Recent ALICE results on $\psi(2S)$ production

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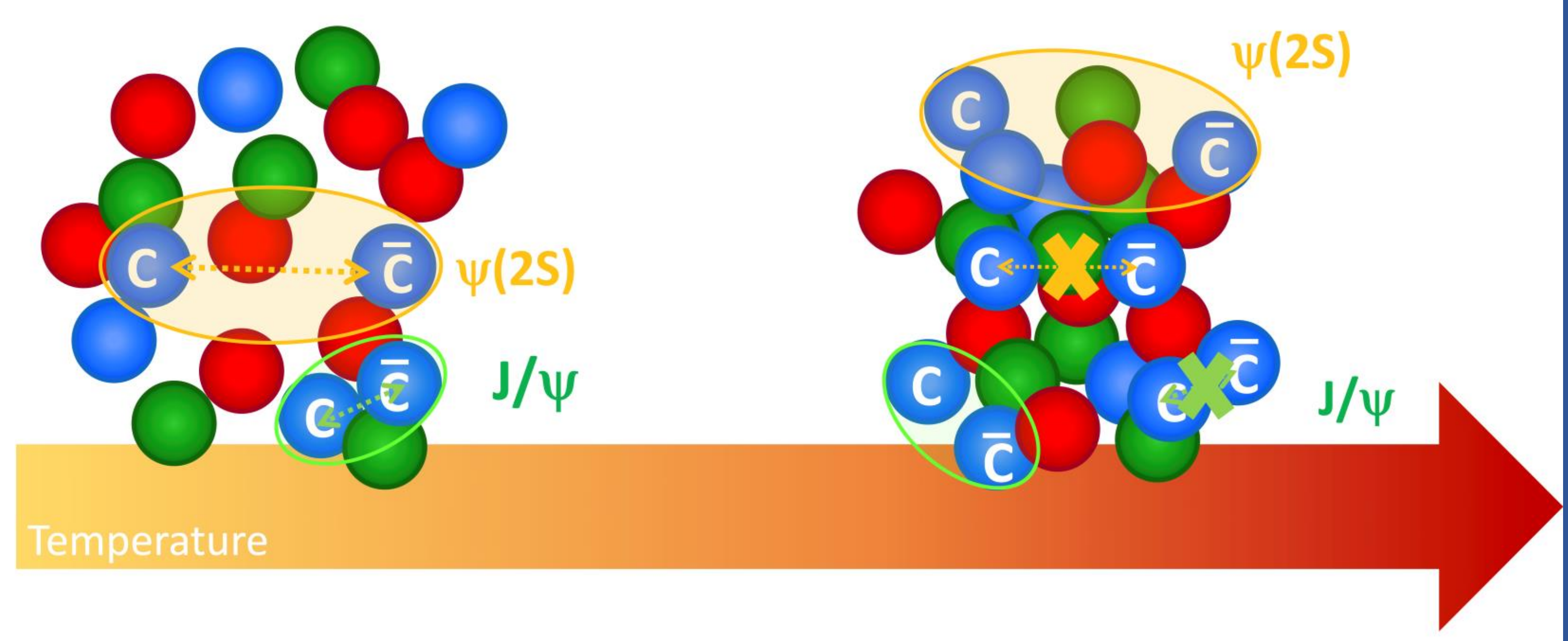
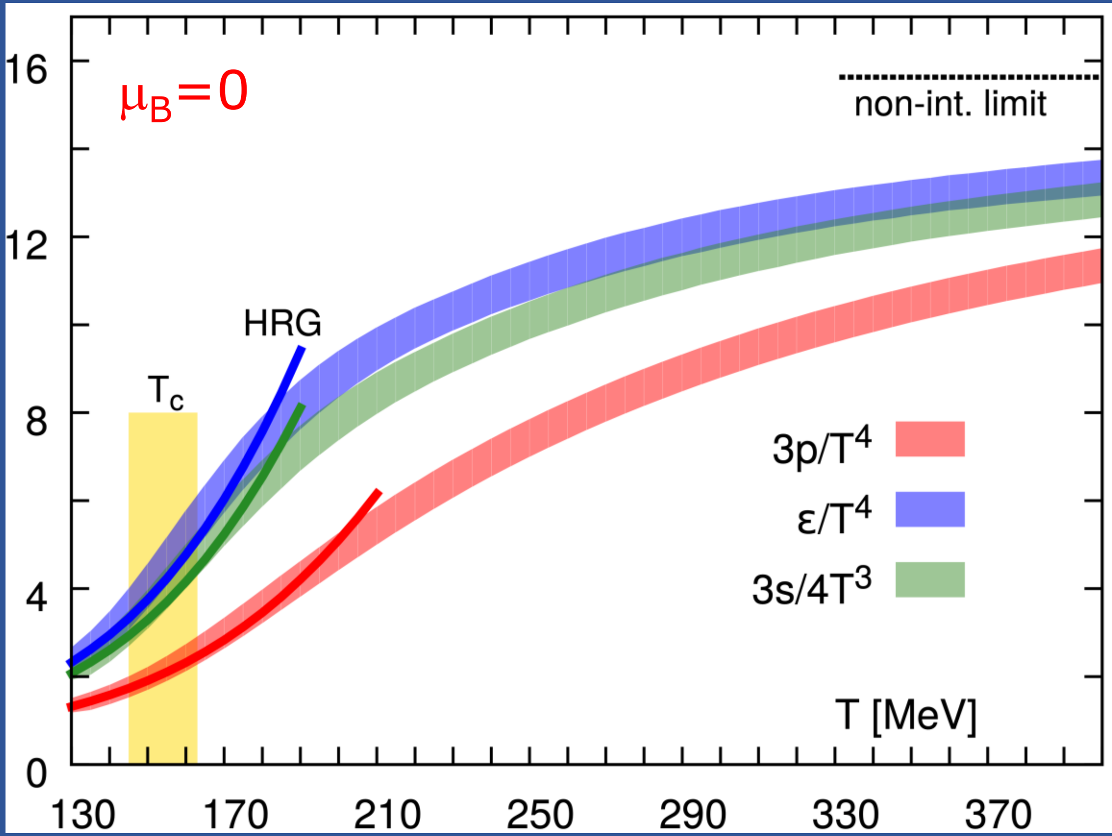
for the ALICE Collaboration

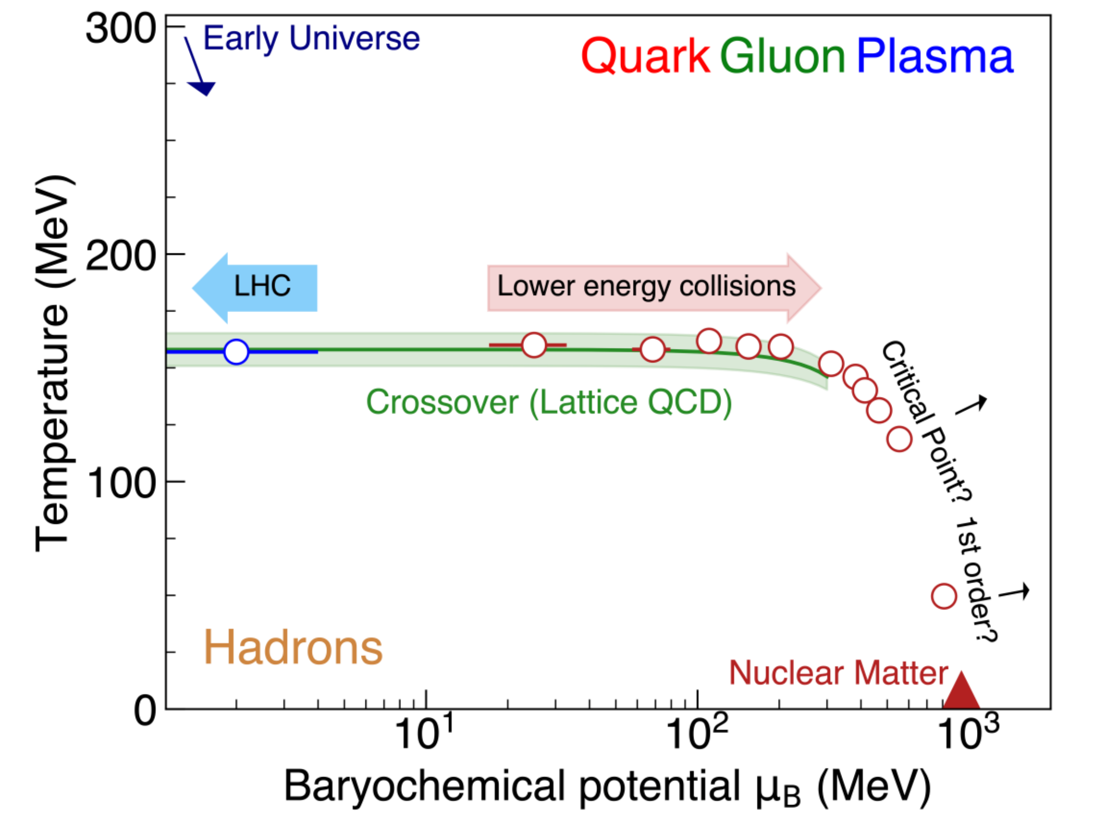
- Quarkonia in the QGP: ground and excited states
- $\psi(2S)$ studies from SPS to LHC energies
- ALICE: analyze $\psi(2S)$ behaviour from large to small systems
- Prospects for Run 3



Discovering and analyzing the properties of the quark-gluon plasma (QGP)

A. Bazavov et al.,Phys. Rev. D 90 (2014) 094503

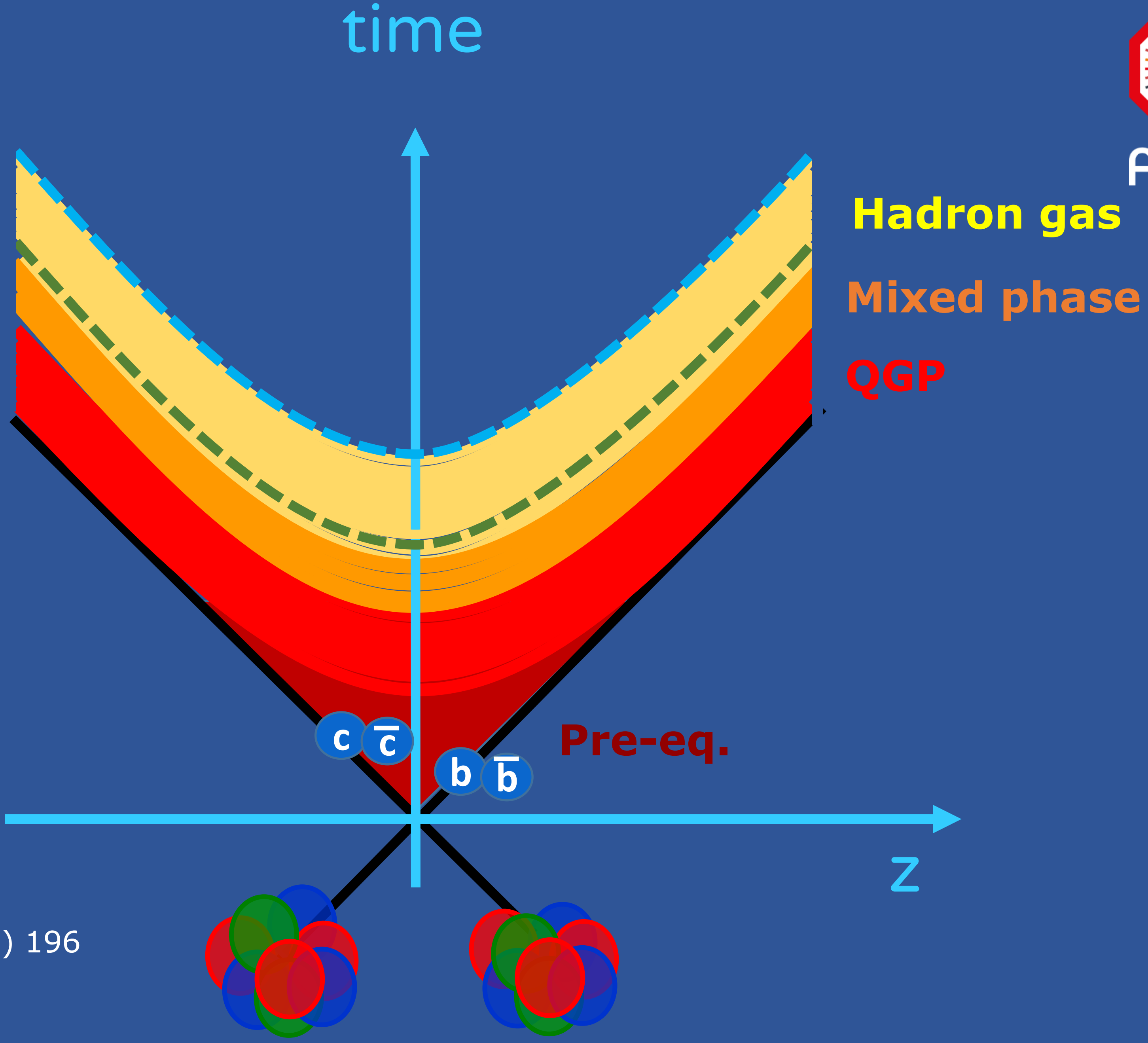




- Quarkonium properties are strongly affected by the QGP. How ?

Quarkonium

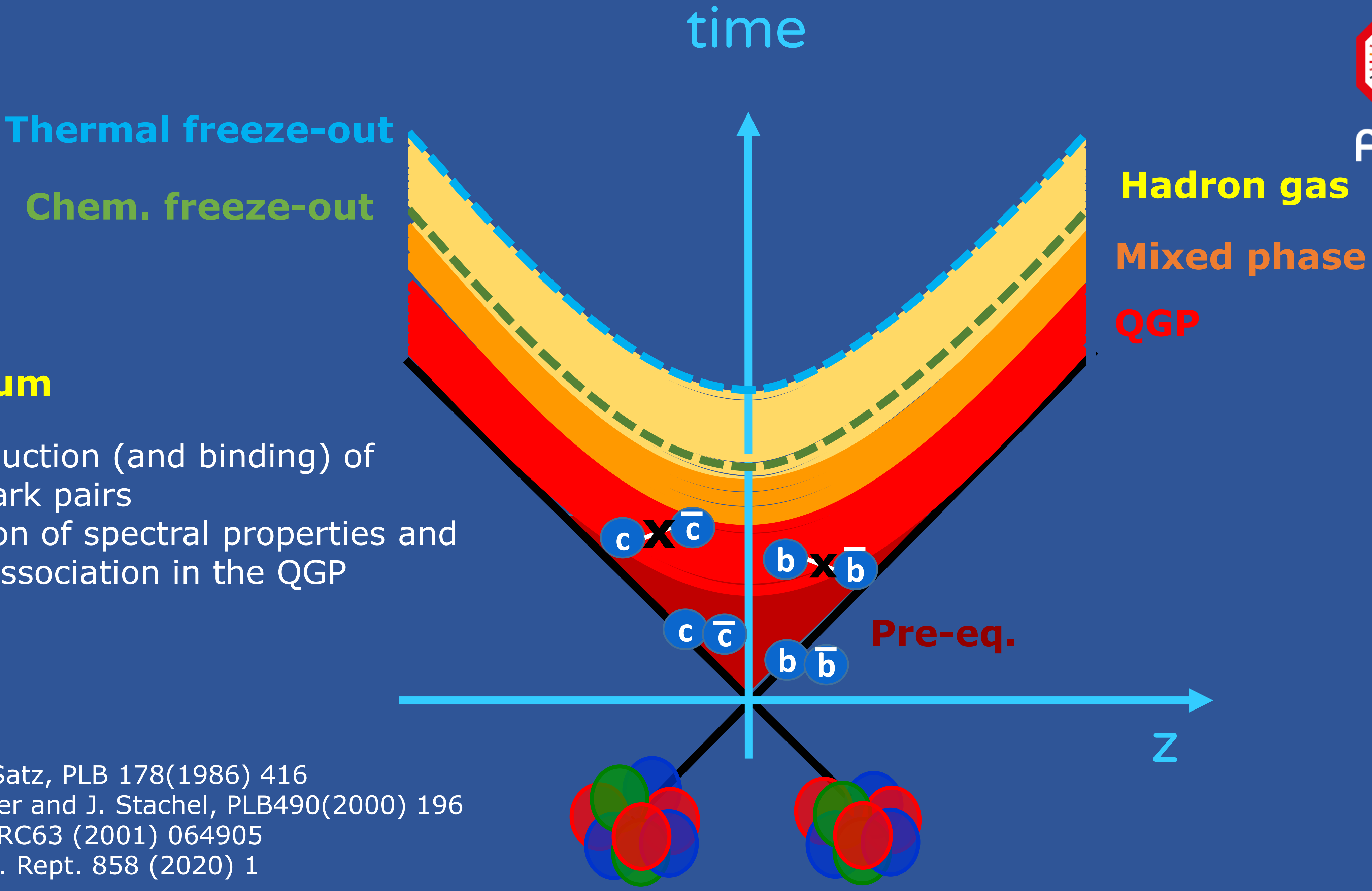
- Early production (and binding) of heavy quark pairs



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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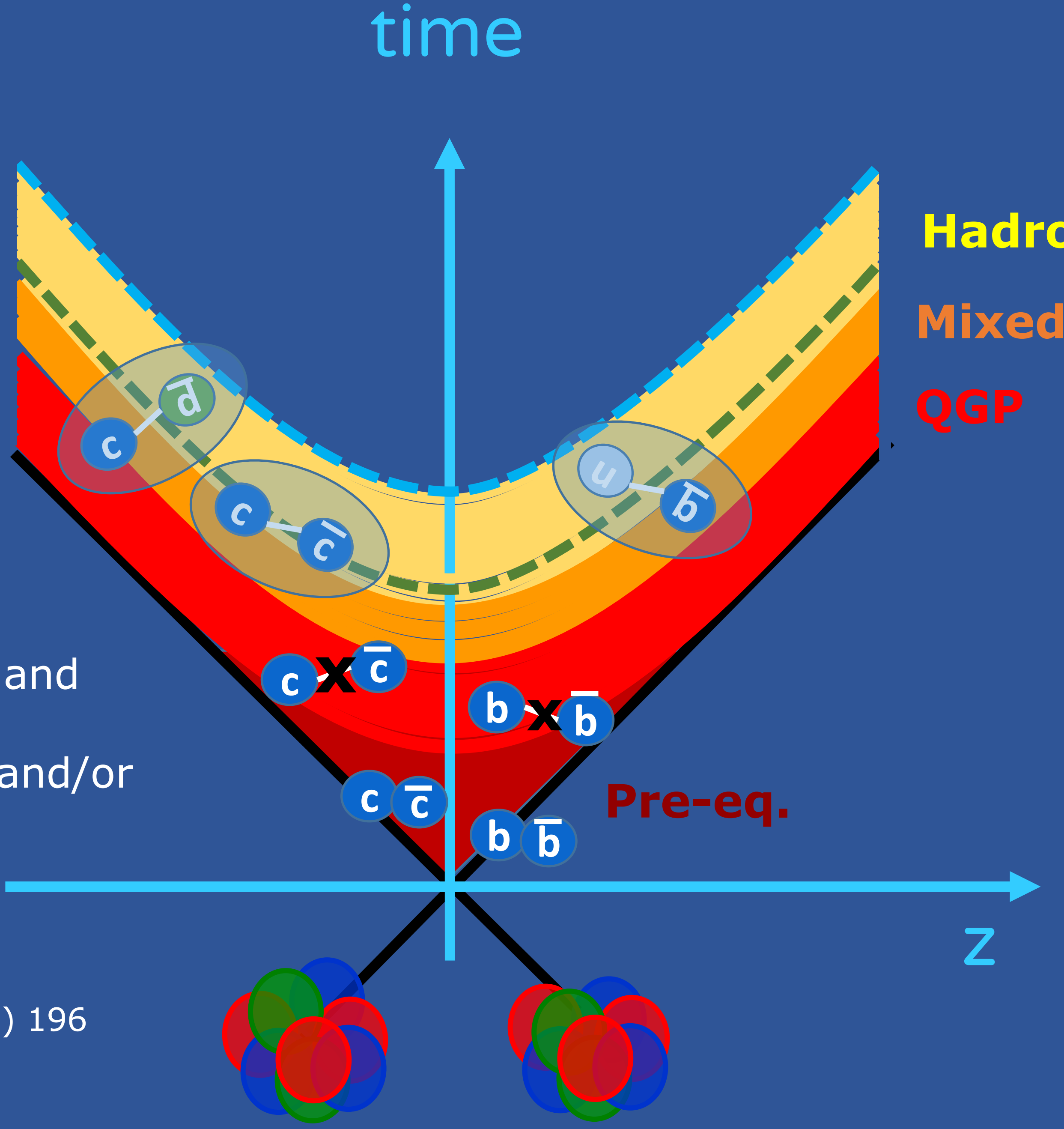
R. Thews et al., PRC63 (2001) 064905
A. Rothkopf, Phys. Rept. 858 (2020) 1

Quarkonium

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



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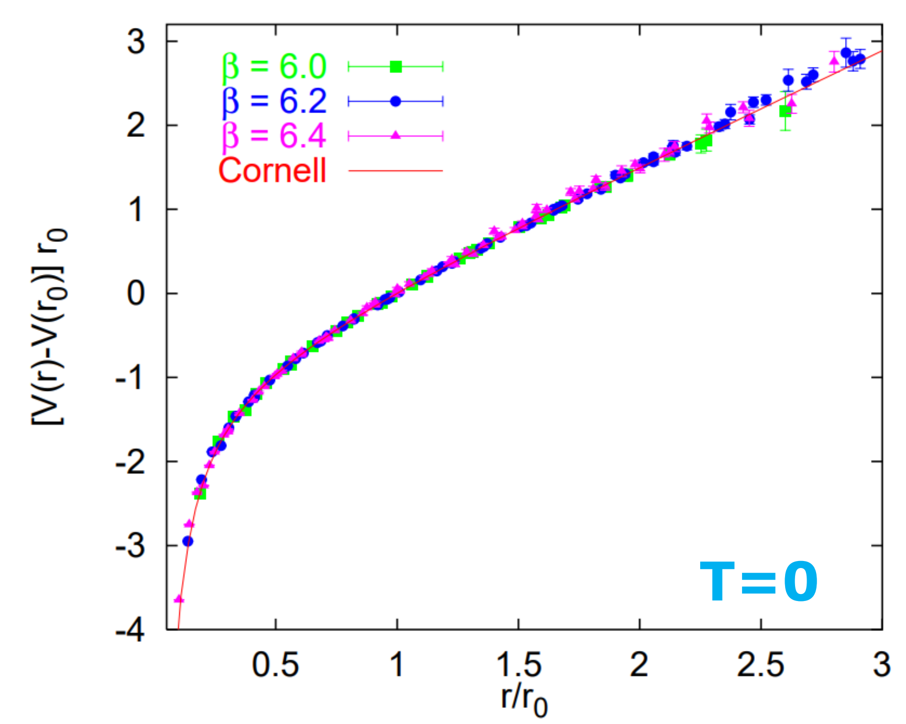
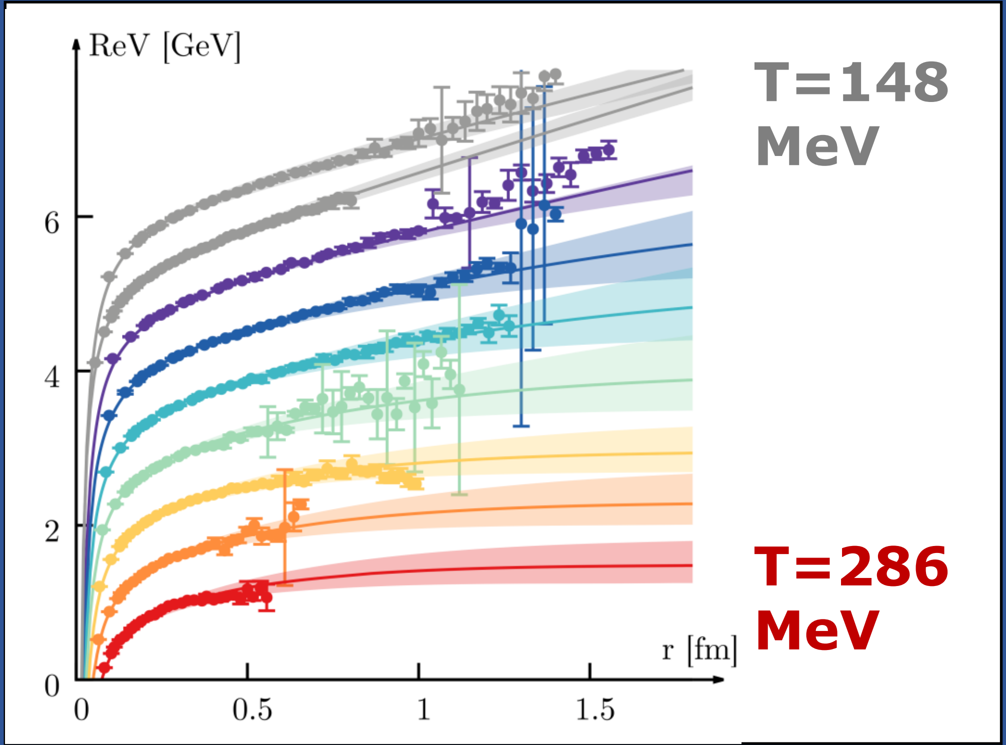
R. Thews et al., PRC63 (2001) 064905
A. Rothkopf, Phys. Rept. 858 (2020) 1

Modification of spectral properties and dissociation

G.S. Bali, Phys. Rep. 343 (2001) 1-136



Lafferty and Rothkopf, Phys. Rev. D 101 (2020) 056010

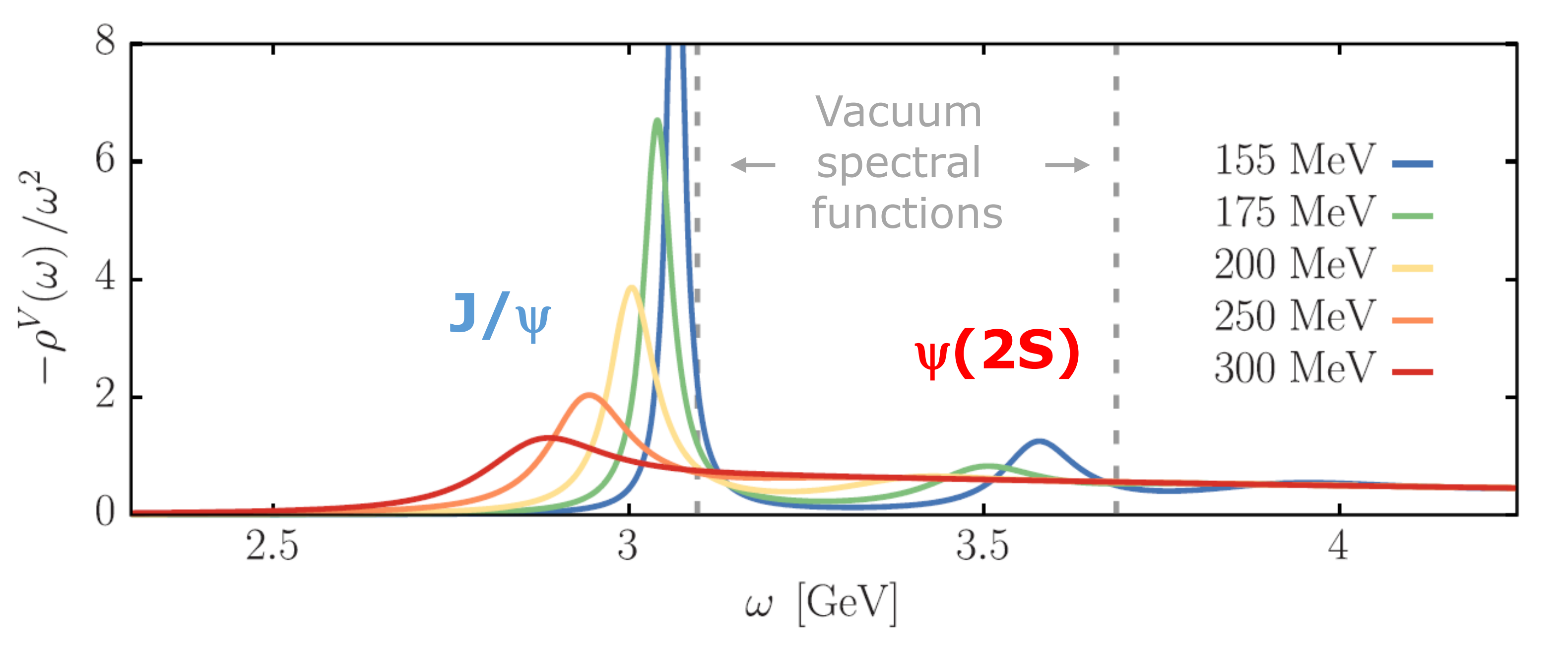


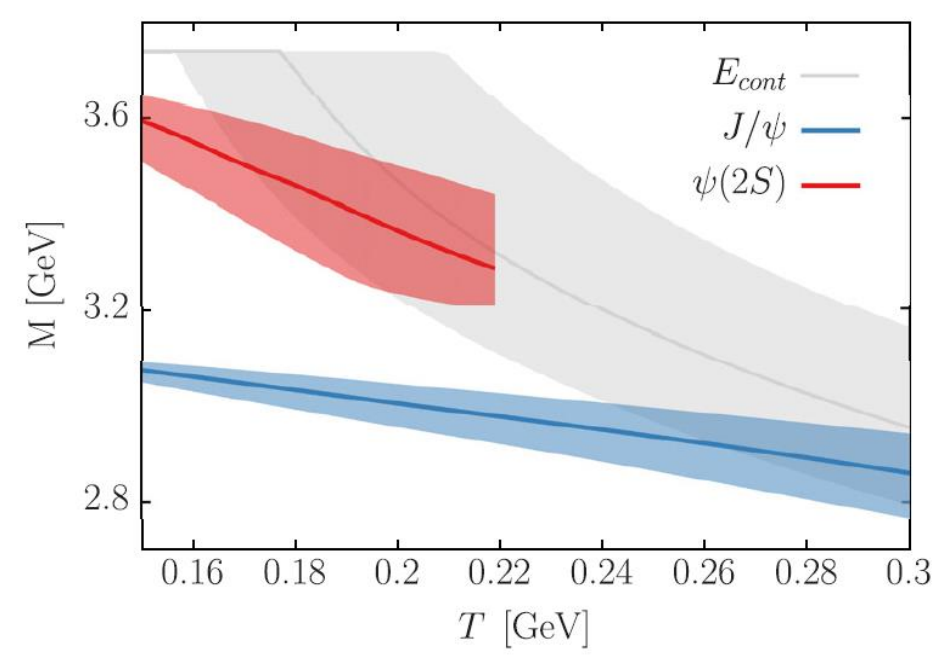
Potential models provide a faithful reproduction of available lattice data

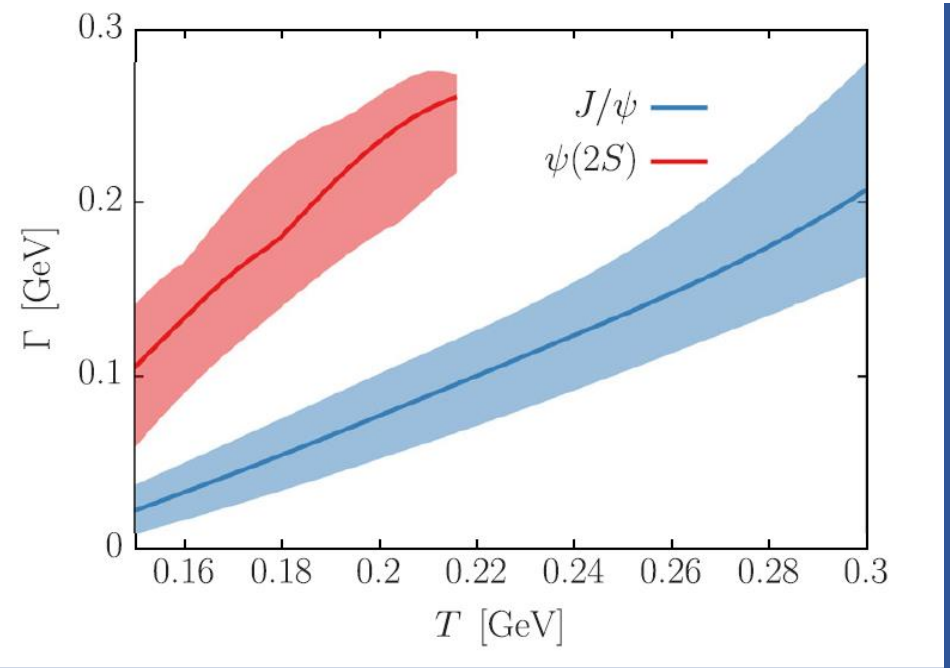
- Gradual transition **from a Cornell to a Debye-screened behaviour** for the (real part of) the potential → **color screening** in a deconfined medium
- Potential also has a finite imaginary part (not shown)
  → decaying of quark-antiquark correlation due to gluonic damping in the plasma

Modification of spectral properties and dissociation

Lafferty and Rothkopf, Phys. Rev. D 101 (2020) 056010



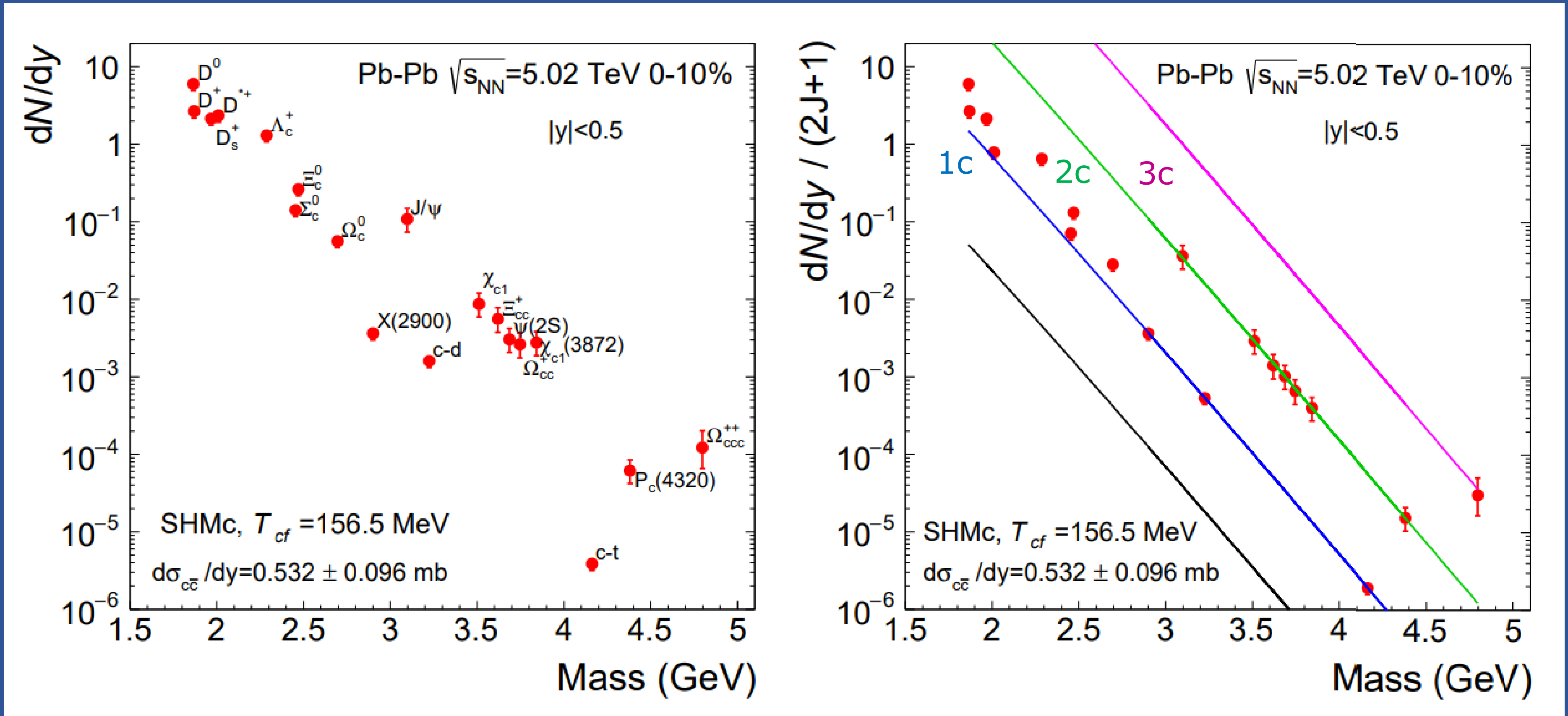




- ❑ Strong effects on the **mass AND width** of the charmonium states, with distinctive **differences between J/ψ and ψ(2S)**
- ❑ As intuitively expected, the more deeply the state is bound, the less is susceptible to medium effects

(Re)generation of quarkonia

- **Statistical Hadronization model** (SHM) has proved to be quite successful in determining the abundances of light hadrons and nuclei in A-A collisions
- Extended to the charm sector (SHMc), assuming thermal distributions and fixing the total charm content of the fireball to the measured charm cross section

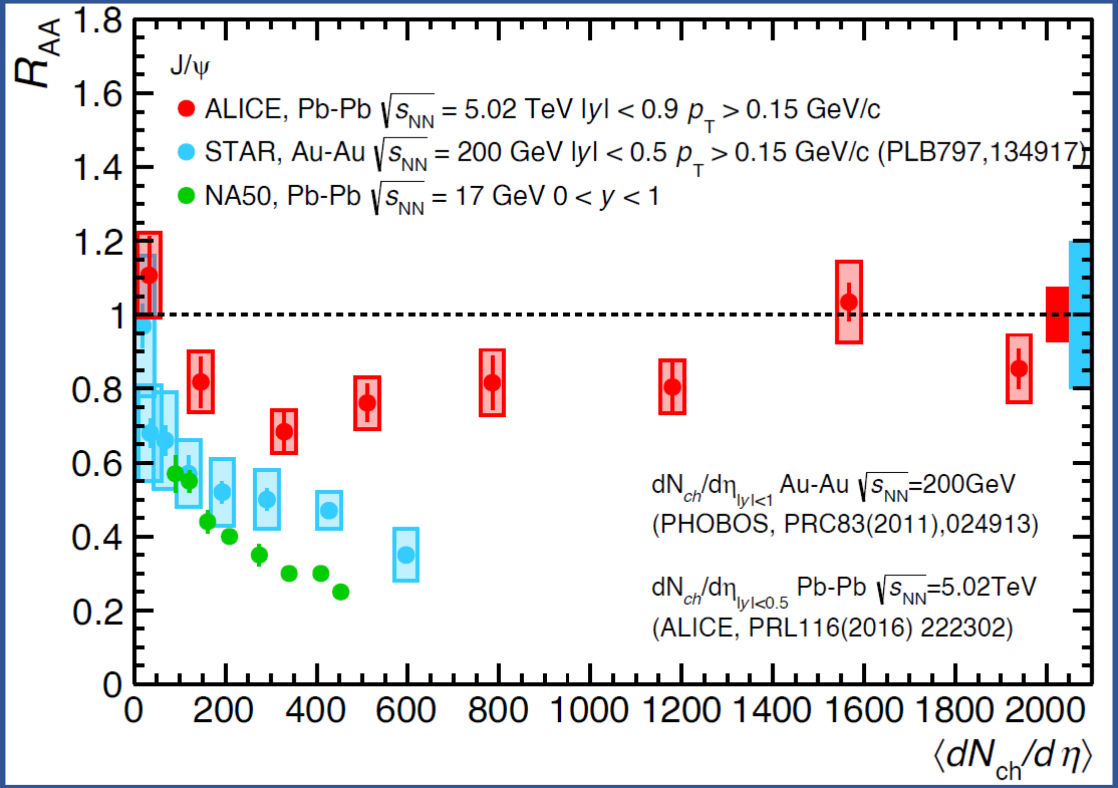


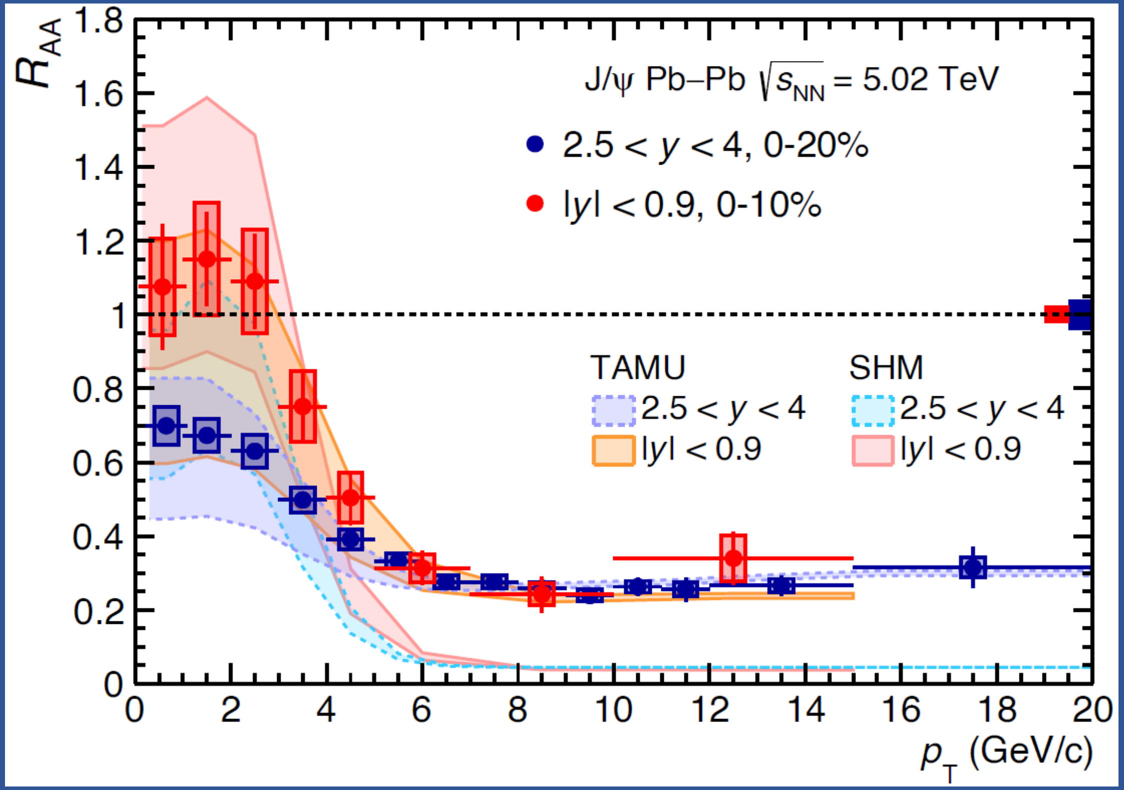
Allows **quantitative predictions** for charmed hadron yields, including quarkonia

A. Andronic et al., JHEP 07 (2021) 035

J/ψ results at LHC energy

ALICE, arXiv:2211.04384





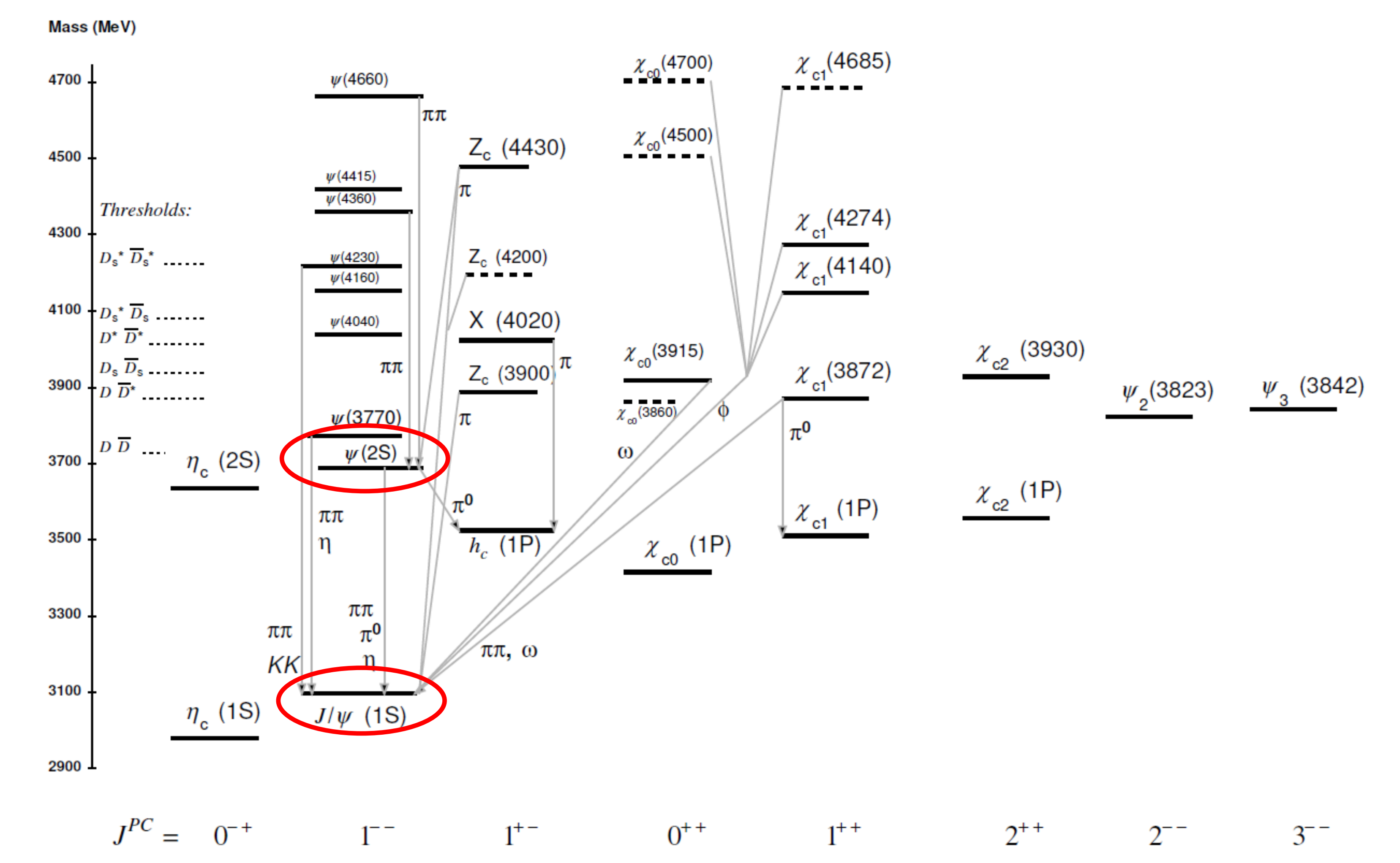
- ❑ Hierarchy of suppression: $R_{AA}^{SPS} < R_{AA}^{RHIC} < R_{AA}^{LHC}$
- ❑ Reduced (or no) suppression at small p_T

Signature of (re)generation

- ❑ Agreement with models where J/ψ is generated at the freeze-out (SHMc) or suppressed and regenerated continuously during the QGP evolution (TAMU)

ψ(2S) vs J/ψ

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



R.L. Workman et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022)

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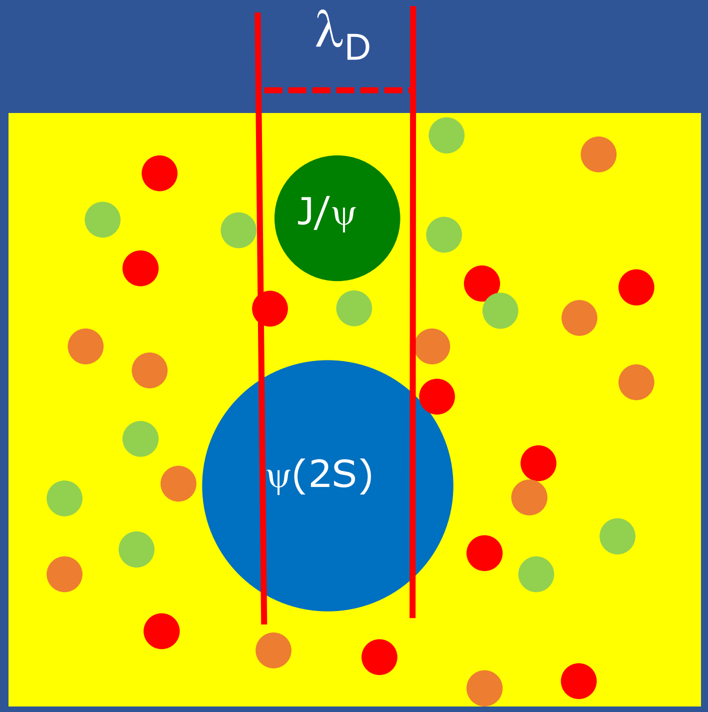
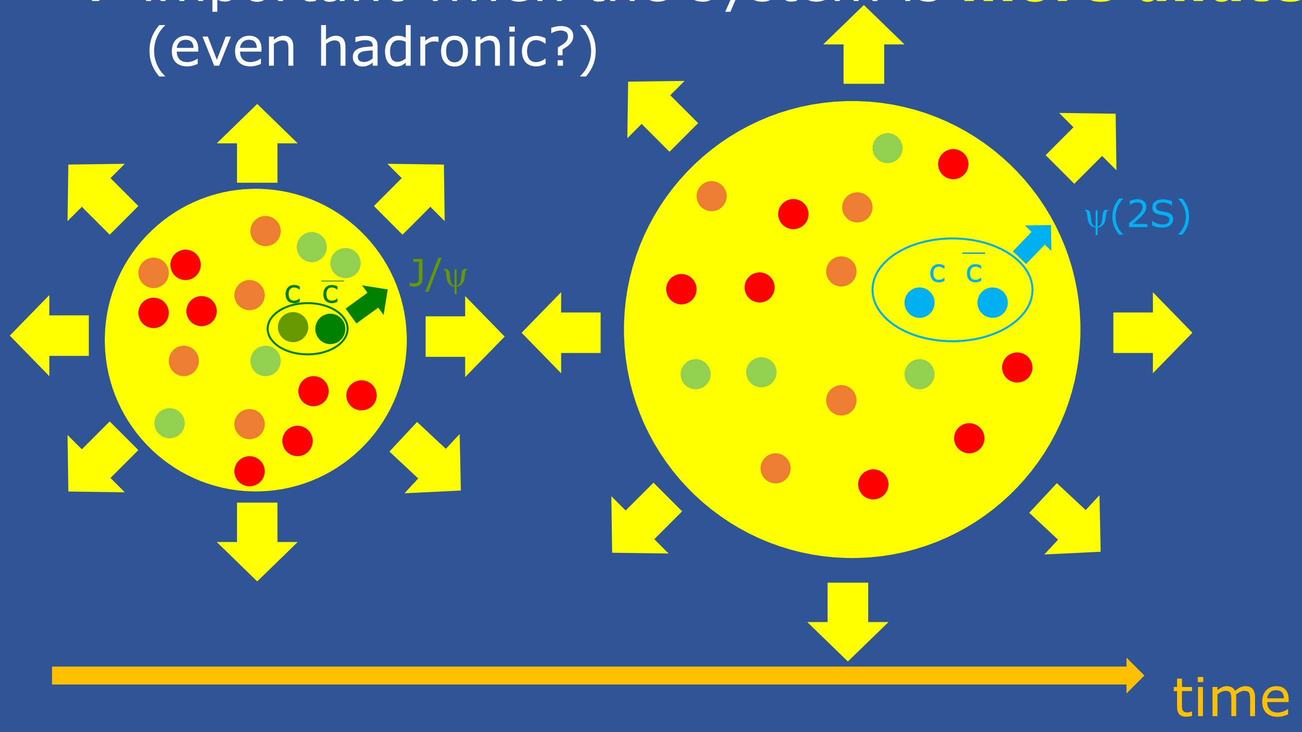


- Expect **much stronger dissociation effects** for the weakly bound ψ(2S) state

- Effect of re-combination on ψ(2S) more subtle
  → important when the system is **more diluted** (even hadronic?)

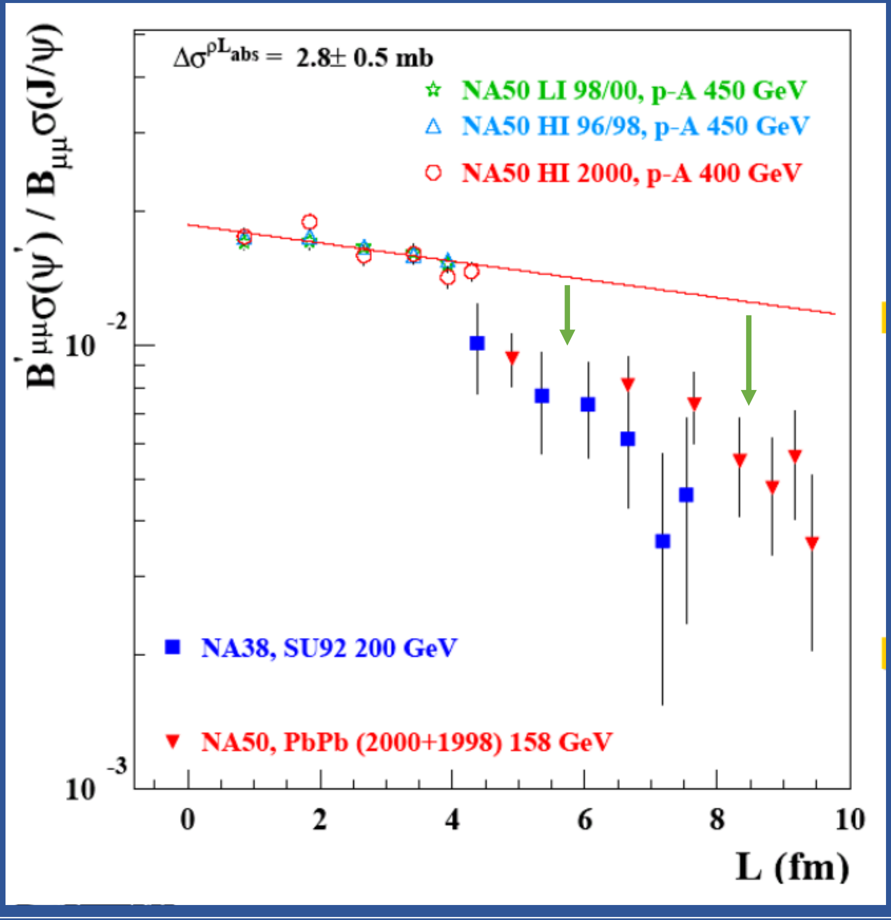


Important for a quantitative test of models!

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)

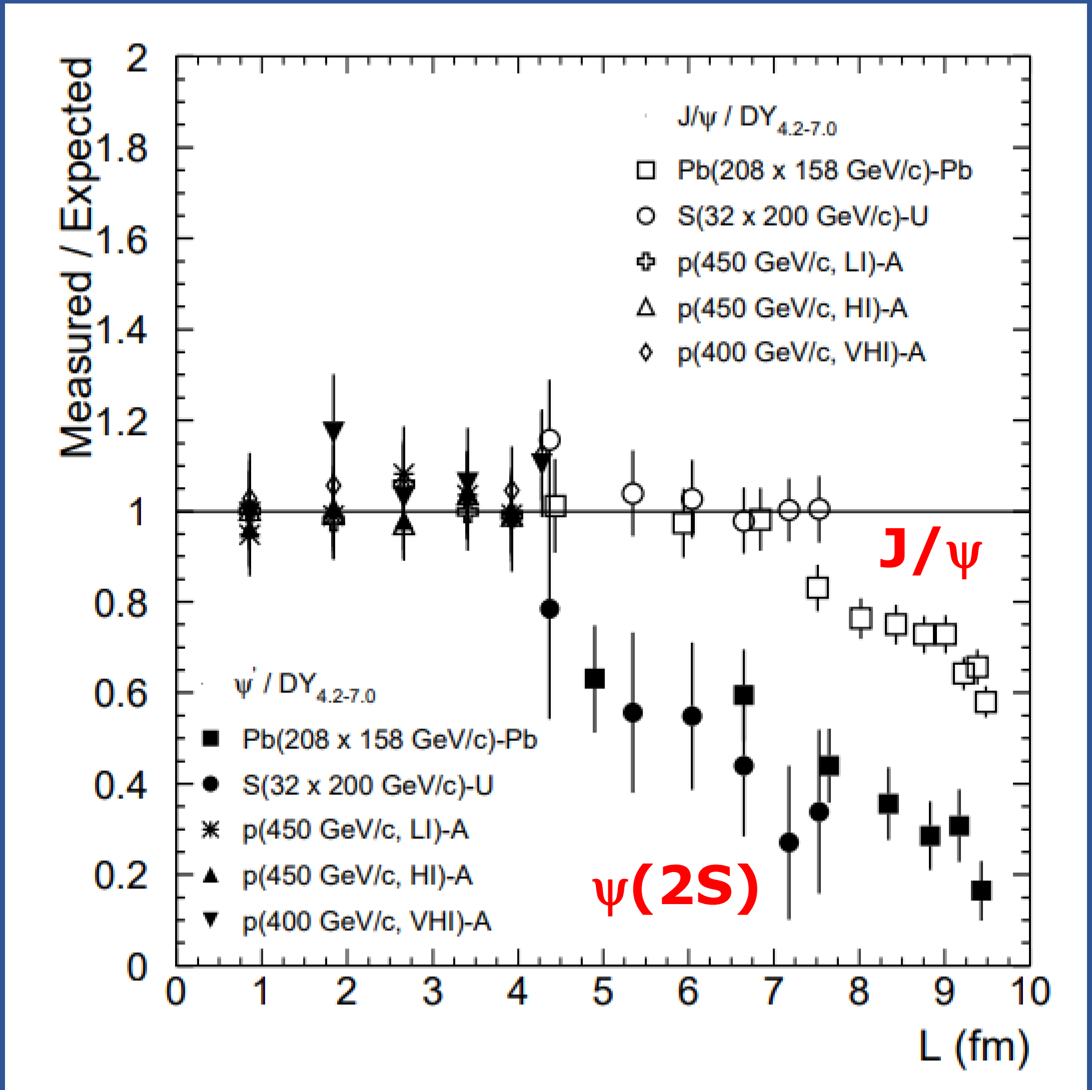
NA50, EPJC49 (2007) 559



- **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



- After correcting for cold nuclear matter effects
- ψ(2S) "hot-matter" suppression
  - is **stronger than the J/ψ** one
  - **sets in at lower energy densities**
    → 1.5 GeV/fm³ wrt ~2.5 GeV/fm³ for the J/ψ
  - is already present in light-ion collisions (S-U)

NA50, PLB477 (2000) 28
NA50, EPJC49 (2007) 559

A-A results at SPS energies

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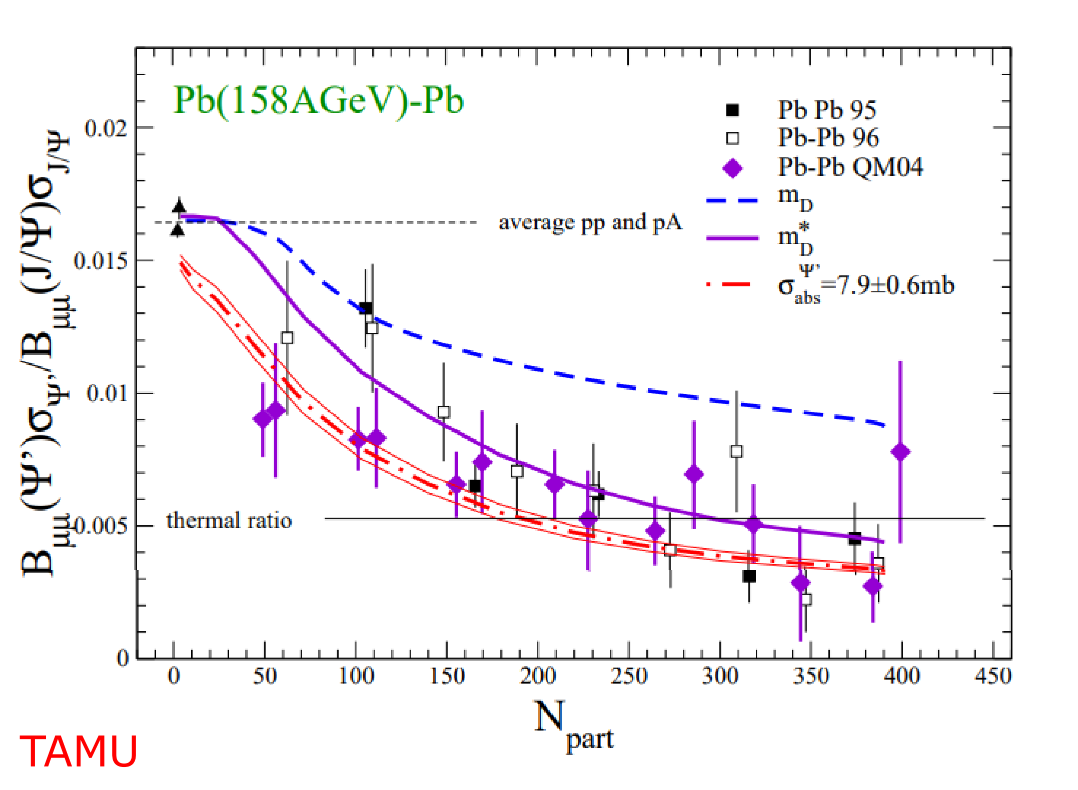
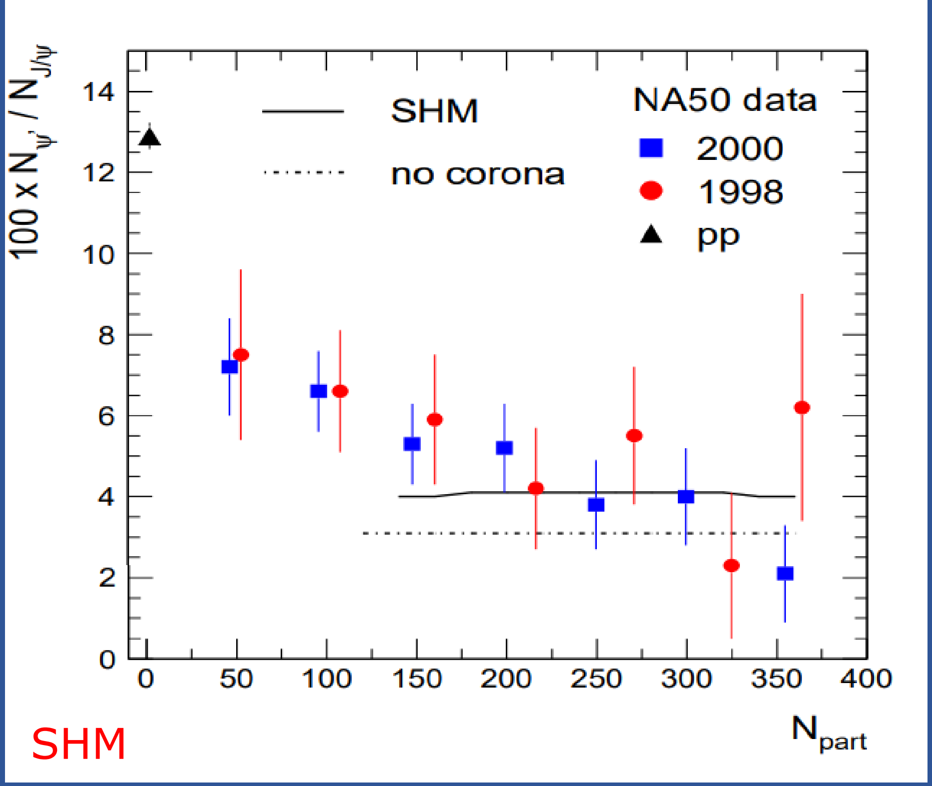




from
Rapp and Van Hees,
arXiv:0903.1096

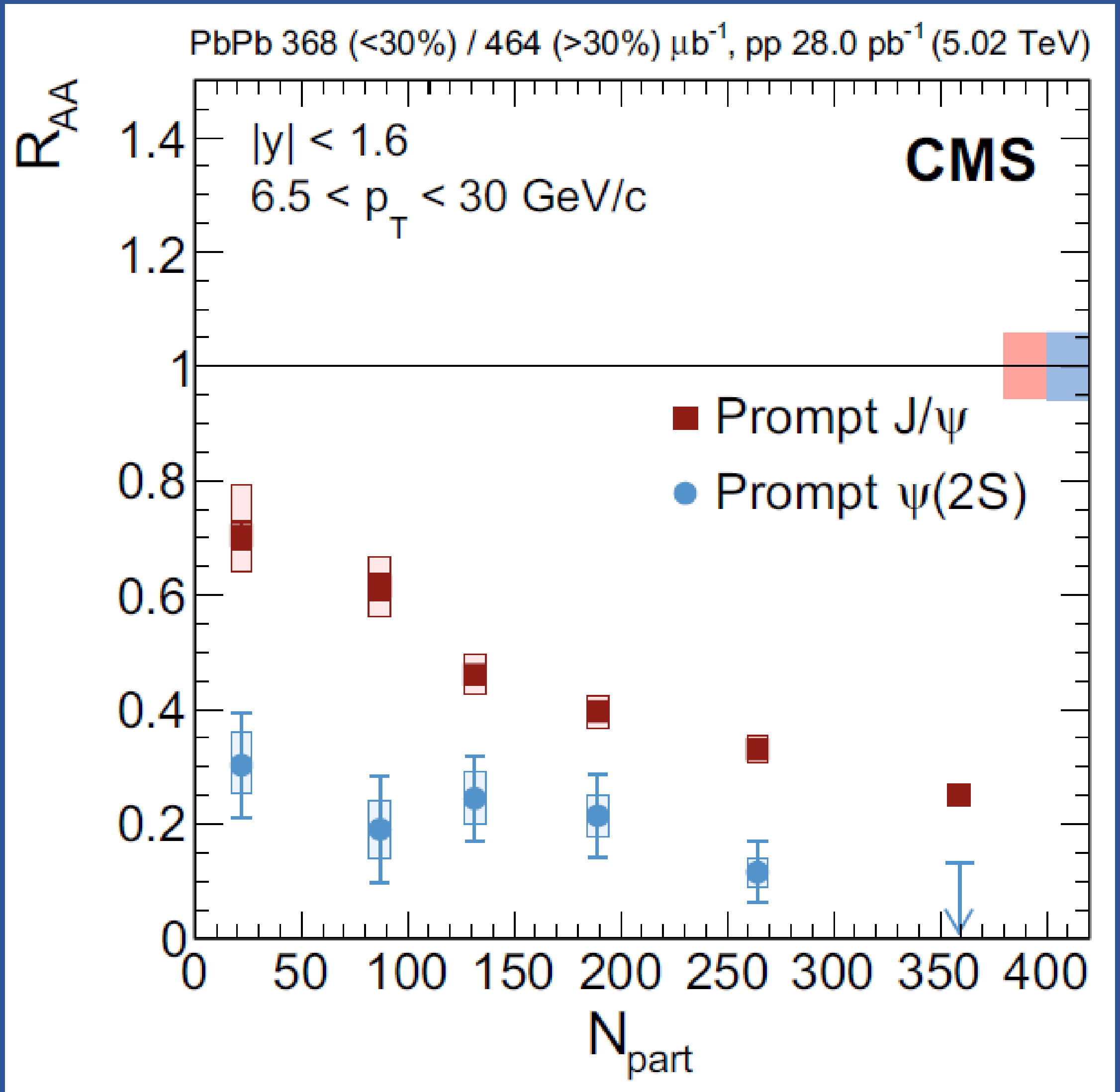
TAMU:
Grandchamp, Rapp and Brown,
PRL92 (2004) 212301

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

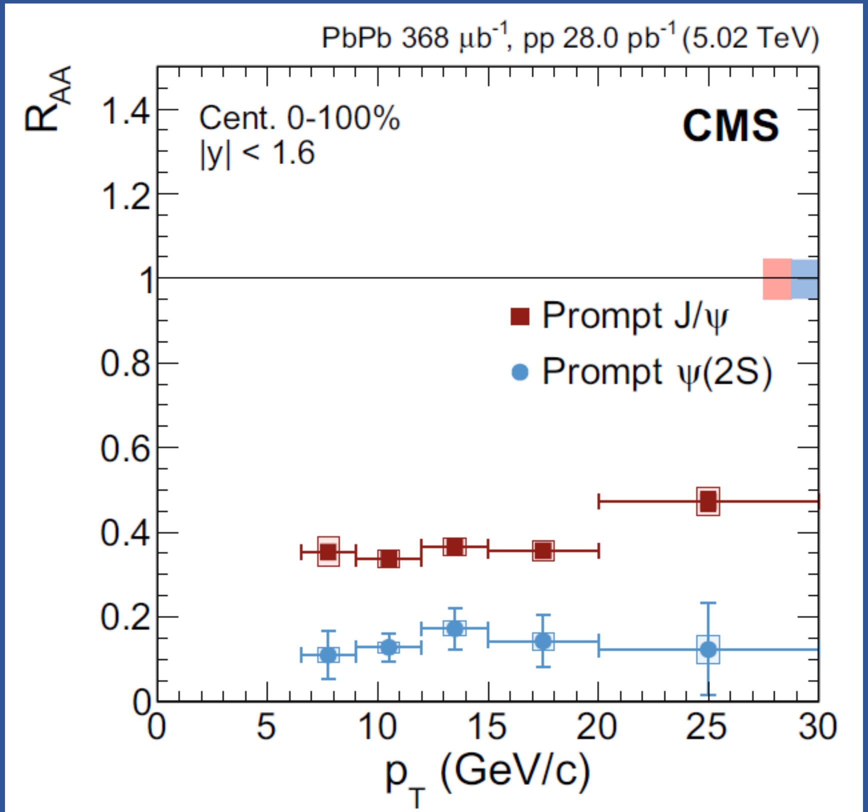
- Both transport (TAMU) and statistical hadronization (SHM) models able to **reproduce data**

Pb-Pb results at LHC energy, high p_T

CMS, EPJC 78 (2018) 509

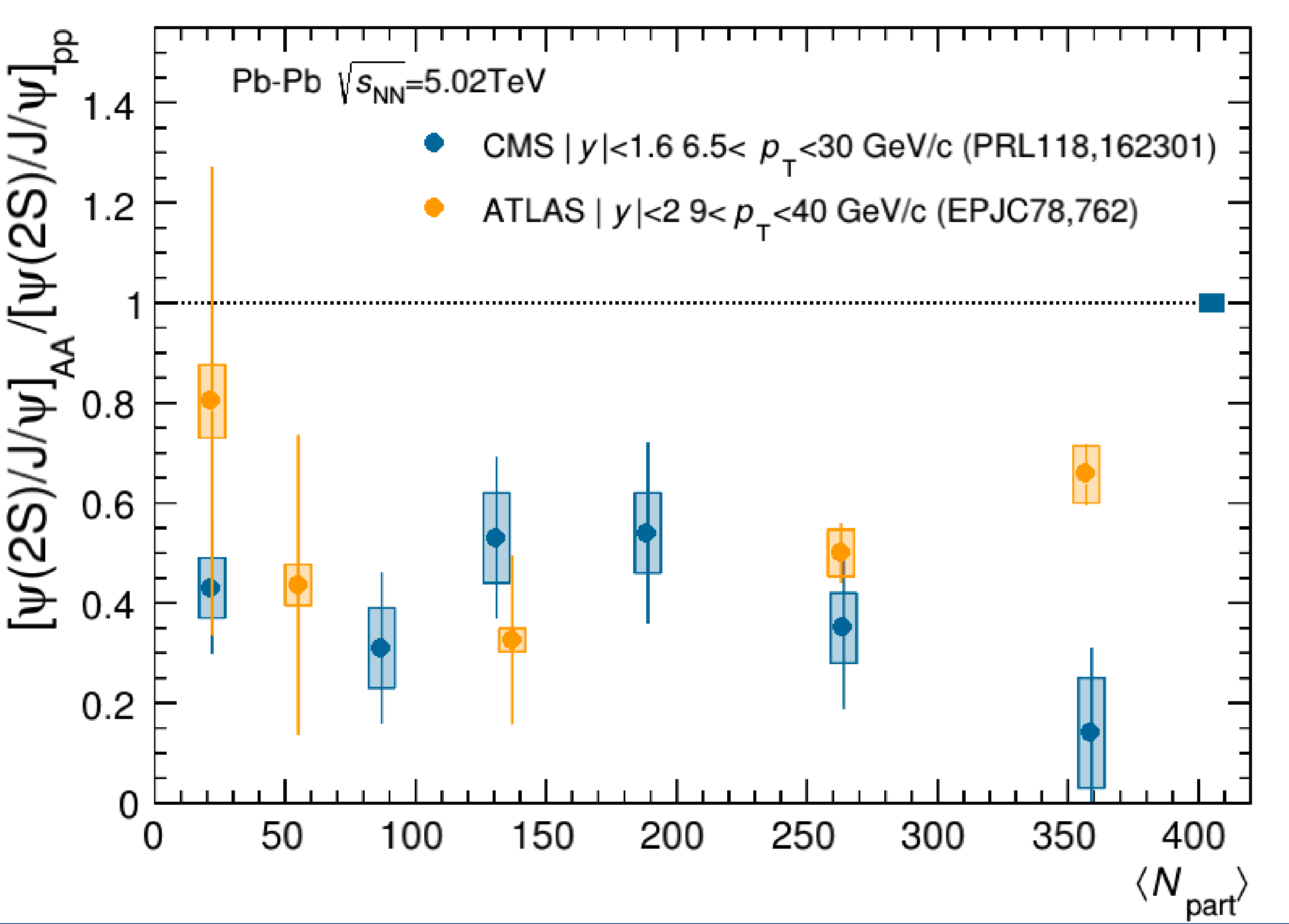


- Strong ψ(2S) suppression, larger than the J/ψ one (factor ~2), observed by **CMS**



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

Pb-Pb results at LHC energy, high p_T



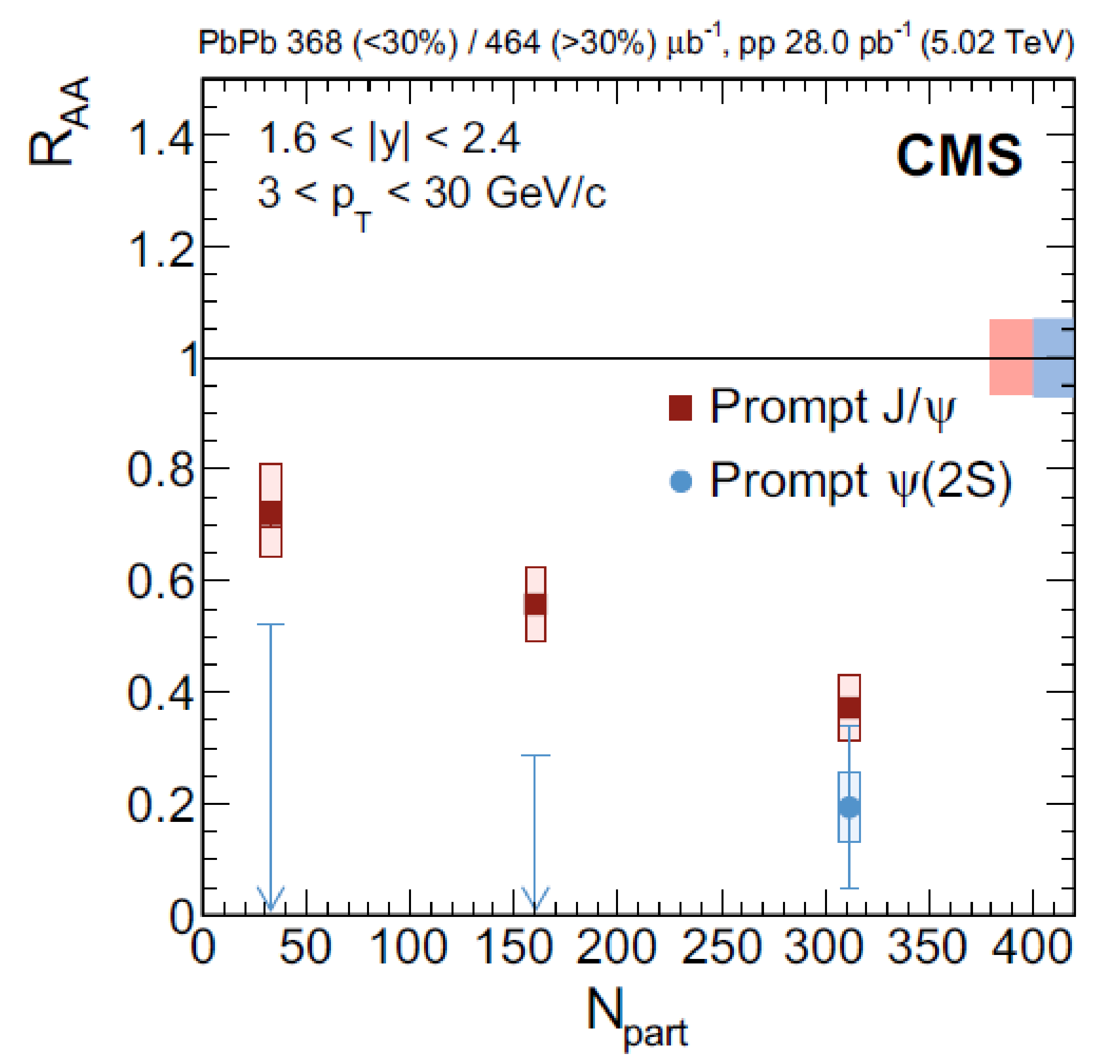
- Strong prompt ψ(2S) suppression also observed by **ATLAS**
- Slightly different kinematic coverage, but apparent tension in central events between ATLAS and CMS

Pb-Pb results at LHC energy, intermediate p_T

ALICE

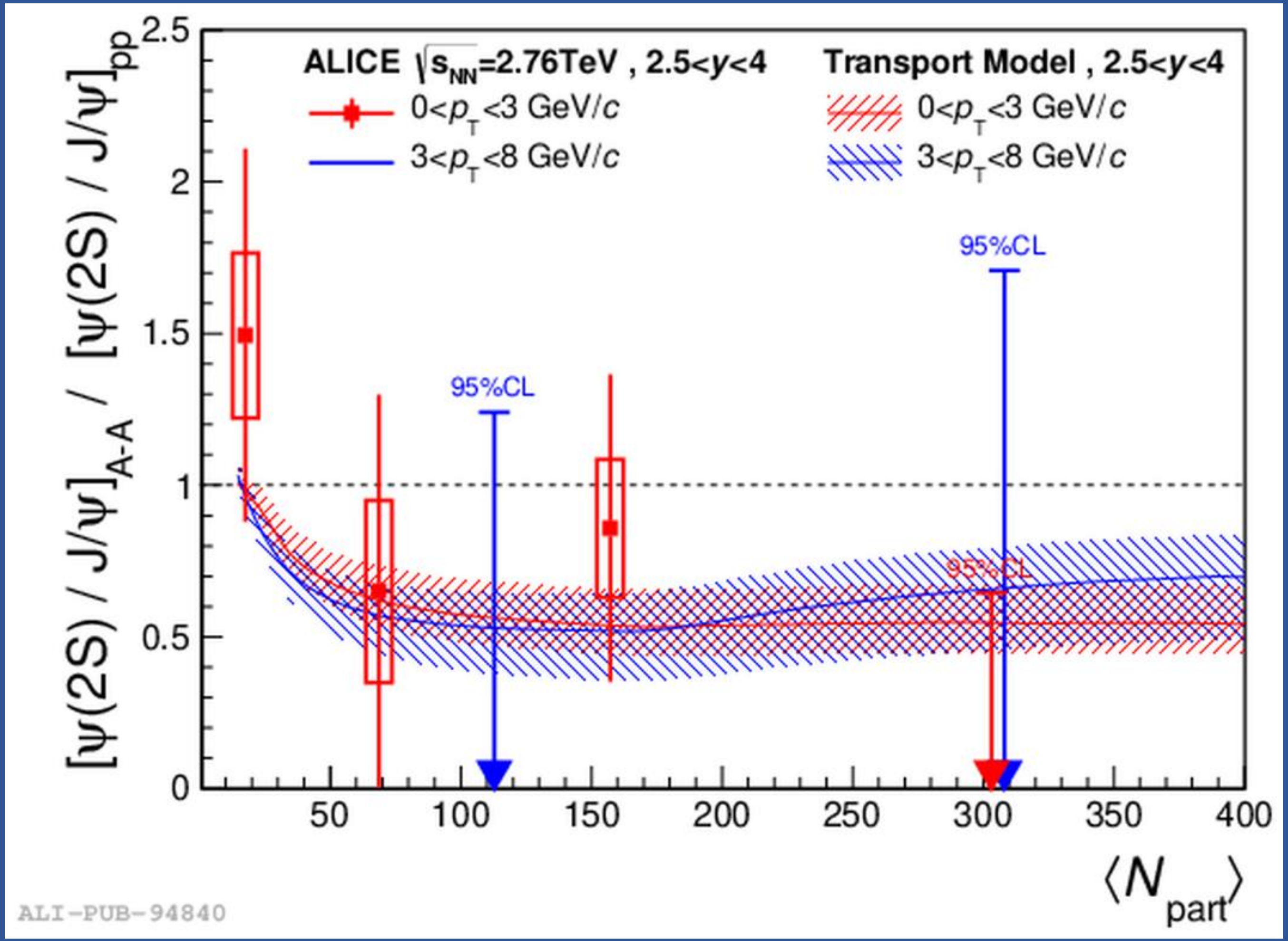
- ❑ Extending the ψ(2S) study towards lower p_T ($3<p_T<30$ GeV/c), **recombination effects** might become sizeable

- ❑ Qualitatively similar to previous results but **limited statistics** prevents clear conclusions



CMS, EPJC 78 (2018) 509

Moving to low p_T, first results



- Regeneration effects should definitely appear
- First result from ALICE (Run 1), **large uncertainties** prevent a real conclusion

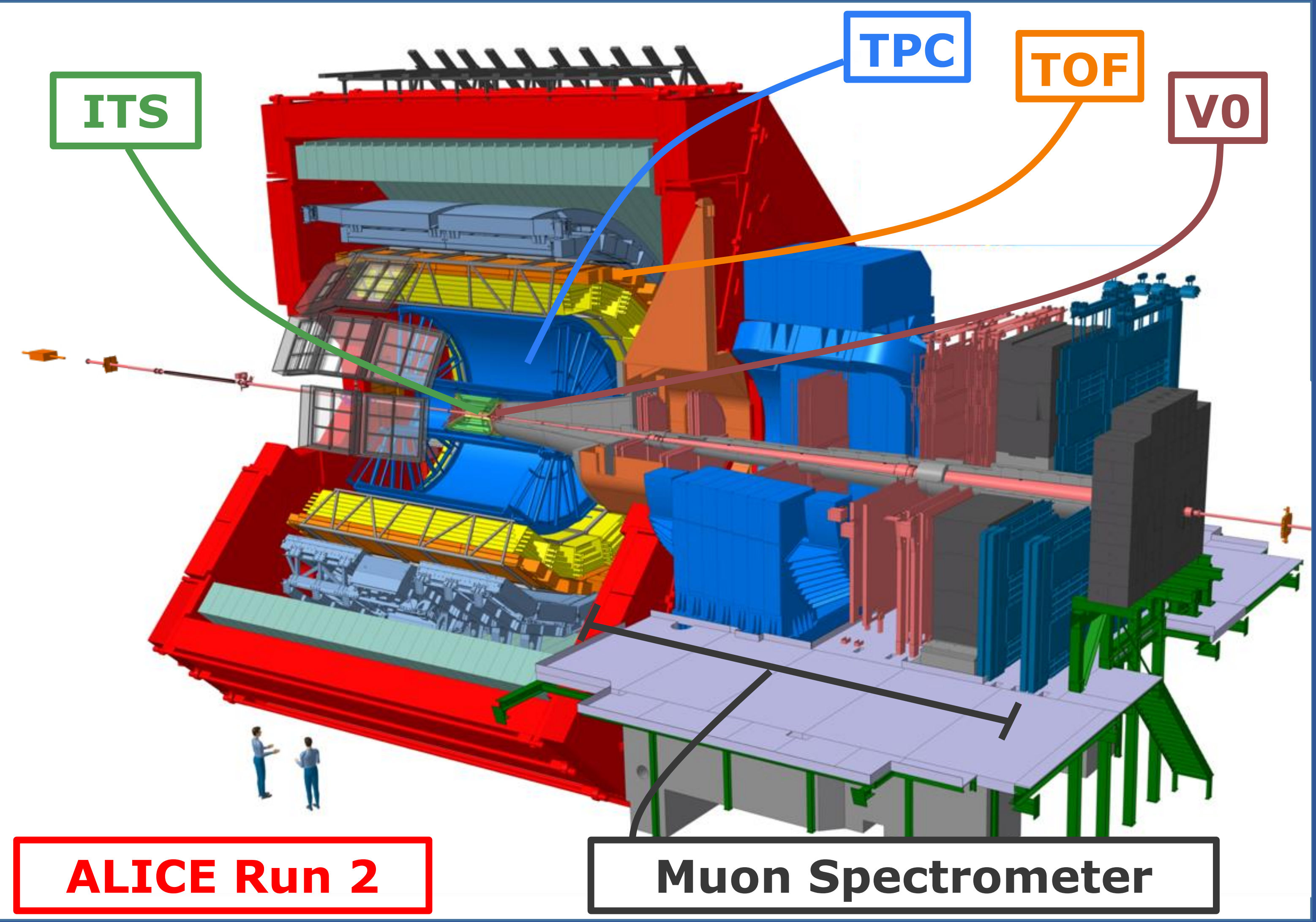
  → Run 1 L_{int} ~ 70 μb^{-1}

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

ALICE, JHEP 05 (2016) 179

Model: B. Chen et al., PLB 726(2013) 725

A Large Ion Collider Experiment



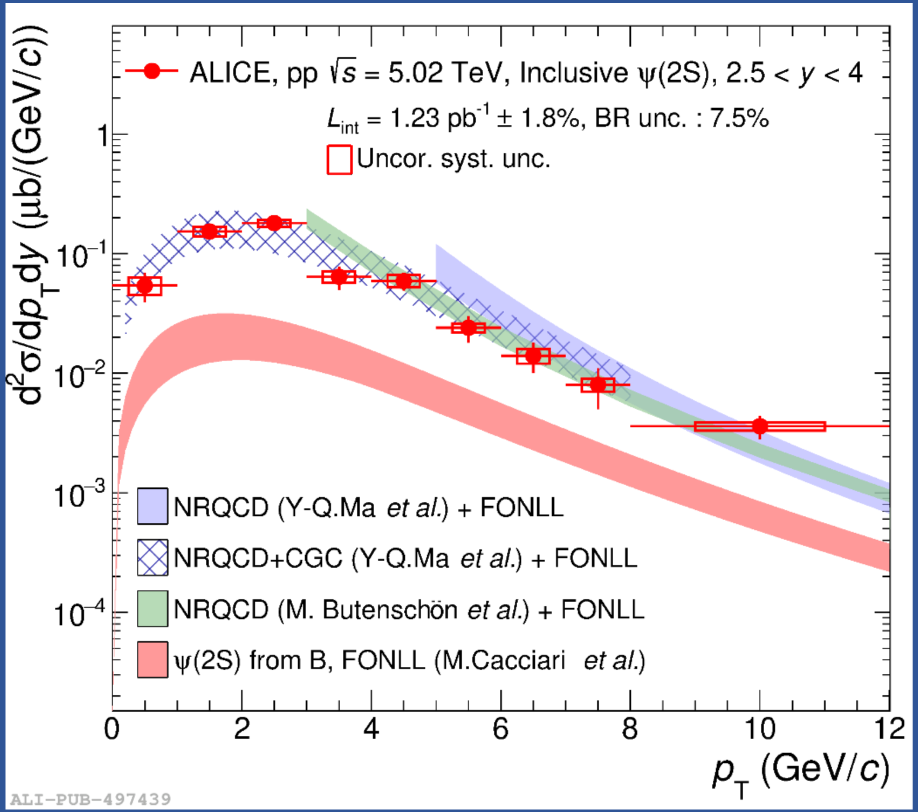
- **Inclusive quarkonium**
  - Central barrel (ee, $|y|<0.9$)
  - Muon spectrometer ($\mu\mu$, $2.5<y<4$)
  - Coverage **down to zero p_T**

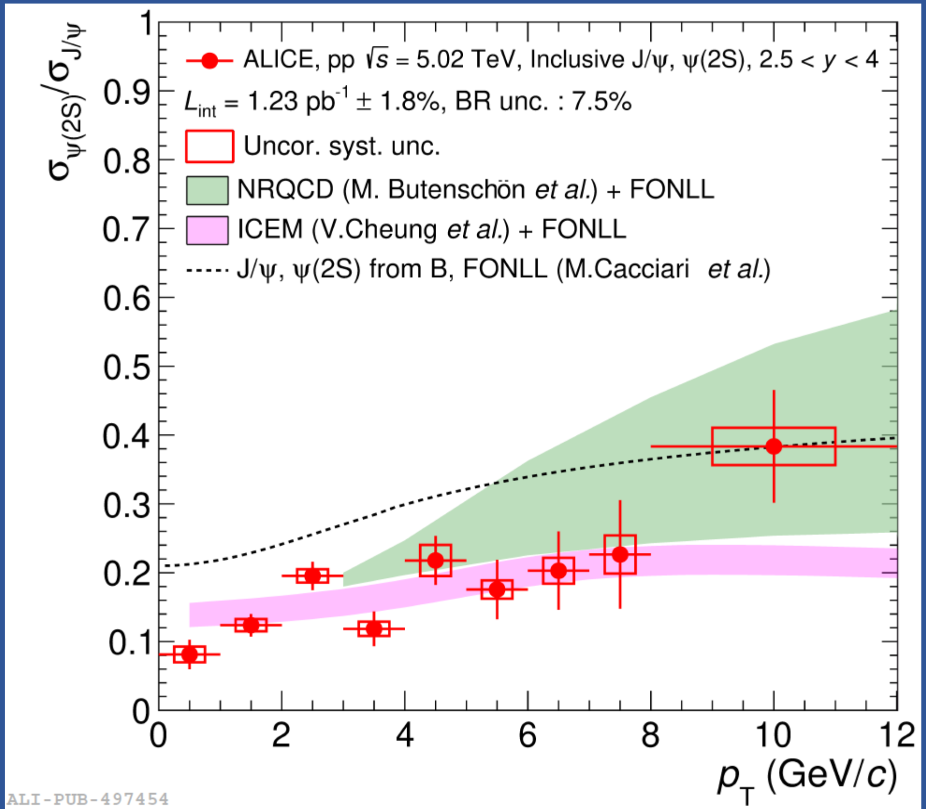
- $\psi(2S)$ results were obtained at **forward rapidity**

- (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





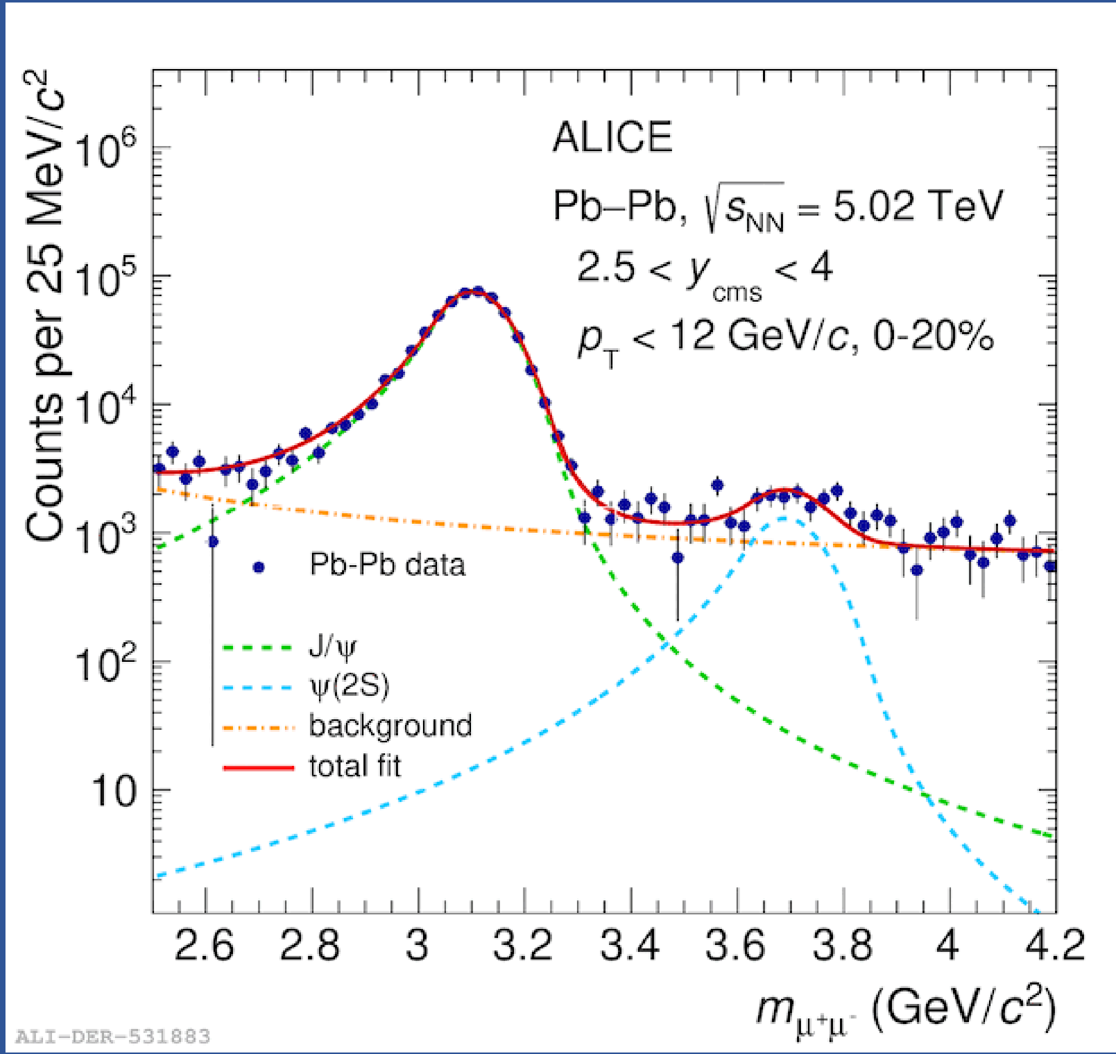
ALICE, arXiv:2109.15240

Inclusive production

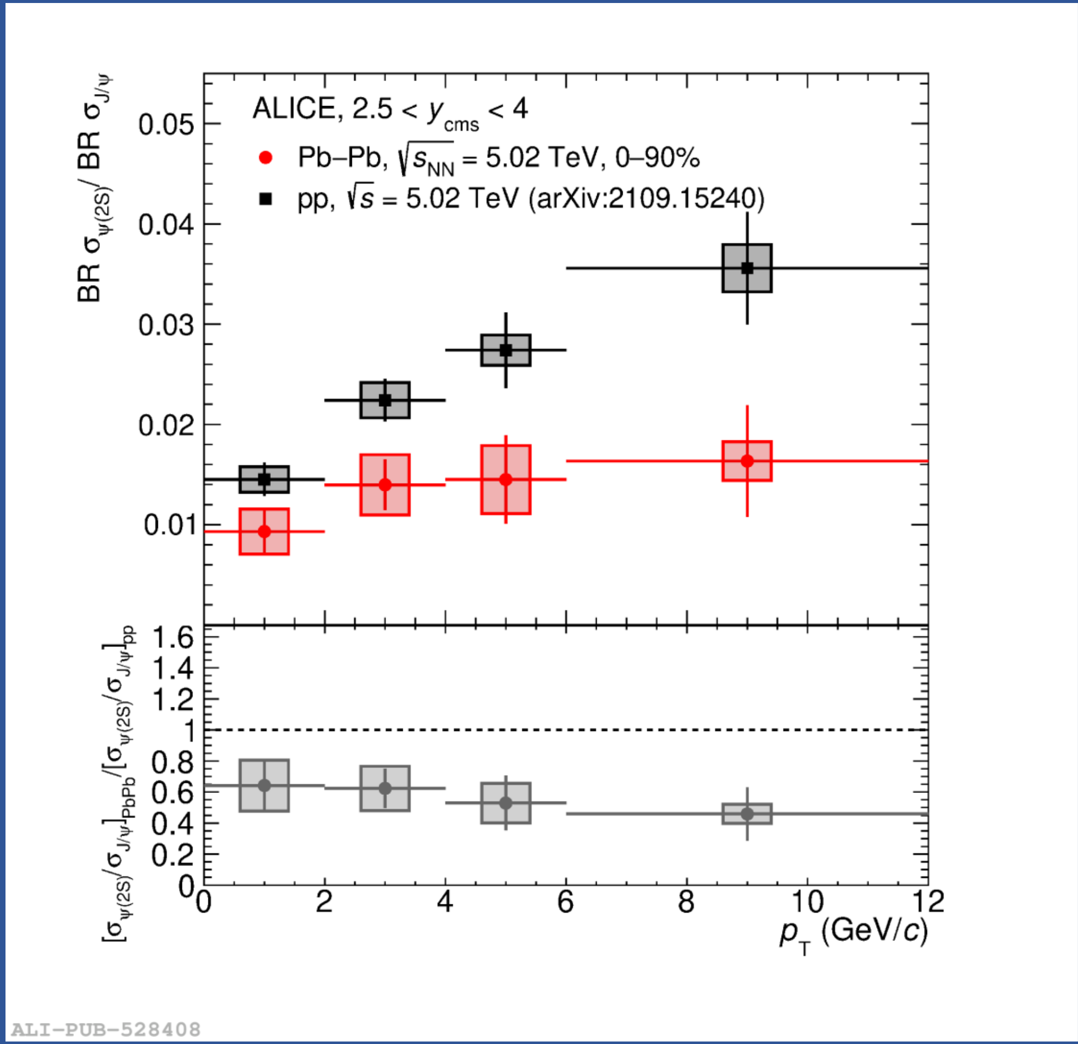
- ❑ Recent cross section measurement with 10 times more statistics than earlier publication
  → y- and p_T-differential studies of $\psi(2S)$
- ❑ **NRQCD+CGC+FONLL provides a good data description** down to zero p_T
- ❑ $\psi(2S)$-to-J/ψ ratio increases with p_T and agrees within uncertainties with theoretical 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 $$\frac{BR_{\psi(2S)\to\mu\mu}\,\sigma_{\psi(2S)}}{BR_{J/\psi\to\mu\mu}\sigma_{J/\psi}}$$

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

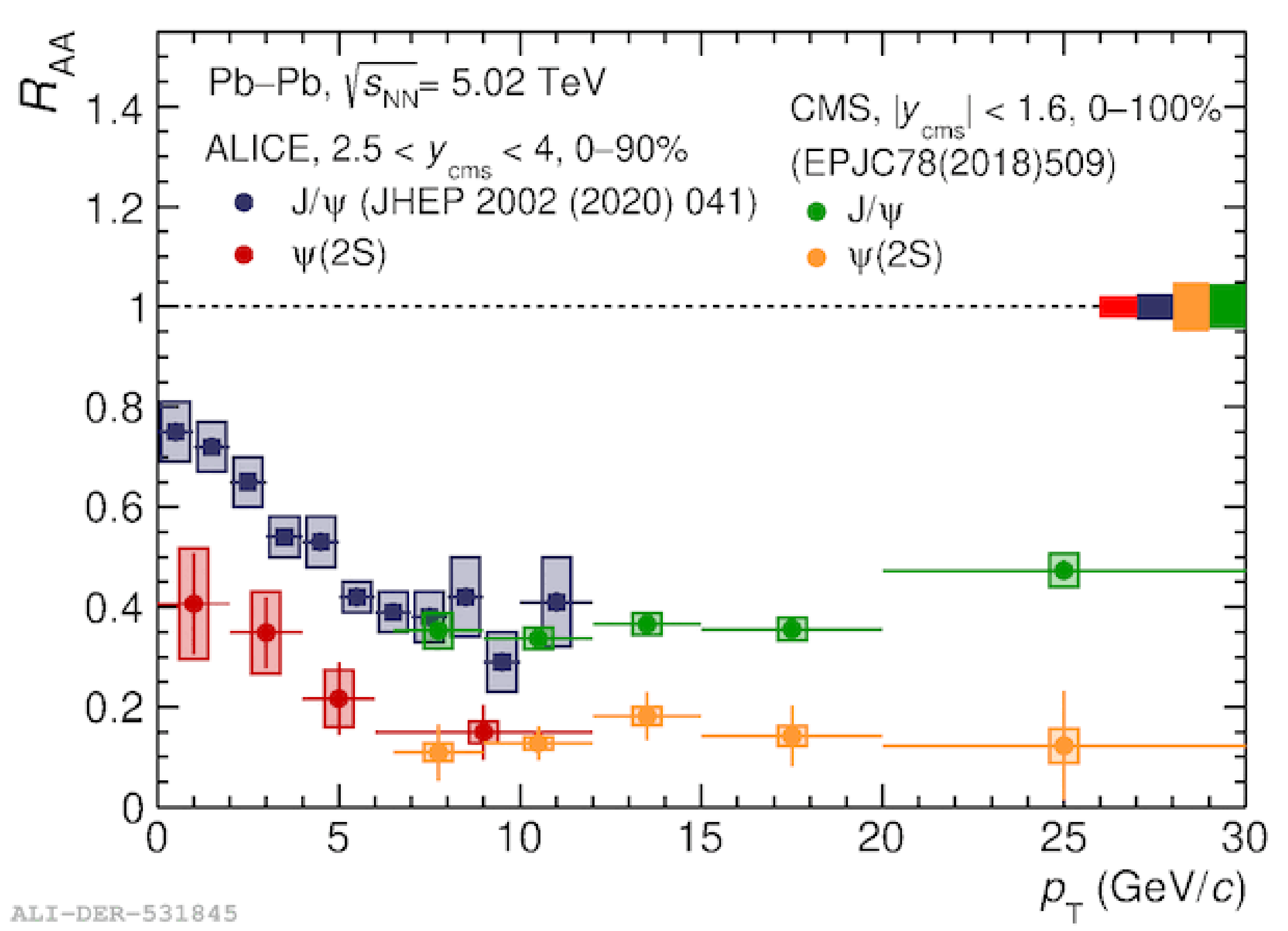
- **Significant suppression of ψ(2S) with respect to J/ψ** in the whole p_T range explored
- Double ratio between Pb-Pb and pp results reaches a value of ~0.5 at high p_T

N.B.: not corrected for branching ratios

ALICE, arXiv:2210.08893

p_T dependence of the nuclear modification factor

ALICE



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

- 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

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

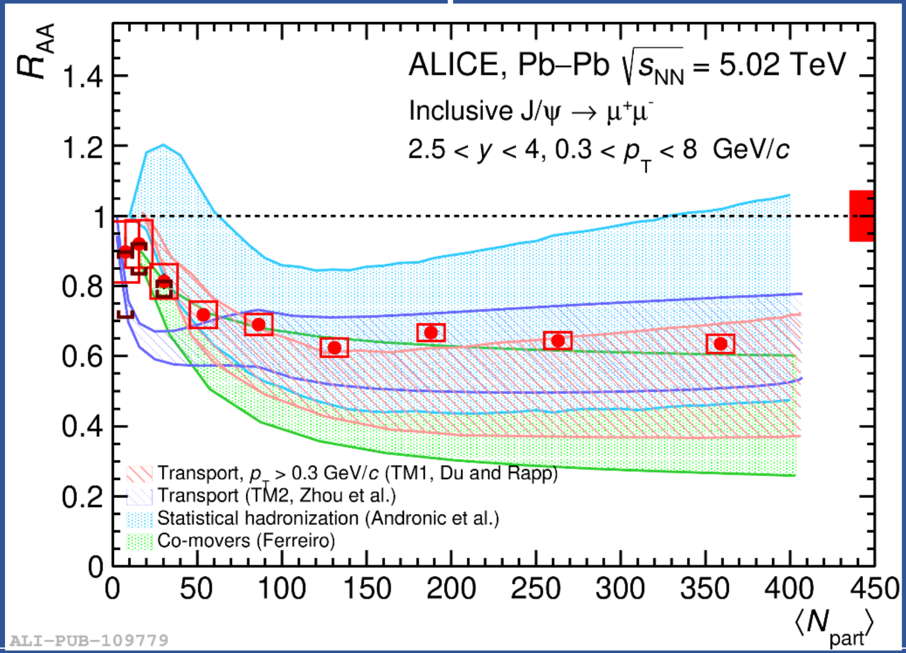
As already mentioned, both approaches fairly **reproduce LHC experimental results on the J/ψ**

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

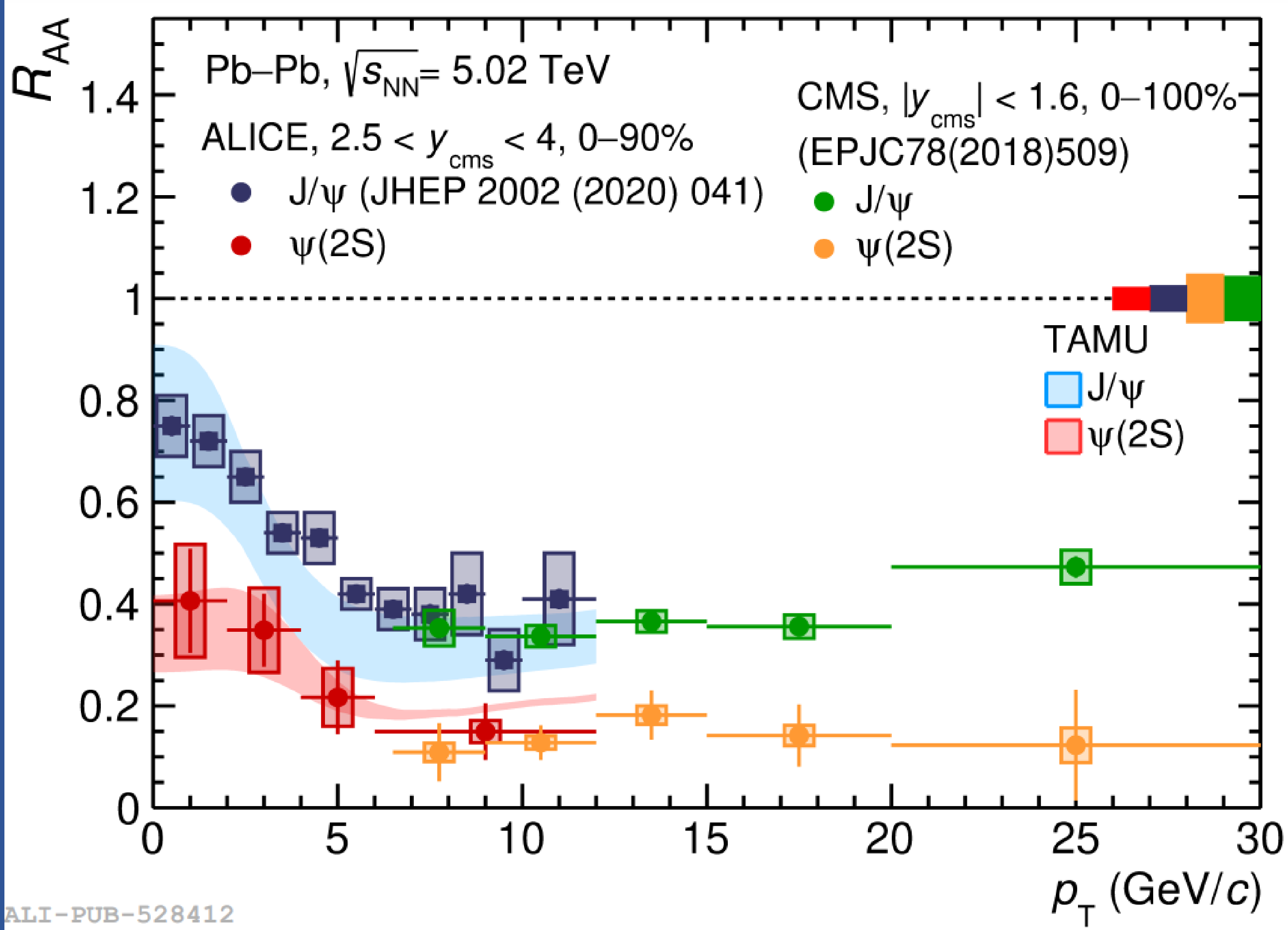
A. Andronic et al., Nature 561 (2018) 321



Other approaches include "comover" models

E. Ferreiro, PLB 731 (2014) 57

p_T dependence of the nuclear modification factor



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- Good agreement between CMS and ALICE data in the common p_T range, regardless of the different rapidity coverage

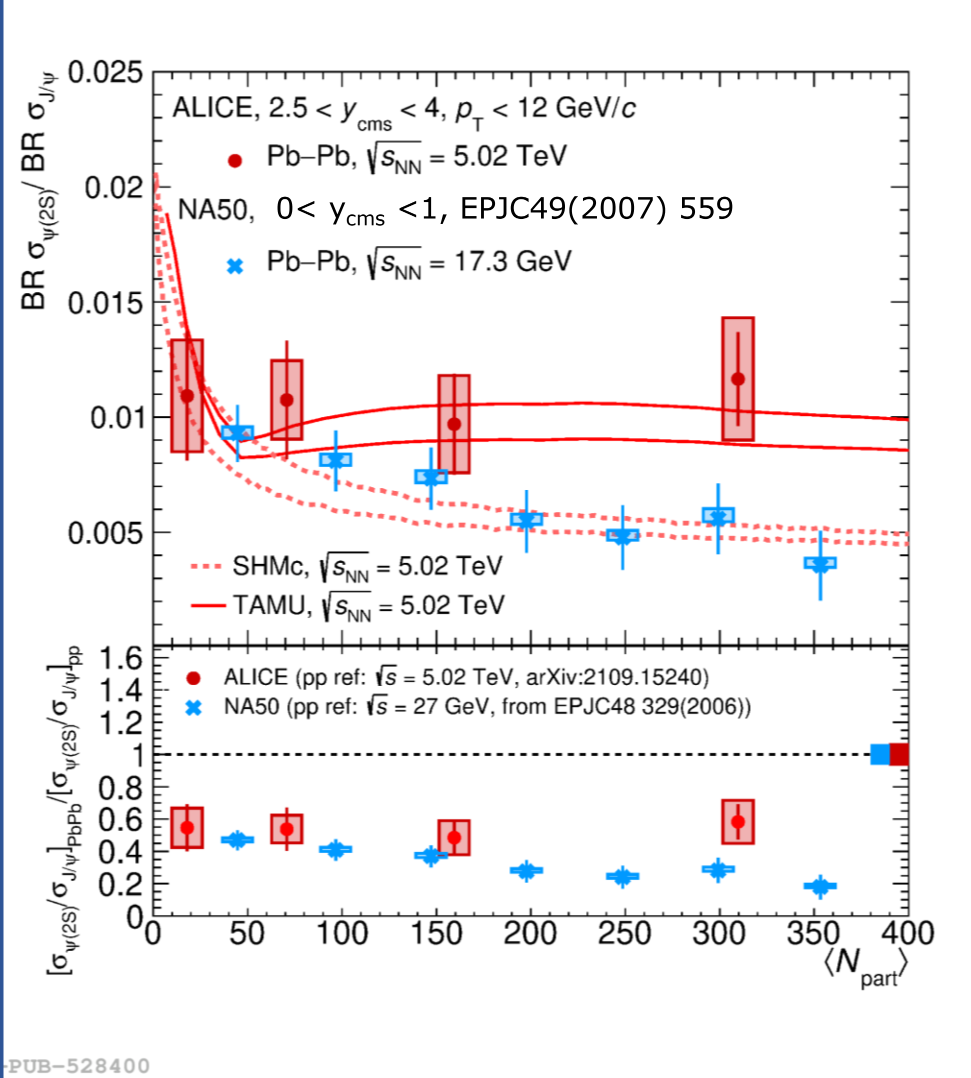
ALICE, arXiv:2210.08893

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

ALICE, arXiv:2210.08893



- 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**

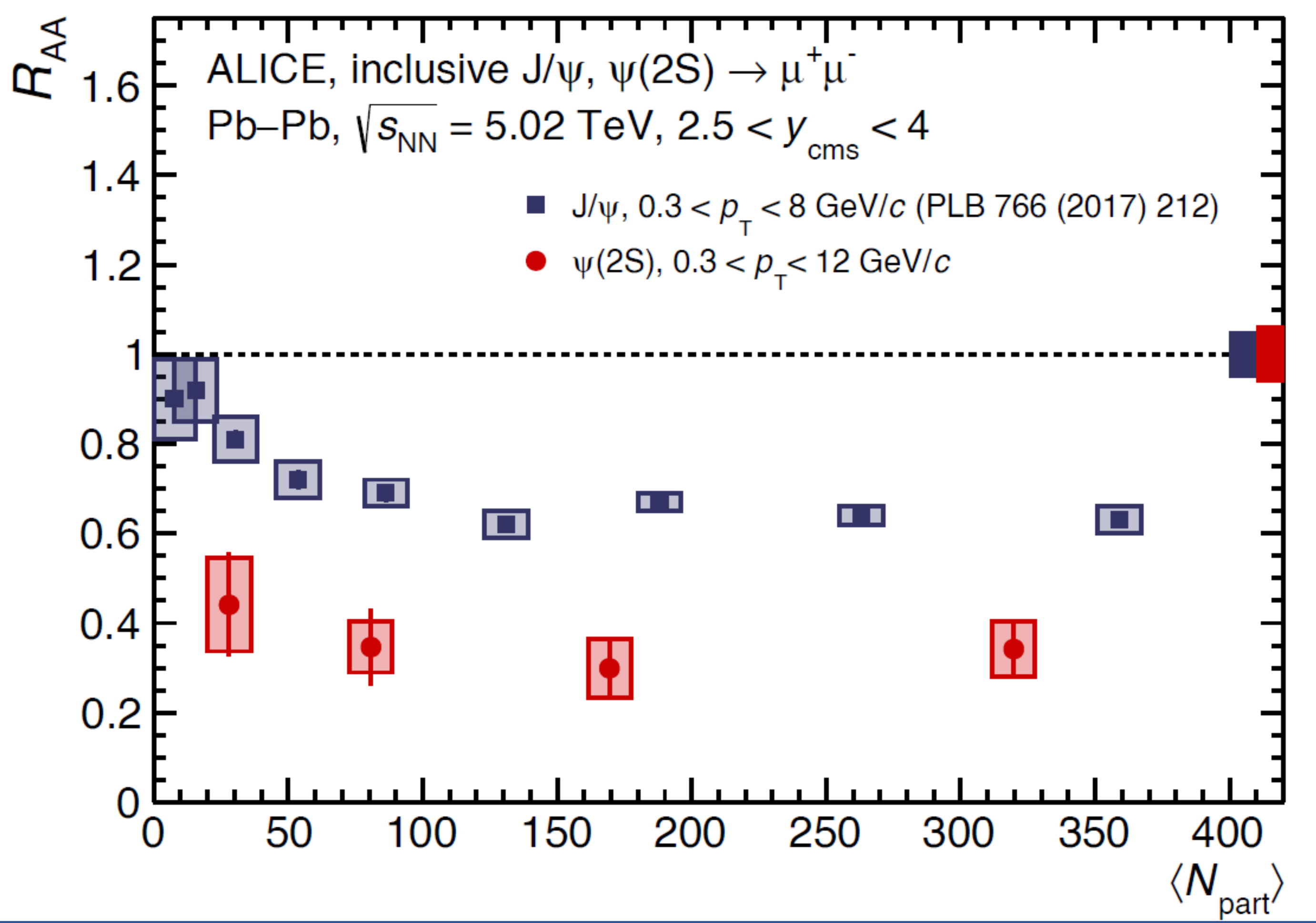
TAMU: X. Du and R. Rapp, NPA 943 (2015) 147
SHMc: A. Andronic et al., Nature 561 no. 7723 (2018) 321

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 $R_{AA} \sim 0.3 - 0.4$

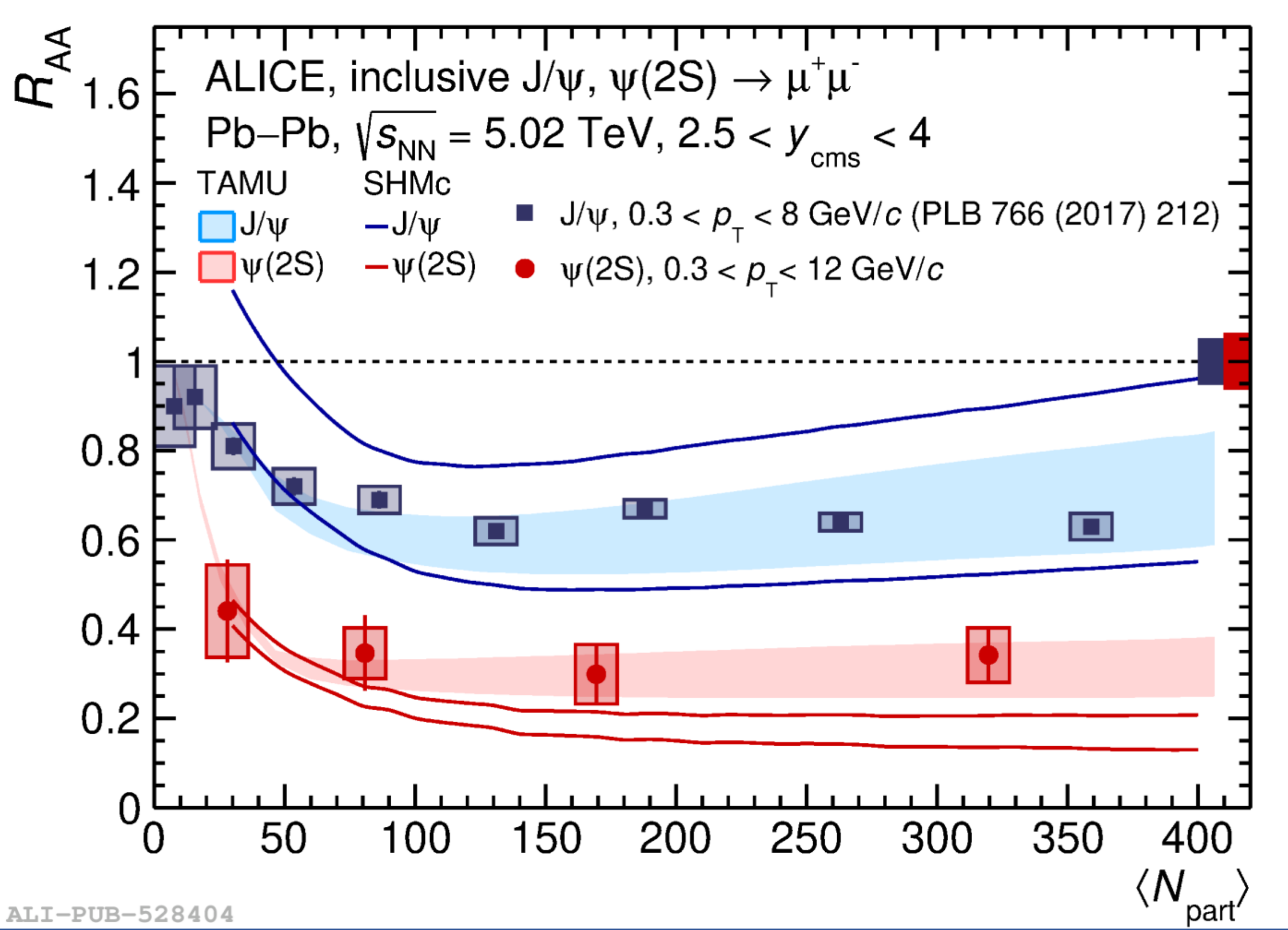
ALICE, arXiv:2210.08893



Centrality dependence of the nuclear modification factor

ALICE

ALICE, arXiv:2210.08893



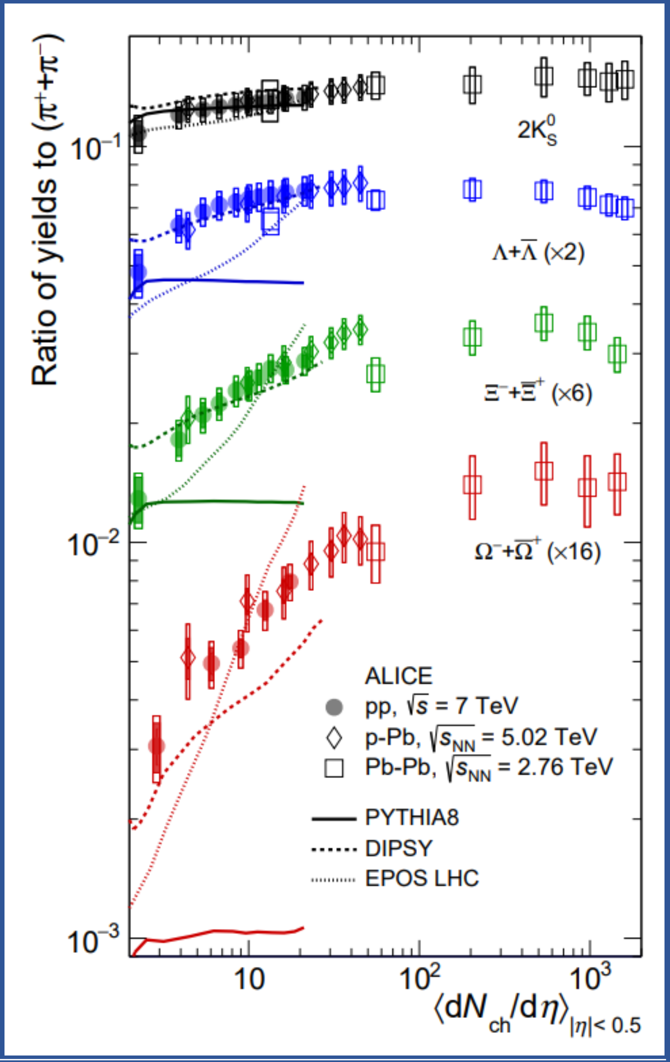
- ❑ Stronger suppression for $\psi(2S)$ compared to J/ψ
- ❑ **Flat centrality dependence of $\psi(2S)$ R_{AA} within uncertainties**, consistent with $R_{AA} \sim 0.3 - 0.4$
- ❑ **TAMU** model reproduces the results for both J/ψ and $\psi(2S)$
- ❑ **SHMc** describes J/ψ data but tends to underestimate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

From heavy to small systems

- **QGP-like effects** have been detected, for several observables, also in small(er) collision systems, as pA and high multiplicity pp
  → one of the **major discoveries** of the LHC program on QGP studies

- Most of these observables are related to bulk properties of the strongly interacting system (anisotropic flow) or soft probes (strangeness)

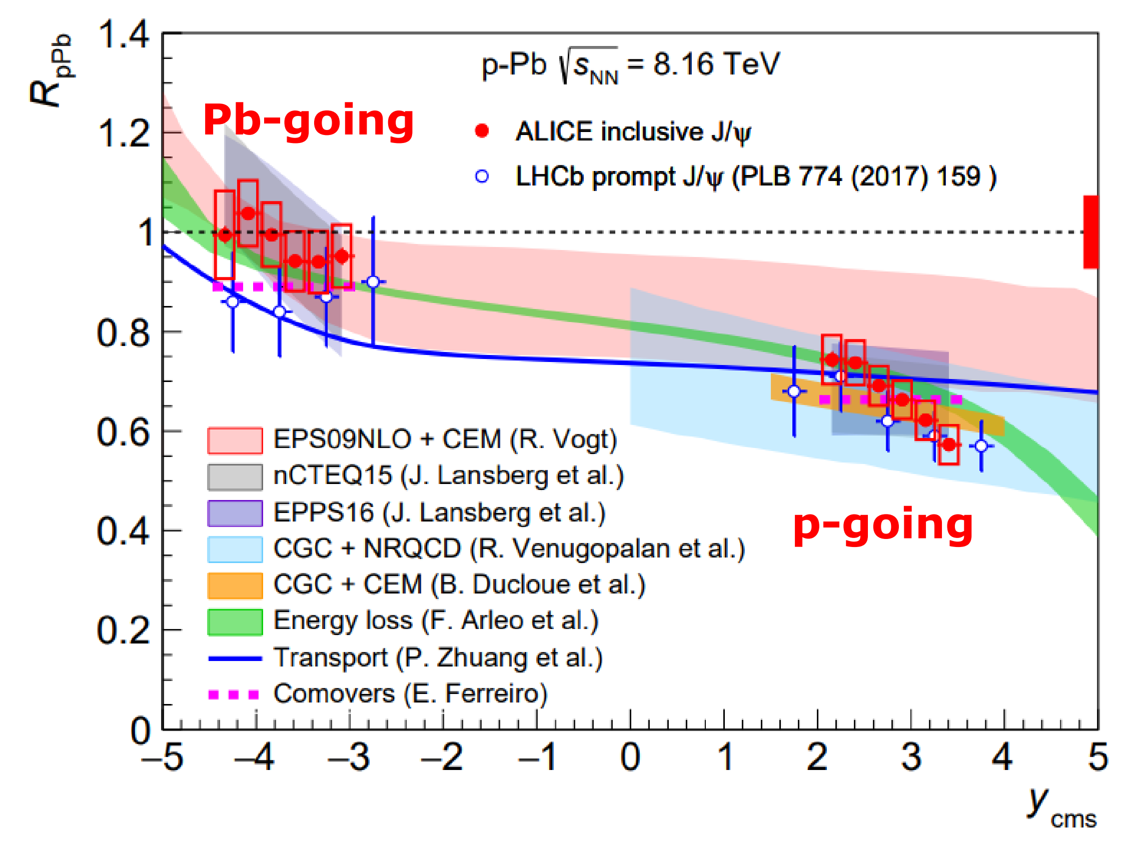
- Do we see hints for such effects also in the **charmonium sector** ?
  → ψ(2S), thanks to its relatively small binding energy, could represent a good testing ground



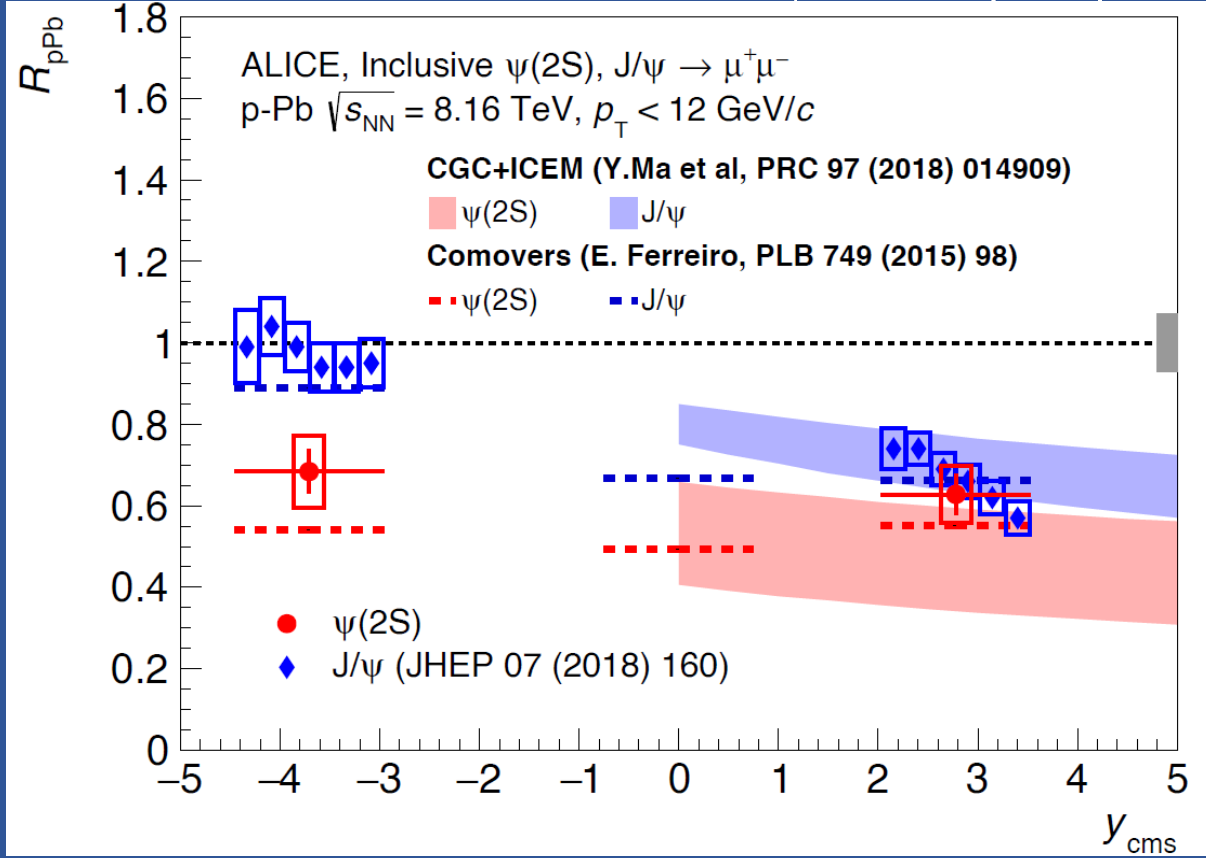
ALICE, Nat. Phys. 13 (2017) 535-539

ψ(2S) production in p-Pb collisions

ALICE, JHEP 07 (2018) 160



ALICE, JHEP 07 (2020) 237



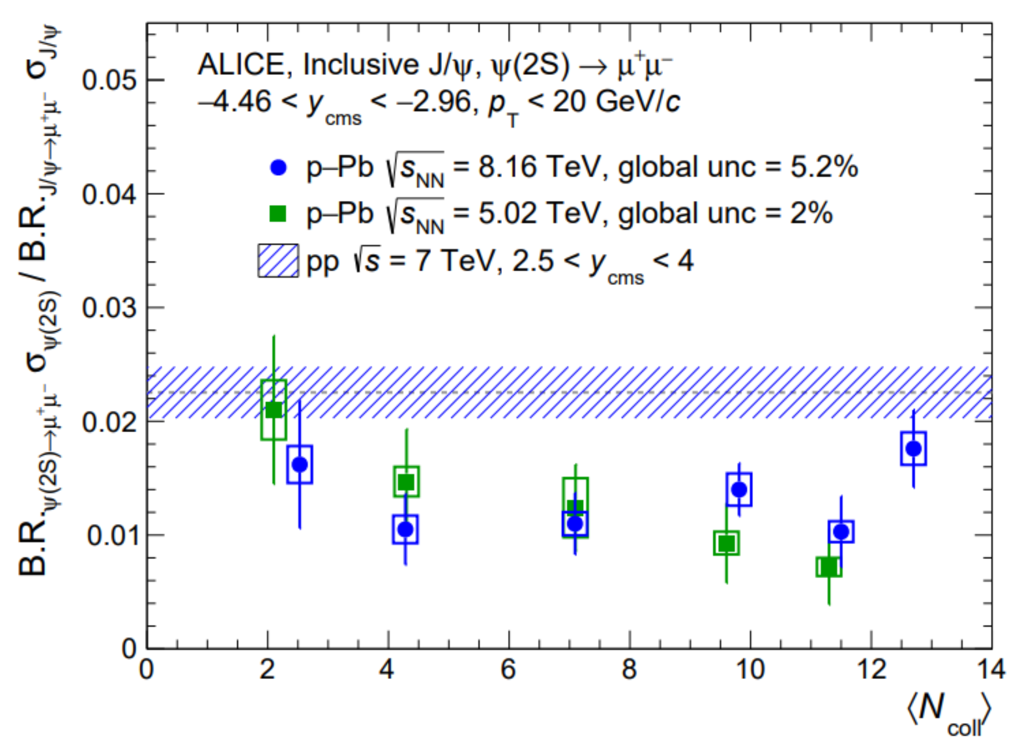
- **J/ψ R_{pPb}** compatible with effects of **nuclear shadowing** (initial state)

→ **No** indications of possible **medium effects**

- Forward rapidity (p-going)
  → $R_{pPb}^{J/\psi}$ and $R_{pPb}^{\psi(2S)}$ compatible
- Backward rapidity (Pb-going)
  → $\boldsymbol{R_{pPb}^{J/\psi} > R_{pPb}^{\psi(2S)}}$

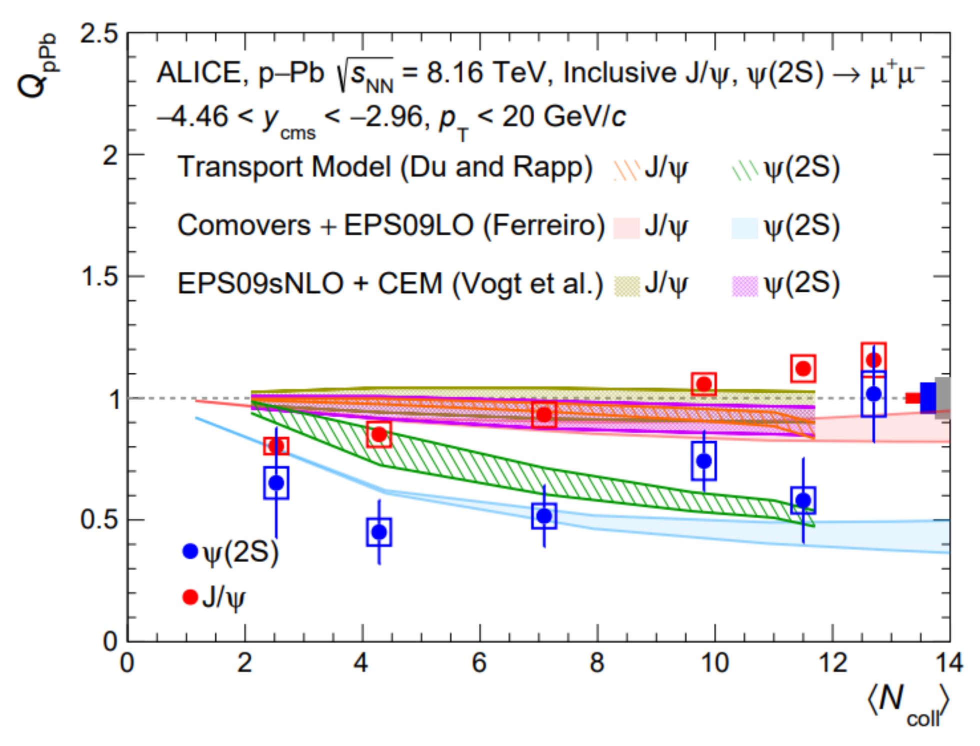
ψ(2S) production in p-Pb collisions

❑ The "double ratio" between ψ(2S) and J/ψ yields in p-Pb and pp allows the cancellation of initial state effects (x_{Bj} intervals are very close for the two mesons)



ALICE, JHEP 02 (2021) 002

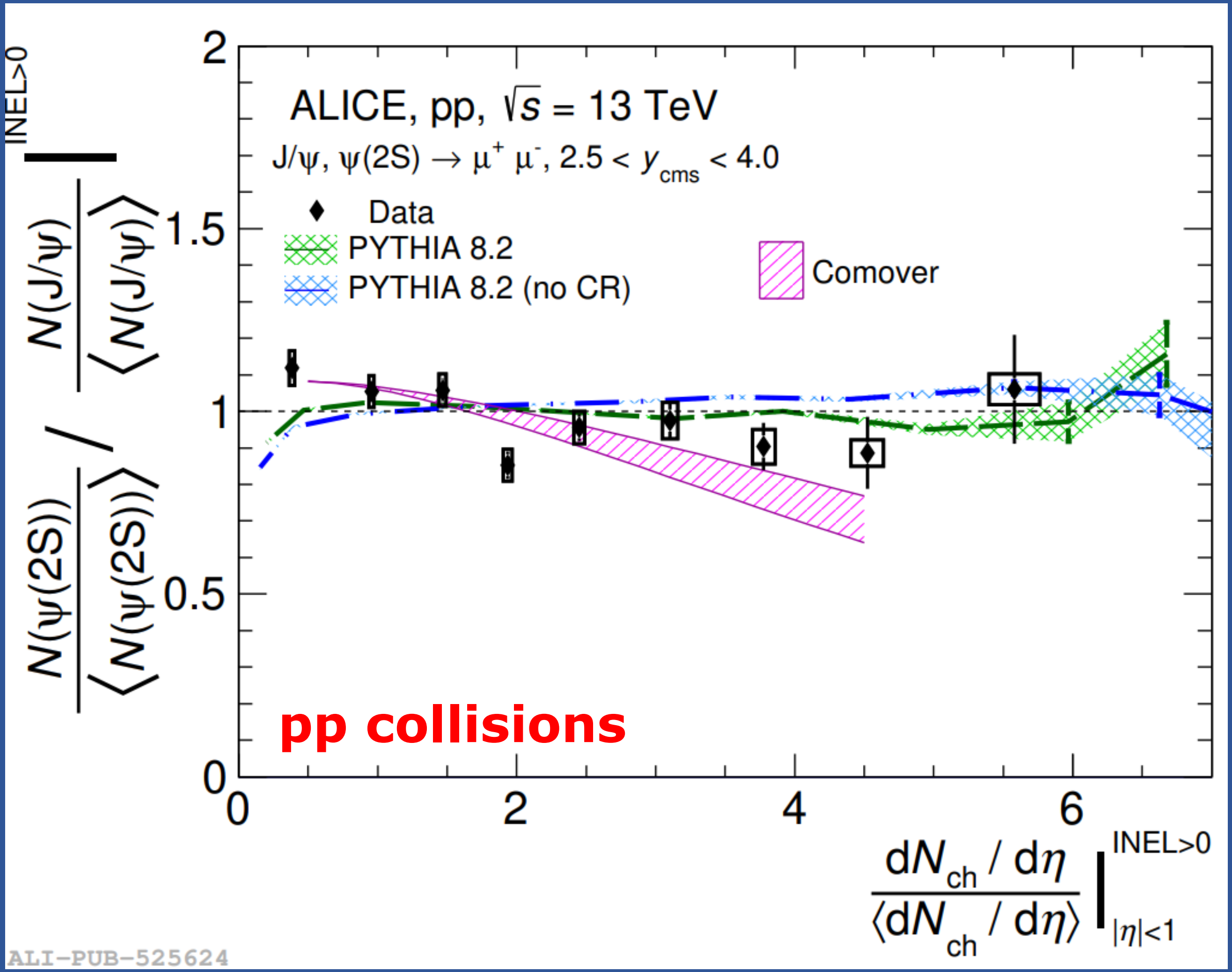
❑ Models including final-state effects fairly reproduce the observed ψ(2S) suppression



→ **Evidence for final-state effects** on the ψ(2S)

→Transport model includes **short-lived QGP** in p-Pb

$\psi(2S)$ in high-multiplicity pp collisions



ALICE, arXiv:2204.10253

- **Self-normalized ratios of $\psi(2S)$ and J/ψ** may exhibit a weak multiplicity dependence
  → 2.4σ indication for a **~15% decrease** between $dN_{ch}/d\eta=7$ and $dN_{ch}/d\eta=35$ ($\langle dN_{ch}/d\eta\rangle^{INEL>0}_{\eta<1}$ = 7.07+0.10-0.08)

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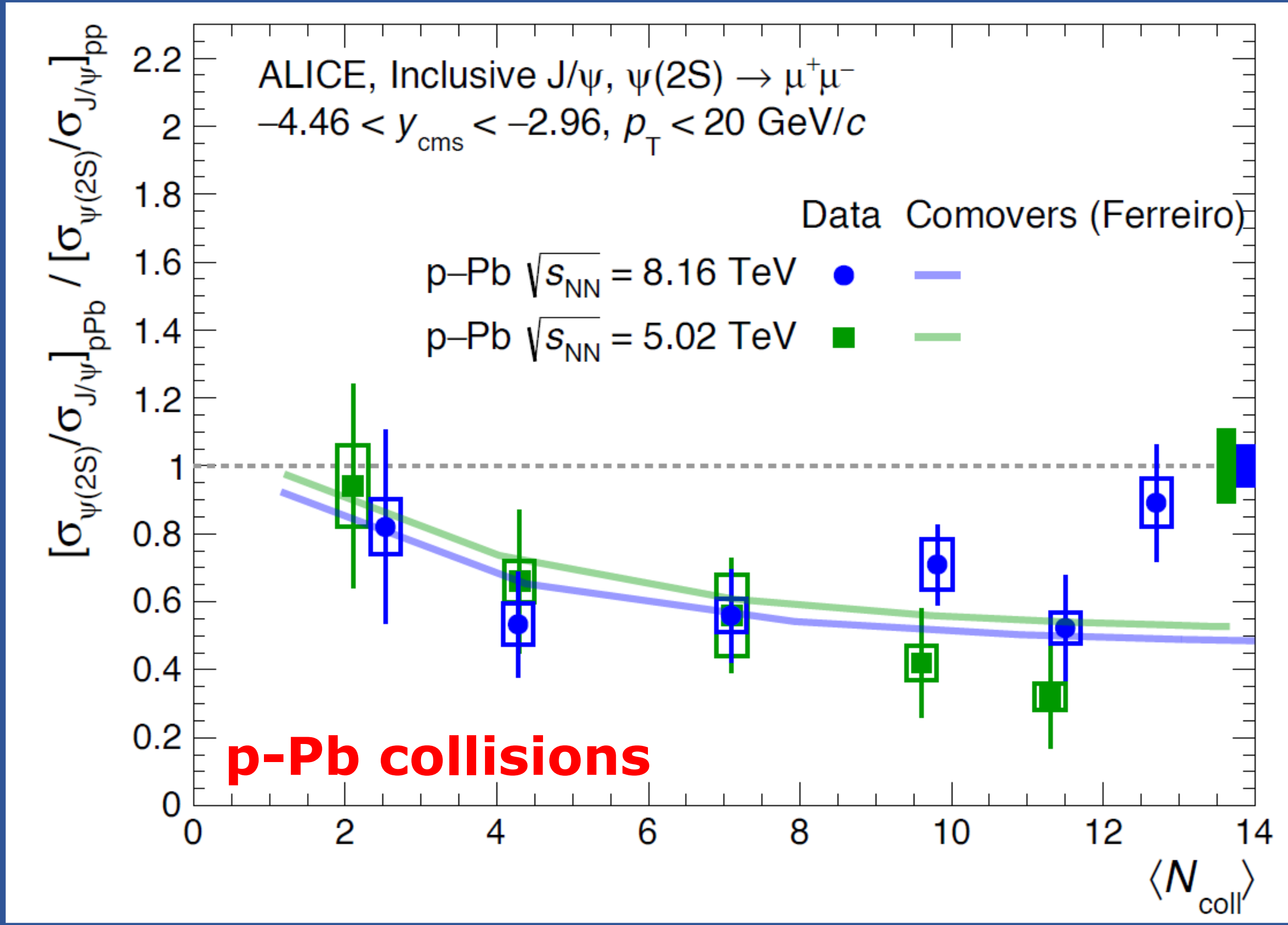

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  → 2.4σ indication for a **~15% decrease** between $dN_{ch}/d\eta$=7 and $dN_{ch}/d\eta$=35 ($\langle dN_{ch}/d\eta\rangle^{INEL>0}_{\eta<1} = 7.07^{+0.10}_{-0.08}$)

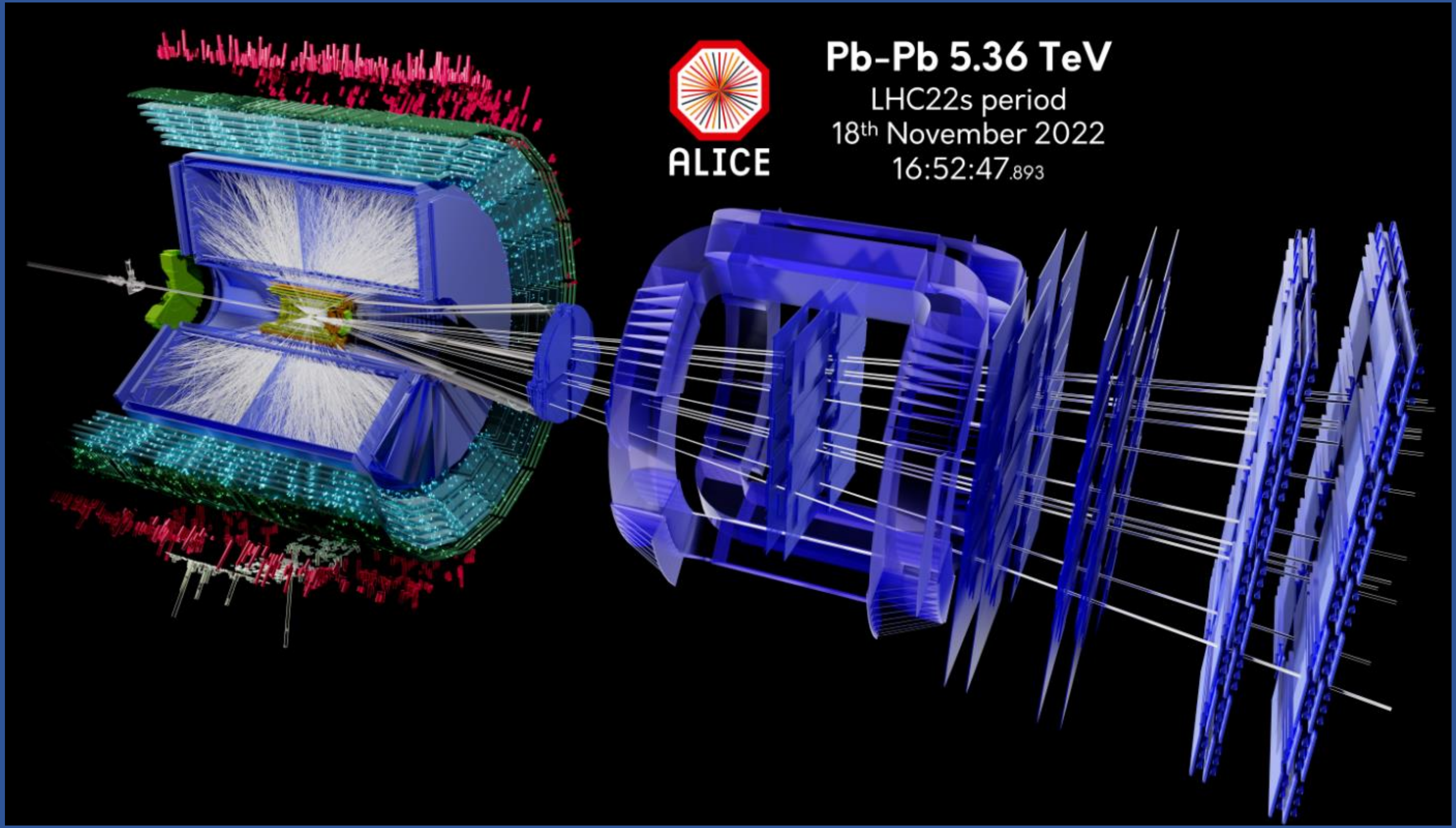
- At constant $dN_{ch}/d\eta$, the decrease of the $\psi(2S)/(J/\psi)$ ratio is larger in p-Pb than in high multiplicity pp

→ **40% decrease in p-Pb** at $\langle N_{coll}\rangle$~11.5, corresponding to $dN_{ch}/d\eta$~30
(from ALICE, EPJC 79 (2019) 307)

- Contrary to strangeness results, $\psi(2S)$ yields do not scale with $dN_{ch}/d\eta$ for different collision systems

Prospects for future measurements

- Many $\psi(2S)$ results are still statistically limited after Run 2



- Excellent opportunities for 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**)

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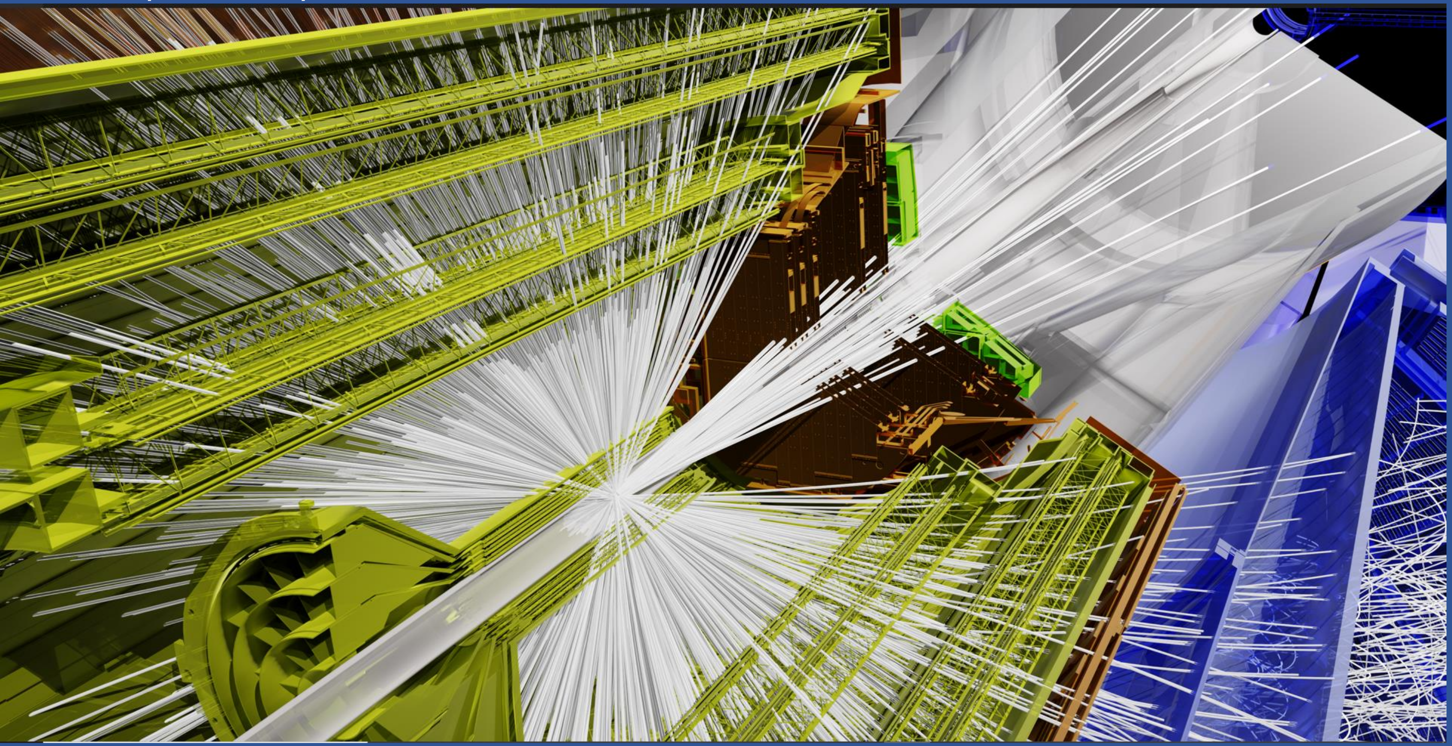
ALICE, Pb-Pb, Run 3

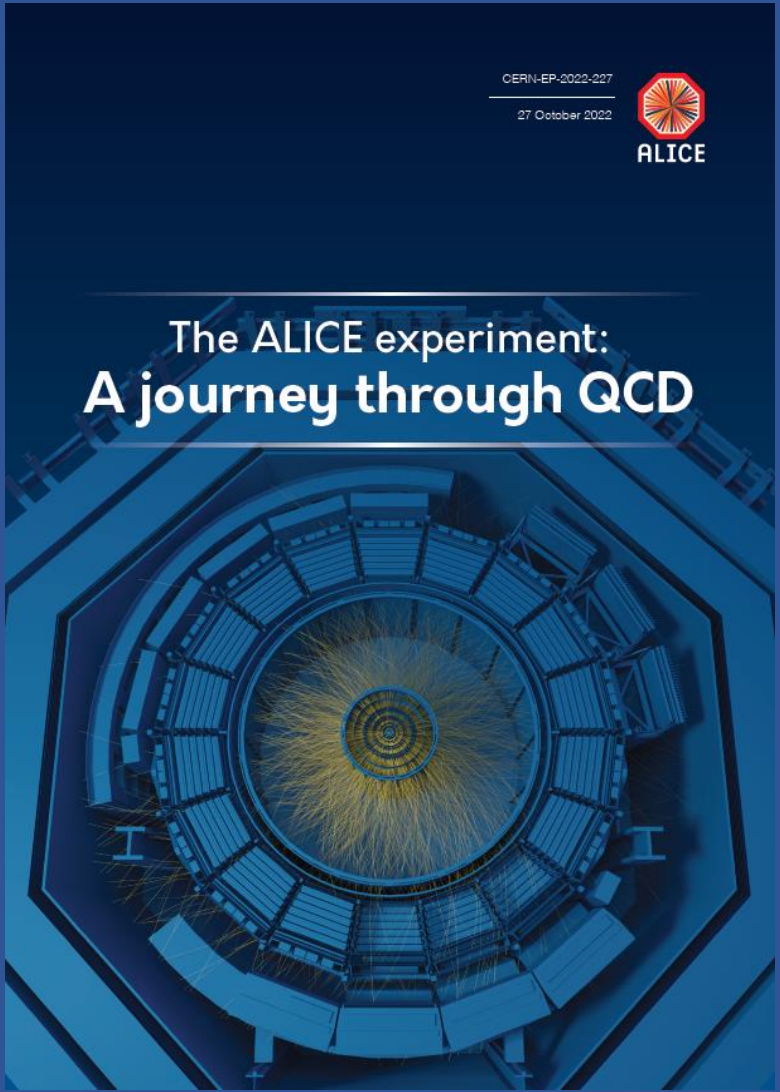


- ❑ Excellent opportunities for Run 3
- ❑ Target Pb-Pb integrated luminosity (Run 3 + 4) → L_{int} ~ 13 nb^{-1}
- ❑ Improved tracking precision by a factor 3 (6) in xy (z) direction at midrapidity (new **Inner Tracker**)
- ❑ New **Muon Forward Tracker (MFT),** enabling prompt/non-prompt separation

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

…and for more news on ALICE physics and results…

- ALICE has recently completed a strong effort to present its results from Run 1-2 (2009-2018) in a systematic and accessible review
- 237 pages + 123 figures
- To give you an idea of the extent and variety of the topics: the content of this seminar is summarized in a mere 3 figures…



arXiv:2211.04384 (submitted to EPJC)

Conclusions

- Charmonium production at LHC in Pb-Pb collisions: **results on J/ψ support a "suppression+regeneration" picture**, with a solid background in theory

- First results on forward **ψ(2S) production at low/intermediate p_T in Pb-Pb collisions by ALICE**, complementing
  - Lower energy results from NA50
  - High-p_T studies by ATLAS/CMS at midrapidity

ALICE, arXiv:2210.08893

- 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

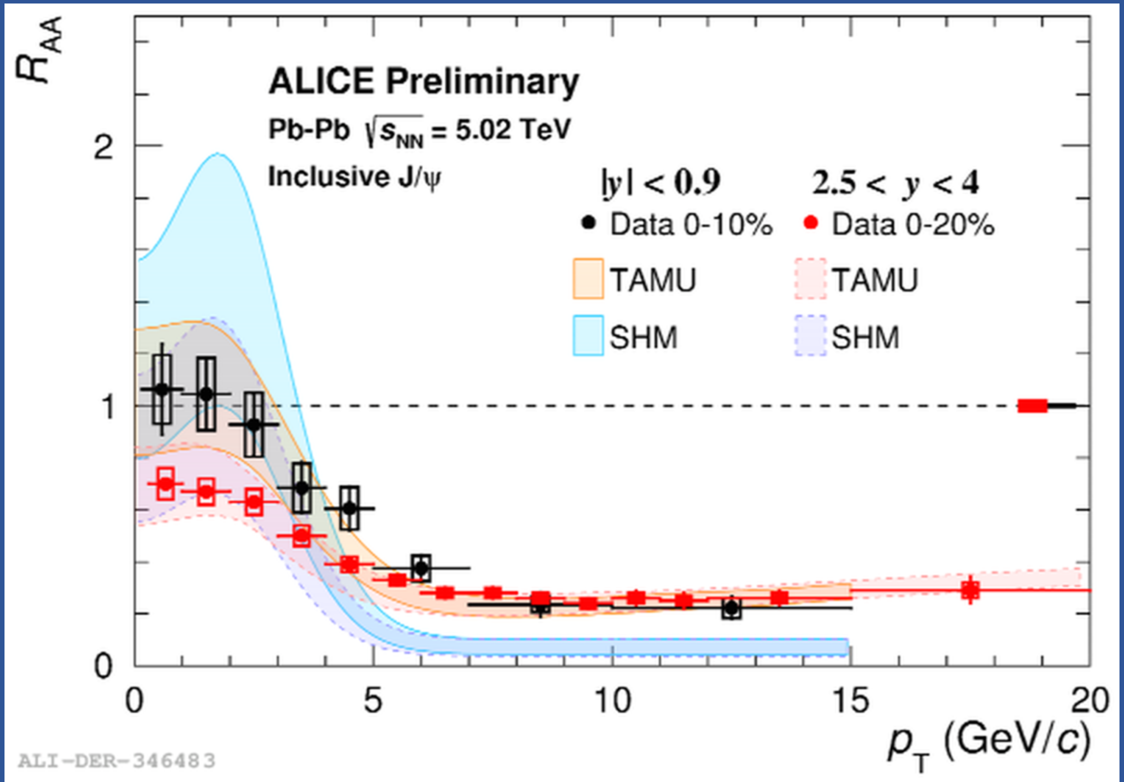
- Model predictions **fairly reproduce data**, except for SHMc in central collisions

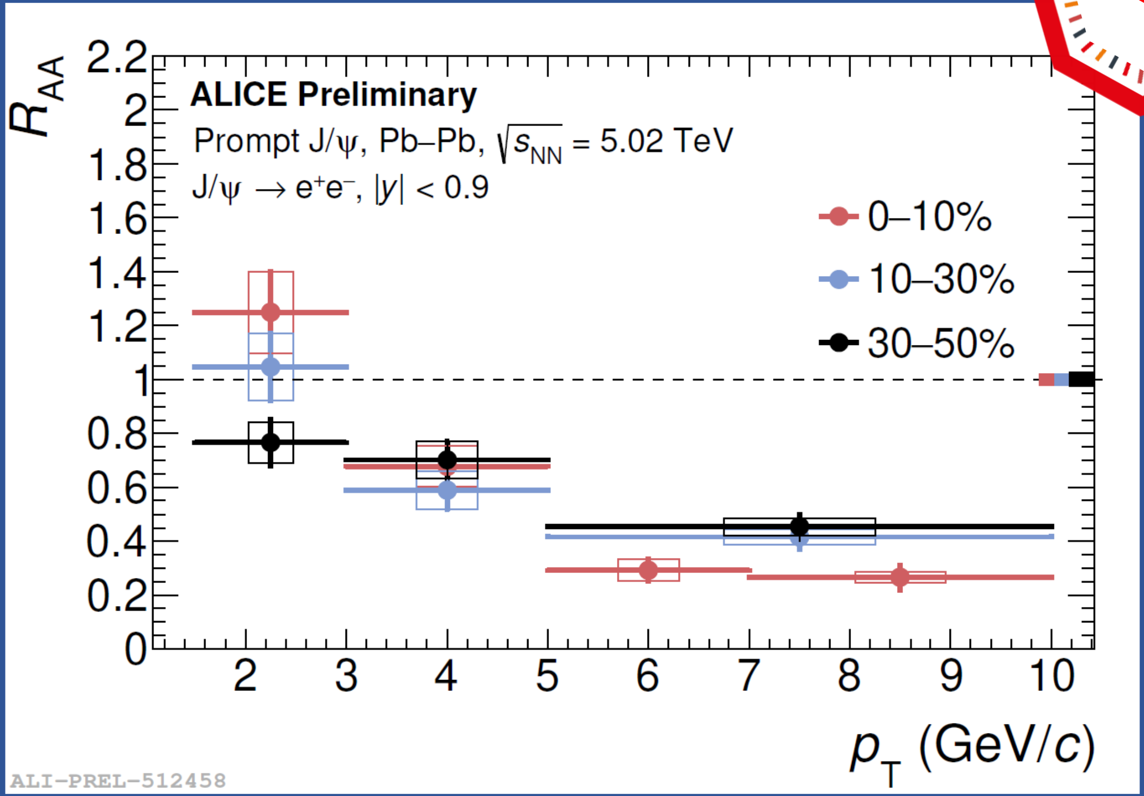
- Evidence for **final state effects on ψ(2S) in p-Pb collisions**
- **Weaker effects**, if any, in **high multiplicity pp collisions**

- Excellent prospects for more accurate results with **Run 3 + 4 data**

Backup

Inclusive and prompt J/ψ production in Pb-Pb

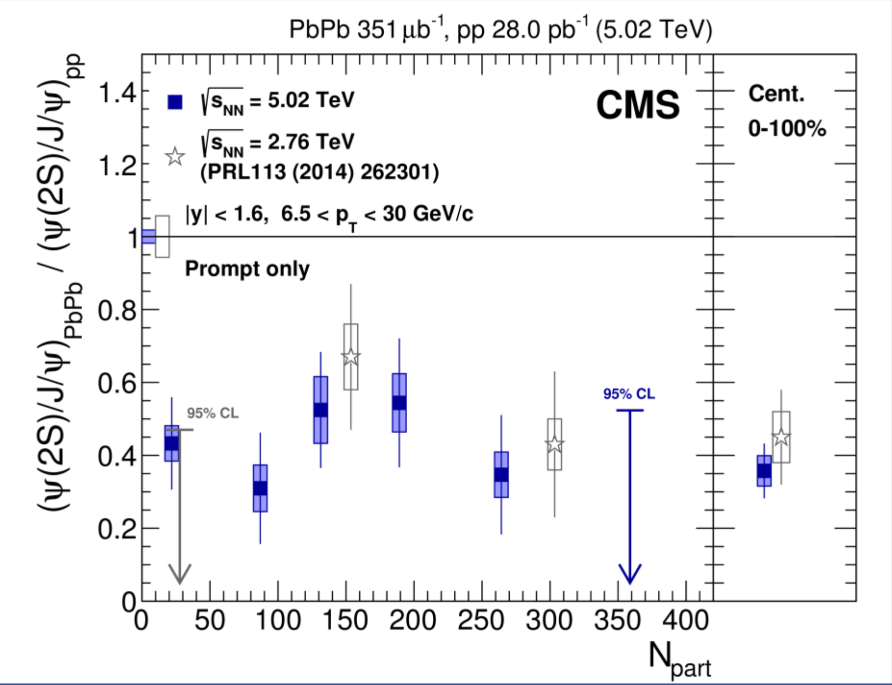




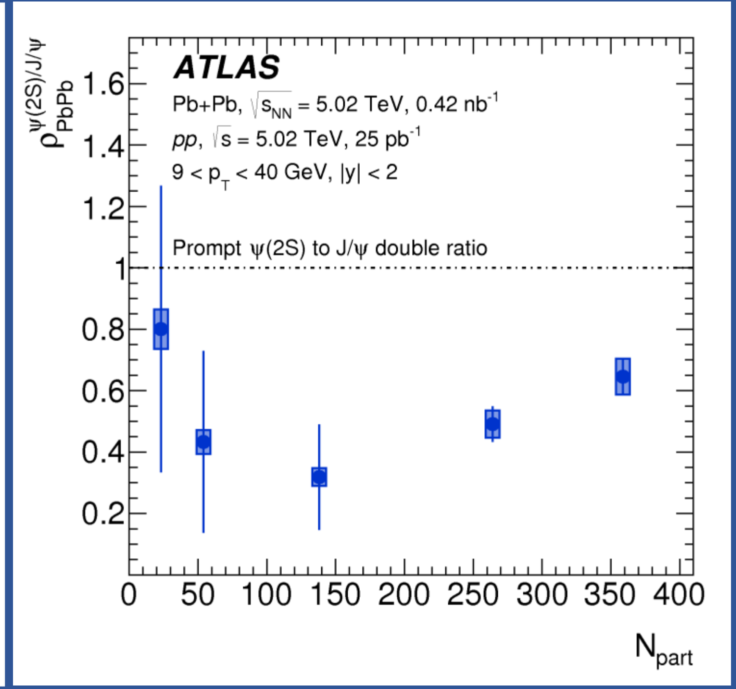
- ❑ Rise of inclusive J/ψ R_{AA} at low p_T, stronger effect at y=0 → decisive signature of recombination
- ❑ Models include regeneration either at the freeze-out (SHMc) or during the medium evolution (TAMU)
  → Both in agreement with data at low p_T

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

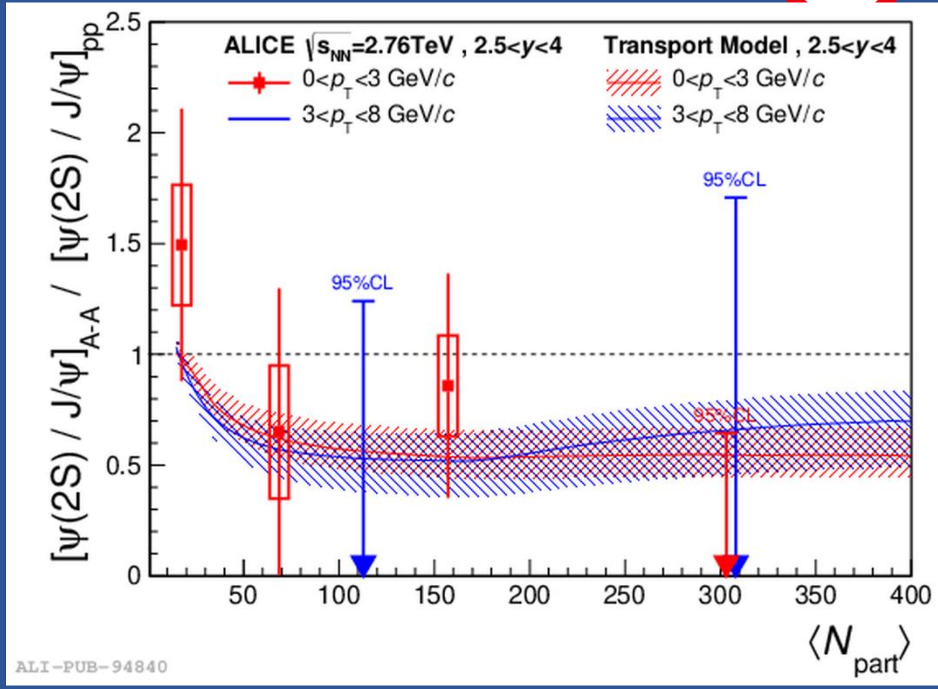
Pb-Pb results at LHC energies



CMS, PRL 118 (2017) 162301

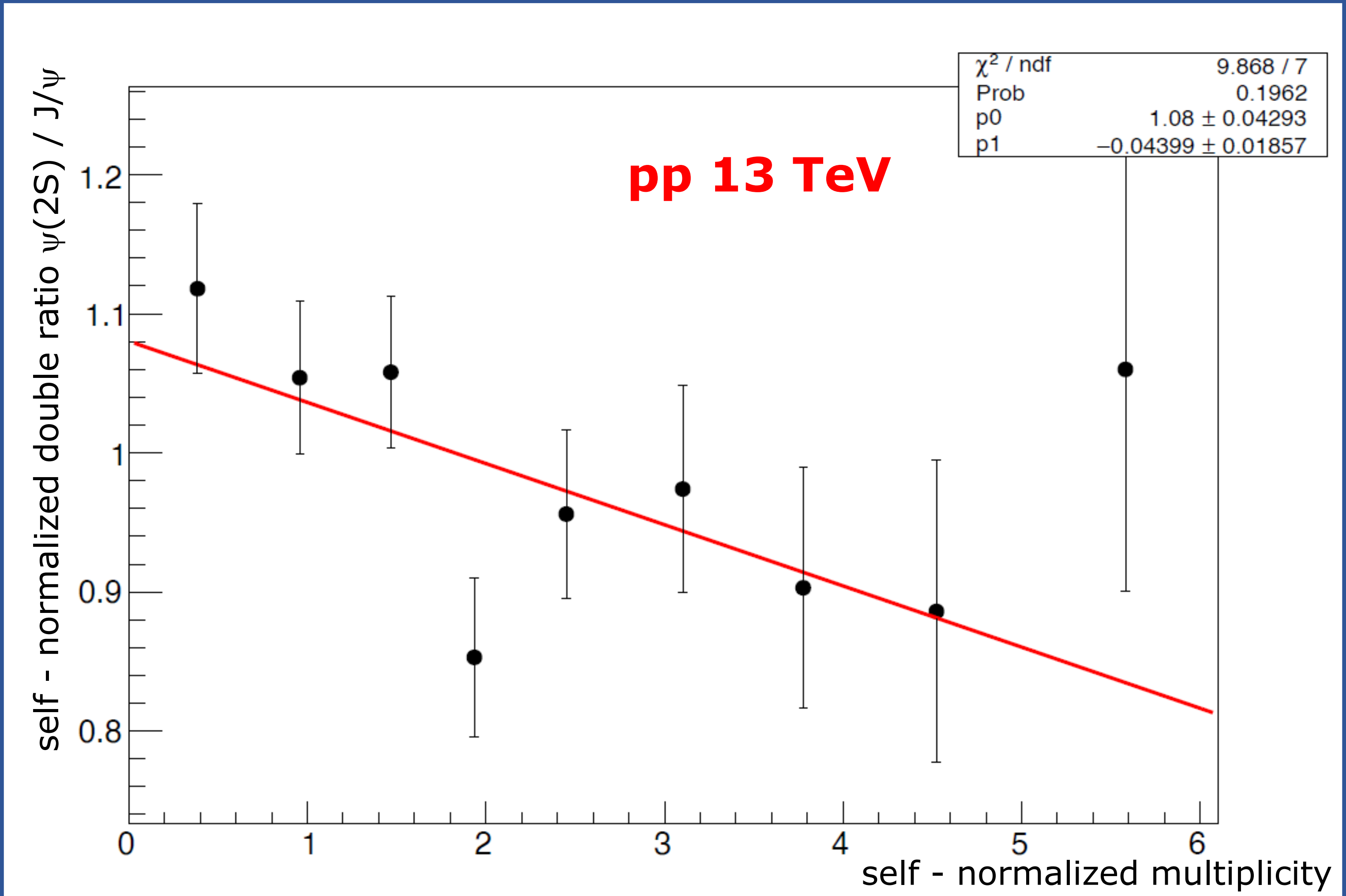


ATLAS, EPJC78 (2018) 762



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



χ^2 / ndf 9.868 / 7
Prob 0.1962
p0 1.08 ± 0.04293
p1 −0.04399 ± 0.01857
pp 13 TeV
self - normalized double ratio ψ(2S) / J/ψ
self - normalized multiplicity
0
1
2
3
4
5
6
0.8
0.9
1
1.1
1.2