The 9th International Symposium on Heavy Flavor Production in Hadron and Nuclear Collisions
6-11 December 2024, Guangzhou, China

Experimental Overview of ~~Quarkonium~~ Charmonium Production

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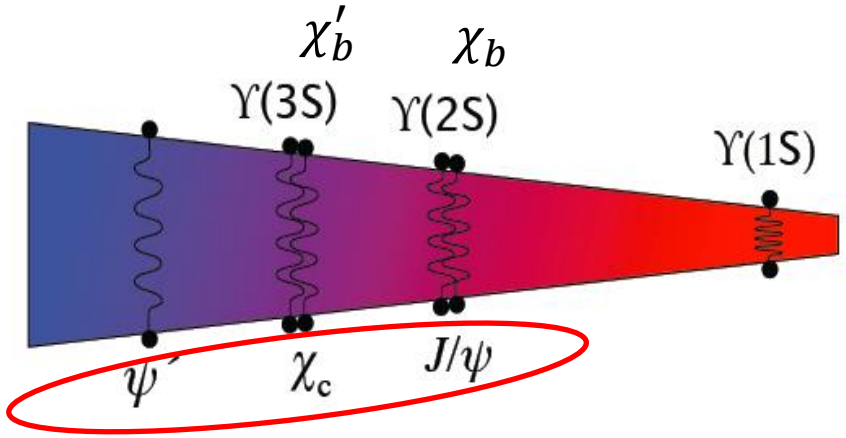
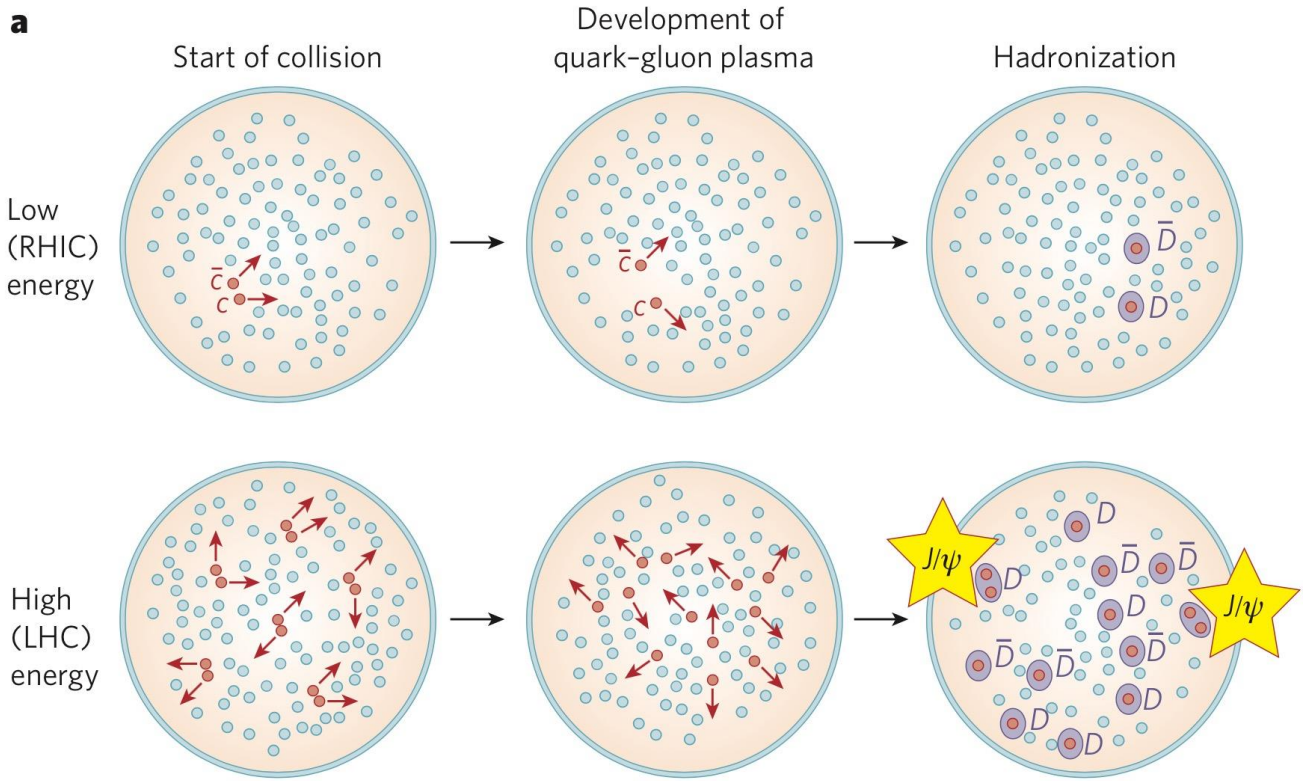
Charmonium in QGP



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

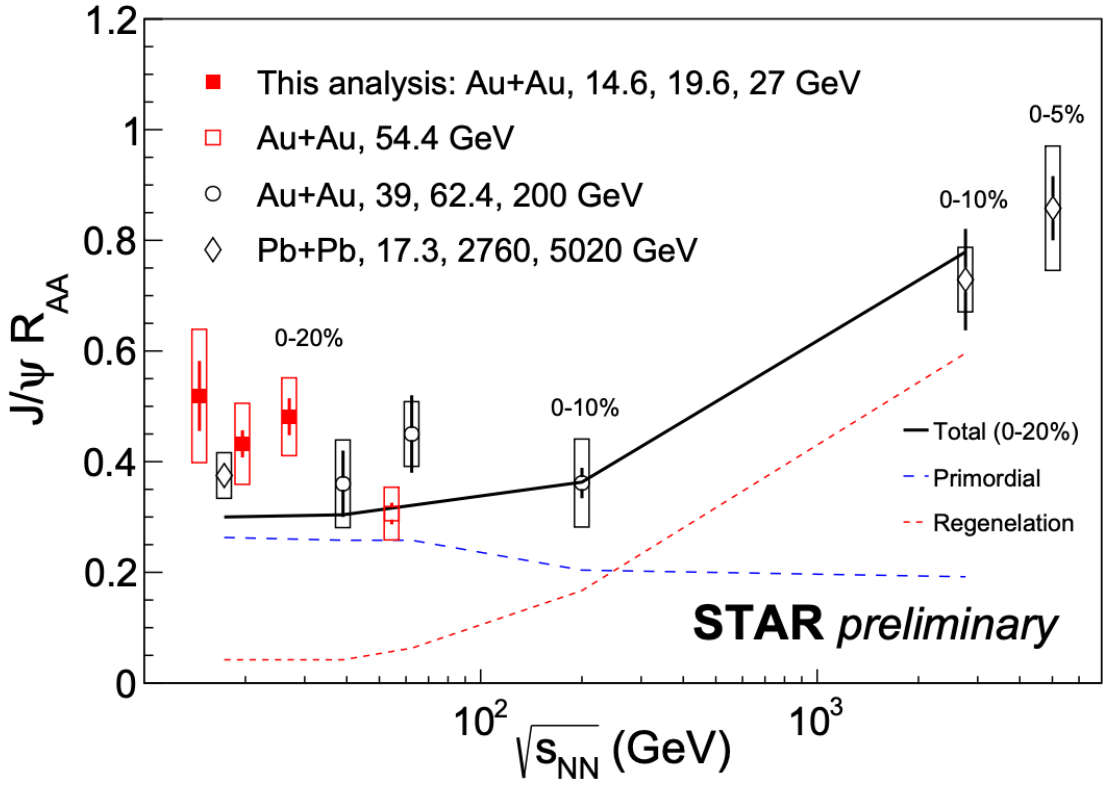


Hot medium effects:

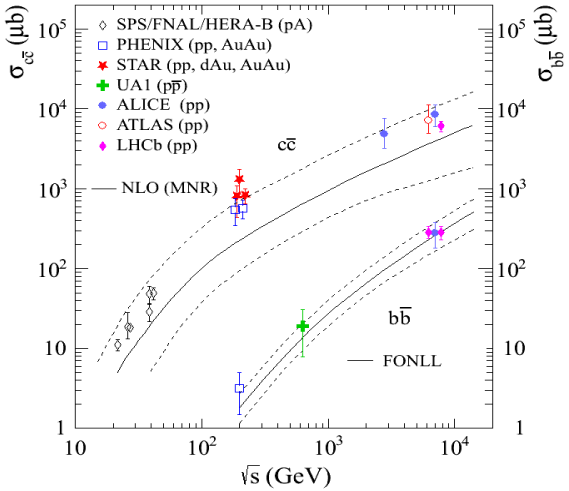
- Melting in QGP
- Regeneration
- Jet quenching?

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, Tuesday
STAR, PLB 771, 13 (2017)
Kaifeng Shen, Tuesday
ALICE, PLB 734, 314 (2014)
ALICE, PLB 849, 138451 (2024)



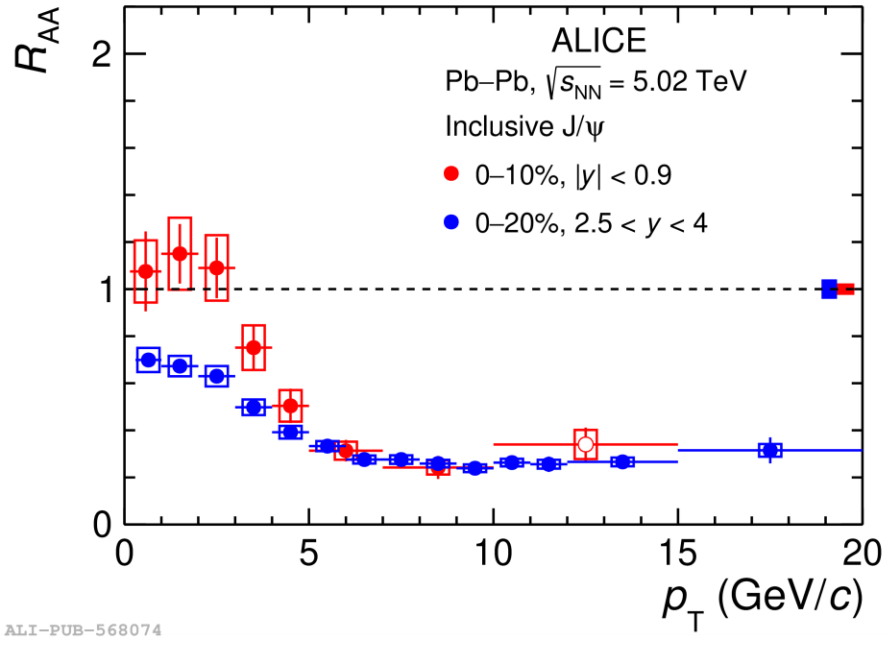
SPS → RHIC → LHC

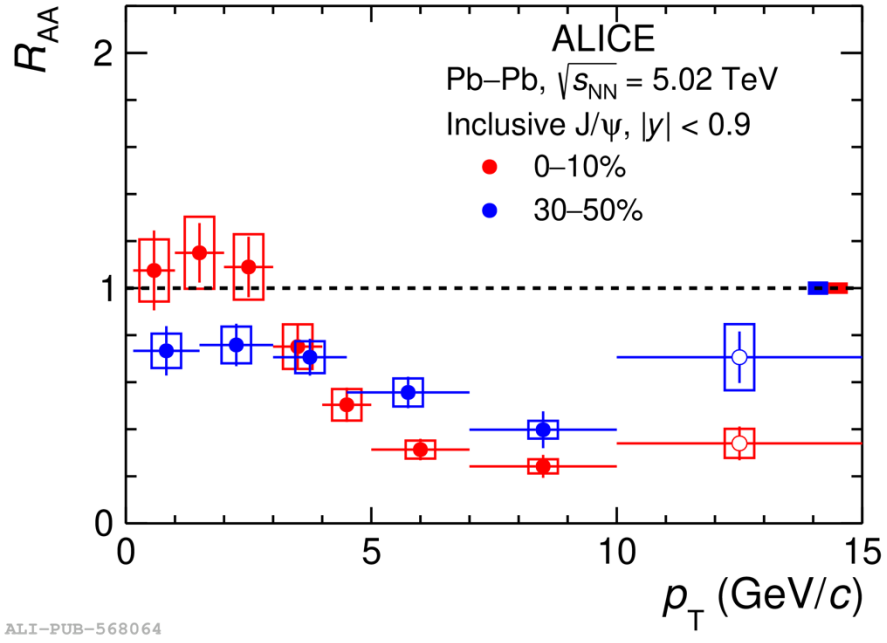
CNM domain CNM + Melting + regeneration Regeneration domain

20 years efforts at STAR and the LHC

Differential Measurements at ALICE

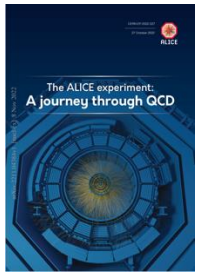
ALICE, PLB 849, 138451 (2024)





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

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

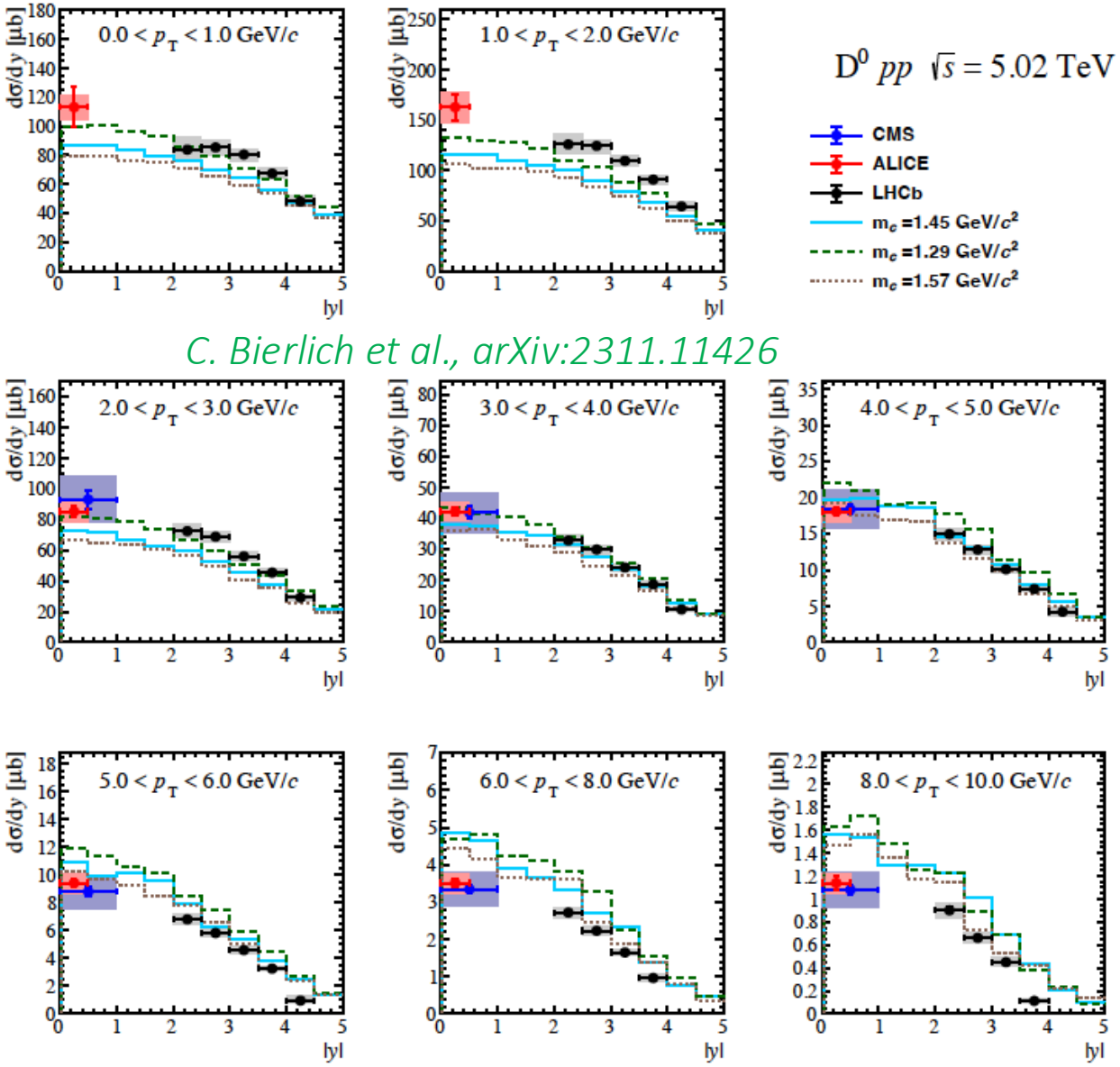


2.5.1 Study of the charmonium ground state: evidence for the (re)generation and demonstration of deconfinement at LHC energies

ALICE, EPJC 84, 8 (2024)

*Energy loss may play an import role at high p_T

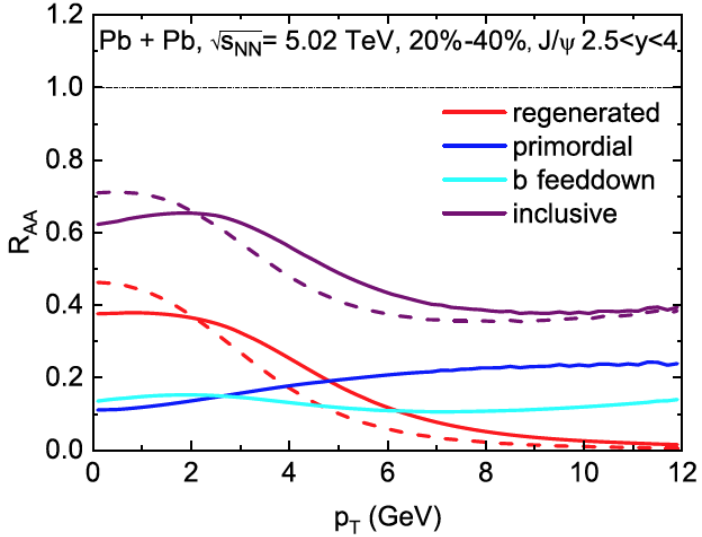
Rapidity Dependence of Charm Cross Section



C. Bierlich et al., arXiv:2311.11426

D-meson cross section at mid-rapidity

>~ 2X of that at forward rapidity

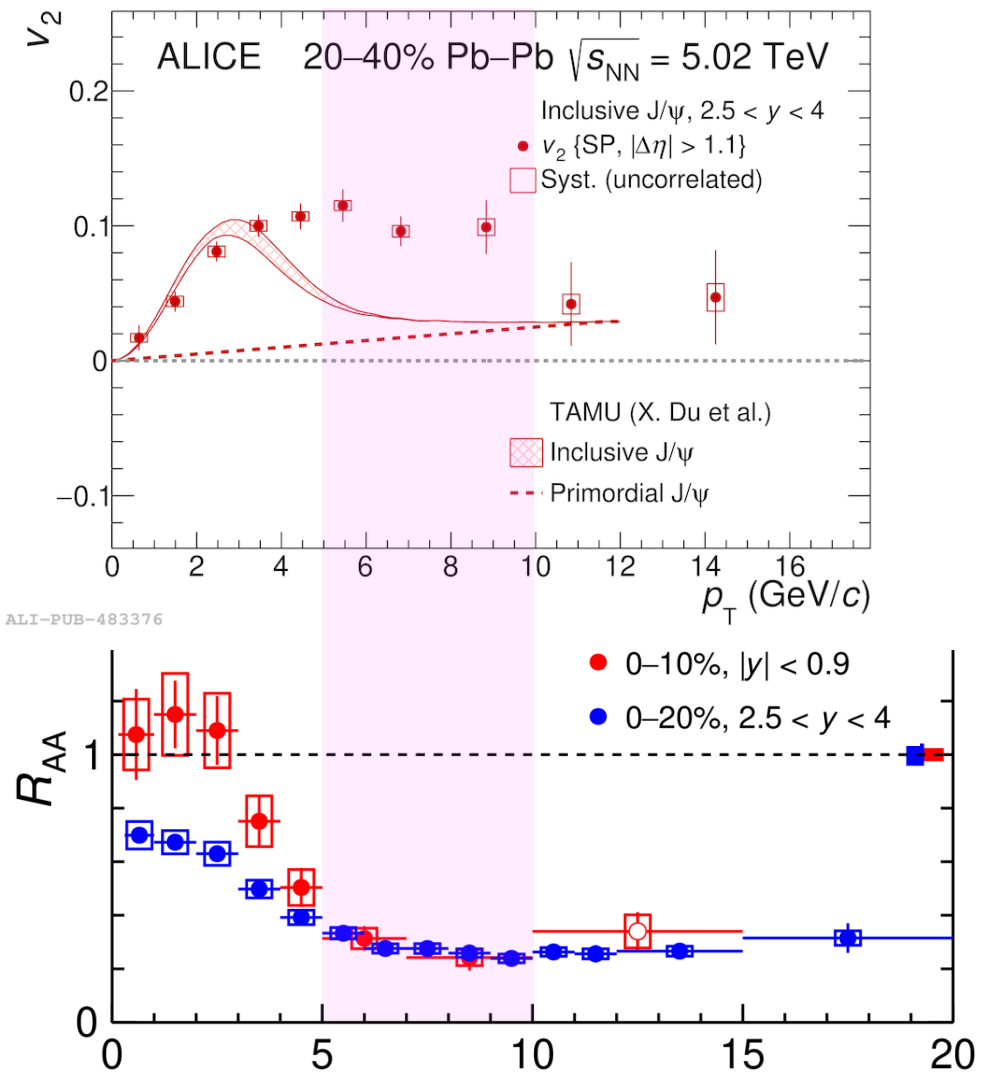


M. He et al, PRL 128, 162301 (2022)

Comparable contribution of regenerated and primordial at p_T~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?

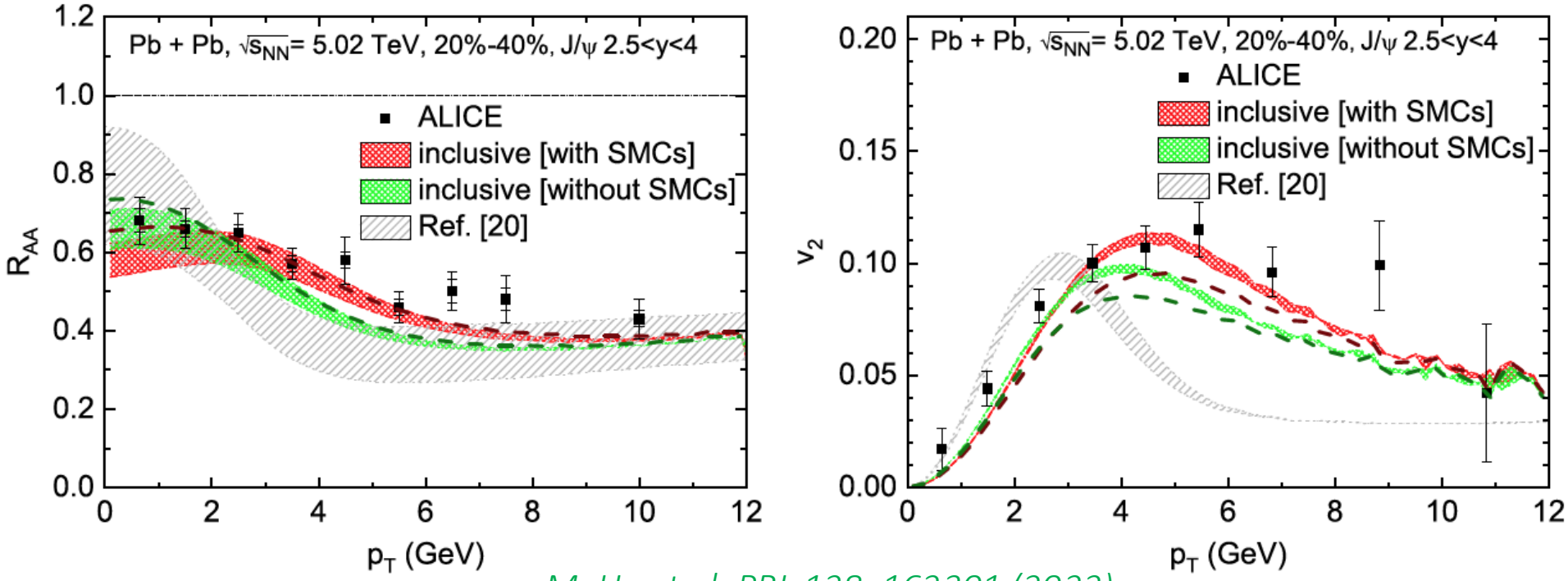
J/ψ Elliptic Flow



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~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

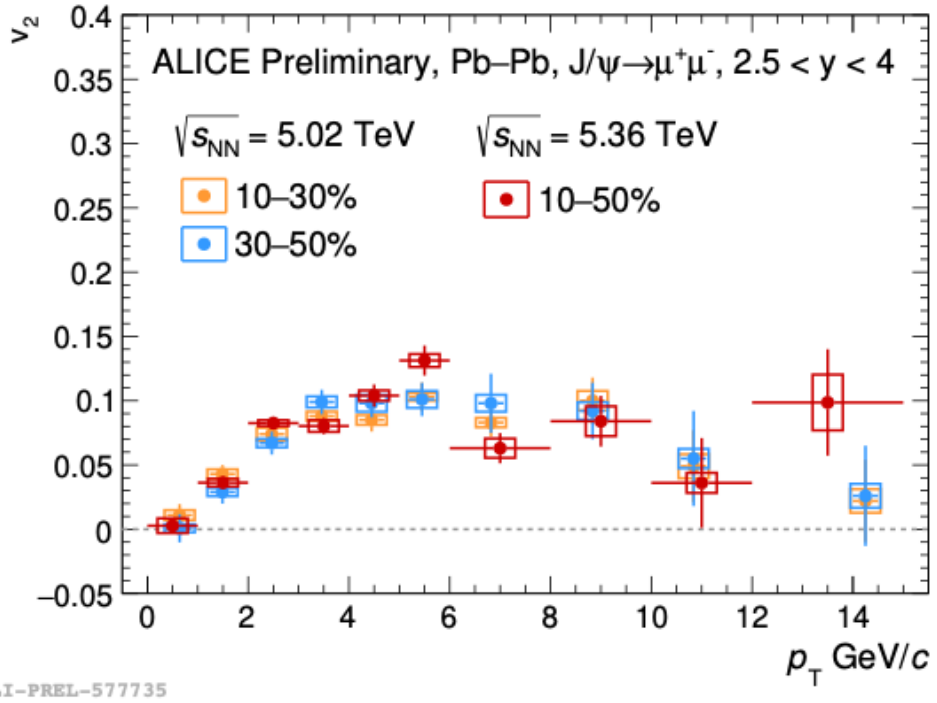
J/ψ R_{AA} and v_2



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

- R_{AA} and v_2 simultaneously described by the improved transport model upto p_T~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 v_2 from ALICE Run3



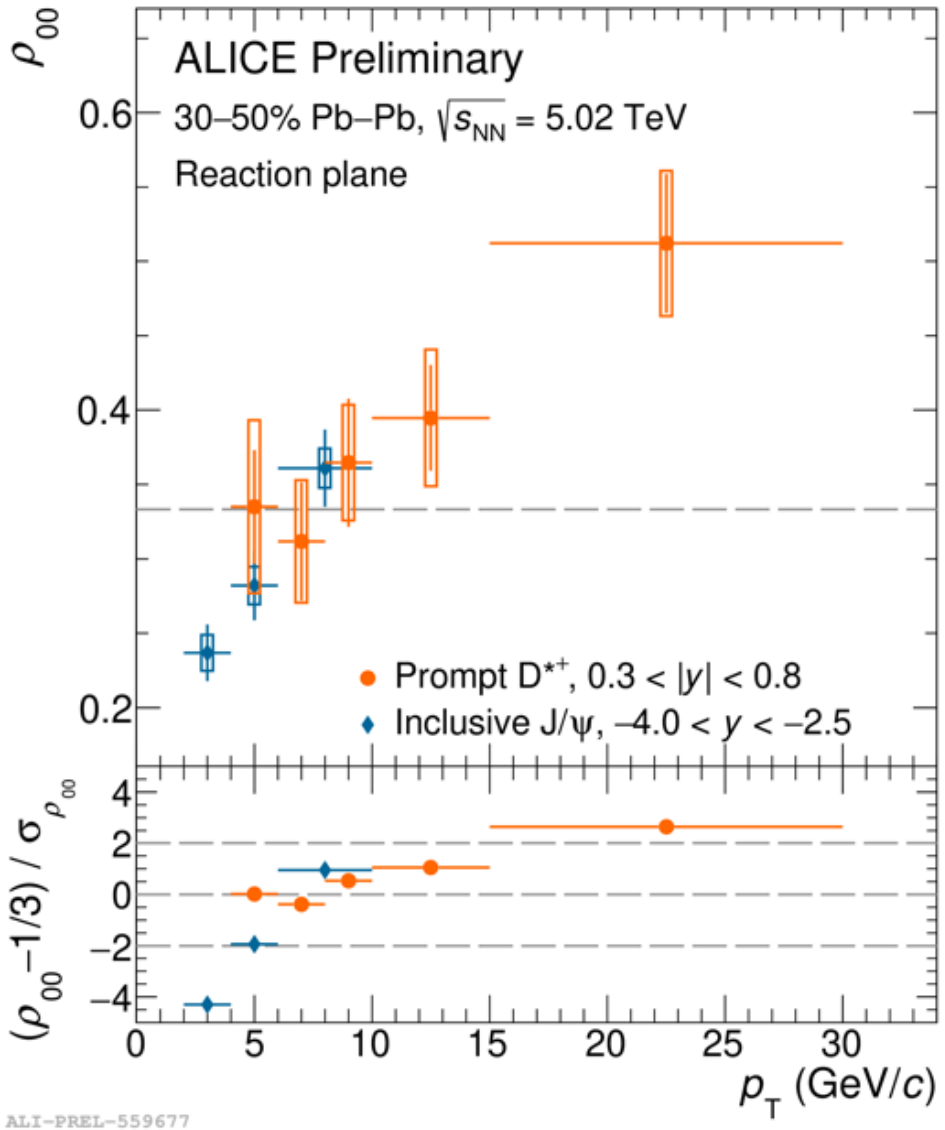
Forward rapidity:

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

Middle rapidity:

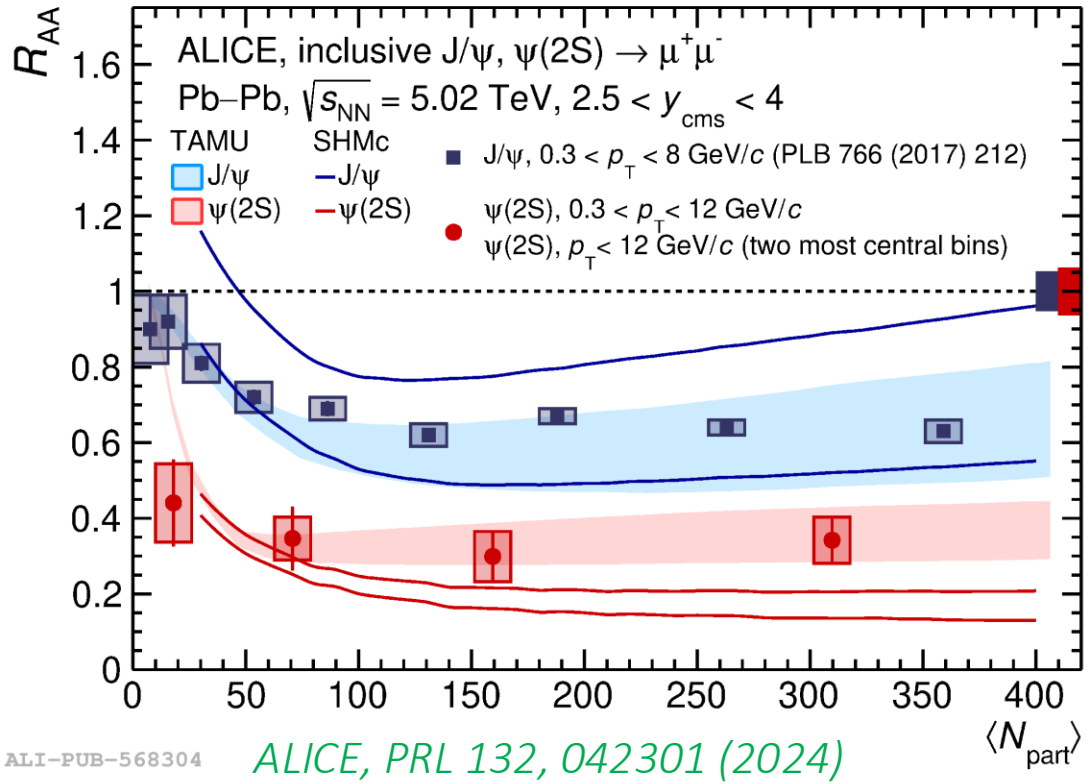
- Significant enhancement of #events in Run3 compared to Run2
- Enables precision v_2 measurement
- Stay tuned!

J/ψ Polarization

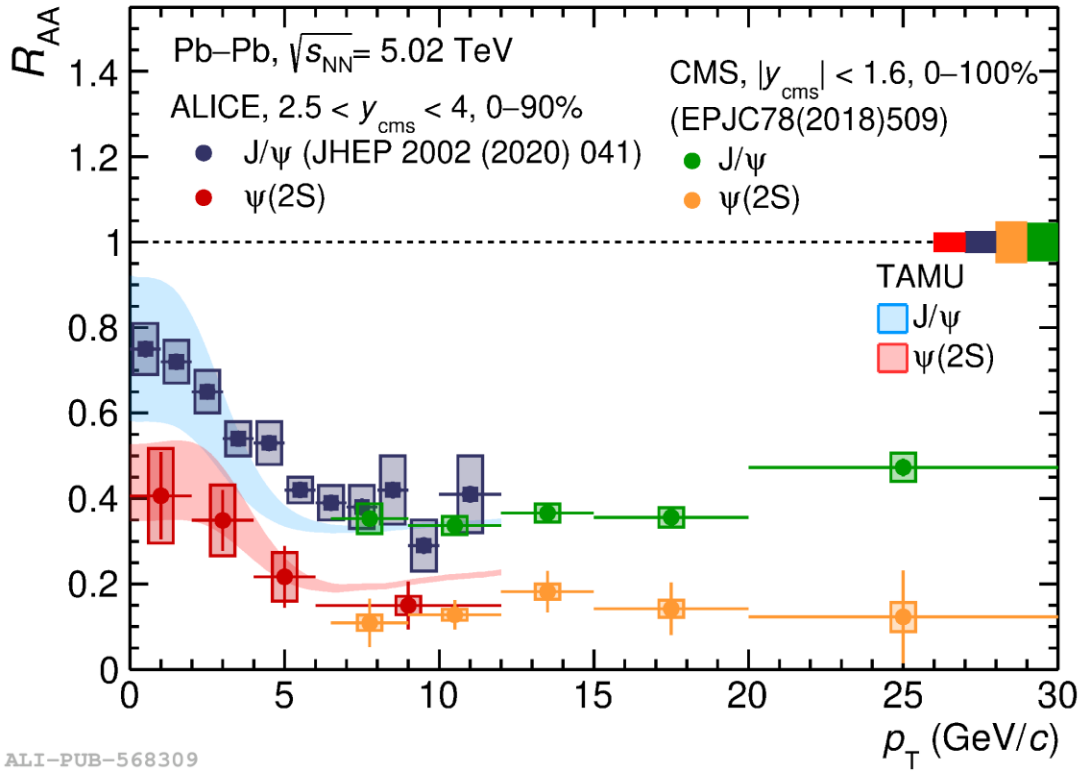


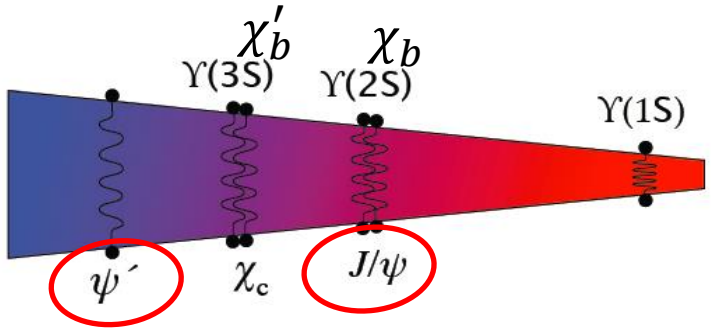
- Polarization of vector meson in vortical QGP depends on its production mechanism
  X.-L. Sheng et al., PRL 131, 042304 (2023)
- Charmed vector meson at LHC is a sensitive probe
  - Thermalized charm
  - Dominant coalescence
- J/ψ and D* seem follow the same trend
  - Increase from <1/3 at low-p_T for J/ψ to >1/3 at high-p_T for D*
  - But they are from different rapidity range
- J/ψ at mid-y and large p_T coverage from ALICE Run3 is crucial

Sequential Suppression of Charmonium



ALICE, PRL 132, 042301 (2024)

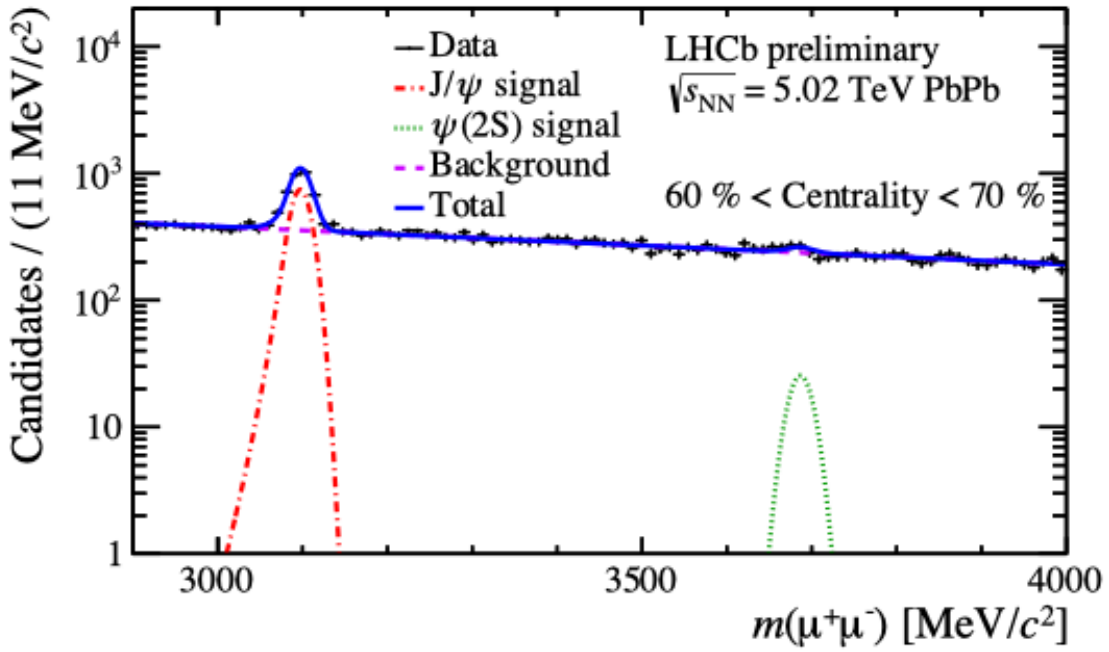


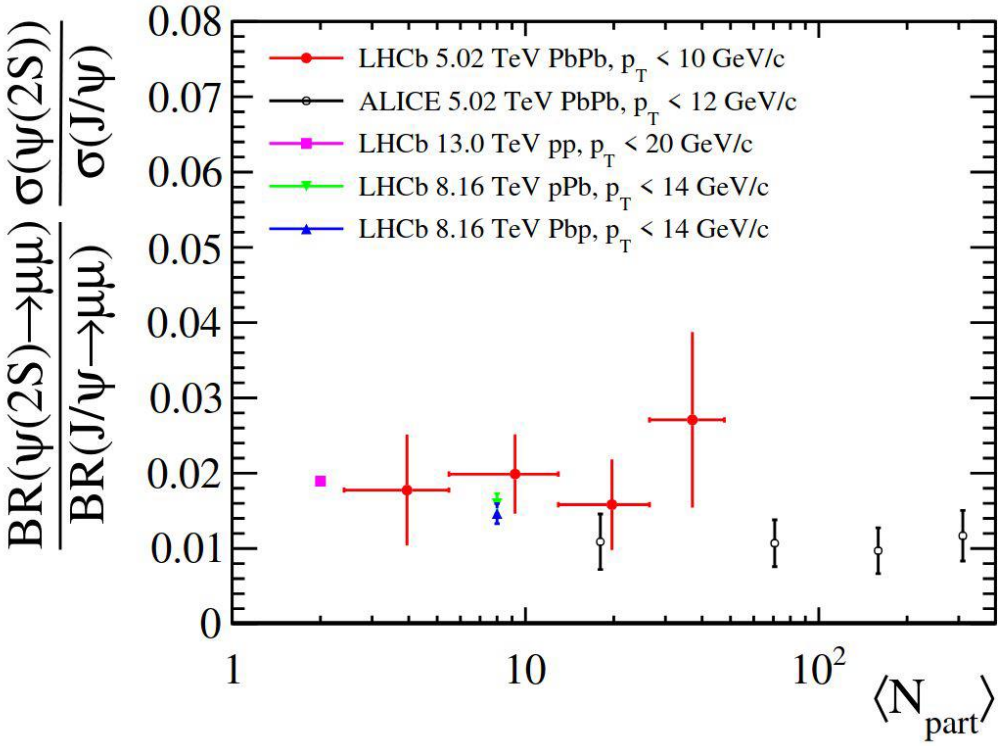


- ψ(2S) more suppressed than J/ψ in all centrality and all p_T
- Described by transport model calculations
- Again, similar suppression at mid- and forward rapidity at intermediate p_T

Results from LHCb

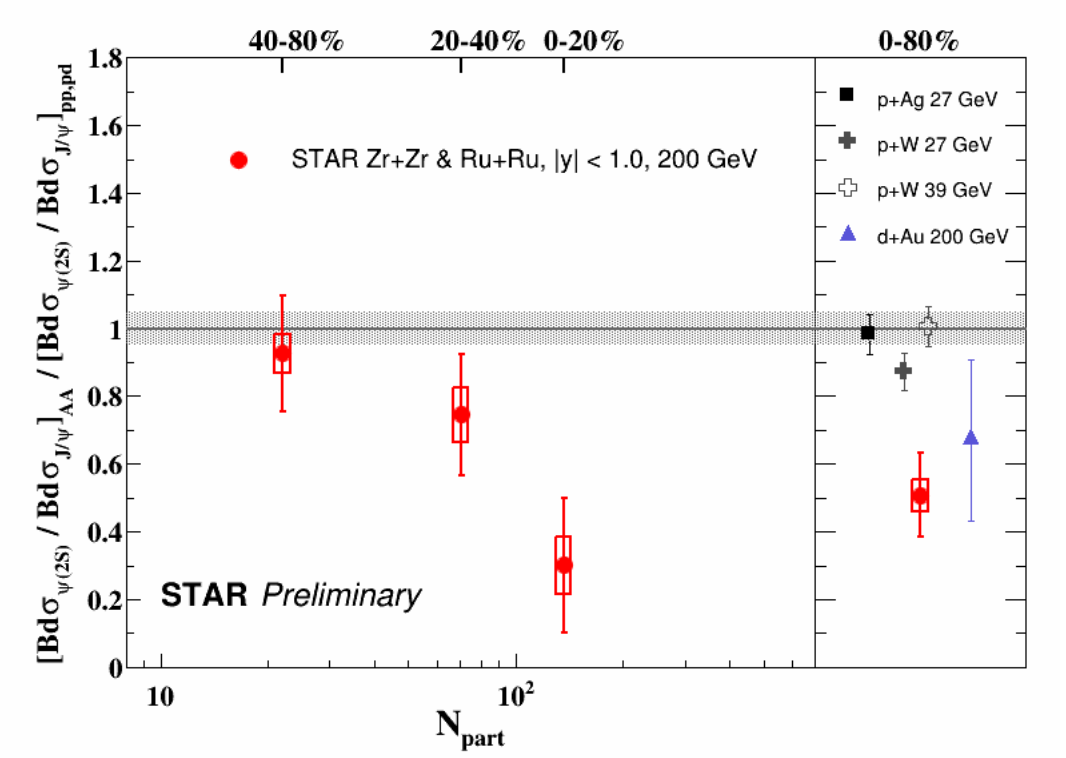
LHCb, arXiv:2411.05669





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

Results from STAR



Yan Wang, Tuesday

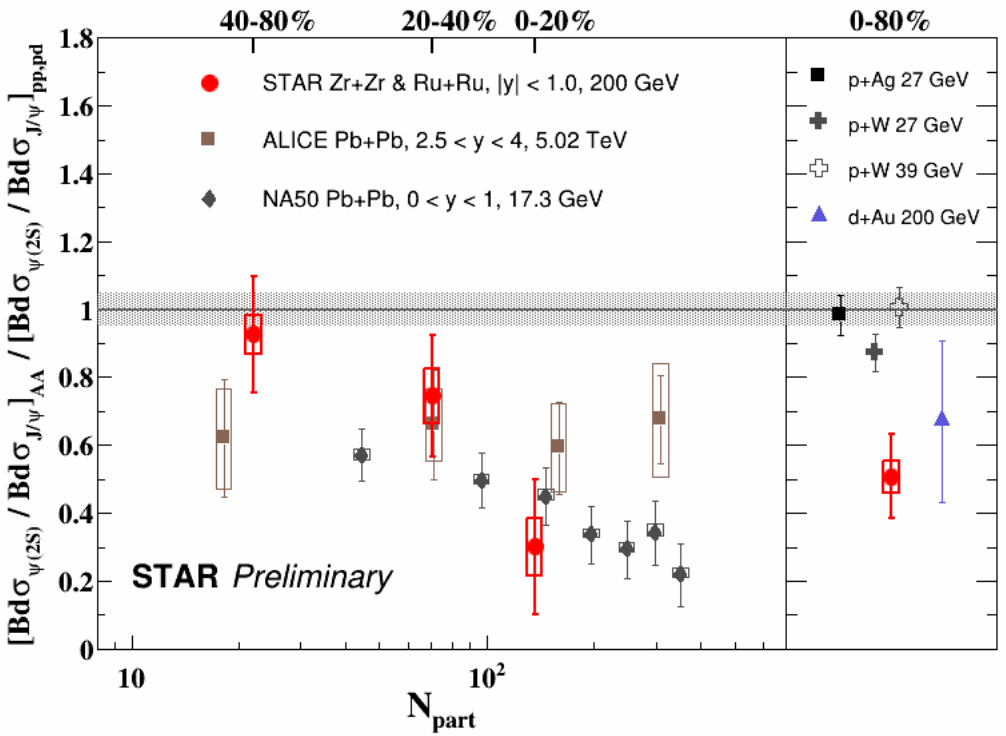
pp reference is the average of measurements in p+p(d) by NA51, ISR and PHENIX

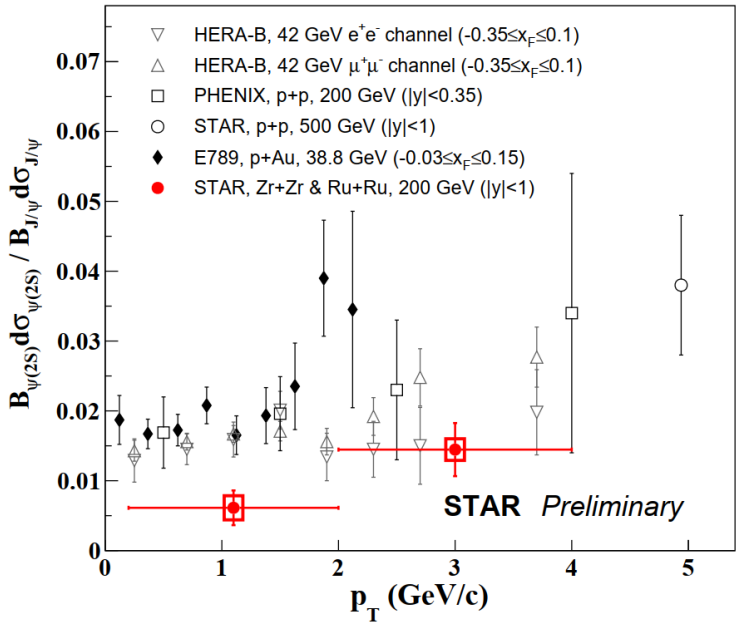
Better pp reference is internally available

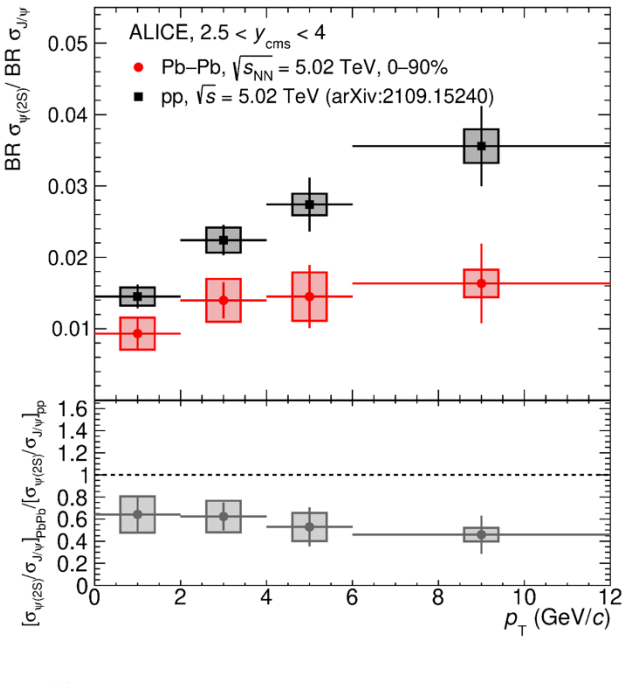
- First measurements in heavy-ion collisions at RHIC thanks to high statistics isobar data
- Significantly more suppression for $\psi(2S)$ than J/ψ ($>3\sigma$)
- The double ratio is lower in A+A collisions than in p+A collisions

Comparison between RHIC and LHC

ALICE, PRL 132, 042301 (2024)







- Decreasing trend at RHIC and SPS
- Flat distribution at LHC

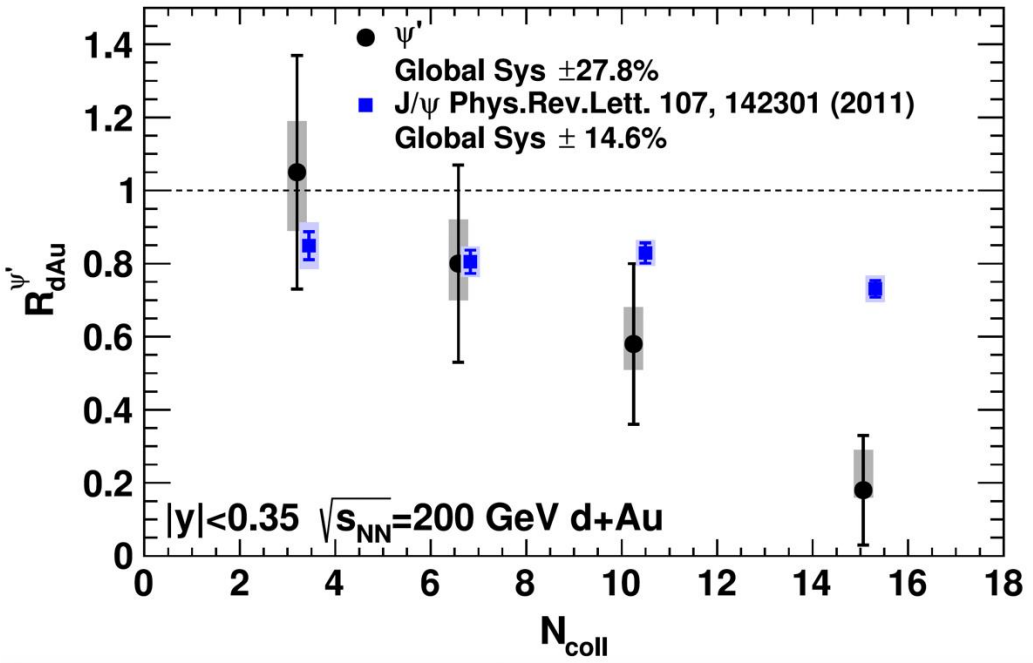
- More regeneration at LHC?
- More non-prompt contribution at LHC?

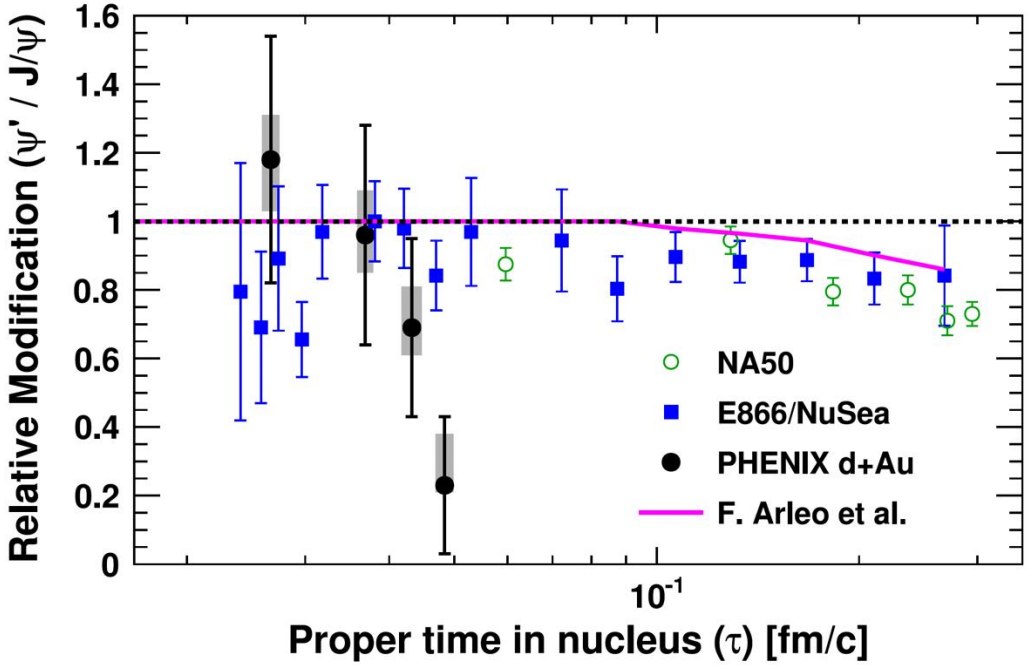
- A hint of increasing trend at RHIC
- Slightly decreasing trend at LHC

- Opposite to expectation from pure non-prompt contribution

Ratio in Small System at RHIC

PHENIX, PRL 111, 202301 (2013)

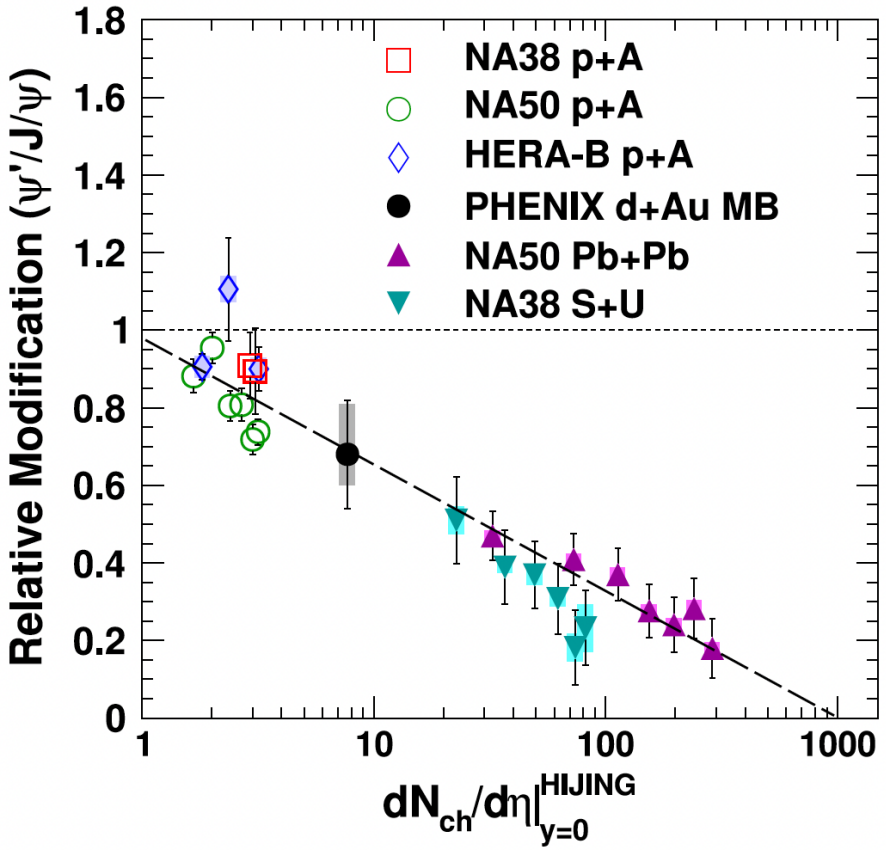




- Stronger suppression of ψ(2S) relative to J/ψ observed in central d+Au collisions at RHIC
- The double ratio at RHIC seems not follow proper time scaling
- ➔ Something beyond nuclear absorption?

Multiplicity Scaling?

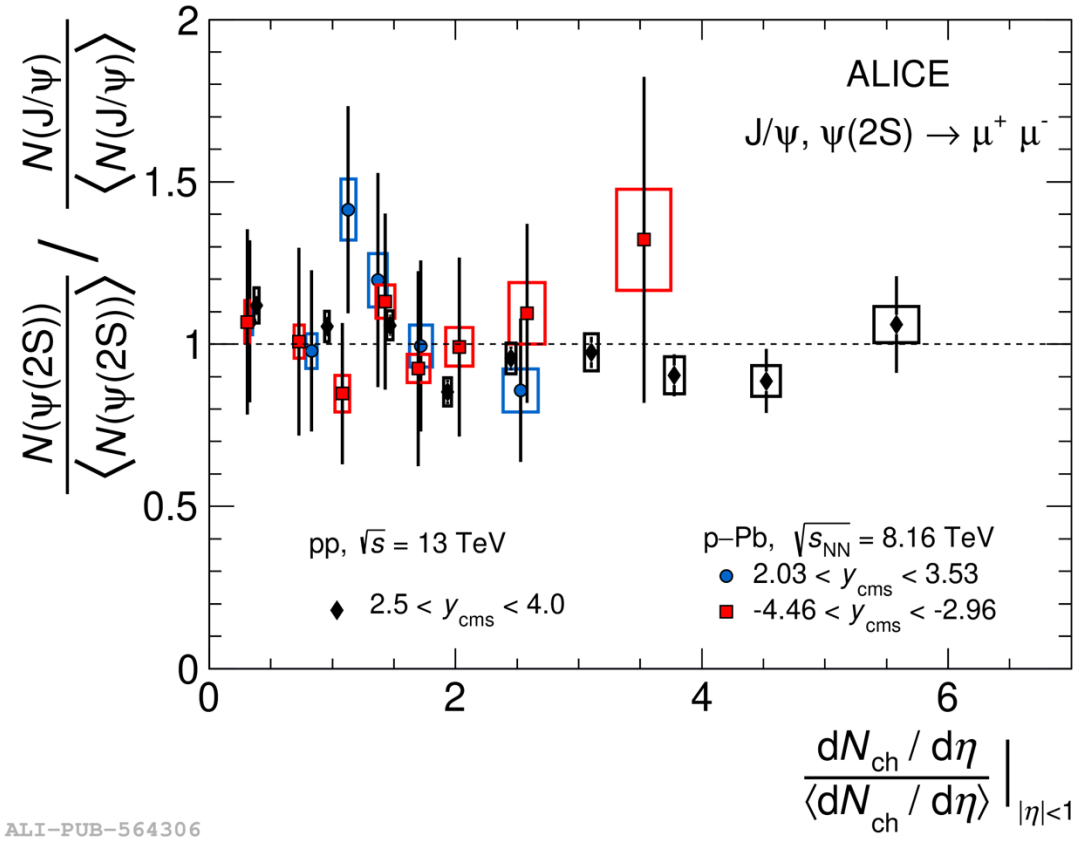
PHENIX, PRL 111, 202301 (2013)



- 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

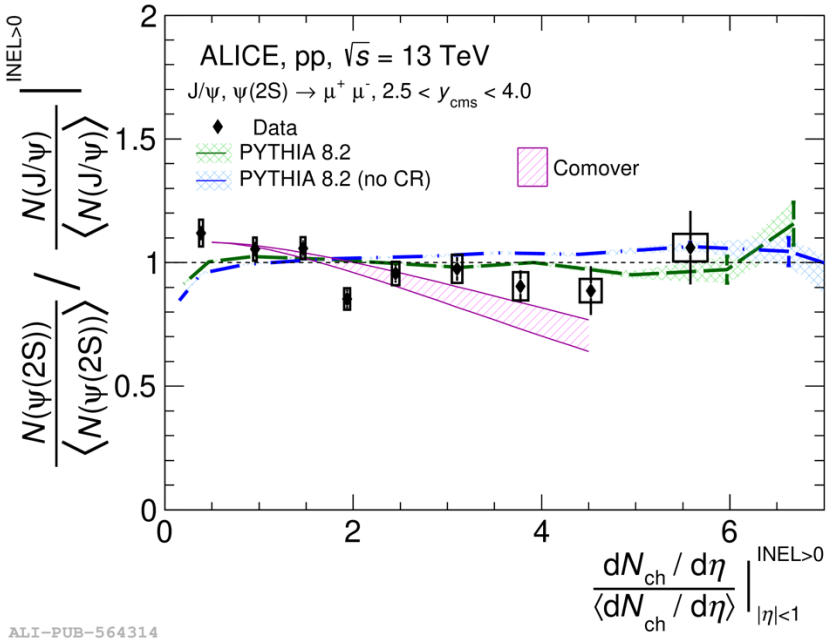
ALICE, JHEP06, 147 (2023)

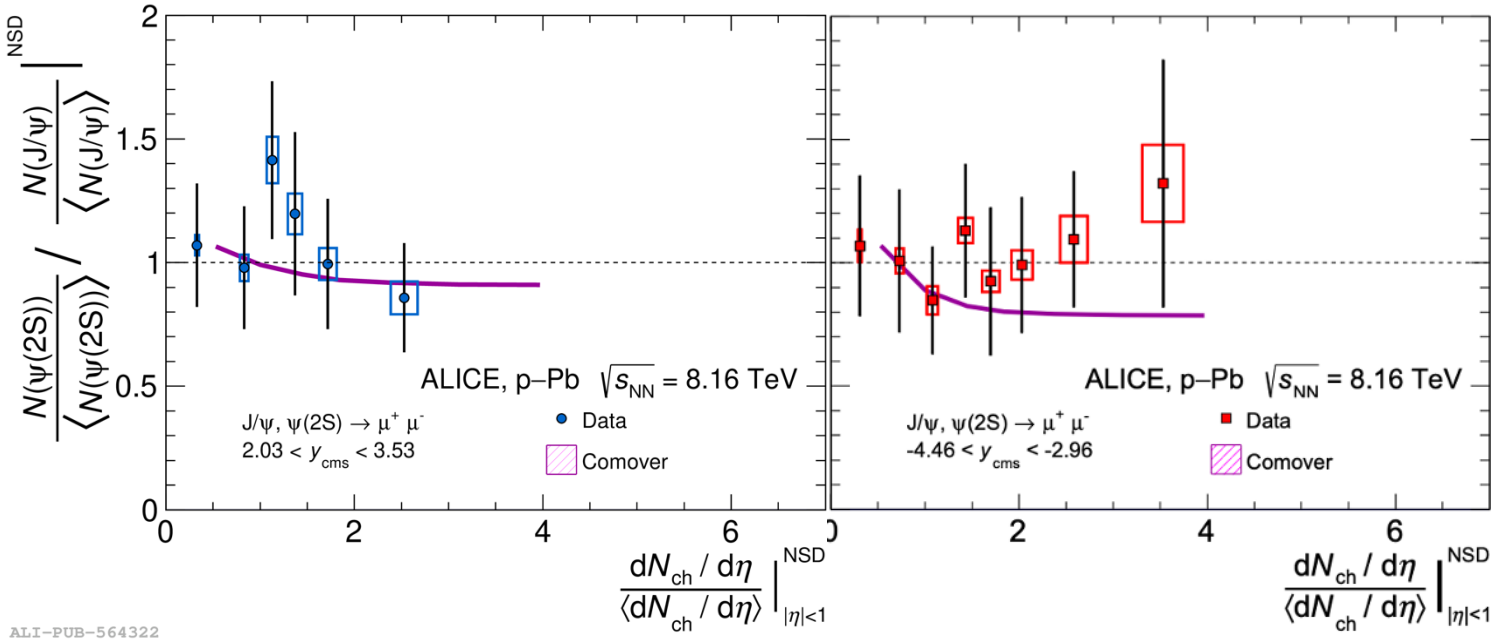


- The double ratio at forward rapidity in p+p and p+Pb consistent with unity
- Independent on charged multiplicity in mid-rapidity
- Challenging to explain RHIC and LHC data with the same mechanisms

Comparison to Theoretical Calculations

ALICE, JHEP06, 147 (2023)

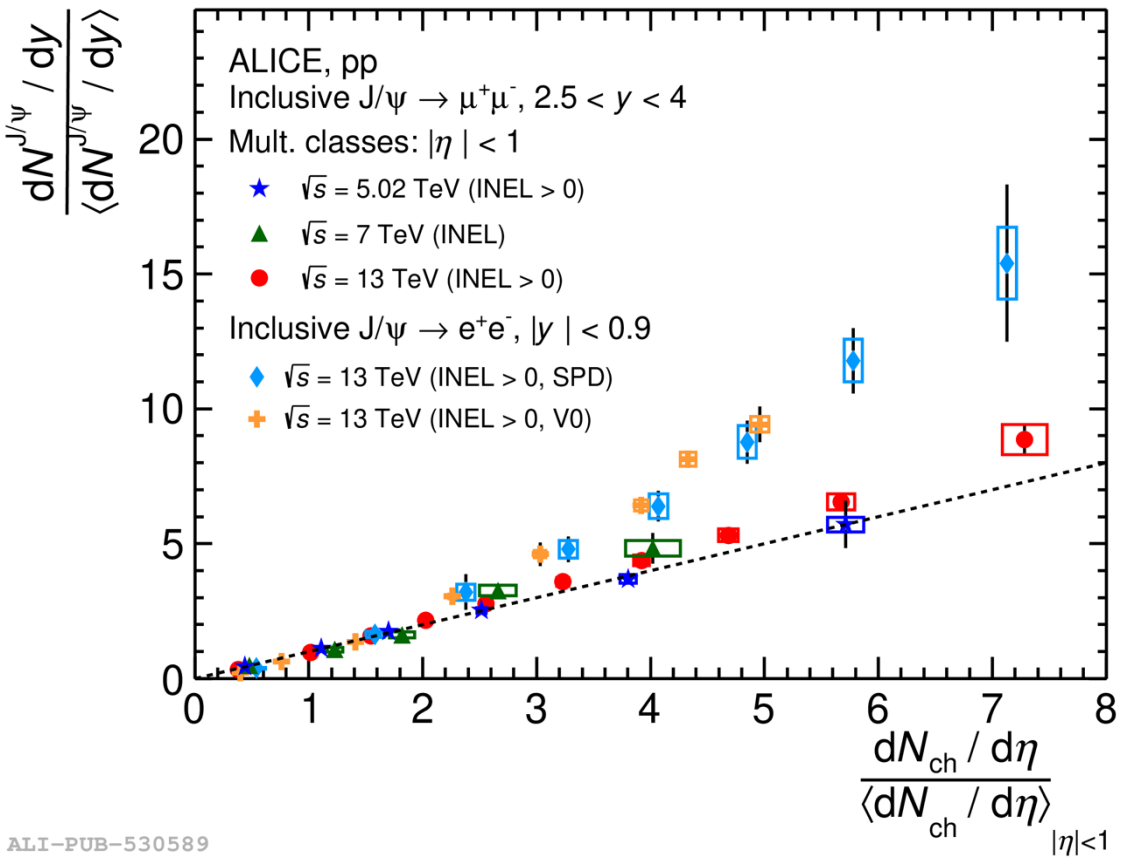




- Data can be described by different models within uncertainties
- Precisions need to be improved

Multiplicity Dependence of J/ψ Production

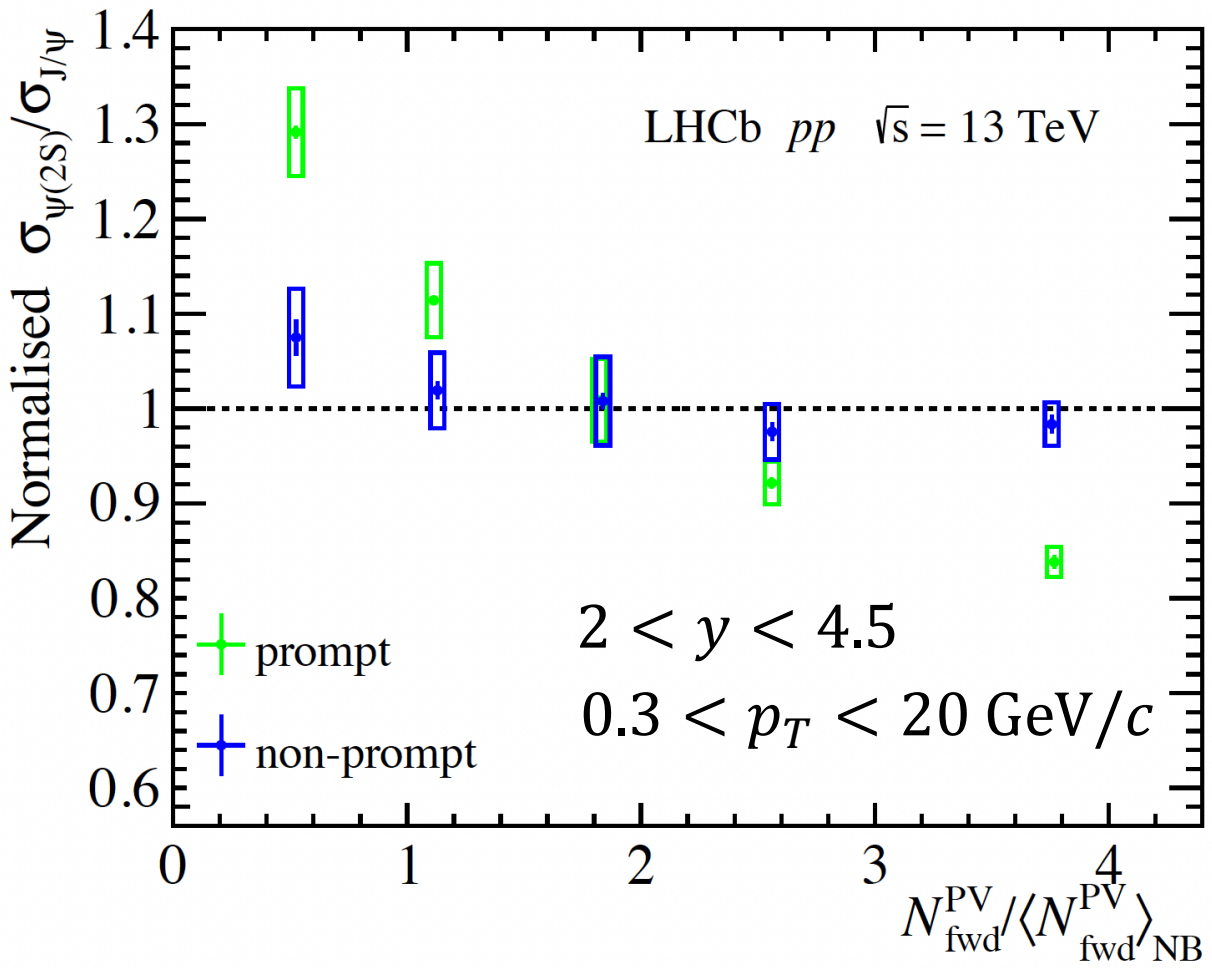
ALICE, JHEP06, 015 (2022)



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

Forward Charmonium vs. Forward Multiplicity in p+p

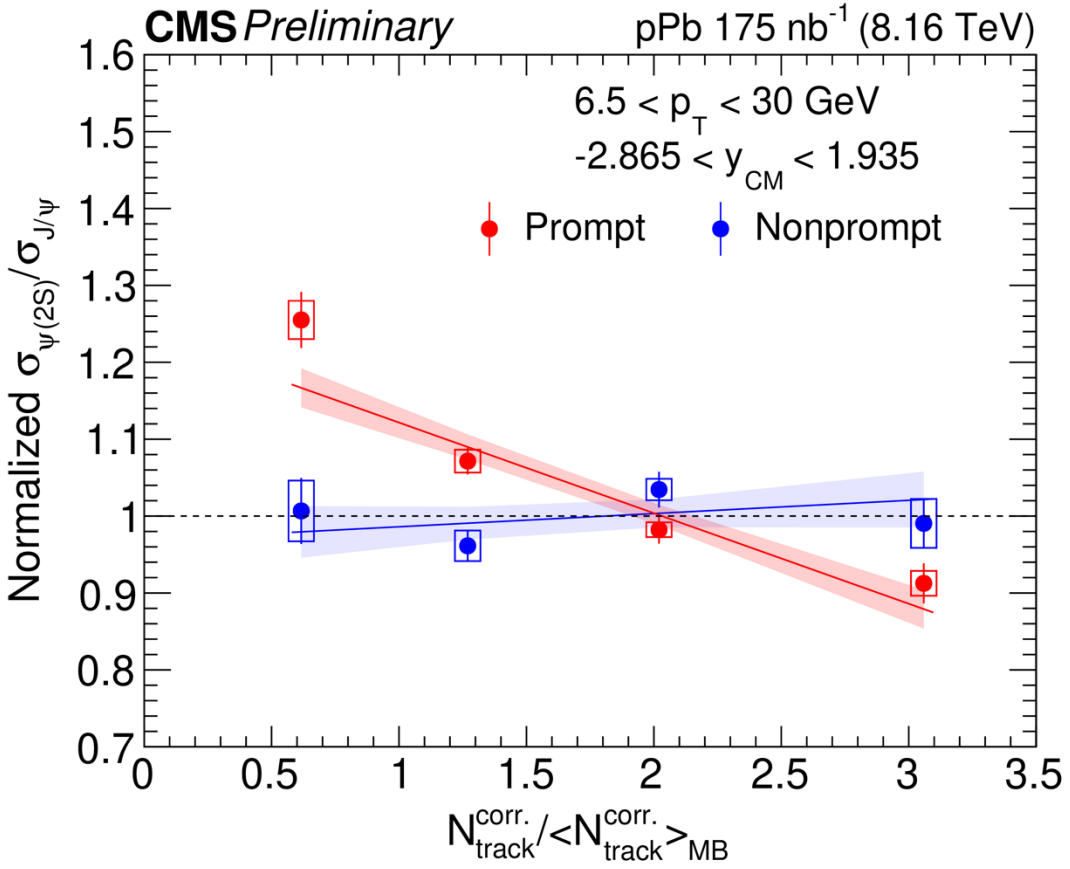
LHCb, JHEP05, 243 (2024)

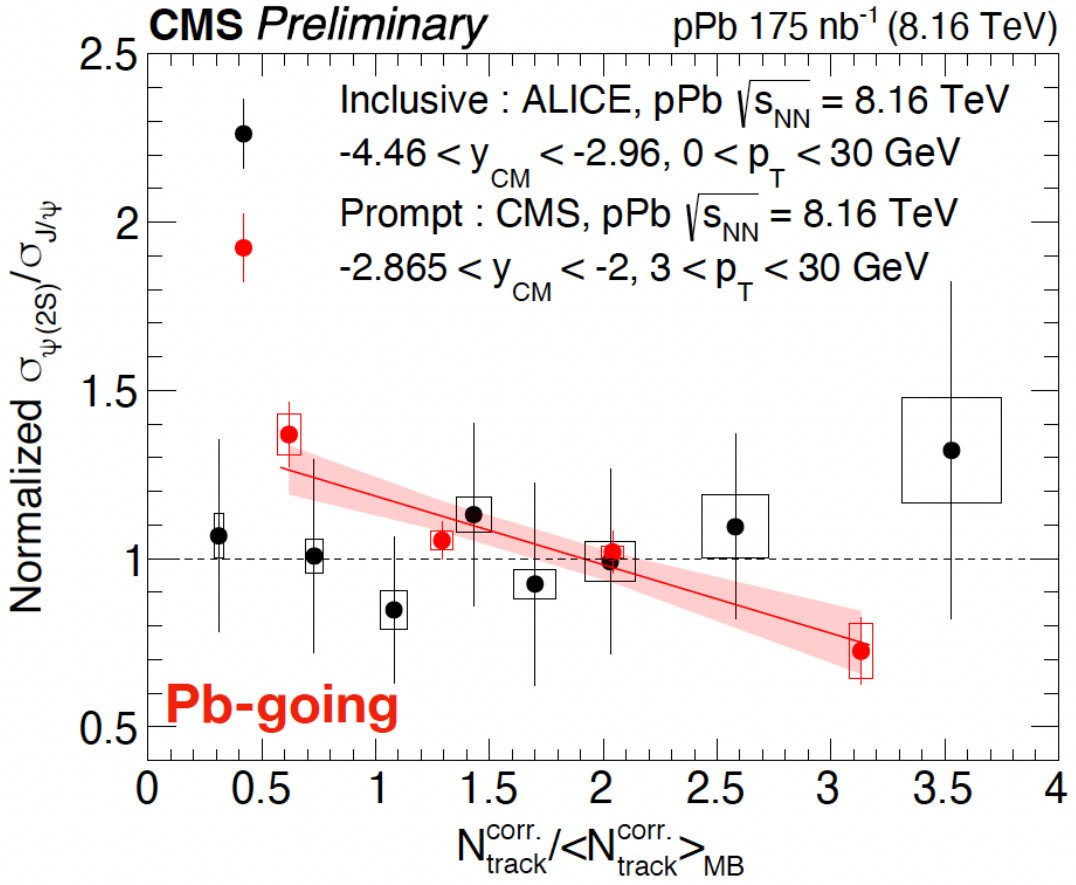


Decreasing trend observed in p+p from LHCb

Measurements at Mid-y and High-p_T from CMS

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

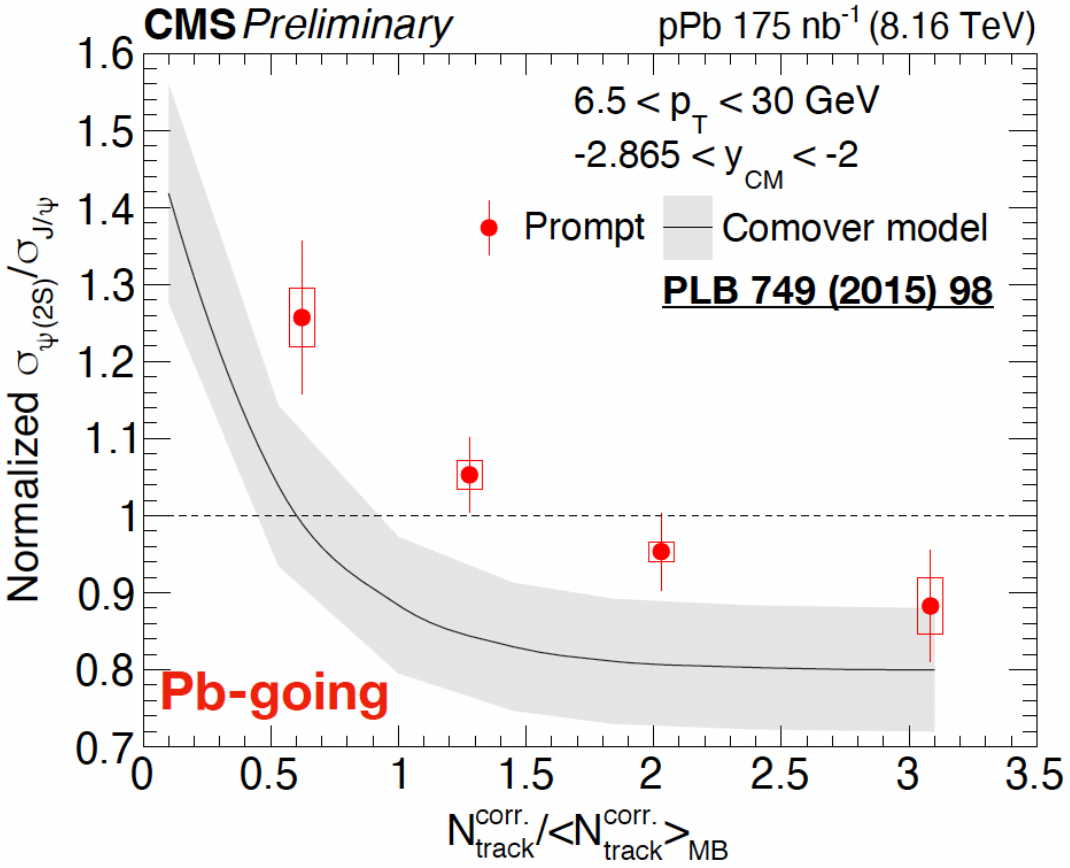


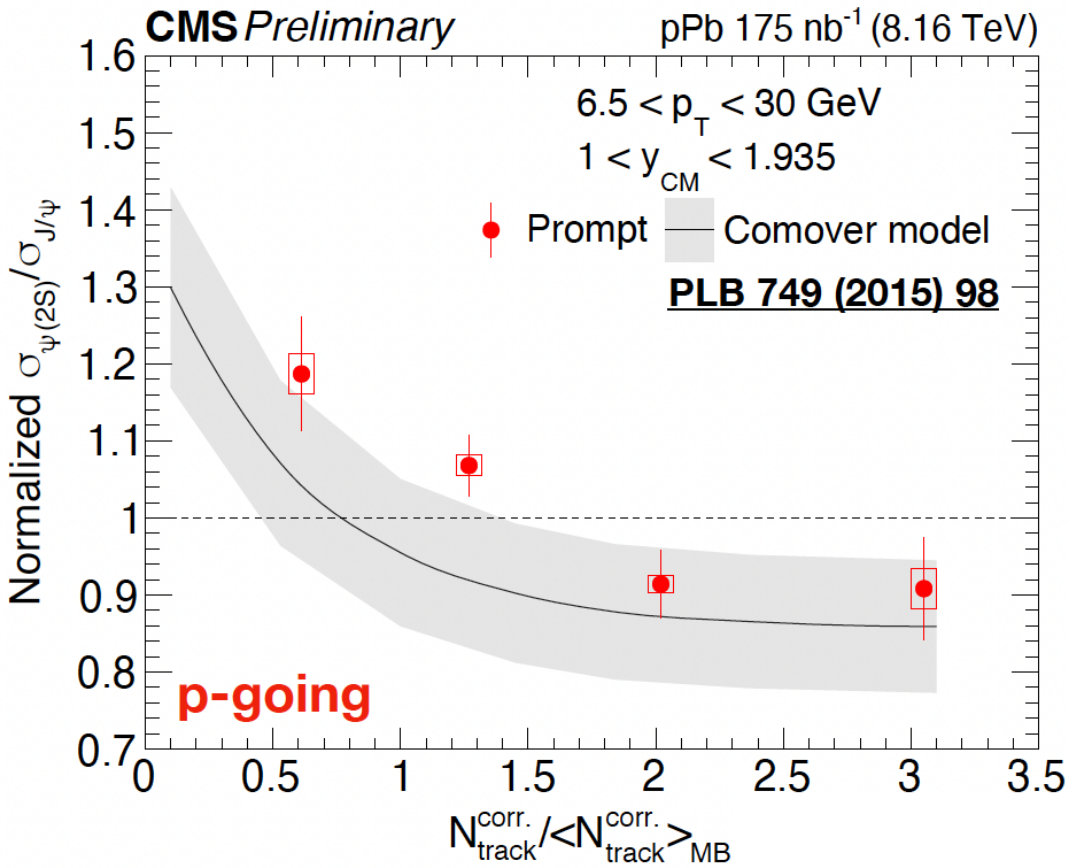


- Significant multiplicity dependence for prompt
- Not multiplicity dependence for non-prompt
- Results do not contradict to ALICE results
- Also note about difference of y and p_T

Mid-y and low-p_T from ALICE Run 3? *Yuan Zhang, Monday*

Compare to Comover Model

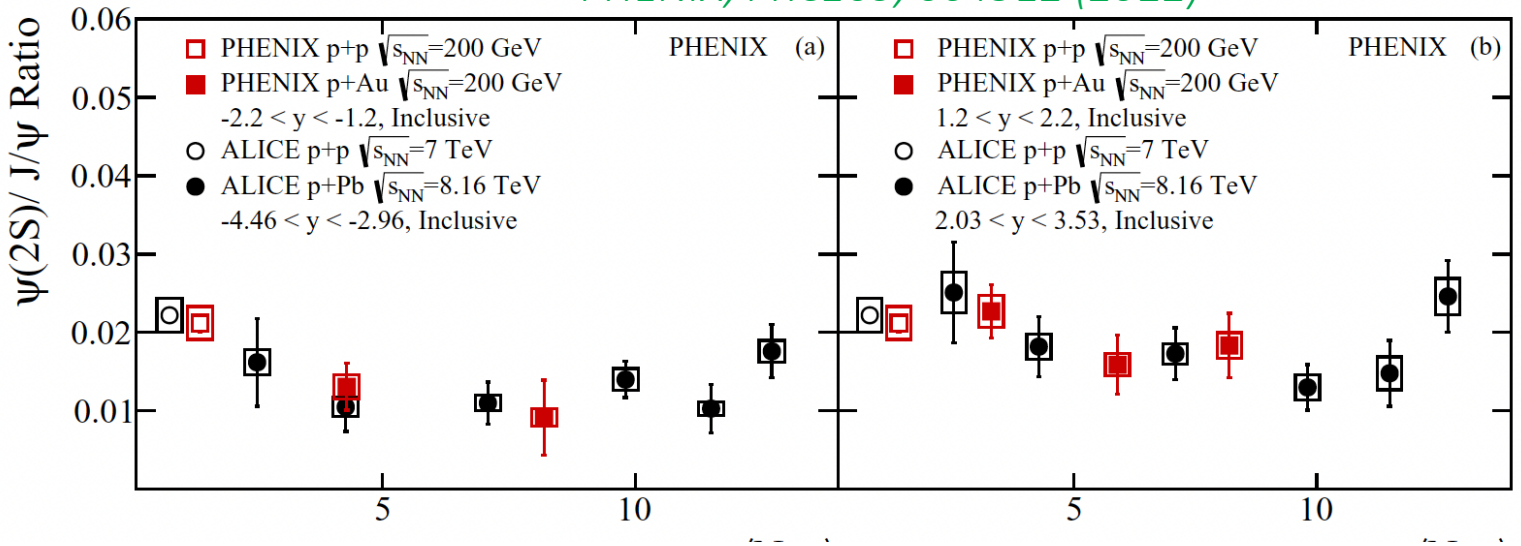


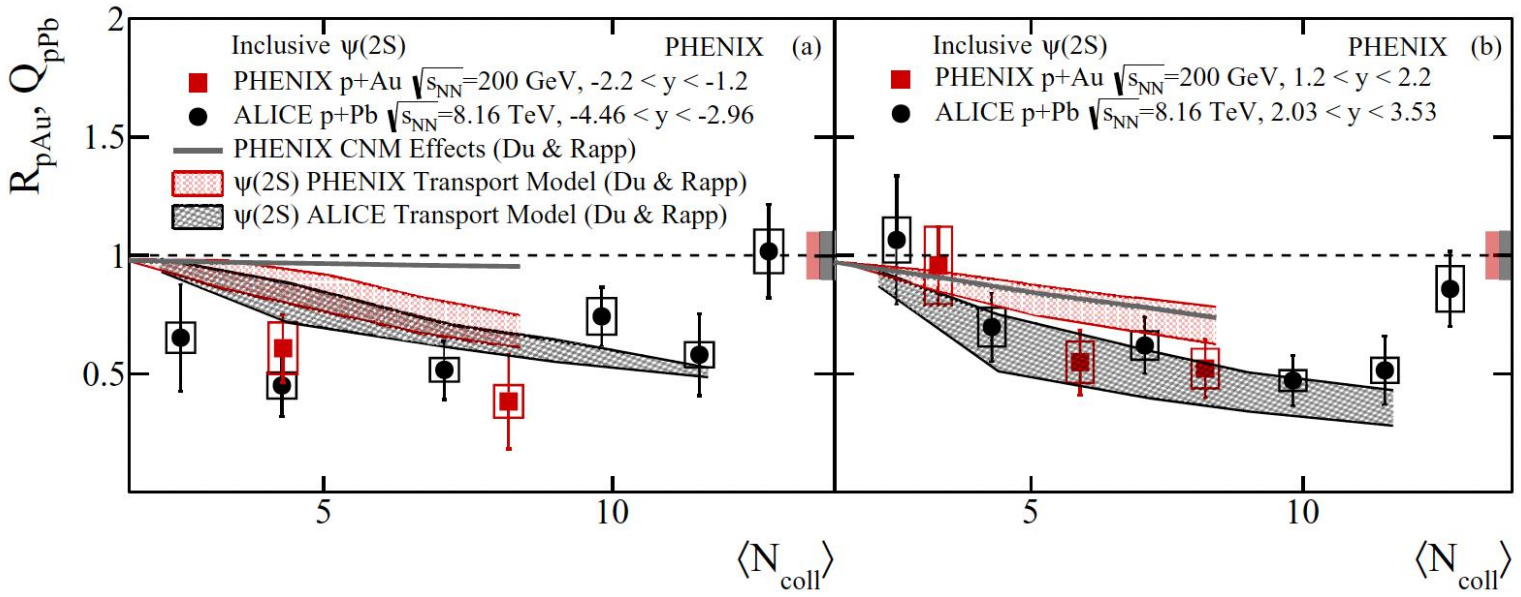


- Comover model consistent with data on p-going side
- But systematically overestimate the relative suppression on Pb-going side

Comparison between RHIC and LHC

PHENIX, PRC105, 064912 (2022)





- There are difference between ratios in p+p and p+A collisions

➔Dependent on multiplicity in forward rapidity

- No significant difference between RHIC and LHC

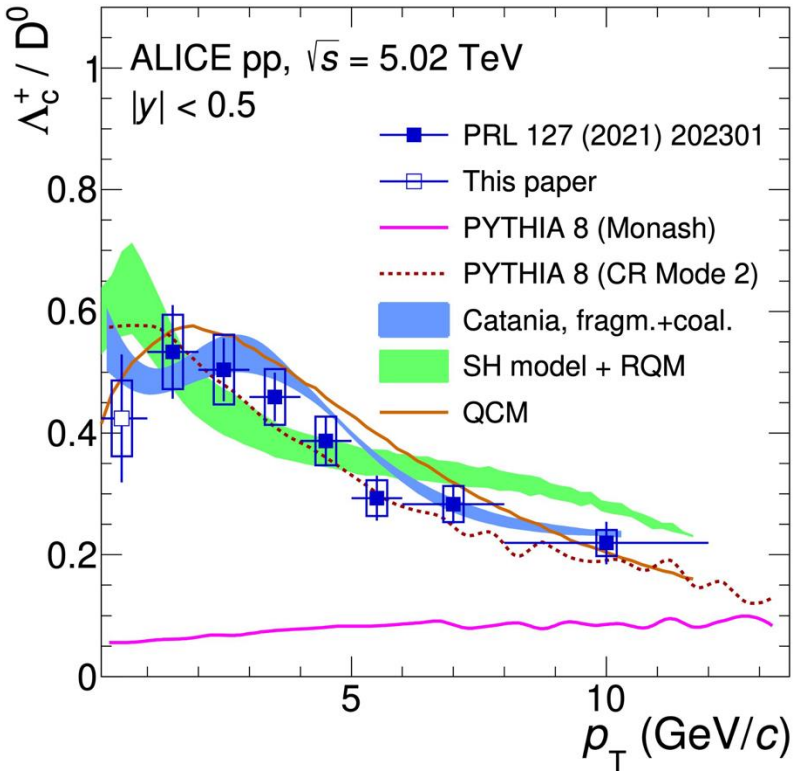
➔Independent on multiplicity?

- Transport model can describe the data from RHIC and LHC

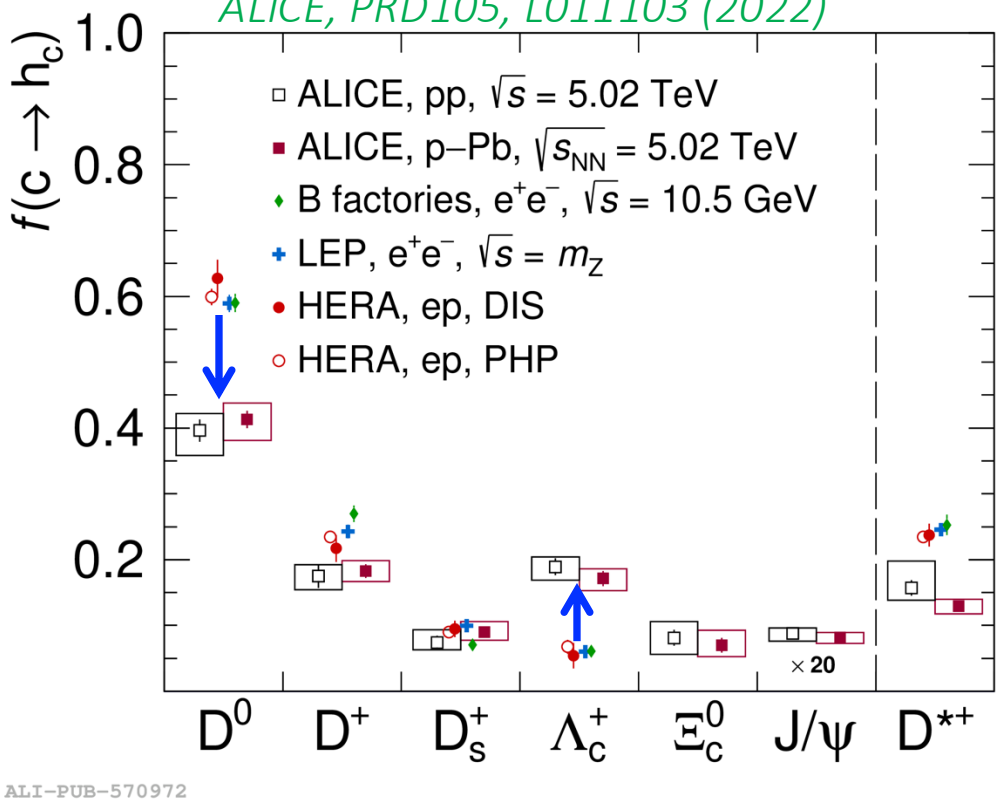
➔Interplay of QGP temperature + lifetime vs. $\langle p_T \rangle$

Charm Hadronization in p+p at LHC

ALICE, PRC107, 064901 (2023)

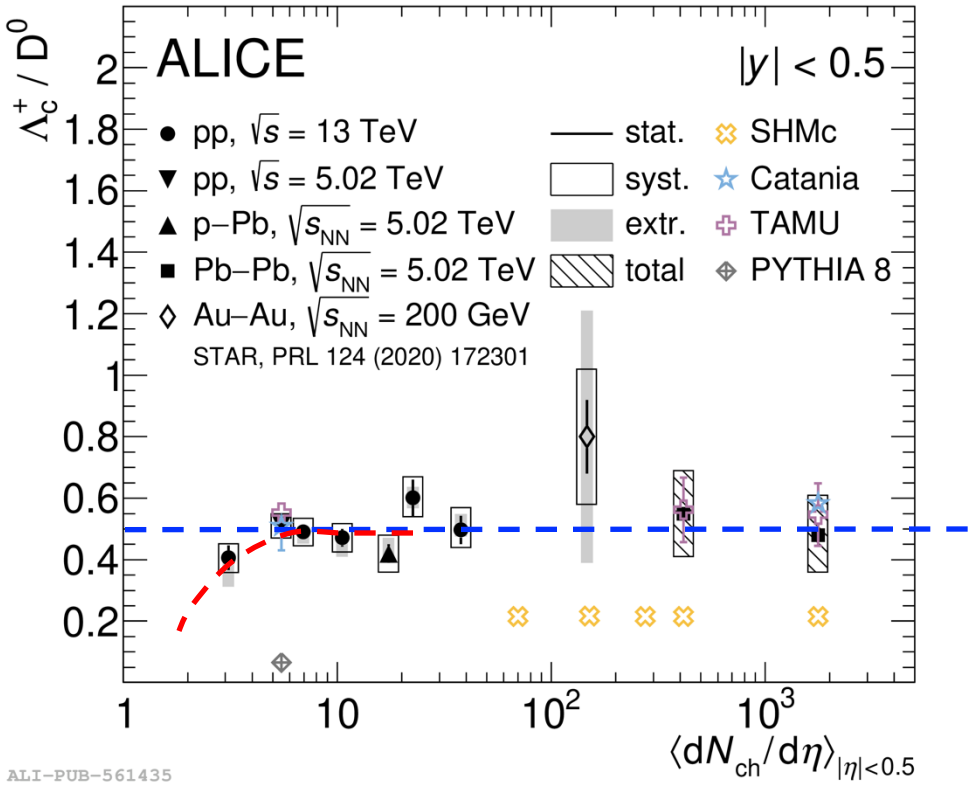


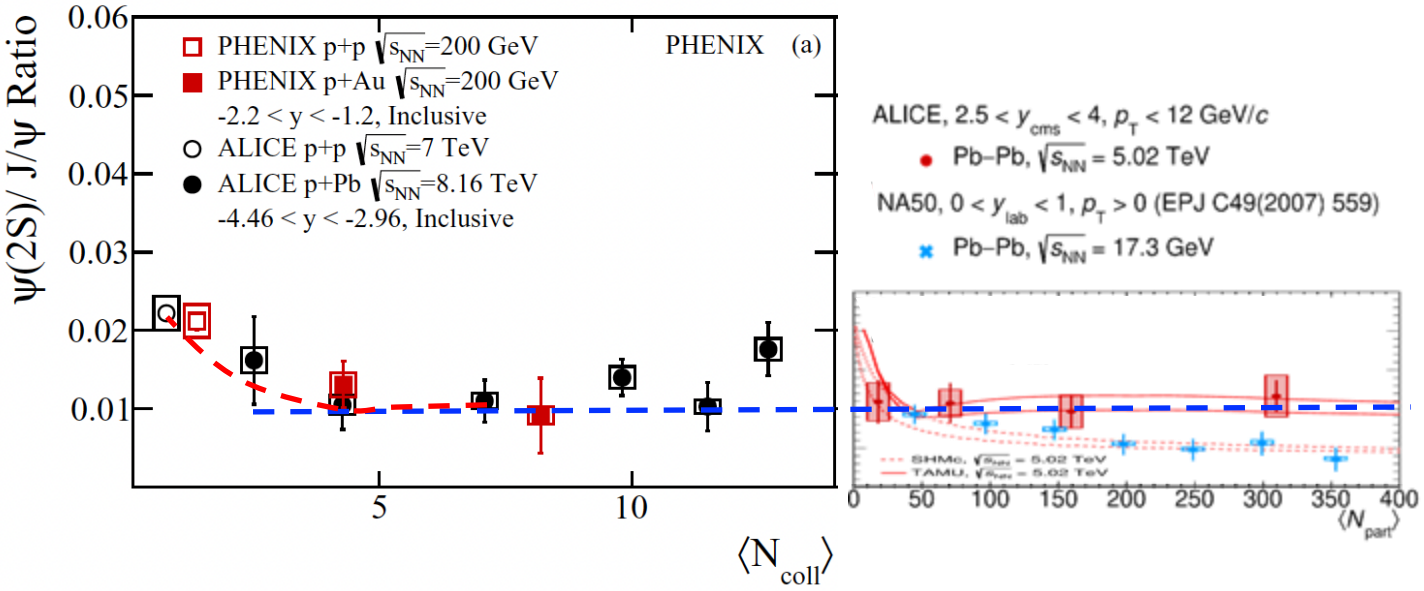
ALICE, arXiv:2405.14571
ALICE, PRD105, L011103 (2022)



- Charm is found to be redistributed in p+p collisions at LHC with respect to ee/ep
- What is the impact on the production of charmonium states?

Charm Hadronization from p+p to A+A at LHC





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

Summary

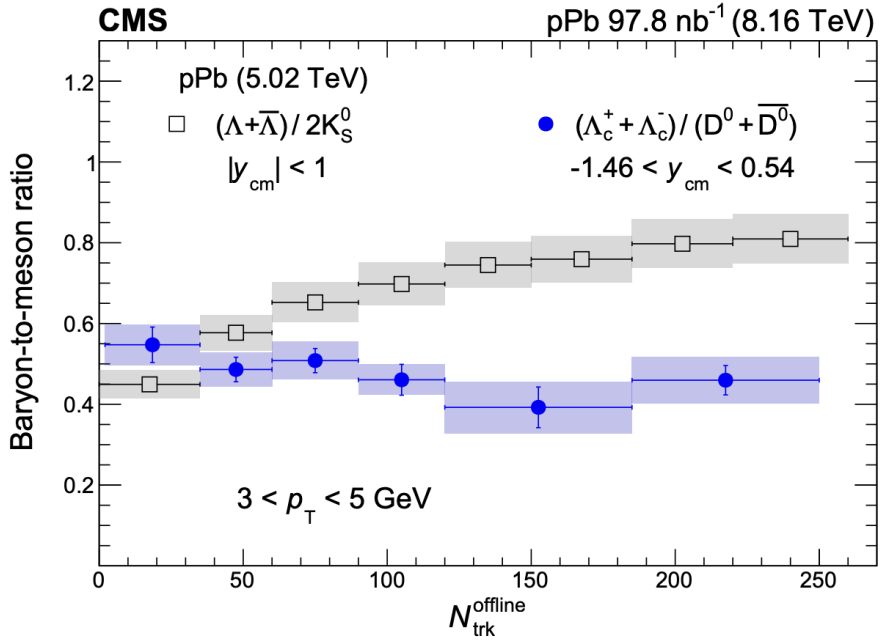
- Many progresses on charmonium measurements in small and large systems (I selected a few based on my own bias)
  - New data and better precisions

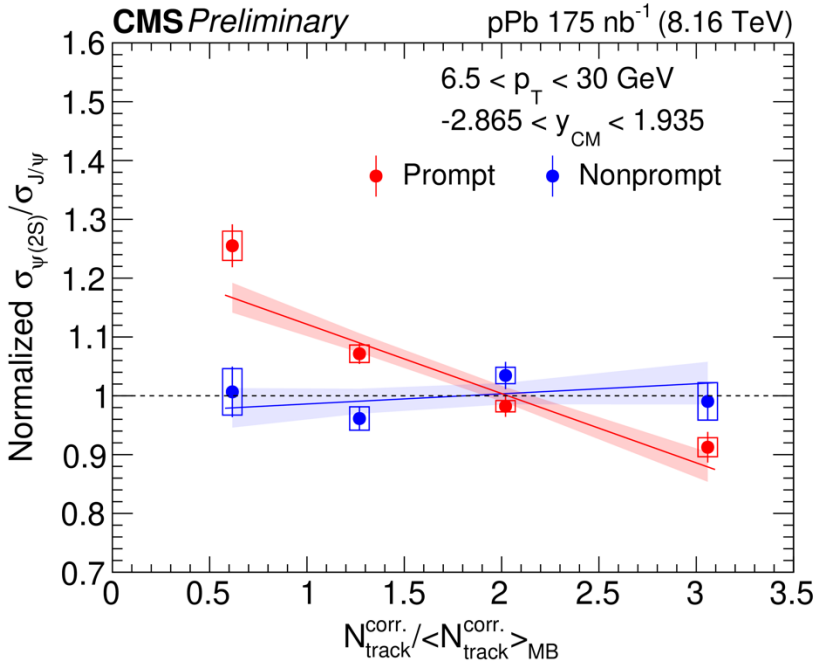
- The improvement on the measurements of J/ψ and ψ(2S) production provide new constraints on theoretical understanding of their production mechanisms

- Looking forward for more precision data from LHC Run3 and RHIC 23-25

- I just expressed my naïve (maybe biased) thinkings about the charmonium production
  - “抛砖引玉”: throw out a brick to attract a jade

Thanks!


CMS
pPb 97.8 nb^{-1} (8.16 TeV)
pPb (5.02 TeV)
$(\Lambda+\overline{\Lambda})/2K^0_S$
$|y_{cm}| < 1$
$(\Lambda_c^+ + \Lambda_c^-)/(D^0 + \overline{D^0})$
$-1.46 < y_{cm} < 0.54$
$3 < p_T < 5$ GeV
Baryon-to-meson ratio
$N_{trk}^{offline}$


CMS Preliminary
pPb 175 nb^{-1} (8.16 TeV)
$6.5 < p_T < 30$ GeV
$-2.865 < y_{CM} < 1.935$
Prompt
Nonprompt
Normalized $\sigma_{\psi(2S)}/\sigma_{J/\psi}$
$N^{corr.}_{track}/\langle N^{corr.}_{track}\rangle_{MB}$