Recent measurements of excited state quarkonium production in *p*A collisions

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11 January 2024

Quarkonia as Tools, Aussois, France

Outline

1. Motivation for studying quarkonia in *p*A collisions
2. Recent results for charmonia in *p*Pb
3. Recent results for bottomonia in *p*Pb
4. Future opportunities

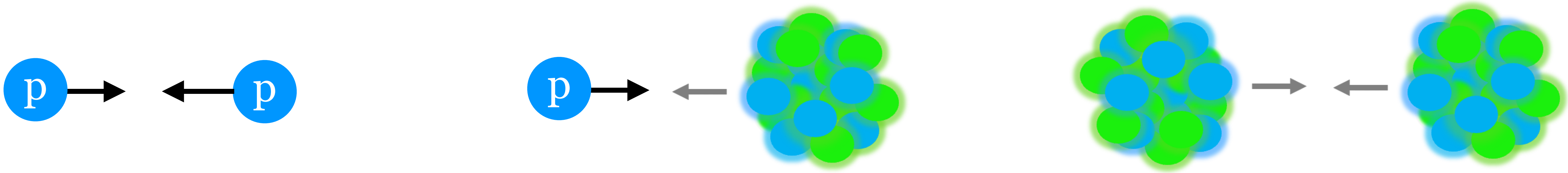
***p*A results discussed elsewhere in the workshop:**

- LHCb fixed target-> see Gabriel Ricart and Shinichi Okamura's talks
- Flow results in *p*A -> see Chenxi Gu's talk
- RHIC results in *p*A -> see Krista Smith's talk
- Detailed summary of recent *p*A measurements -> see Óscar Boente García's talk from QaT2023

A small caveat: this talk was prepared on extremely short notice given the late cancellation of the original speaker. I apologise if your favorite result is not included!

Why study quarkonia production in *p*A collisions?

The traditional approach:



pp collisions:

probe quarkonia production mechanisms in “vacuum”

pA collisions:

probe cold nuclear matter effects on quarkonia production, baseline for AA

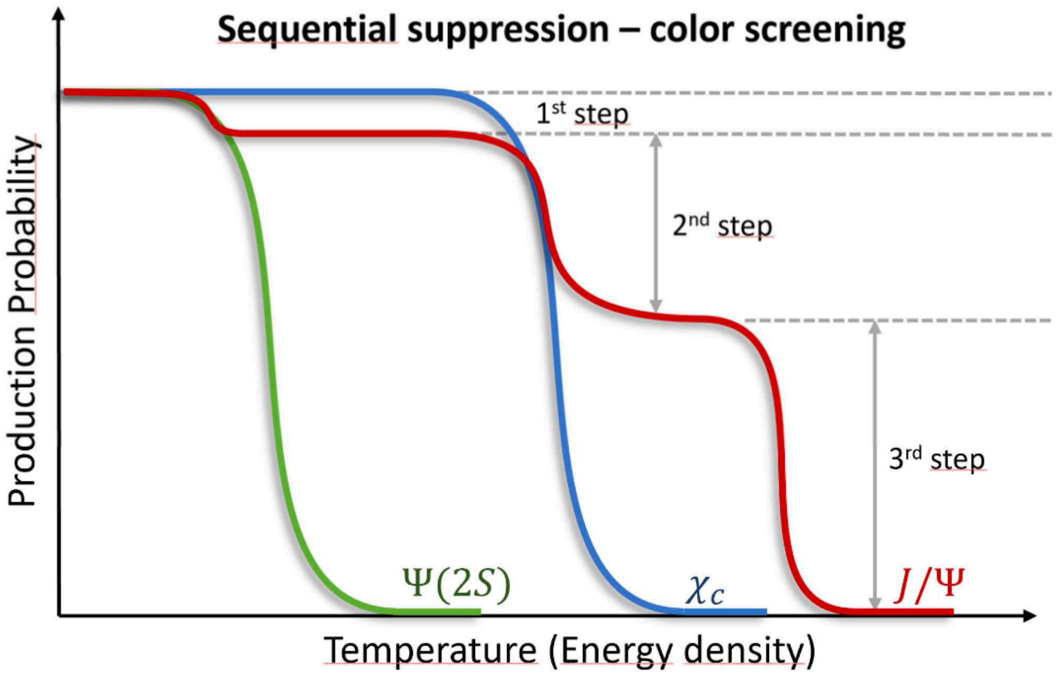
AA collisions:

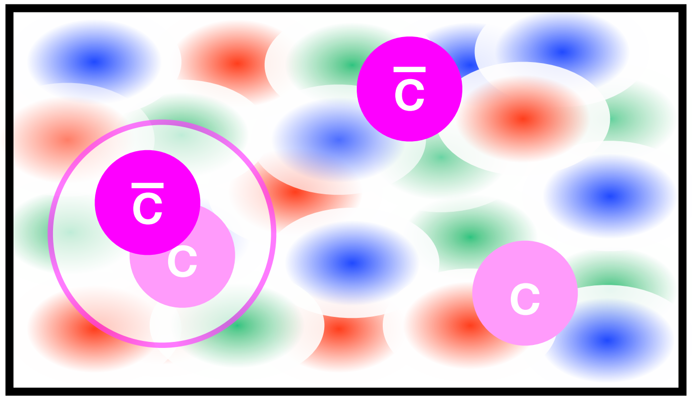
probe hot nuclear matter effects on quarkonia production

- *p*A collision systems are intermediate between extremely large nuclear systems (AA collisions) and the QCD “vacuum” system of *pp* collisions
- *p*A provides access to study and constrain non-QGP nuclear effects, so-called Cold Nuclear Matter (CNM) effects
- ***because pA collisions are interesting in their own right, not just as baselines for AA!*** Access to studying nuclear structure and emergence of large-scale nuclear properties from partonic interactions -> connecting particle and nuclear physics

Quarkonia meausurements in *pA* are crucial for measuring melting in a QGP

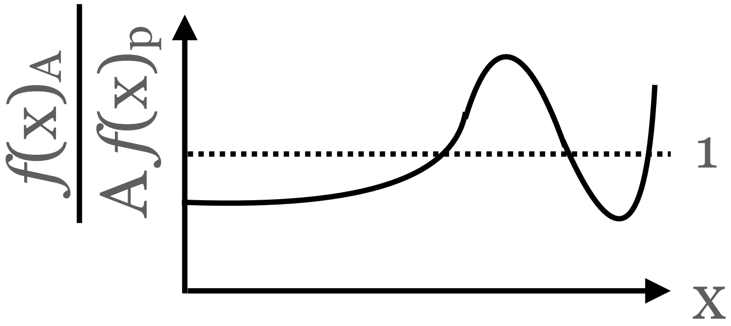
To measure sequential dissociation of quarkonia due to color charge screening in a QGP…



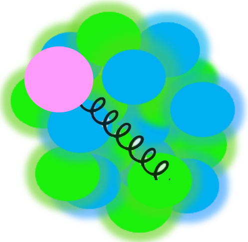


…we have to understand the CNM effects that can also dissociate quarkonia:

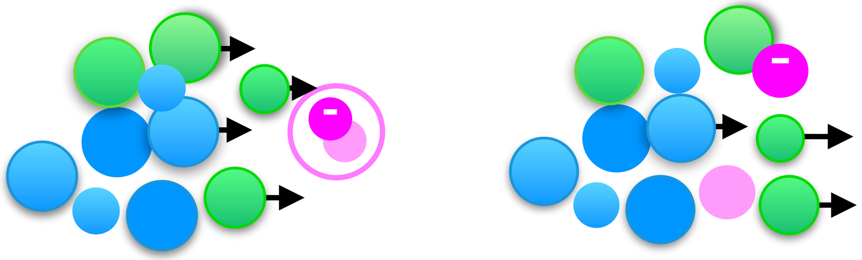
Nuclear structure & internal parton dynamics (nPDFs)



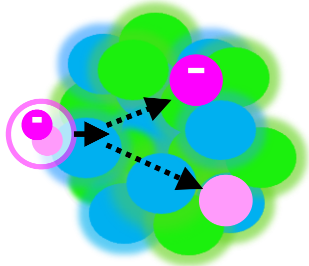
Parton energy loss



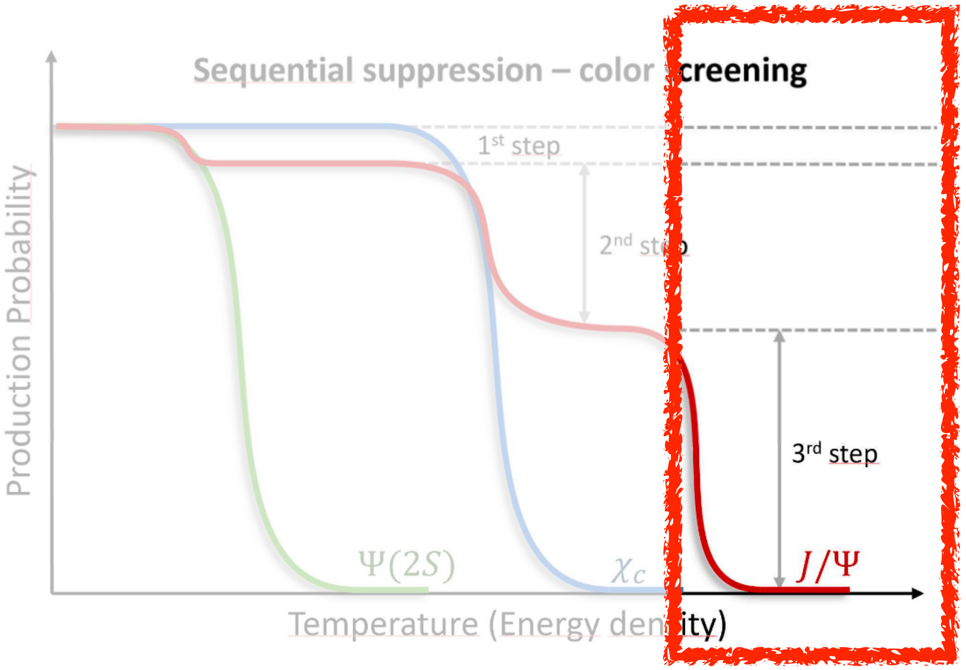
Breakup due to "co-moving" particles



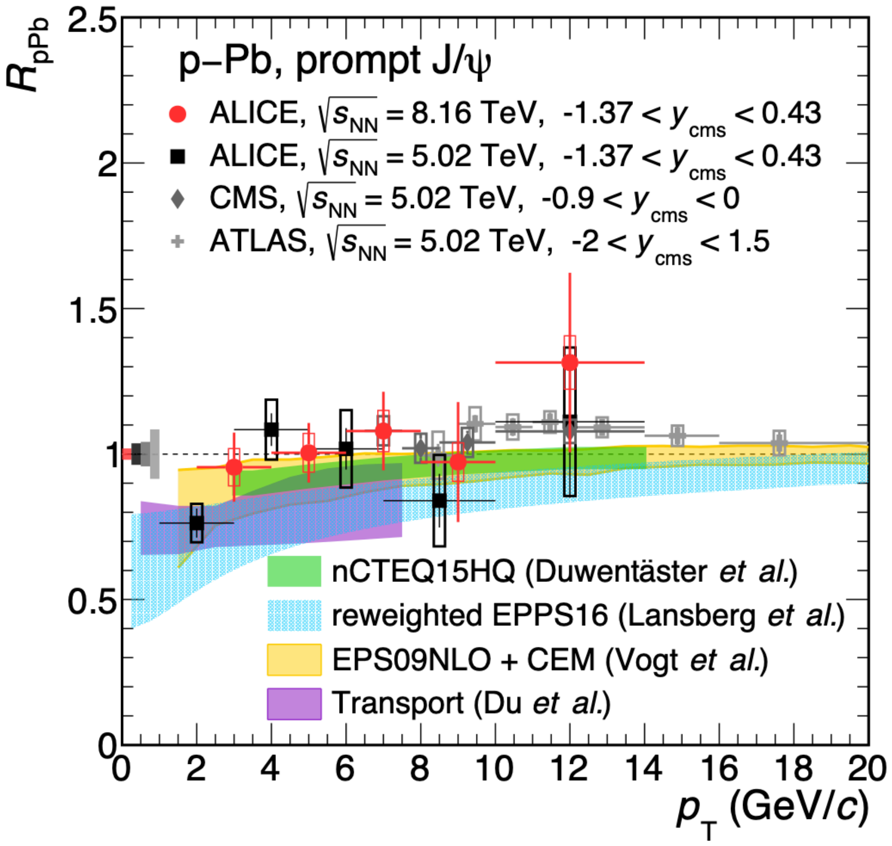
Nuclear "absorption" - breakup by the interaction with the nucleus

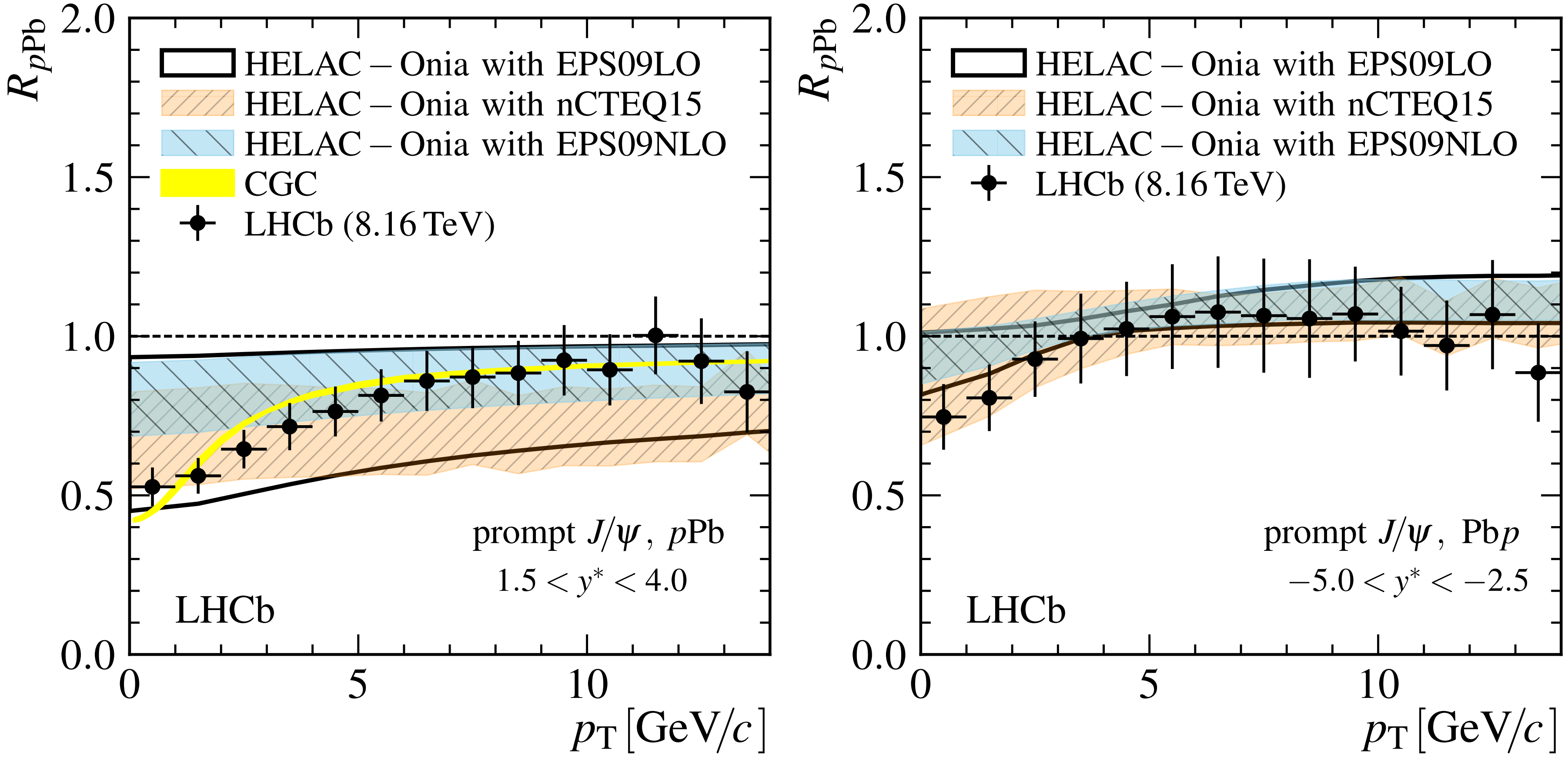


Charmonia in *p*Pb: J/ψ



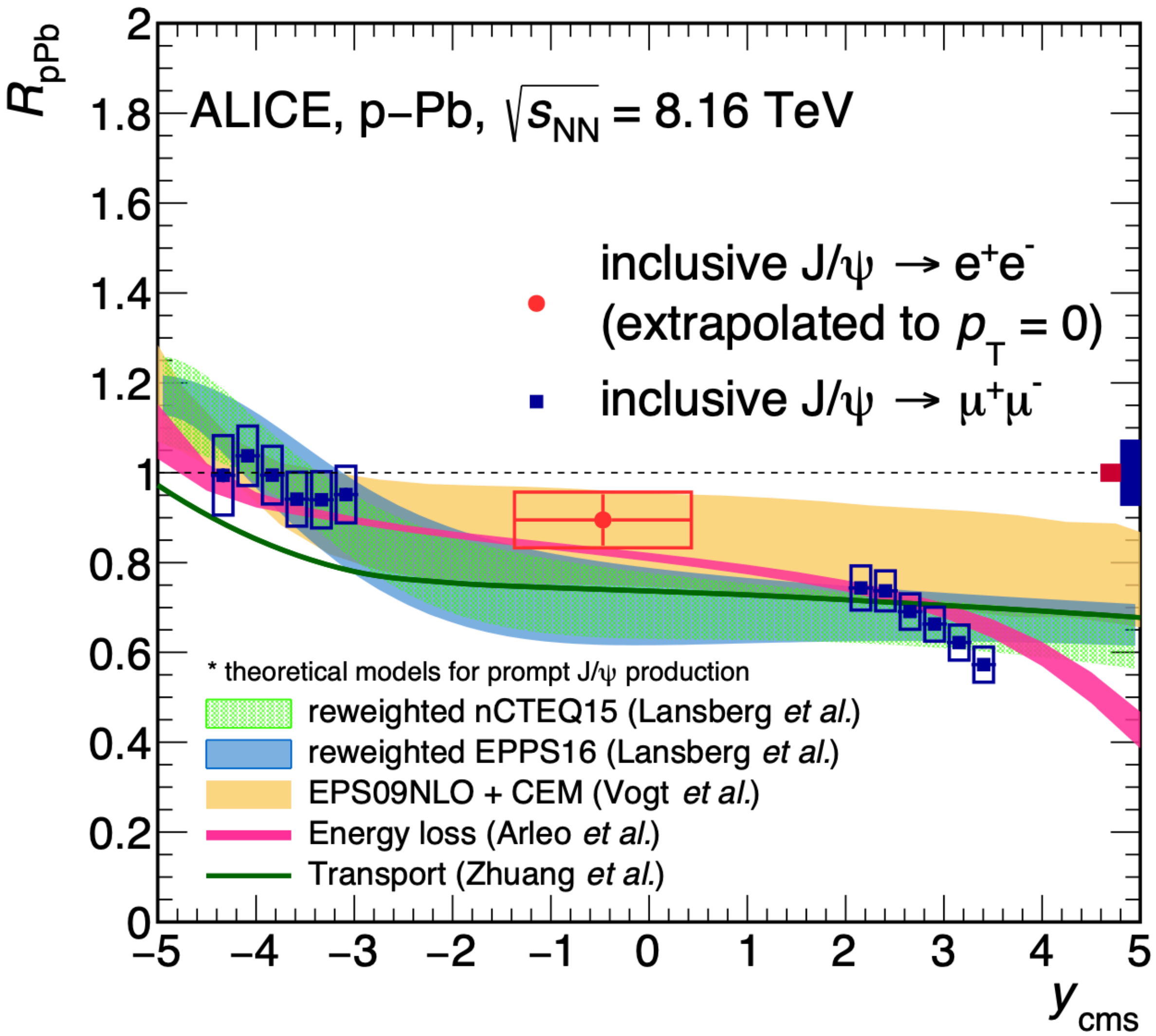
- $J/\psi\ R_{pPb}$ has been measured extensively at the LHC. ALICE measured it most recently at $\sqrt{s}$ = 8.16 TeV
- Compare to LHCb data which has more statistics at low p_T
- Suppression can be described by nPDFs

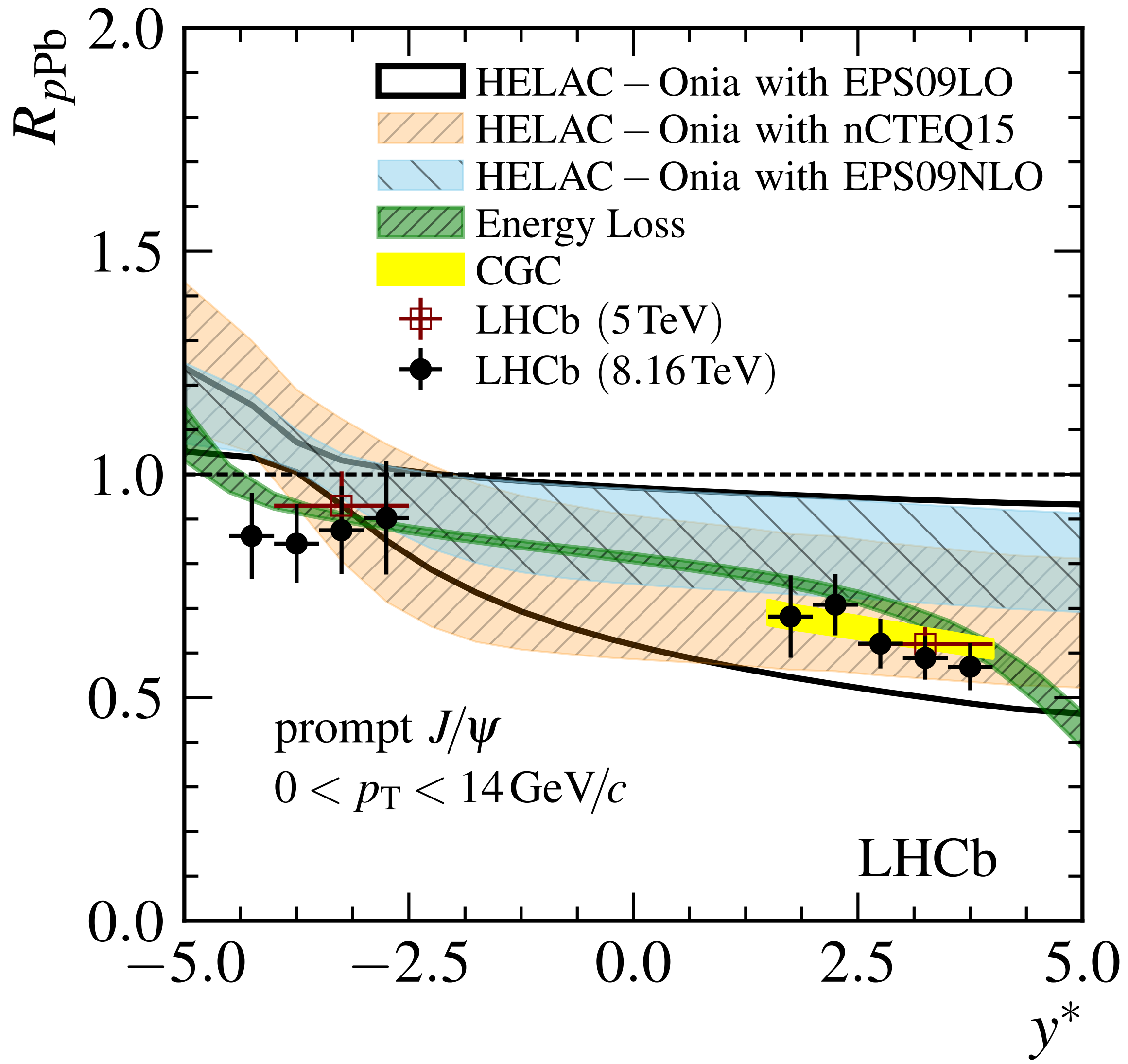




ALICE: JHEP 07 (2023) 137 LHCb: PLB 774 (2017) 159

Prompt J/ψ R_{pPb} as a function of y*

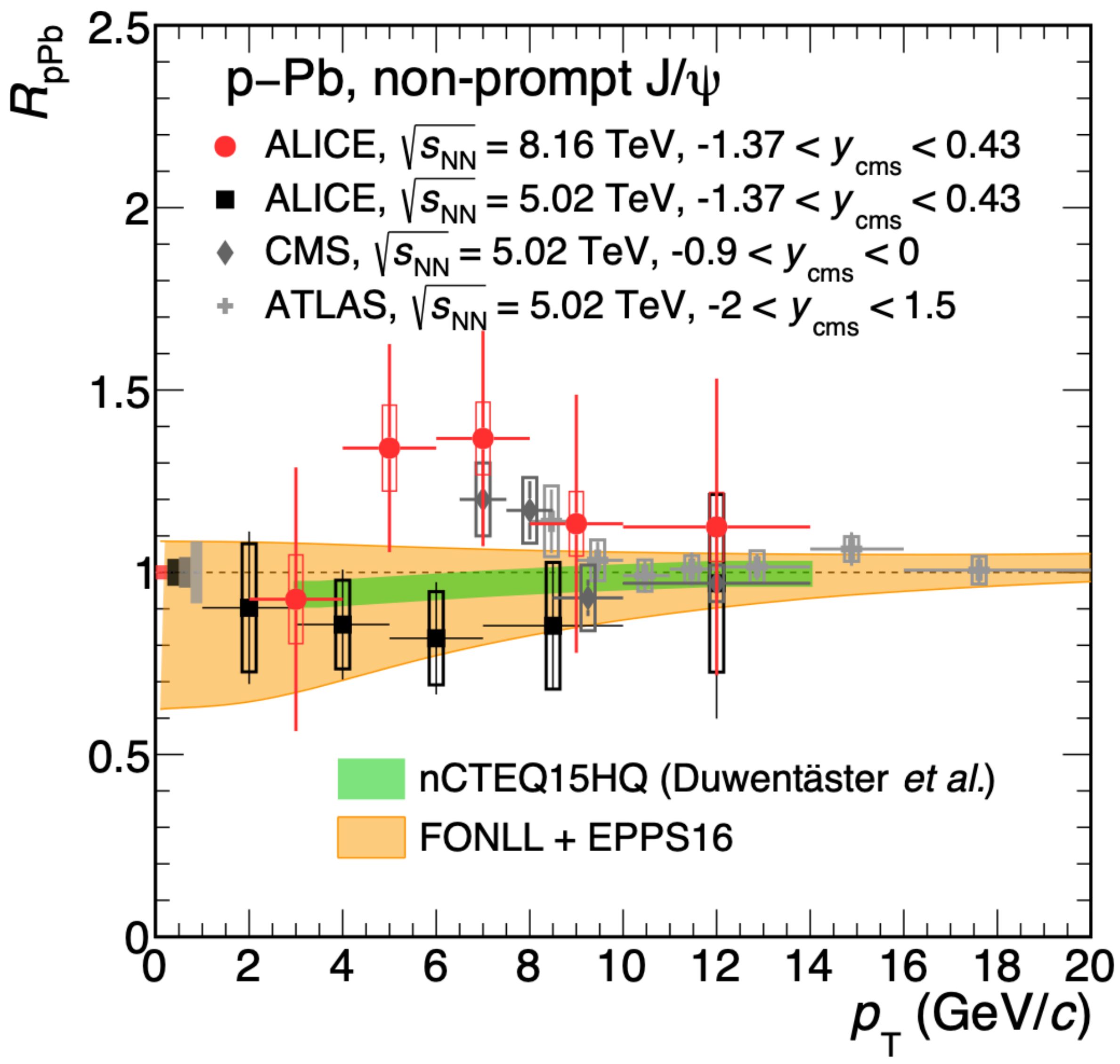


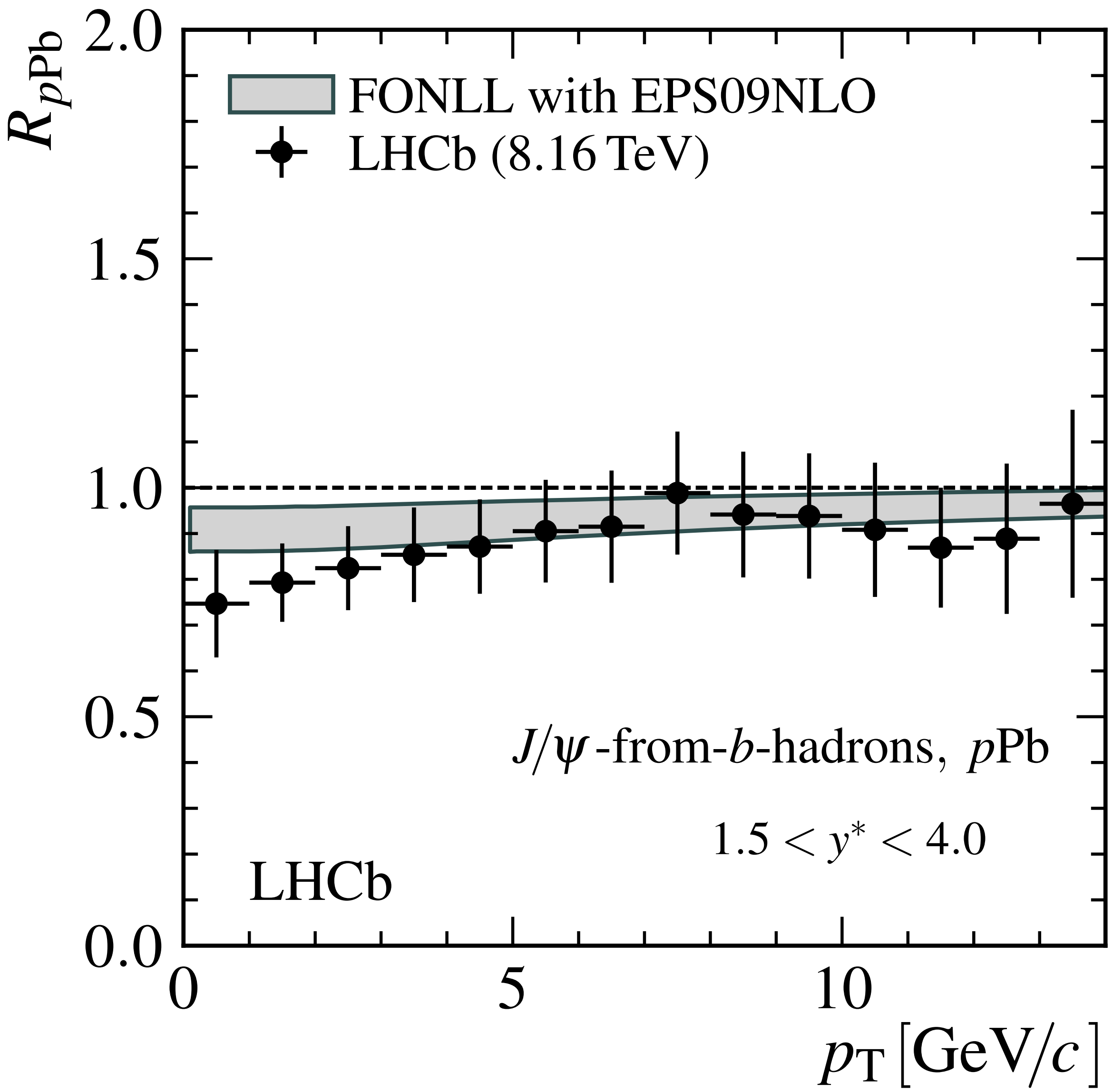


- Several theoretical models incorporating different CNM effects are able to describe the data
  - Agreement with data is great! But how can we go further towards determining which CNM effects are dominant / the relative contributions of different CNM effects?

ALICE: JHEP 07 (2023) 137 LHCb: PLB 774 (2017) 159

Non-prompt J/ψ in pPb



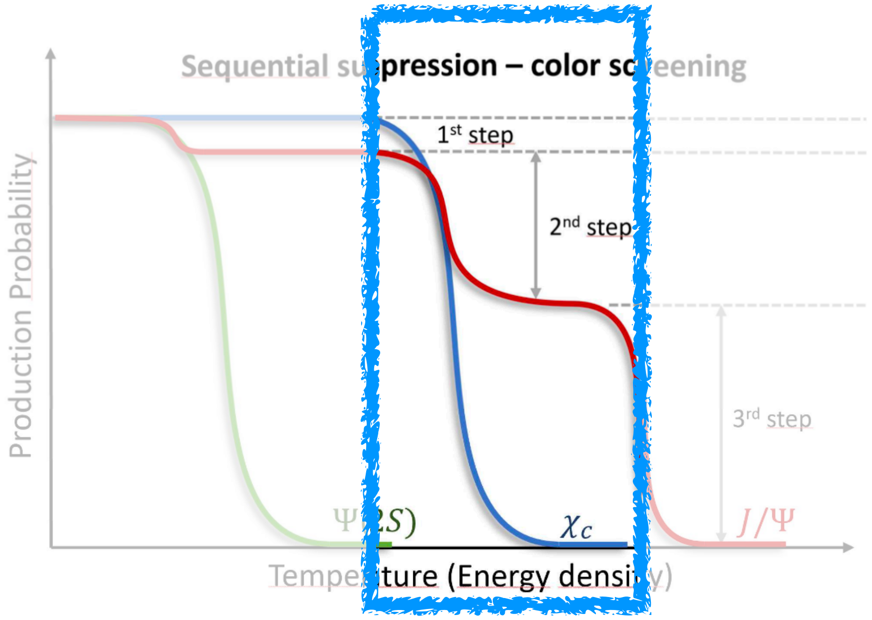


- Less suppression than for prompt J/ψ
- FONLL + nPDF calculations are able to describe the data

ALICE: JHEP 07 (2023) 137 LHCb: PLB 774 (2017) 159

Measuring the χ_c in *p*Pb collisions at LHCb

- Decay channel: $\chi_c \to J/\psi(\to \mu^+\mu^-)\gamma,\ \ \chi_c = \chi_{c1} + \chi_{c2}$
- Challenging to measure experimentally due to the low-energy photon reconstruction and the large combinatorial background from $\pi^0 \to \gamma\gamma$ decays
- LHCb measurement is the 3rd measurement in pA collisions and the first in pPb collisions at the LHC

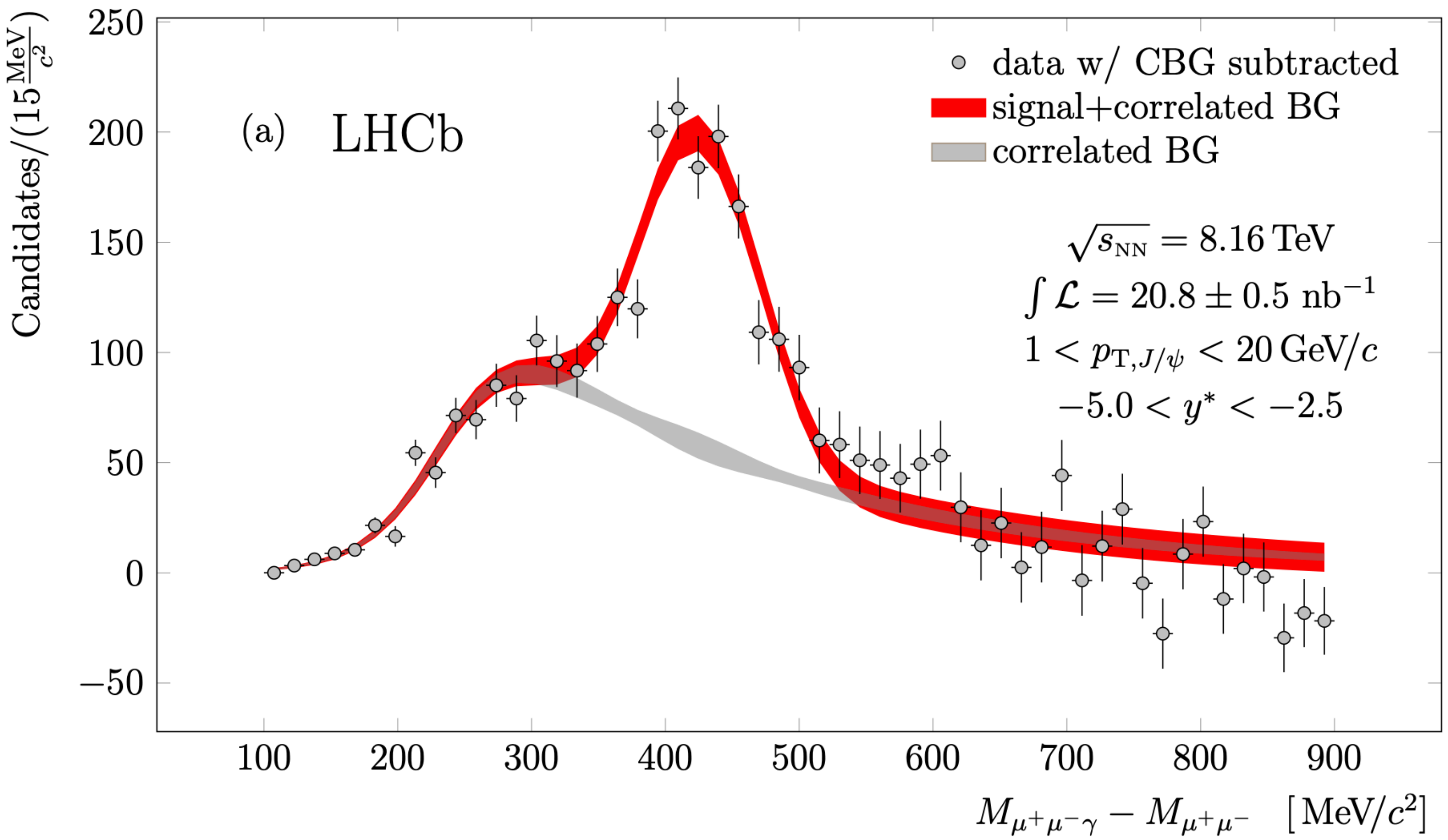


Candidate selection criteria :

μ	Identified using dedicated muon stations in LHCb p_T > 600 MeV/c, p > 8 GeV, 2 < η_μ < 5 (LHCb acceptance)
γ	Identified as isolated clusters in LHCb electromagnetic calorimeter (ECAL), clusters must be incompatible with a π^0 or charged particle hypothesis p_T > 400 MeV/c, 2 < η_γ < 4.5 (LHCb ECAL acceptance)
J/ψ	$m(\mu^+\mu^-)$ within 80 MeV of known J/ψ mass p_T > 1 GeV/c, Prompt J/ψ (not from b-decay)

arxiv: 2311.01562

$\mu\mu\gamma$ invariant mass spectrum contributions



- Fit the invariant mass difference, $\Delta M = M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$ to reduce the impact of the dimuon pair mass resolution

3 components to invariant mass distribution:

$$Y_{\mu^+\mu^-\gamma}(\Delta M) = N_{CBG}Y_{CBG}(\Delta M) + N_{corr}Y_{corr}(\Delta M) + N_{\chi_c \to J/\psi\gamma}Y_{\chi_c}(\Delta M)$$

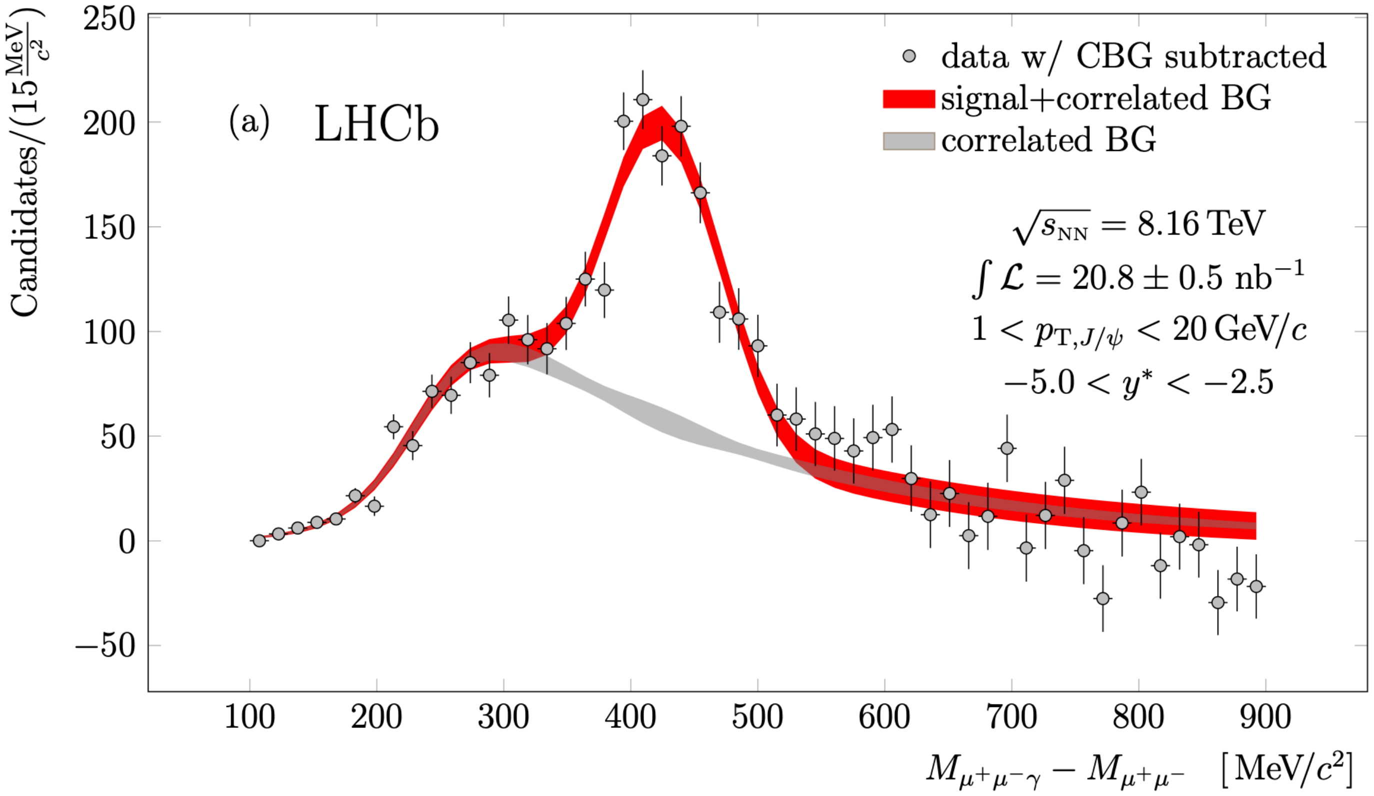
Combinatorial background (CBG)

Correlated background

χ_c signal

arxiv: 2311.01562

Correlated background and χ_c signal



Combinatorial background:

- Estimated by combining J/ψ and γ candidates from different events (mixed event background subtraction)

Correlated background:

- Radiative J/ψ: $J/\psi \to \mu^+\mu^-\gamma$
- Partially reconstructed $\psi(2S)$:

  $\psi(2S) \to J/\psi\pi^0\pi^0 \to \mu^+\mu^-\gamma$
- Parameters fixed from simulation:

$$Y_{\rm corr}(\Delta M) = \frac{A_{\rm corr} e^{B\cdot\Delta M}}{1 + e^{-\frac{\Delta M - \Delta M_0}{\sigma_{\Delta M_b}}}}$$

χ_c signal:

- Sum of two Gaussians with a common resolution
- $f_{\chi_{c1}}$ = fraction of χ_{c1} in total χ_c yield, 0.4-0.6
- $\Delta M_{1,2} = M(\chi_{c2}) - M(\chi_{c1})$

$$\begin{aligned} Y_{\chi_c}(\Delta M) &= f_{\chi_{c1}} G(\Delta M; \Delta M_{\chi_{c1}}, \sigma_{\Delta M}) \\ &+ (1 - f_{\chi_{c1}}) G(\Delta M; \Delta M_{\chi_{c1}} + \Delta M_{1,2}, \sigma_{\Delta M}) \end{aligned}$$

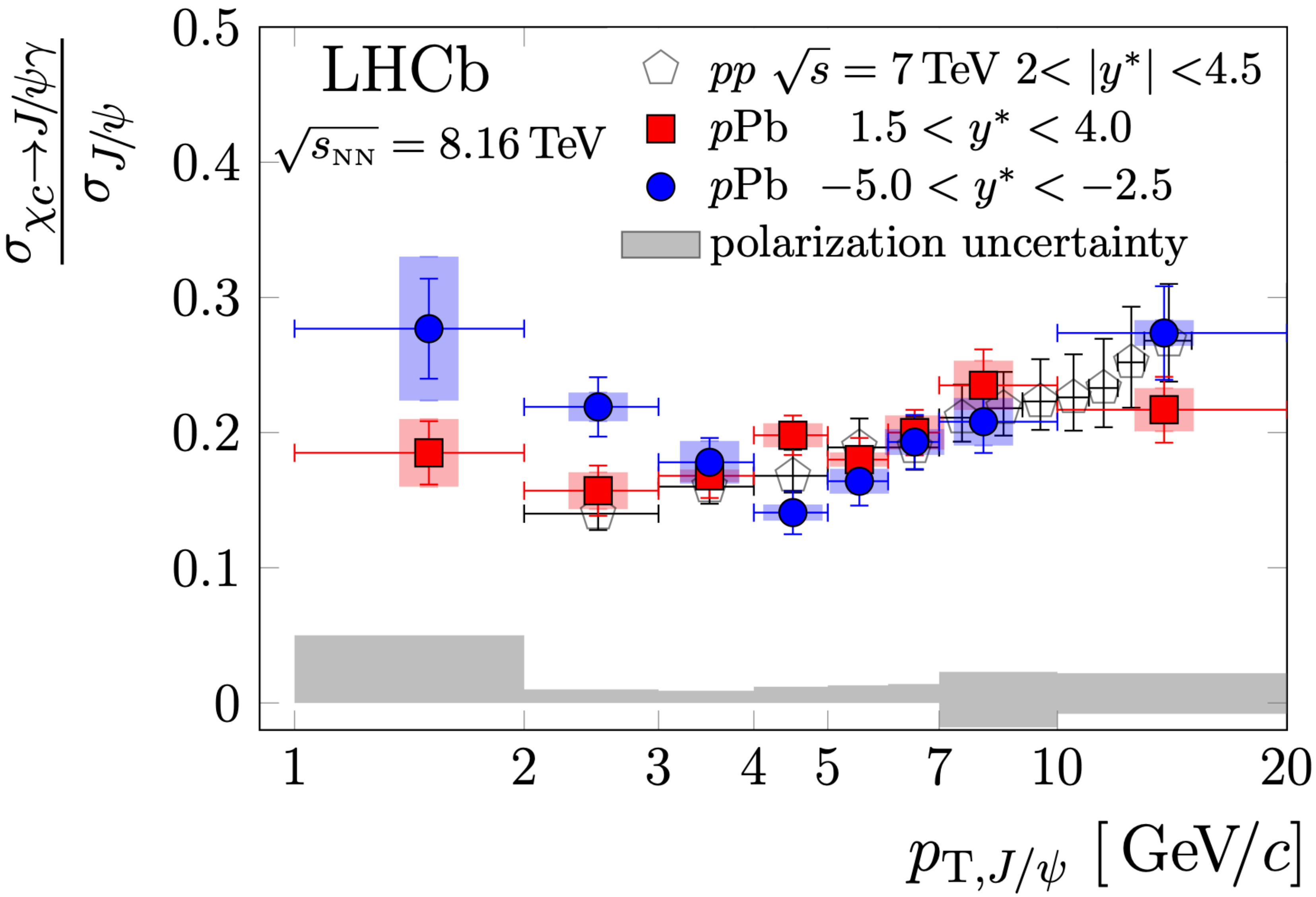
arxiv: 2311.01562

Fraction of χ_c in prompt J/ψ decays

new!

$$F_{\chi_c \to J/\psi} \equiv \frac{\sigma_{\chi_c \to J/\psi\gamma}}{\sigma_{J/\psi}} = \frac{N_{\chi_c \to J/\psi\gamma}}{N_{J/\psi}\ \varepsilon_{\chi_c/J/\psi}}$$

$$\epsilon_{\chi_c/J/\psi} = \frac{\text{N}(\chi_c \to J/\psi\gamma)\text{ detected in LHCb}}{\text{N(only } J/\psi\text{) detected in LHCb}}$$

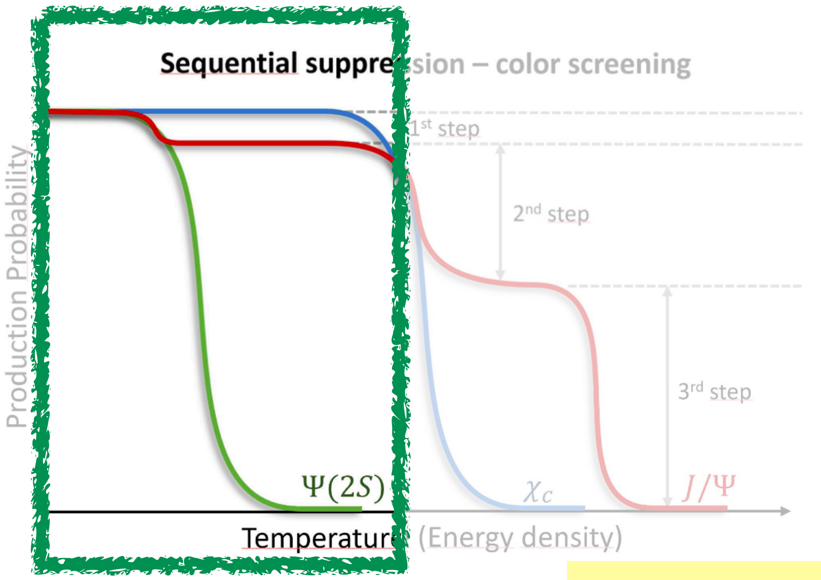


Consistent with χ_c measurement in pp collisions

-> χ_c does not break up in pPb collisions!

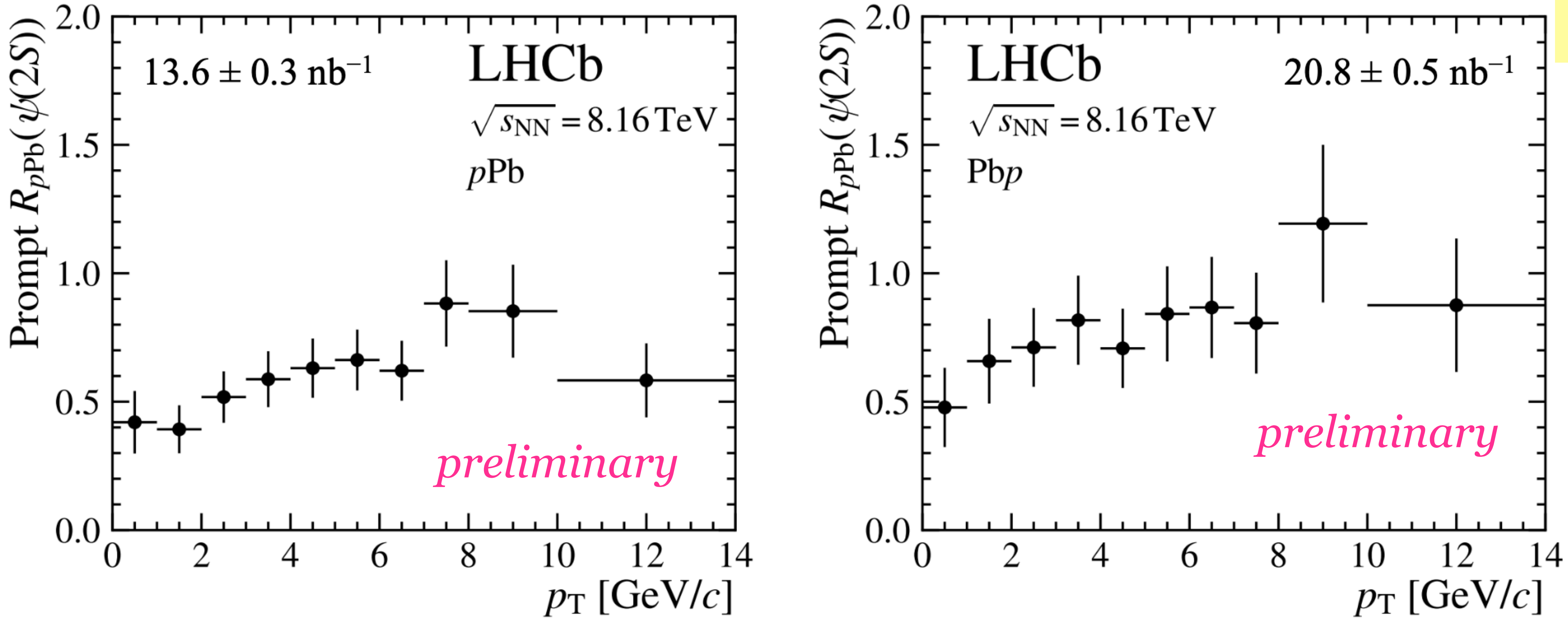
arxiv: 2311.01562

Prompt $\psi(2S)$ in pPb collisions at $\sqrt{s}$ = 8.16 TeV



- New more precise result with × 20 larger dataset than previous one (at $\sqrt{s}$ = 5 TeV)
  - compare with J/ψ (PLB774 (2017) 159) in pPb, described by initial state effects

new!



- Suppression at low p_T more pronounced at forward rapidity

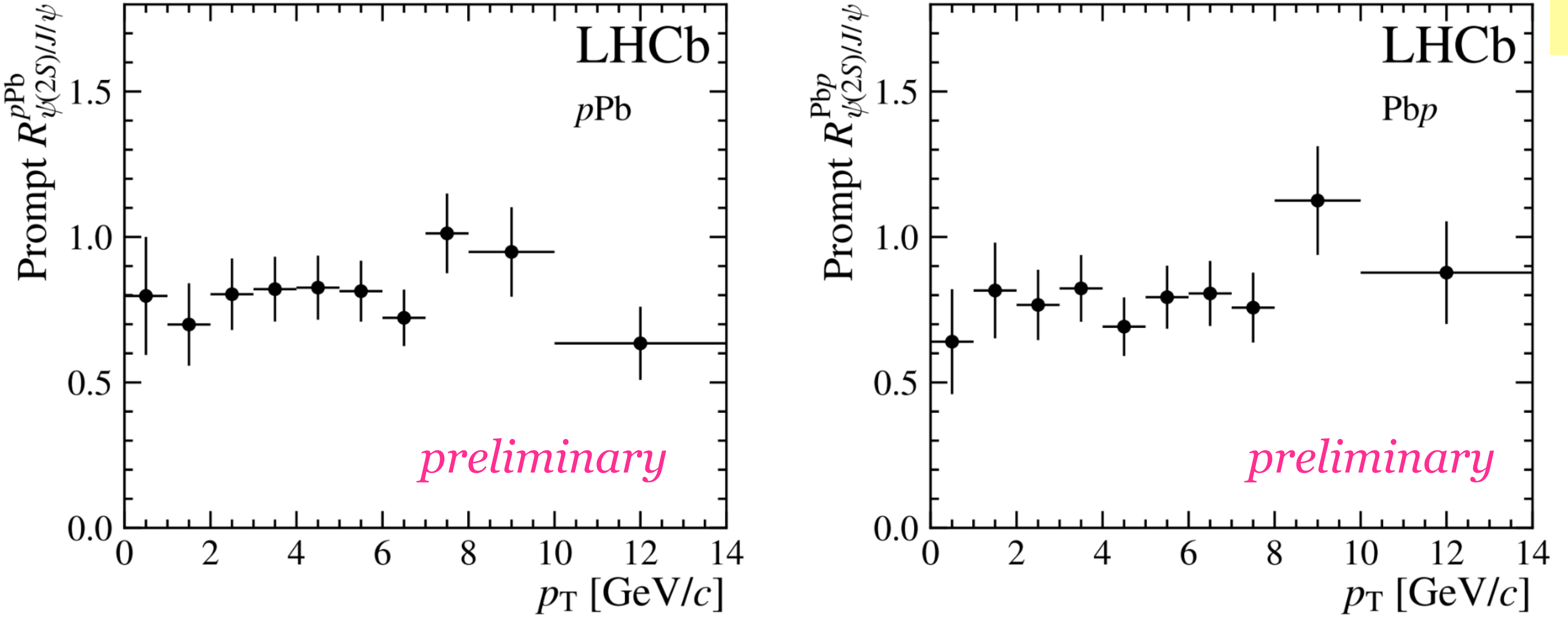
LHCb-PAPER-2023-024, in preparation

Double ratio of $\psi(2S)$ and J/ψ R_{pPb} at $\sqrt{s}$ = 8.16 TeV

$$R^{p\text{Pb}\,(\text{Pb}p)}_{\psi(2S)/J/\psi} = \frac{R_{p\text{Pb}\,(\text{Pb}p)}(\psi(2S))}{R_{p\text{Pb}\,(\text{Pb}p)}(J/\psi)} = \frac{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{p\text{Pb}\,(\text{Pb}p)}}{\left[\frac{\sigma(\psi(2S))}{\sigma(J/\psi)}\right]_{pp}}$$

Double ratio probes final state effects on quarkonium production

new!

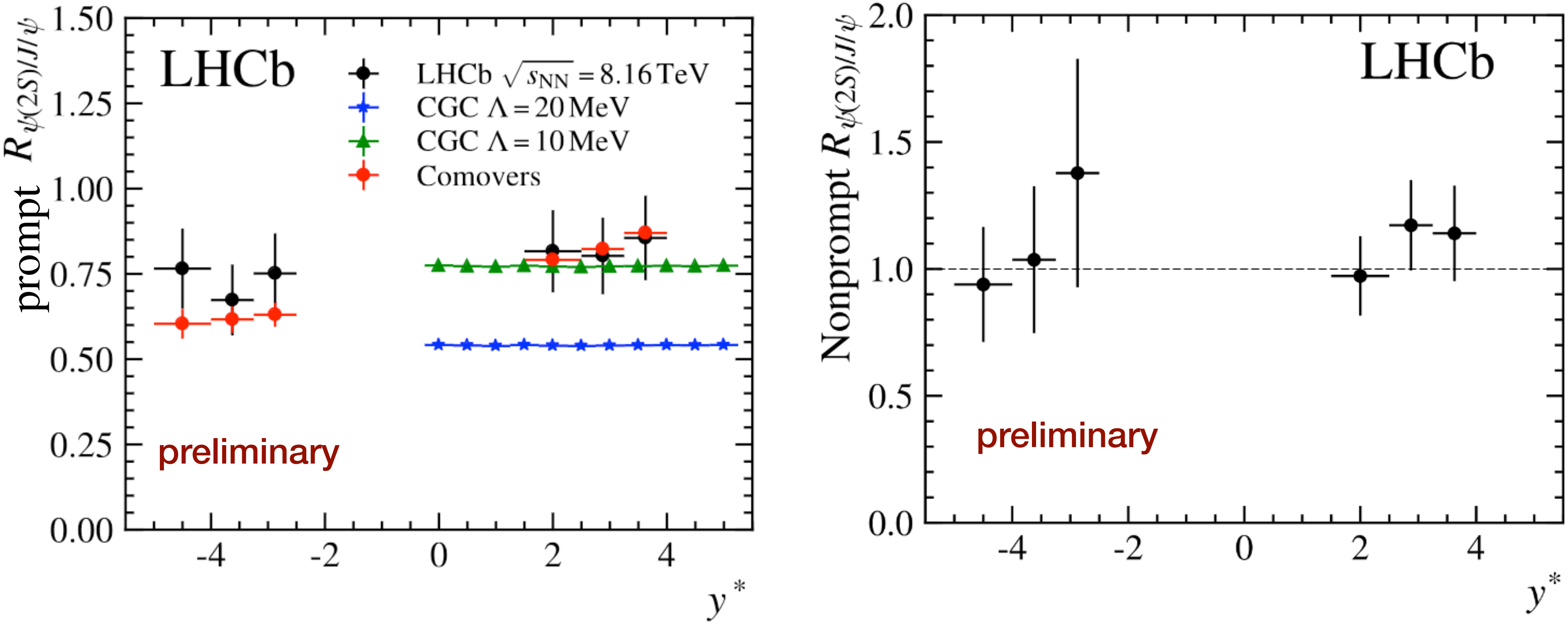


- $\psi(2S)$ is more suppressed than J/ψ across almost the entire p_T range studied

LHCb-PAPER-2023-024, in preparation

Double ratio of $\psi(2S)$ and J/ψ R_{pPb} as a function of y*

new!

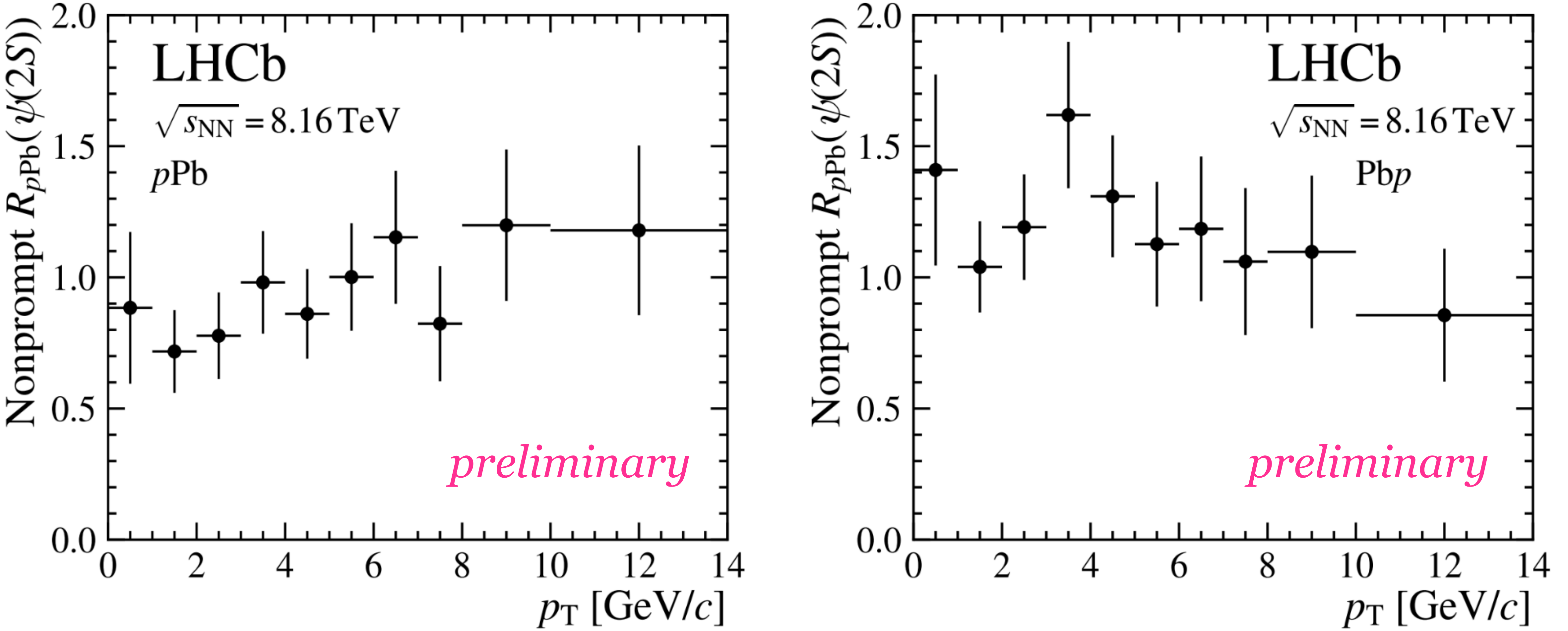


- Non-prompt double ratio still compatible with unity
- Prompt double ratio shows suppression of $\psi(2S)$, compatible with break-up for comovers and CGC
  - CGC models shown on plot also include comover interactions

LHCb-PAPER-2023-024, in preparation

Non-prompt $\psi(2S)$ in pPb collisions at $\sqrt{s}$ = 8 TeV

new!

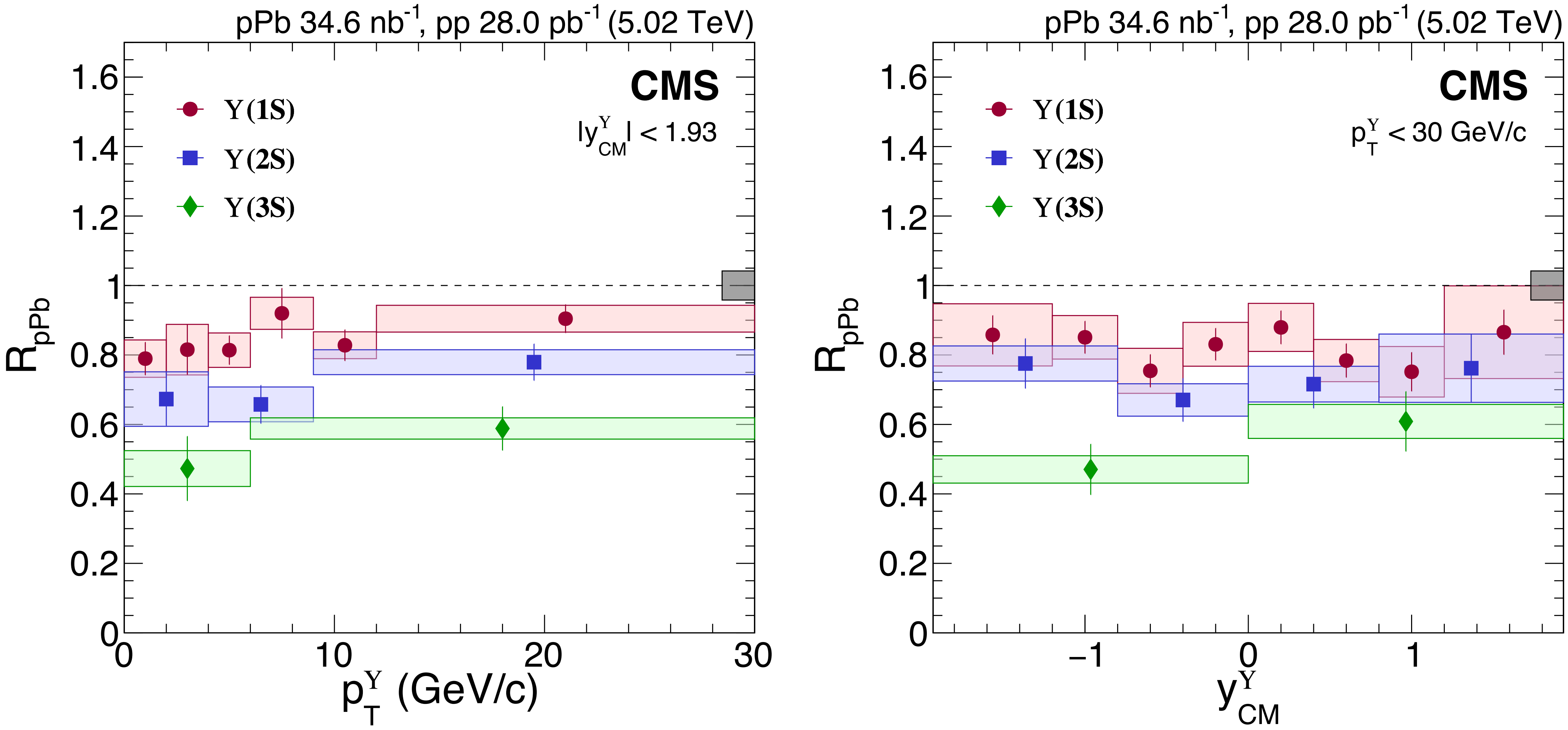


- Non-prompt R_{pPb} is consistent with one, indicating little to no nuclear effects for $\psi(2S)$mesons produced from b-decays

LHCb-PAPER-2023-024, in preparation

Bottomonia in *p*Pb

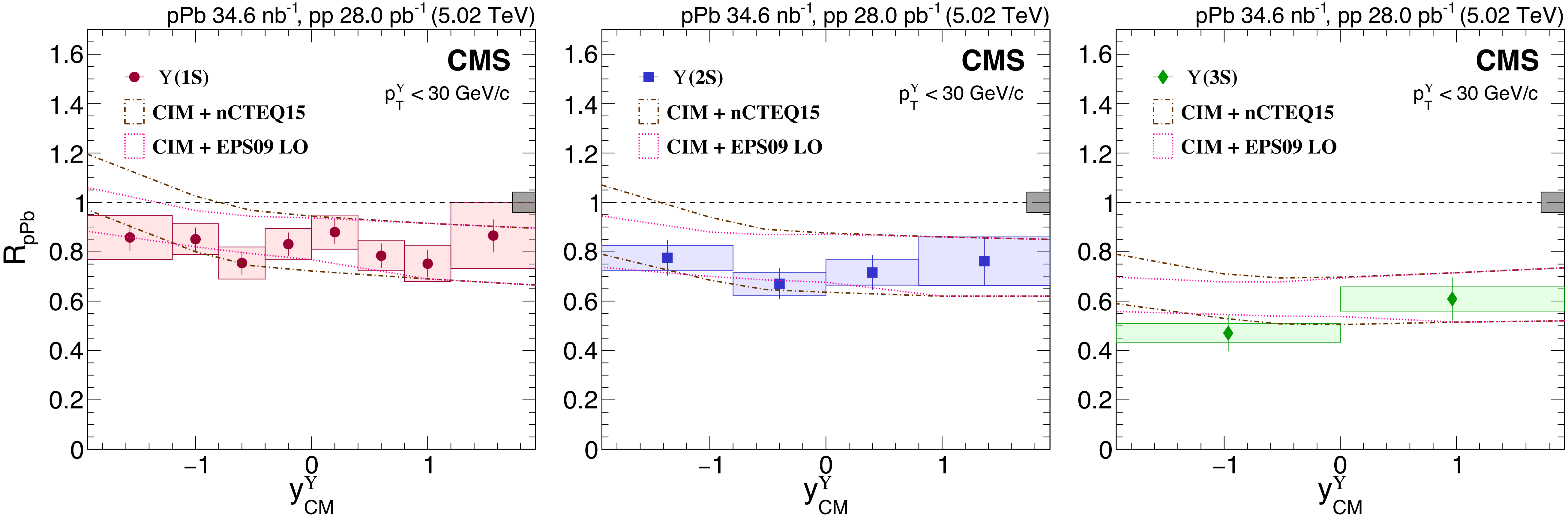
- The most recent measurement of bottomonia R_{pPb} are from CMS:



- Clear sequential suppression is observed for the three upsilon states, with the $\Upsilon(3S)$ being the most suppressed
- No strong p_T dependence of the suppression

PLB 835 (2022) 137397

Comparisons with Comover + nPDF calculations



- Comover Interaction Model (CIM) + nPDFs with shadowing can describe the suppression of all three Υ states
  - EPS09 is a pre-LHC nPDF set and does not include any LHC data
  - nCTEQ15 is more recent and includes LHC data
  - Both are consistent with the data within the large experimental and theoretical uncertainties

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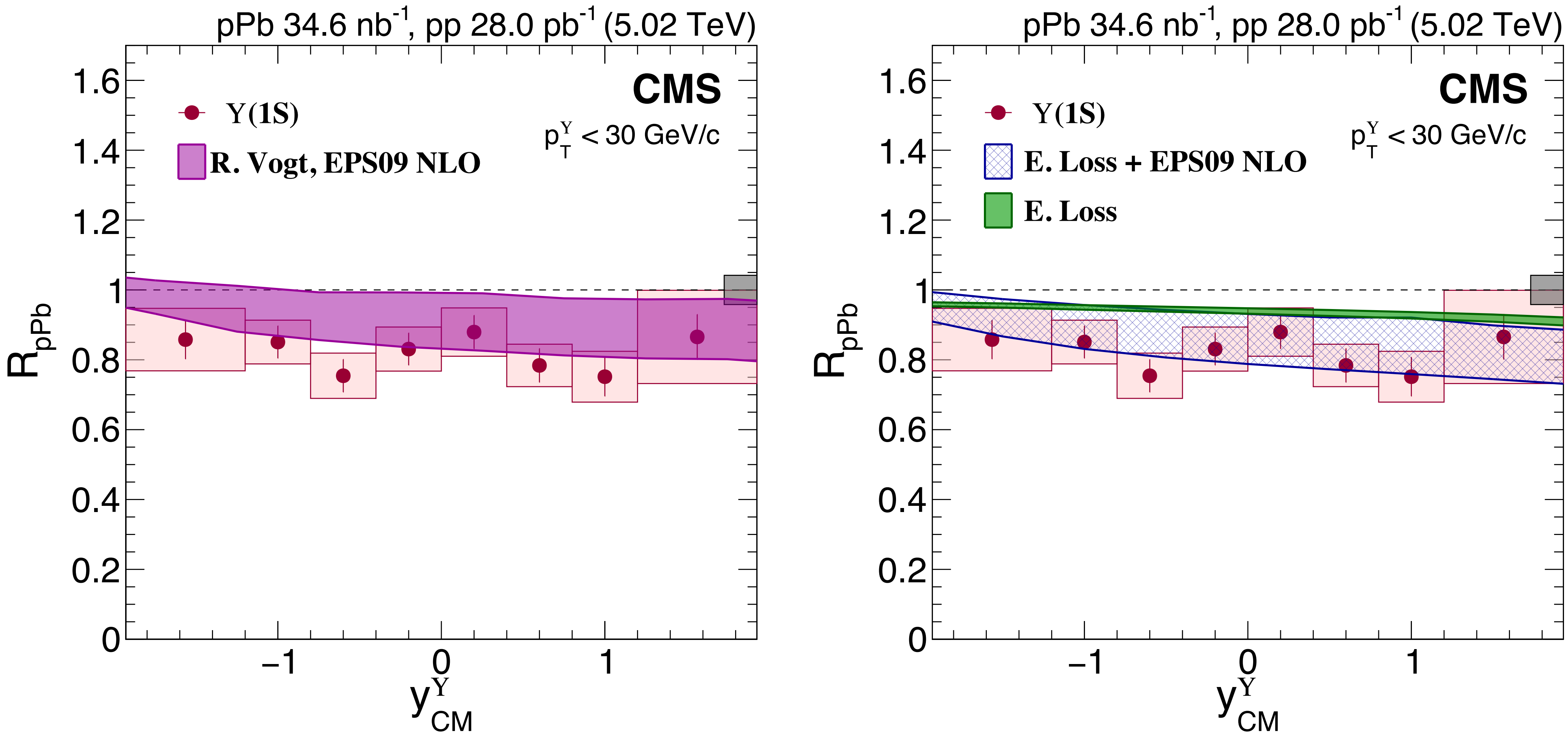
Comparisons with energy loss calculations



- Comparisons to the $\Upsilon(1S)$ R_{pPb} were made with and without nuclear shadowing effects (added via EPS09 PDFs)
- Shadowing + energy loss calculation is in better agreement with the data

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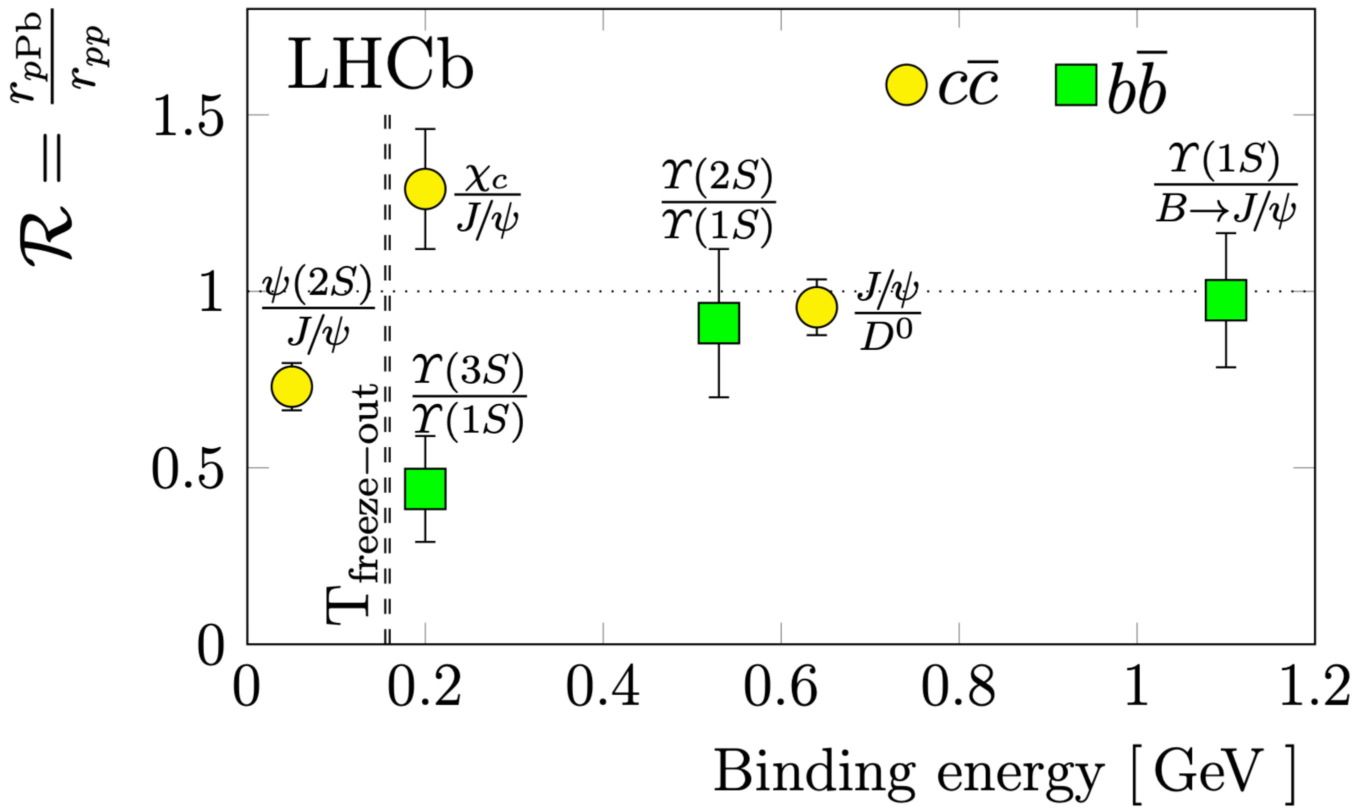
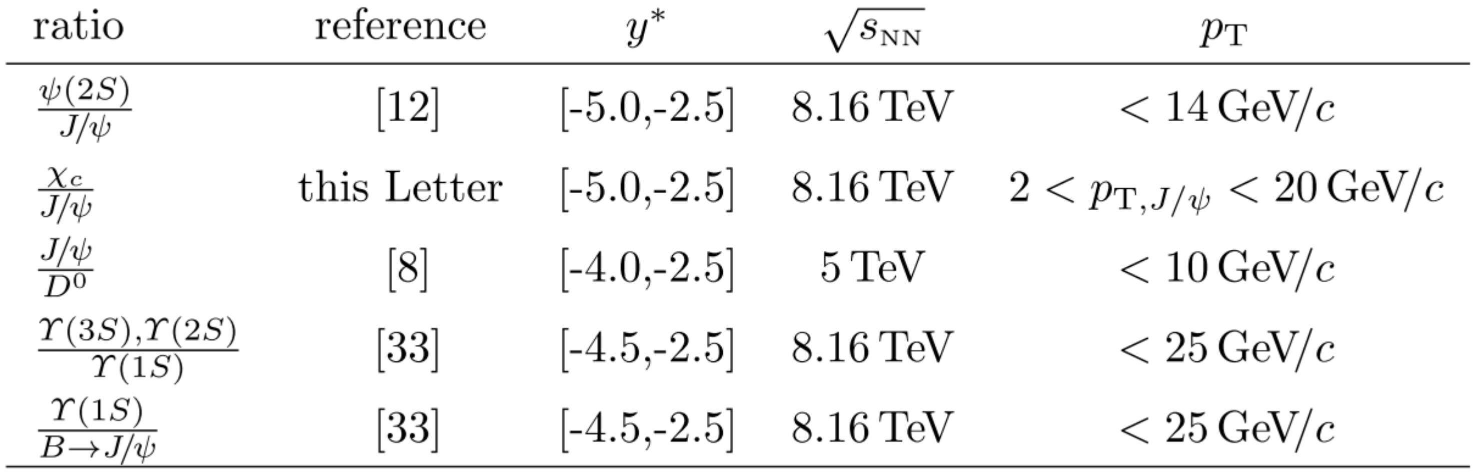
What do we know about quarkonia dissociation in pPb?



- Look at the double ratio of the ratio of states measured in *p*Pb to the ratio in *pp* collisions, as a function of the binding energy of the quarkonium state

- The χ_c and $\Upsilon(3S)$ have almost exactly the same binding energy, but the $\Upsilon(3S)$ breaks up while the χ_c does not
  - If melting in a hot medium occurred, both states should break up.
  - The fact that the χ_c remains intact suggests that the $\Upsilon(3S)$ could be breaking up from comover interactions



ratio	reference	y^*	$\sqrt{s_{\mathrm{NN}}}$	p_{T}
$\frac{\psi(2S)}{J/\psi}$	[12]	[-5.0,-2.5]	8.16 TeV	< 14 GeV/c
$\frac{\chi_c}{J/\psi}$	this Letter	[-5.0,-2.5]	8.16 TeV	$2 < p_{\mathrm{T},J/\psi} < 20$ GeV/c
$\frac{J/\psi}{D^0}$	[8]	[-4.0,-2.5]	5 TeV	< 10 GeV/c
$\frac{\Upsilon(3S),\Upsilon(2S)}{\Upsilon(1S)}$	[33]	[-4.5,-2.5]	8.16 TeV	< 25 GeV/c
$\frac{\Upsilon(1S)}{B\to J/\psi}$	[33]	[-4.5,-2.5]	8.16 TeV	< 25 GeV/c

Towards the future

- pPb is clearly a valuable collision system for studying CNM effects and an important baseline for quarkonia measurements in PbPb collisions

- However, pPb alone is not sufficient to fully constrain and understand CNM effects - we need pA data in a variety of nuclei and kinematic regions

- **It is not yet known if we will have pPb data-taking during the LHC Run 3.** At the moment, priority seems to be given to PbPb and OO/pO collisions.

- **pO collisions at the LHC** are expected in 2025

- **pA collisions with the LHCb fixed-target system, SMOG2** are planned in 2024 (and 2025)
  - pAr, pH for sure in 2024 and possibly other targets as well, such as pHe

- **PbA collisions with the LHCb fixed-target system, SMOG2** are also planned
  - PbAr in 2024, other targets also possible in the future (H, Kr, Xe...)

Conclusions

- pA collision systems provide an important baseline for measuring cold nuclear matter effects on quarkonia production
- J/ψ R_{pPb} has been studied extensively at the LHC, but all three charmonium states: the J/ψ, χ_c and $\psi(2S)$ are needed to establish a CNM baseline for sequential suppression in PbPb collisions
- LHCb has measured for the first time the fraction of χ_c in prompt J/ψ decays in pPb collisions
- New measurement of $\psi(2S)$ R_{pPb} also available from LHCb - paper in preparation
- Upsilon suppression in pPb can be described by several models incorporating different CNM effects
- The $\Upsilon(3S)$ breaks up in pPb collisions while the χ_c does not break up, which implies that the dissociation mechanism is not temperature related and therefore not due to the formation of a hot medium in pPb collisions

Thank you for your attention!