

The 10th Asian Triangle Heavy-Ion Conference – ATHIC 2025
13-16 January 2025, Berhampur, Odisha, India

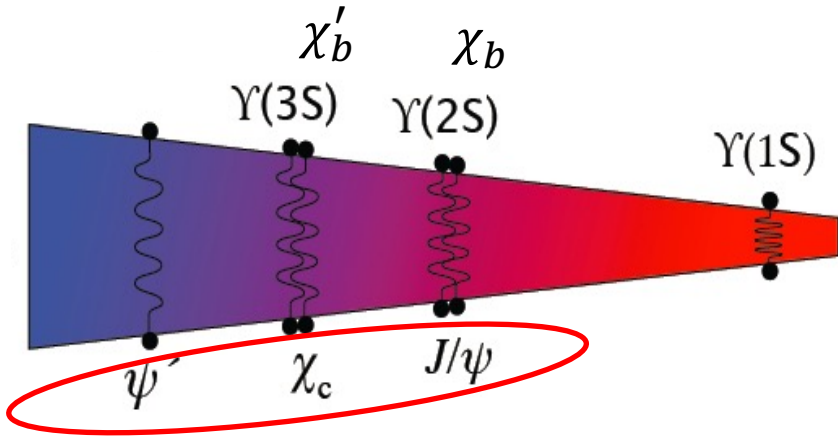


Charmonium Measurements in Relativistic Heavy Ion Collisions

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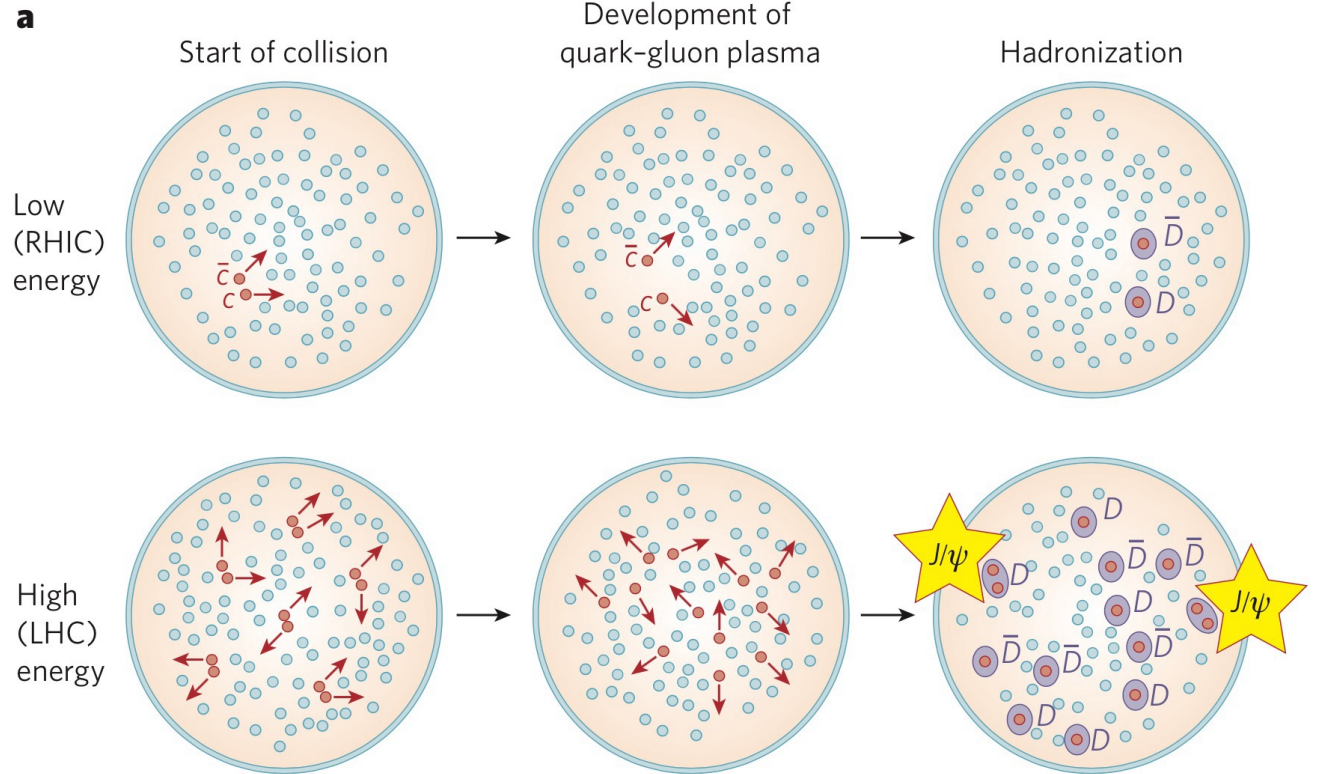




S. Digal, P. Petreczky, H. Satz, PLB514, 57 (2001)

Hot medium effects:

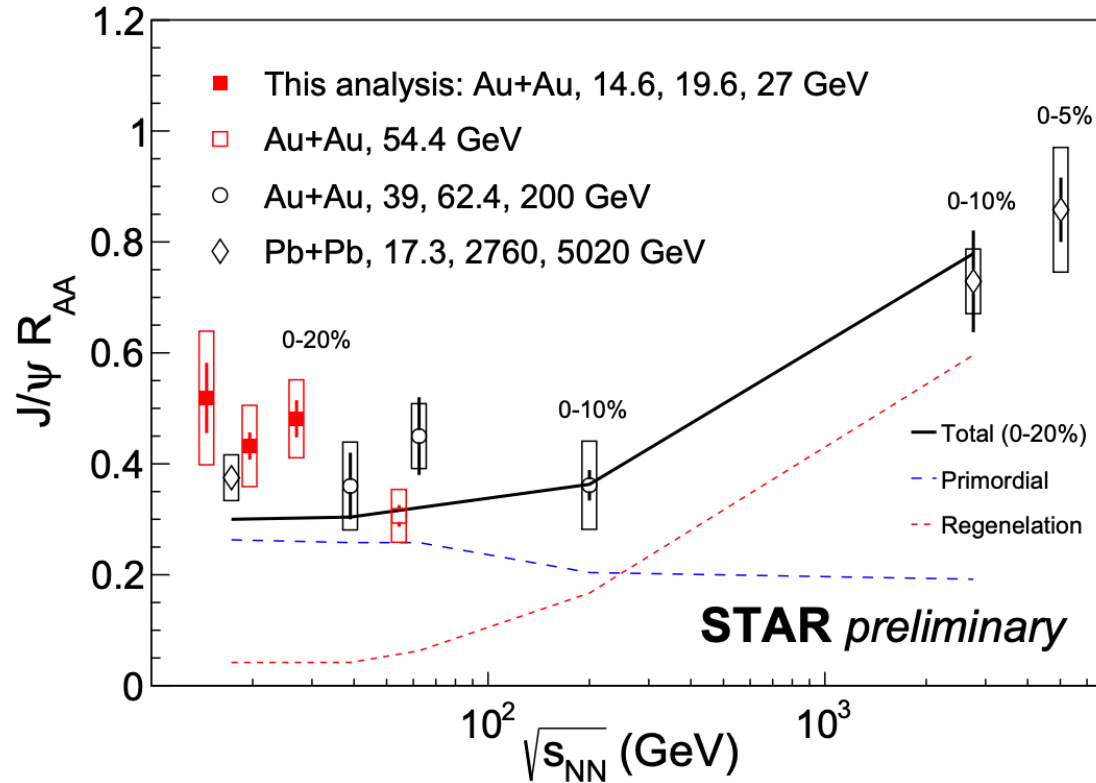
- Melting in QGP
- Regeneration
- Jet quenching?



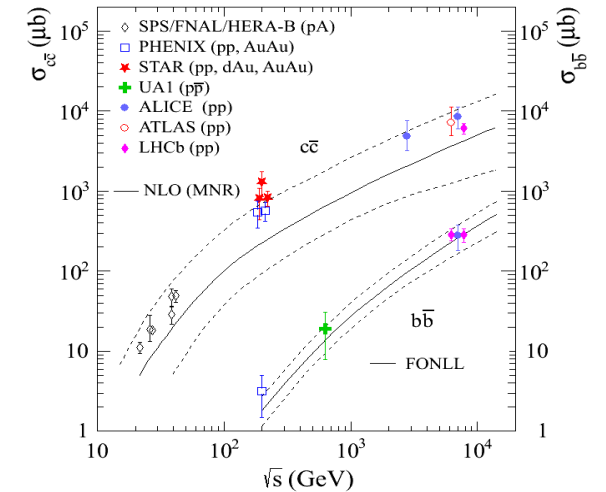
P. Braun-Munzinger, J. Stachel, Nature 448, 302 (2007)
A. Andronic et. al., Nature 561, 321 (2018)



Energy Dependence of J/ψ Suppression



NA50, PLB 477, 28 (2000)
 Wei Zhang, QM2023
 STAR, PLB 771, 13 (2017)
 Kaifeng Shen, SQM2021
 ALICE, PLB 734, 314 (2014)
 ALICE, PLB 849, 138451 (2024)



SPS



RHIC



LHC

CNM domain

CNM + Melting + regeneration

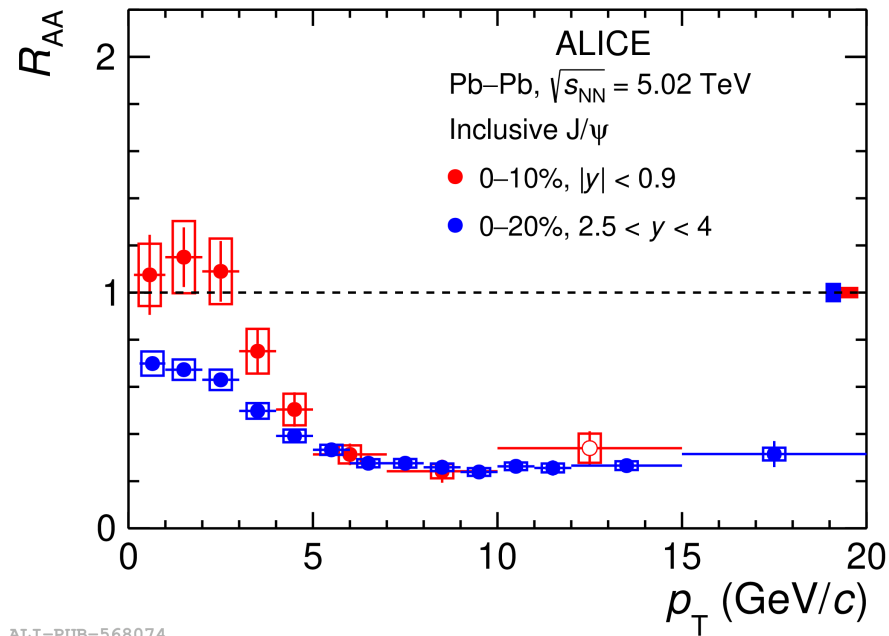
Regeneration domain

20 years efforts at STAR and the LHC



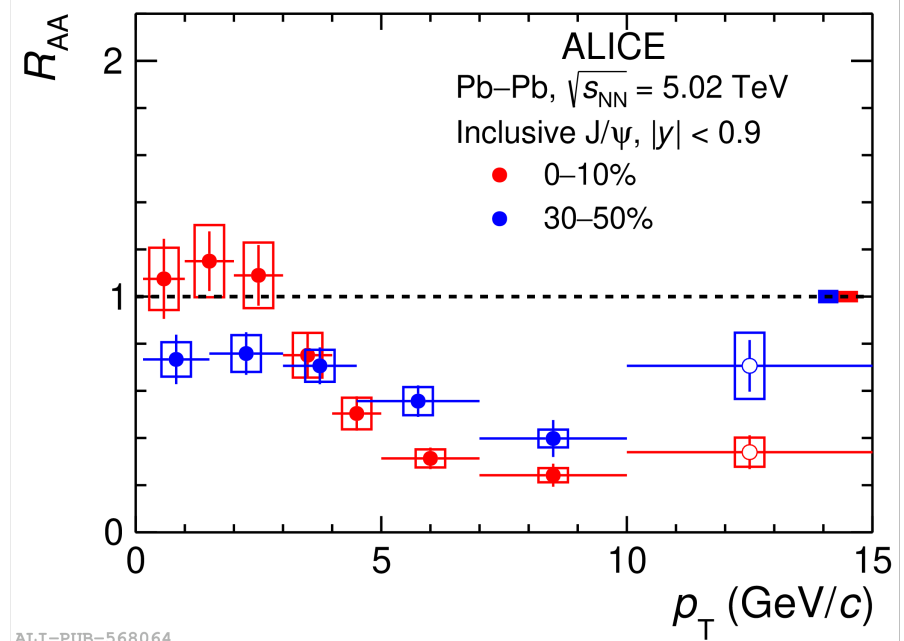
Differential Measurements at ALICE

ALICE, PLB 849, 138451 (2024)



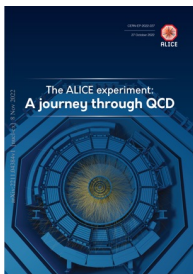
ALI-PUB-568074

- Clear rapidity dependence at low p_T
- Surprisingly same suppression at high p_T



ALI-PUB-568064

- Clear centrality dependence
- Opposite at low and high p_T region



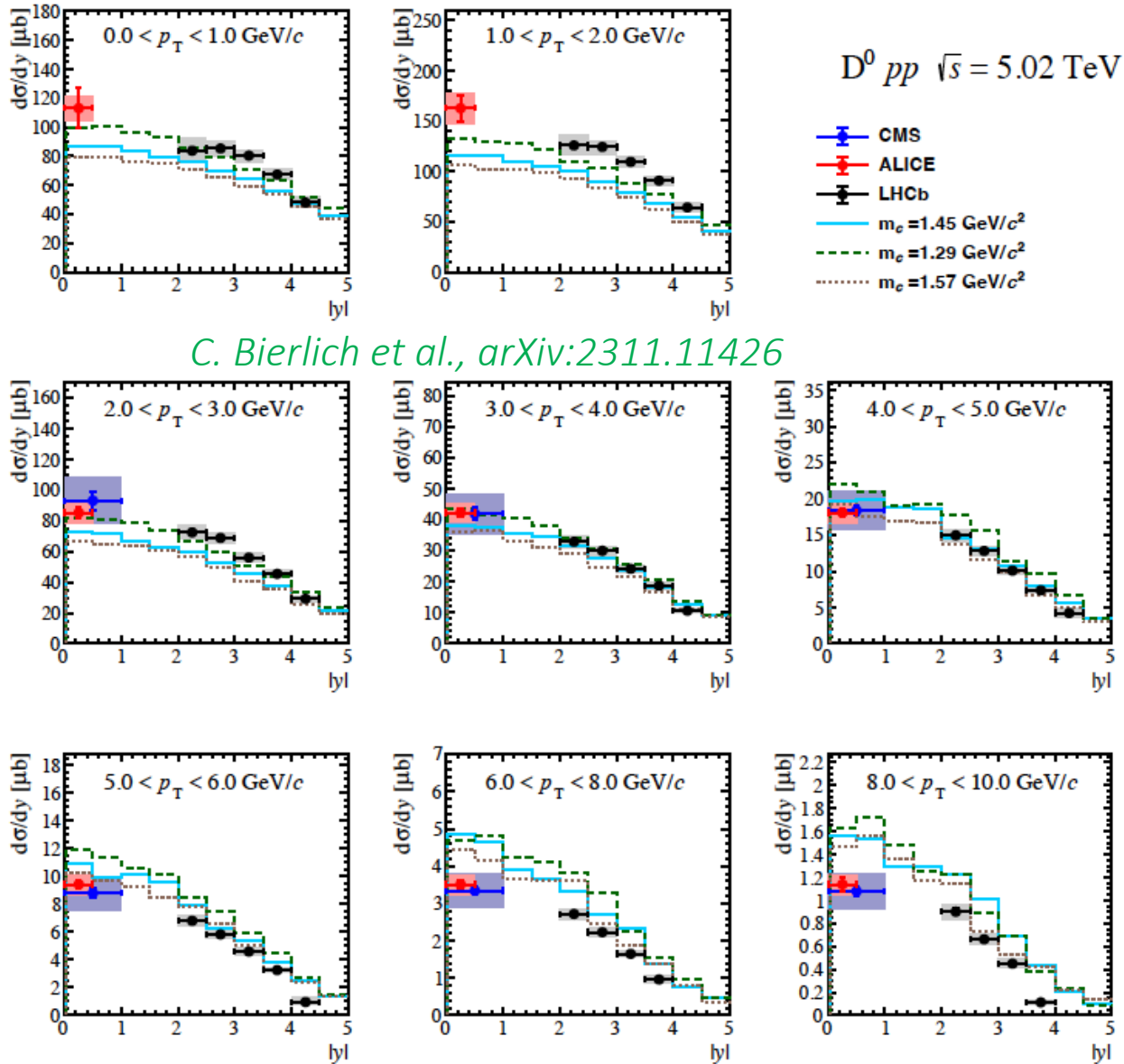
2.5.1 Study of the charmonium ground state: **evidence** for the (re)generation and demonstration of **deconfinement** at LHC energies

ALICE, EPJC 84, 8 (2024)

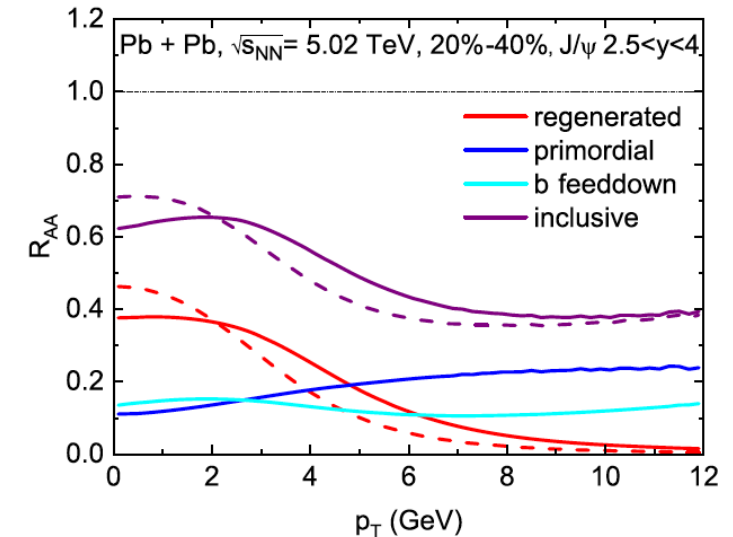
*Energy loss may play an important role at high p_T



Rapidity Dependence of Charm Cross Section



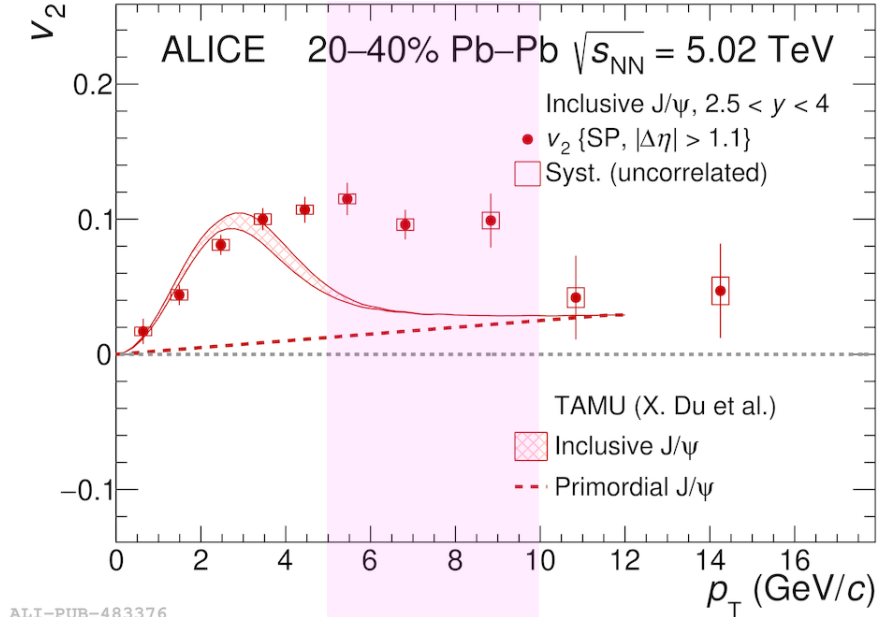
D-meson cross section at mid-rapidity
 $> \sim 2X$ of that at forward rapidity



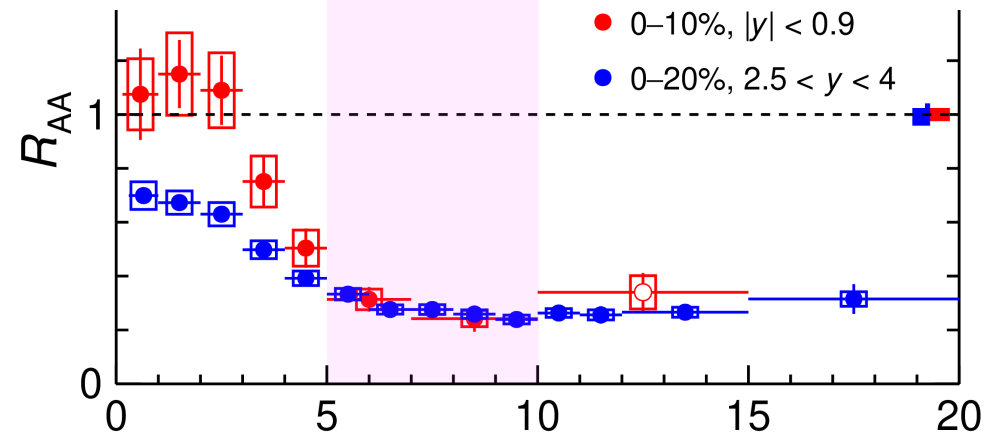
M. He et al, PRL 128, 162301 (2022)

Comparable contribution of regenerated and primordial at $p_T \sim 5$ GeV/c at $2.5 < y < 4$ in 20-40% centrality from transport model calculations

Expect larger R_{AA} at mid-y than forward?



ALI-PUB-483376

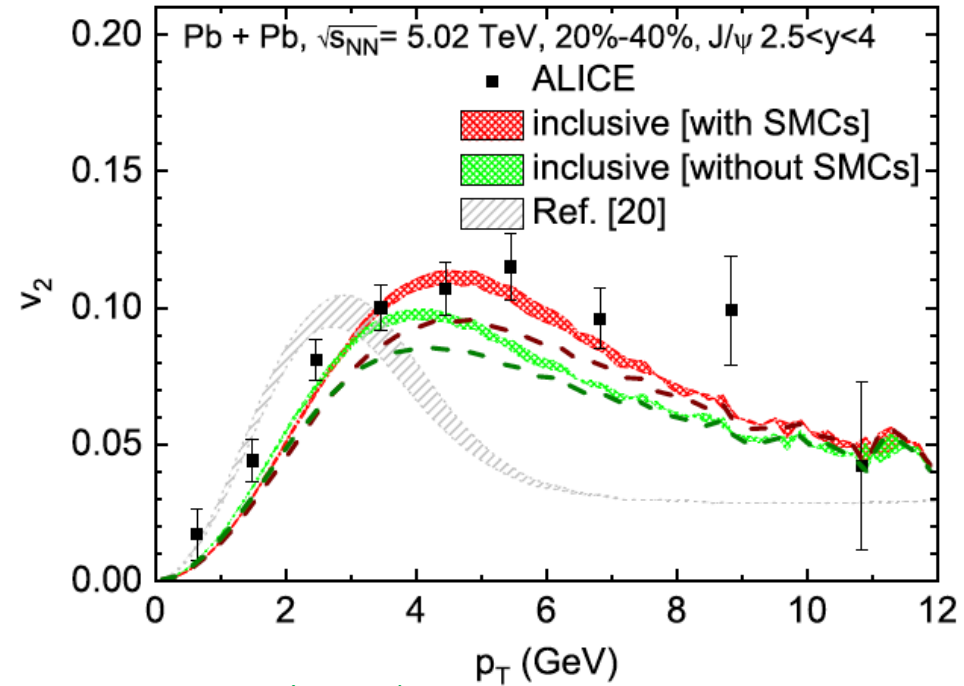
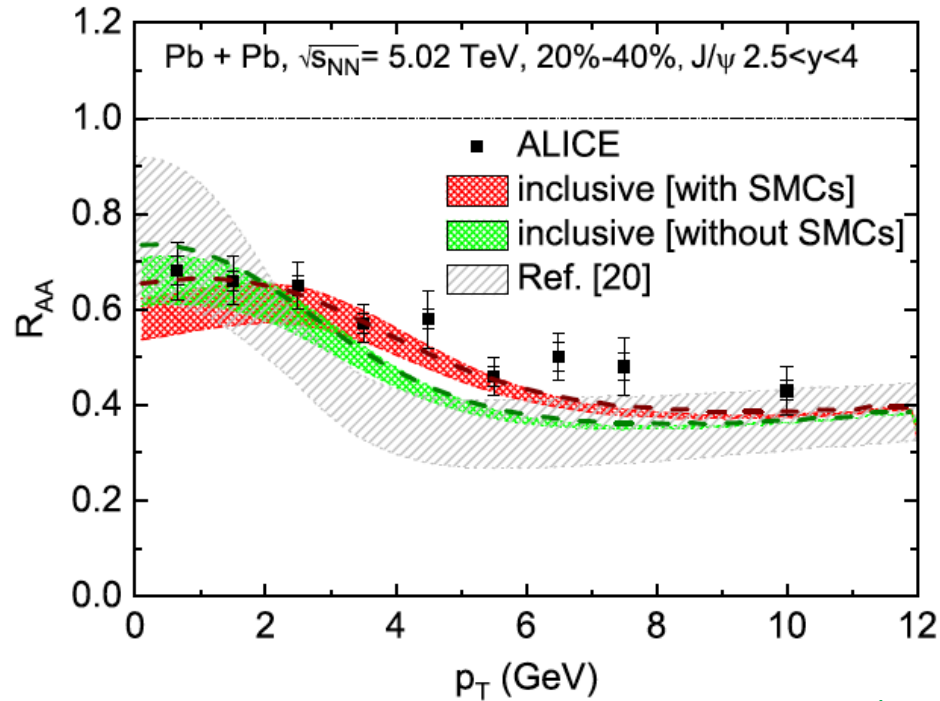


ALICE, JHEP 10, 141 (2020), PLB 849, 138451 (2024)

- Significant v_2 observed at low and intermediate p_T by ALICE at forward rapidity
- Peaking at $p_T \sim 5$ GeV/c, where R_{AA} at mid and forward rapidity converge
- Low- p_T v_2 data described by transport model calculation with dominate contribution from (re)generation of thermalized charm with Blast Wave approximation
- Underestimated at intermediate p_T



J/ψ R_{AA} and v_2

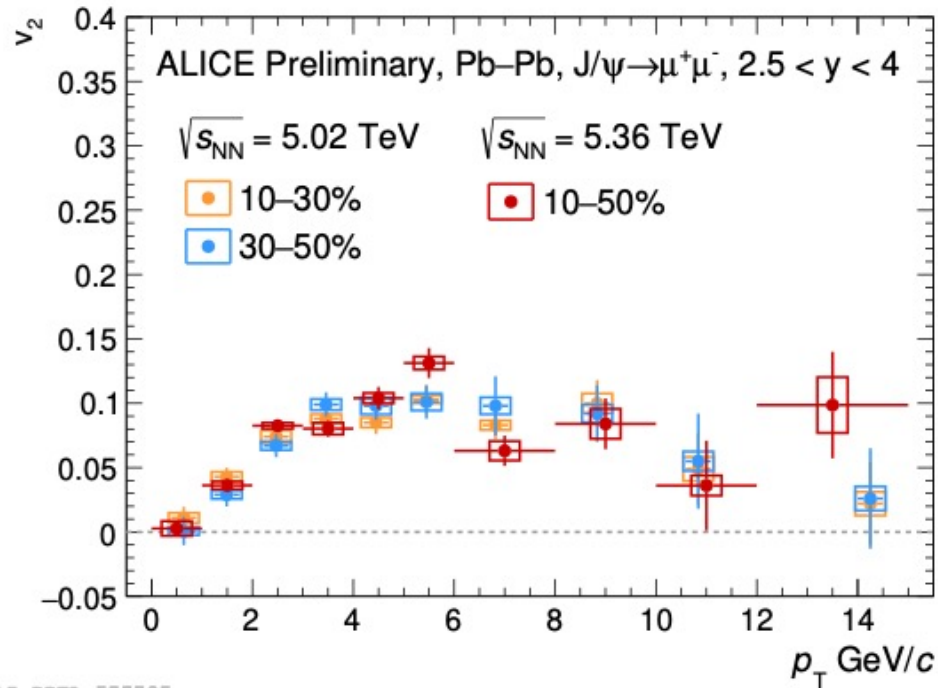


M. He et al, PRL 128, 162301 (2022)

- R_{AA} and v_2 simultaneously described by the improved transport model upto $p_T \sim 10$ GeV/c
Resonance Recombination Model + Space Momentum Correlation
- Can it simultaneously describe mid- and forward rapidity $R_{AA}+v_2$ results?
- What is the contribution of jet fragmentation?



J/ψ v₂ from ALICE Run3



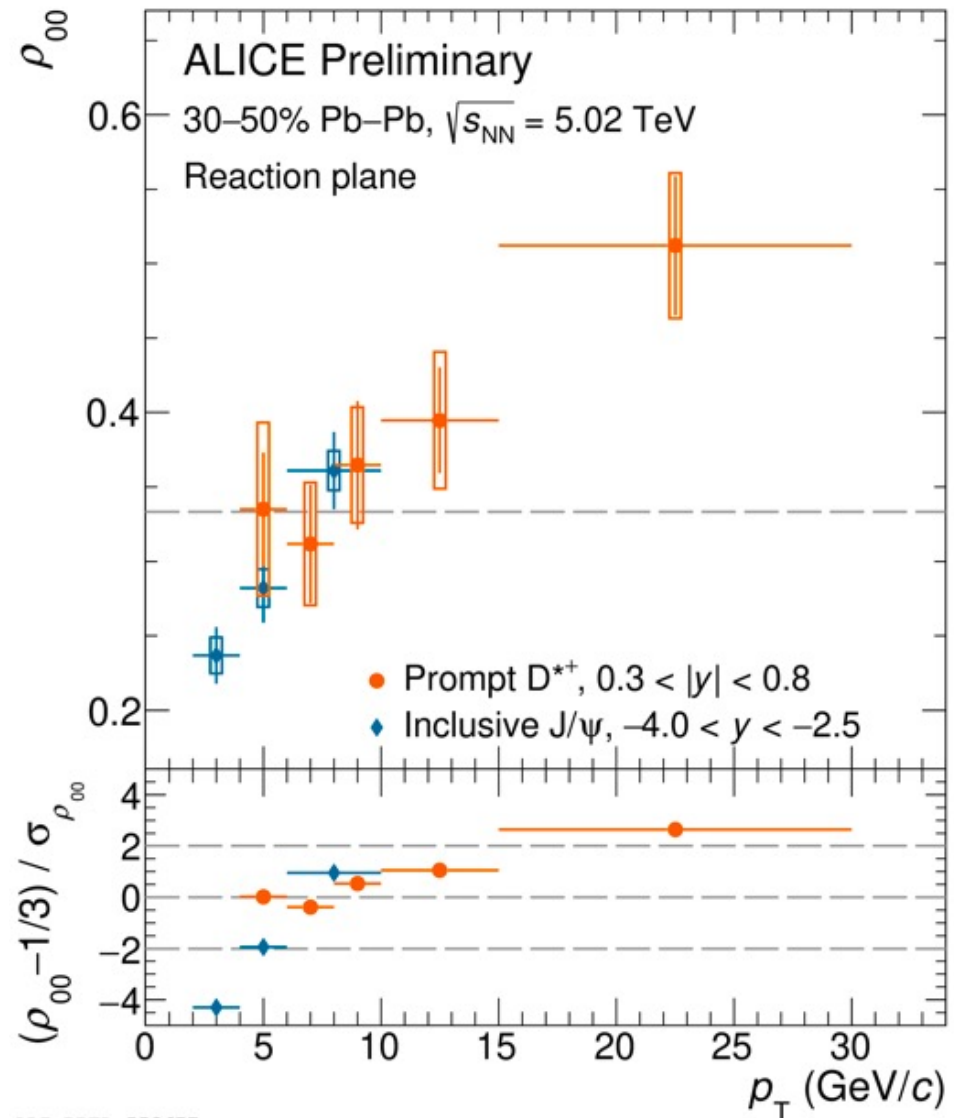
ALI-PREL-577735

Forward rapidity:

- ALICE preliminary results from Run3 consistent with Run2 results but with better precision
- Looking forward to final precision measurements

Middle rapidity:

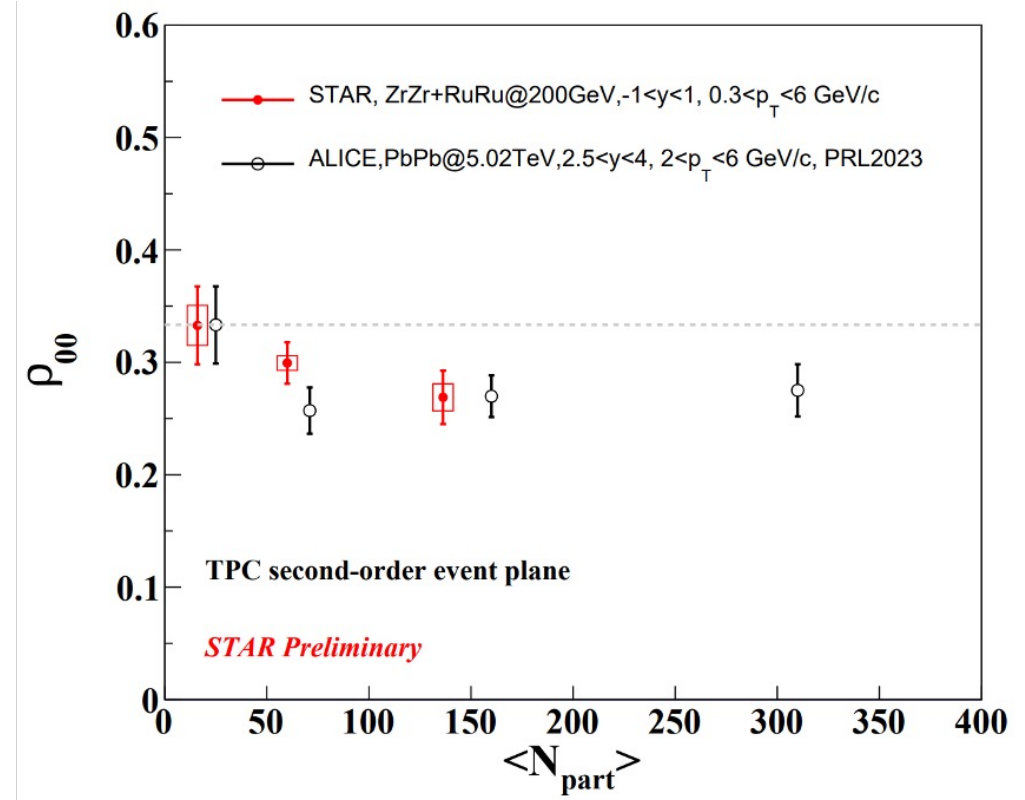
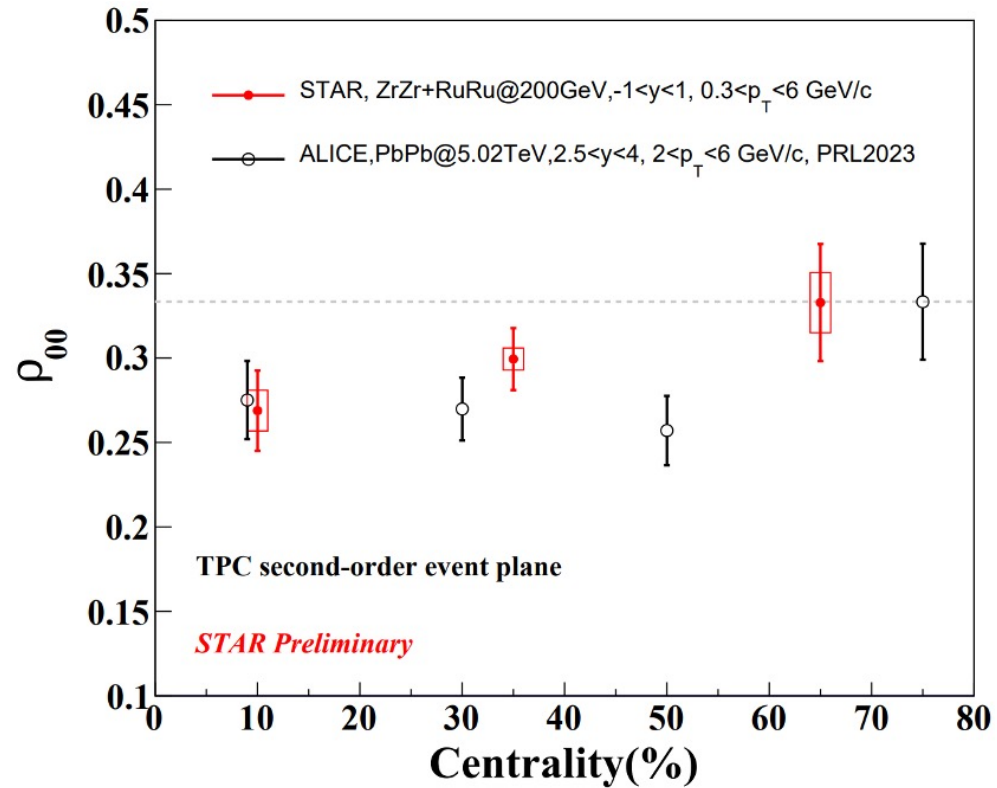
- Significant enhancement of #events in Run3 compared to Run2
- Enables precision v₂ measurement
- **Stay tuned!**



- Polarization of vector meson in vortical QGP depends on its production mechanism
X.-L. Sheng et al., PRL 131, 042304 (2023)
- Charmed vector meson at LHC is a sensitive probe
 - Thermalized charm
 - Dominant coalescence
- J/ψ and D^{*+} seem follow the same trend
 - Sign changed from low- p_T J/ψ to high- p_T D^{*+}
 - But they are from different rapidity range and charm constituents.
- J/ψ at mid- y and large p_T coverage from ALICE Run3 is crucial

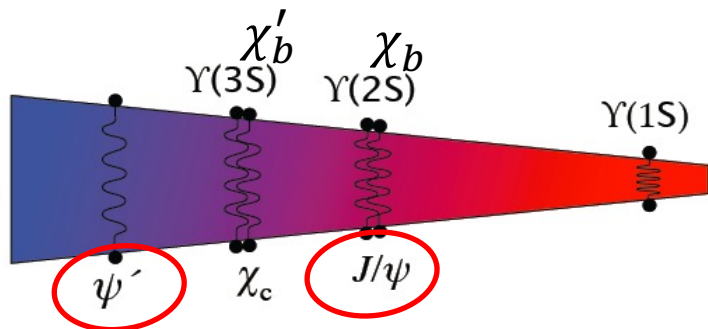
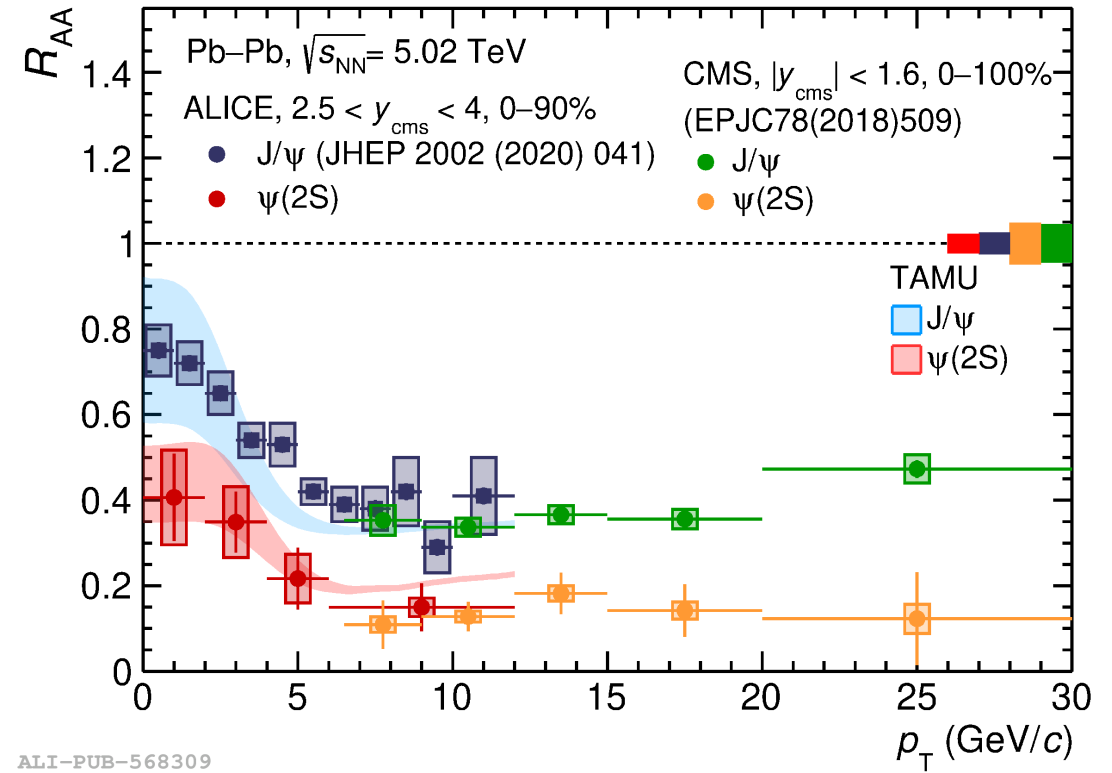
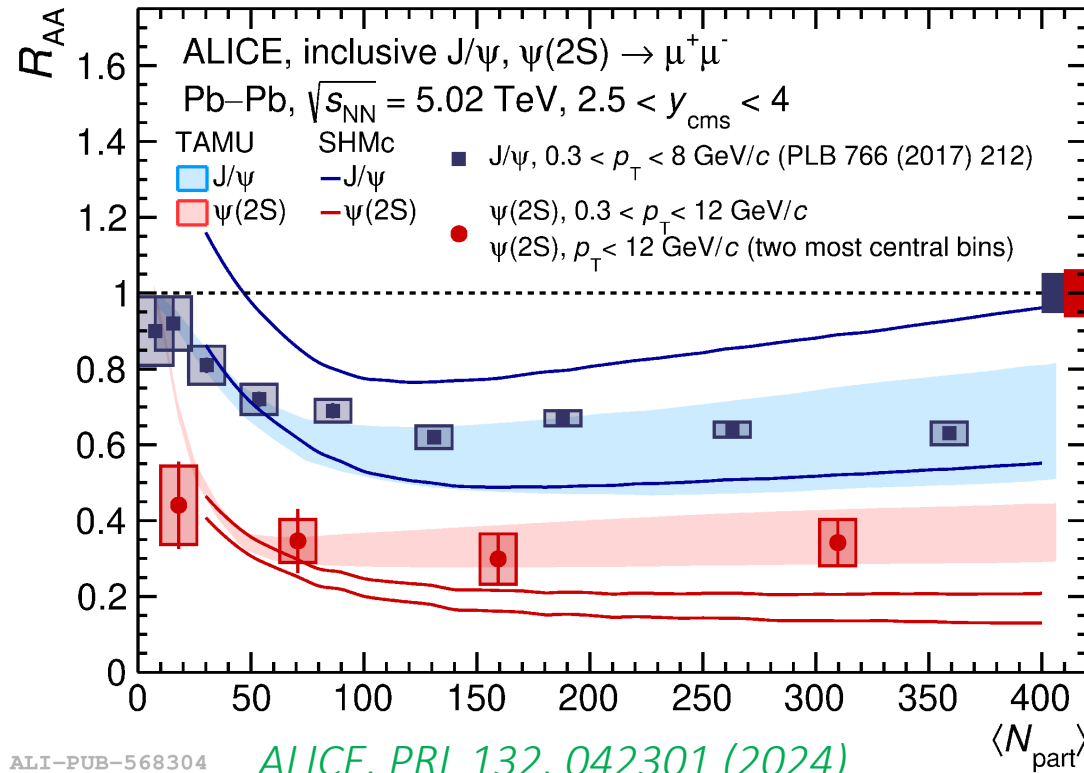


RHIC vs. LHC



- Comparable between RHIC and LHC, despite different contribution from coalescence
- Looking forward to ALICE Run3 Pb+Pb and RHIC Run2023+2025 Au+Au

Sequential Suppression of Charmonium

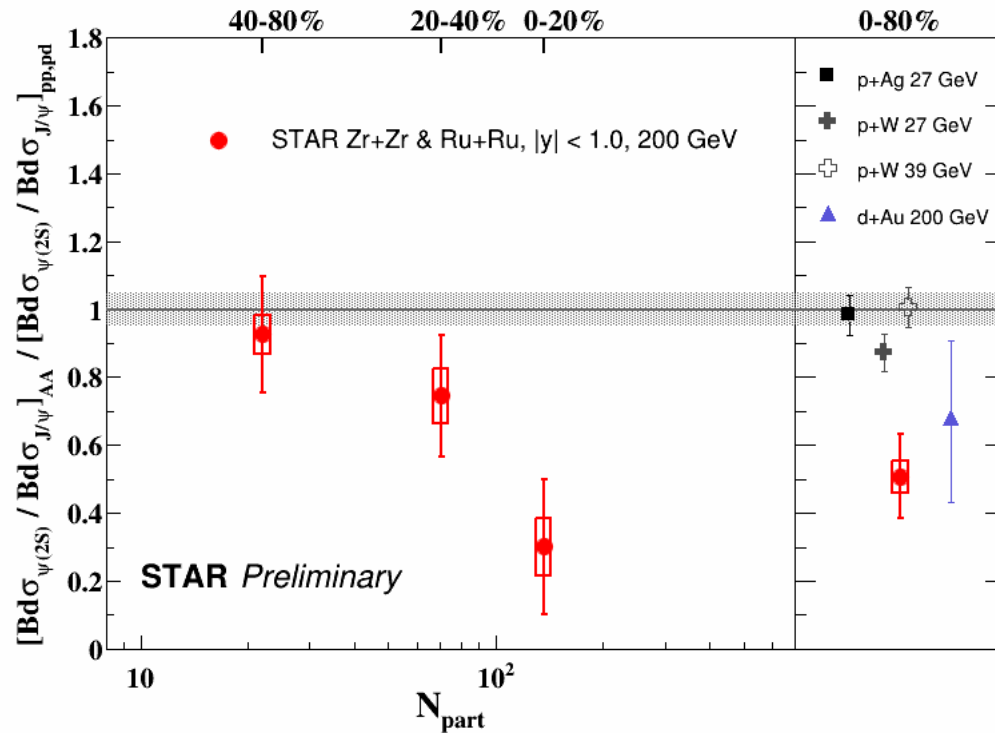


- $\psi(2S)$ more suppressed than J/ψ in all centrality and all p_T
- Described by transport model calculations
- Again, similar suppression at mid- and forward rapidity at intermediate p_T



Results from STAR

Yan Wang, QM2023



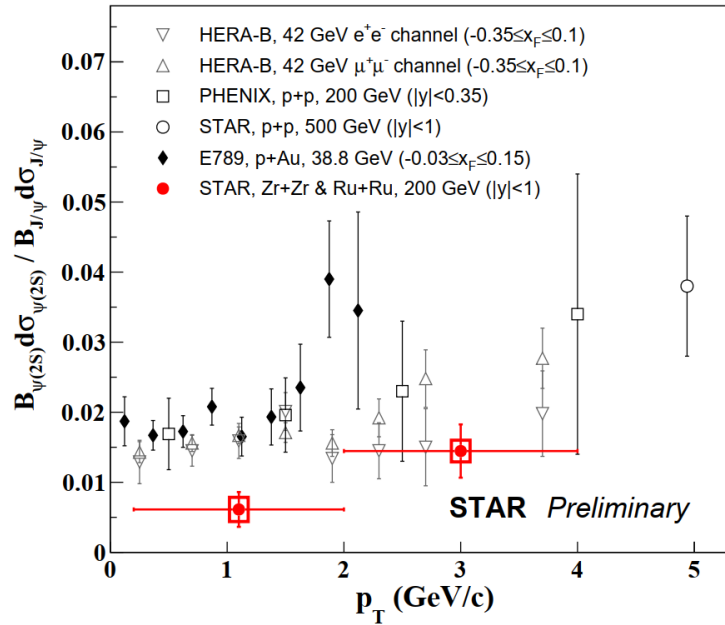
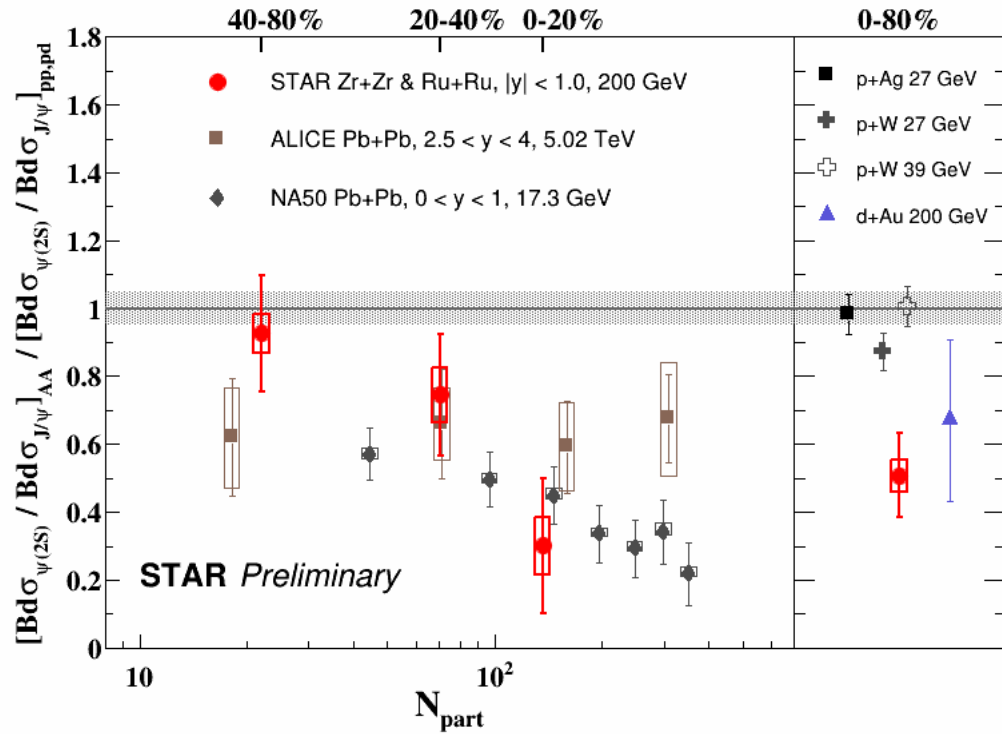
pp reference is the average of measurements in p+p(d) by NA51, ISR and PHENIX

Better pp reference is internally available

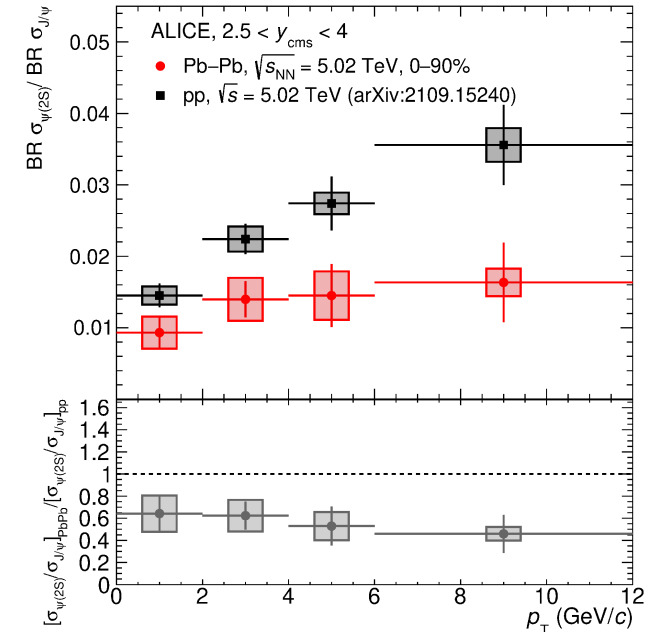
- First measurements in heavy-ion collisions at RHIC thanks to high statistics isobar data
- Significantly more suppression for $\psi(2S)$ than J/ψ ($>3\sigma$)
- The double ratio is lower in A+A collisions than in p+A collisions



Comparison between RHIC, SPS and LHC



ALICE, PRL 132, 042301 (2024)



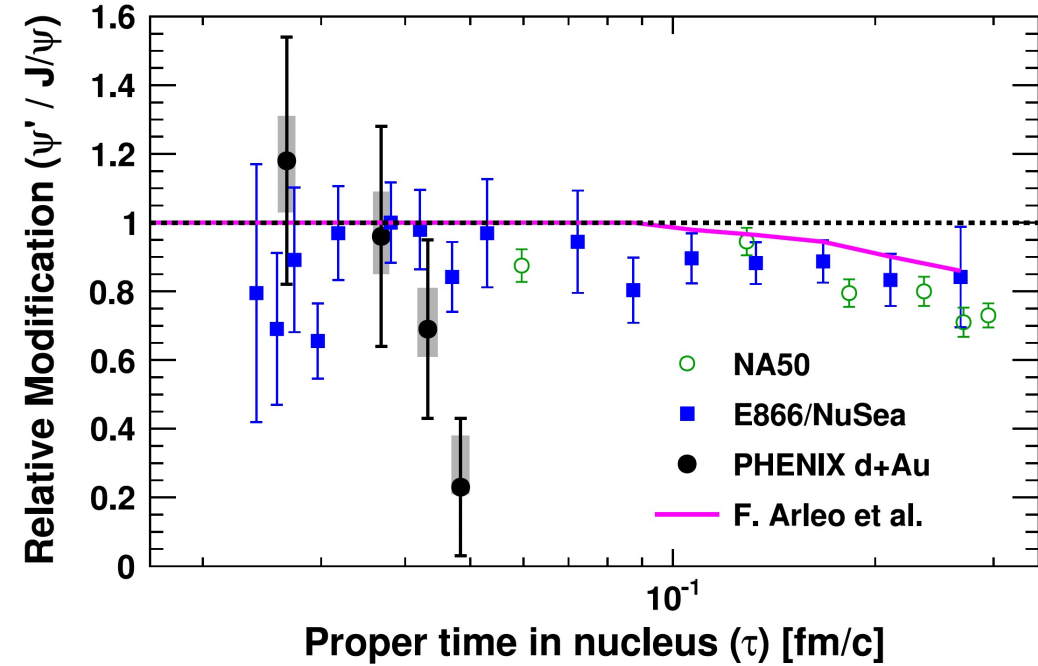
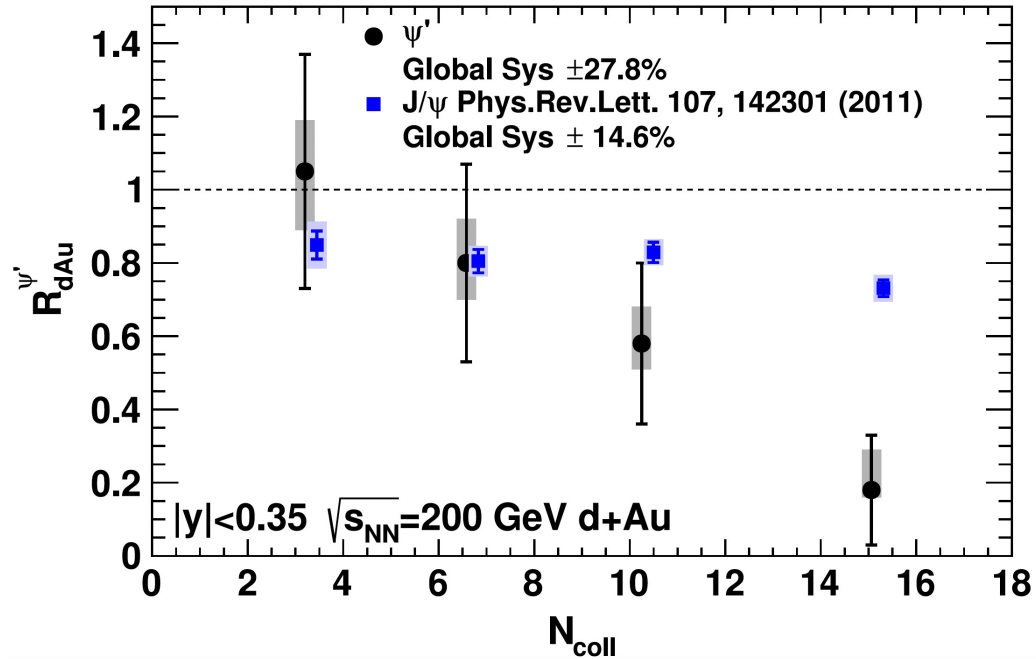
- Decreasing trend at RHIC and SPS
- Flat distribution at LHC
- More regeneration at LHC?
- More non-prompt contribution at LHC?

- A hint of increasing trend at RHIC
- Slightly decreasing trend at LHC
- Opposite to expectation from pure non-prompt contribution



Ratio in Small System at RHIC

PHENIX, PRL 111, 202301 (2013)



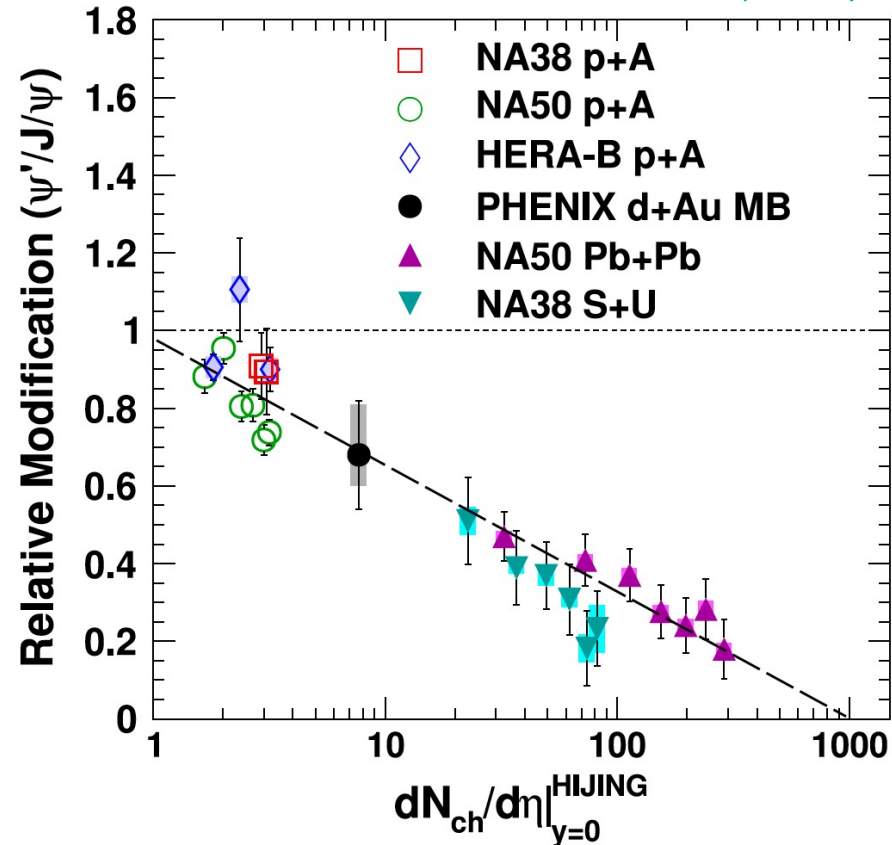
- Stronger suppression of $\psi(2S)$ relative to J/ψ observed in central d+Au collisions at RHIC

- The double ratio at RHIC seems not follow proper time scaling
- ➔ Something beyond nuclear absorption?



Multiplicity Scaling?

PHENIX, PRL 111, 202301 (2013)

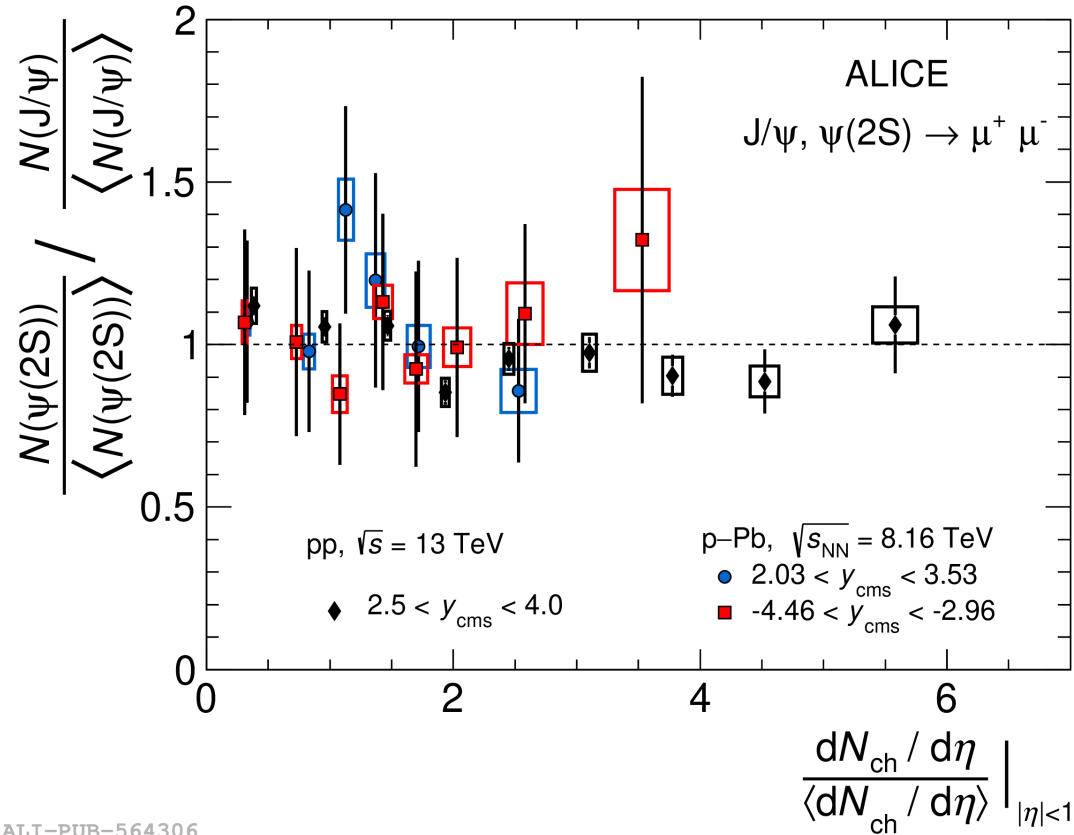


- The double ratio seem scale with charged multiplicity
- nPDF effects cancels out in the double ratio
- Interaction with final-state hadrons (comovers) play a role?



Ratio in Small System at LHC

ALICE, JHEP06, 147 (2023)



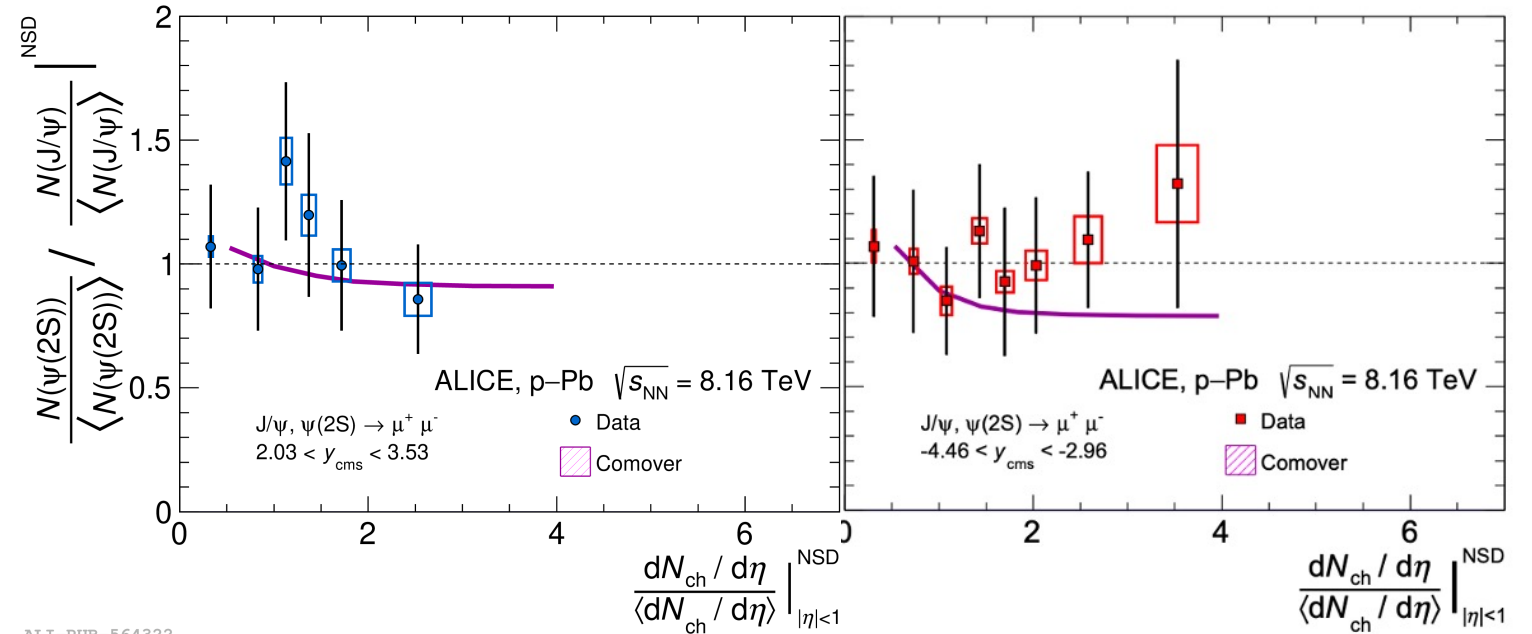
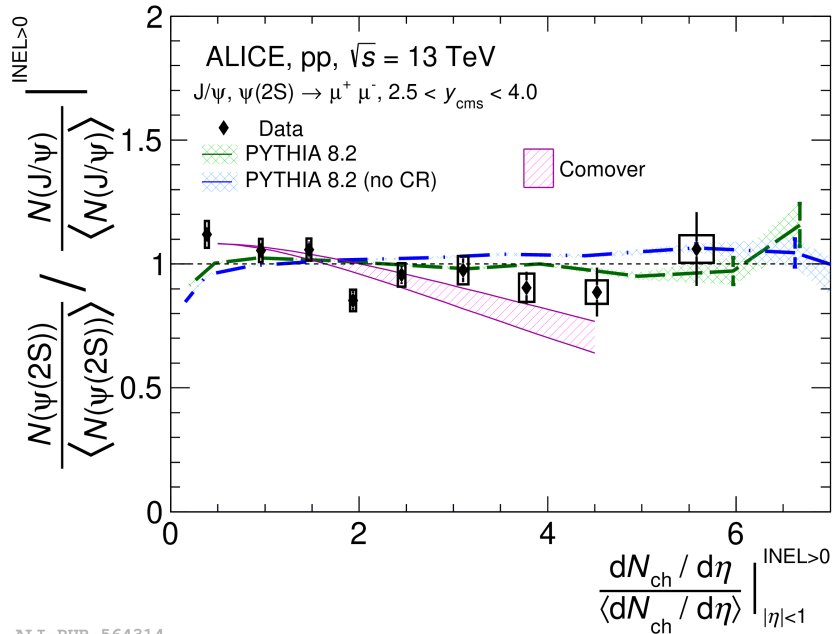
ALI-PUB-564306

- The double ratio at forward rapidity in p+p and p+Pb consistent with unity
- Independent on charged **multiplicity in mid-rapidity**
- Challenging to explain RHIC and LHC data with the same mechanisms



Comparison to Theoretical Calculations

ALICE, JHEP06, 147 (2023)

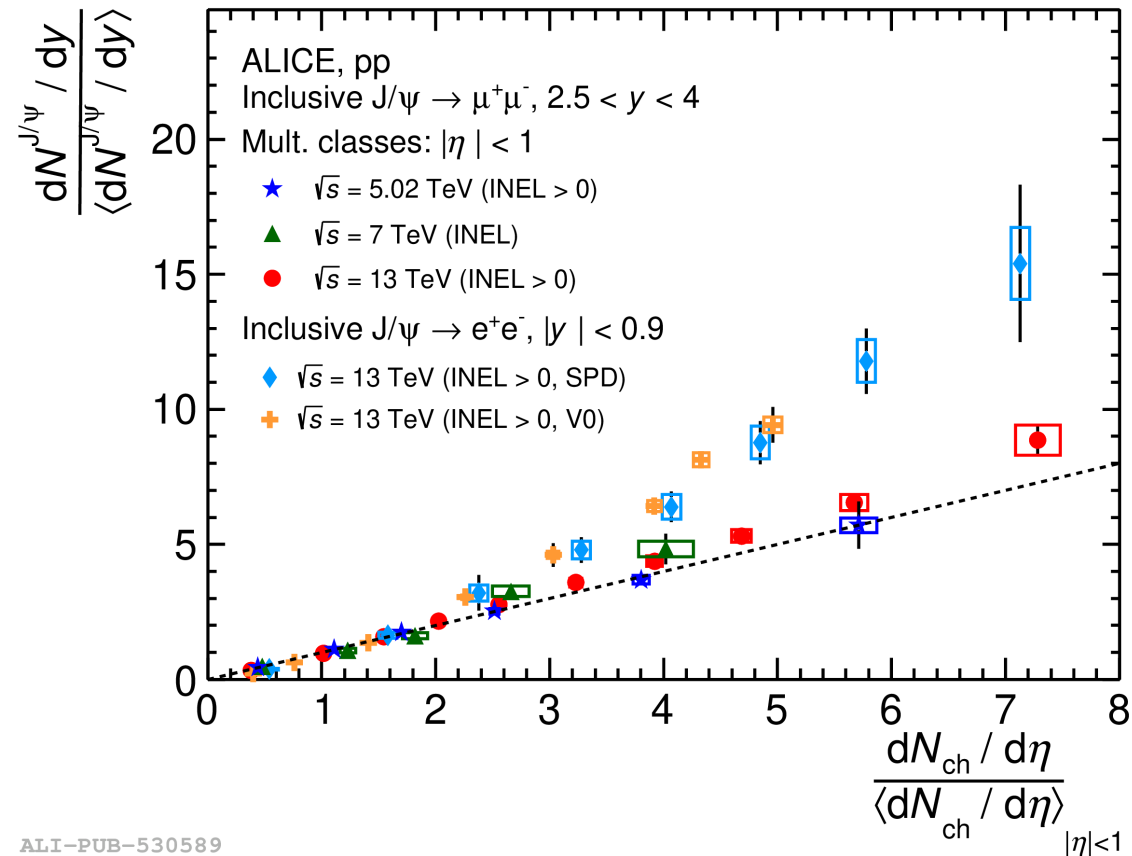


- Data can be described by different models within uncertainties
- Precisions need to be improved
- Note that J/ψ is measured at forward and charged multiplicity at mid-rapidity



Multiplicity Dependence of J/ψ Production

ALICE, JHEP06, 015 (2022)

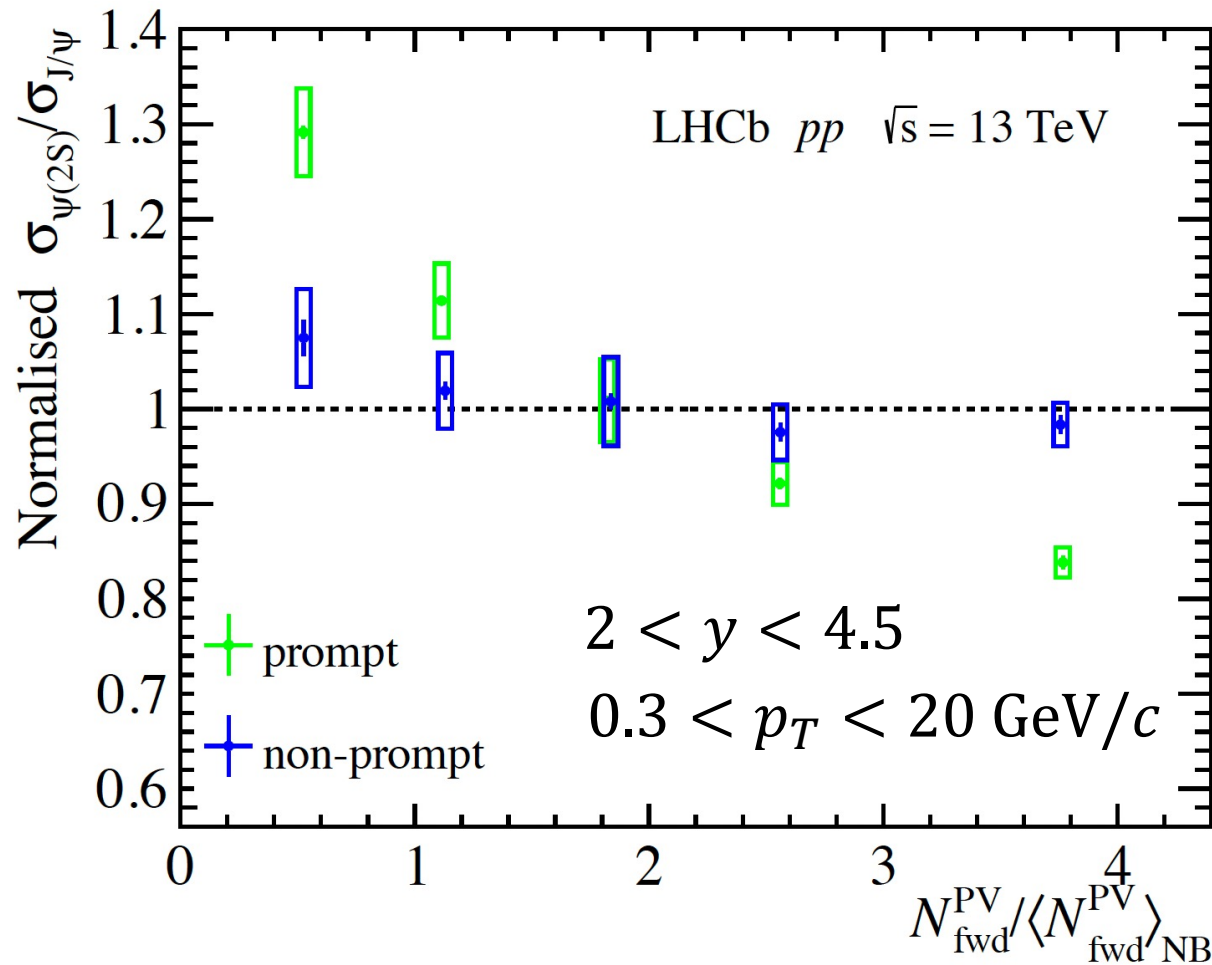


- Forward rapidity J/ψ less sensitive to multiplicity at mid-rapidity
- Looking forward to $\psi(2S)$ measurements at mid-rapidity from ALICR Run3



Forward Charmonium vs. Forward Multiplicity in p+p

LHCb, JHEP05, 243 (2024)

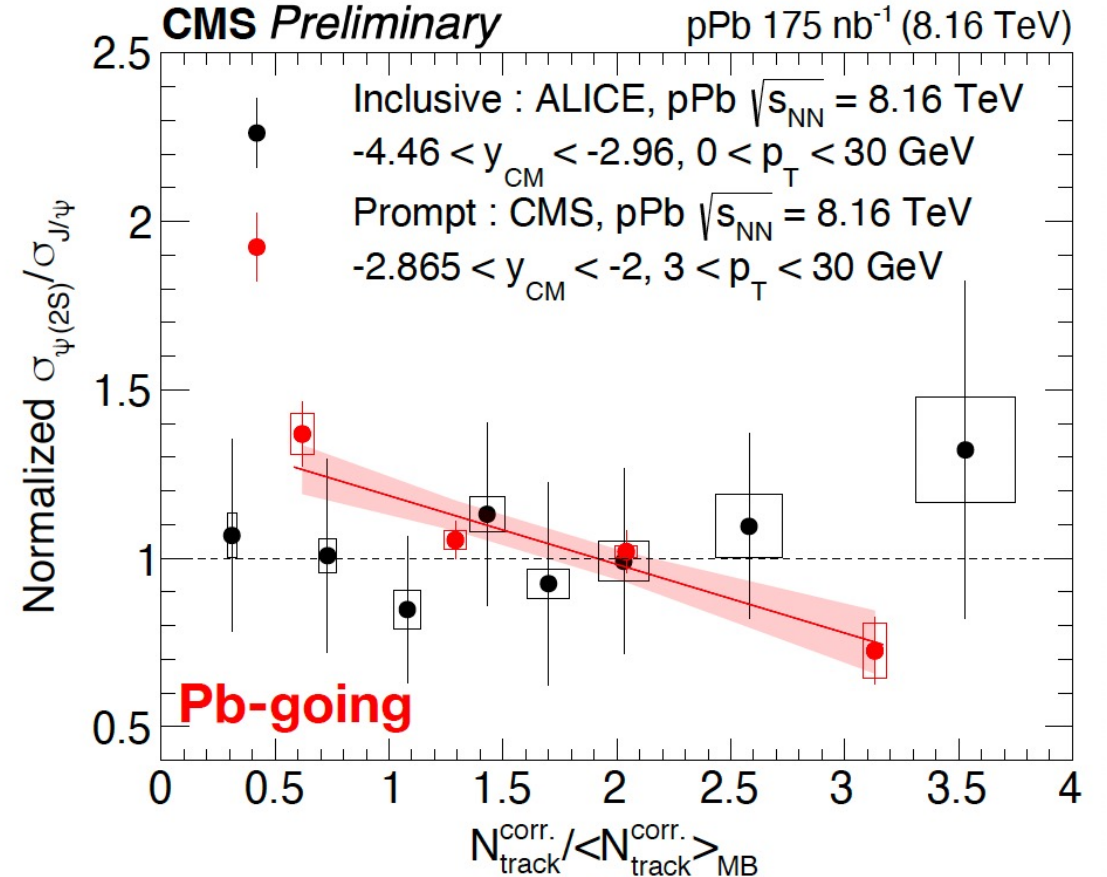
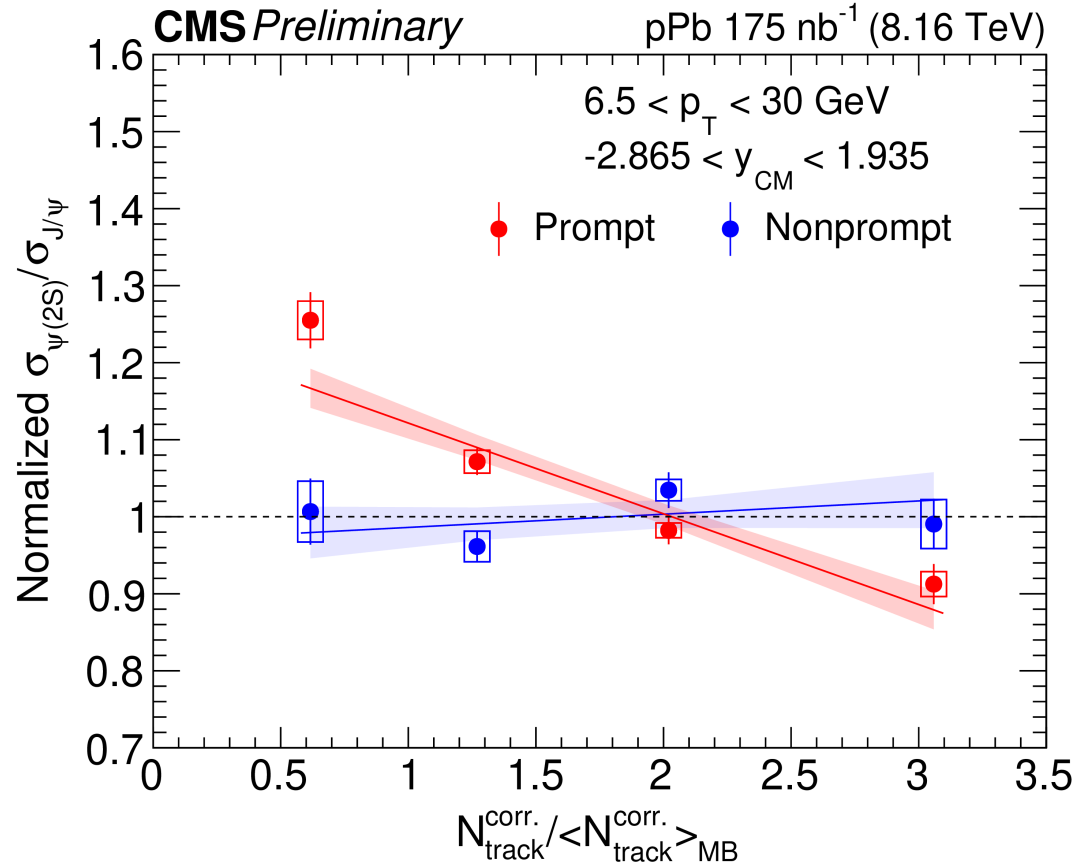


Decreasing trend observed in p+p from LHCb



Measurements at Mid- y and High- p_T from CMS

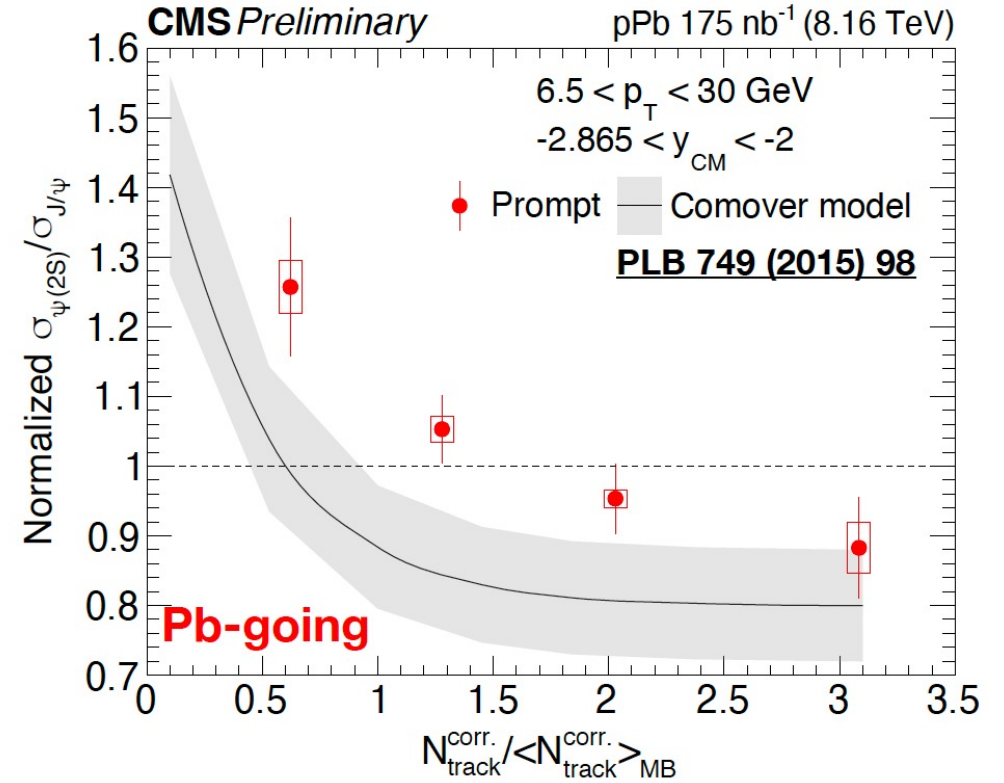
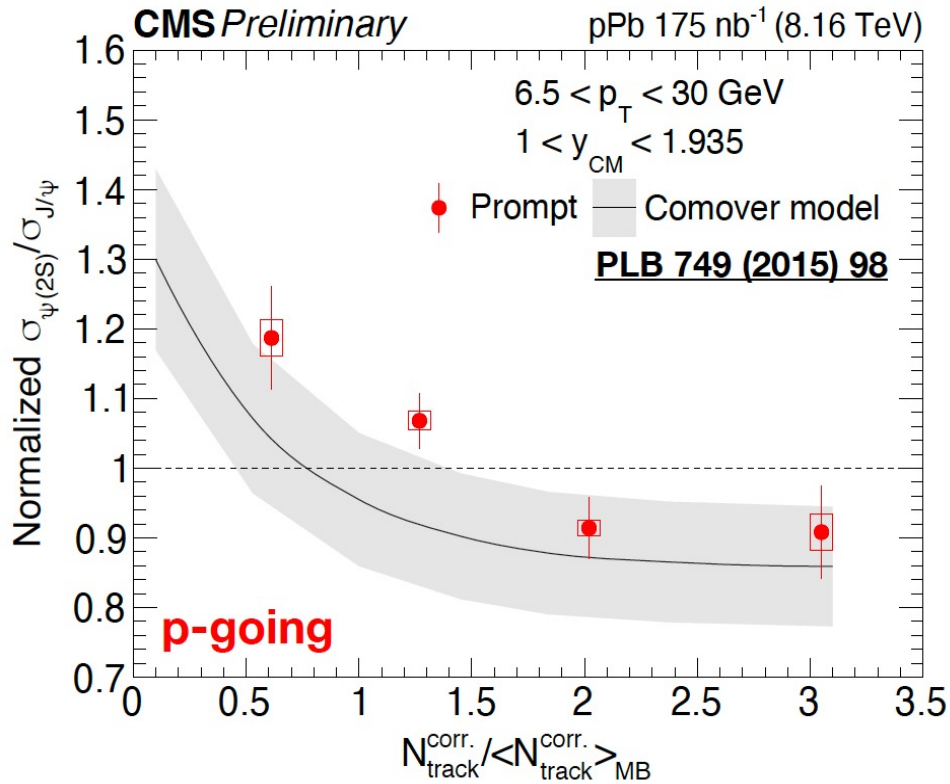
CMS, CMS-PAS-HIN-24-001 (2024)



- Significant multiplicity dependence for prompt
- Not multiplicity dependence for non-prompt
- Results do not contradict to ALICE results
- Also note about difference of y and p_T



Compare to Comover Model

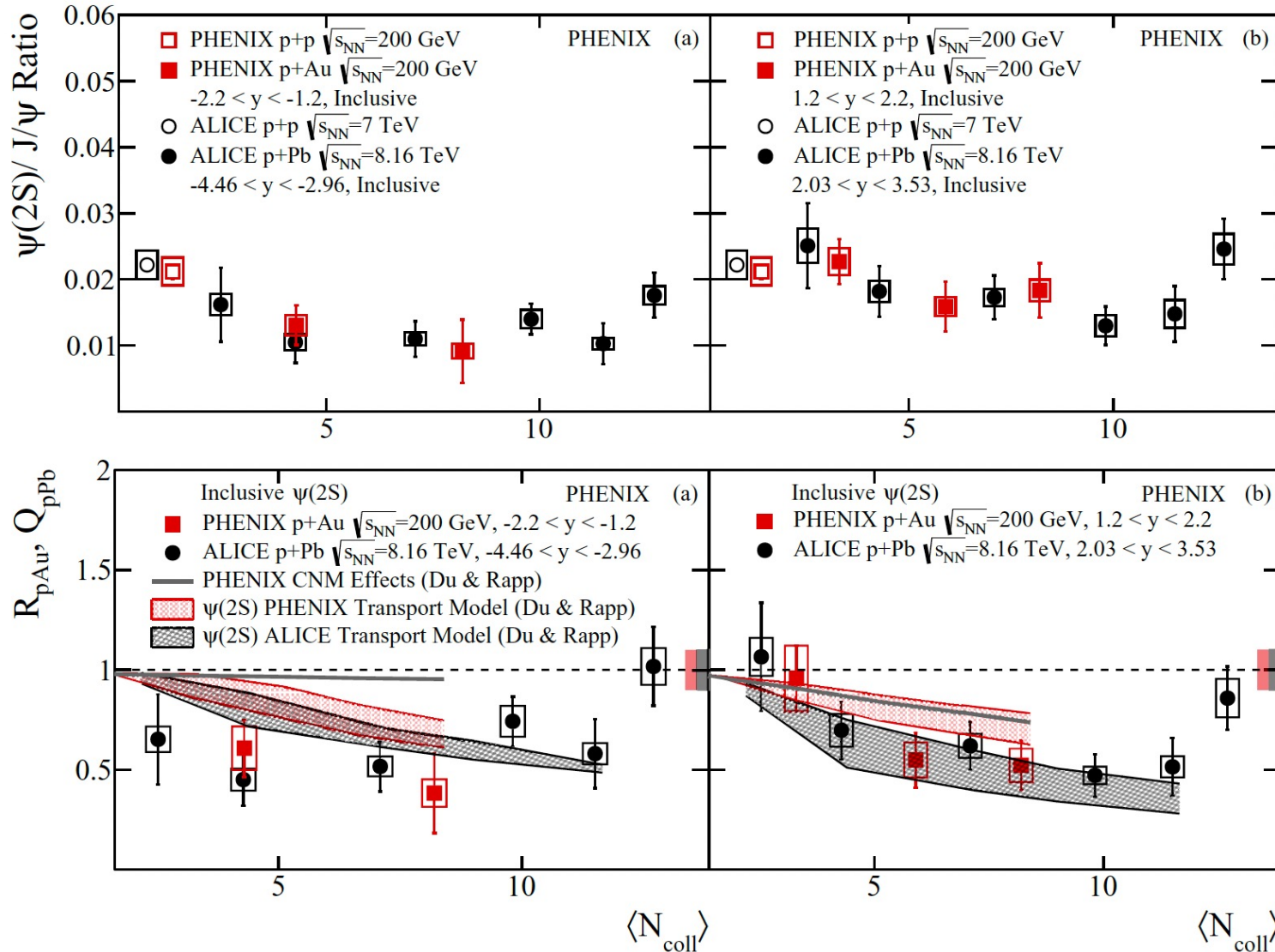


- Comover model consistent with data on p-going side
- But systematically overestimate the relative suppression on Pb-going side
- Measurements at mid-y and low-p_T from ALICE Run 3 will be a complementary



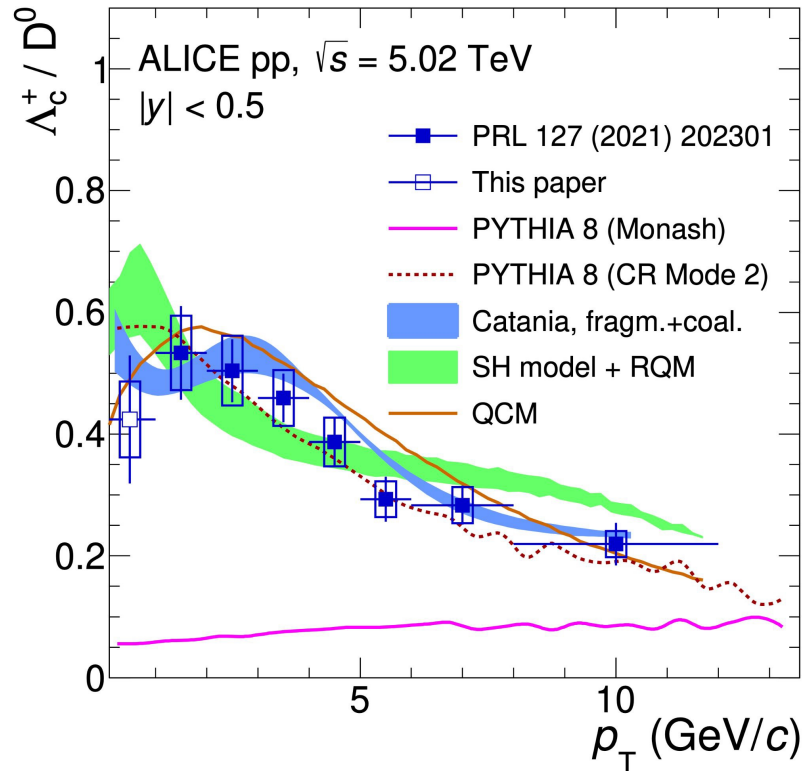
Comparison between RHIC and LHC

PHENIX, PRC105, 064912 (2022)



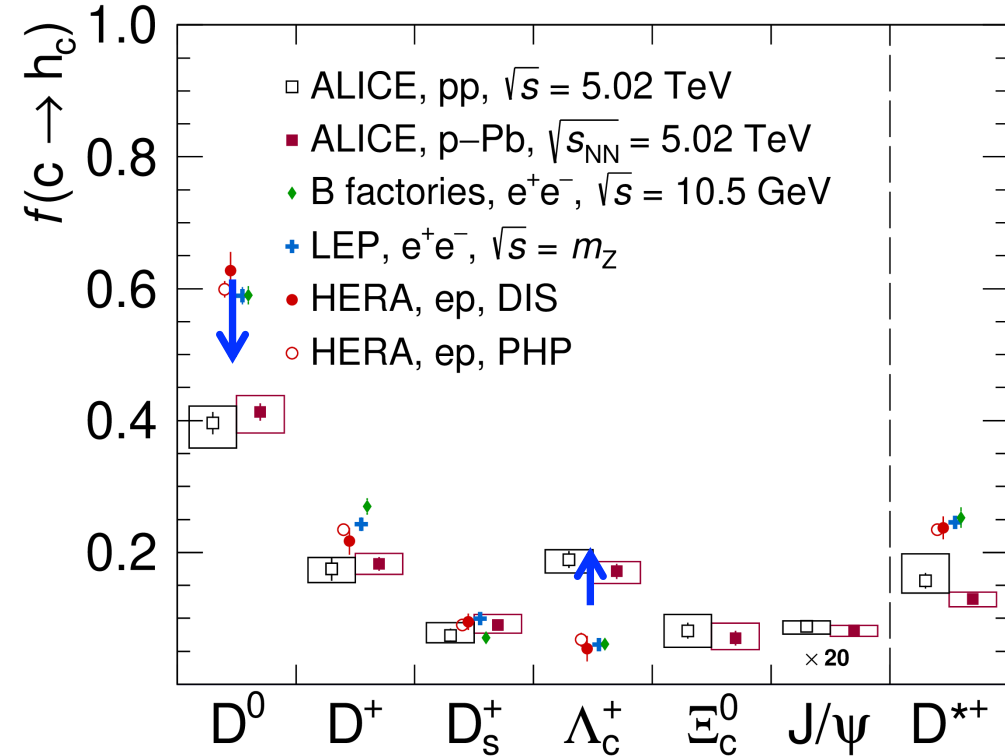
- There are difference between ratios in p+p and p+A collisions
 → Depend on multiplicity for charmonium at forward rapidity
- However, no significant difference between RHIC and LHC in p+A
 → Independent on multiplicity?
- Transport model can describe the data from RHIC and LHC
 → Interplay of QGP temperature + lifetime vs. $\langle p_T \rangle$

ALICE, PRC107, 064901 (2023)



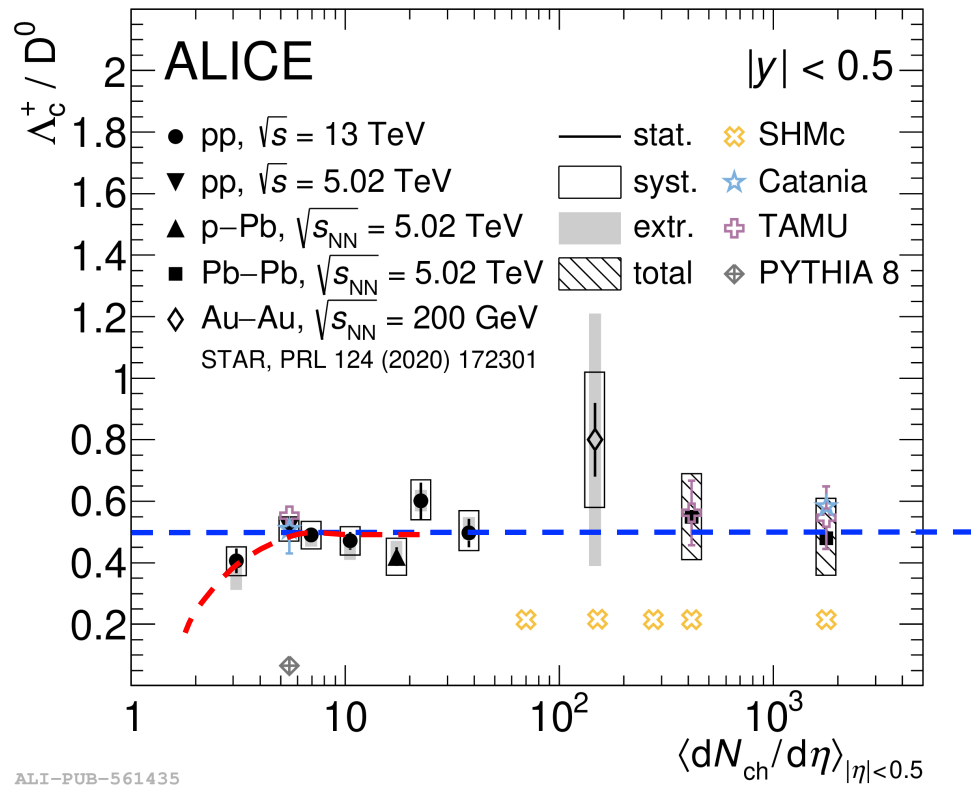
ALICE, arXiv:2405.14571

ALICE, PRD105, L011103 (2022)

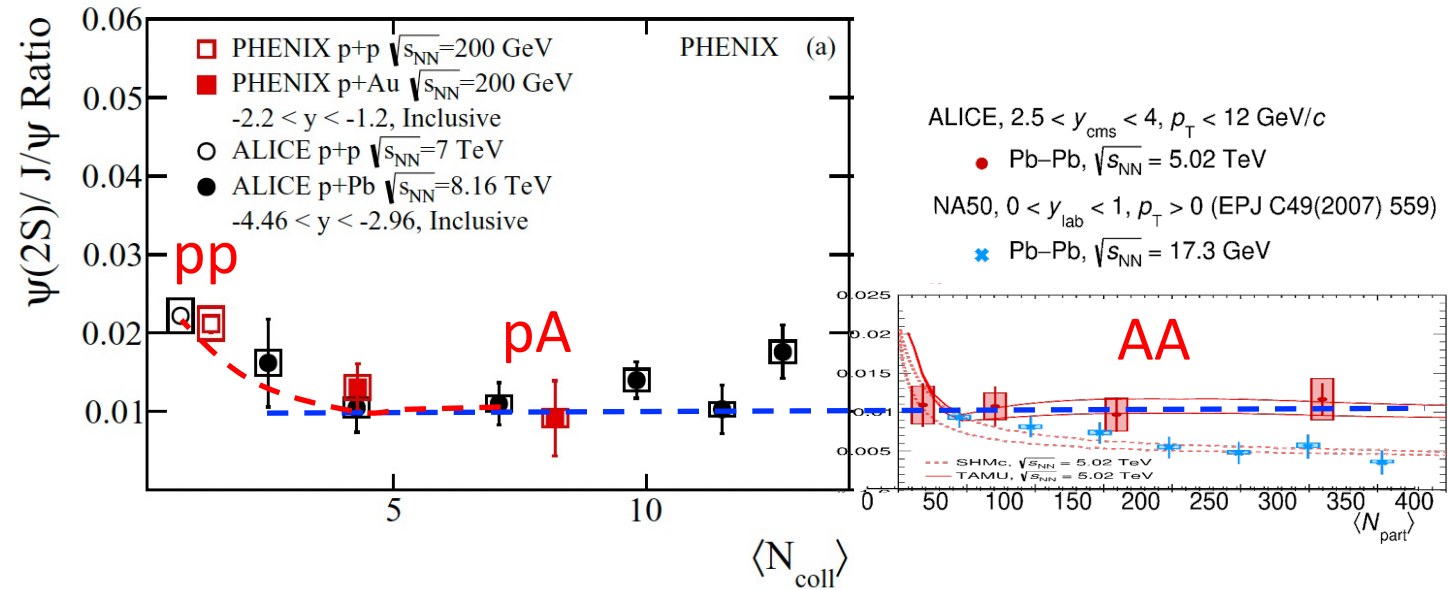


ALI-PUB-570972

- Charm is found to be redistributed in p+p collisions at LHC with respect to ee/ep
- What is contribution of coalescence in small system considering the high local density?



ALI-PUB-561435



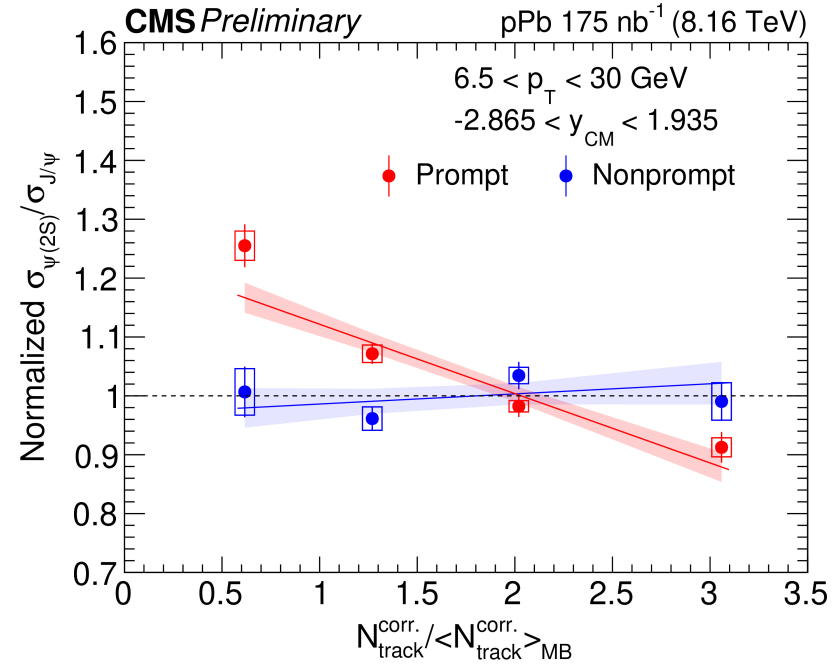
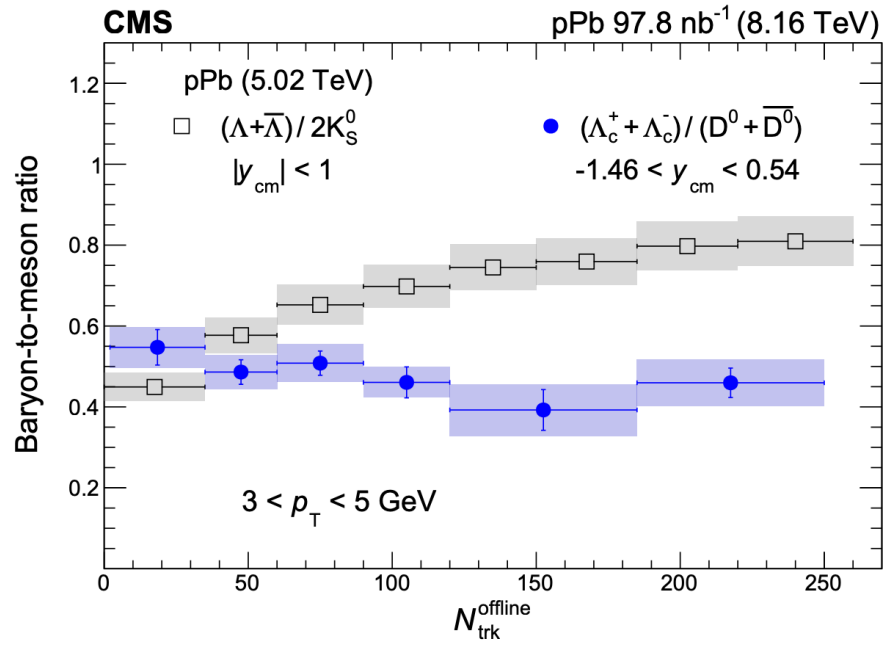
- Do we have a consistent picture from p+p to A+A
and from open to closed heavy flavor?



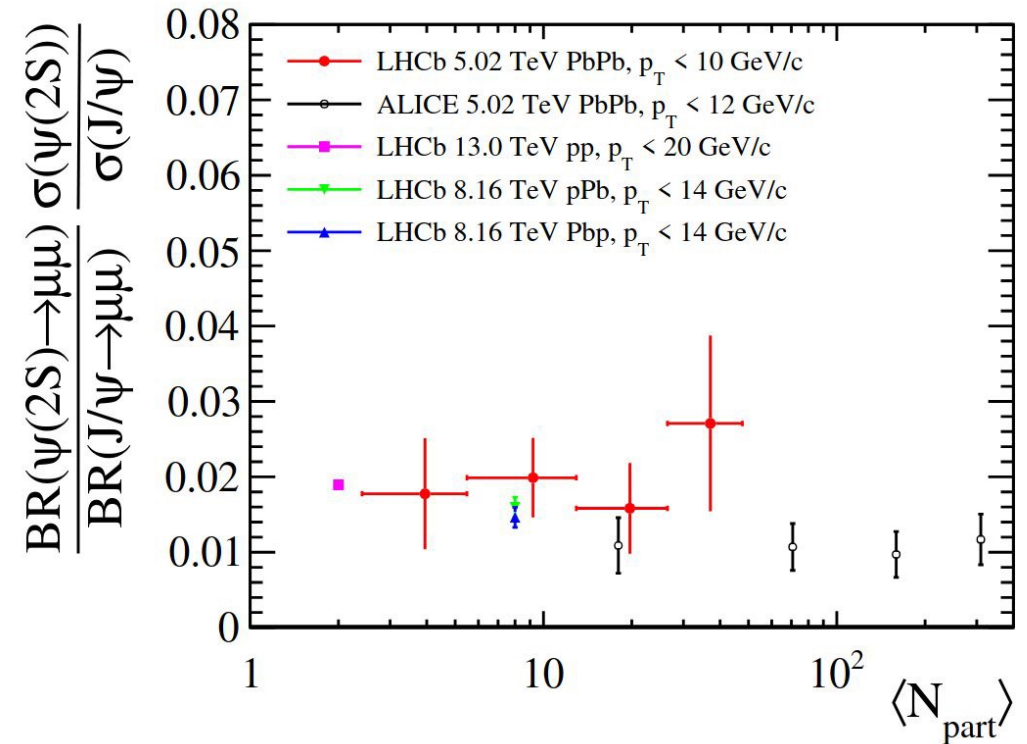
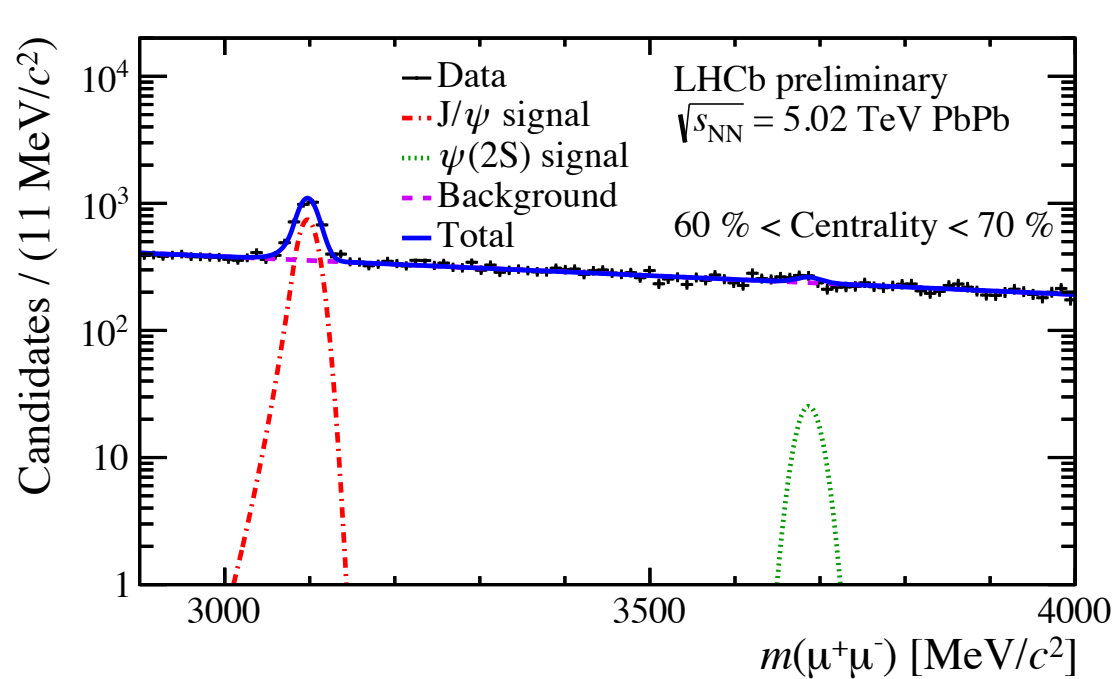
Summary

- Many progresses on charmonium measurements in small and large systems (I selected a few based on my own bias)
 - New data and better precisions
- The improvement on the measurements of J/ψ and $\psi(2S)$ production provide new constraints on theoretical understanding of their production mechanisms
- However, many questions need further investigations
- Looking forward for more precision data from LHC Run3 and RHIC 23-25

Thanks!



LHCb, arXiv:2411.05669



- Measured in peripheral and semi-peripheral Pb+Pb collisions
- Inconclusive due to limited statistics
- Looking forward to Run3 results