Recent Quarkonia results at LHC and Future Prospects at EIC

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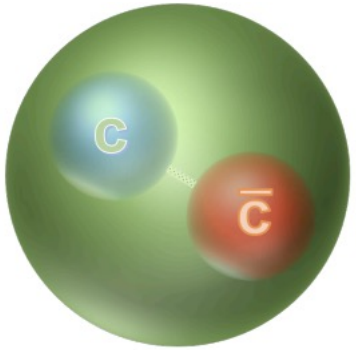
Why quarkonia are interesting?

Quarkonia are made of charm and bottom quarks (m_c, m_b >> Λ_{QCD}):

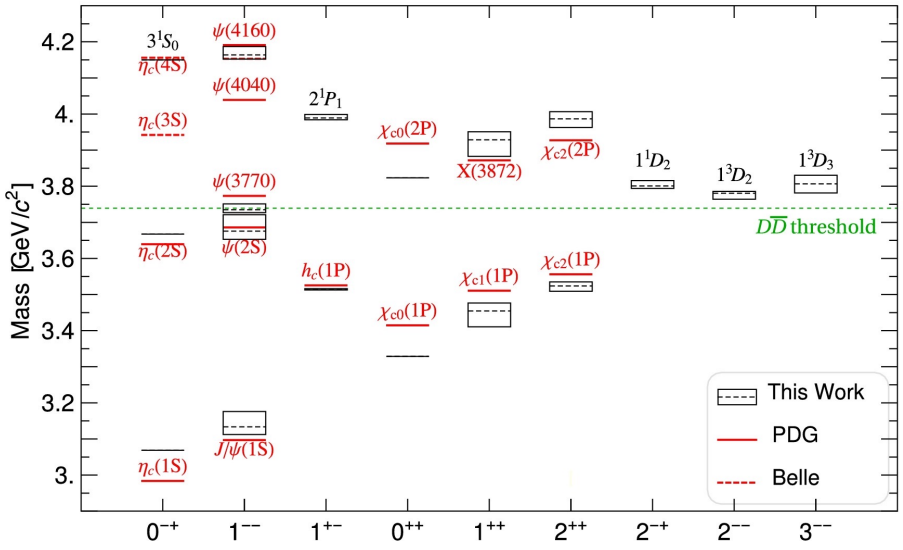
- Produced in initial hard partonic scattering

  → Experience full evolution of heavy-ion collision (HI)

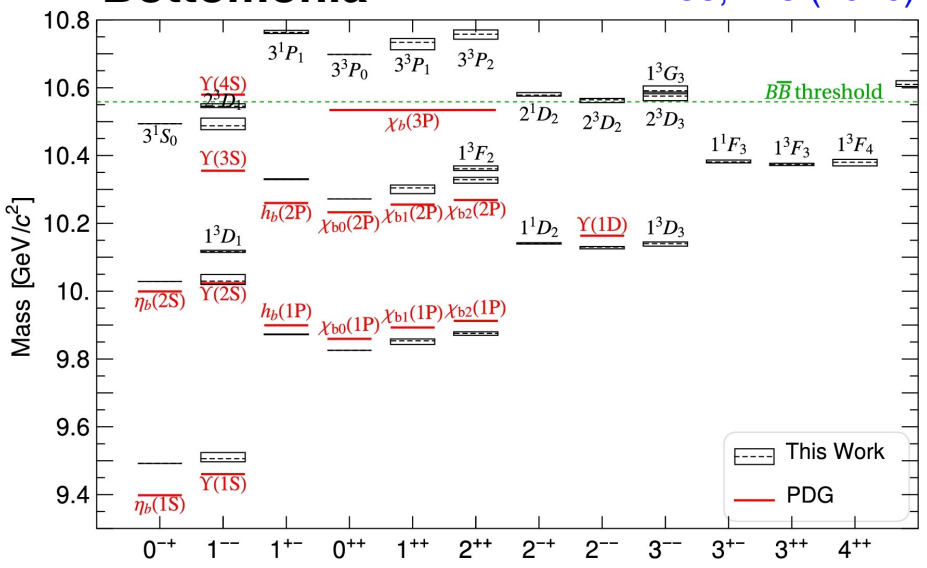
- Powerful probe to study properties of **Quark-gluon plasma (QGP)**
- Characterized by different masses and binding energies



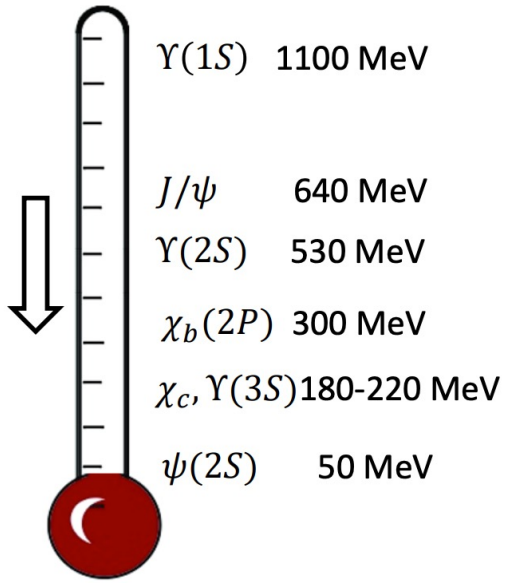
Charmonia



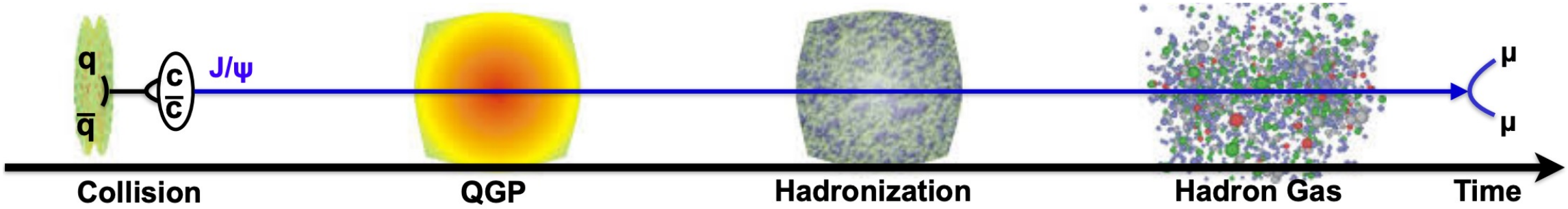
Bottomonia PLB 758, 118 (2016)



Agnes Mocsy's thermometer

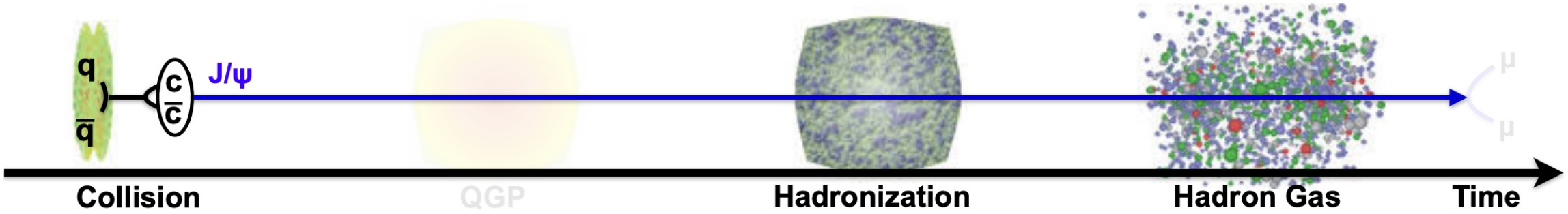


Quarkonia in HI collisions

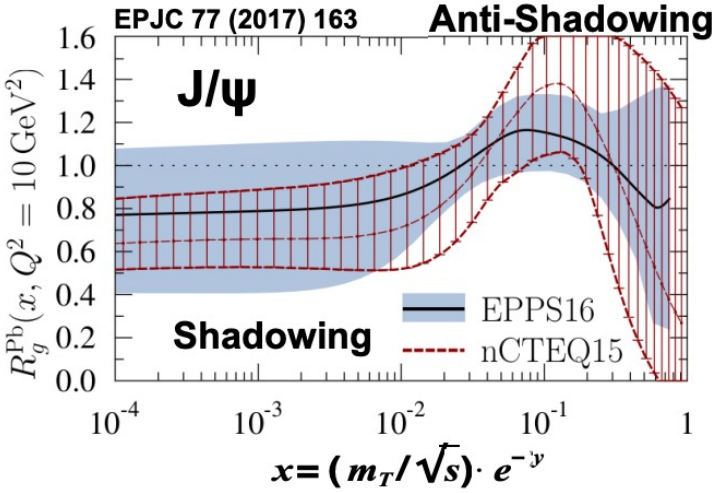


Quarkonia are produced in the early stages of the collision

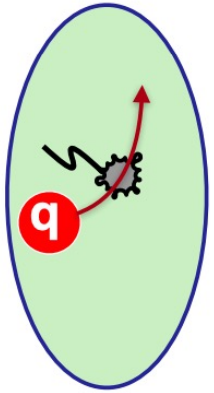
Cold nuclear matter effects



nPDF modification

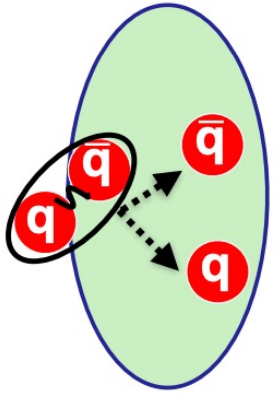


Coherent energy loss



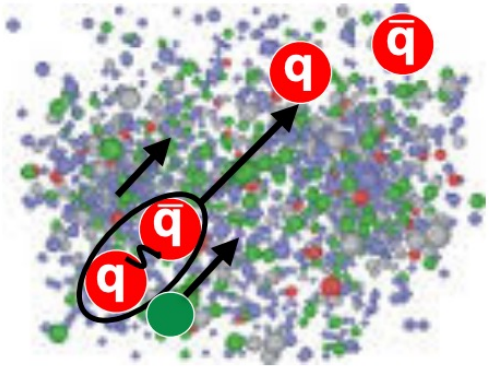
Nuclear medium

Nuclear absorption



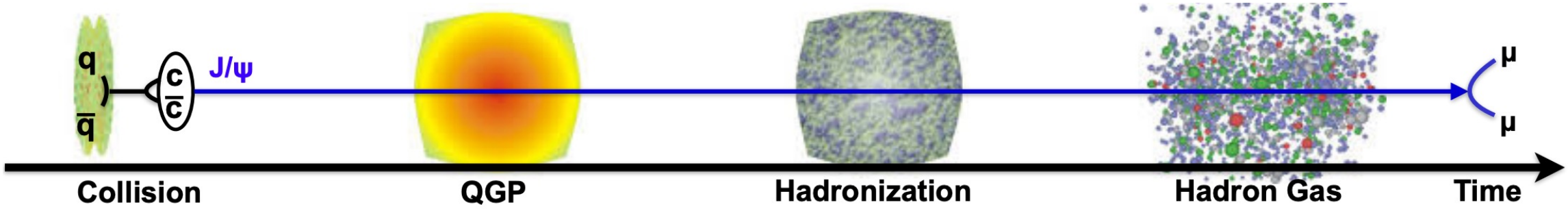
Nuclear medium

Co-mover breakup

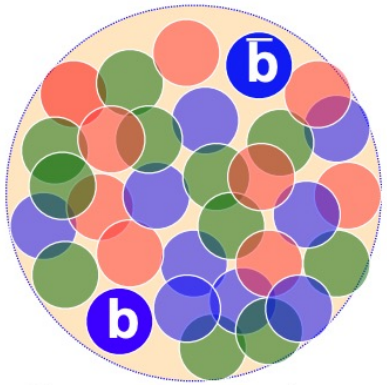


Hadronic matter

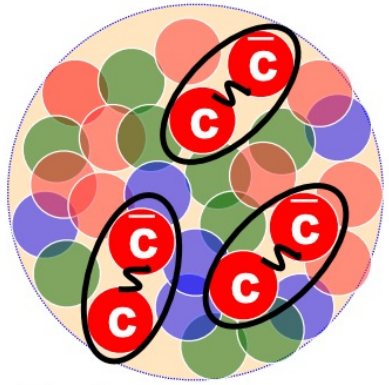
QGP medium effects



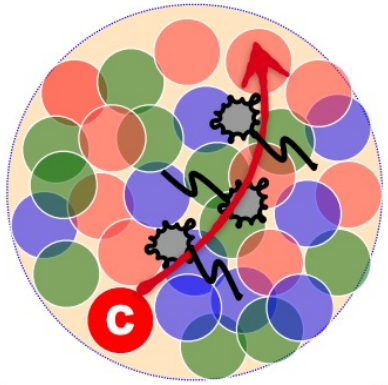
QGP is expected to modify the quarkonium production



Suppression
Medium-induced dissociation

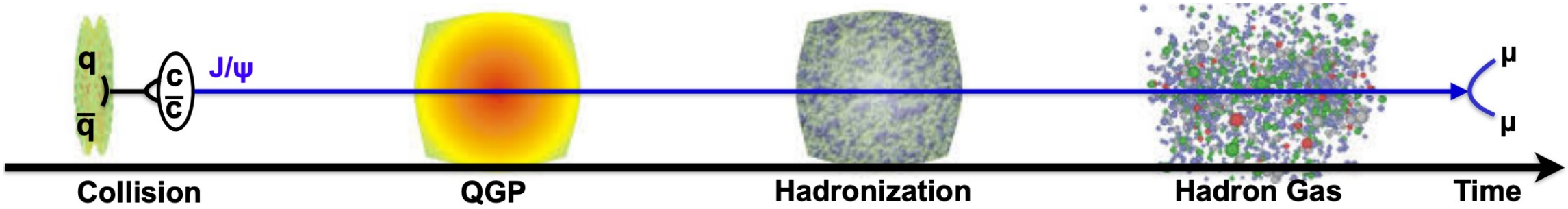


+Enhancement
Regeneration at high energy density



+Parton energy loss
at high p_T

Outline



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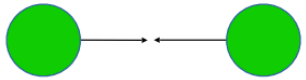
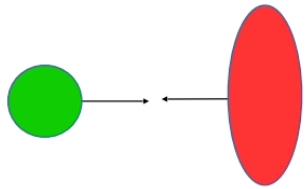


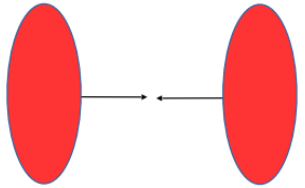
Production mechanism:

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



Cold nuclear effects:

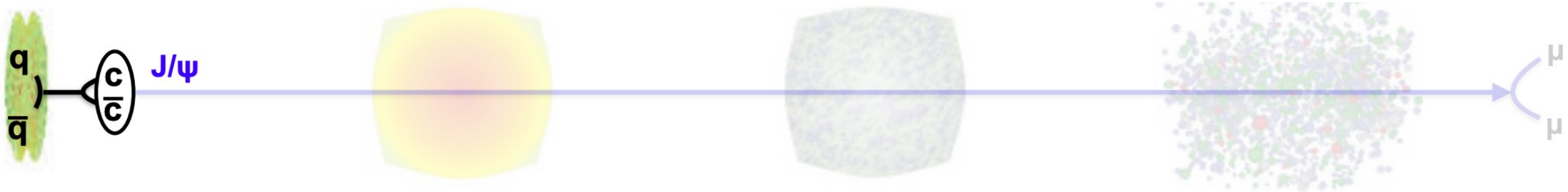
- $Q\bar{Q}$ results in pA

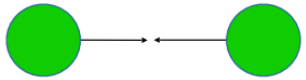


QGP effects:

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

Quarkonia production in pp





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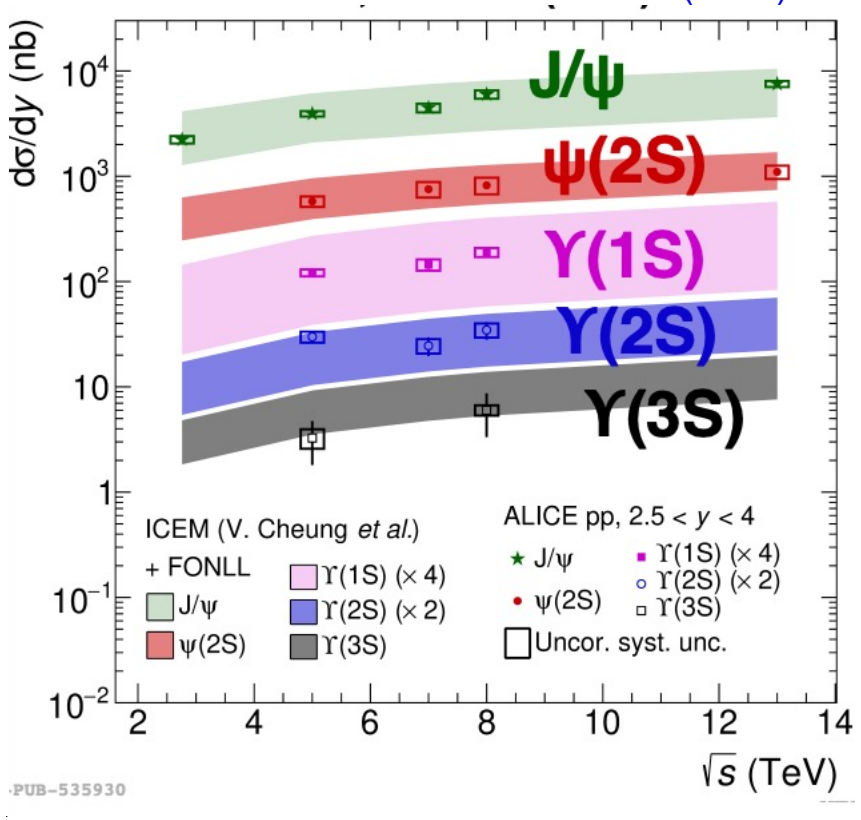
Quarkonium production in pp

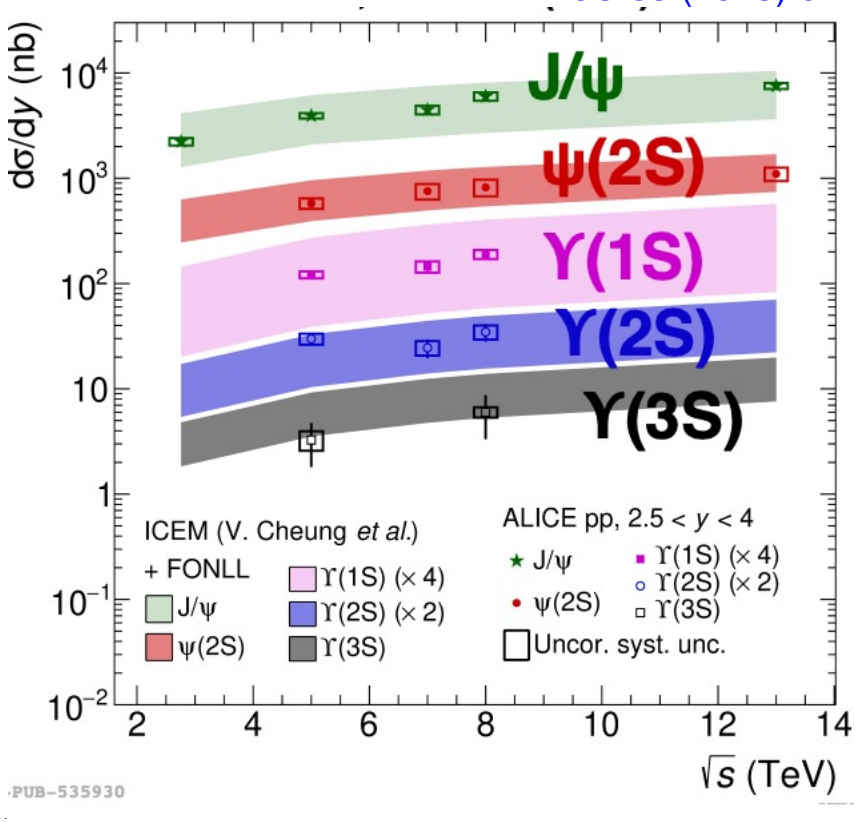
EPJC 83 (2023) 61



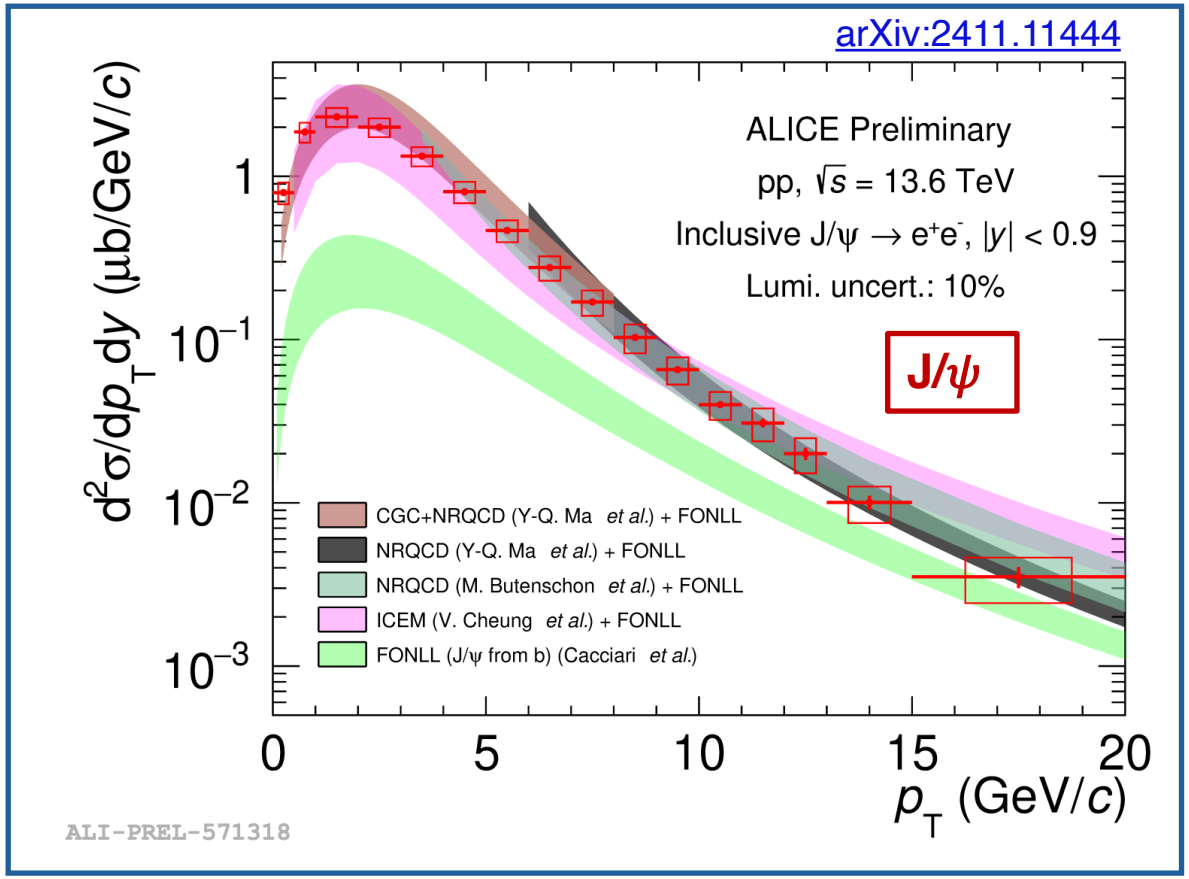
- Precise pp data measured over a wide range up to 13.6 TeV
- ICEM with FNOLL can describe the data but model uncertainties larger than data

Quarkonium production in pp

EPJC 83 (2023) 61

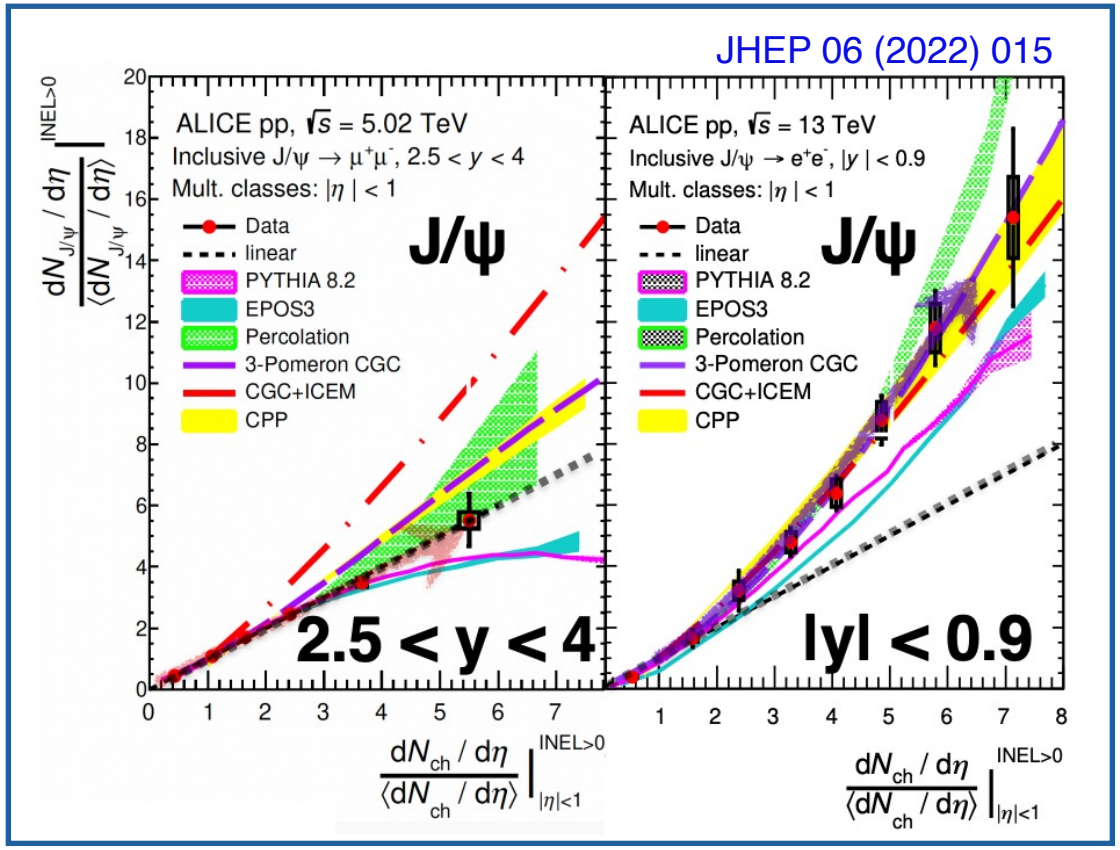


arXiv:2411.11444



- Both NRQCD and ICEM with FNOLL can describe the data
- Latest results will help to further constrain quarkonium production models

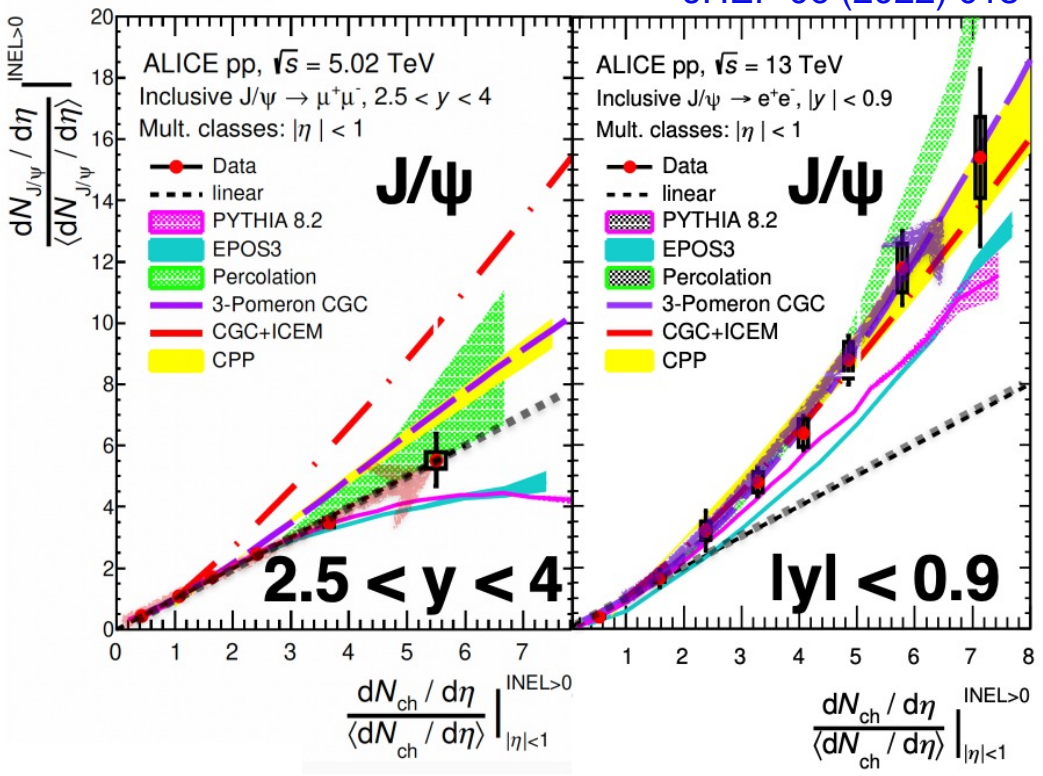
Multiplicity dependence of quarkonia production in pp



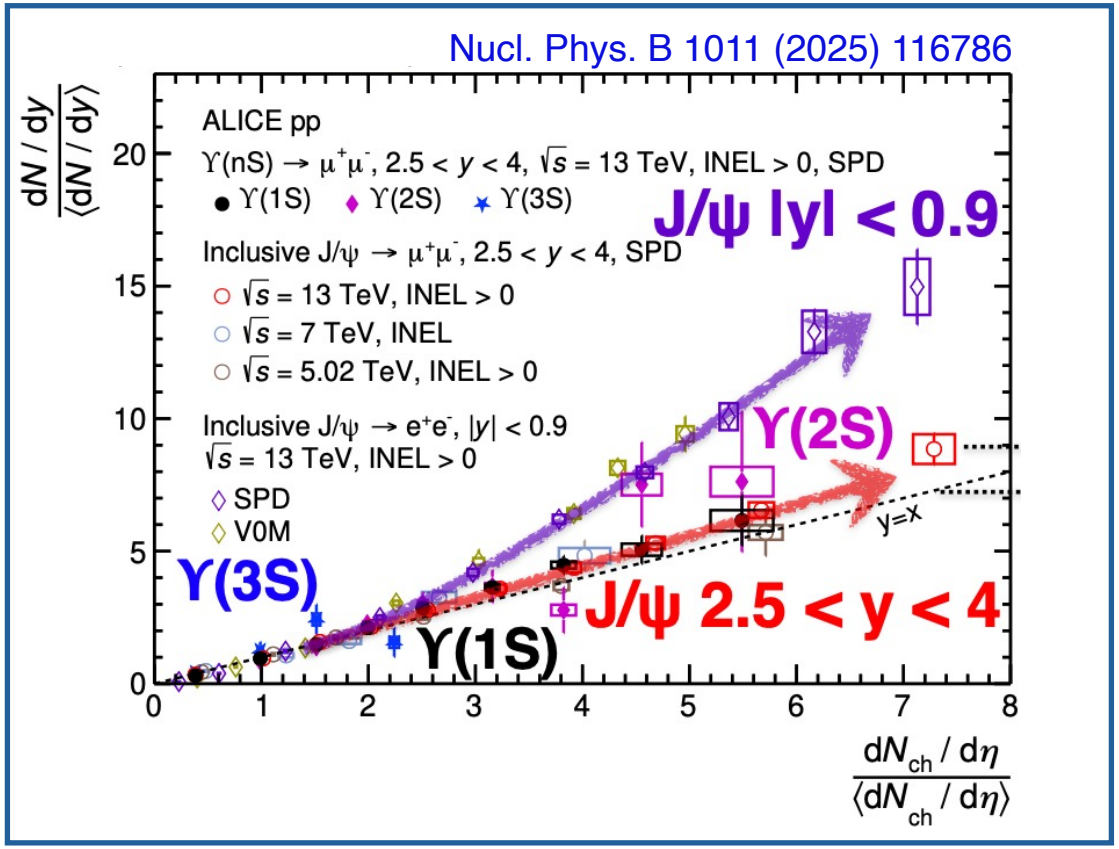
- Forward-rapidity: QQ yields consistent with linear growth
- Mid-rapidity: J/ψ yield grows faster than linear

Multiplicity dependence of quarkonia production in pp

JHEP 06 (2022) 015



Nucl. Phys. B 1011 (2025) 116786



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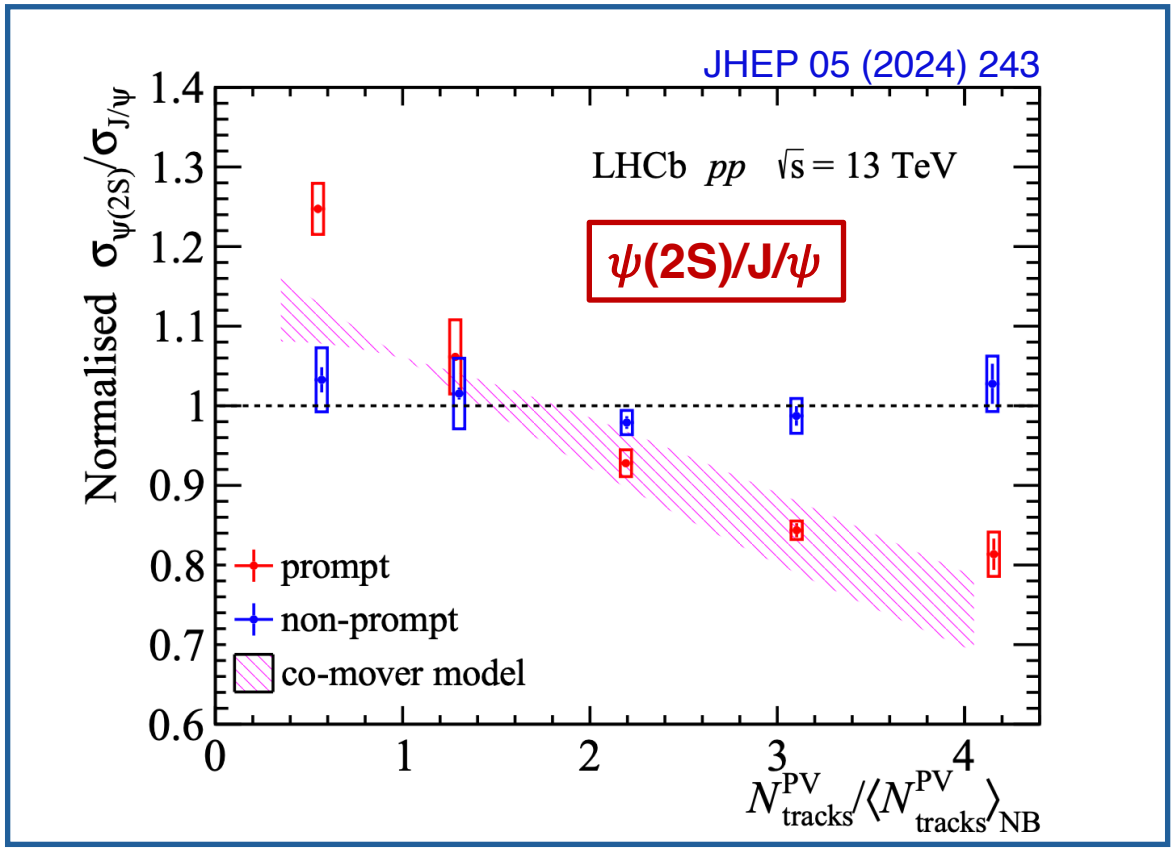
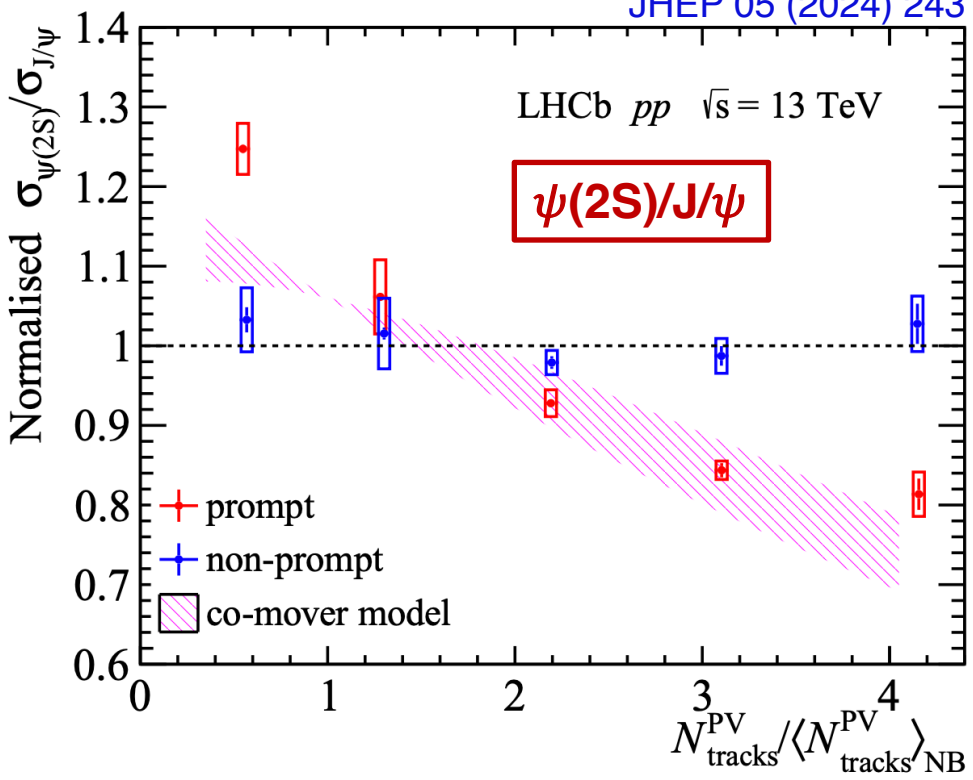


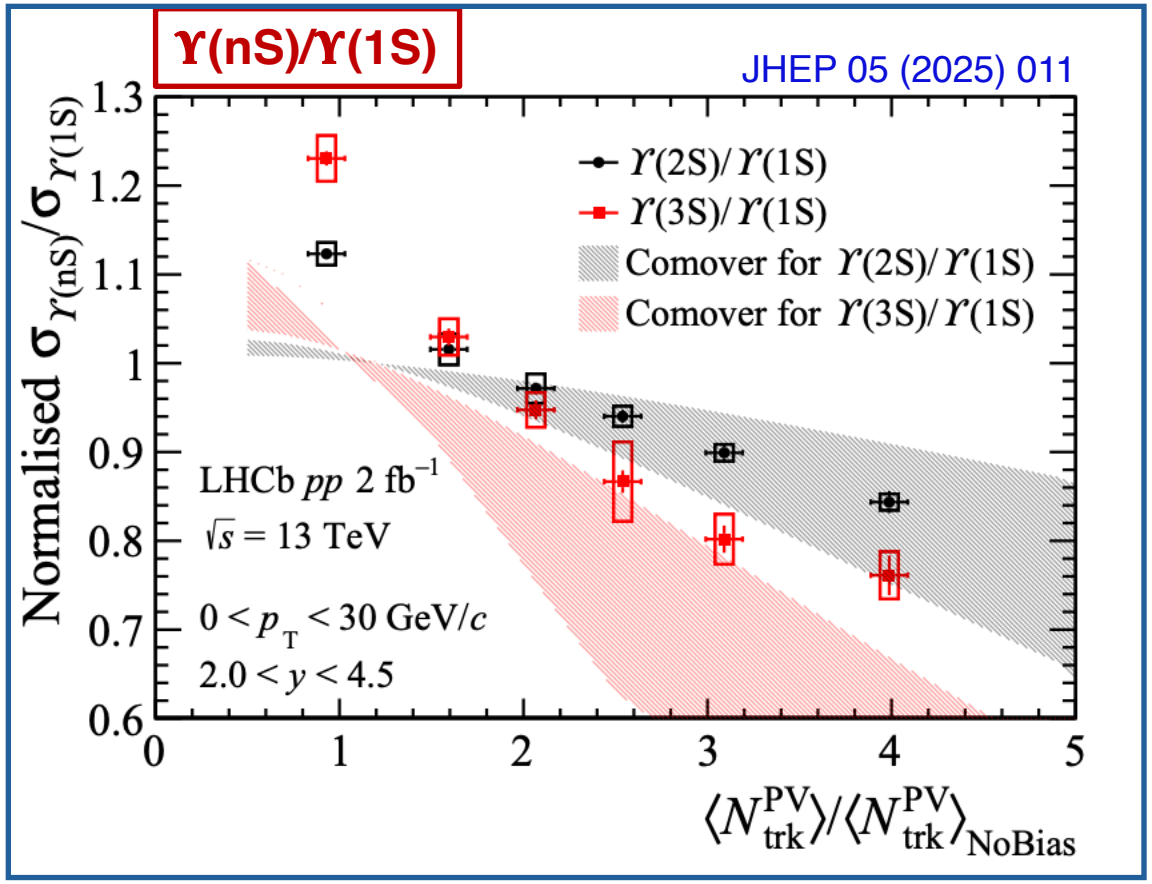
- Charmonia from b-hadron decays shows no multiplicity dependence
- Prompt charmonia measurements:

  → decrease of ratio with charged particle multiplicity (co-mover scenario)

Multiplicity dependence of quarkonia production in pp

JHEP 05 (2024) 243





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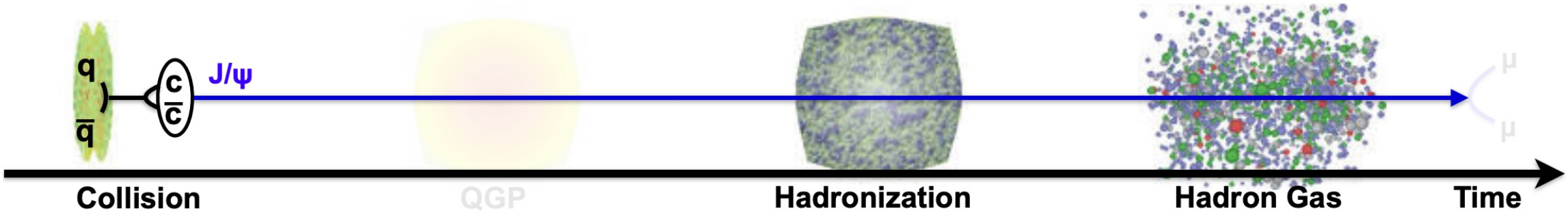
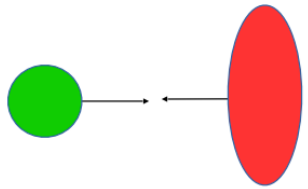
Quarkonia production in pA



nuclear modification factor

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



Cold nuclear effects:

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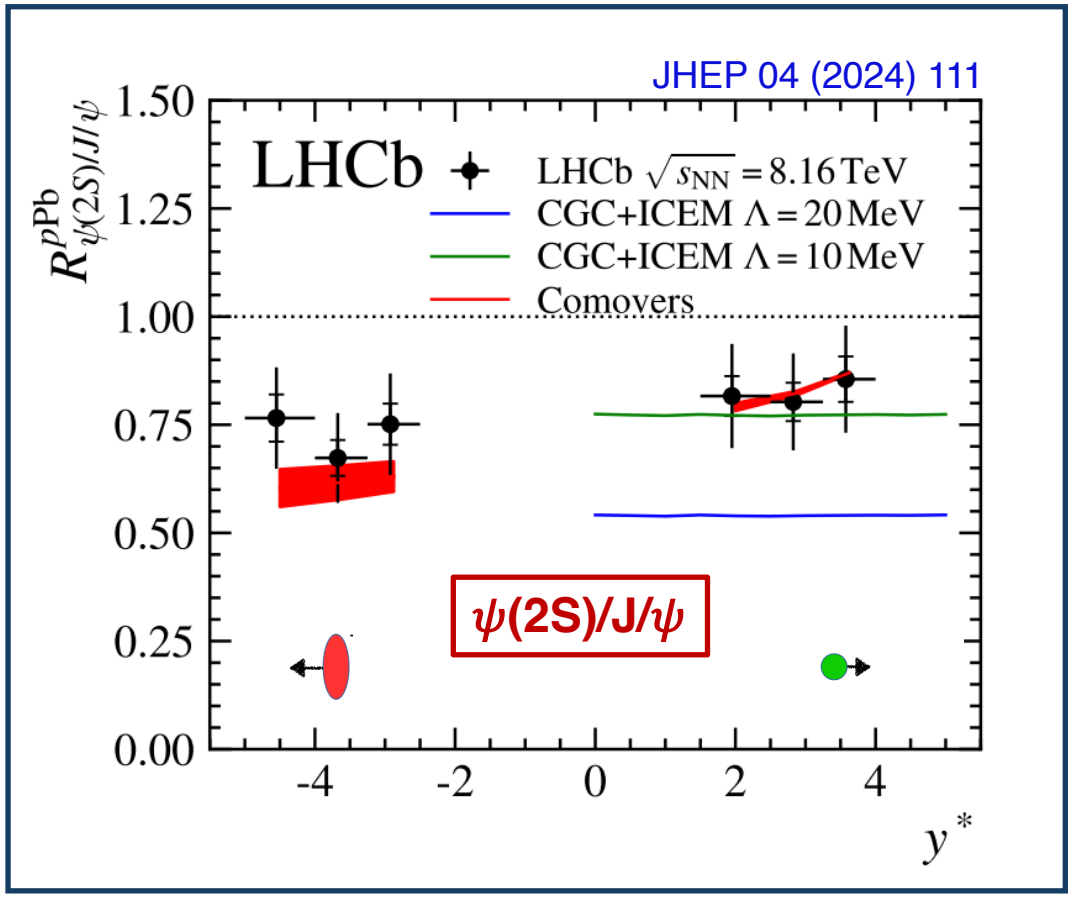
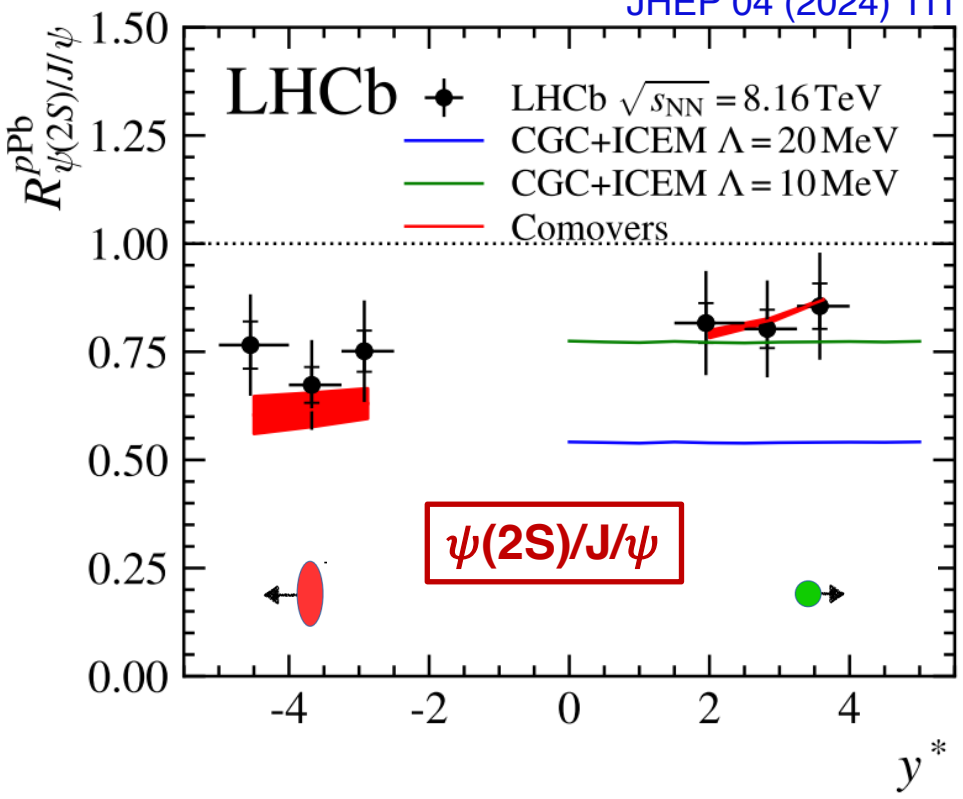
Quarkonia production in pPb



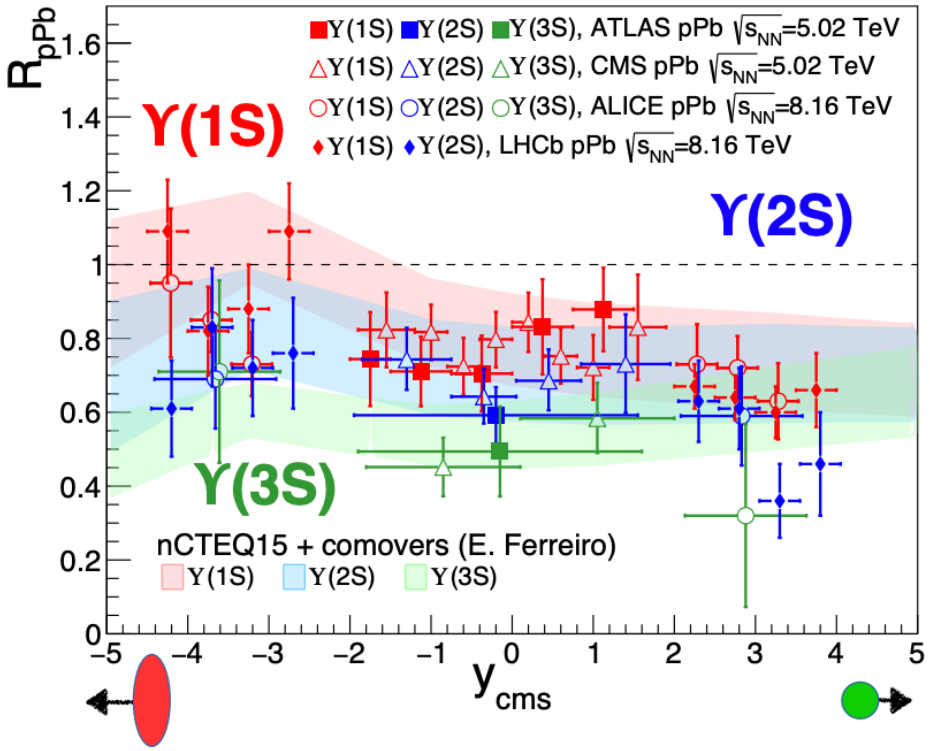
- ψ(2S) R_{pPb} < J/ψ R_{pPb} in pPb → trend described well by co-mover model

Quarkonia production in pPb

JHEP 04 (2024) 111

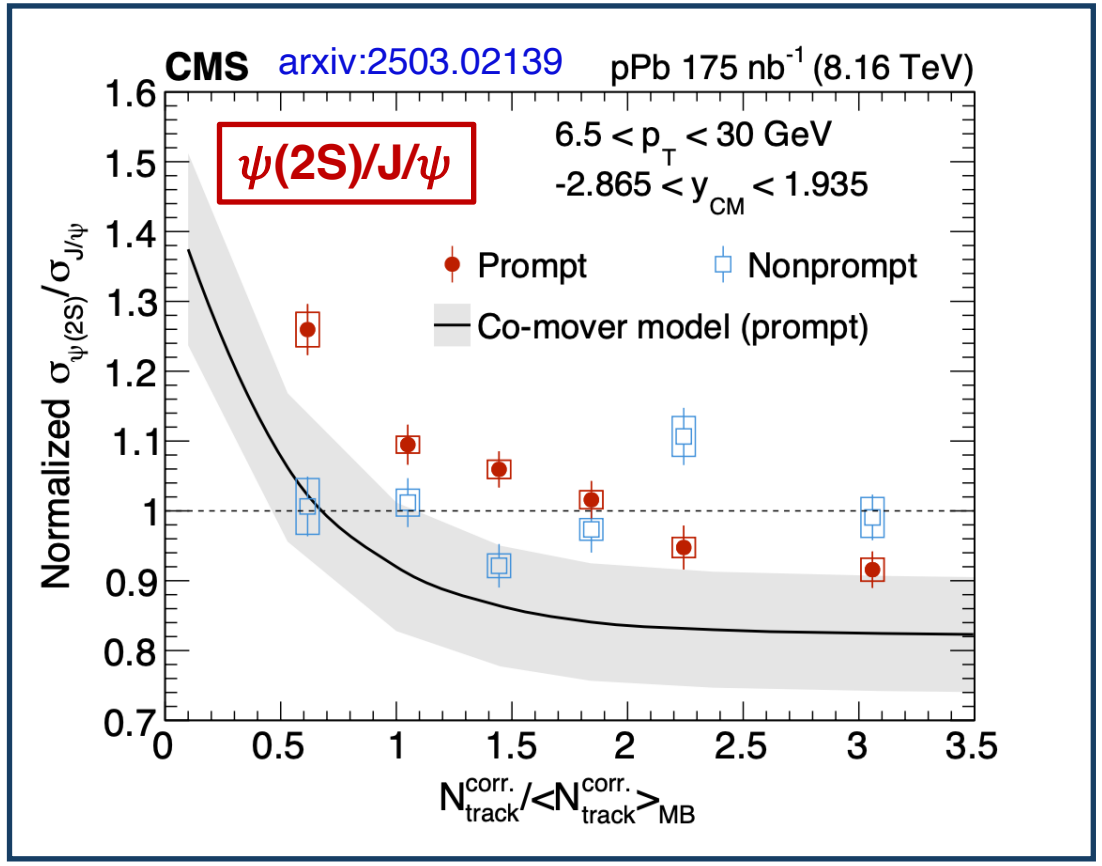


LHCb, JHEP 11 (2018) 194
ATLAS, EPJC 78 (2018) 3, 171
ALICE, PLB 806 (2020) 135486



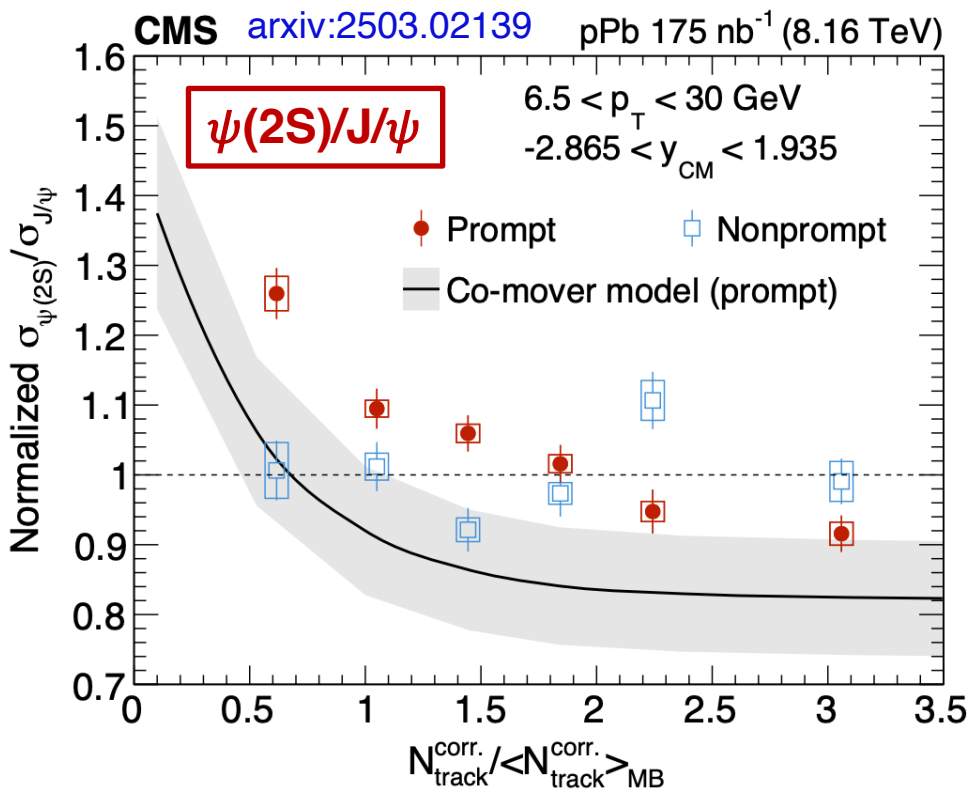
- ψ(2S) R_{pPb} < J/ψ R_{pPb} in pPb → trend described well by co-mover model
- Υ(1S) > Υ(2S) > Υ(3S) → Co-mover + nPDF model predicts the suppression trend

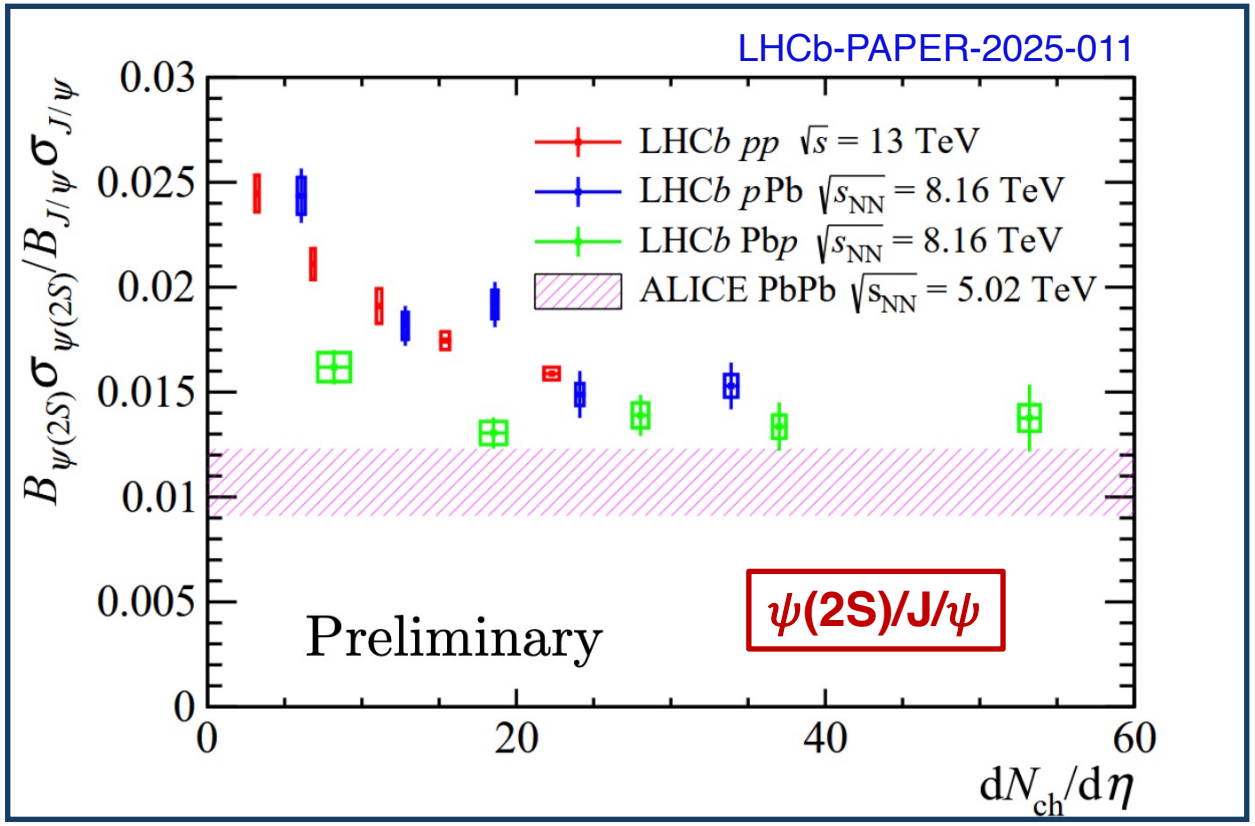
Multiplicity dependence of quarkonia production in pPb



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

Multiplicity dependence of quarkonia production in pPb





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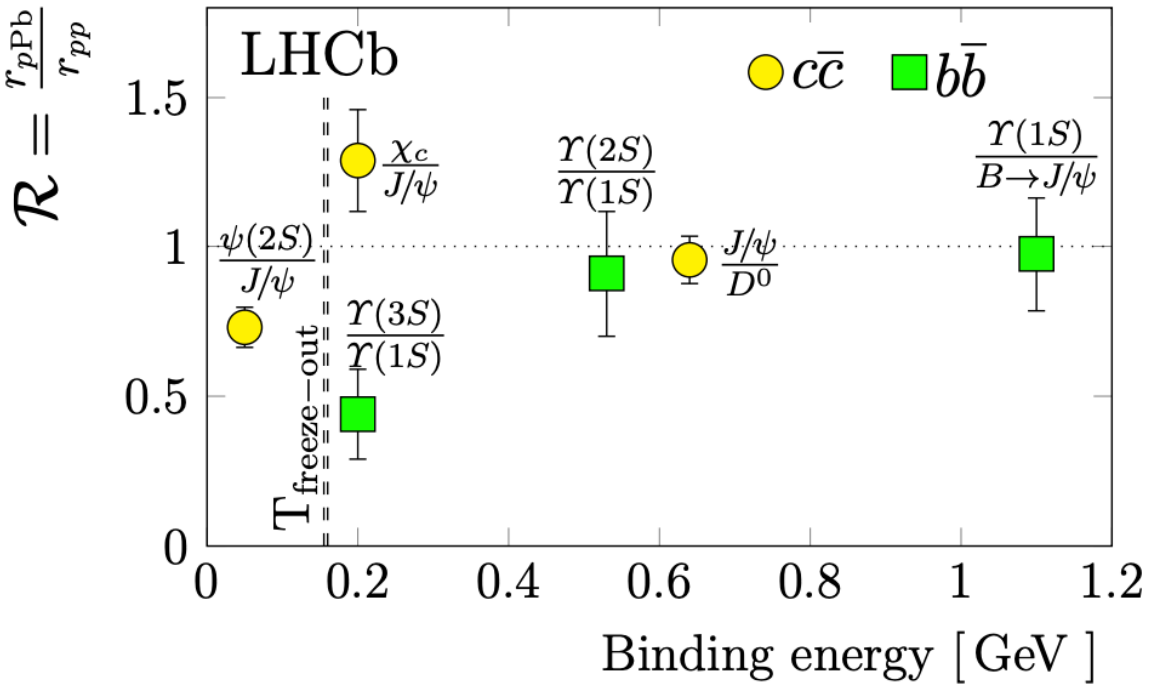
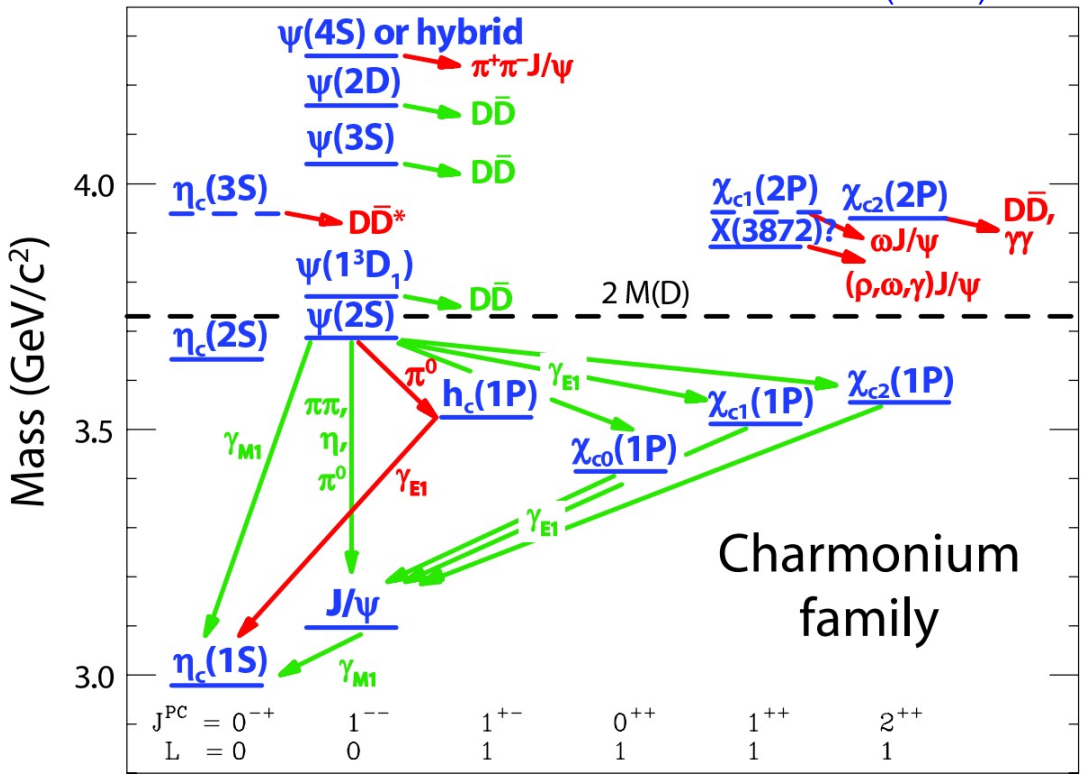
χ_c production in pPb

PRL132 (2024) 102302



RMP 80 (2008) 1161



- Fraction of J/ψ production from higher charmonium states (feed-down)
- R(Y(3S) / Y(1S)) < R(χ_c / J/ψ) ~ 1 despite χ_c ~ Y(3S) binding energy:

  → Impact of QQ feed-down? or mass-dependent effects? or P vs S-wave?

χ_c production in pPb

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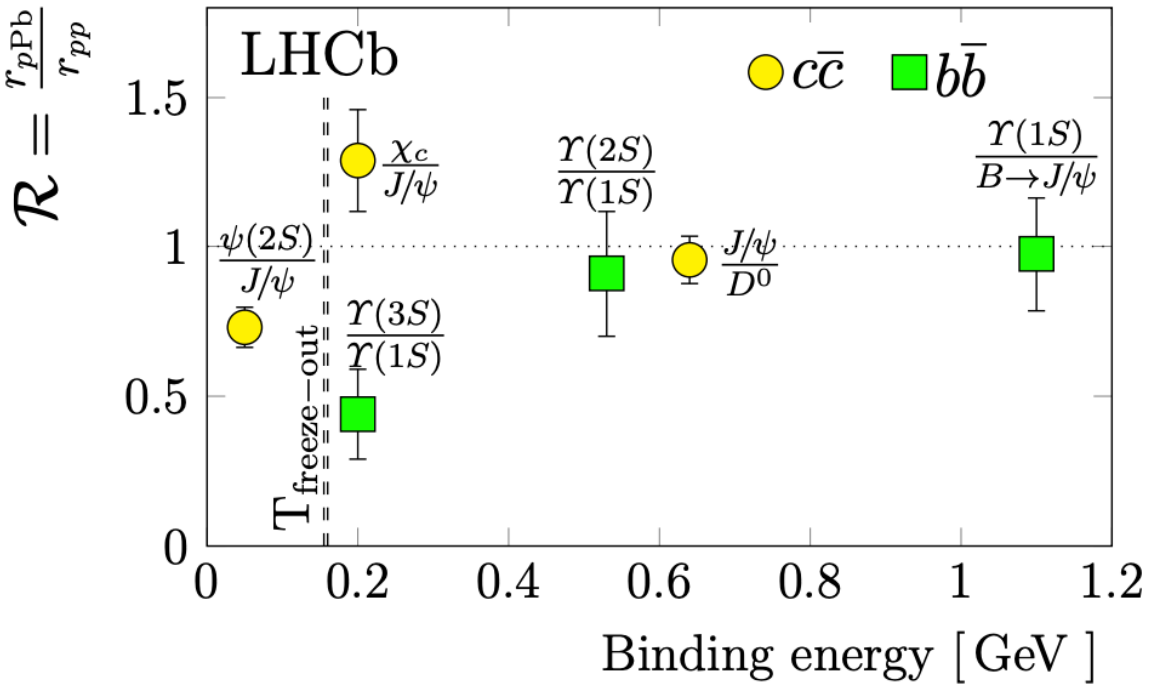
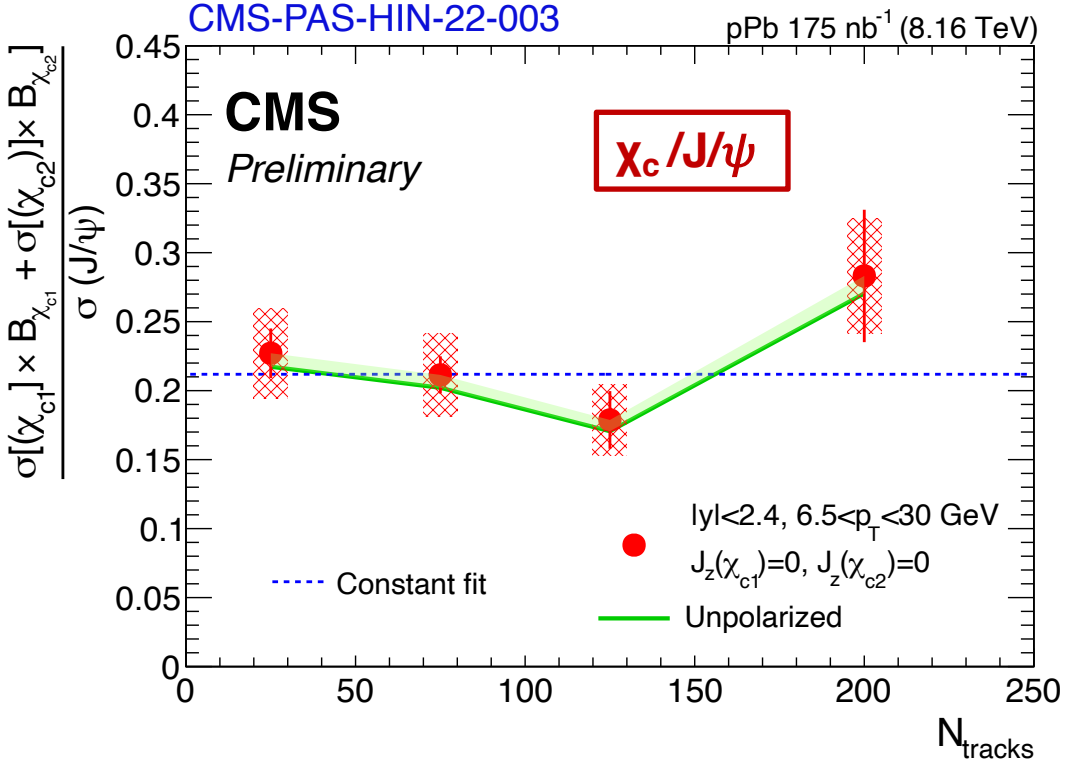


CMS-PAS-HIN-22-003



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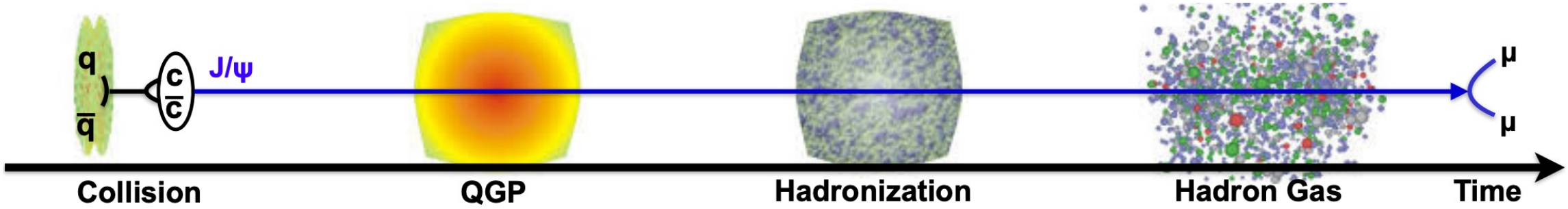
  → Impact of QQ feed-down? or mass-dependent effects? or P vs S-wave?

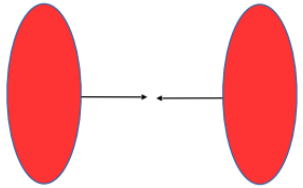
- No multiplicity dependence observed at high p_T, Co-mover picture doesn't hold?

Quarkonia production in PbPb



nuclear modification factor

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



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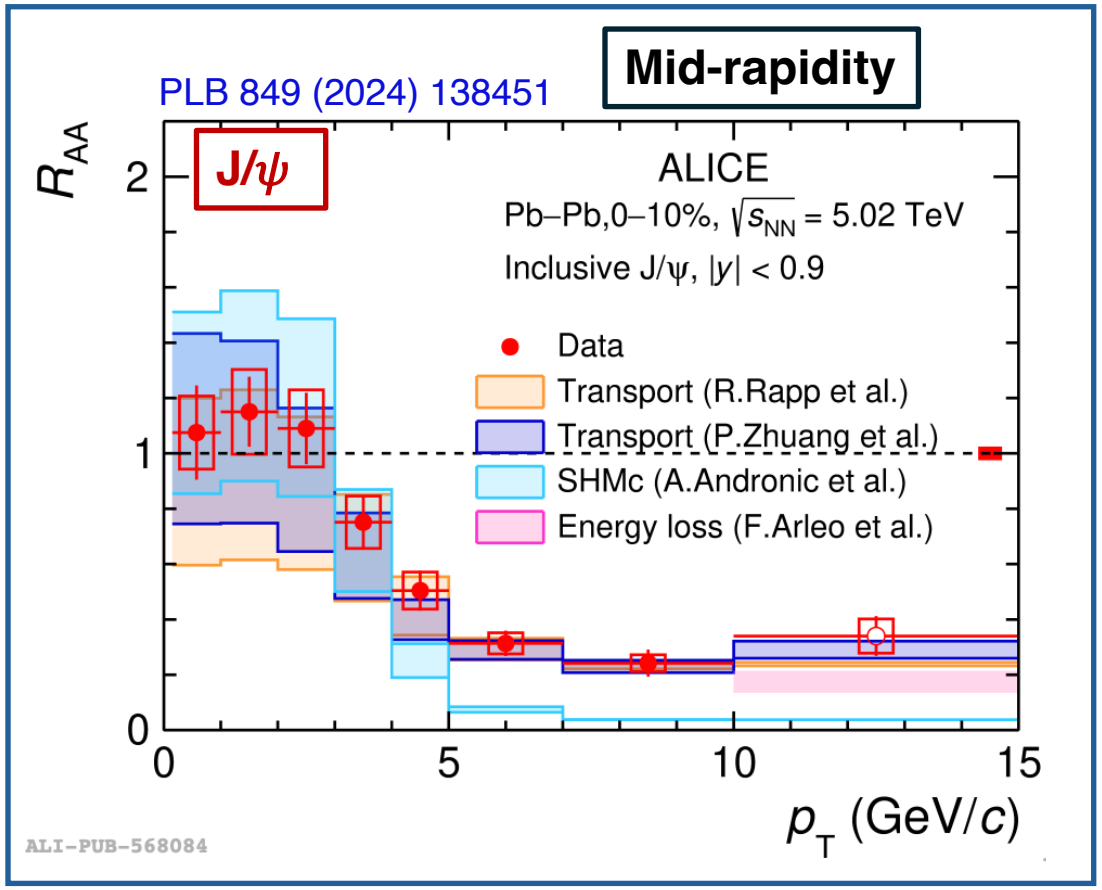
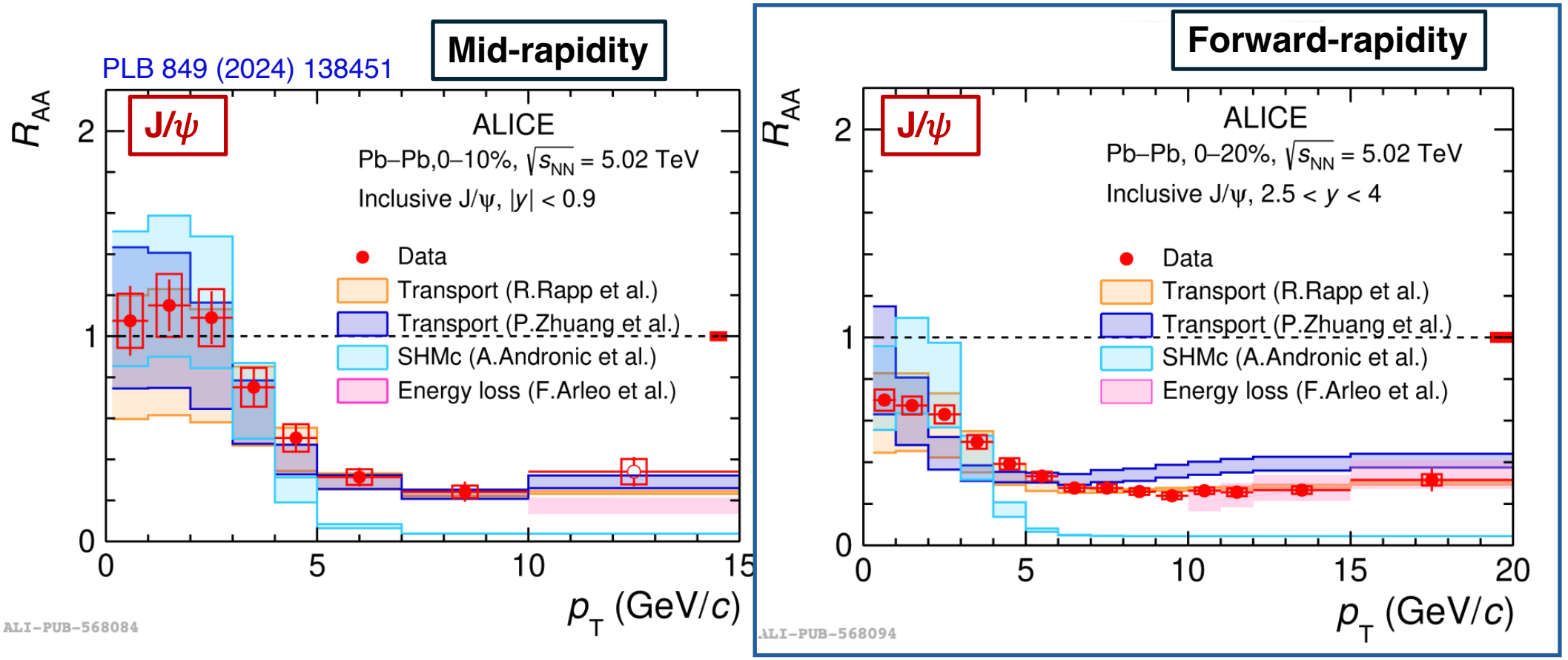
- $Q\bar{Q}$ results in AA

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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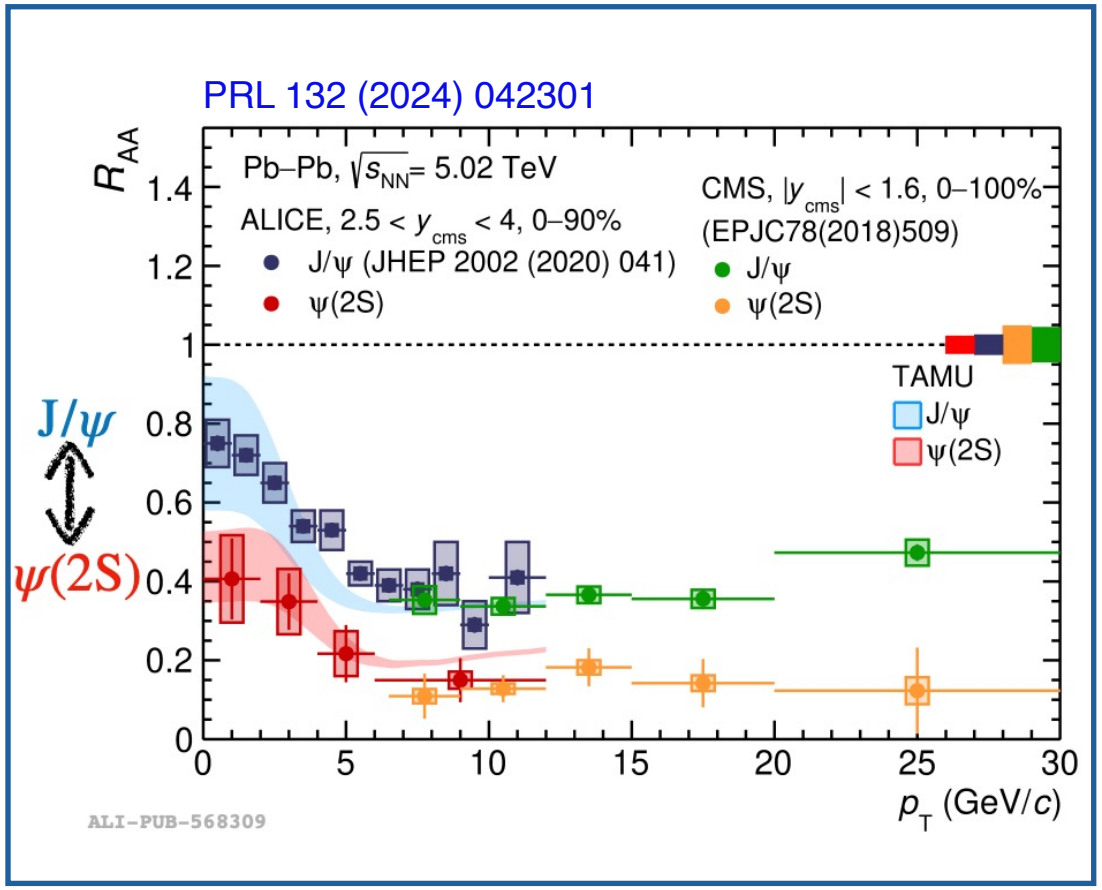
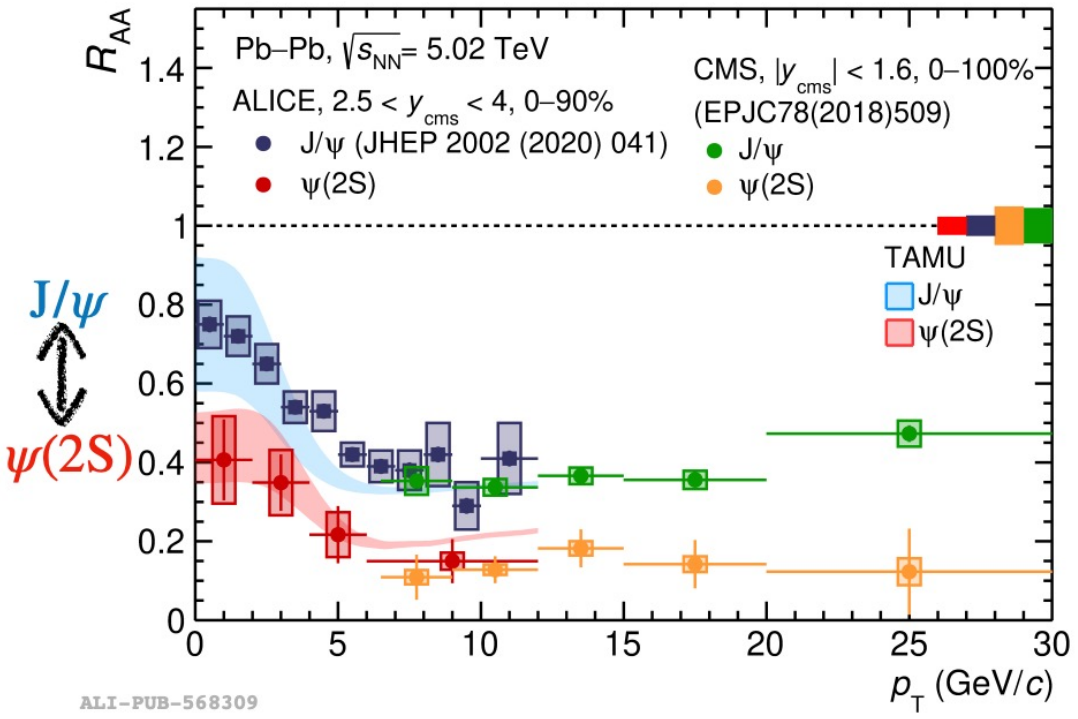
Charmonium in PbPb

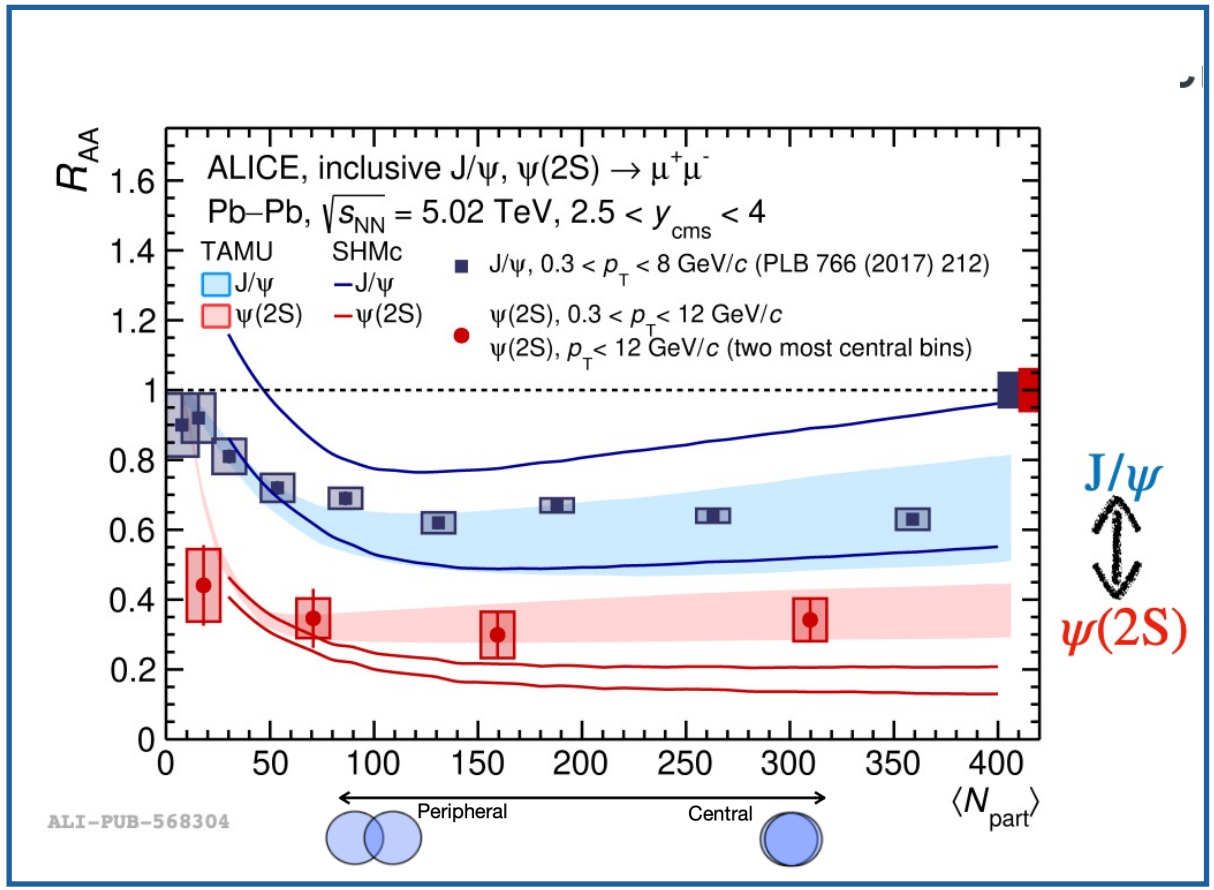


- ψ(2S) more suppressed than J/ ψ
- Enhancement at low p_T → hint at possible regeneration of ψ(2S)

Charmonium in PbPb

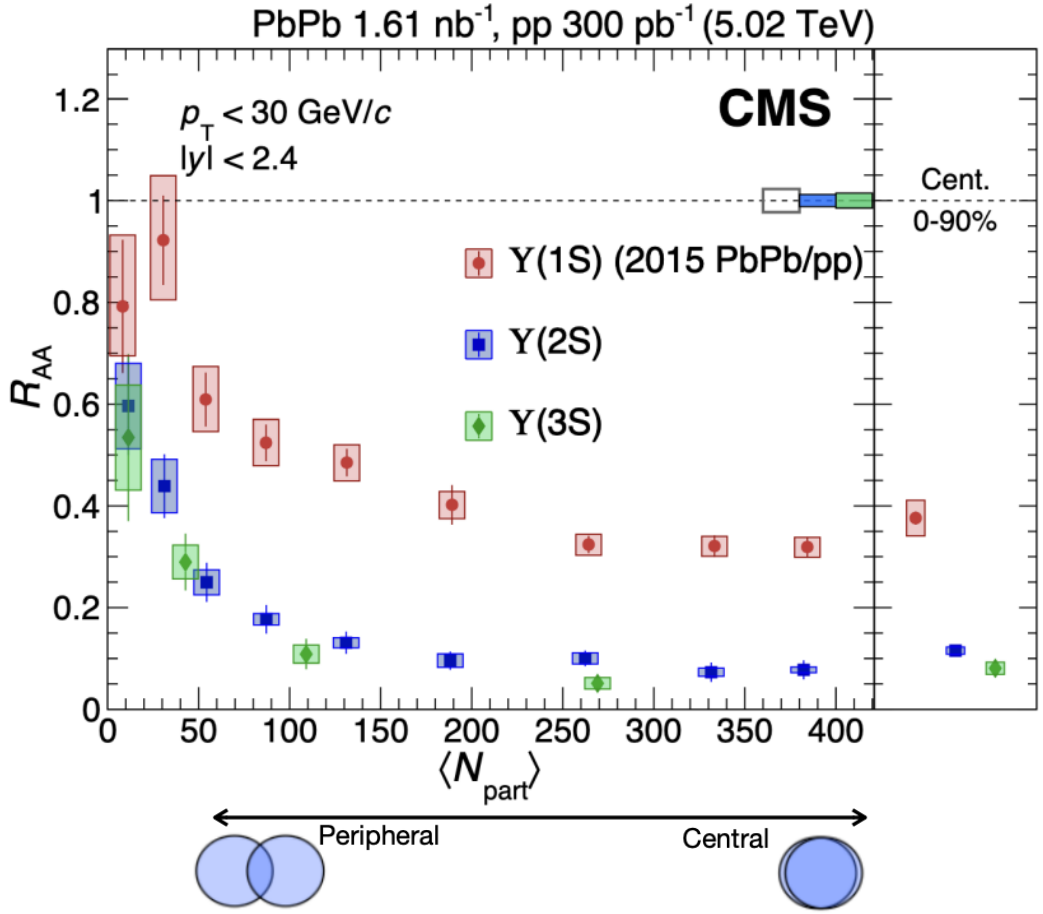
PRL 132 (2024) 042301



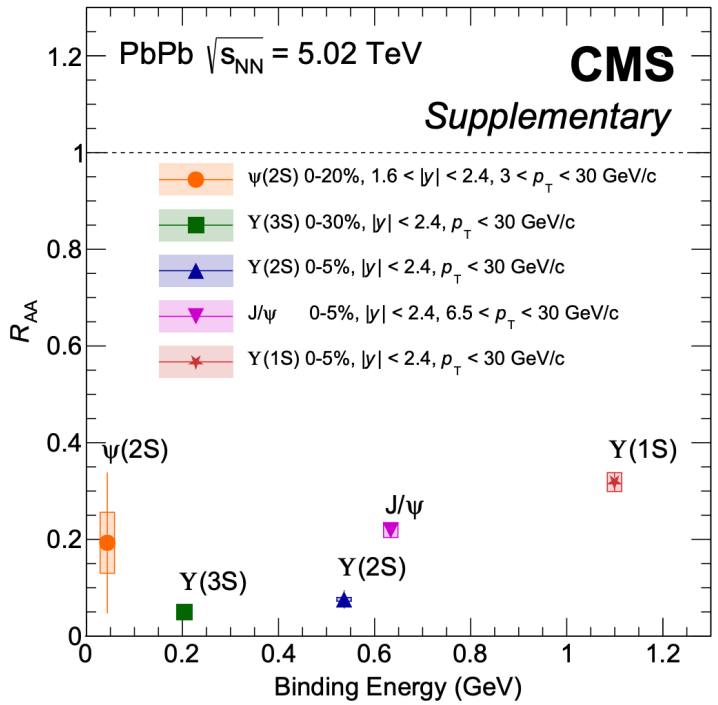


- ψ(2S) more suppressed than J/ψ
- Enhancement at low p_T → hint at possible regeneration of ψ(2S)
- Both states well described by TAMU, ψ(2S) underpredicted by SHMc

Bottomonia in PbPb

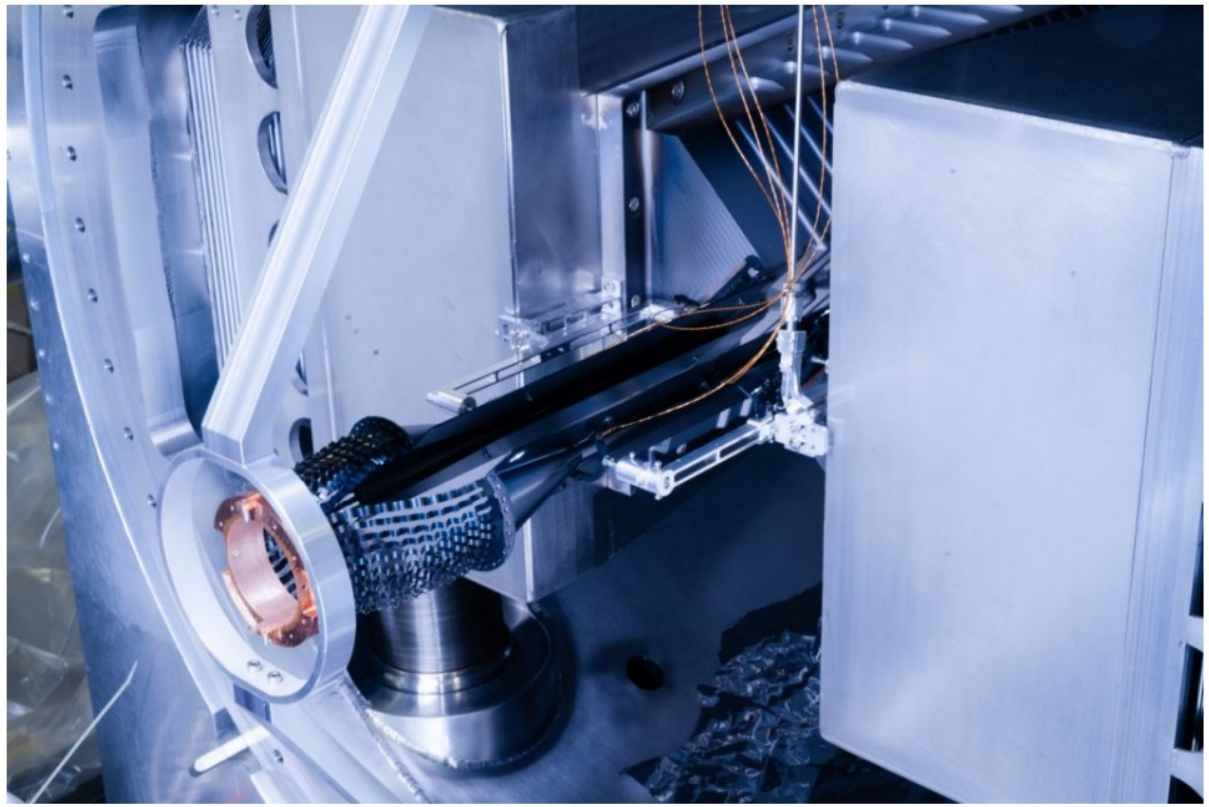


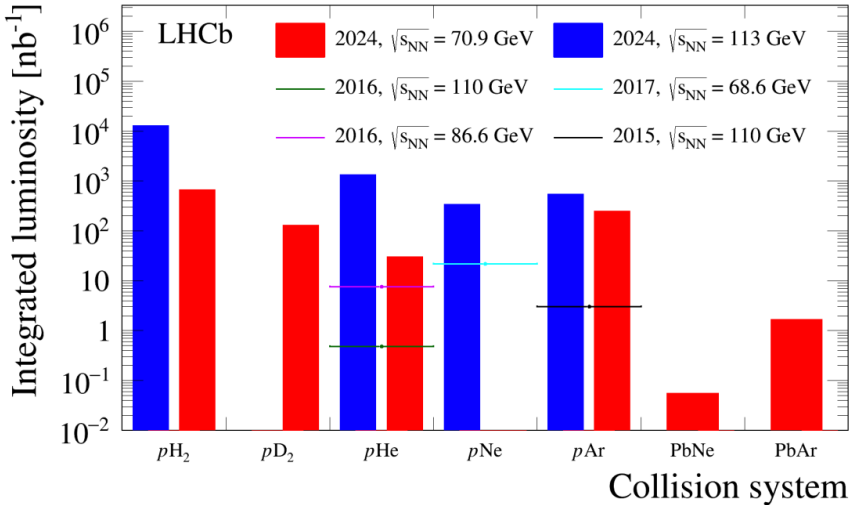
PRL133 (2024) 022302

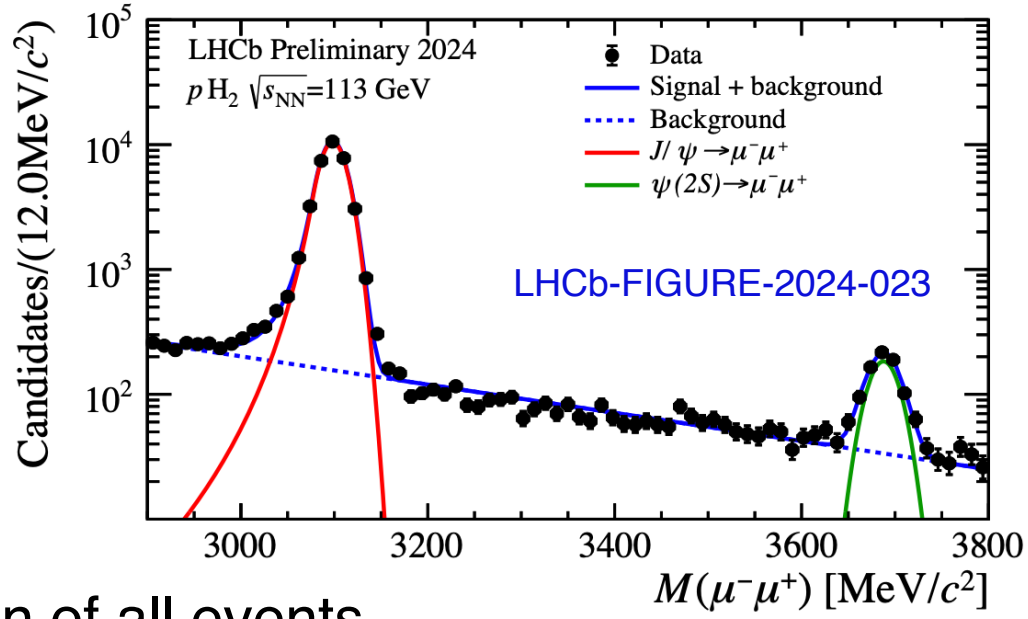


- First Υ(3S) measurement (> 5σ) in AA collisions.
- Υ(3S) R_{AA} < Υ(2S) R_{AA} < Υ(1S) R_{AA} → sequential suppression of bottomonia
- Important to assess impact of feed-down!

SMOG2 in LHCb:





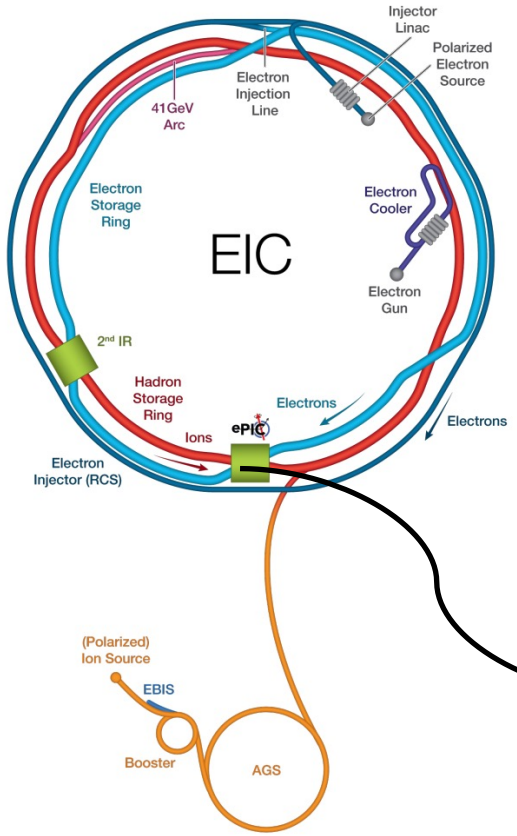


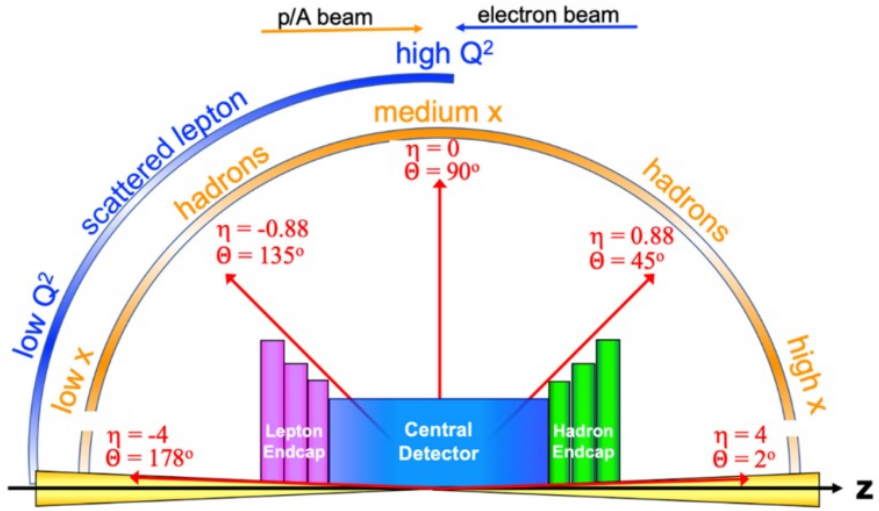
- Concurrent collider and fixed-target data
  → dedicated gas cell and real-time reconstruction of all events
- Early measurements of charmonium production in progress

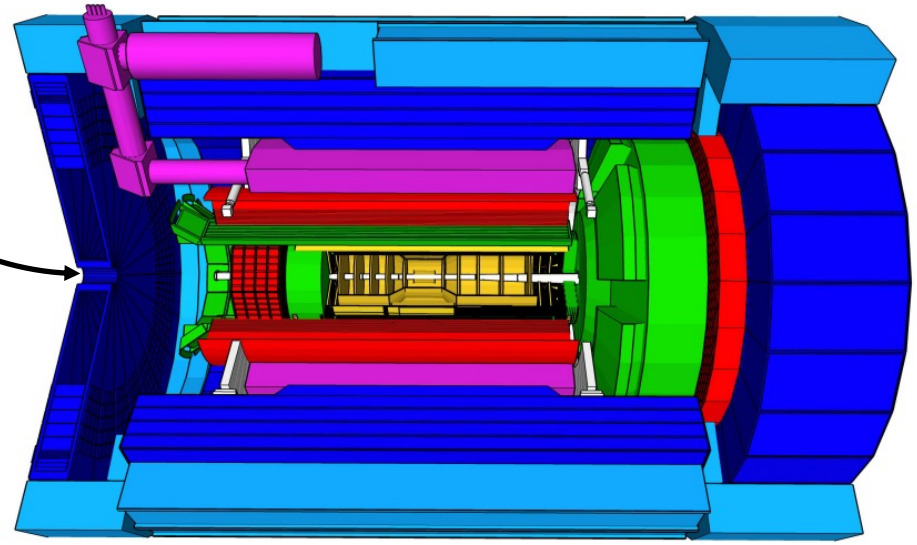
Prospect in EIC:

https://arxiv.org/pdf/2506.17454

- Electron-Ion Collider (EIC)
  - → First collisions in the early 2030s
- Heavy quarkonia are multiscale systems
  - → **Quarkonium-production mechanisms**
  - → **Study parton content of nucleons**
  - → **Study parton content of nuclei**

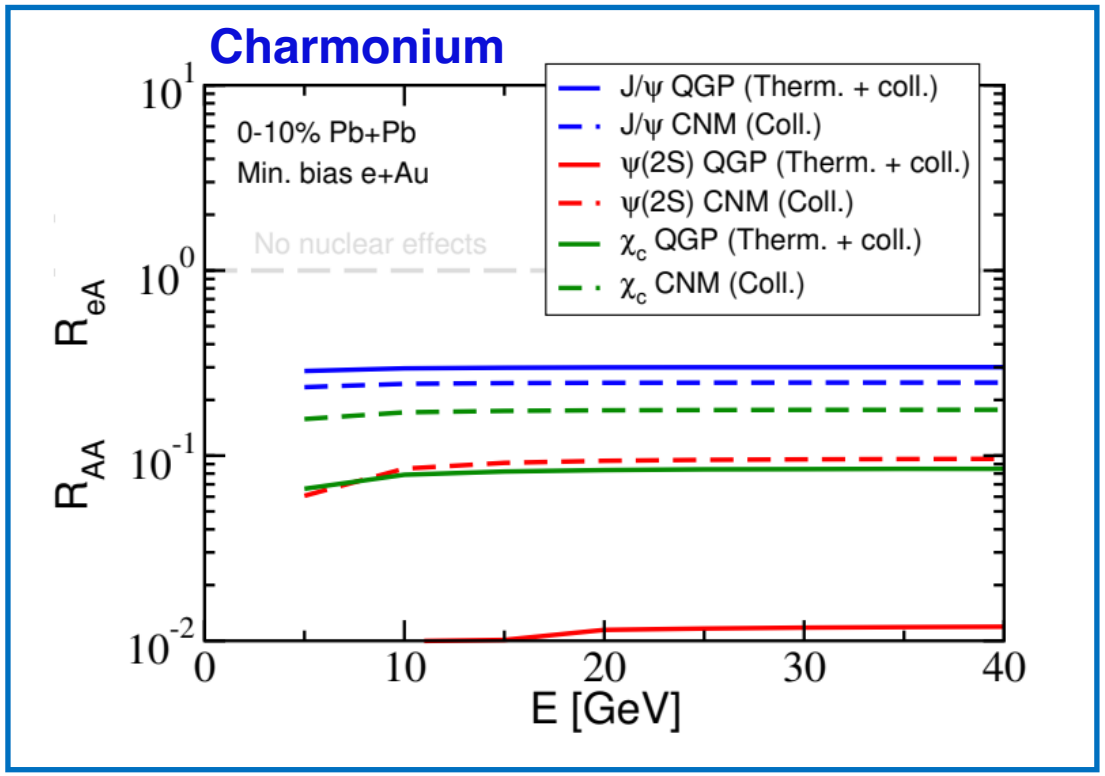






Prospect in EIC:

https://arxiv.org/pdf/2506.17454

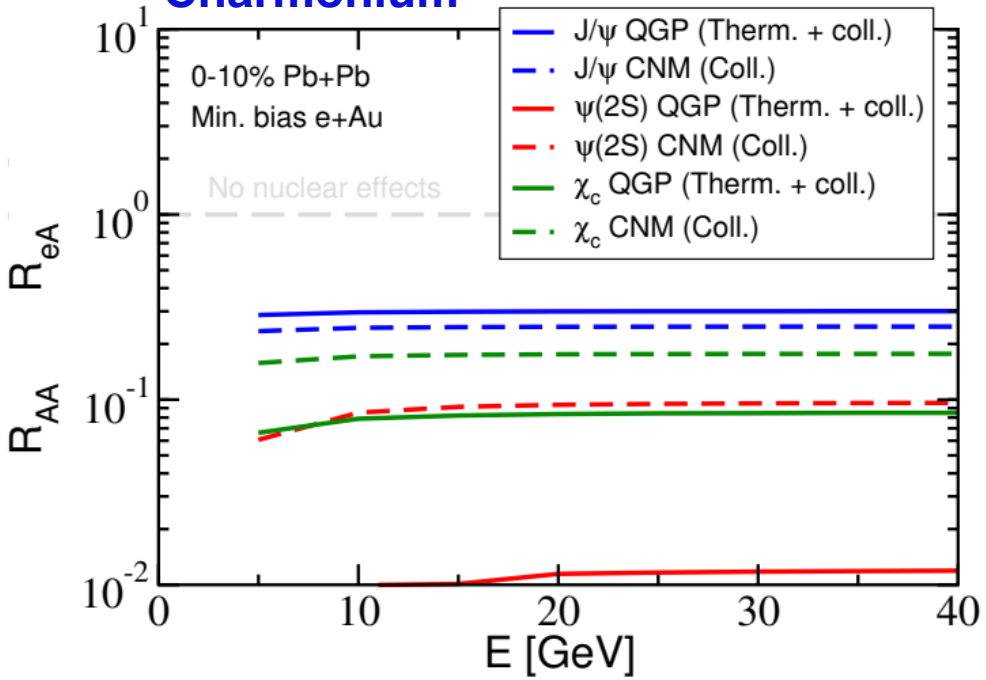


- Significant modification due to CNM effects
- Larger R_{eA} compared to $R_{AA,}$ other than J/ψ

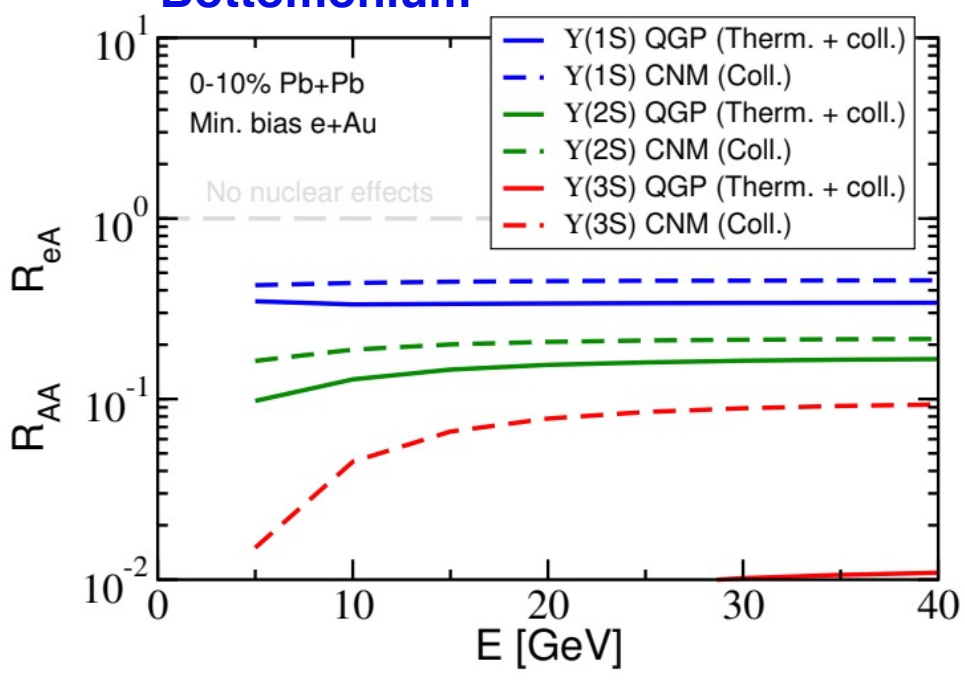
Prospect in EIC:

https://arxiv.org/pdf/2506.17454

Charmonium



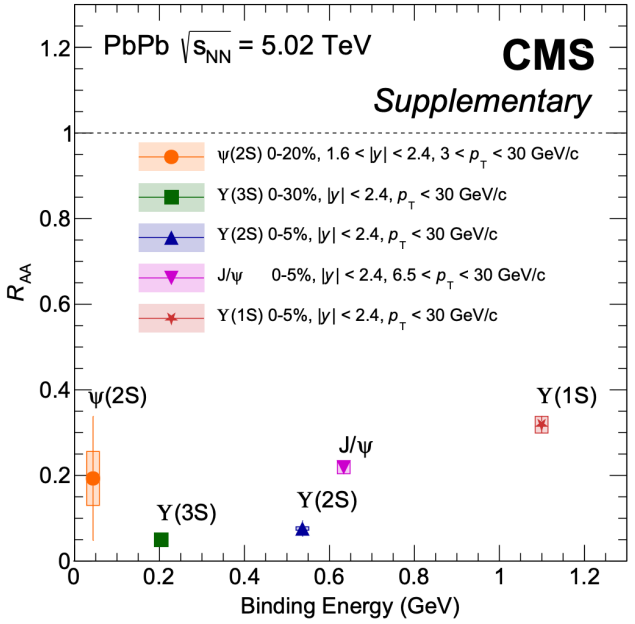
Bottomonium

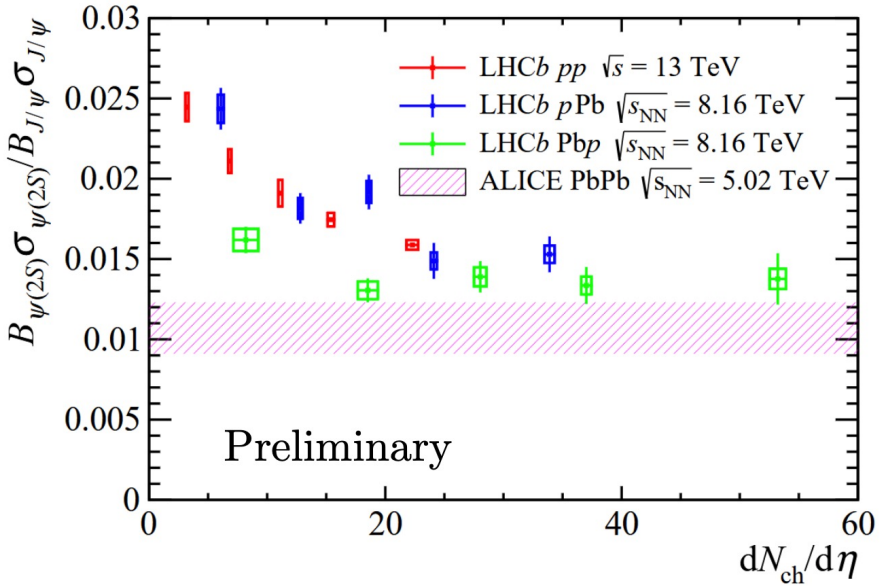


- Significant modification due to CNM effects
- Larger R_{eA} compared to $R_{AA,}$ other than J/ψ
- Impact of transport coefficients on quarkonium production
- Calibrate quarkonium as a probe in high-energy pA and AA collisions

Summary:

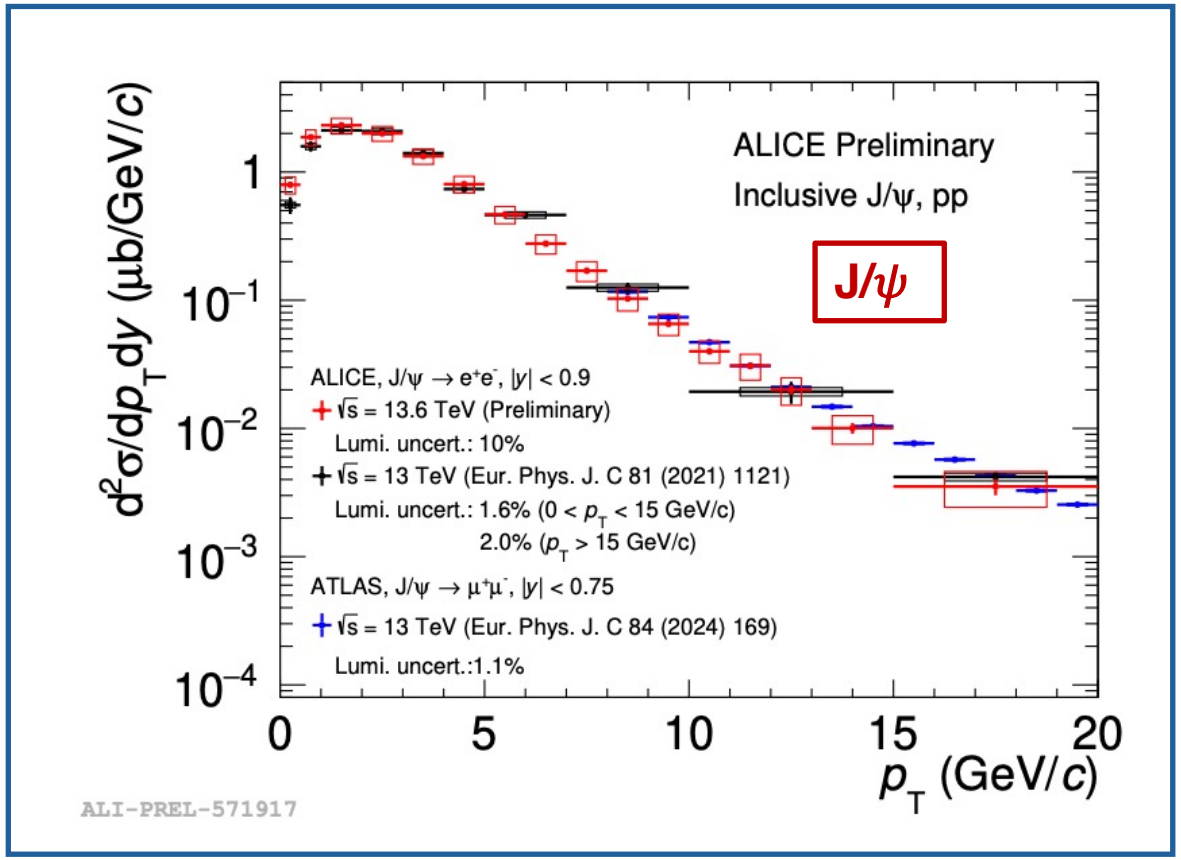
- **Clear qualitative signatures**
  - → Regeneration for charmonium
  - → Suppression hierarchy for bottomonium vector states
- **Quarkonia suppression in pp and pPb**
  - → Presence of final state effects
- **Run 3 collider data, SMOG2**
  - → New data & improved precision in near future
- **Future quarkonia measurements at EIC**





Extra:

Quarkonium production in pp

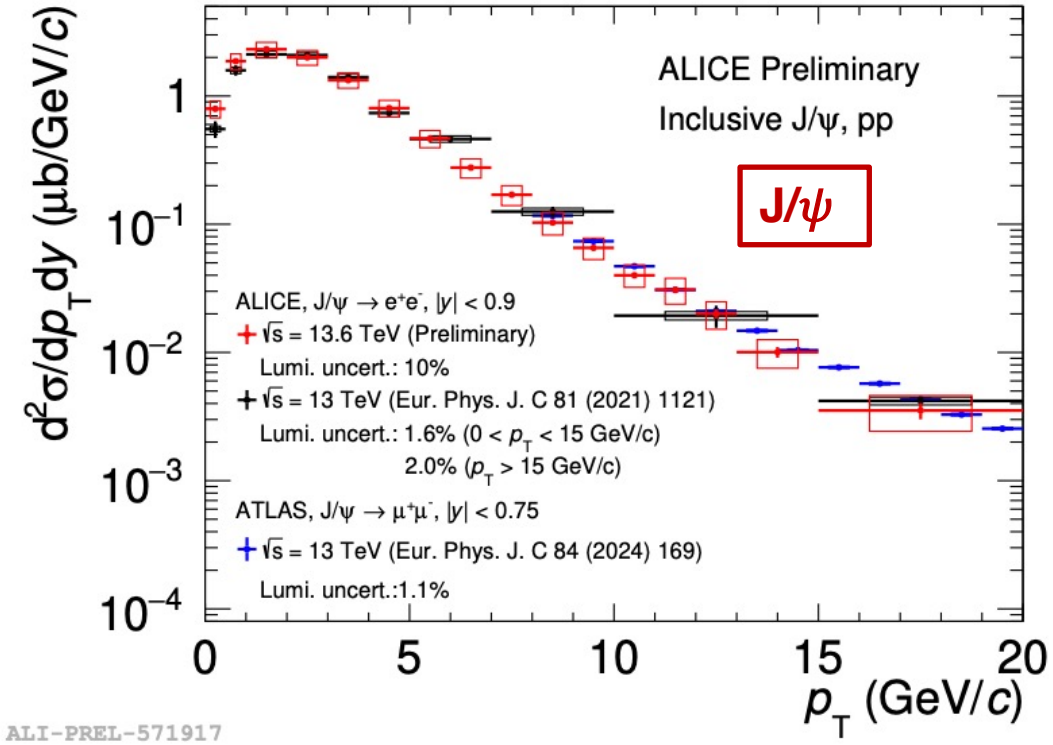


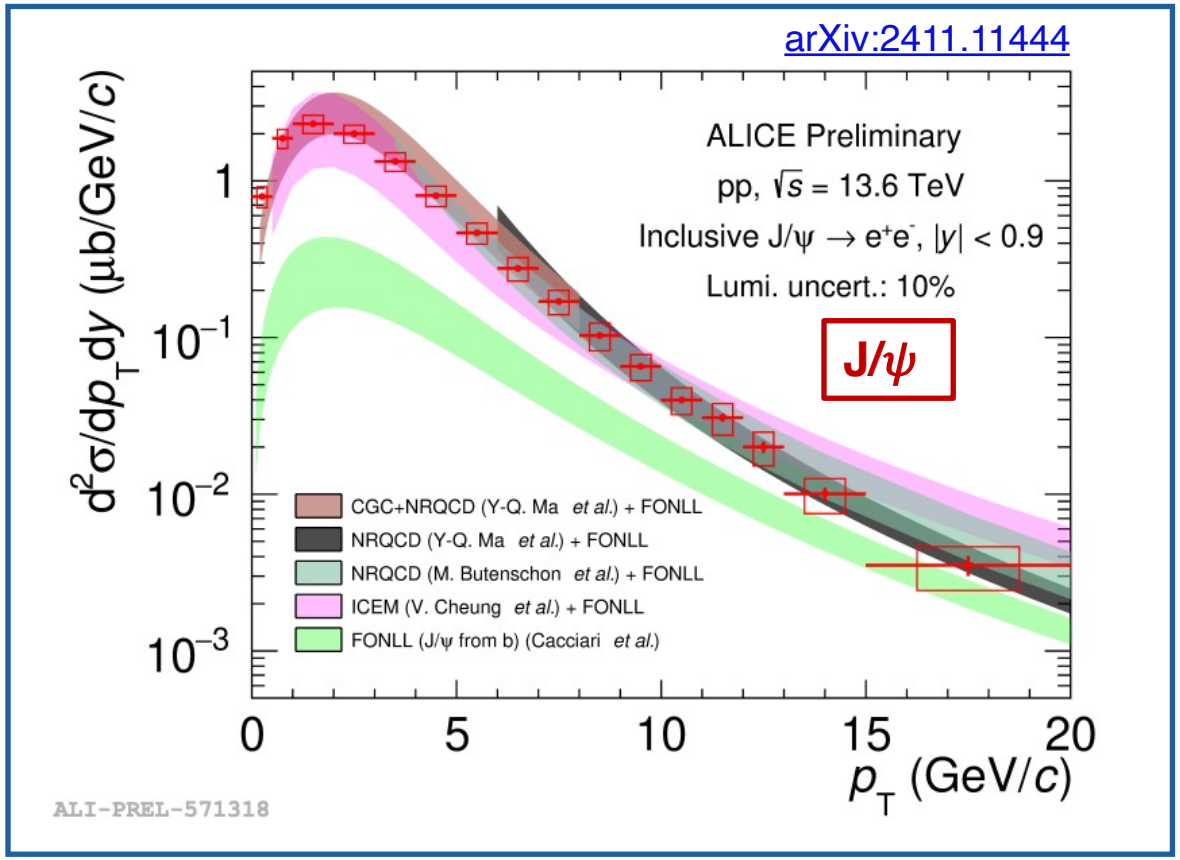
arXiv:2411.11444

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

ls

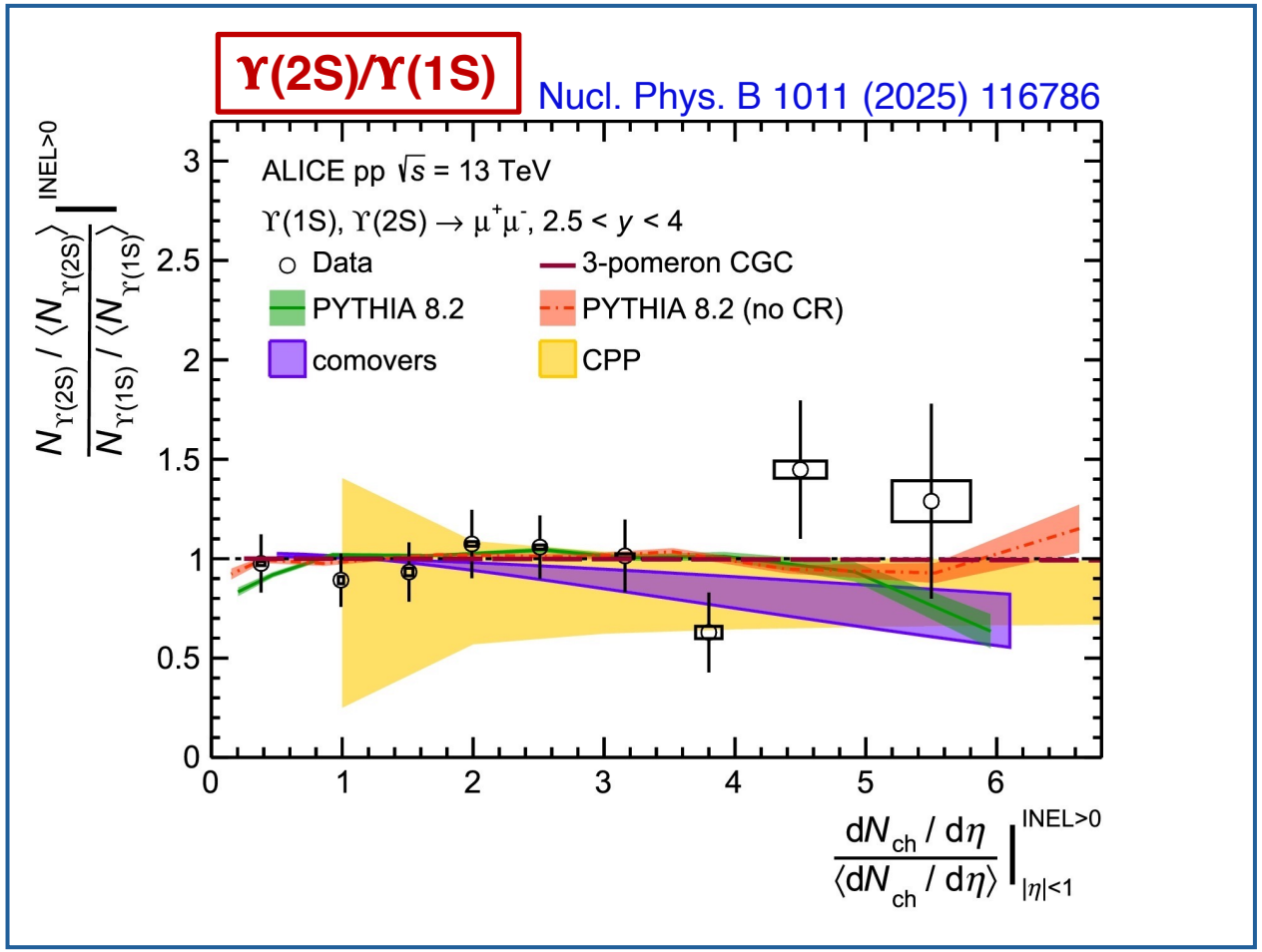
Quarkonium production in pp





- 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

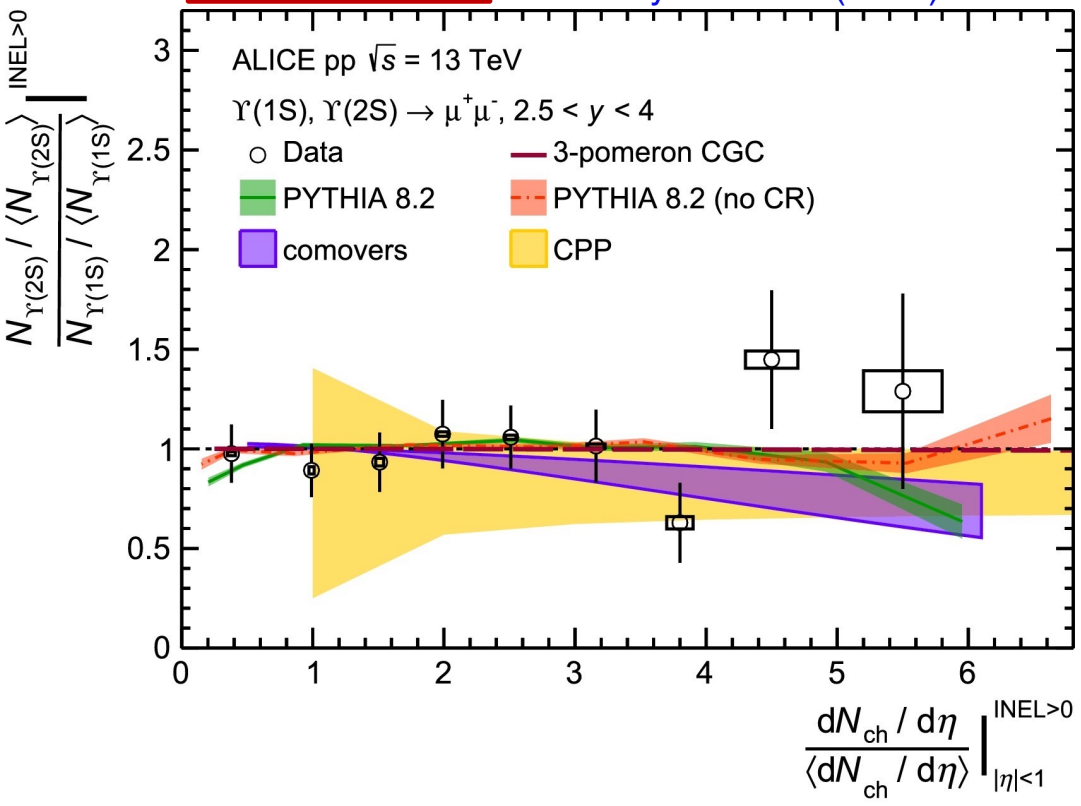
Multiplicity dependence of quarkonia production in pp



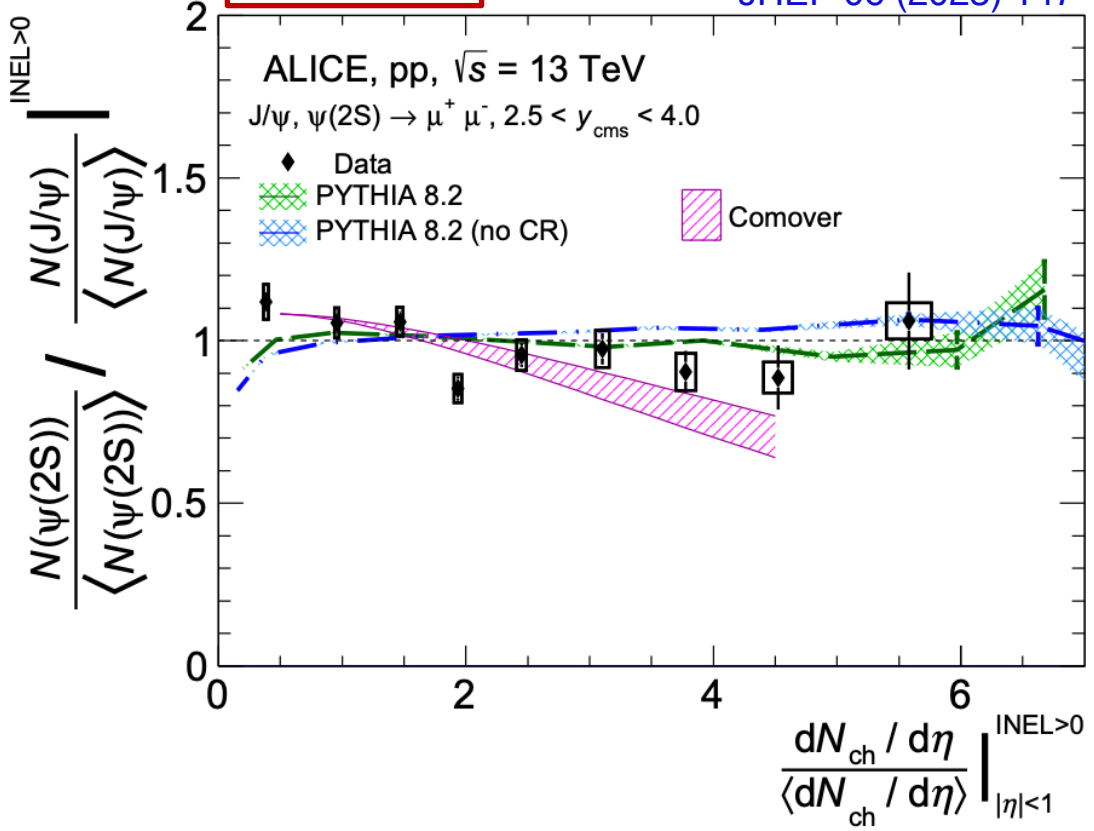
- Excited to ground state ratio flat with multiplicity → larger uncertainty

Multiplicity dependence of quarkonia production in pp

ϒ(2S)/ϒ(1S) Nucl. Phys. B 1011 (2025) 116786



ψ(2S)/J/ψ JHEP 06 (2023) 147



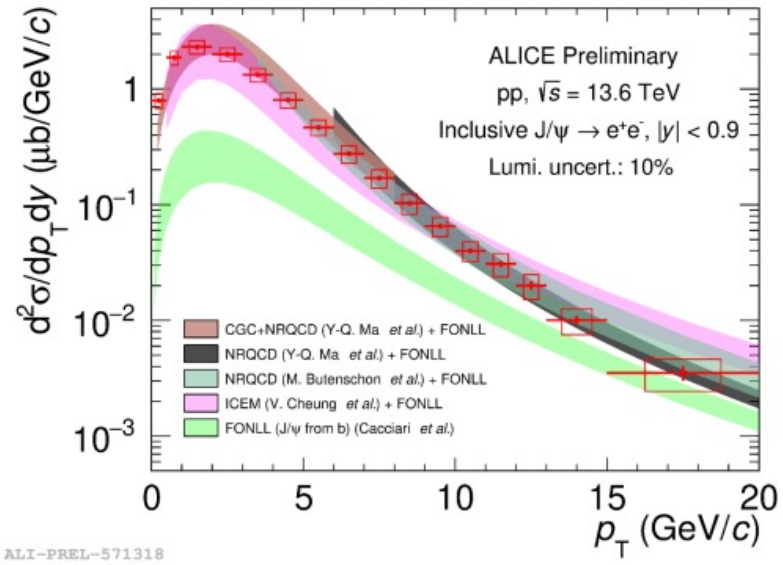
- Excited to ground state ratio flat with multiplicity → larger uncertainty

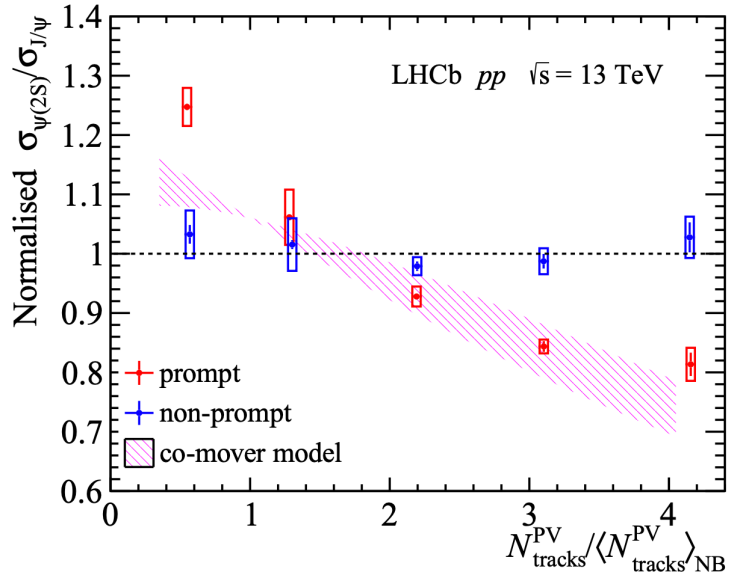
Take-home note: Quarkonia in pp

- ✓ **Quarkonia production in pp:**
  - Precision data to constrain models
  - Major effort needed to improve theory uncertainty

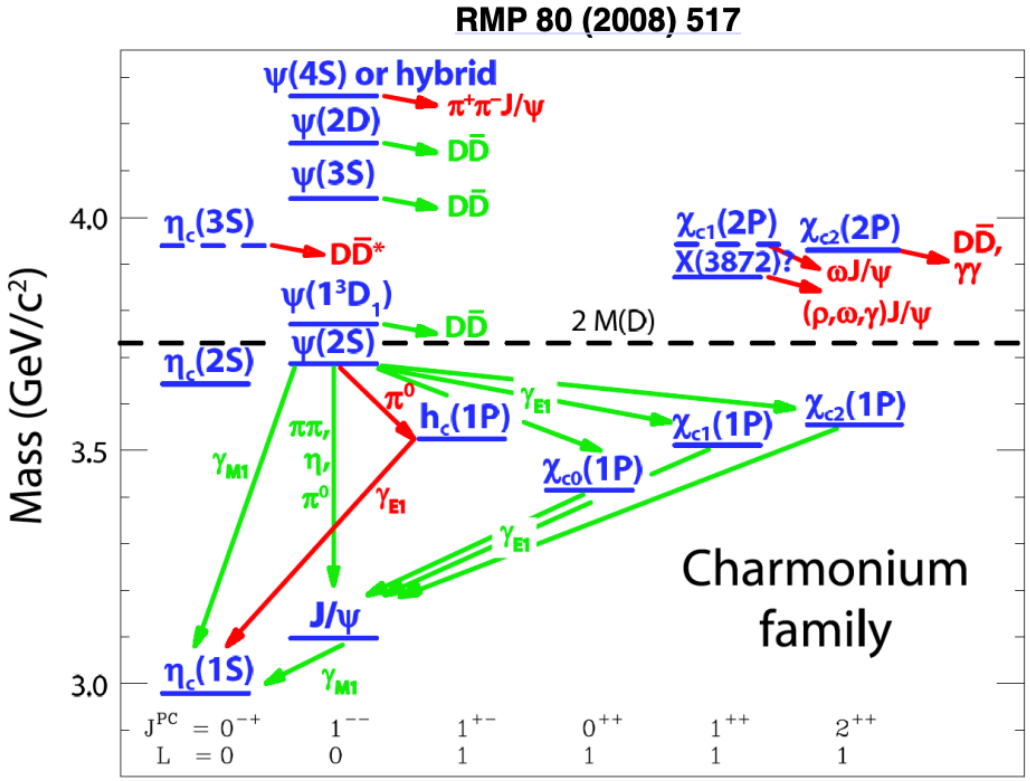
- ✓ **Event activity dependence:**
  - Evidence of the presence of final state effects

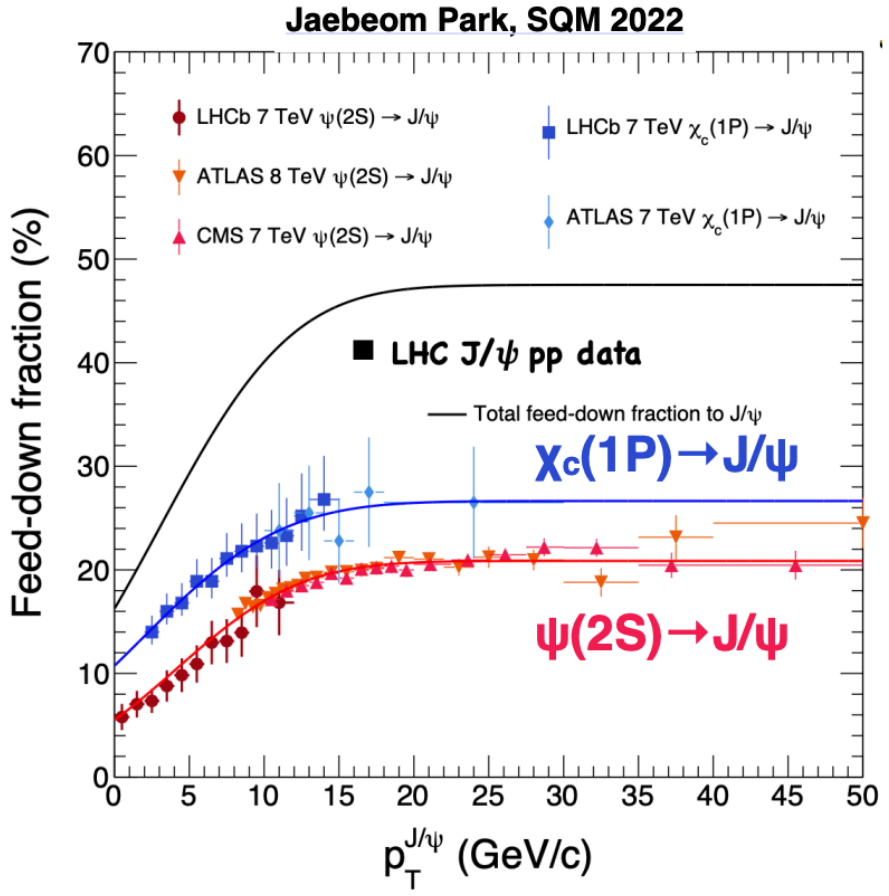
    → Qualitative agreement with “co-mover” prediction





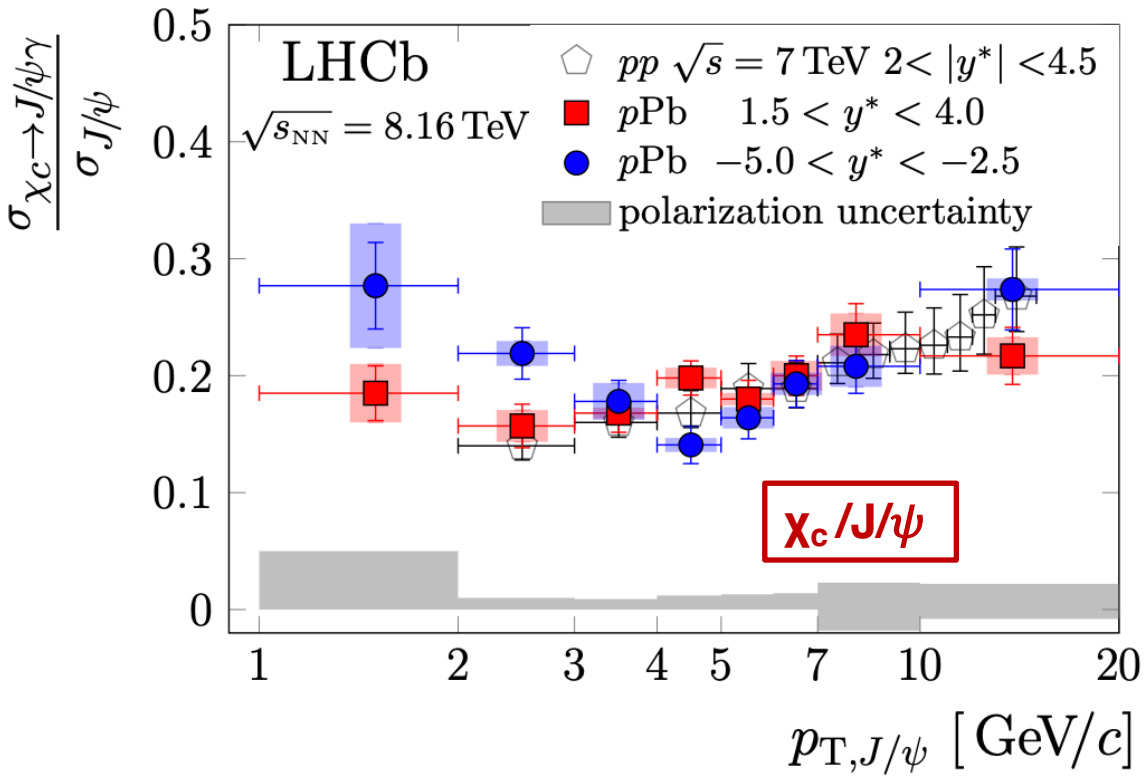
Charmonium feed-down

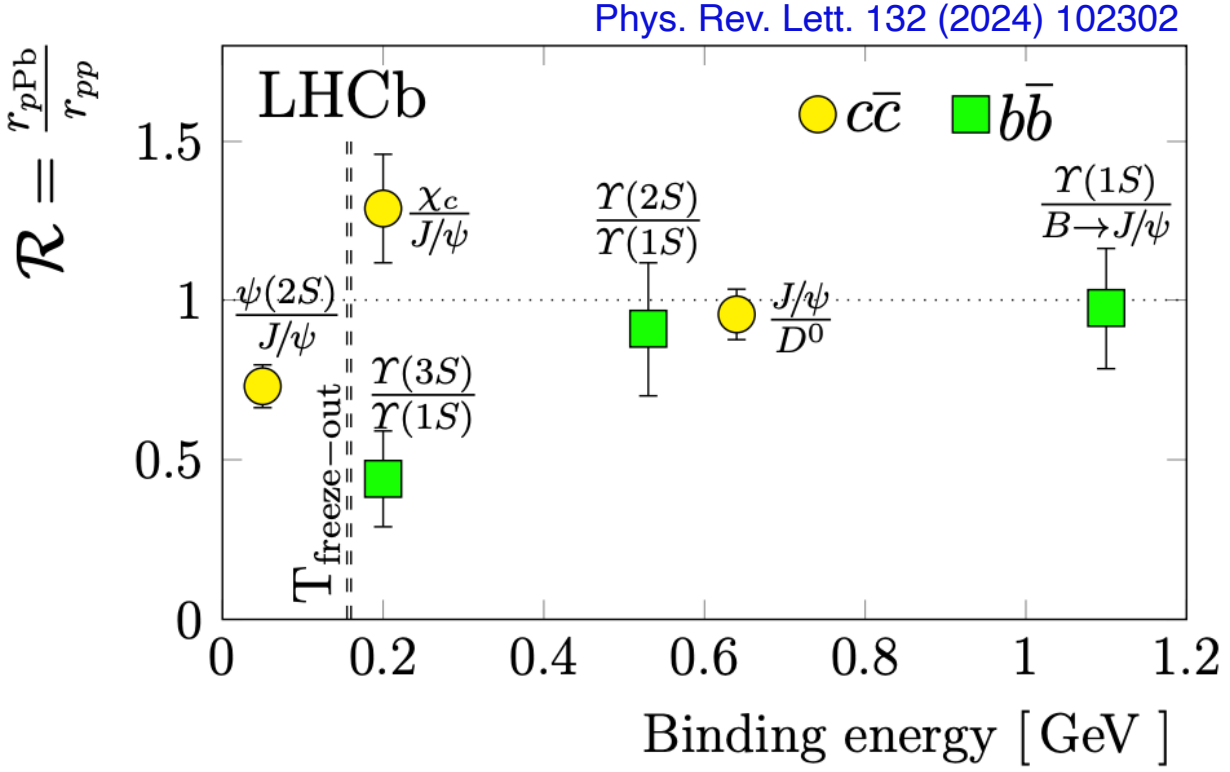




- Fraction of J/ψ production from higher charmonium states (feed-down)
- Excited states with weaker binding energies more affected by final-state effects

χ_c production in pPb



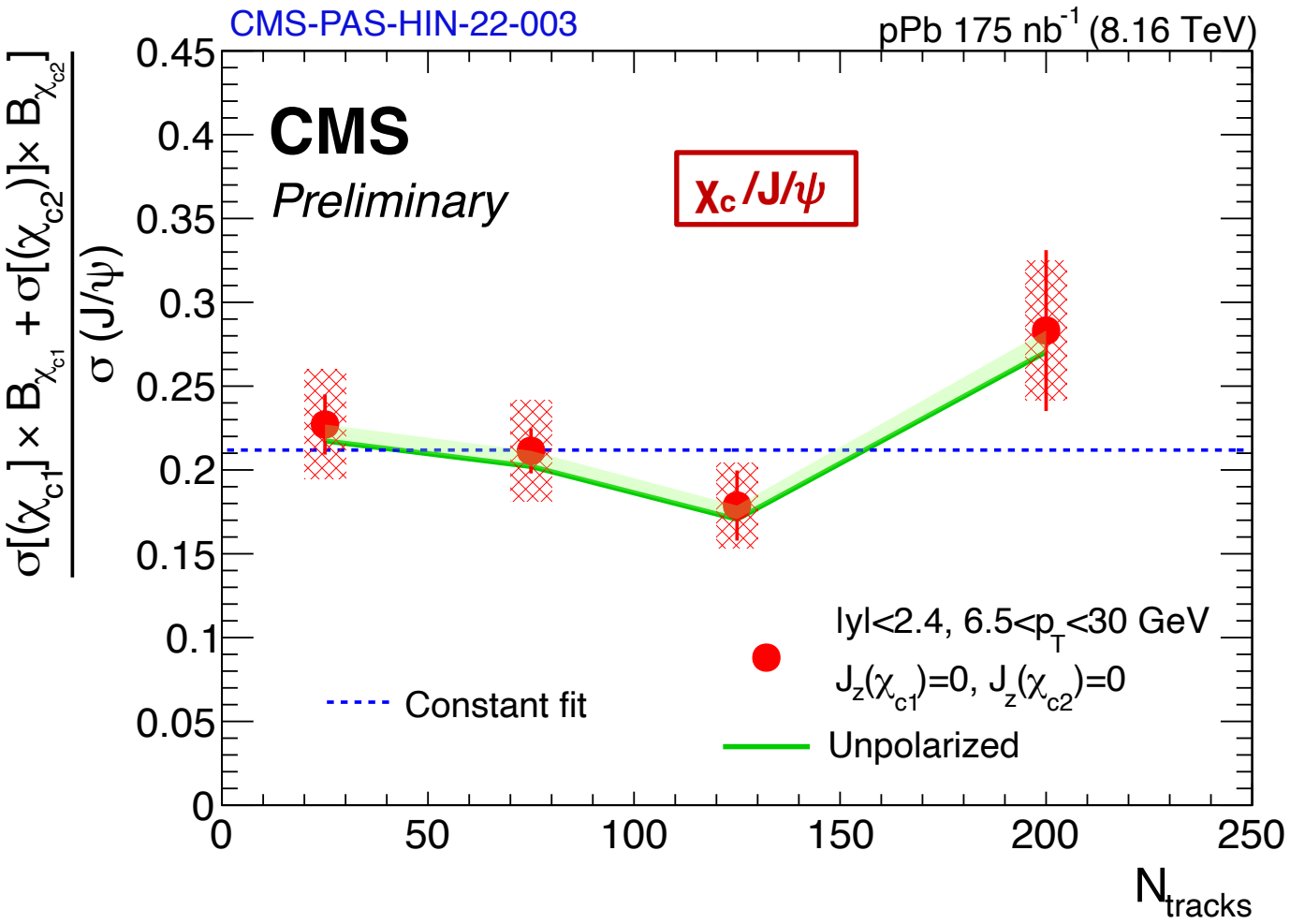


Phys. Rev. Lett. 132 (2024) 102302

- Slight difference low p_T between backward and forward rapidities
- R(Y(3S) / Y(1S)) < R(χ_c / J/ψ) ~ 1 despite χ_c ~ Y(3S) binding energy:

  → Impact of QQ feed-down? or mass-dependent effects? or P vs S-wave?

χ_c production in pPb

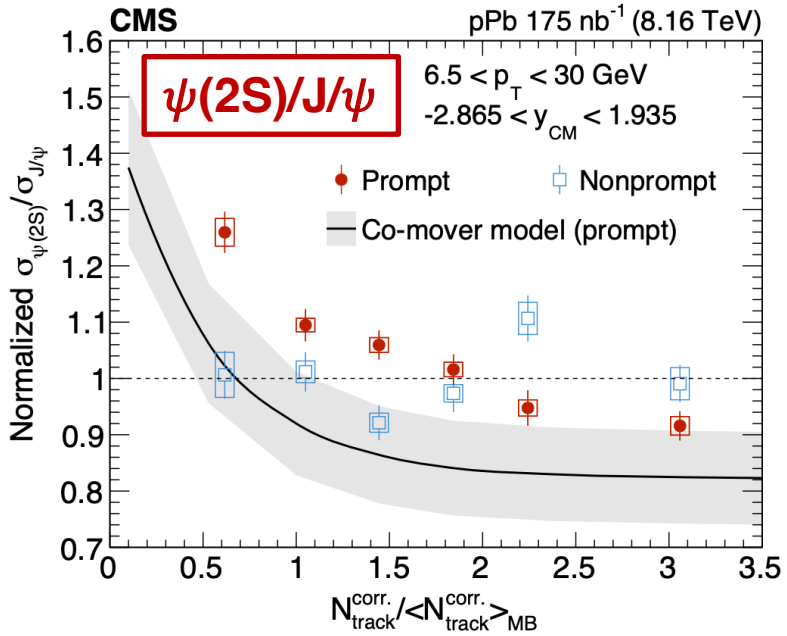


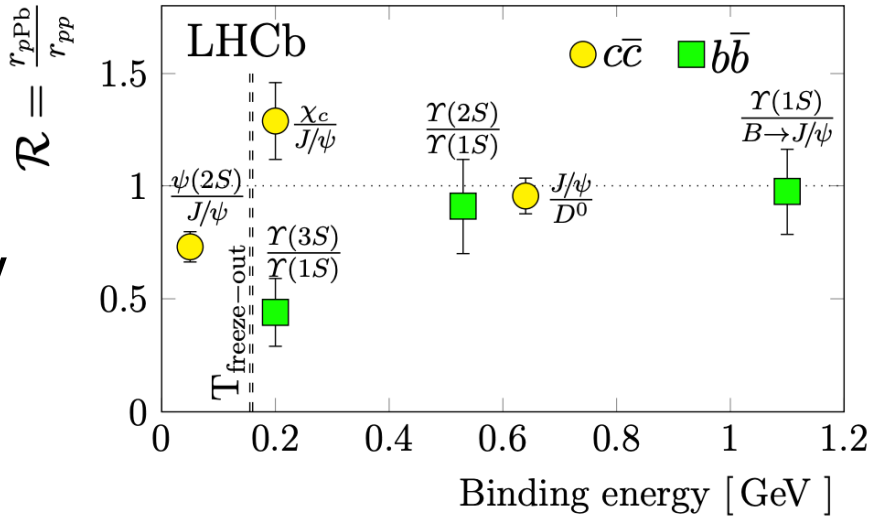
- No multiplicity dependence observed at high p_T
  - → Co-mover/dissociation picture doesn't hold?
  - → Angular momenta change final state interactions?
- Consistent picture with LHCb at forward rapidity

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) < χ_c/J/ψ despite Y(3S) ~ χ_c binding energy

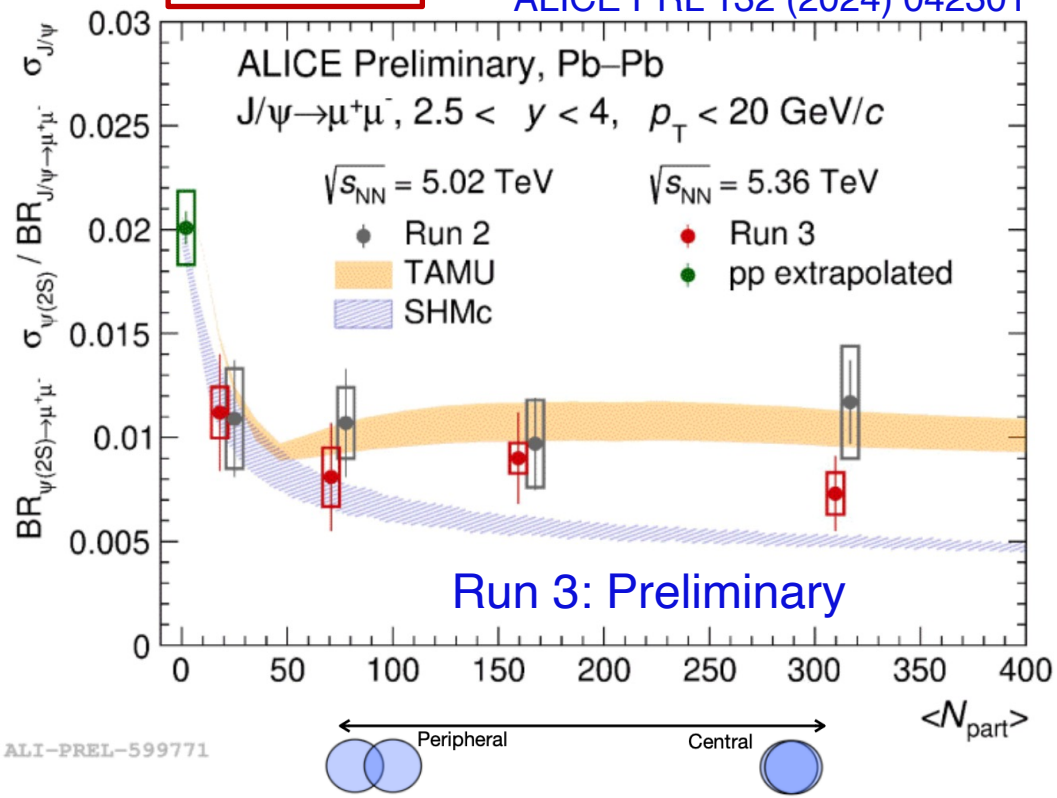




Charmonium in PbPb

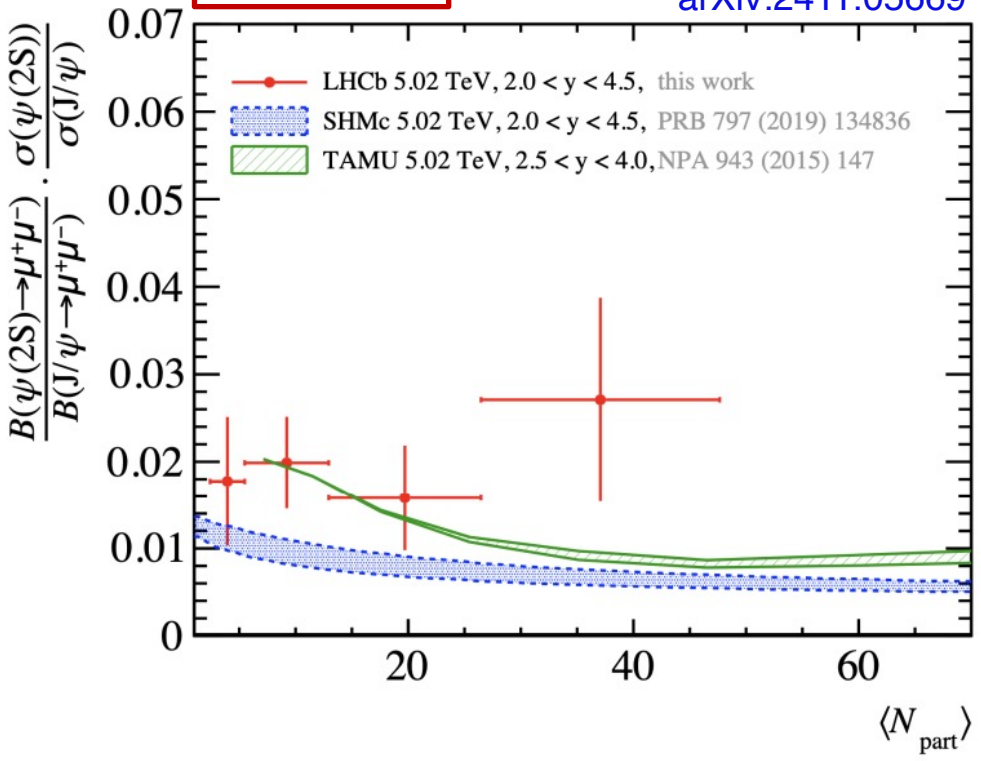
ψ(2S)/J/ψ

ALICE PRL 132 (2024) 042301



ψ(2S)/J/ψ

arXiv:2411.05669



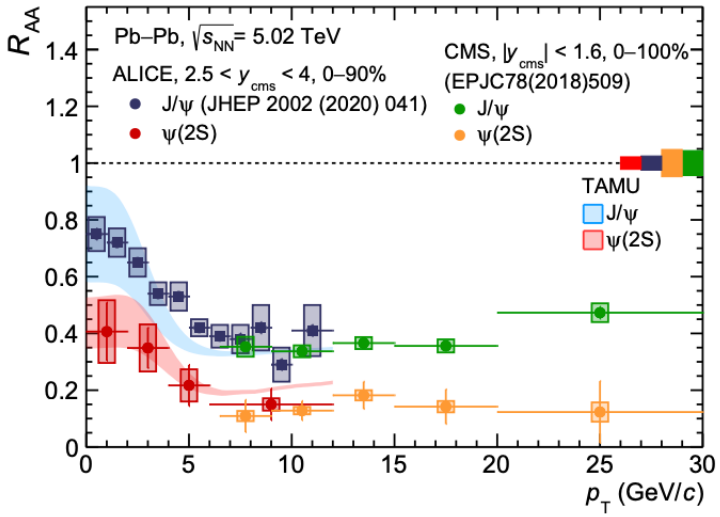
- Run 2: inclusive from ALICE & prompt LHCb (periph.)

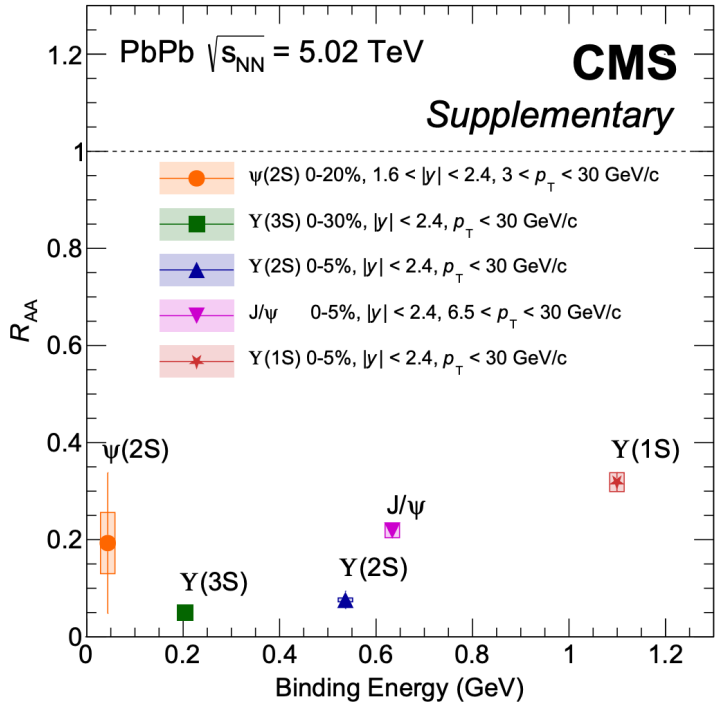
  → stronger suppression of ψ(2S) as predicted by regeneration models

- Preliminary ALICE Run 3 data with smaller uncertainties → between both models

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**





Prospect in EIC:

- Electron-Ion Collider (EIC)
- Heavy quarkonia are multiscale systems
  - → Quarkonium-production mechanisms
  - → study the parton content of the nucleons
  - → study the parton content of the nuclei