Quarkonia and exotic hadron production in pPb collisions at LHCb

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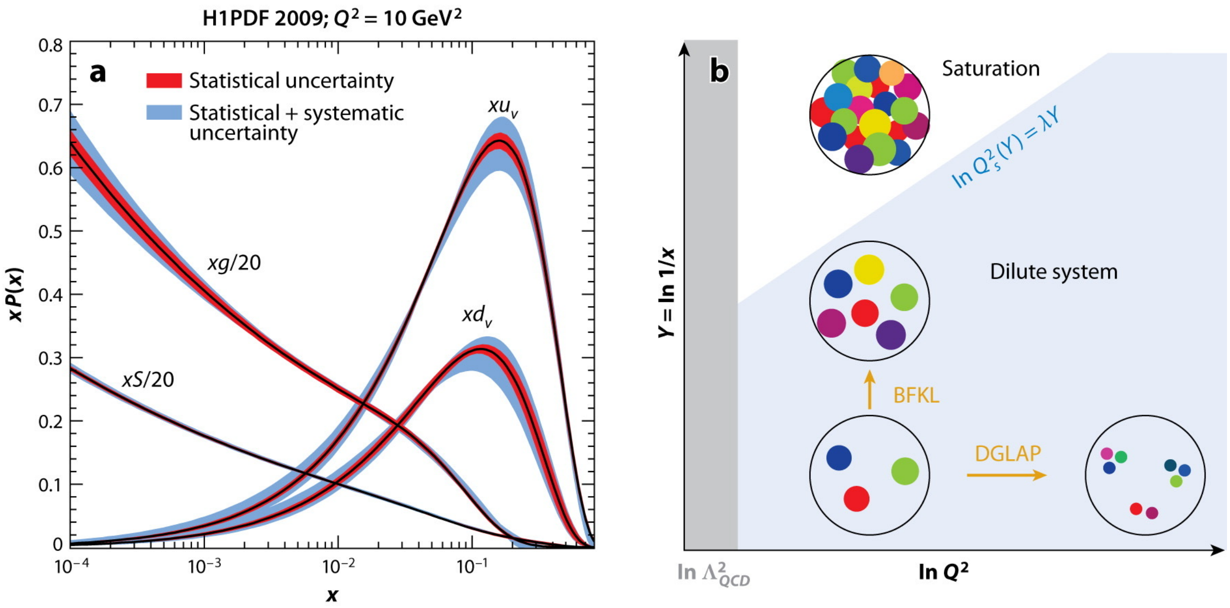
1. Motivation.
Why study pPb collisions?

Cold nuclear matter effects

- nPDFs - Nuclear effects on parton densities (shadowing/antishadowing).
- Colour Glass Condensate – Saturation at low x.
- Energy loss traversing the nucleus.
- Hadronic comovers.



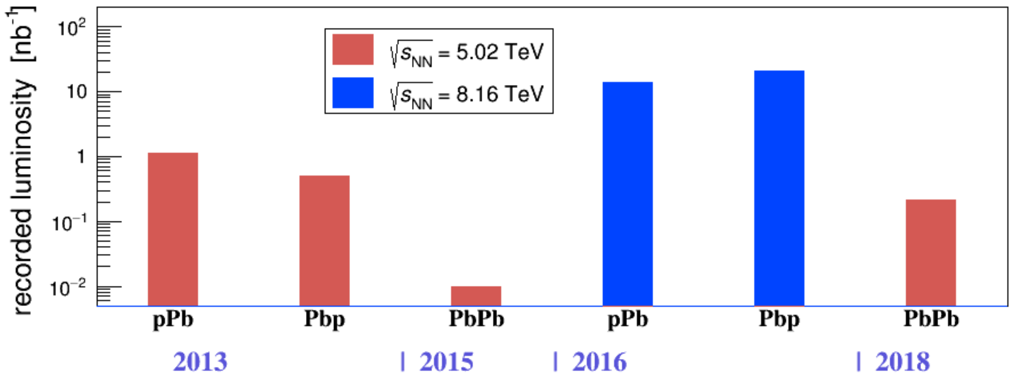
Gelis F, et al. 2010.
Annu. Rev. Nucl. Part. Sci. 60:463–89

1. Motivation.
Why study pPb collisions?

Cold nuclear matter effects	Hot matter
• nPDFs - Nuclear effects on parton densities (shadowing/antishadowing). • Colour Glass Condensate – Saturation at low x. • Energy loss traversing the nucleus. • Hadronic comovers.	Studies with multiplicity show possibility of **QGP-droplet** in small systems. $\Downarrow$ • Quarkonia suppression due to colour screening. • Coalescence rises as hadronisation mechanism. • Energy loss in plasma?

2. The LHCb experiment. More than $b$eauty.

- Fully instrumented forward detector
$$2 < \eta < 5.$$
- Excellent tracking, momentum resolution and particle identification.



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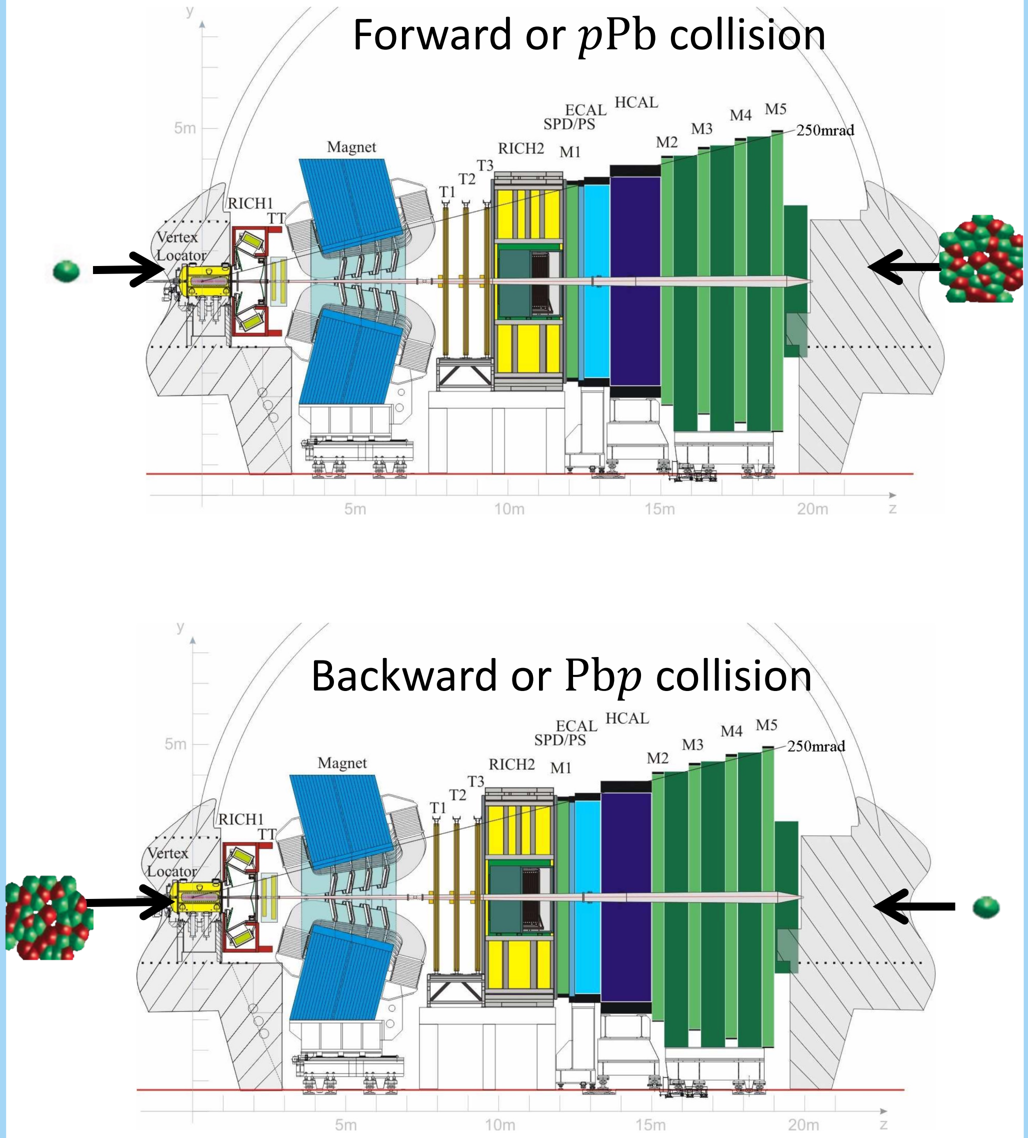


3. LHCb results in pPb collisions. J/ψ production at $\sqrt{s_{\mathrm{NN}}} = 8$ TeV.

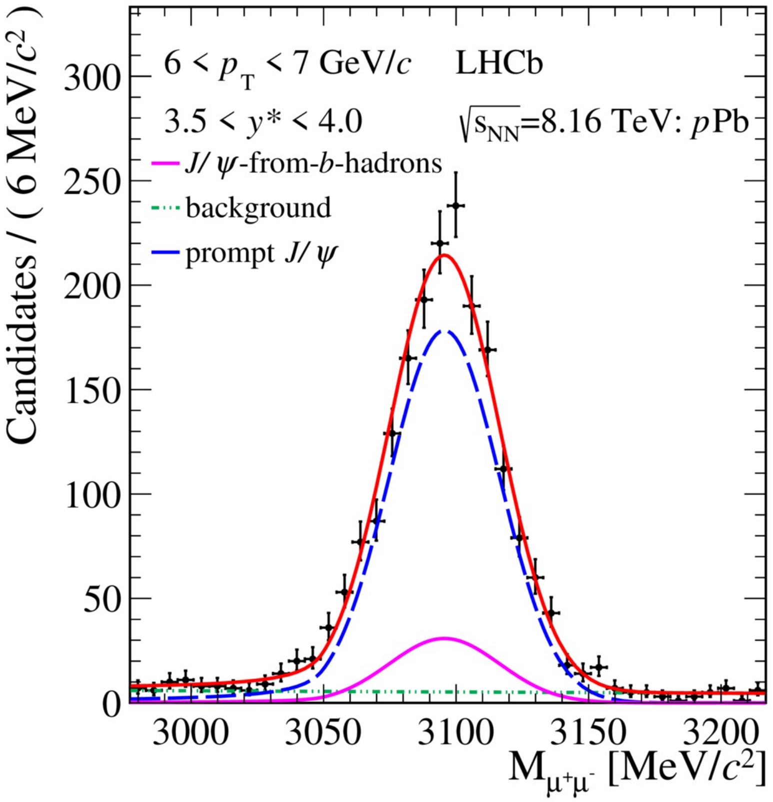
Phys. Lett. B774 (2017) 159

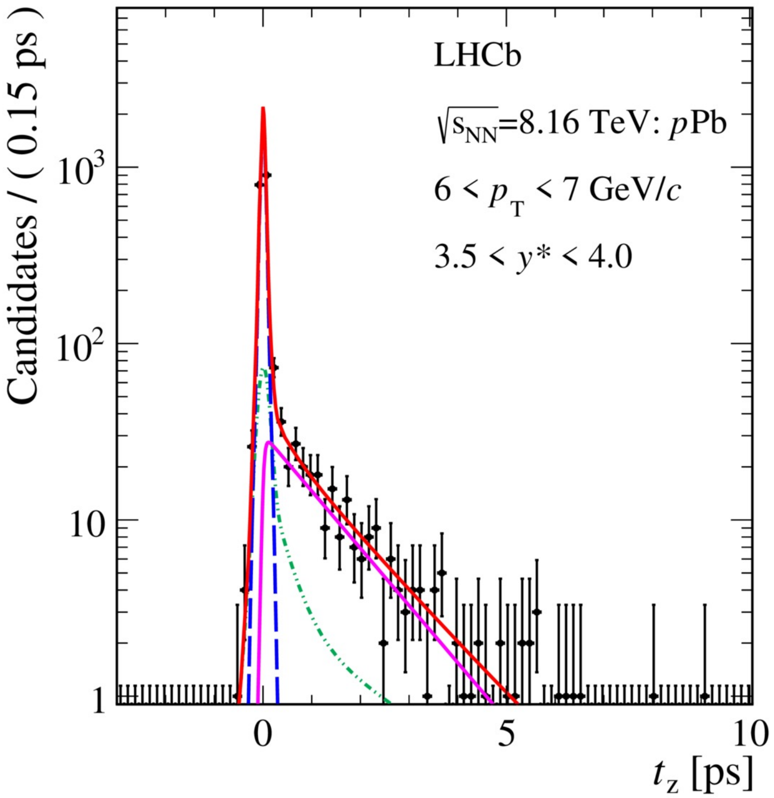
The reconstruction of the candidates is performed through the decay channel:

$$J/\psi \to \mu^+\mu^-,\ \mathcal{B} = (5.961 \pm 0.033)\%.$$

The pseudo-proper time was used to separate the prompt and non-prompt contribution,

$$t_z \equiv \frac{(z_{J/\psi} - z_{\mathrm{PV}}) \times M_{J/\psi}}{p_z}.$$





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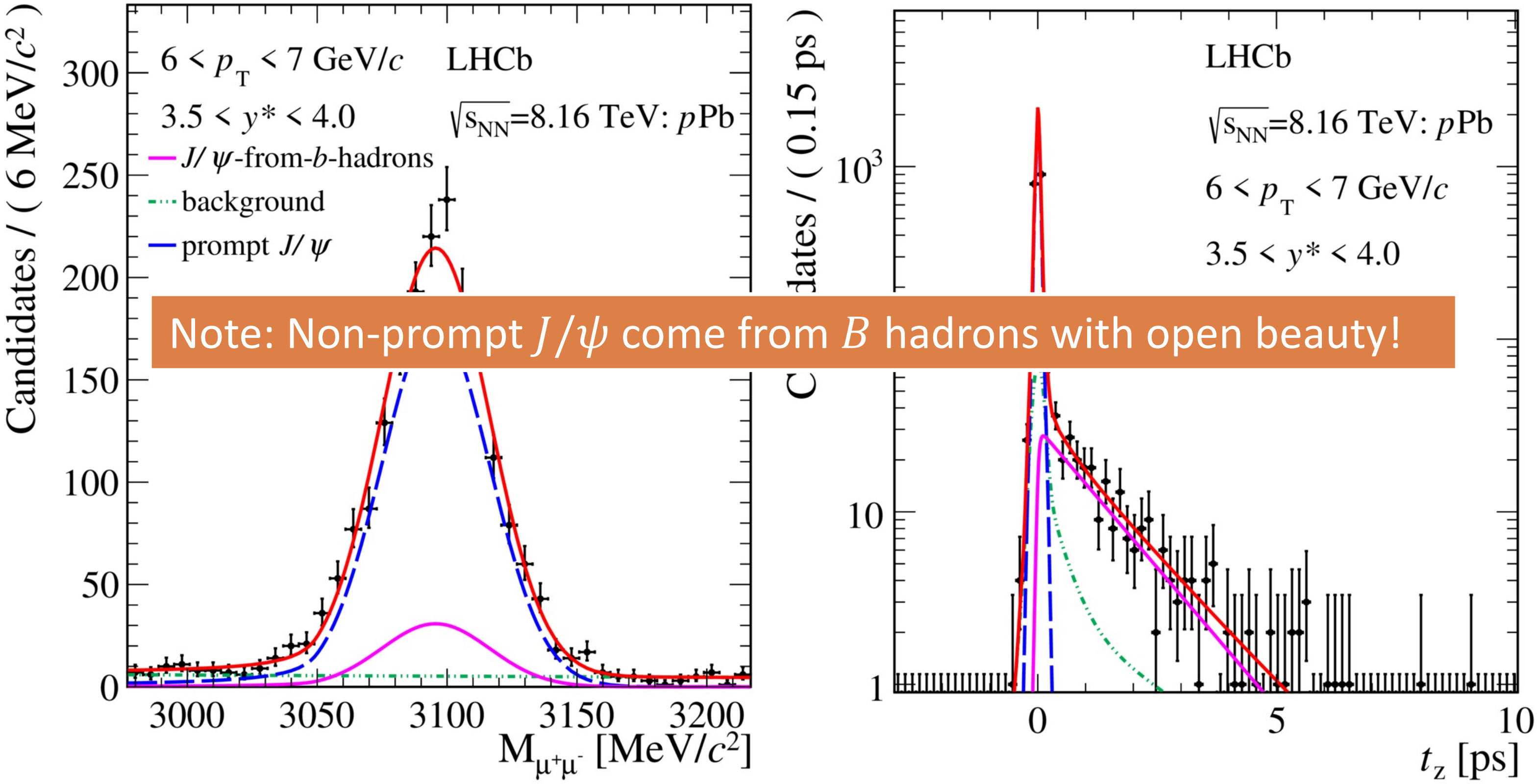


Note: Non-prompt J/ψ come from B hadrons with open beauty!

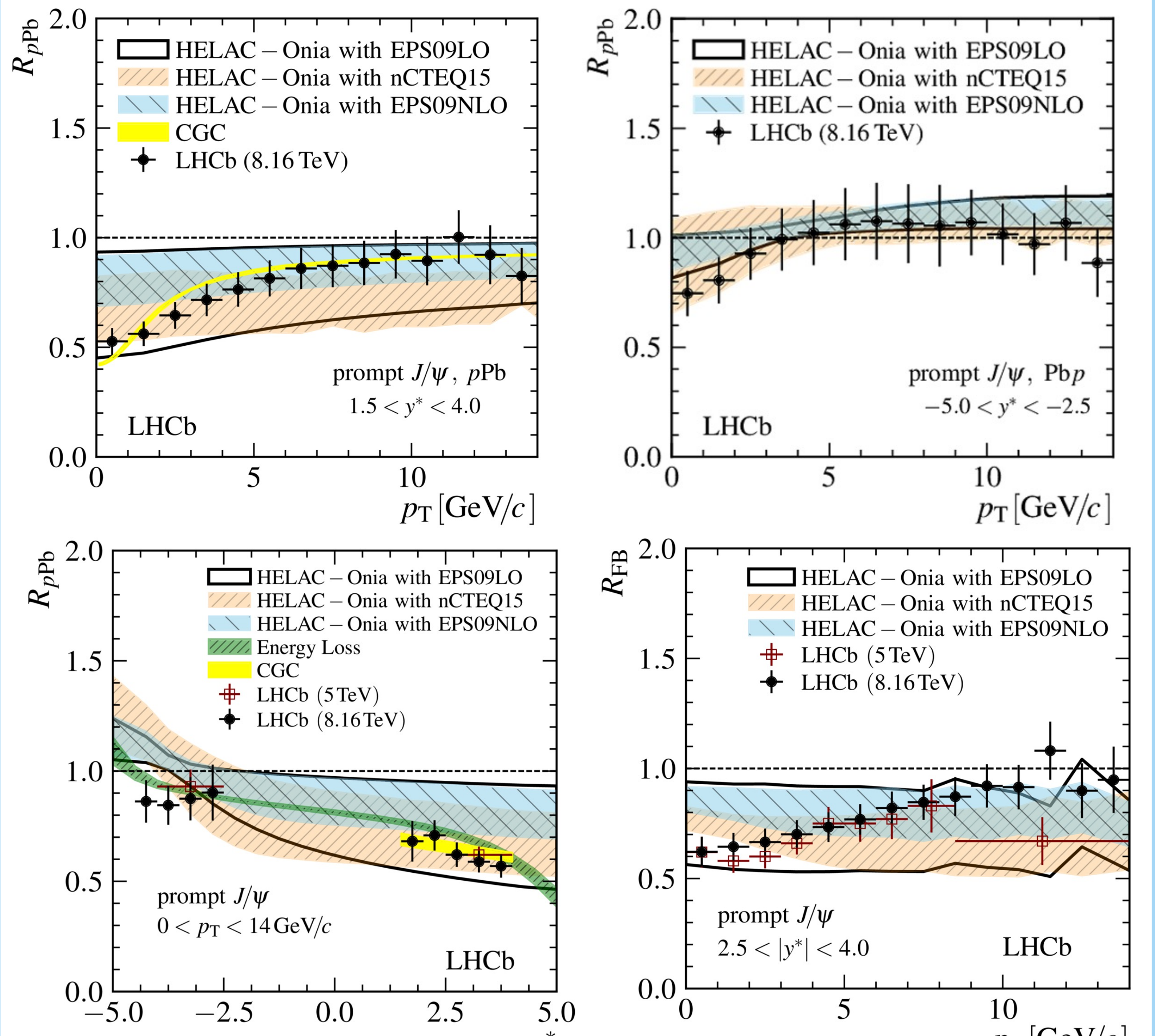
J/ψ production at $\sqrt{s_{NN}} = 8$ TeV.

Nuclear modification factor

$$R_{p\mathrm{Pb}}(p_\mathrm{T}, y^*) = \frac{1}{208} \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{pp}(p_\mathrm{T}, y^*)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}$$

and Forward-Backward ratio

$$R_\mathrm{FB}(p_\mathrm{T}, |y^*|) = \frac{\mathrm{d}^2\sigma_{p\mathrm{Pb}}(p_\mathrm{T}, |y^*|)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}{\mathrm{d}^2\sigma_{\mathrm{Pb}p}(p_\mathrm{T}, -|y^*|)/\mathrm{d}p_\mathrm{T}\mathrm{d}y^*}.$$

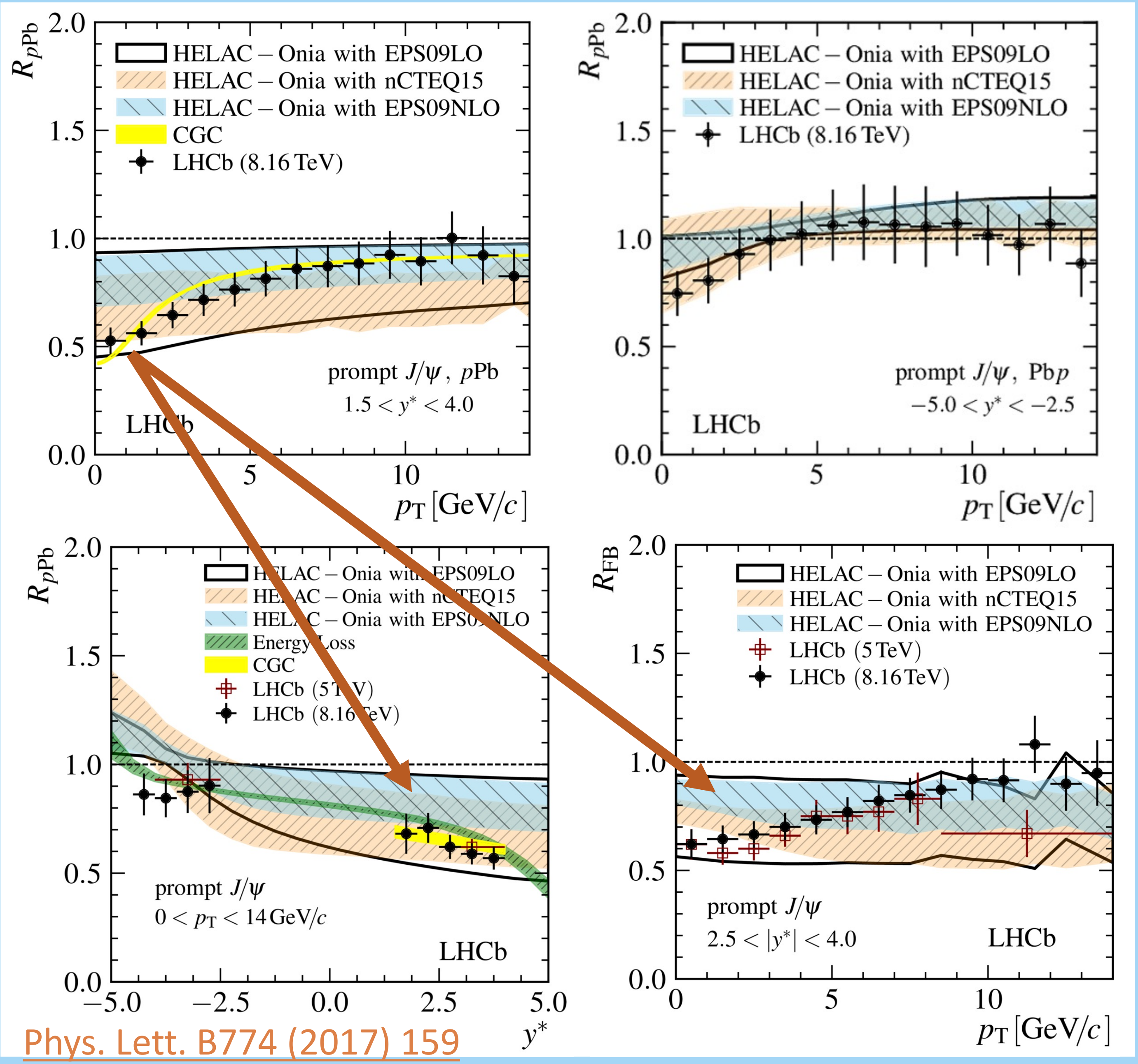


Phys. Lett. B774 (2017) 159

J/ψ production at $\sqrt{s_{NN}} = 8$ TeV.

$R_{p\mathrm{Pb}}$ and R_{FB} for **prompt J/ψ**:

- Stronger suppression at **forward rapidity** $(1.5 < y^* < 4.0) \implies \downarrow x$.
- A strong suppression is shown at **low p_{T}**.
- At high p_{T}, the nuclear modification factor approaches 1.



Phys. Lett. B774 (2017) 159

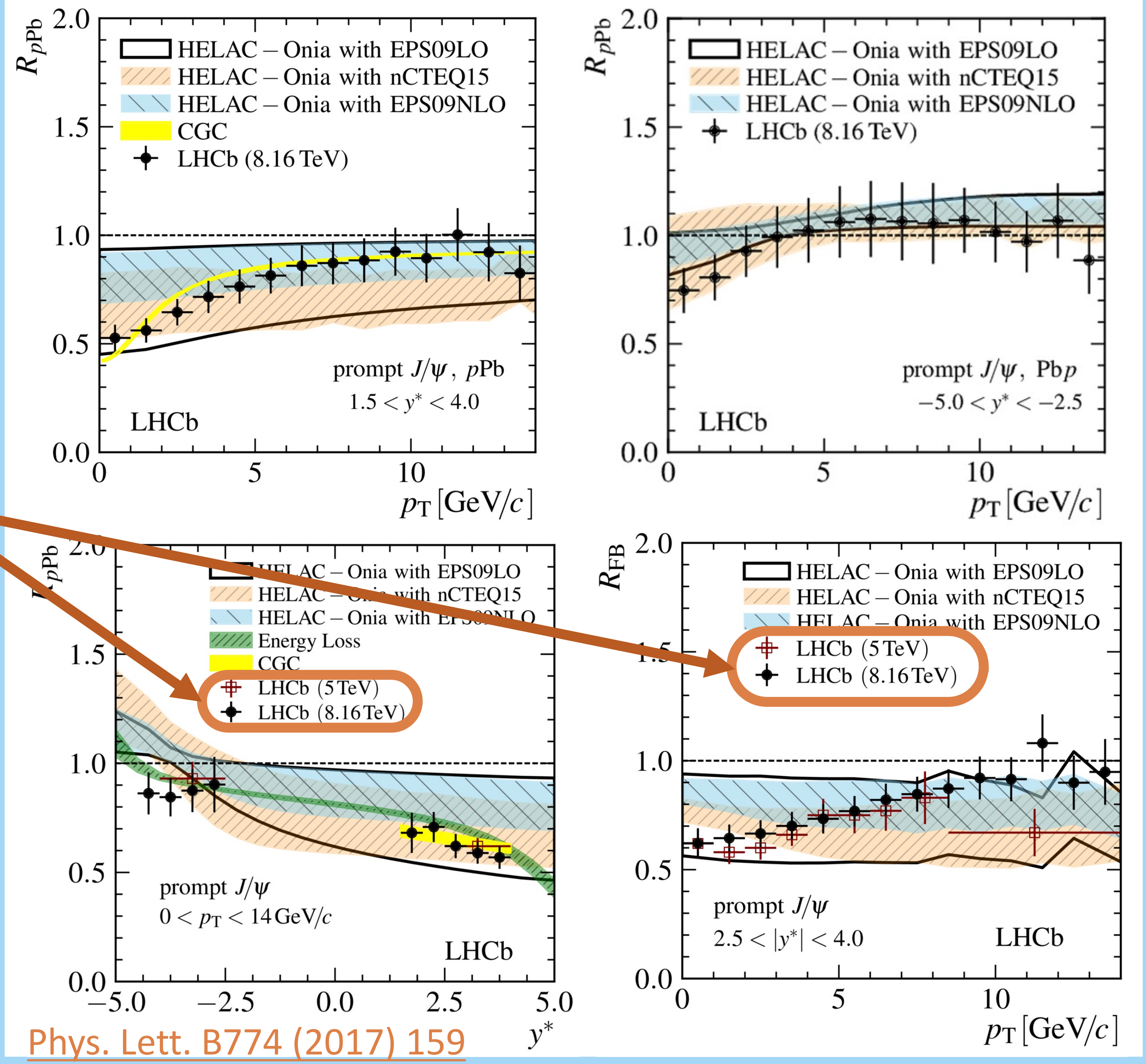
J/ψ production at $\sqrt{s_{NN}} = 8$ TeV.

R_{pPb} and R_{FB} for **prompt J/ψ**.

- Suppression pattern described by all calculations.
- No evidence of energy dependence for CNM effects at LHC energy scales.

Available models:

1. HELAC-Onia event generator with different nPDFs:
   - EPS09LO,
   - nCTEQ15,
   - EPS09NLO.
2. CGC effective field theory in the dilute-tense approximation. Not available at backward rapidity.
3. Coherent energy loss.



Phys. Lett. B774 (2017) 159

3. LHCb results in pPb collisions. $\psi(2S)$ production at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV.

JHEP 03 (2016) 133

The reconstruction of the candidates is performed through the decay channel:

$$\boldsymbol{\psi(2S) \rightarrow \mu^+\mu^-},$$

$$\mathcal{B}(\psi(2S) \rightarrow \mu^+\mu^-) = (7.9 \pm 0.9)\times 10^{-3}$$

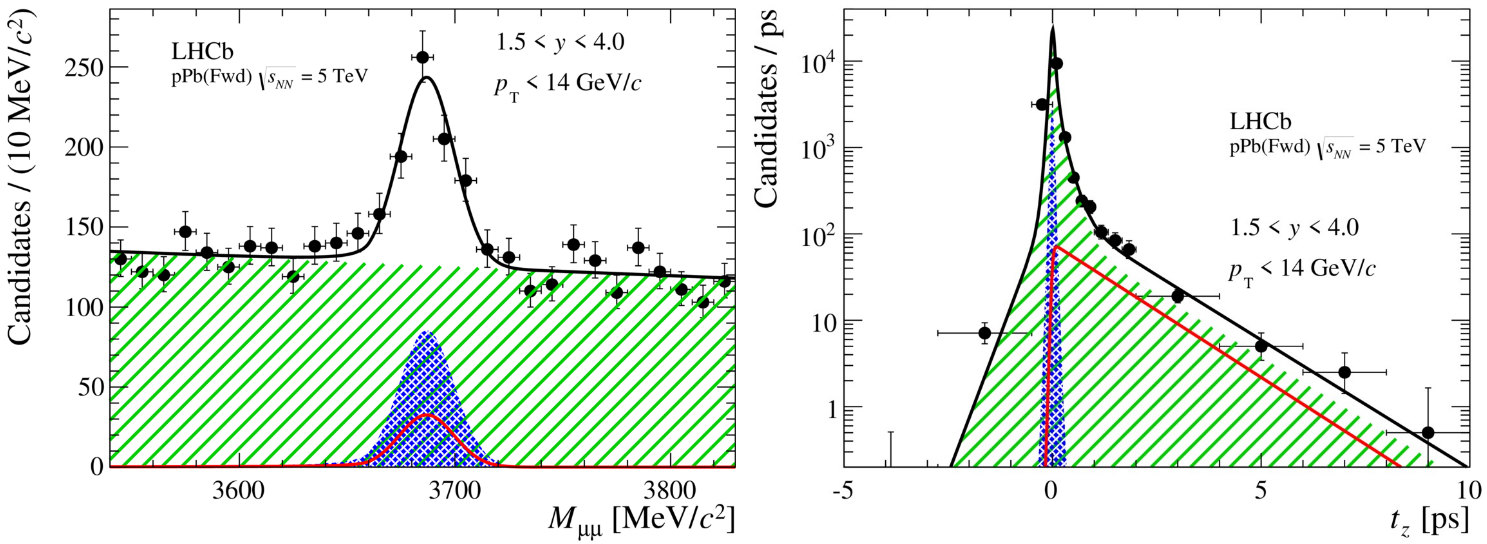
But, assuming lepton universality…

$$\mathcal{B}(\psi(2S) \rightarrow \mu^+\mu^-) = \mathcal{B}(\psi(2S) \rightarrow e^+e^-) =$$

$$= (7.89 \pm 0.17)\times 10^{-3}.$$

The pseudo-proper time was used to separate the prompt and non-prompt contribution.

►Upcoming results at 8TeV!



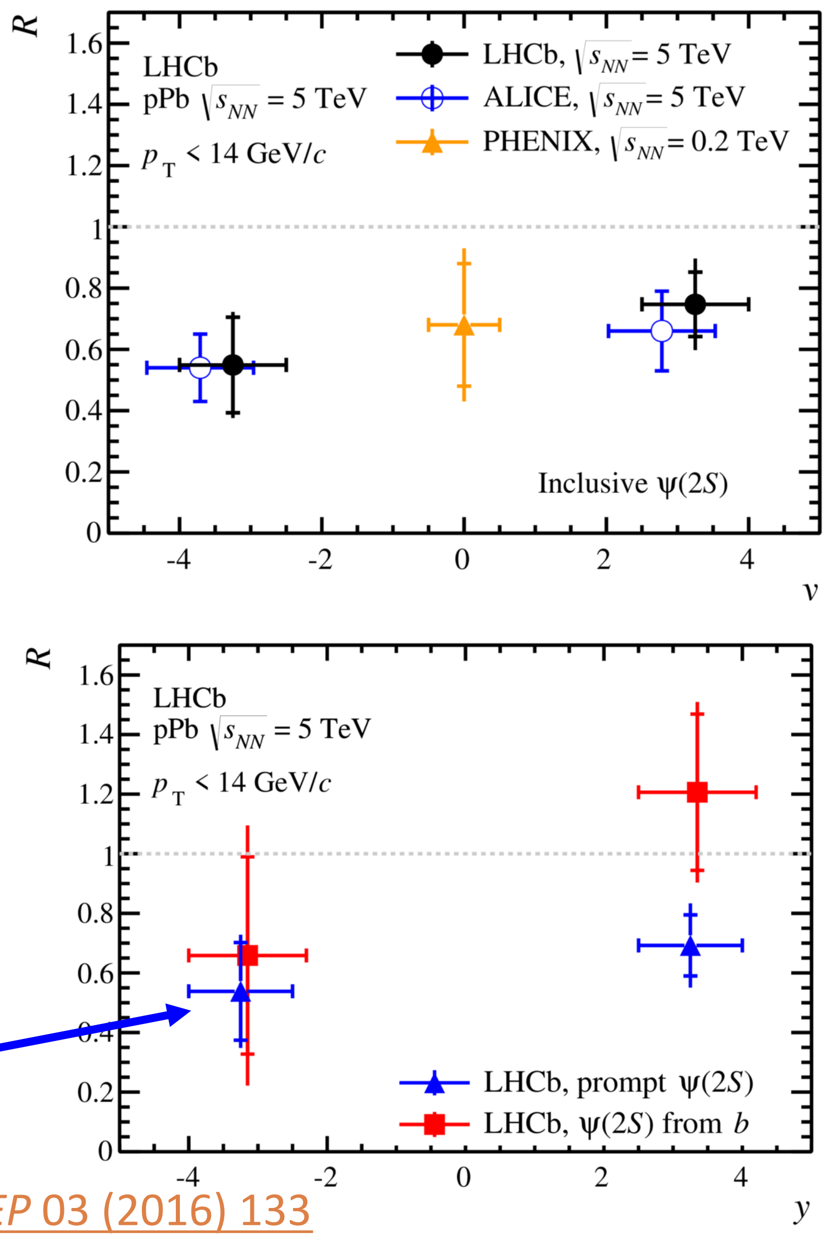
$\psi(2S)$ production at $\sqrt{s_{\rm NN}} = 5$ TeV

$$R \equiv \frac{R^{\psi(2S)}_{p\rm Pb}}{R^{J/\psi}_{p\rm Pb}} = \frac{\sigma^{\psi(2S)}_{p\rm Pb}(5\rm TeV)}{\sigma^{J/\psi}_{p\rm Pb}(5\rm TeV)} \times \frac{\sigma^{J/\psi}_{pp}(5\rm TeV)}{\sigma^{\psi(2S)}_{pp}(5\rm TeV)} \cong \frac{\sigma^{\psi(2S)}_{p\rm Pb}(5\rm TeV)}{\sigma^{J/\psi}_{p\rm Pb}(5\rm TeV)} \times \frac{\sigma^{J/\psi}_{pp}(7\rm TeV)}{\sigma^{\psi(2S)}_{pp}(7\rm TeV)}.$$

unavailable

- R indicates whether there is relative suppression between $\psi(2S)$ and J/ψ:

  $R < 1 \Rightarrow$ more relative suppression of the $\psi(2S)$.
- The results are compatible with ALICE.
- The suppression is only observed for prompt $\psi(2S)$.

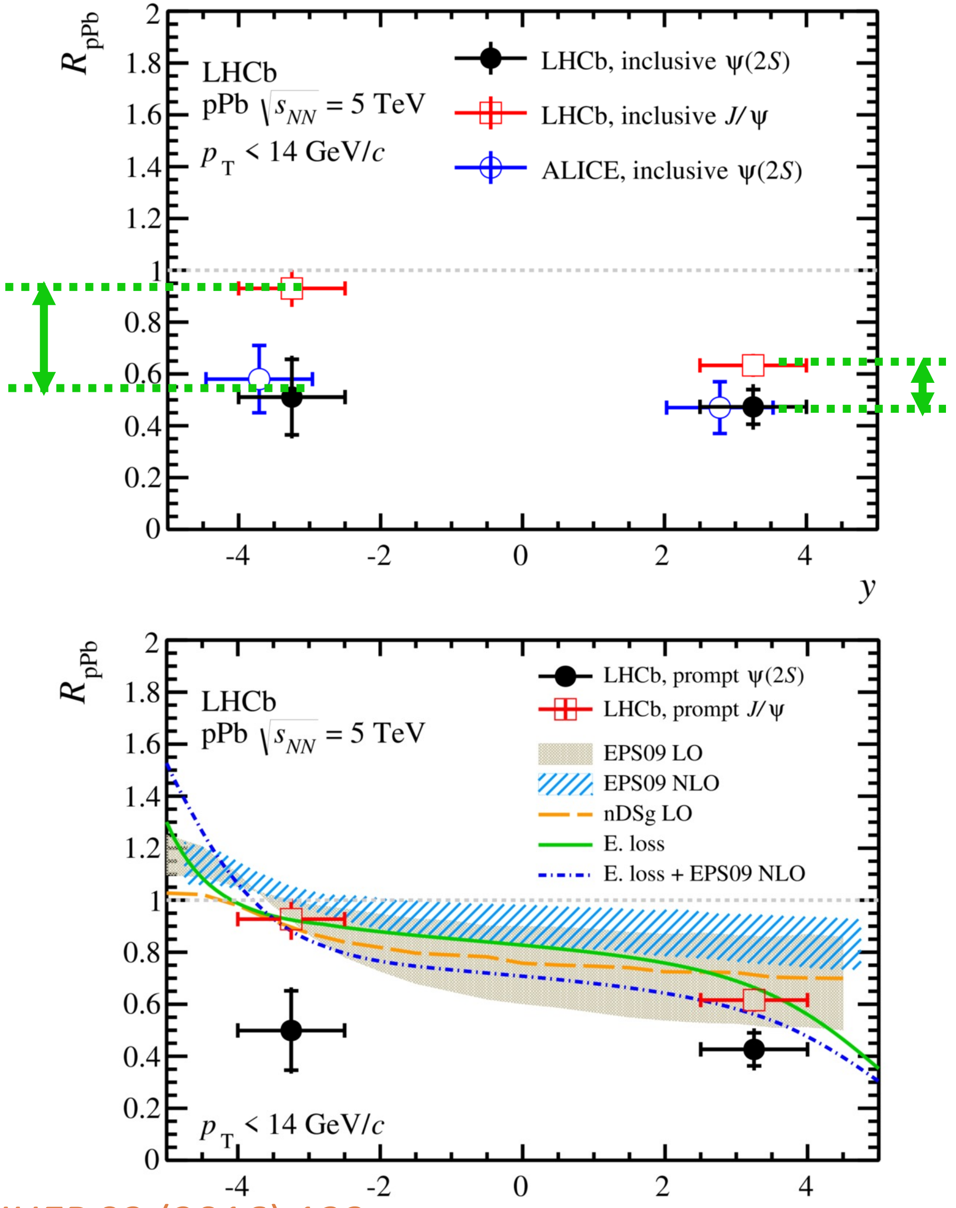


JHEP 03 (2016) 133

$\psi(2S)$ production at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV

$$R_{p\mathrm{Pb}}^{\psi(2S)} = R_{p\mathrm{Pb}}^{J/\psi} \times R.$$

- The nuclear modification is in agreement with previous ALICE measurements.
- **Prompt $\psi(2S)$ mesons** are more suppressed with respect to pp collisions than prompt J/ψ mesons.



JHEP 03 (2016) 133

$\psi(2S)$ production at $\sqrt{s_{\mathrm{NN}}} = 5$ TeV

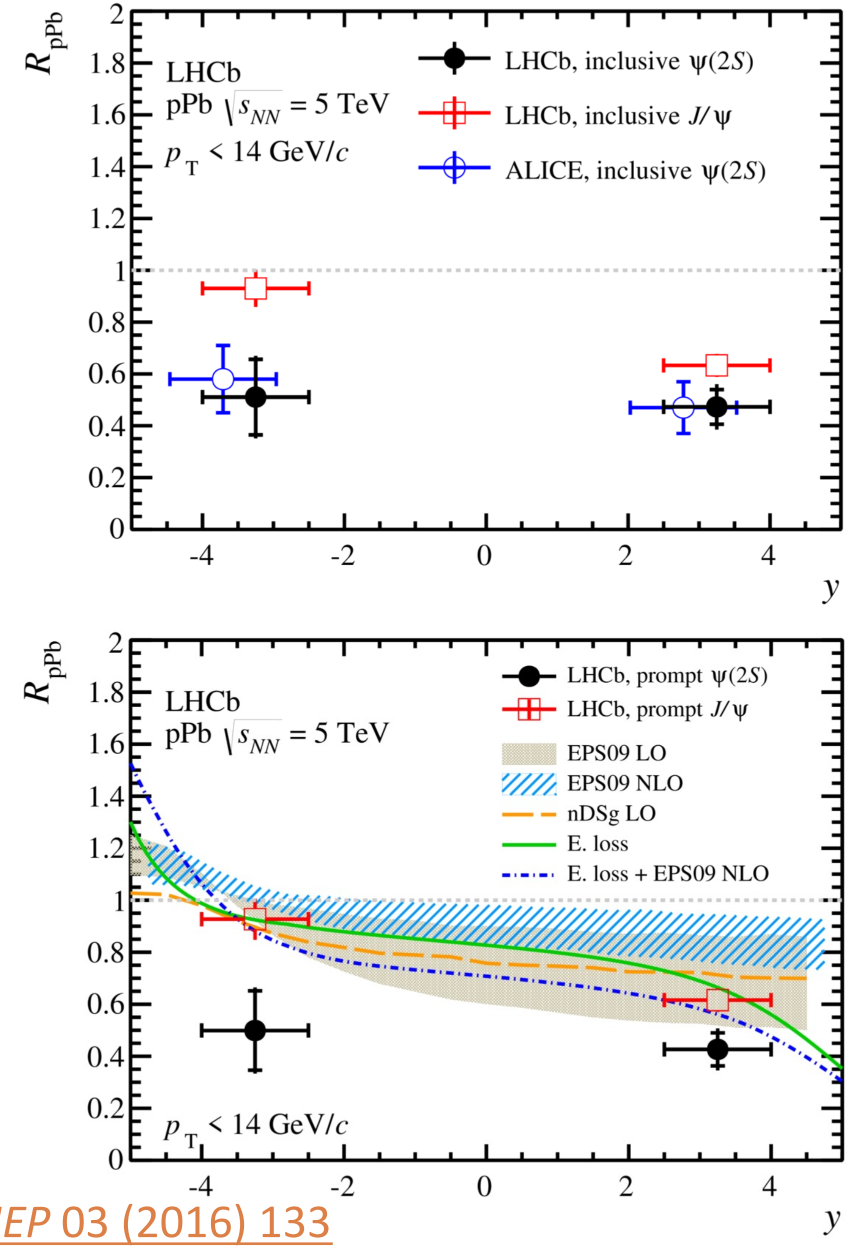
$$R_{pPb}^{\psi(2S)} = R_{pPb}^{J/\psi} \times R.$$

- The results are not well described by theoretical predictions.
- Models with initial state effects can't explain the difference between the two $c\bar{c}$ states

  $\Longrightarrow$ **Final state effects are necessary to explain the relative suppression of $\boldsymbol{\psi(2S)}$** (lower binding energy) **with respect to $\boldsymbol{J/\psi}$.**

Available models:

1. LO Colour Singlet Model with nPDFs: EPS09, nDSg.
2. NLO Colour Evaporation Model (NLO CEM) with EPS09.
3. Coherent parton energy loss that affects initial and final states, with EPS09 or without.



JHEP 03 (2016) 133

3. LHCb results in pPb collisions. Υ production and $\sqrt{s_{NN}} = 8$ TeV.

JHEP 11 (2018) 194

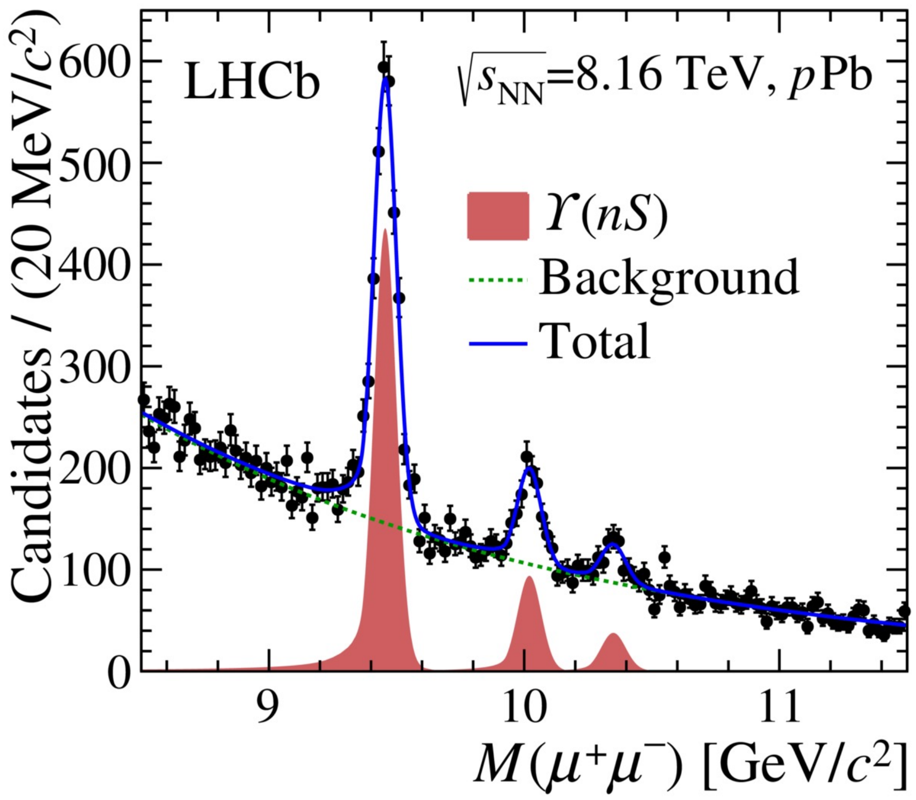
The reconstruction of the $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$ candidates is performed through the decay channel:

$$\Upsilon(nS) \to \mu^+\mu^-,$$

$$\mathcal{B}(\Upsilon(1S)) = (2.48 \pm 0.05)\%$$

$$\mathcal{B}(\Upsilon(2S)) = (1.93 \pm 0.17)\%$$

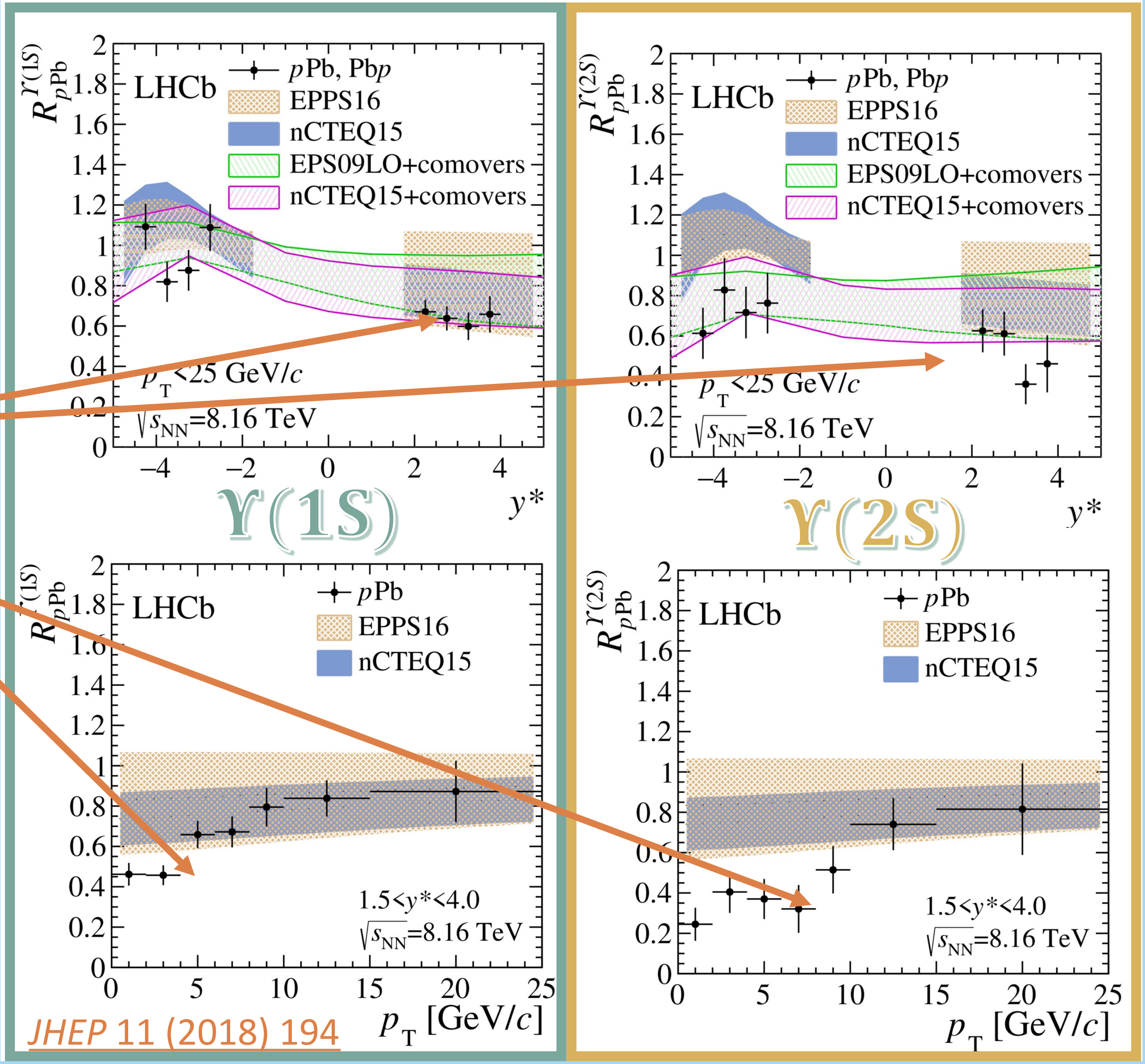
$$\mathcal{B}(\Upsilon(3S)) = (2.18 \pm 0.21)\%$$



Υ production at $\sqrt{s_{NN}} = 8$ TeV.

The nuclear modification factor shows similar behaviour as for the J/ψ for $\Upsilon(1S)$ and $\Upsilon(2S)$:

- Stronger suppression at **forward rapidity** $(1.5 < y^* < 4.0) \implies \downarrow x$.
- A strong suppression is shown at **low p_T**.
- At high p_T, the nuclear modification factor approaches 1.



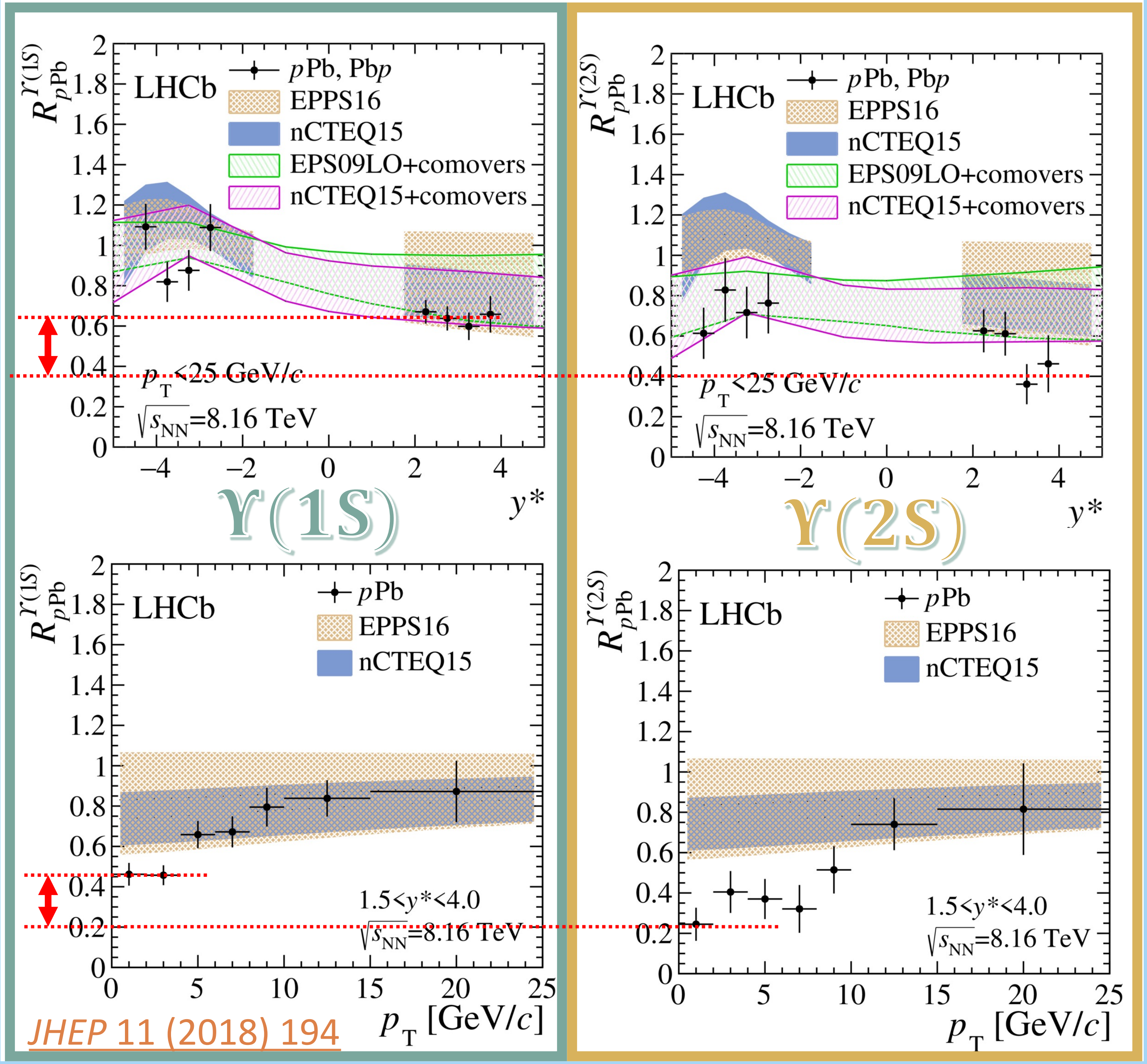
JHEP 11 (2018) 194

Υ production at $\sqrt{s_{NN}} = 8$ TeV.

The nuclear modification factor shows similar behaviour as for the J/ψ for $\Upsilon(1S)$ and $\Upsilon(2S)$:

- Stronger suppression at **forward rapidity** $(1.5 < y^* < 4.0) \implies \downarrow x$.
- A strong suppression is shown at **low p_T.**
- At high p_T, the nuclear modification factor approaches 1.
- **The suppression is more pronounced for the excited state $\Upsilon(2S)$.**

Other observables can help to measure this difference!



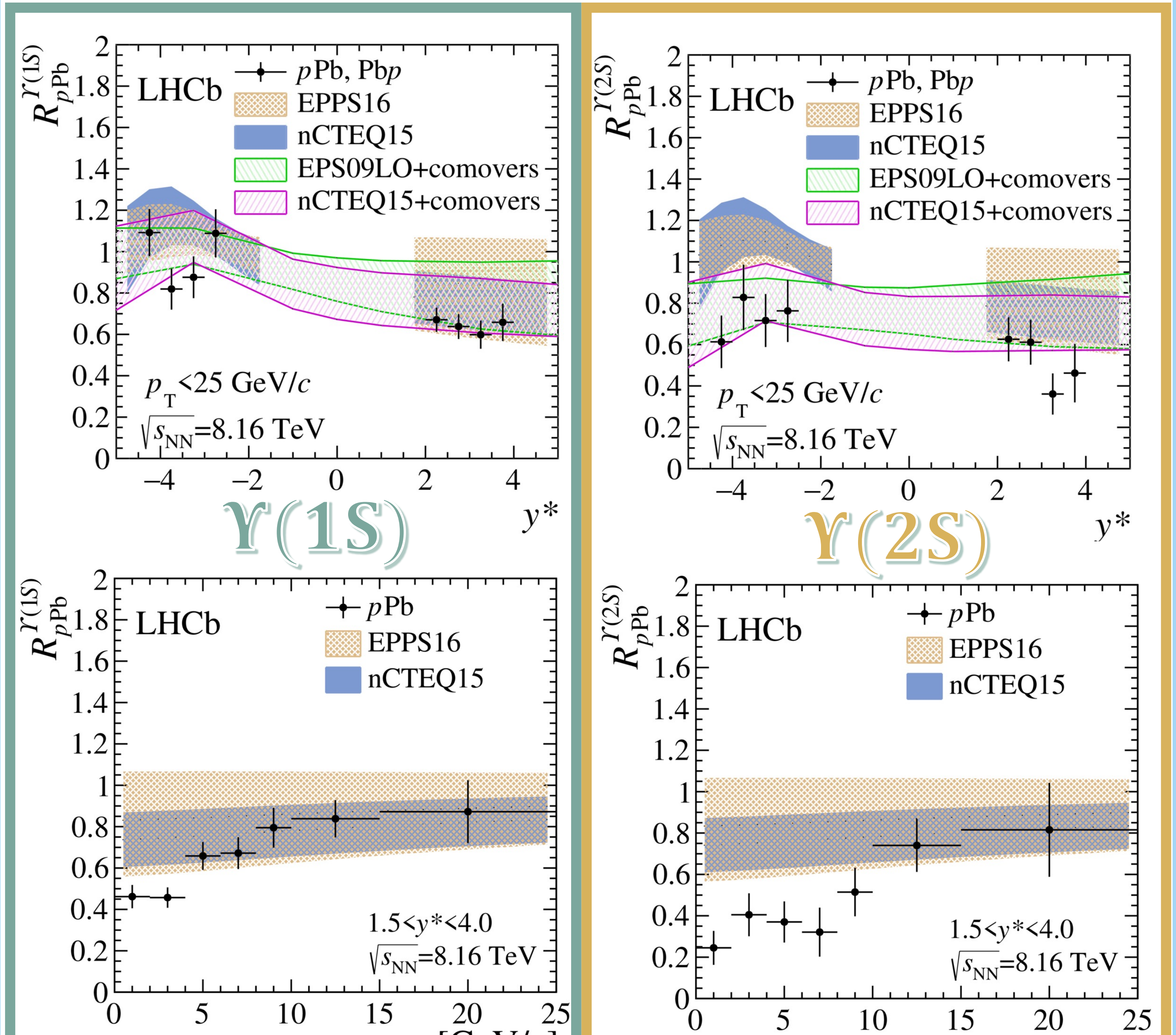
JHEP 11 (2018) 194

Υ production at $\sqrt{s_{\mathrm{NN}}} = 8$ TeV.

Available models:

1. HELAC-Onia event generator with nPDFs: EPPS16, nCTEQ15.
2. Calculations that add interactions with comovers to nPDFs: EPS09-LO, nCTEQ15.

- The calculations that include **final state** interactions with comovers seem in better agreement with the data.

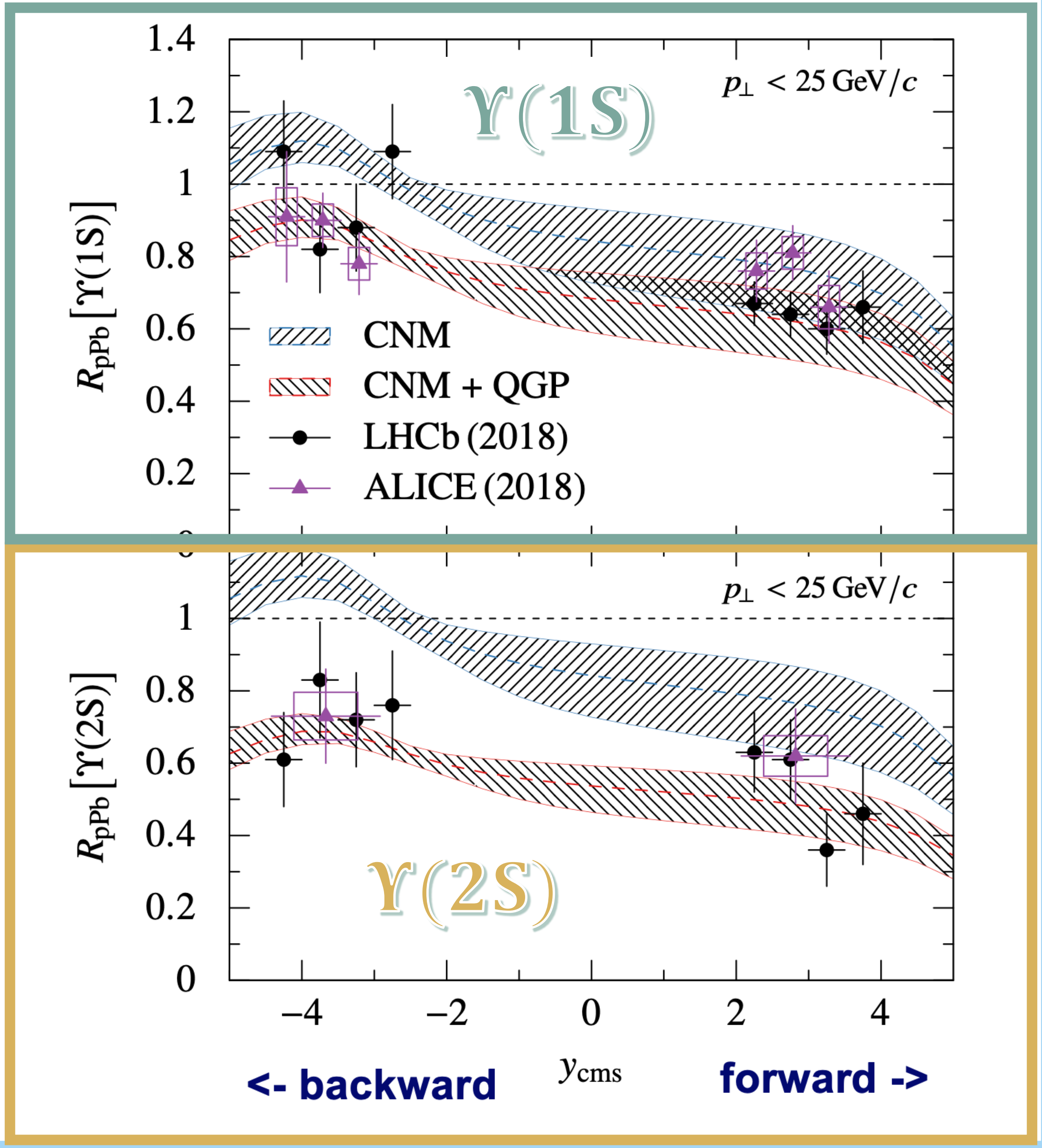


JHEP 11 (2018) 194

Υ production at $\sqrt{s_{\mathrm{NN}}} = 8$ TeV.

- New models include **hot-medium effects!**

Phys. Rev. C **100**, 024906 – Published 13 August 2019



Υ production at $\sqrt{s_{NN}} = 8$ TeV. JHEP 11 (2018) 194

Sample	$R\left(\Upsilon(2S)\right)$	$R\left(\Upsilon(3S)\right)$
pp	0.328(4)	0.137(2)
pPb	0.28(5)	0.11(2)
Pbp	0.29(7)	**0.06**(2)

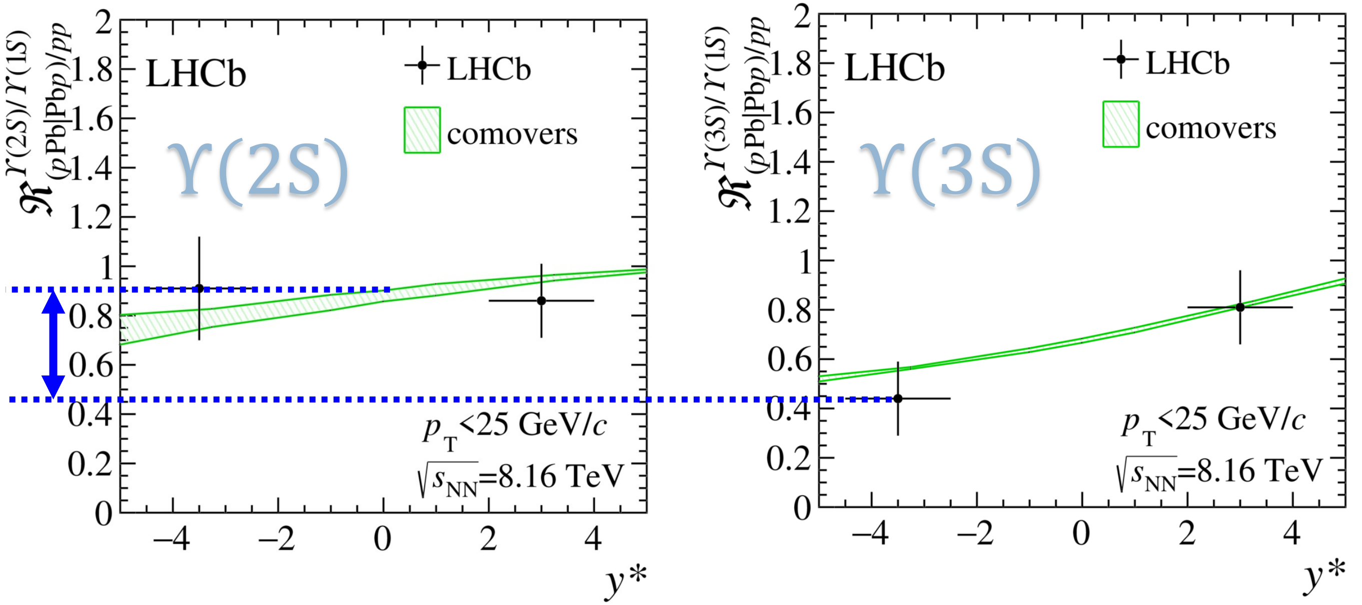
Ratio of $\Upsilon(2S)$ and $\Upsilon(3S)$ to the $\Upsilon(1S)$:

$$R\left(\Upsilon(nS)\right) = \frac{\left[\frac{d^2\sigma_{p\mathrm{Pb}}(p_T, y^*)}{dp_T dy^*}\right](\Upsilon(nS))}{\left[\frac{d^2\sigma_{p\mathrm{Pb}}(p_T, y^*)}{dp_T dy^*}\right](\Upsilon(1S))}$$

Double ratio with respect to pp collisions:

$$\mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(p\mathrm{Pb}|\mathrm{Pb}p)/pp} = \frac{R\left(\Upsilon(nS)\right)_{p\mathrm{Pb}|\mathrm{Pb}p}}{R\left(\Upsilon(nS)\right)_{pp}} = \frac{R^{\Upsilon(nS)}_{p\mathrm{Pb}}}{R^{\Upsilon(1S)}_{p\mathrm{Pb}}}$$

- $R\left(\Upsilon(3S)\right)$ decreases notably with respect to pp for **backward** collisions.
- $\mathfrak{R}^{\Upsilon(nS)/\Upsilon(1S)}_{(p\mathrm{Pb}|\mathrm{Pb}p)/pp}$ consistent with 1 for $\Upsilon(2S)$, 0.44(15) for $\Upsilon(3S)$ at backward rapidity.



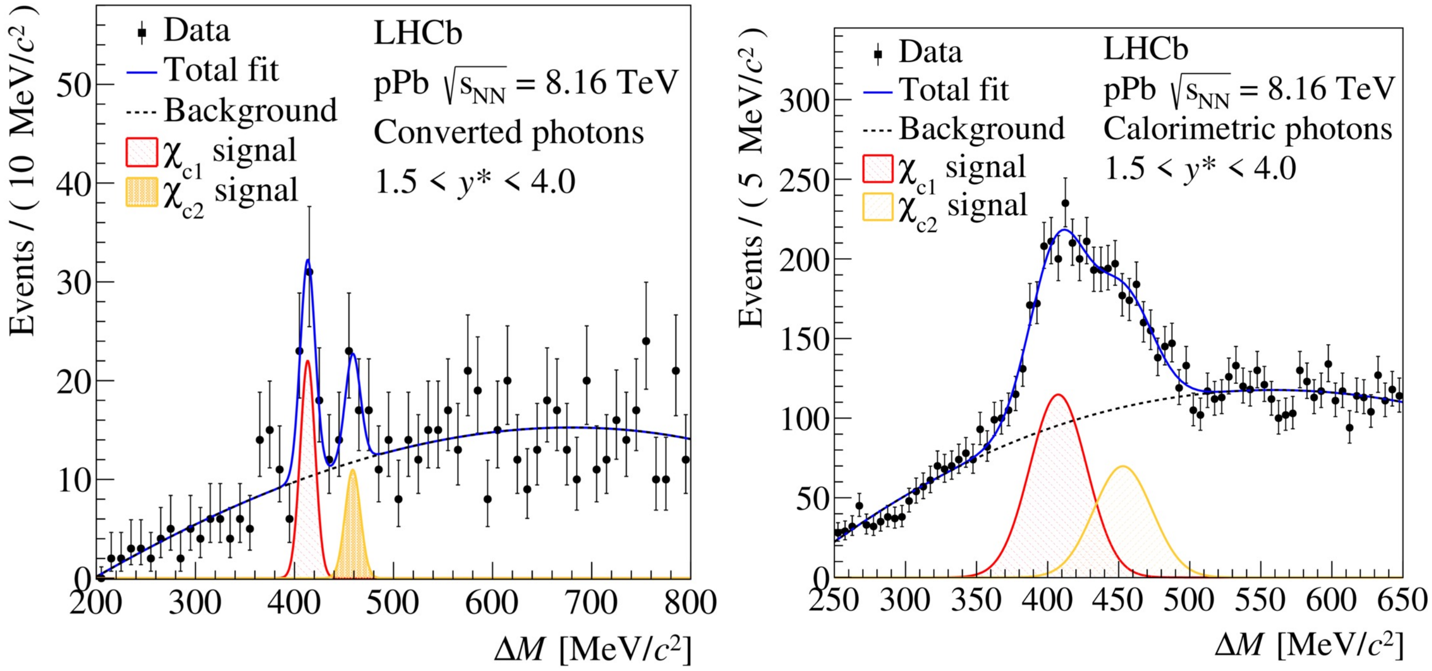
3. LHCb results in pPb collisions.
Prompt-production cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ at $\sqrt{s_{NN}} = 8$ TeV.

PHYS. REV. C103 (2021) 064905

- The ratio of the charmonium states χ_{c2} and χ_{c1} are measured through their decay:

$$\sigma(\chi_{ci}) \rightarrow (J/\psi \rightarrow \mu^+\mu^-)\gamma$$

- $t_z < 0.1$ ps.
- Two independent results are shown:
  - Converted photons: reconstructed through $\gamma \rightarrow e^+e^-$.
  - Calorimetric photons: reconstructed through the energy deposited in the calorimetric system.



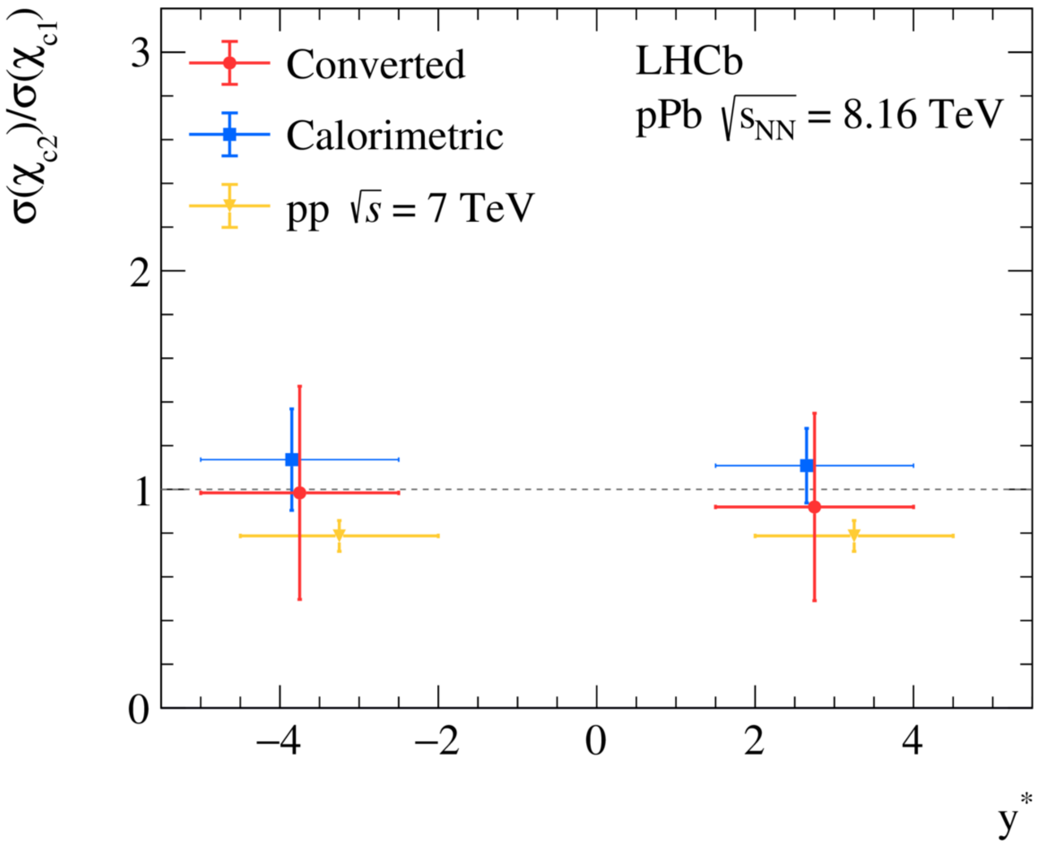
$$\Delta M = M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$$

Prompt-production cross-section ratio $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ at $\sqrt{s_{NN}} = 8$ TeV.

PHYS. REV. C103 (2021) 064905

- **The ratio is consistent with unity** for forward and backward rapidity regions.
- The binding energies of χ_{c2} and χ_{c1} are small compared to J/ψ but similar among them.
- The results hint that the **nuclear effects have same impact on the two states** within uncertainties.

►Ongoing efforts to measure $\sigma(\chi_c \to J/\psi)/\sigma(J/\psi)$ at 8TeV!



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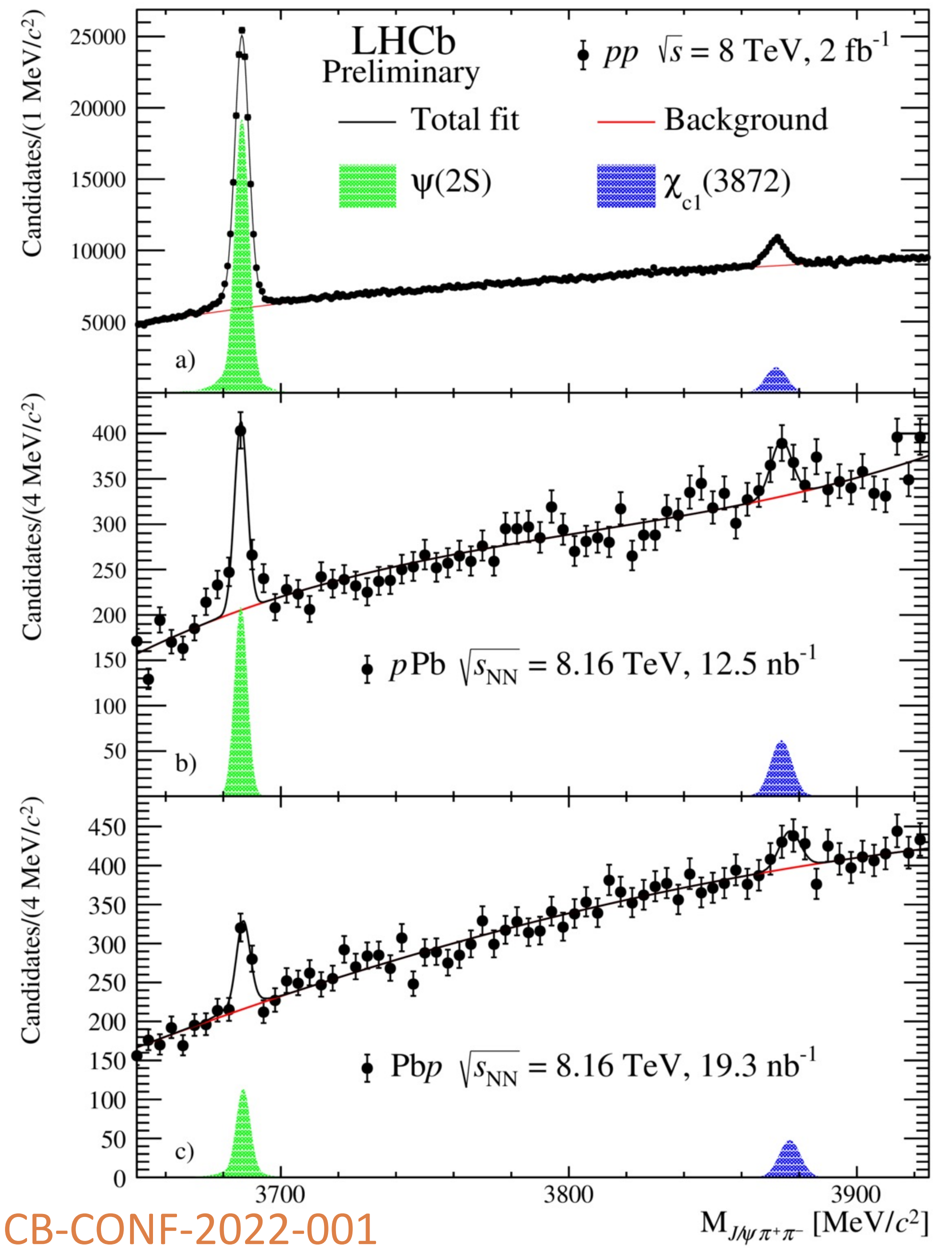
3. LHCb results in pPb collisions. Prompt-production cross-section ratio $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ at $\sqrt{s_{NN}} = 8$ TeV.

- First measurement of any exotic hadron in pPb collisions.
- $t_z < 0.1$ ps.
- Both $\chi_{c1}(3872)$ and $\psi(2S)$ are reconstructed through their decays to $(J/\psi \to \mu^+\mu^-)\pi^+\pi^-$.

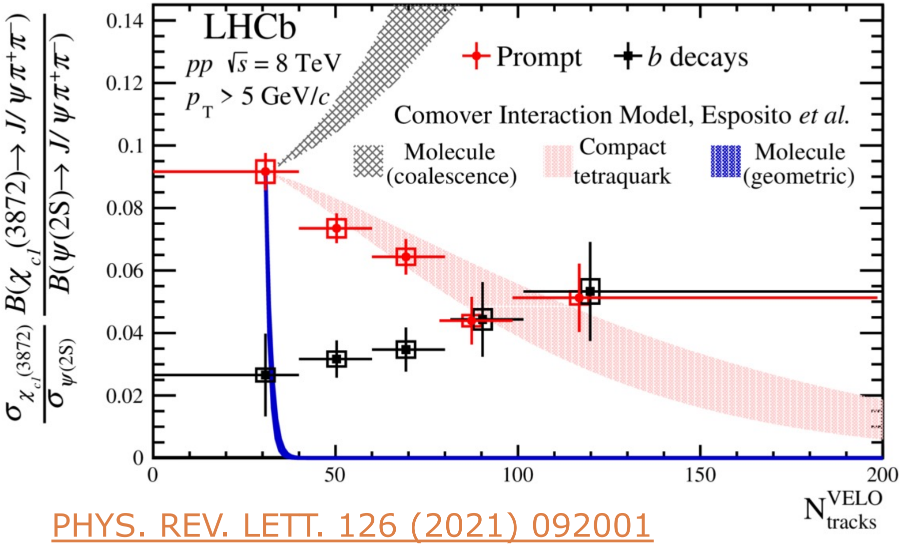


LHCB-CONF-2022-001

Prompt-production cross-section ratio $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ at $\sqrt{s_{NN}} = 8$ TeV.

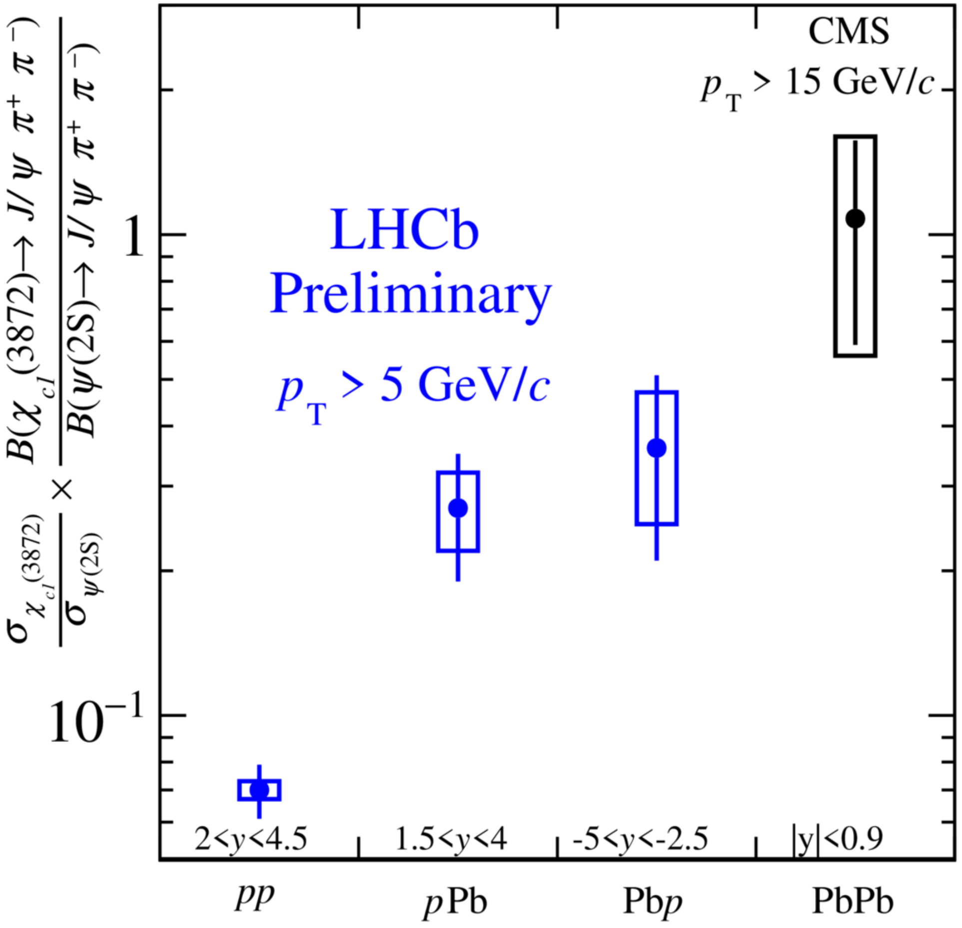
LHCB-CONF-2022-001

- **Increase of the ratio** of cross-sections from pp to pPb to Pbp collisions.
- pp collisions show a decreasing trend with multiplicity.
- May indicate that $\chi_{c1}(3872)$ experiences **different dynamics in the nuclear medium** than the conventional charmonium state.
- Possibility that hadronic densities allow **quark coalescence** to become a more relevant production mechanism.



∝ charged particle multiplicity

PHYS. REV. LETT. 126 (2021) 092001



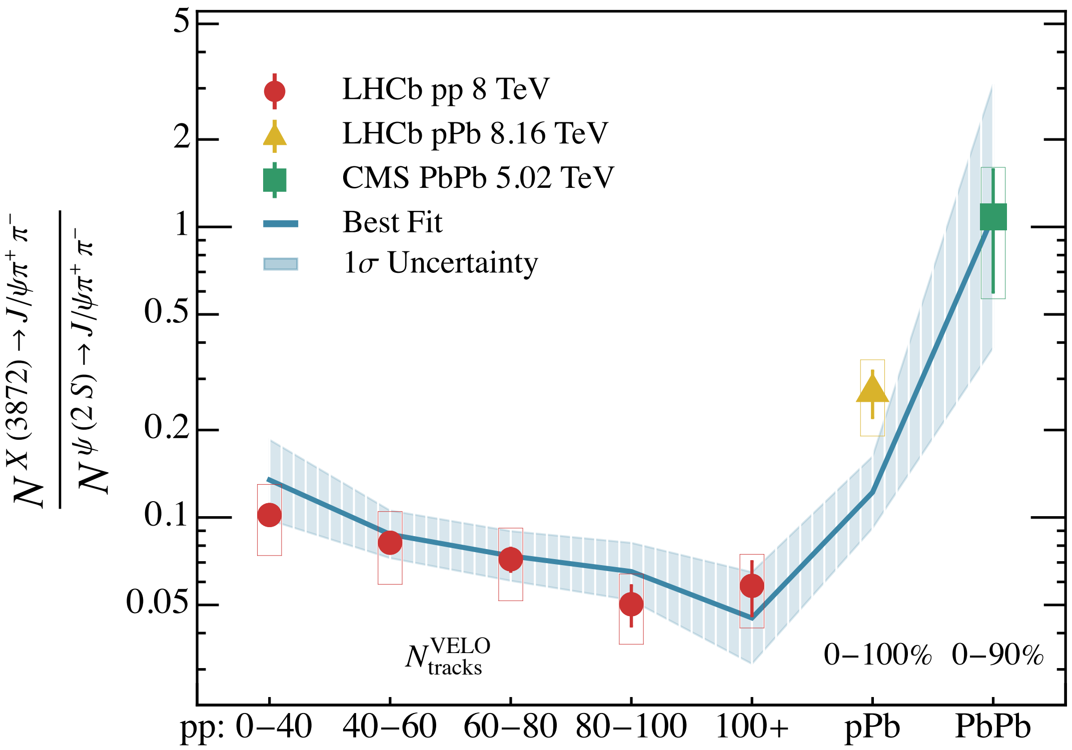
Prompt-production cross-section ratio $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ at $\sqrt{s_{NN}} = 8$ TeV. LHCB-CONF-2022-001

The increase on the ratio can be due to:

1. A larger relative suppression of the $\psi(2S)$ with respect to the exotic hadron.
2. An enhancement of the $\chi_{c1}(3872)$ in high density medium. New theoretical results explain the behaviour of the ratio through *medium-assisted enhancement* .

   arXiv:2302.03828v1 [hep-ph] 8 Feb 2023

▶ Upcoming results on the R_{pPb} of the $\chi_{c1}(3872)$ will help to clarify this.



4. Summary and outlook: Quarkonia and exotic hadron production in $p\mathrm{Pb}$ collisions at LHCb.

- So far, LHCb has measured the production of $\boldsymbol{J/\psi}$ **and** $\boldsymbol{\Upsilon(nS)}$ at 5 and 8 TeV and the production of $\boldsymbol{\psi(2S)}$ at 5TeV. ▶Upcoming results at 8TeV!
- The prompt-production cross-section ratio $\boldsymbol{\sigma(\chi_{c2})/\sigma(\chi_{c1})}$ has been measured at 8 TeV ▶Ongoing efforts to measure $\sigma(\chi_c \to J/\psi)/\sigma(J/\psi)$ at 8TeV!

➢ Measurements of charmonia and bottomonia in $p\mathrm{Pb}$ show **stronger suppression with respect to $\boldsymbol{pp}$ of excited states, with lower binding energy**. This effect is better reproduced by models with final-state effects.

➢ The prompt-production cross-section ratio $\sigma(\chi_{c1}(3872))/\sigma(\psi(2S))$ has been measured at 8 TeV. It constitutes the first measurement of the **exotic hadron $\boldsymbol{\chi_{c1}(3872)}$** in $p\mathrm{Pb}$ collisions. ▶ Upcoming results on the $R_{p\mathrm{Pb}}$ of the $\chi_{c1}(3872)$!

Backup

1. Motivation.
Quarkonia production in heavy ion collisions.

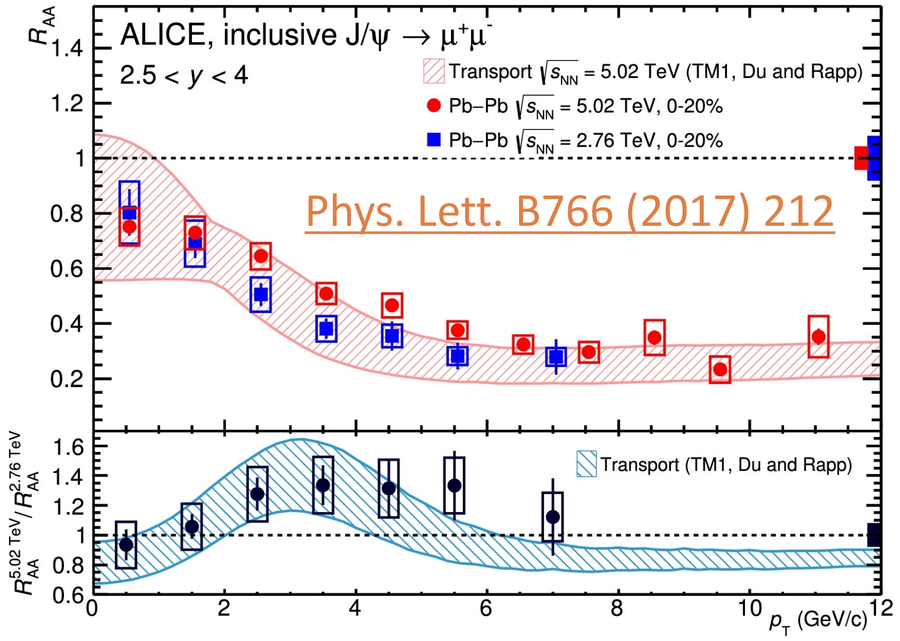
In heavy ion collisions, in which high energy densities are achieved, the formation of Quark Gluon Plasma is expected.

⇓

Colour screening prevents heavy flavour ($q\bar{q}$) from hadronising

⇓

Charmonium ($\bar{c}c$) and bottonium ($\bar{b}b$) suppression with respect to pp collisions.



This suppression is generally quantified by the nuclear modification factor:

$$R_{AA} \propto \frac{\mathrm{d}^2\sigma_{\mathrm{AA}}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}^2\sigma_{pp}/\mathrm{d}y\mathrm{d}p_{\mathrm{T}}}$$

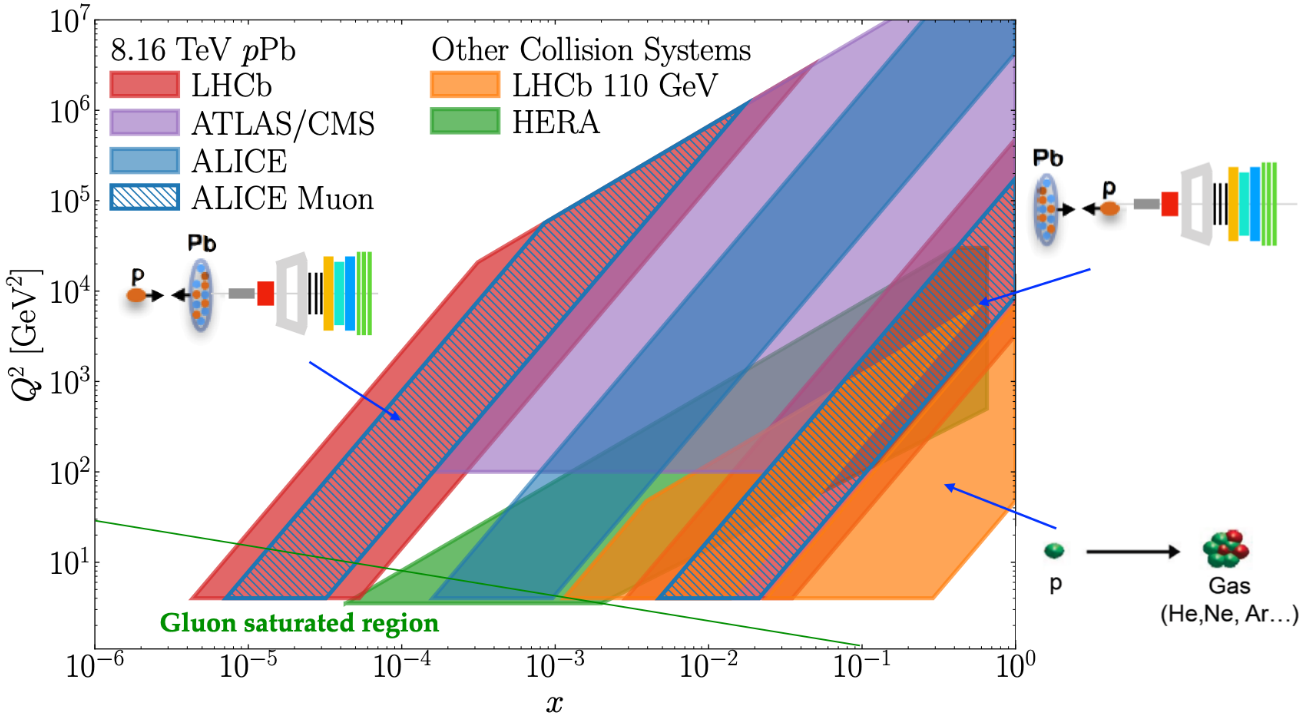
2. The LHCb experiment.
More than *b*eauty.

pPb and Pbp collisions are asymmetric:

there is a centre-of-mass rapidity shift

$$\Delta y = \pm 0.465.$$

- $p\text{Pb}\ 1.5 < y^* < 4.0 \Longrightarrow x \sim 10^{-6}$,
- $\text{Pb}p\ -5.0 < y^* < -2.5 \Longrightarrow x \sim 10^{-2}$.



Binding energies

J. Phys. G 32 (2006) R25

observed stable charmonium states are summarized in table 1 and the corresponding bottomonium ($b\,\bar{b}$) states in table 2. The binding energies ΔE listed there are the differences between the quarkonium masses and the open charm or beauty threshold, respectively.

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Table 1: Charmonium states and binding energies

state	Υ	χ_{b0}	χ_{b1}	χ_{b2}	Υ'	χ'_{b0}	χ'_{b1}	χ'_{b2}	Υ''
mass [GeV]	9.46	9.86	9.89	9.91	10.02	10.23	10.26	10.27	10.36
ΔE [GeV]	1.10	0.70	0.67	0.64	0.53	0.34	0.30	0.29	0.20

Table 2: Bottomonium states and binding energies

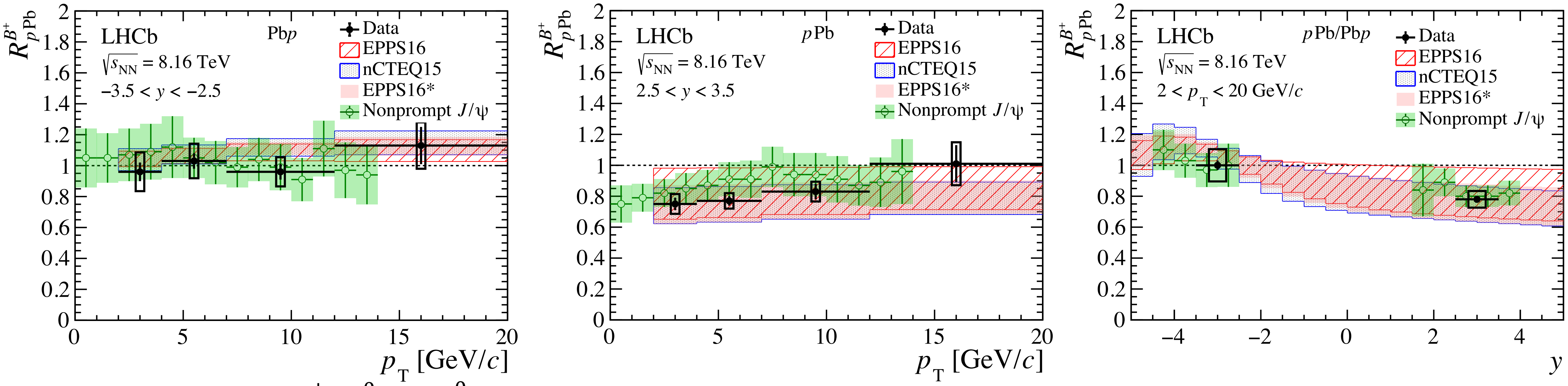
J/ψ production at $\sqrt{s_{NN}} = 5$ TeV and $\sqrt{s_{NN}} = 8$ TeV.

R_{pPb} for **non-prompt** J/ψ:

- Less suppression but similar trend to prompt measurements (higher suppression at forward rapidity and low p_T).
- Compatible with the more recent measurements of B^+ production.

The results are compared to HELAC-Onia event generator with different nPDFs:

- EPPS16, EPPS16*,
- nCTEQ15.



PRD 99 (2019) 052011 B^+, B^0 and Λ_b^0 production

Υ production at $\sqrt{s_{\rm NN}} = 8$ TeV.

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- The ratio of $\Upsilon(1S)$ to non-prompt J/ψ (open beauty) in pp and pPb are compatible within uncertainty for backward collisions, but there is a **small suppression at forward rapidity.**

  $\Longrightarrow$ hints of different final CNM effects affecting bottonium production