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

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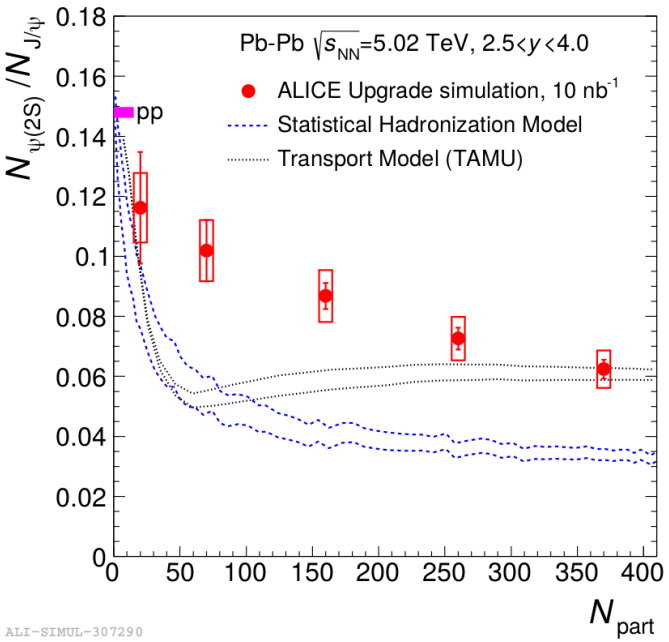
Motivation for ψ(2S) measurement in Pb–Pb

- Sequential melting: Differences in the binding energies lead to a sequential melting of the quarkonium states with increasing temperature of the quark-gluon plasma (QGP)

T. Matsui and H. Satz, PLB 178 (1986) 416
A Rothkopf, Phys. Rept. 858 (2020) 1-117

- Quarkonium recombination: Increase of $c\bar{c}$ production cross section at the LHC energies → Enhanced quarkonium production via recombination at the phase boundary or during the QGP phase

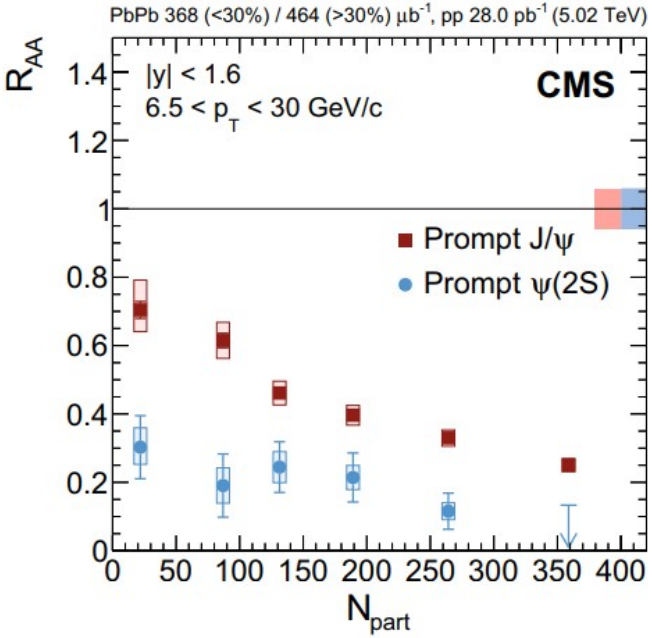
P. Braun-Muzinger, J. Stachel, PLB 490 (2000) 196
R. Thews et al, Phys. Rev. C 63 (2001) 054905

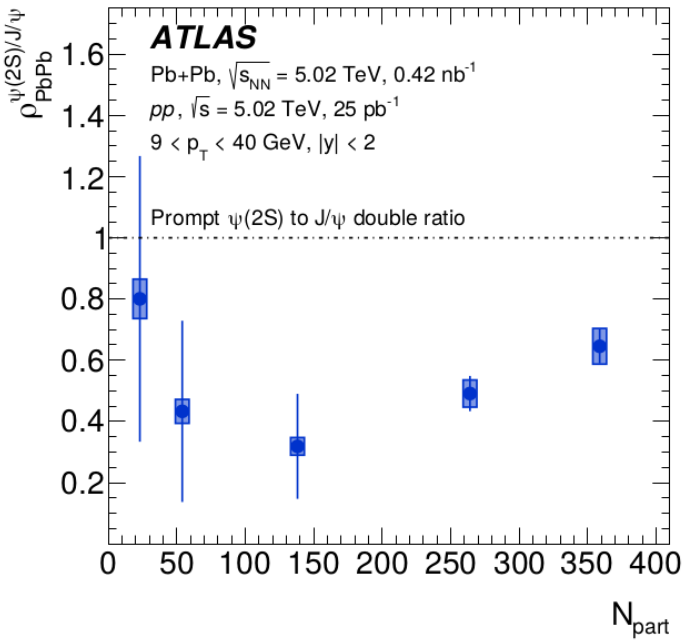


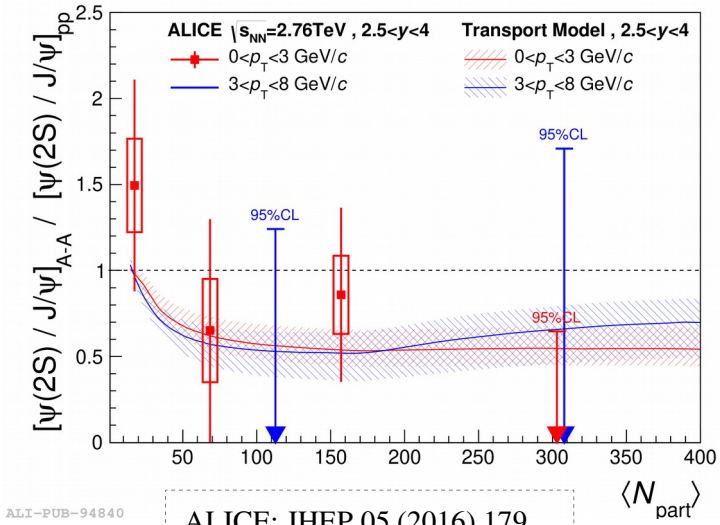
- ψ(2S) to J/ψ ratio weakly depends on charm production cross section employed as input to the models in Pb–Pb collisions → important constraints on models

TAMU: X. Du and R. Rapp, NPA 943 (2015) 147
SHMc: A. Andronic et. al., Nature 561 no. 7723 (2018) 321

ψ(2S) measurements at the LHC energies



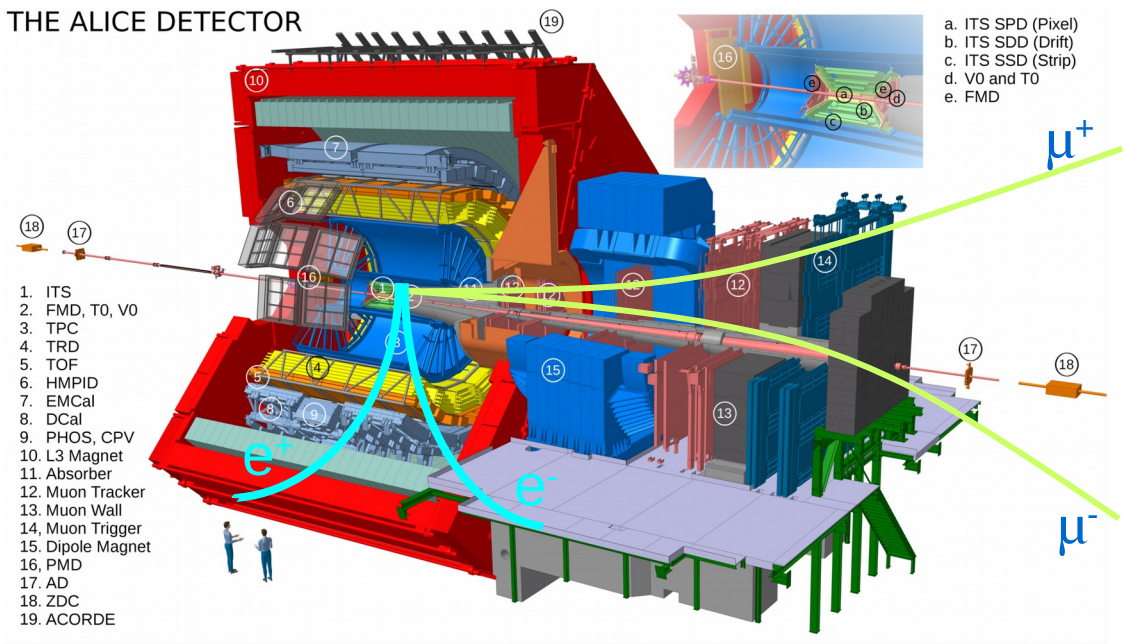




ALICE: JHEP 05 (2016) 179
CMS: EPJC 78 (2018) 509
ATLAS: EPJC 78 (2018) 762

- Stronger ψ(2S) suppression observed at high-p_T by ATLAS and CMS compared to J/ψ at $\sqrt{s_{NN}}$ = 5.02 TeV
- For complete characterization of ψ(2S) production an extension to low-p_T is needed where recombination mechanism is at play
- At low-p_T only ALICE Run 1 results available, but large uncertainties prevent a firm conclusion → Significantly higher statistics (by a factor of ~11) available in full Run 2 Pb–Pb data at $\sqrt{s_{NN}}$ = 5.02 TeV!

A Large Ion Collider Experiment



For more ALICE quarkonium results, see talks from
Raphaelle Marie Bailhache, 7th July at 18.30
Theraa M A Tork, 8th July at 18:35
Yanchun Ding, 9th July at 10:10
Maurice Louis Coquet, 9th July at 11.15
Himanshu Sharma, 9th July at 12:05

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

Electrons reconstructed using ITS and TPC
Particle identification: TPC dE/dx

Forward muon arm:
J/ψ, $\psi(2S)$, $\Upsilon(nS) \rightarrow \mu^+\mu^-$ ($2.5 < y < 4$)

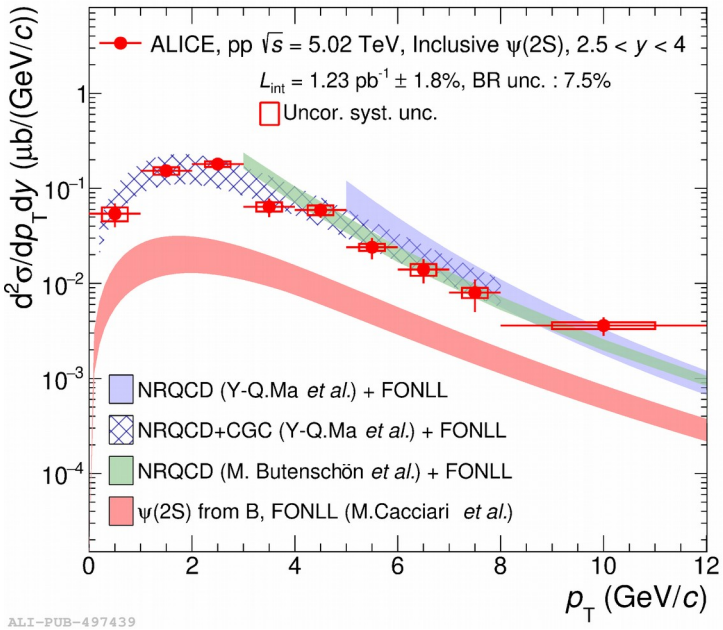
Muons identified and tracked in the muon spectrometer

V0:
(V0A: $2.8 < \eta < 5.1$ & V0C: $-3.7 < \eta < -1.7$)

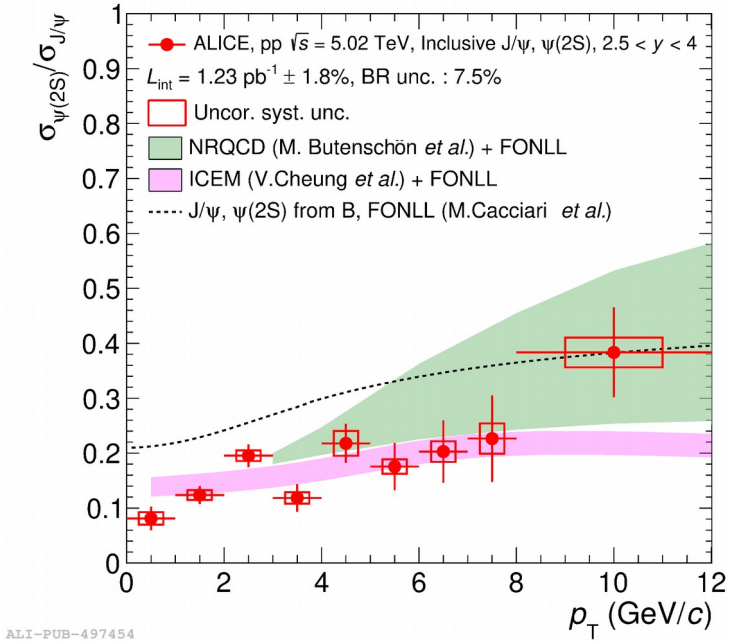
Trigger, background rejection and centrality measurements in A-A collisions

→ Inclusive quarkonium measurements are down to zero p_T

ψ(2S) reference cross section in pp collisions



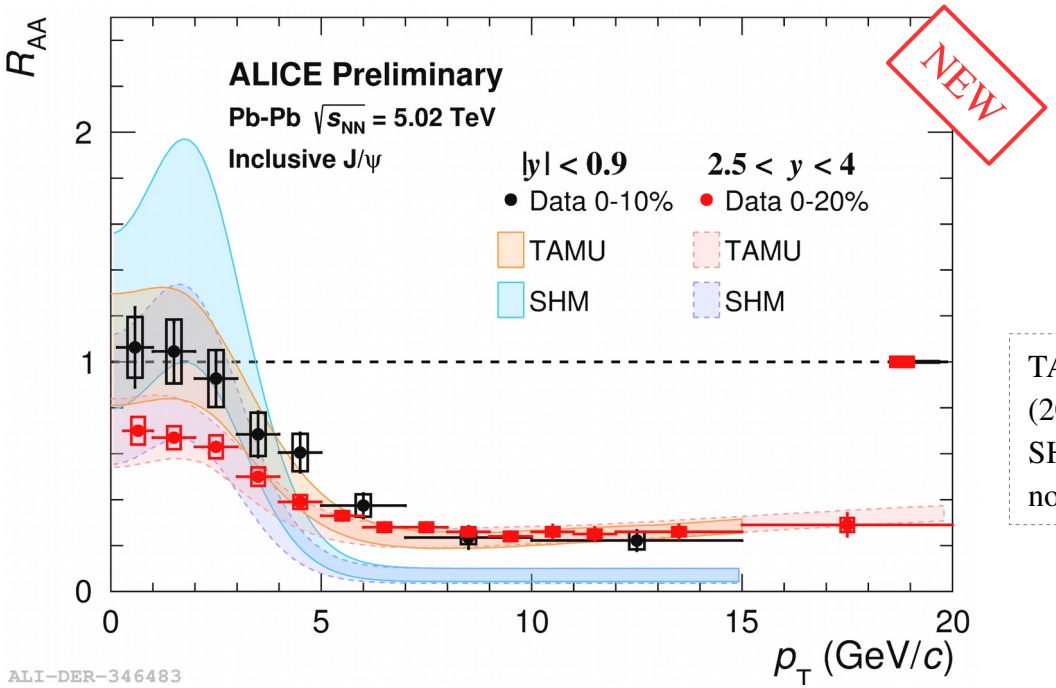
arXiv:2109.15240



- New measurement with 10 times more statistics than earlier publication allows for p_T and y-differential studies of ψ(2S)
- NRQCD+CGC+FONLL provides a good data description down to zero p_T
- ψ(2S)-to-J/ψ ratio shows an increasing trend with p_T and an overall good agreement within uncertainties with theoretical models

NRQCD (Butenschon et al): PRL 106 (2011) 022003
NRQCD (Y-Q. Ma et al): PRL. 106 (2011) 042002
NRQCD+CGC (Y-Q. Ma et al): PRL 113 no. 19, (2014) 192301
ICEM (V. Cheung et al): PRD 98 no. 11, (2018) 114029
FONLL (M, Cacciari et al): JHEP 10 (2012) 137

J/ψ in Pb–Pb collisions

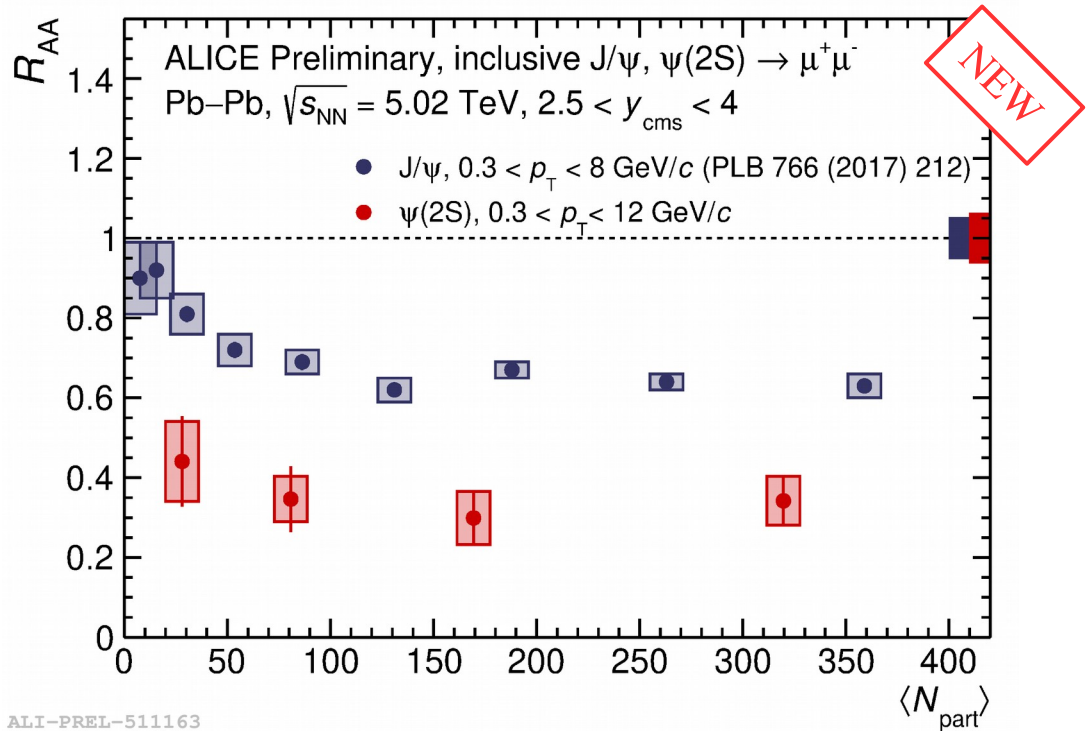


TAMU: X. Du and R. Rapp, NPA 943 (2015) 147
SHMc: A. Andronic et. al., Nature 561 no. 7723 (2018) 321

- Rise of inclusive J/ψ R_{AA} at low p_T, stronger effect at midrapidity → strong signature of recombination
- Models that include regeneration either at the freeze-out (SHMc) or during the medium evolution (TAMU) are both in agreement with data at low p_T

  → not possible to disentangle between the two different regeneration scenarios using J/ψ only

Centrality dependence of ψ(2S) production in Pb–Pb collisions



- Stronger suppression for ψ(2S) compared to J/ψ
- Flat centrality dependence of ψ(2S) R_{AA} within uncertainties, consistent with $R_{AA} \sim 0.3 - 0.4$

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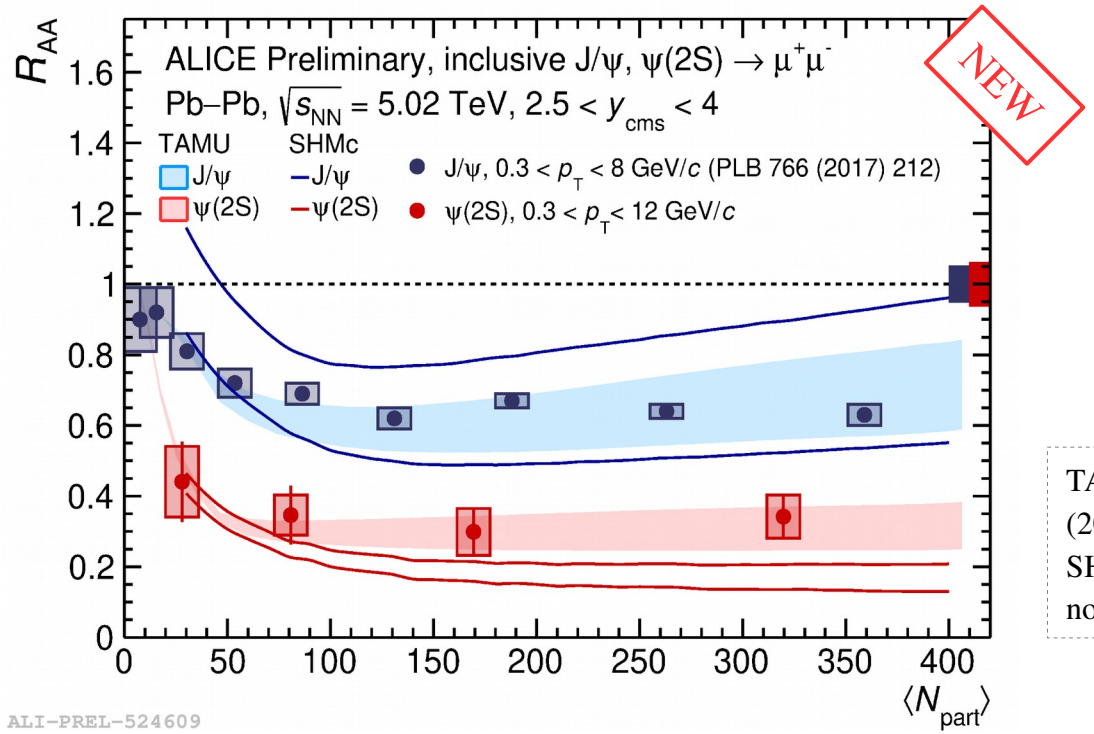

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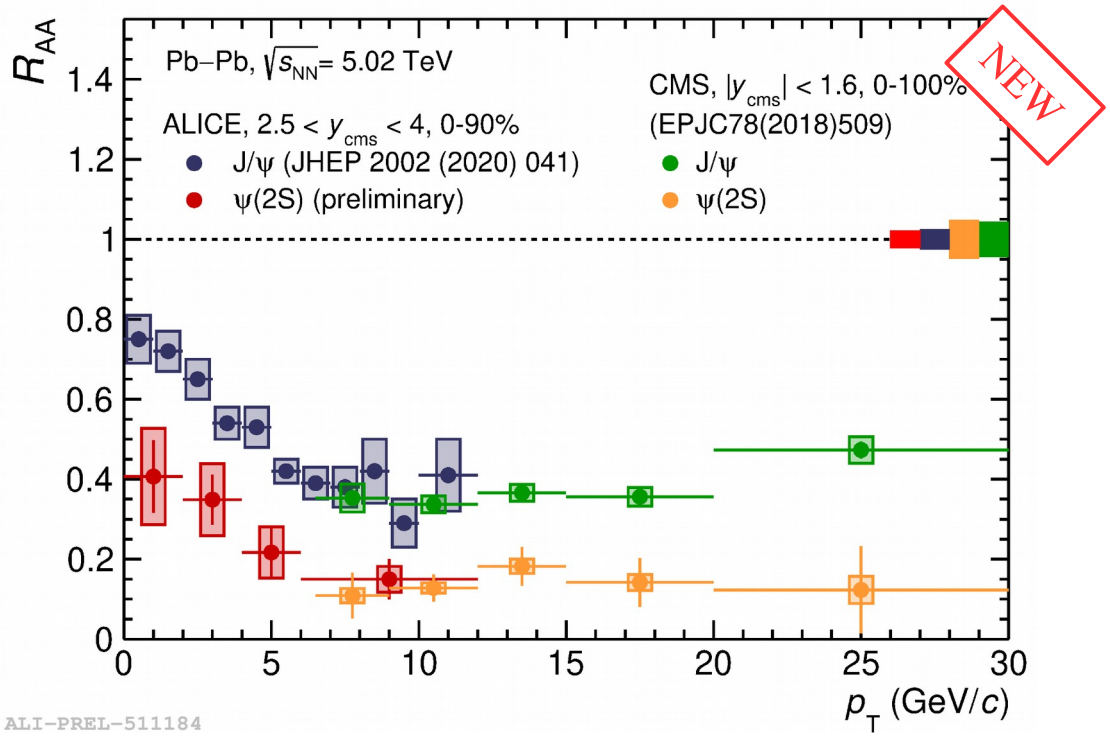
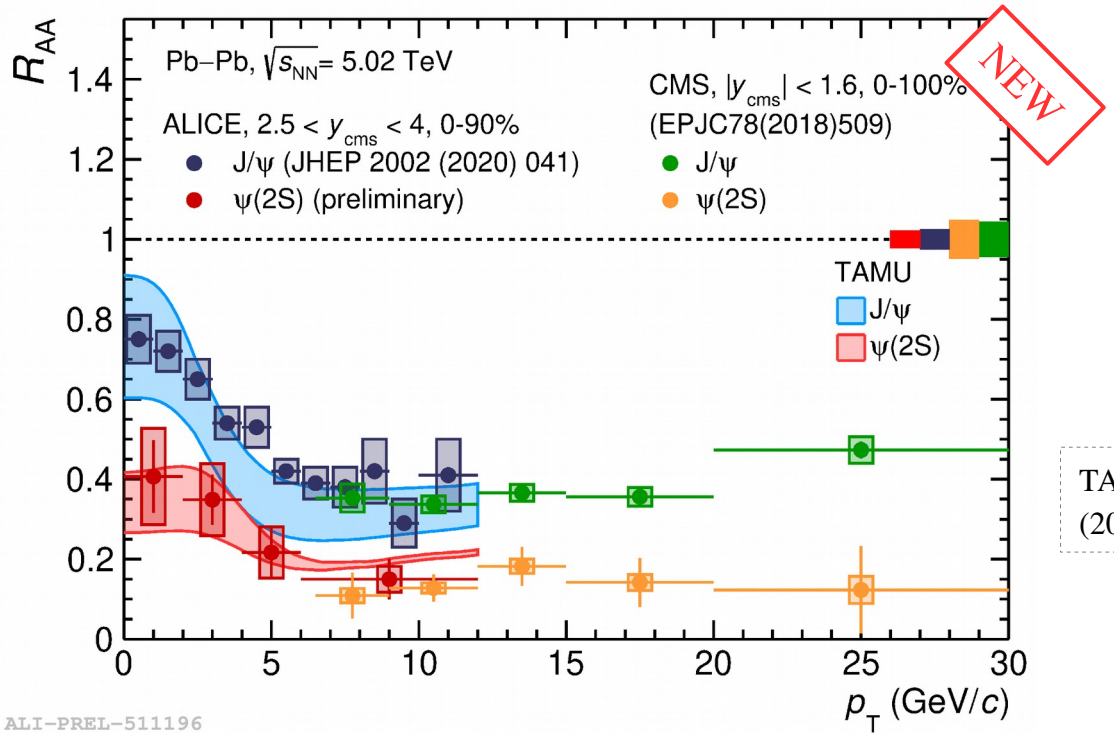
- Stronger suppression for ψ(2S) compared to J/ψ
- Flat centrality dependence of ψ(2S) R_{AA} within uncertainties, consistent with $R_{AA} \sim 0.3 - 0.4$
- TAMU model reproduces the results for both J/ψ and ψ(2S)
- SHMc describes J/ψ data but tends to underestimate the ψ(2S) result in central Pb–Pb collisions

p_T dependence of ψ(2S) production in Pb–Pb collisions



- Stronger suppression at high-p_T and increasing trend of R_{AA} towards low-p_T for both charmonium states
  → hint of regeneration
- Good agreement between CMS and ALICE data in the common p_T range, regardless of the different rapidity coverage

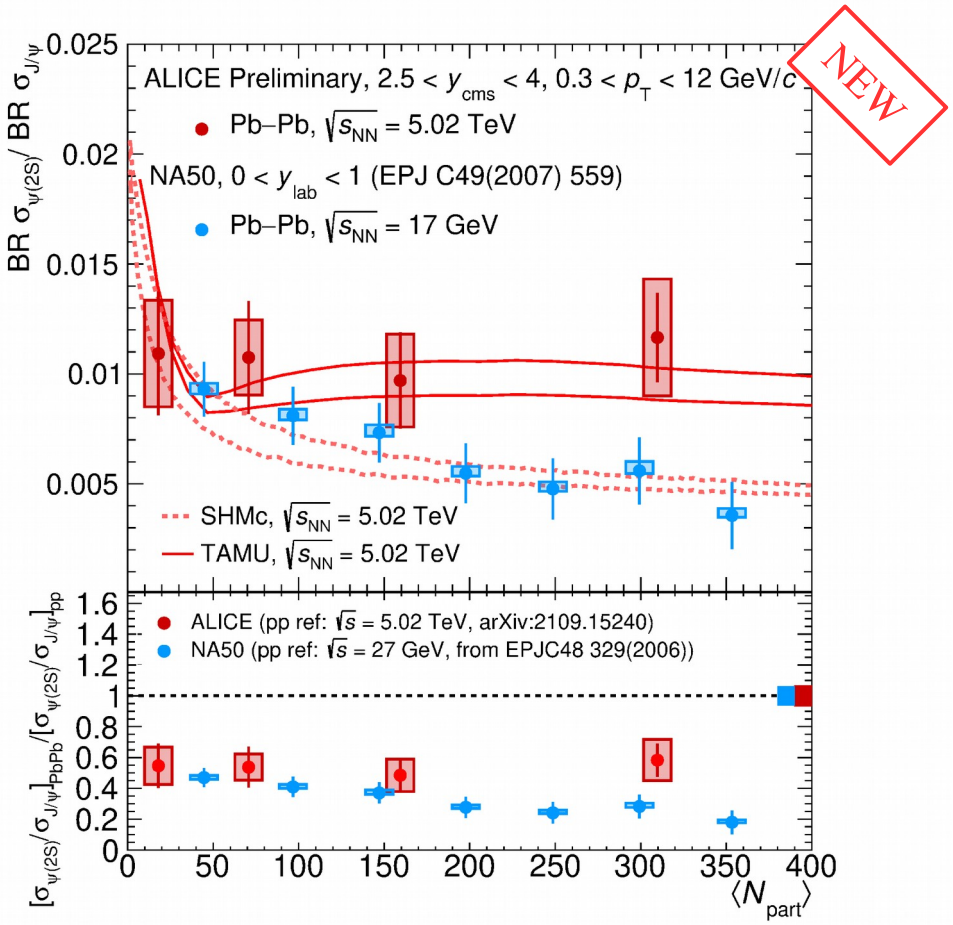
p_T dependence of ψ(2S) production in Pb–Pb collisions



TAMU: X. Du and R. Rapp, NPA 943 (2015) 147

- Stronger suppression at high-p_T and increasing trend of R_{AA} towards low-p_T for both charmonium states
  → hint of regeneration
- Good agreement between CMS and ALICE data in the common p_T range, regardless of the different rapidity coverage
- TAMU model reproduces the p_T dependence for both J/ψ and ψ(2S)

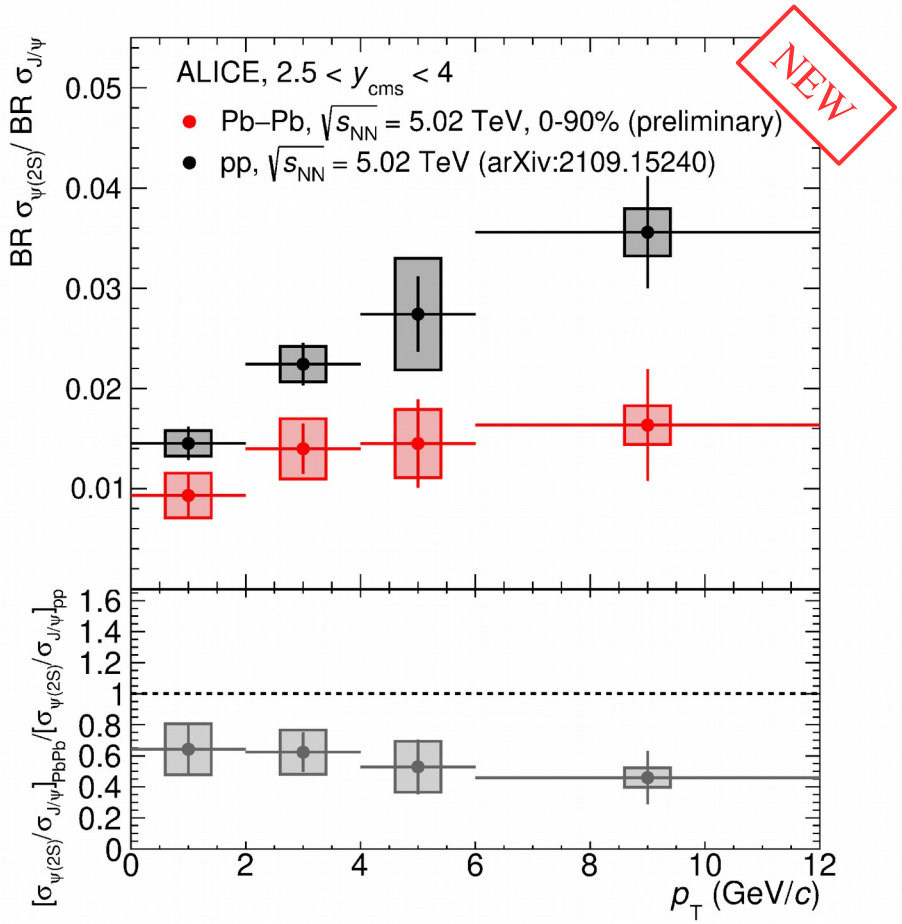
Centrality dependence of ψ(2S)-to-J/ψ ratio in Pb–Pb collisions



- Flat centrality dependence of ψ(2S)-to-J/ψ ratio in ALICE
- NA50 results show a slightly more pronounced centrality dependence
- Indication of larger ψ(2S)-to-J/ψ ratio in ALICE than in NA50 in central event
- The TAMU model reproduces the cross section ratios over centrality, while SHMc tends to underestimate the ALICE data in central Pb–Pb collisions

TAMU: X. Du and R. Rapp, NPA 943 (2015) 147
SHMc: A. Andronic et. al., Nature 561 no. 7723 (2018) 321

p_T dependence of ψ(2S)-to-J/ψ ratio



- The double ratio values indicate a significant suppression of the ψ(2S) relative to J/ψ, reaching a value of about 0.5 at high p_T

Conclusions and outlook

pp collisions:

→ ψ(2S) cross section and ψ(2S)-to-J/ψ ratio have been measured at $\sqrt{s}$ = 5.02 TeV, with significantly improved precision compared to earlier publication

→ Theoretical models reproduce the ψ(2S) cross section within uncertainties

Pb–Pb collisions:

→ The ψ(2S) is more suppressed than the J/ψ

→ Comparison of J/ψ and ψ(2S) R_{AA} with transport model shows a fair agreement within uncertainties

→ Transport model, which 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 Run 3/4

→ Significant increase of statistical precision expected with L_{int} ~ 10 nb^{-1}, thanks to continuous readout

→ The Muon Forward Tracker (MFT) will allow to separate the prompt charmonium from the contribution originating from beauty hadron decays at forward rapidity

Thank you

Signal extraction