ψ(2S) production in AA collisions at LHC energies

Roberta Arnaldi
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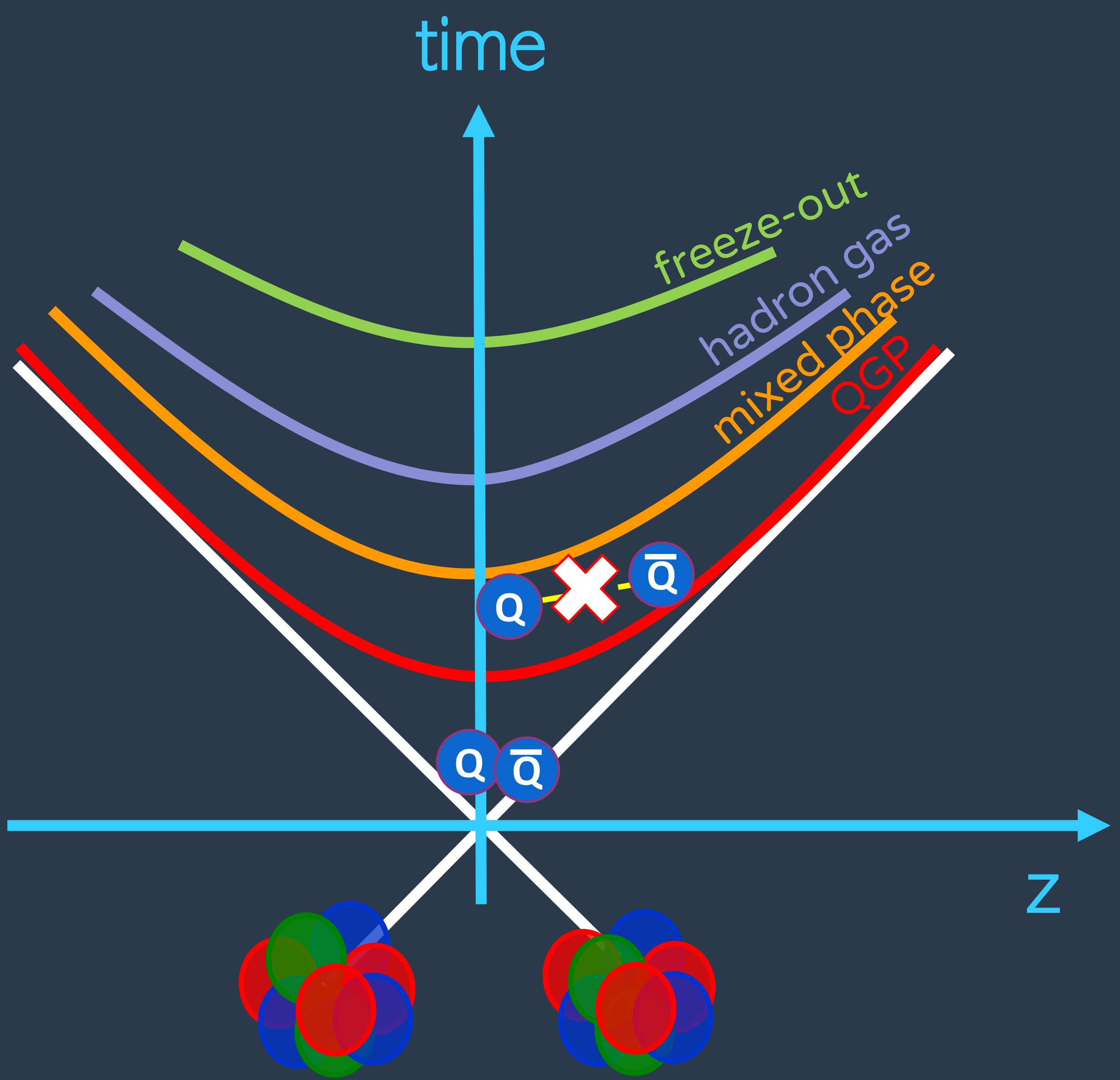
INT PROGRAM INT-22-3
Heavy Flavor Production in Heavy-Ion and Elementary Collisions

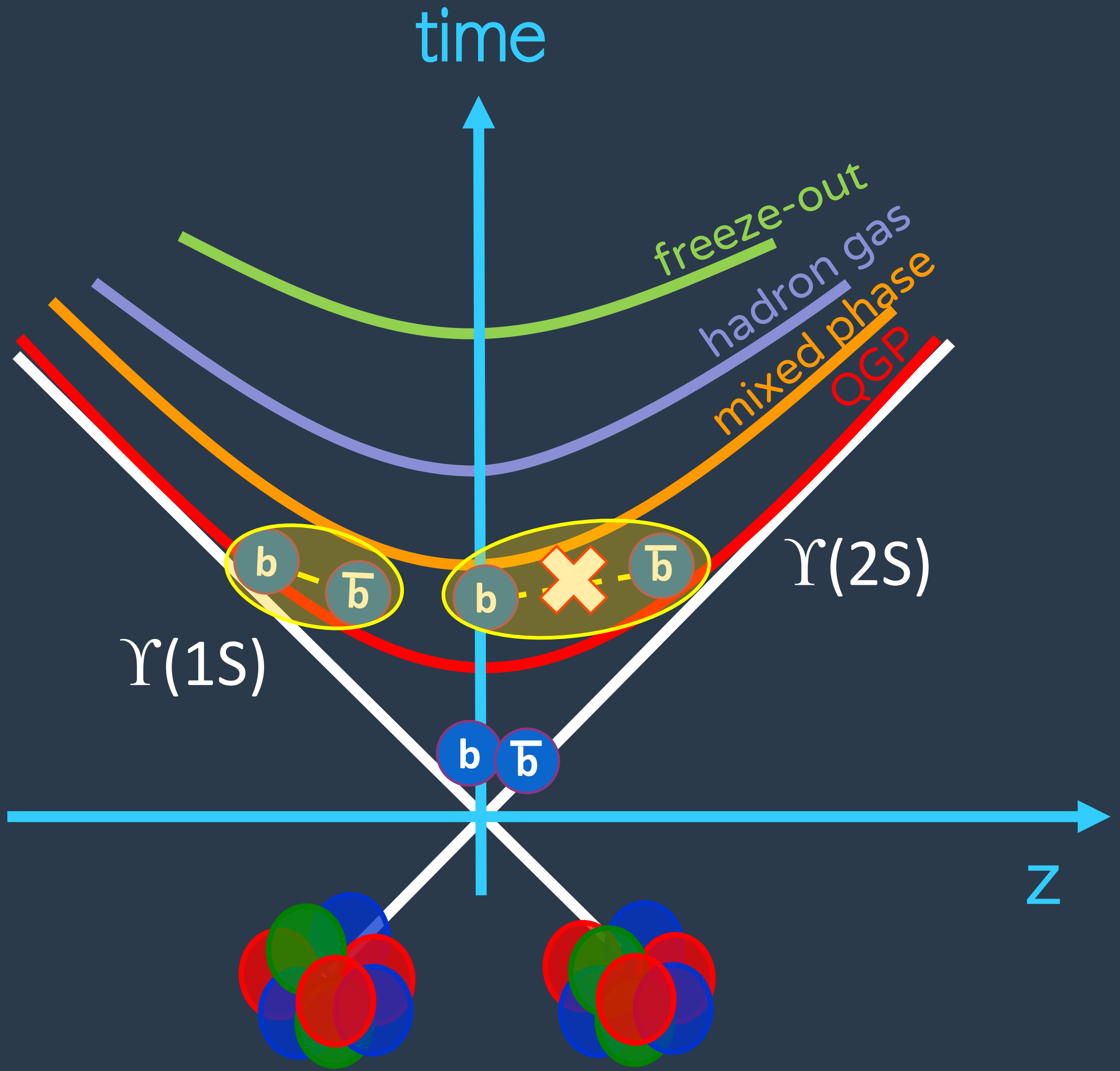
Quarkonium in AA



Heavy quarks produced in the early stages of the collisions

the original idea:
quarkonium production suppressed sequentially via color screening in QGP (T.Matsui,H.Satz, PLB178 (1986) 416)

Bottomonium in AA



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⇩

Sequential suppression clearly observed at LHC in the Υ family

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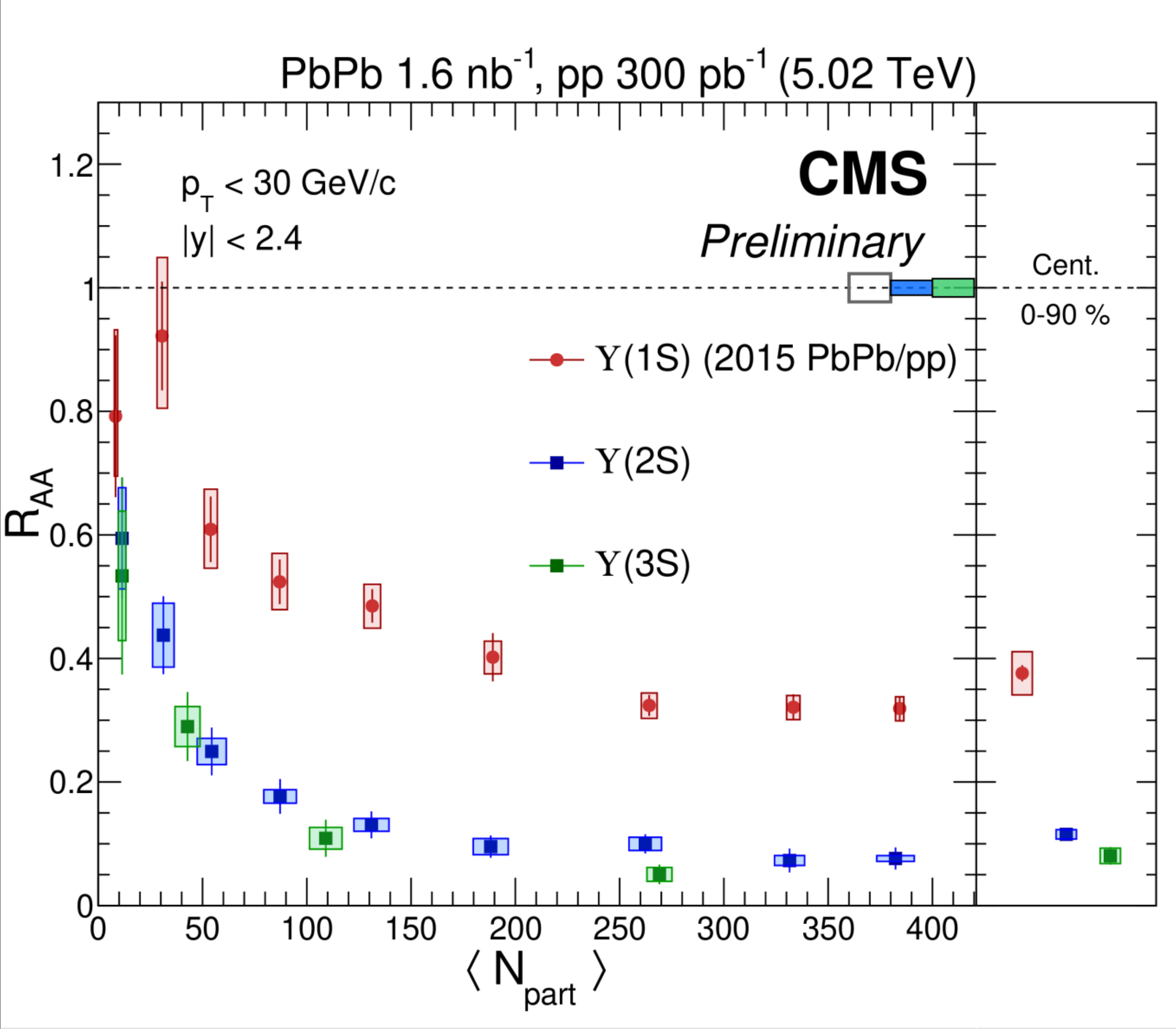

CMS-PAS-HIN-21-007

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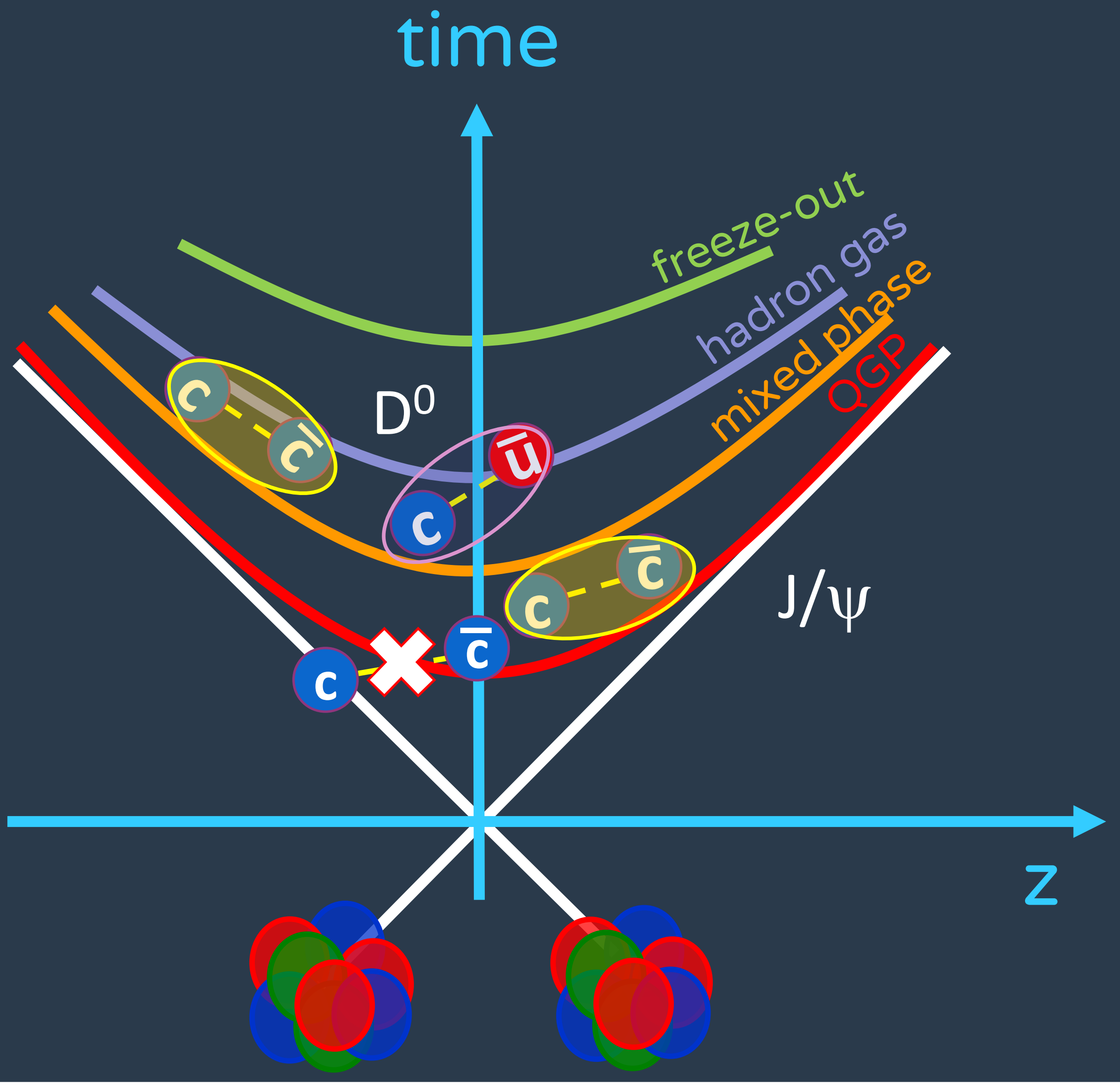
⇩

Sequential suppression clearly observed at LHC in the ϒ family

Charmonium in AA



Heavy quarks produced in the early stages of the collisions

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(re)combination:
production enhanced at hadronization or in QGP

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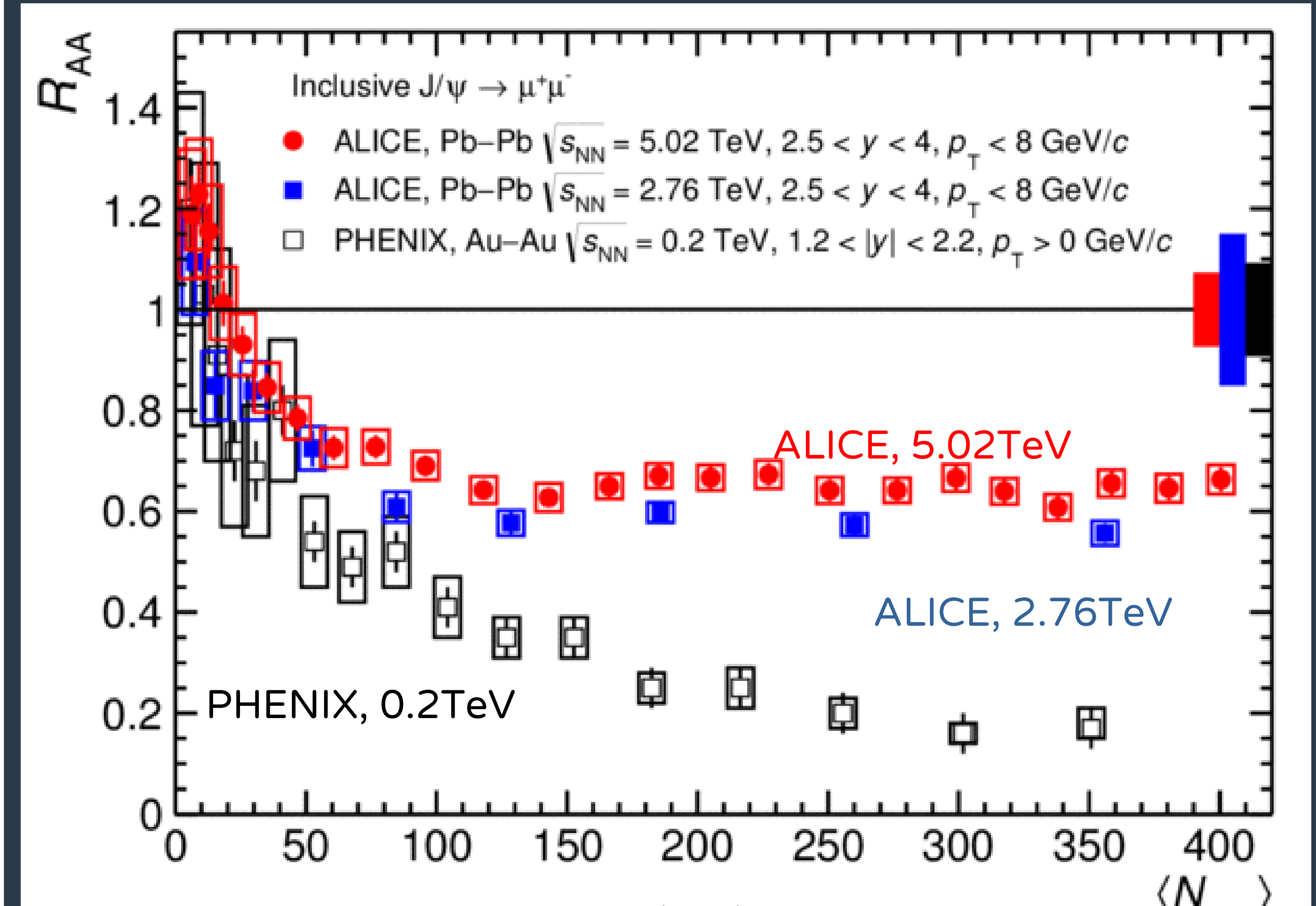
recombination clearly observed at LHC in the charmonium sector

Charmonium in AA



ALICE, PLB766 (2017) 212

Heavy quarks produced in the early stages of the collisions

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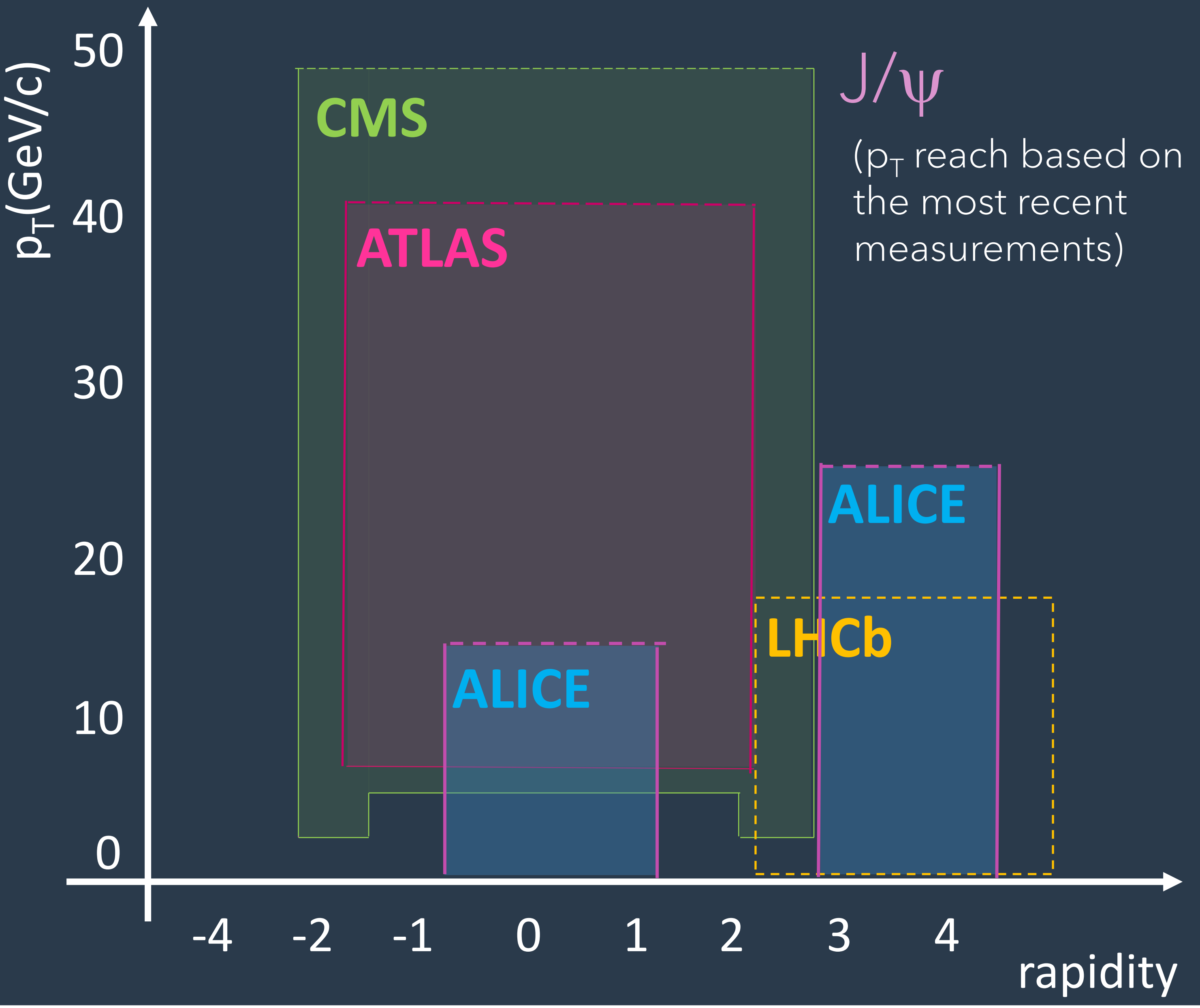
Quarkonium at LHC

- ✓ Quarkonium extensively studied at LHC by all the experiments in pp, pA, AA
- ✓ Complementary kinematic coverages
- ✓ Very high precision results for J/ψ, ϒ(1S,2S)



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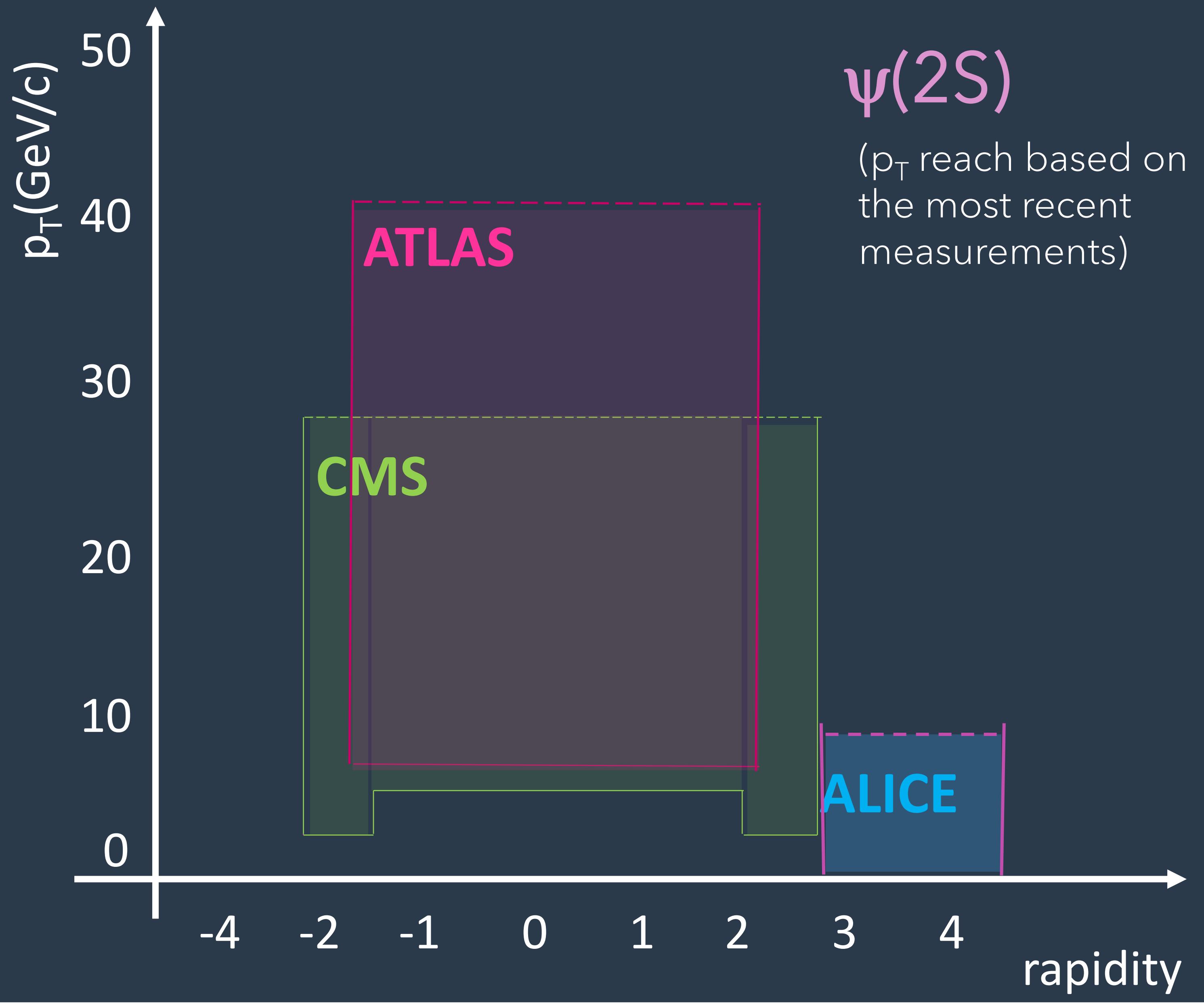
⇨ What about ψ(2S)?

Focus on AA results



$\psi(2S)$ vs J/ψ

Study of $\psi(2S)$ is more challenging wrt J/ψ due to:

✓ ~ 7.5 lower branching ratio to muon pairs

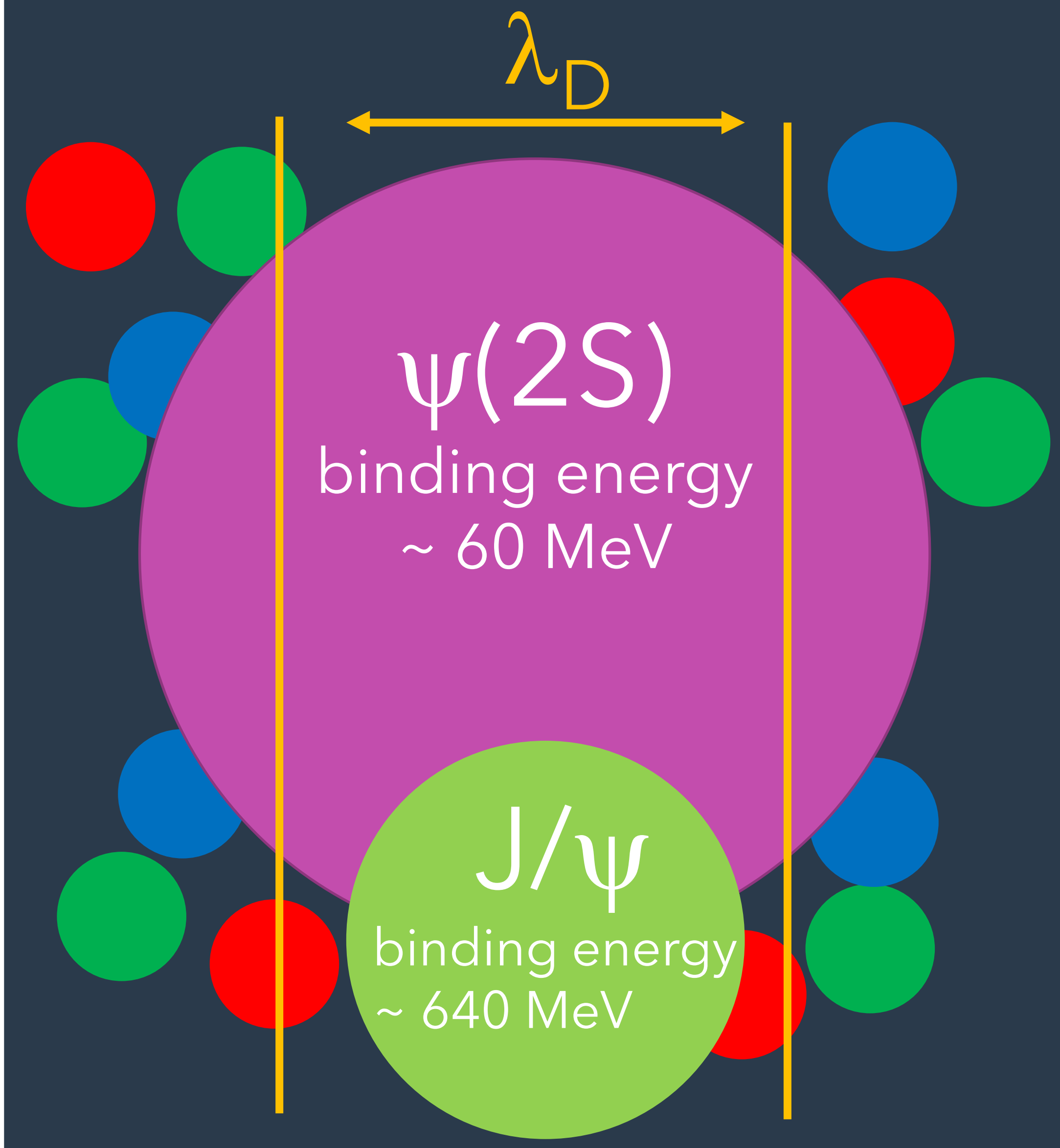
$BR(\psi(2S) \rightarrow \mu^+\mu^-) = (0.80 \pm 0.06)\ \%$
$BR(J/\psi \rightarrow \mu^+\mu^-) = (5.96 \pm 0.03)\ \%$

✓ ~ 6 times smaller production cross section in pp collisions at LHC energy

$\sigma_{\psi(2S)} = 0.87 \pm 0.06 \pm 0.10\ \mu b$
$\sigma_{J/\psi} = 5.88 \pm 0.03 \pm 0.34\ \mu b$

(pp, 5.02TeV, $2.5<y<4$ ALICE, arXiv:2109.15240)

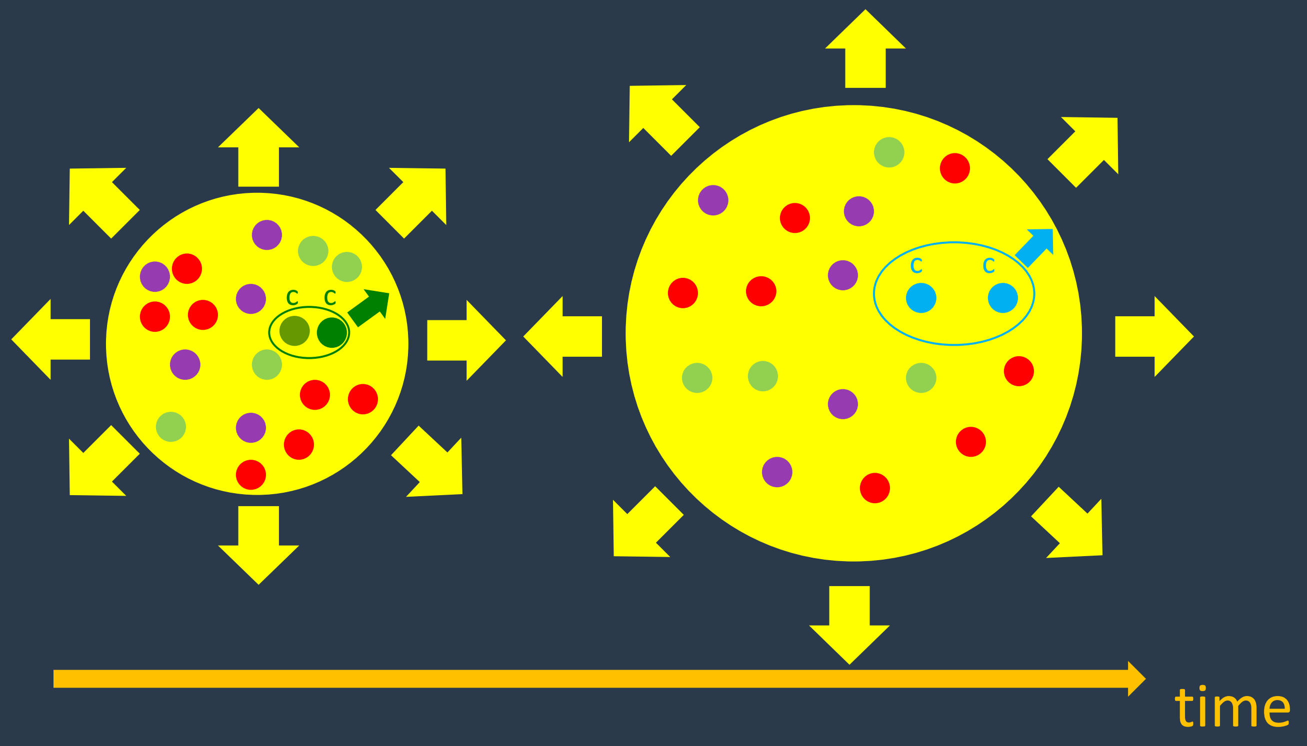
ψ(2S) vs J/ψ



Expect much stronger dissociation effects for the weakly bound ψ(2S) state

⇨ Do we observe the sequential suppression also in the charmonium sector?

ψ(2S) vs J/ψ



What is the impact of recombination on the ψ(2S)?

Larger size charmonium produced later in the evolution of the system

→ recombination at play also when the system is more diluted (even hadronic?)

Comparison between J/ψ and ψ(2S) is an important test for models

Theory models

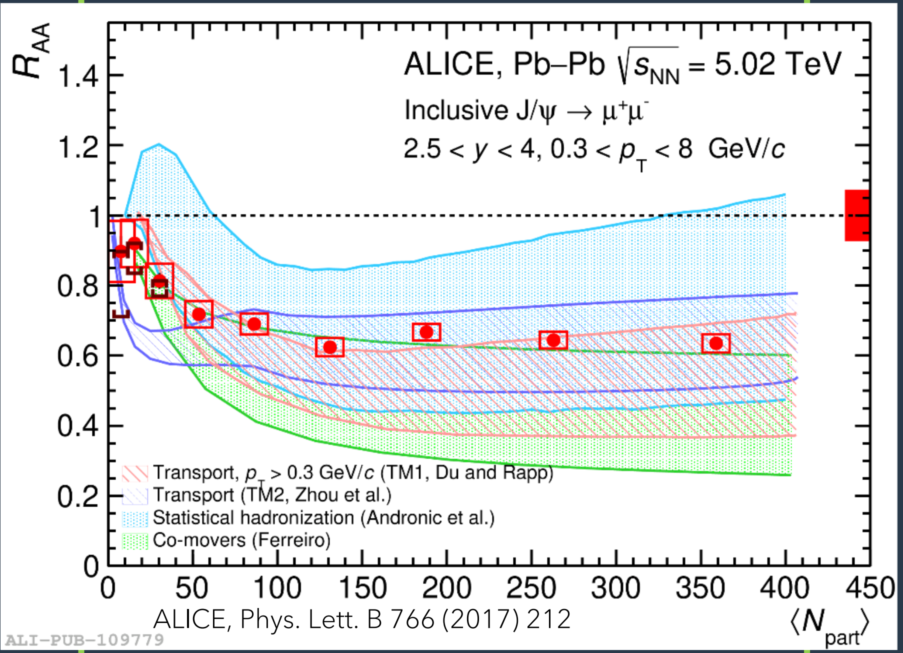
Transport

Macroscopic rate equation including suppression and regeneration in the QGP

Suppression → computed from modification of charmonium spectral functions, constrained by LQCD validated potentials

Regeneration → tuned from measured heavy quark yields

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



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

Statistical hadronization

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

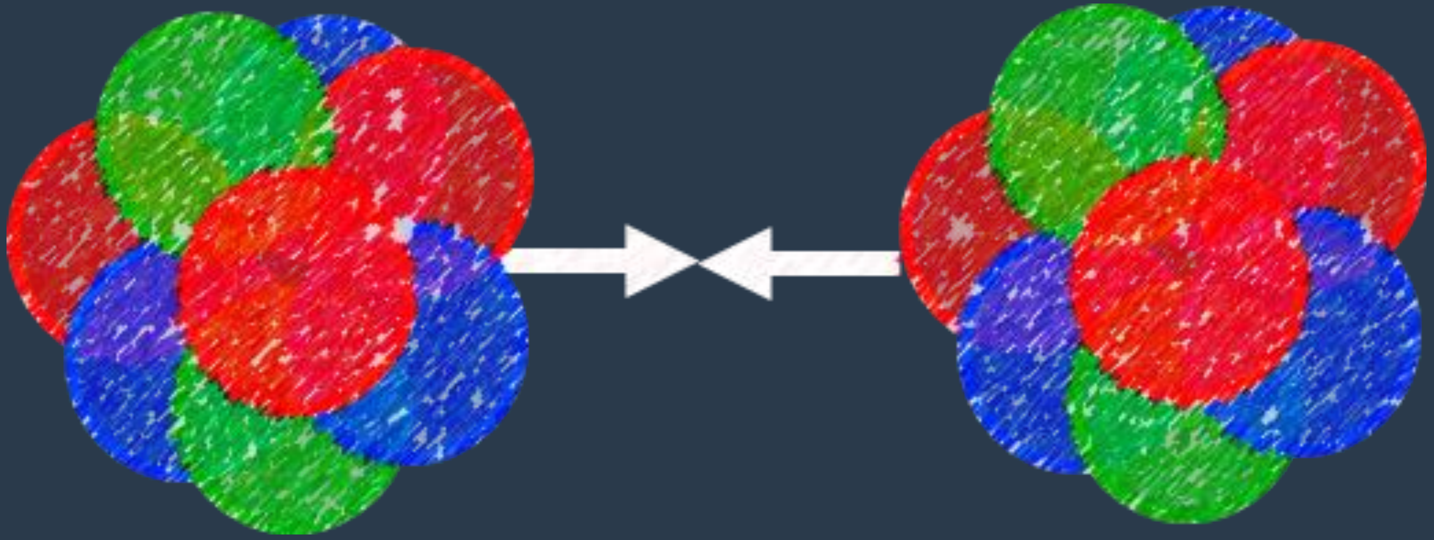
A. Andronic et al., Nature 561 (2018) 321

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

Other approaches include "comover" models

E. Ferreiro, PLB 731 (2014) 57

ψ(2S) at SPS energies



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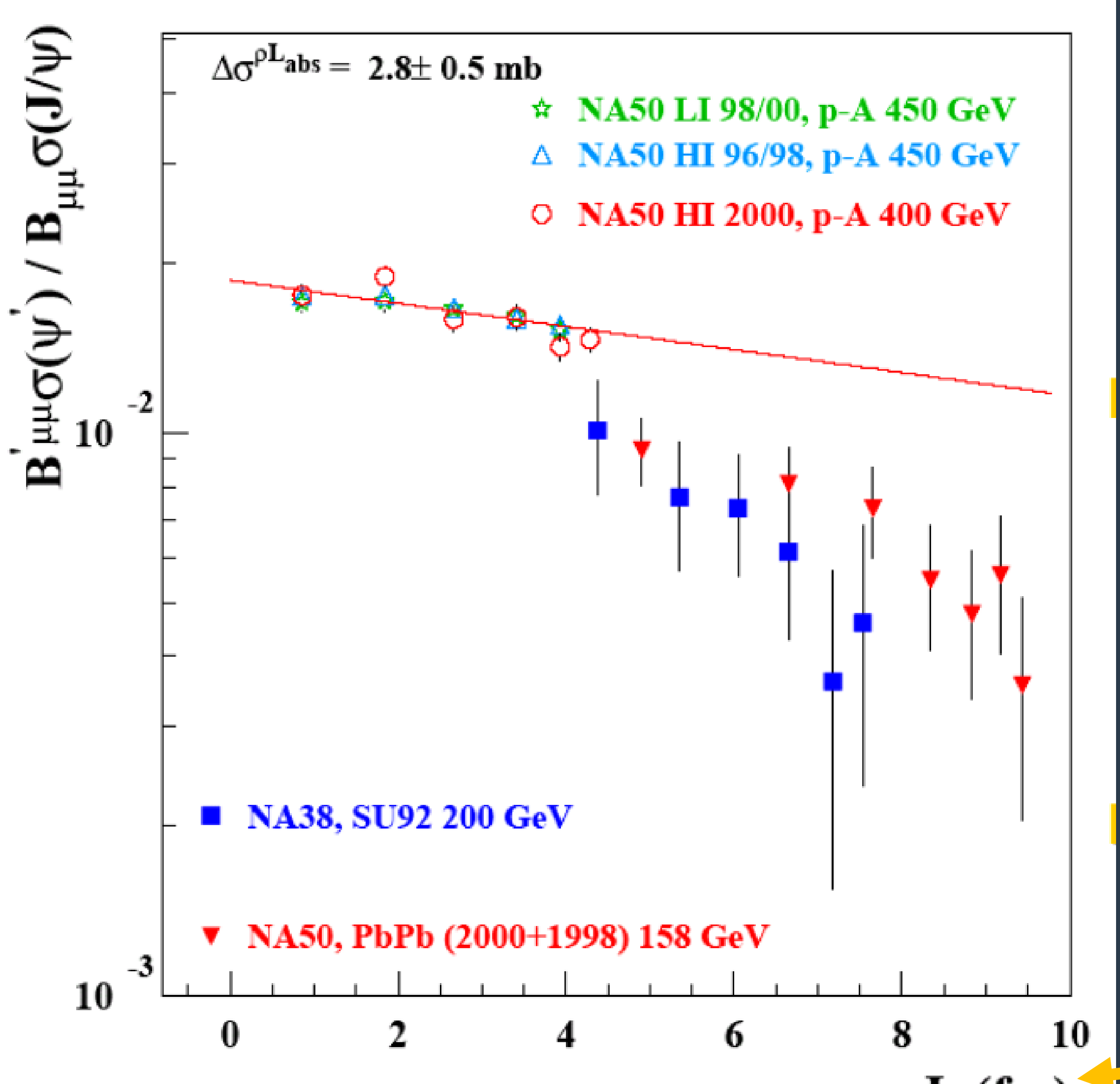
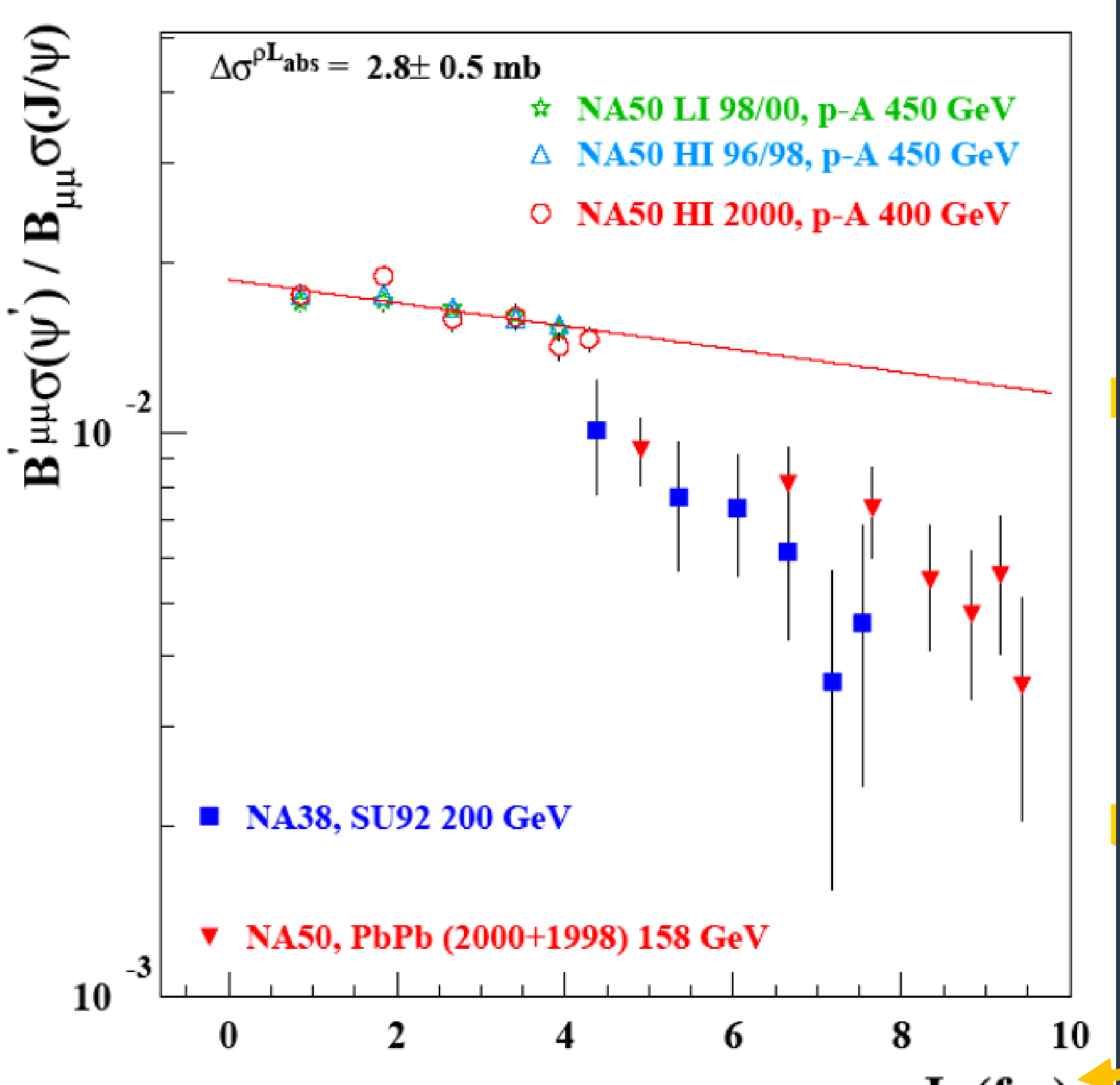


NA50, EPJC49 (2007)

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

L: thickness of nuclear matter crossed by the $c\bar{c}$ pair

ψ(2S) at SPS energies



NA50, EPJC49 (2007)

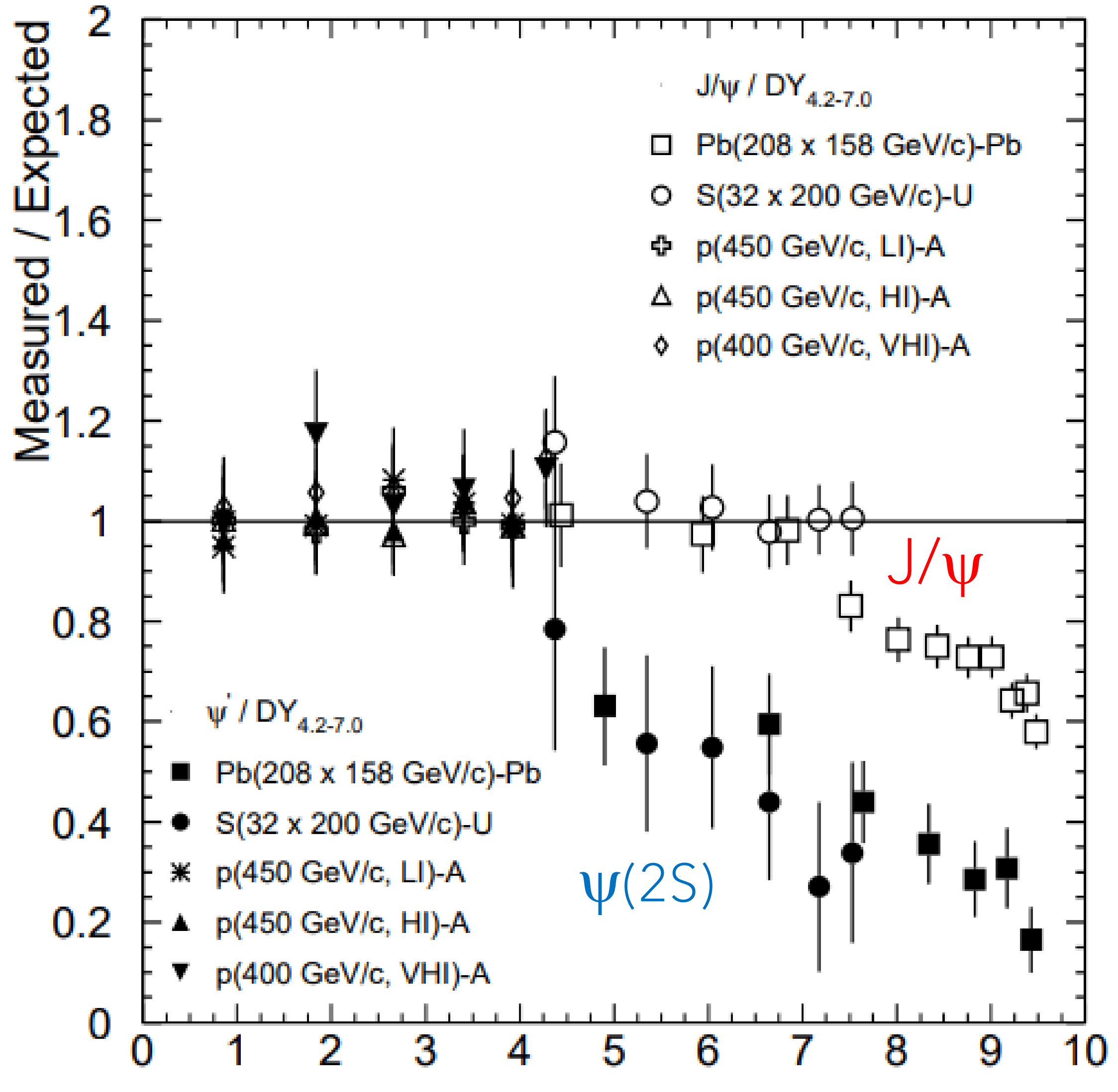
ψ(2S)/J/ψ

- ✓ Stronger relative dissociation of ψ(2S) wrt J/ψ already in p-A collisions
- ✓ The effect becomes even stronger in AA collisions approximately scaling with L

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

L: thickness of nuclear matter crossed by the $c\bar{c}$ pair

ψ(2S) at SPS energies

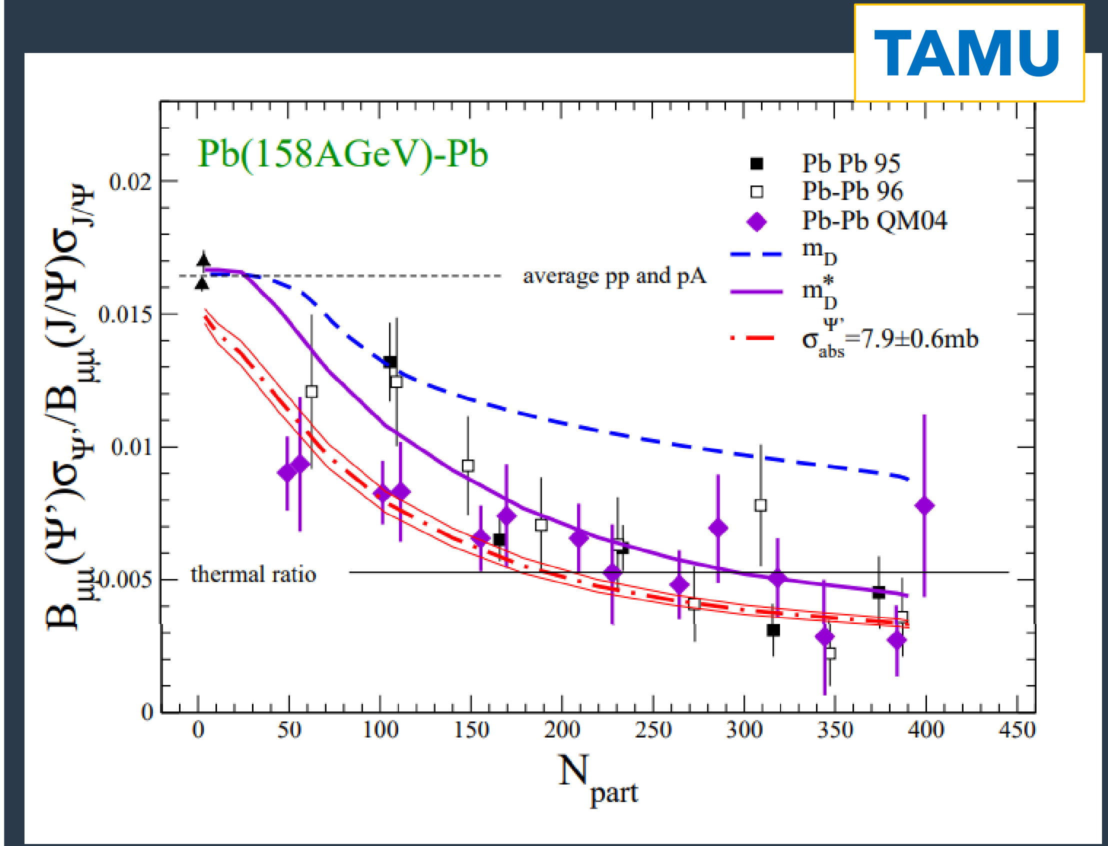


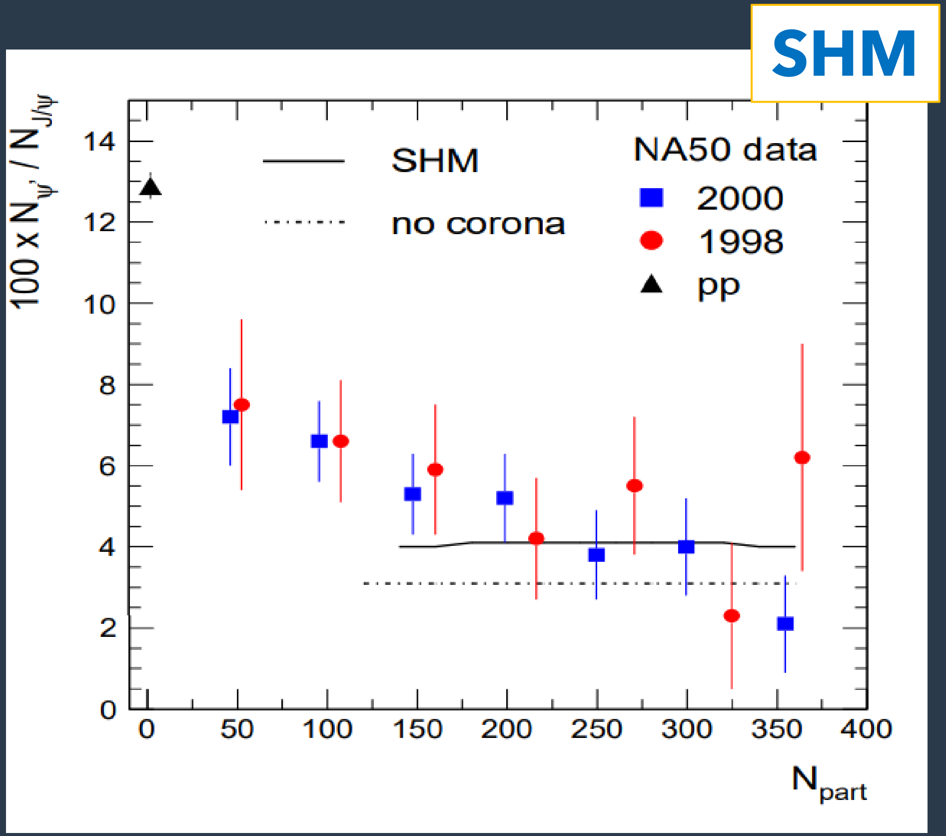
NA50, EPJC49 (2007)

Measured/expected ratio

- ✓ ψ(2S) anomalous suppression is stronger than the J/ψ one
- ✓ sets in earlier, at lower energy densities
  → 1.5 GeV/fm^3 wrt ~2.5 GeV/fm^3 for the J/ψ
- ✓ ψ(2S) suppressed already in SU collisions, beyond CNM effects

SPS: comparison to theory





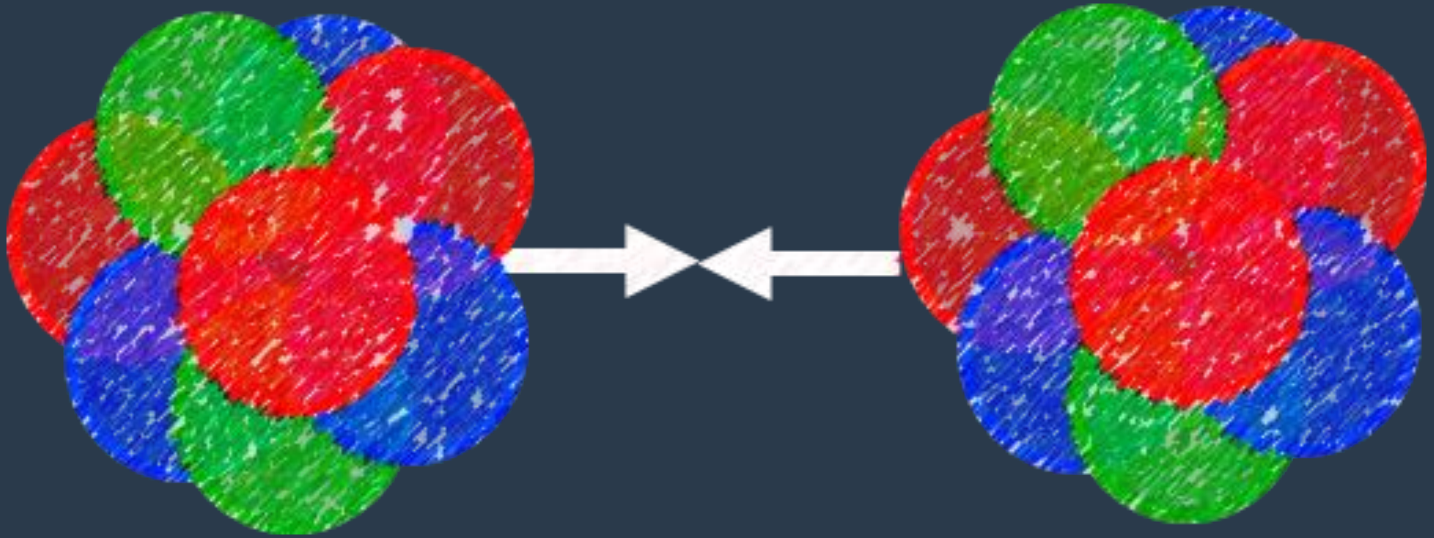
from
Rapp and Van Hees,
arXiv:0903.1096

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

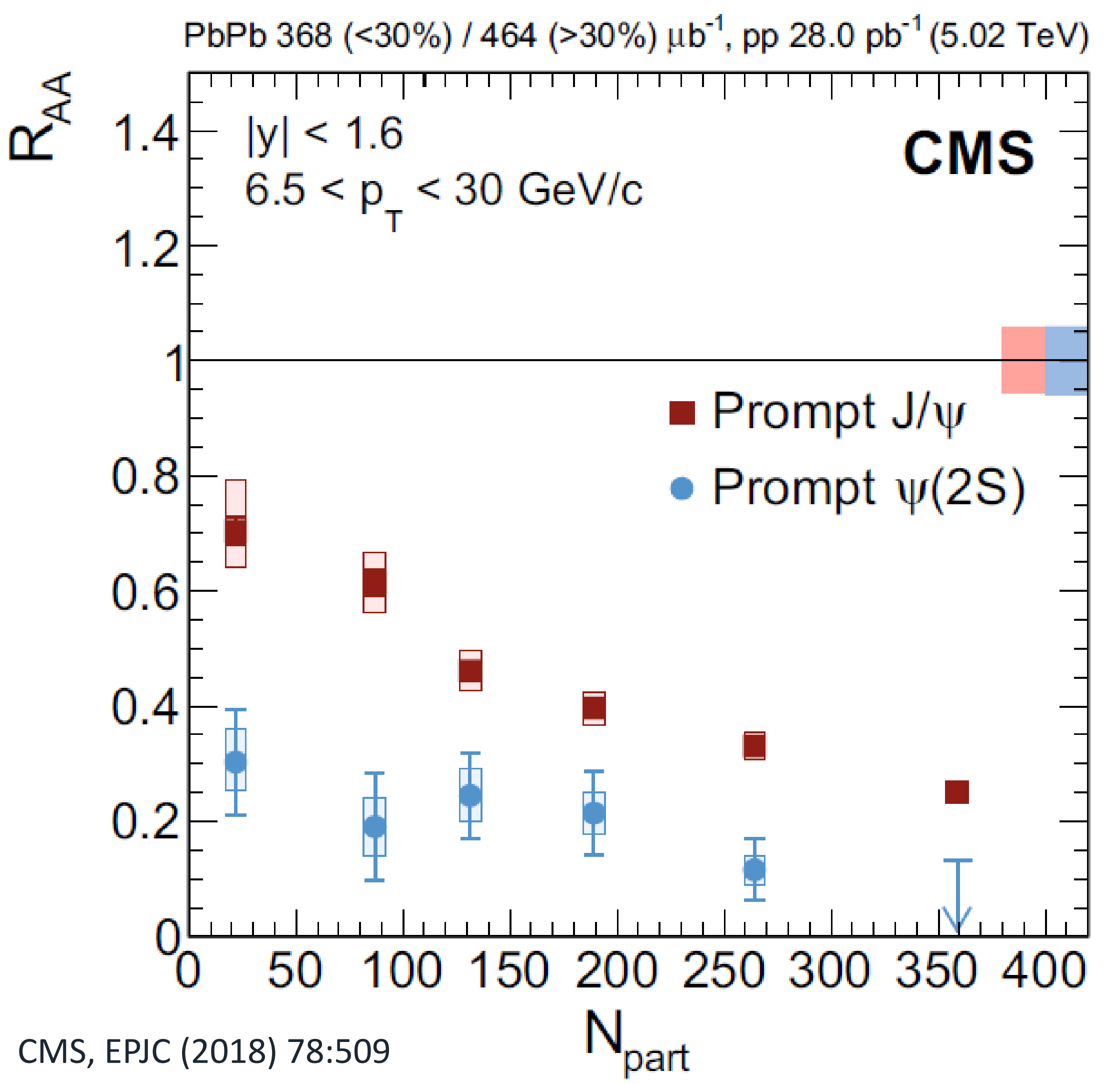
SHMc:
Andronic, Braun-Munzinger, Redlich and Stachel,
NPA789 (2007) 334

Both transport (TAMU) and statistical hadronization (SHM) models reproduce data

ψ(2S) at LHC energies



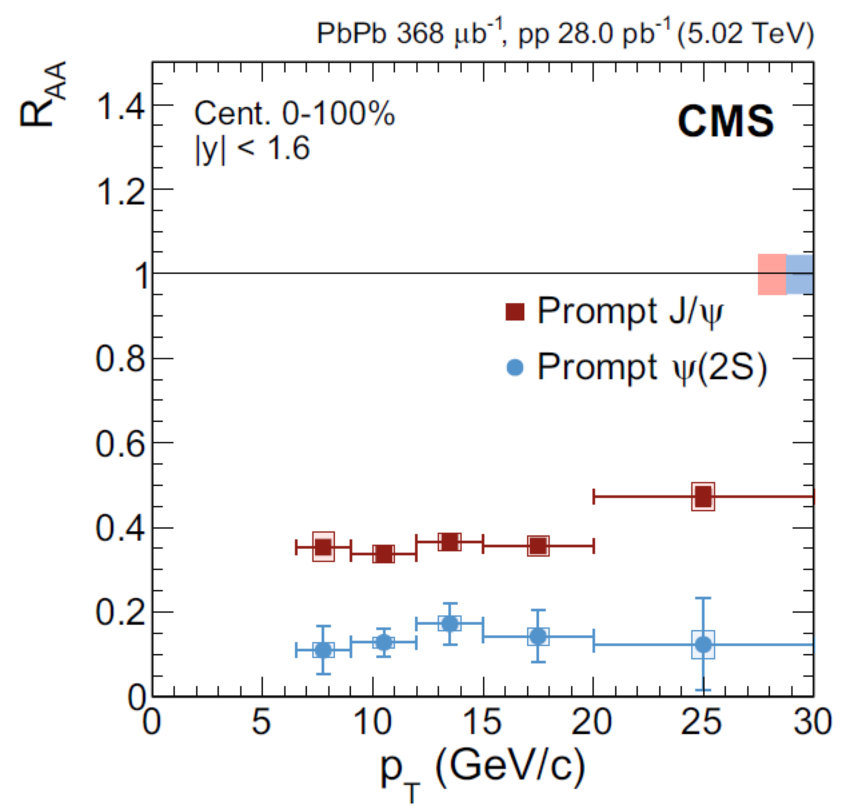
ψ(2S) at LHC energies



CMS, EPJC (2018) 78:509

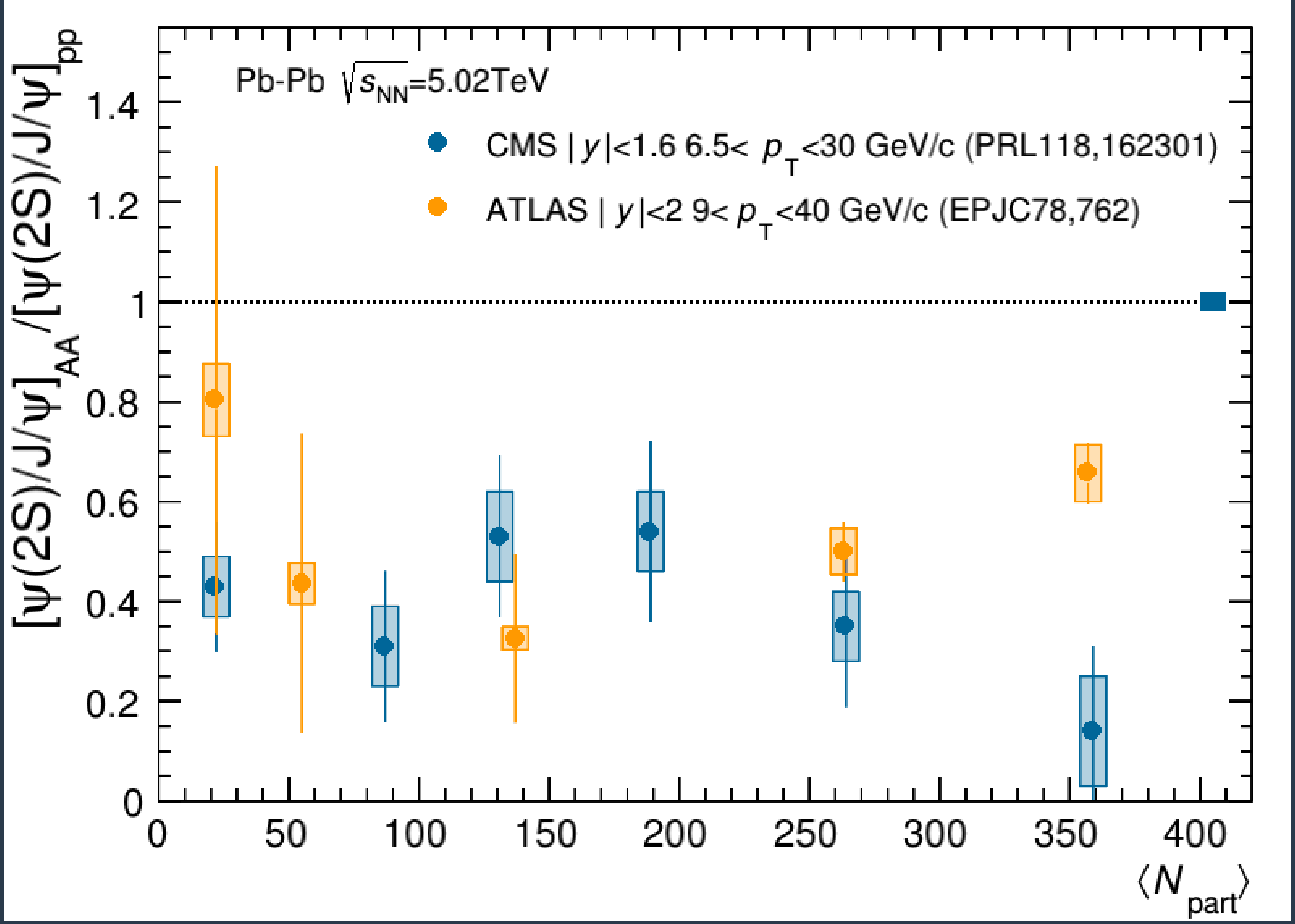
High p_T

Strong ψ(2S) suppression, larger than the J/ψ one (factor ~2), observed by CMS



Hint for an increasing ψ(2S) suppression vs centrality, while no significant p_T dependence

ψ(2S) at LHC energies



High p_T

Strong prompt ψ(2S) suppression observed also by ATLAS

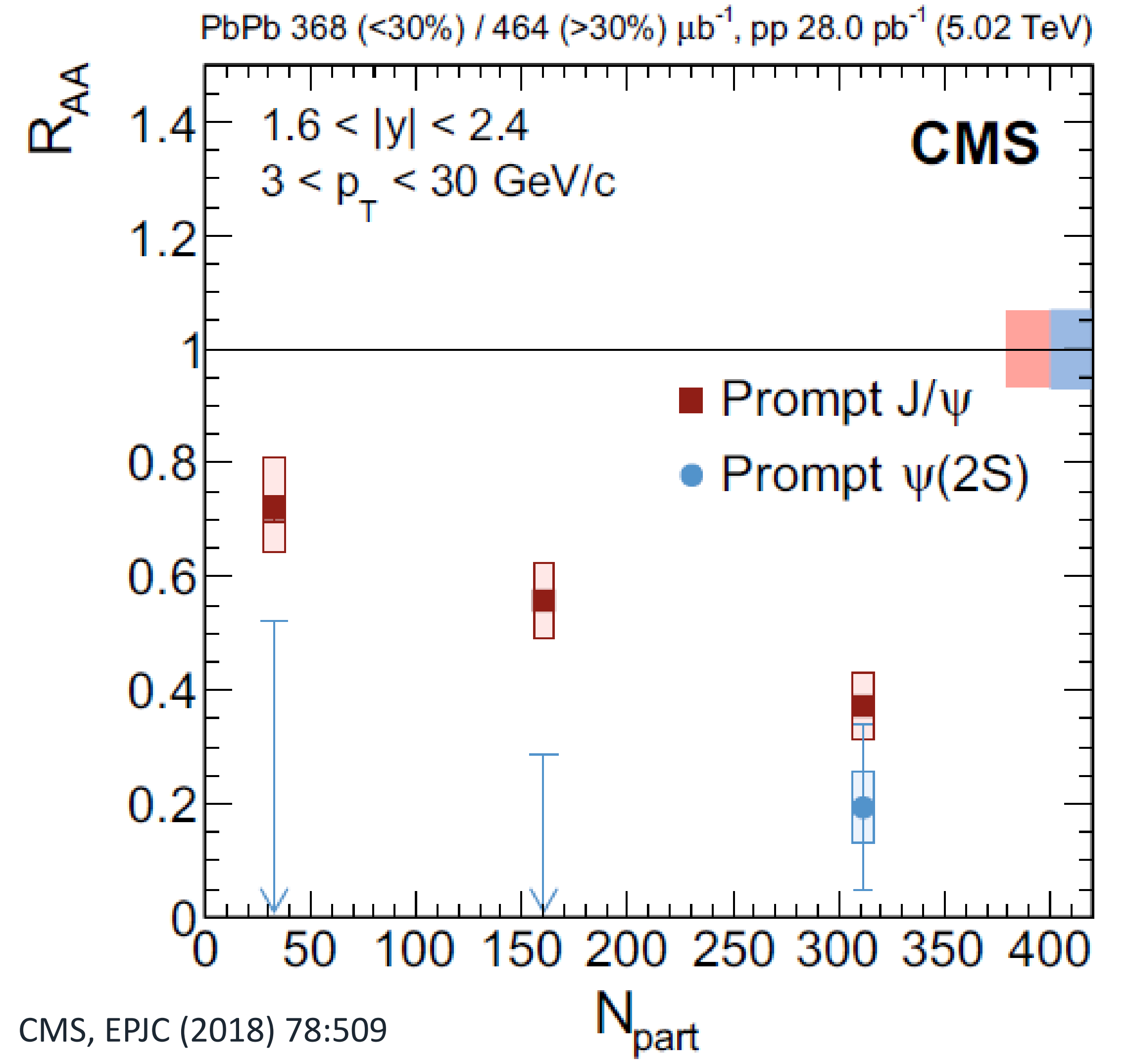
Tension in central events between ATLAS and CMS?

ψ(2S) at LHC energies

Important to extend the ψ(2S) study even lower in p_T, where recombination effects might be at play

Towards low p_T

ψ(2S) is more suppressed than the J/ψ down to $p_T = 3$ GeV/c, but limited statistics prevents clear conclusions



CMS, EPJC (2018) 78:509

ψ(2S) at LHC energies

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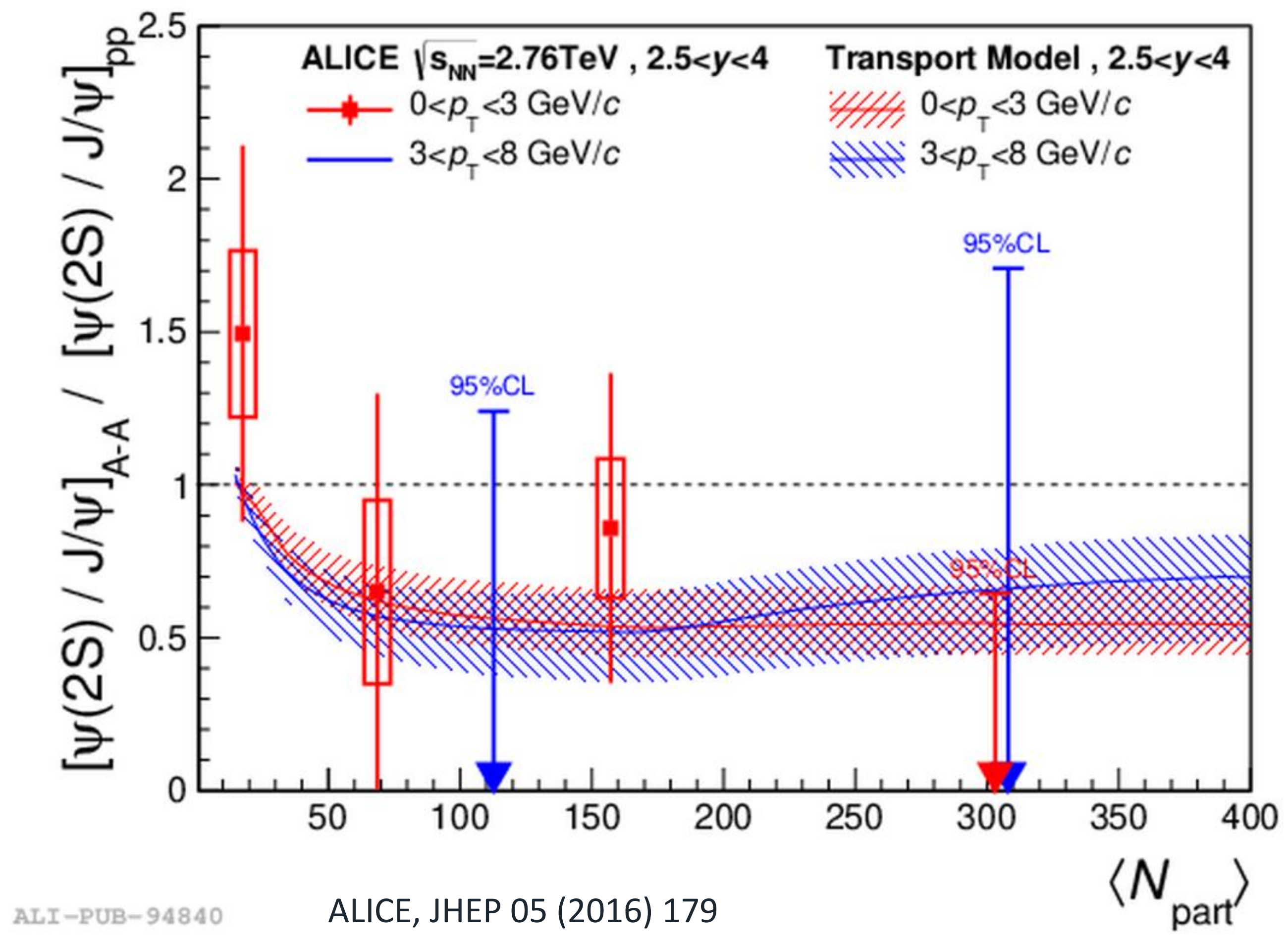


ALICE, JHEP 05 (2016) 179

Low p_T

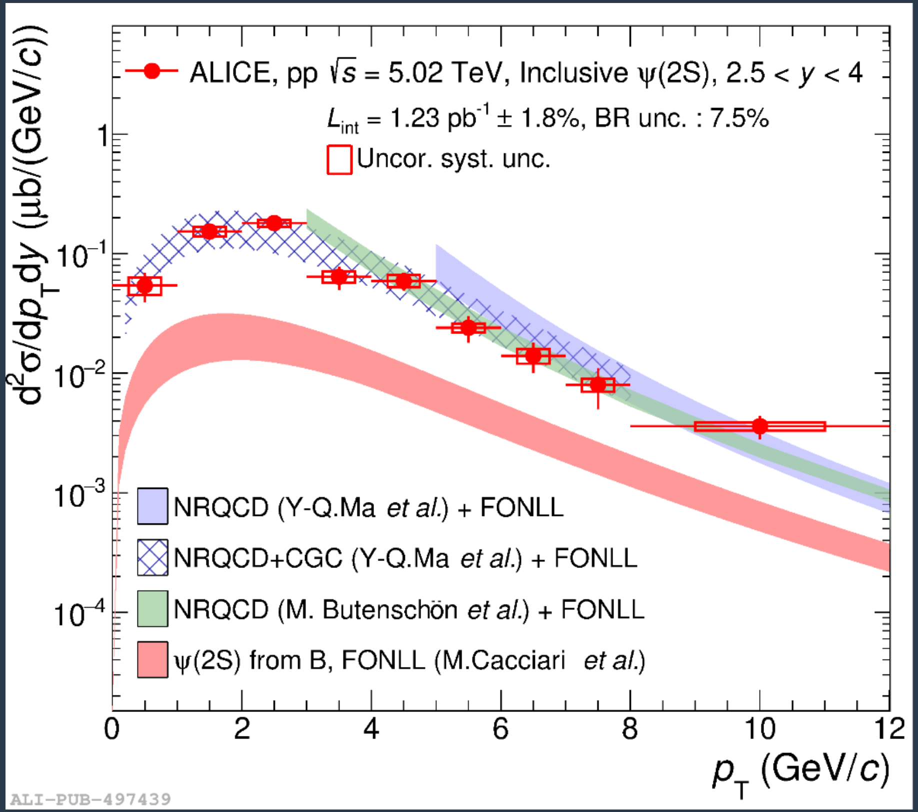
ALICE Run 1 results available, but large uncertainties prevent a firm conclusion on ψ(2S)/J/ψ ratio

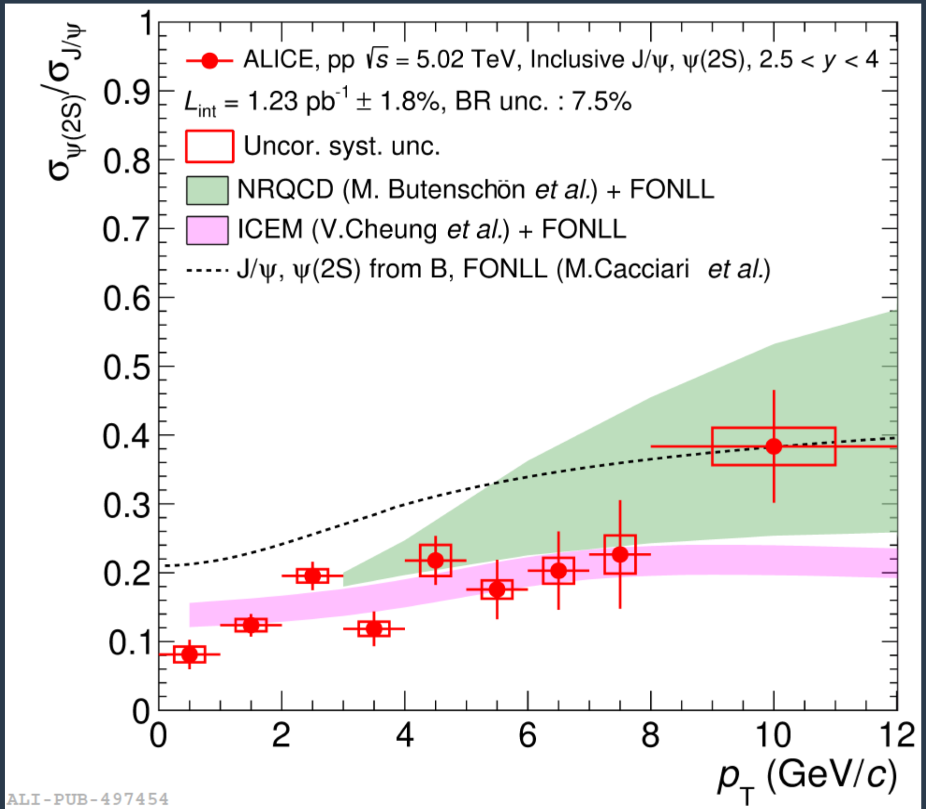
Run 1 L_{int} ~ 70 μb^{-1}

Higher statistics (by a factor of ~11 wrt Run 1) now available from the full Run 2 Pb–Pb data at $\sqrt{s_{NN}}$ = 5.02 TeV

ψ(2S) in pp

ALICE, arXiv:2109.15240





Inclusive ψ(2S) production

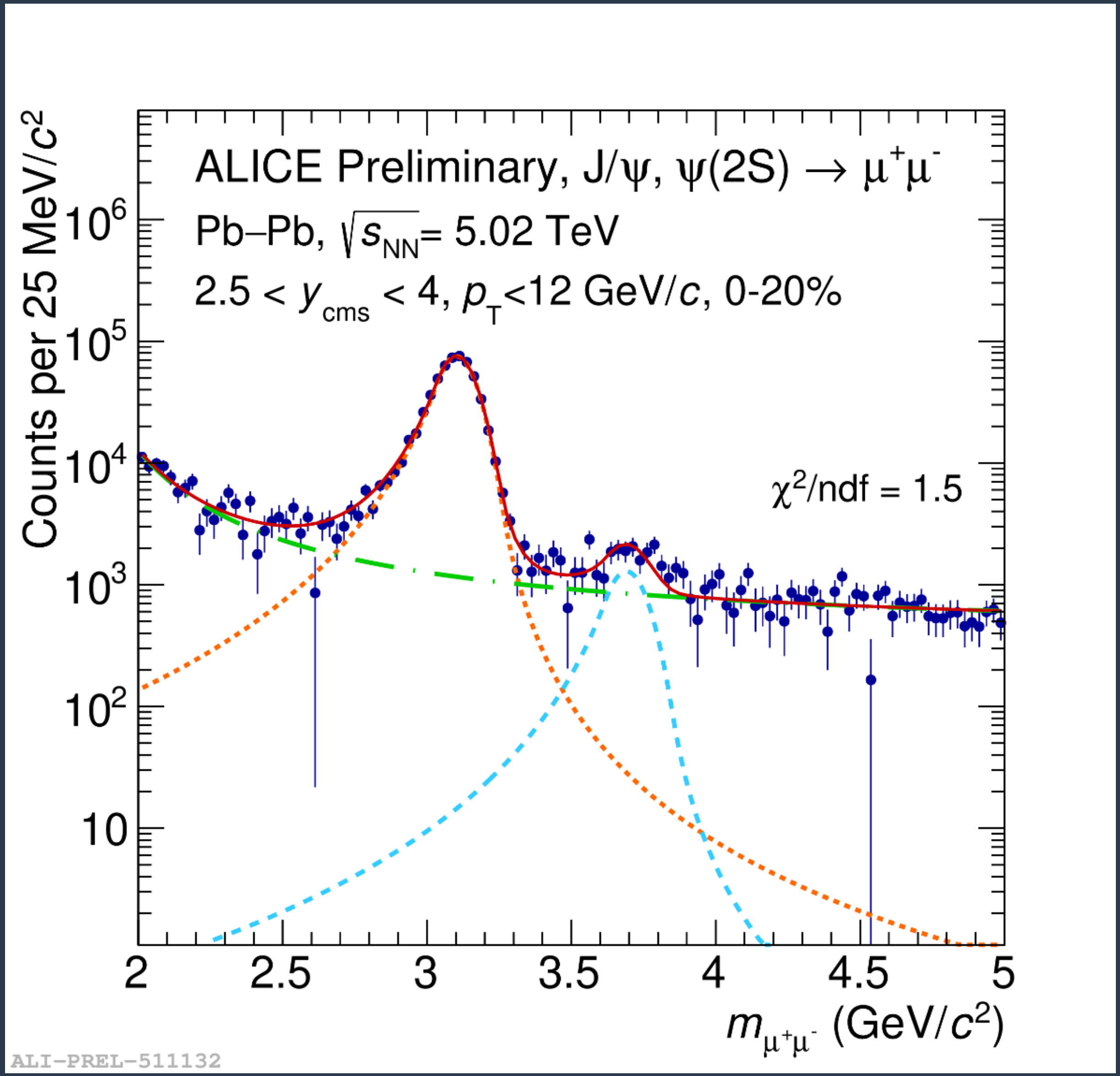
Recent ALICE cross-section measurement with 10 times more statistics than earlier publication

→ *y*- and p_T-differential studies of ψ(2S)

→ ψ(2S) cross sections nicely described by NRQCD+CGC+FONLL down to zero p_T

→ ψ(2S)-to-J/ψ ratio increases with p_T, showing good agreement with theory models

$\psi(2S)$ in PbPb, low p_T



ALICE low p_T

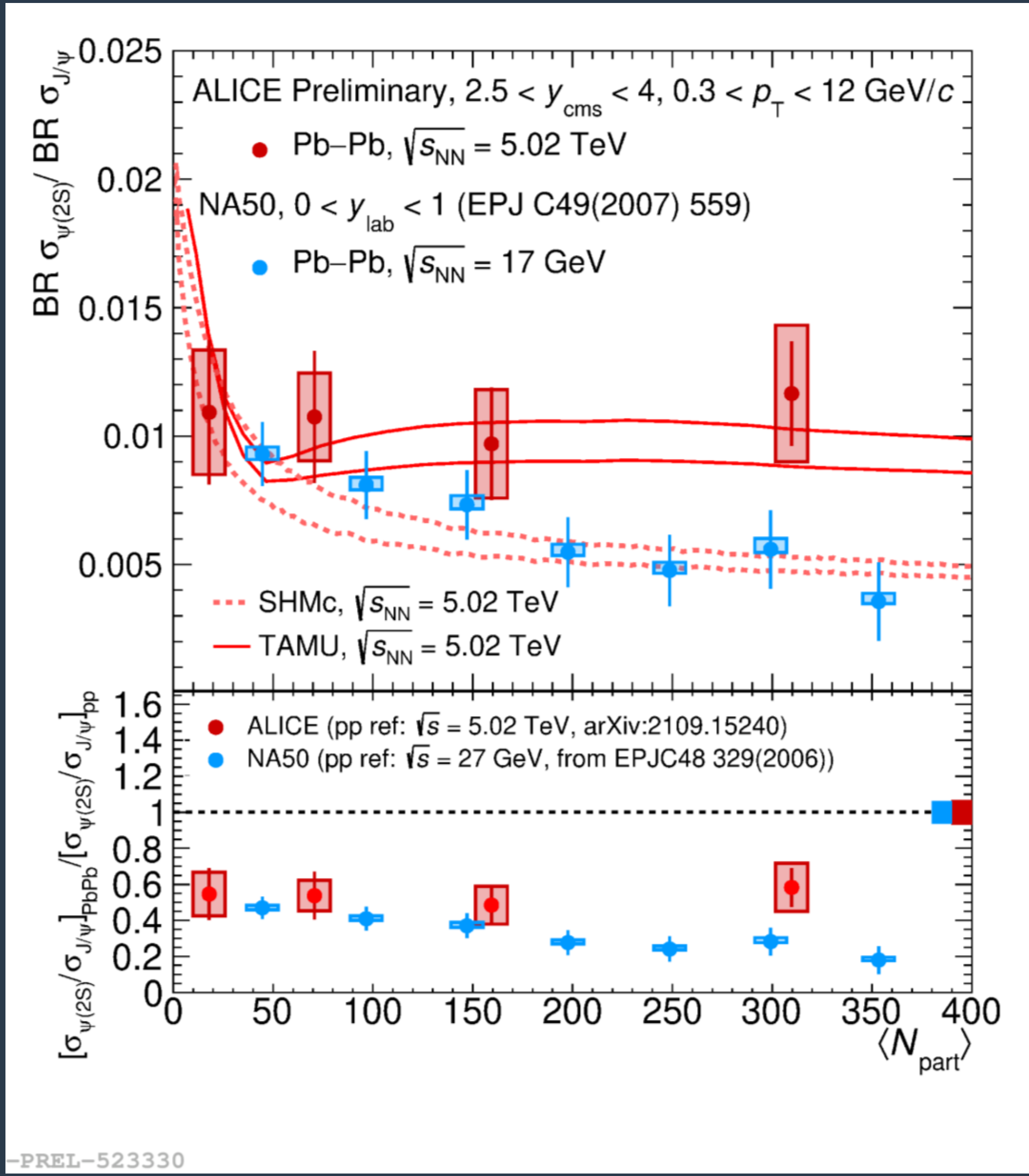
✓ $\psi(2S)$ signal extracted by using an event-mixing background subtraction technique

$\psi(2S) \sim 1.3\times10^4$
$J/\psi \sim 9.2\times10^5$

✓ Significant signal observed in most central collisions and down to zero p_T, thanks to the full Run 2 statistics

ALICE, arXiv:2210.08893

ψ(2S)/J/ψ vs centrality

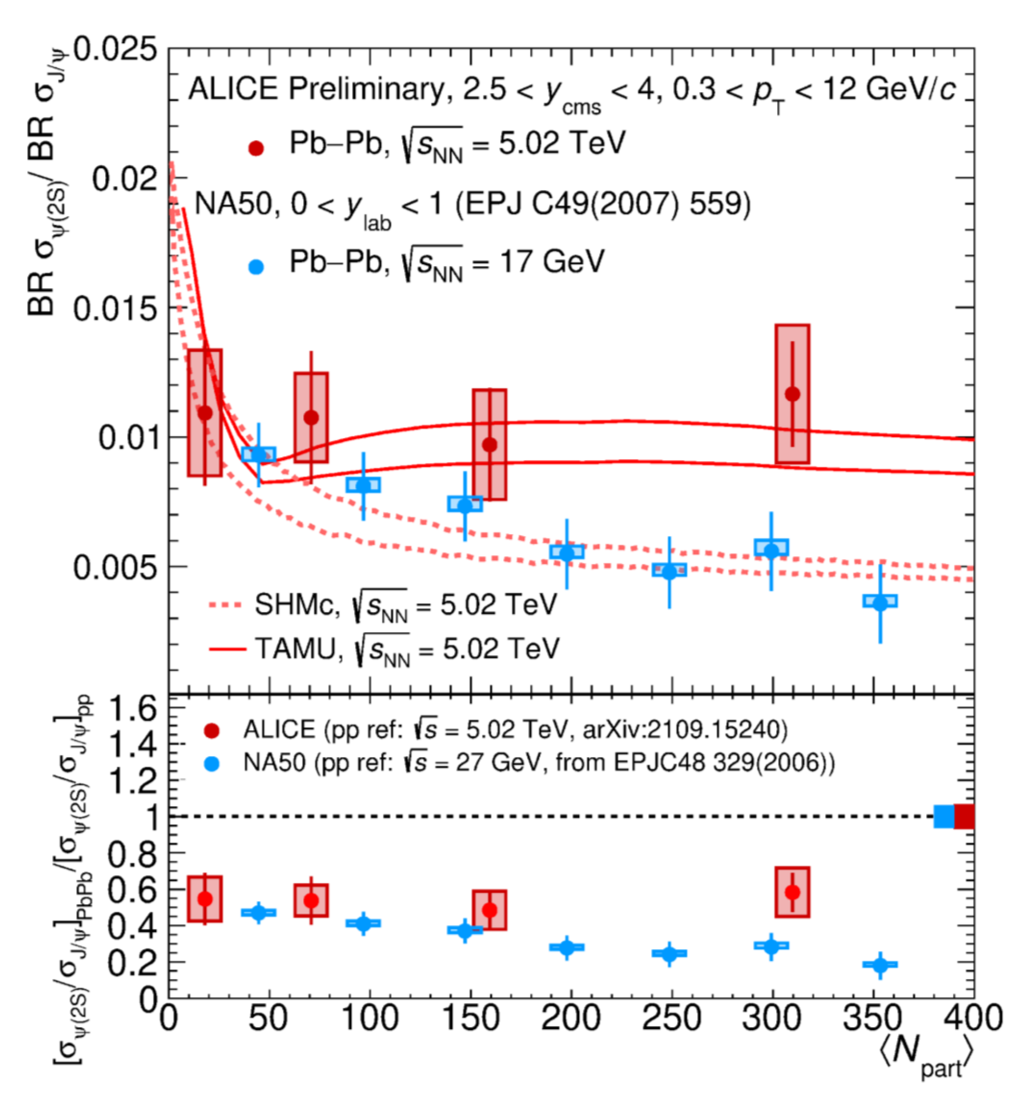


Ratio $\frac{B_{\psi(2S)\to\mu\mu}\,\sigma_{\psi(2S)}}{B_{J/\psi\to\mu\mu}\sigma_{J/\psi}}$

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

N.B.: not corrected for branching ratios

$\psi(2S)/J/\psi$ vs centrality



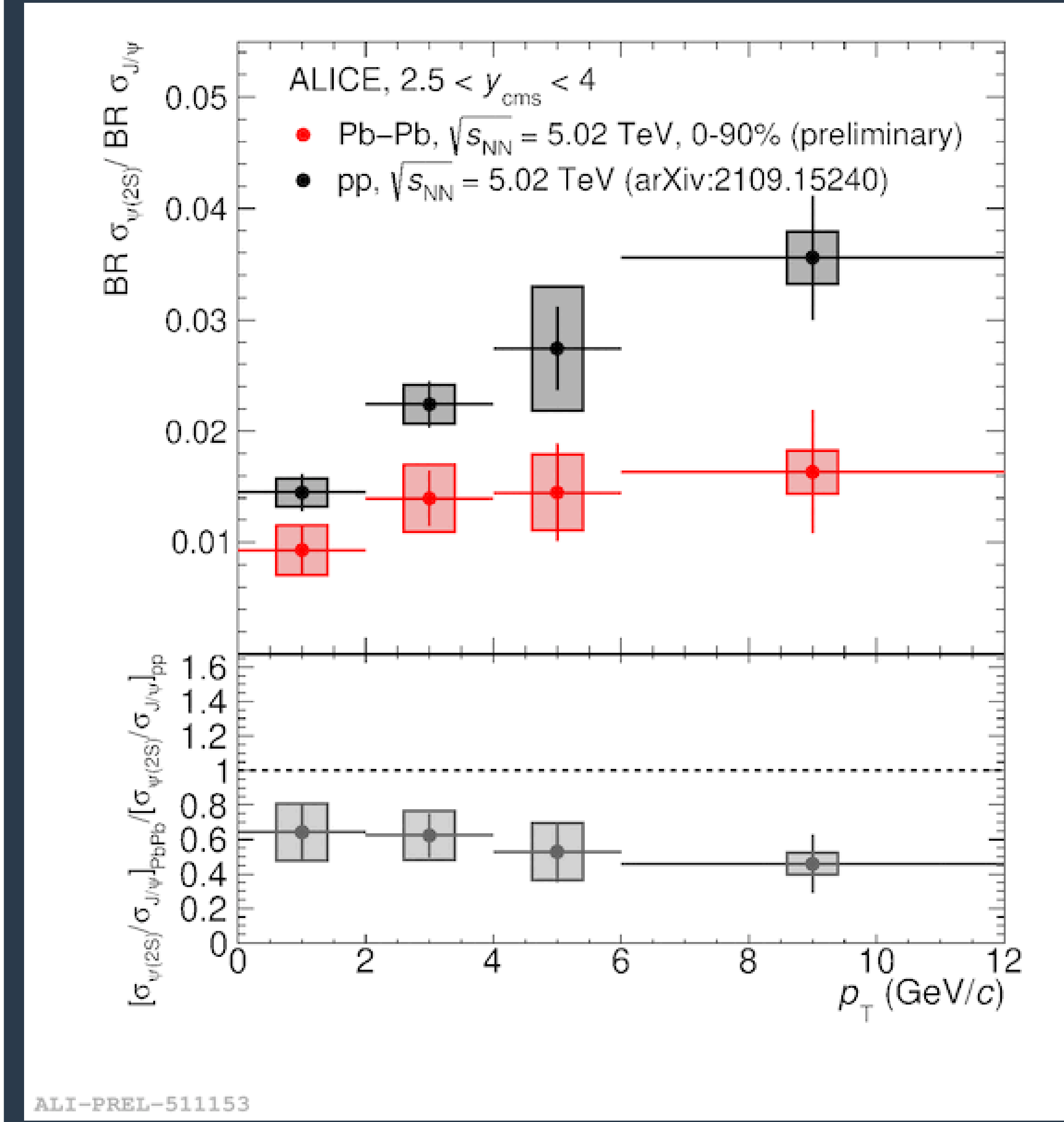
TAMU: X. Du and R. Rapp, NPA 943 (2015) 147
SHMc: A. Andronic et al., Nature 561 no. 7723 (2018) 321

ALICE:
flat $\psi(2S)$-to-J/ψ (double) ratio centrality dep.

NA50:
slightly more pronounced centrality dependence

- ✓ Indication of larger $\psi(2S)$-to-J/ψ (double) ratio in ALICE than in NA50 in central events
- ✓ TAMU model reproduces the cross section ratios over centrality, while SHMc tends to underestimate the ALICE data in central collisions

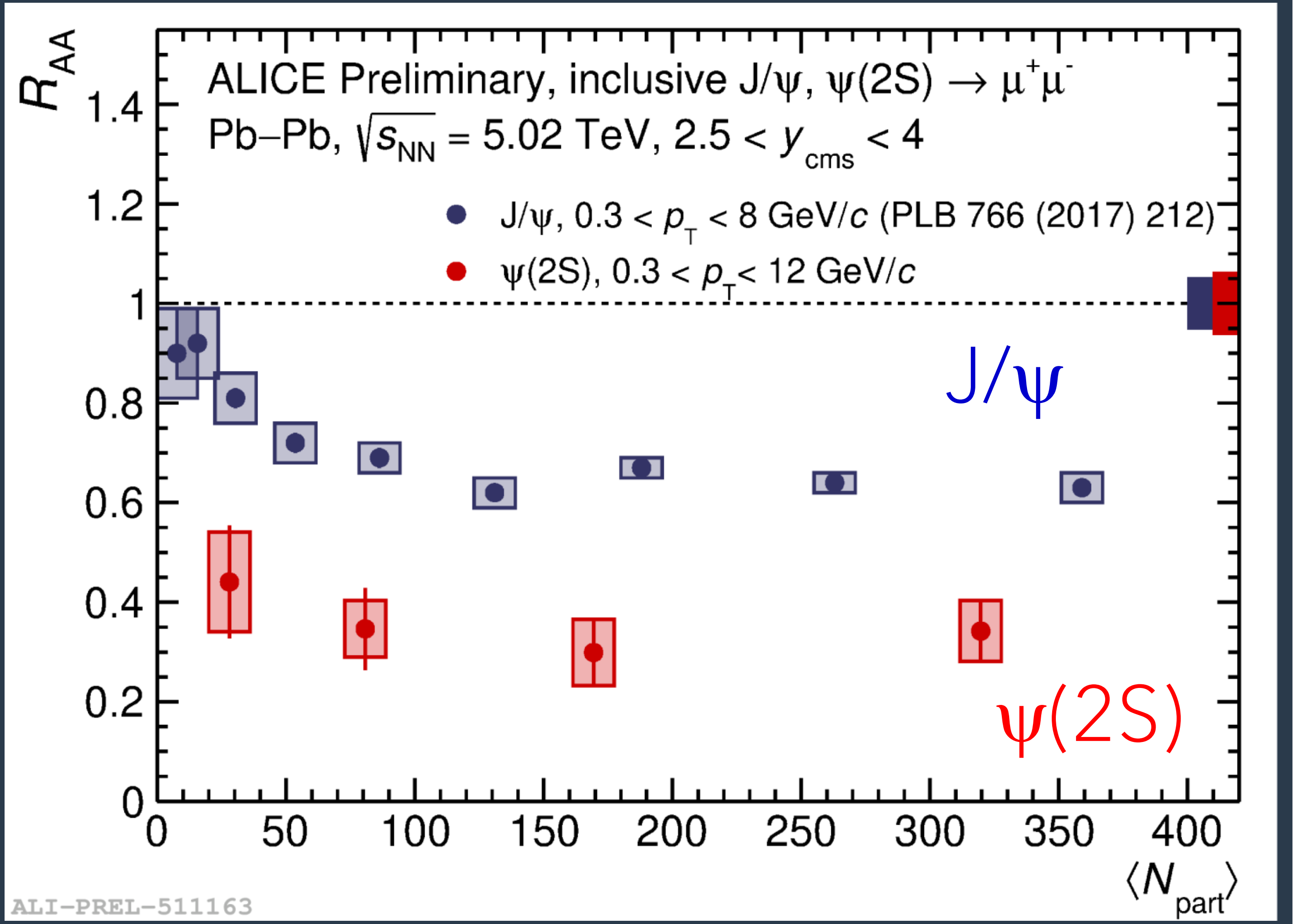
$\psi(2S)/J/\psi$ vs p_T



- ✓ Significant suppression of $\psi(2S)$ 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

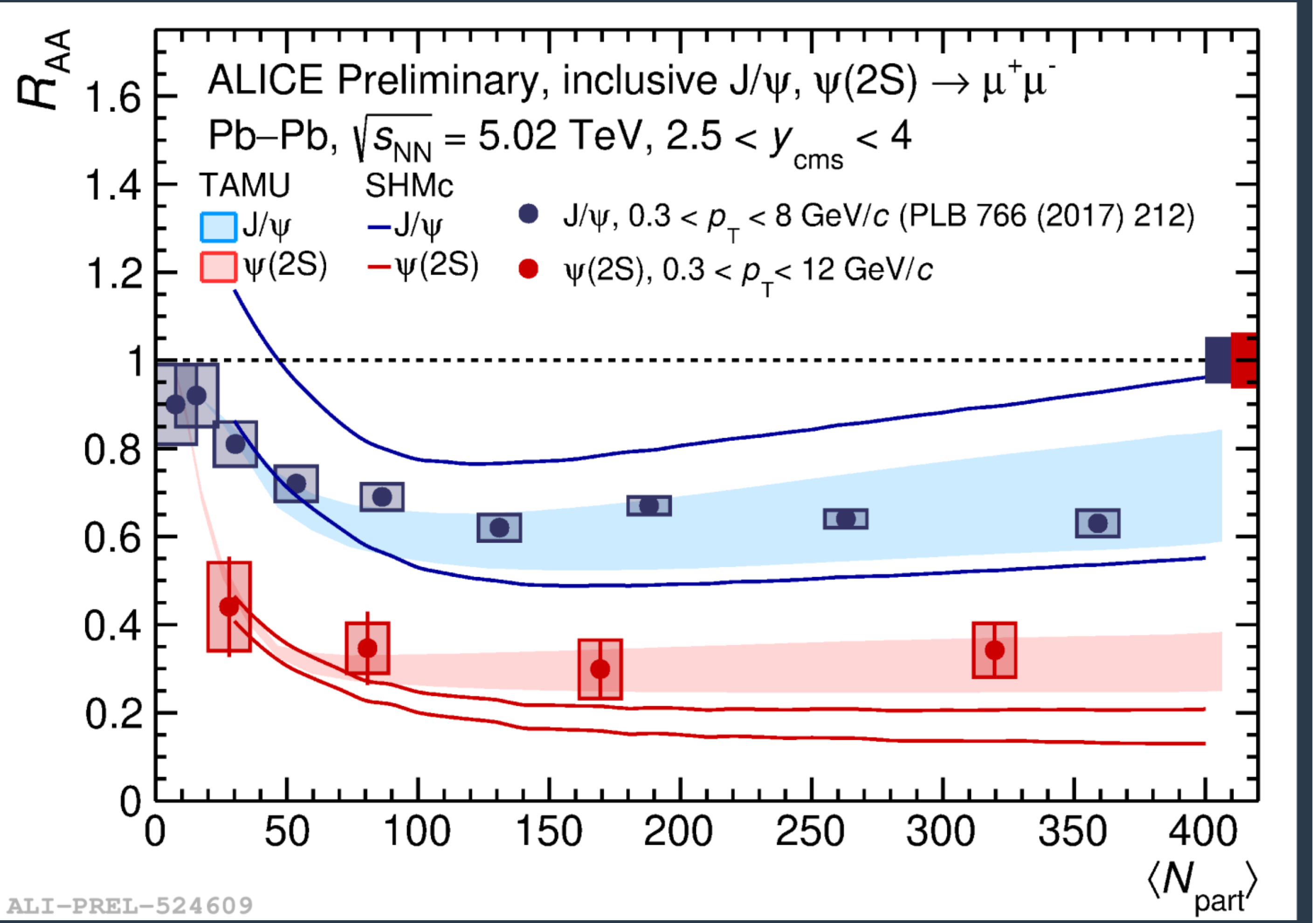
ψ(2S) R_{AA} vs centrality

- ✓ 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

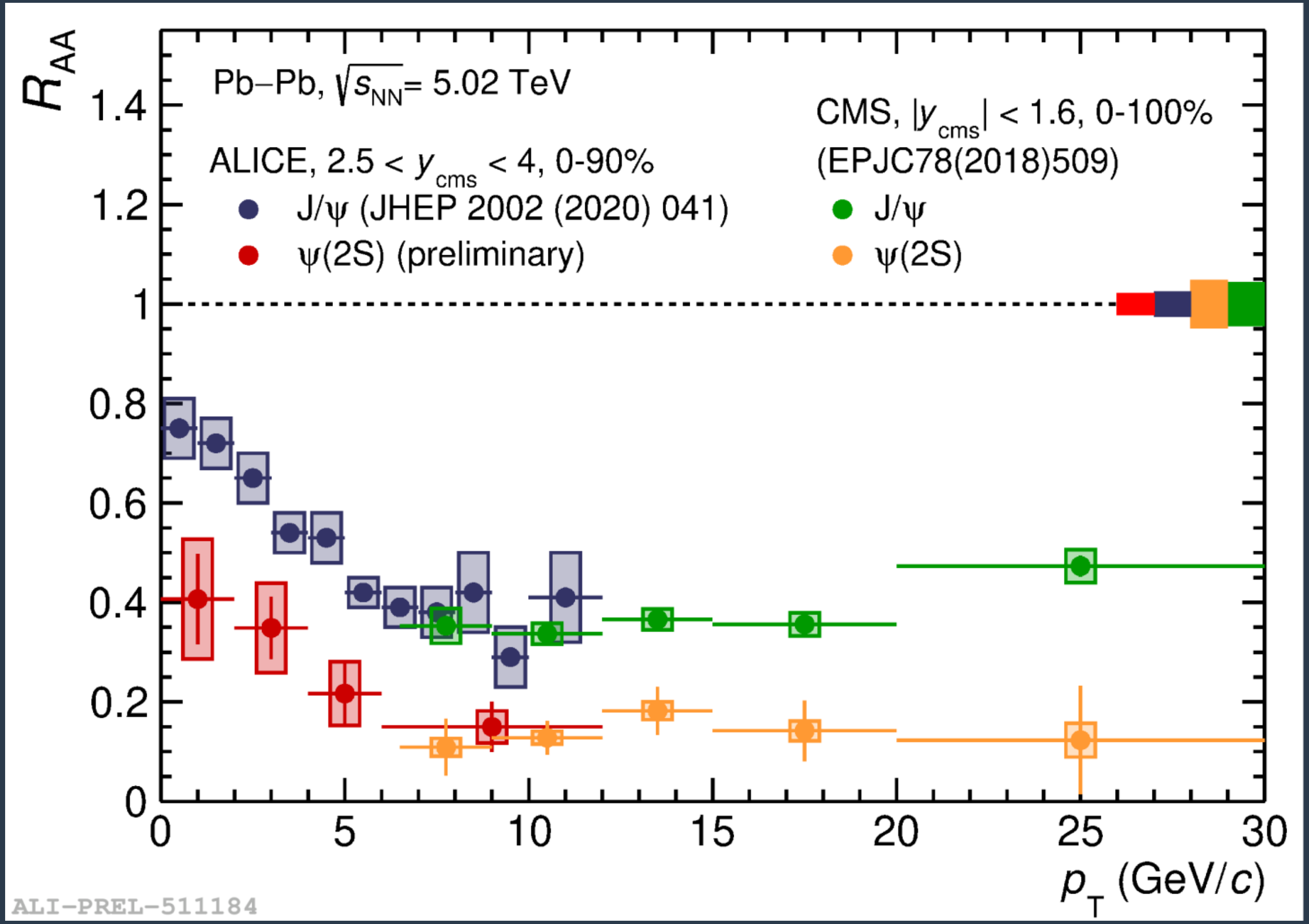


ψ(2S) R_{AA} vs centrality

- ✓ 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

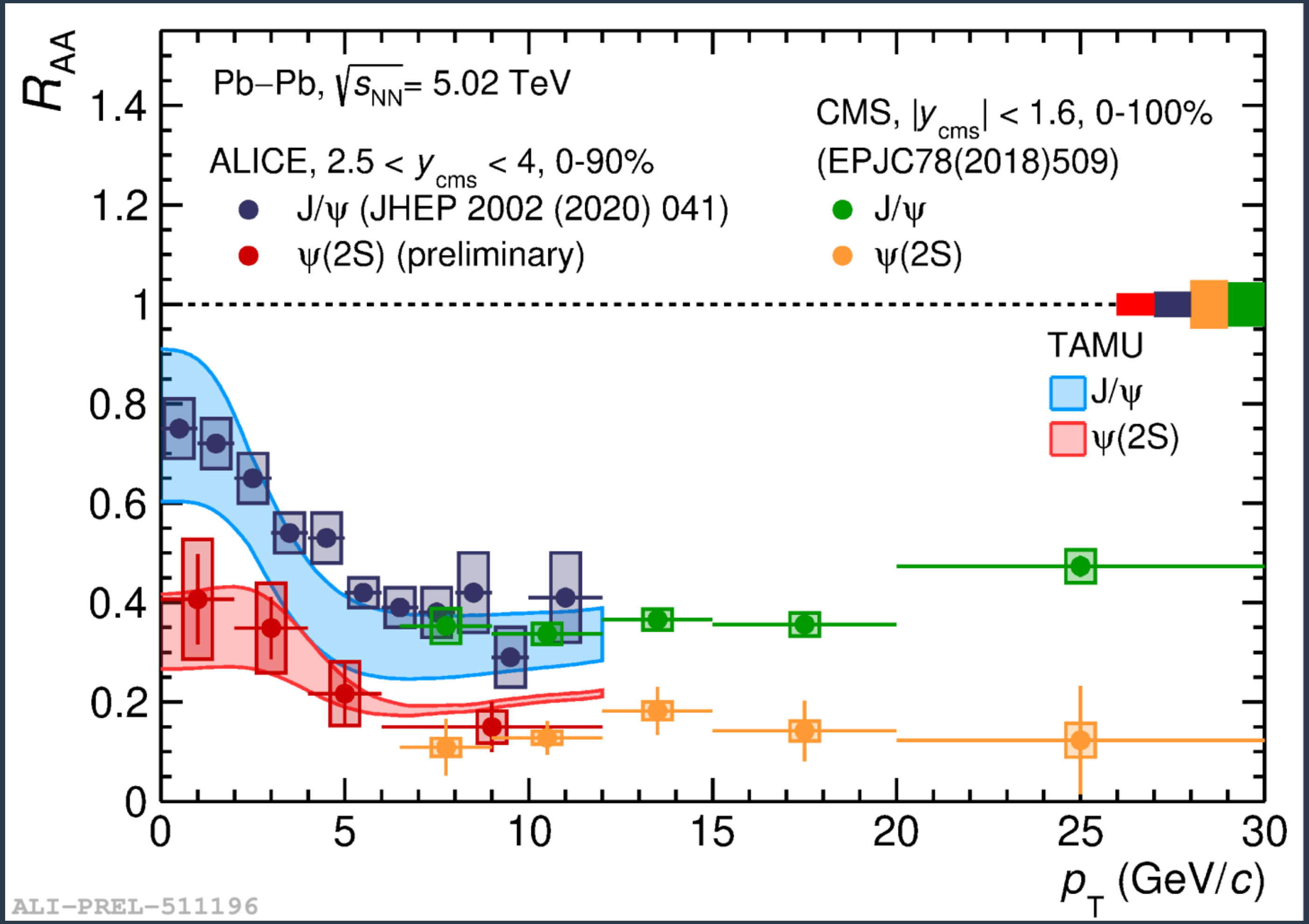


$\psi(2S)$ R_{AA} vs p_T



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

ψ(2S) R_{AA} vs p_T



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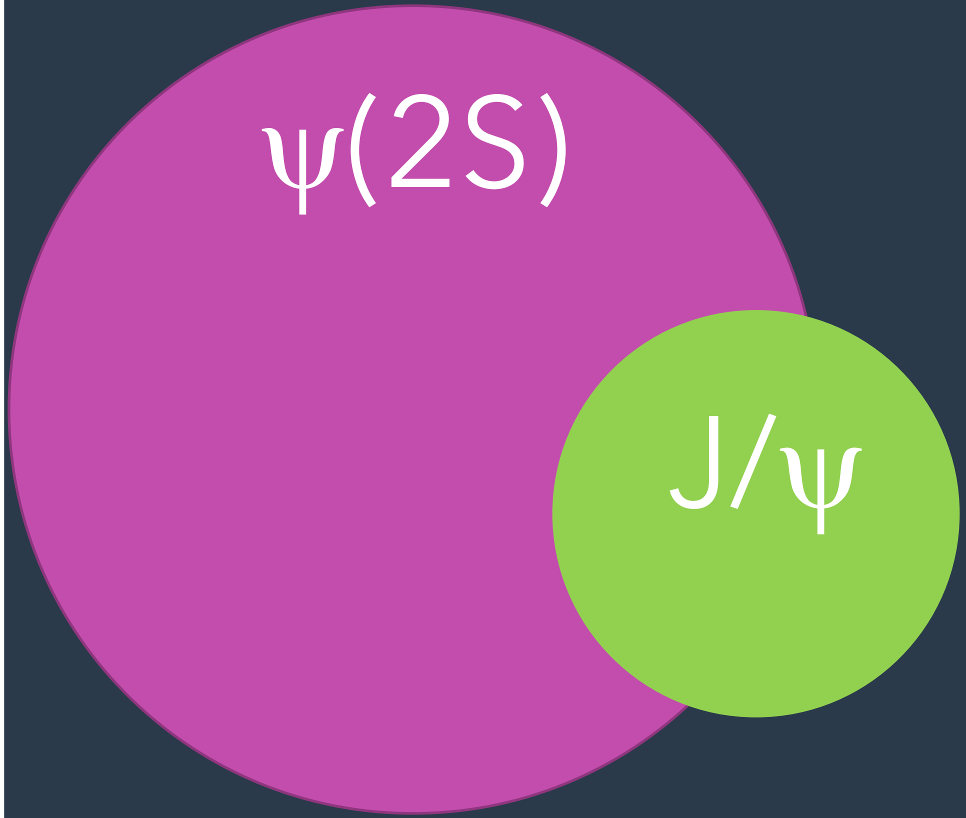
- ✓ Increasing trend of R_{AA} at low-p_T for both charmonium states
  → hint of ψ(2S) regeneration
- ✓ Good agreement between CMS and ALICE data in the common p_T range, regardless of the different rapidity coverage
- ✓ Transport model (TAMU) well reproduces J/ψ and ψ(2S) results, within uncertainties

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

Summary

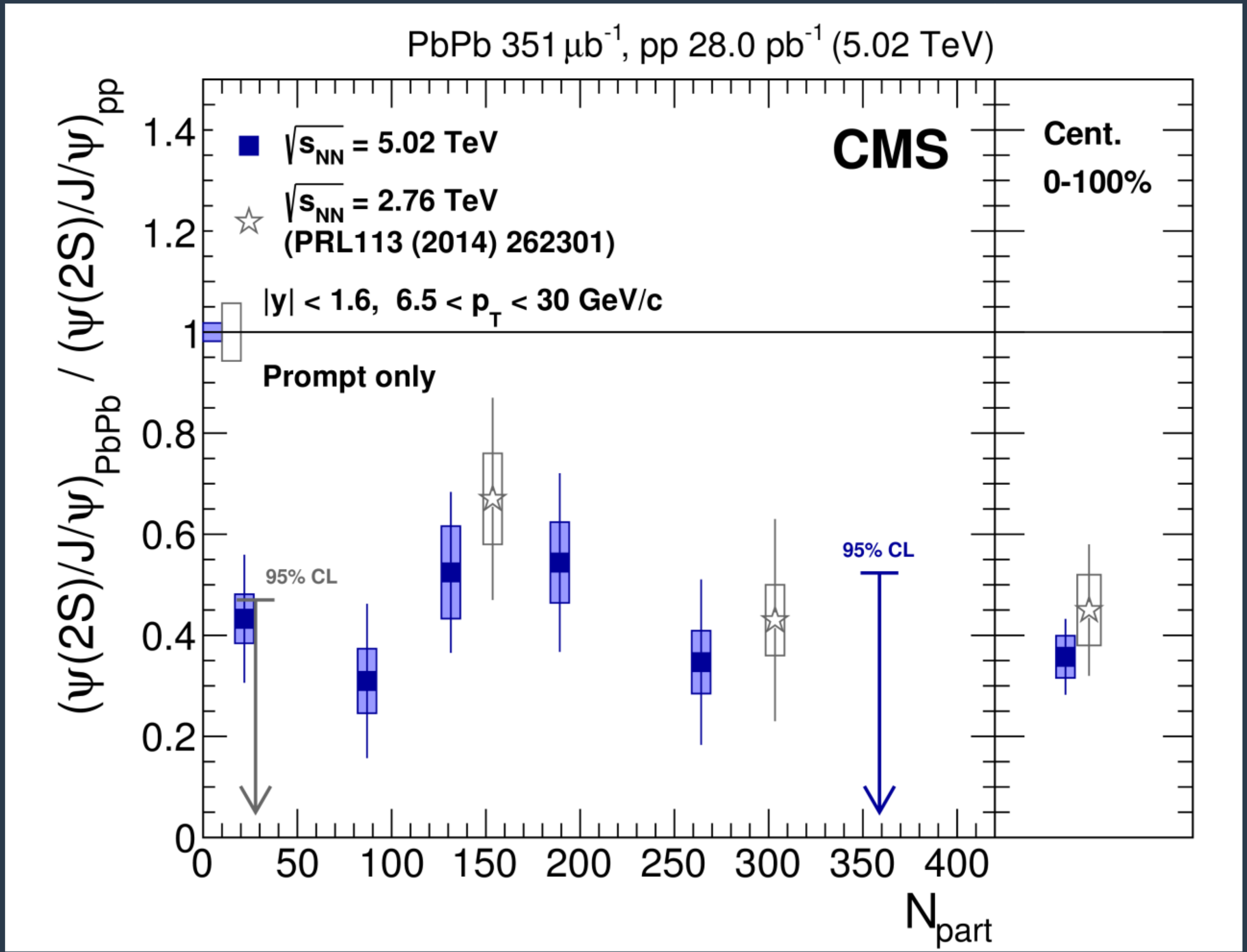
New precise $\psi(2S)$ measurements down to $p_T = 0$ in PbPb collisions at LHC



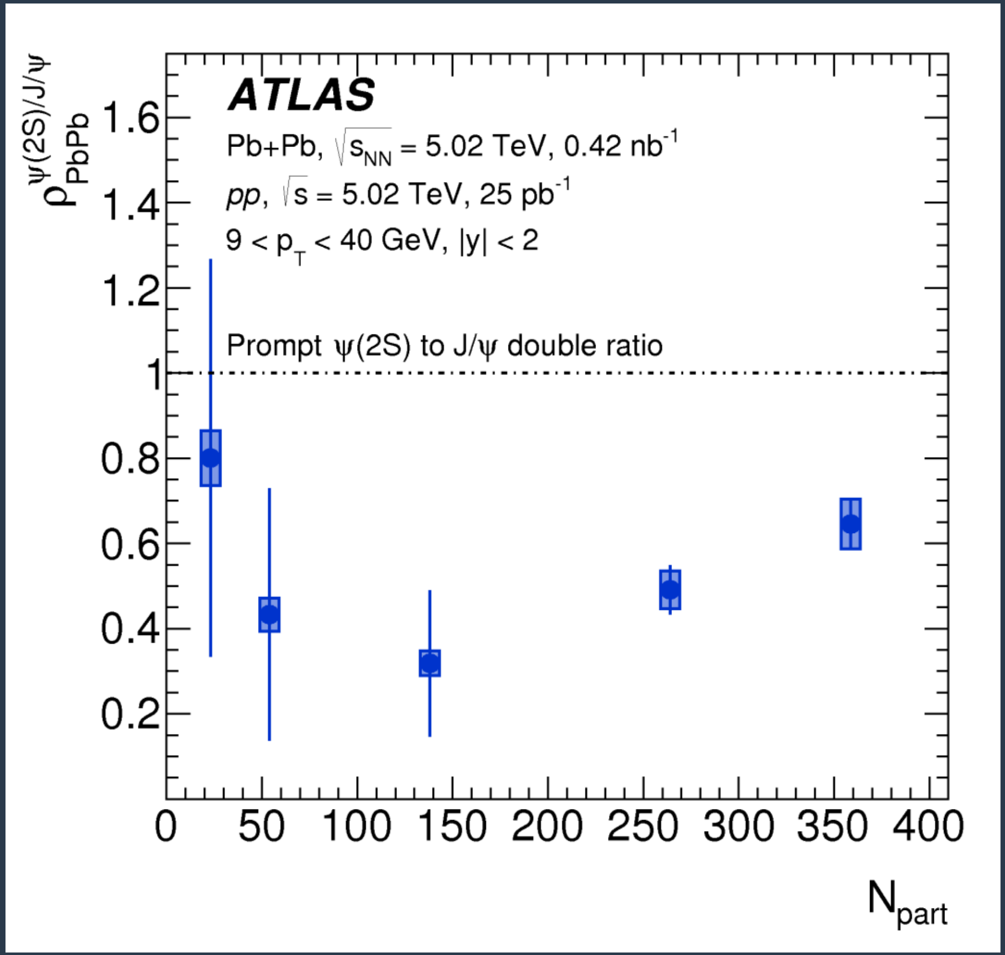
- ✓ Clear J/ψ and $\psi(2S)$ suppression hierarchy over p_T and centrality (~factor 2)
- ✓ Similar rise towards low p_T for both J/ψ and $\psi(2S)$, suggesting regeneration at play for both states
- ✓ Stronger $\psi(2S)$ suppression in central events, at low SPS energy
- ✓ Transport model fairly describes the results, while SHMc slightly overpredict the suppression in central collisions
- ✓ Looking forward Run 3 results!

Backup

$\psi(2S)$ & J/ψ at LHC energies

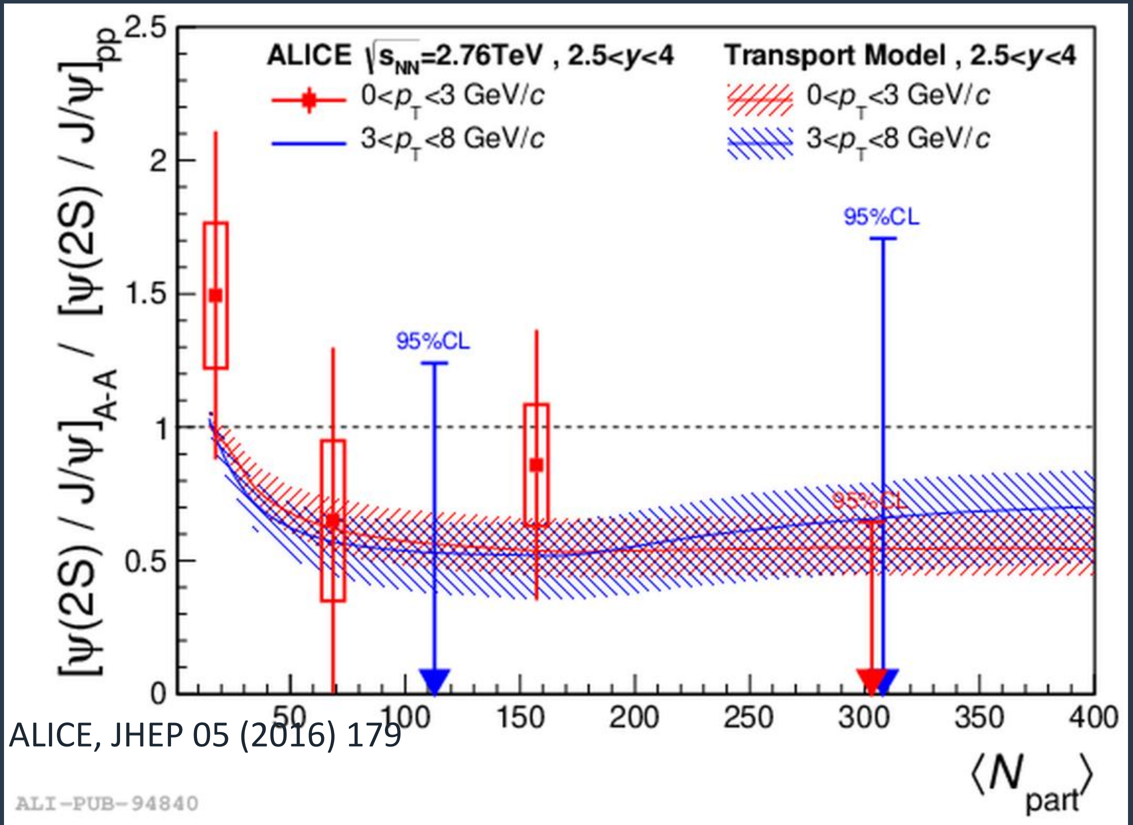


CMS, PRL 118 (2017) 162301

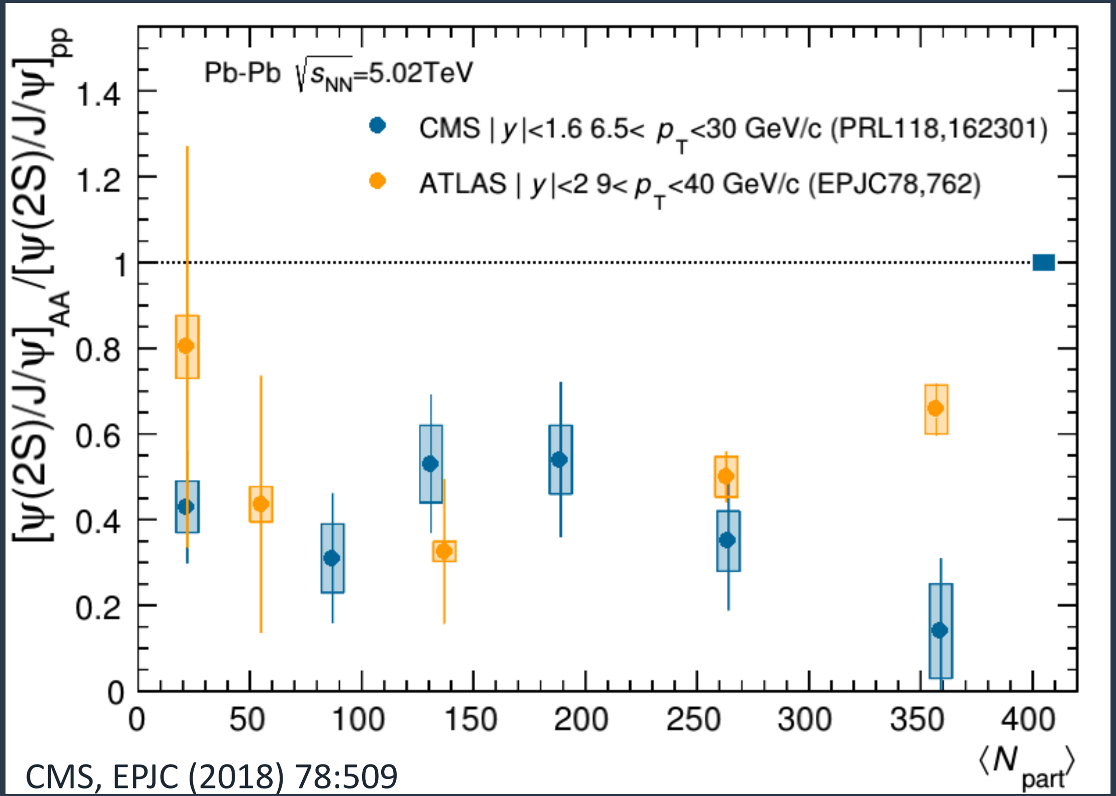


ATLAS, EPJC78 (2018) 762

ψ(2S) & J/ψ at LHC energies



ALICE, JHEP 05 (2016) 179



CMS, EPJC (2018) 78:509

Low p_T

ψ(2S) is strongly suppressed in central collisions, but size of uncertainties prevents a detailed comparison with J/ψ

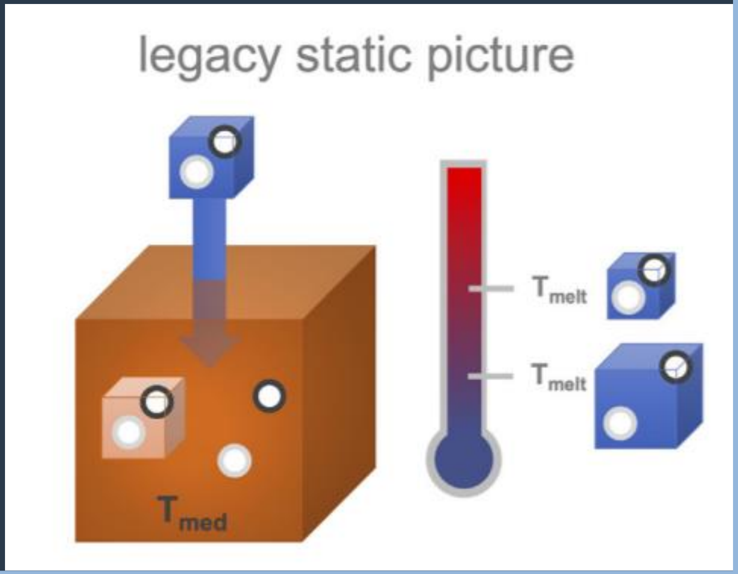
High p_T

Tension in central events between ATLAS and CMS?

Quarkonium as a probe

This intuitive suppression picture assumes static in-medium states

→ quarkonium as a thermometer of the system

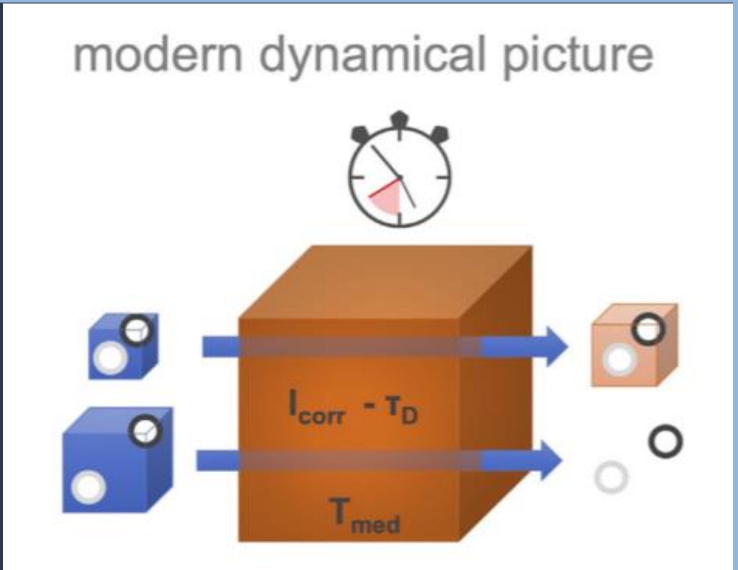


Recent theory developments introduce a dynamical approach

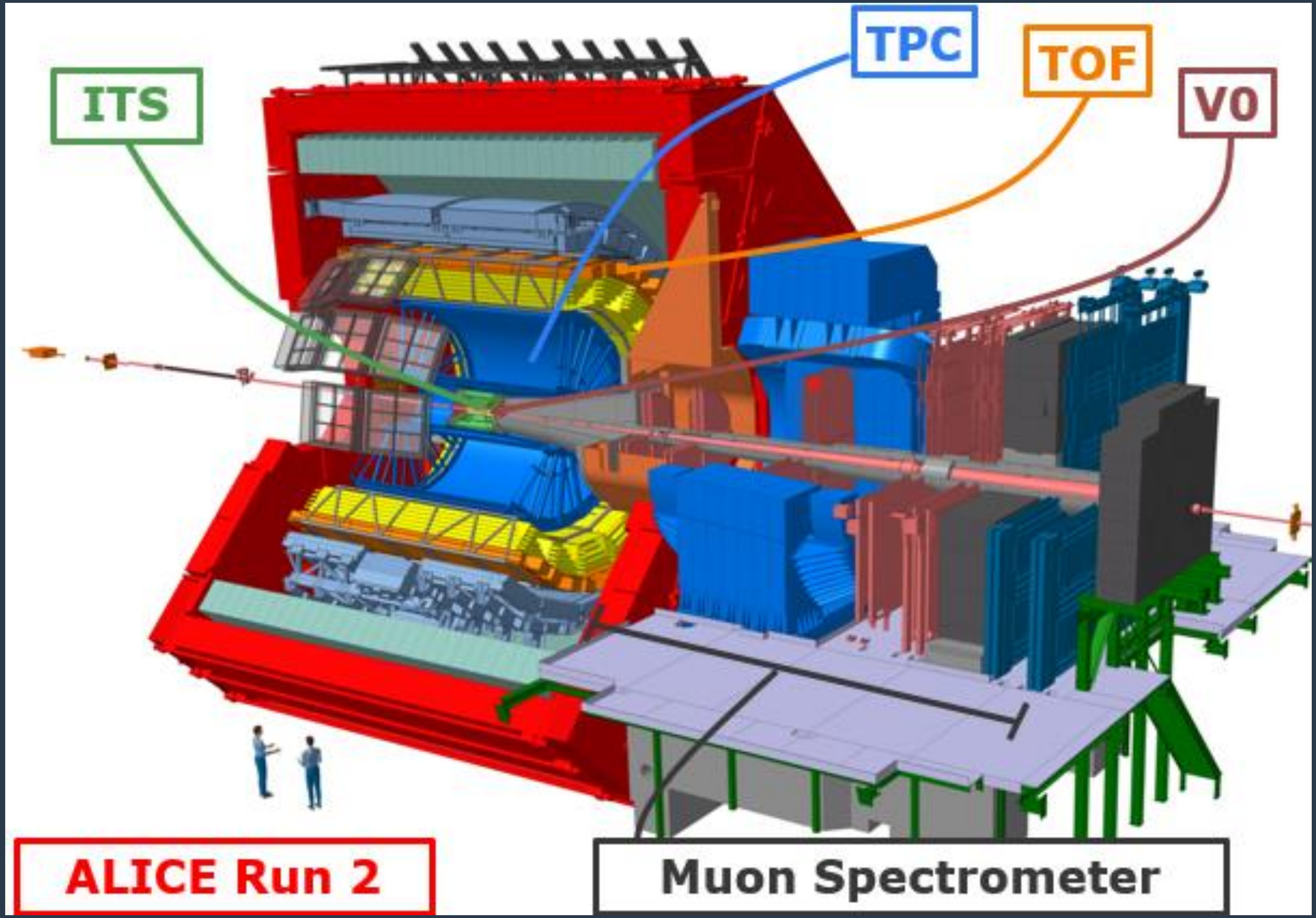
→ quarkonium survival depends on how strongly it interferes with the medium and on the time spent in the medium

→ medium as a "sieve" that filters quarkonia, over time, depending on the strength of their binding

A. Rothkopf, Physics Reports 858 (2020)



ψ(2S) in ALICE



Inclusive quarkonium

Central barrel (ee, |y|<0.9)

Muon spectrometer (μμ, 2.5<y<4)

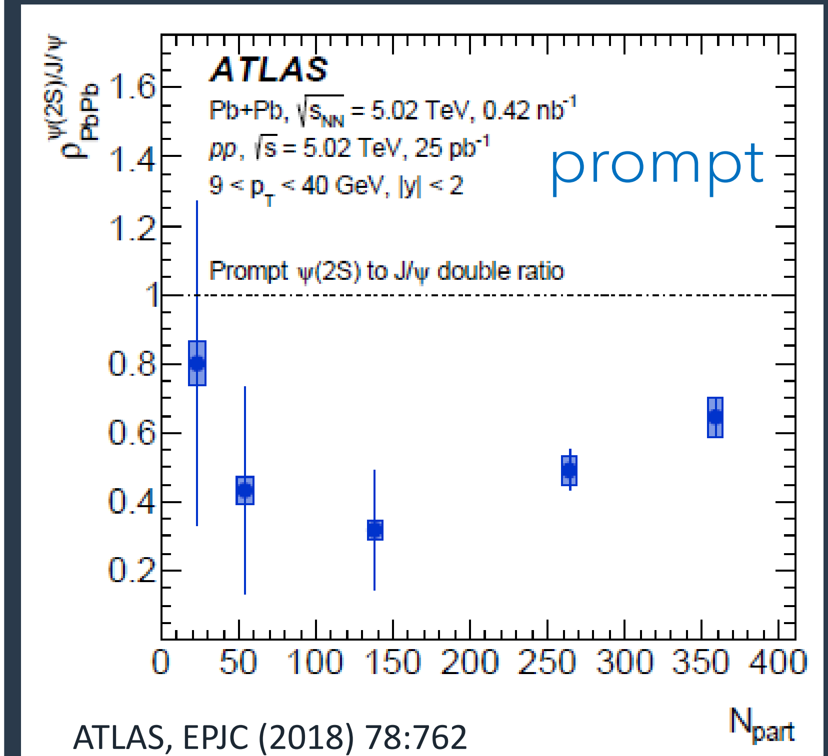
Coverage **down to zero p_T**

ψ(2S) results were obtained **at forward rapidity**

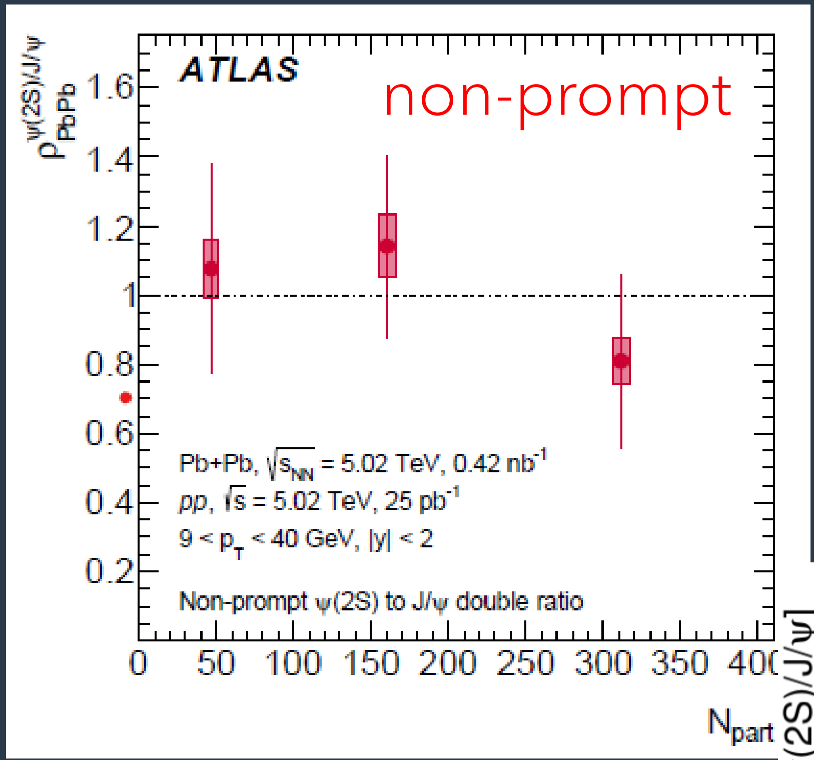
(Di)muon trigger selects track candidates with p_T> 1 GeV/c in Pb-Pb collisions

LHC Run 2 → L_{int} ~ 750 μb^{-1}

ψ(2S) at LHC energies

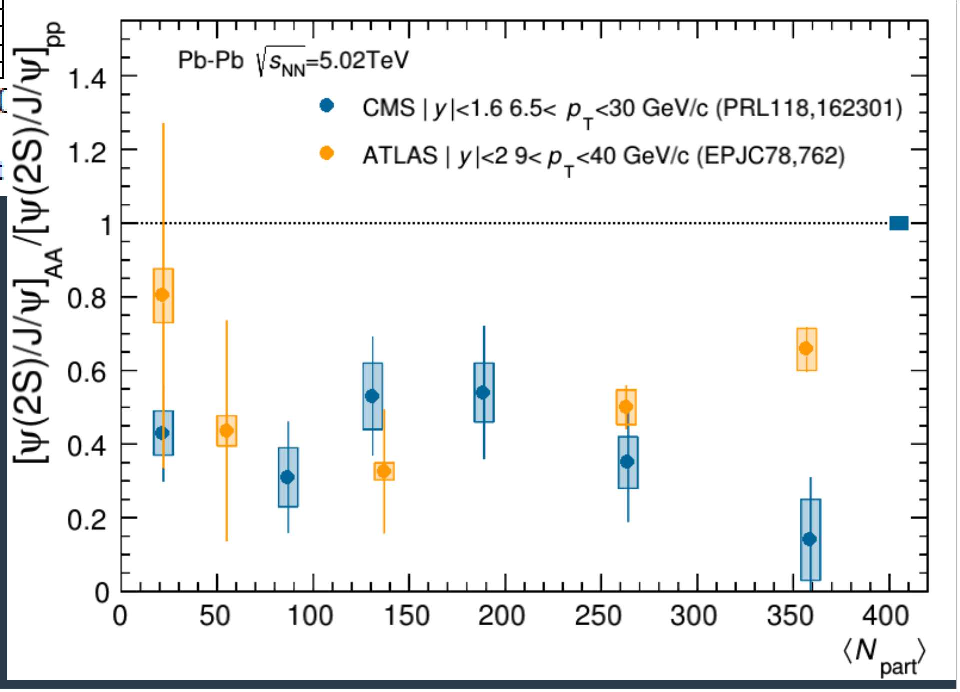


ATLAS, EPJC (2018) 78:762



High p_T

Strong prompt ψ(2S) suppression observed also by ATLAS, while non-prompt ψ(2S)-to-J/ψ consistent with unity



Tension in central events between ATLAS and CMS?