

Recent Quarkonia Results from LHC Heavy-Ions

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Madison, Wisconsin

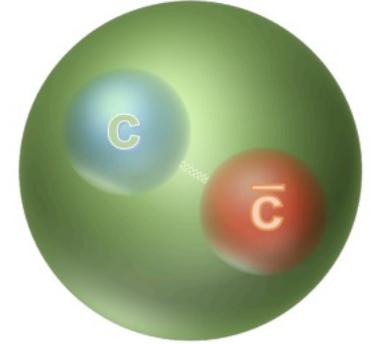
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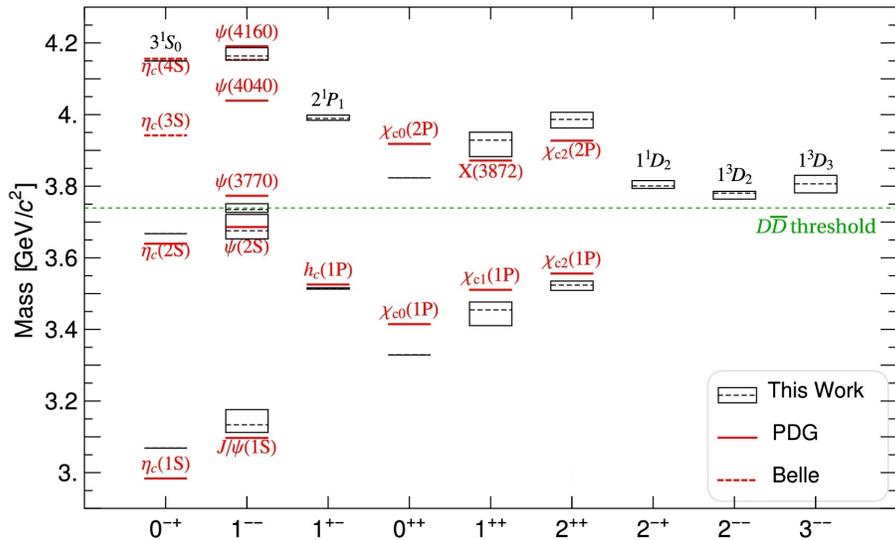
Why quarkonia are interesting?

Quarkonia are made of charm and bottom quarks ($m_c, m_b \gg \Lambda_{\text{QCD}}$):

- Produced in initial hard partonic scattering
 - Experience full evolution of heavy-ion collision (HI)
- Powerful probe to study properties of **Quark-gluon plasma (QGP)**
- Characterized by different masses and binding energies

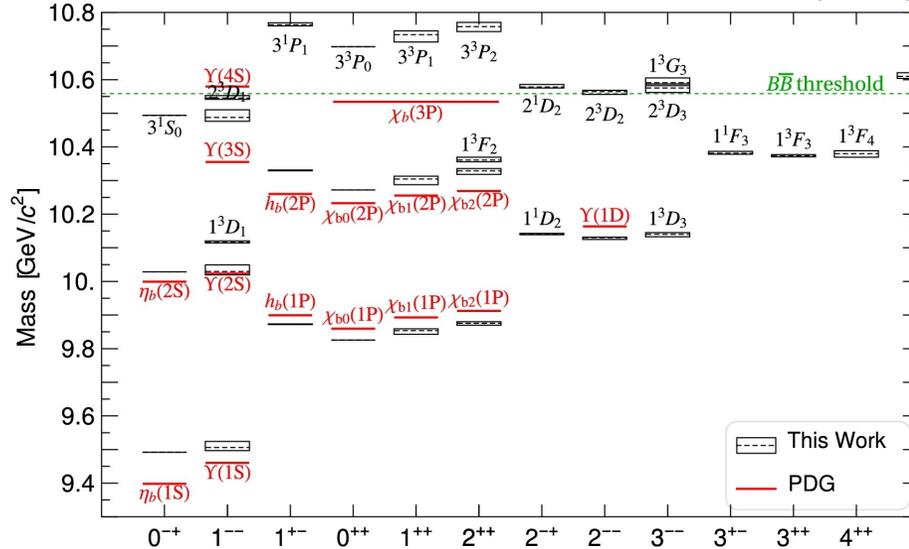


Charmonia

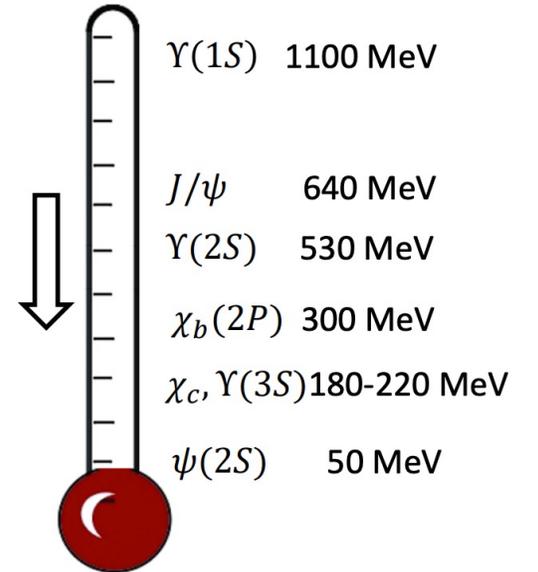


Bottomonia

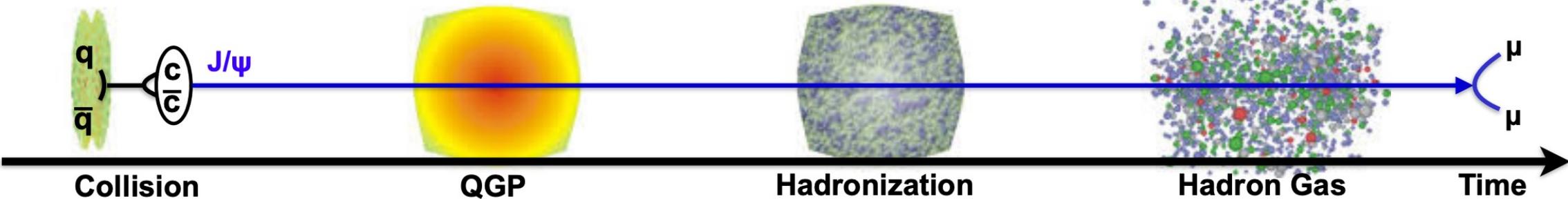
PLB 758, 118 (2016)



Agnes Mocsy's thermometer

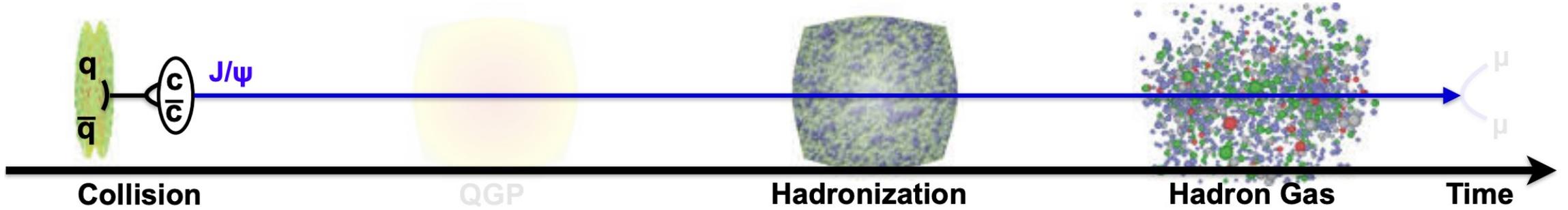


Quarkonia in HI collisions

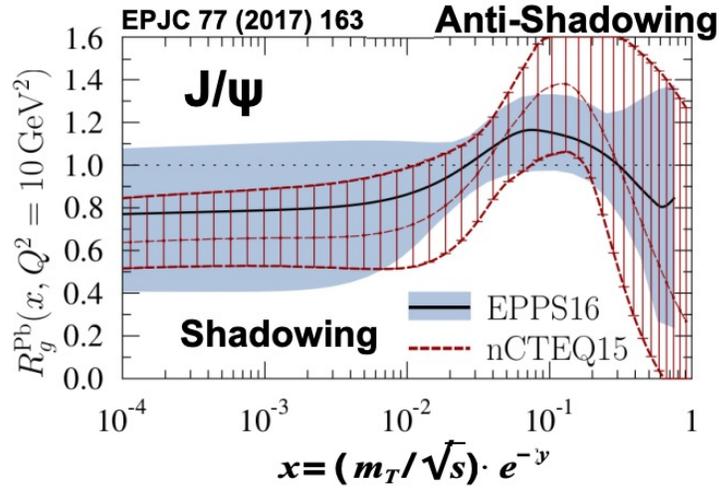


Quarkonia are produced in the early stages of the collision

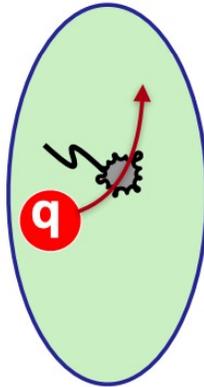
Cold nuclear matter effects



nPDF modification

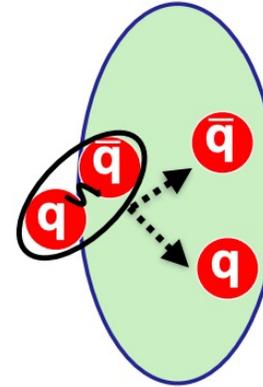


Coherent energy loss



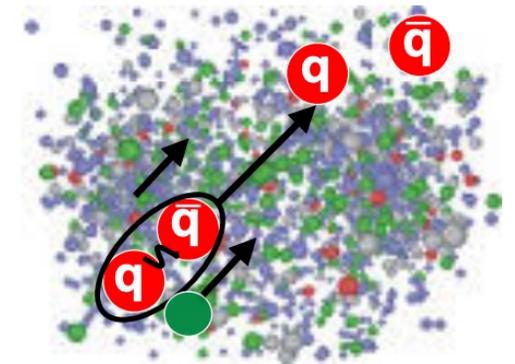
Nuclear medium

Nuclear absorption



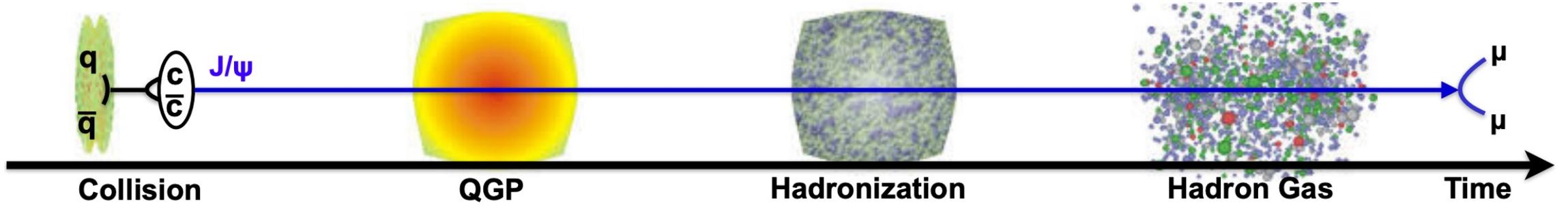
Nuclear medium

Co-mover breakup

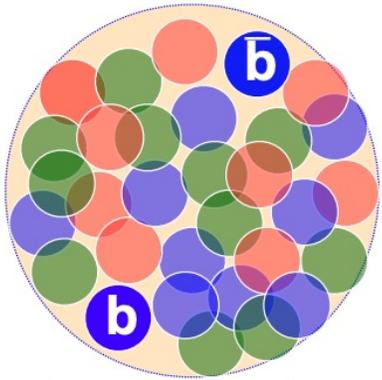


Hadronic matter

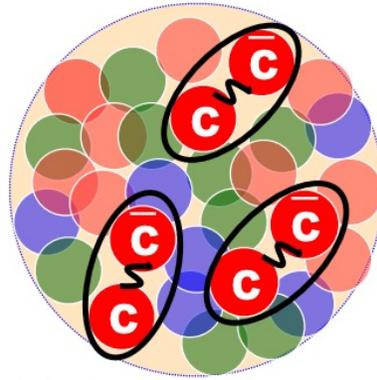
QGP medium effects



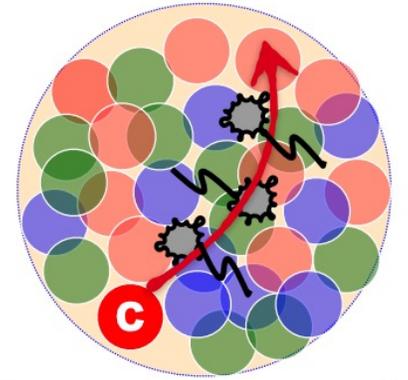
QGP is expected to modify the quarkonium production



Suppression
Medium-induced
dissociation

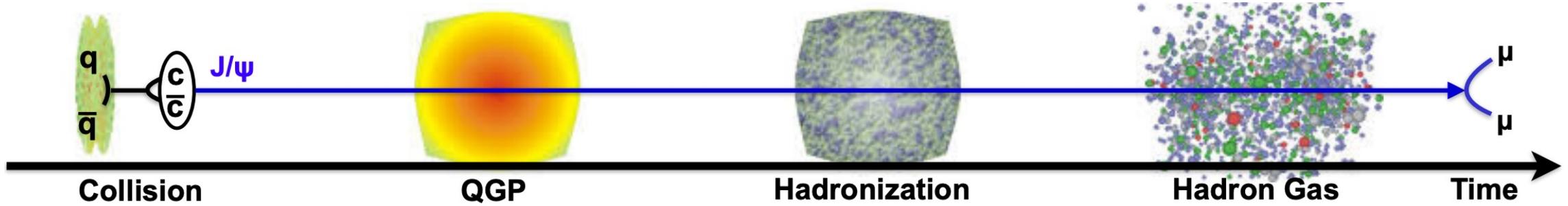


+Enhancement
Regeneration
at high energy density

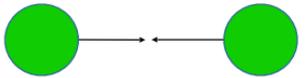
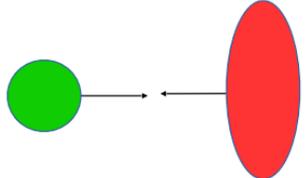
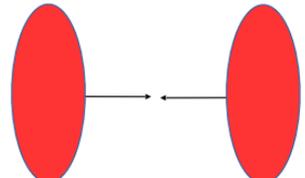


+Parton energy loss
at high p_T

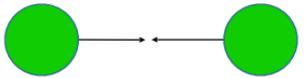
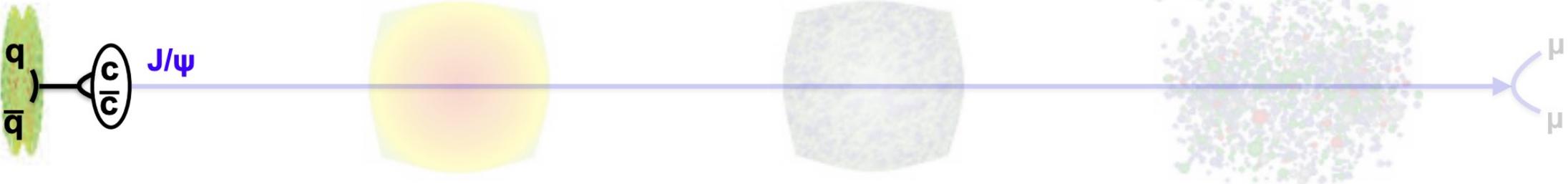
Outline



Quarkonia are produced in the early stages of the collision

		
Production mechanism:	Cold nuclear effects:	QGP effects:
▪ $Q\bar{Q}$ results in pp	▪ $Q\bar{Q}$ results in pA	▪ $Q\bar{Q}$ results in AA

Quarkonia production in pp

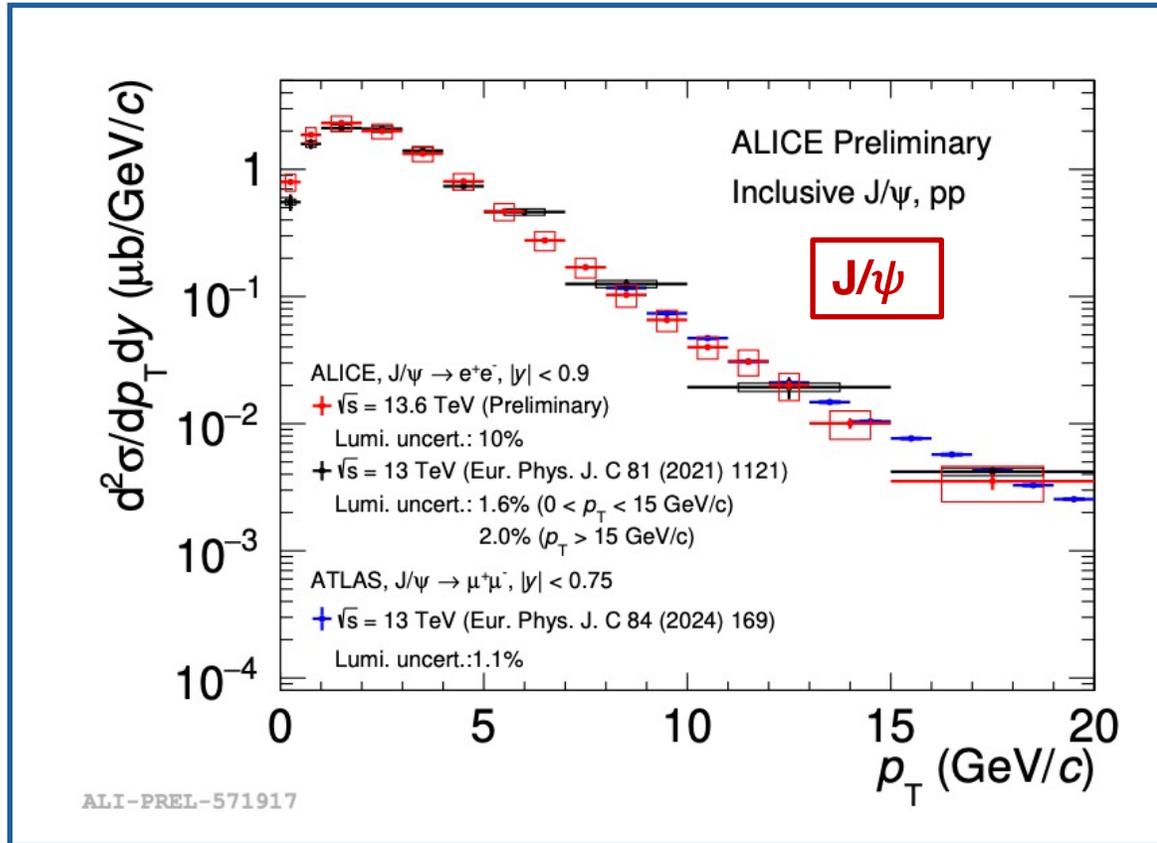


Production mechanism:

- $Q\bar{Q}$ results in pp

Quarkonium production in pp

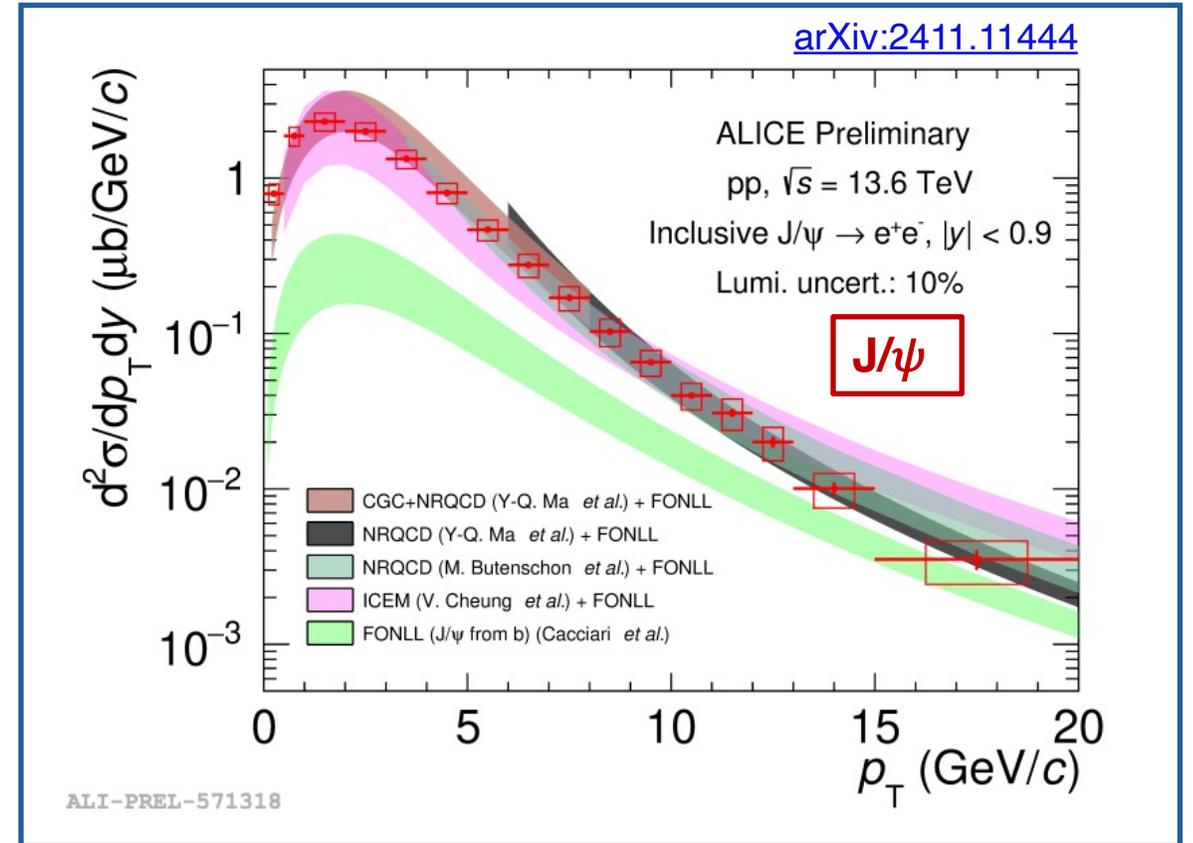
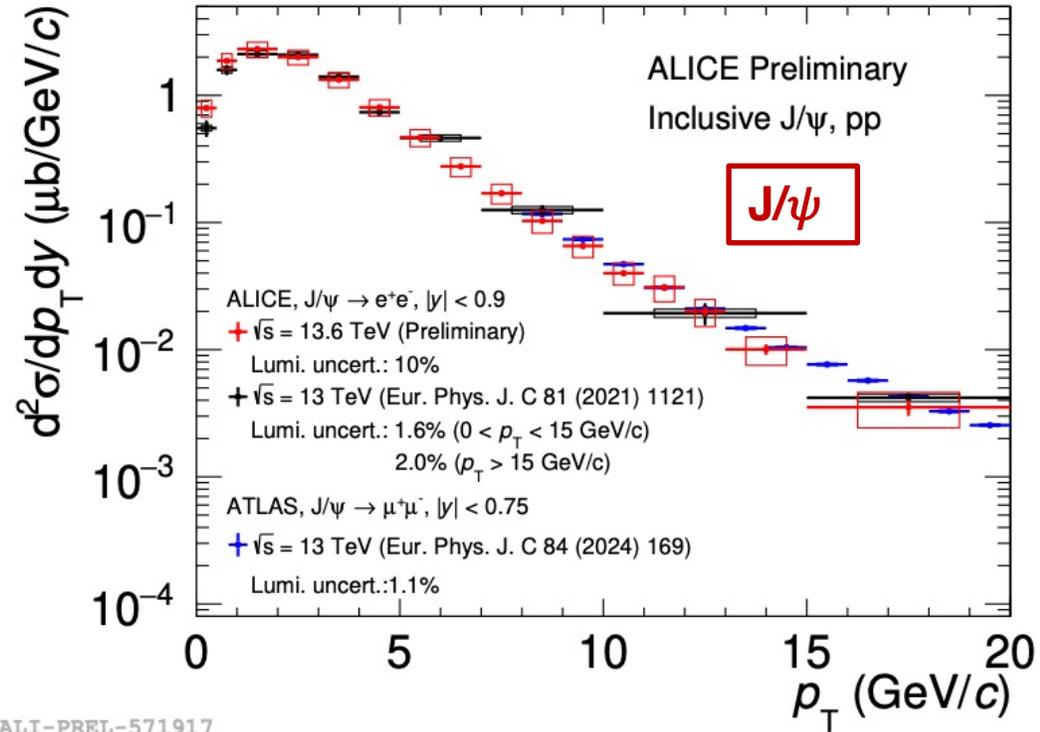
[arXiv:2411.11444](https://arxiv.org/abs/2411.11444)



- p_T spectra are in consistent with results at similar collision energy

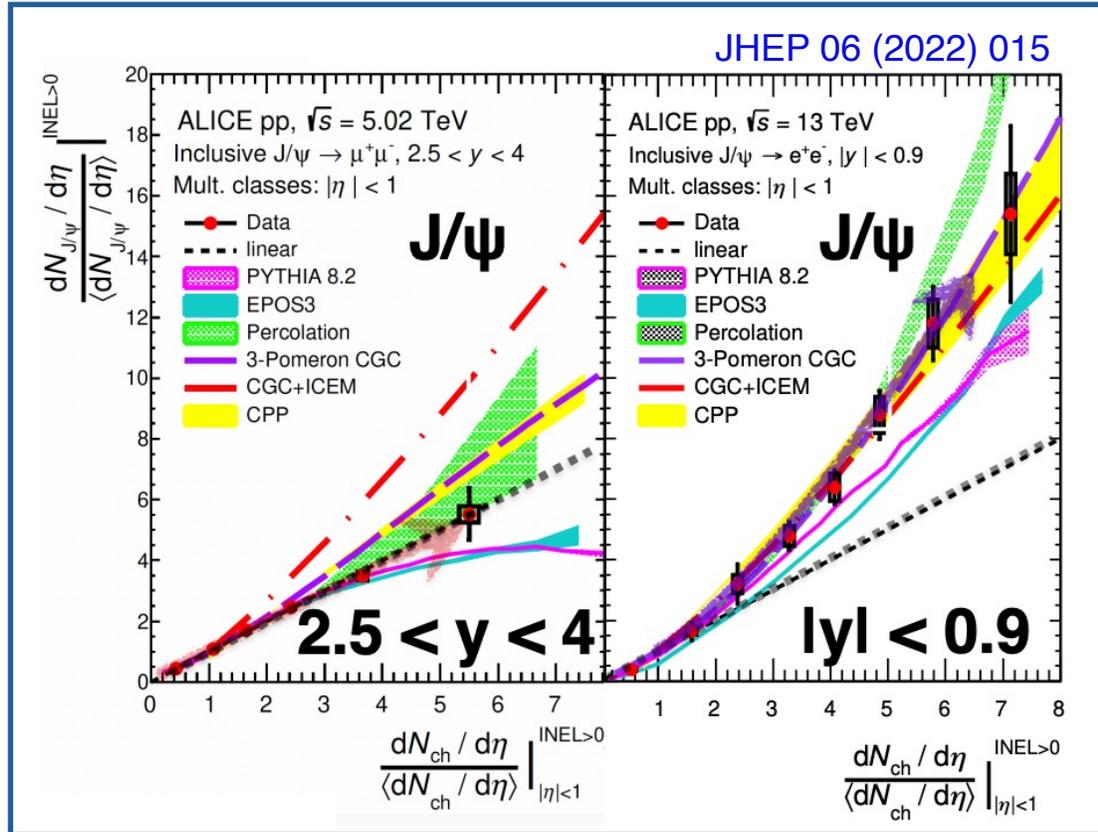
ls

Quarkonium production in pp



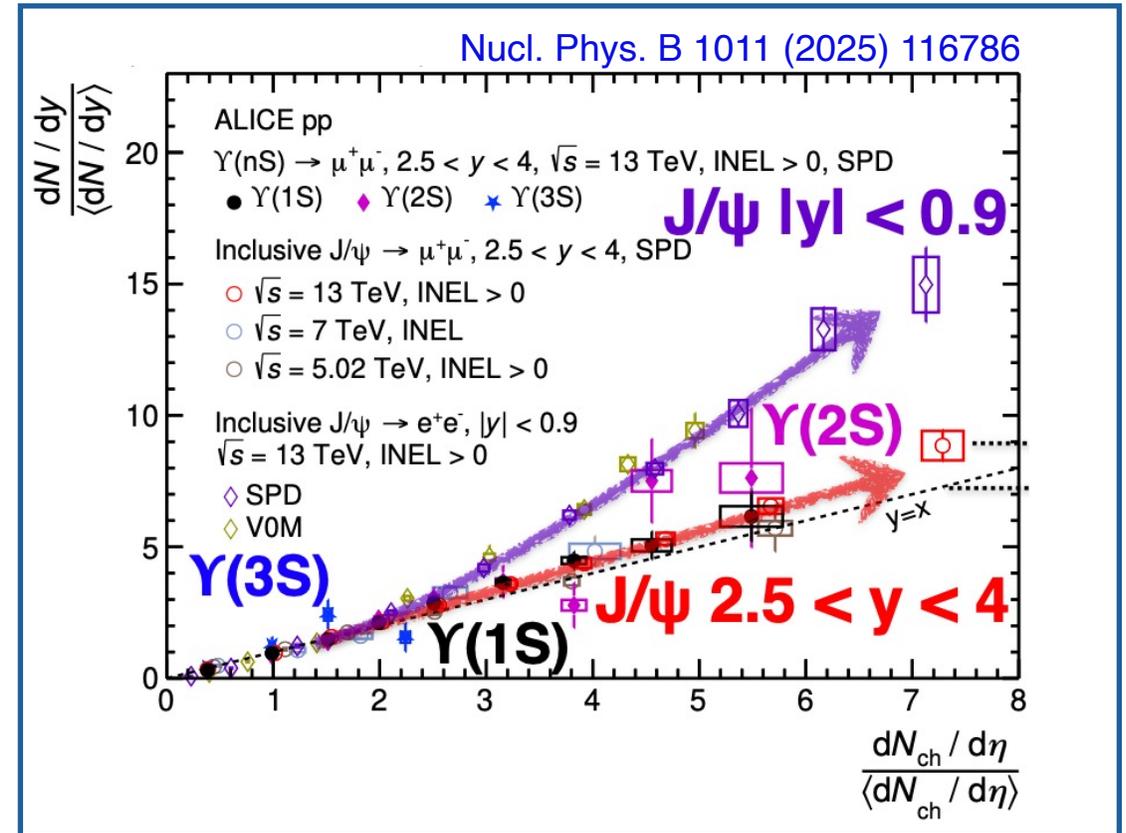
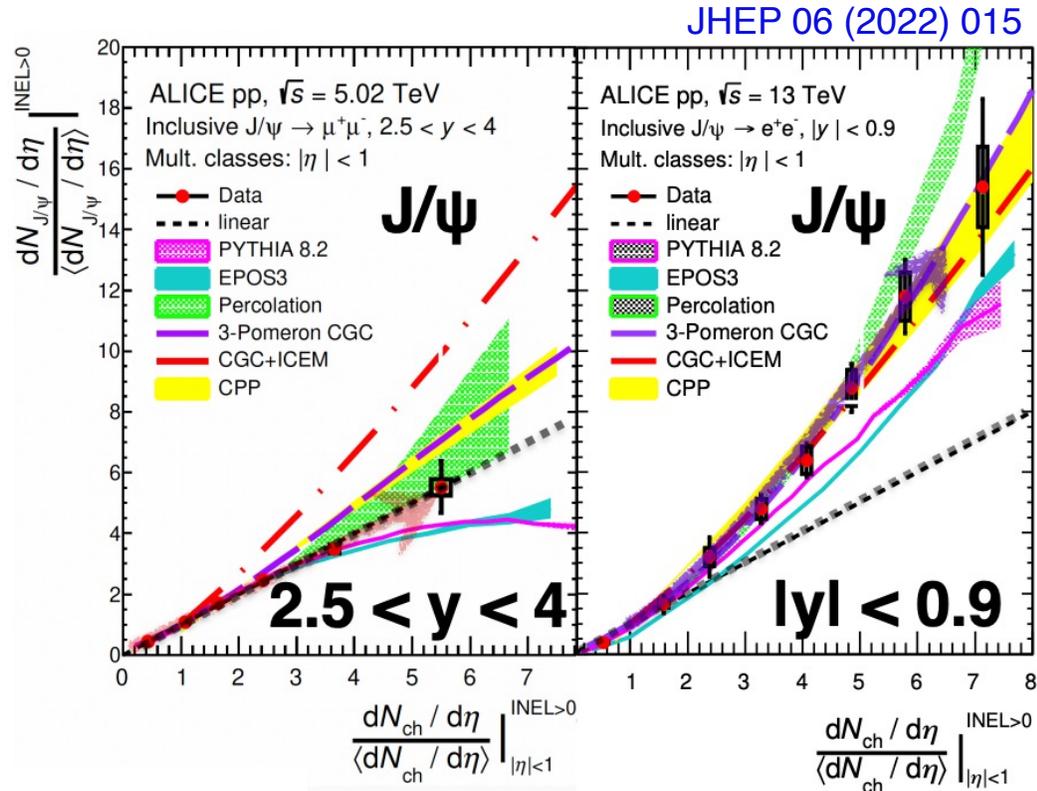
- p_T spectra are in consistent with results at similar collision energy
- Both NRQCD and ICEM can describe the data
- Latest results will help to further constrain quarkonium production models

Multiplicity dependence of quarkonia production in pp



- Forward-rapidity: QQ yields consistent with linear growth
- Mid-rapidity: J/ψ yield grows faster than linear

Multiplicity dependence of quarkonia production in pp

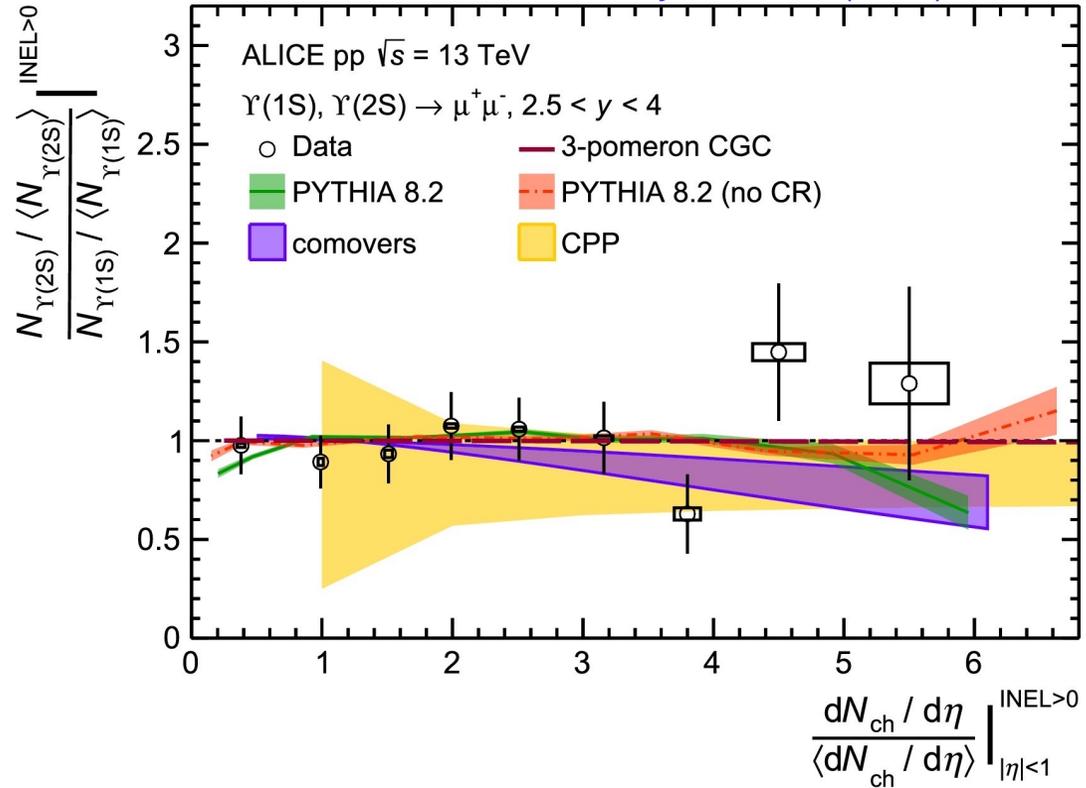


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Multiplicity dependence of quarkonia production in pp

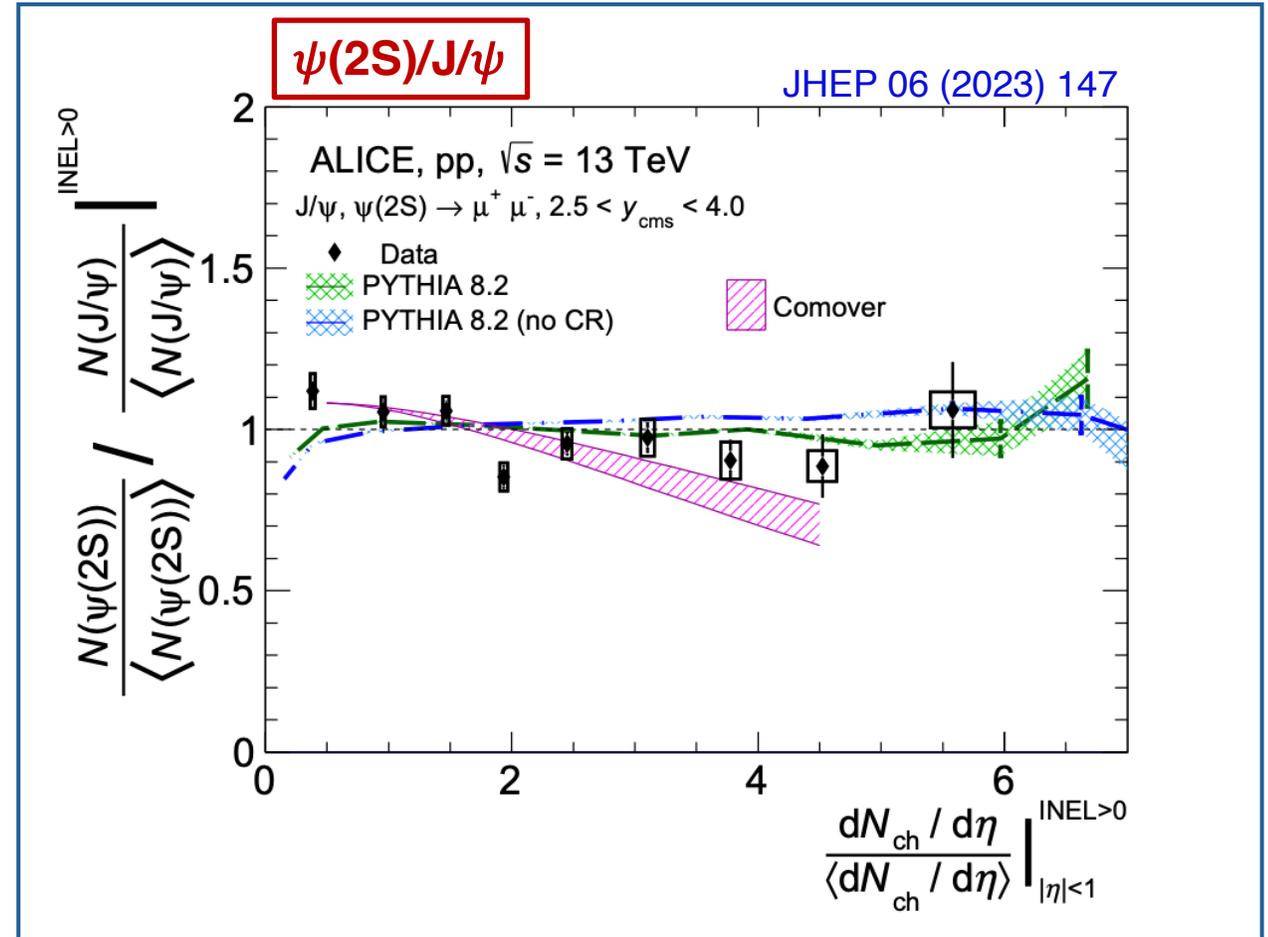
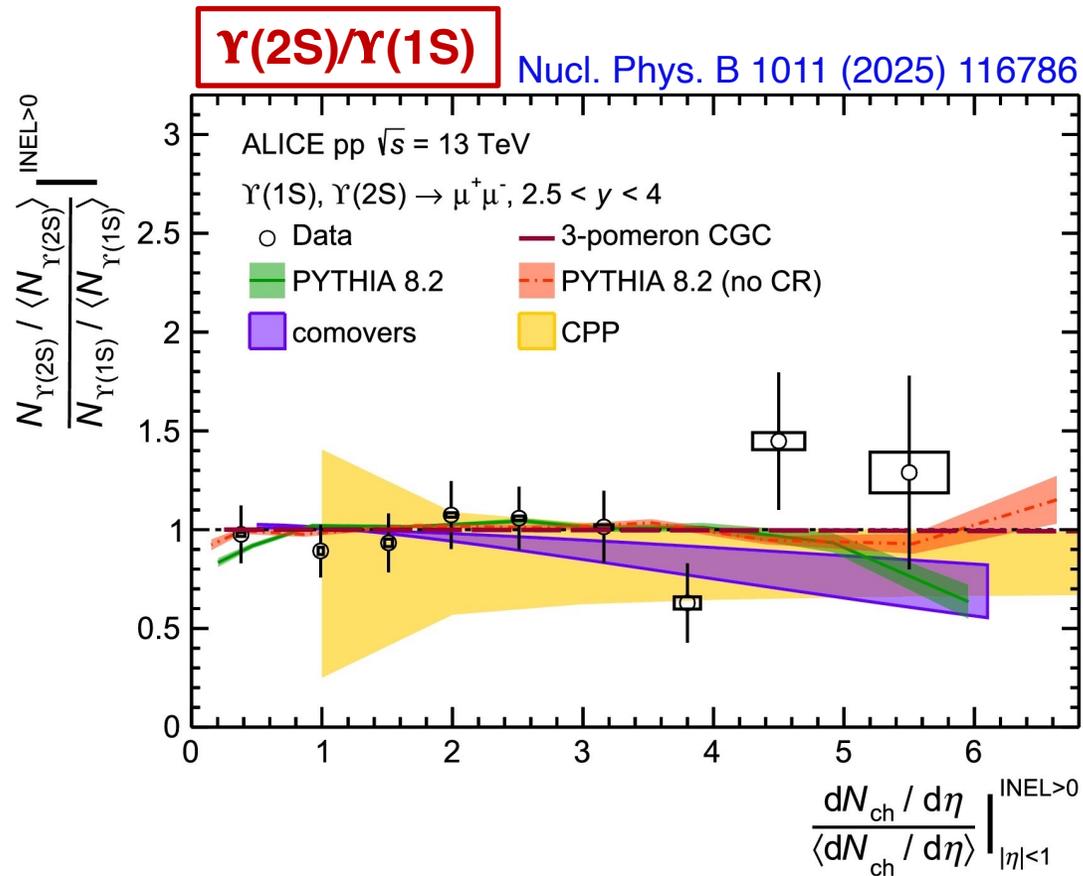
$\Upsilon(2S)/\Upsilon(1S)$

Nucl. Phys. B 1011 (2025) 116786



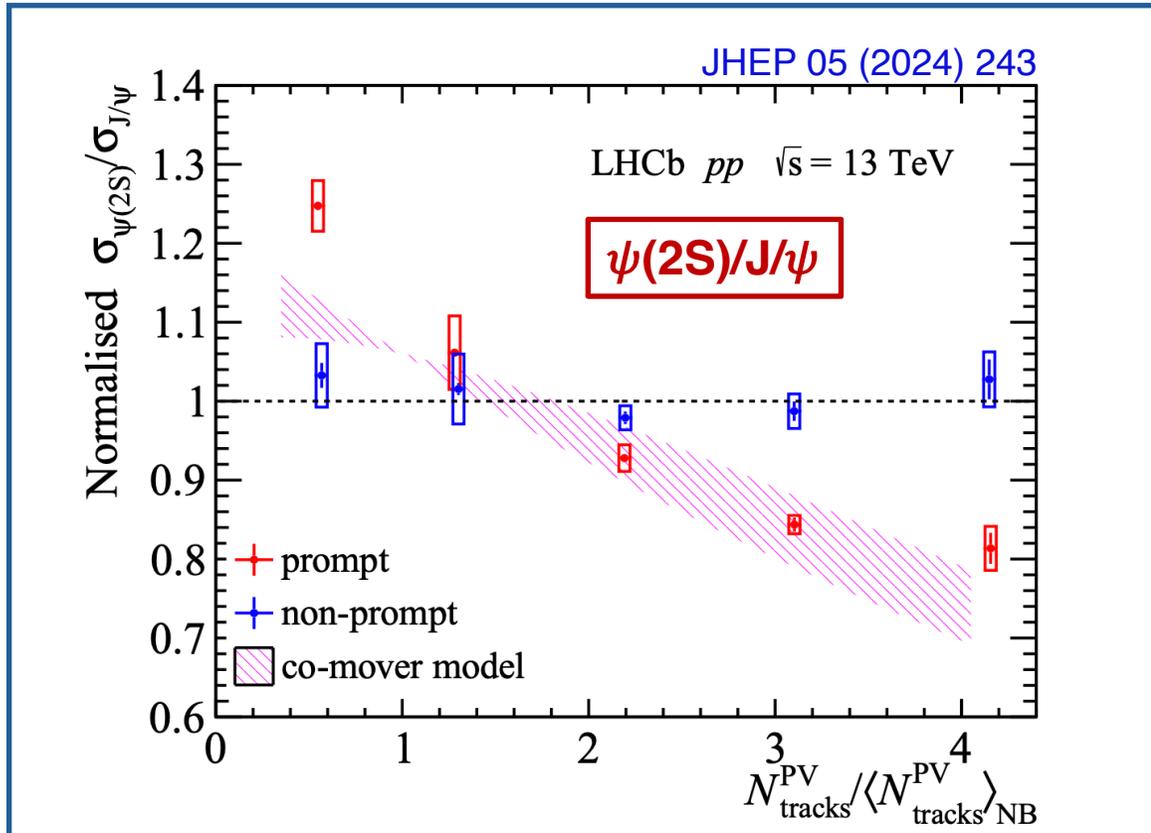
- Excited to ground state ratio flat with multiplicity → larger uncertainty

Multiplicity dependence of quarkonia production in pp



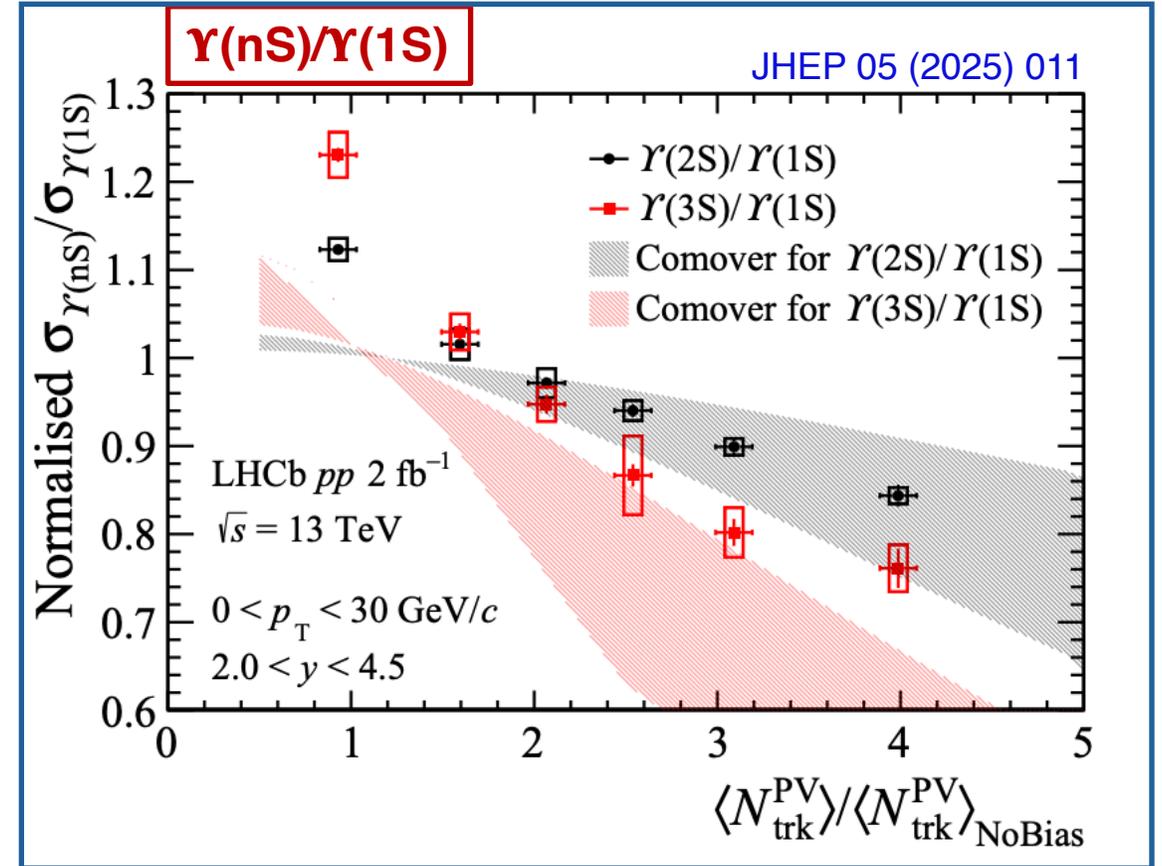
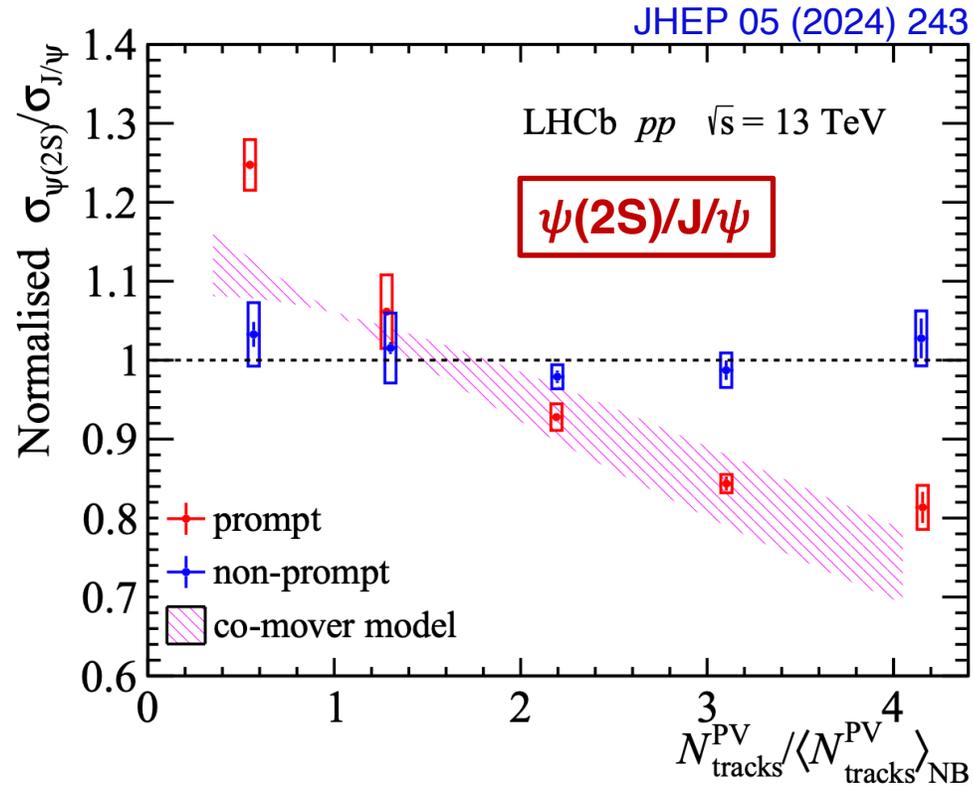
- Excited to ground state ratio flat with multiplicity \rightarrow larger uncertainty

Multiplicity dependence of quarkonia production in pp



- Charmonia from b-hadron decays shows no multiplicity dependence
- Prompt charmonia measurements:
 - decrease of ratio with charged particle multiplicity (co-mover scenario)

Multiplicity dependence of quarkonia production in pp



- Charmonia from b-hadron decays shows no multiplicity dependence
- Bottomonia and prompt charmonia measurements:
 - decrease of ratio with charged particle multiplicity (co-mover scenario)

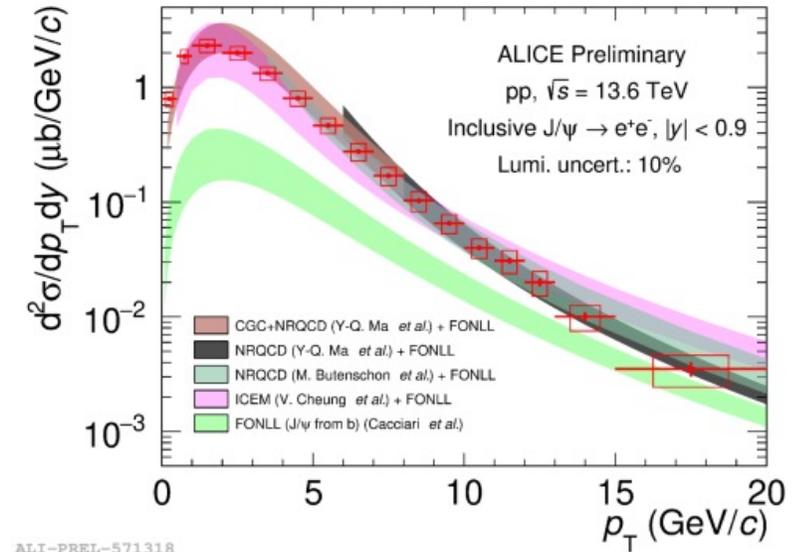
Take-home note: Quarkonia in pp

✓ Quarkonia production in pp:

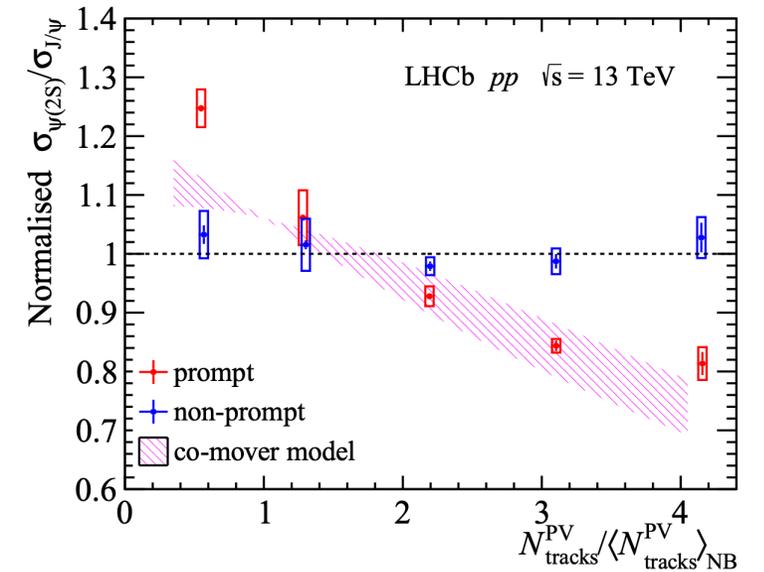
- Precision data to constrain models
- Major effort needed to improve theory uncertainty

✓ Event activity dependence:

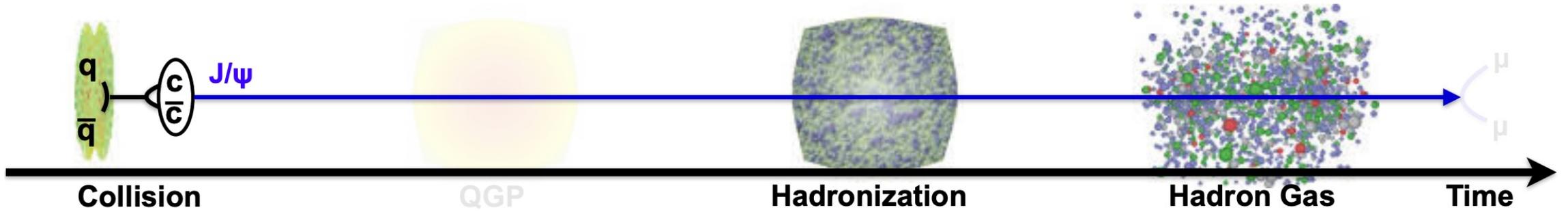
- Evidence of the presence of final state effects
→ Qualitative agreement with “co-mover” prediction



ALI-PREL-571318

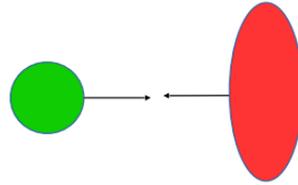


Quarkonia production in pA



nuclear modification factor

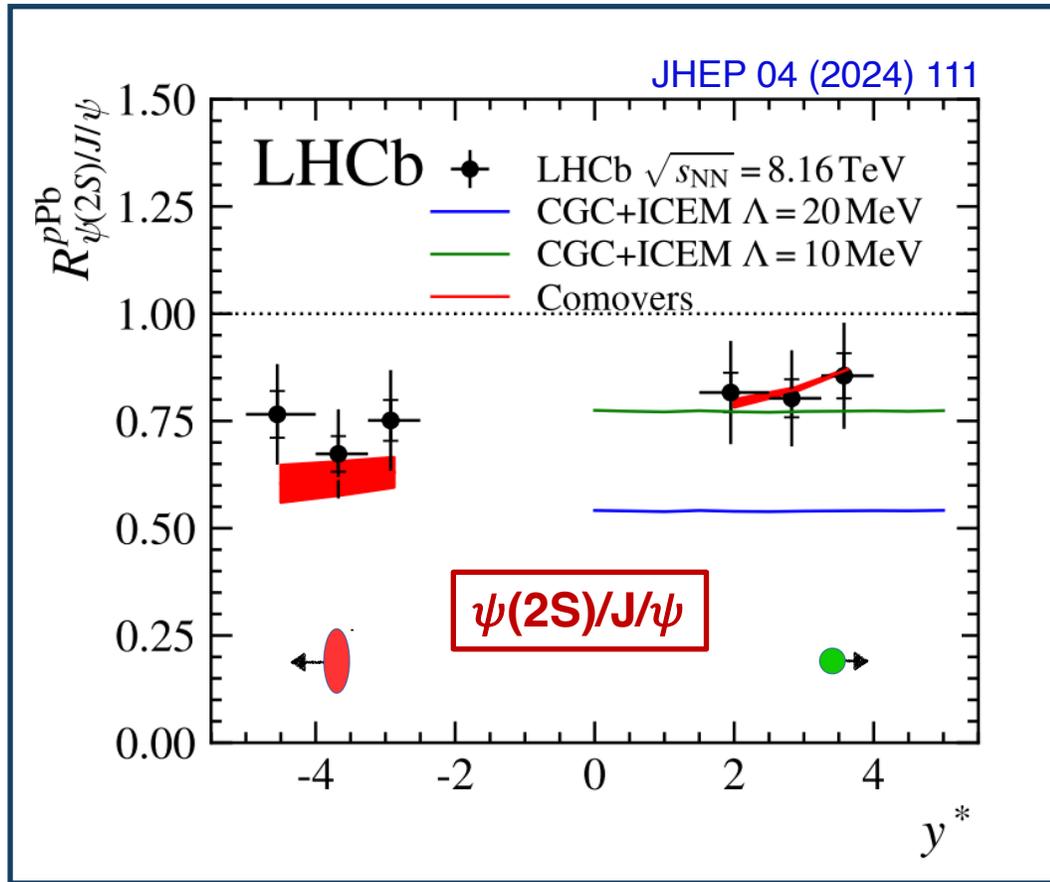
$$R_{pPb}(p_T, y^*) \equiv \frac{1}{A} \frac{d^2\sigma_{pPb}(p_T, y^*)/dp_T dy^*}{d^2\sigma_{pp}(p_T, y^*)/dp_T dy^*},$$



Cold nuclear effects:

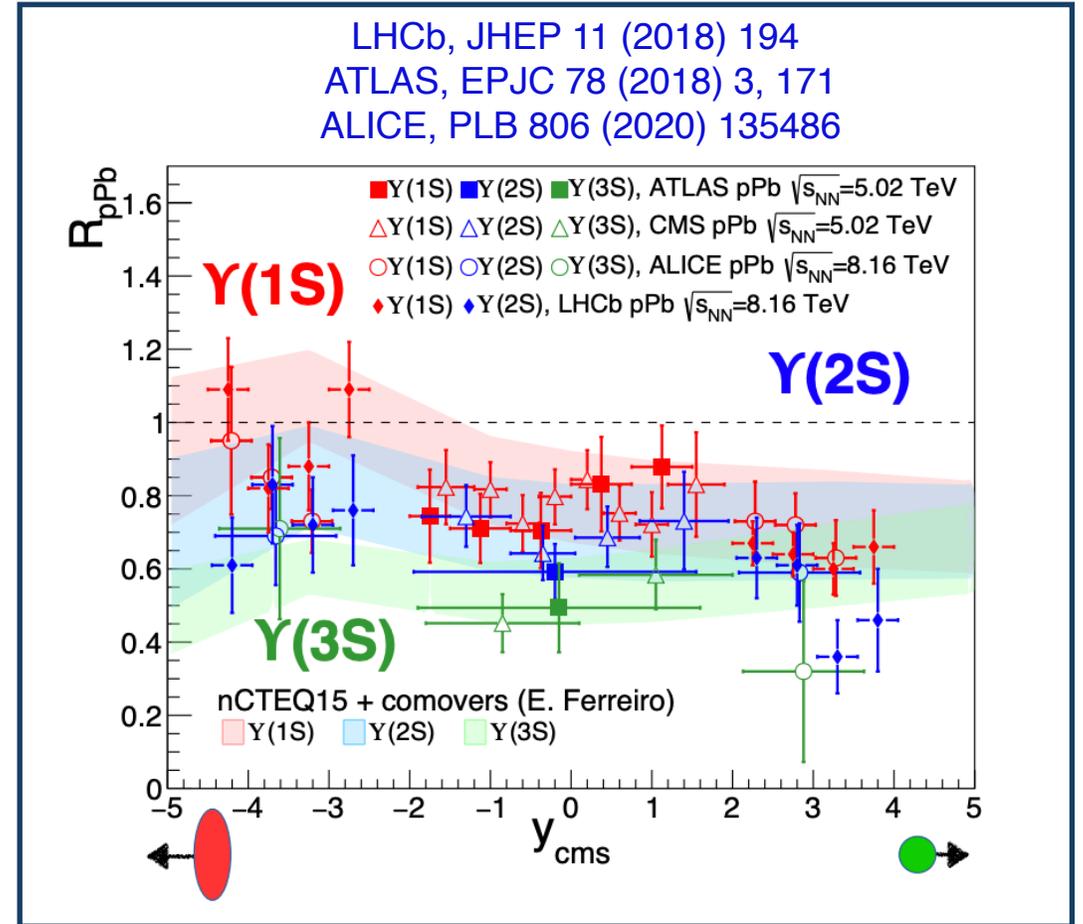
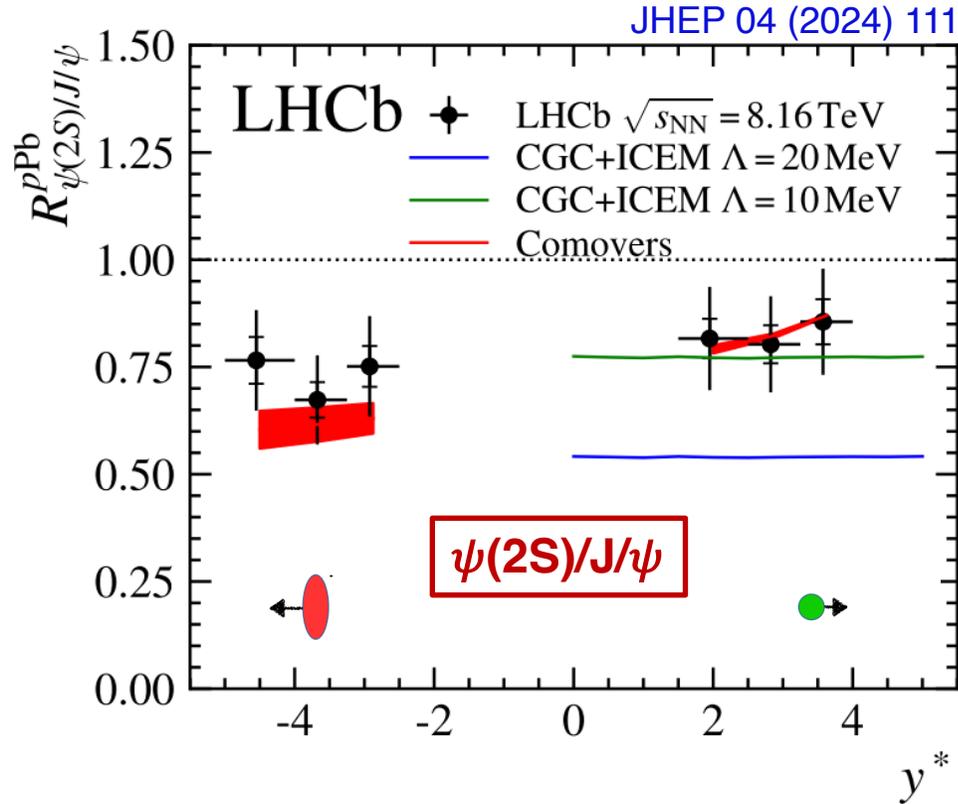
- $Q\bar{Q}$ results in pA

Quarkonia production in pPb



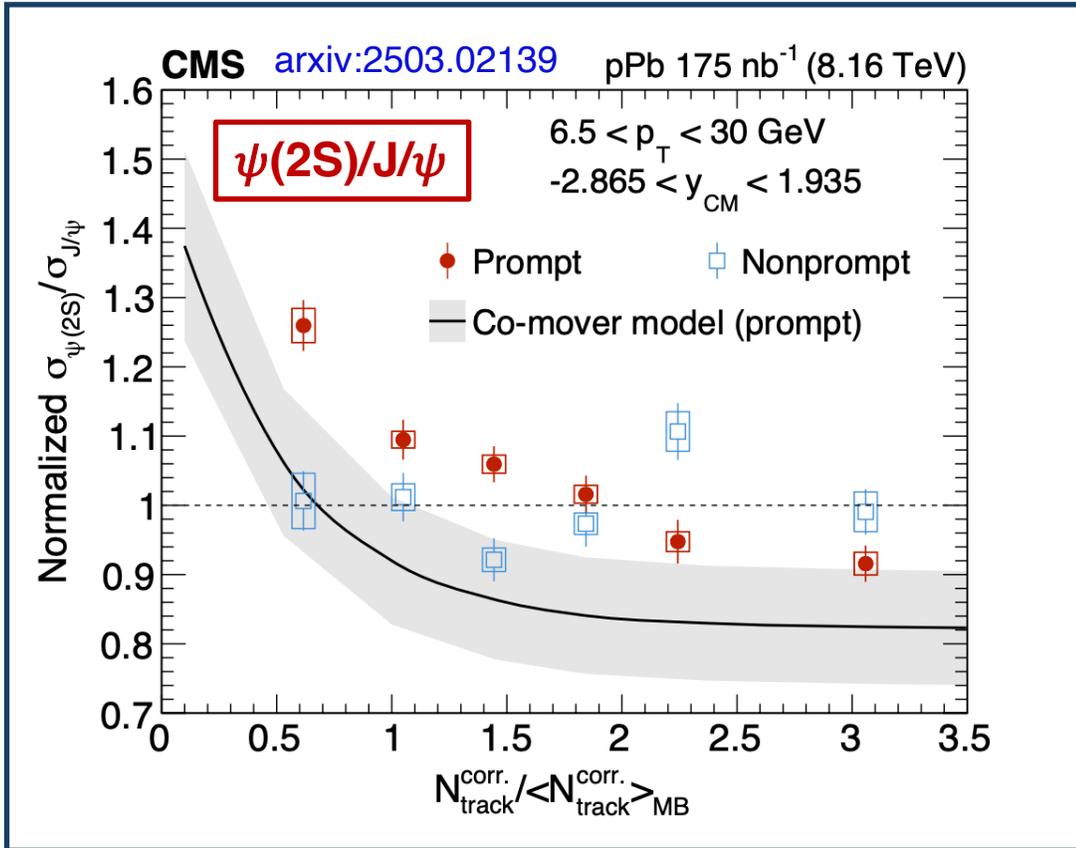
- $\psi(2S) R_{pPb} < J/\psi R_{pPb}$ in pPb \rightarrow trend described well by co-mover model

Quarkonia production in pPb



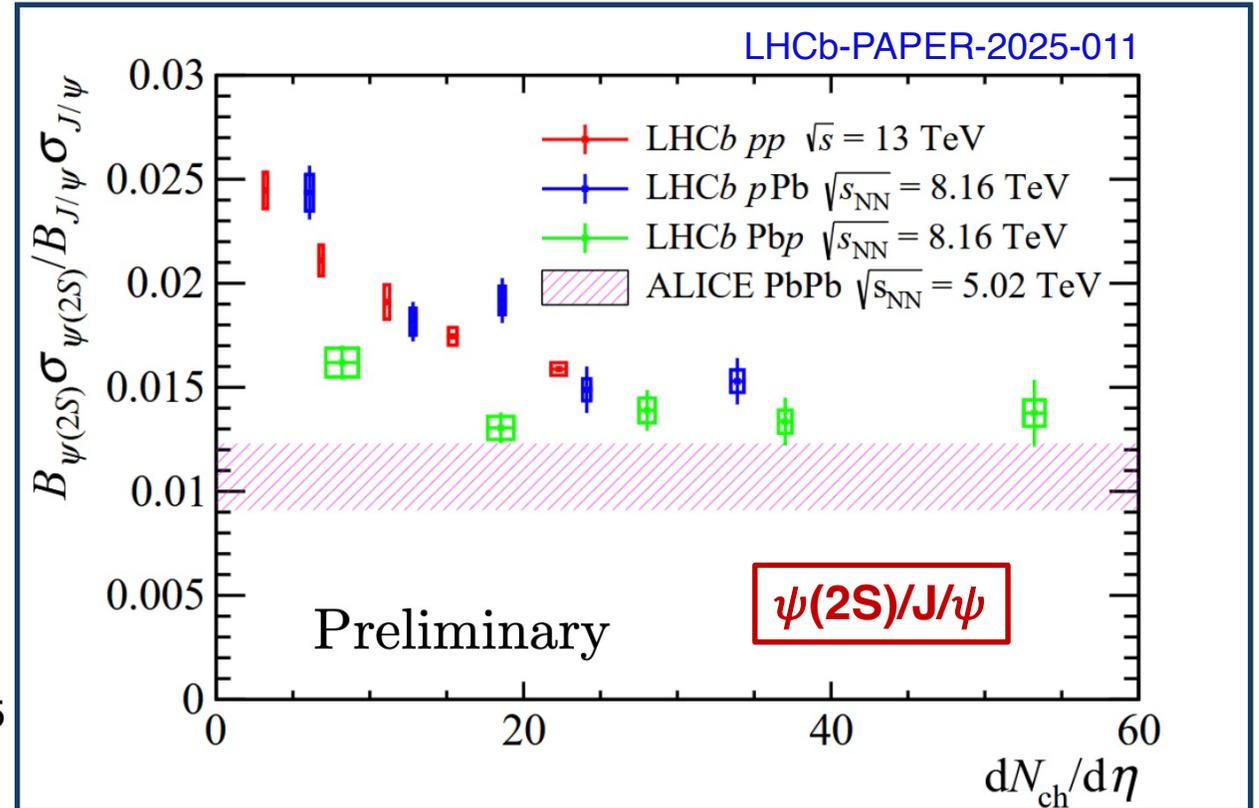
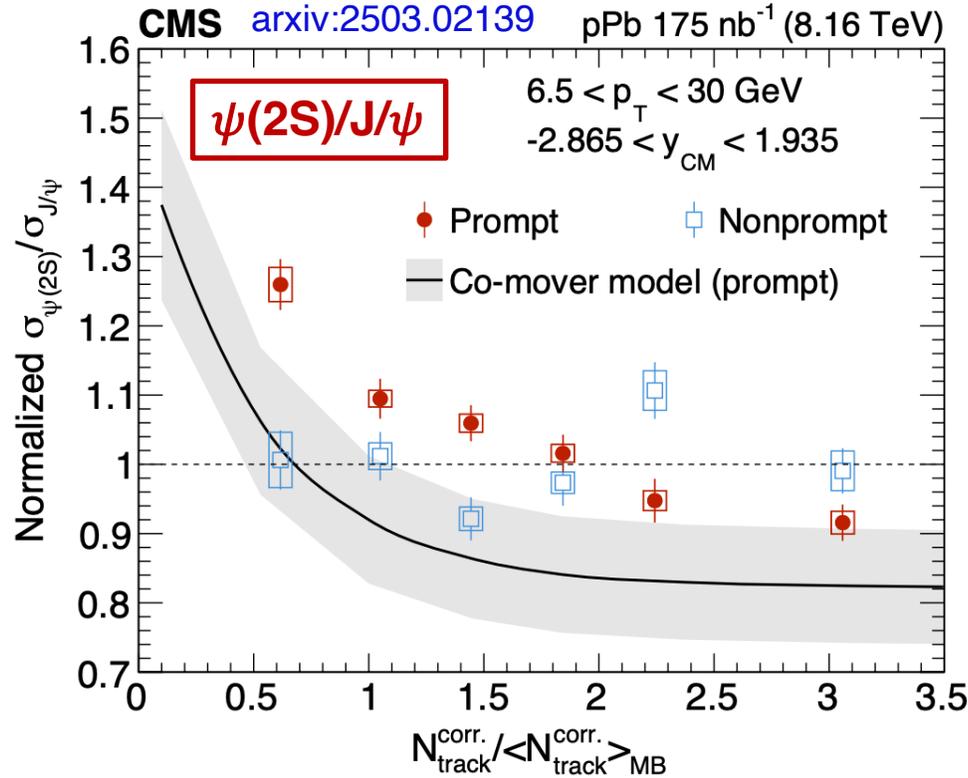
- $\psi(2S) R_{pPb} < J/\psi R_{pPb}$ in pPb \rightarrow trend described well by co-mover model
- $Y(1S) > Y(2S) > Y(3S) \rightarrow$ Co-mover + nPDF model predicts the suppression trend

Multiplicity dependence of quarkonia production in pPb



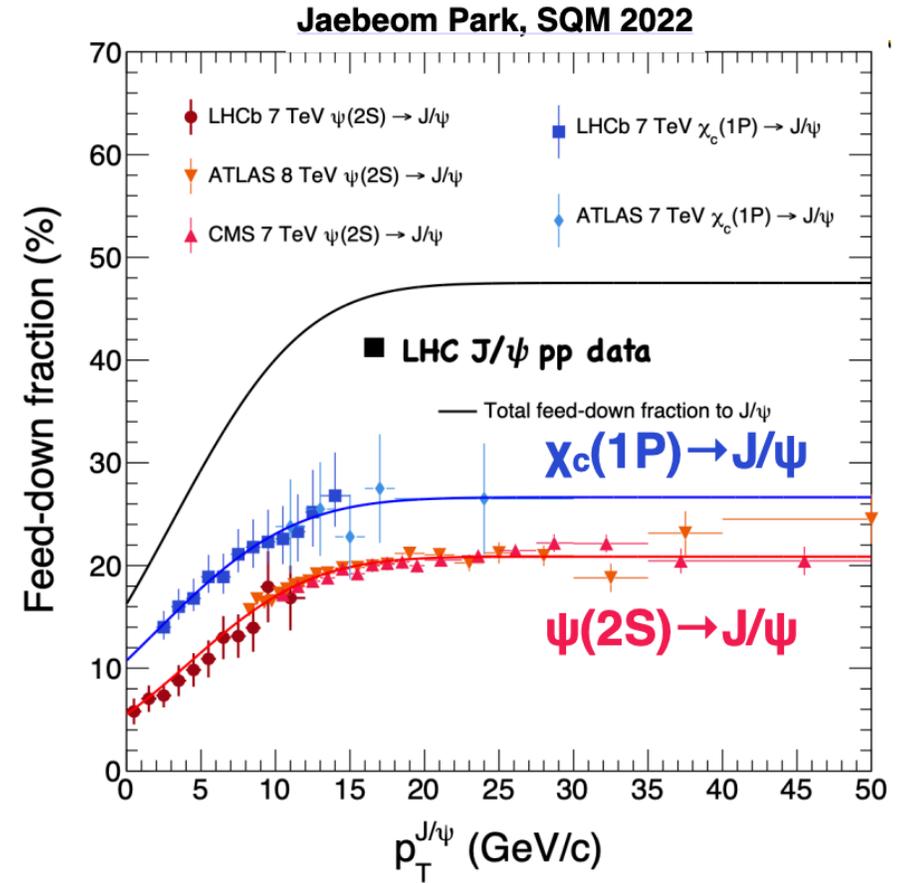
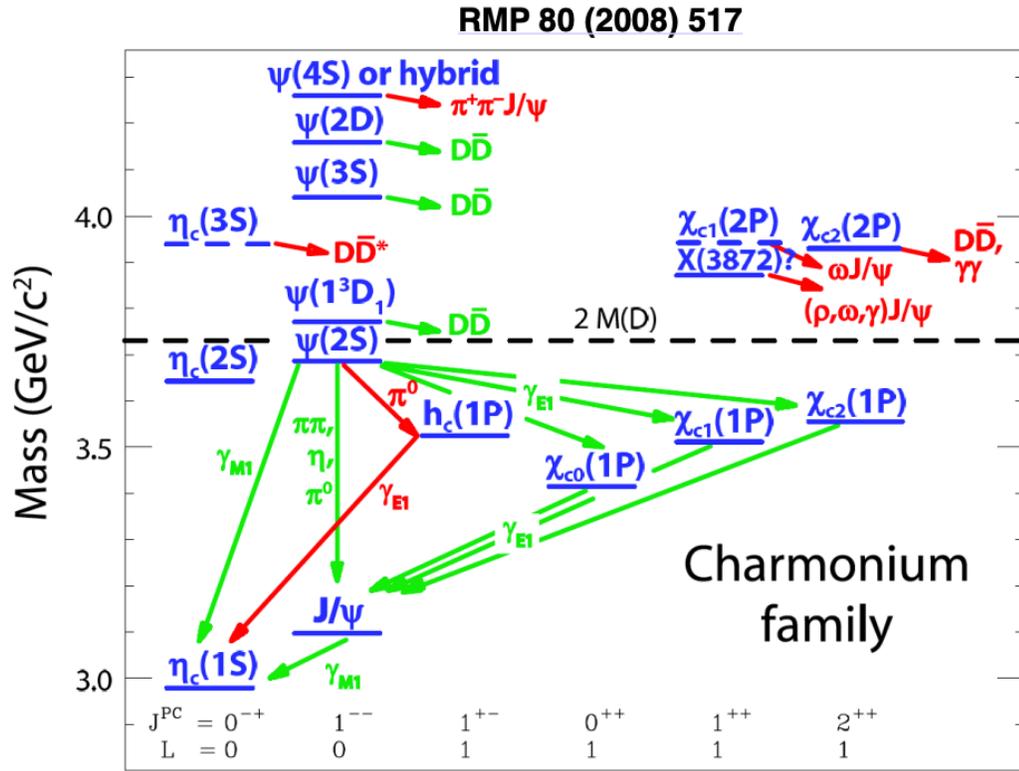
- $\psi(2S)$ suppression effects observed at high multiplicity
- Ratio from b-hadron decays show no dependence on multiplicity
- Qualitative agreement with “co-mover” scenario for prompt ratio

Multiplicity dependence of quarkonia production in pPb



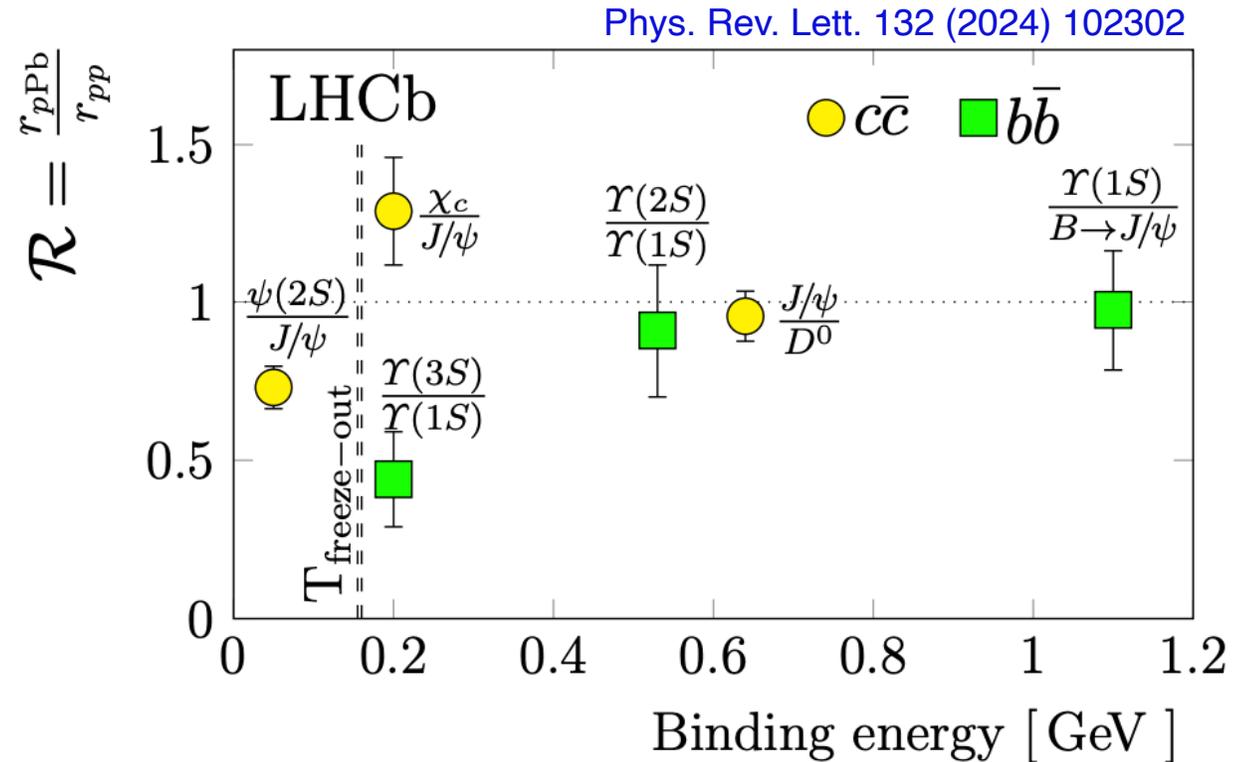
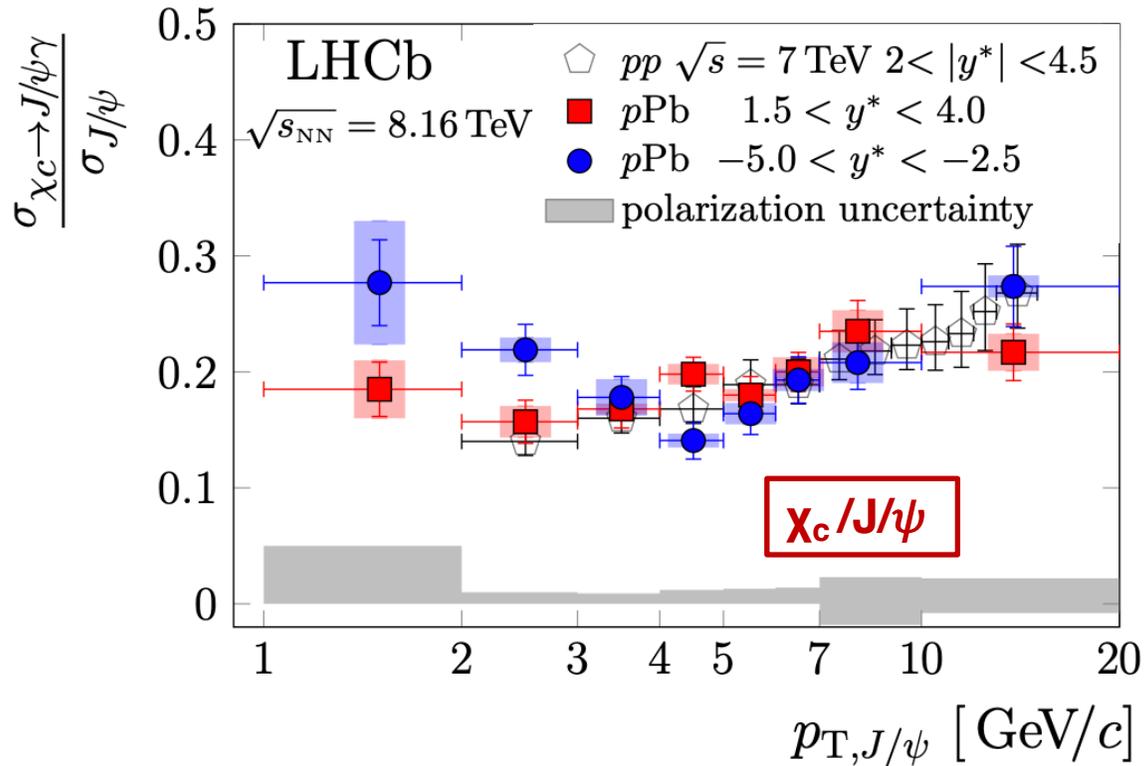
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Charmonium feed-down



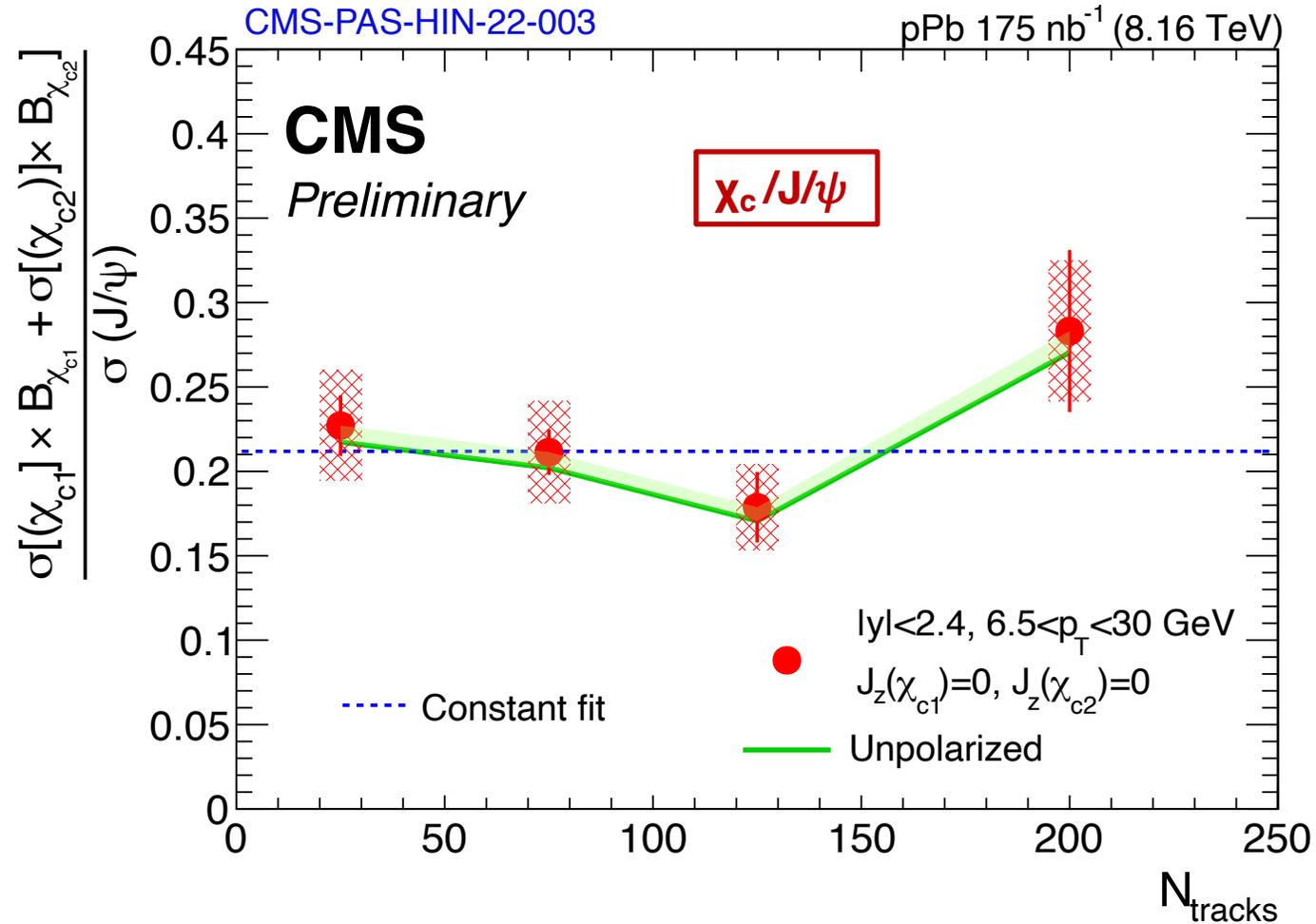
- Fraction of J/ψ production from higher charmonium states (feed-down)
- Excited states with weaker binding energies more affected by final-state effects

χ_c production in pPb



- Slight difference low p_T between backward and forward rapidities
- $R(Y(3S) / Y(1S)) < R(\chi_c / J/\psi) \sim 1$ despite $\chi_c \sim Y(3S)$ binding energy:
 \rightarrow Impact of QQ feed-down? or mass-dependent effects? or P vs S-wave?

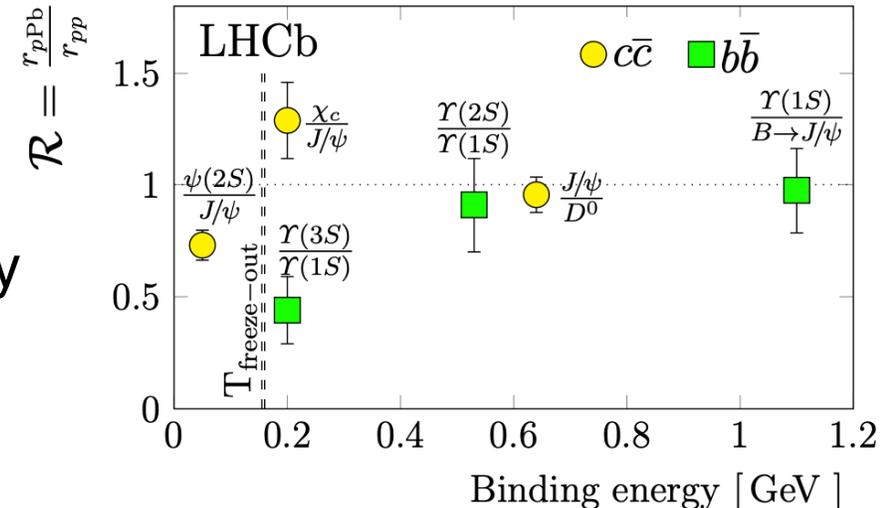
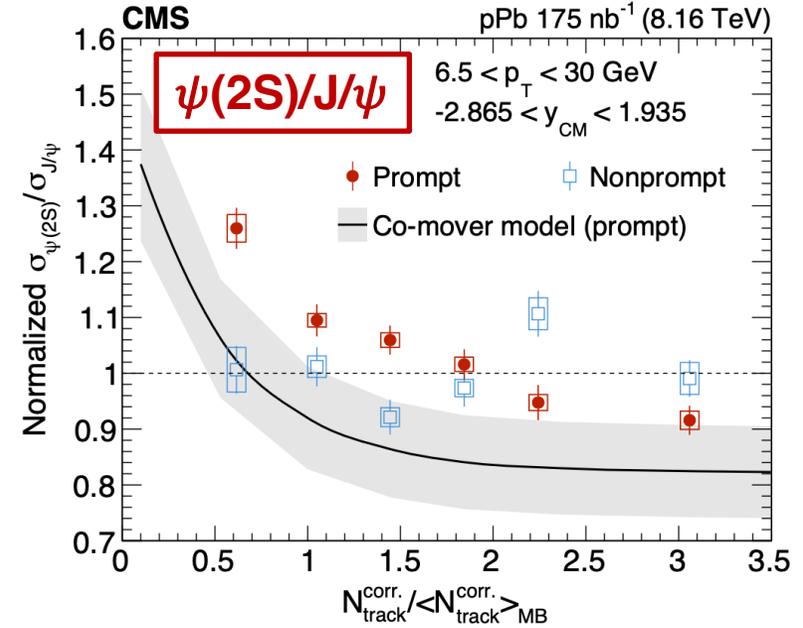
χ_c production in pPb



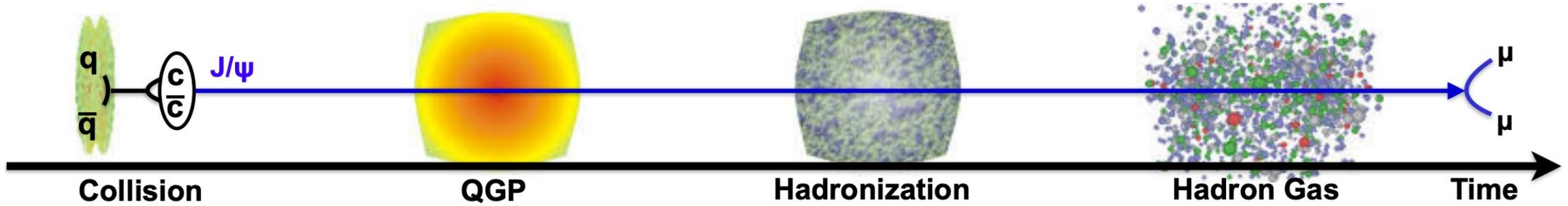
- No multiplicity dependence observed at high p_T
 - Co-mover/dissociation picture doesn't hold?
 - Angular momenta change final state interactions?
- Consistent picture with LHCb at forward rapidity

Take-home note: Quarkonia in pPb

- ✓ Sequential suppression of $Q\bar{Q}$ states in pPb
- ✓ Event activity dependence:
 - Evidence of the presence of final state effects
 - Qualitative agreement with “co-mover” prediction
- ✓ χ_c measured in pPb
 - Crucial for studying final state effects of charmonia
 - $Y(3S)/Y(1S) < \chi_c/J/\psi$ despite $Y(3S) \sim \chi_c$ binding energy

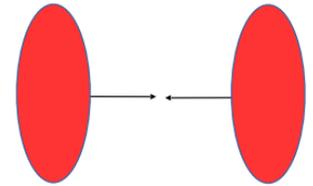


Quarkonia production in PbPb



nuclear modification factor

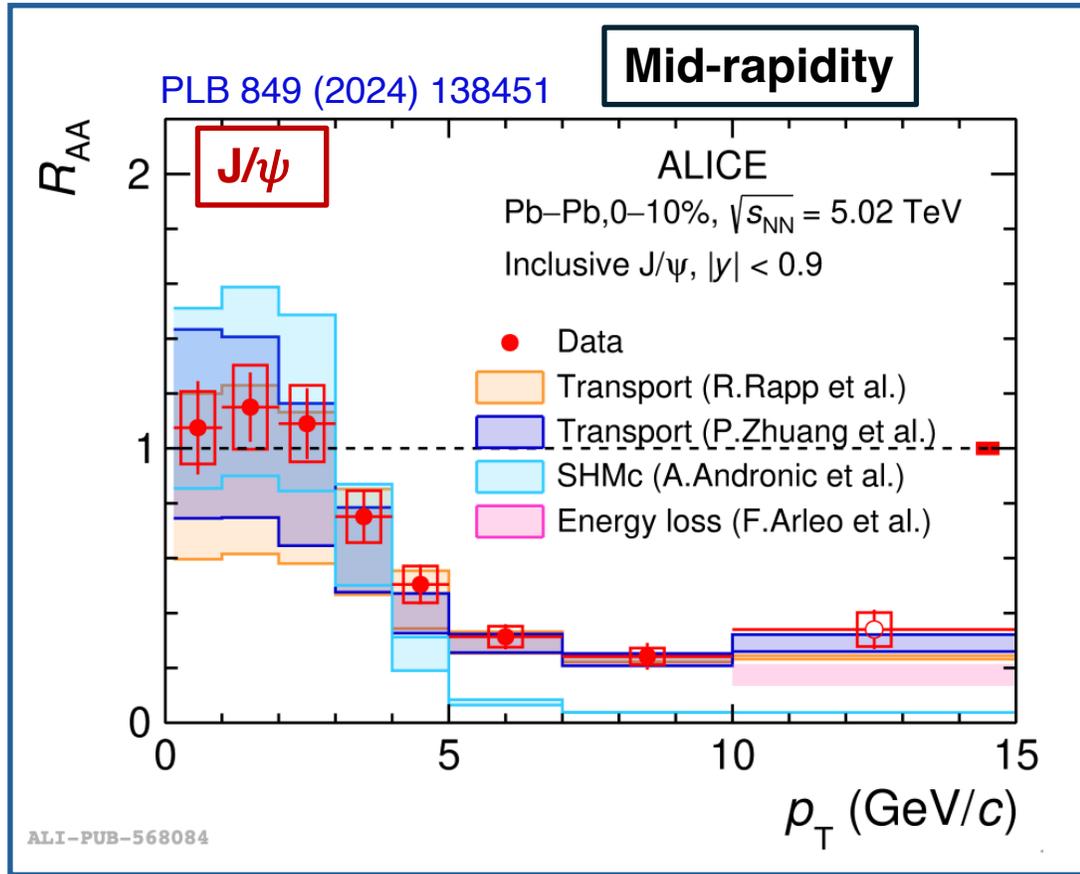
$$R_{AA} = \frac{1}{T_{AA}} \frac{dN_{AA}/dp_T}{d\sigma_{pp}/dp_T} = \frac{1}{N_{\text{coll}}} \frac{dN_{AA}/dp_T}{dN_{pp}/dp_T}$$



QGP effects:

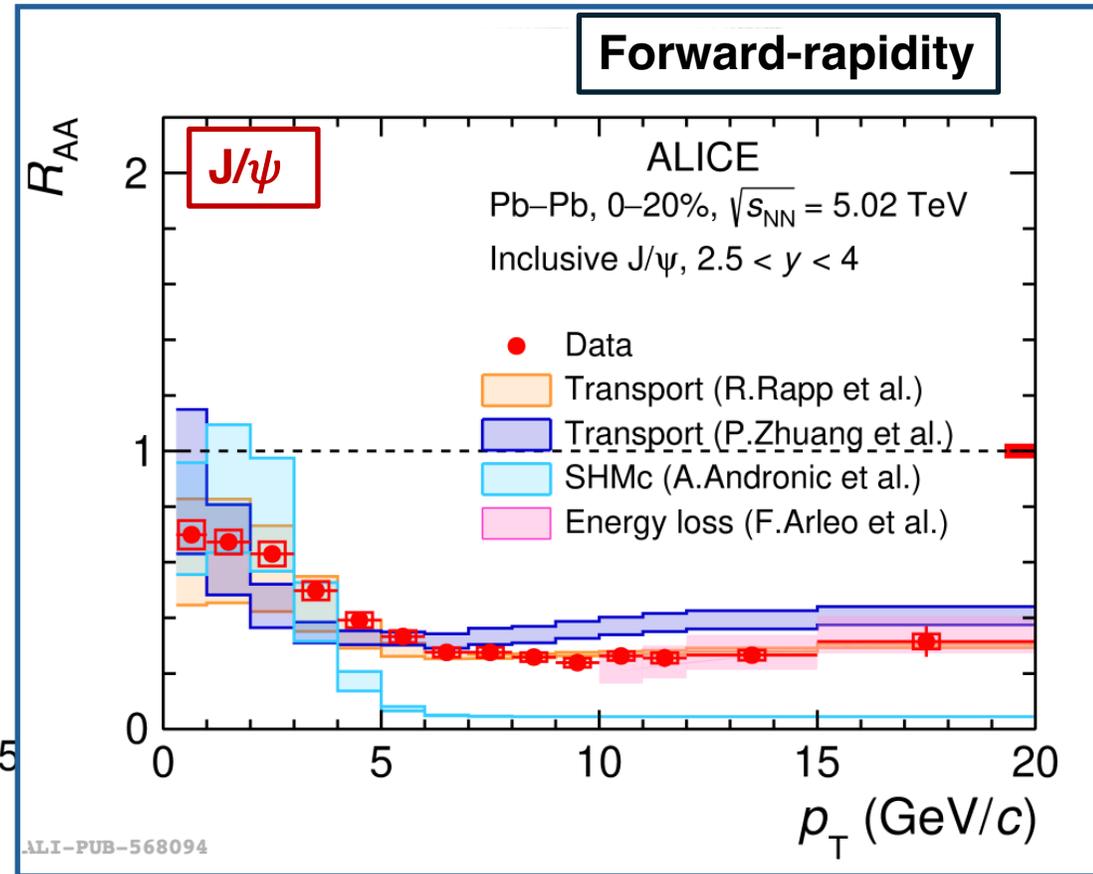
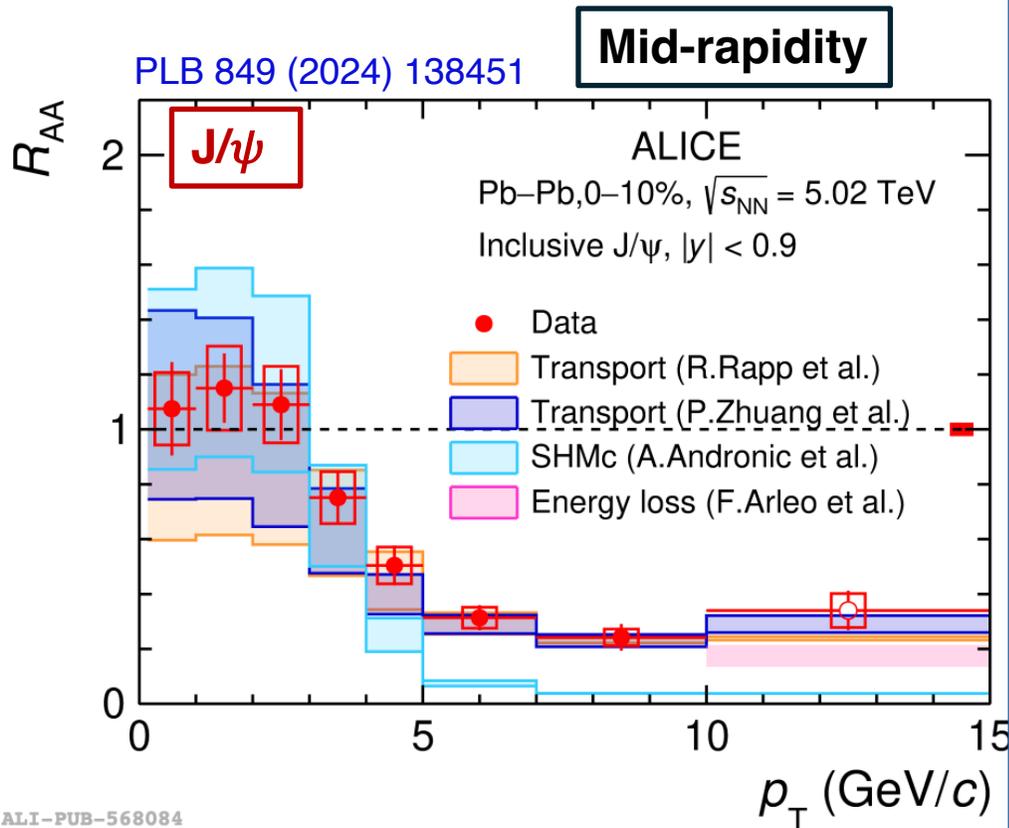
- $Q\bar{Q}$ results in AA

Charmonium in PbPb



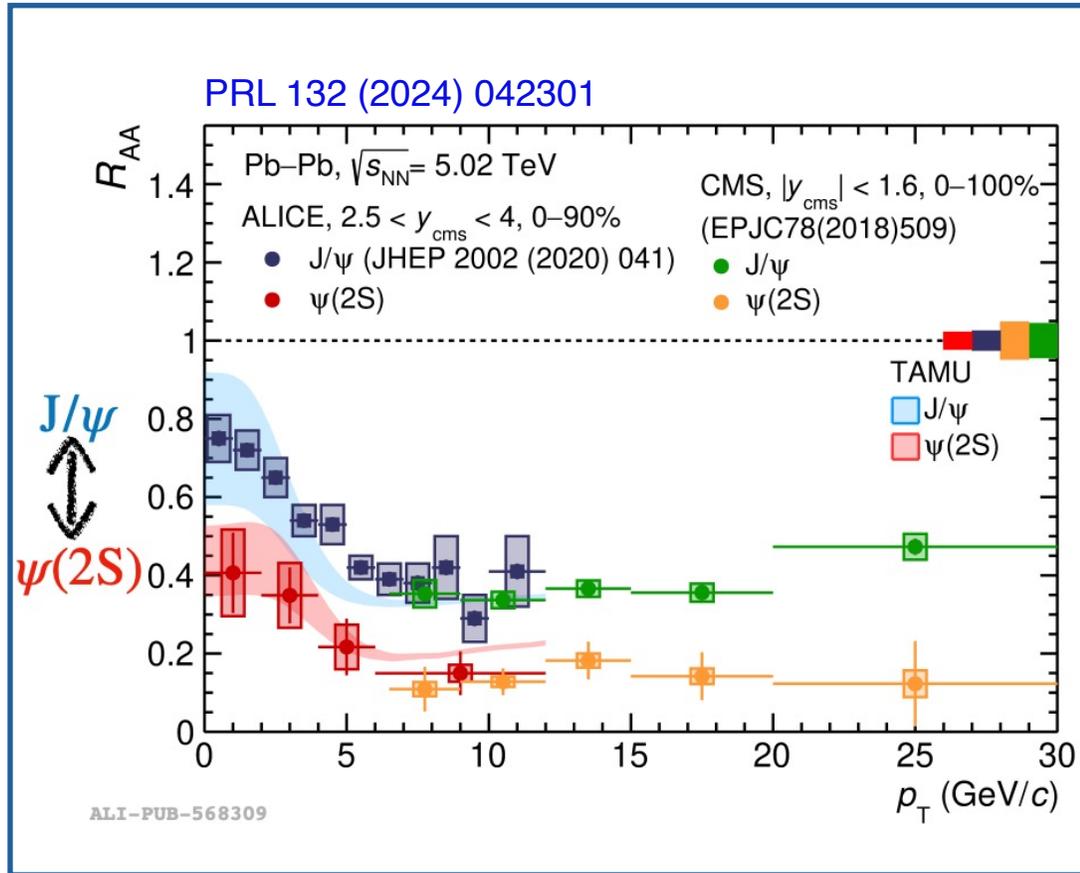
- **Transport models:** Production throughout fireball evolution
- **Statistical Hadronization model:** Rapid hadronization at phase boundary
- **Energy loss model:** Quenching due to radiative energy loss

Charmonium in PbPb



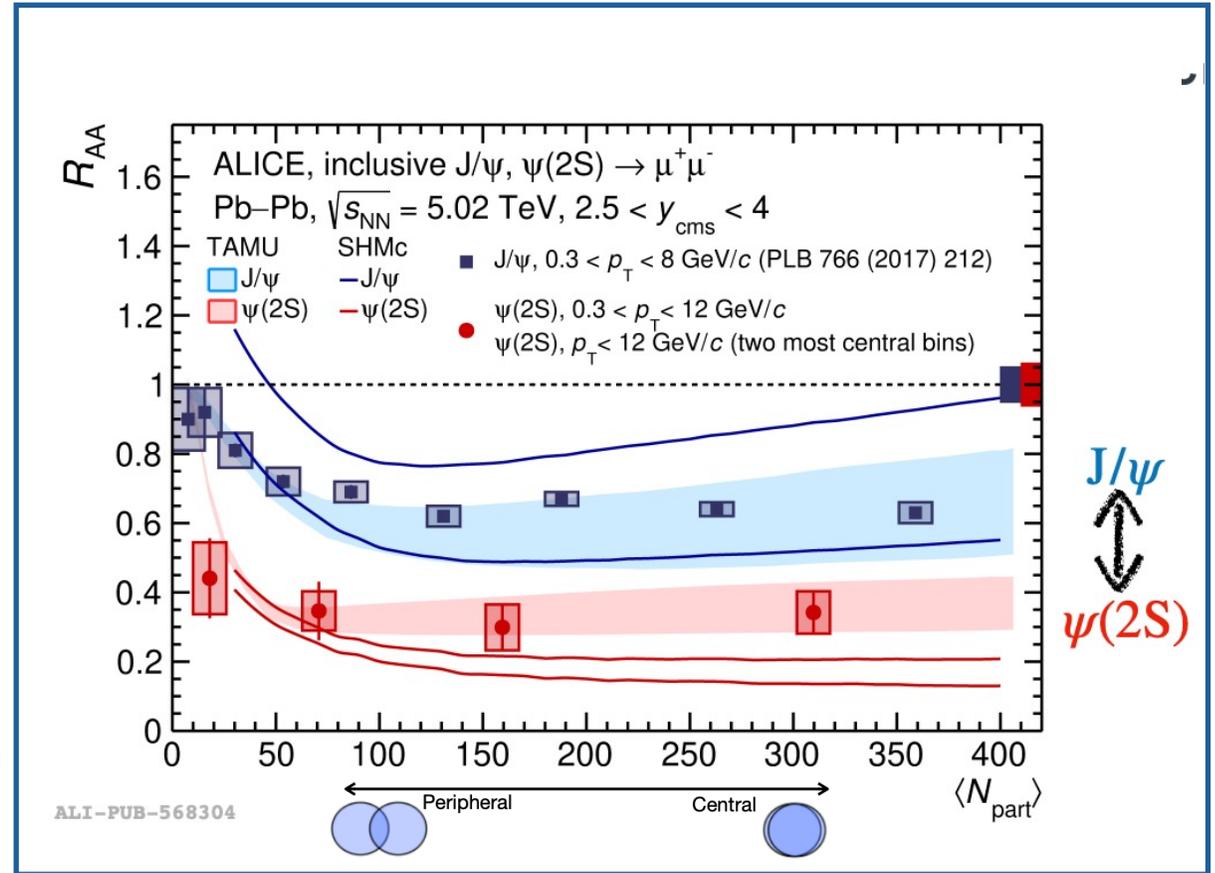
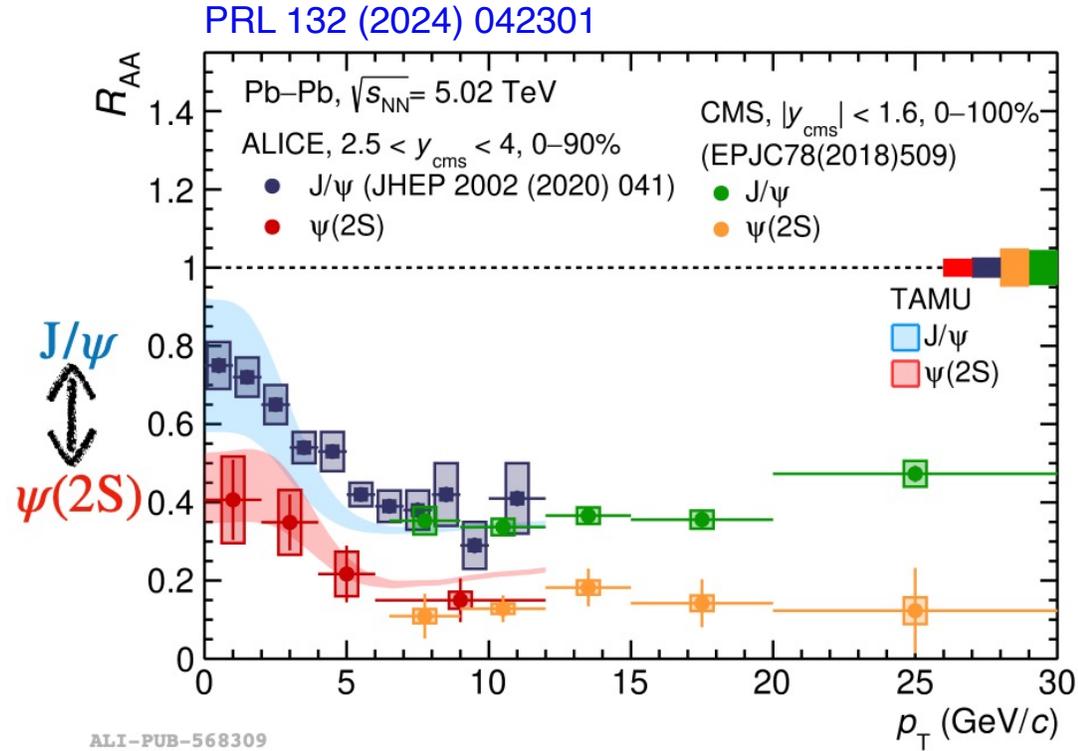
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Charmonium in PbPb



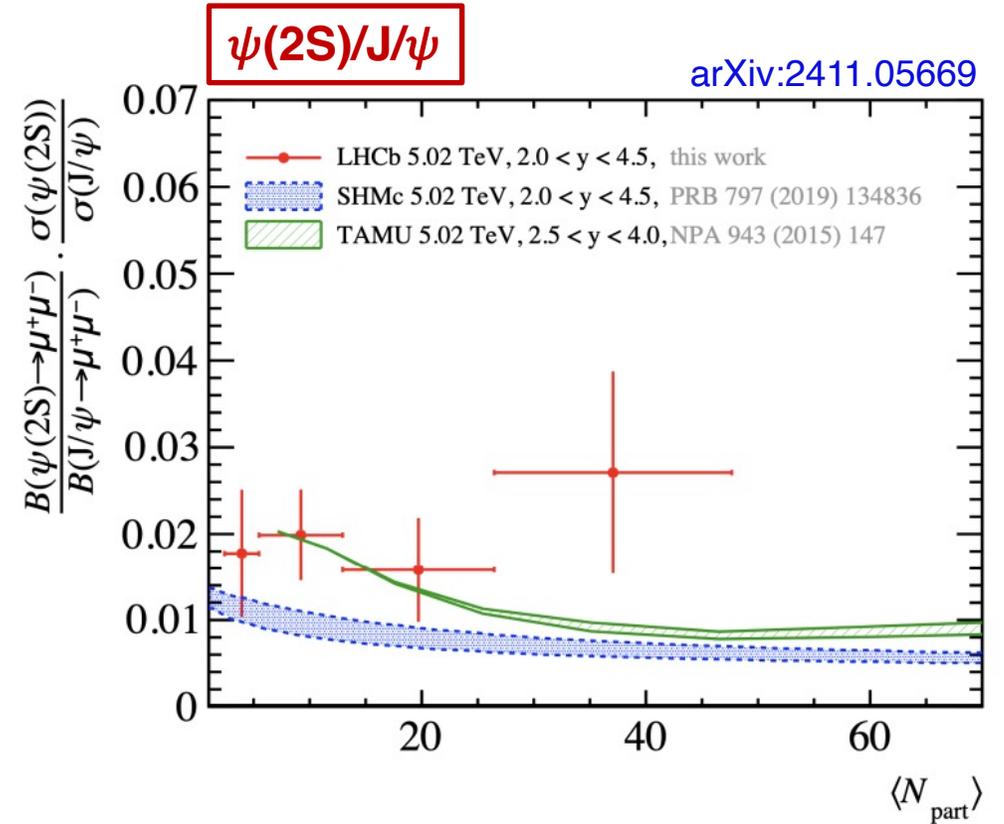
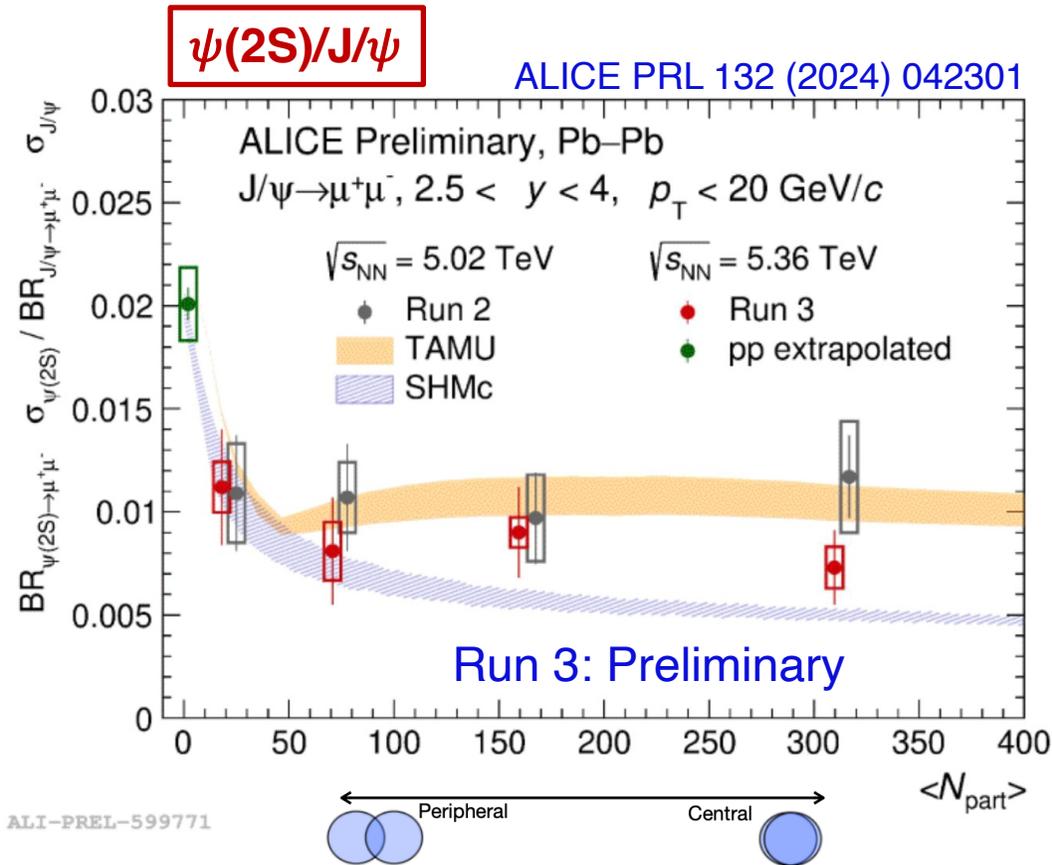
- $\psi(2S)$ more suppressed than J/ψ
- Enhancement at low $p_T \rightarrow$ hint at possible regeneration of $\psi(2S)$

Charmonium in PbPb



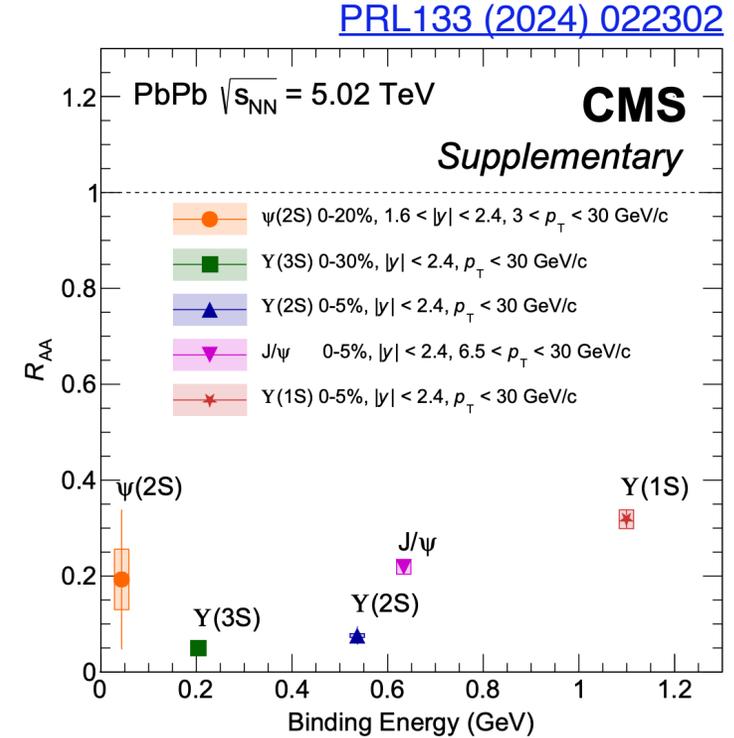
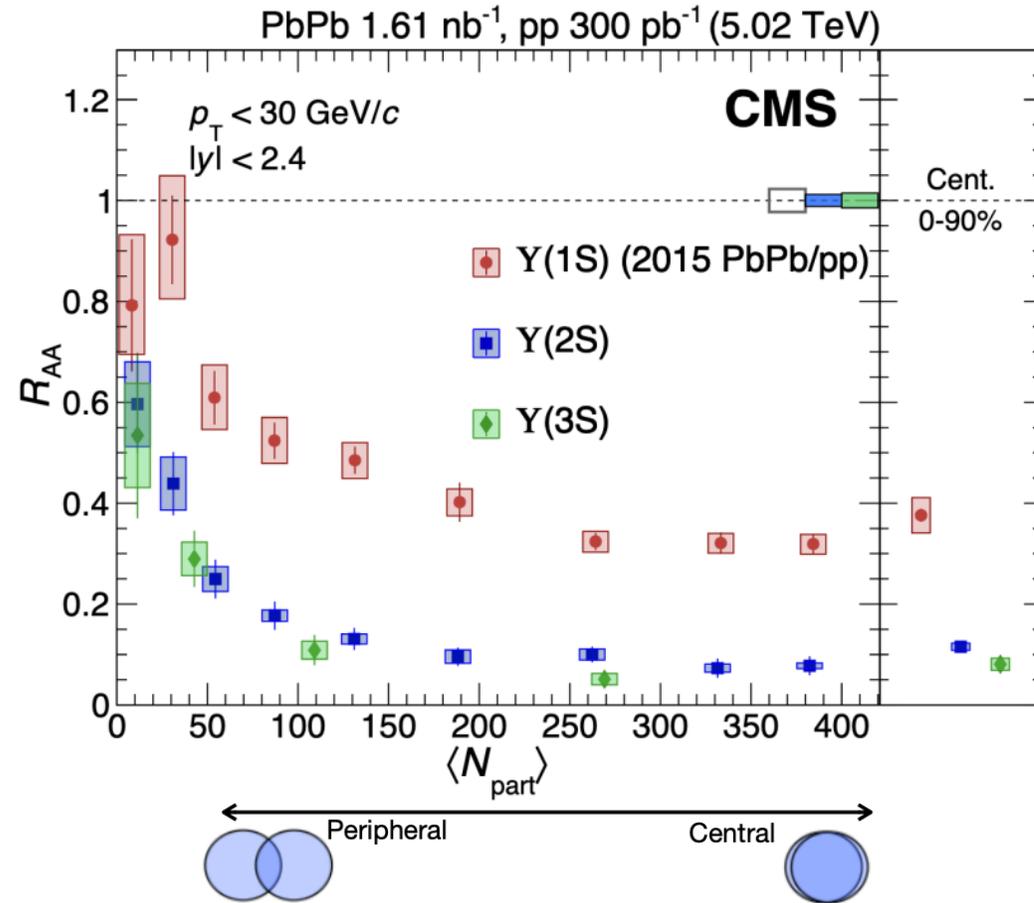
- $\psi(2S)$ more suppressed than J/ ψ
- Enhancement at low $p_T \rightarrow$ hint at possible regeneration of $\psi(2S)$
- Both states well described by TAMU, $\psi(2S)$ underpredicted by SHMc

Charmonium in PbPb



- Run 2: inclusive from ALICE & prompt LHCb (periph.)
 → stronger suppression of $\psi(2S)$ as predicted by regeneration models
- Preliminary ALICE Run 3 data with smaller uncertainties → between both models

Bottomonia in PbPb



- First Y(3S) measurement ($> 5\sigma$) in AA collisions.
- $Y(3S) R_{AA} < Y(2S) R_{AA} < Y(1S) R_{AA} \rightarrow$ sequential suppression of bottomonia
- Important to assess impact of feed-down!

Take-home note: Quarkonia in PbPb

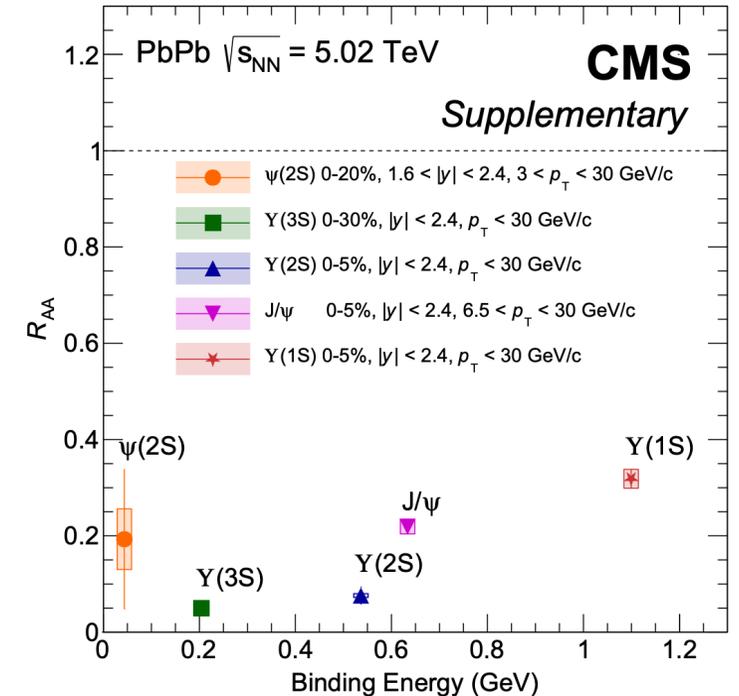
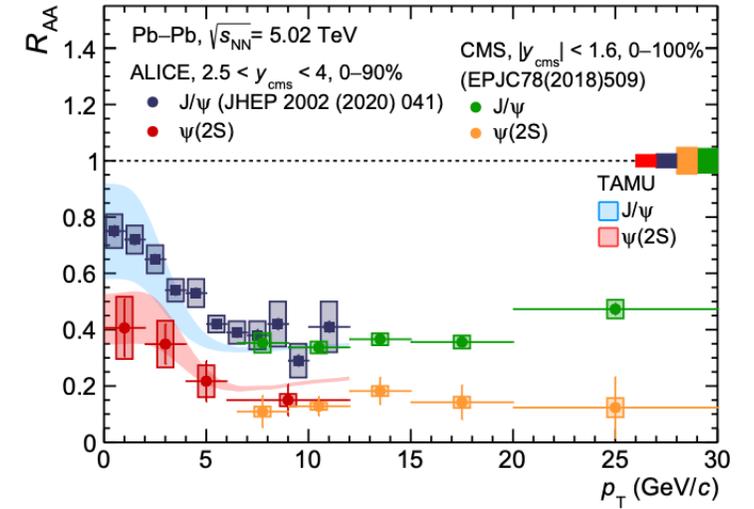
✓ **Results consistent with**

→ dissociation and regeneration picture

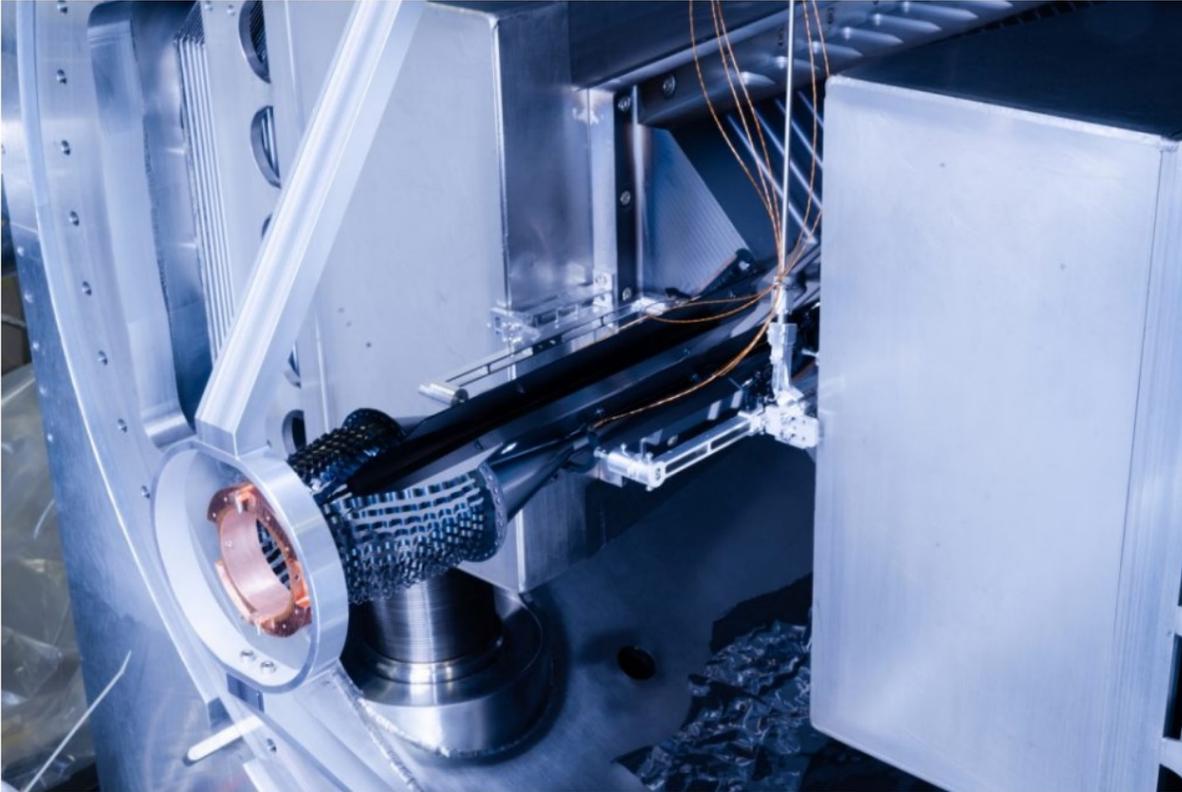
✓ **Sequential suppression of $Q\bar{Q}$ states in PbPb**

- First $Y(3S)$ measurement in AA collisions

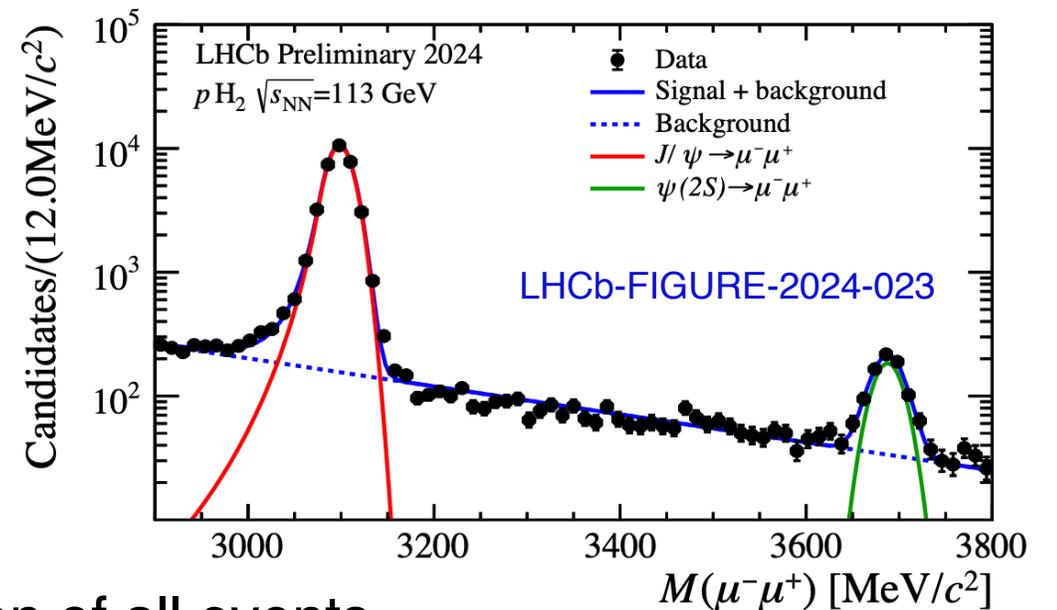
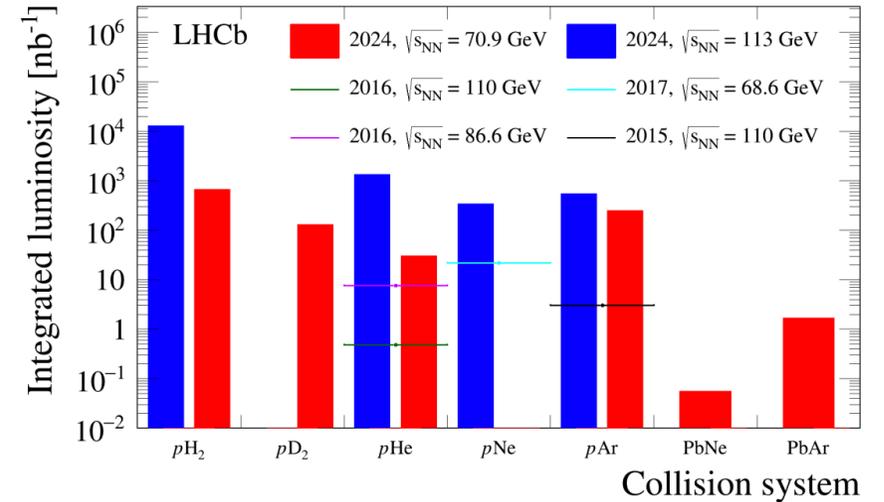
✓ **Important to disentangle feed-down contribution**



SMOG2 in LHCb:



- Concurrent collider and fixed-target data
→ dedicated gas cell and real-time reconstruction of all events
- Early measurements of charmonium production in progress



Summary:

- **Clear qualitative signatures**

- Regeneration for charmonium

- Suppression hierarchy for bottomonium vector states

- **Quarkonia suppression in pp and pPb**

- Presence of final state effects

- **Run 3 collider data, SMOG2**

- New data & improved precision in near future

