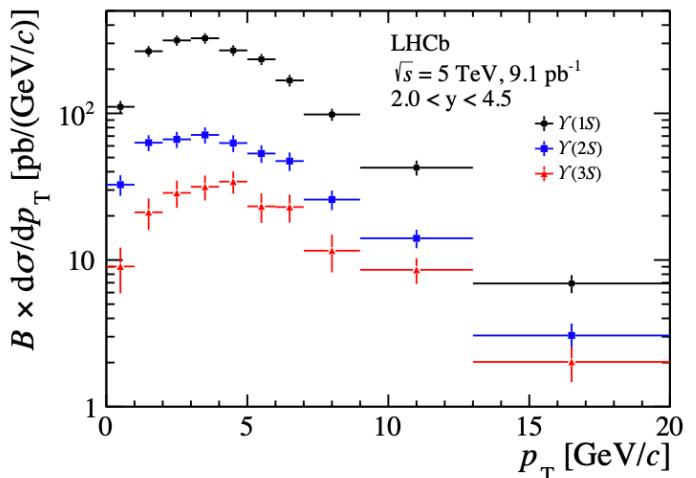


- Integrated cross-sections of $\Upsilon(nS)$ ($0 < p_T < 20\text{GeV}/c$, $2.0 < y < 4.5$)

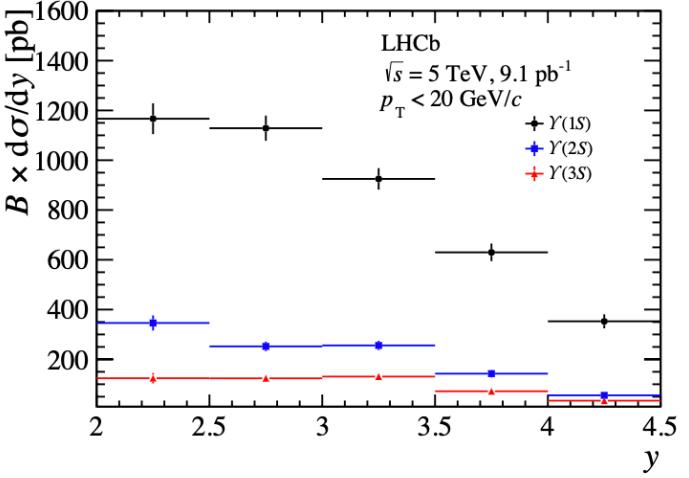
$$\begin{aligned}\sigma(\Upsilon(1S)) \times \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+ \mu^-) &= 2101 \pm 33 \text{ (stat)} \pm 83 \text{ (syst)} \text{ pb}, \\ \sigma(\Upsilon(2S)) \times \mathcal{B}(\Upsilon(2S) \rightarrow \mu^+ \mu^-) &= 526 \pm 20 \text{ (stat)} \pm 21 \text{ (syst)} \text{ pb}, \\ \sigma(\Upsilon(3S)) \times \mathcal{B}(\Upsilon(3S) \rightarrow \mu^+ \mu^-) &= 242 \pm 16 \text{ (stat)} \pm 10 \text{ (syst)} \text{ pb}.\end{aligned}$$



- Differential cross-sections of $\Upsilon(nS)$



$d\sigma/dp_T$ of $\Upsilon(nS)$

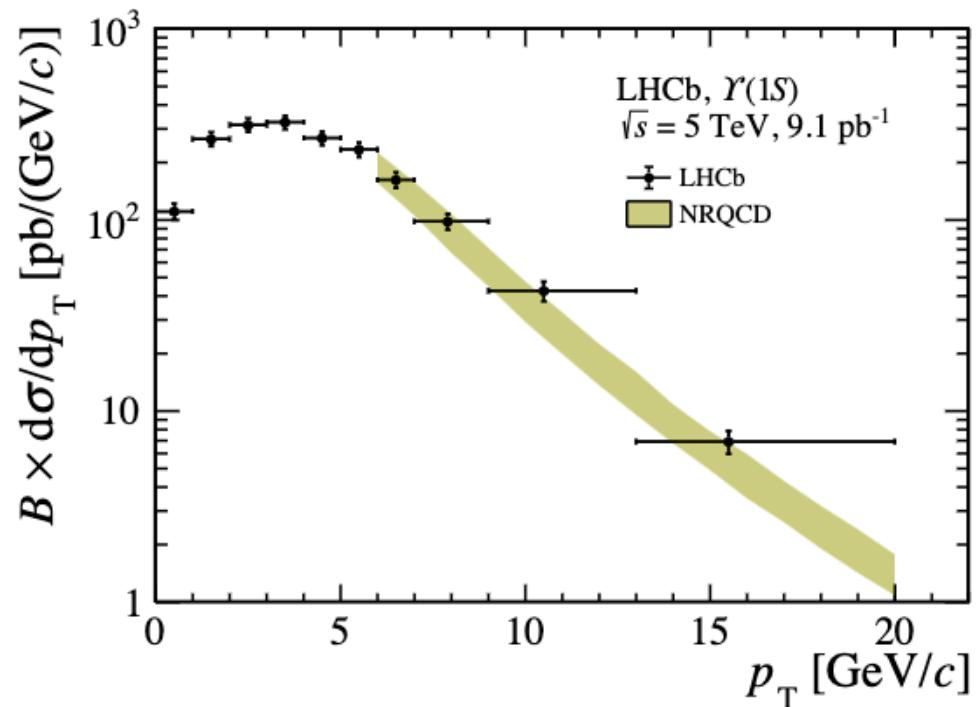


$d\sigma/dy$ of $\Upsilon(nS)$

Cross-sections

[arXiv:2212.12664 \[hep-ex\]](https://arxiv.org/abs/2212.12664)

- ★ Comparison with NRQCD [[Chin. Phys. C 39 \(2015\) 123102](https://doi.org/10.1088/1674-1137/39/12/123102), Jianxiong Wang, Yu Feng, Bin Gong etc.]



J/ψ production cross-section at $\sqrt{s} = 5 \text{ TeV}$

[JHEP 11 \(2021\) 081](#)

Analysis strategy

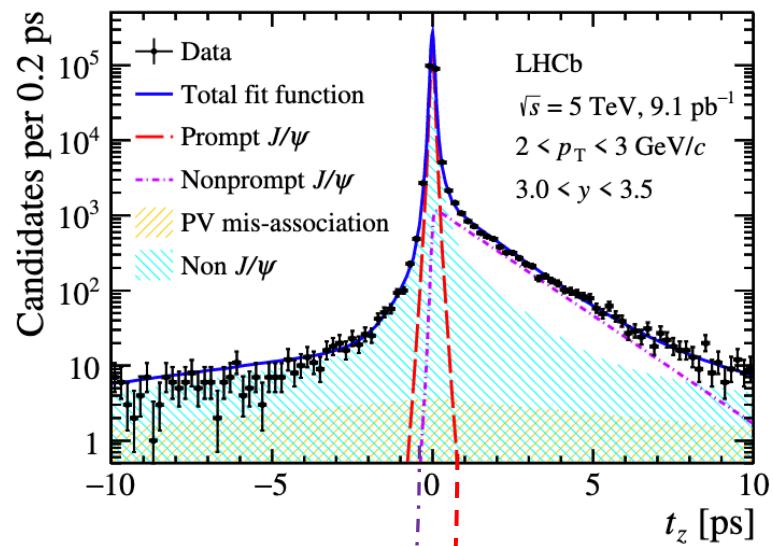
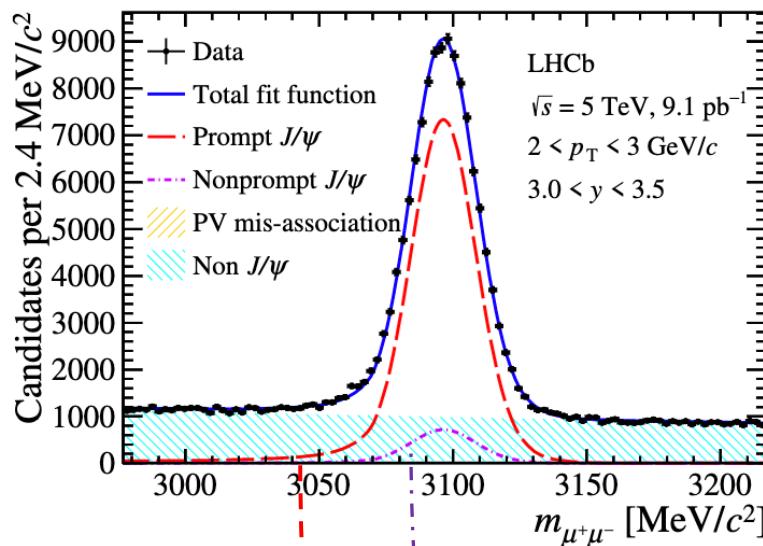
[JHEP 11 \(2021\) 081](#)

- ★ Differential cross-section:

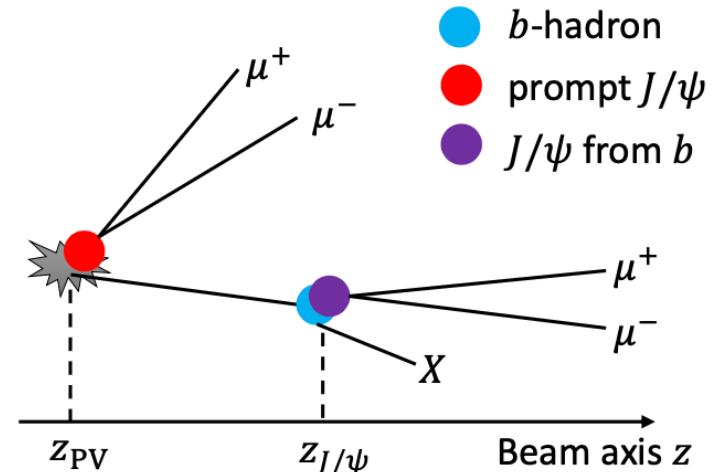
$$\frac{d^2\sigma}{dydp_T} = \frac{N_{\text{observed}}(J/\psi \rightarrow \mu^+\mu^-)/\epsilon_{\text{tot}}}{\Delta y \times \Delta p_T \times \mathcal{L} \times \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}$$

Kinematic range: $0 < p_T < 20 \text{ GeV}/c$, $2.0 < y < 4.5$

- ★ Two-dimensional fit to **mass** and **pseudo decay time** $t_z = \frac{z_{J/\psi} - z_{\text{PV}}}{p_z/m_{J/\psi}}$



J/ψ from b
prompt J/ψ



- ★ Use t_z to separate **prompt J/ψ** and **J/ψ from b**

Cross-sections

[JHEP 11 \(2021\) 081](#)

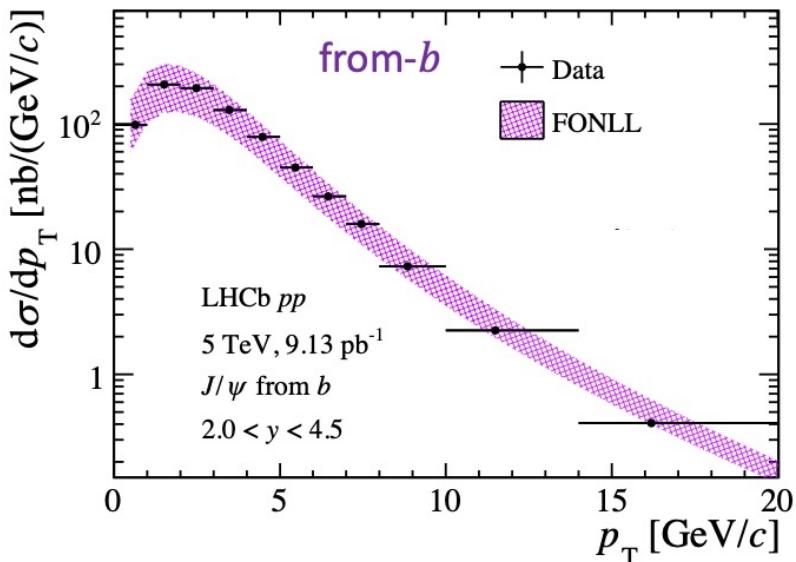
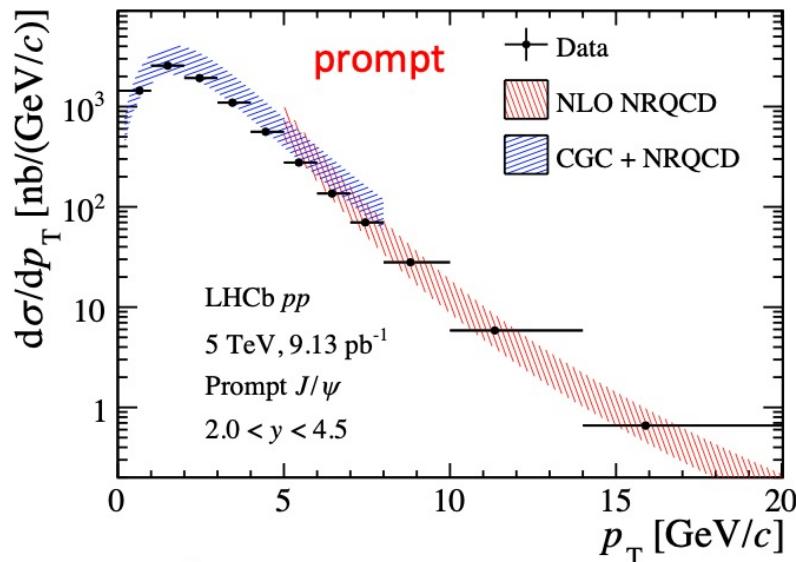
LHCb
THCP



- Integrated cross-sections ($0 < p_T < 20 \text{ GeV}/c$, $2.0 < y < 4.5$)

$$\sigma_{\text{prompt}} = 8.154 \pm 0.010 \text{ (stat.)} \pm 0.283 \text{ (syst.) } \mu\text{b}$$

$$\sigma_{\text{from-}b} = 0.820 \pm 0.002 \text{ (stat.)} \pm 0.034 \text{ (syst.) } \mu\text{b}$$



★ High p_T : NLO NRQCD [Phys. Rev. Lett. 106, 042002](#)

★ Low p_T : NRQCD + CGC

(Color Glass Condensate effective theory)

[Phys. Rev. Lett. 113, 192301](#)

★ FONLL [JHEP 10 \(2012\) 137](#)

Fixed Order plus Next-to-Leading Logarithms

- Good agreement with predictions both for **prompt J/ψ** and J/ψ from b .

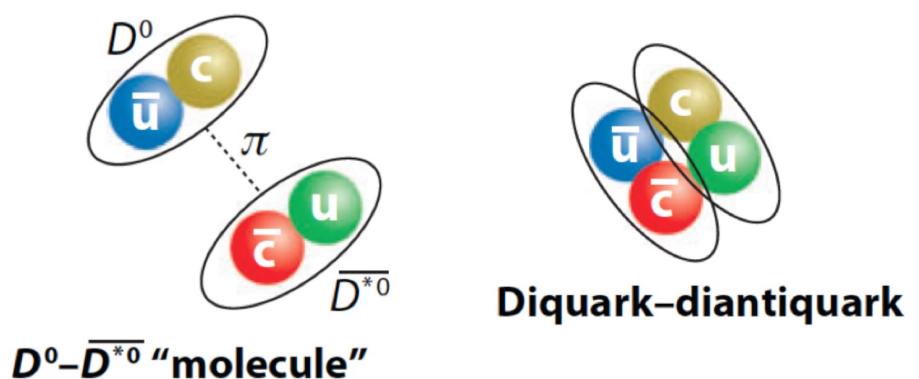
$\chi_{c1}(3872)$ production measurements at $\sqrt{s} = 8$ TeV and 13 TeV

[JHEP 01 \(2022\) 131](#)

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

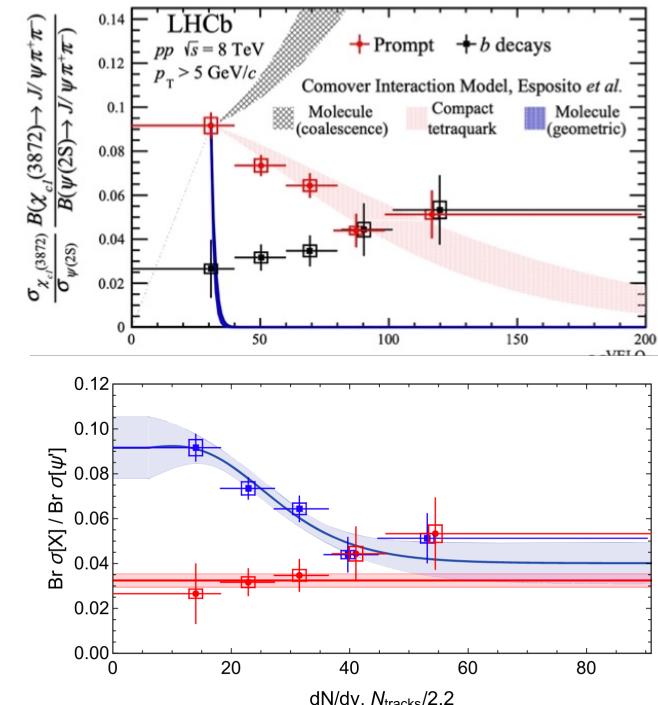
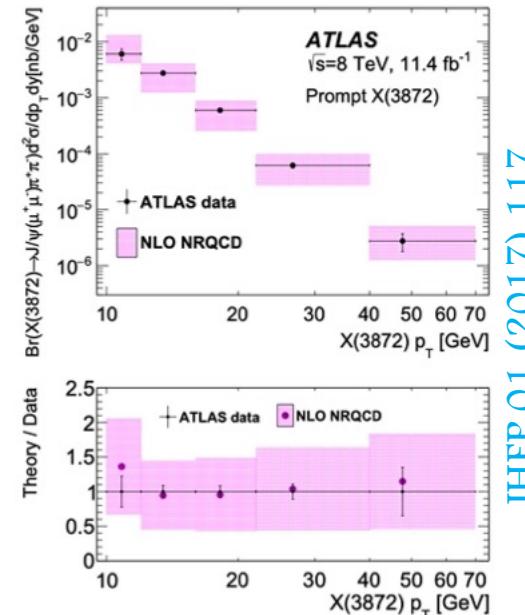
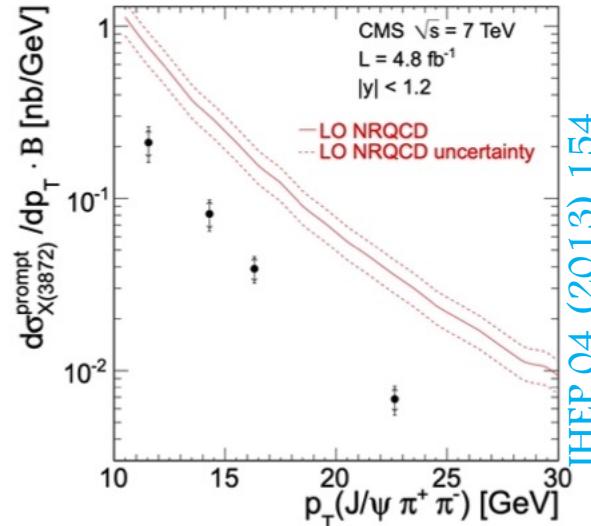
AKA X(3872)

- ★ An exotic hadron discovered by Belle in 2003, and quickly confirmed by BaBar, CDF and D0.
[Phys. Rev. Lett. 91, 262001](#)
- ★ $\delta E = m_{D^0} + m_{\bar{D}^{*0}} - m_{\chi_{c1}(3872)} = 70 \pm 120 \text{ keV}$
[Phys. Rev. D102, 092005](#) [JHEP 08 \(2020\) 123](#)
- ★ $J^{pc} = 1^{++}$ determined by LHCb [Phys. Rev. Lett. 110, 222001](#)
- ★ The nature of $\chi_{c1}(3872)$ is still unclear
 - ★ Charmonium?
 - Mass inconsistent with predicted $\chi_{c1}(2P)$ & Isospin breaking
[Phys. Rev. Lett. 110, 222001](#)
 - ★ Hadronic molecule? [Phys. Rev. B590, 209](#)
 - ★ Compact tetraquark? [Phys. Rev. D71, 014028](#)
 - ★ Mixture of states? [Phys. Rev. D96, 074014](#)
 - $\chi_{c1}(2P) + D^0 - \bar{D}^{*0}$?



Hadro-production of $\chi_{c1}(3872)$ at LHC

- CMS results $d\sigma/dp_T <$ LO NRQCD for D^0 - \bar{D}^{*0} molecule [JHEP 04 \(2013\) 154](#)
- ATLAS results are consistent with NLO NRQCD prediction for a mixed $\chi_{c1}(2P) - D^0 \bar{D}^{*0}$ state [JHEP 01 \(2017\) 117](#)



- LHCb: $\chi_{c1}(3872)/\psi(2S)$ vs multiplicity in pp collisions
 - ★ Prompt: $\chi_{c1}(3872)$ suppressed relative to $\psi(2S)$ as multiplicity increases
 - ★ From b : no significant dependence on multiplicity is observed

Production measurements of $\chi_{c1}(3872)$ help us better understand its nature !

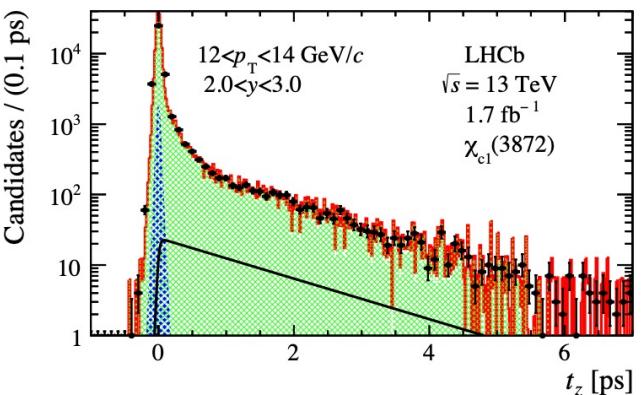
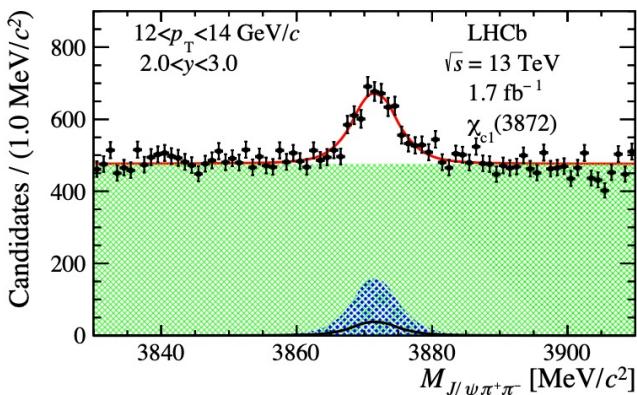
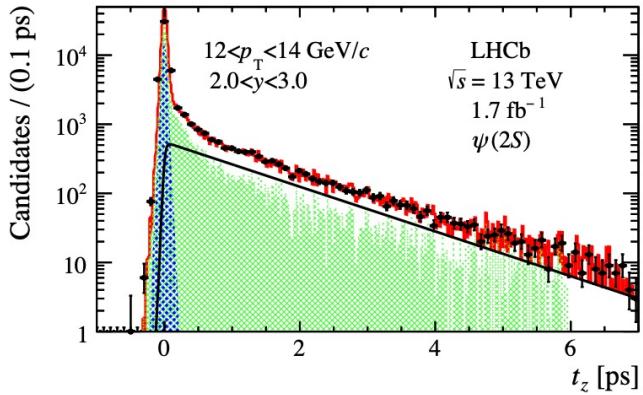
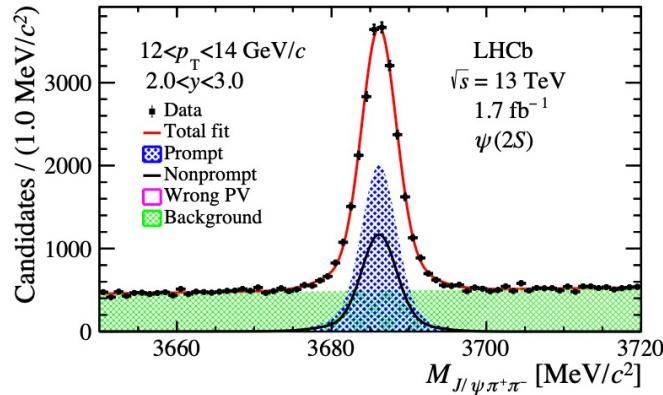
Analysis strategy

[JHEP 01 \(2022\) 131](#)

$$R \equiv \frac{\sigma_{\chi_{c1}(3872)}}{\sigma_{\psi(2S)}} \times \frac{\mathcal{B}(\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} = \frac{N_{\chi_{c1}(3872)}}{N_{\psi(2S)}} \times \frac{\epsilon_{\psi(2S)}}{\epsilon_{\chi_{c1}(3872)}}$$

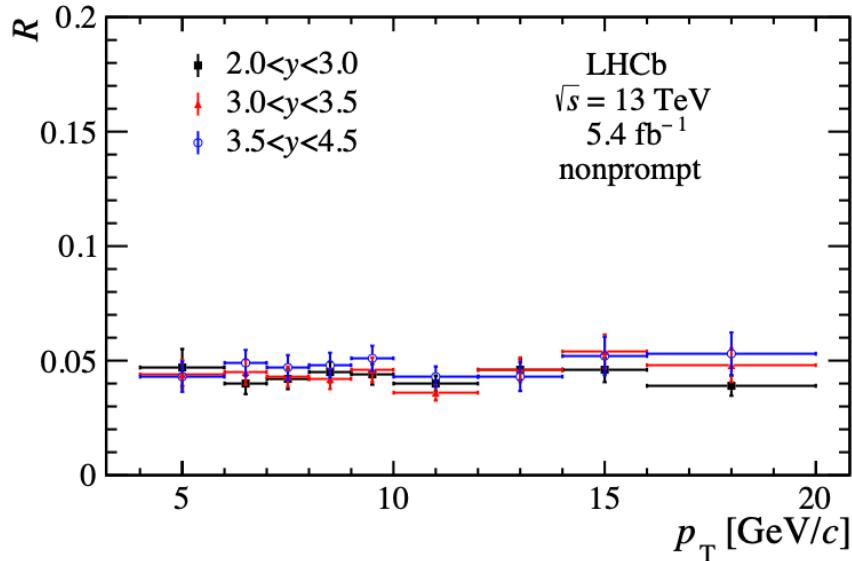
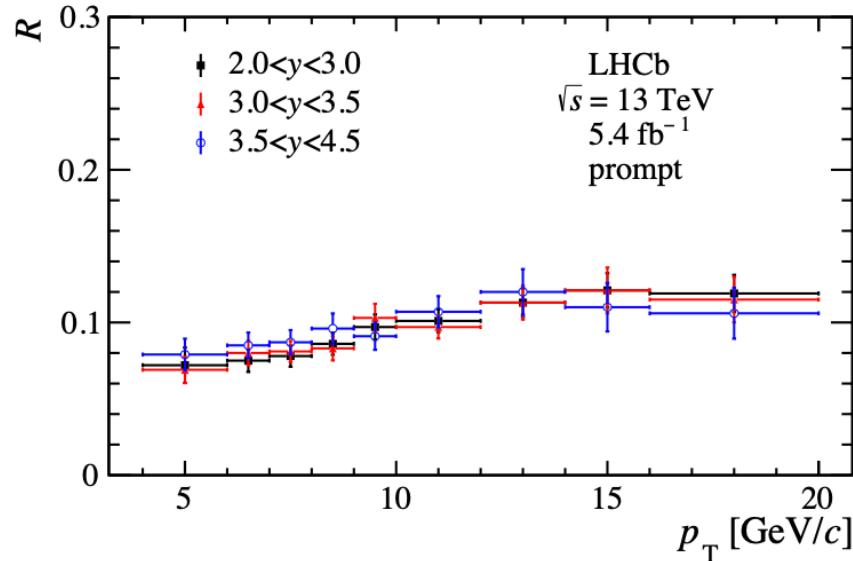
Kinematic range: $4 < p_T < 20 \text{ GeV}/c$, $2.0 < y < 4.5$

- Two-dimensional fit to **mass** and **pseudo decay time** $t_z = \frac{z - z_{\text{PV}}}{p_z/m}$ (m is known value of $\chi_{c1}(3872)$ or $\psi(2S)$ mass)

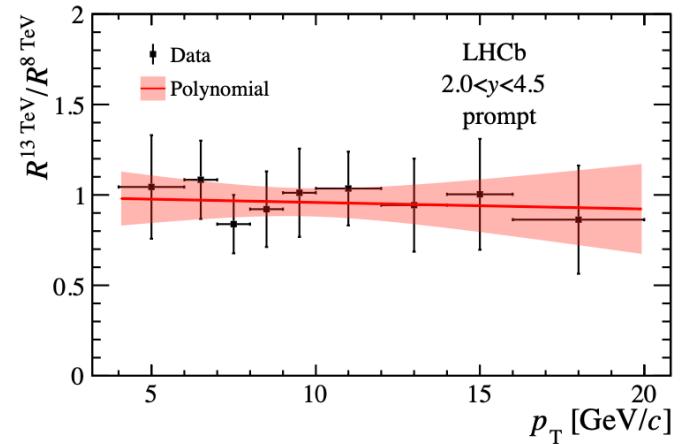


- Use t_z to separate **prompt** $\chi_{c1}(3872)/\psi(2S)$ and $\chi_{c1}(3872)/\psi(2S)$ from **b**

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



- ★ Prompt: increased as functions of p_T
 - $\chi_{c1}(3872)$ production is enhanced relative to $\psi(2S)$ in high p_T region
- ★ Nonprompt: consistent with a flat trend as functions of p_T
- ★ Prompt & nonprompt: no significant dependence on rapidity
- ★ The double ratio of $\chi_{c1}(3872)/\psi(2S)$ at 13 TeV and 8 TeV is consistent with unity



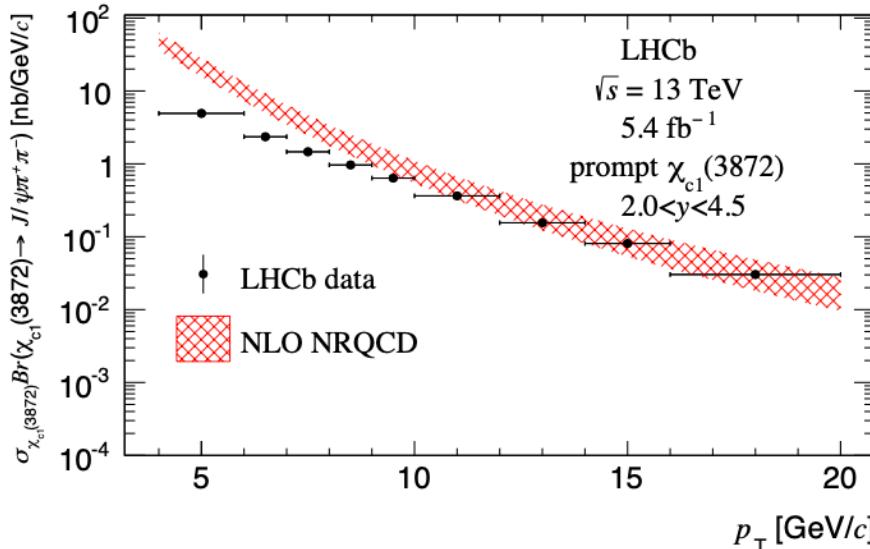
$\chi_{c1}(3872)$ Cross-sections

[JHEP 01 \(2022\) 131](#)

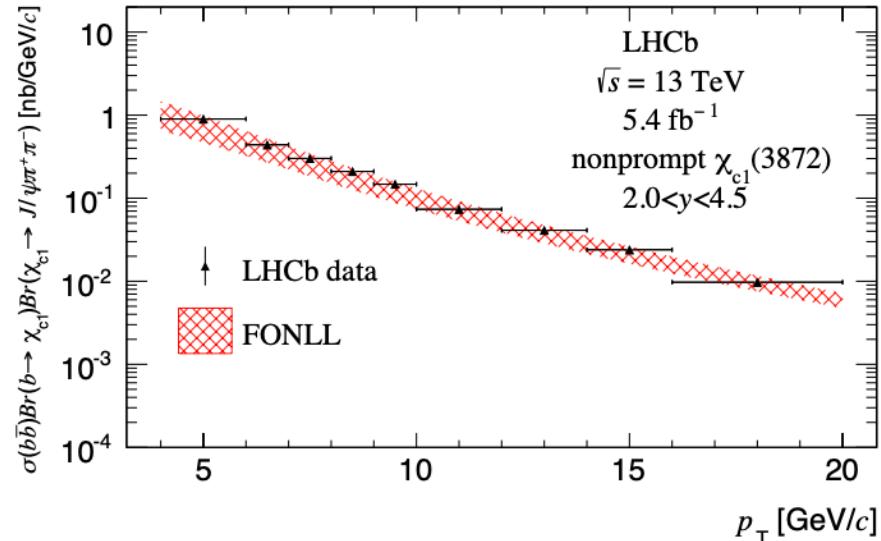
LHCb
FNAL
21st
FPCP



- ★ $\psi(2S)$ production cross-section is taken as an input



[Eur. Phys. J. C80 \(2020\) 185](#)



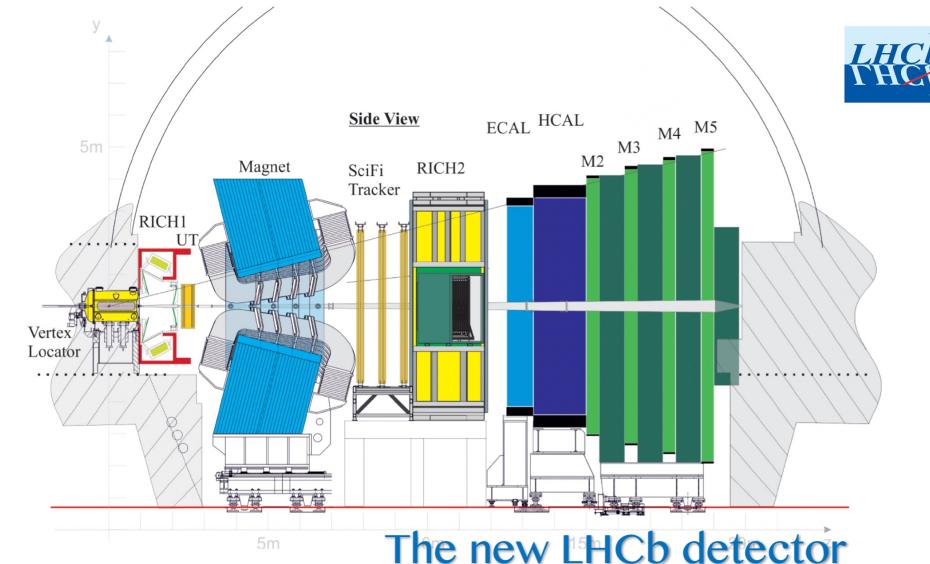
- ★ Prompt compared with NLO NRQCD, and nonprompt compared with FONLL
 - ★ NLO NRQCD: [Phys. Rev. Lett. 106, 042002](#)
 - Assume $\chi_{c1}(2P) - D^0 \bar{D}^{*0}$ mixing mode
 - ★ FONLL [JHEP 10 \(2012\) 137](#)
 - Fixed Order plus Next-to-Leading Logarithms

Summary and outlook

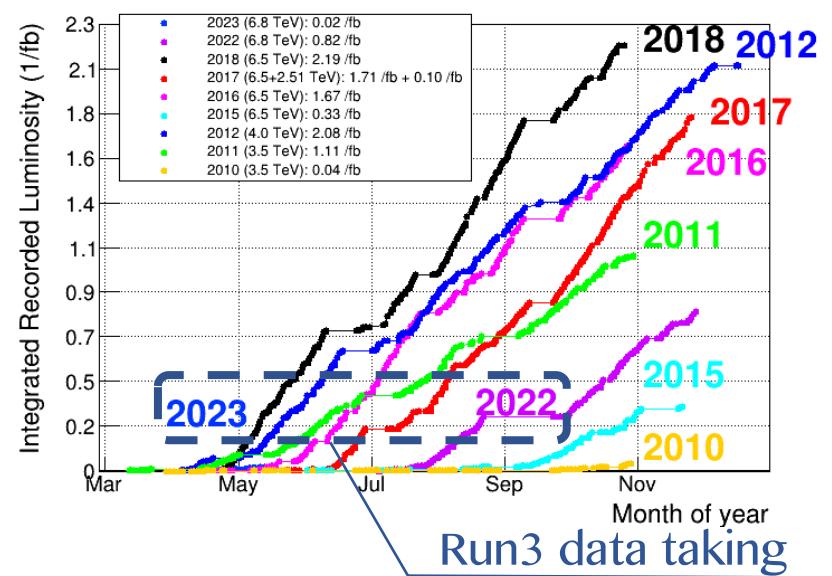
Heavy flavour production measurements are important topics at LHCb.

- ★ Latest heavy flavour production measurements in pp collisions at LHCb are reported
- ★ $\Upsilon(nS)$ production cross-sections at 5 TeV & J/ψ production cross-sections at 5 TeV
 - ★ Results are consistent with theoretical predictions
- ★ $\chi_{c1}(3872)$ production measurements at 8 and 13 TeV
 - ★ Provide new inputs to probe its nature

- ★ In the future, with huge increased luminosity at $\sqrt{s} = 13.6$ TeV, LHCb will process more analyses on heavy flavour production



The new LHCb detector



Thank you for attention!

Back up

LHCb detector

- ★ Key detector systems for heavy flavour production measurement

- ★ Vertex reconstruction with **Vertex Locator (Velo)**

- Separate primary and secondary vertices

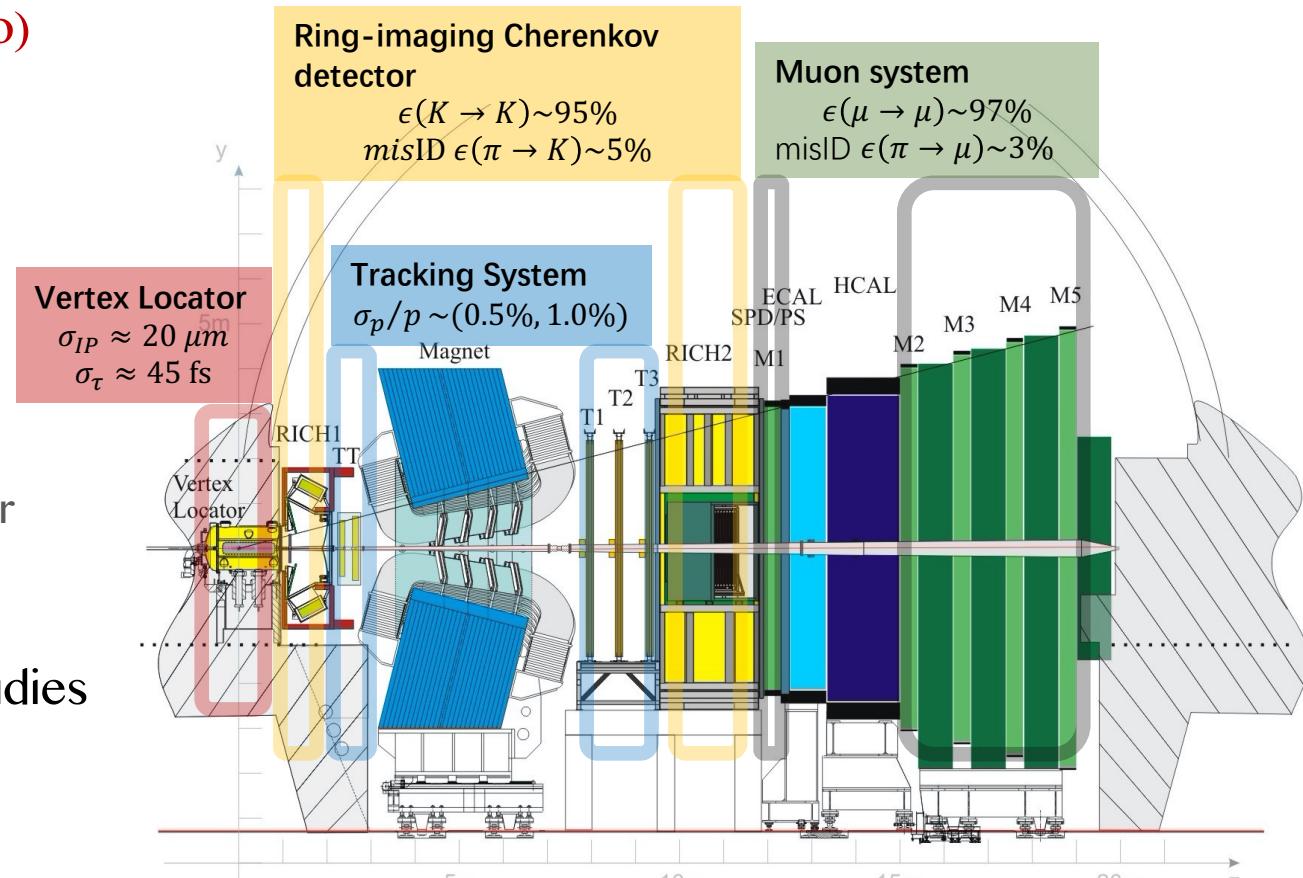
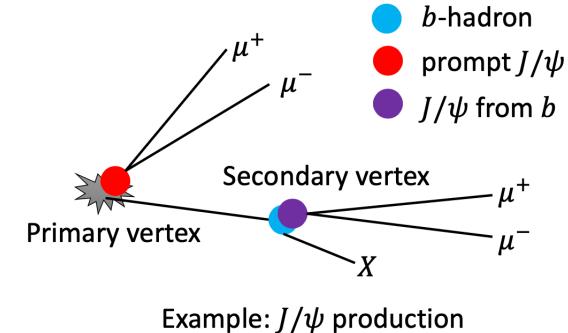
- ★ Track reconstruction with **Tracking System**

- Resolution of momentum from 0.5% to 1%

- ★ Particle identification (**RICH & Muon System**)

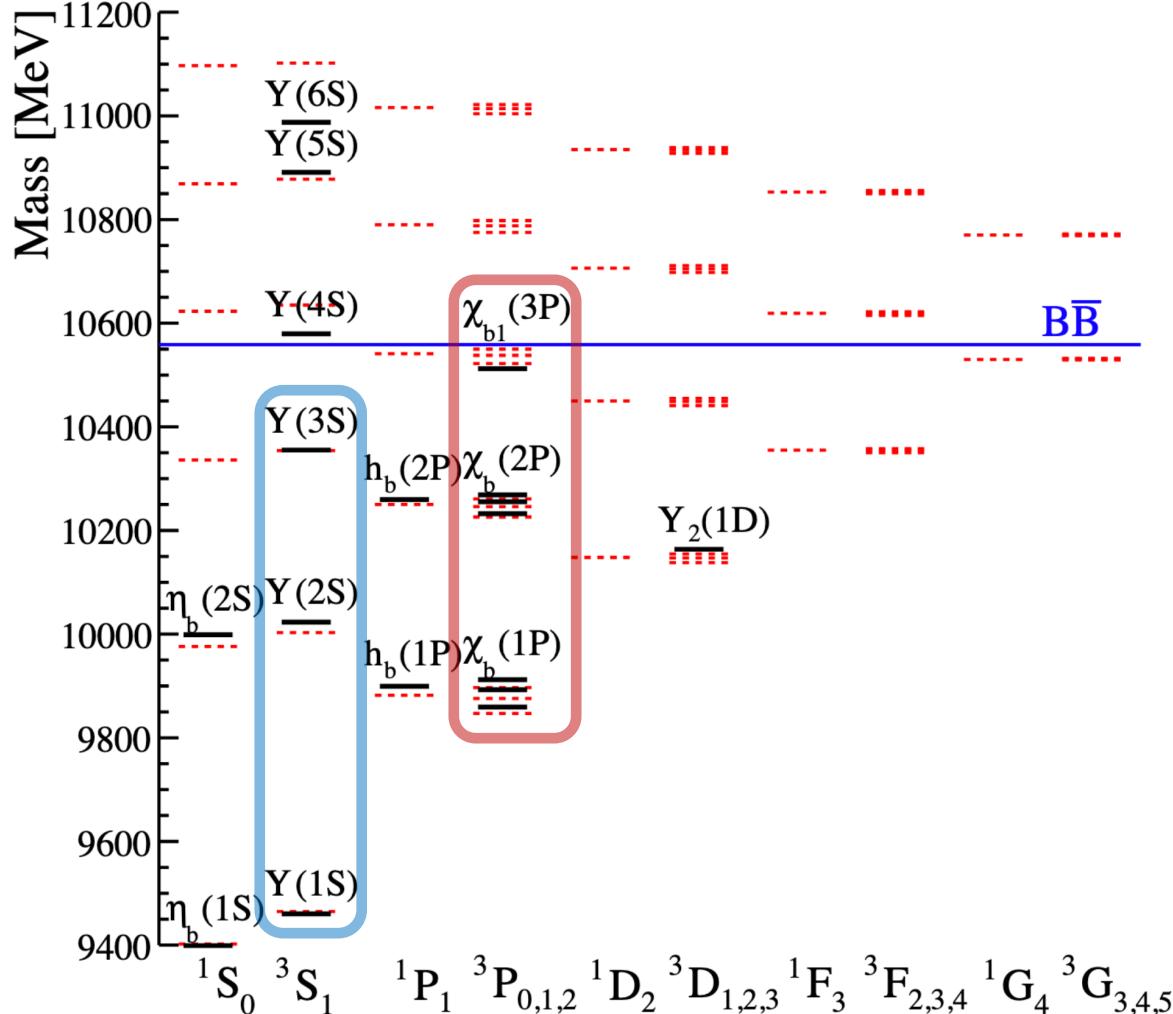
- Charged hadron: ring-imaging Cherenkov detector
 - μ : muon detector

- ★ An ideal laboratory for heavy flavour production studies



JINST 3 (2008) S08005, IJMPA 30 (2015) 1530022

Bottomonium studies at LHCb



The current status of the bottomonium spectrum.

[[Rev.Mod.Phys 90 \(2018\) 015003](#)]

The dashed lines: the expected states and their masses;

The solid lines: the experimentally established bottomonium states, with masses and spin-parity quantum number

- ★ $\Upsilon(nS)$ production measured via $\mu\mu$
 - ★ 2.76 TeV: [Eur.Phys.J.C 74 \(2014\) 2835](#)
 - ★ 7 & 8 TeV: [JHEP 11 \(2015\) 103](#)
 - ★ 13 TeV: [JHEP 07 \(2018\) 134](#)
- ★ $\Upsilon(nS)$ polarization measured via $\mu\mu$
 - ★ 7 & 8 TeV: [JHEP 12 \(2017\) 110](#)

- ★ $\chi_b(nP)$ production measured via $\Upsilon(nS)\gamma$
 - ★ 7 & 8 TeV: [Eur.Phys.J.C74 \(2014\)3092](#)

This analysis: $\Upsilon(nS)$ production at new energy point

- ★ Dataset: LHCb 2015 pp collision at $\sqrt{s} = 5$ TeV
- ★ Integrated Luminosity: $9.13 \pm 0.18 \text{ pb}^{-1}$

LHCb-PAPER-2022-036

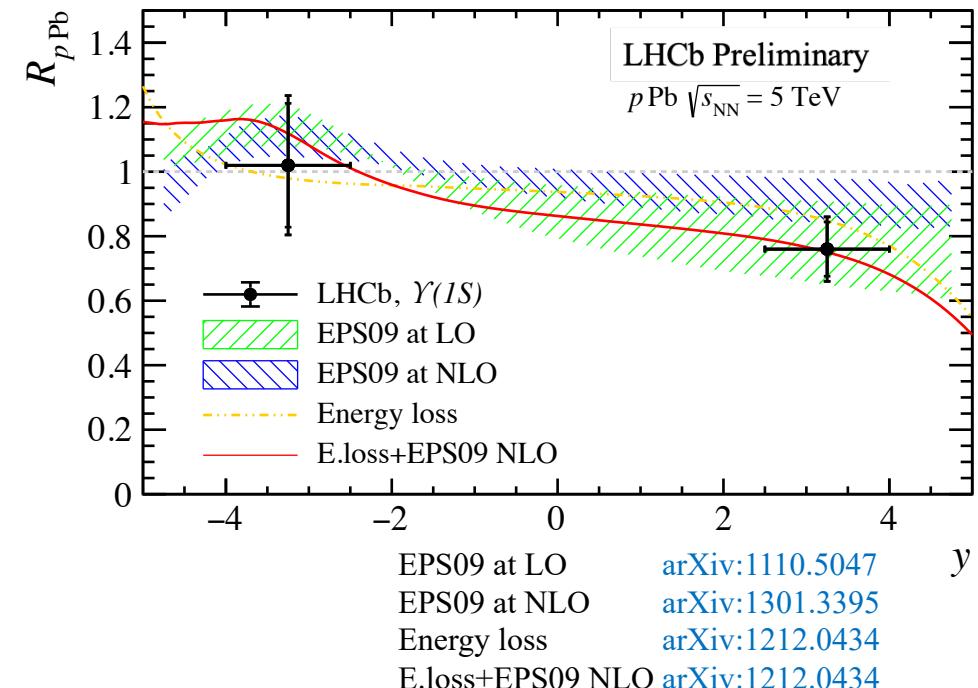
Nuclear modification factor

[arXiv:2212.12664 \[hep-ex\]](https://arxiv.org/abs/2212.12664)



$$R_{p\text{Pb}}(\sqrt{s_{NN}}) = \frac{1}{A} \frac{\sigma_{p\text{Pb}}(\sqrt{s_{NN}})}{\sigma_{pp}(\sqrt{s_{NN}})}$$

- ★ γ production cross-section in pp collisions (σ_{pp}) was used as a reference to determine the nuclear modification factor $R_{p\text{Pb}}$ in proton-lead collisions at $\sqrt{s_{NN}} = 5 \text{ TeV}$ [[JHEP 07 \(2014\) 094](https://doi.org/10.1007/JHEP07(2014)094)],
 ★ σ_{pp} (5 TeV, $p_T < 15 \text{ GeV}/c$, $2.5 < y < 4.0$) is
 $\sigma(\gamma(1S)) \times \mathcal{B}(1S) = 1.12 \pm 0.11 \text{ nb}$
 ★ Obtained by a interpolation of previous LHCb measurements
- ★ Update the $R_{p\text{Pb}}$ using the directly measured
 $\sigma(\gamma(1S)) \times \mathcal{B}(1S) = 1.34 \pm 0.02 \pm 0.05 \text{ nb}$



The updated $R_{p\text{Pb}}$:

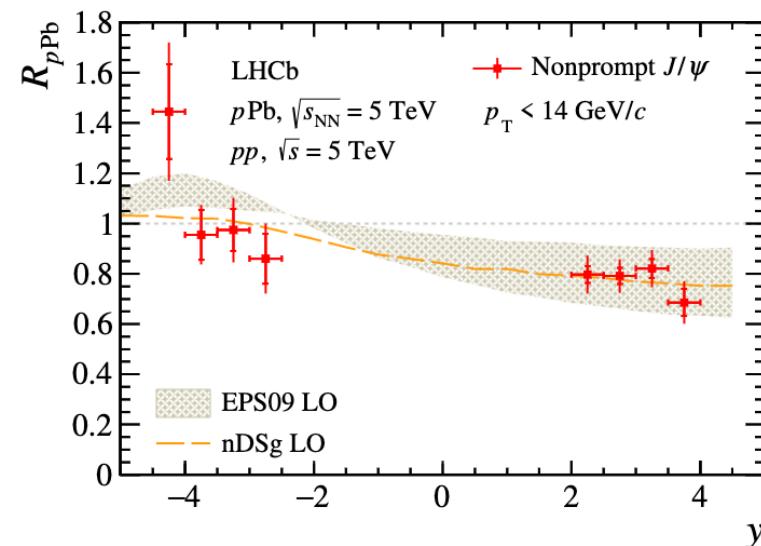
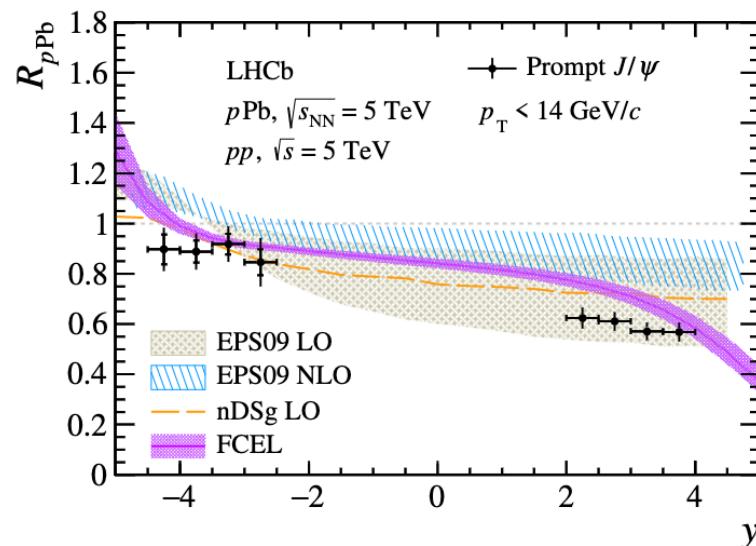
$$R_{p\text{Pb}} = \begin{cases} 1.02 \pm 0.19 \pm 0.10, & (-4.0 < y < -2.5) \\ 0.76 \pm 0.08 \pm 0.05, & (2.5 < y < 4.0) \end{cases}$$

More Precise
 Consistent with theory

Nuclear modification factor

[JHEP 11 \(2021\) 081](#)

- $R_{p\text{Pb}}$ at 5 TeV was calculated using interpolated pp collision cross-sections
- $R_{p\text{Pb}}$ is updated using direct measured pp collision cross-sections

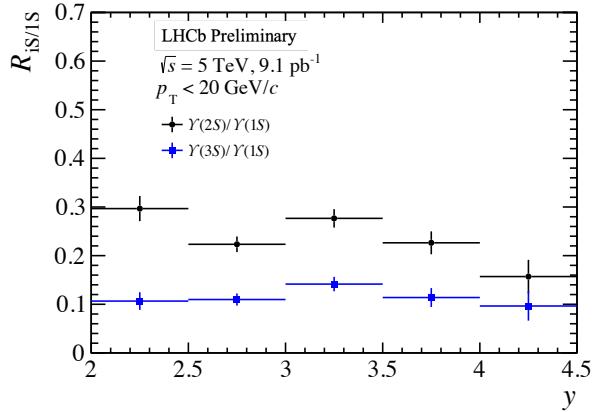
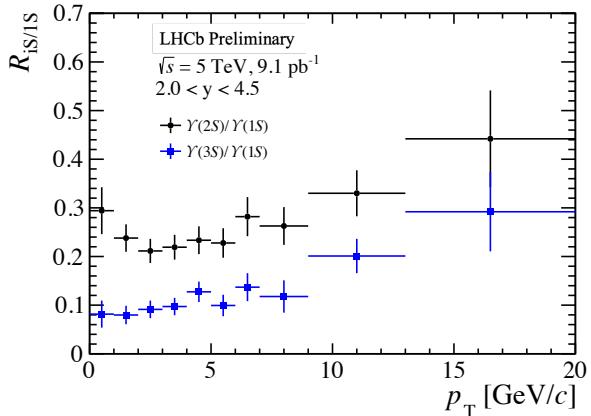


- ★ Agree with most predictions
- ★ EPS09 NLO provides a poorer description in the forward region for prompt J/ψ

- 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](#)

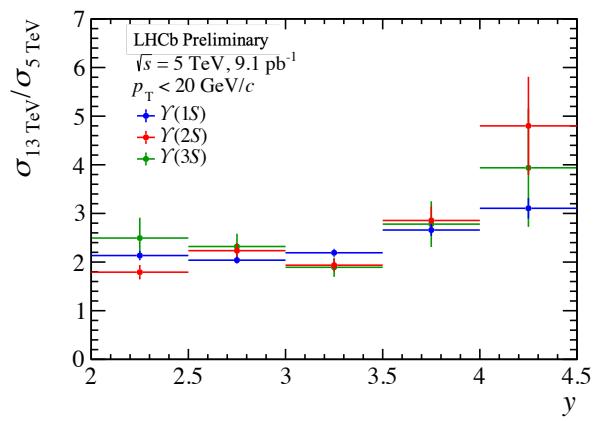
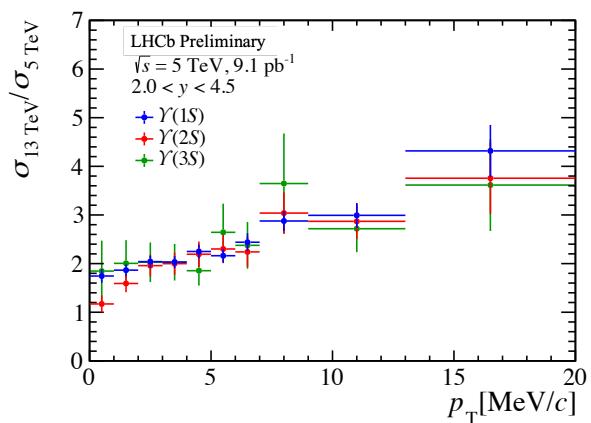
- ★ Cross-section ratios between different Υ states.

- ★ Most of the systematic uncertainties are fully cancelled



- ★ Cross-section ratios between 13 TeV and 5 TeV.

- ★ Systematic uncertainties are partially cancelled



Systematic uncertainty

LHCb-PAPER-2022-036

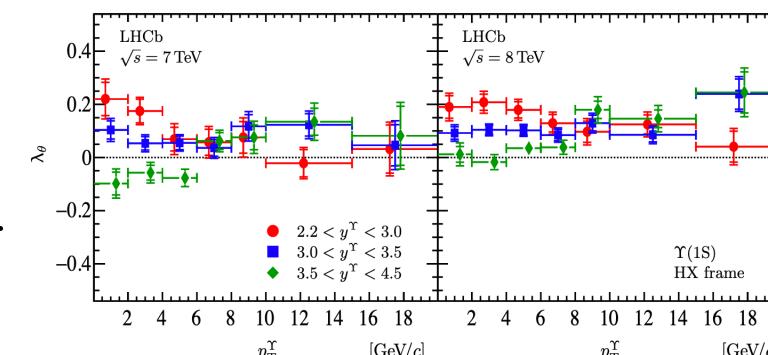
LHCb
21st
FPCP



$$\mathcal{B}(\Upsilon(nS) \rightarrow \mu^+ \mu^-) \times \frac{d^2\sigma}{dy dp_T} = \frac{N_{\text{observed}}(\Upsilon(nS) \rightarrow \mu^+ \mu^-) / \varepsilon_{\text{tot}}}{\Delta y \times \Delta p_T \times \mathcal{L}}$$

Variable	Sources	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	Comment
Signal yields	Fit models	2.5	2.8	3.1	Bin-correlated
	Trigger	0.7-1.9	0.7-2.1	0.7-1.9	Bin-correlated
	Track reconstruction	1.7-3.1	1.7-3.2	1.7-3.4	Bin-correlated
	MuonID	0.5-5.3	0.5-5.1	0.5-5.2	Bin-correlated
Efficiency ϵ	Kinematic spectrum	0.0-4.9	0.0-4.5	0.0-6.3	Bin-independent
	Final-state radiation	1.0	1.0	1.0	Bin-correlated
	Simulation size	0.5-4.5	0.4-3.3	0.4-3.4	Bin-independent
Luminosity		2.0	2.0	2.0	Bin-correlated

- ❖ Polarization: Assume unpolarized $\Upsilon(nS)$
 - ★ Only small polarizations have been found
 - ★ Assume $\lambda_\theta \sim 0.1$, cross-sections vary less than 1.0%.



$\Upsilon(1S)$ polarization in pp collisions at $\sqrt{s} = 7$ TeV and 8 TeV (LHCb)

[JHEP 12 (2017) 110]