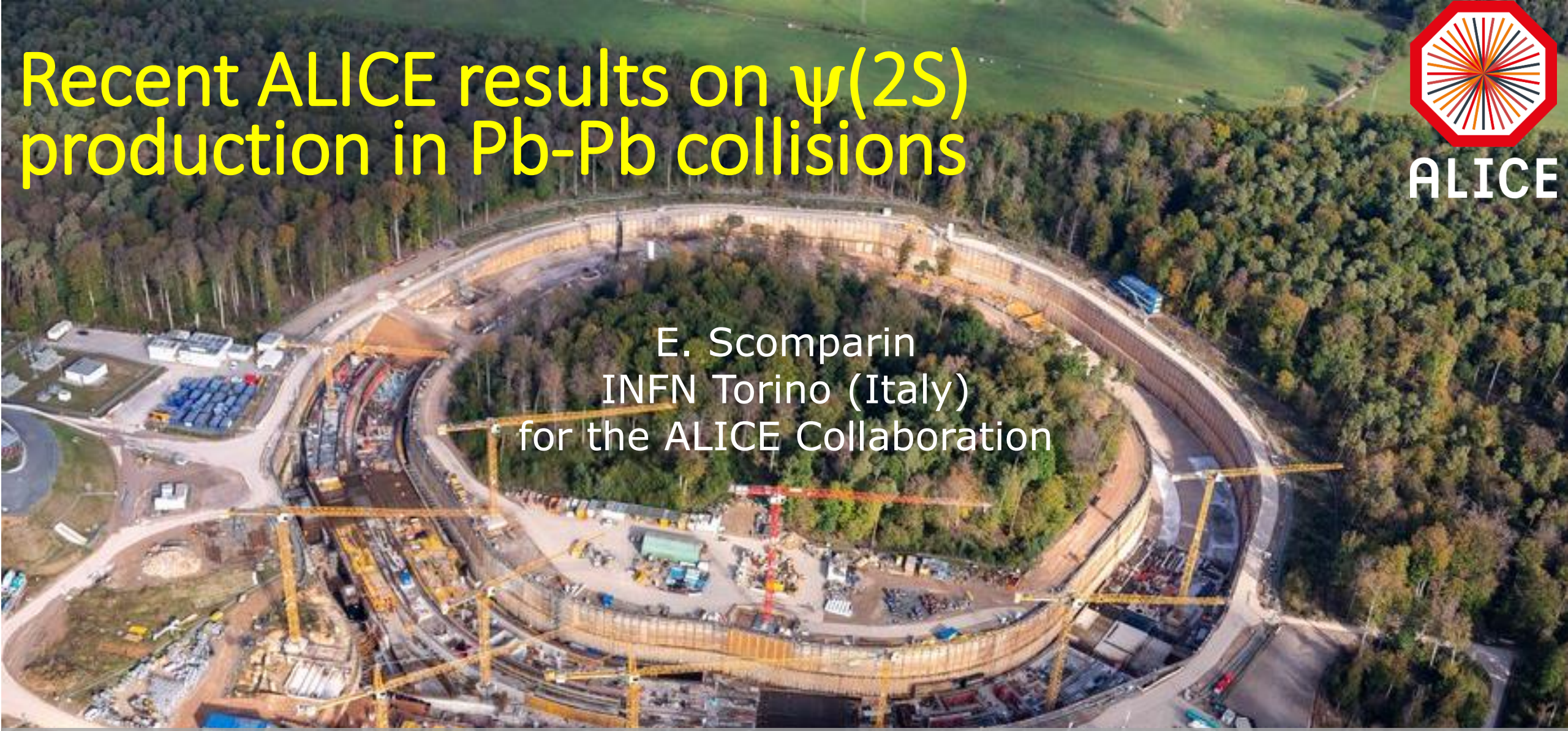
Recent ALICE results on ψ(2S) production in Pb-Pb collisions

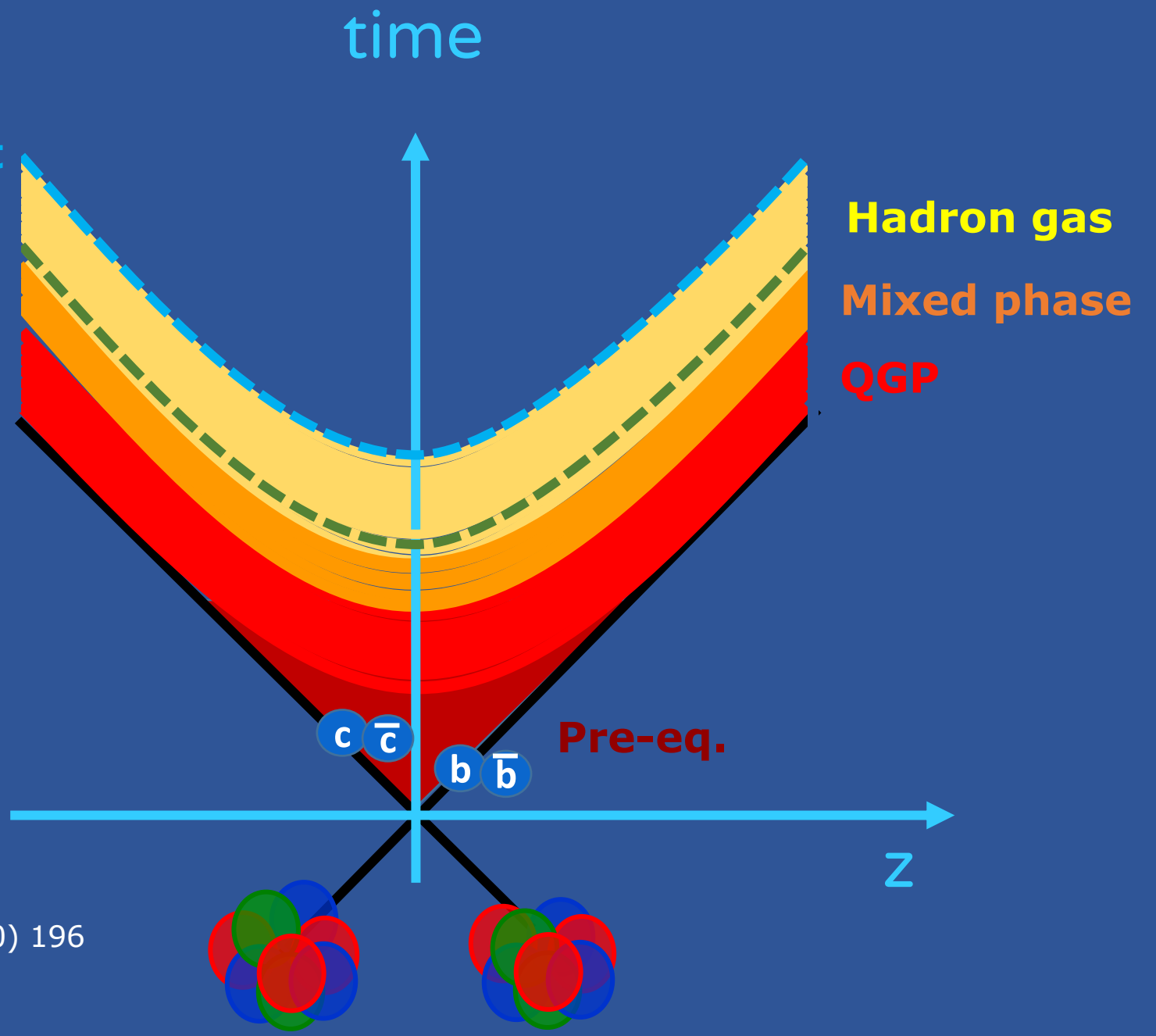


E. Scomparin
INFN Torino (Italy)
for the ALICE Collaboration

ALICE

QWG

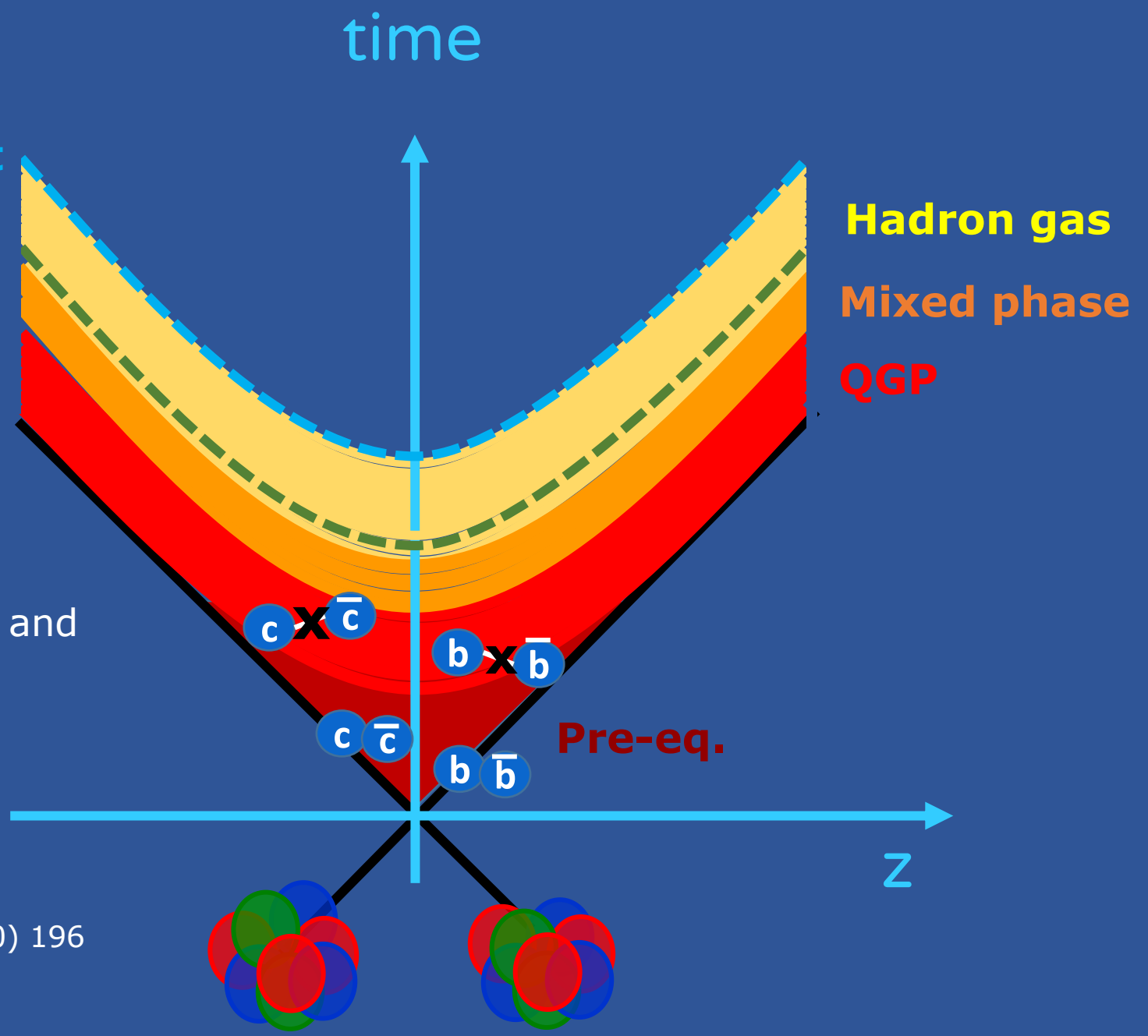
QWG 2022 – The 15th International Workshop on Heavy Quarkonium, GSI



Quarkonium

- Early production (and binding) of heavy quark pairs

T. Matsui and H. Satz, PLB 178(1986) 416
P. Braun-Munzinger and J. Stachel, PLB490(2000) 196
R. Thews et al., PRC63 (2001) 064905
A. Rothkopf, Phys. Rept. 858 (2020) 1



Quarkonium

- Early production (and binding) of heavy quark pairs
- Modification of spectral properties and possible dissociation in the QGP

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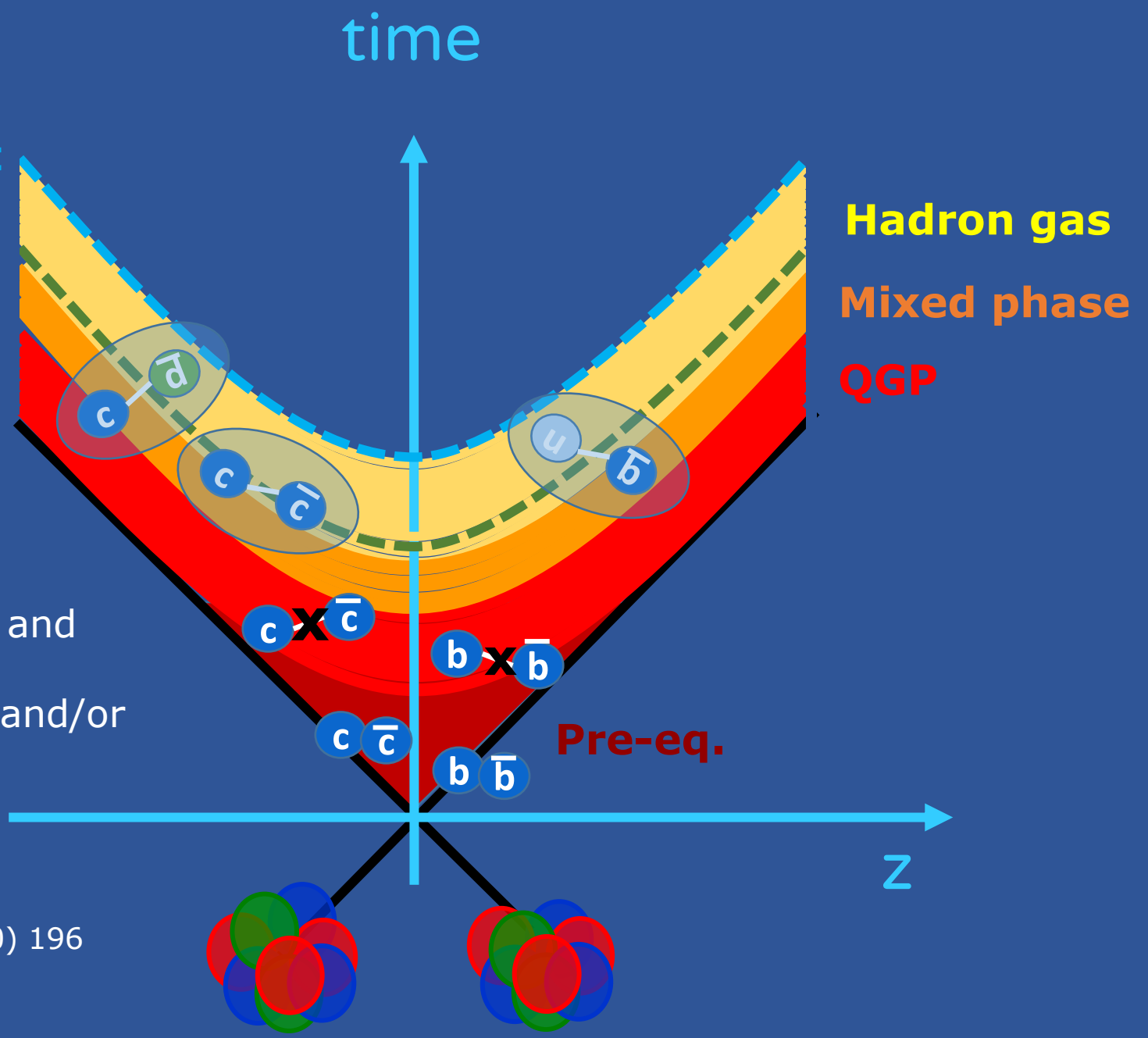


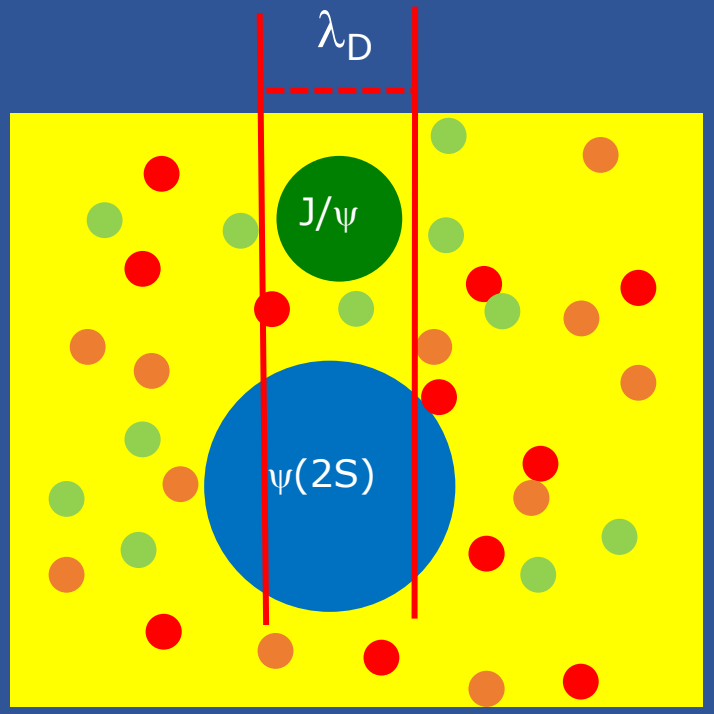
Quarkonium

- Early production (and binding) of heavy quark pairs
- Modification of spectral properties and possible dissociation in the QGP
- Recombination effects in the QGP and/or at phase boundary

T. Matsui and H. Satz, PLB 178(1986) 416
P. Braun-Munzinger and J. Stachel, PLB490(2000) 196
R. Thews et al., PRC63 (2001) 064905
A. Rothkopf, Phys. Rept. 858 (2020) 1

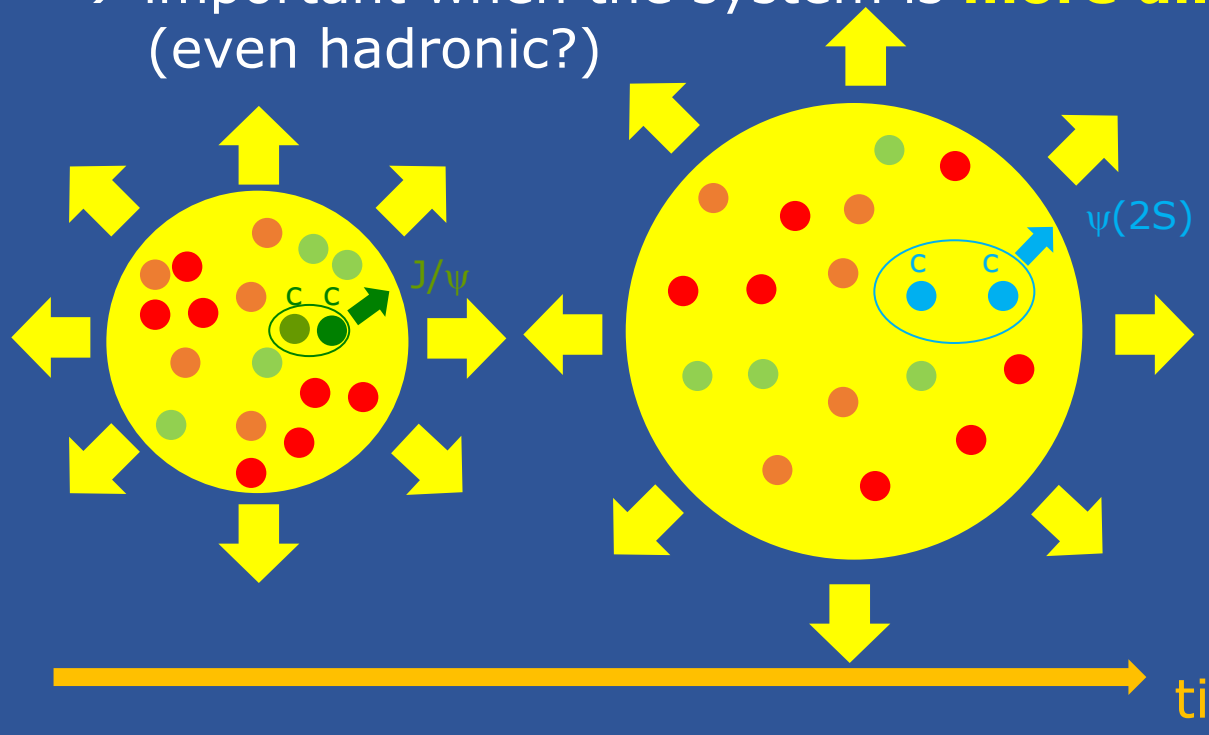
ψ(2S) vs J/ψ

- Binding energy ~$(2m_D - m_\psi)$ → **ψ(2S) ~ 60 MeV, J/ψ ~ 640 MeV**



Important for a quantitative test of models!

- Expect **much stronger dissociation effects** for the weakly bound ψ(2S) state
- Effect of re-combination on ψ(2S) more subtle
  → important when the system is **more diluted** (even hadronic?)



Two theory approaches for phenomenology

Transport

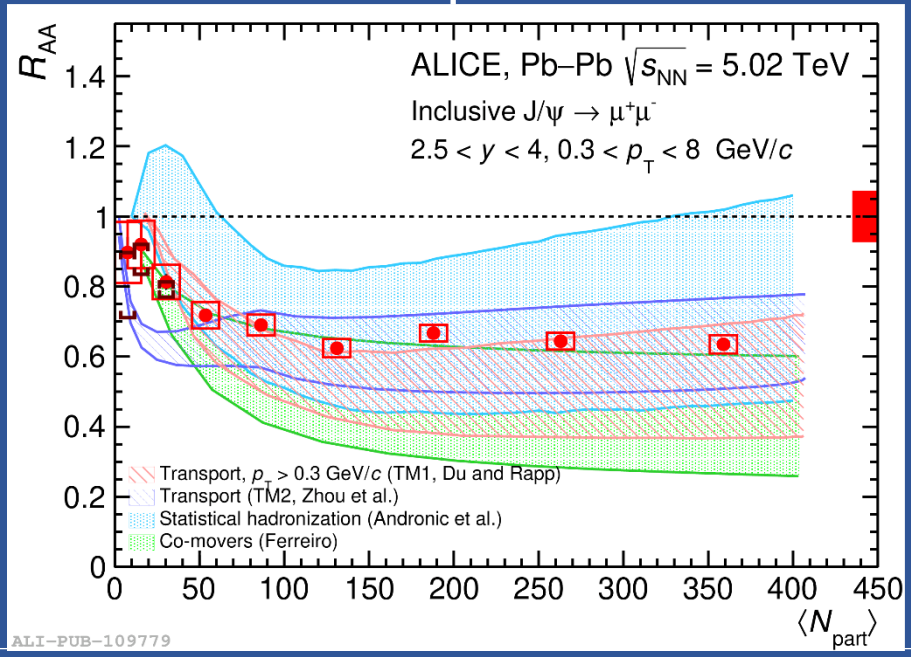
X. Du and R. Rapp, NPA 943(2015) 14P.7
P. Zhou et al., PRC89 (2014) 054911

- Macroscopic rate equation including suppression and regeneration in the QGP
- Suppression
  - Calculated starting from modifications of charmonium spectral functions, constrained by LQCD-validated potentials
- Regeneration
  - Tuned from measured heavy-quark yields

Statistical hadronization

A. Andronic et al., Nature 561 (2018) 321

- Charmonium yields determined at chemical freeze-out according to their statistical weights
- Charm fugacity factor related to charm conservation and based on experimental data on production cross sections



Both approaches fairly **reproduce LHC experimental results on the J/ψ**

ALICE, Phys. Lett. B 766 (2017) 212

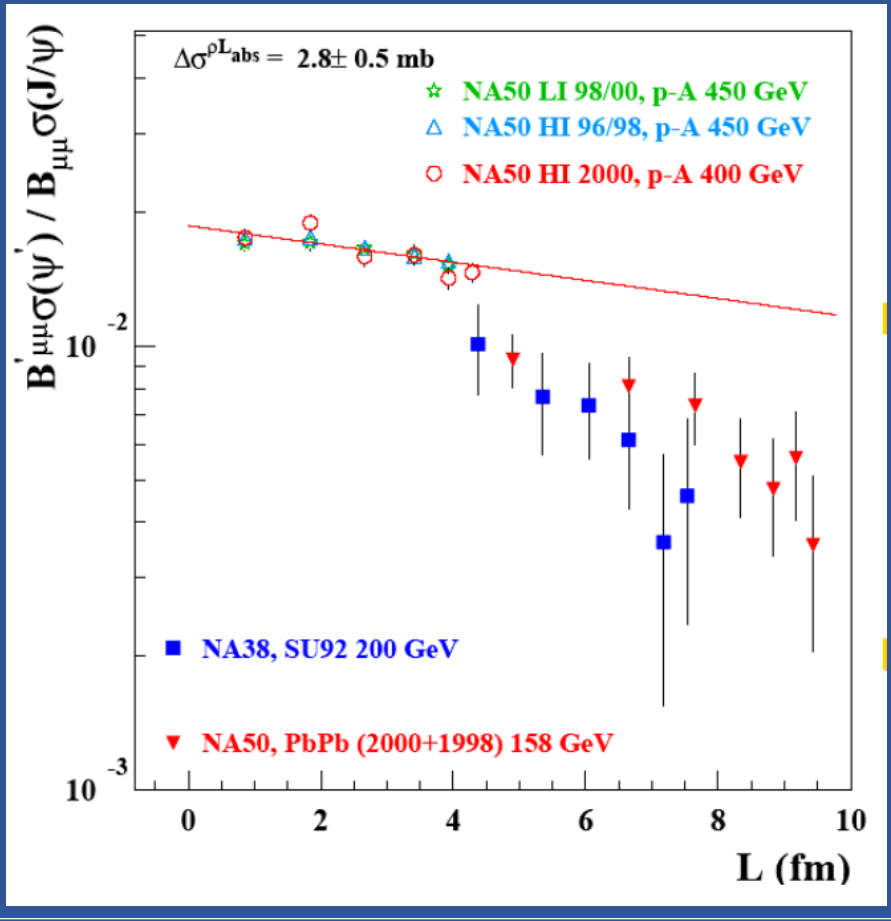
Other approaches include "comover" models

E. Ferreiro, PLB 731 (2014) 57

A-A results at SPS energies

- First and (up to now) most accurate result on ψ(2S) for nuclear collisions
- Studies in p-A, S-U and Pb-Pb collisions at $\sqrt{s_{NN}}$~20 GeV
- Recombination effects negligible (charm pair multiplicity <<1)

NA50, EPJC49 (2007)



- **Stronger relative dissociation of ψ(2S) wrt J/ψ** already in p-A collisions
- The effect becomes **even stronger in A-A** collisions (approximately scaling with L, the thickness of nuclear matter crossed by the $c\bar{c}$ pair)

N.B.: CM energy changes between p-A and A-A, but effect on cross section ratios should be small

A-A results at SPS energies

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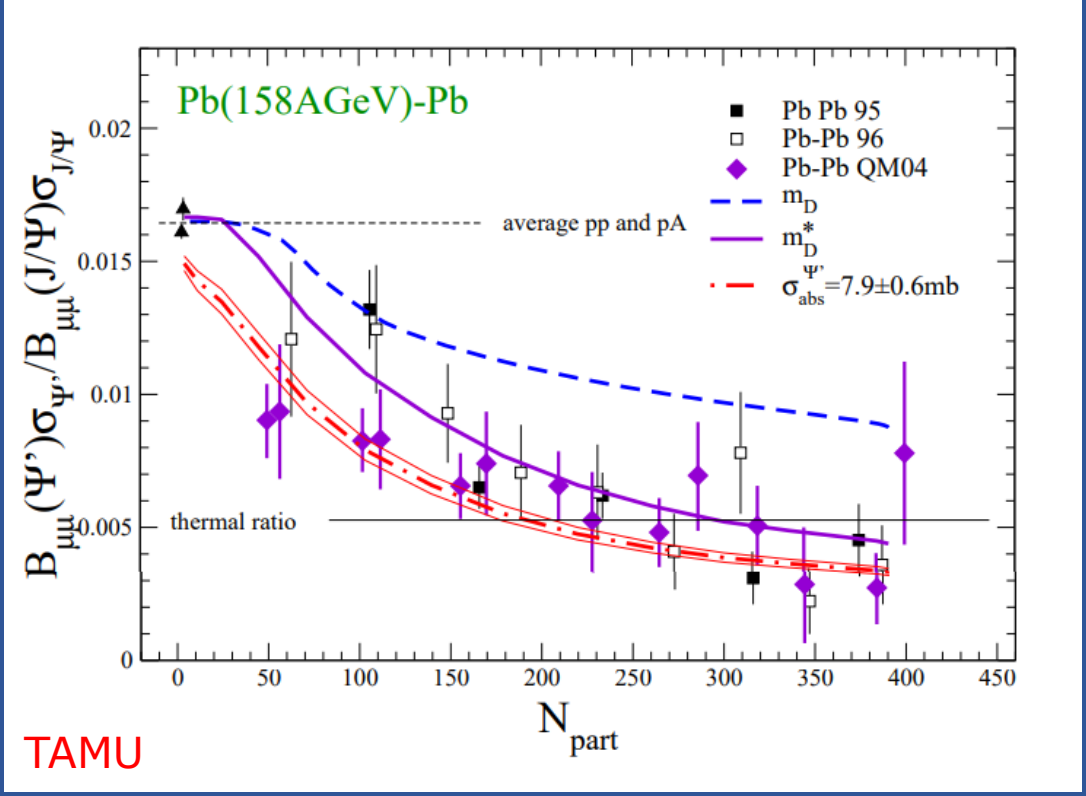
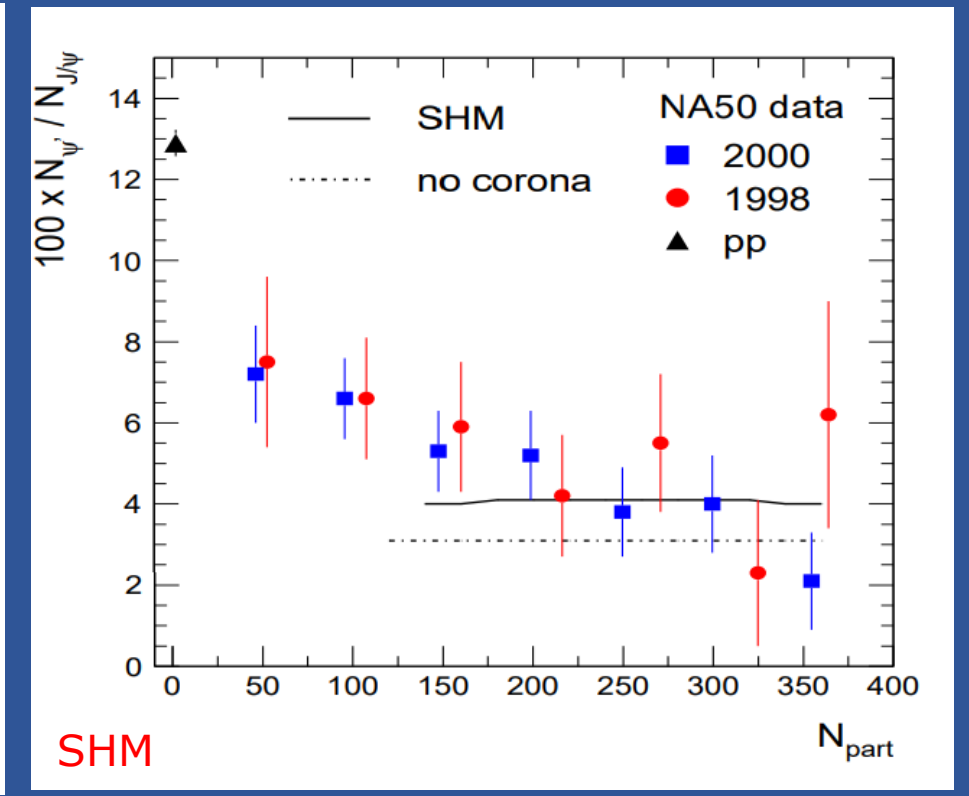




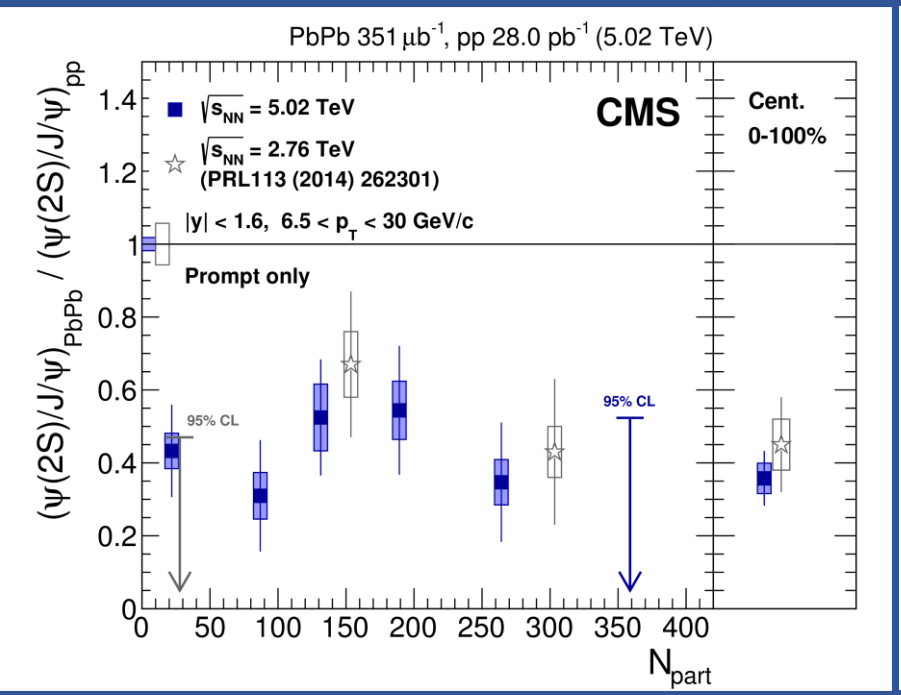
from
Rapp and Van Hees,
arXiv:0903.1096

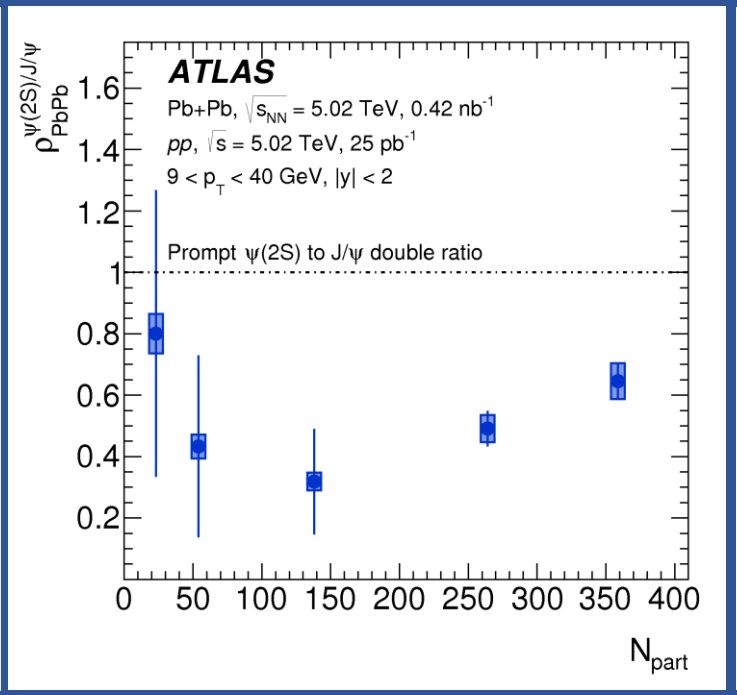
TAMU:
Grandchamp, Rapp and Brown,
PRL92 (2004) 212301

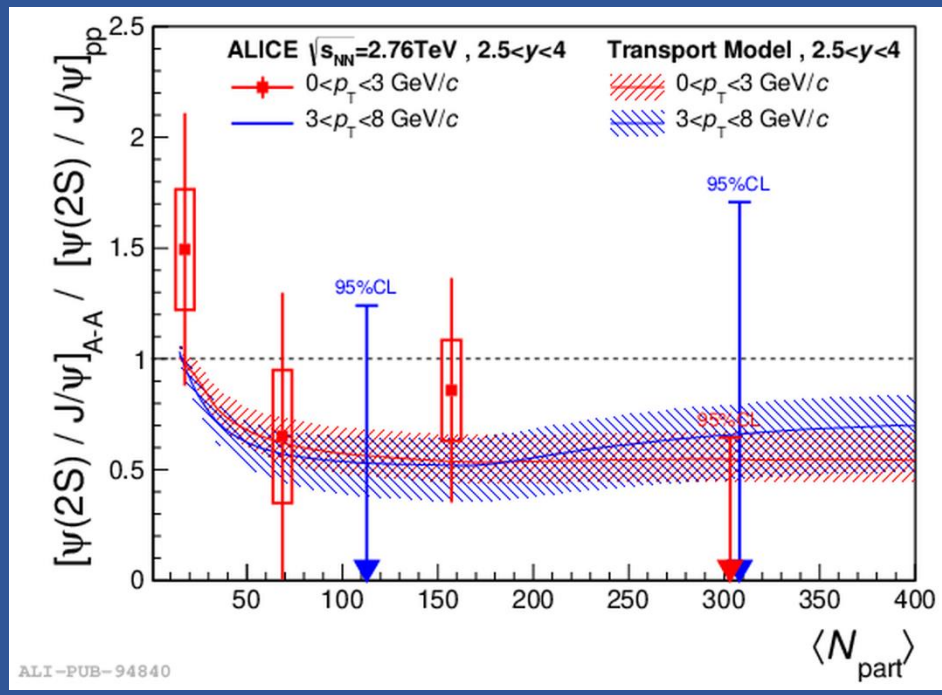
SHMc:
Andronic, Braun-Munzinger, Redlich and Stachel,
NPA789 (2007) 334

- Both transport (TAMU) and statistical hadronization (SHM) models able to **reproduce data**

Pb-Pb results at LHC energies



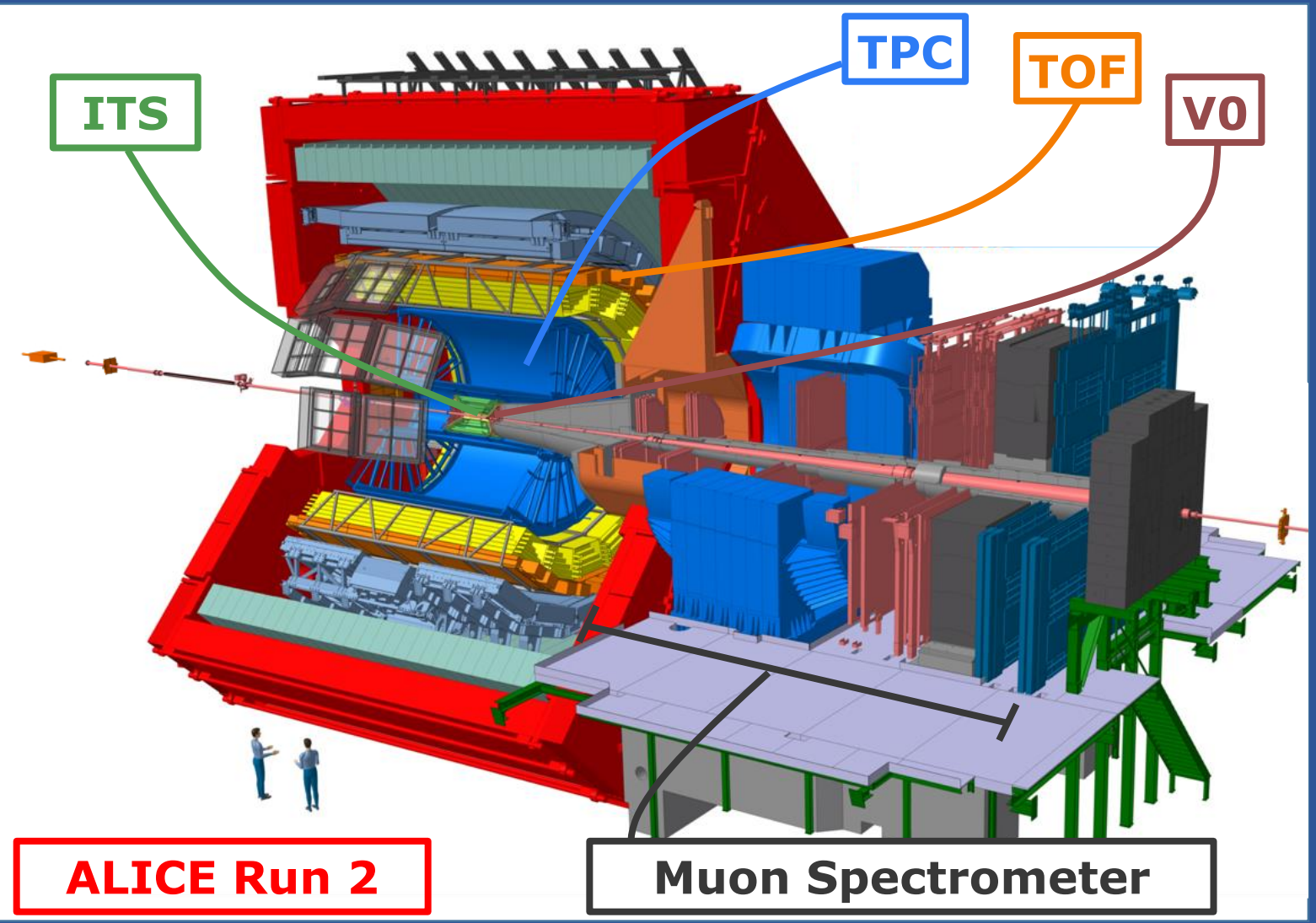




CMS, PRL 118 (2017) 162301 ATLAS, EPJC78 (2018) 762 ALICE, JHEP 05 (2016) 179

- Stronger ψ(2S) suppression wrt J/ψ observed at high-p_T by ATLAS and CMS 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 may become dominant
- At low-p_T only ALICE Run 1 results available, but large uncertainties prevent a firm conclusion
  → Higher statistics (by a factor of ~11) now available from Run 2 Pb–Pb data at $\sqrt{s_{NN}}$ = 5.02 TeV

A Large Ion Collider Experiment



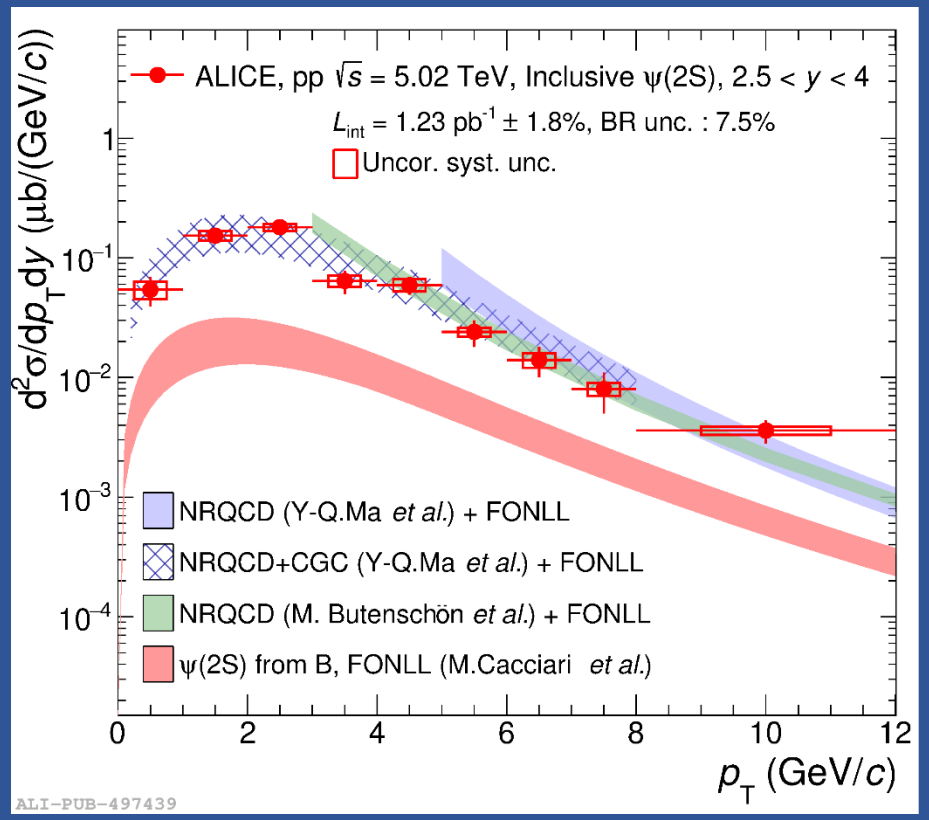
- **Inclusive quarkonium**
  - Central barrel (ee, $|y|<0.9$)
  - Muon spectrometer ($\mu\mu$, $2.5<y<4$)
  - Coverage **down to zero p_T**

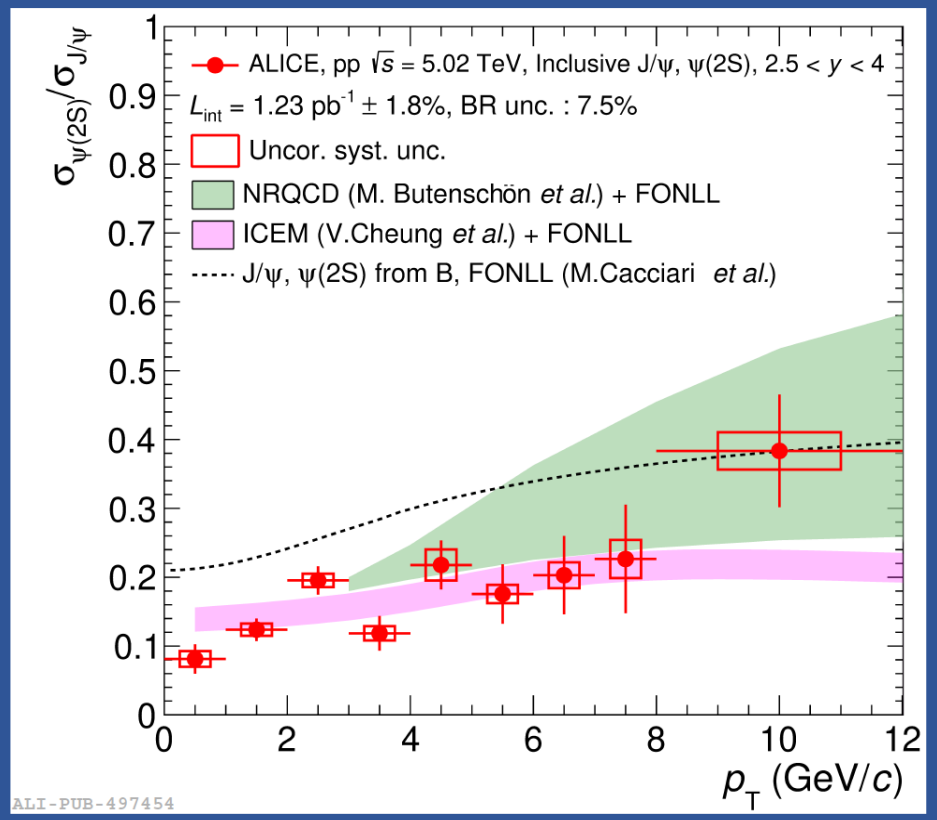
- $\psi(2S)$ results were obtained at **forward rapidity**

- (Di)muon trigger selects track candidates with $p_T > 1$ GeV/c in Pb-Pb collisions

- LHC Run 2 → $L_{int} \sim 750\ \mu b^{-1}$

Reference pp measurements





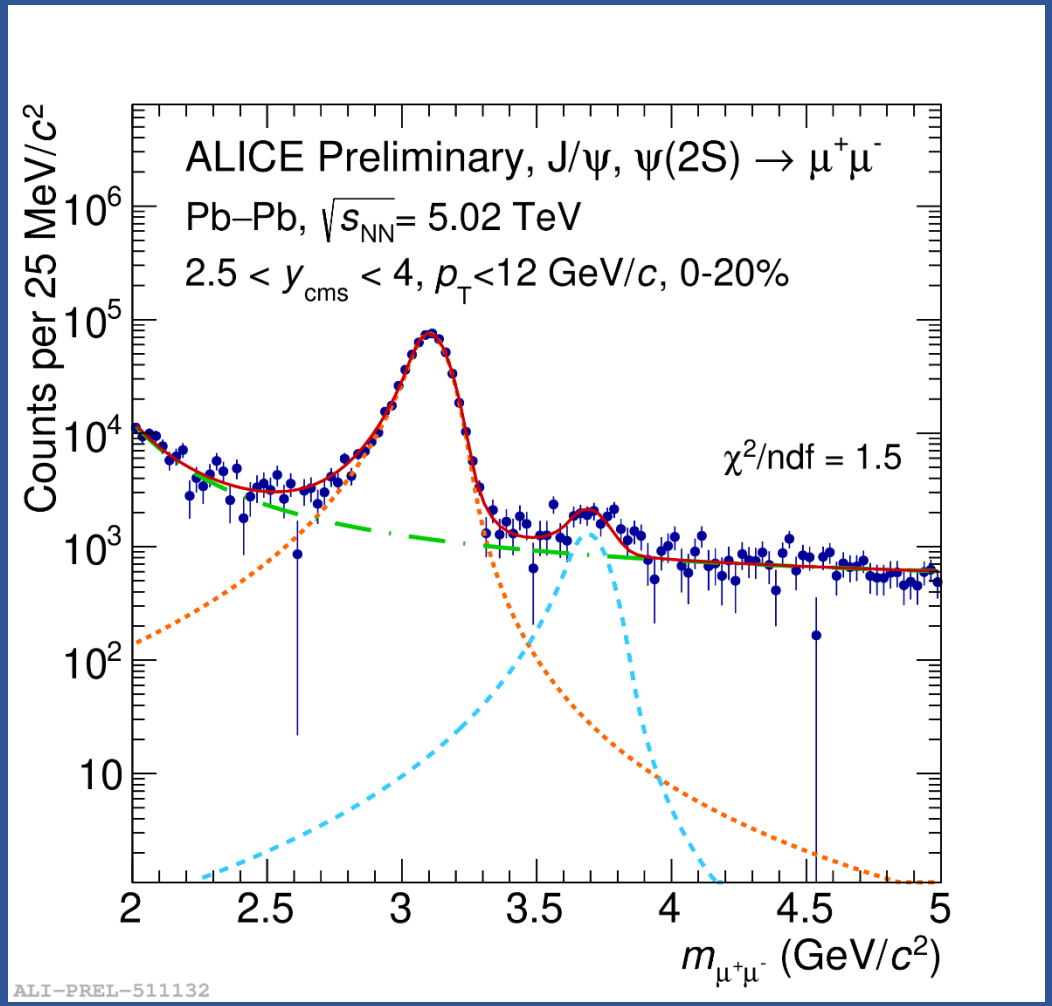
ALICE, arXiv:2109.15240

Inclusive production

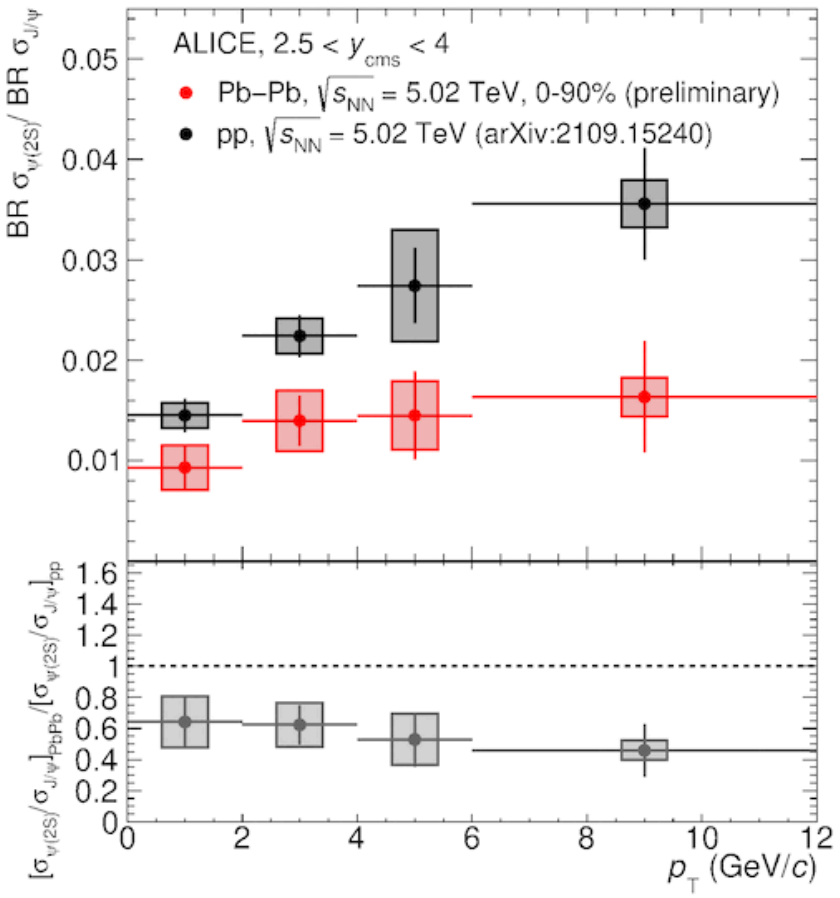
- Recent cross-section measurement with 10 times more statistics than earlier publication
  → y- and p_T-differential studies of ψ(2S)
- **NRQCD+CGC+FONLL provides a good data description** down to zero p_T
- ψ(2S)-to-J/ψ ratio increases with p_T and agrees within uncertainties with theoretical models

ψ(2S) signal extraction in Pb-Pb

- ψ(2S) signal extracted by using an **event-mixing background subtraction** technique
- Significant signal observed in most central collisions and down to zero p_T, thanks to the usage of full Run 2 statistics



p_T dependence of the inclusive cross-section ratios



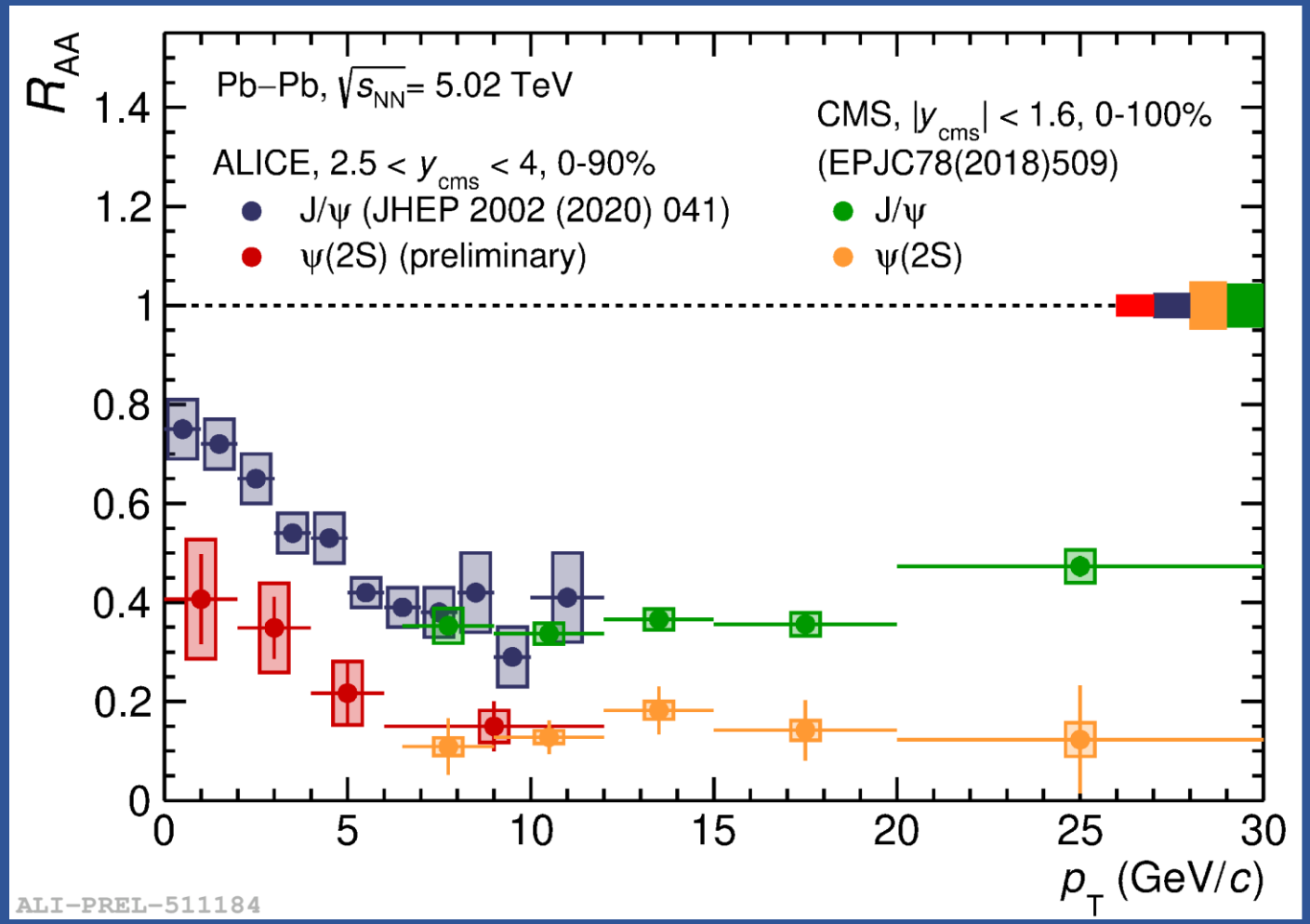
Ratio $\dfrac{B_{\psi(2S)\to\mu\mu}\,\sigma_{\psi(2S)}}{B_{J/\psi\to\mu\mu}\sigma_{J/\psi}}$

Double ratio $\dfrac{\left[\dfrac{\sigma_{\psi(2S)}}{\sigma_{J/\Psi}}\right]_{Pb-Pb}}{\left[\dfrac{\sigma_{\psi(2S)}}{\sigma_{J/\Psi}}\right]_{pp}}$

- **Significant suppression of ψ(2S) with respect to J/ψ** in the whole p_T range explored
- Double ratio between Pb-Pb and pp results reaches a value of ~0.5 at high p_T

N.B.: not corrected for branching ratios

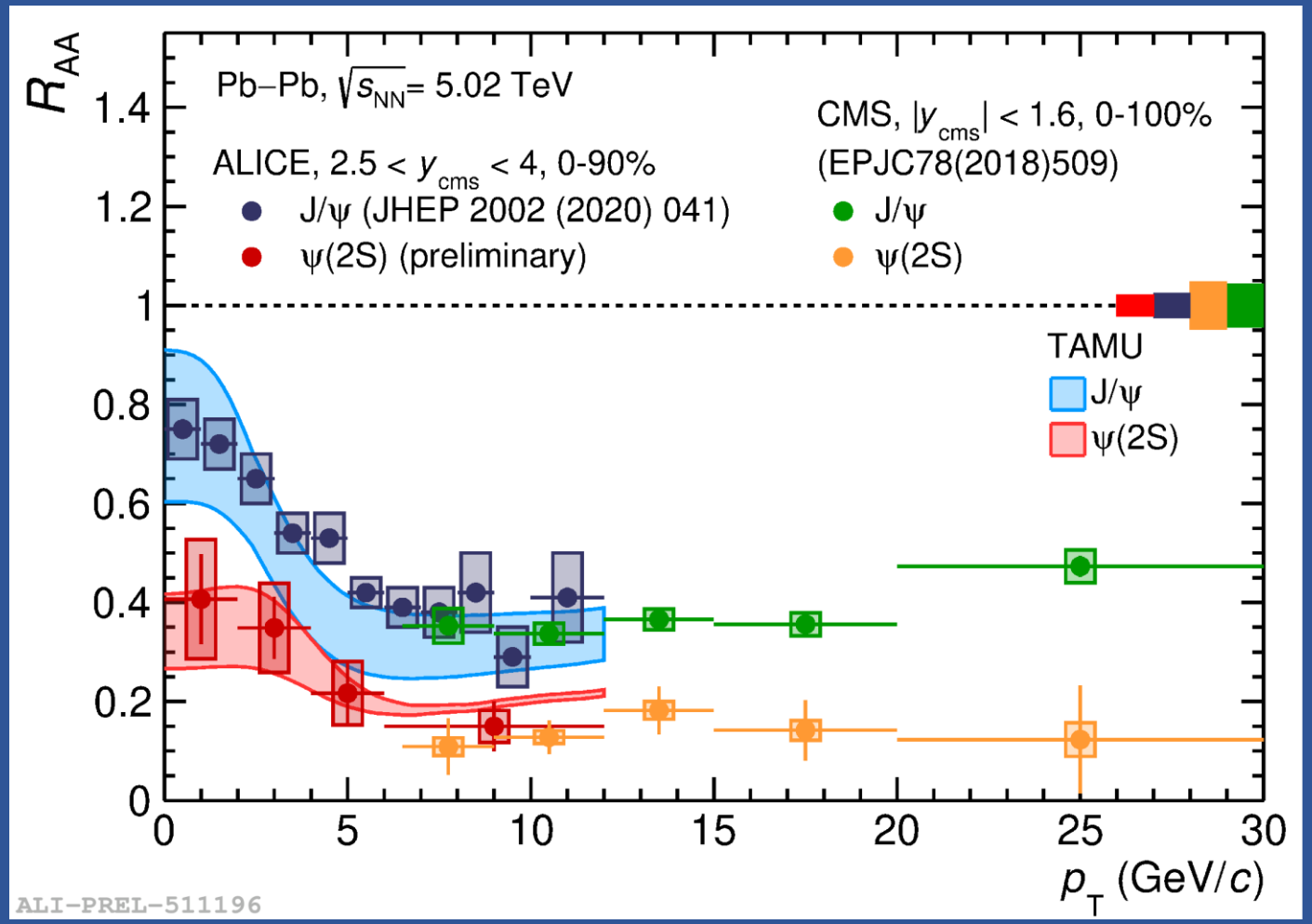
p_T dependence of the nuclear modification factor



$$R_{AA} = \frac{\left(dN/dp_T\right)_{Pb-Pb}}{\left(d\sigma/dp_T\right)_{pp} \langle T_{AA} \rangle}$$

- Strong suppression at high-p_T
- Increasing trend of R_{AA} at low-p_T for both charmonium states
  → **hint of ψ(2S) regeneration**
- Good agreement between CMS and ALICE data in the common p_T range, regardless of the different rapidity coverage

p_T dependence of the nuclear modification factor



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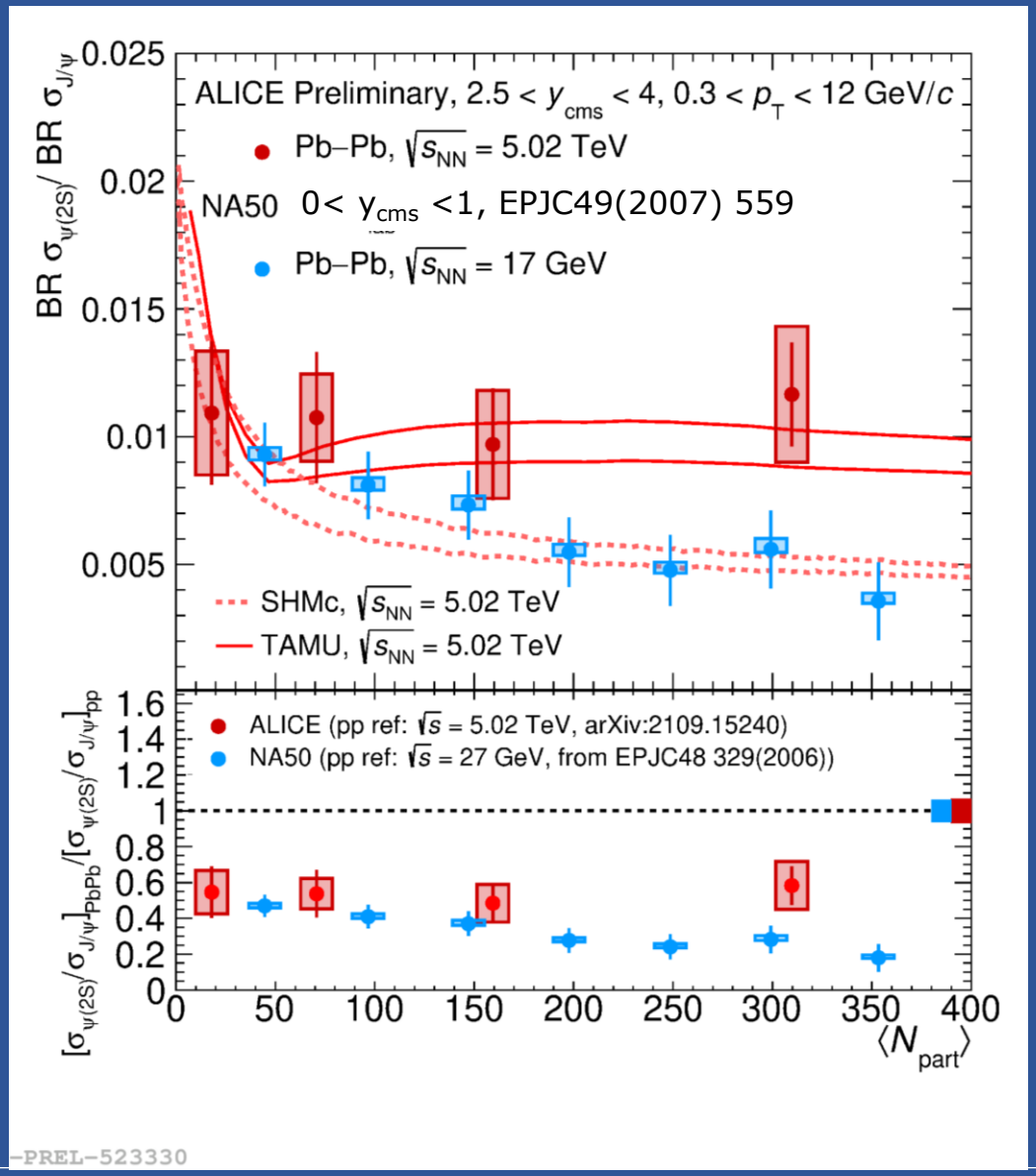
TAMU: X. Du and R. Rapp, NPA 943 (2015) 147

Transport model (TAMU) well reproduces J/ψ and ψ(2S) results, within uncertainties

Centrality dependence of the inclusive cross-section ratios

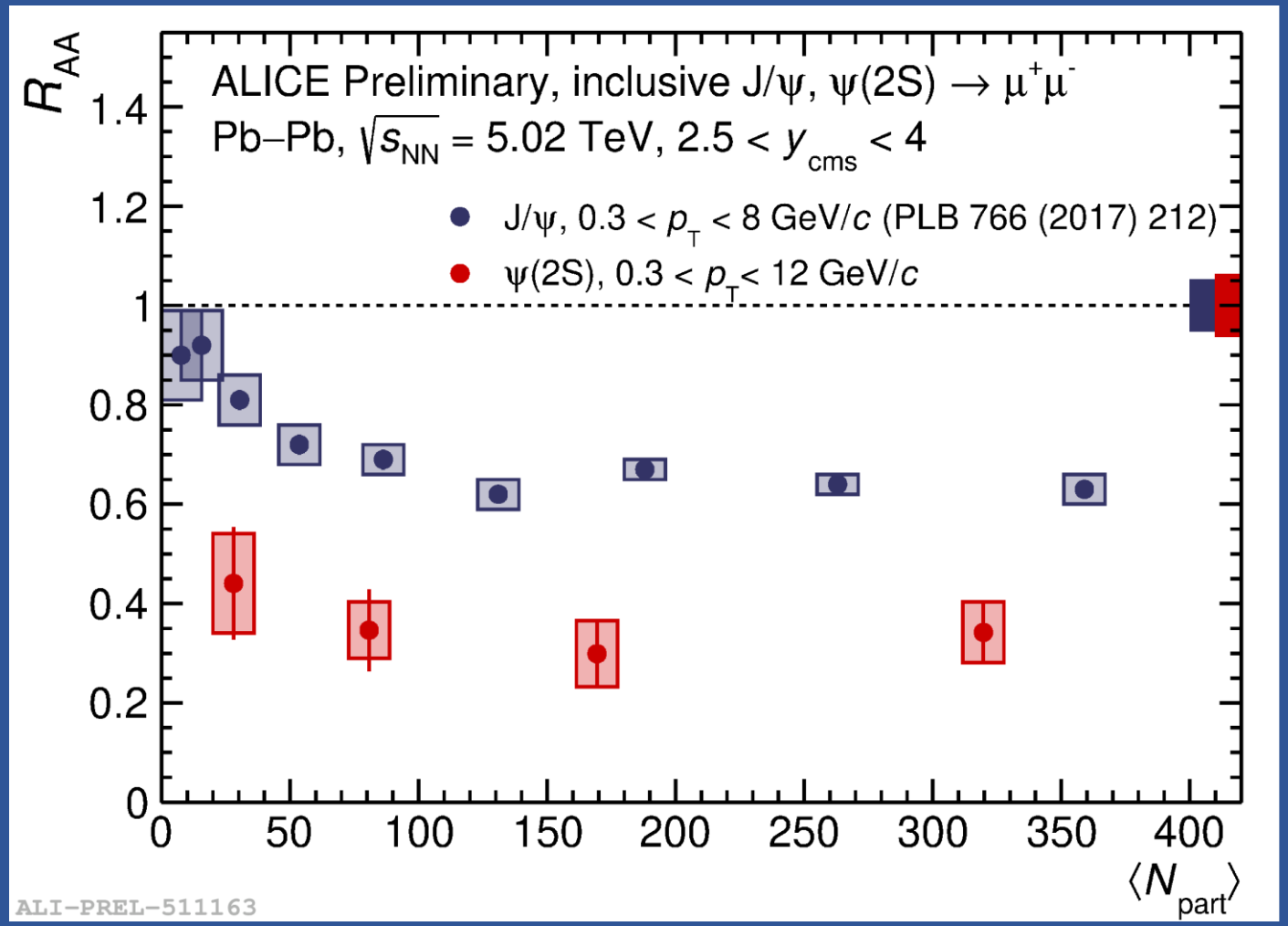
- Flat centrality dependence of ALICE ψ(2S)-to-J/ ψ (double) ratio
- NA50 results show a slightly more pronounced centrality dependence
- **Indication of larger ψ(2S)-to-J/ψ (double) ratio in ALICE than in NA50 in central events**
- The **TAMU model reproduces the cross section ratios** over centrality, 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



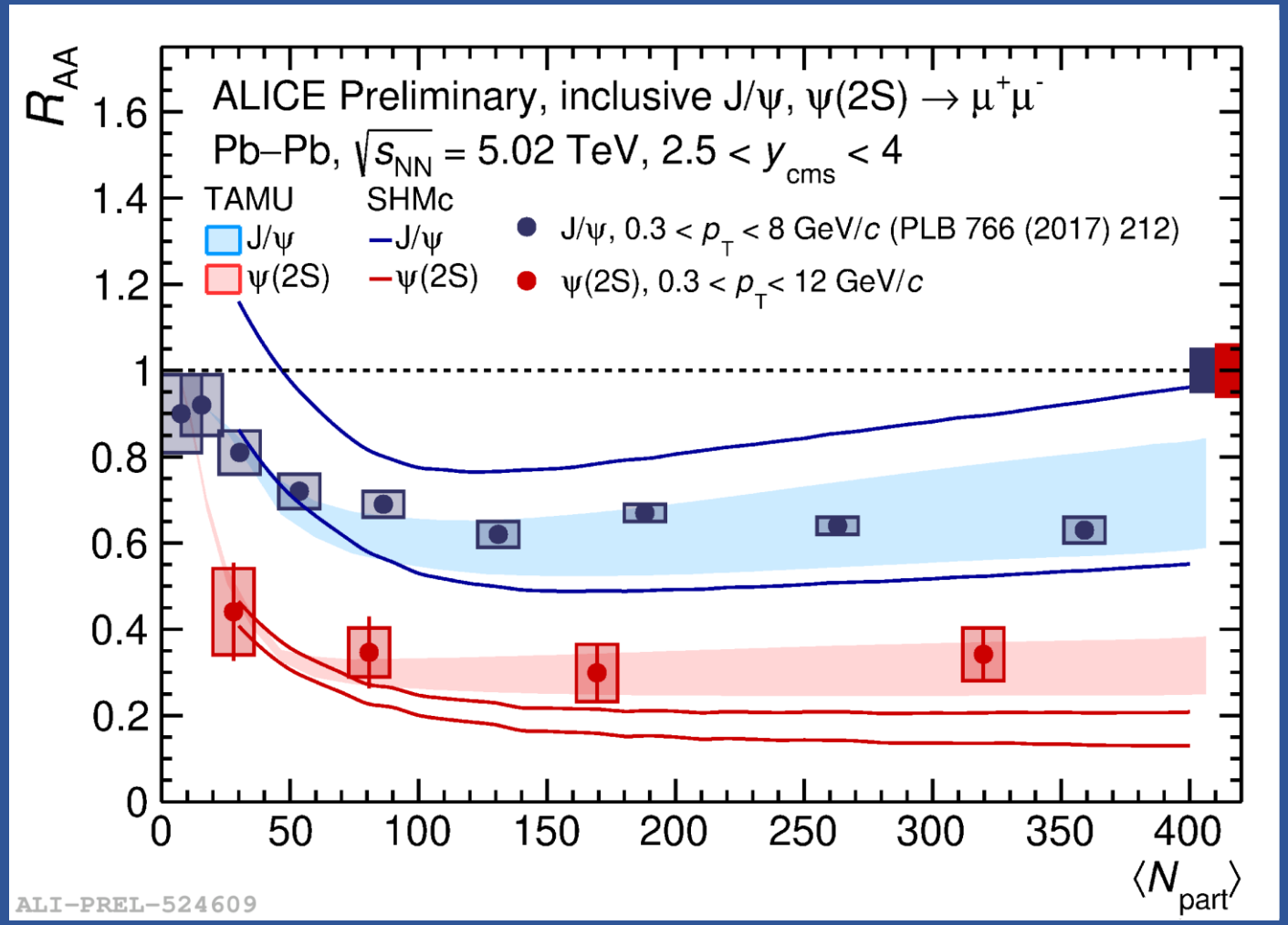
Centrality dependence of the nuclear modification factor

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



Centrality dependence of the nuclear modification factor

- Stronger suppression for ψ(2S) compared to J/ψ
- **Flat centrality dependence of ψ(2S) R_{AA} within uncertainties**, consistent with R_{AA} ~ 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



Conclusions

- Charmonium production at LHC in Pb-Pb collisions: **results on J/ψ support a "suppression+regeneration" picture**, well reproduced by models

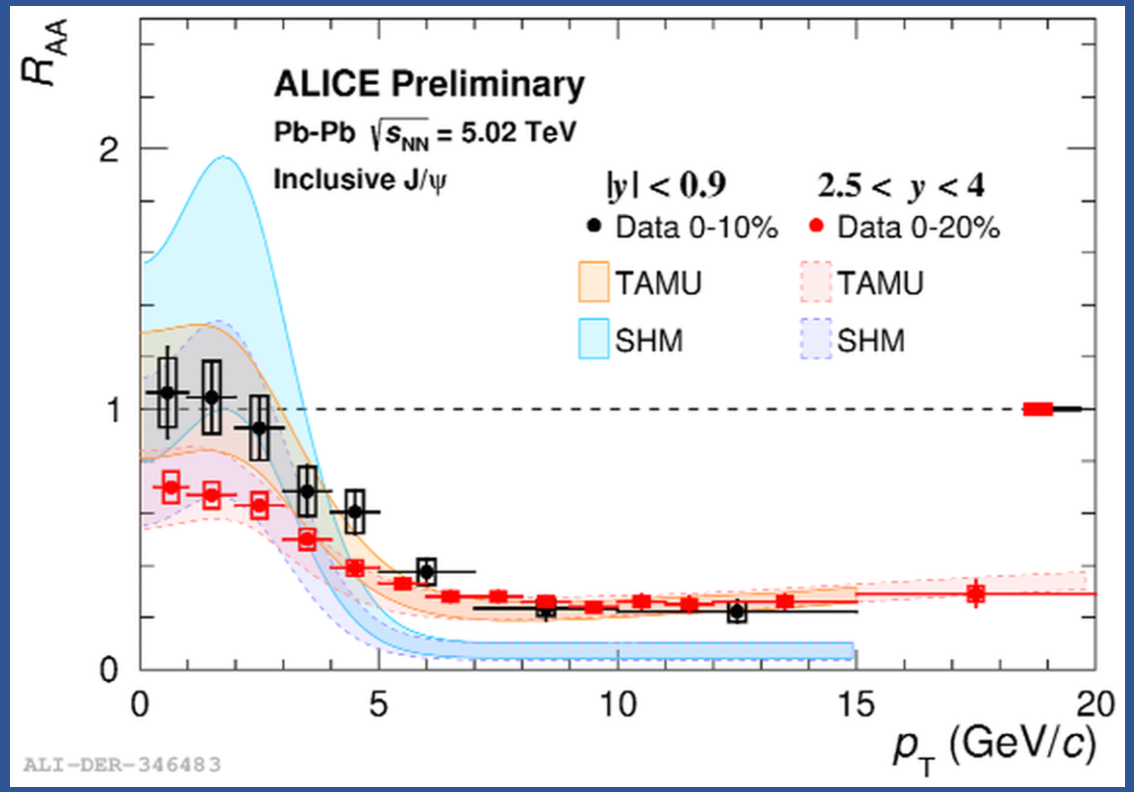
- First results on forward **ψ(2S) production at low/intermediate p_T by ALICE**, complementing high-p_T studies by ATLAS/CMS at midrapidity
  - Cross section ratios and double ratios wrt J/ψ, together with R_{AA} studies, indicate a **stronger suppression for ψ(2S), at all p_T and centralities**
  - Hint of **ψ(2S) regeneration effects** are observed
  - **Model predictions fairly reproduce data, except for SHMc in central collisions**

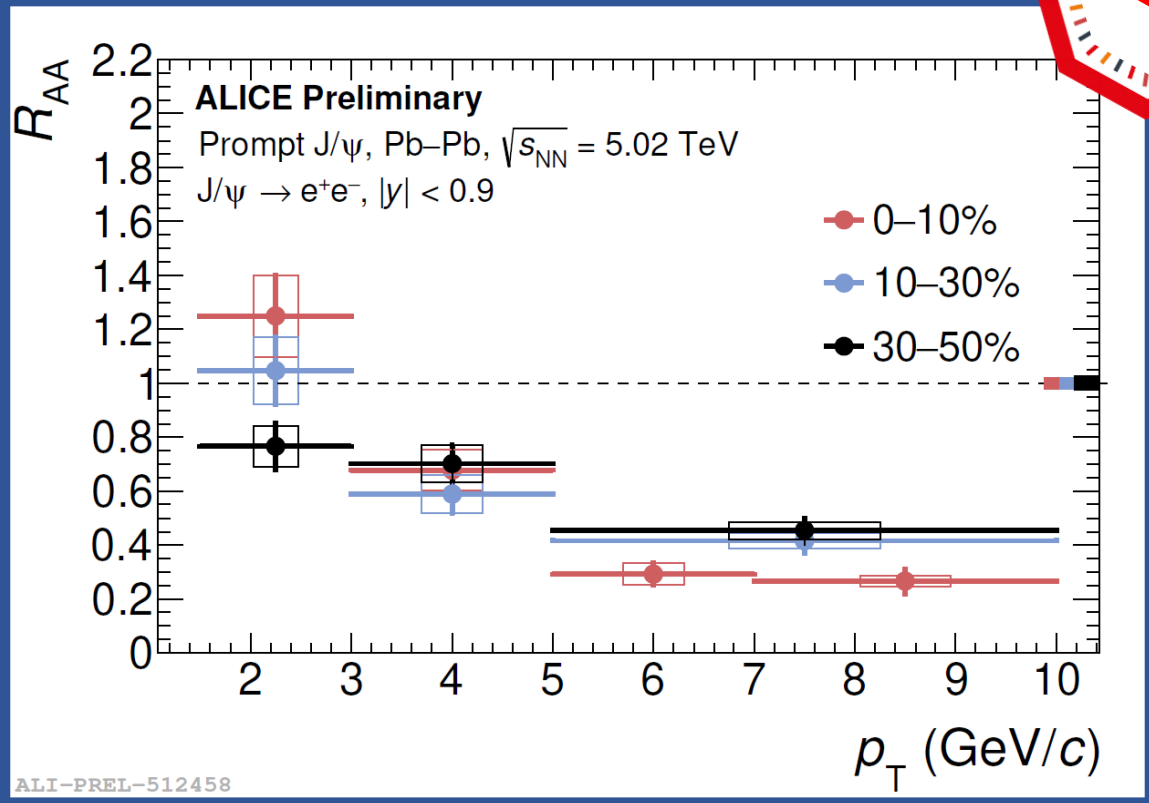
- **LHC Run 3**
  - Target Pb-Pb integrated luminosity (Run 3 + 4) → $L_{int} \sim 13\ nb^{-1}$
  - Improved tracking precision by a factor 3 (6) in xy (z) direction at midrapidity (new Inner Tracker)
  - New Muon Forward Tracker (MFT), enabling prompt/non-prompt separation

  → **Extend ψ(2S) studies to midrapidity and significantly reduce uncertainties at forward *y***

Backup

Inclusive and prompt J/ψ production in Pb-Pb





- Rise of inclusive J/ψ R_{AA} at low p_T, stronger effect at y=0 → decisive signature of recombination
- Models include regeneration either at the freeze-out (SHMc) or during the medium evolution (TAMU)
  → Both in agreement with data at low p_T

- Effect confirmed when looking at prompt J/ψ production at midrapidity, clear centrality dependence