Quarkonium production in proton-nucleus at LHC

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Quarkonia as Tools, Aussois
13/01/2022

Introduction: quarkonium in proton-nucleus

- Quarkonium states are a benchmark for QCD studies
  - High mass ➡ mostly produced in the initial state of the collision (hard scattering)
  - probe of QGP in PbPb ➡ Sequential melting of quarkonia states
  - simpler systems (pPb) gateway to more complex (PbPb)
- Cold Nuclear Matter (CNM) effects: modifications of particle production yields in ion collisions with respect to pp that are not due to formation of a deconfined medium
- Many applicable approaches (not necessarily factorisable):
  - PDF modification (nPDF) → (anti)shadowing — HELAC-ONIA: CPC 198 (2016) 238; FONLL: JHEP 05 (1998) 007
  - gluon saturation → Color Glass Condensate — B. Ducloué et al., PRD 91 (2015) 114005, PRD 94 (2016) 074031
  - parton propagation in medium → Coherent energy loss — F. Arleo, S. Peigné, JHEP 03 (2013) 122
  - break up in nuclear matter
  - break up by comoving particles — E. G. Ferreiro *et* al., arXiv:1804.04474; Phys. Lett. B749 (2015) 98, arXiv:1411.0549

Initial state effects (first three items)

Final state effects (last two items)

- Different approaches can describe data simultaneously, look at
  - dependencies (η, p_{T}, $\sqrt{s_{NN}}$, multiplicity …)
  - different (excited) states

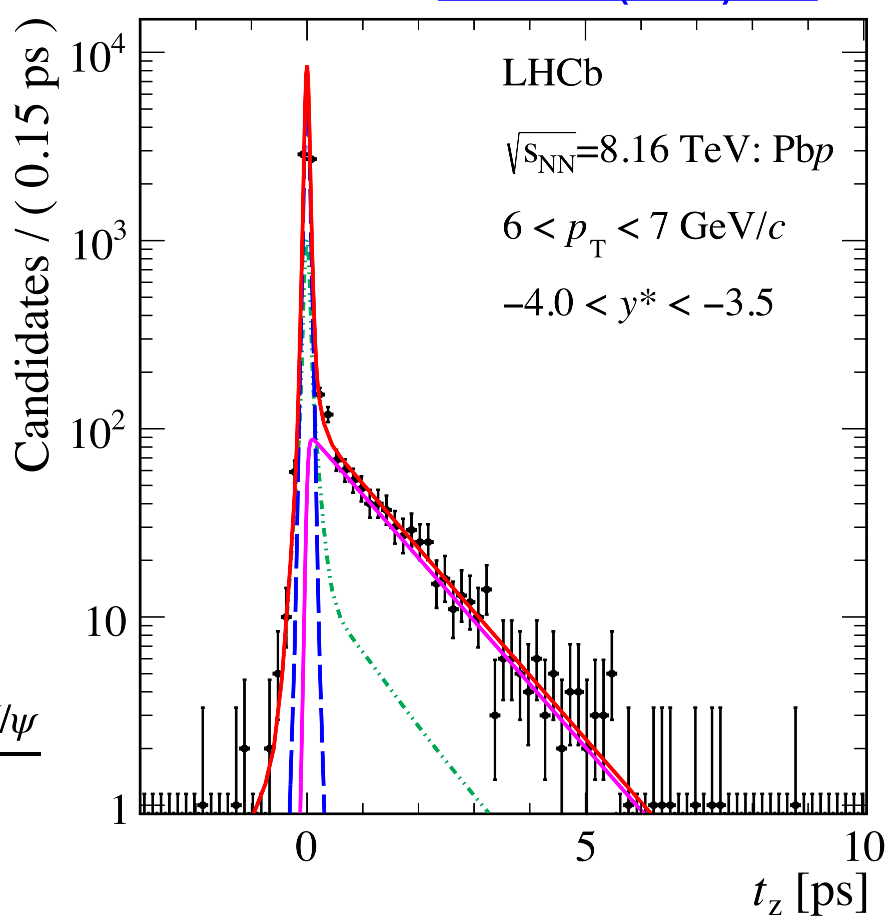
Experimental considerations in collider mode

- Similar techniques to pp measurements
- J/ψ, $\psi(2s)$, $\Upsilon(nS)$ $\rightarrow$ dilepton decays
- Experimentally at LHC, we distinguish:
  - prompt → from primary collision vertex + feed-down
  - non-prompt → from displaced vertices (B hadron decays)

(bottomonium states always prompt)

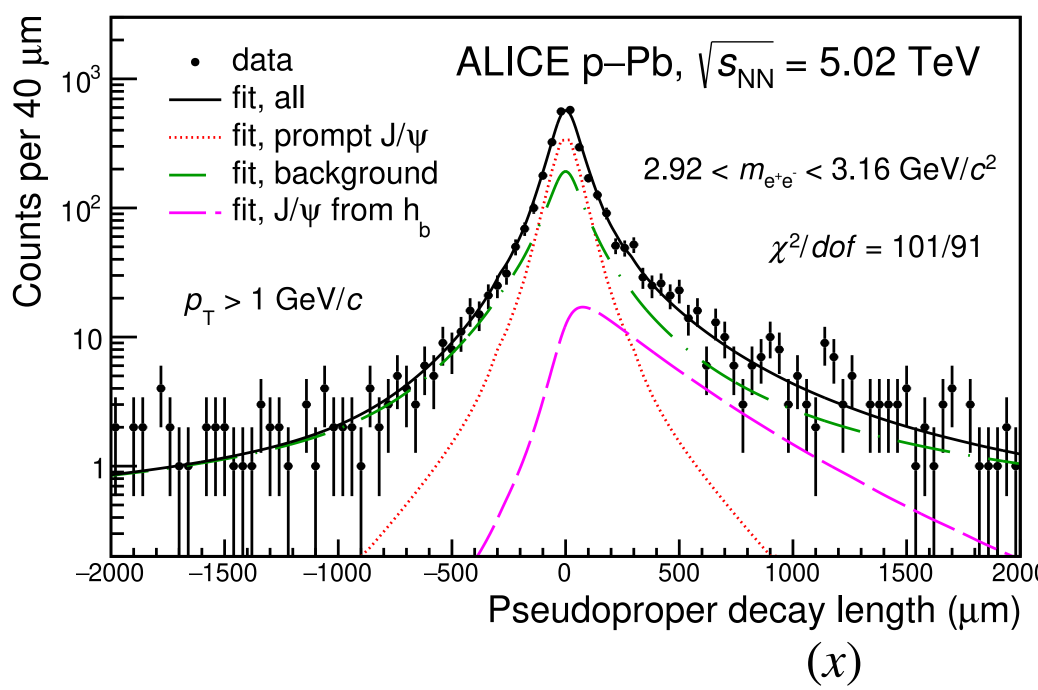
$$t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}$$

PLB 774 (2017) 159



- Other states/decay channels not yet (much) explored:
  - Radiative decays: $\chi_{cn} \rightarrow \gamma J/\psi(\rightarrow \mu^- \mu^+)$
  - decays to hadrons: $\rightarrow p\bar{p}$; $\rightarrow hhhh$; $\rightarrow hh$...
    - ✳ small BF or experimental difficulties (large combinatorial background)

$$x = \frac{c \times L_{xy} \times m_{J/\psi}}{p_T}$$



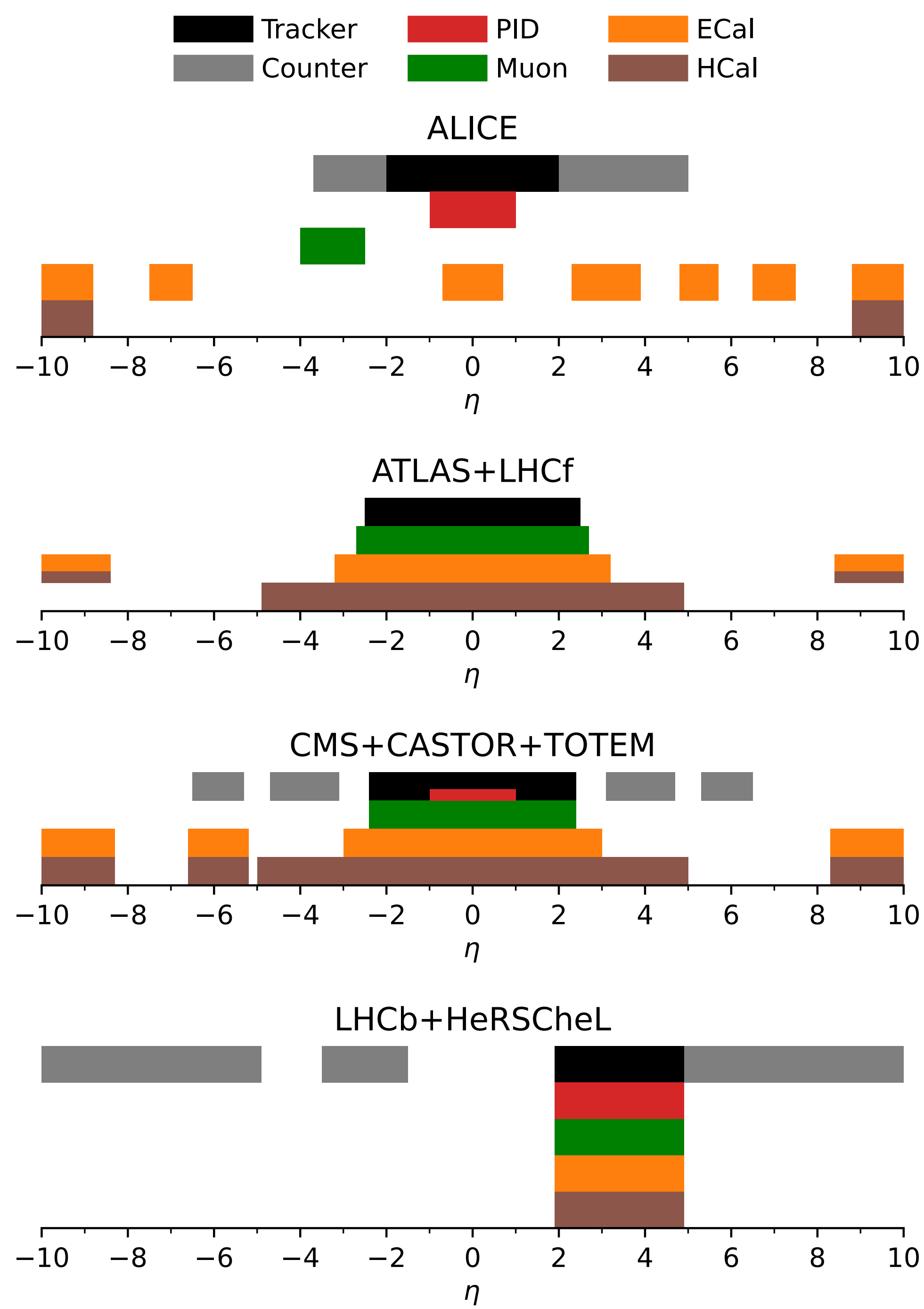
JHEP06 (2022) 011

LHC experiment capabilities (Run 1/2)

ATLAS JINST 3 (2008) S08003 ALICE JINST 3 (2008) S08002

CMS JINST 3 (2008) S08004 LHCb JINST 3 (2008) S08005

- ALICE:
  - central barrel (J/ψ in $-1.37 < y^* < 0.43$)
    - reconstruction with e^+e^- decay
    - smaller data set due to lower data-rate
    - prompt-non prompt separation down to $p_{\mathrm{T}} > 1\,\mathrm{GeV}/c$
  - forward muon spectrometer ($2.03 < y^* < 3.53$, $-4.46 < y^* < -2.96$)
    - only inclusive charmonium in Run1/2
- LHCb ($1.5 < \eta^* < 4.0$, $-4.5 < \eta^* < -2.5$)
  - prompt vs non-prompt separation down to $p_{\mathrm{T}} = 0$
  - hadronic final states
- CMS ($-2.4 < y^* < 1.93$) & ATLAS ($|y^*| < 2$)
  - prompt vs non-prompt separation for $p_{\mathrm{T}} \gtrsim 4\,\mathrm{GeV}/c$
  - best for high-mass ($\Upsilon(nS)$) and high p_{T} region



from Astrophys.Space Sci. 367 (2022) 3, 27

Observables

- Differential cross-section $\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}} \rightarrow$ hard to predict in $p\mathrm{Pb}$ since production in pp not yet understood

- Nuclear Modification Factor: test of nuclear effects

$$R_{p\mathrm{A}} = \frac{\mathrm{d}\sigma_{p\mathrm{A}}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{A}\cdot \mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

$R_{p\mathrm{A}} < 1$: suppression
$R_{p\mathrm{A}} = 1$: no nuclear effects
$R_{p\mathrm{A}} > 1$: enhancement

- Dependence with y^*, p_{T}

- Production with multiplicity:
  - Number of charged particles per event at some η
  - Centrality: including a Glauber model calculation to get $\langle N_{\mathrm{coll}} \rangle \rightarrow$ complicated in $p\mathrm{Pb}$

- Azimuthal correlations with charged hadrons: ("flow")

JHEP 02 (2021) 002

$$\frac{1}{N_{J/\psi}}\frac{\mathrm{d}N^{\mathrm{pair}}}{\mathrm{d}\Delta\phi} = \frac{N_{\mathrm{assoc}}}{2\pi}[1 + \sum_{n=1}^{3} 2V_{n\Delta}\cos(n\Delta\phi]$$

$$v_n(J/\psi) = V_{n\Delta}(J/\psi,\mathrm{ref})/\sqrt{V_{n\Delta}(\mathrm{ref},\mathrm{ref})}$$

flow extracted from reference charged particles

- In $p\mathrm{Pb}$, measuring flow difference in high multiplicity events with respect low multiplicity events

Prompt J/ψ production

- Long list of prompt J/ψ production measurements in pPb
  - Central rapidities: ALICE, ATLAS and CMS (not down to $p_{\mathrm{T}} = 0$)
  - forward/backward rapidities: LHCb and ALICE (inclusive)
- Suppression pattern described by most approaches:
  - nPDF(s)
  - CGC (forward region)
  - Coherent energy loss (with and without nPDF)
  - nPDF + final state interaction

At $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$:

LHCb: JHEP 11 (2021) 181, JHEP 02 (2014) 72)

ALICE: JHEP06 (2022) 011, Eur. Phys. J. C 78 (2018) 466, JHEP 02 (2014) 073

CMS: EPJC 77 (2017) 269

ATLAS: Eur. Phys. J. C 78 (2018) 171

At $\sqrt{s_{\mathrm{NN}}} = 8\,\mathrm{TeV}$:

LHCb: PLB 774 (2017) 159

ALICE: arXiv:2211.14153, JHEP 07 (2018) 160

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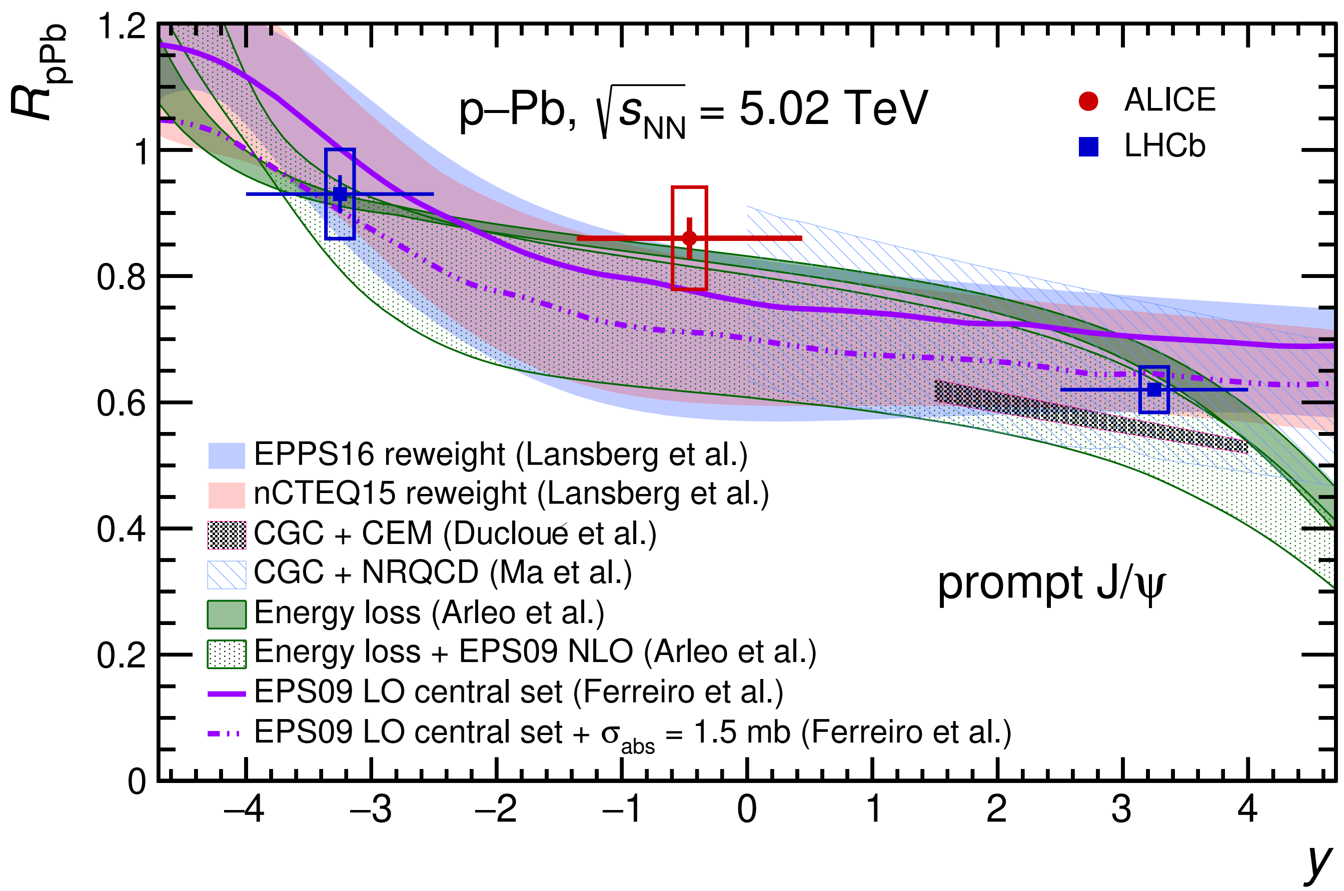

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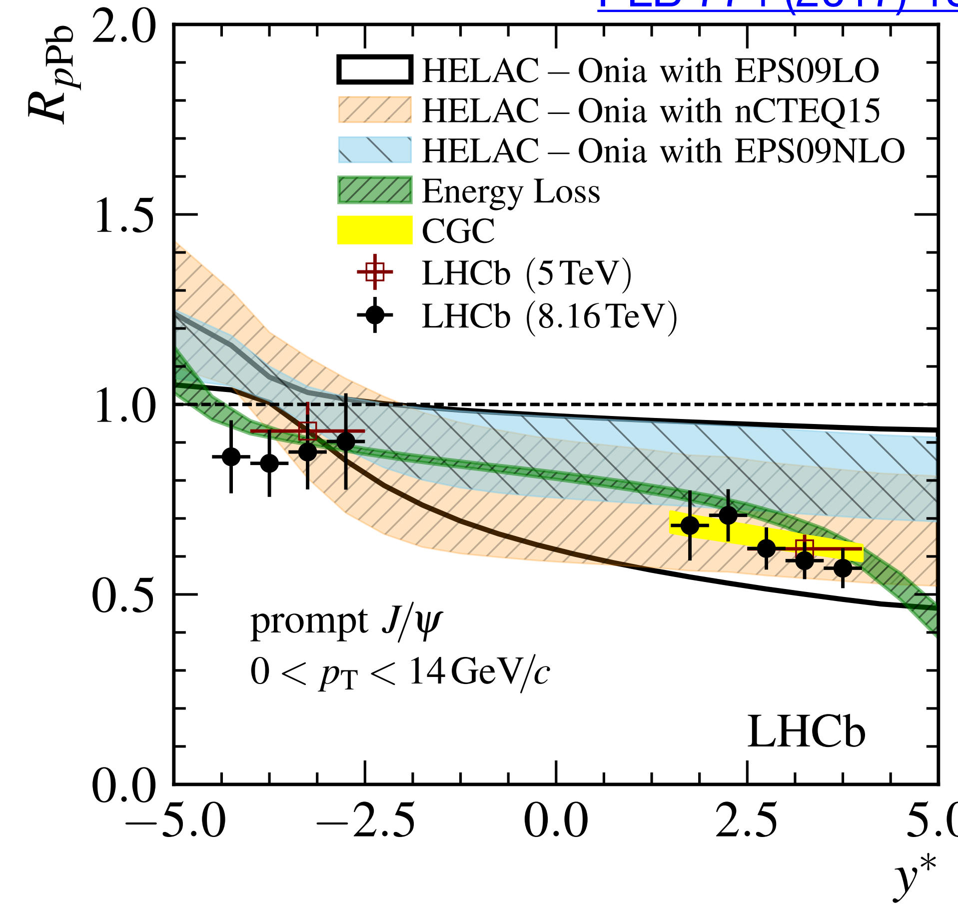
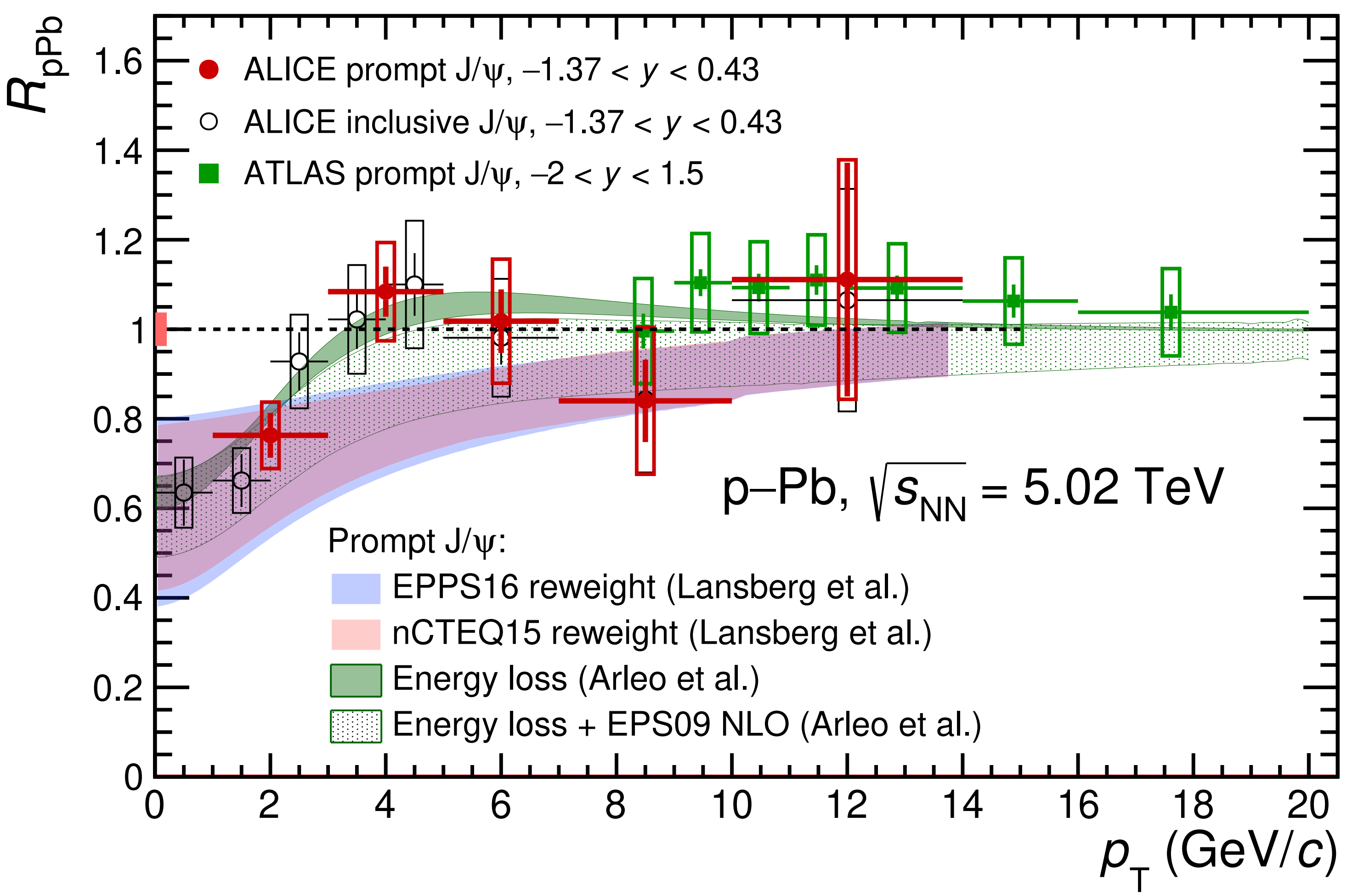
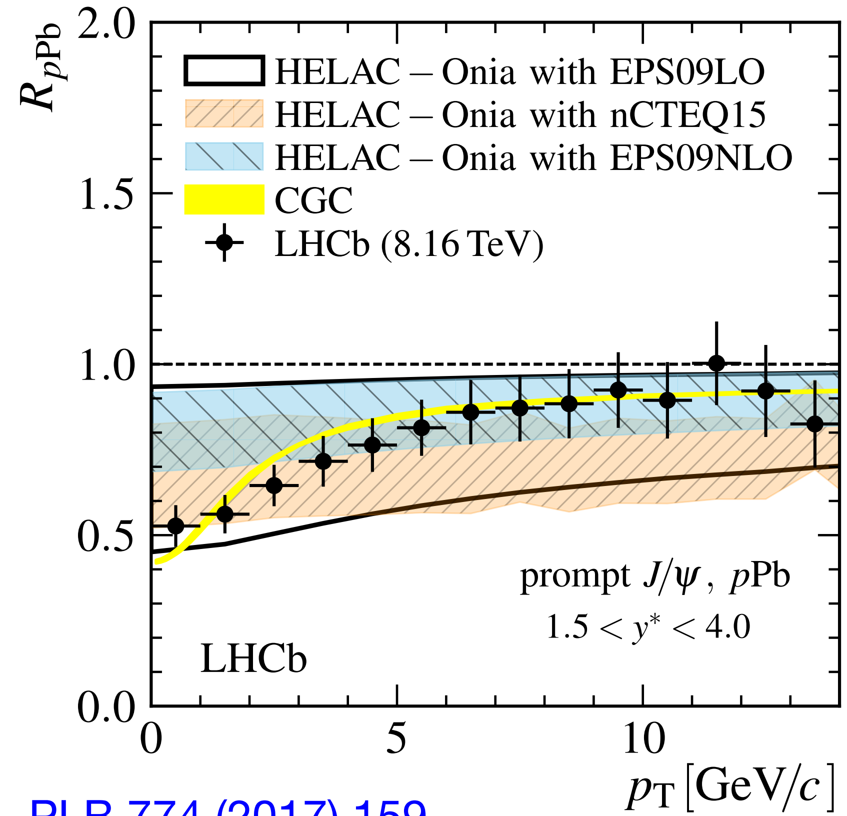


Prompt J/ψ production - p_{T} dependence

- Suppression at low p_{T}
- Transverse momentum dependence also fairly described by models

JHEP06 (2022) 011





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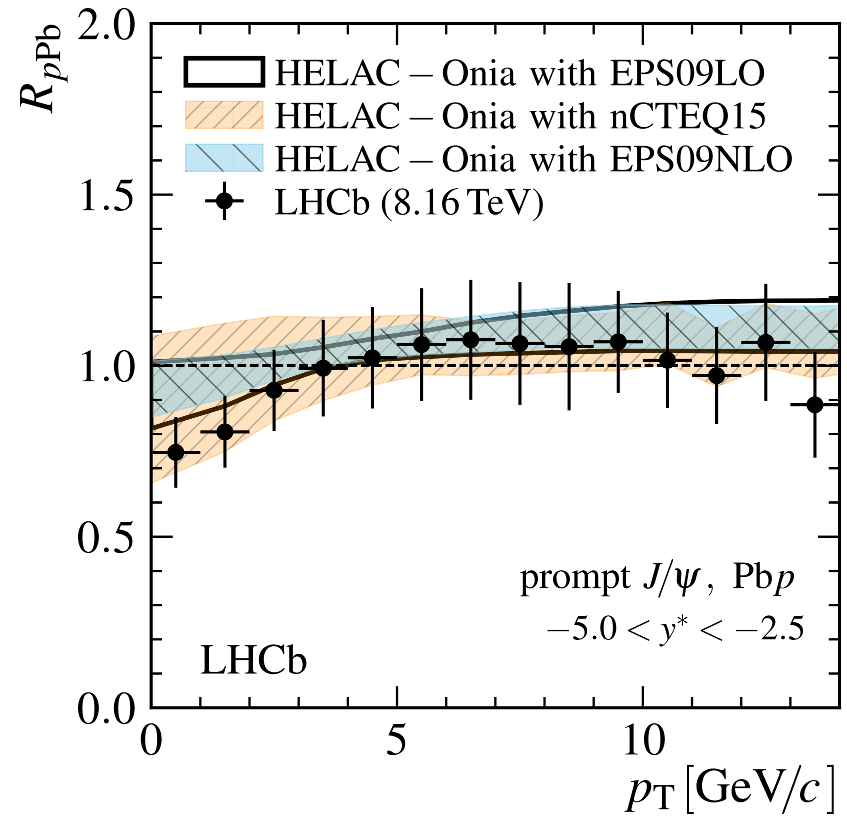
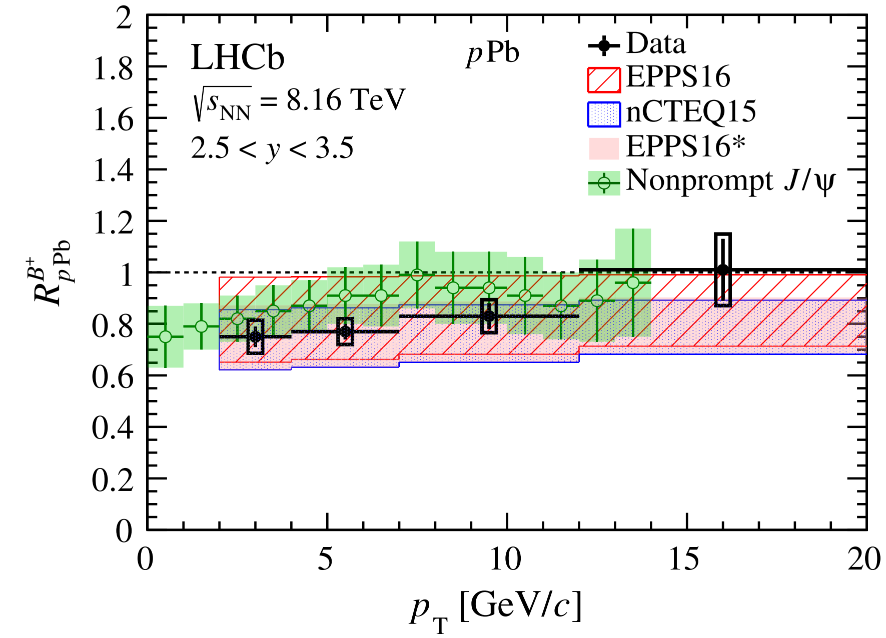


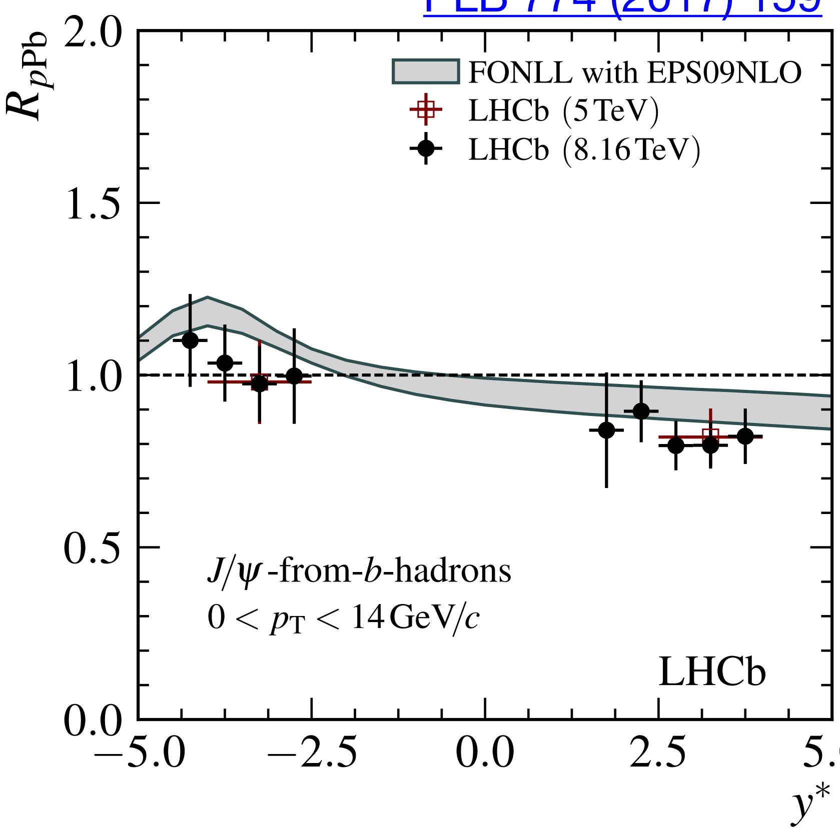
Non-prompt J/ψ production

- Less suppression than for prompt data
- Non-prompt compatible with R_{pPb} of B^+
- Data in general agreement with FONLL and nPDF calculations

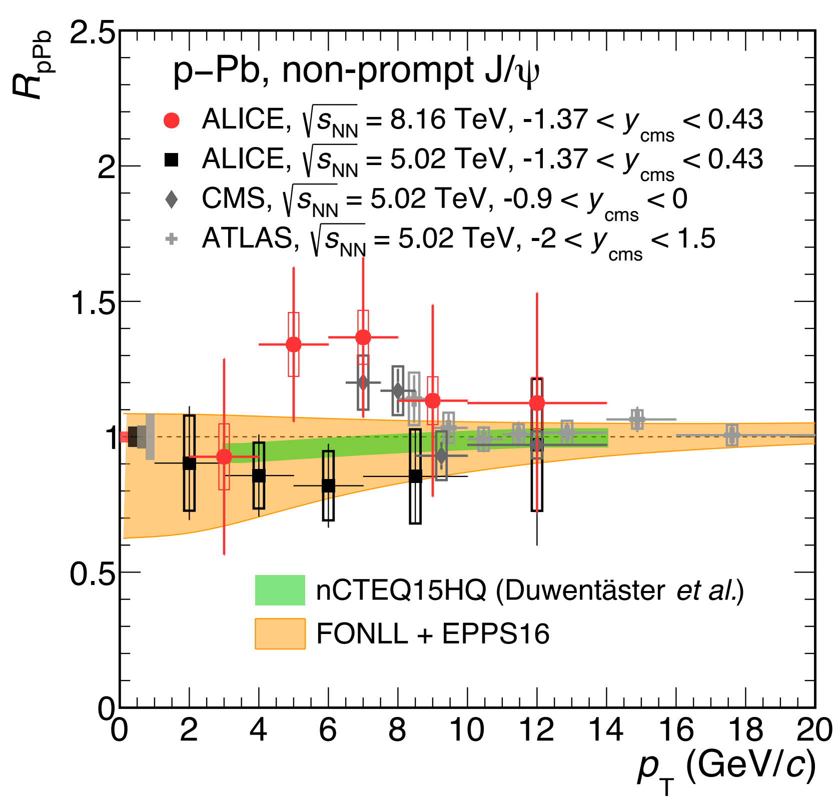
[Phys. Rev. D 99, 052011 (2019)](https://doi.org/10.1103/PhysRevD.99.052011)



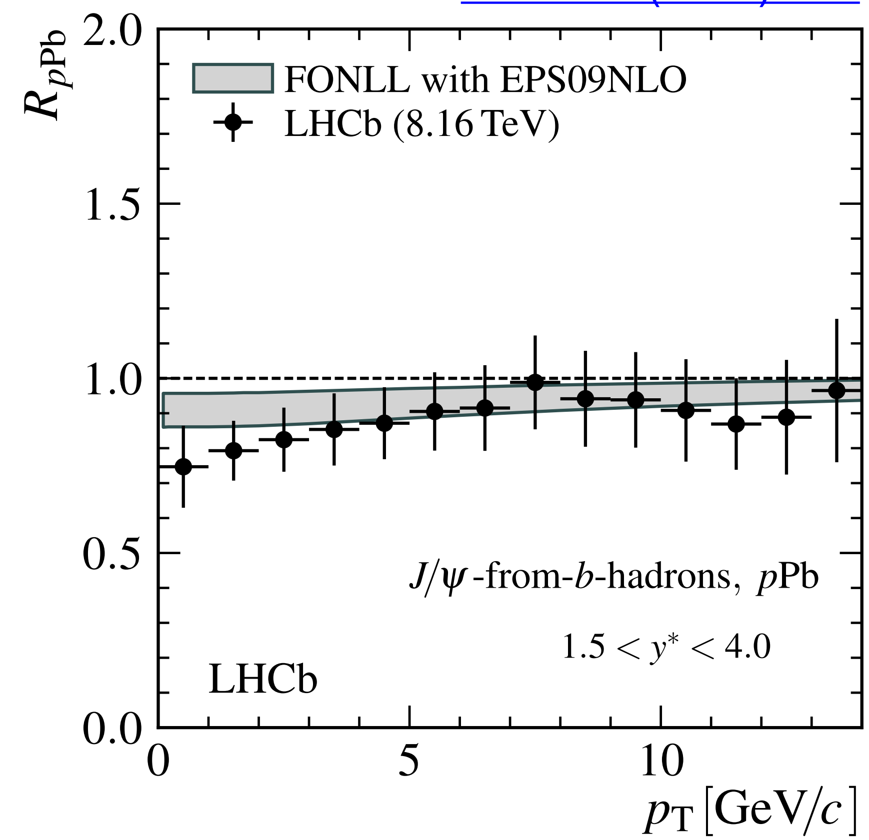
[PLB 774 (2017) 159]



[arXiv:2211.14153]



[PLB 774 (2017) 159]



Excited states: $\psi(2S)$ production

- Several measurements in pPb:
  - Central rapidities: CMS (not down to $p_{\mathrm{T}} = 0$, only prompt), ATLAS ($p_{\mathrm{T}} > 4\,\mathrm{GeV}/c$)
  - forward/backward rapidities: LHCb and ALICE (inclusive)
- CNM models underestimate suppression, specially in the backward region
- Non-prompt fraction from LHCb statistically limited at $5\,\mathrm{TeV}$

At $\sqrt{s_{\mathrm{NN}}} = 5\,\mathrm{TeV}$:

LHCb: JHEP 03 (2016) 133

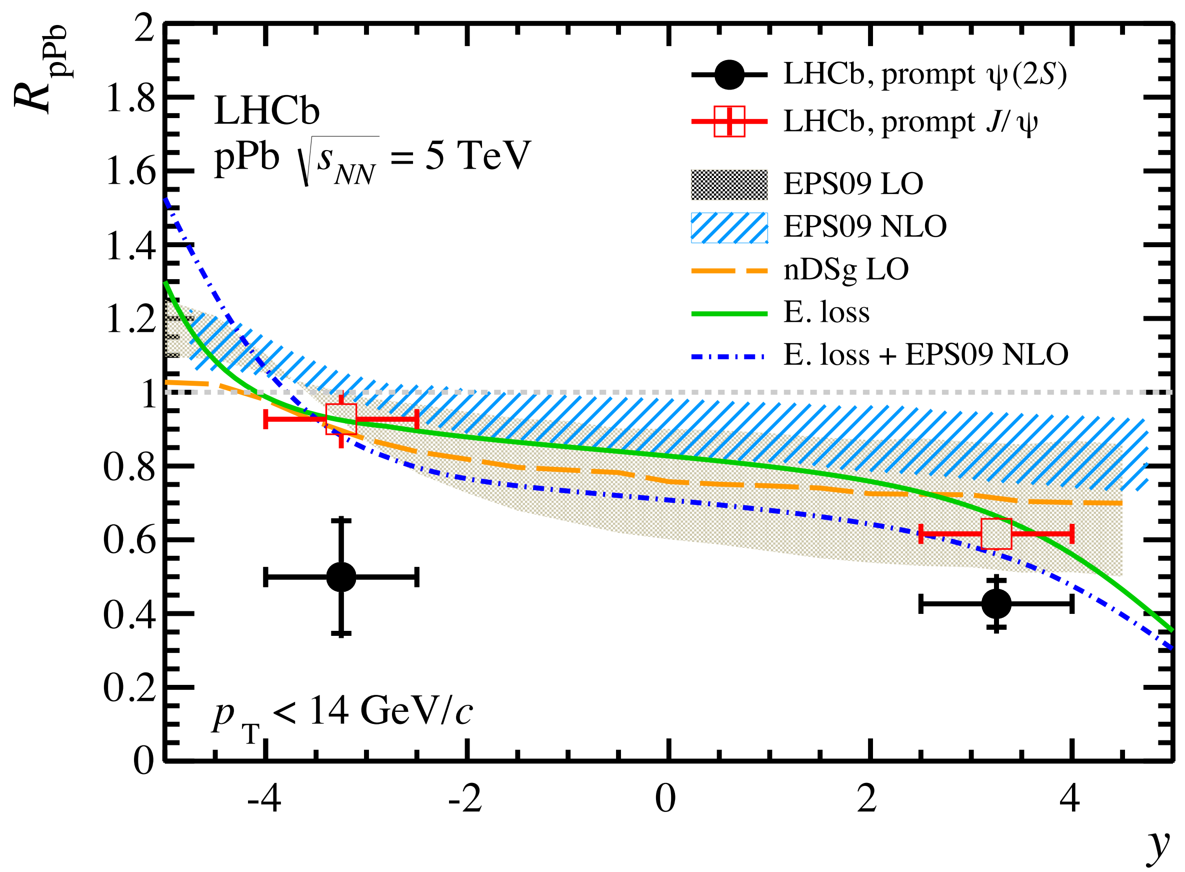
ALICE: JHEP 12 (2014) 073

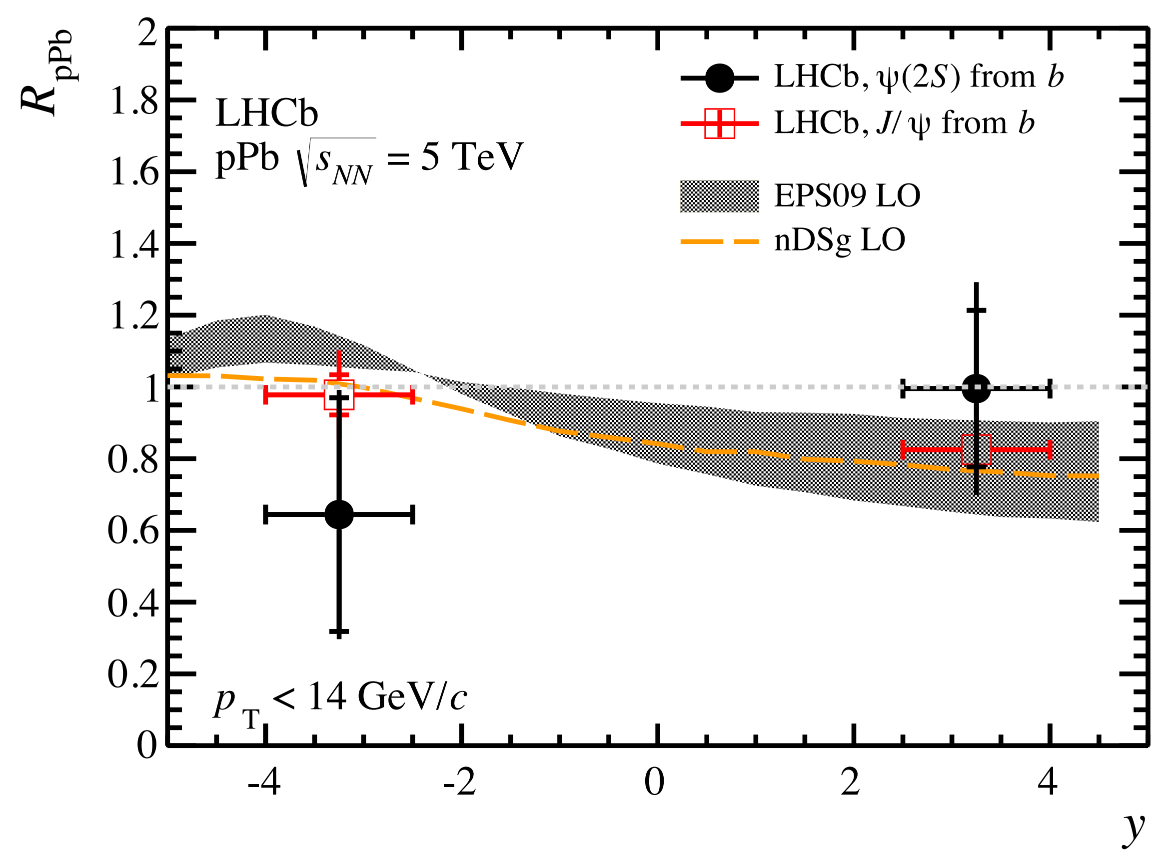
CMS: PLB 790 (2019) 509

ATLAS: Eur. Phys. J. C 78 (2018) 171

At $\sqrt{s_{\mathrm{NN}}} = 8\,\mathrm{TeV}$:

ALICE: JHEP07 (2020) 237

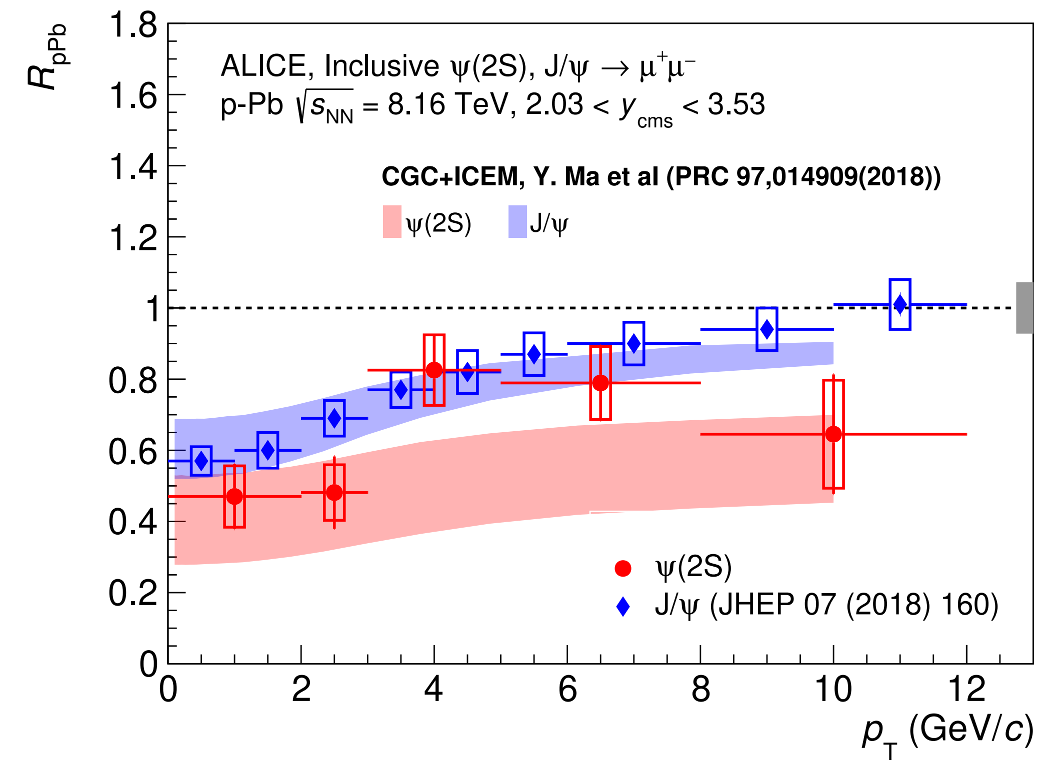


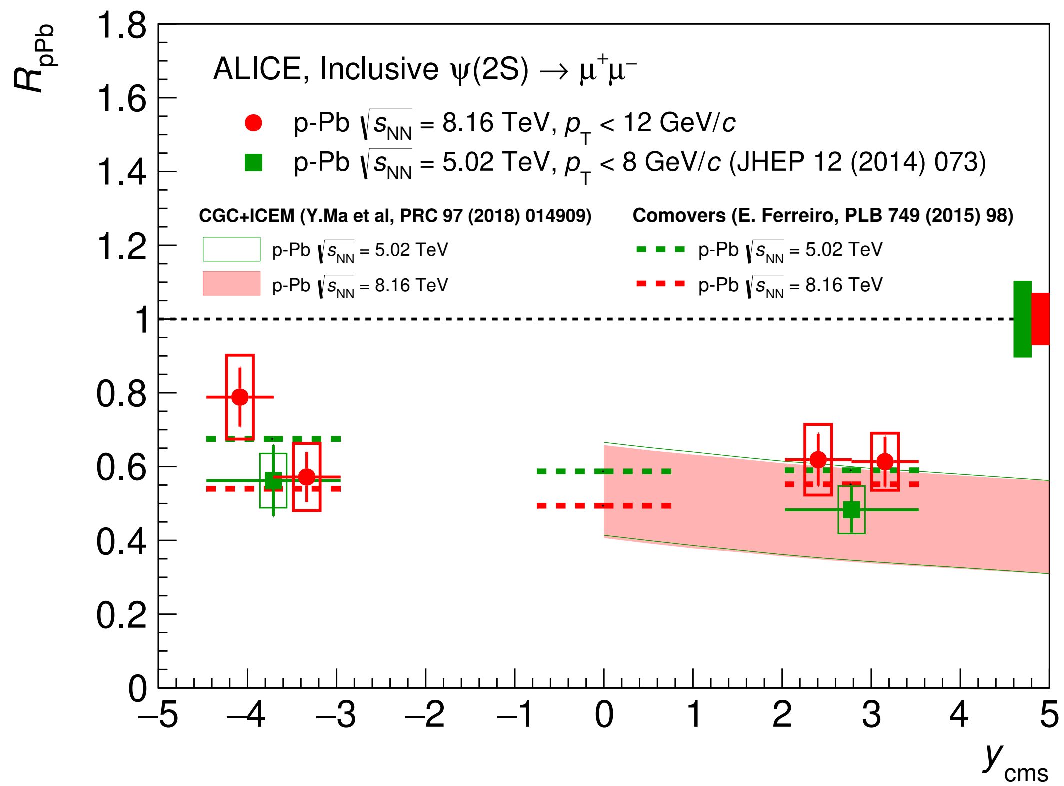


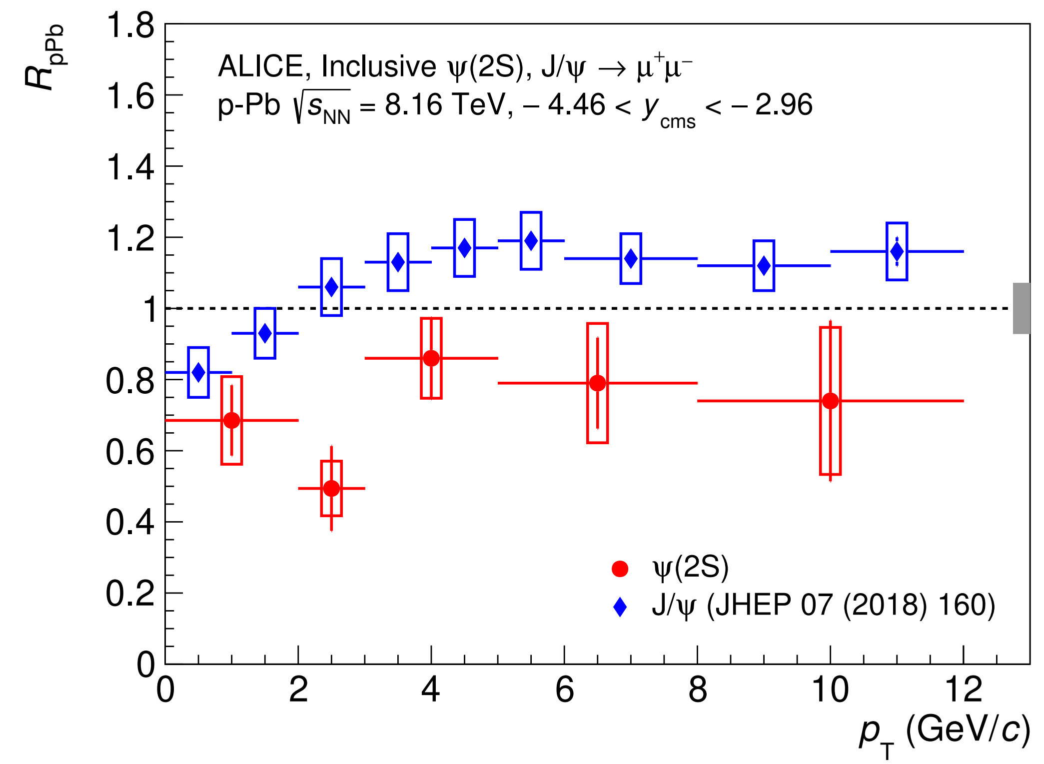
Excited states: $\psi(2S)$ production

JHEP07 (2020) 237

- p_{T} spectrum in the forward/backward region extracted by ALICE
- Relative $\psi(2s)/J/\psi$ suppression stronger at backward rapidity → relation with multiplicity?
  - hint of final state interaction with hadrons (comovers)
  - Initial-state effects cancel in ratio, binding energy of $\psi(2S)$ lower than that of J/ψ
  - non-prompt contribution not affected, important to separate



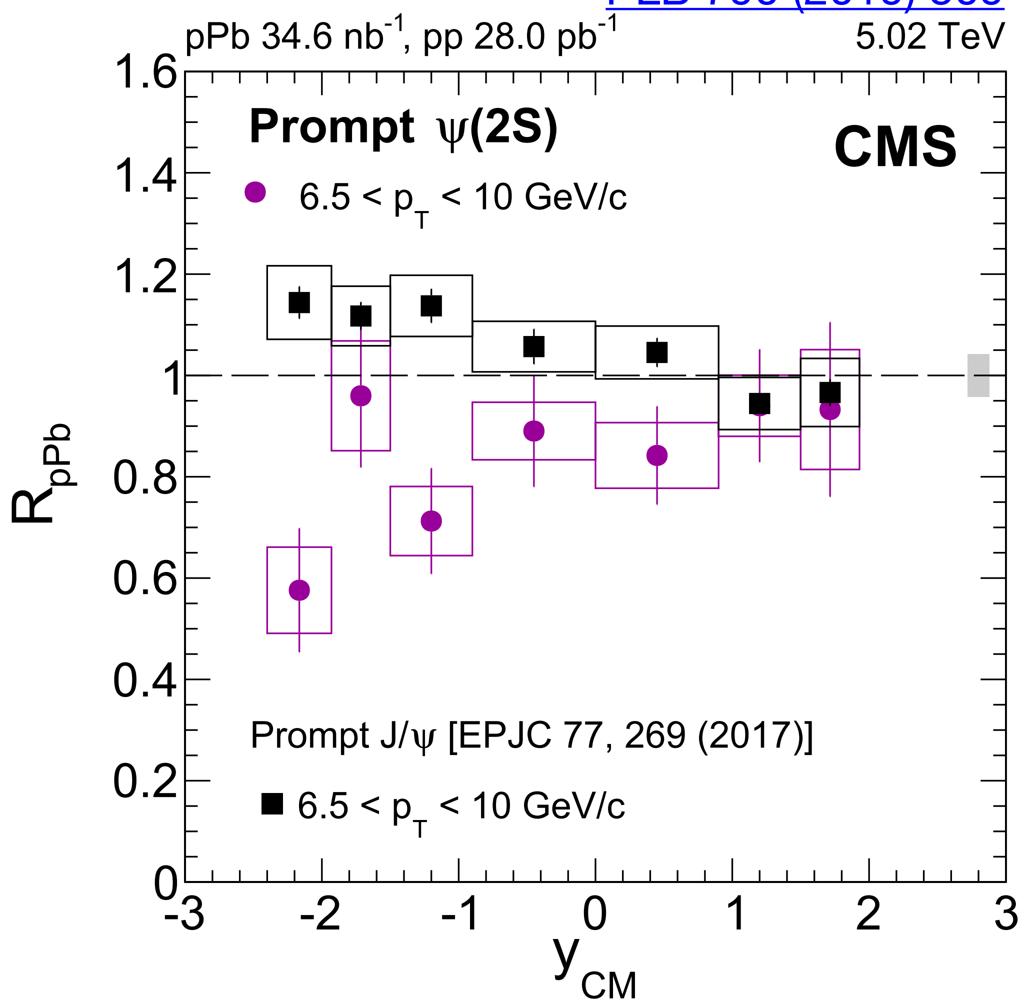




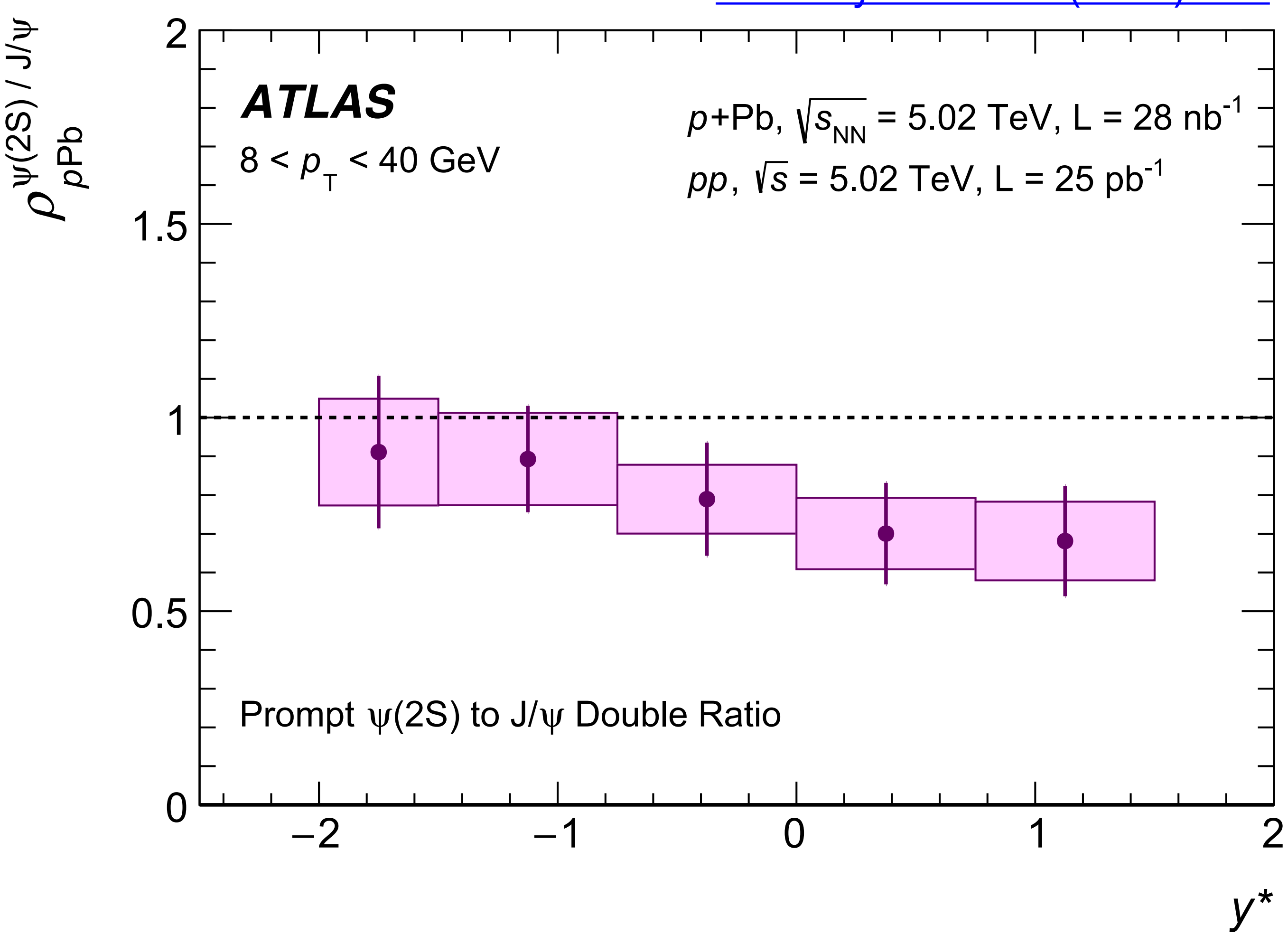
Excited states: $\psi(2S)$ production

- CMS also sees a stronger $\psi(2S)$ in backward rapidities
- ATLAS measured double ratio: $\rho_{pPb}^{\psi(2S)/J/psi} = \dfrac{\sigma_{pPb}^{\psi(2S)}/\sigma_{pPb}^{J/\psi}}{\sigma_{pp}^{\psi(2S)}/\sigma_{pp}^{J/\psi}}$
  - opposite trend seen at high p_{T}

PLB 790 (2019) 509



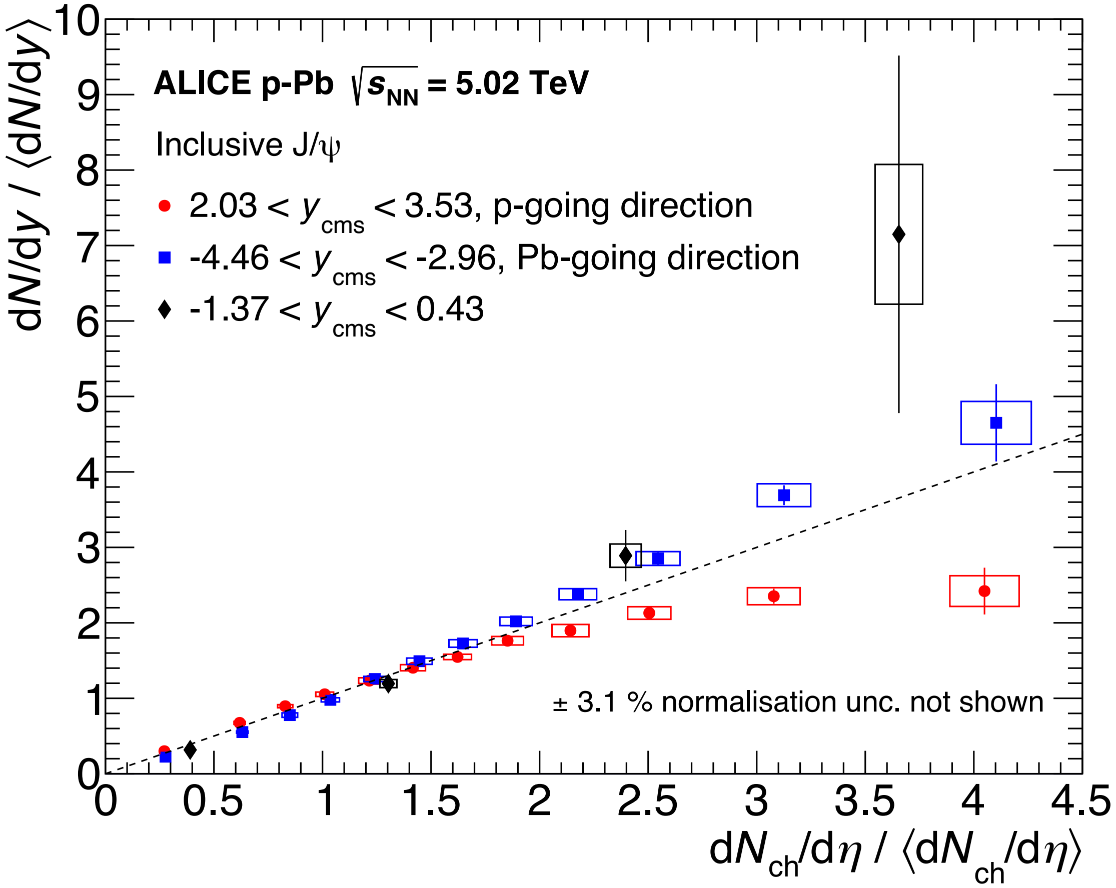
Eur. Phys. J. C 78 (2018) 171



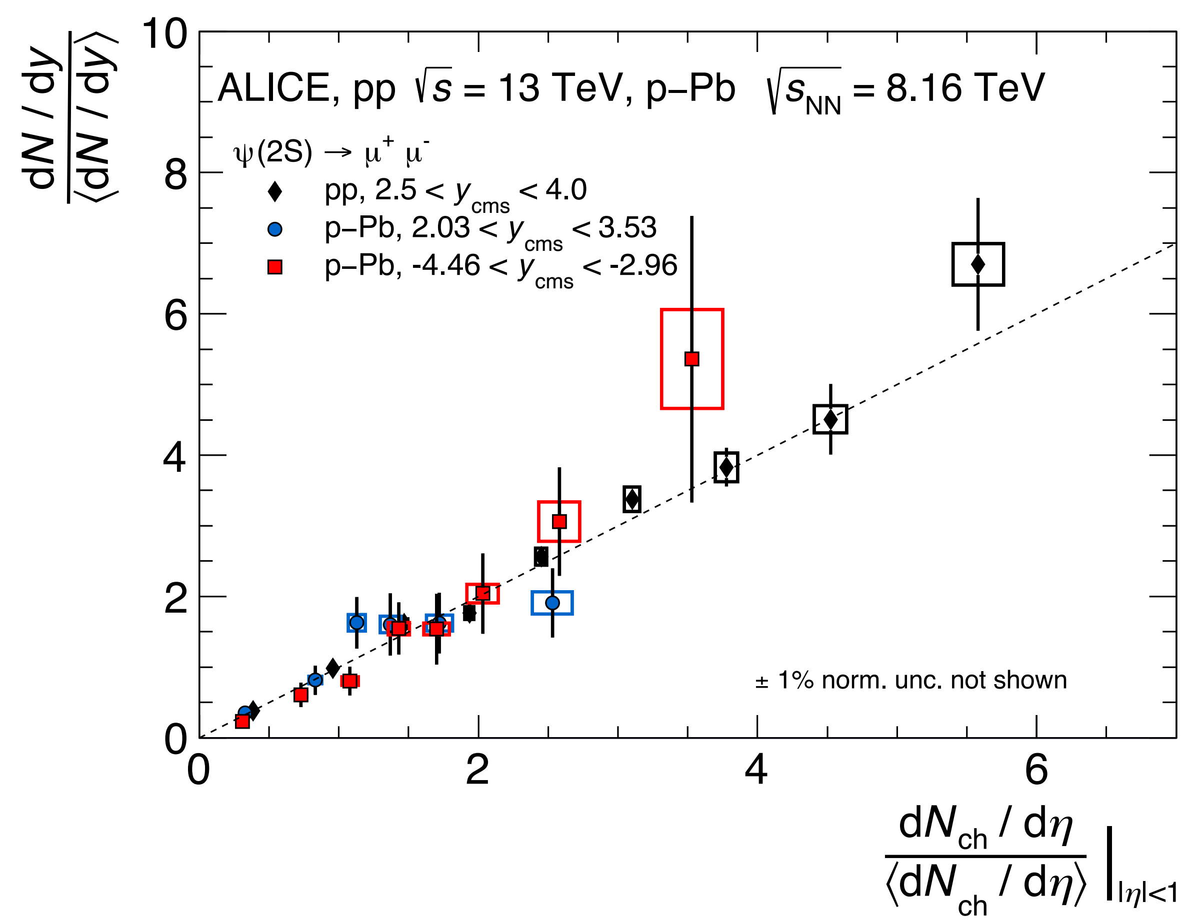
Production with multiplicity of J/ψ and $\psi(2S)$

- Study production with event charged particle multiplicity normalised by mean multiplicity in NSD events $\langle \mathrm{d}N_{\mathrm{ch}}/d\eta \rangle$
- Charged hadron multiplicity measured from SPD tracklets at $|\eta| < 1$
- Trends depend on quarkonium rapidity for $\mathrm{d}N_{\mathrm{ch}}/d\eta / \langle \mathrm{d}N_{\mathrm{ch}}/d\eta \rangle > 2$
- Saturation or MPIs could explain the trend at mid-rapidity
  - Need to understand how the η region where N_{ch} is measured affects the result

Inclusive J/ψ [Phys. Lett. B 776 (2018) 91]



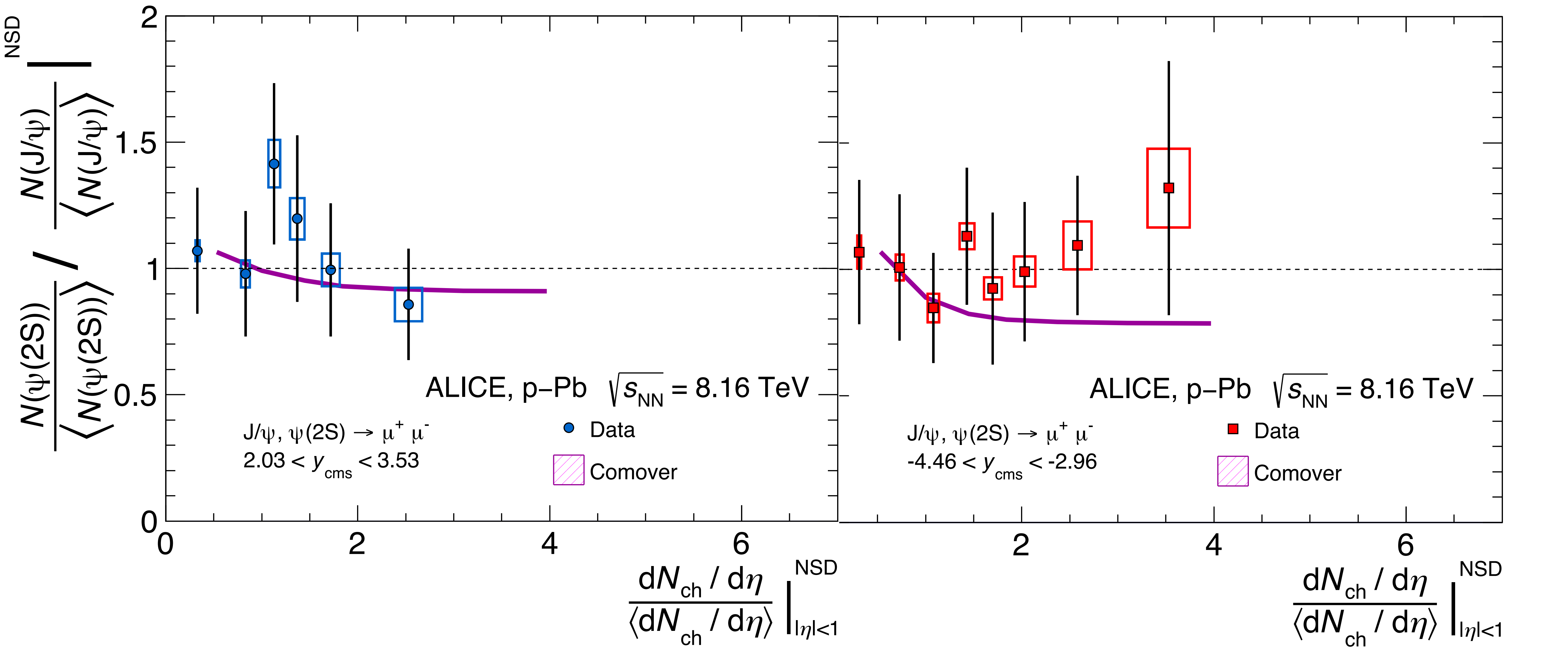
[arXiv:2204.10253] **Inclusive $\psi(2S)$**



Production with multiplicity: ratio

arXiv:2204.10253

- Ratio of $\psi(2s)$ with J/ψ can be a way to test comover model
- Uncertainties prevent from making conclusions
  - More measurements with prompt-nonprompt separation with more statistics are needed



$\Upsilon(nS)$ production in PbPb

[PRL 120, 199903](#)

[PLB P790 (2019) 270–293](#)

- $\Upsilon(nS)$ sequential suppression seen in PbPb by CMS
- Signature of QGP:
  - more direct probe at LHC energies than J/ψ , in principle cannot be produced by recombination
  - however, CNM effects could also explain similar patterns
- Need to explore $\Upsilon(nS)$ production in pPb

At $\sqrt{s_{NN}} = 5$ TeV:

LHCb: arXiv:2212.12664

ALICE: Phys. Lett. B 740 (2015) 105-117

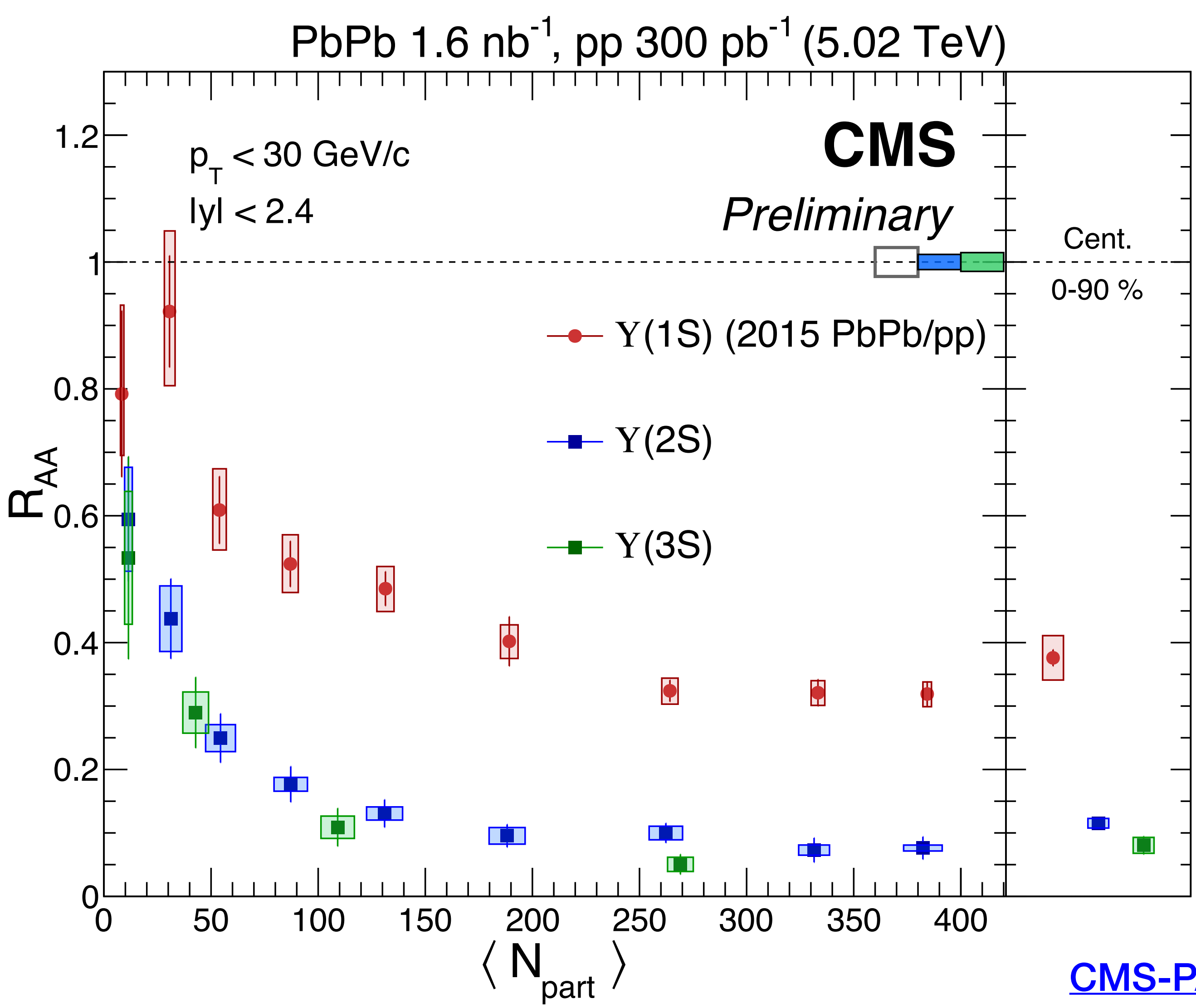
CMS: PLB 835 (2022) 137397

ATLAS: Eur. Phys. J. C 78 (2018) 171

At $\sqrt{s_{NN}} = 8$ TeV:

LHCb: JHEP 11 (2018) 194

ALICE: PLB 806 (2020) 135486

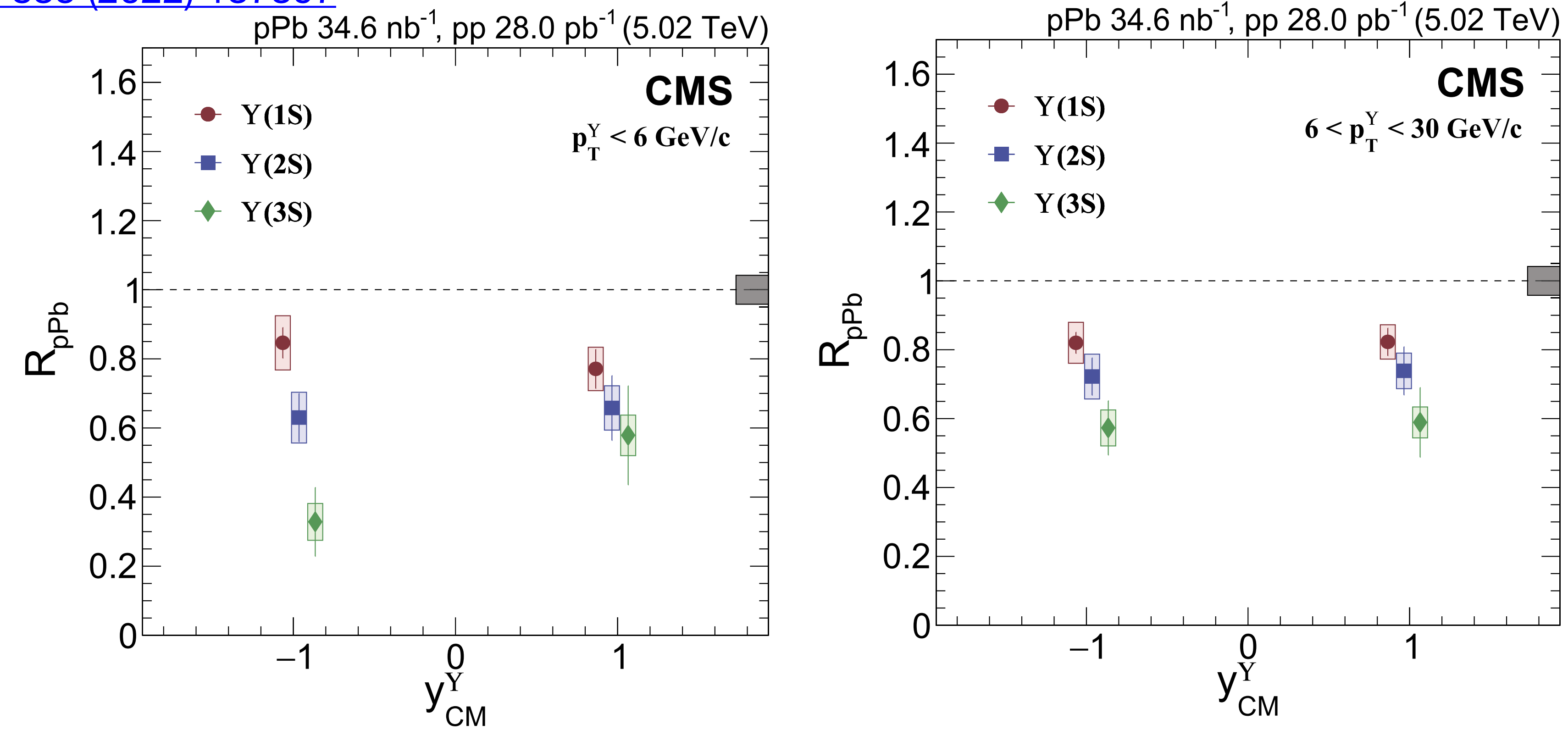


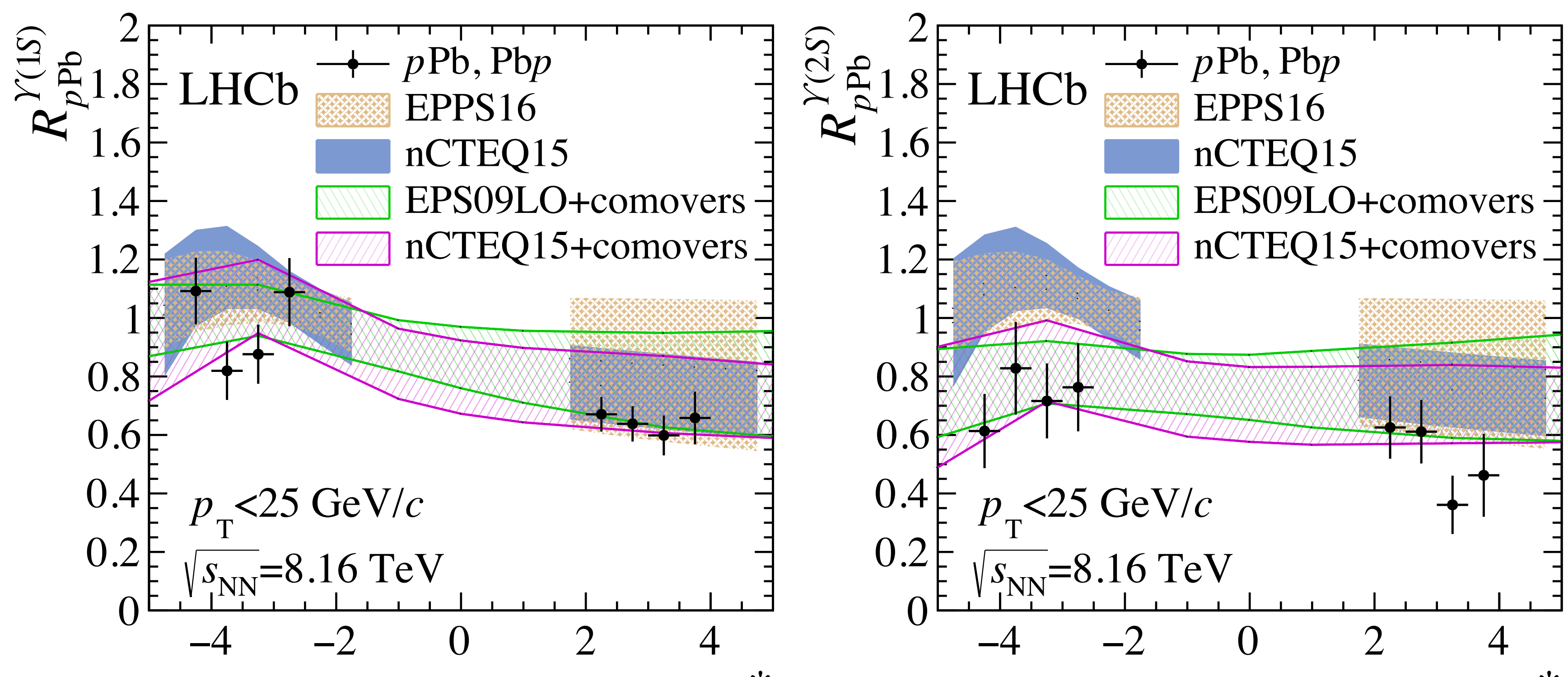
CMS-PAS-HIN-21-007

$\Upsilon(nS)$ production - y^* dependence

- Stronger suppression of excited states
  - CMS data shows stronger effect at low p_T
- LHCb data for the $\Upsilon(2S)$ not compatible with nPDF calculation alone
  - agreement improves by considering final-state interaction
  - model including QGP can also explain the data (PRC 100, 024906 (2019))

PLB 835 (2022) 137397



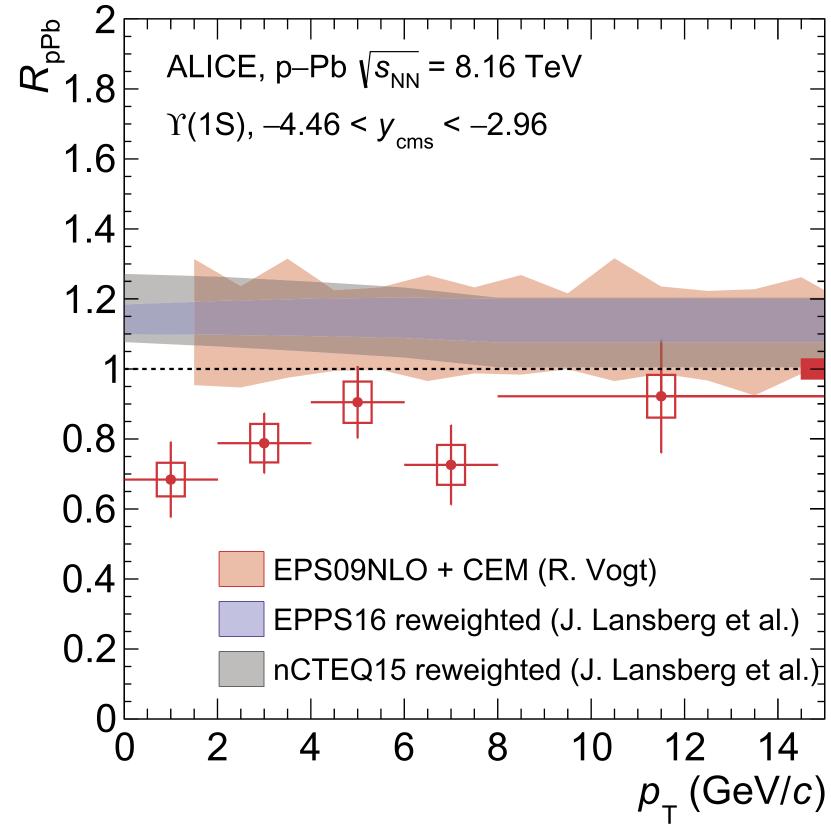


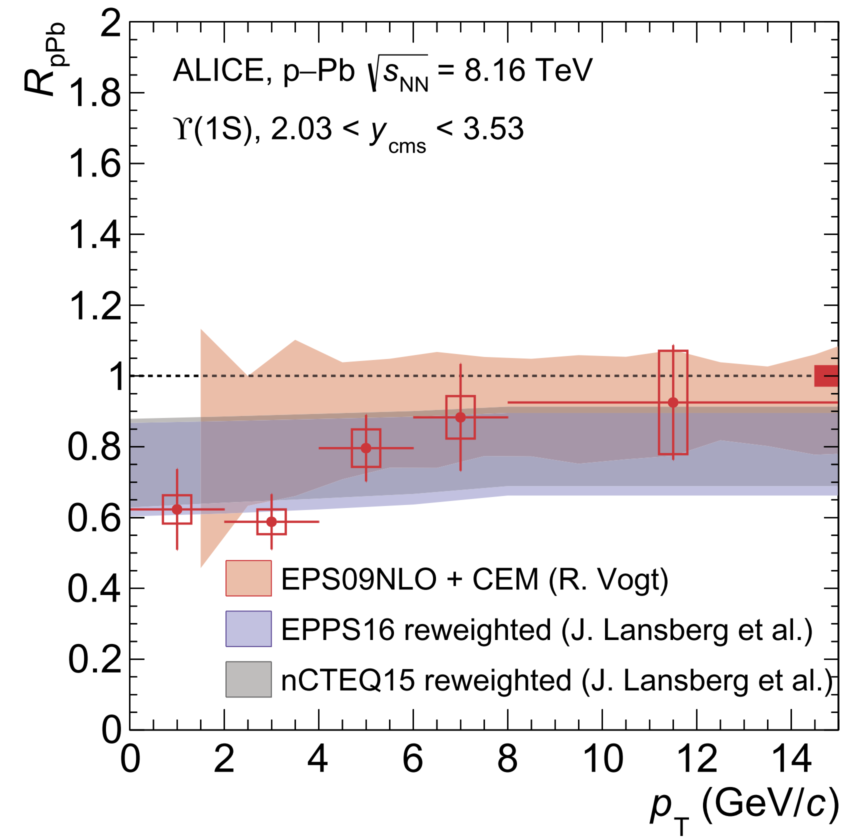
JHEP 11 (2018) 194

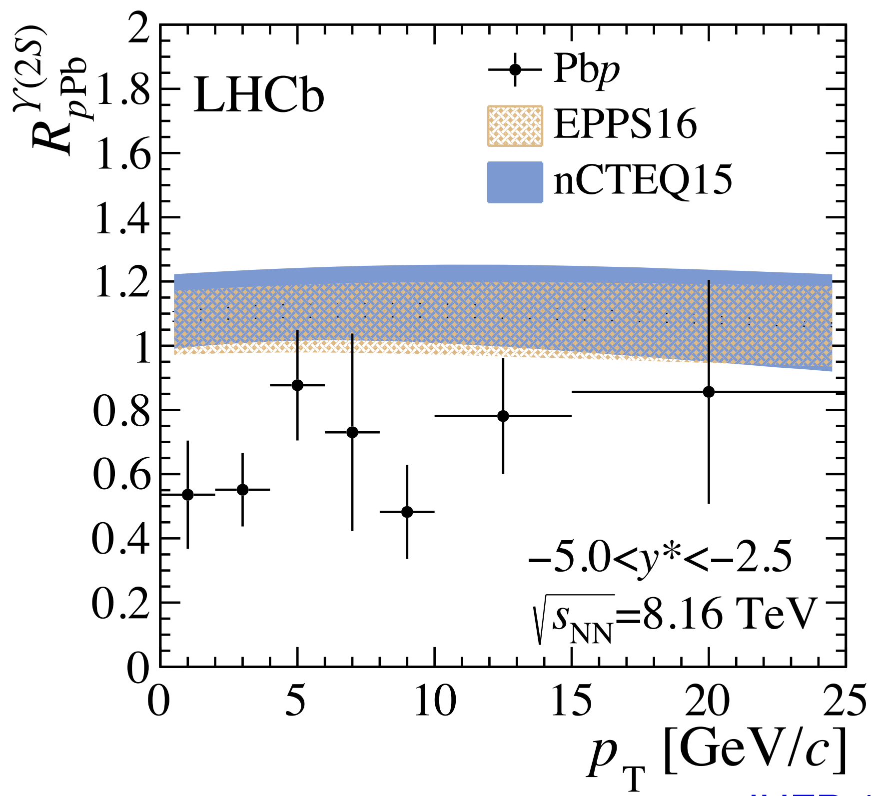
$\Upsilon(nS)$ production - p_{T} dependence

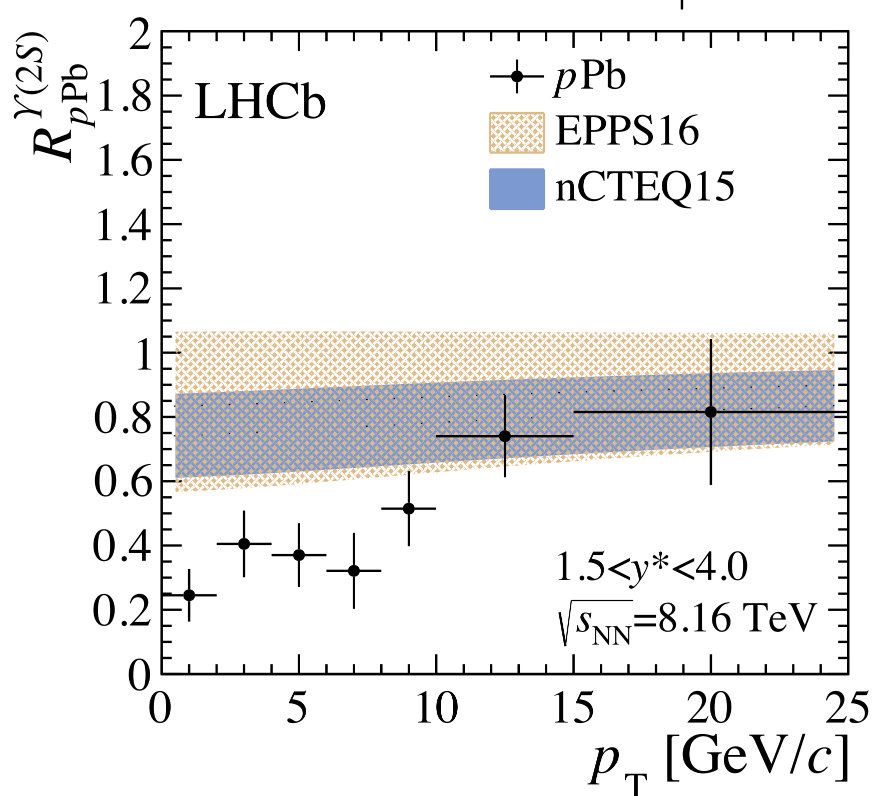
- Similar predictions for $\Upsilon(1S)$ and $\Upsilon(2S)$ from initial-state effects
- Suppression in the forward region and at low p_{T}
- Discrepancies with nPDF calculations at low p_{T} for backward $\Upsilon(1S)$ and forward $\Upsilon(2S)$

Backward [PLB 806 (2020) 135486] **Forward**







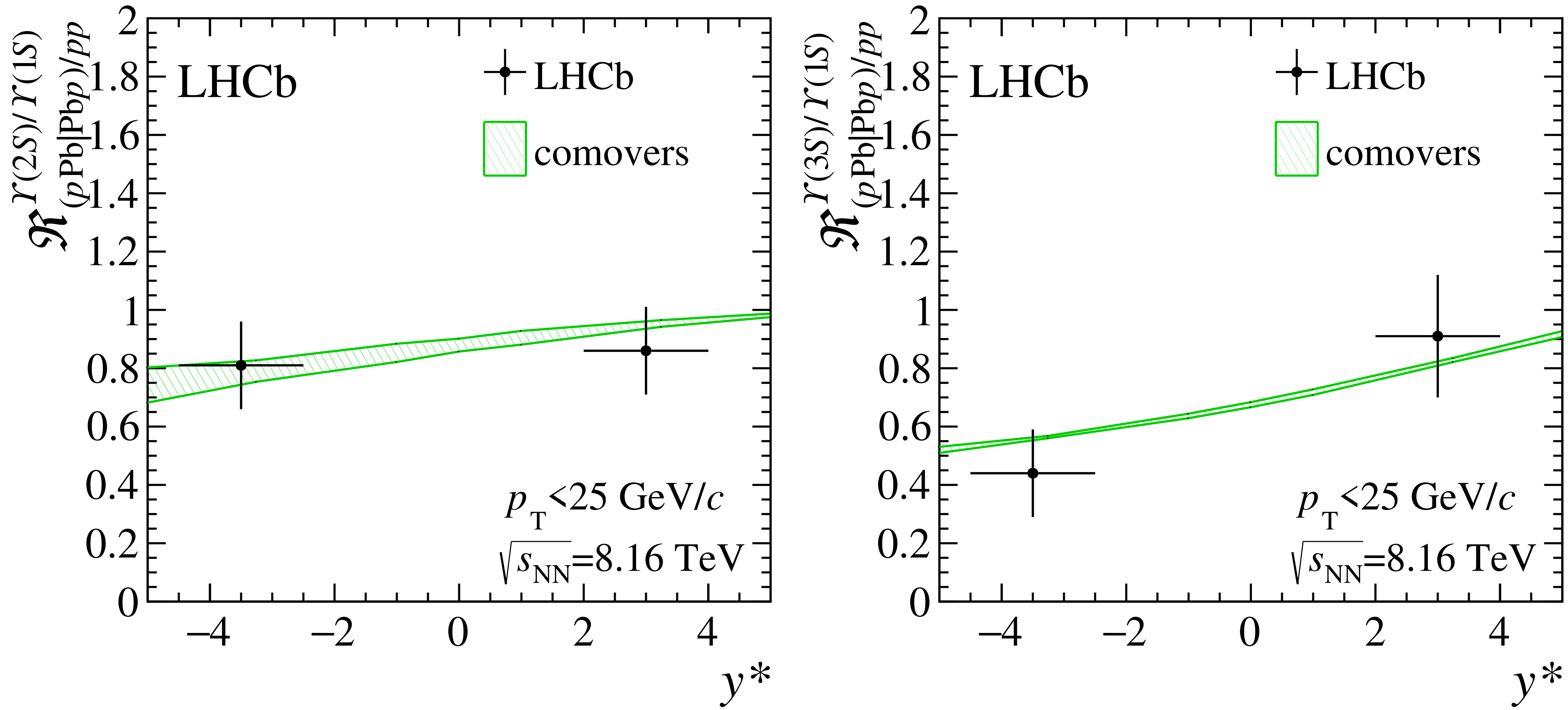


[JHEP 11 (2018) 194]

$\Upsilon(nS)$ production - double ratio

- Double ratio $$\mathfrak{R}^{\Upsilon(ns)/\Upsilon(1s)}_{(p\mathrm{Pb}|\mathrm{Pb}p)/pp} = \frac{R(\Upsilon(nS))_{p\mathrm{Pb}|\mathrm{Pb}p}}{R(\Upsilon(nS))_{pp}}$$
  - Initial-state effects should mostly cancel
  - Double ratio consistent with prediction of comover model

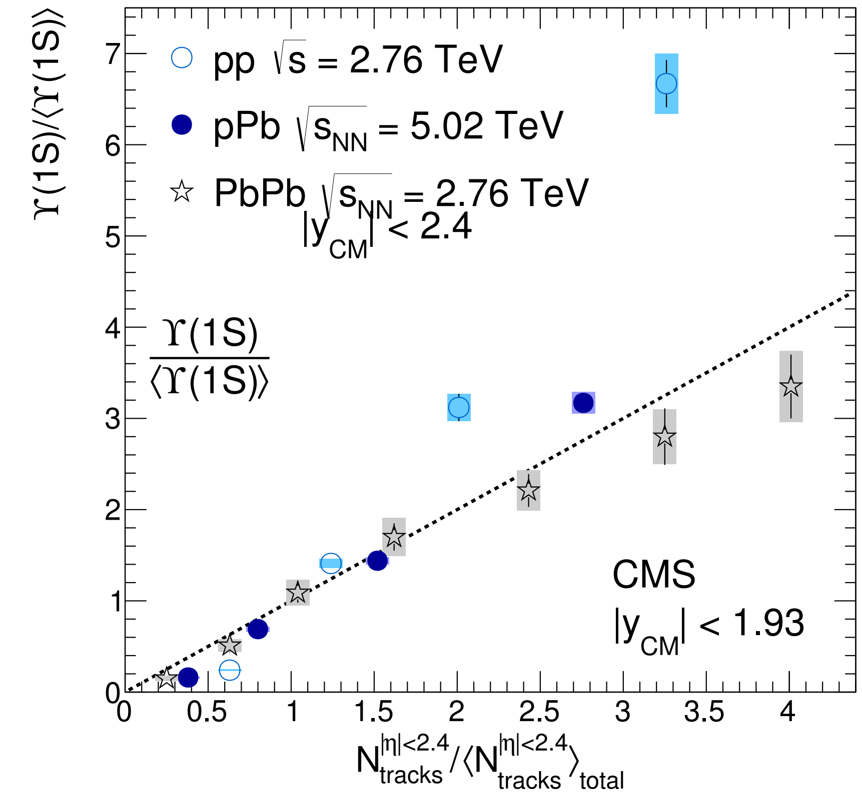
JHEP 11 (2018) 194

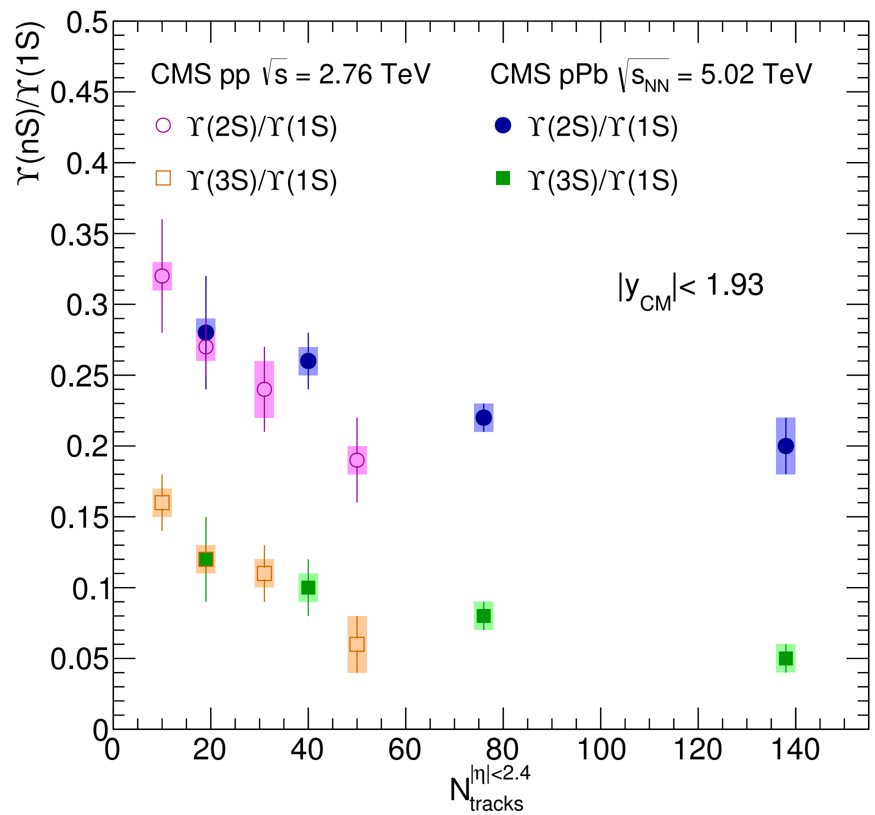


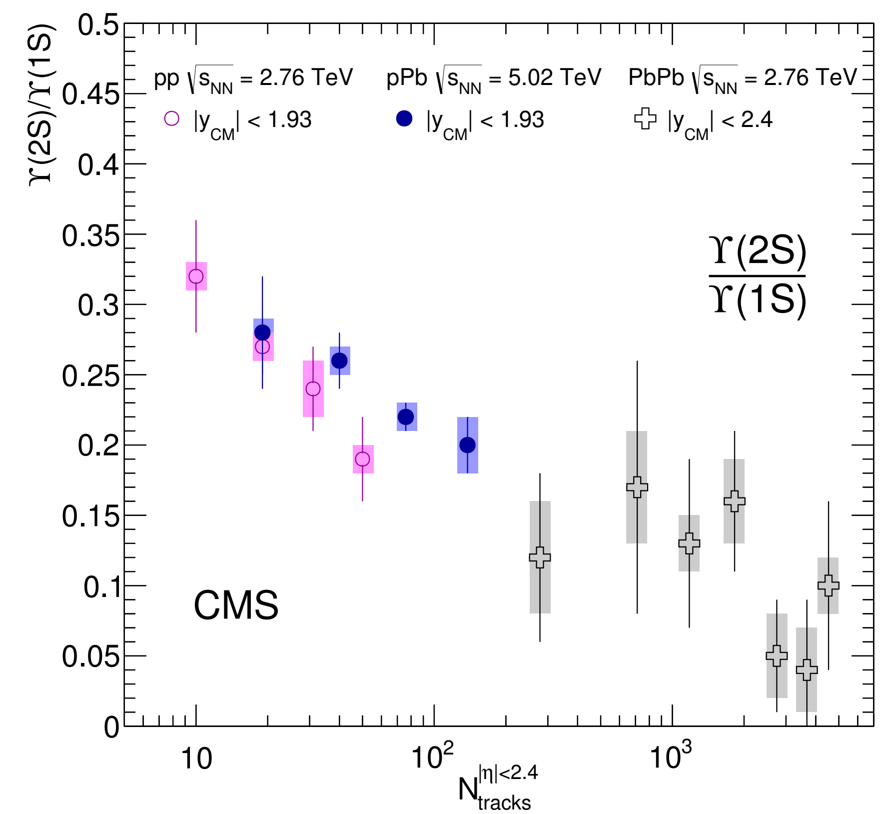
$\Upsilon(nS)$ production with event multiplicity

CMS: [JHEP 04 (2014) 103]

- CMS measured $\Upsilon(1S)$ and $\Upsilon(2S)$ with respect to the event track multiplicity in $|\eta| < 2.4$
- Self-normalised ratio $\Upsilon(1S)/\langle\Upsilon(1S)\rangle$ vs $N_{\text{tracks}}^{|\eta|<2.4}/\langle N_{\text{tracks}}^{|\eta|<2.4}\rangle_{\text{total}}$ shows different trend at high multiplicity for pp, pPb and PbPb
- Excited-to-ground state ratio with $N_{\text{tracks}}^{|\eta|<2.4}$
  - decreasing trend of $\Upsilon(2S)/\Upsilon(1S)$ ratio down to PbPb



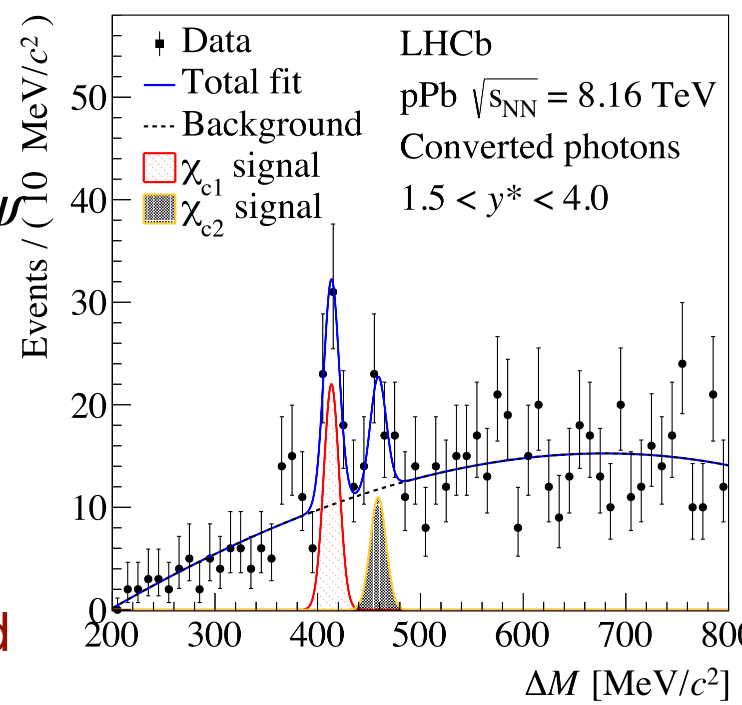


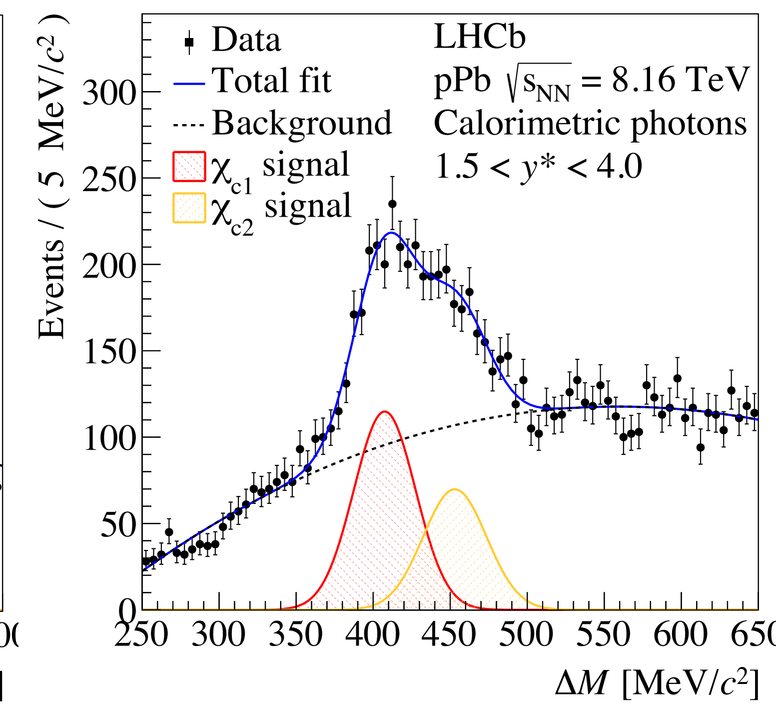


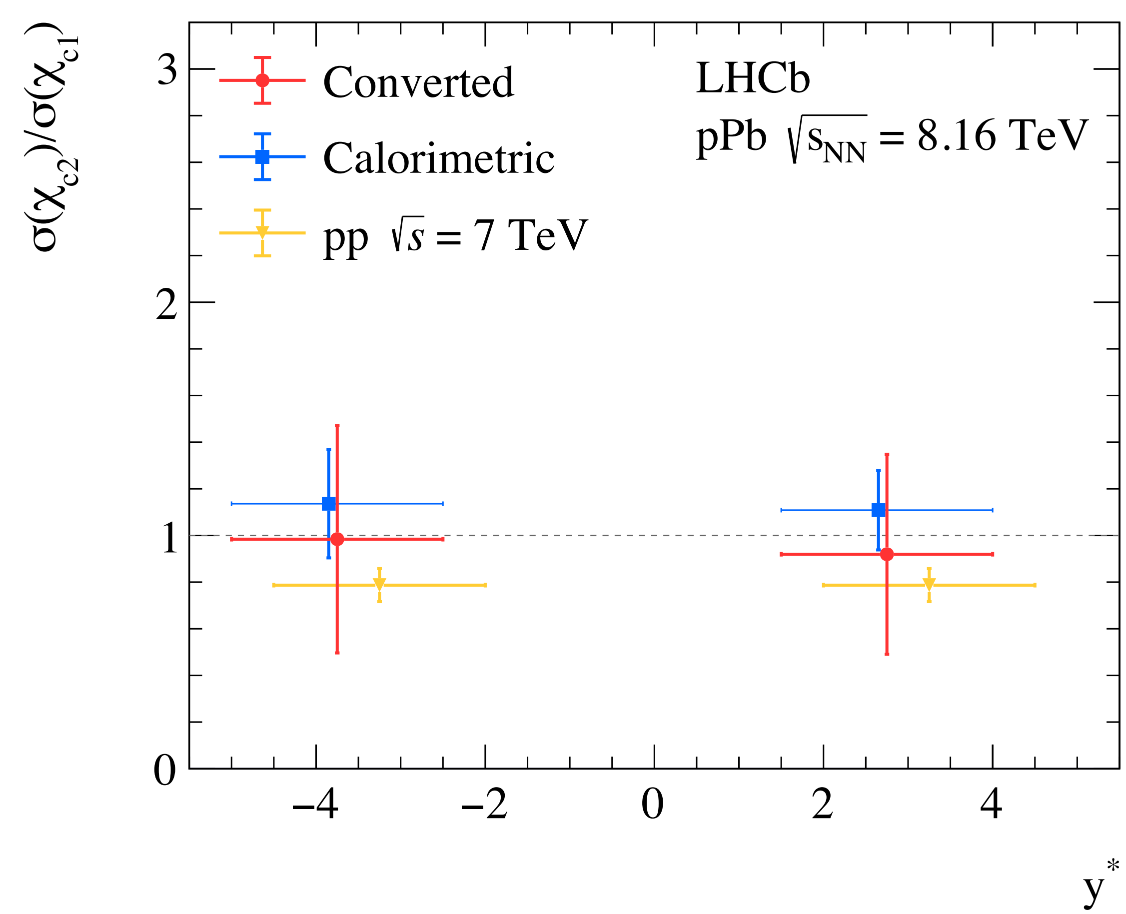
χ_{cn} production in pPb

[Phys. Rev. C103 (2021) 064905]

- Measuring χ_{cn} is important:
  - feed-down to J/ψ production
  - different binding energy with respect to J/ψ and $\psi(2S)$
  - but photon of $\chi_c \rightarrow J/\psi\,\gamma$ hard to detect
- LHCb measured prompt $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ ratio in pPb collisions
  - two photon detection strategies: converted and calorimetric
  - cancellation of efficiencies in cross-section ratio
  - work ongoing in photon efficiency determination
- Ratio consistent with unity
  - No rapidity dependence within uncertainty
- Consistent with pp $7\,\mathrm{TeV}$ ratio within 2σ ([JHEP10(2013) 115])
  - similar nuclear effects for both states
- Measurement with converted photons would benefit a lot from a larger dataset





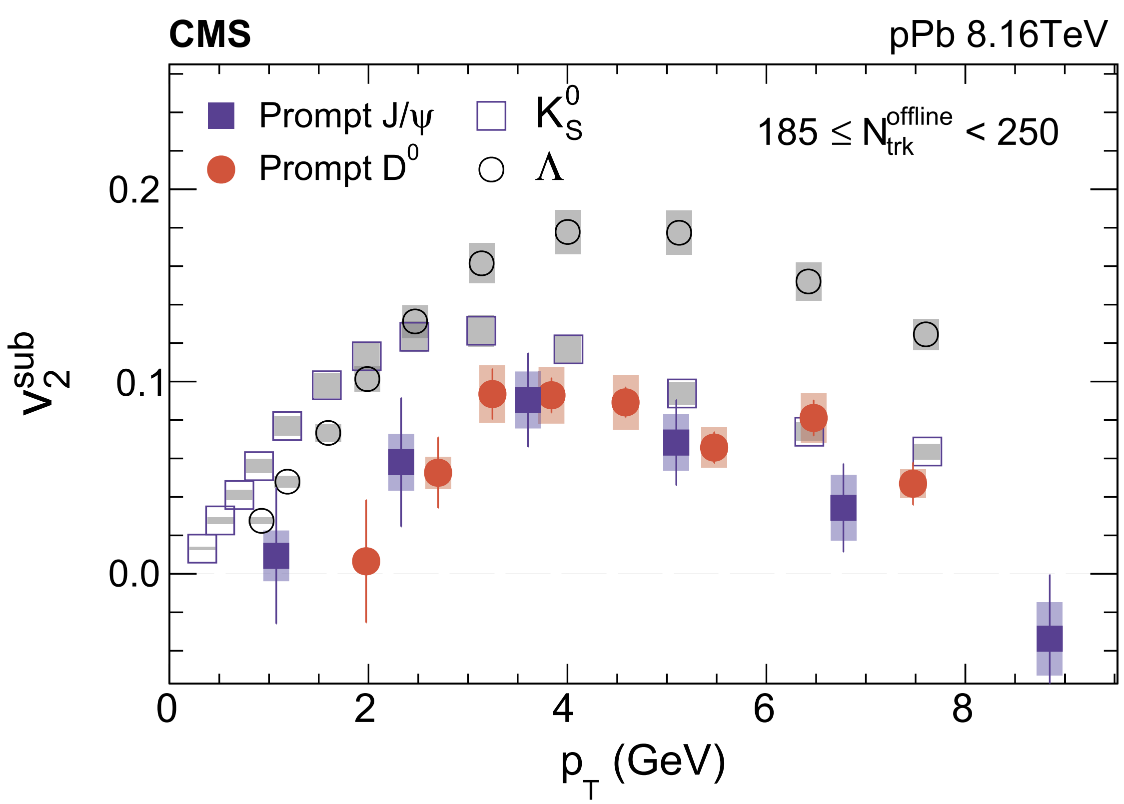


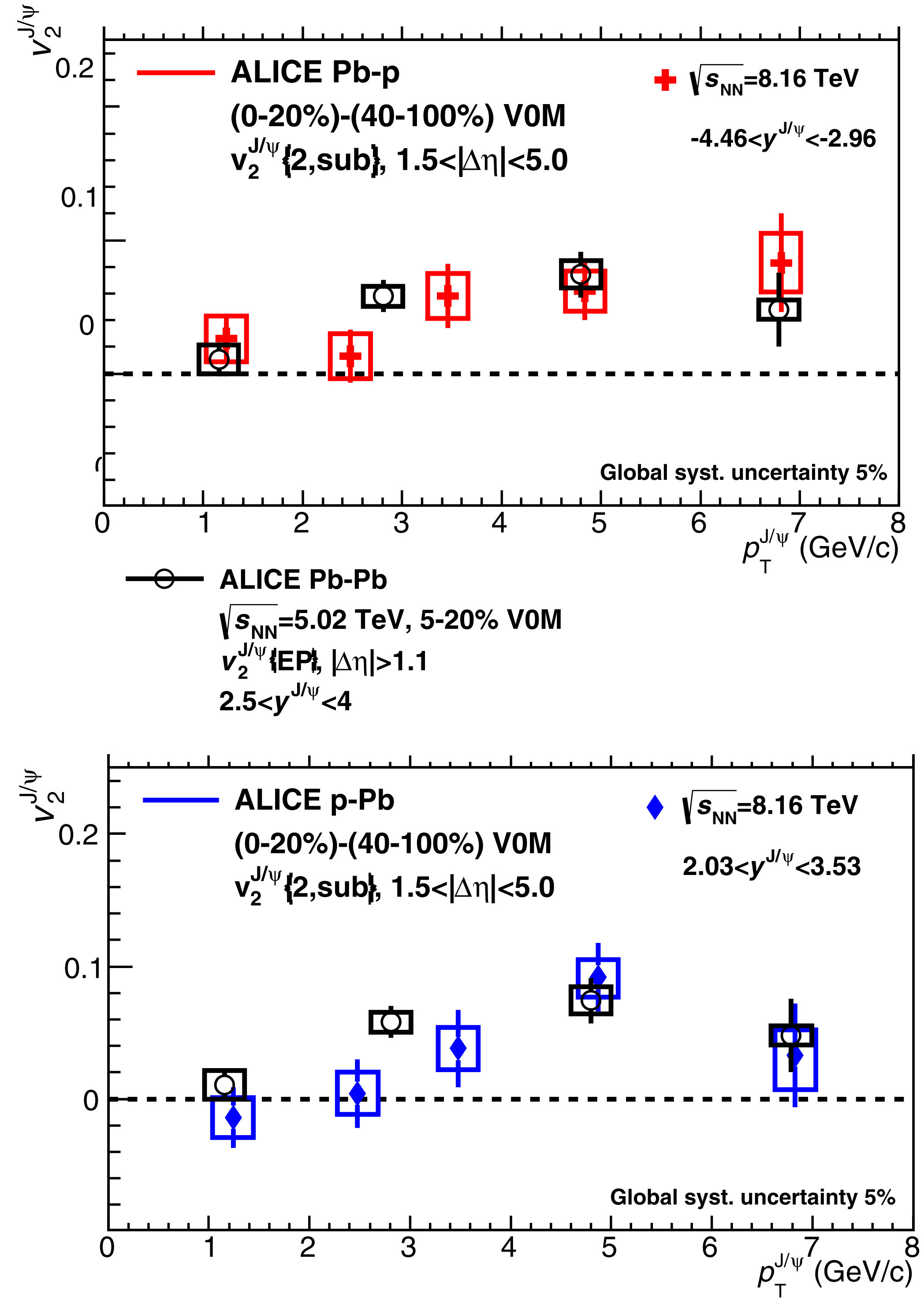
Azimuthal correlations: flow of J/ψ

- Azimuthal correlations with charged hadrons → study collectivity in quarkonium production
- Observable → v_2^{sub}: elliptic flow difference in high multiplicity with respect to low multiplicity
- Flow of J/ψ observed in high-multiplicity events in:
  - forward + backward rapidities (CMS)
  - central rapidities (ALICE)
- Explanations for observed collectivity unclear, similar magnitude to PbPb (5-20%) collisions at high p_T

ALICE: Phys. Lett. B 780 (2018) 7-20
CMS: PLB 791 (2019) 172

$-2.86 < y^* < -1.86$ and $0.94 < y^* < 1.94$

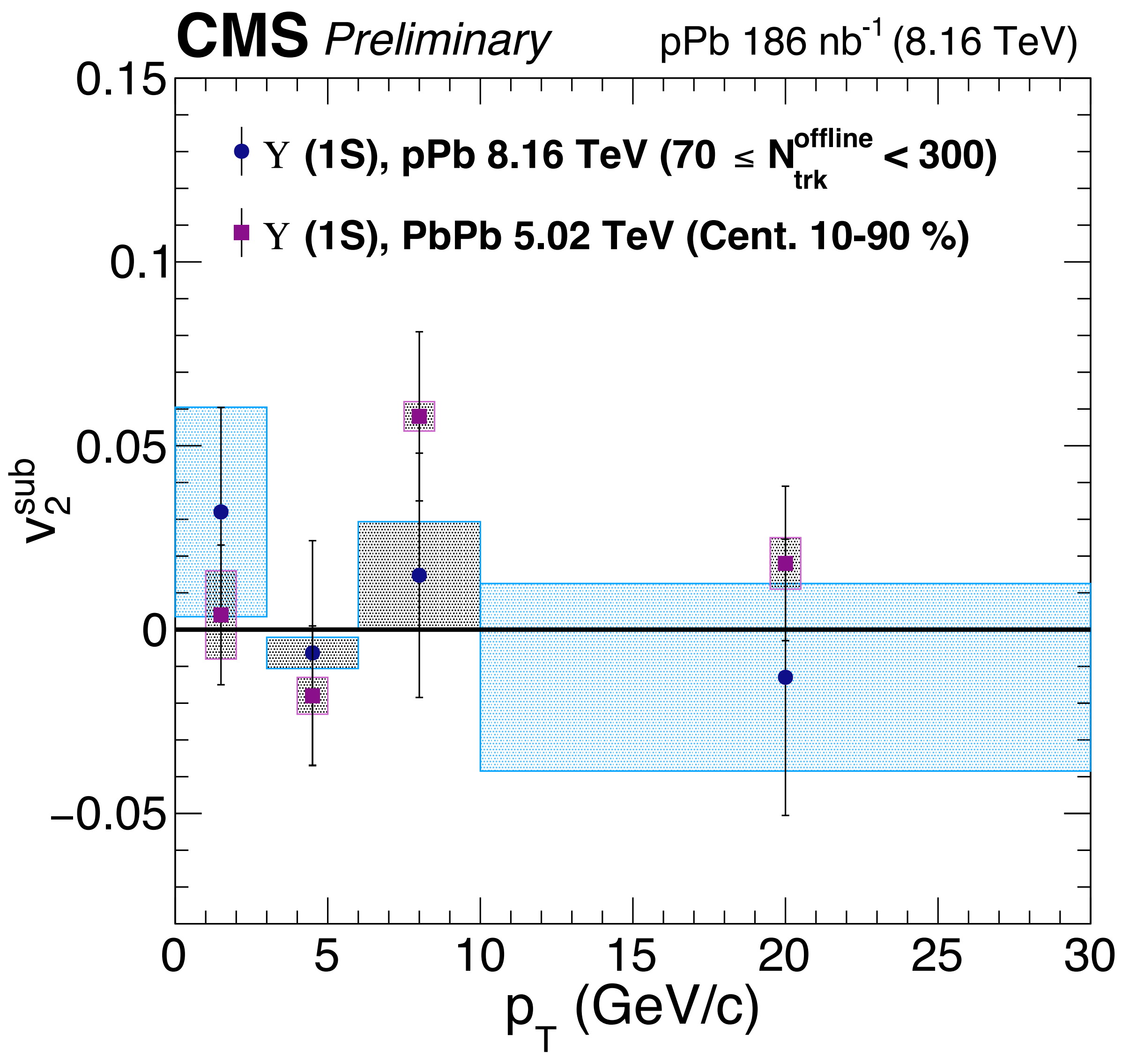


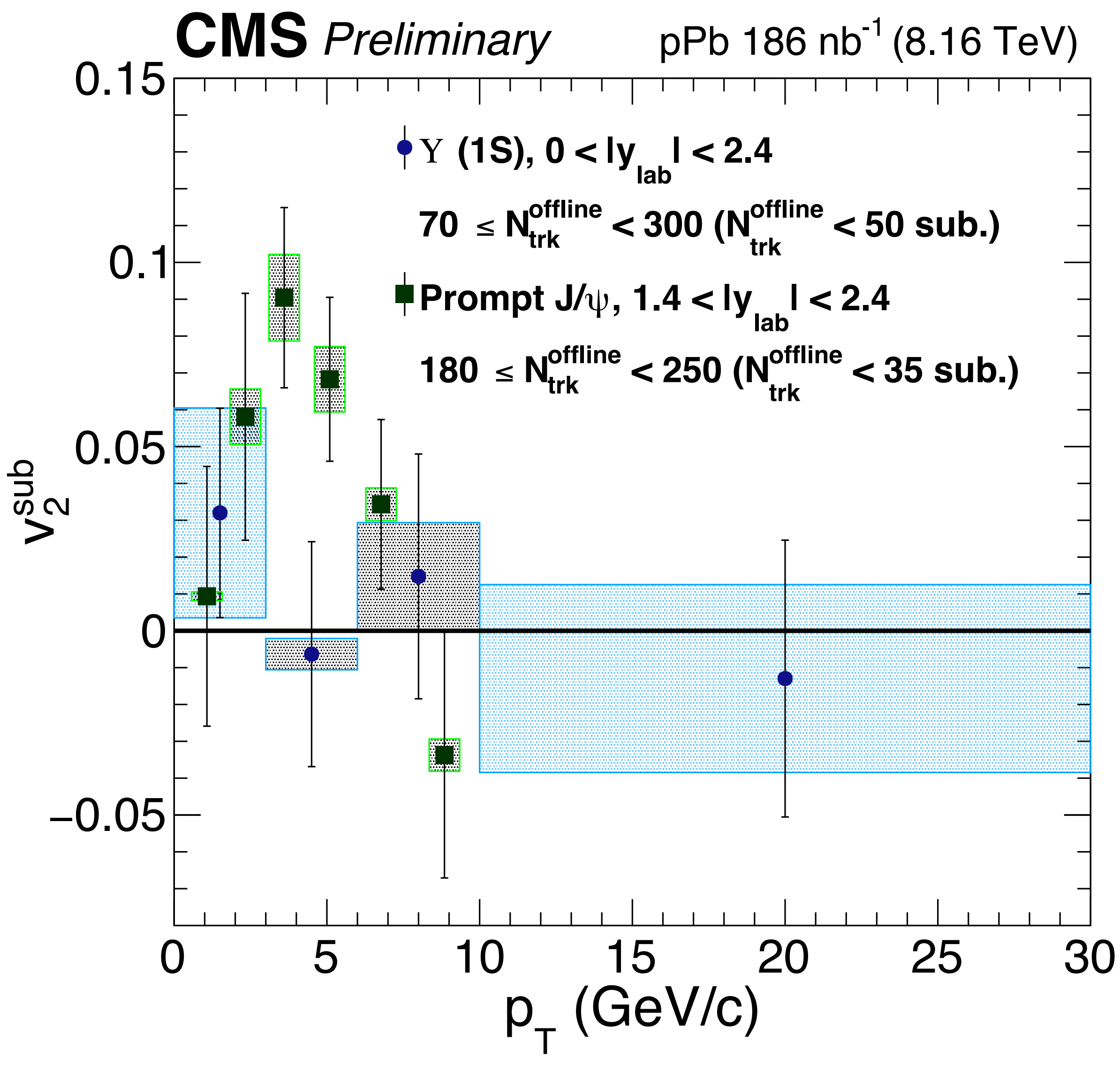


$\Upsilon(1S)$ flow

CMS-PAS-HIN-21-001

- Preliminary CMS result
  - No significant flow observed in high-multiplicity events for $\Upsilon(1S)$, like for PbPb collisions
  - More precision (and excited states) reachable with higher statistics





Conclusions

- Progress on the understanding of quarkonium modification in $p\mathrm{Pb}$ collisions:
  - Crucial for a correct interpretation of PbPb data
  - Initial-state effects seem to explain most observed nuclear effects in $R_{p\mathrm{Pb}}$ of ground states
  - Final-state effects could explain the differences in the excited states
  - Signs of collectivity from J/ψ flow in high-multiplicity $p\mathrm{Pb}$ collisions, although their origin is unclear
- A larger $p\mathrm{Pb}$ dataset would open many possibilities:
  - More precise measurements of excited states ($\psi(2S)$, $\Upsilon(3S)$, …)
  - Improve χ_{cn} measurement, specially with converted photon
  - Quarkonium from hadronic decays at LHCb in $p\mathrm{Pb}$?
- Possible $p\mathrm{O}$ run during Run3/Run4:
  - Study of quarkonia modification in medium size nucleus. Important if OO run takes place

Backup

Prompt J/ψ production at $5\ \text{TeV}$

- Recent update of the pp reference for $R_{p\text{Pb}}$ for prompt J/ψ production at $5\ \text{TeV}$

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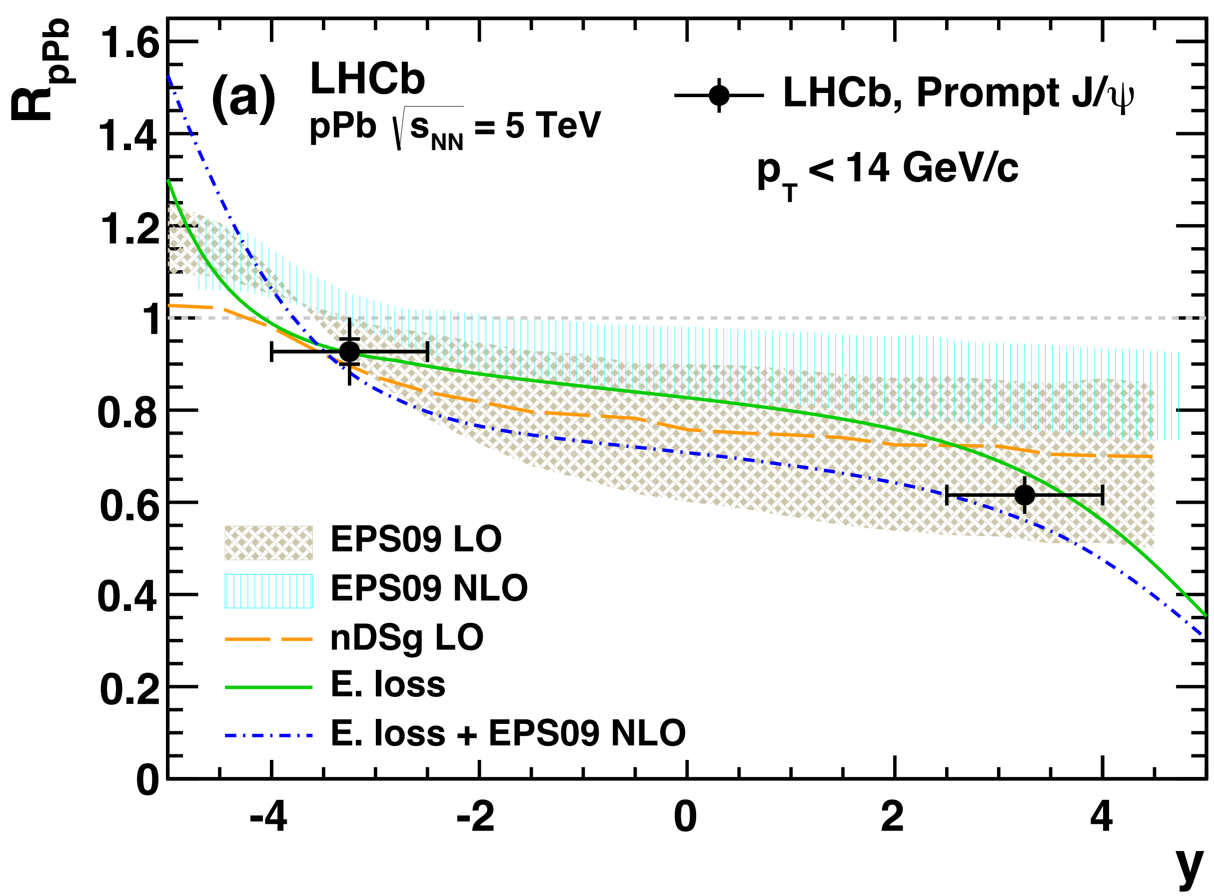

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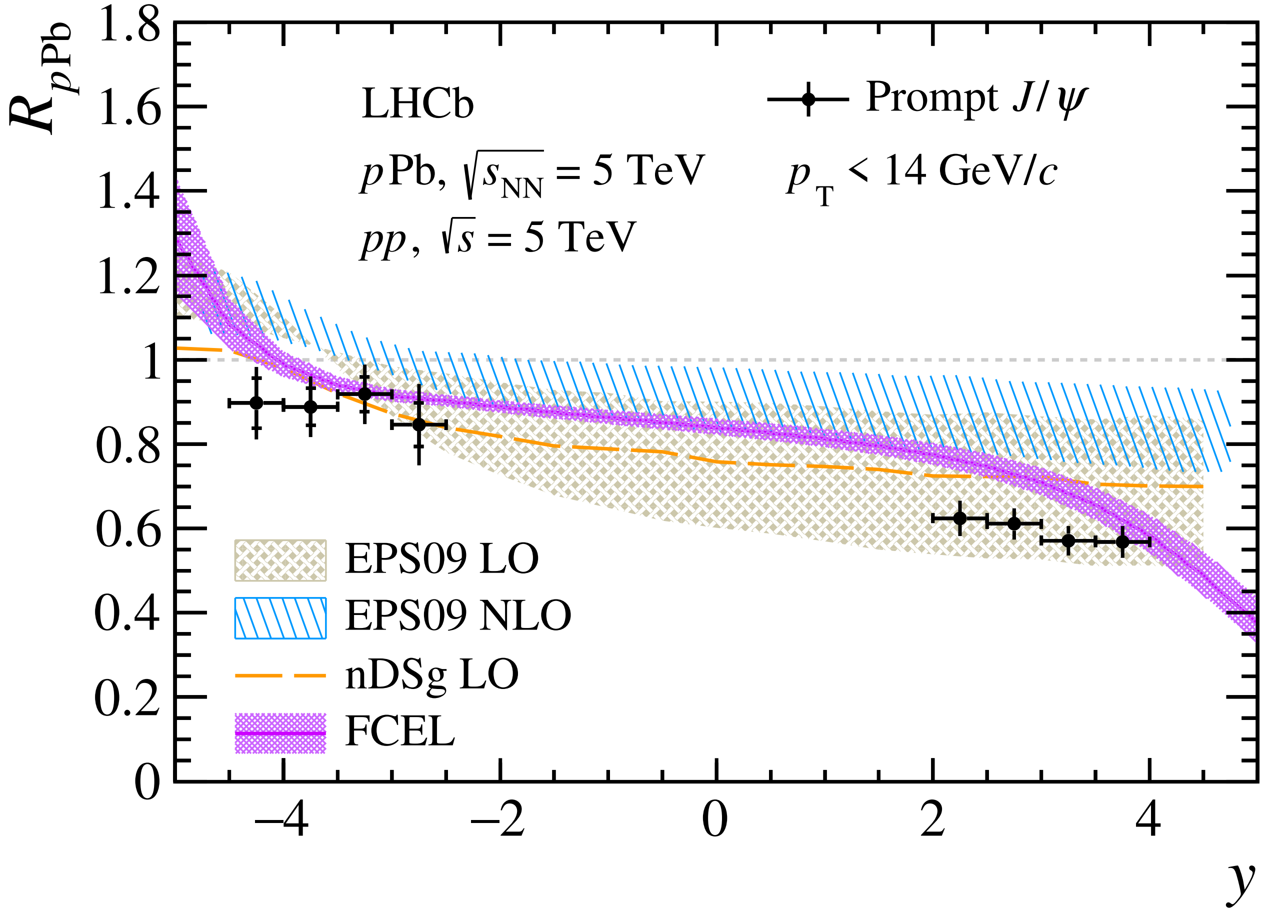

Production of $\chi_{c1}(3872)$ in pPb

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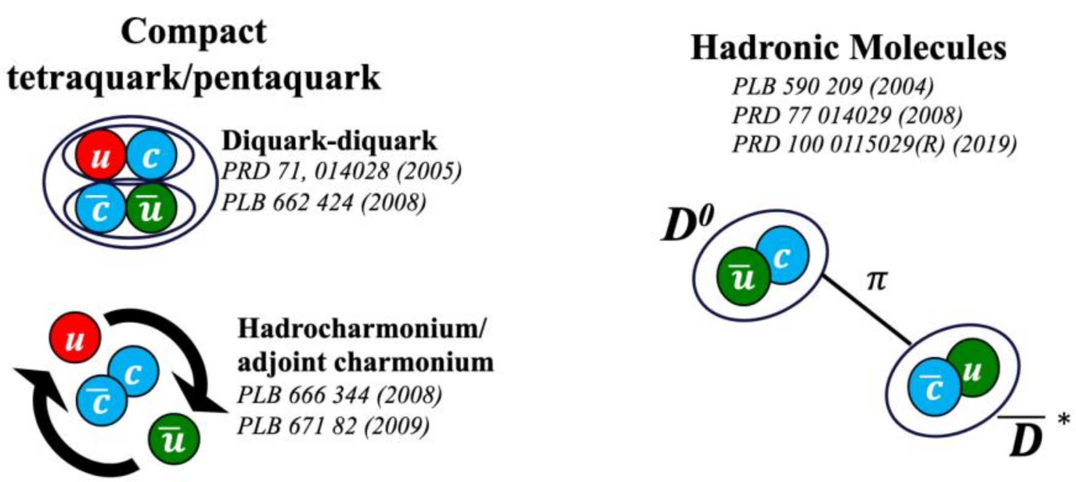
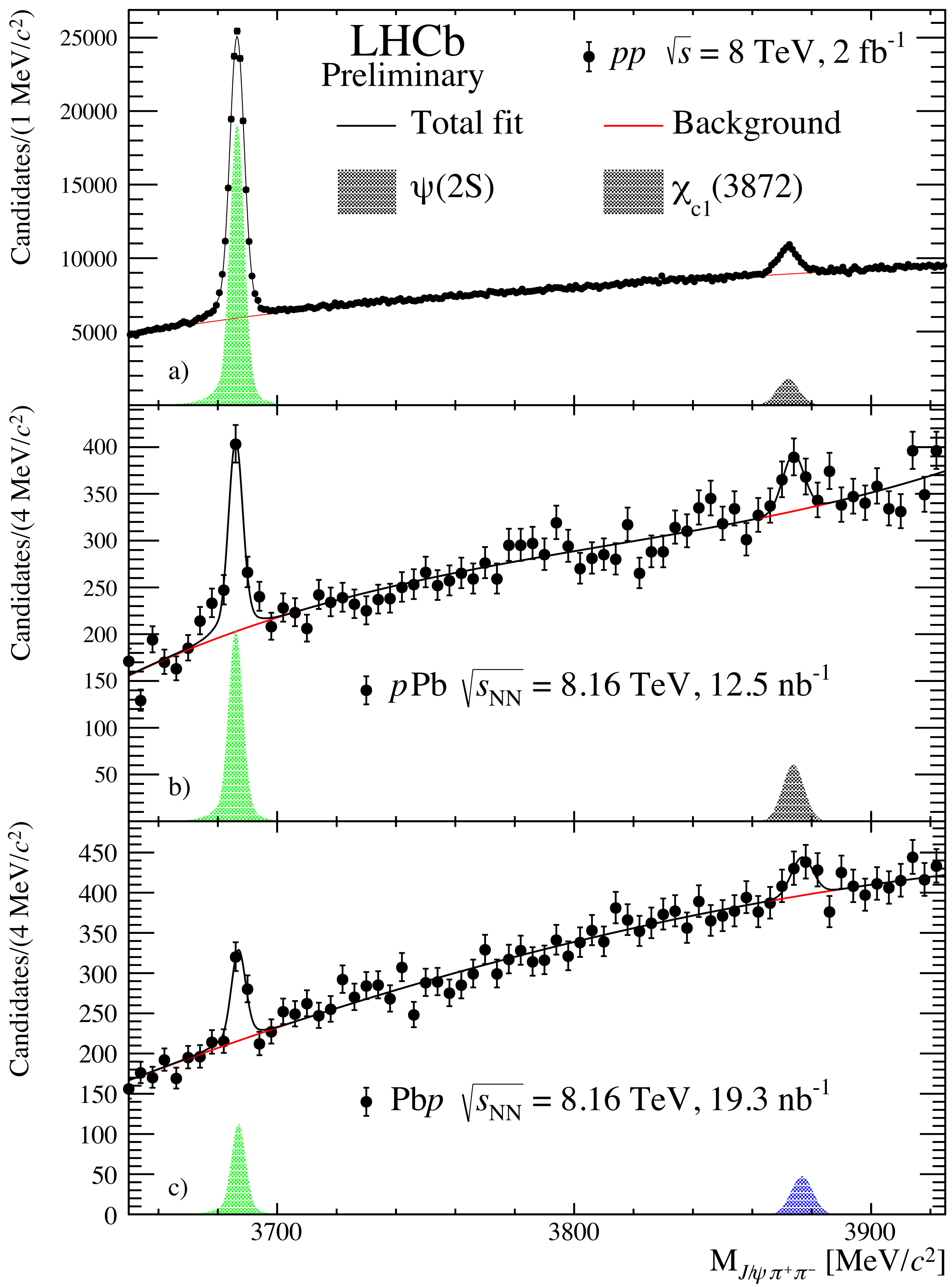
- Nature of $\chi_{c1}(3872)$ not clear (tetraquark, molecule, combination?)
  - Study production with respect to the QCD medium
  - Non conventional hadrons → new probes of hadronisation mechanisms

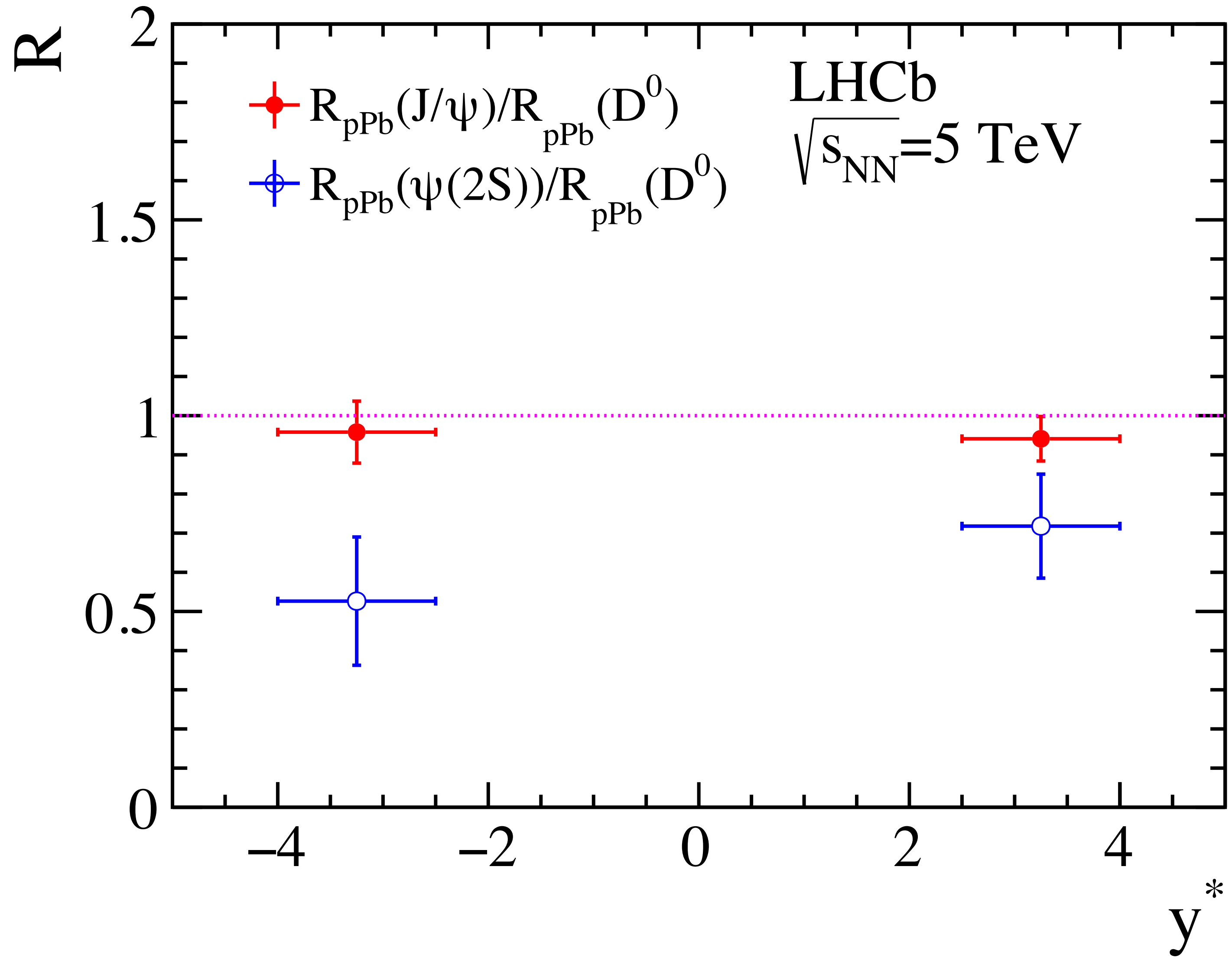




- Measure ratio of prompt $\chi_{c1}(3872)$, $\psi(2S)$with $\chi_{c1}(3872), \psi(2S) \to J/\psi\pi^+\pi^-$
- Use full $\sqrt{s_{NN}} = 8.16\,\text{TeV}$ dataset

Ratio J/ψ and $\psi(2S)$ with D^0

JHEP 10 (2017) 090



Production of $\chi_{c1}(3872)$ in pPb

- Increase of the $\chi_{c1}(3872)/\psi(2S)$ ratio with system size
- Different behaviour of $\chi_{c1}(3872)$ and $\psi(2S)$
  - $\psi(2S)$ suppressed in pPb
  - Enhancement of $\chi_{c1}(3872)$?
- Contrast with trend in pp with multiplicity

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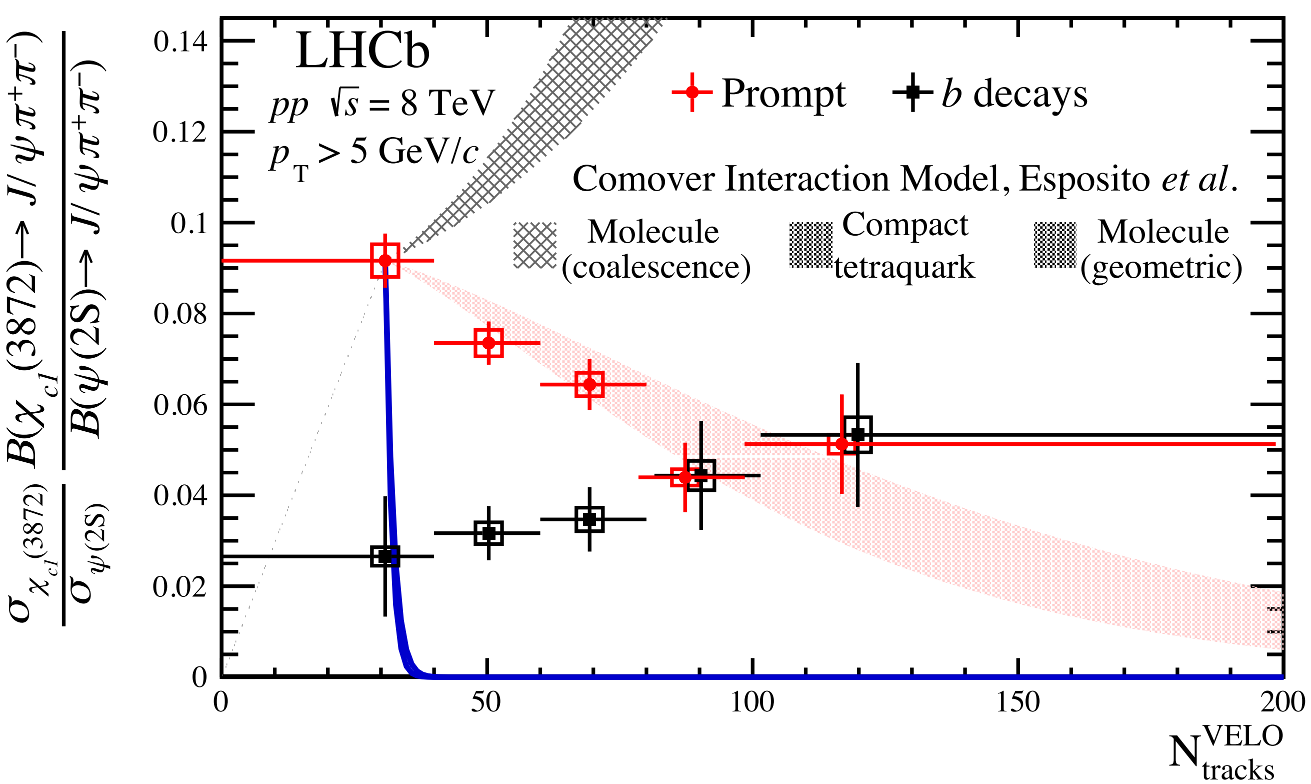

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