Measurements of quarkonium production at the LHC

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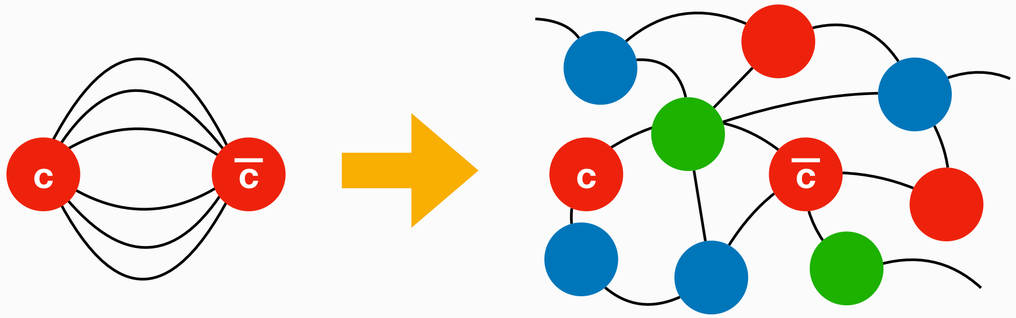
UC Berkeley, CFNS Stony Brook U

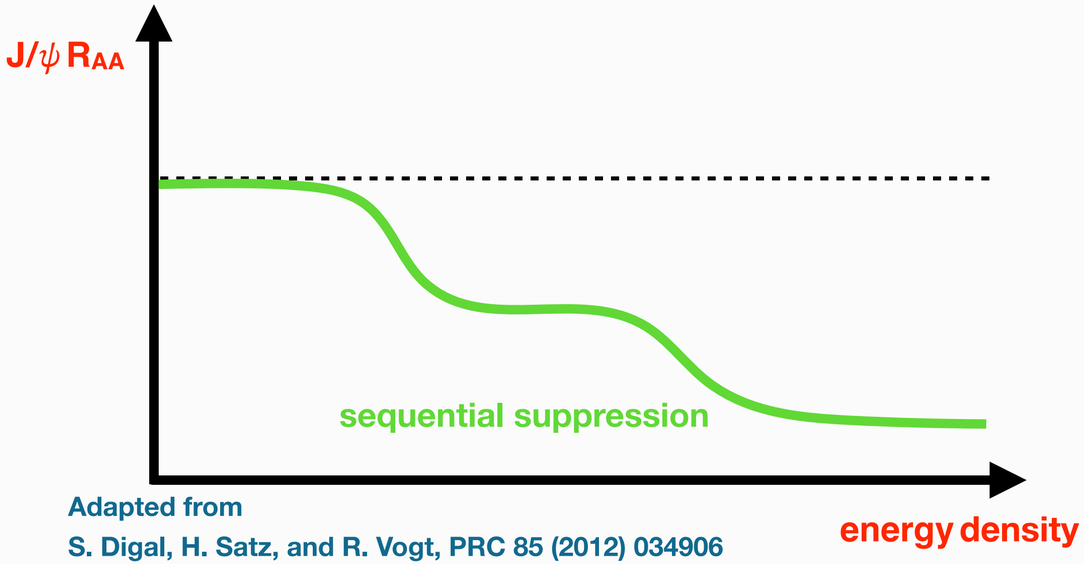
2024 RHIC/AGS Annual Users' Meeting
12. June. 2024 (Wed.)

Quarkonium production in heavy-ion collisions

Matsui and Satz, PLB 178 (1986) 416 Digal, Petrecki and Satz PRD 6



- Initial idea: quarkonium production suppressed via colour screening in QGP
- Sequential melting: differences in the quarkonium binding energies lead to a sequential melting with increasing temperature



Adapted from
S. Digal, H. Satz, and R. Vogt, PRC 85 (2012) 034906

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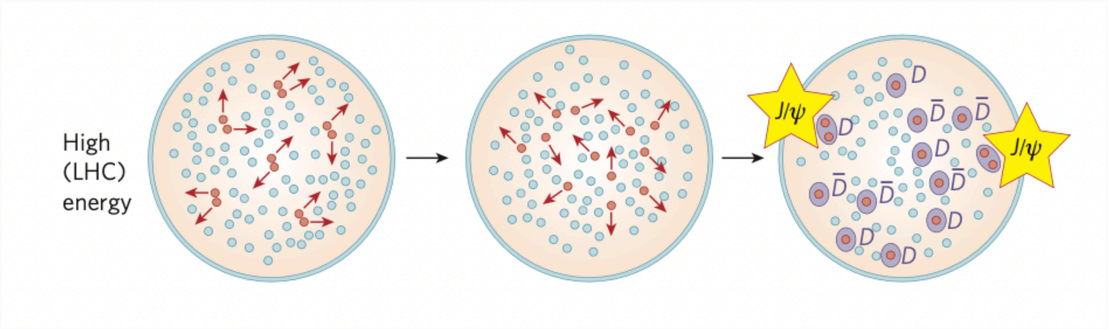

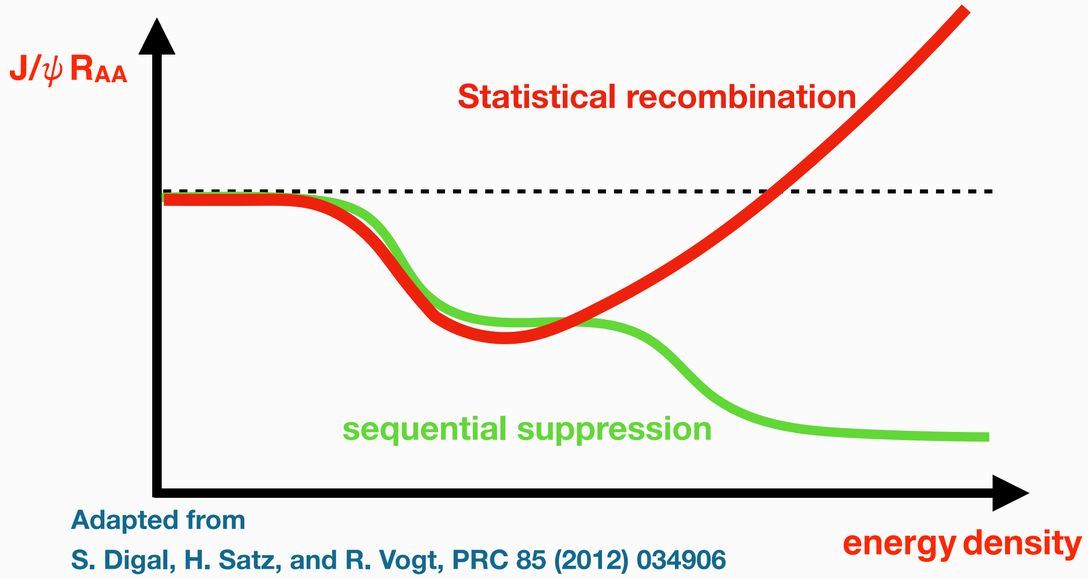

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P. Braun-Muzinger, J. Stachel, PLB 490(2000) 196 R. L. Thews et al. PRC 63 (2001) 054905

- With larger $c\bar{c}$ cross section at the LHC energies, (N_{cc} per central PbPb collisions ~115 (~10 @ RHIC)), (re)generation of charmonium and charmed hadron production take place at the phase boundary or in QGP

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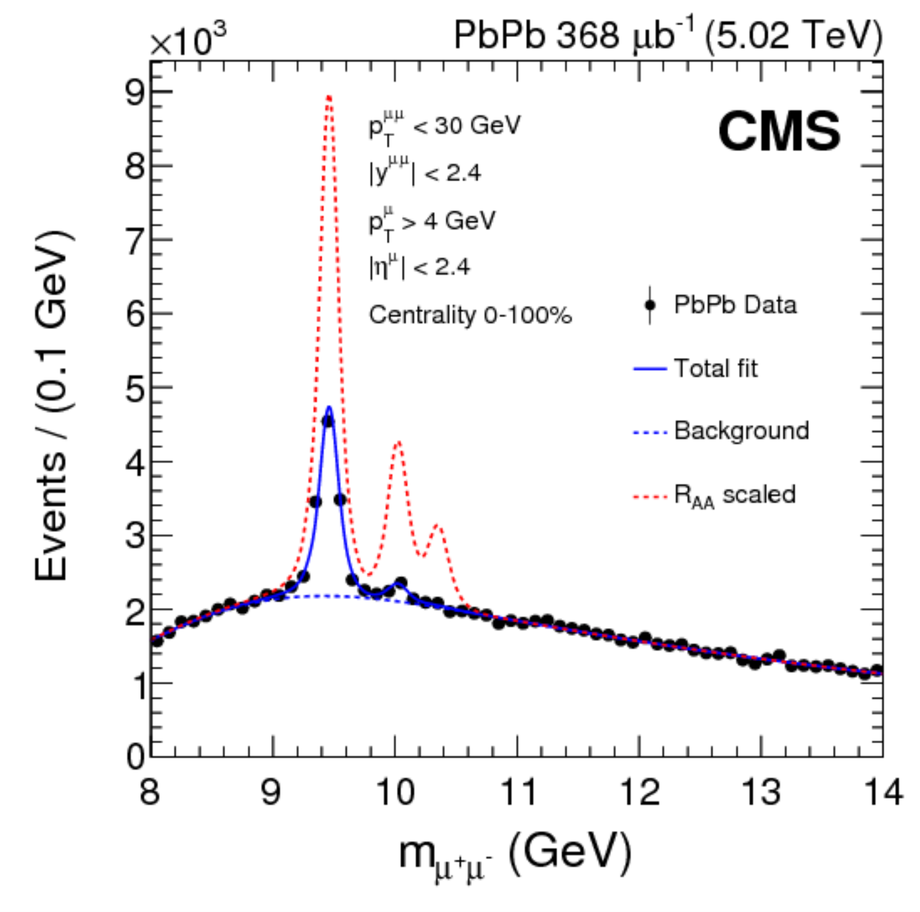
CMS, PLB 790 (2019) 270



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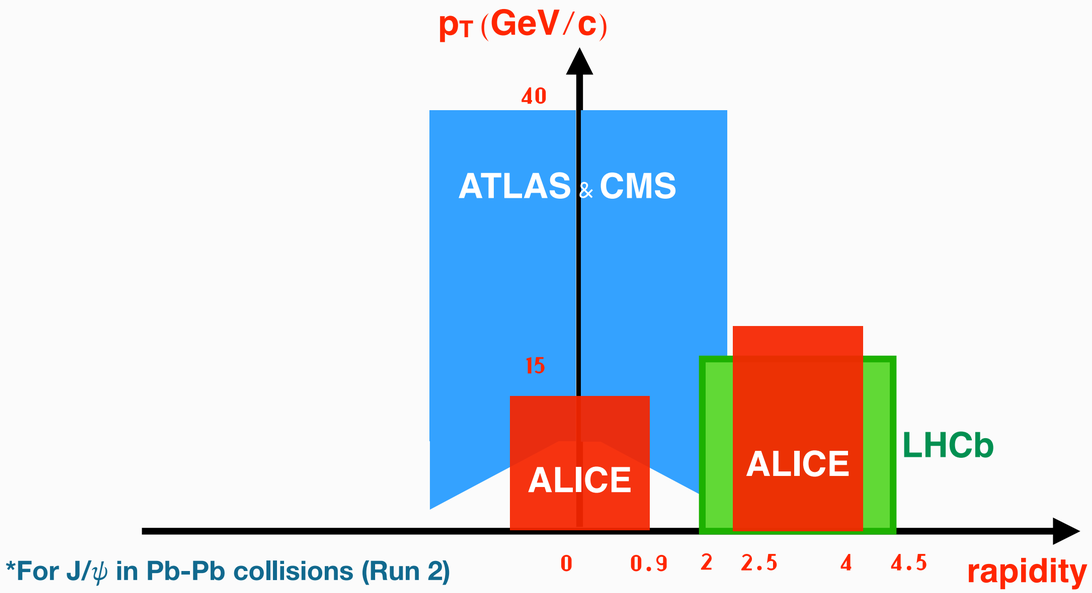
  A. Rothkopf, Phys.Rept. 858 (2020) 1, recent summary: J.Zhao's talk@SQM2
- Bottomonium @ LHC spends a longer time in a hotter medium, yet no significant regeneration
  ➡ genuine non-equilibrium probe of the full time evolution of QGP

Quarkonium measurements at the LHC



- S-wave quarkonium decays to dilepton pair:
  - J/ψ→ee (5.971±0.032)%, J/ψ→$\mu\mu$ (5.961±0.032)%
  - Υ(1S)→$\mu\mu$ (2.48±0.05)%
- Four experiments provide complementary measurements different kinematic coverages

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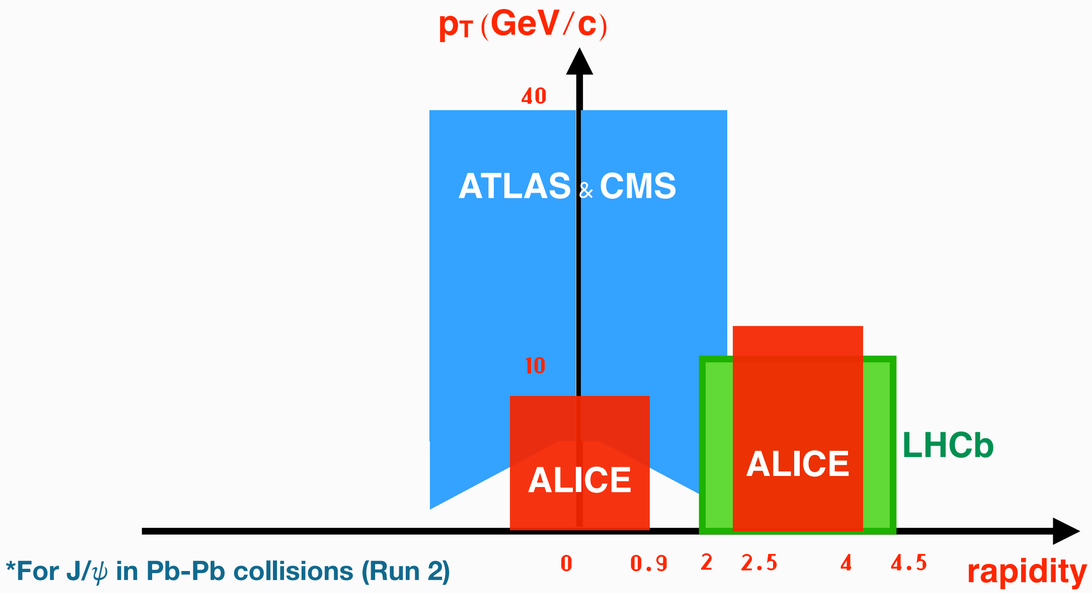
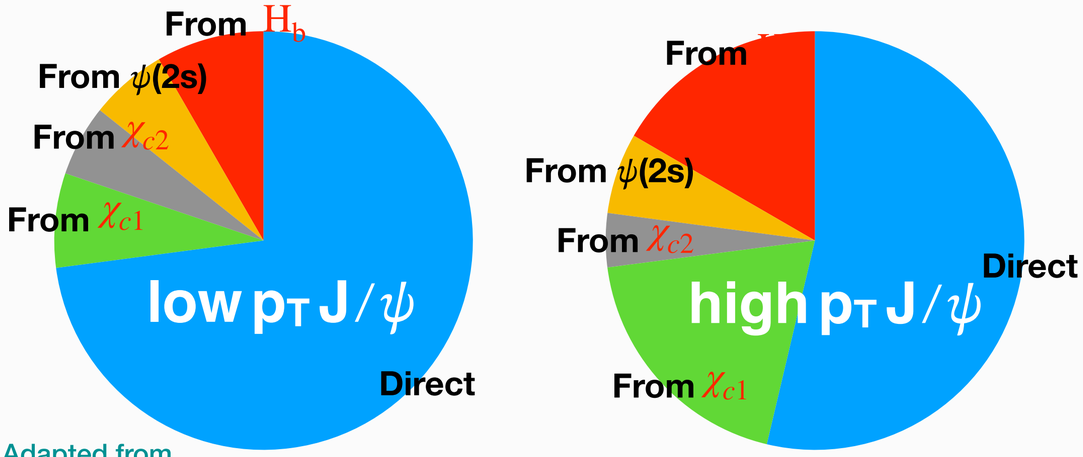


*For J/ψ in Pb-Pb collisions (Run 2)



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J.P. Lansberg Physics Reports 889 (2020) 1

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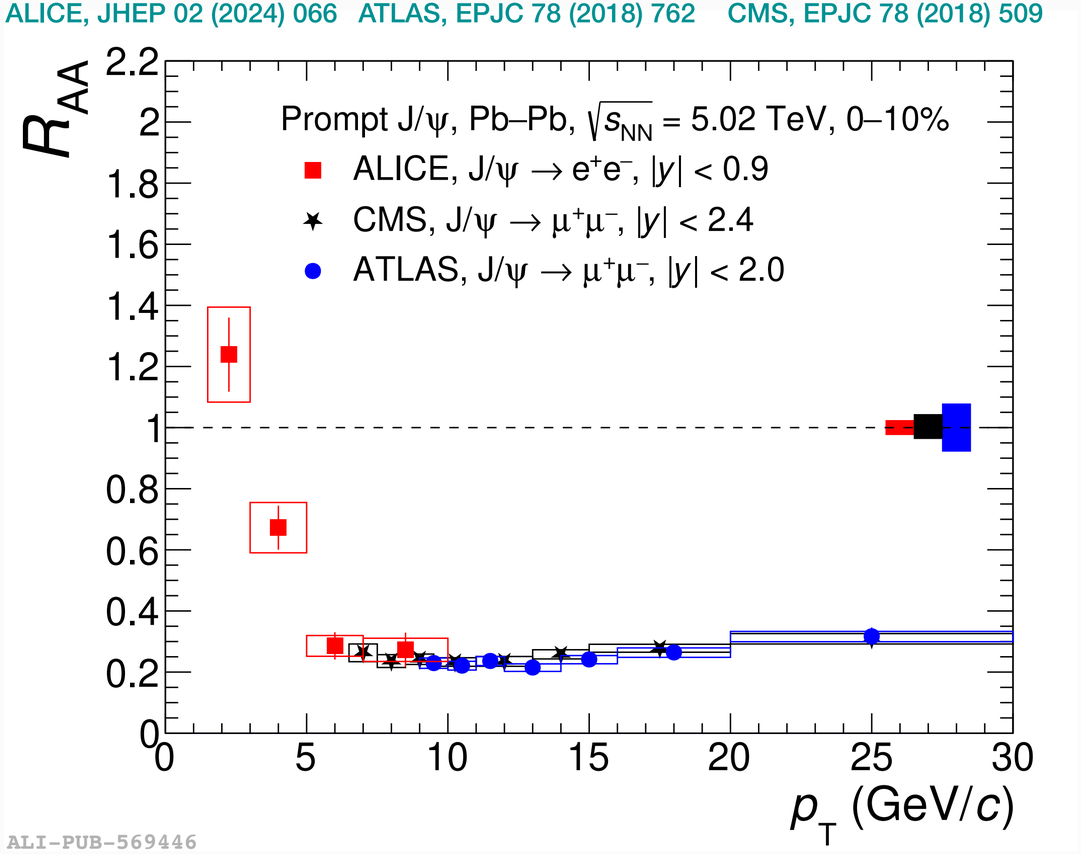
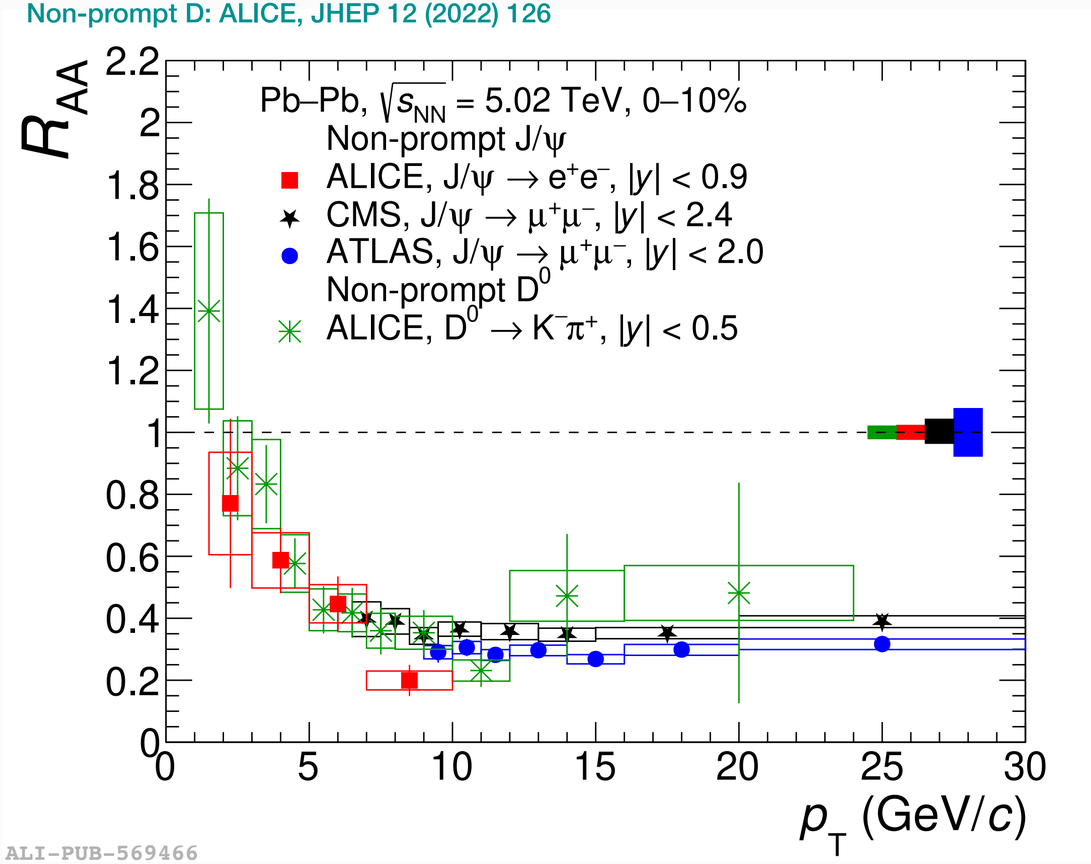
  - Υ(1S)$\rightarrow\mu\mu$ (2.48±0.05)%
- Four experiments provide complementary measurements different kinematic coverages
- Caveat: significant, p_T dependent, feed-down contributions
  - From excited states
  - From beauty hadron (H_b) for charmonium; separation relying on long lifetime of H_b

Nuclear modification factor (R_{AA}) of J/ψ at the LHC

ALICE, JHEP 02 (2024) 066 ATLAS, EPJC 78 (2018) 762 CMS, EPJC 78 (2018) 509



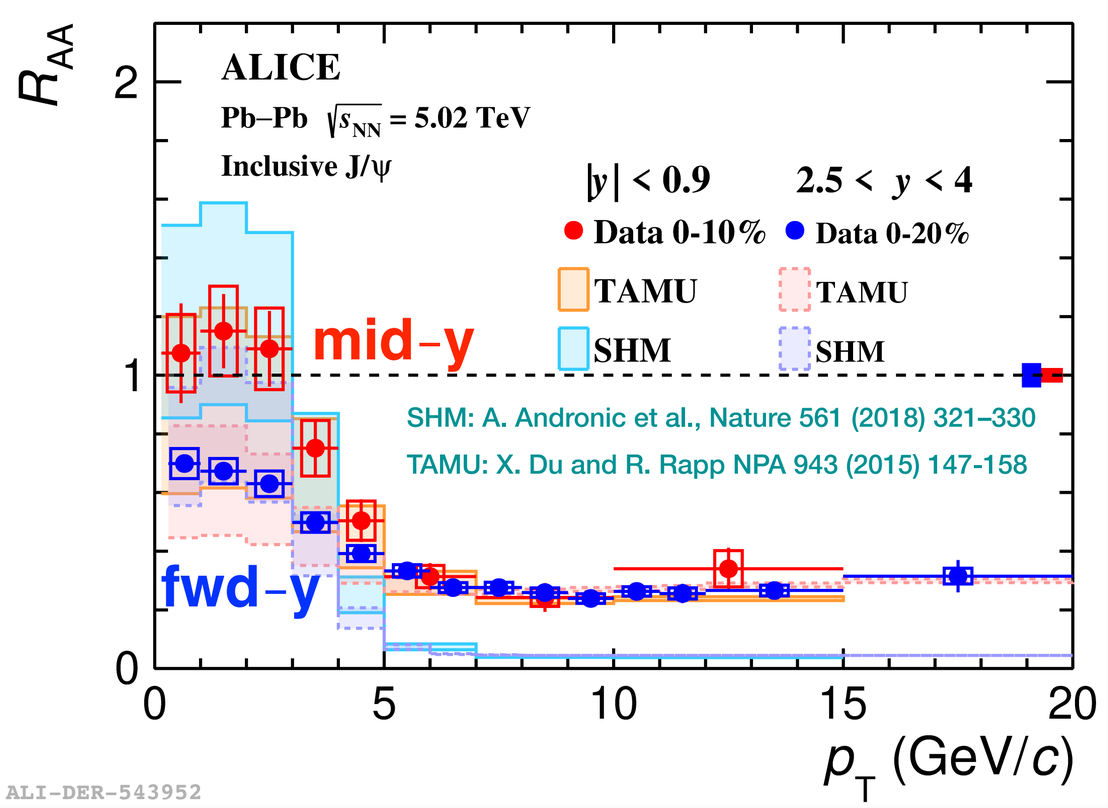
Non-prompt D: ALICE, JHEP 12 (2022) 126



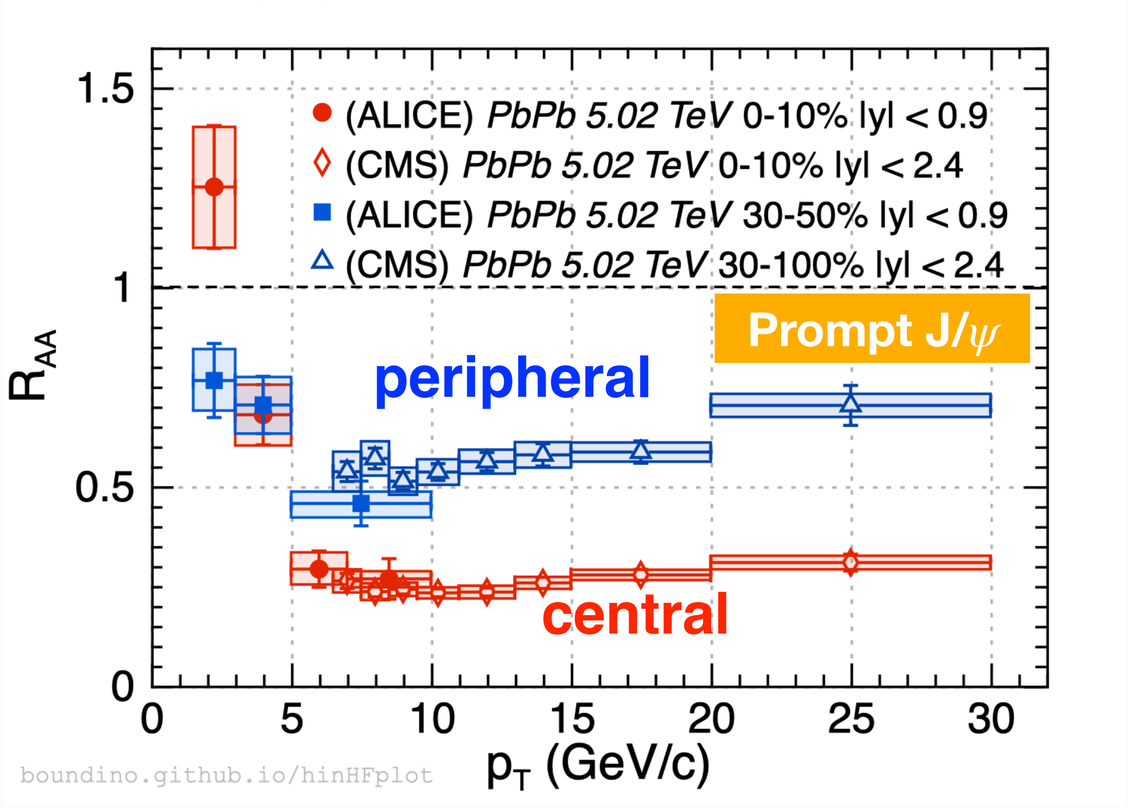
- Complementary measurements from different experiments, covering wide p_T range
- Separate measurements of prompt and non-prompt J/ψ originate from h_B

J/ψ R_{AA}: interplay between regeneration and suppression

ALICE, PLB 849 (2024) 138451



ALICE, JHEP 02 (2024) 066 CMS, EPJC 78 (2018) 509

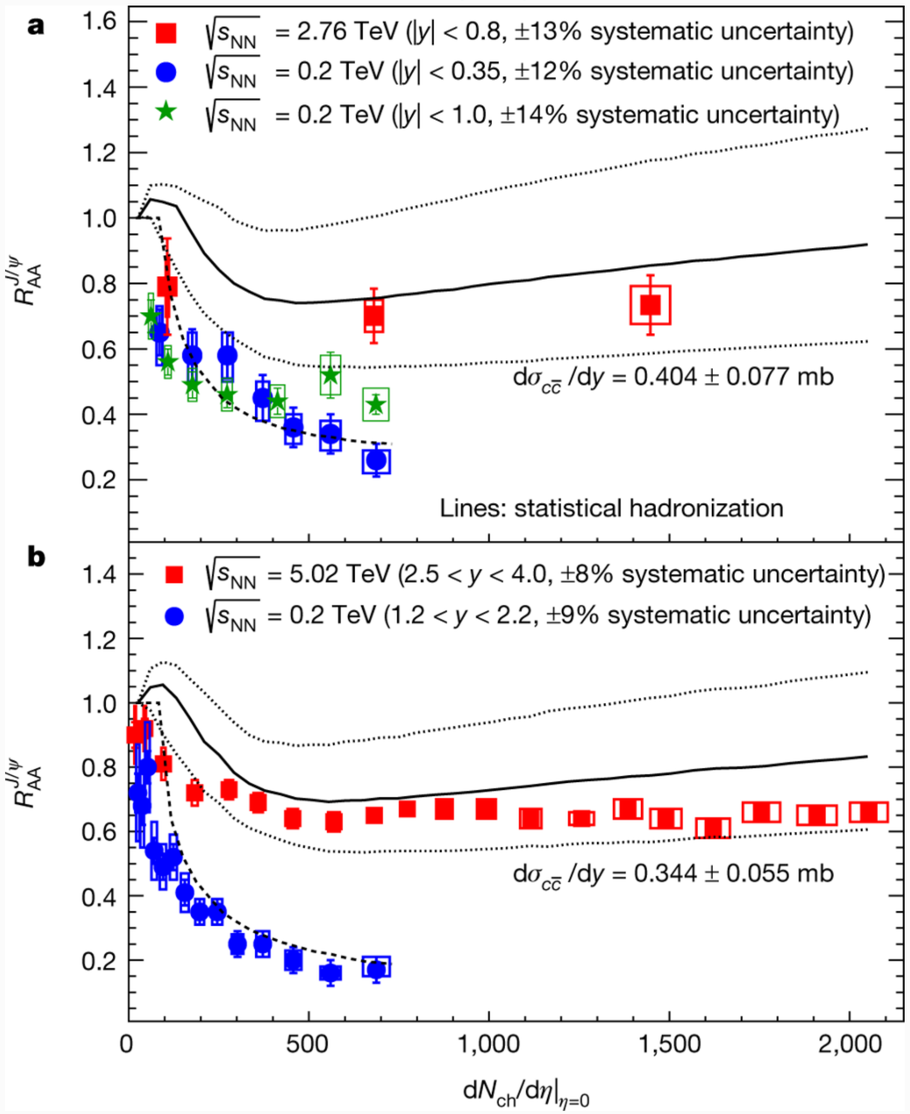


- **Stronger R_{AA} increase** towards lower p_T in midrapidity, exhibiting comparable suppression at high p_T
- **Stronger R_{AA} increase** towards lower p_T in central events, exhibiting larger suppression at high p_T

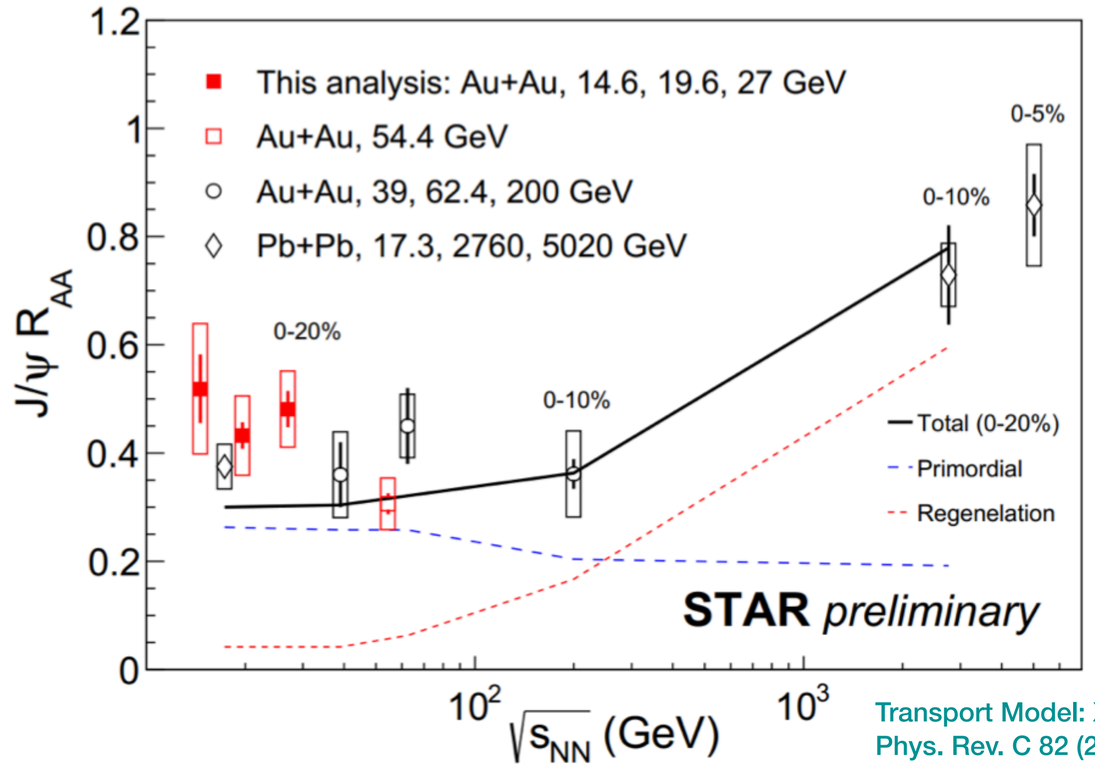
➡ Theoretical predictions support (re)generated J/ψ concentrated at low p_T at midrapidity with larger cc cross section

J/ψ R_{AA} in different system energies

SHM: A. Andronic et al., Nature 561 (2018) 321–330



Y. Wang for STAR, QM2023 proceedings

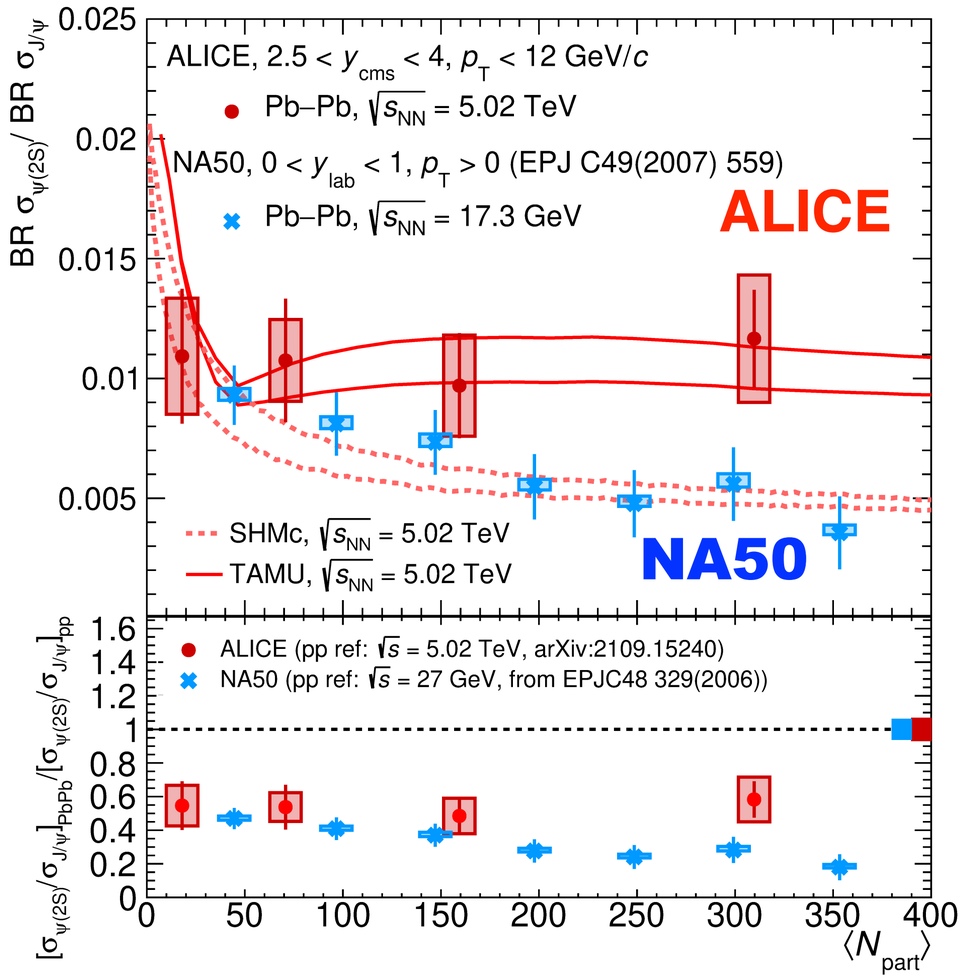


Transport Model: X. Zhao, R. Rapp, Phys. Rev. C 82 (2010) 064905

- Strong rise of the J/ψ RAA from RHIC to LHC energies: interplay between regeneration and suppression
- Both SHM and Transport model simultaneously describe RHIC/LHC data Review: A. Andronic, et. al. arXiv:2402.04366

$\psi(2S)$ production in Pb-Pb collisions

ALICE, PRL 132 (2024) 042301

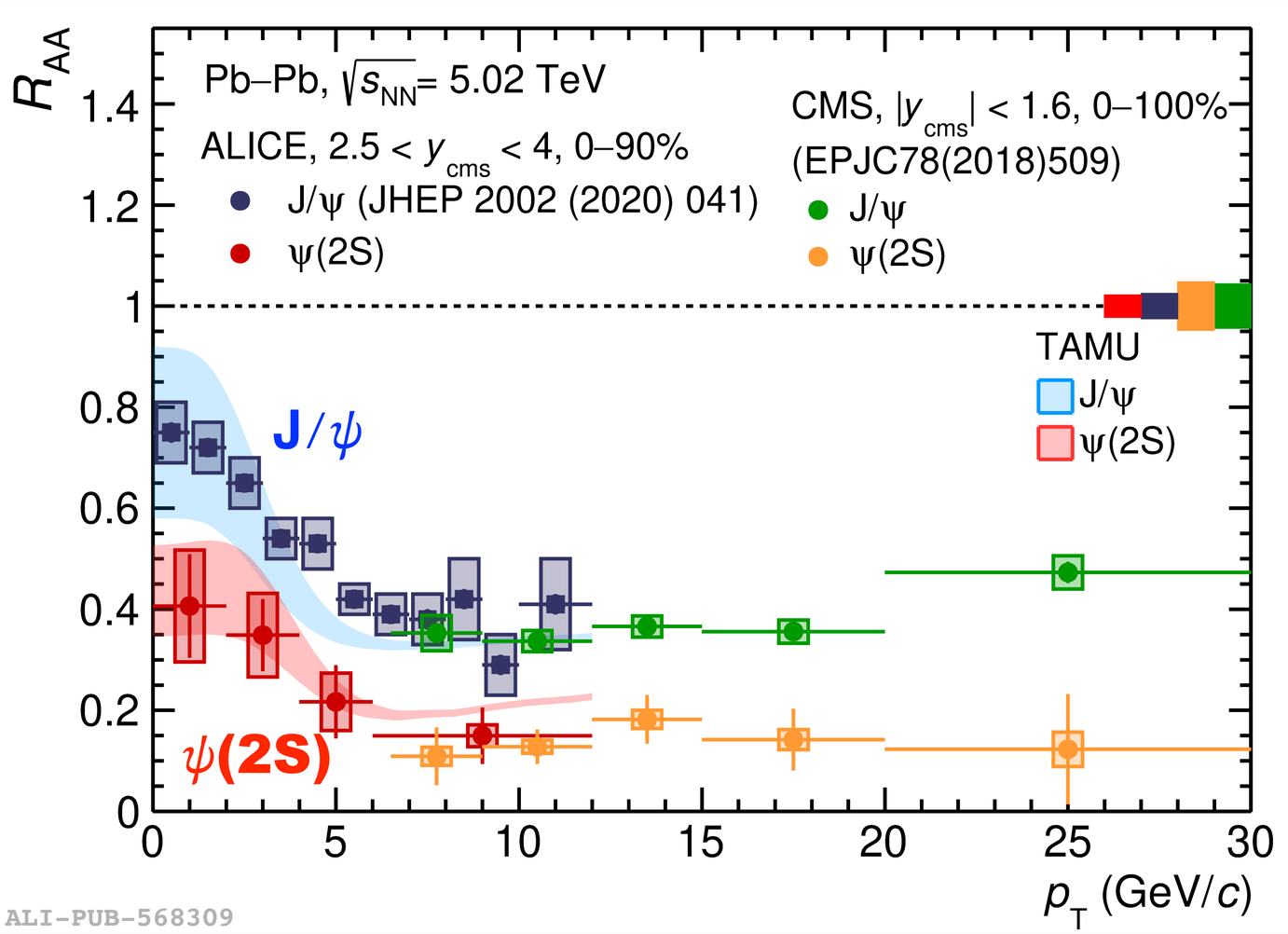


ALI-PUB-568299

- Smaller theoretical uncertainties in the observable:
  - initial state effects, such as shadowing, largely cancelled
  - less dependent on the charm quark cross section
- Hint of larger ratio over centrality and less pronounced centrality dependence w.r.t. NA50
- TAMU reproduces the cross section ratios over centrality; while SHM underestimates

$\psi(2S)$ production in Pb-Pb collisions

ALICE, PRL 132 (2024) 042301



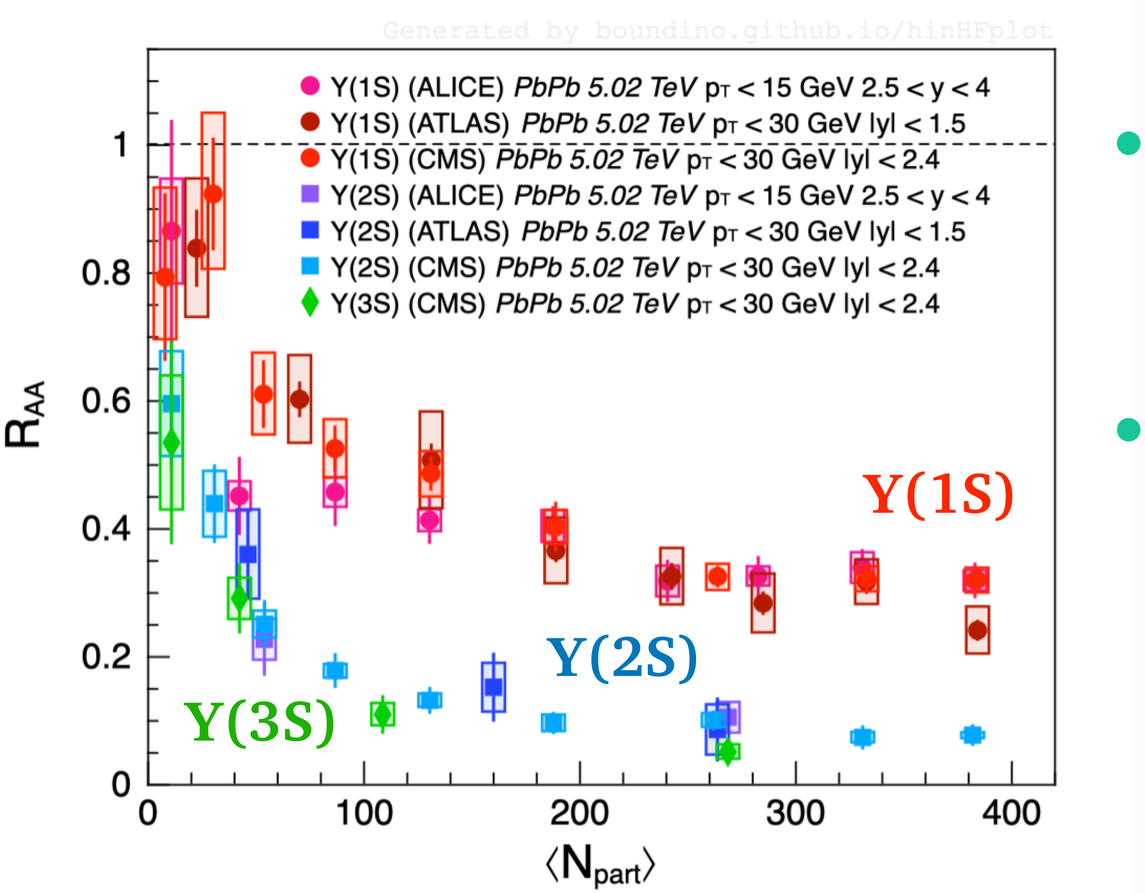
- Larger suppression for $\psi(2S)$ than J/ψ in measured p_T range
- Increasing trend at low p_T also in $\psi(2S)$ → hint of $\psi(2S)$ regeneration
- More differential and improved precision measurements required → Run 3 + Run 4

Bottomonium production in Pb-Pb collisions

ALICE, PLB 822 (2021) 136579

ATALAS, PRC 107 (2023) 054912

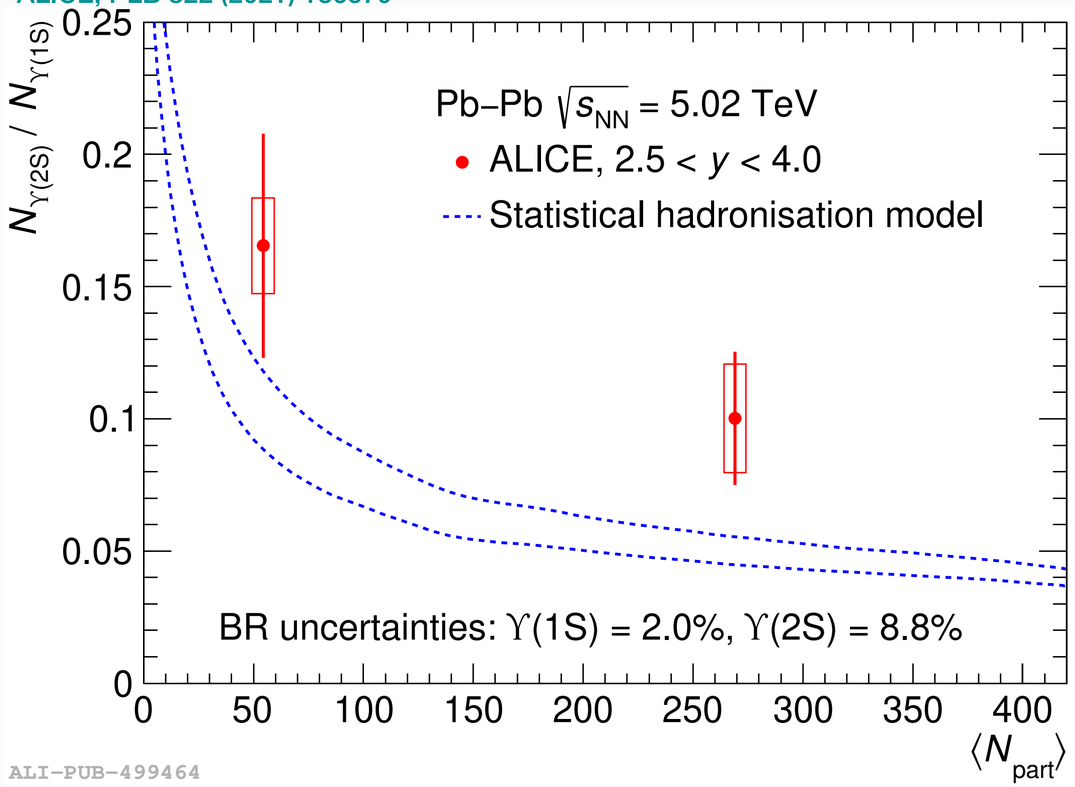
CMS, arXiv:2303.17026

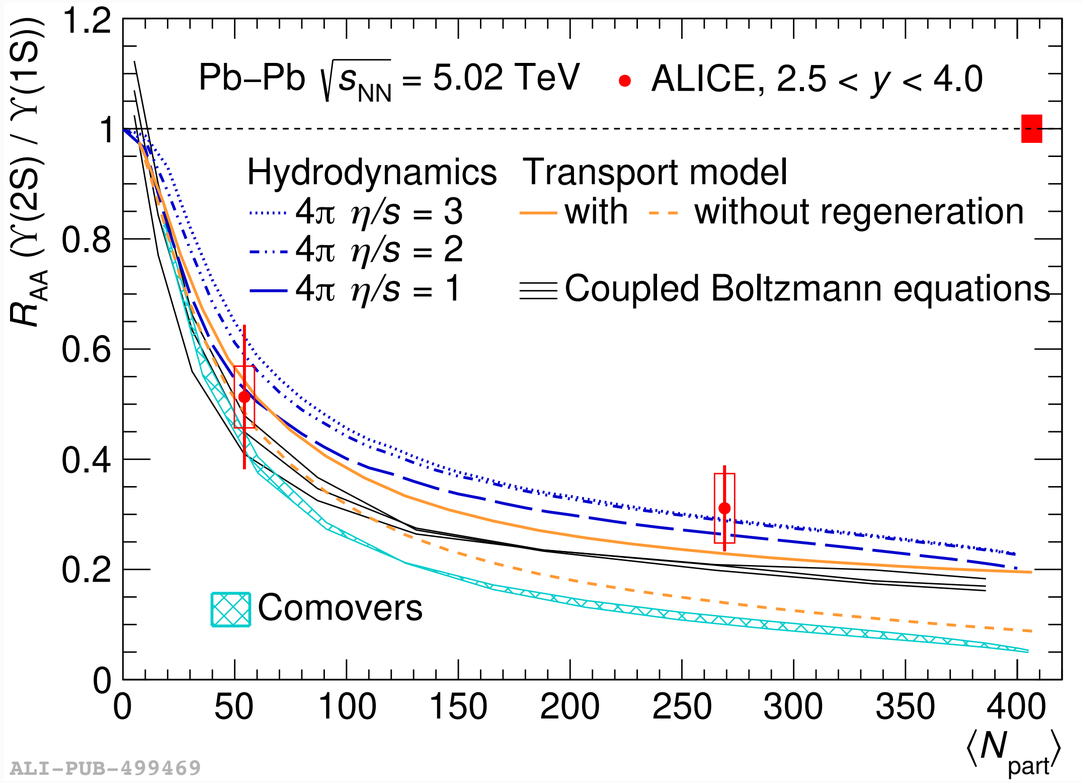


- Different sensitivity to the medium:
  Υ(1S):~1100 MeV Υ(2S):~500 MeV Υ(3S):~200 MeV
- Strong suppression vs centrality with sequential melting pattern:
  ➡ $R_{AA}(\Upsilon(1S)) > R_{AA}(\Upsilon(2S)) > R_{AA}(\Upsilon(3S))$
- Is bottomonium genuine thermometer of QGP?
  - ✓Feed-down contribution
    (i.e. P-wave states → excited Υ not measured)
  - ✓Regeneration contribution
  - ✓Cold nuclear matter effects?

Bottomonium production in Pb-Pb collisions

ALICE, PLB 822 (2021) 136579





SHM: A. Andronic et al., Nature 561 (2018) 321–330

Transport model: X. Du, R. Rapp, M. He PRC 96 (5) (2017) 054901

Coupled Boltzmann equations: X. Yao et al., JHEP (2020) 046

Comover: E.G. Ferreiro, J.-P. Lansberg, JHEP 10 (2018) 094

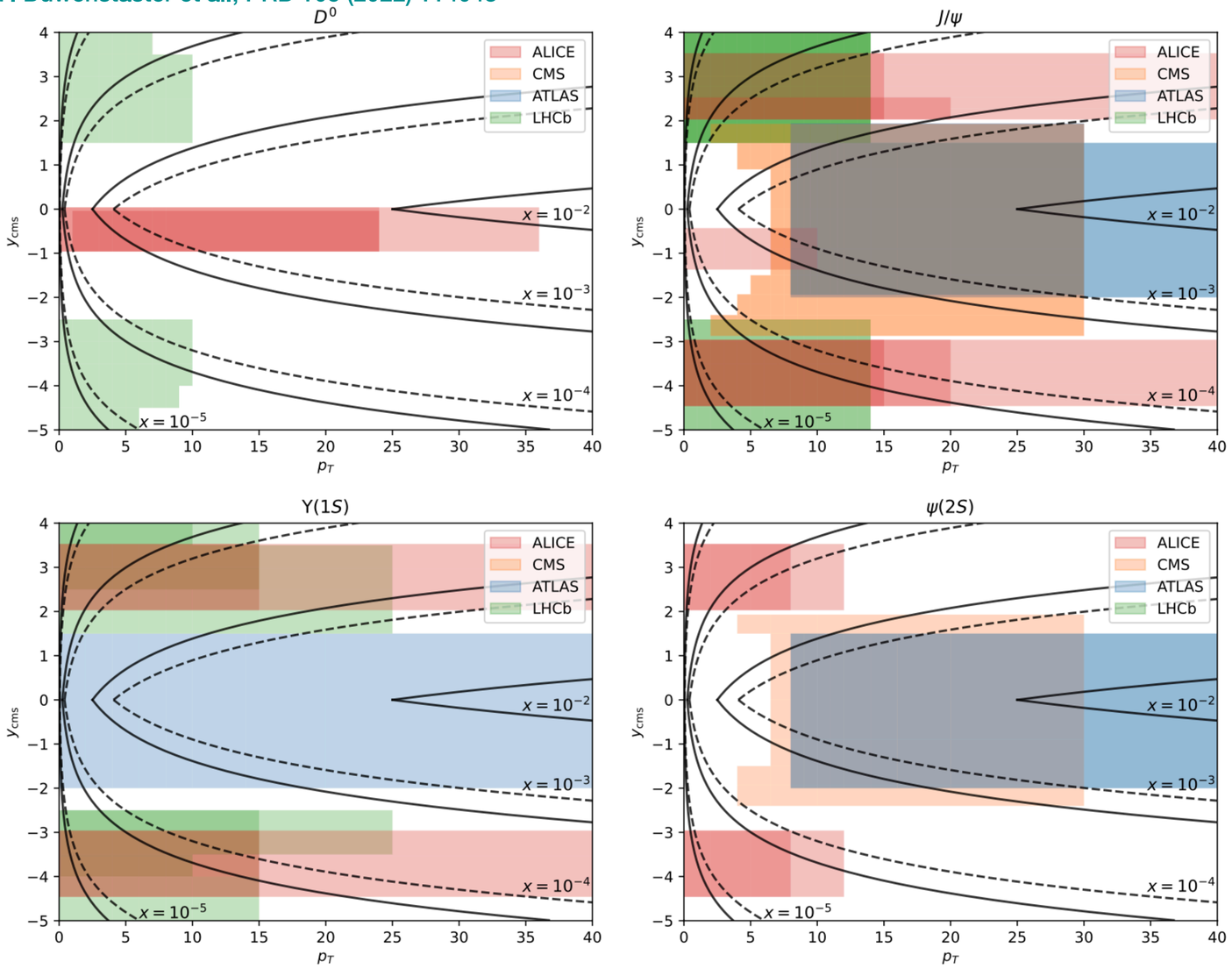
Hydrodynamics: B. Krouppa, M. Strickland, Universe, 2 (3) (2016) 16

- Relative yield (R_{AA}) of excited state w.r.t. ground state: model discriminator
  - ➡Cancellation of sources of uncertainty both in measurement and theoretical predictions
  - ➡Different slopes between the models - in tension with Comovers and SHM

Quarkonium production in p-Pb collisions at the LHC

- A baseline for quark-gluon plasma study in HI collisions
- Probes the **cold (or?) nuclear matter effects** i.e.
  - nuclear modification of parton distribution functions
  - saturation in the colour Glass Condensate (CGC) approach
  - multiple scattering and energy loss
  - breakup by comovers …

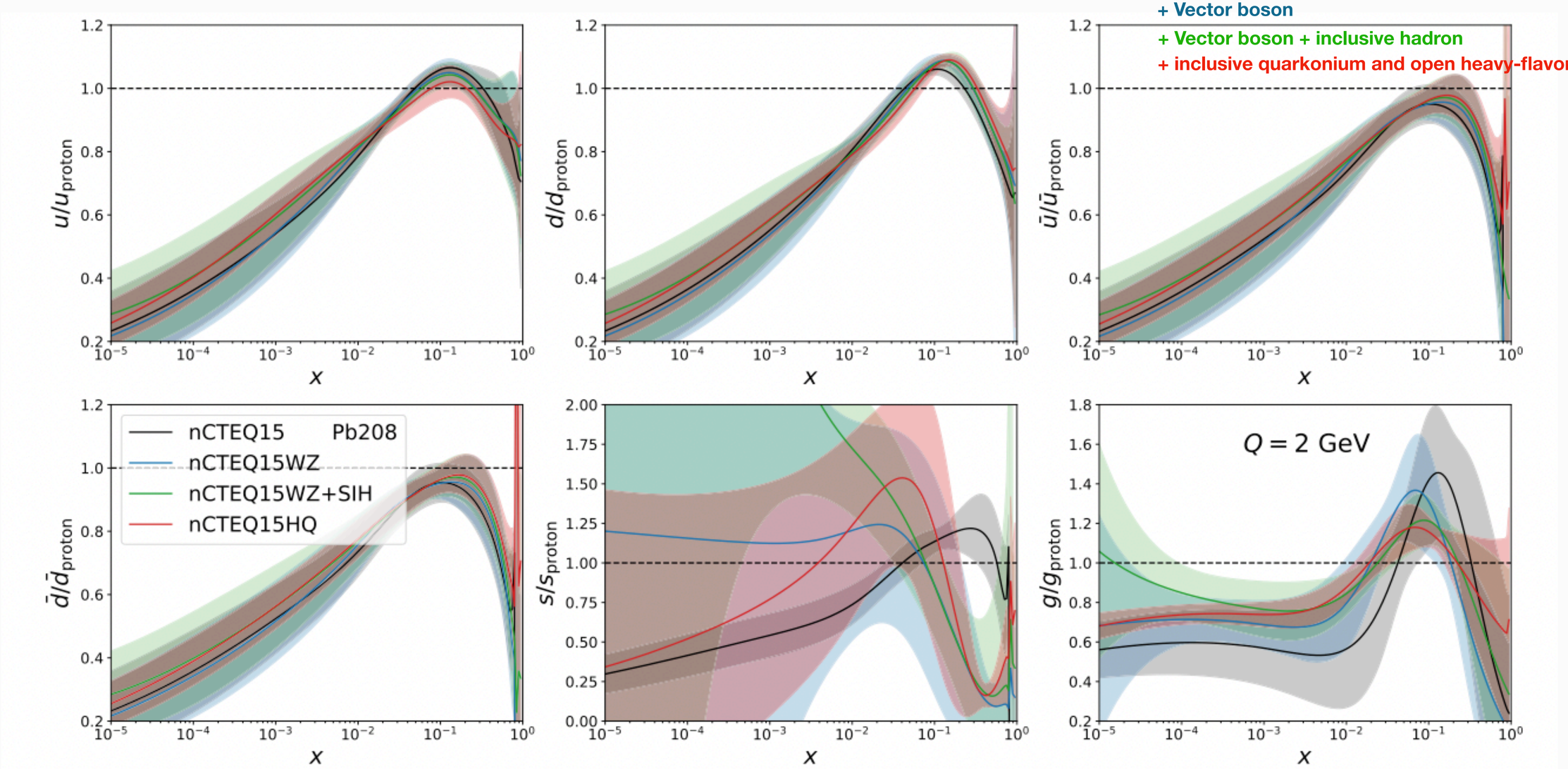
P. Duwenstäster et al., PRD 105 (2022) 114043



nPDFs@NLO: improved precision using LHC measurements

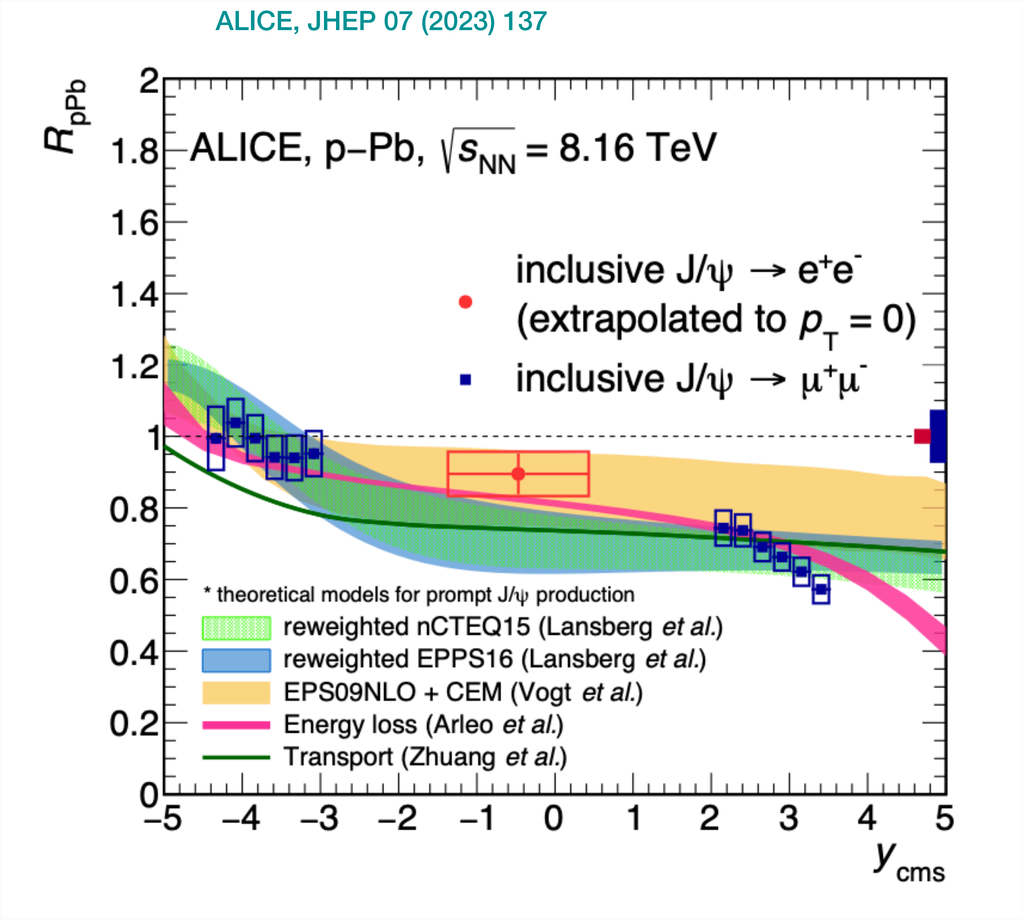
P. Duwenstäster et al., PRD 105 (2022) 114043

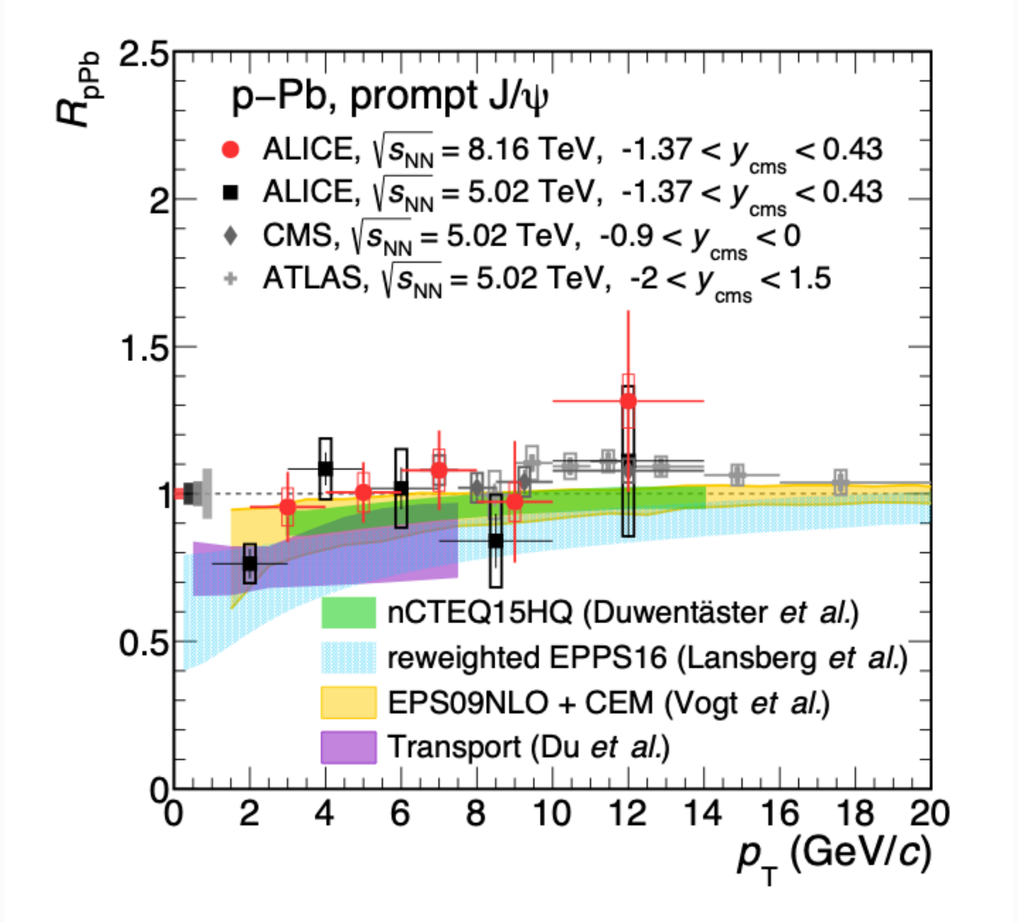
+ Vector boson
+ Vector boson + inclusive hadron
+ inclusive quarkonium and open heavy-flavor production



J/ψ R_{pA} in p-Pb collisions

ALICE, JHEP 07 (2023) 137

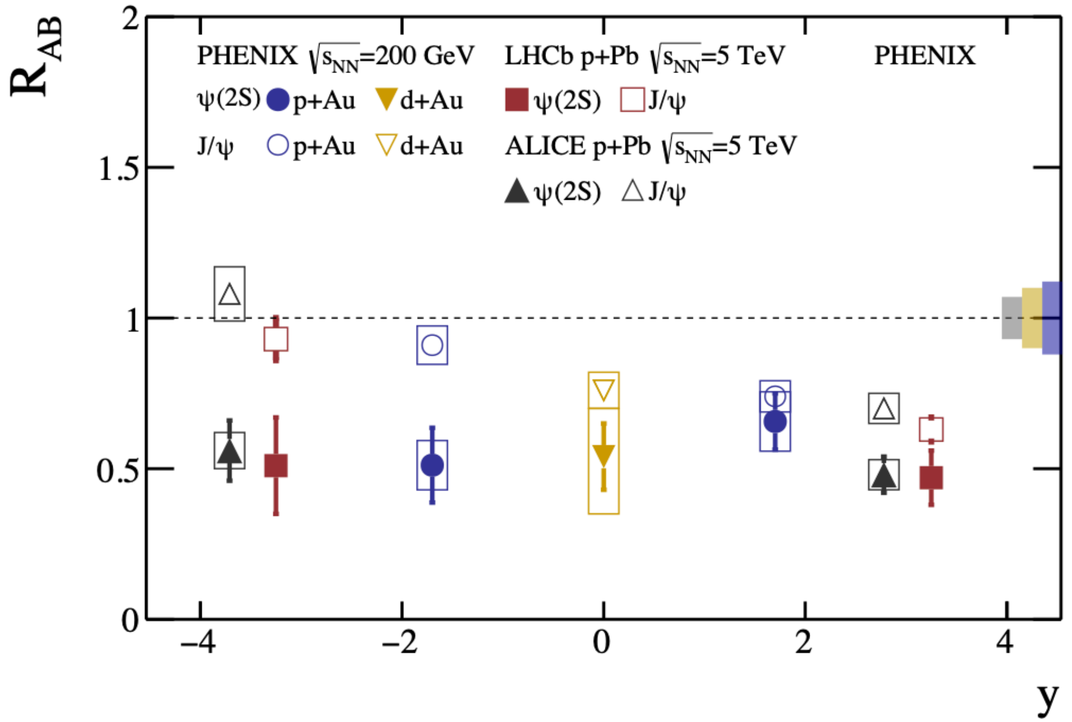




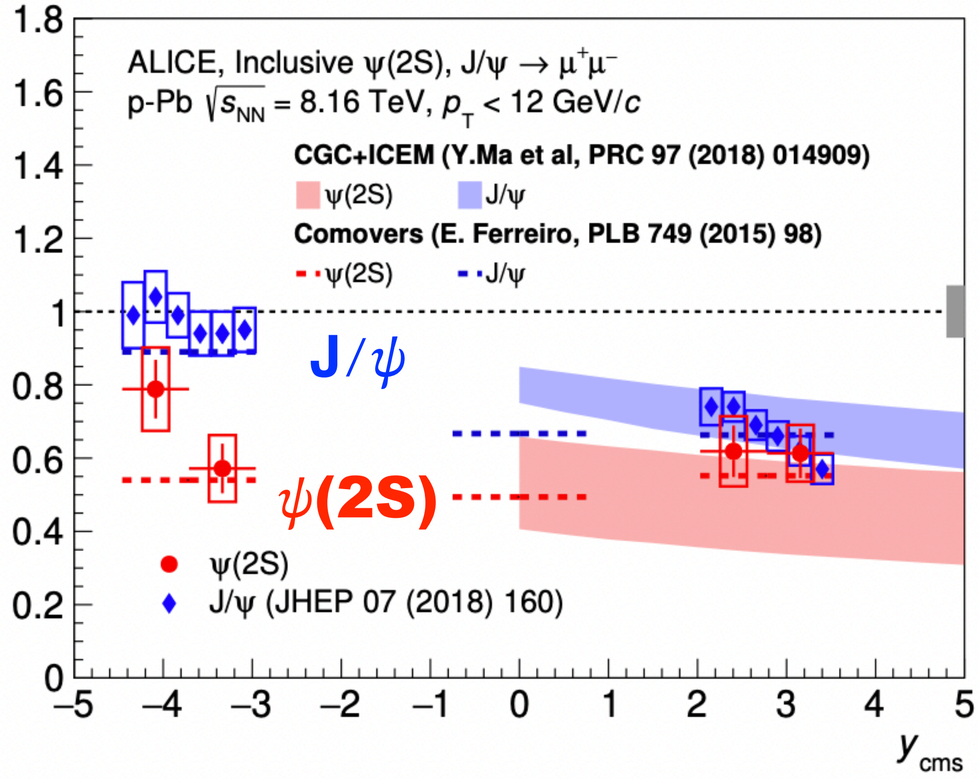
- Influence of rapidity dependent CNM effects; compatible with models including nPDF effects
- Mild suppression concentrated at low in p_T midrapidity

Excited charmonium states in p-Pb collisions

PHENIX, PRC 105 (2022) 064912



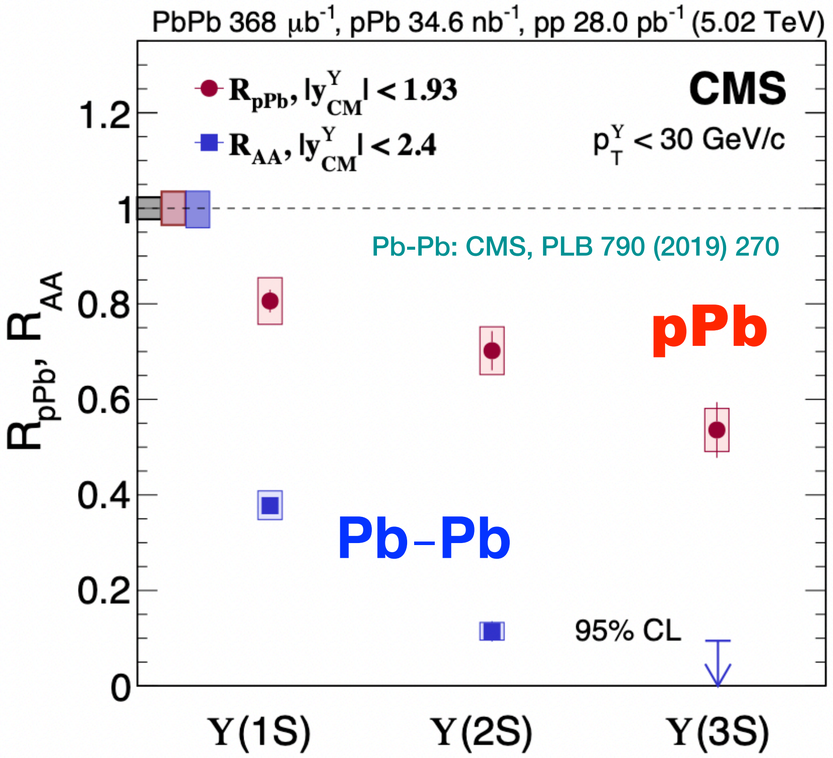
ALICE, JHEP 07 (2020) 237



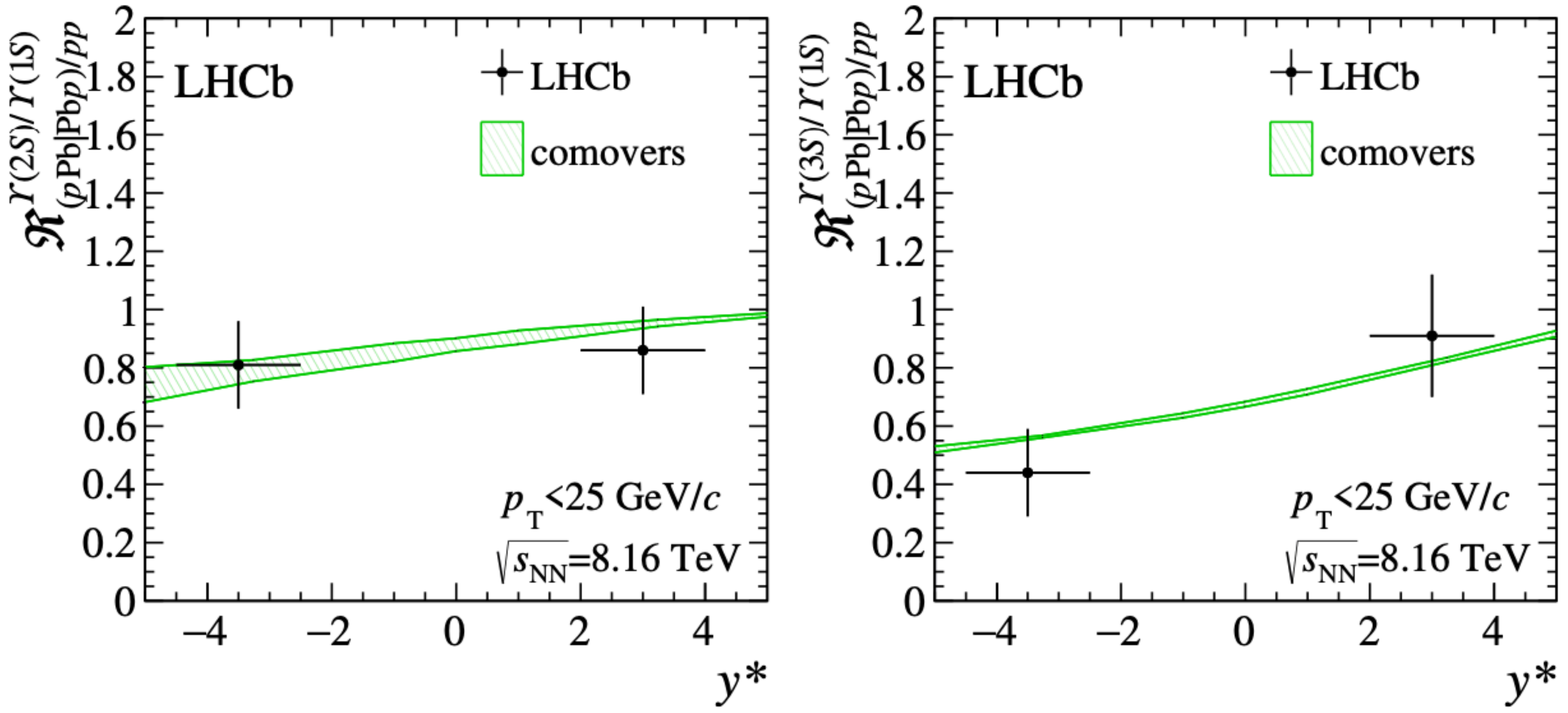
- Stronger suppression of ψ(2S) in backward-y both at RHIC/LHC
- Initial-state effects or coherent energy loss; largely independent on the specific charmonium resonance→ final-state effects? Comover model agrees with the measurement within uncertainty

Bottomonium R_{pA}

CMS, PLB, 835 (2022) 137397



LHCb, JHEP11(2018)194



- Sequential suppression observed in p-Pb collisions with improved precision for Y(1S), Y(2S) and Y(3S)
  → yet much less than in Pb-Pb collisions
- Suppression trend reproduced by nPDF + comover breakup Model

Bottomonium R_{pA}

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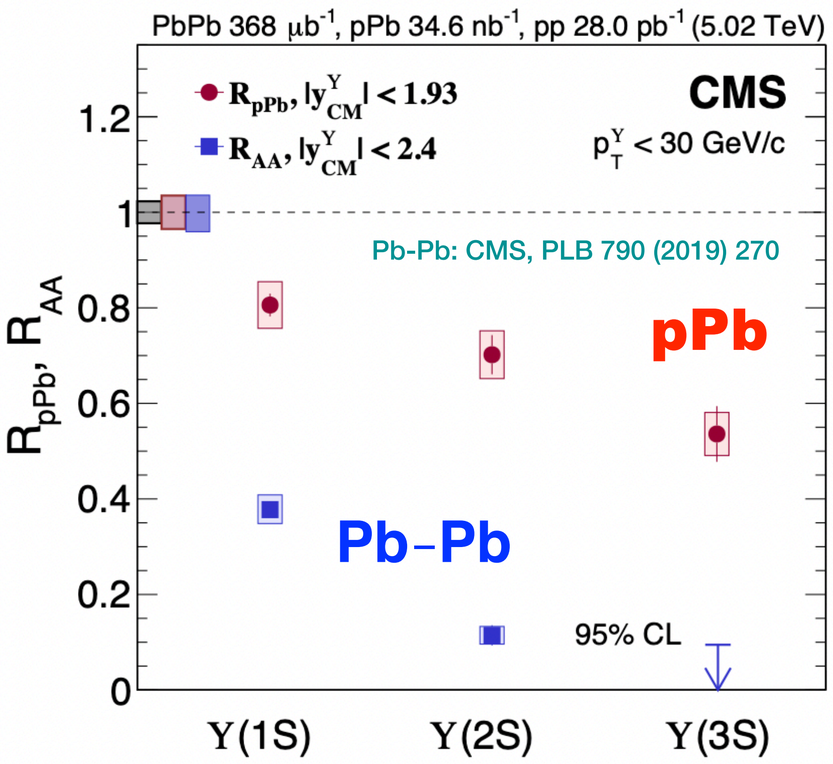
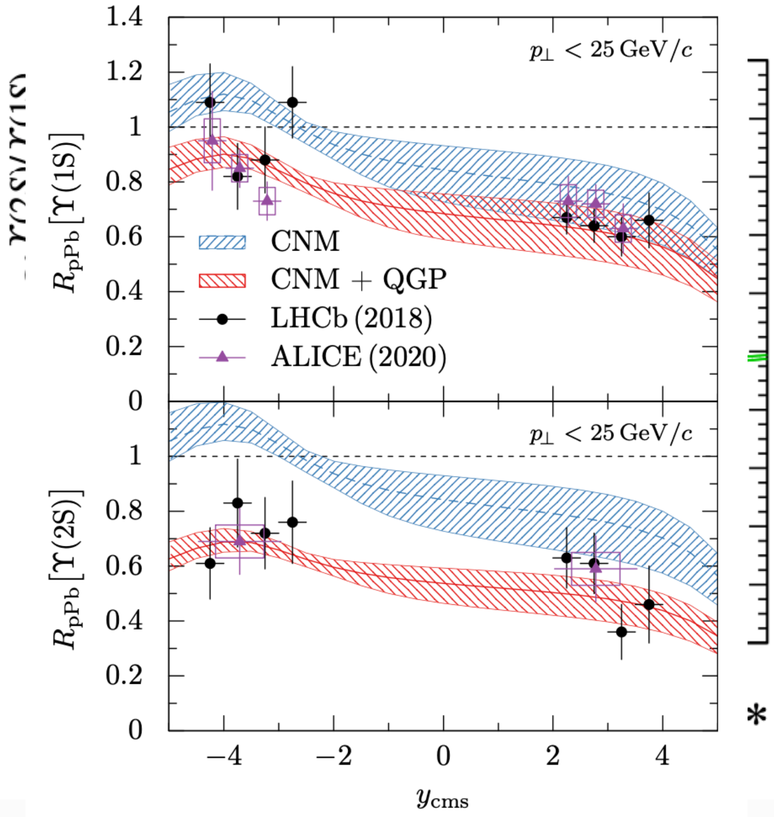
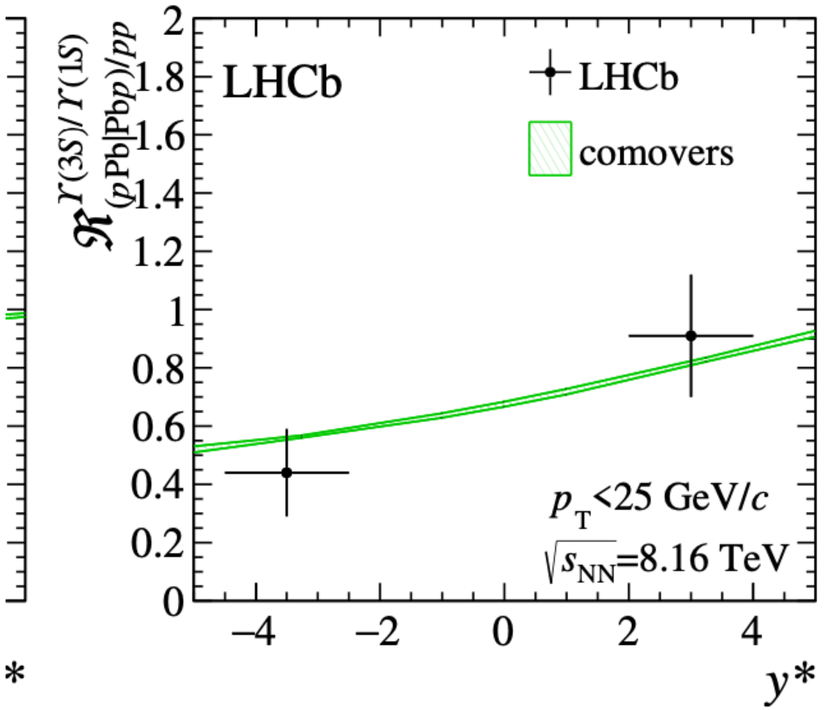


G. Wolschin, Int.J.Mod.Phys.A 35 (2020) 29, 2030016

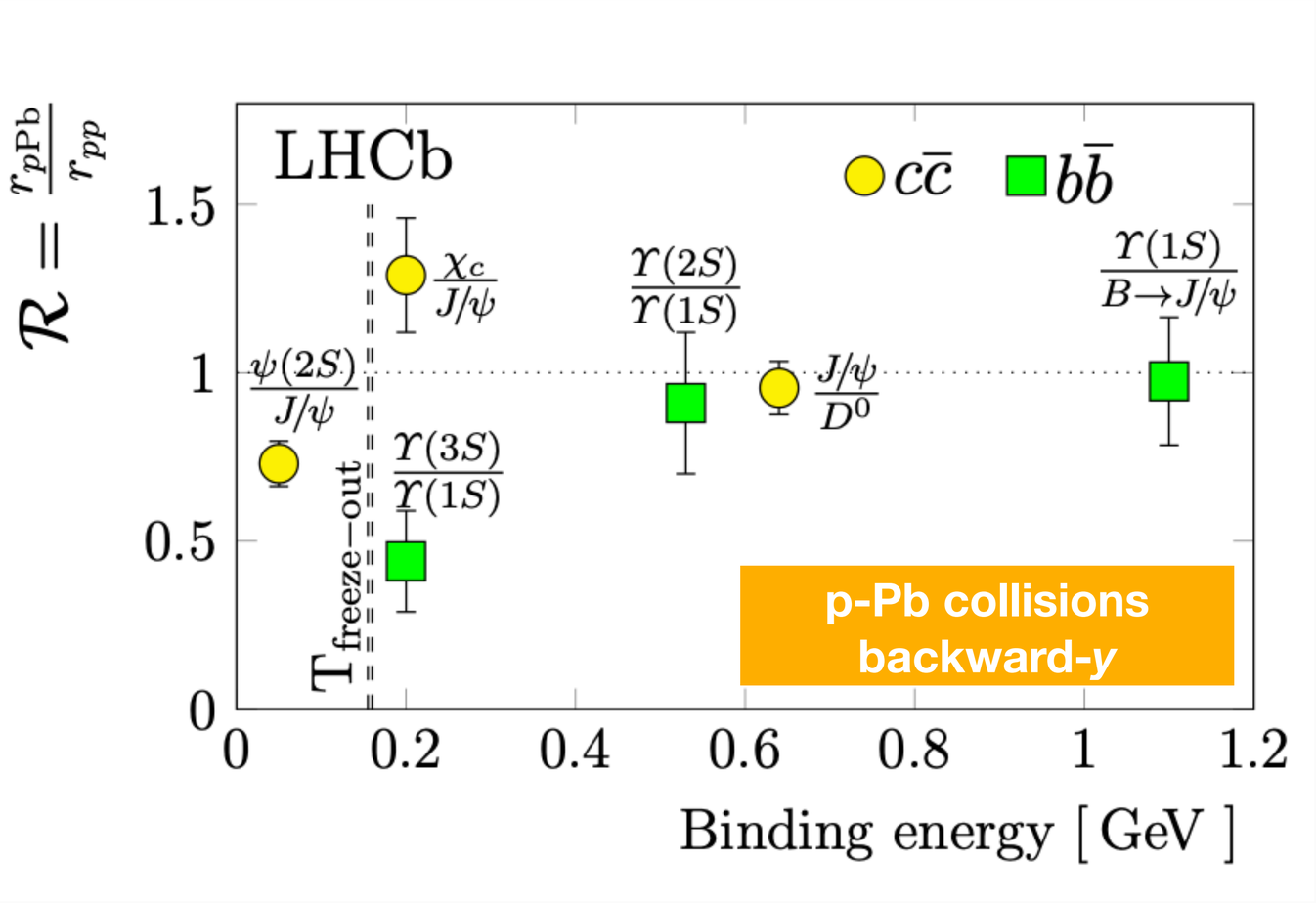




- Sequential suppression observed in p-Pb collisions with improved precision for Y(1S), Y(2S) and Y(3S) → yet much less than in Pb-Pb collisions
- Suppression trend reproduced by nPDF + comover breakup Model
- Hot-medium effects describe Y suppression in pPb collisions as well

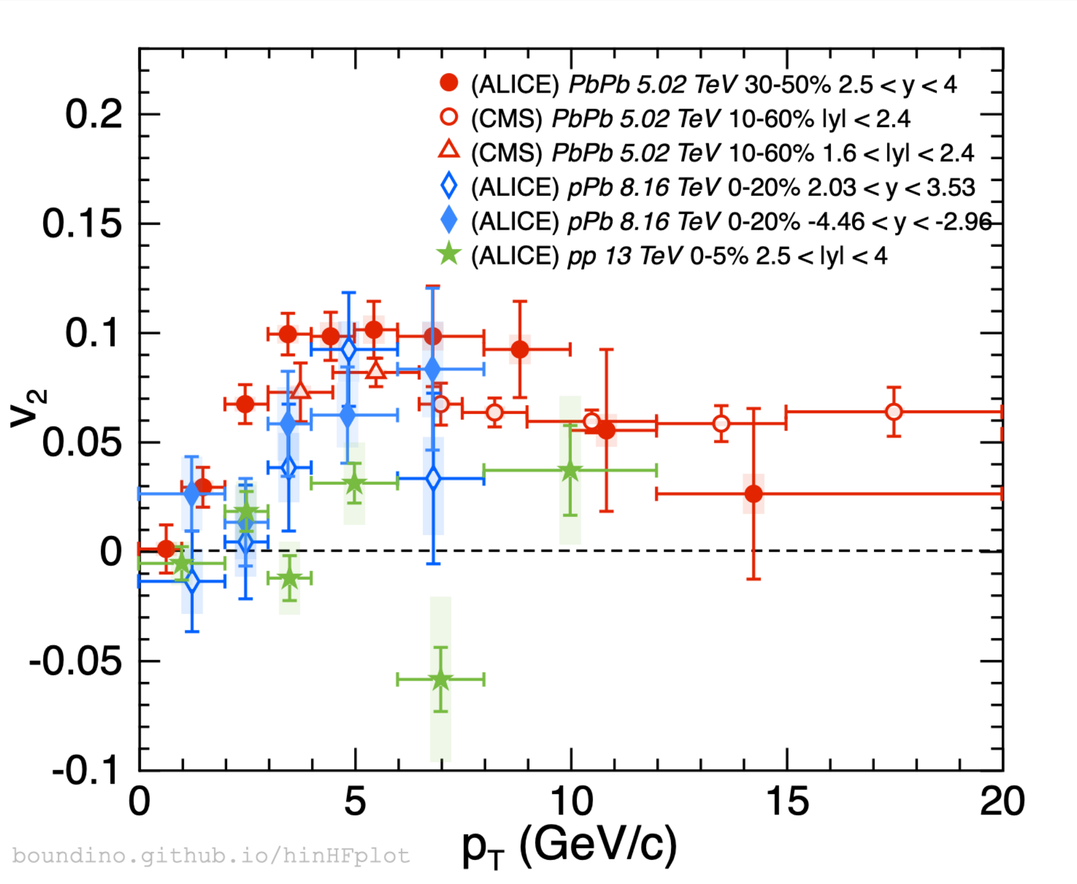
What kind of system is formed in p-Pb collisions?

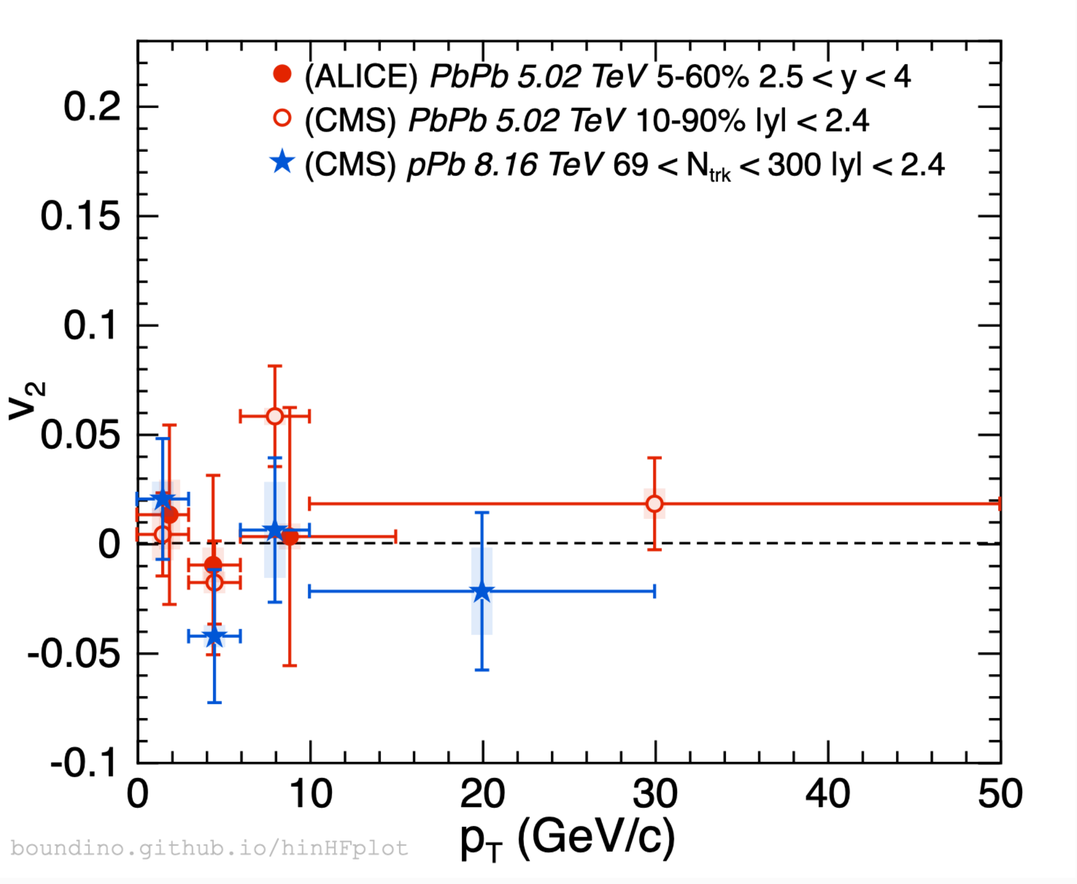
LHCb, PRL 132 (2024) 102302



- Systematic studies of quarkonium production in p-Pb collisions in backward-y as a function of binding energy
- R(χc / J/ψ) ~ 1: If there's a collective system formed in p-Pb collisions, the free energy (or temperature) of the system to be no larger than 180 MeV
  - Caveat: χc /J/ψ for p_T > 2 GeV/c
- R(Y(3S) / Y(1S)) < R(χc / J/ψ) ~ 1 despite of similar binding energies of χc and Y(3S)
  - Impact of feed-down?
  - Mass-dependent effects?
  - P vs S-wave?

Quarkonium elliptic flow

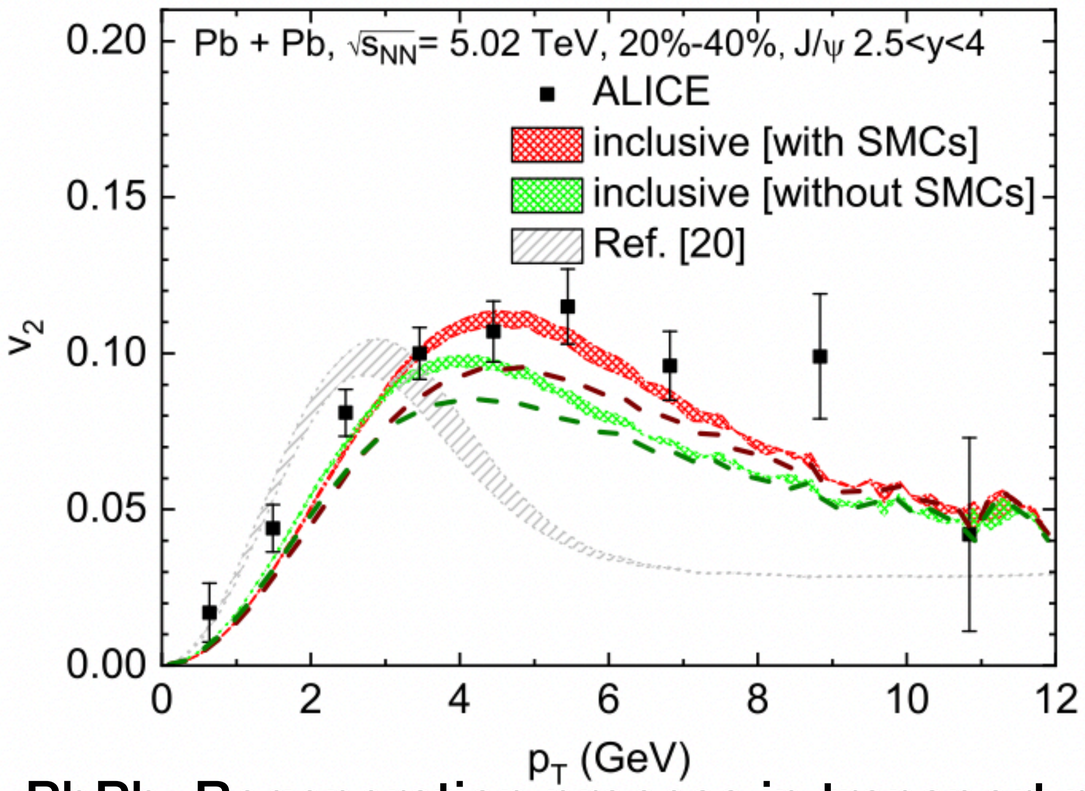




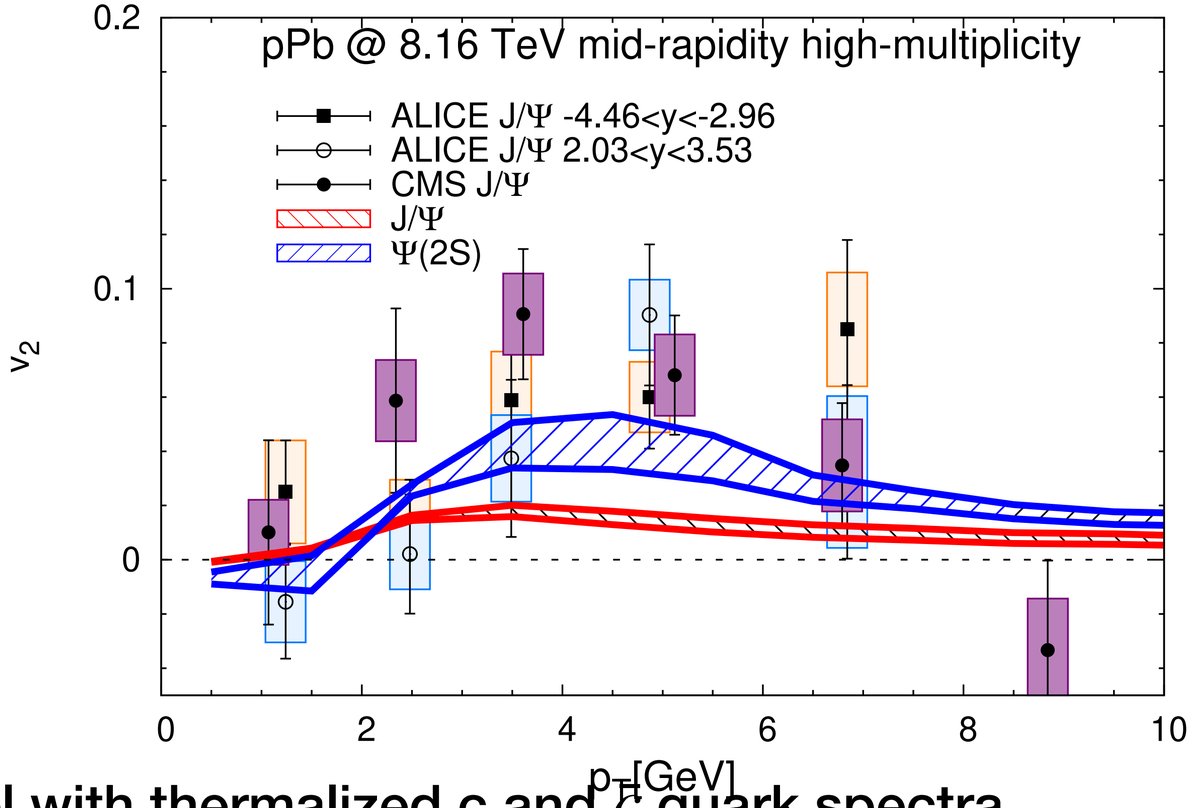
- Good agreement in CMS and ALICE in various systems; without strong rapidity dependence found in current precision
  - J/ψ : PbPb $v_2 \geq$ pPb $v_2 >$ pp $v_2 \approx 0$
  - Y(1S): PbPb $v_2 \approx$ pPb $v_2 \approx 0$

Quarkonium elliptic flow

M. He, B. Wu and R. Rapp, PRL 128 (2022) 162301



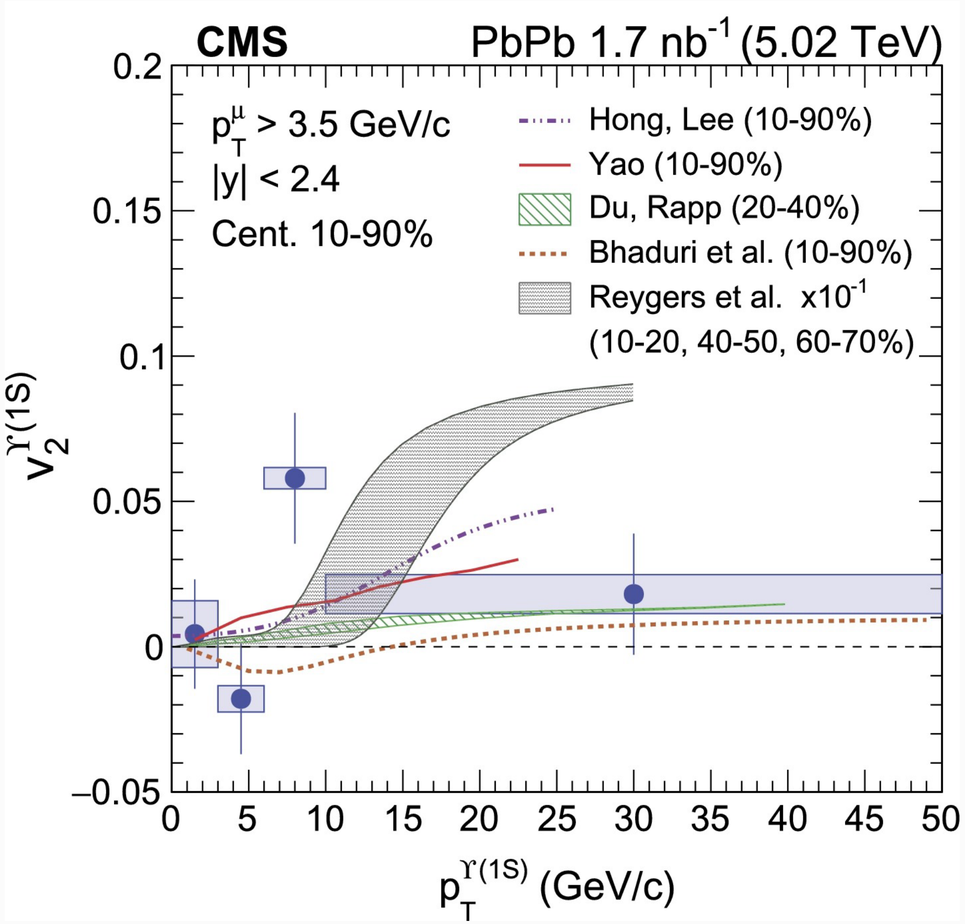
X. Du, R. Rapp, JHEP 03 (2019) 015 Review: A. Andronic, et. al. arXiv:2402.04366



- PbPb: Regeneration process in transport model with thermalized c and $\bar{c}$ quark spectra → c-quark phase space distributions from relativistic Langevin simulations (off-equilibrium spectra)
- Non-zero J/ψ v_2 in high multiplicity p-Pb collisions, underpredicted by theory including final-state collectivity at intermediate p_T

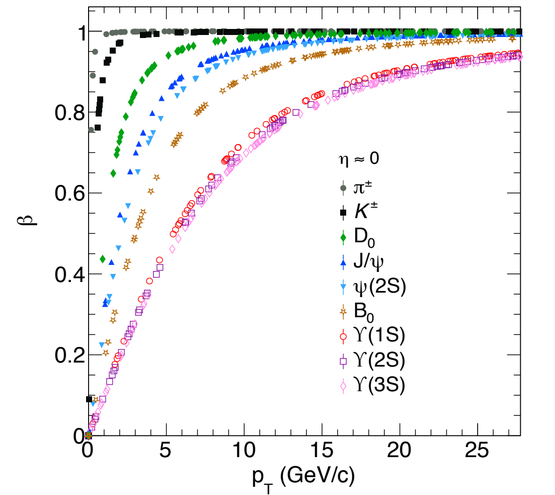
Υ(1S) elliptic flow

CMS Collaboration, PLB 819 (2021) 136385



Hong, Lee, PLB 801 (2020) 135147
Du, Rapp, PRC 96 (2017) 054901
Reygers et al., PRC 101 (2020) 064905
Yao et al., JHEP01 (2021) 046
Bhaduri et al., PRC 100 (2019) 051901

- No evidence for finite Υ(1S) v_2 over measured p_T range as in previous measurement
- Consistent with the different model predictions; but tension at high p_T
- Y mesons much slower than other species due to their heavy mass
  - Low-p_T: $v^{\Upsilon} < v_{flow}^{QGP}$ → Cannot escape QGP
  - Intermediate p_T : $v^{\Upsilon} \simeq v_{flow}^{QGP}$ → Long effective travel distance (depending on axis direction)
  - High-p_T : $v^{\Upsilon} > v_{flow}^{QGP}$ → Experience initial geometry from fast QGP escape
- Requires better precision measurement at high p_T

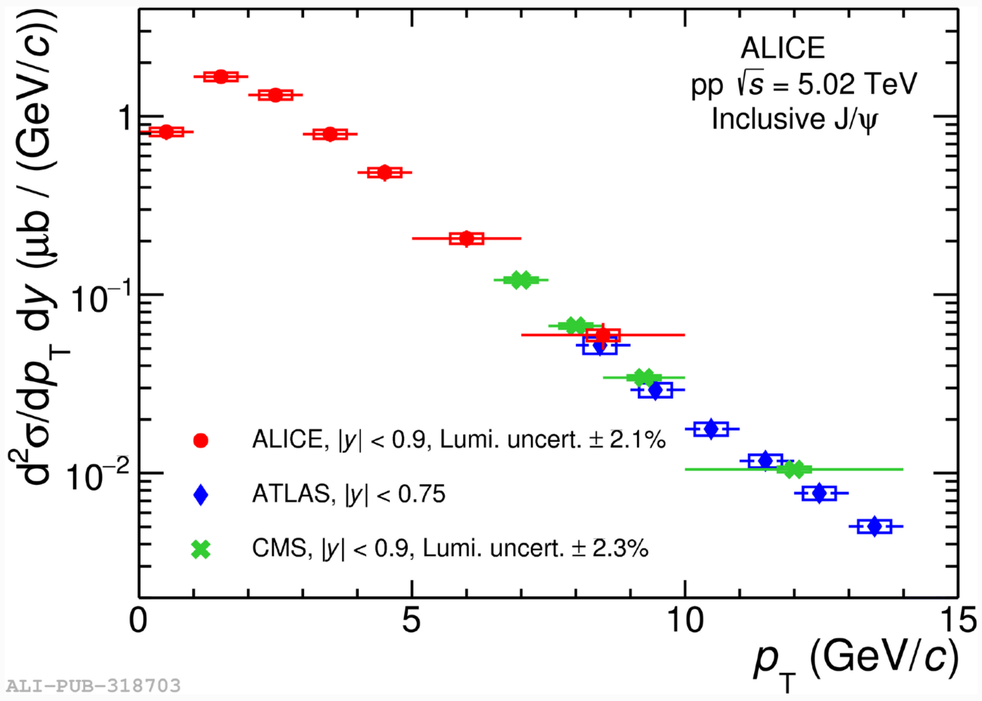


J. Park, Private communication

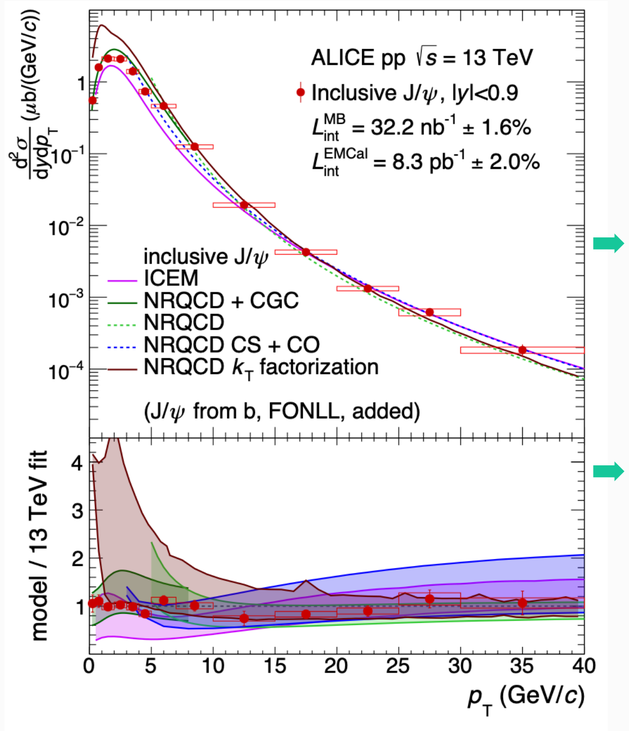
Measurements in pp collisions

- Provide reference for p-Pb and Pb-Pb collisions
- Understand production mechanism; both perturbative and non-perturbative QCD processes involved
- Quarkonium production associated with event properties: interplay between hard and soft particle, possible collectivity

ALICE Collaboration, JHEP 10 (2019) 084



ALICE Collaboration, EPJC 81 (2021) 1121

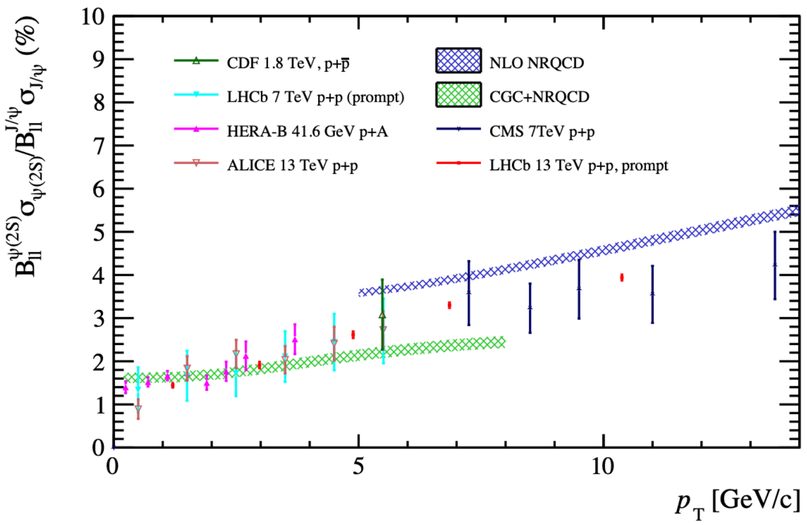


➡ complementary measurements different kinematic coverages with good agreements

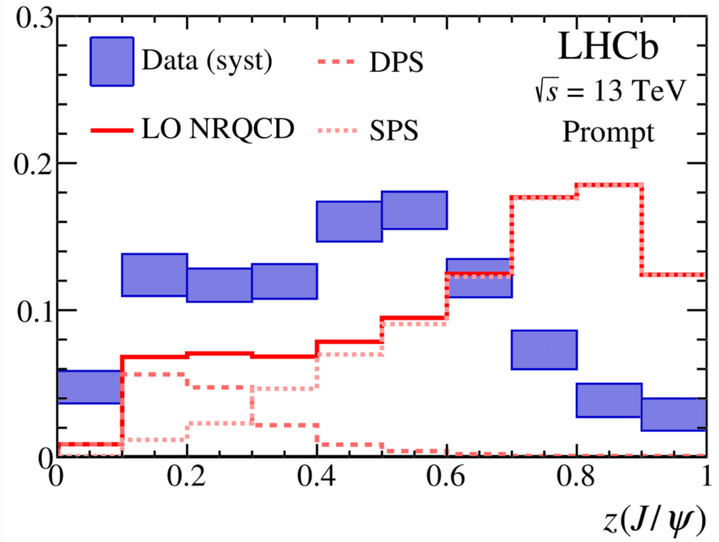
➡ Small experimental uncertainties compared to theoretical uncertainties

Constraining models with various observables

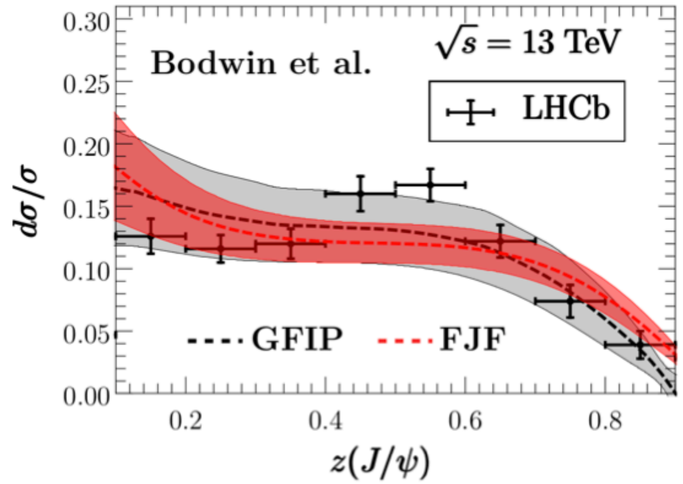
LHCb. JHEP 05 (2024) 243



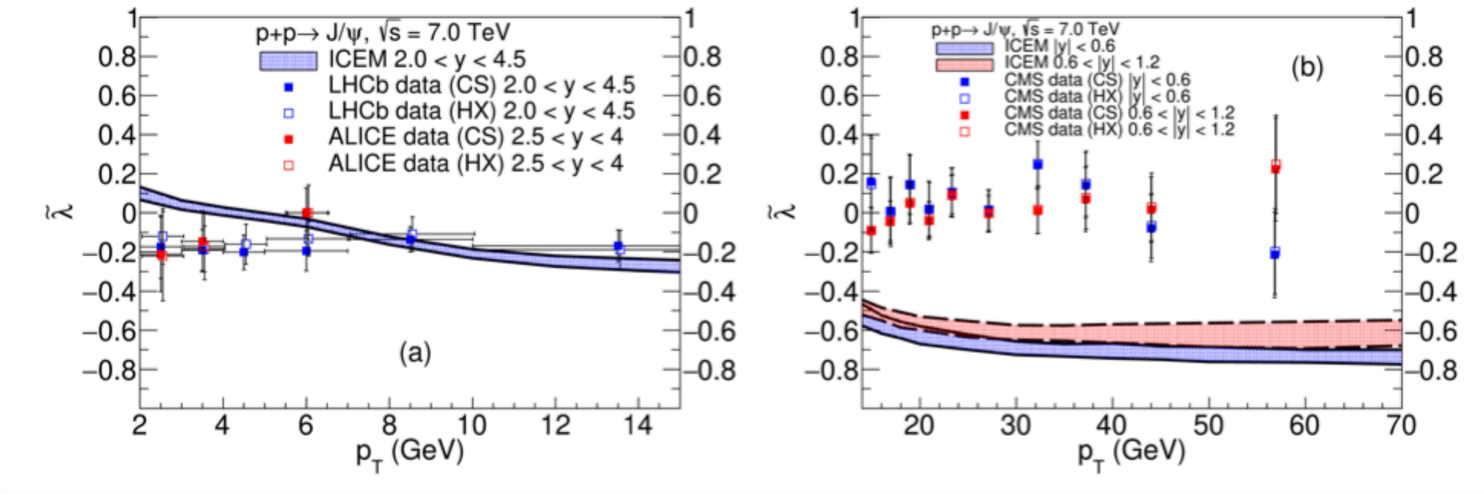
LHCb, PRL 118 (2017), 192001



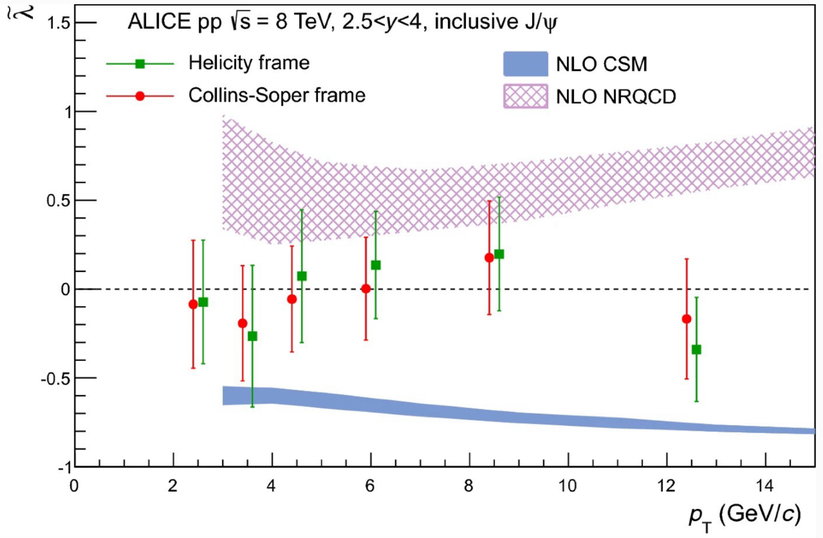
Bain et al., PRL 119 (2017), 032002



V. Cheung and R. Vgt, PRD 104 (2021) 9, 094026

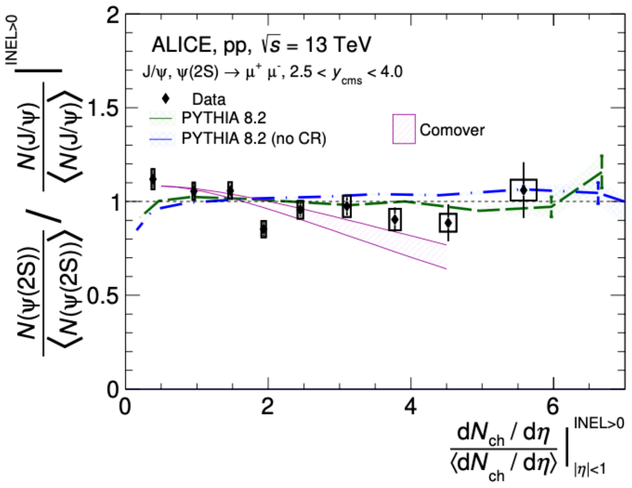


ALICE, EPJC 78 (2018) 562

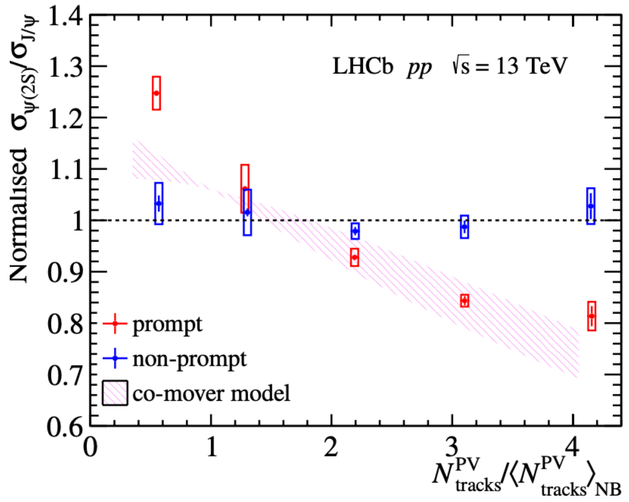


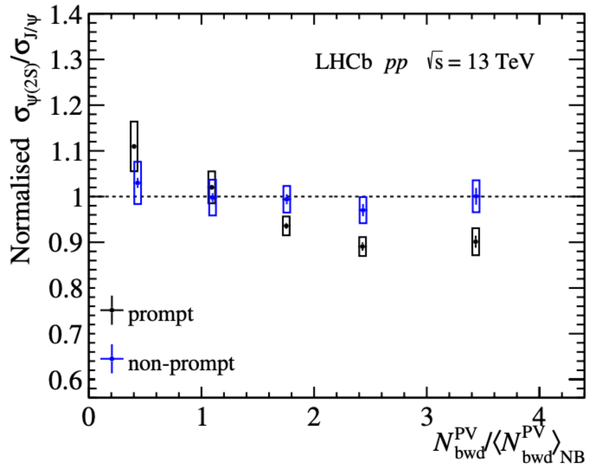
Charmonium production vs. event activity

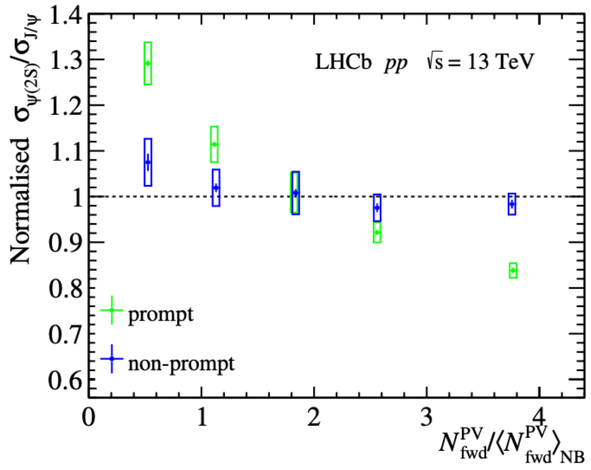
ALICE, JHEP 06 (2023) 147



LHCb, JHEP 05 (2024) 243

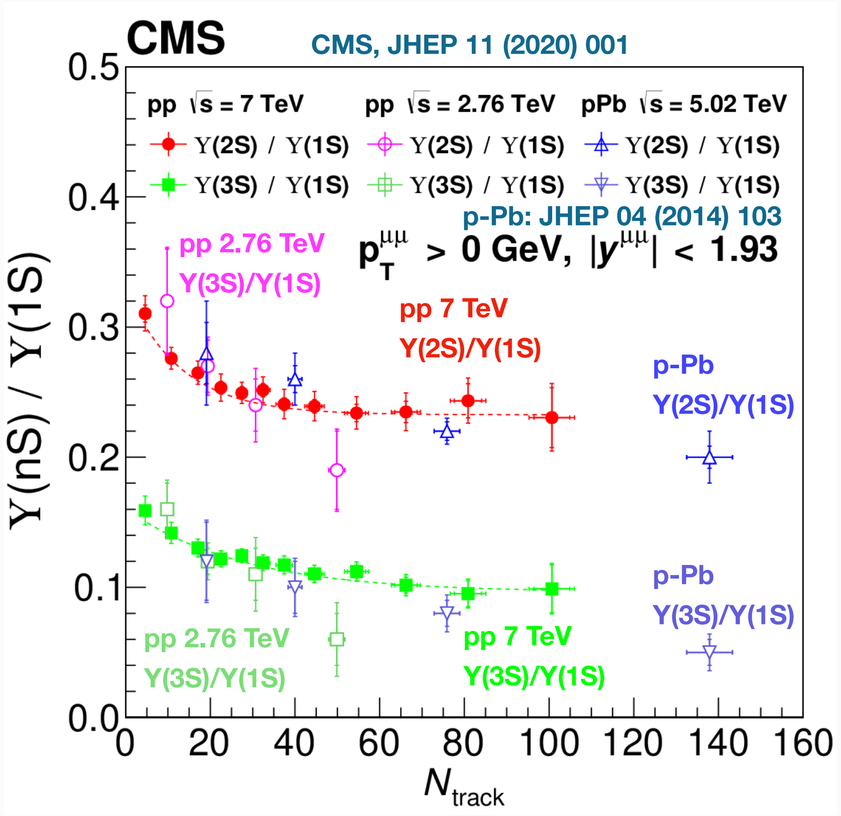


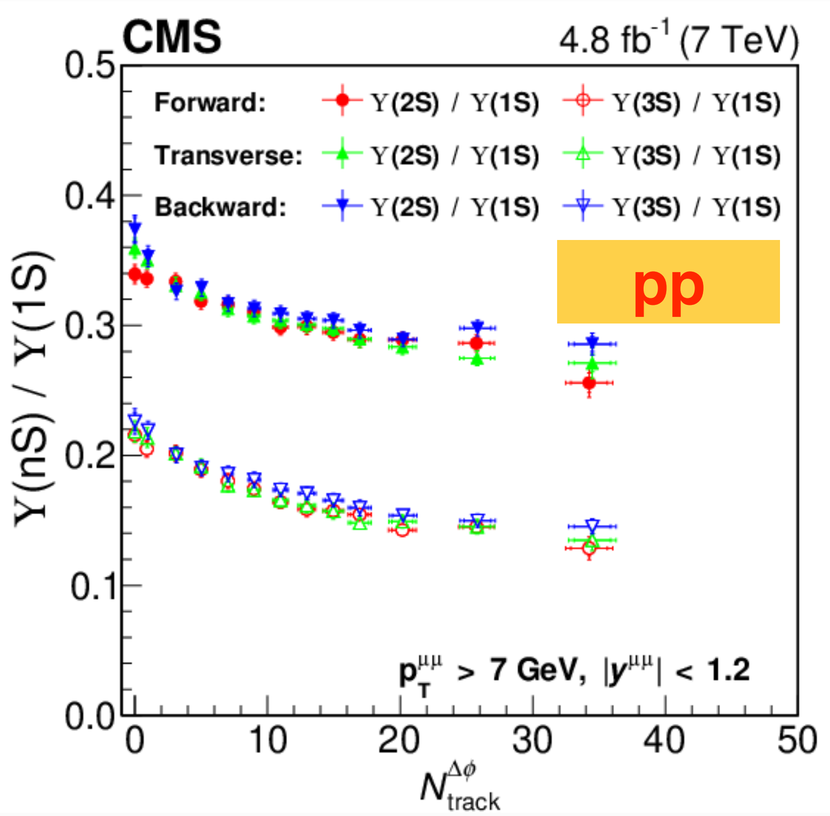


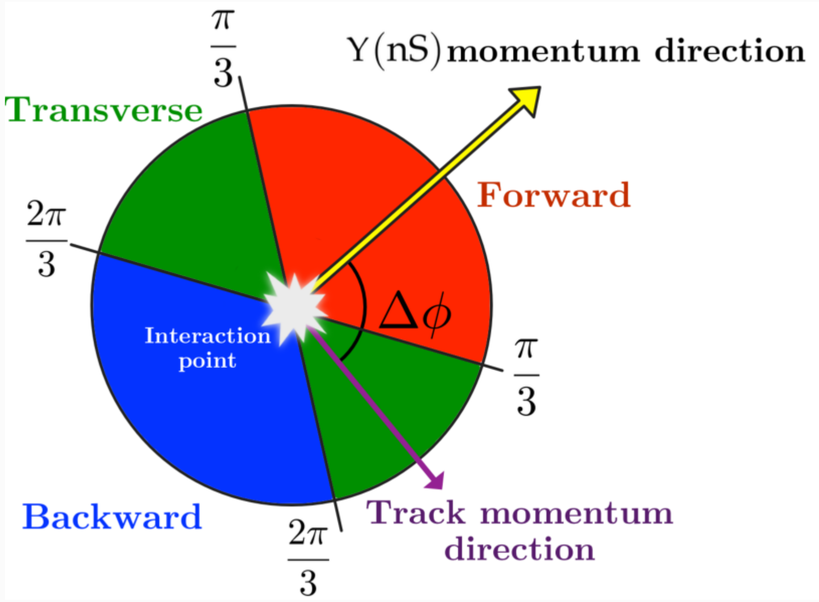


- ALICE ψ(2S)/J/ψ (fwd-y) vs. mid-y mult. compatible with
  - unity presented in PYTHIA
  - Linear decrease trend in comover model
- LHCb prompt ψ(2S)/J/ψ (fwd-y) vs. mult. favored in linear decrease trend in comover model; slope changes based on $\Delta\eta$ difference between quakonium and multiplicity window
- Non-prompt ψ(2S)/J/ψ (fwd-y) vs. mult. consistent with unity and no $\Delta\eta$ dependence seen

Bottomonium production vs. event activity







- Y(2S)/Y(1S) and Y(3S)/Y(1S) decreases with multiplicity in pp as well as in p-Pb collisions
- Decreasing trend with multiplicity seen for all azimuthal angles at high p_T
  → Connection to underlying event (UE)

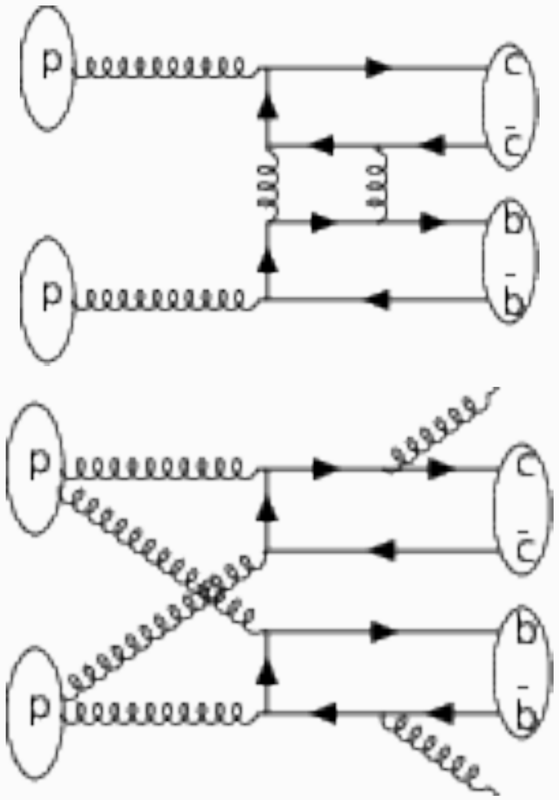
Summary and outlook

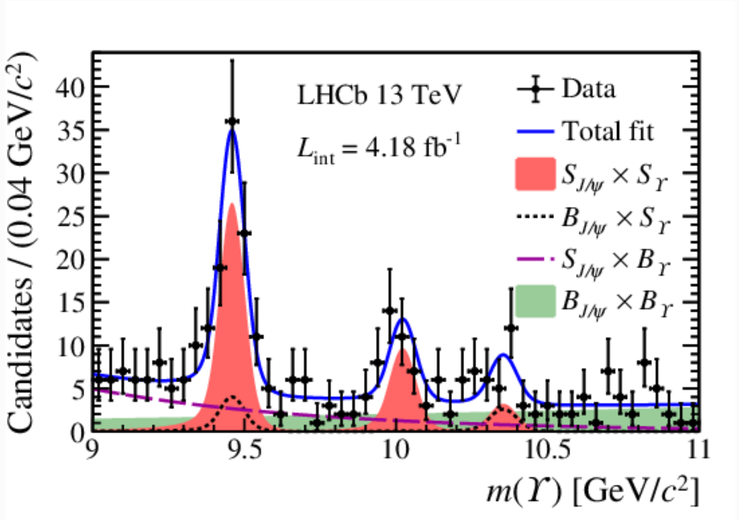
- Higher precision, more differential measurements achieved in all collision systems and **new observables become accessible** for quarkonium sector
- **Pb-Pb collisions:**
  - interplay of suppression and regeneration
  - strong hints for charm quark thermalization in QGP, yet open questions left
- **p-Pb collisions:** more than initial state cold nuclear matter effects?
- **pp collisions:** deeper understanding of quarkonium production mechanism and effects of underlying event

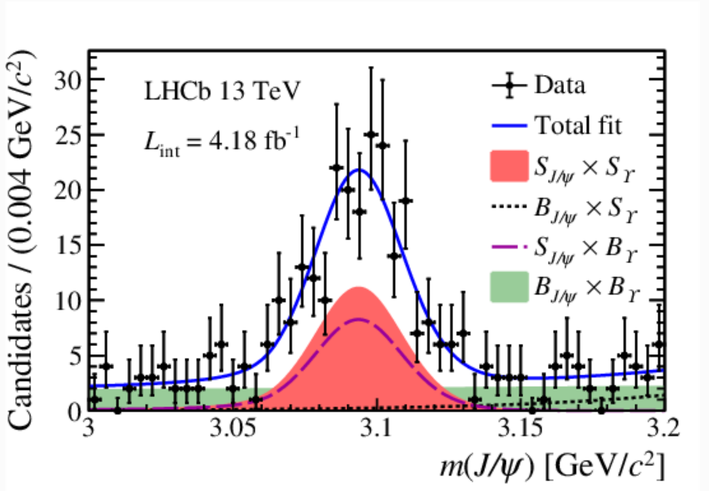
Topics not covered today: Double Parton Interaction

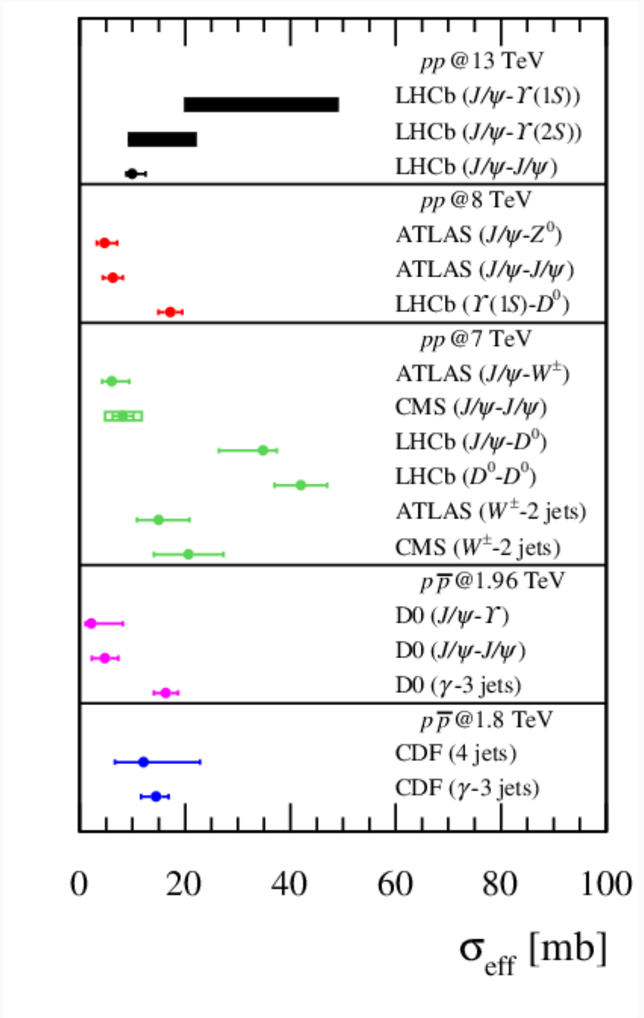
Associated quarkonium production → Direct probe for MPI

LHCb, *JHEP* 2308 (2023) 093



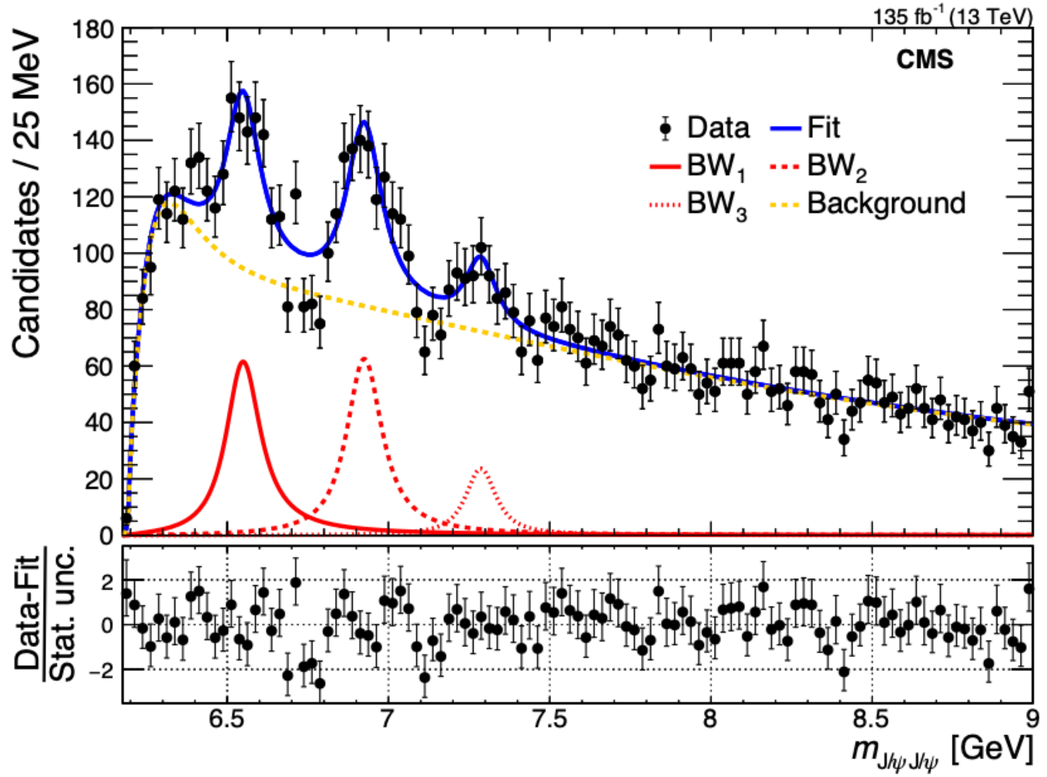


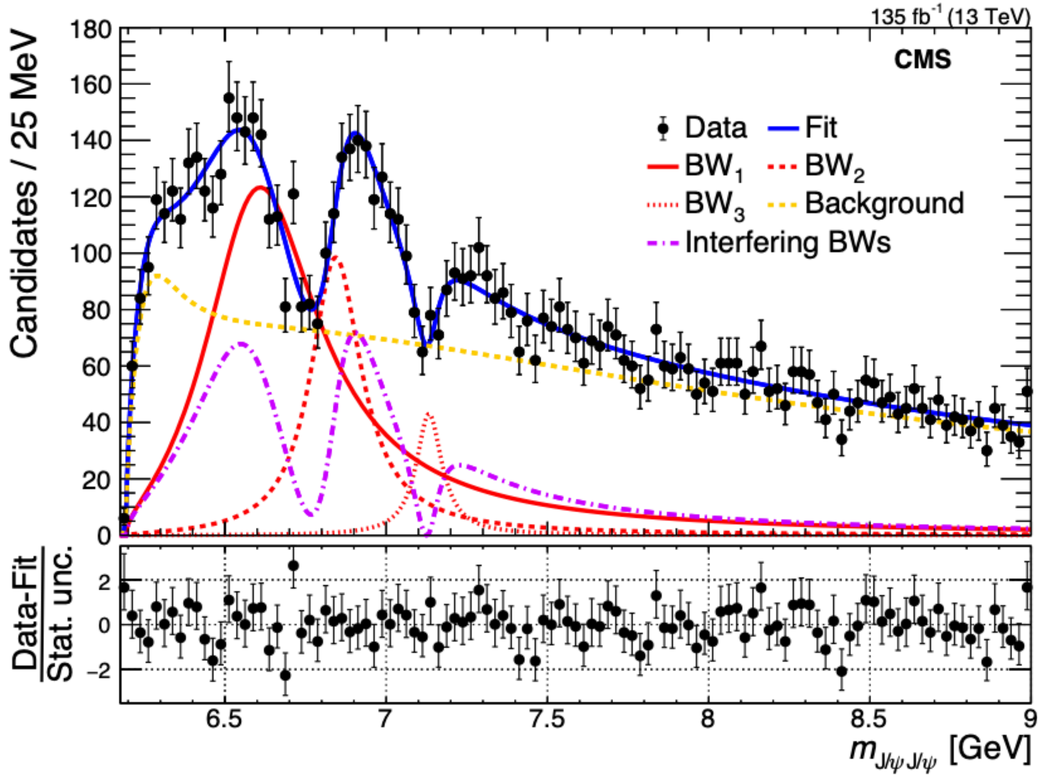




Topics not covered today: Search for exotica

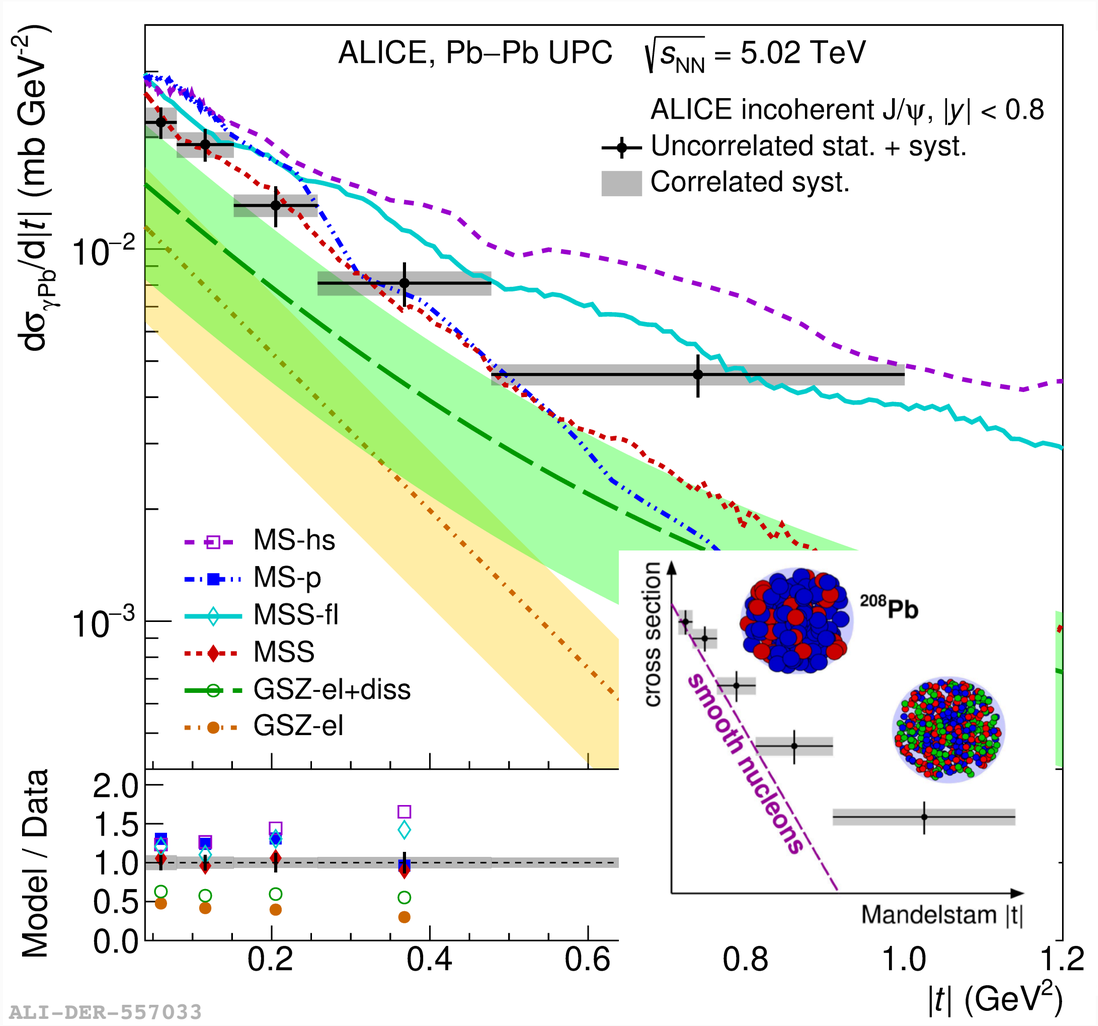
CMS, PRL 132 (2024) 111901



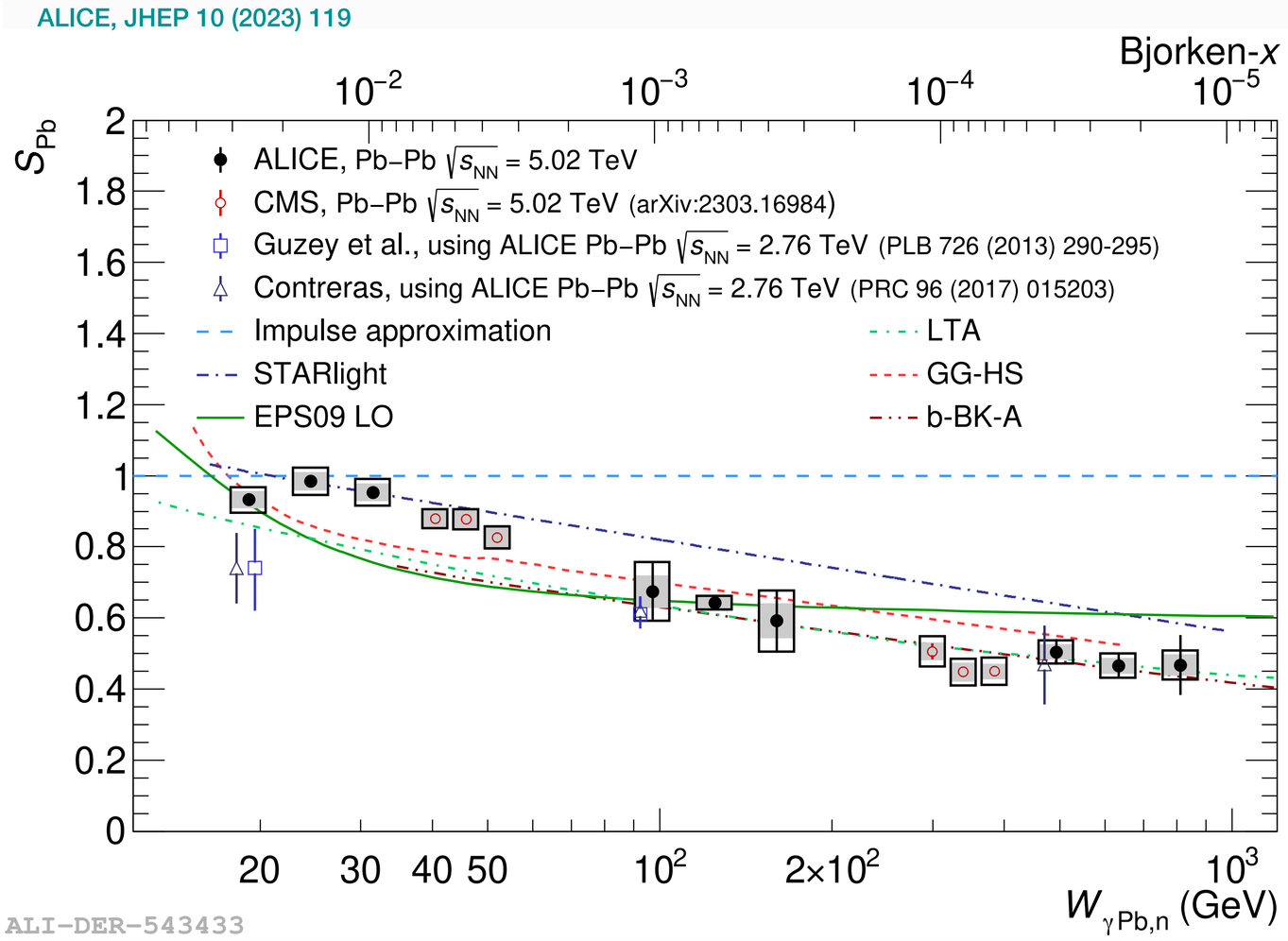


Topics not covered today: Role of quarkonium in UPCs

ALICE, PRL 132 (2024) 162302



ALICE, JHEP 10 (2023) 119



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- Not covered today:

LHC Run 3 program started and smoothly ongoing!!
→ much larger data sample expected with upgrade detectors

STAY TUNED!!