Charmonium production in Pb–Pb collisions with ALICE

Jon-Are Sætre on behalf of the ALICE Collaboration
University of Bergen (NO)

Quark Matter - April 4th to 10th, 2022

Outline

Many NEW results!

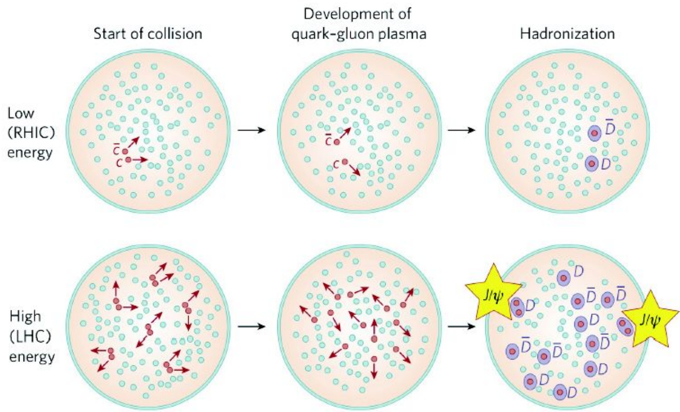
- Physics motivation
- J/ψ and ψ(2S) nuclear modification factor (R_{AA})
- Open to hidden charm ratio
- Open beauty R_{AA} via non-prompt J/ψ
- Conclusions

Charmonium production as probe of QGP in heavy-ion collisions

- Sequential dissociation →
  expectation of stronger suppression for ψ(2S) w.r.t J/ψ

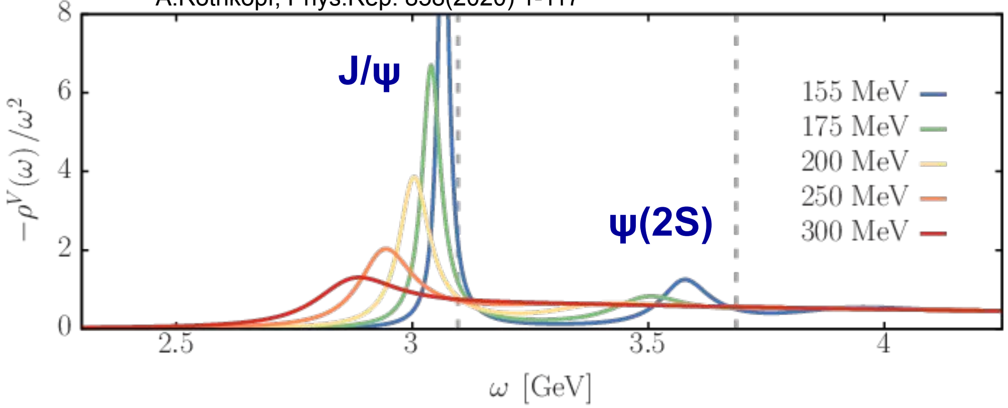
- (Re)generation of charmonium states at the LHC energies, at the phase boundary and/or during the QGP phase

- Charmonium excited-to-ground state ratios useful to disentangle between the two regeneration scenarios



Braun-Munzinger, P., Stachel, J. The quest for the quark–gluon plasma. *Nature* 448, 302–309 (2007)

A.Rothkopf, Phys.Rep. 858(2020) 1-117



The in-medium heavy quarkonium spectral functions in the S-wave channel for charmonium evaluated at different temperatures

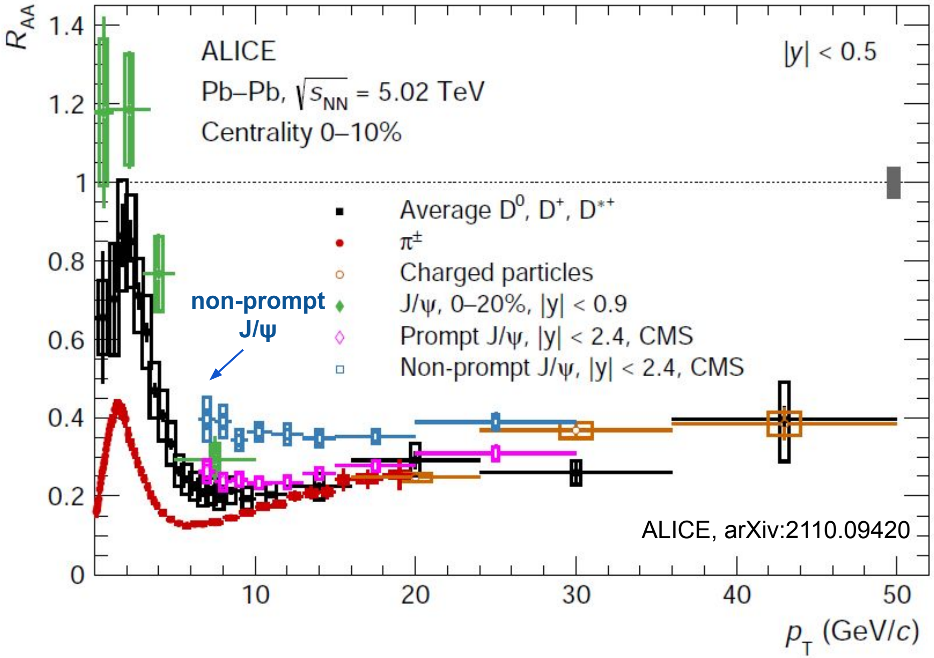
Measuring Beauty via non-prompt J/ψ

- A sizeable fraction of charmonia comes from beauty hadron decays
  → possibility to access open heavy-flavor production!

- Heavy quarks, charm and beauty, produced early in heavy-ion collisions via hard parton-parton scatterings → lose energy in the QGP via collisional and radiative processes
  - Dead cone effect reduces radiative losses for beauty

Mass dependence of parton energy loss →
Hierarchy expected for R_{AA} of light and heavy-flavor hadrons!

$$R_{AA} = \frac{1}{N_{coll}} \times \frac{(dN/dy)_{AA}}{(dN/dy)_{pp}}$$



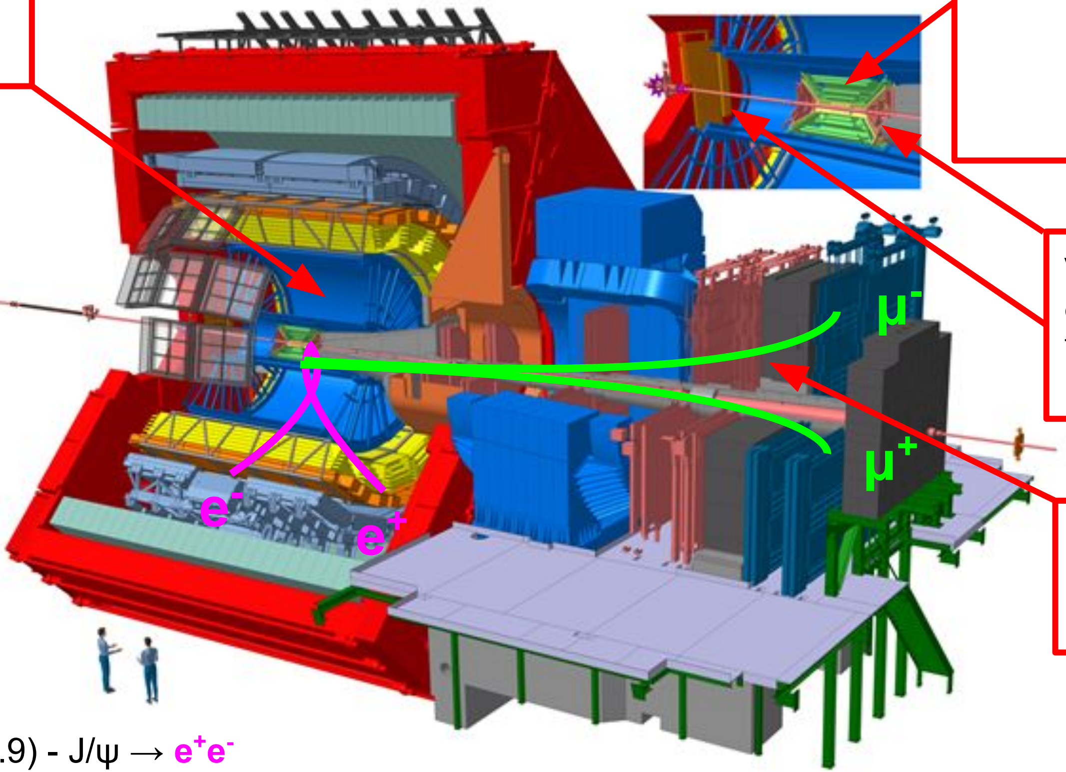
Charmonium measurements in ALICE

Time Projection Chamber
tracking, particle identification

Other Pb–Pb ALICE talks:

Quarkonium polarization in Pb–Pb and pp collisions with ALICE
Luca Micheletti
Tuesday, 4:50 PM

J/ψ photoproduction and the production of dileptons via photon-photon interactions in hadronic Pb–Pb collisions measured with ALICE
Alexandra Neagu
Thursday, 9.20 AM



Inner Tracking System
tracking, vertex reconstruction

Silicon Pixel Detector
primary and secondary vertices
Separation of prompt and non-prompt J/ψ

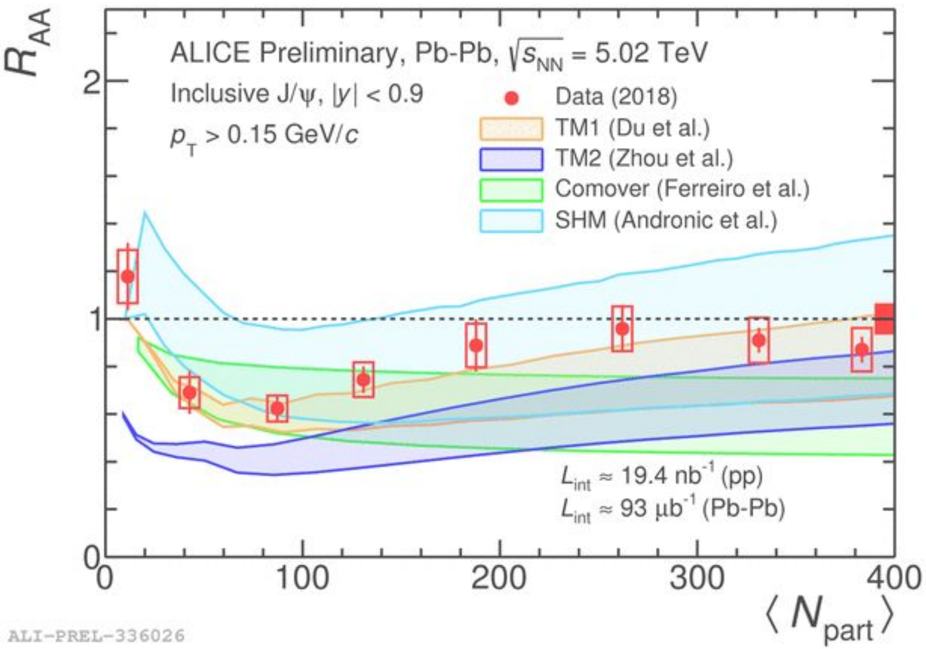
V0 Detector
centrality determination, triggering, background rejection

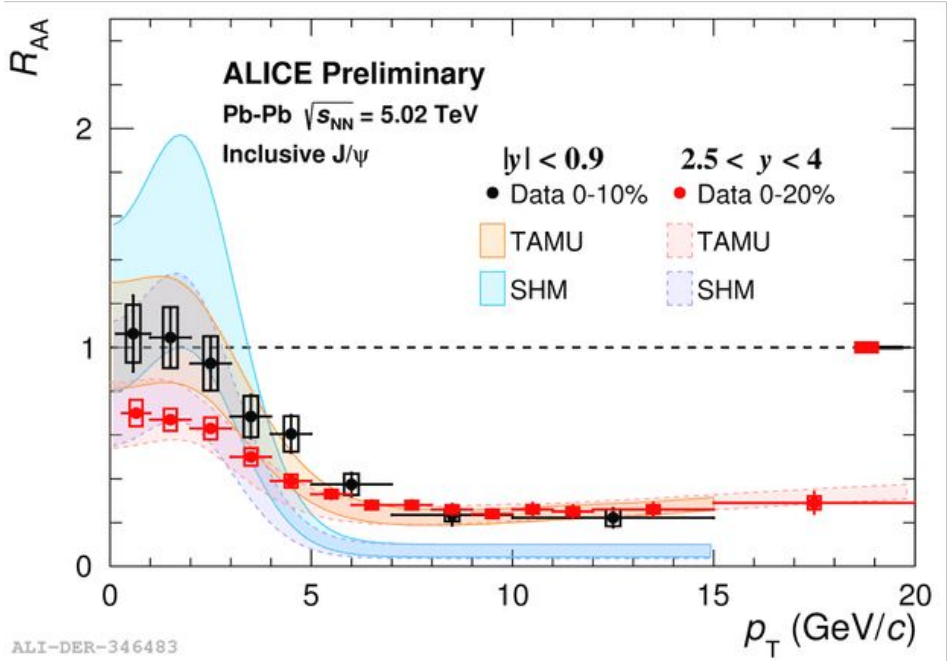
Muon spectrometer
trigger and tracking for muons

- Central barrel ($|y| < 0.9$) - J/ψ → e^+e^-
  - Possibility to separate prompt and non-prompt J/ψ down to low p_T
- Muon Spectrometer ($2.5 < y < 4$) - J/ψ, ψ(2S) → $\mu^+\mu^-$
- Mid- and forward-y inclusive charmonium measurements down to zero p_T

J/ψ

Inclusive J/ψ R_{AA} results





- Models implementing charmonium regeneration, either at the freeze-out (SHM) or during the fireball lifetime (transport models), in agreement with data
  - Both centrality and p_T dependencies are qualitatively well described
  - Rapidity dependence is also described by recombination models when we compare mid- and forward-y

- Conclusions on the J/ψ production phenomenology are hindered by the large model uncertainties

TM2: Zhou *et al.*, Phys. Rev. C 89, 054911 (21 May 2014)
Comover: Ferreiro E. *et al.*, PLB 731 (2014) 57

SHM: Andronic A. *et al.*, Phys. Lett. B797 (2019) 134836,
TM1/TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158

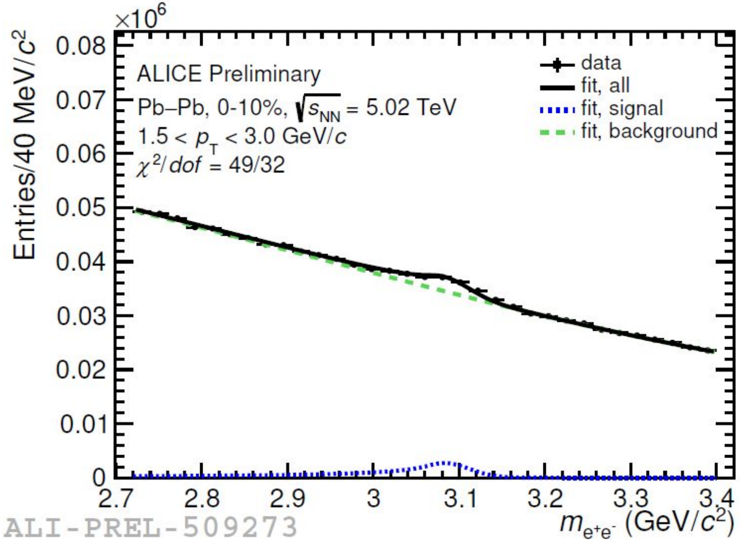
Non-prompt J/ψ fraction in Pb–Pb collisions

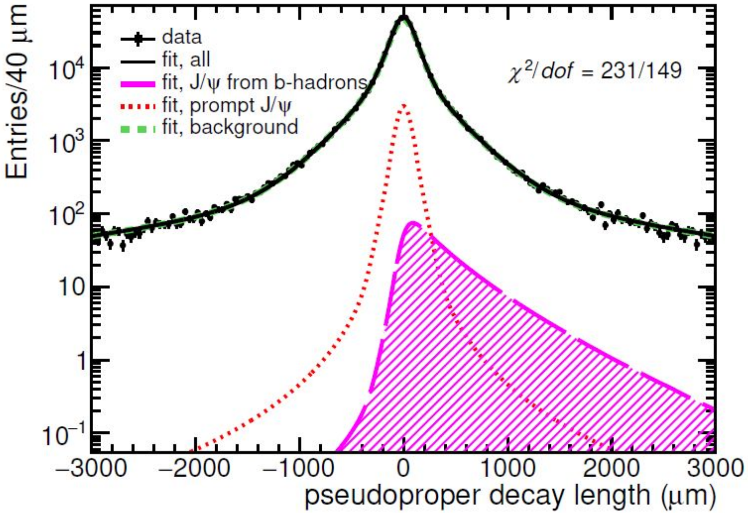
mid-y NEW!

$$\ln L = \sum_{i=1}^{N} \ln F(x, m_{e^+e^-}) \qquad x = \frac{c\, L_{xy}\, m_{J/\psi}}{p_t^{J/\psi}}$$

$$L_{xy} = \vec{L} \cdot \vec{p}_t^{\,J/\psi} / p_t^{J/\psi}$$

Analysis technique based on maximization of 2D likelihood function → invariant mass (m_{ee}) and **pseudo-proper decay length (x)** fitted simultaneously



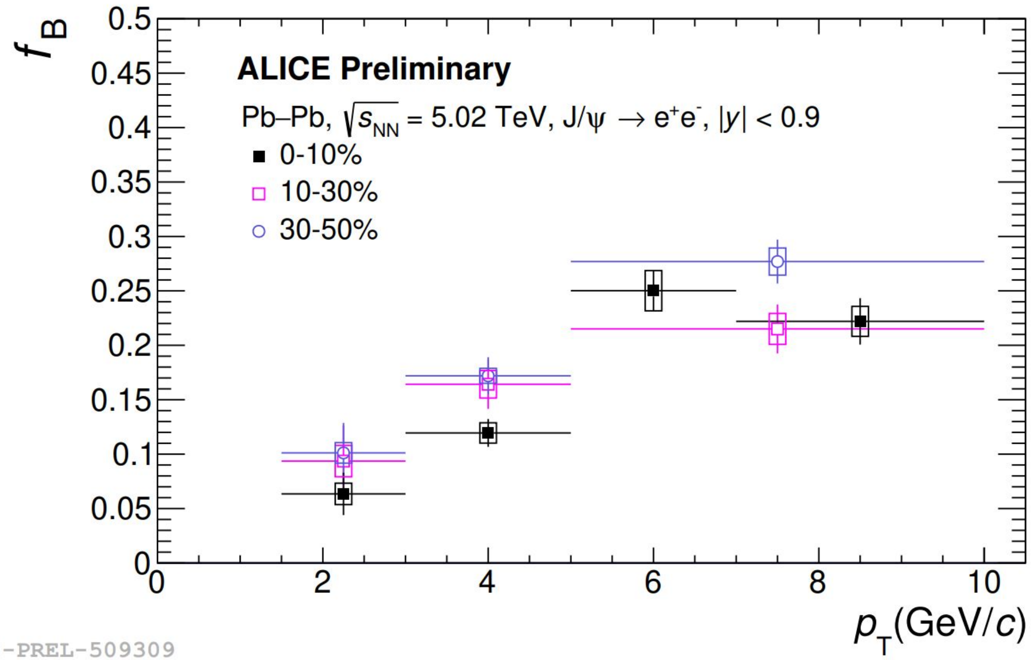


See Himanshu Sharma's poster Friday at 2.24pm for more!

Non-prompt J/ψ fraction in Pb–Pb collisions

mid-y

NEW!



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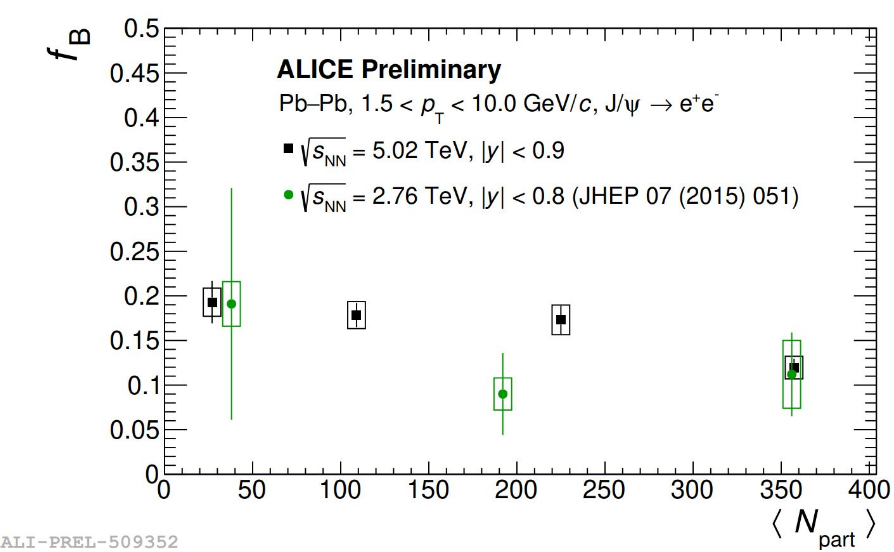
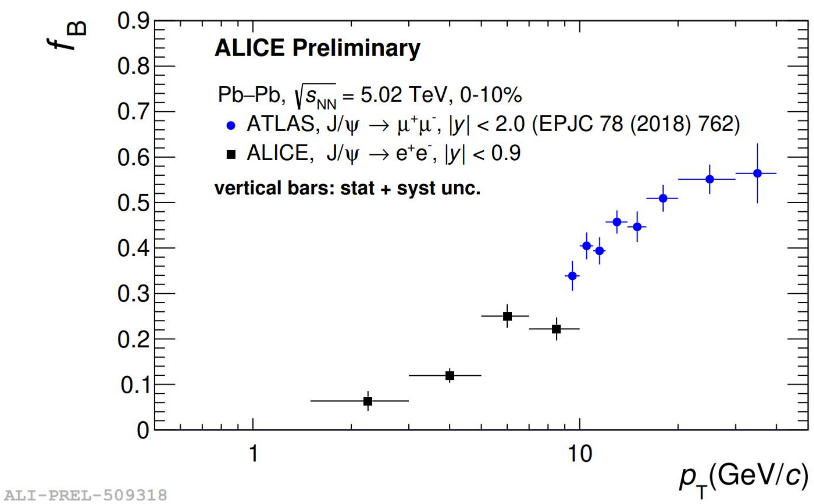
Analysis technique based on maximization of 2D likelihood function → invariant mass (m_{ee}) and **pseudo-proper decay length (x)** fitted simultaneously

See Pengzhong Lu's poster for a machine learning approach
Friday, 2:36 PM

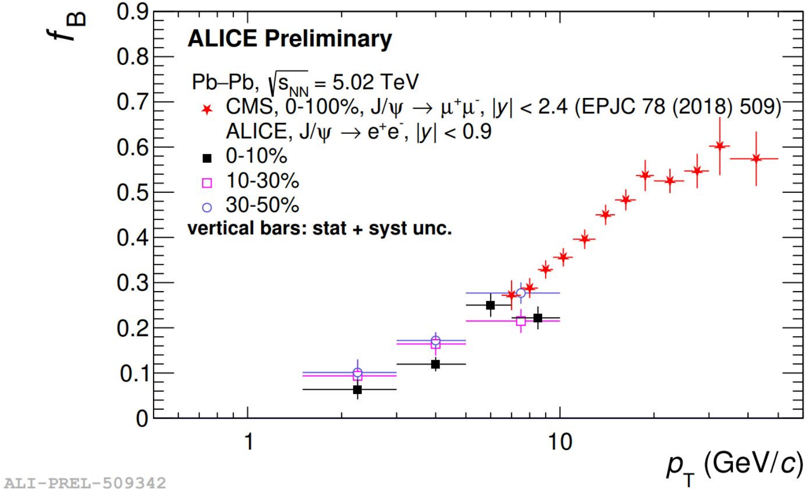
- Non-prompt J/ψ fraction measured down to p_T = 1.5 GeV/*c* in different centralities:
  - Smaller non-prompt J/ψ fraction towards low p_T

Non-prompt J/ψ fraction in Pb–Pb collisions





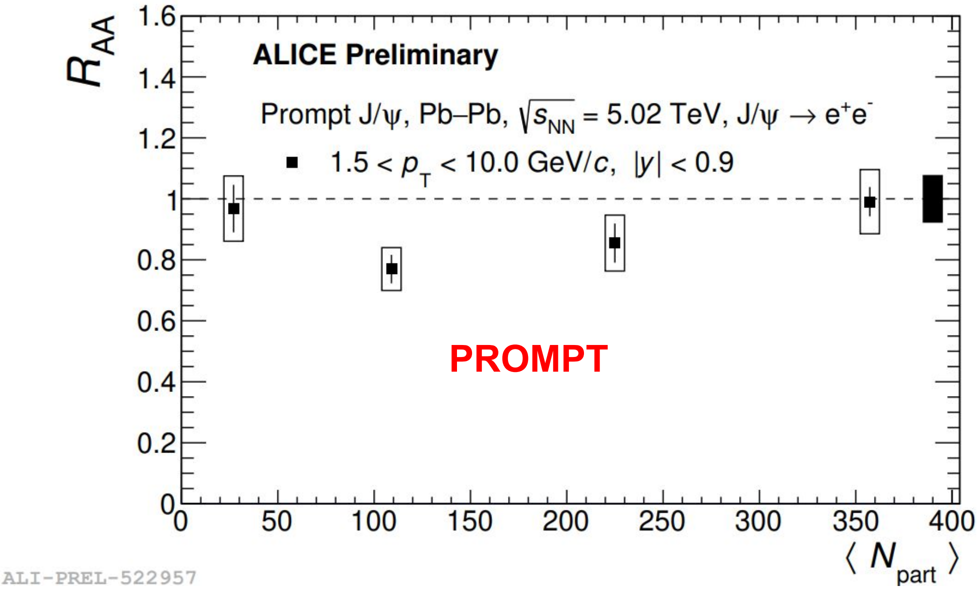
mid-y
NEW!

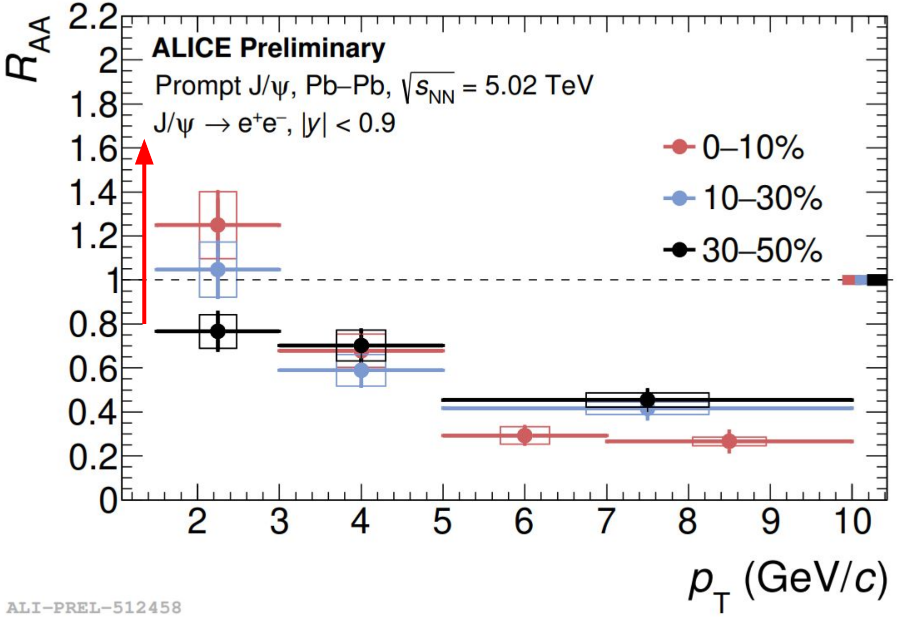


- No major centrality dependence observed within uncertainties
- The precision of the new measurement is improved significantly compared to Run 1
- In agreement with trends of CMS and ATLAS
  - ALICE extends measurements down to very low p_T

Prompt J/ψ R_{AA} as a function of ⟨N_{part}⟩ and p_T

mid-y
NEW!

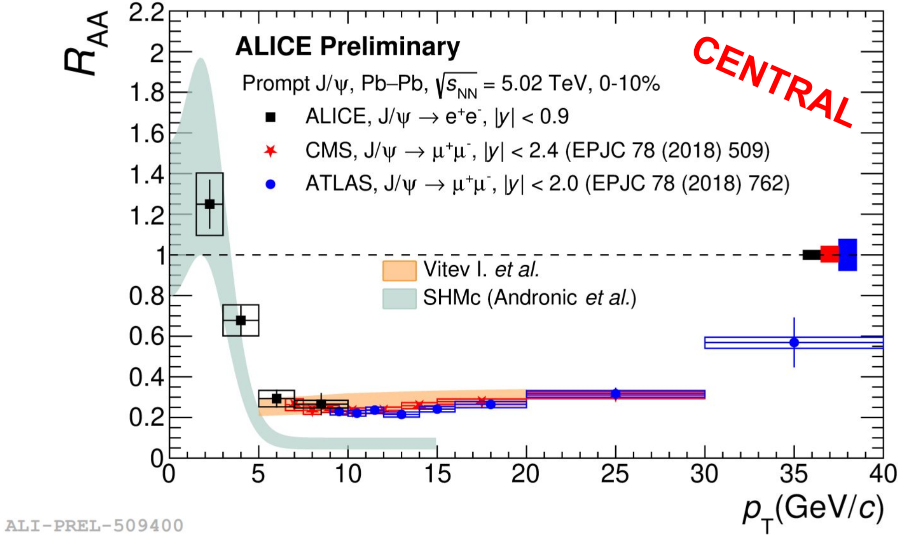


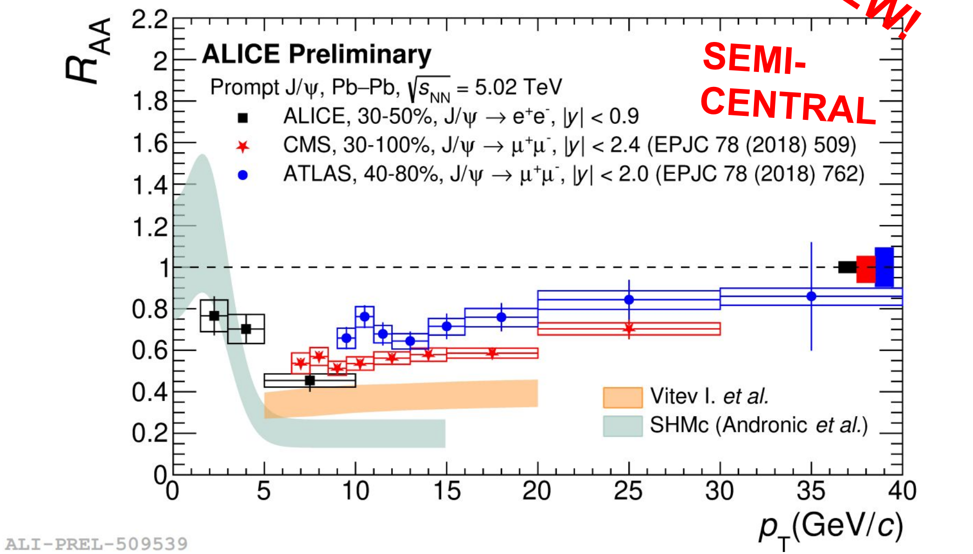


- Prompt J/ψ R_{AA} increases towards more central collisions (effect more visible at low p_T) → expected trend from J/ψ regeneration

Prompt J/ψ R_{AA} in central and semicentral Pb–Pb collisions

mid-y NEW!





- Increasing R_{AA} at low p_T in central collisions compatible with a regeneration scenario
- Overlapping with ATLAS and CMS measurements in central collisions at high p_T
- Vitev: Dissociation of charmonia via microscopic description of interactions inside the medium
  - ALICE results compatible within uncertainties with the model for p_T > 5 GeV/c
- Good agreement with calculations from SHM extended to the charm sector (SHMc) for p_T < 5 GeV/c

SHMc: A. Andronic et al., JHEP07 (2021) 035
(+ private communication)
Vitev I. et al. arXiv:1709.02372, arXiv:1906.04186

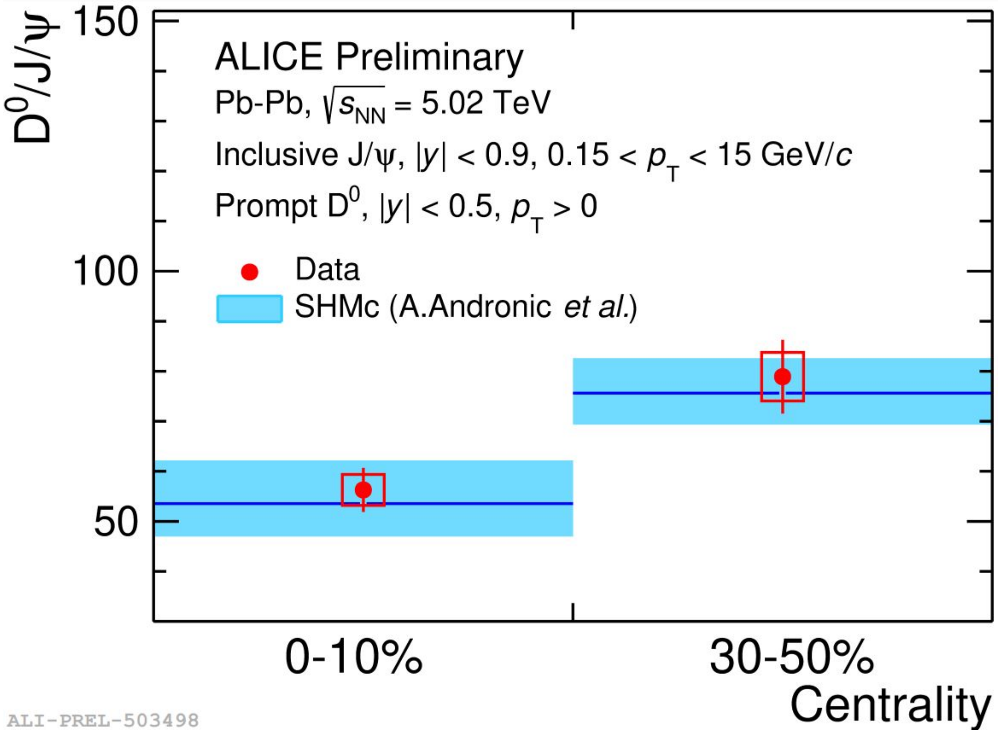
Qualitatively compatible with transport models TM1 and TM2 at low p_T which include also non-prompt J/ψ (not shown)

Models shown in the same centrality and rapidity ranges of ALICE measurements

D^0-to-J/ψ ratio at midrapidity in Pb–Pb collisions

mid-y NEW!

- Sensitive to hadronization mechanisms for open and hidden charm hadrons
  - For SHMc: most of the thermodynamic parameters cancel out → charm fugacity only degree of freedom
- Common experimental (theoretical) uncertainties cancel out in data (model) respectively
- Reduction of the D^0/J/ψ ratio with centrality could be explained by increase of charm fugacity towards most central collisions according to SHMc prediction
- Contribution from the non-prompt J/ψ ranges from 10 to 20% depending on centrality



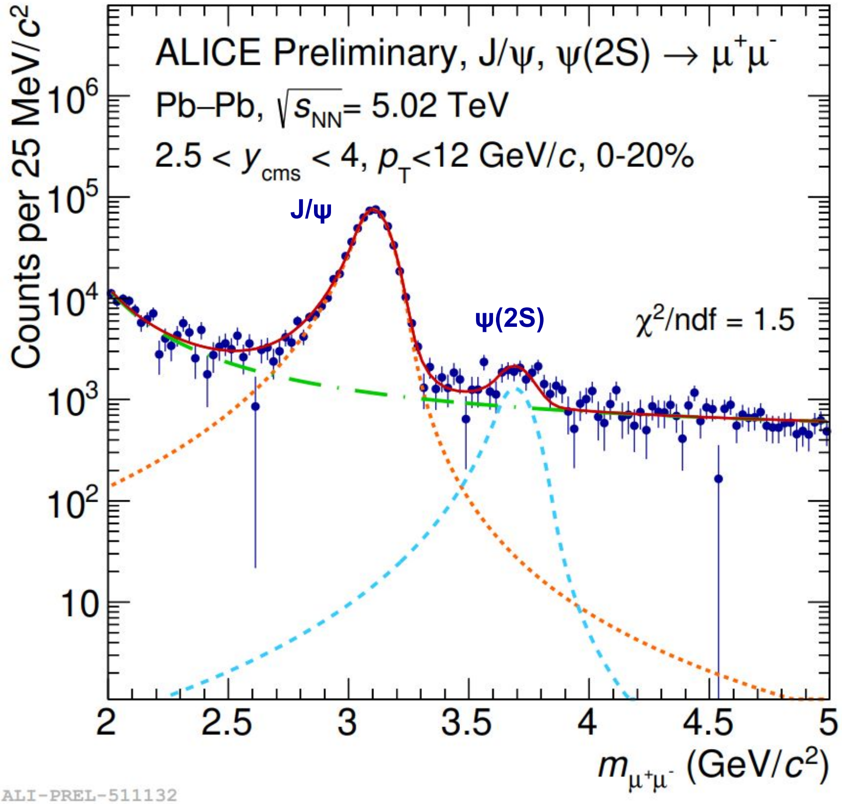
SHMc: A. Andronic et al., JHEP07 (2021) 035 (+ private communication)

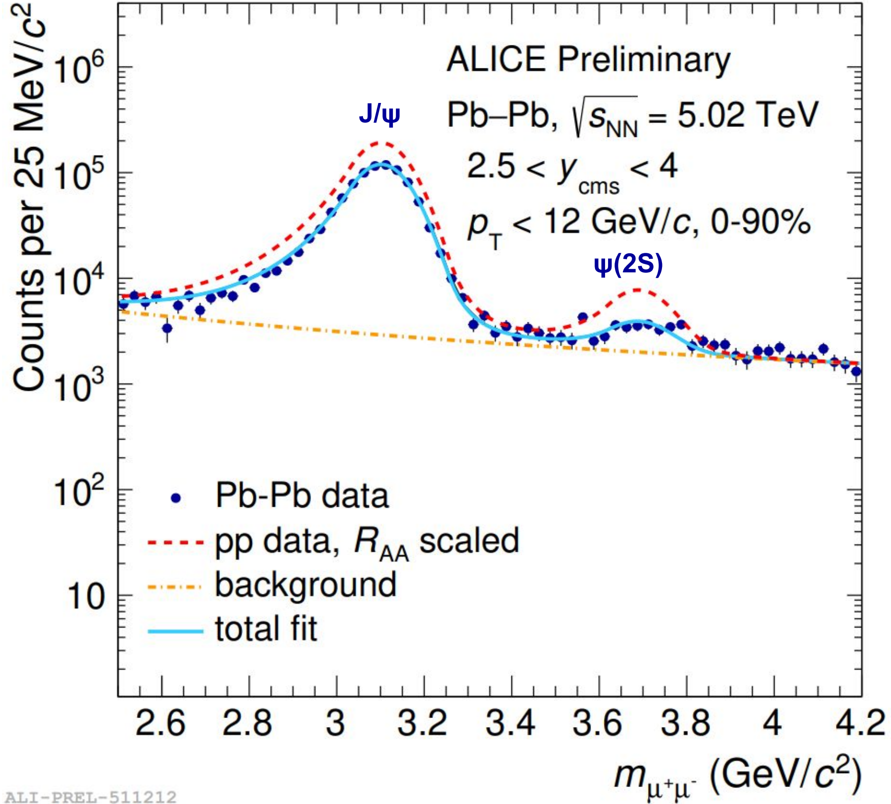
ψ(2S)

ψ(2S) and J/ψ signal extraction

- New results based on full Run 2 statistics
  - ψ(2S) signal now significant in all centrality ranges, including most central!
- Signal extraction performed down to $p_T = 0$

fwd-y NEW!

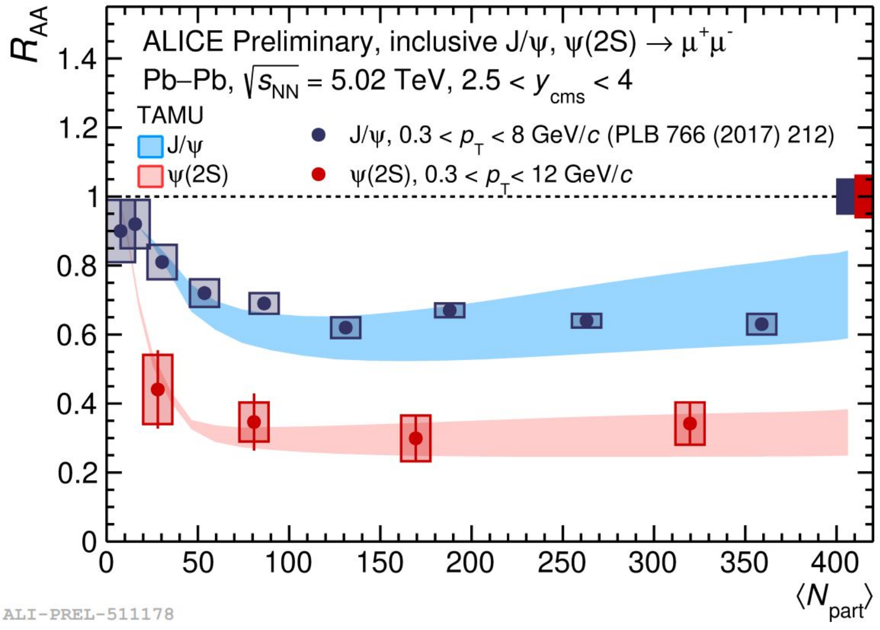


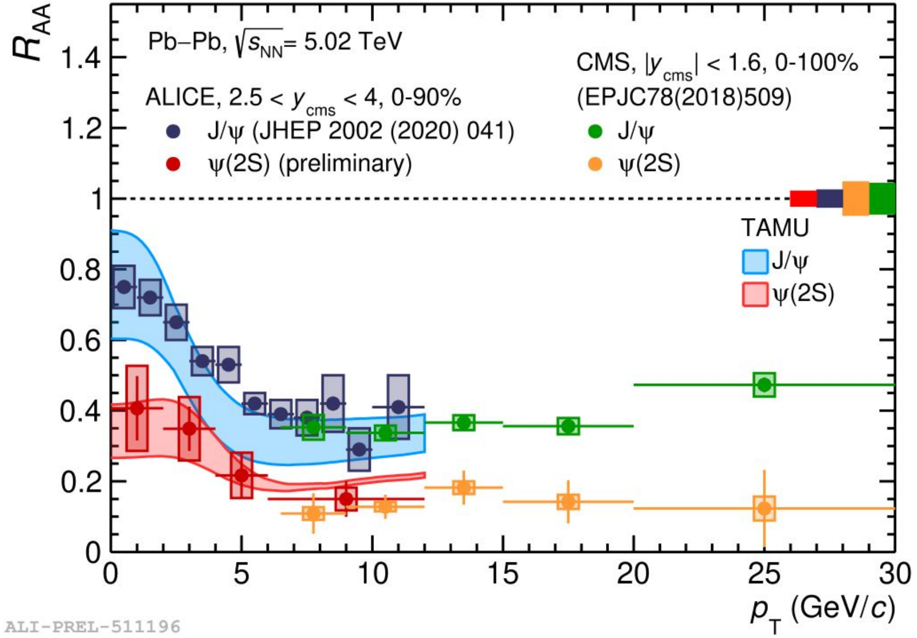


ψ(2S) and J/ψ R_{AA} as function of centrality and p_T

fwd-y
NEW!

- Higher suppression observed for ψ(2S) compared to J/ψ
- Increasing trend of R_{AA} towards low p_T for both J/ψ and ψ(2S)
  - Hint of ψ(2S) production via regeneration!
- Centrality and p_T dependence well reproduced by TAMU model for both J/ψ and ψ(2S)
- Compatible with midrapidity CMS results available for higher p_T



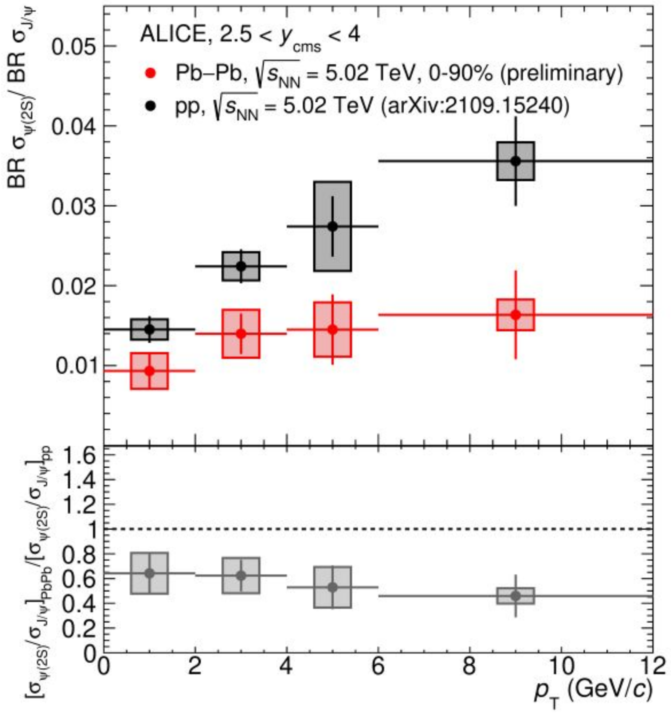


TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158

The ψ(2S) / J/ψ ratio

fwd-y NEW!

- Initial state effects, such as shadowing, largely cancel in this ratio → smaller theoretical uncertainties
  - Theoretically the ψ(2S)/J/ψ ratio is weakly dependent on the charm production cross section



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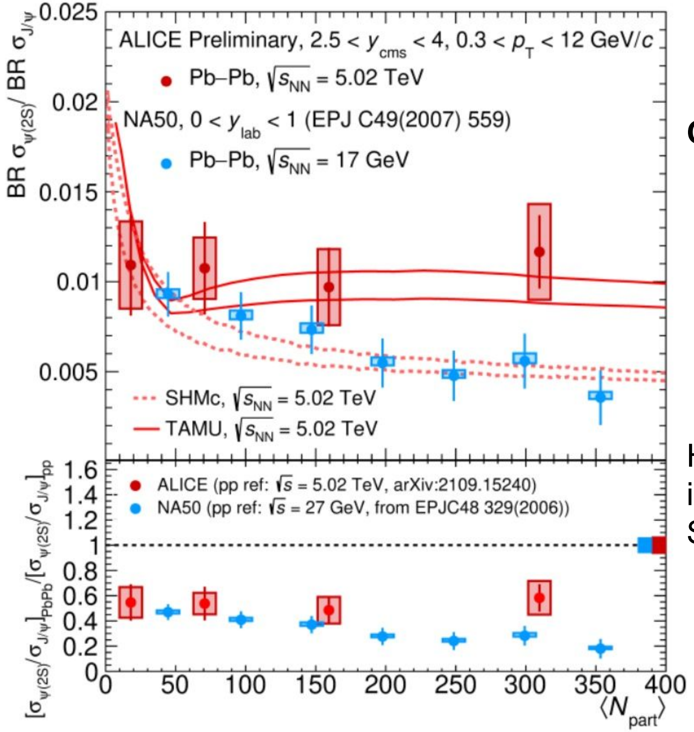

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Comparison with models:

- TAMU reproduces the cross section ratios over centrality
- SHMc tends to underestimate the data in central Pb–Pb collisions

Hint of a larger ψ(2S)/J/ψ ratio in central collisions at LHC w.r.t SPS

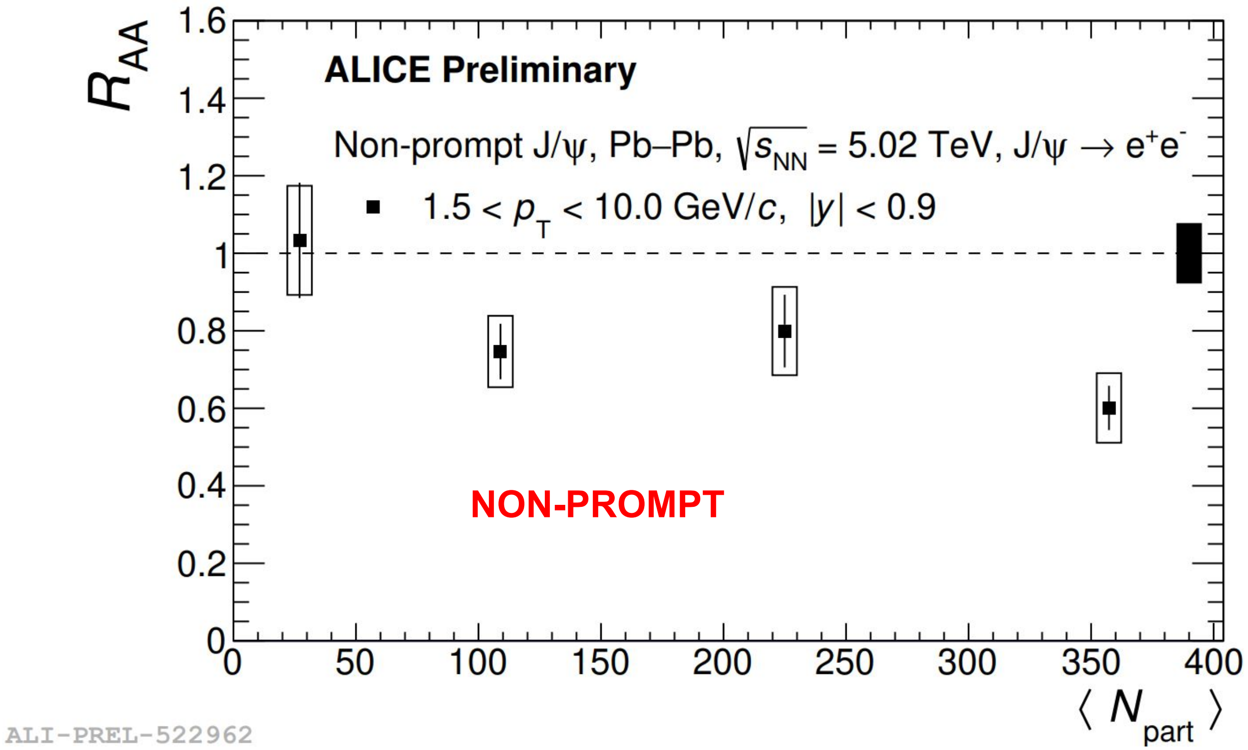
- Smaller ψ(2S)/J/ψ ratio in Pb–Pb w.r.t. pp

TAMU: Du X. and Rapp R., Nucl.Phys.A 943 (2015) 147-158
SHMc: Andronic A. et al., Nature 561, 321–330 (2018)

Open beauty

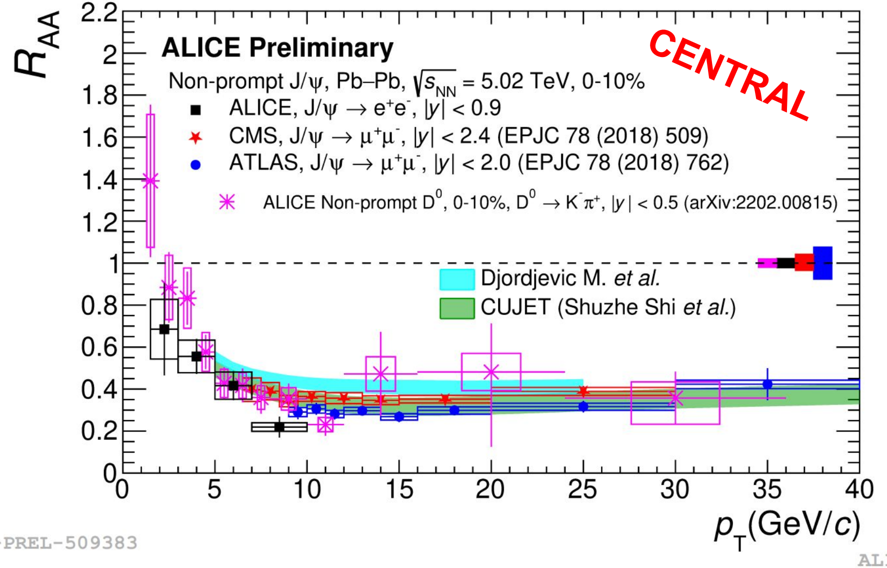
Non-prompt J/ψ R_{AA} as a function of $\langle N_{part} \rangle$

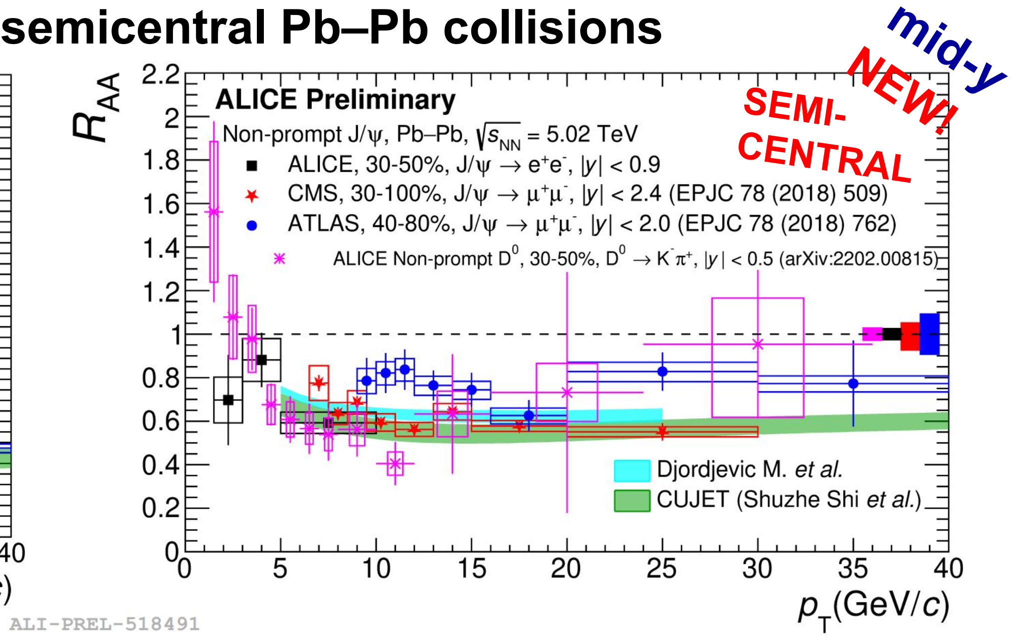
mid-y
NEW!



- Non-prompt J/ψ R_{AA} more suppressed towards more central collisions
  → expected trend from heavy quark energy loss

Non-prompt J/ψ R_{AA} in central and semicentral Pb–Pb collisions





- Similar trends for non-prompt J/ψ and non-prompt D^0 R_{AA} (differences can arise due to the decay kinematic in two cases)
  - Strong suppression at high p_T (> 5 GeV/*c*)
  - Increase towards low p_T (< 5 GeV/*c*) → hints that heavy quarks are pushed towards lower p_T
- Models containing collisional and radiative energy loss consistent with data (p_T > 5 GeV/*c*)
- ALICE measurements complementary to ATLAS and CMS

CUJET: Shuzhe S. *et al.* *Chin.Phys.C* 43 (2019) 4, 044101, *Chin.Phys.C* 42 (2018) 10, 104104
Djordjevic M. *et al*. arXiv:2110.01544

Conclusions

Many NEW results!

J/ψ and ψ(2S) R_{AA}

- ψ(2S) and prompt/inclusive J/ψ R_{AA} show similar trends → regeneration at low p_T, suppression at high p_T
- Models implementing charmonium regeneration manage to describe data!
- ψ(2S)/J/ψ described by TAMU model, slightly underestimated by SHMc

Open to hidden charm ratio

- SHMc describes the D^0 / J/ψ ratio well vs centrality

Open beauty R_{AA} via non-prompt J/ψ

- Increasing suppression towards central collisions
- ALICE measurements
  - Extend down to very low p_T
  - Compatible with models implementing energy loss mechanisms!

Thank you for listening!