ψ(2S) production and nuclear modification factor in nucleus-nucleus collisions with ALICE

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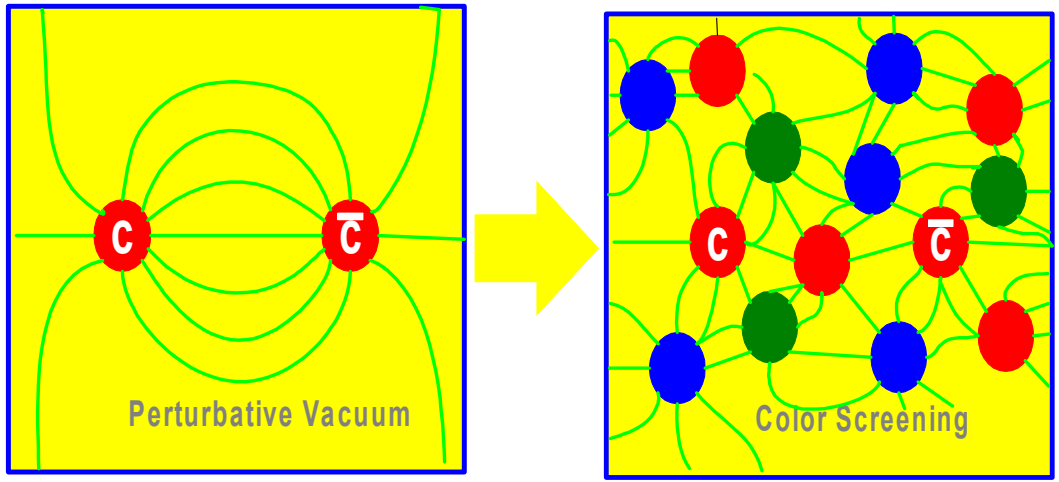
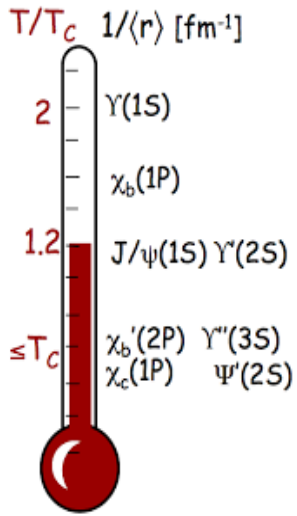
SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

Charmonium suppression in QGP

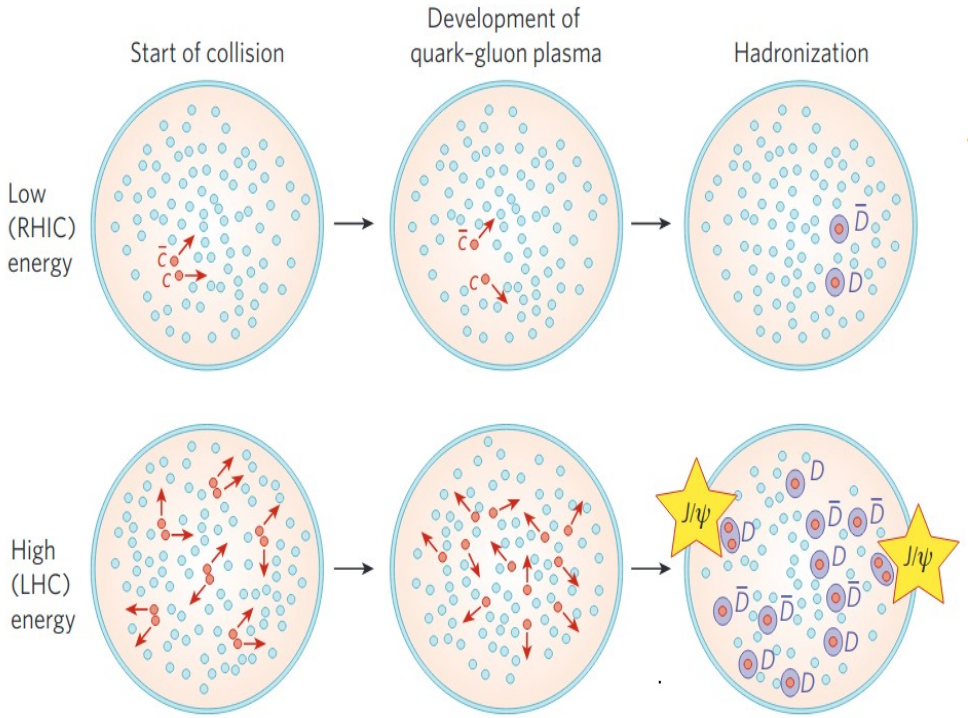


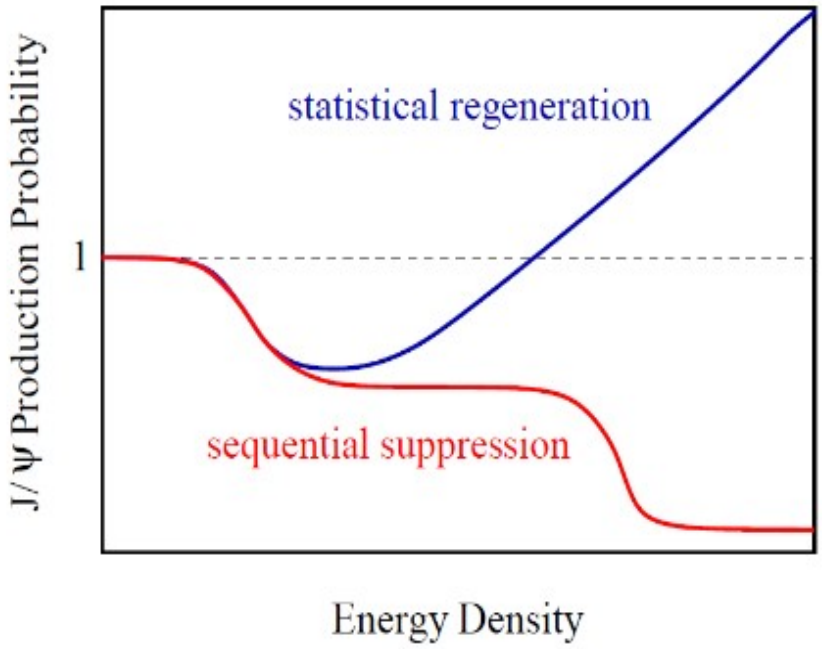


T. Matsui and H. Satz, PLB 178 (1986) 416
Digal, Petrecki, Satz PR D64 (2001) 094150

- At high energy density (>> 1 GeV/fm^3): phase transition of nuclear matter → quark-gluon plasma (QGP)
- In deconfined medium, quarkonia show suppression due to the Debye screening and dissociation
- Excited states (less bound) are more easily dissociated → sequential suppression (quarkonia as QGP thermometer)

Charmonium regeneration in QGP or at phase boundary





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

- At LHC: enhancement of charmonia states $(\mathbf{c}\,\bar{\mathbf{c}})$ via recombination due to large charm quark densities.

Charmonium observables in Pb–Pb collisions

- **Nuclear modification factor R_{AA}:** Ratio of the quarkonium yield in AA (Y_{AA}) with respect to the pp one (Y_{pp}), scaled by the average number of binary collisions $\langle N_{coll} \rangle$ (from Glauber model)

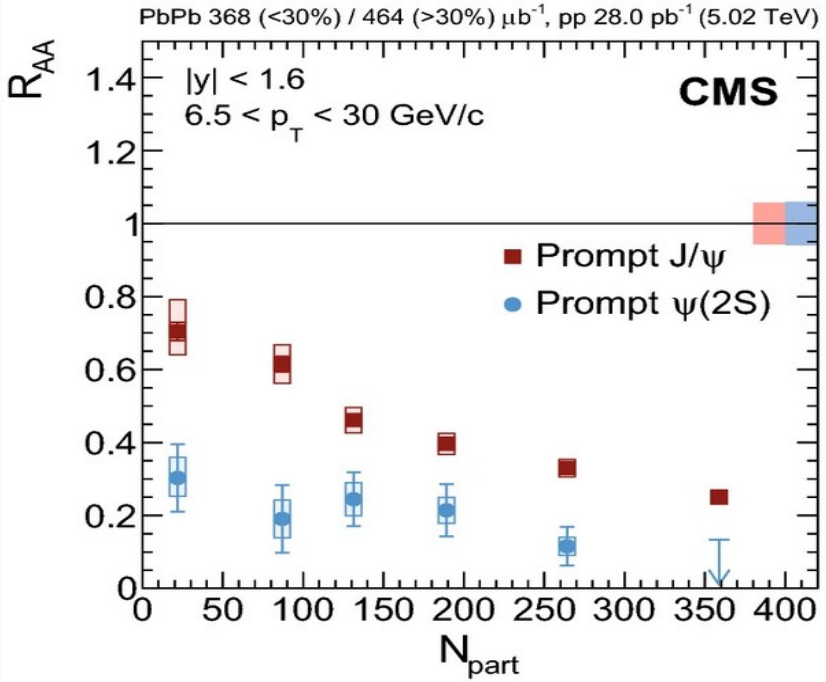
$$R_{AA} = \frac{Y_{AA}^{\psi(2S)}}{\langle N_{Coll} \rangle . Y_{pp}^{\psi(2S)}}$$

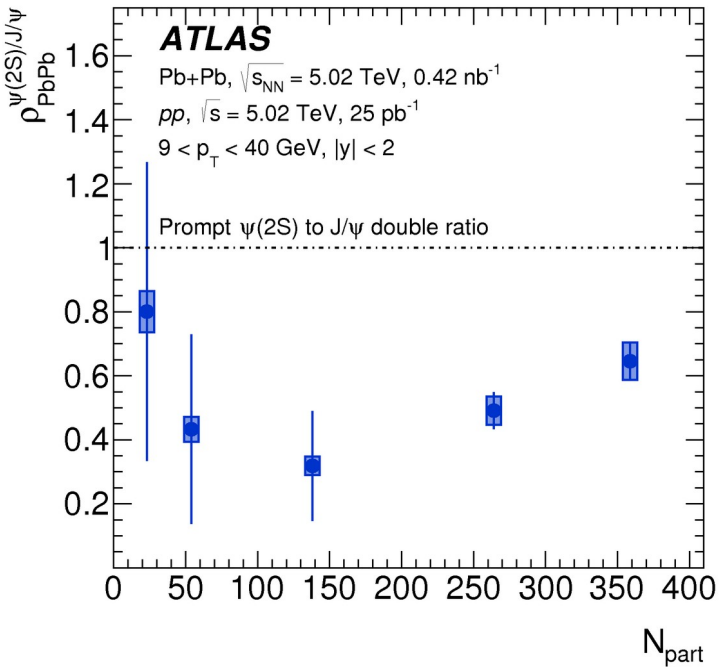
- **Ratio of ψ(2S)-to-J/ψ:**

$$Single\ Ratio = \frac{BR\,\sigma_{\psi(2S)}}{BR\,\sigma_{J/\psi}}$$

$$Double\ Ratio = \frac{\left[\sigma_{\psi(2S)}/\sigma_{J/\psi}\right]_{PbPb}}{\left[\sigma_{\psi(2S)}/\sigma_{J/\psi}\right]_{pp}}$$

ψ(2S) measurements at the LHC energies





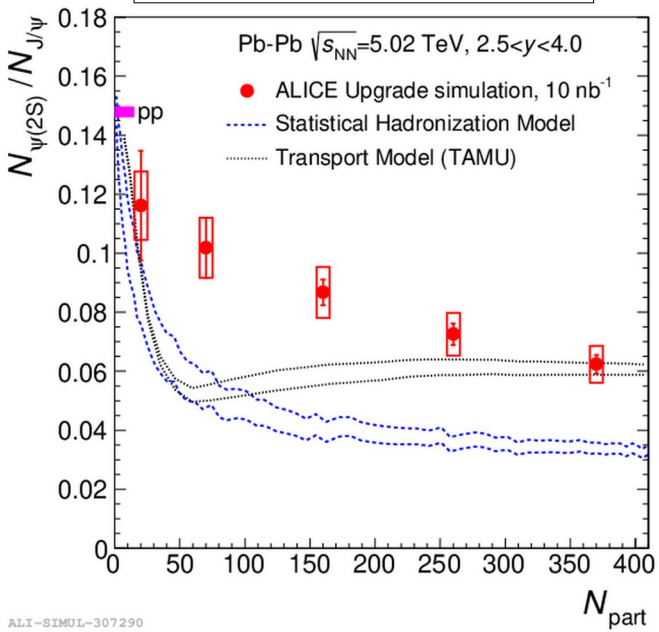
- Stronger suppression of the ψ(2S) with respect to J/ψ by a factor ~ 2 at high-p_T
- Strong suppression observed at high-p_T by ATLAS and CMS

For complete characterization of ψ(2S) production an extension to low-p_T is needed where recombination mechanism is at play

CMS collaboration, Phys. Rev. Lett. 118 no. 16 (2017) 162301;
CMS collaboration, Eur. Phys. J. C78 (2018) 509;
ATLAS collaboration, Eur. Phys. J. C78 no.9 (2018) 762

Motivation for ψ(2S) measurement in Pb–Pb collisions

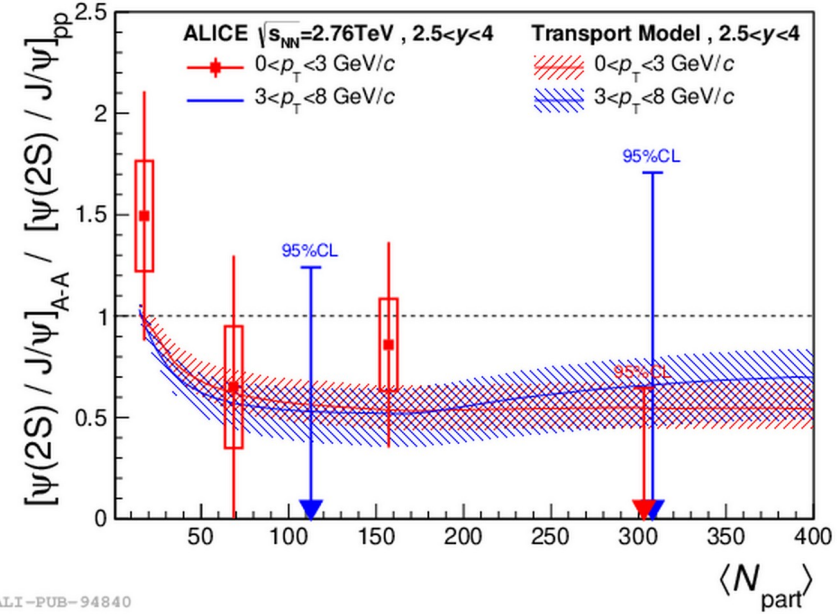
ALICE upgrade projection



- Hint for stronger suppression of ψ(2S) compared to J/ψ observed in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV, but large uncertainties prevent a strong conclusion.

→ Significantly higher statistics (by a factor of ~11) available using full Run 2 Pb–Pb data at $\sqrt{s_{NN}}$ = 5.02 TeV!

- ψ(2S)-to-J/ψ ratio measurements weakly dependent on charm production cross section employed as input to the models in Pb–Pb collisions → **important constraints on models**



TAMU:X. Du. and R. Rapp, Nucl. Phys. A 943 (2015) 147; SHM: A. Andronic *et. al.*, Nature 561 no. 7723 (2018) 321; JHEP 05 (2016) 179

A Large Ion Collider Experiment

Central barrel:

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

Electrons reconstructed using ITS and TPC

Particle identification: TPC dE/dx

Forward muon spectrometer:

$J/\psi, \psi(2S) \rightarrow \mu^+\mu^-$ ($2.5 < y < 4.0$)

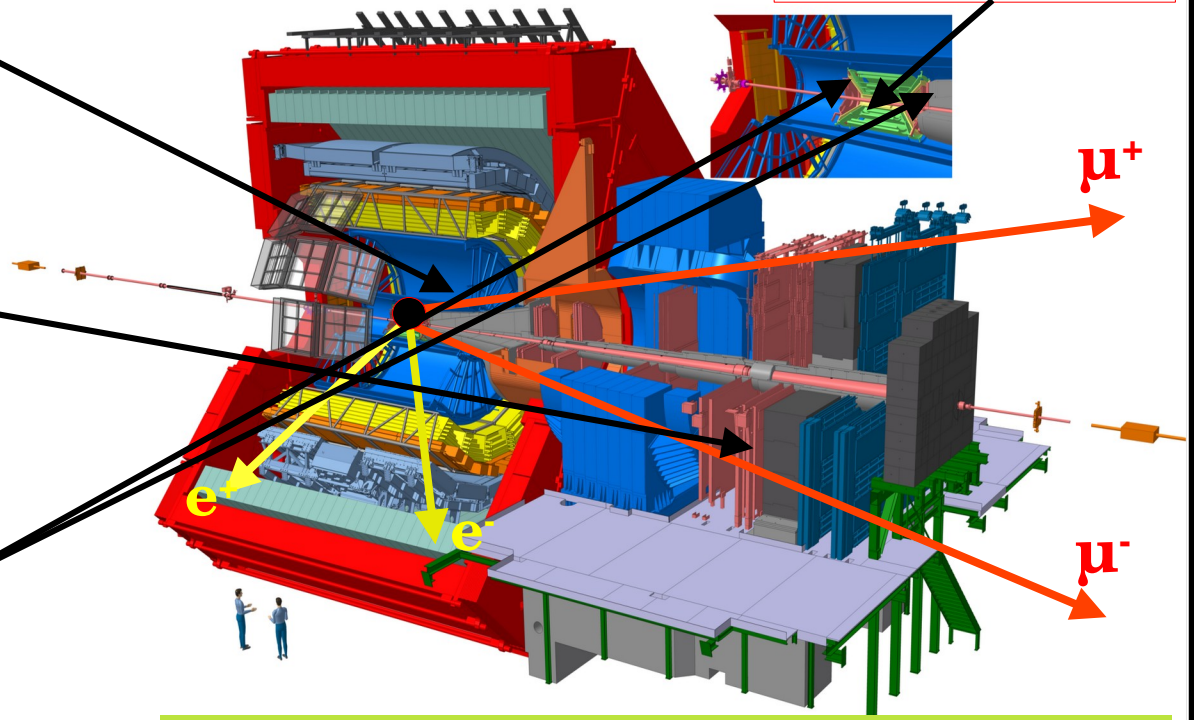
Reconstruction of muon tracks; triggering of events with muon candidates

V0

(V0A: $2.8 < \eta < 5.1$ & V0C: $-3.7 < \eta < -1.7$)

Trigger, background rejection and centrality measurements in AA collisions

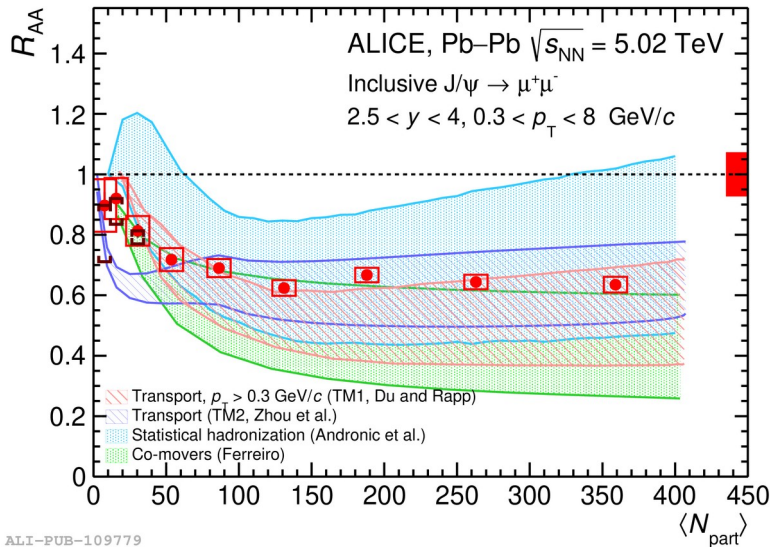
SPD: Primary vertex

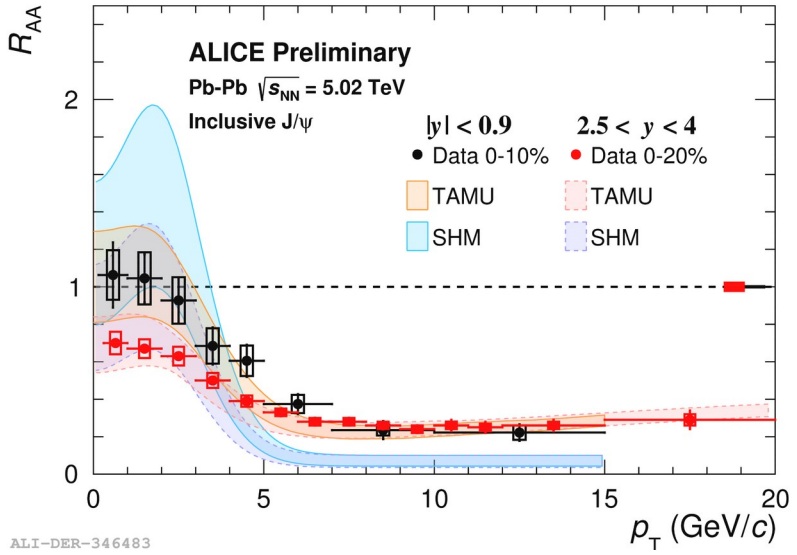


For ALICE quarkonium results in Pb–Pb, see talks from
X. Bai on Tues. 14th June, 9 am
L. Massacrier on Tues. 14 June, 2.40 pm

Acceptance coverage in both y regions is down to zero p_T

Inclusive J/ψ R_{AA}





- **SHM :** J/ψ produced at the QGP phase boundary
- **TAMU:** J/ψ produced according to rate equation with gain (regeneration) and loss (melting) terms

Theoretical models, in agreement with data

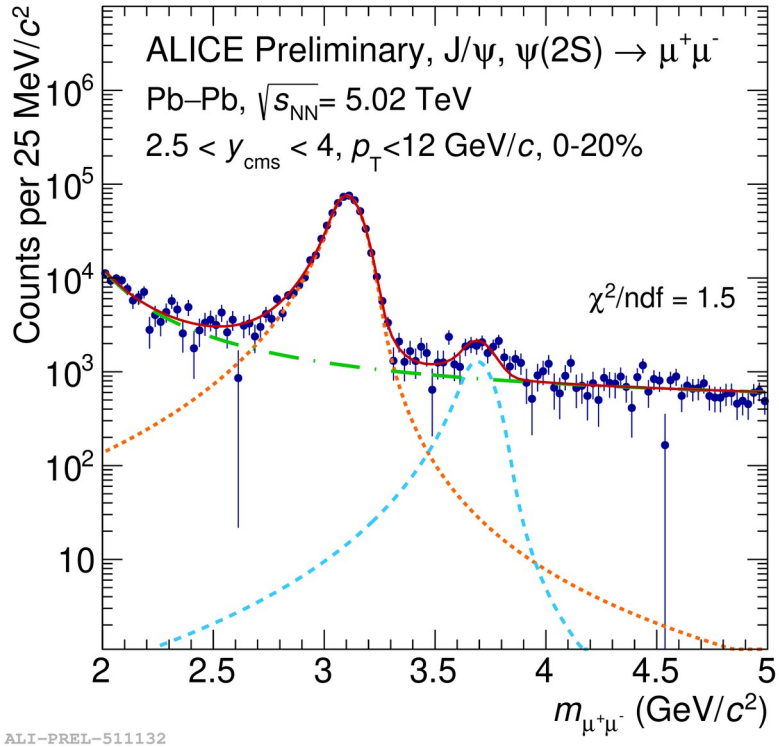
- Both centrality and p_T dependencies (at low-p_T) are qualitatively well described
- Rapidity dependence is also described by recombination models

→ Not possible to disentangle between the two different (re)generation scenarios using J/ψ

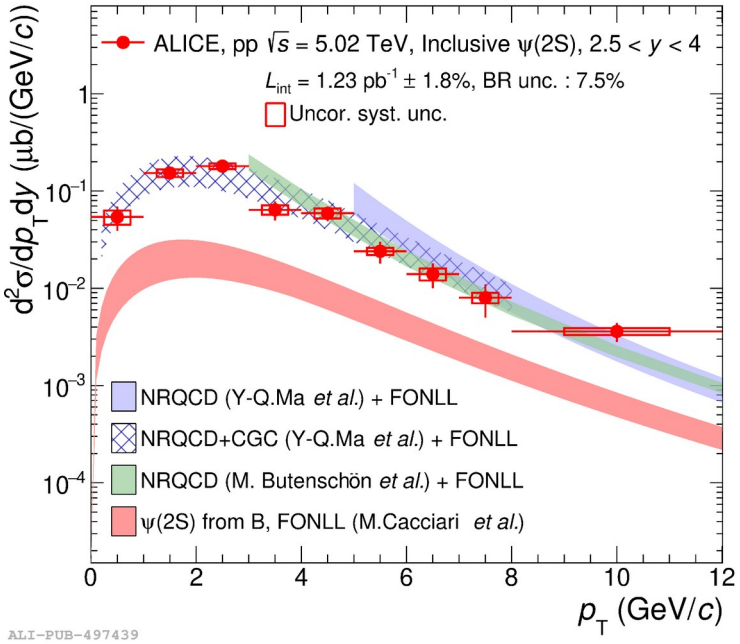
TM1/TAMU: R. Rapp *et. al.*, Nucl. Phys. A 849 (2011) 114;
SHM: A. Andronic *et. al.*, Phys. Lett. B797 (2019) 134836 ;
TM2: Zhou et. al. Phys. Rev. C89 (2014) 054911;
Co-movers: Phys. Lett. B 731 (2014) 57

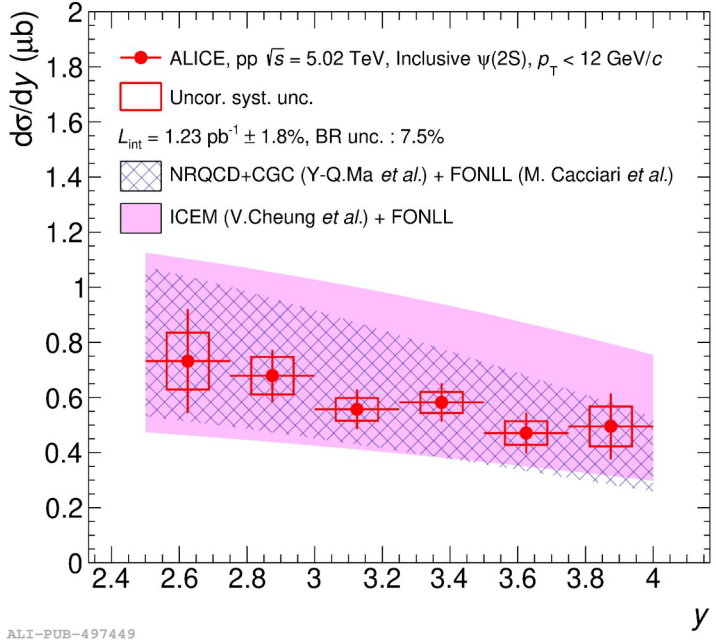
ψ(2S) signal extraction in Pb–Pb

- ψ(2S) signal extracted by using event mixing subtraction technique
- Significant signal observed in most central collisions and down to zero p_T, thanks to the usage of full Run 2 statistics
- Reference measurement is obtained from the study of ψ(2S) cross sections in pp collisions at $\sqrt{s}$ = 5.02 TeV [arXiv: 2109.15240]



ψ(2S) pp reference measurements

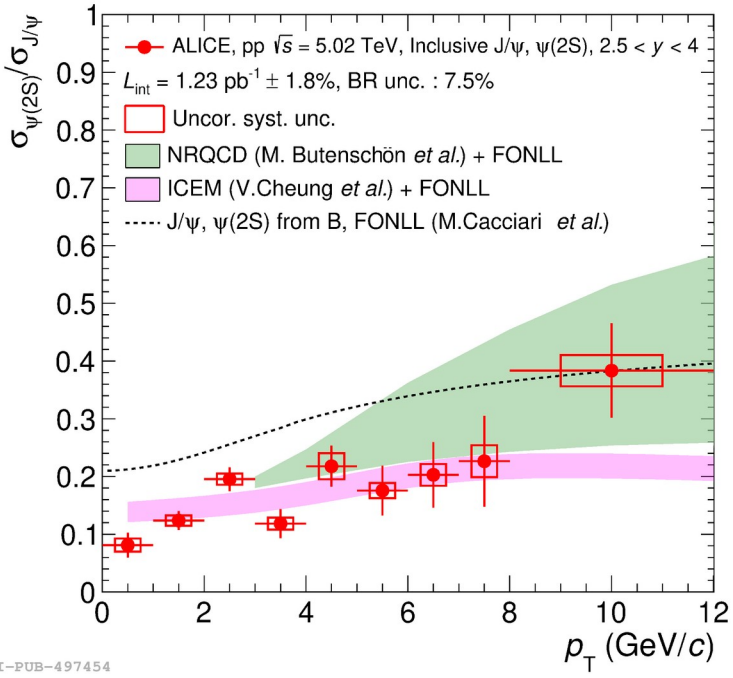


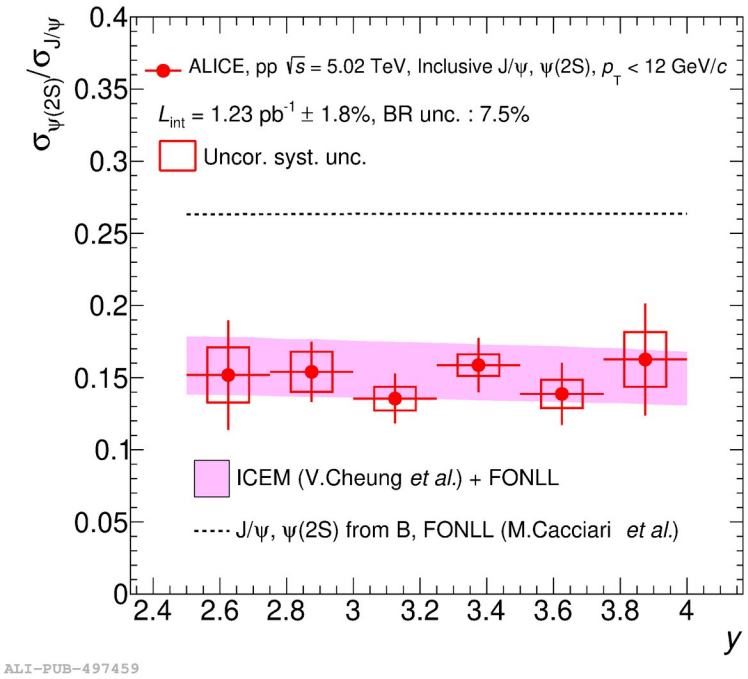


- NRQCD+CGC+FONLL is able to describe cross section for p_T > 4 GeV/c at forward rapidity
- NRQCD+CGC provides a good description down to zero p_T
- Good agreement with theoretical models observed also as a function of rapidity

NRQCD (Butenschön *et al.*): M. Butenschön et al. , Phys. Rev. Lett. 106 (2011) 022003;
NRQCD (Y-Q. Ma *et al.*): Y-Q. Ma *et al.*, Phys. Rev. Lett. 106 (2011) 042002;
NRQCD+CGC (Y-Q. Ma *et al.*):Y.-Q. Ma and R. Venugopalan, Phys. Rev. Lett. 113 no. 19, (2014) 192301
ICEM (V. Cheung *et al.*):V. Cheung and R. Vogt, Phys. Rev. D 98 no. 11, (2018) 114029
FNOLL (M. Cacciari et. al.): M. Cacciari et. al., JHEP 10 (2012) 137;
arXiv:2109.15240

ψ(2S)-to-J/ψ cross section ratio

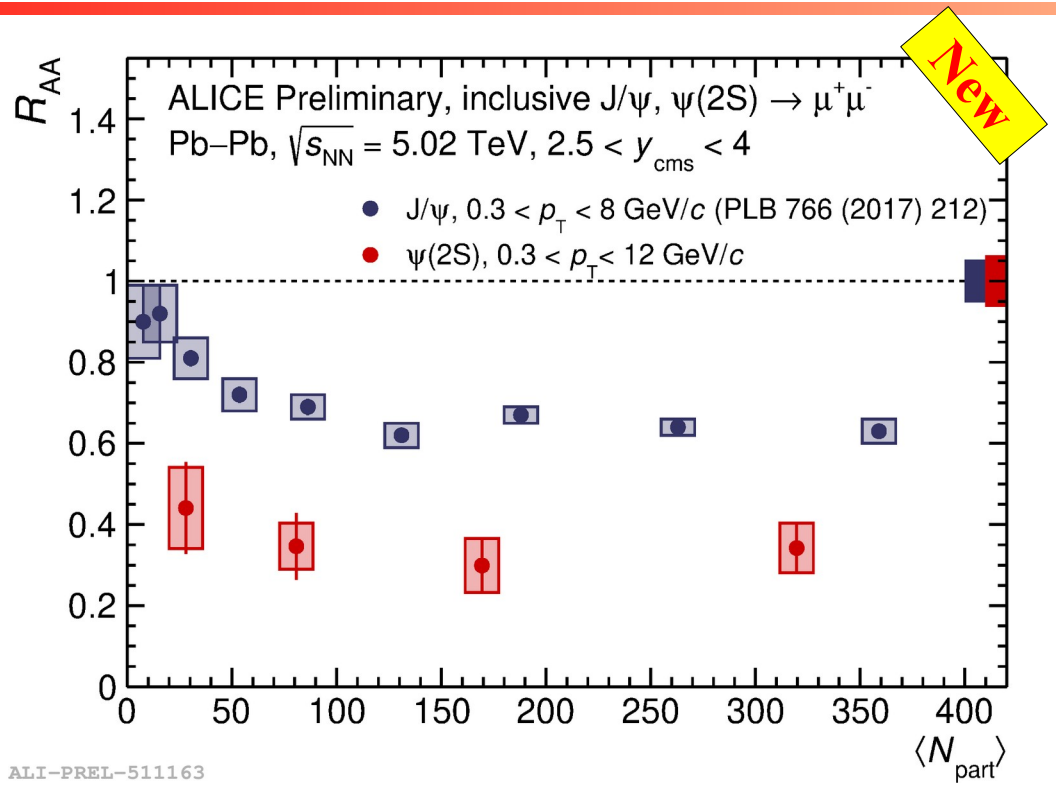




- ψ(2S)-to-J/ψ cross-section ratio shows an increasing trend with p_T
- No significant dependence with rapidity
- Theoretical models show an overall good agreement within uncertainties

NRQCD (Butenschön *et al.*): M. Butenschön *et al.*, Phys. Rev. Lett. 106 (2011) 022003;
ICEM (V. Cheung *et al.*):V. Cheung and R. Vogt, Phys. Rev. D 98 no. 11, (2018) 114029
FNOLL (M. Cacciari et. al.): M. Cacciari et. al., JHEP 10 (2012) 137;
arXiv:2109.15240

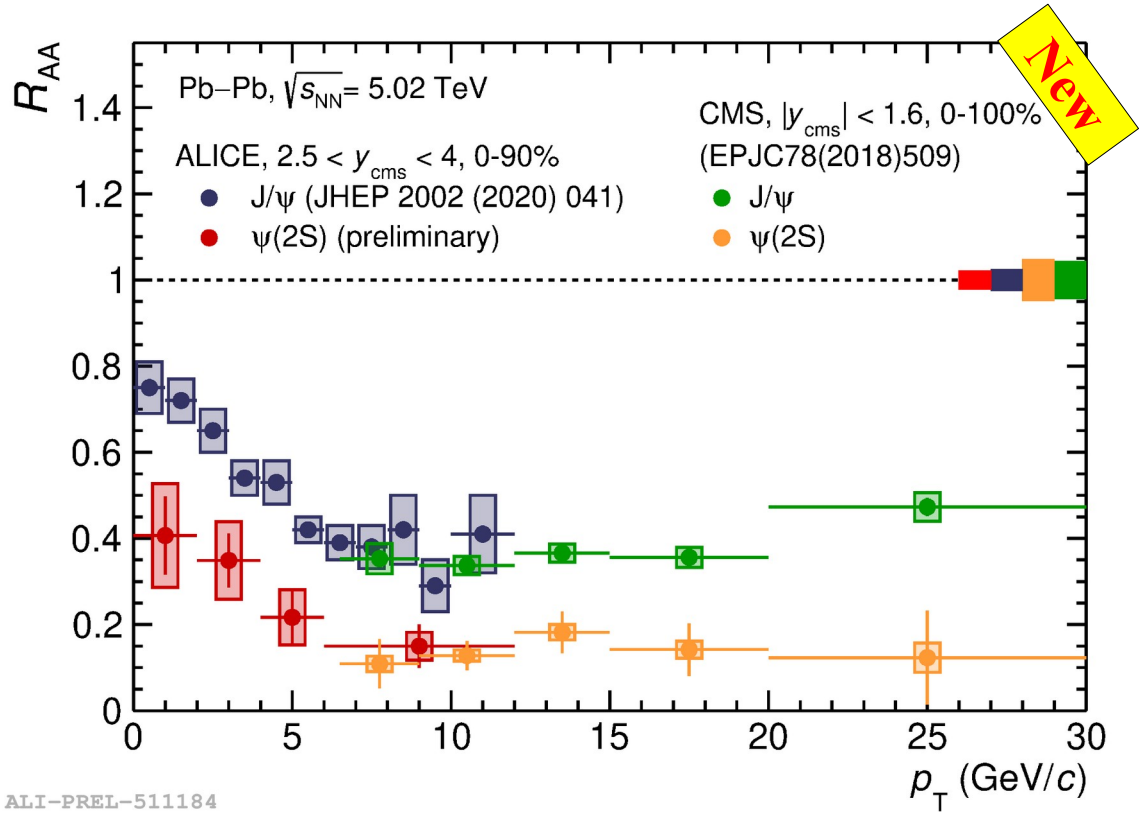
Centrality dependence of the ψ(2S) R_{AA}



- ψ(2S) significantly suppressed as a function of centrality, R_{AA} almost flat above $N_{part} \sim 75$
- ψ(2S) shows stronger suppression than the J/ψ

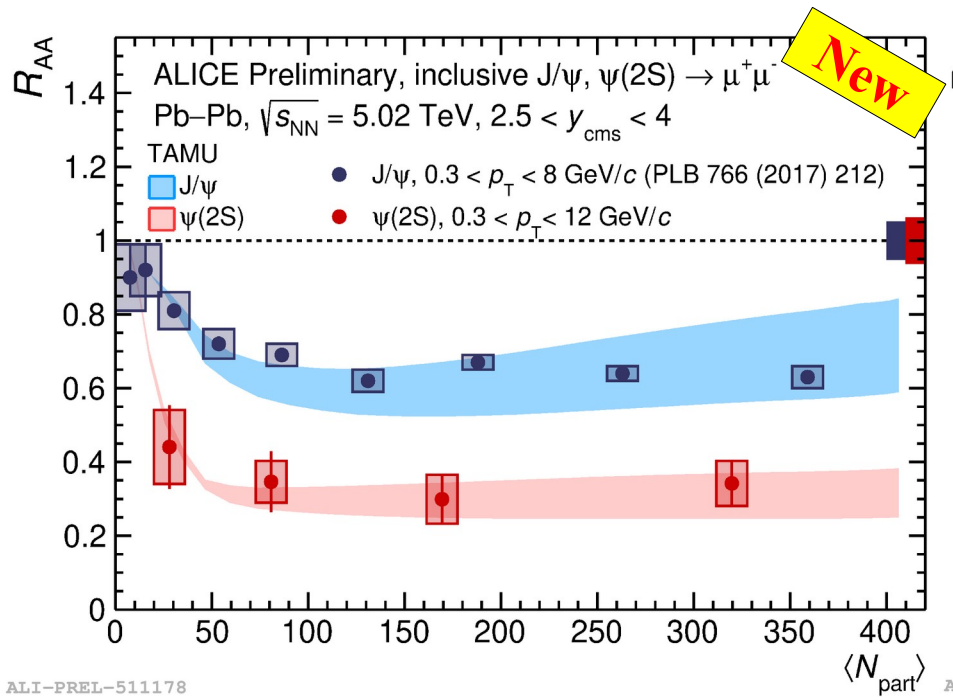
p_T dependence of the ψ(2S) R_{AA}

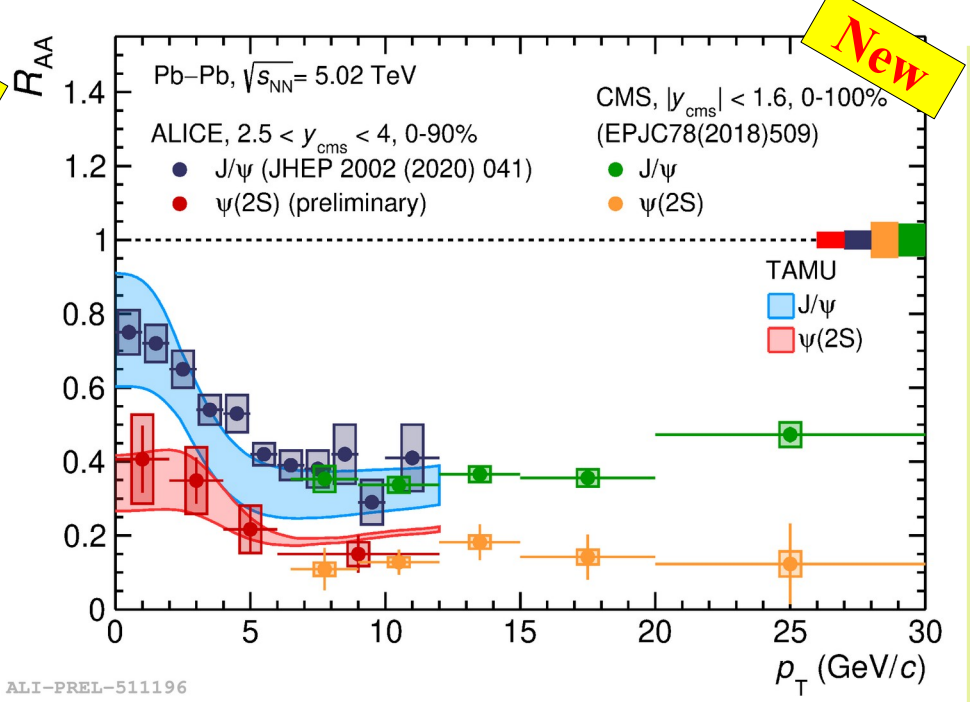
- ψ(2S) significantly suppressed as a function of p_T, and shows stronger suppression than the J/ψ.
- Stronger suppression at high-p_T and increasing trend of R_{AA} towards low-p_T for both charmonium states.
- Good agreement between CMS and ALICE data in the common p_T range, in spite of different rapidity coverages.



CMS collaboration, Eur. Phys. Jour. C 78 (2018) 509
JHEP 2002 (2020) 041

R_{AA} results: comparison to theoretical model



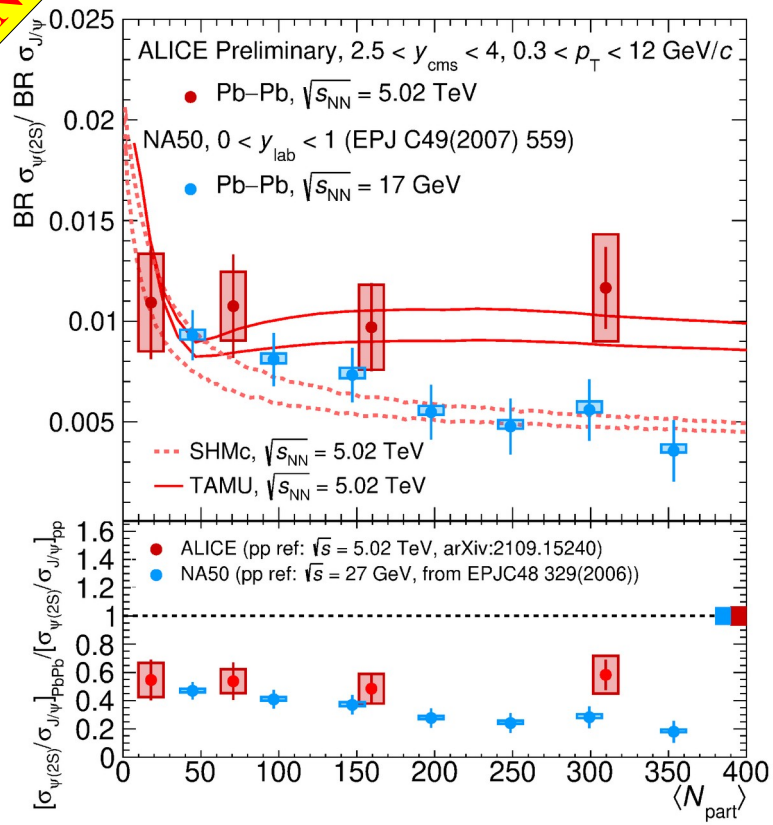


TAMU: X. Du and R. Rapp, Nucl. Phys. A 943 (2015) 147;
CMS collaboration, Eur. Phys. Jour. C 78 (2018) 509;
Phys. Lett. B766 (2017) 212;
JHEP 2002 (2020) 041

- TAMU model, which includes charmonium regeneration, reproduces p_T and centrality dependence of R_{AA} for both J/ψ and ψ(2S)

Centrality dependence of ψ(2S)-to-J/ψ

New



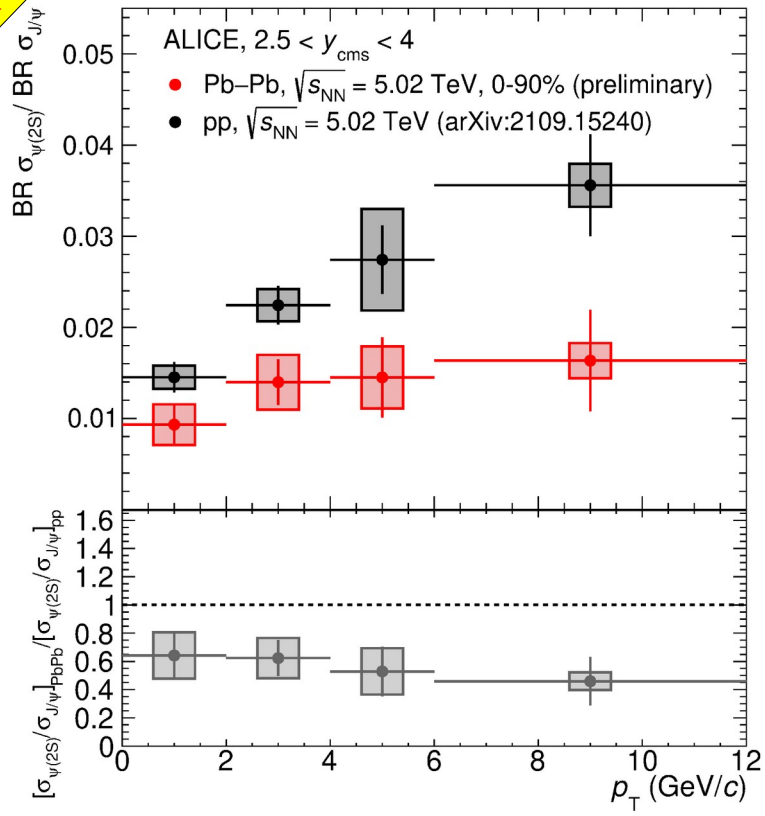
- Significant suppression of ψ(2S)-to-J/ψ ratio in Pb–Pb with respect to pp
- No significant centrality dependence
- Hint of a larger ψ(2S)-to-J/ψ ratio in central collisions at the LHC compared to SPS
- TAMU model well reproduces the cross section ratio at the LHC energy while SHMc tends to underestimate the data

TAMU: X. Du. And R. Rapp, Nucl. Phys. A 943 (2015) 147;
SHMc: A. Andronic et. al., Nature 561 no. 7723 (2018) 321;
NA50 collaboration, Eur. Phys. Journ. C48 (2006) 329;
arXiv:2109:15240

ALI-PREL-523330

p_T dependence of ψ(2S)-to-J/ψ in Pb–Pb collisions

New



- A significant suppression of ψ(2S)-to-J/ψ ratio in Pb–Pb with respect to pp also observed as a function of p_T
- The double ratio reaches ~ 0.5 at high-p_T

ALI-PREL-511153

Summary

- pp collisions:
  - ✔ ψ(2S) cross section and ψ(2S)-to-J/ψ measurements carried out by ALICE at $\sqrt{s}$ = 5.02 TeV.
  - ✔ Theoretical models reproduce the ψ(2S) cross section well within uncertainties.
- Pb–Pb collisions:
  - ✔ The ψ(2S) R_{AA} is larger at low-p_T than at high-p_T as expected from the contribution of charm quark regeneration at low-p_T.
  - ✔ Stronger suppression of the ψ(2S)-to-J/ψ ratio in Pb–Pb with respect to pp, no significant p_T or centrality dependence observed within uncertainties.
  - ✔ Comparison of J/ψ and ψ(2S) R_{AA} with transport model shows a fair agreement within uncertainties.
  - ✔ Transport model, that includes recombination of charm quarks in the QGP phase, reproduces the ψ(2S)-to-J/ψ ratio better than SHMc model for central events.
- Prospects for Run3/4
  - ✔ Significant increase of statistical precision expected with $L_{int} \sim 10$ nb^{-1}, thanks to continuous readout.


Thank You!