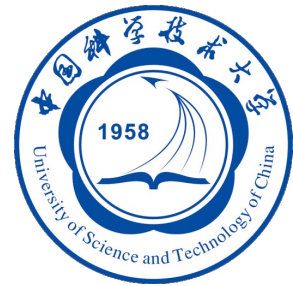


# Recent charmonium measurements in heavy-ion collisions with ALICE

Xiaozhi Bai (for the ALICE Collaboration)

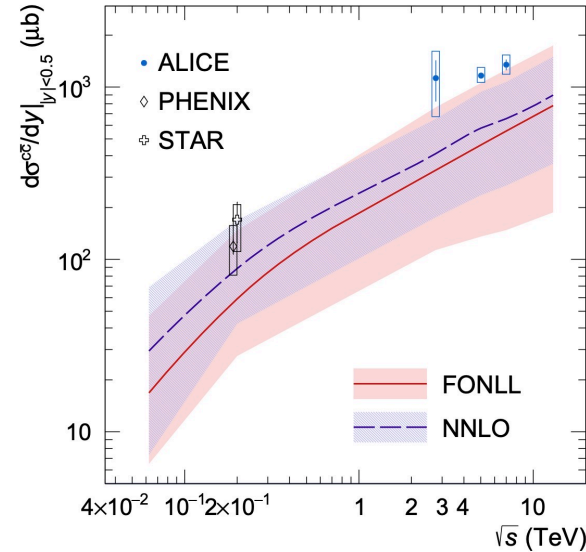
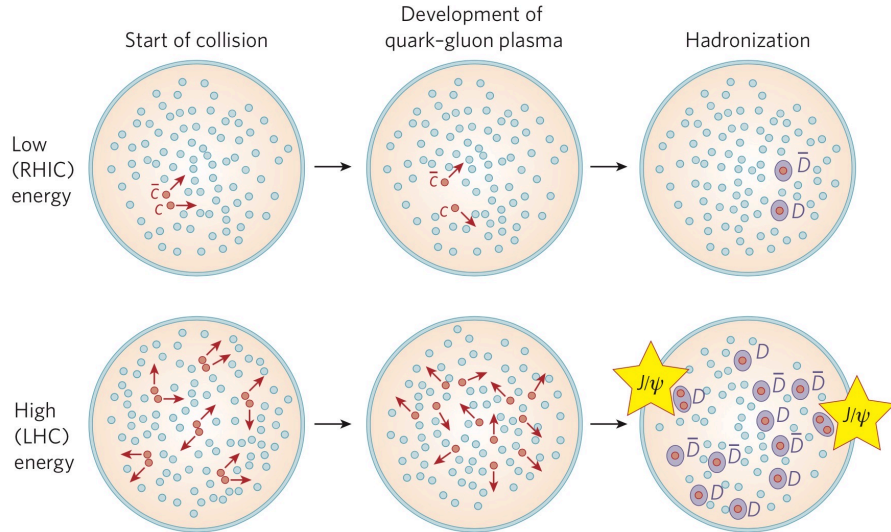
University of Science and Technology of China

Zhuhai China, Nov 6–10, 2023



P. Braun-Munzinger, J. Stachel, Nature 448 (2007) 302

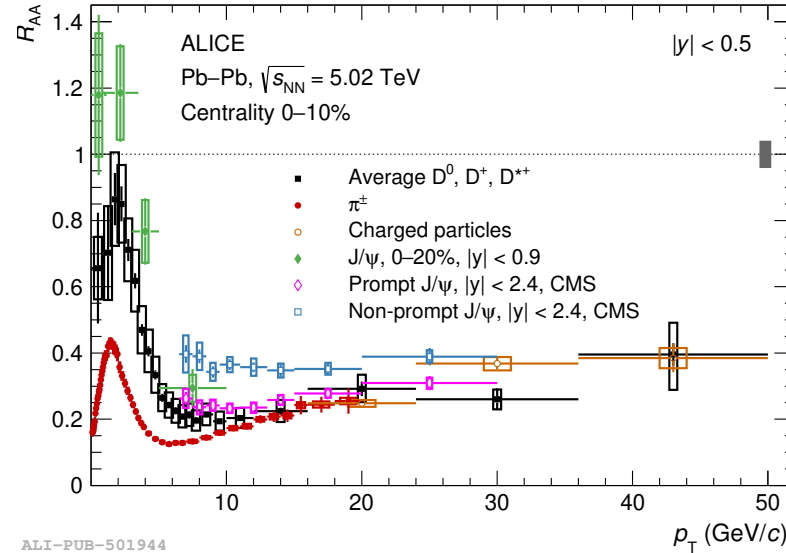
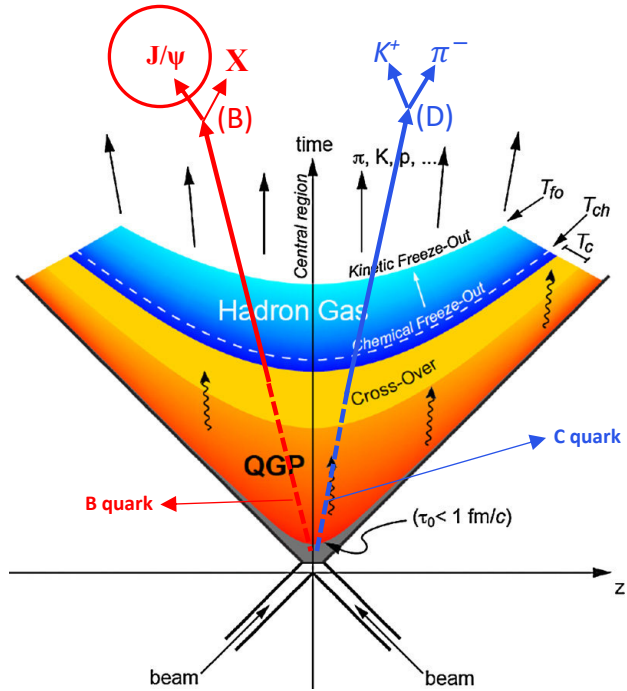
Phys. Rev. D 105, 011103 (2022)



- Suppression of the direct charmonium due to **colour screening** and the **dynamic dissociation**
- Charm quark production cross section at the LHC is much larger compared to RHIC energies, and the **(re)generation** contribution to the  $J/\psi$  is significantly higher than at RHIC

# Mass dependent parton energy loss

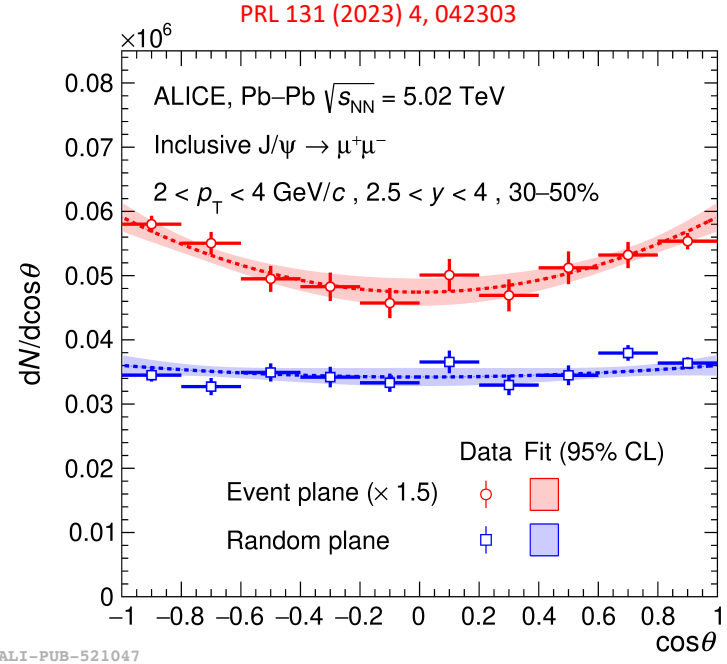
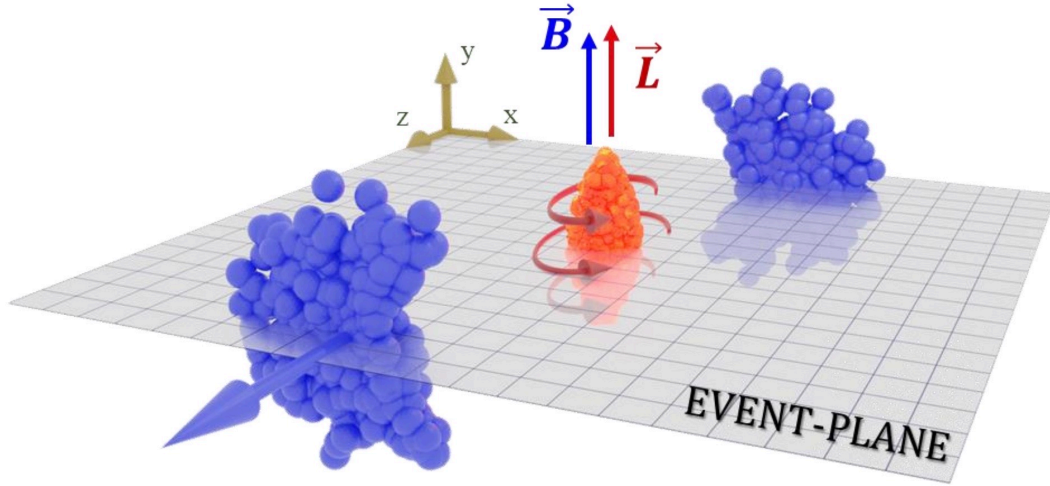
JHEP 01 (2022) 174



ALI-PUB-501944

Non-prompt charmonium is from the beauty hadron decays: corresponding measurements can contribute to the study of the **mass dependence of parton energy loss**

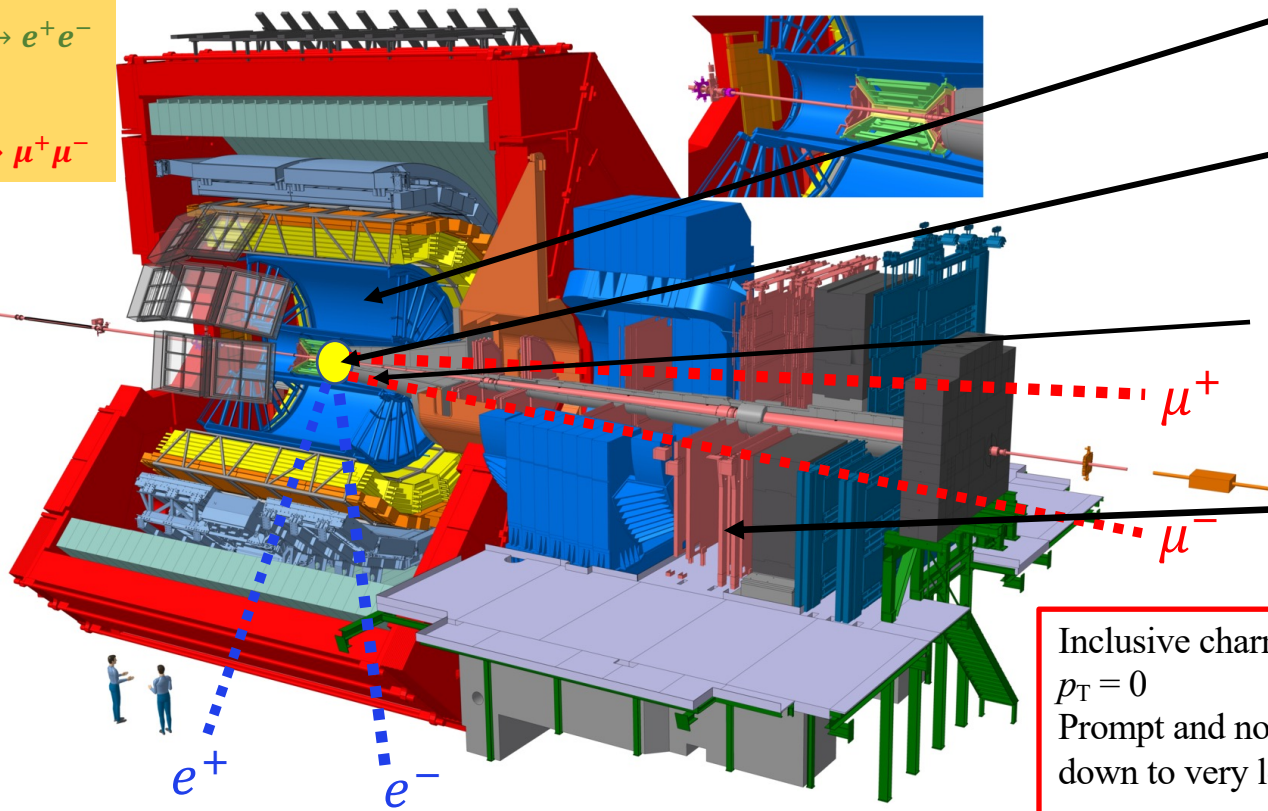
# Charmonium polarization



Heavy-quark pairs are produced in the early stage of AA collision and can experience both the **short living  $B$**  and the  **$L$  of the rotating medium**, polarization w.r.t. an axis orthogonal to the event plane can be affected.

$|y| < 0.9$   
 $J/\psi, \psi(2S) \rightarrow e^+e^-$

$2.5 < y < 4$   
 $J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$



**Time Projection Chamber**  
 Tracking, particle identification

**Inner Tracking System**  
 Tracking, vertex reconstruction,  
 Event plane determination

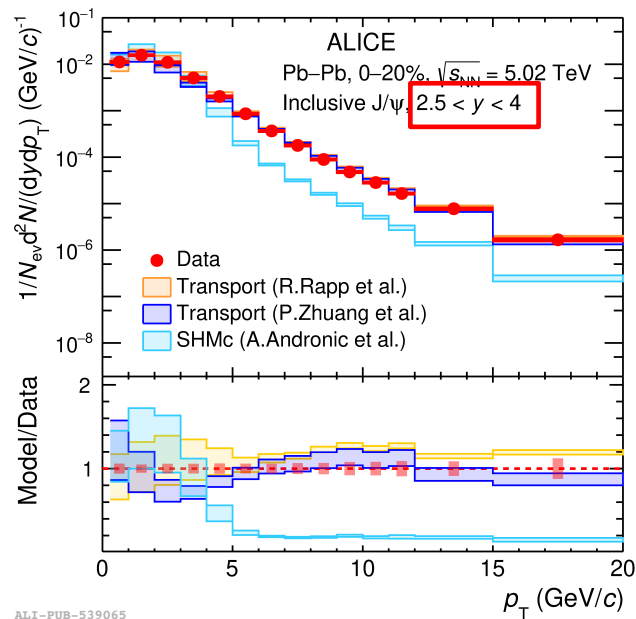
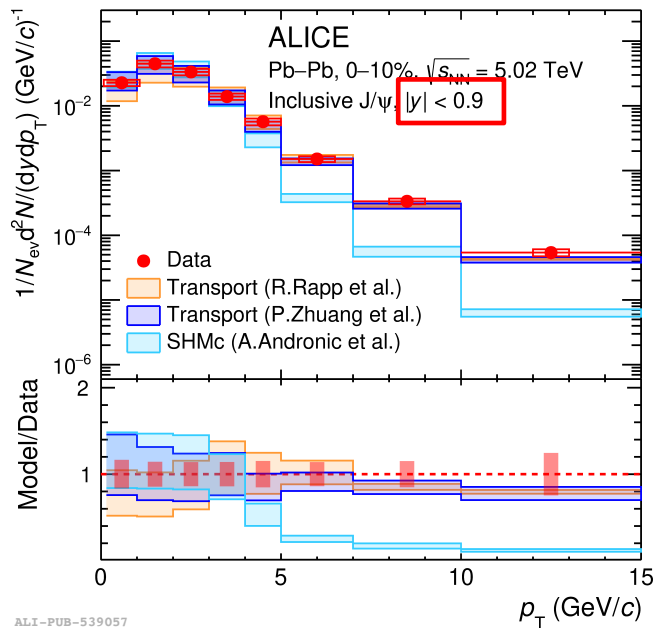
**V0 Detector**  
 Centrality determination,  
 triggering, event plane  
 determination, and background  
 rejection

**Muon spectrometer**  
 Trigger and tracking for muons

Inclusive charmonium measurement down to  $p_T = 0$   
 Prompt and non-prompt  $J/\psi$  can be separated  
 down to very low  $p_T$  at midrapidity

# Inclusive $J/\psi$ yield in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv:2303.13361

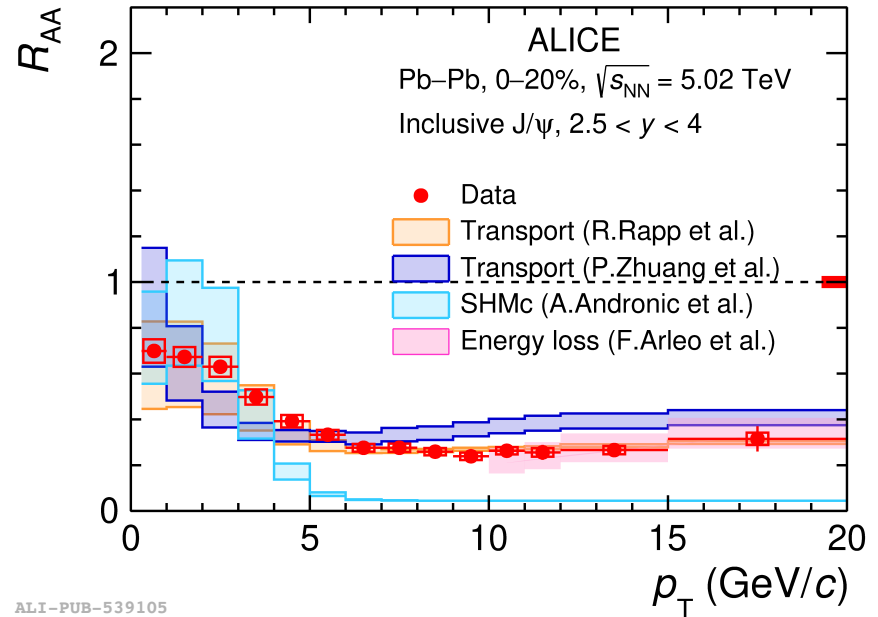
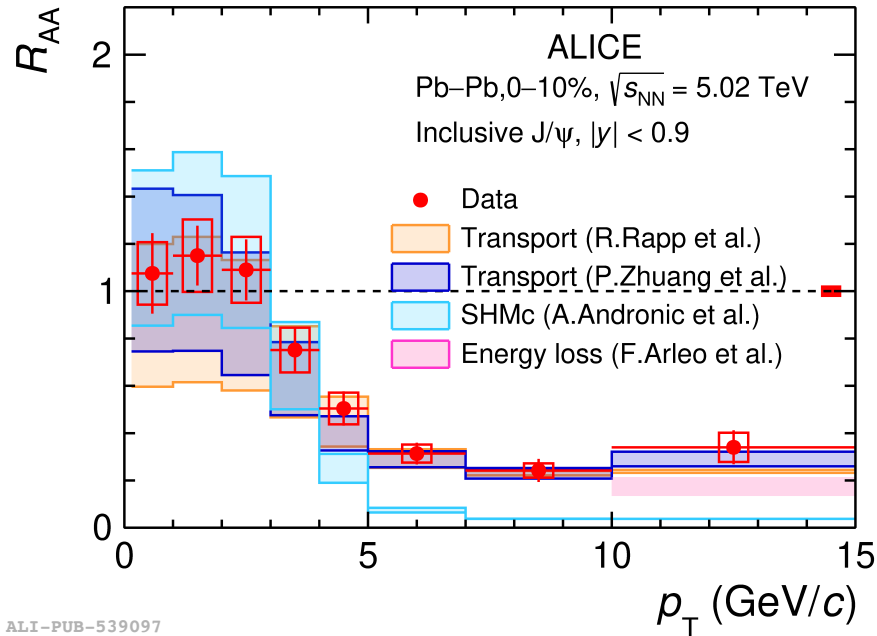


- Inclusive  $J/\psi$  yields are shown as a function of  $p_T$  at **mid- (left) and forward (right)** rapidity in central collisions
- Two transport models describe the data within uncertainties
- SHMc agrees with data at low  $p_T$ , and underestimates the measurement at high  $p_T$

Du, X. et al., NPA 943, 147–158 (2015)  
Zhou, K., et al., PRC 89, 054911 (2014)  
Andronic, A, et al, PLB 797, 134836 (2019)

# Inclusive $J/\psi$ $R_{AA}$ vs $p_T$

arXiv:2303.13361

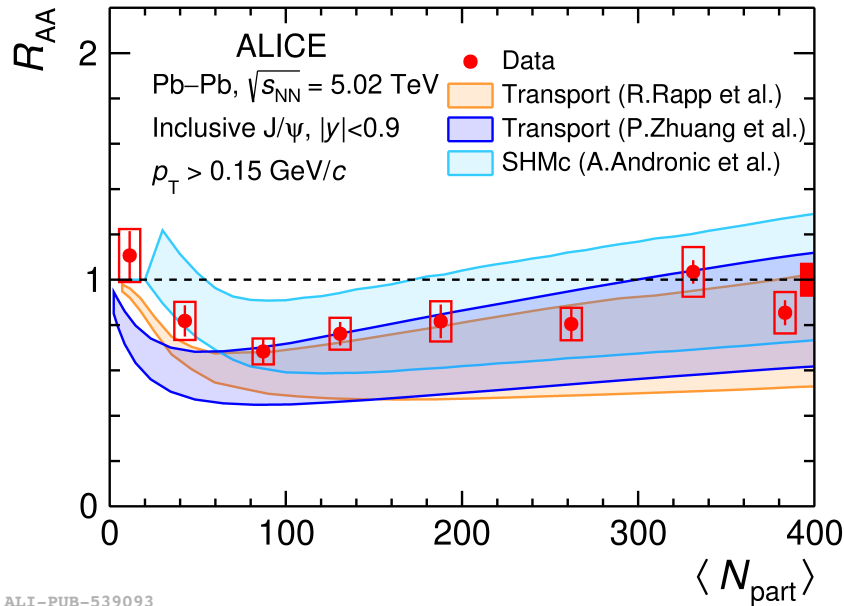


- Evidence for  $J/\psi$  (re-)generation at low  $p_T$
- Transport and SHMc models describe data at low  $p_T$ , while SHMc underestimates the measurement at high  $p_T$ . The energy loss model agrees with data at high  $p_T$

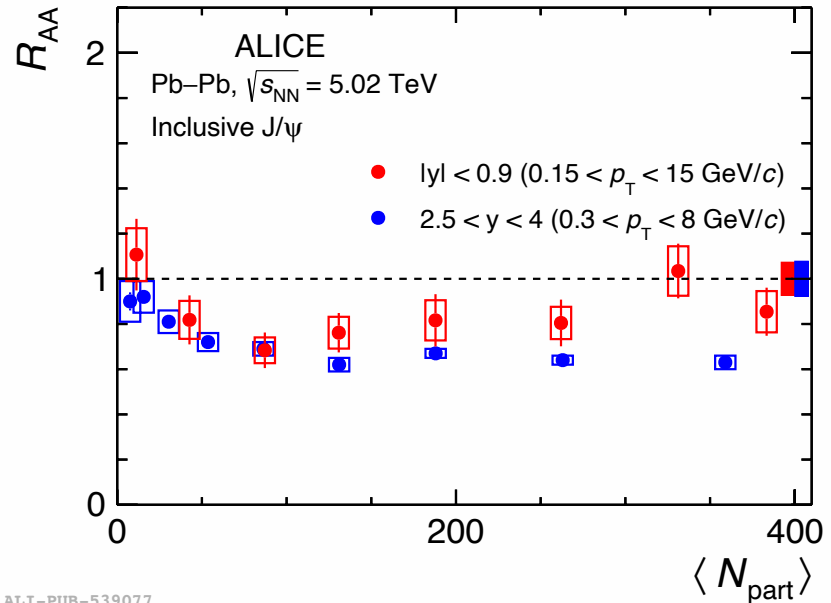
Du, X. et al., NPA 943, 147-158 (2015)  
Zhou, K., et al., PRC 89, 054911 (2014)  
Andronic, A., et al., PLB 797, 134836 (2019)  
Arleo, F., PRL 119, 062302 (2017)

# Inclusive $J/\psi$ $R_{AA}$ vs centrality

arXiv:2303.13361



ALI-PUB-539093



ALI-PUB-539077

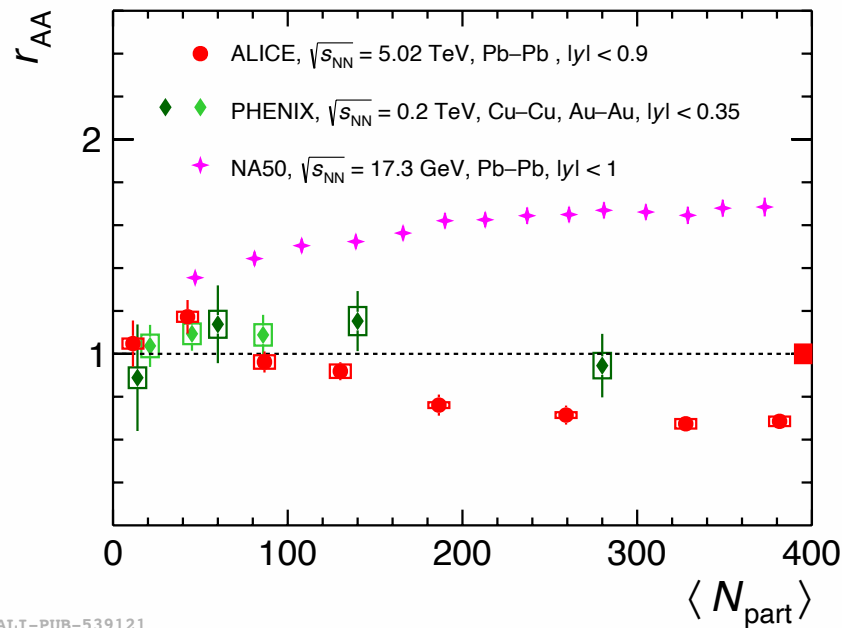
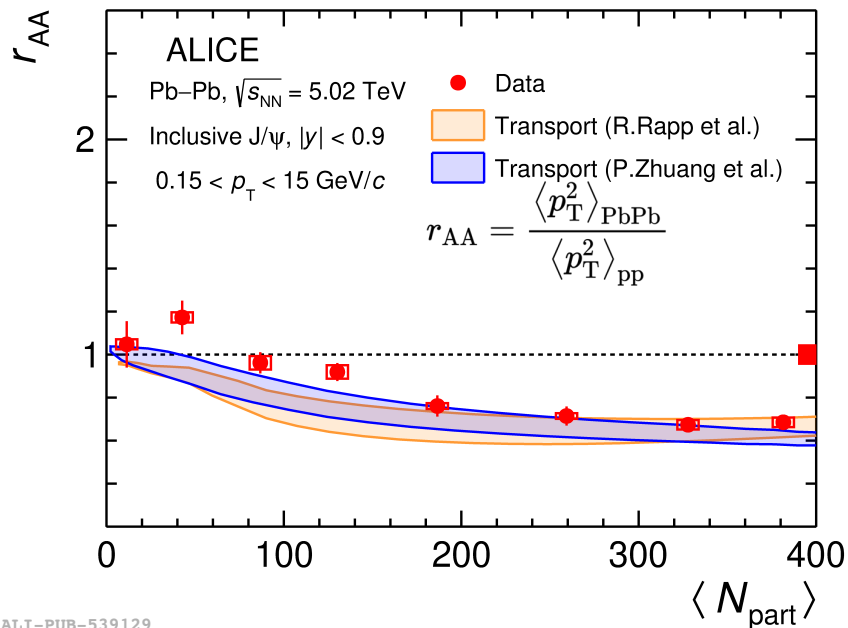
- Evidence for  $J/\psi$  (re-)generation in central collisions, with a larger contribution at midrapidity compared to forward rapidity
- All models can describe the data but suffer from large uncertainties related to inputs used in calculations (eg. charm cross section, shadowing).

Du, X. et al., NPA 943, 147–158 (2015)  
Zhou, K., et al., PRC 89, 054911 (2014)  
Andronic, A, et al, PLB 797, 134836 (2019)



# Inclusive $J/\psi$ $r_{AA}$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

arXiv:2303.13361



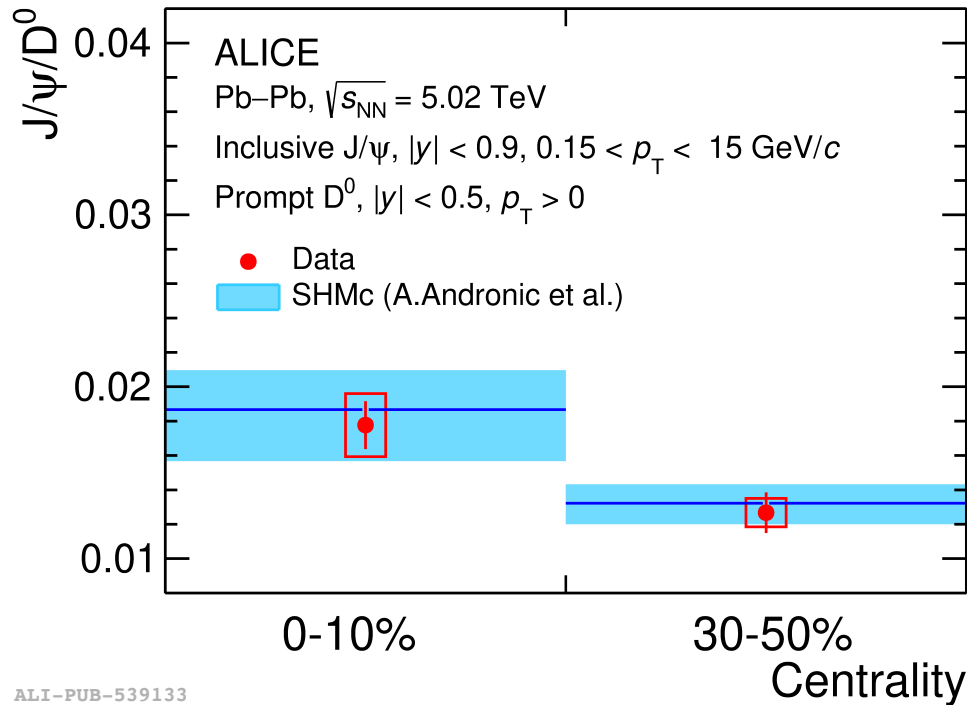
➤ Decreasing trend for  $r_{AA}$  from semicentral toward central collisions

➤  $r_{AA}$  below unity indicates a softening of the  $J/\psi$   $p_T$  shape in Pb–Pb collisions compared to pp collisions, the behavior is different from the lower center-of-mass energies

Du, X. et al., NPA 943, 147–158 (2015)  
Zhou, K., et al., PRC 89, 054911 (2014)

# J/ψ-to-D<sup>0</sup> ratio in Pb–Pb collisions

arXiv:2303.13361



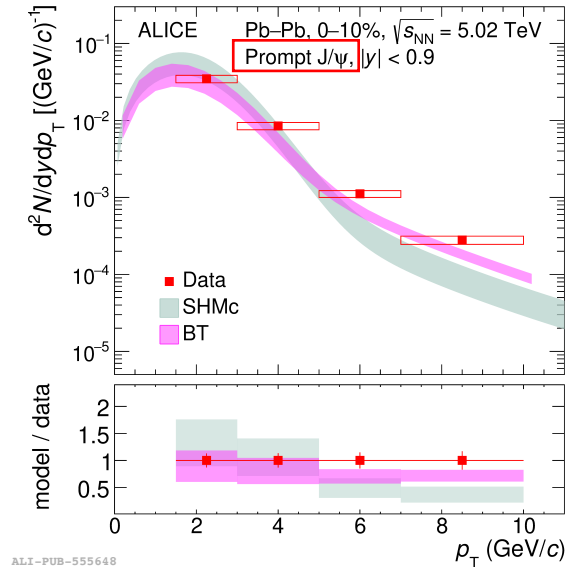
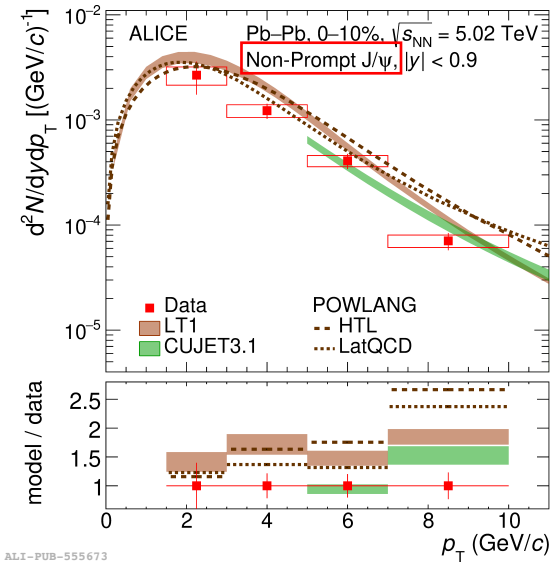
ALI-PUB-539133

A. Andronic et al., JHEP07, 035 (2021)

- Sensitive to hadronization mechanisms for open and hidden charm hadrons
- The centrality-dependent trend of the D<sup>0</sup> to J/ψ ratio can be explained by the increase of charm fugacity towards most central collisions according to SHMc prediction

# Non-prompt and prompt $J/\psi$ $p_T$ spectrum

arXiv:2308.16125



LT1: PRC107, 054917(2023)

POWLANG:

JHEP 05 (2021) 279,

EPJC 75 (2015) 121

CUJET3.1: CPC 43 (2019)

044101

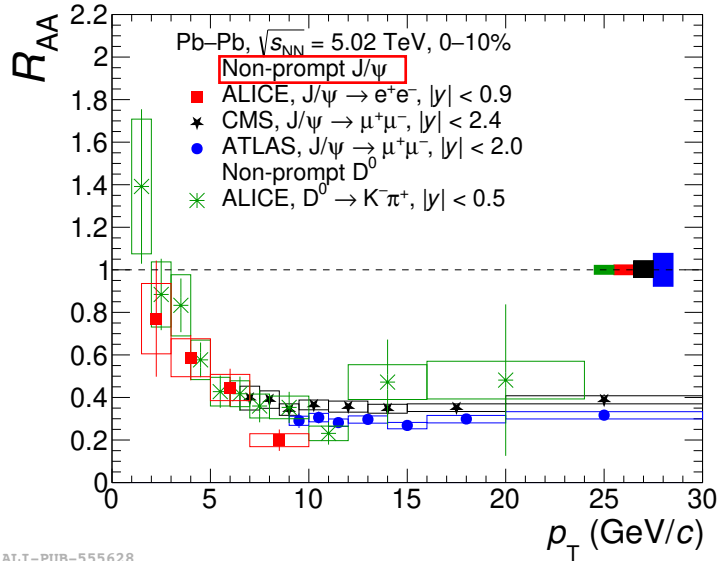
SHMc: PLB 797 (2019) 134836

BT: CPC43 (2019) 124101

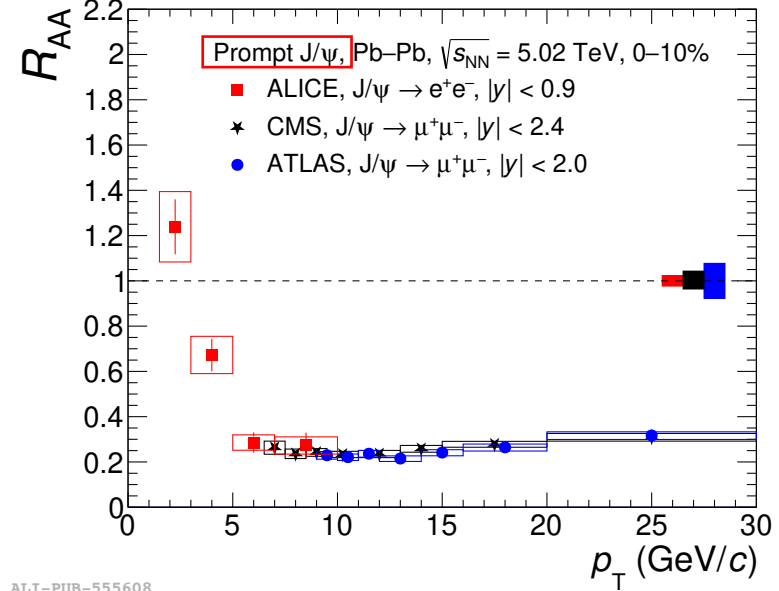
- Non-prompt (left) and prompt (right)  $J/\psi$   $p_T$  spectrum are compared with several different models.
- All the models seem to over estimate measured data of non-prompt  $J/\psi$ , the SHMc and BT agree with data within uncertainties for the prompt  $J/\psi$  at low  $p_T$

# $p_T$ dependence of prompt and non-prompt $J/\psi$ $R_{AA}$

arXiv:2308.16125



ALI-PUB-555628

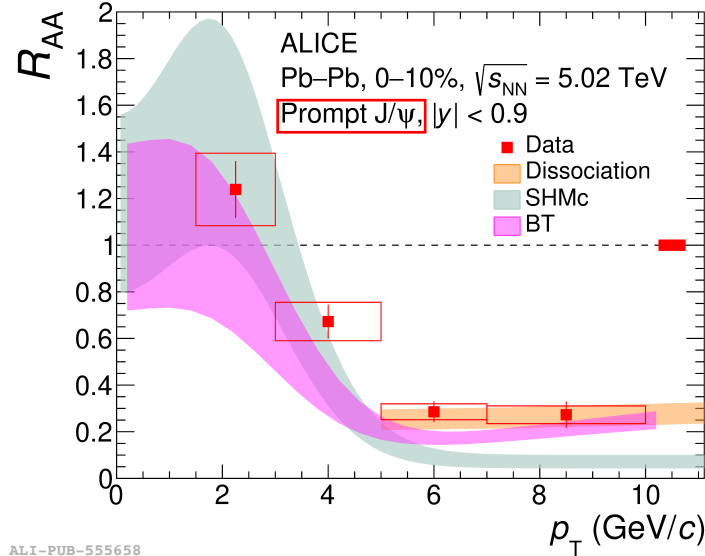
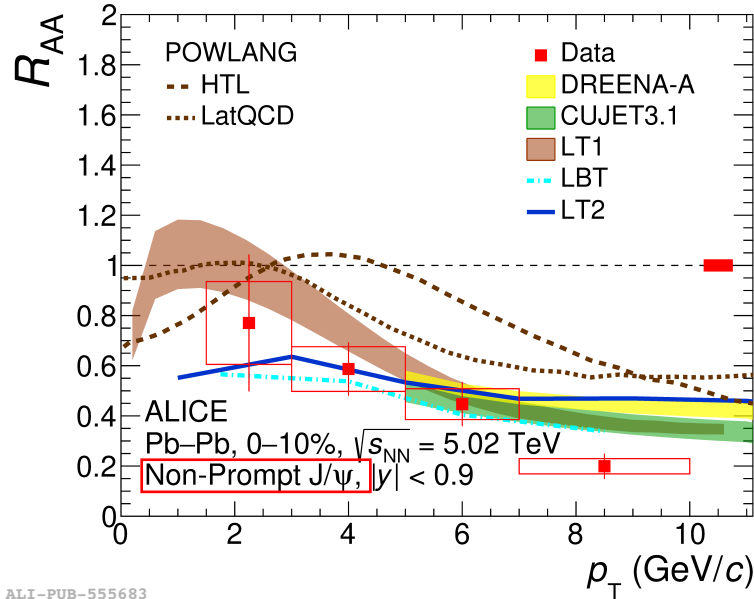


ALI-PUB-555608

- $R_{AA}$  extended down to  $p_T = 1.5$  GeV/c and compatible within uncertainties with ATLAS and CMS measurements in the common  $p_T$  range
- ALICE non-prompt  $J/\psi$  and  $D^0$  are compatible within uncertainties

JHEP 12 (2022) 126  
 ATLAS, Eur. Phys. J. C 78 (2018) 762  
 CMS, Eur. Phys. J. C 78 (2018) 509

arXiv:2308.16125



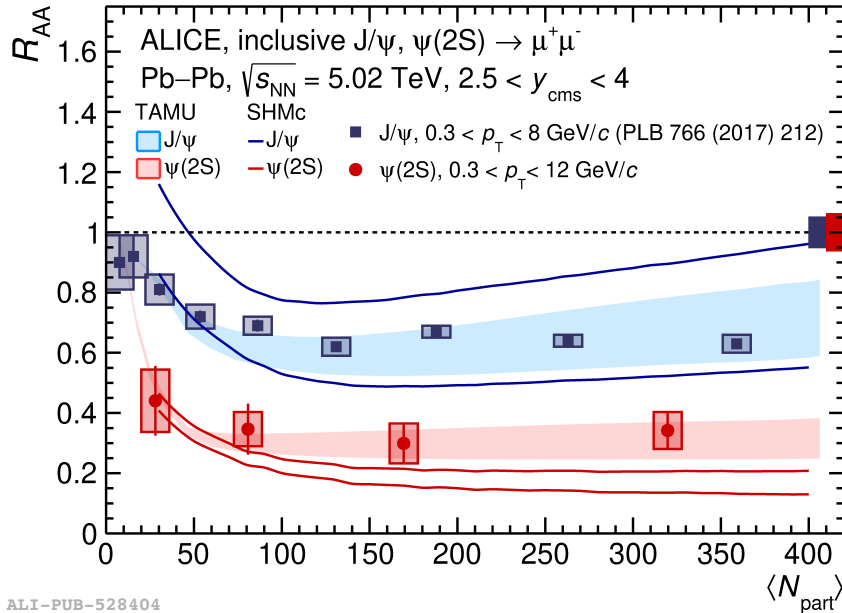
- DREENA-A:**  
Front. Phys. 10:957019 (2022),  
Phys. Rev. C 105, L021901
- CUJET3.1:** CPC 43 (2019) 044101
- LT1:** PRC107, 054917(2023)
- LBT:** PLB838(2023) 137733
- LBT2:** EPJC 81 848 (2021) 1035
- Dissociation:**  
PLB 778 (2018) 384-391
- SHMc:** PLB 797 (2019) 134836
- BT:** CPC43 (2019) 124101

ALI-PUB-555683

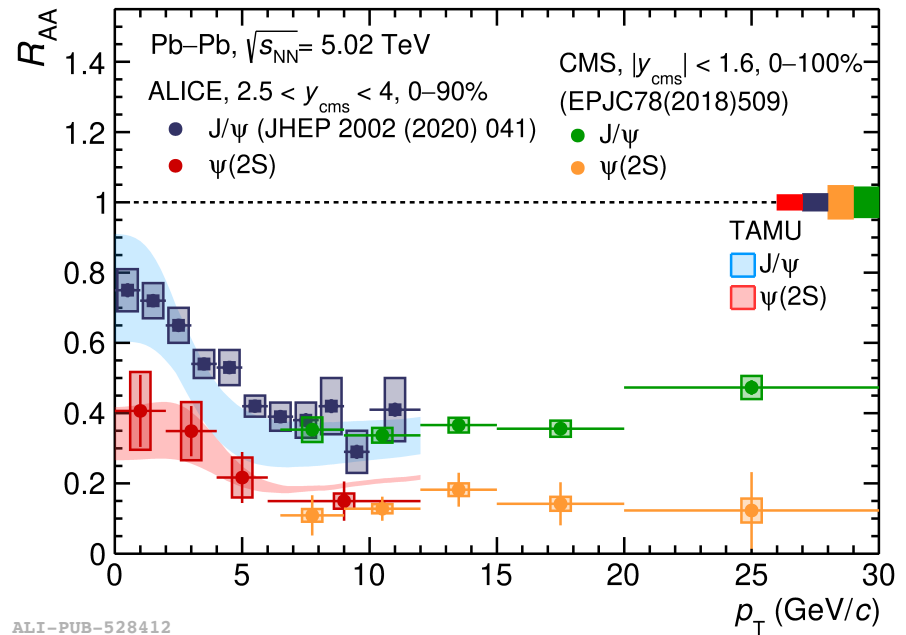
ALI-PUB-555658

- The SHMc model and transport microscopic calculations that include a contribution from **regeneration** are compatible with the measured **prompt  $J/\psi$   $R_{AA}$  at low  $p_T$**
- **Non-prompt  $J/\psi$   $R_{AA}$**  described within uncertainties by models implementing **collisional and radiative energy loss** contributions
- POWLANG calculations, which include only collisional contributions, overestimate the  $R_{AA}$  at intermediate and high  $p_T$

arXiv:2210.08893



ALI-PUB-528404



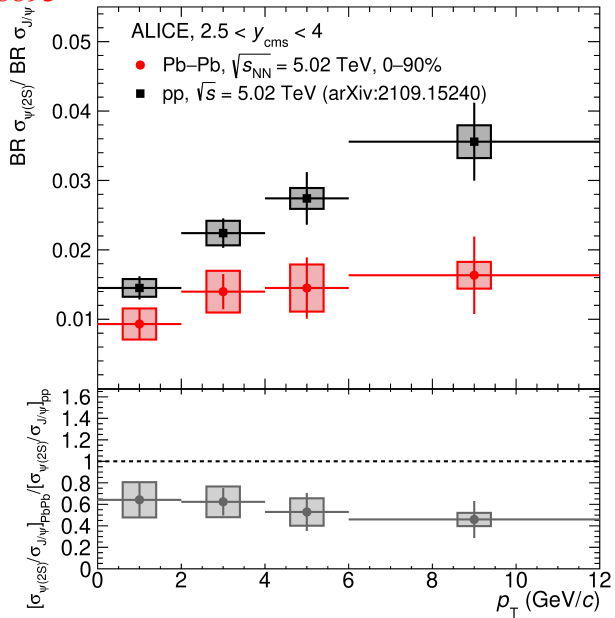
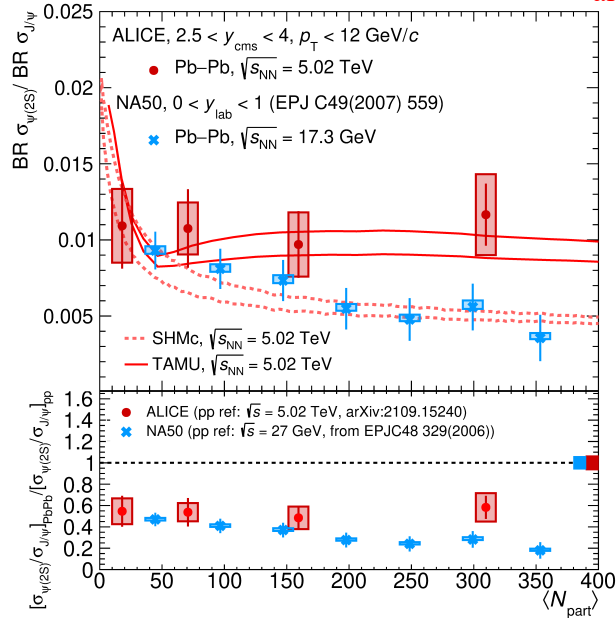
ALI-PUB-528412

- A **larger suppression** of the  $\psi(2S)$  w.r.t the  $J/\psi$  is observed
- The  $\psi(2S) R_{AA}$  increases at low  $p_T$ , which is a **hint of  $\psi(2S)$  regeneration**
- The TAMU model describes data better than SHMc in central collisions

(TAMU) X. Du, et al., NPA943,147-158(2015)  
 (SHMc) A. Andronic, et al., PLB797,134836(2019)

# Single and double ratios of $\psi(2S)$ over $J/\psi$

arXiv:2210.08893



ALI-PUB-528400

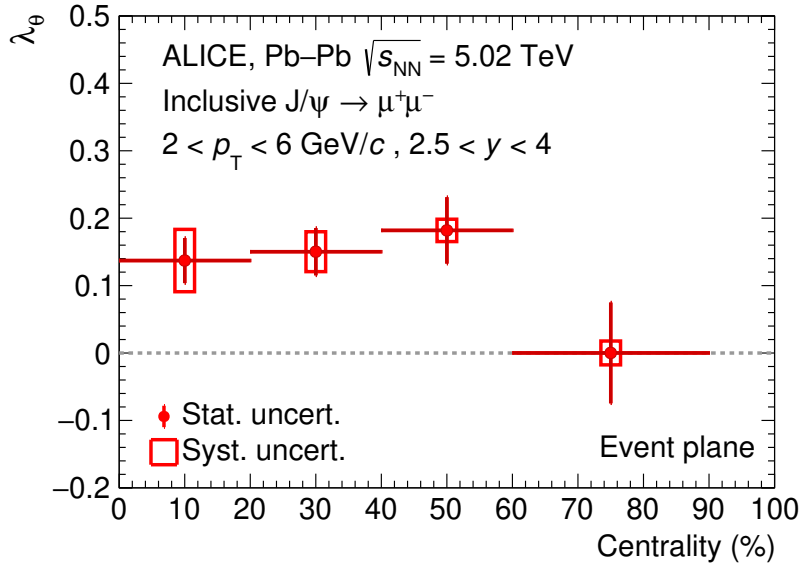
ALI-PUB-528408

- The  $\psi(2S)$ -to- $J/\psi$  ratio shows **no significant centrality and  $p_T$  dependence** at 5.02 TeV,
- Stronger centrality dependence of the  $\psi(2S)$ -to- $J/\psi$  ratio at lower energy
- The TAMU model describes data slightly better than SHMc in central collisions

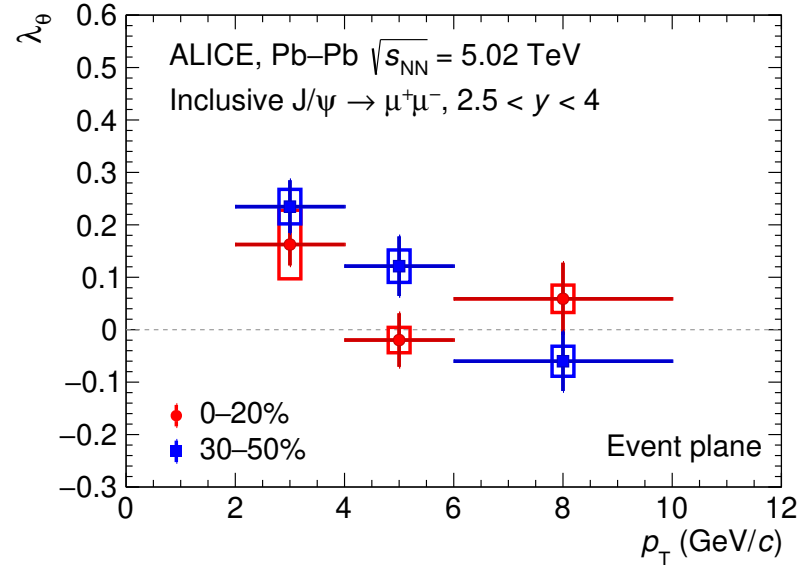
(TAMU) X. Du, et al.,NPA943,147-158(2015)  
 (SHMc) A. Andronic, et al.,PLB797,134836(2019)

# J/ψ polarization in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

PRL 131 (2023) 4, 042303



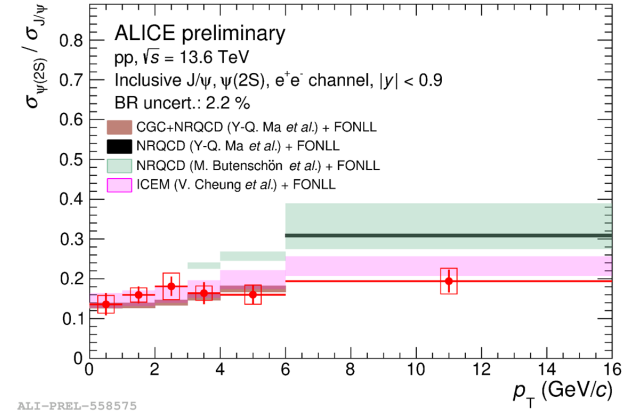
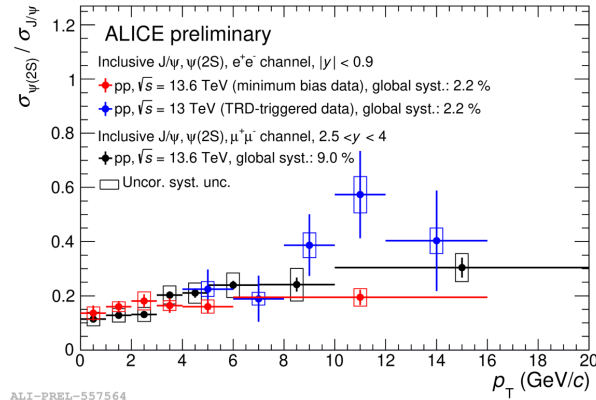
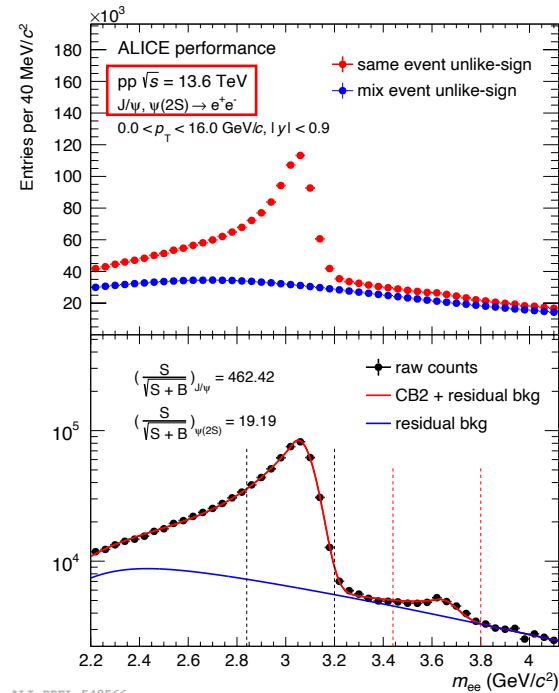
ALI-PUB-521052



ALI-PUB-521057

- First measurement of quarkonium polarization **w.r.t the event plane**
- **Significant polarization ( $\sim 3.5\sigma$ )** observed in semicentral collisions (40–60%) in  $2 < p_T < 6$  GeV/c
- The significance of the polarization reaches  $\sim 3.9\sigma$  at low  $p_T$  ( $2 < p_T < 4$  GeV/c) in 30–50%
- Interpretation of results requires inputs from theoretical models





- Run 3 pp data collected with **upgraded detectors**
- **Significantly improved statistics** w.r.t to Run 2
- Allows one to measure the  $\psi(2S)$  to  $J/\psi$  ratio at both mid- and forward rapidity
- The **high statistics Pb–Pb** data analyses are ongoing

# Summary and outlook

## ➤ $J/\psi$ and $\psi(2S)$ production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

- Dominant contribution from (re-)generation in central collisions and low  $p_T$  for inclusive and prompt  $J/\psi$
- Strong suppression observed for non-prompt  $J/\psi$
- A larger suppression of the  $\psi(2S)$  with respect to the  $J/\psi$  is observed
- Significant non-zero  $J/\psi$  polarization observed w.r.t event plane in semicentral Pb–Pb collisions at low  $p_T$

## ➤ Detector upgrade for Run 3

- More precise measurements can be expected from the upgraded detector and higher statistic samples, a factor  $\sim 10^4$  for pp and  $\sim 10^2$  for Pb–Pb w.r.t Run 2
- The newly installed MFT enables the separation between prompt and non-prompt charmonium at forward rapidity

# Thanks