Recent ALICE results on ψ(2S) production

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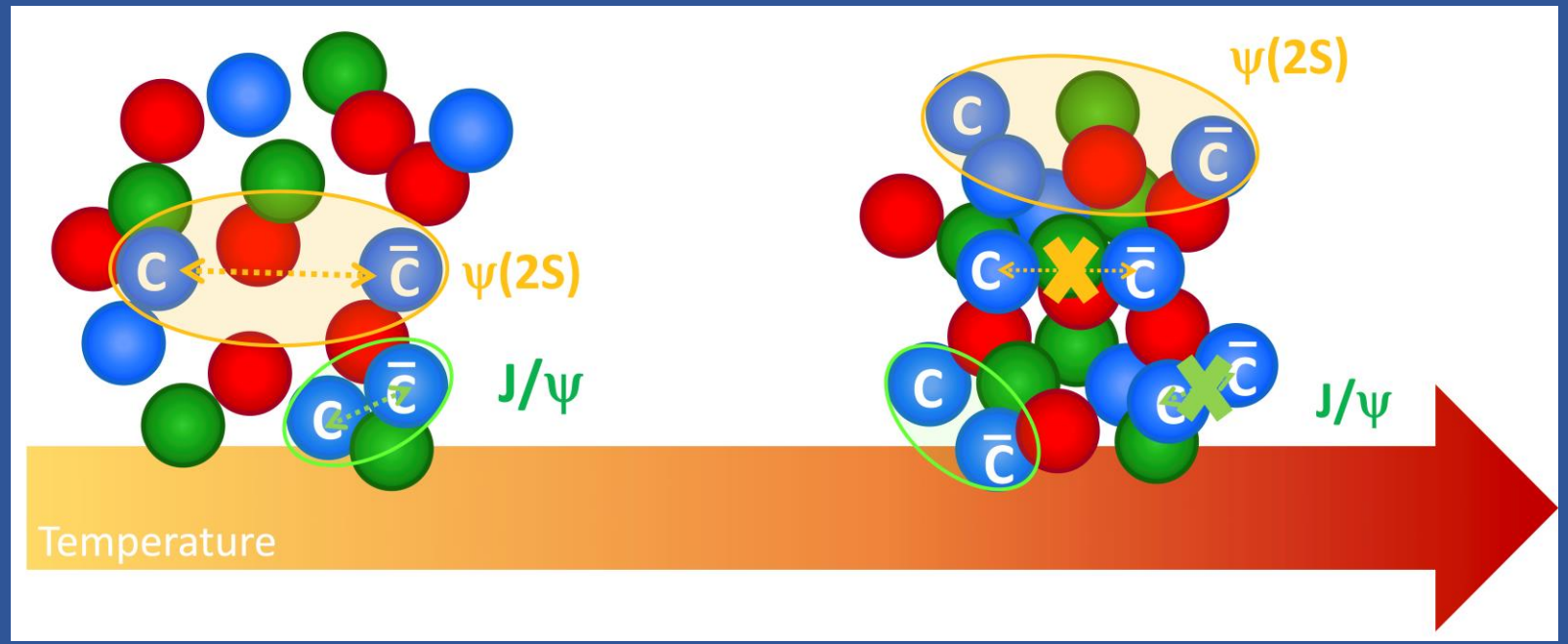
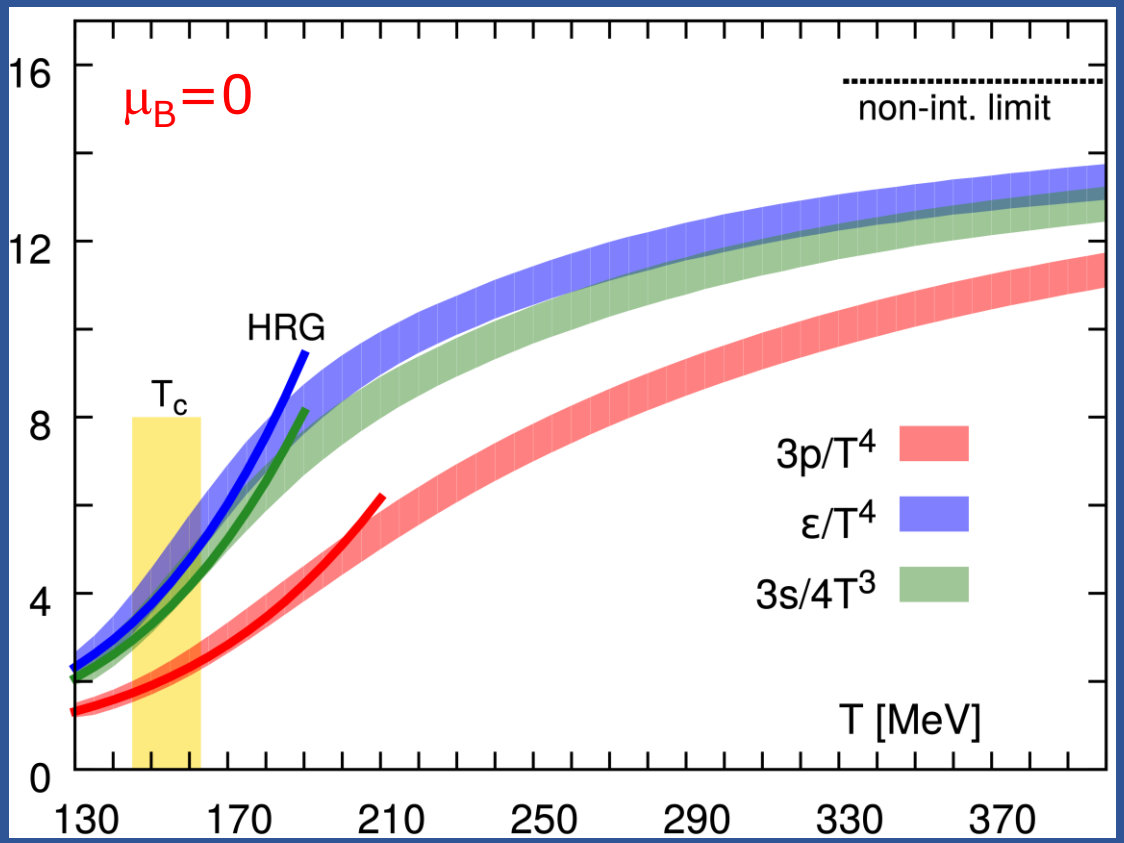
for the ALICE Collaboration

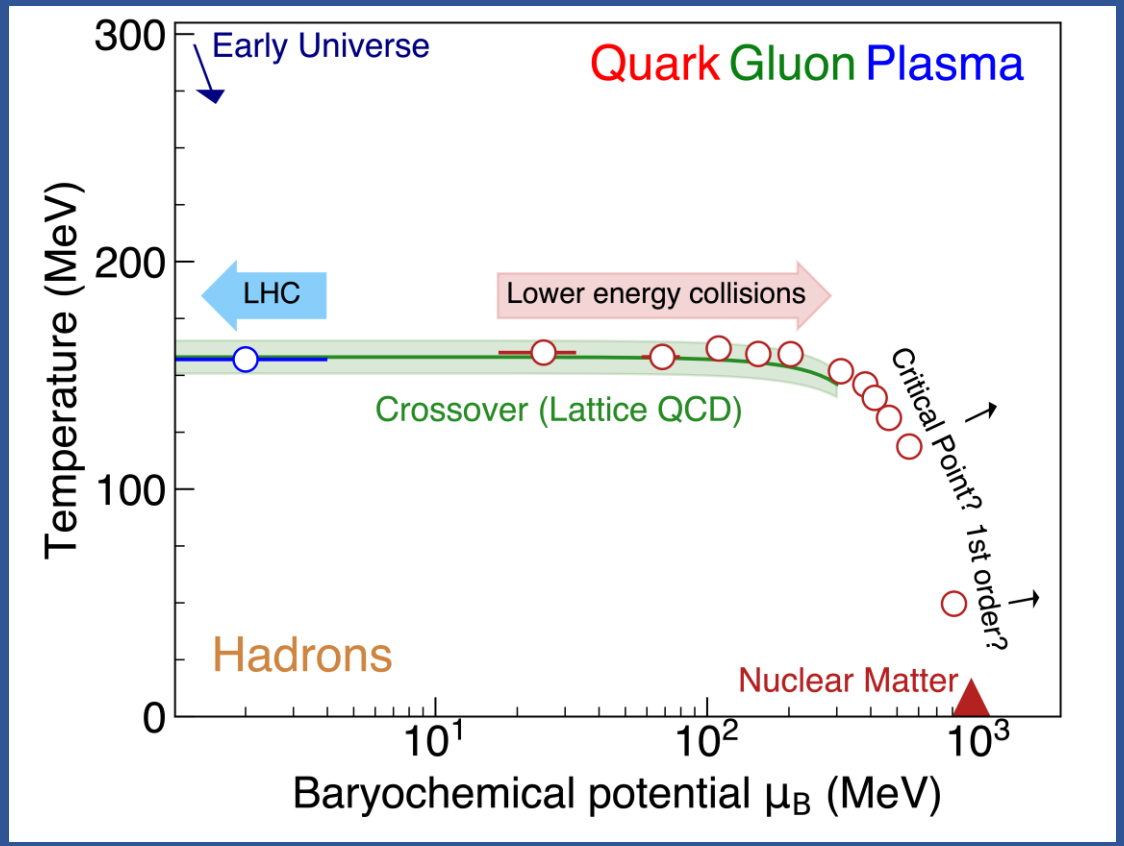
- Quarkonia in the QGP: ground and excited states
- ψ(2S) studies from SPS to LHC energies
- ALICE: analyze ψ(2S) behaviour from large to small systems
- Prospects for Run 3



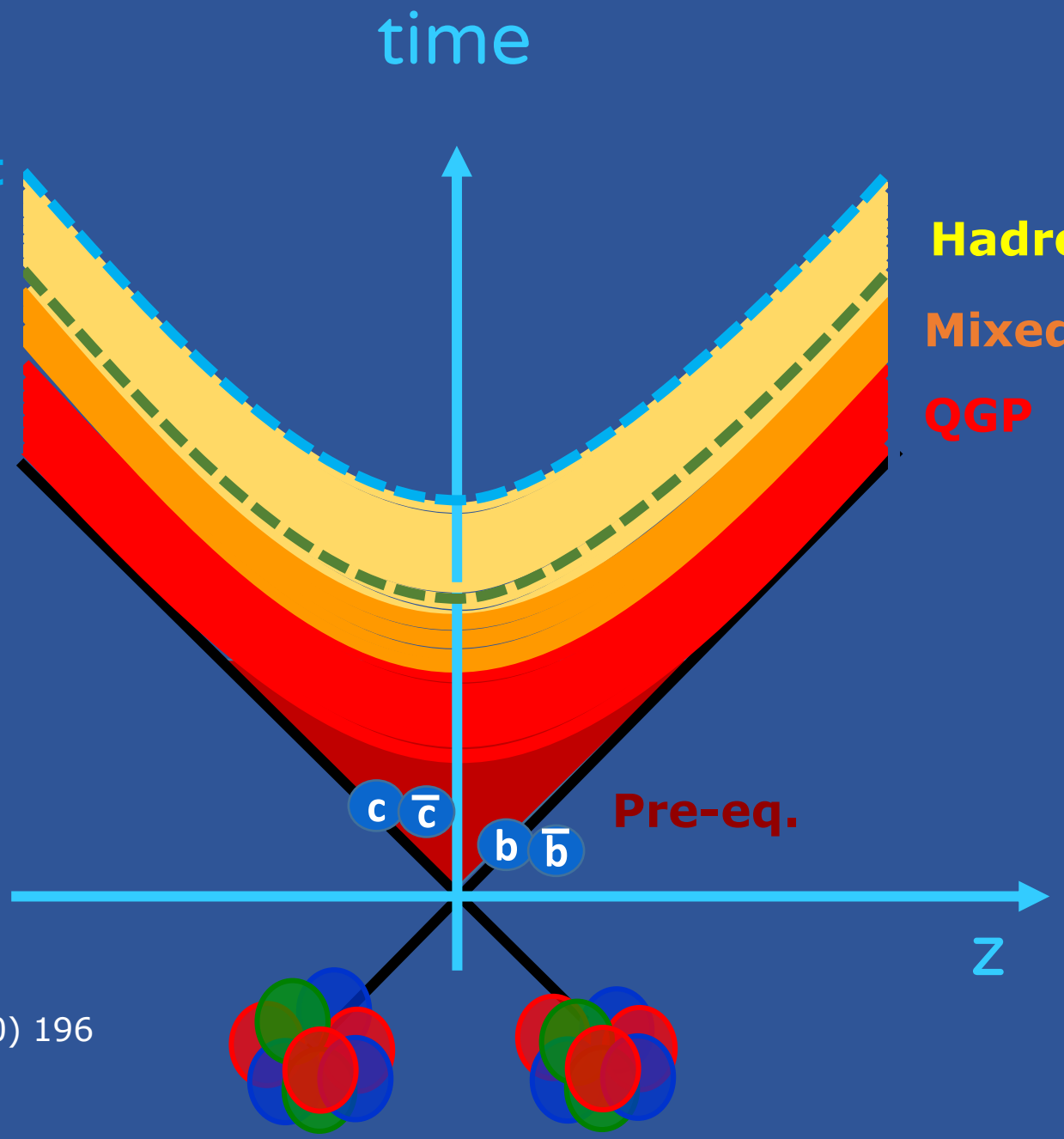
Discovering and analyzing the properties of the quark-gluon plasma (QGP)

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





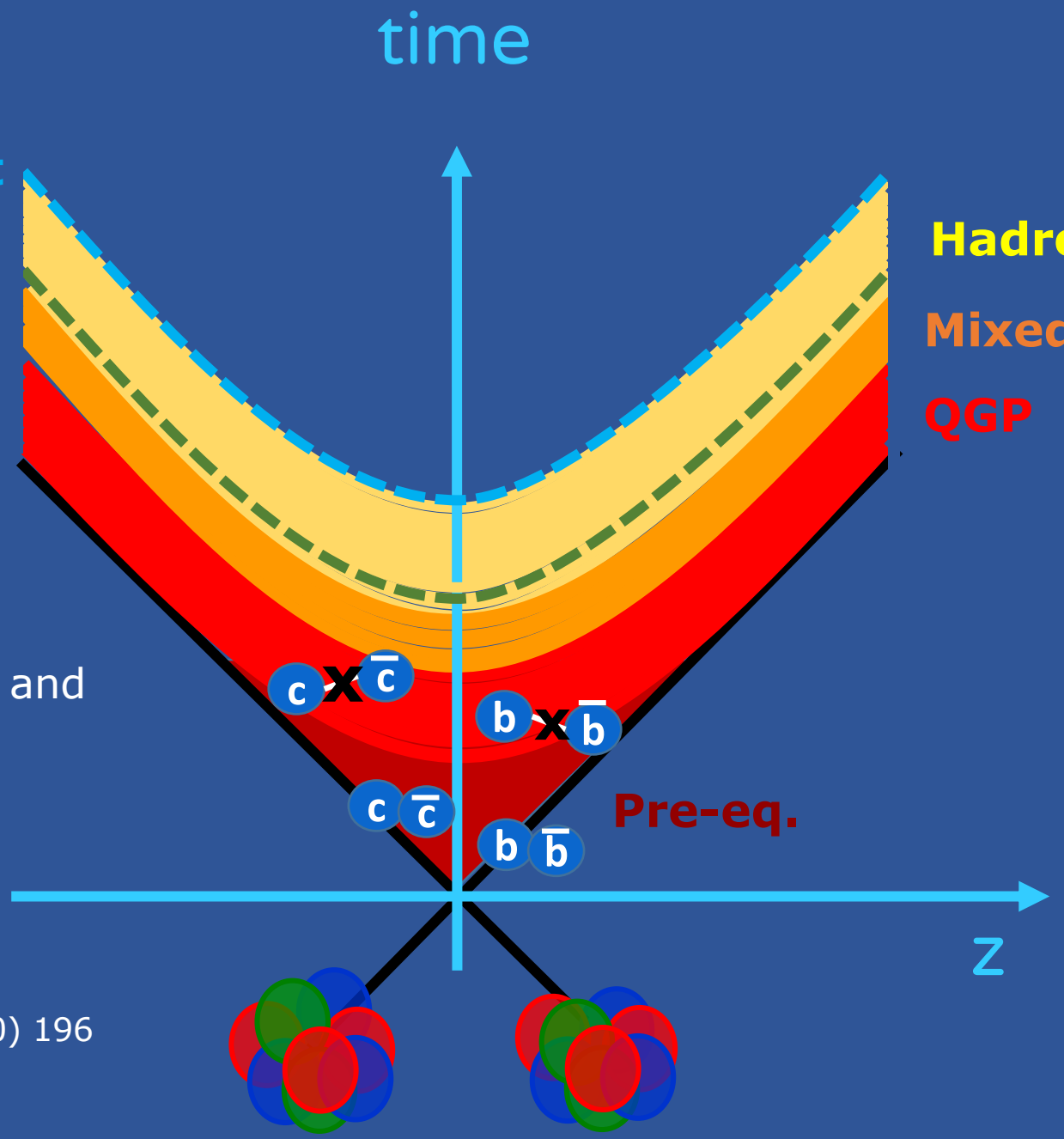
- Quarkonium properties are strongly affected by the QGP. How ?



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

T. Matsui and H. Satz, PLB 178(1986) 416
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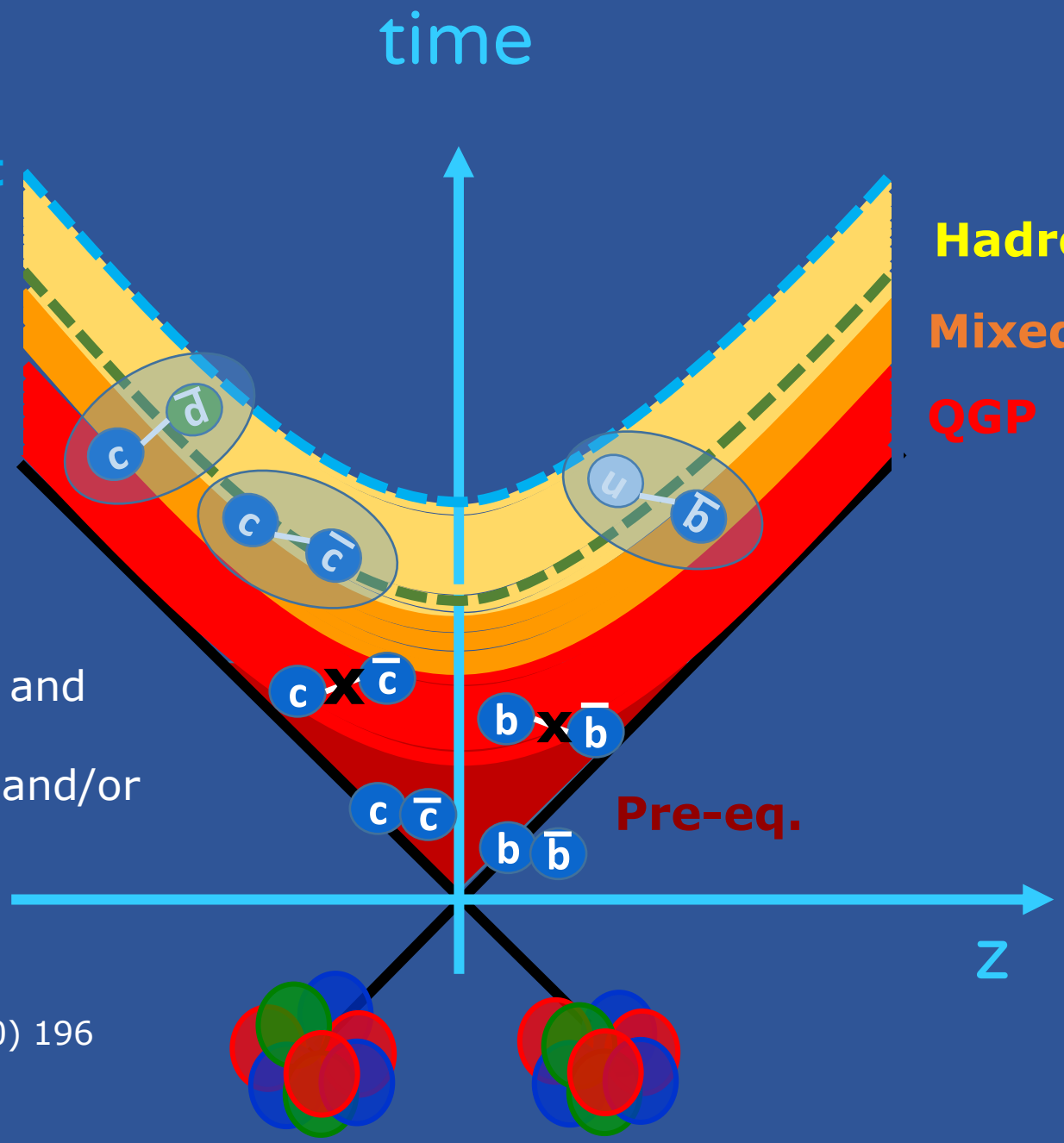


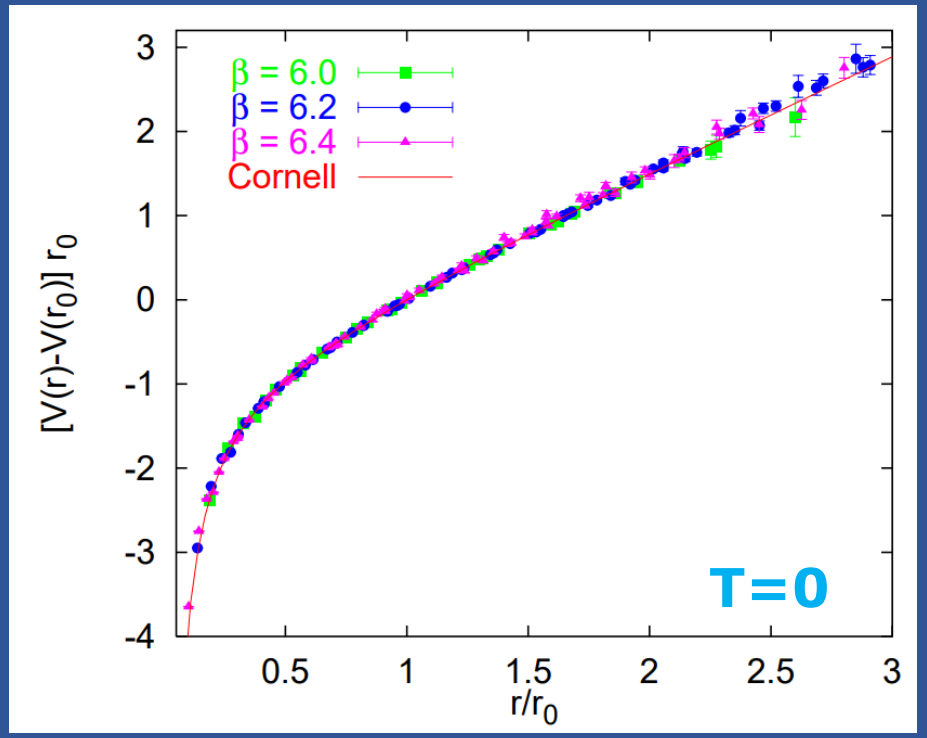
Quarkonium

- 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

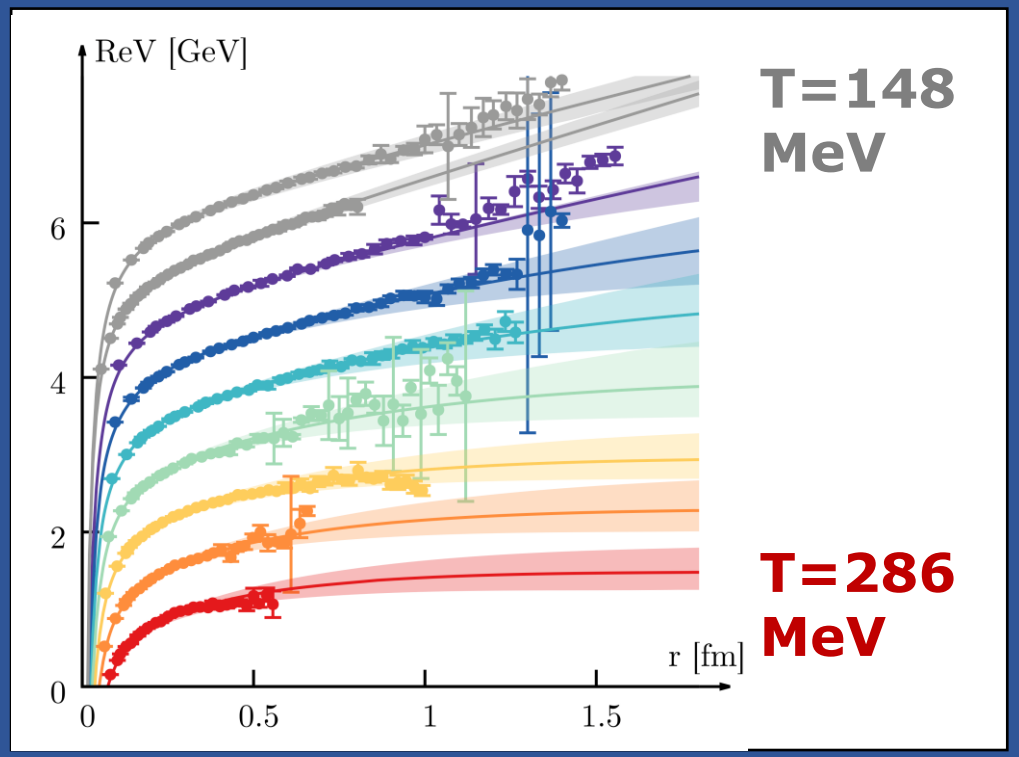
T. Matsui and H. Satz, PLB 178(1986) 416
P. Braun-Munzinger and J. Stachel, PLB490(2000) 196
R. Thews et al., PRC63 (2001) 064905
A. Rothkopf, Phys. Rept. 858 (2020) 1

Modification of spectral properties and dissociation

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



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

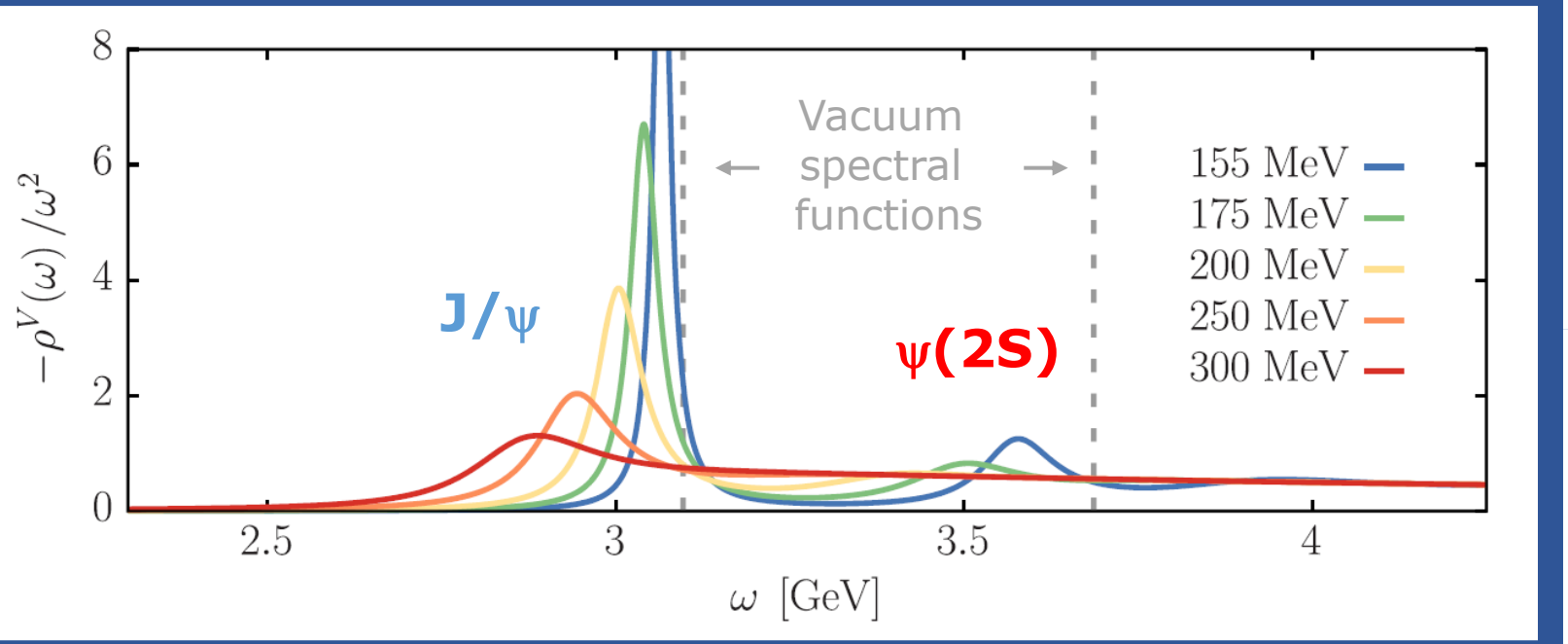


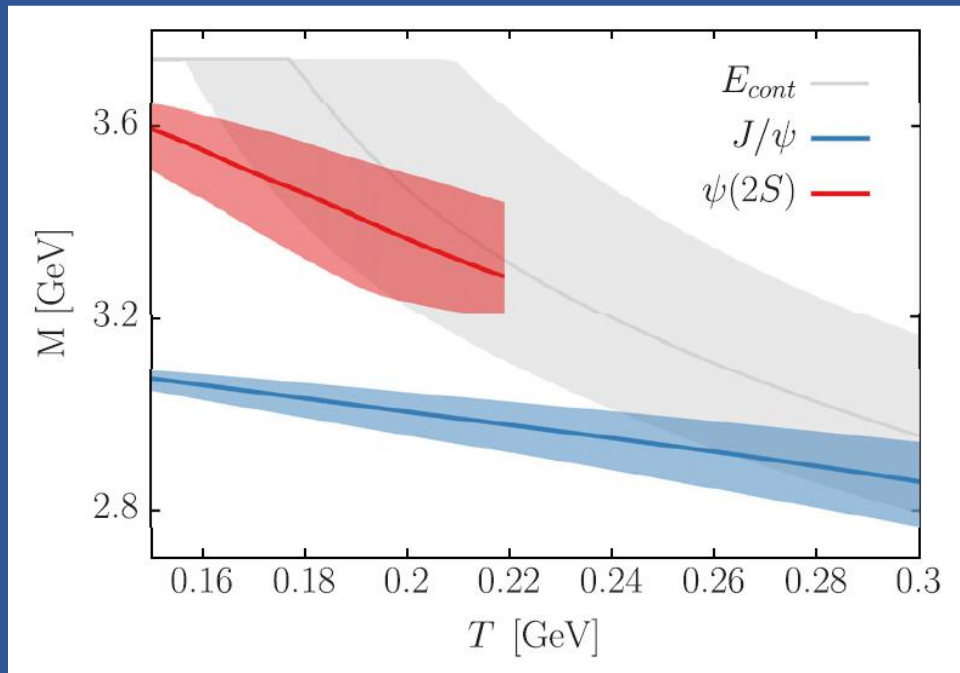
Potential models provide a faithful reproduction of available lattice data

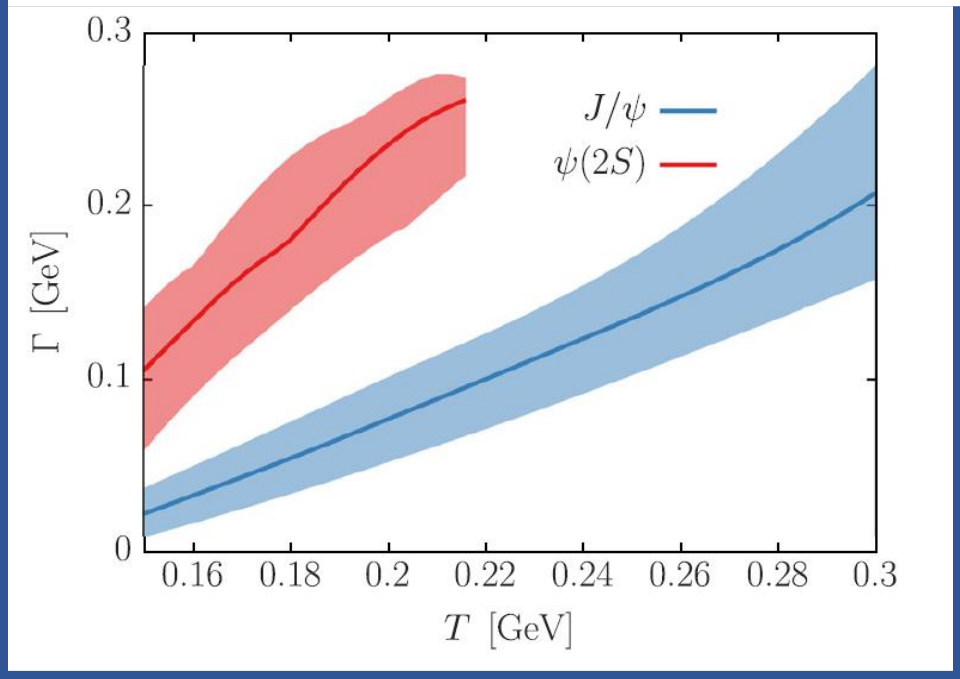
- Gradual transition **from a Cornell to a Debye-screened behaviour** for the (real part of) the potential → **color screening** in a deconfined medium
- Potential also has a finite imaginary part (not shown)
  → decaying of quark-antiquark correlation due to gluonic damping in the plasma

Modification of spectral properties and dissociation

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



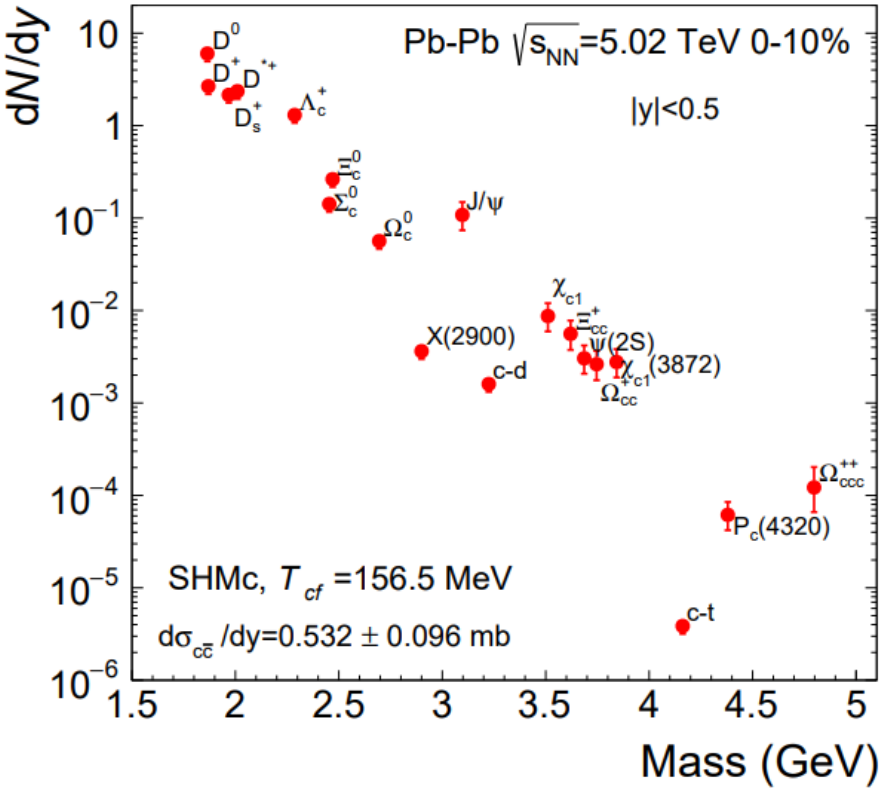


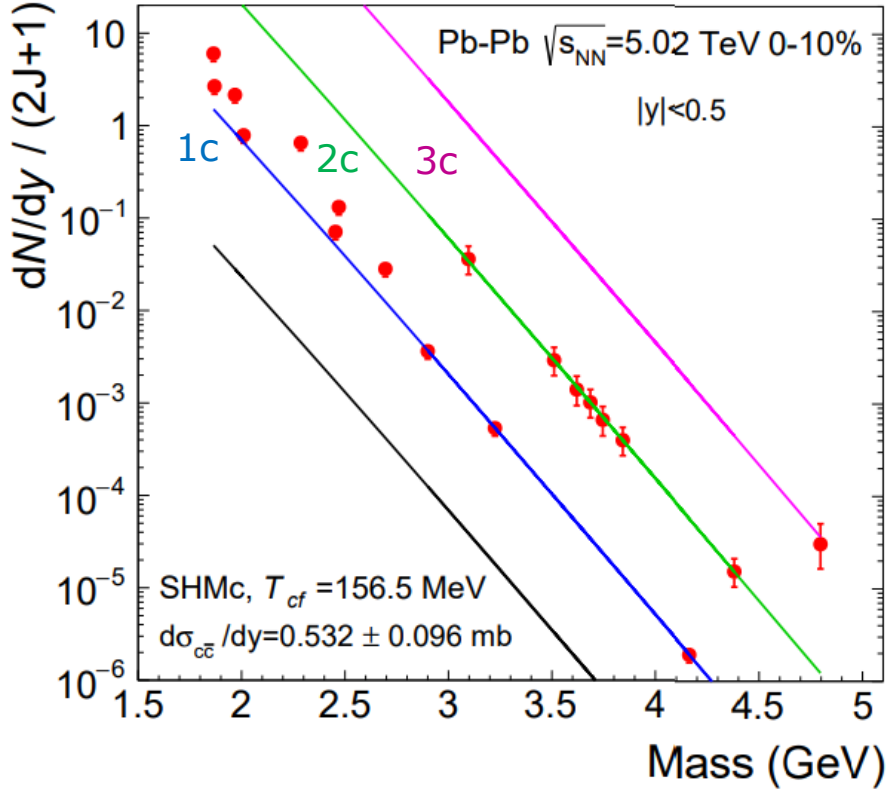


- Strong effects on the **mass AND width** of the charmonium states, with distinctive **differences between J/ψ and ψ(2S)**
- As intuitively expected, the more deeply the state is bound, the less is susceptible to medium effects

(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



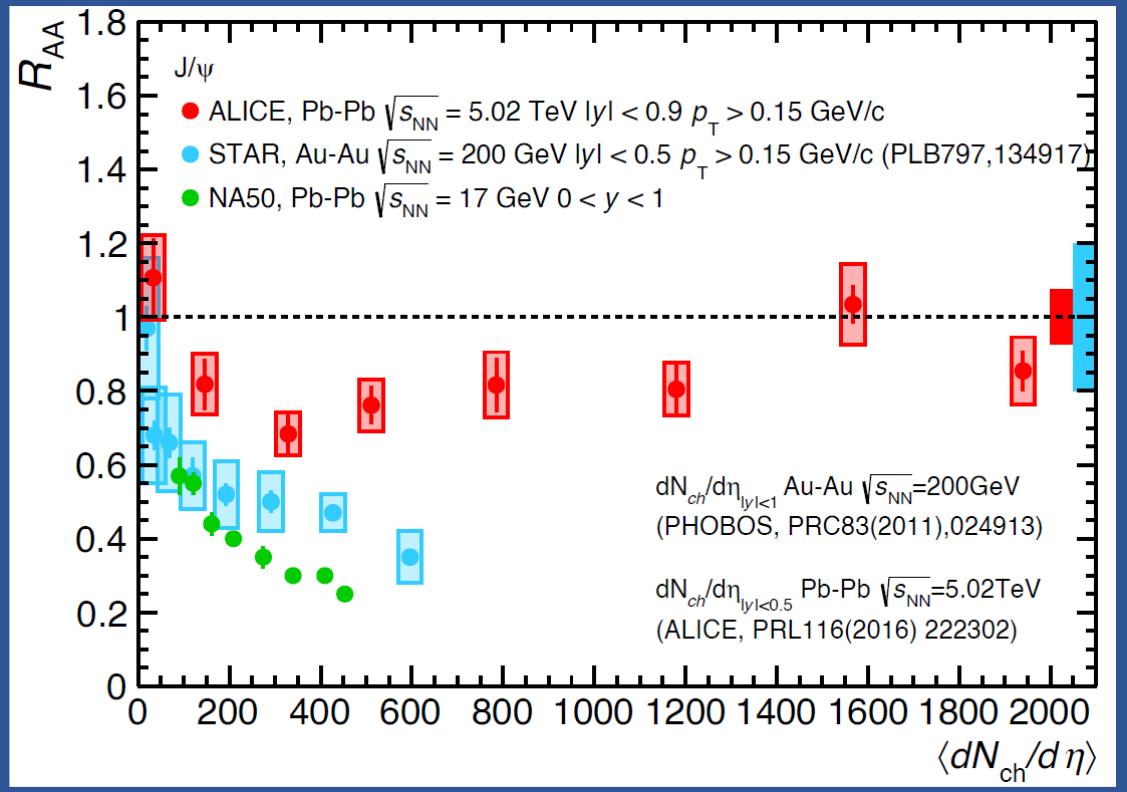


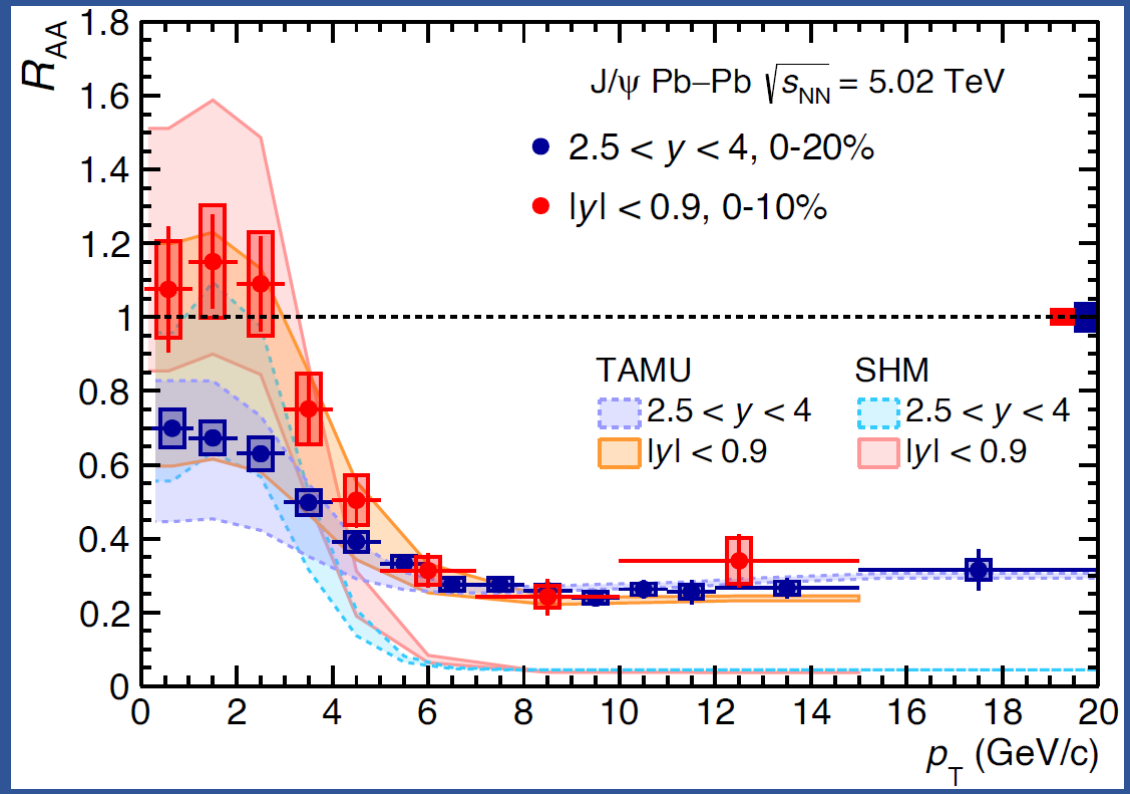
Allows **quantitative predictions** for charmed hadron yields, including quarkonia

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

J/ψ results at LHC energy

ALICE, arXiv:2211.04384





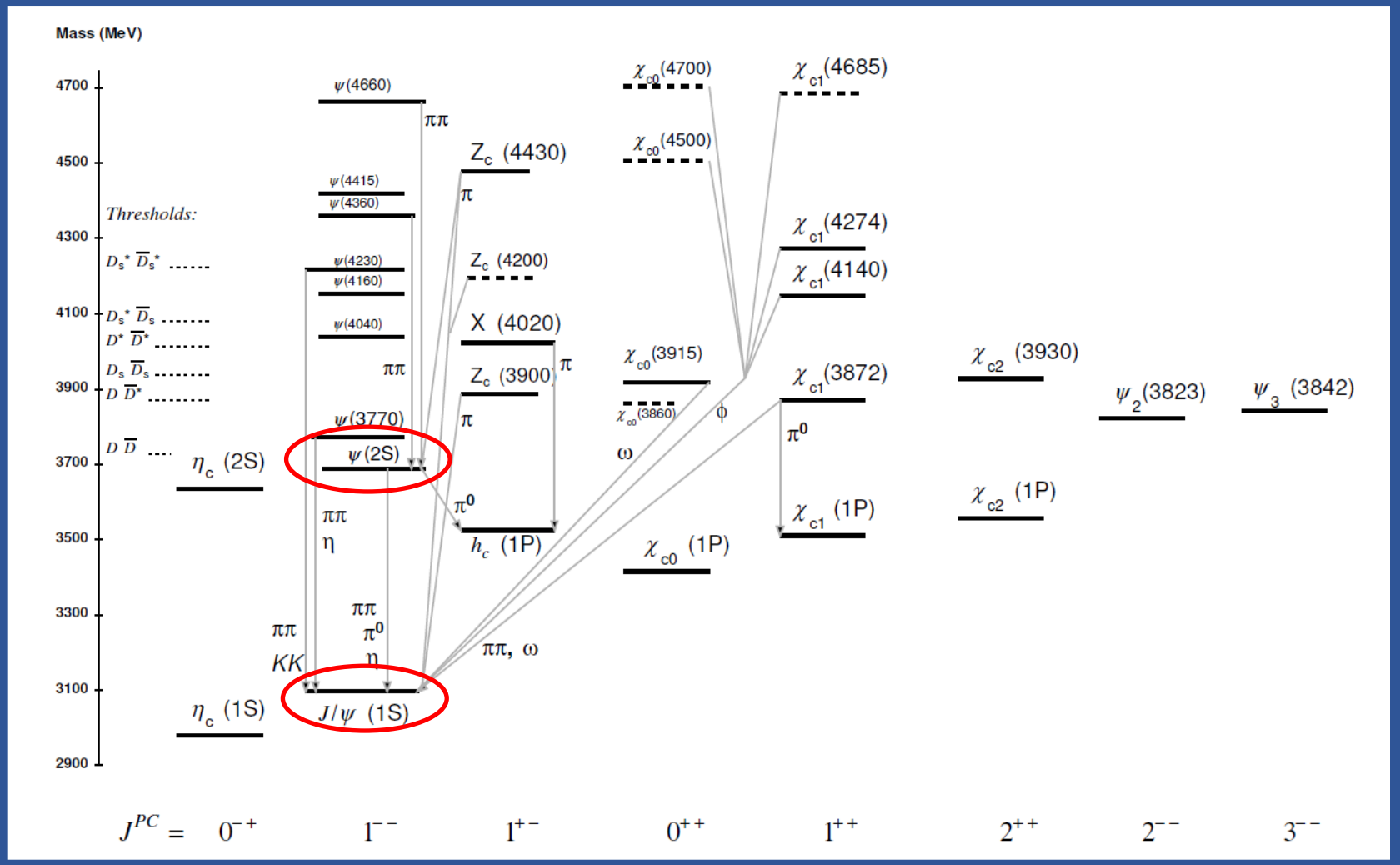
- Hierarchy of suppression: $R_{AA}^{SPS} < R_{AA}^{RHIC} < R_{AA}^{LHC}$
- Reduced (or no) suppression at small p_T

} 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_ψ) → **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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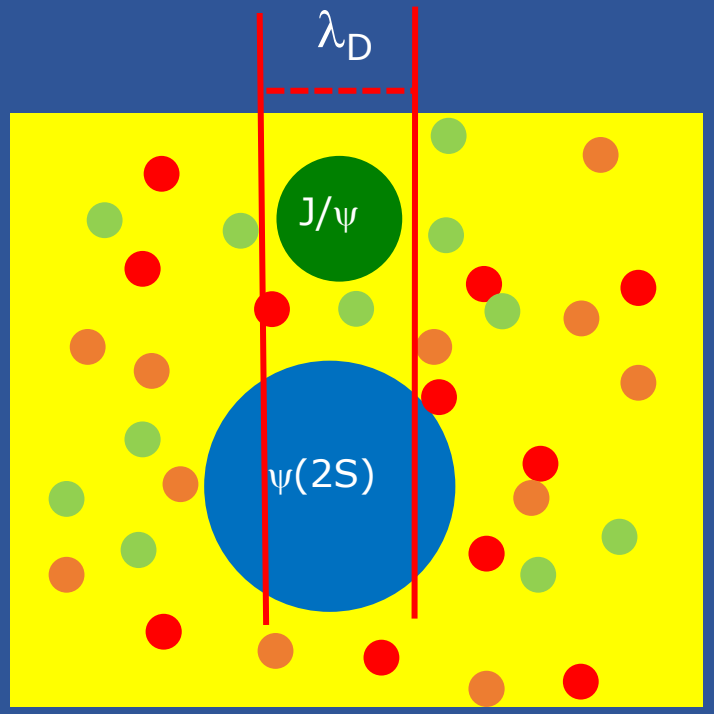
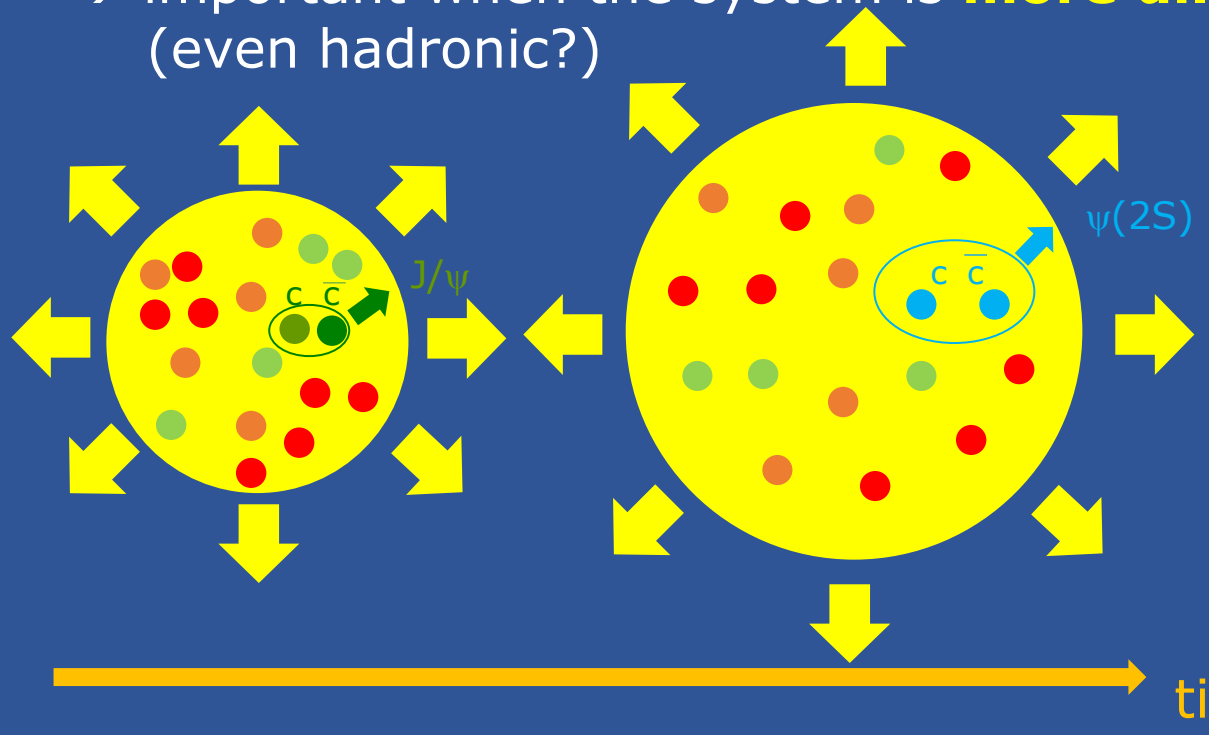


Important for a quantitative test of models!

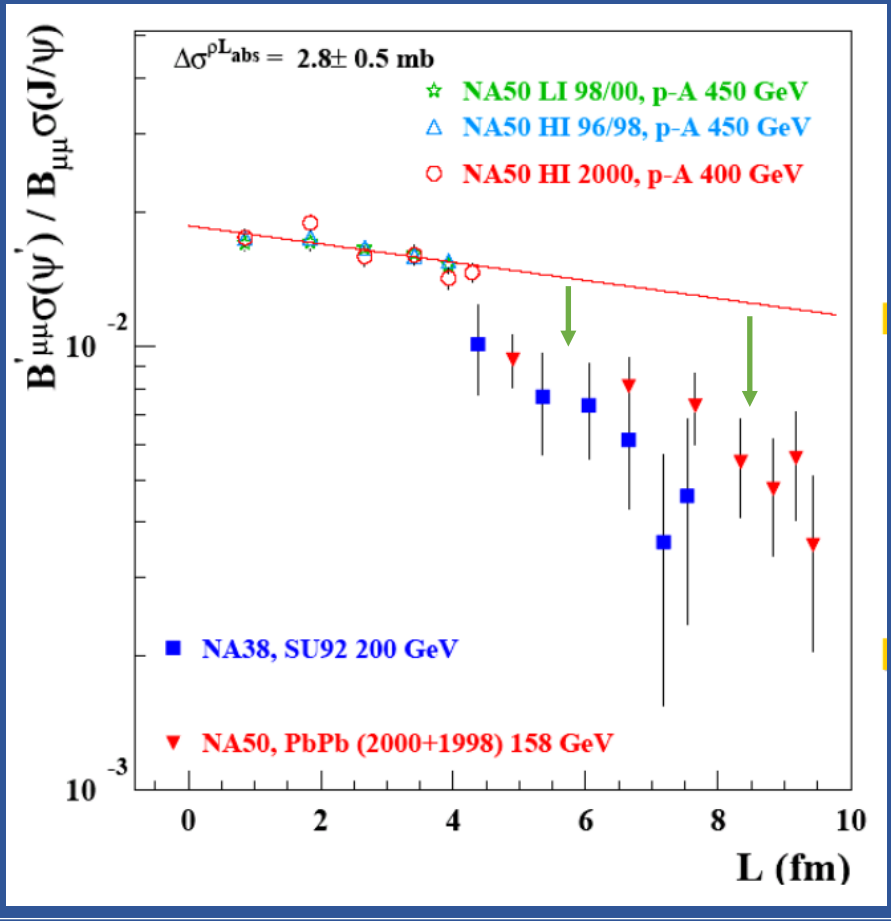
- Expect **much stronger dissociation effects** for the weakly bound ψ(2S) state
- Effect of re-combination on ψ(2S) more subtle
  → important when the system is **more diluted** (even hadronic?)



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)

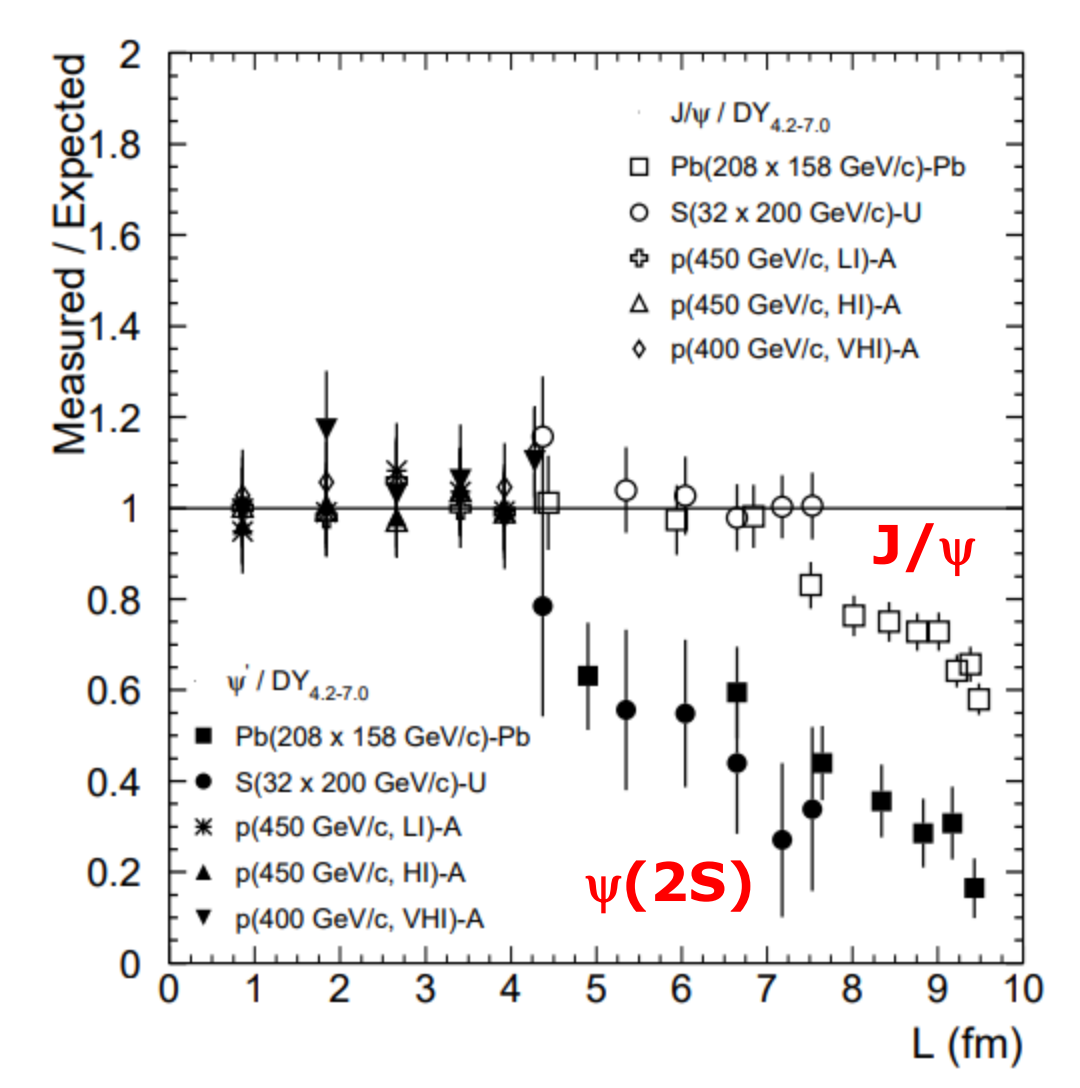
NA50, EPJC49 (2007) 559



- **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/fm^3 wrt ~2.5 GeV/fm^3 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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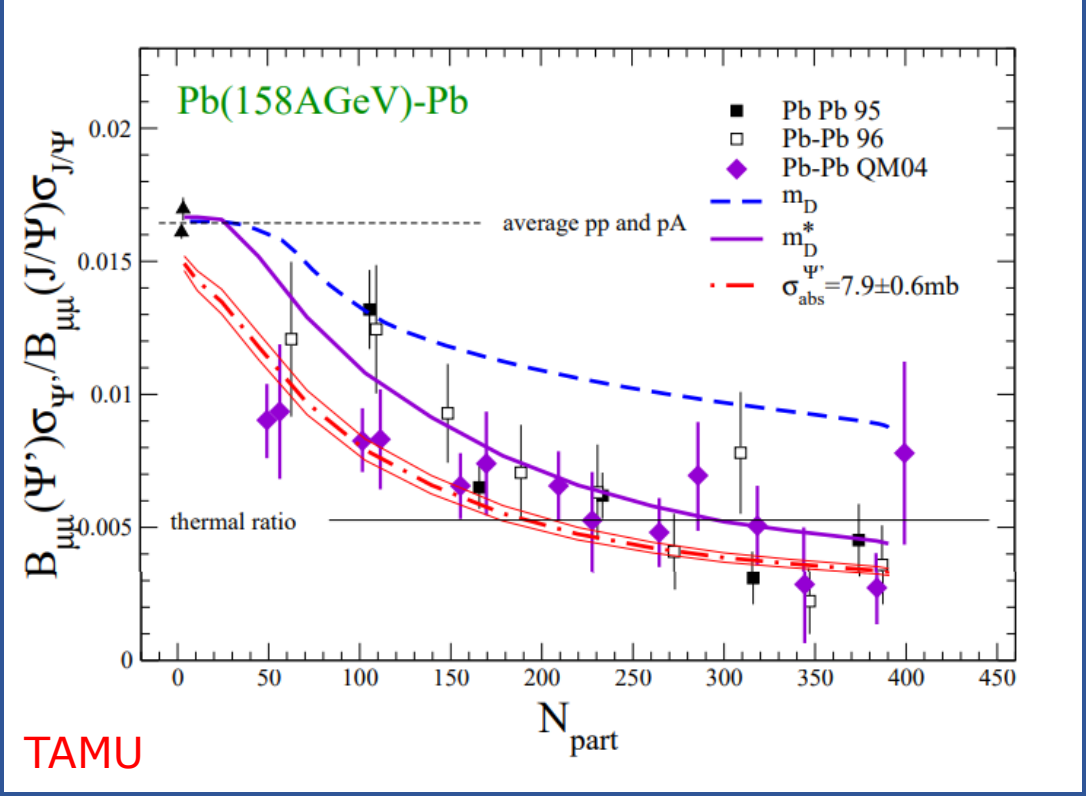
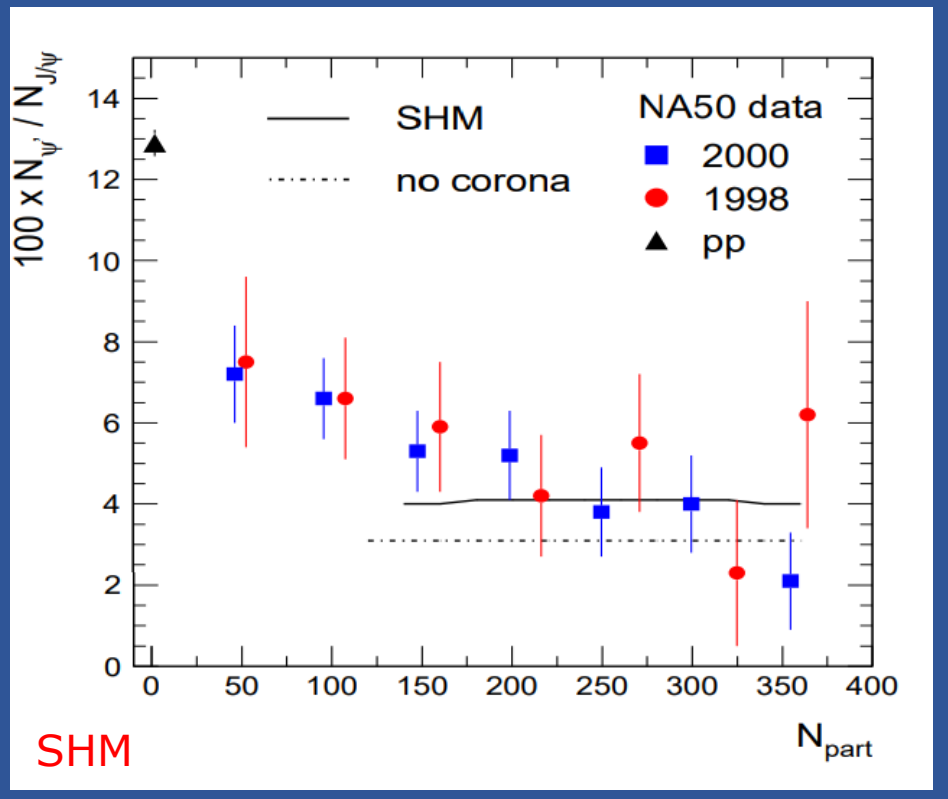




from
Rapp and Van Hees,
arXiv:0903.1096

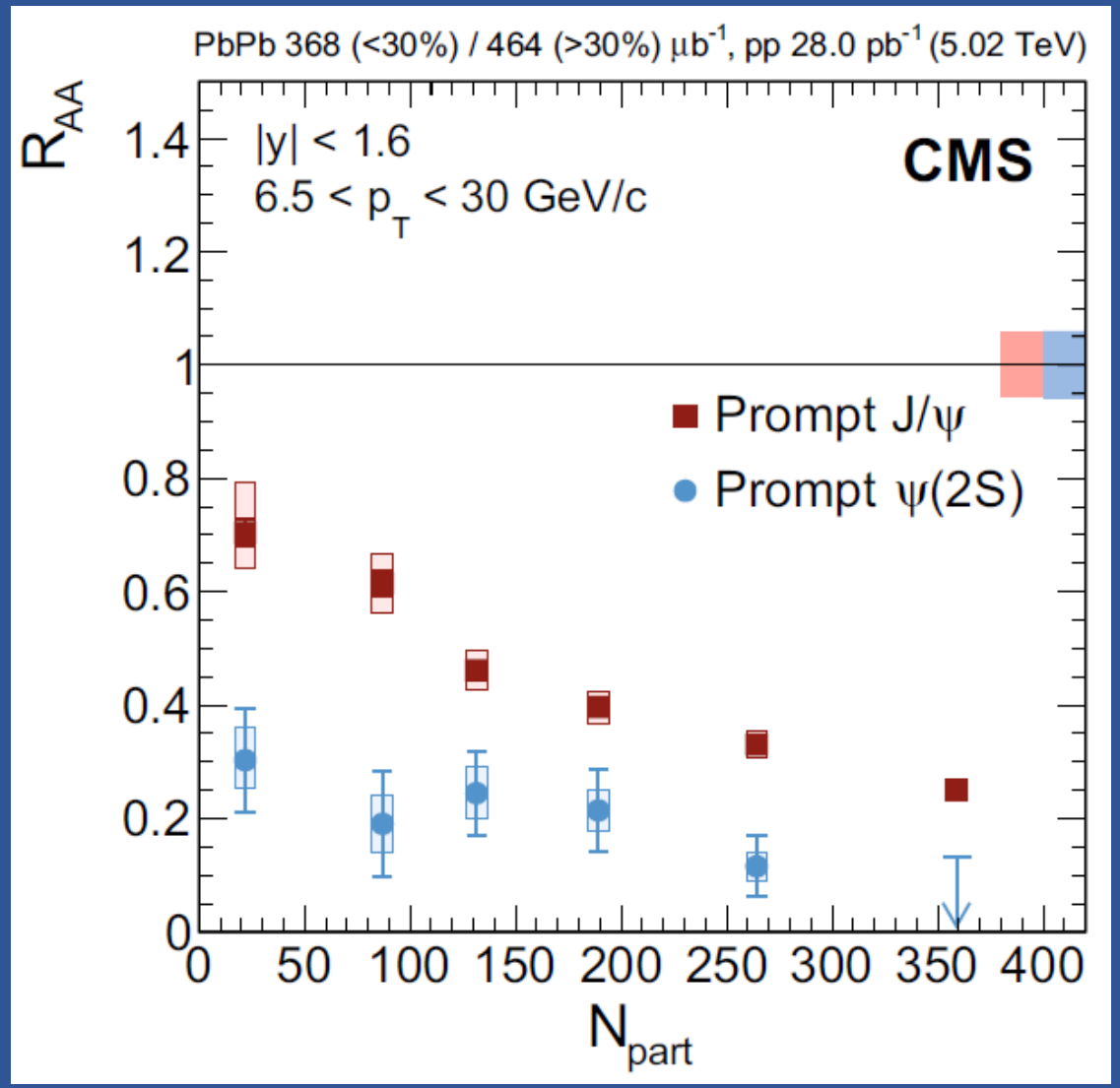
TAMU:
Grandchamp, Rapp and Brown,
PRL92 (2004) 212301

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

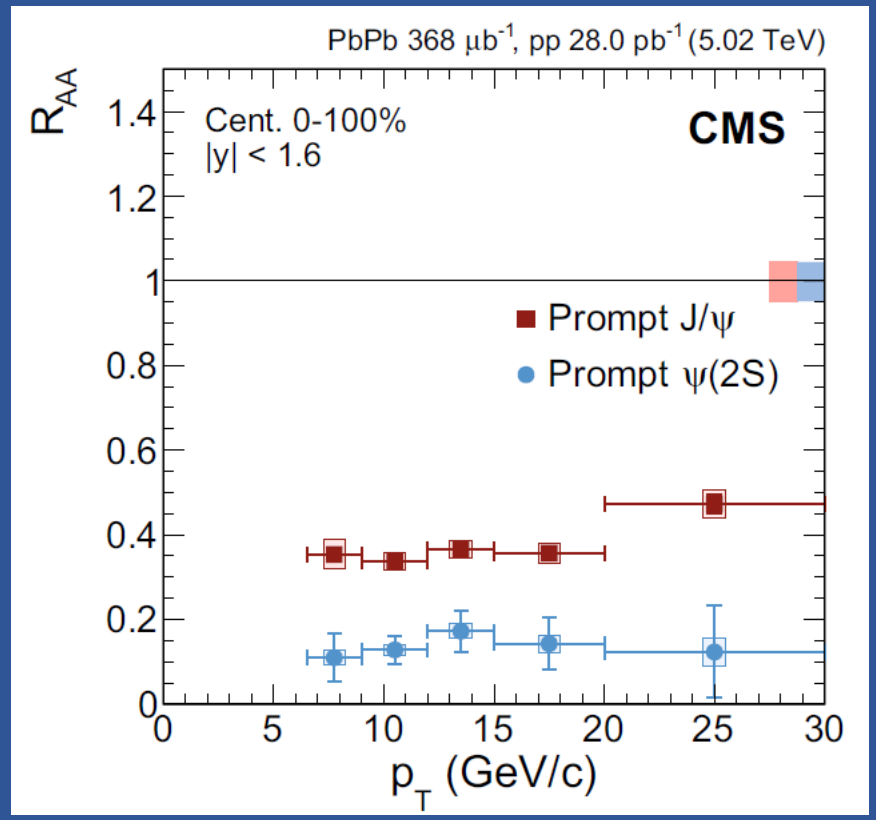
- Both transport (TAMU) and statistical hadronization (SHM) models able to **reproduce data**

Pb-Pb results at LHC energy, high p_T

CMS, EPJC 78 (2018) 509

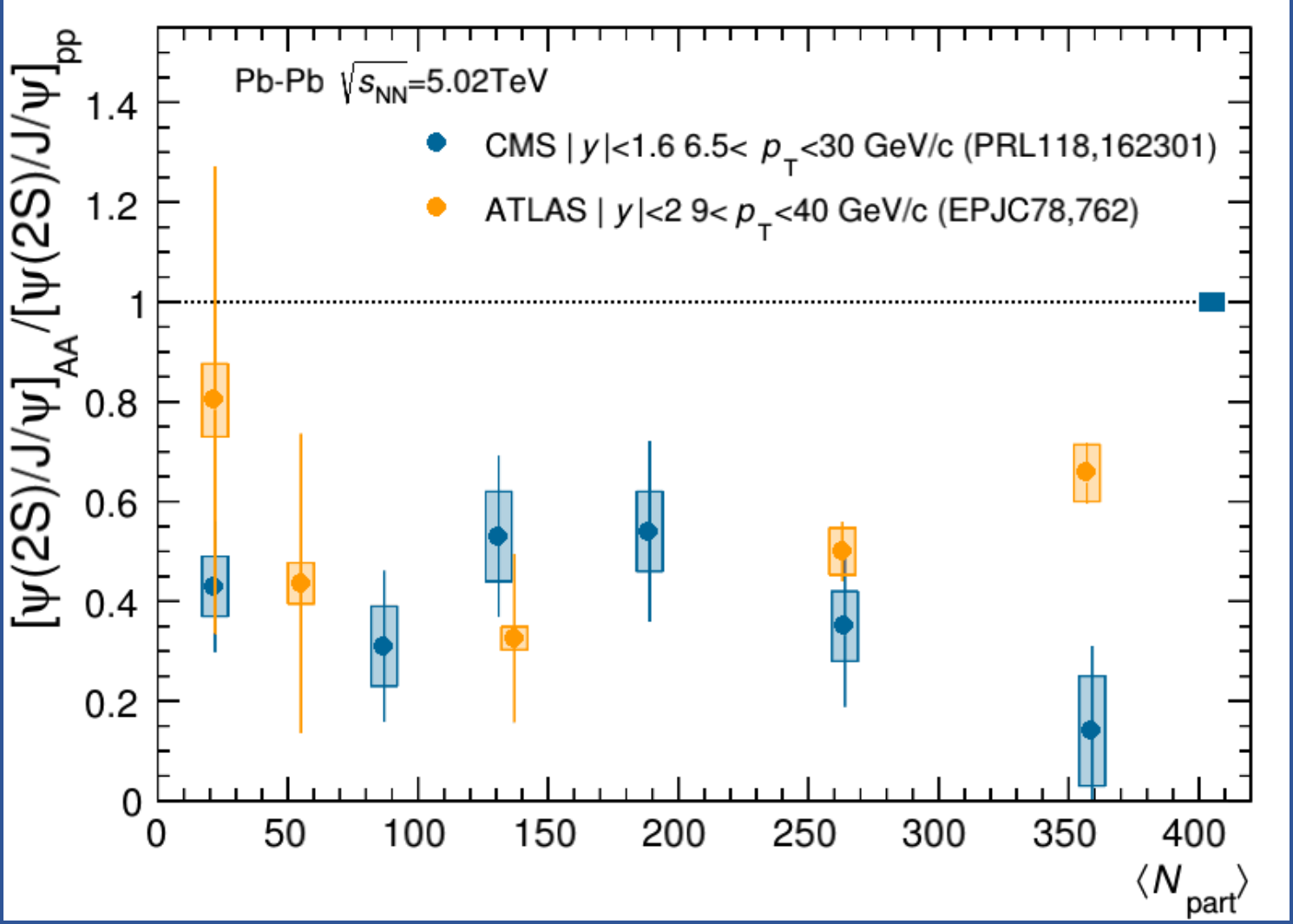


- Strong ψ(2S) suppression, larger than the J/ψ one (factor ~2), observed by **CMS**



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

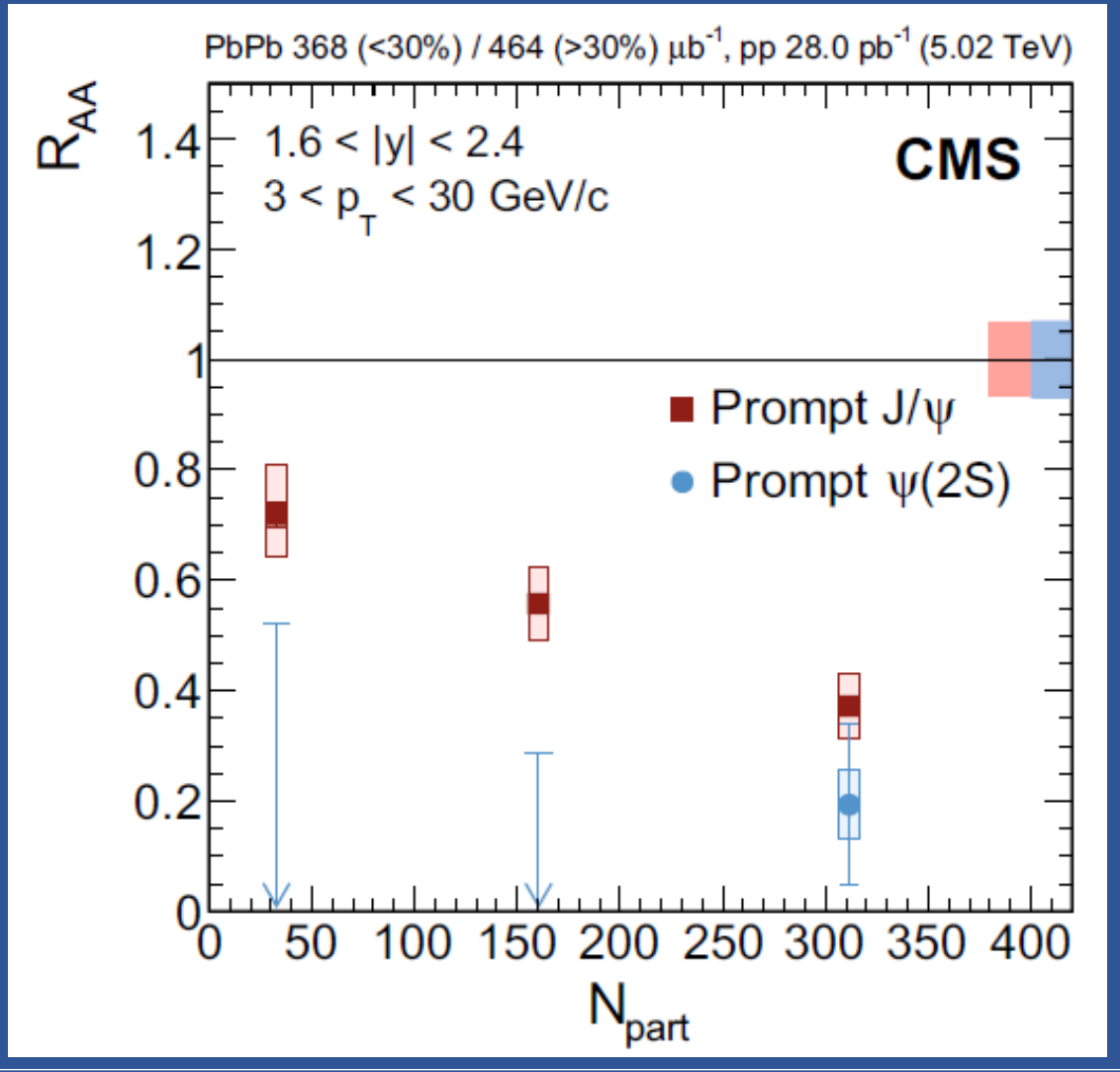
Pb-Pb results at LHC energy, high p_T



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

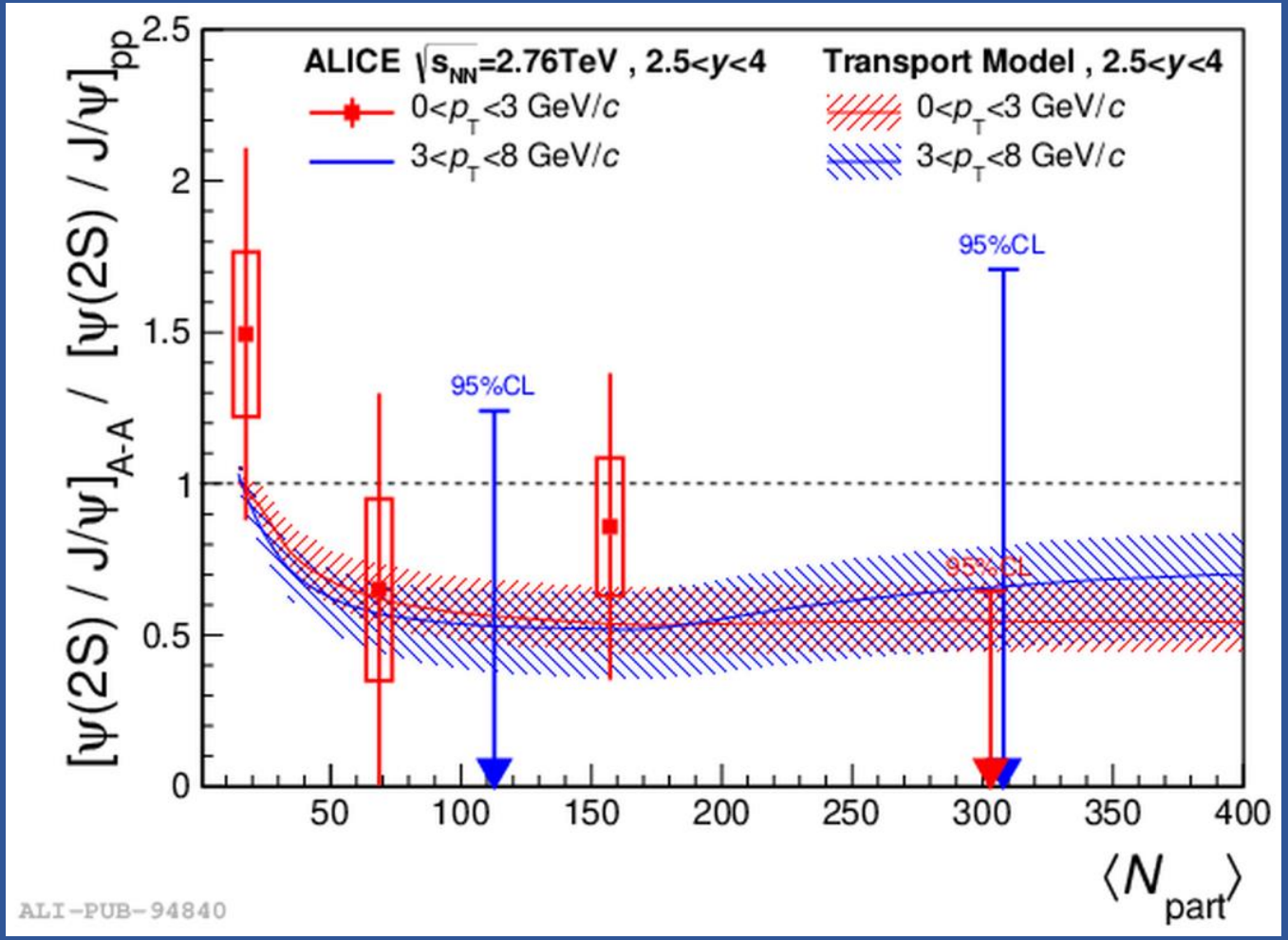
Pb-Pb results at LHC energy, intermediate p_T

- 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



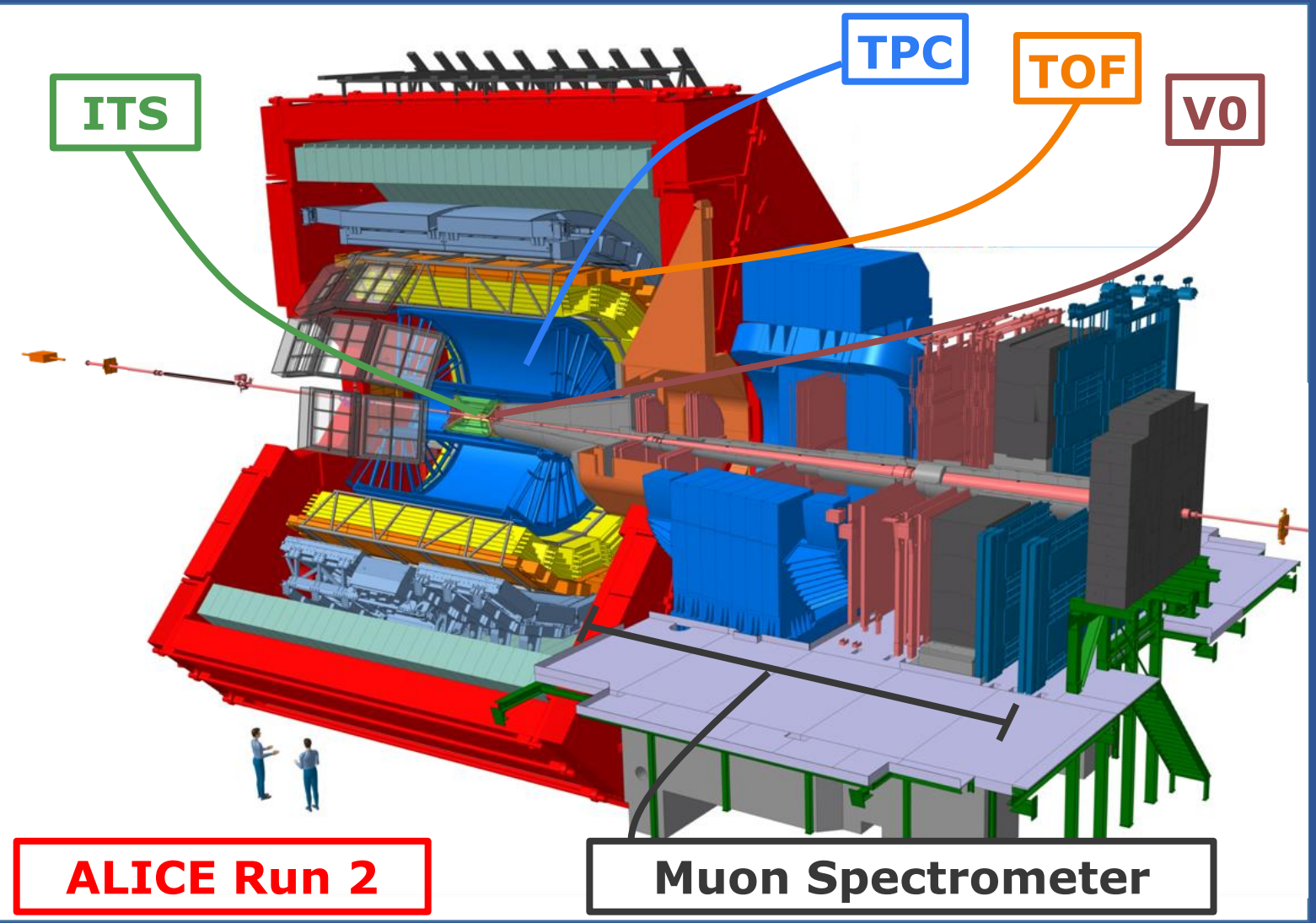
- Regeneration effects should definitely appear
- First result from ALICE (Run 1), **large uncertainties** prevent a real conclusion

  → Run 1 $L_{int} \sim 70\ \mu b^{-1}$
- 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



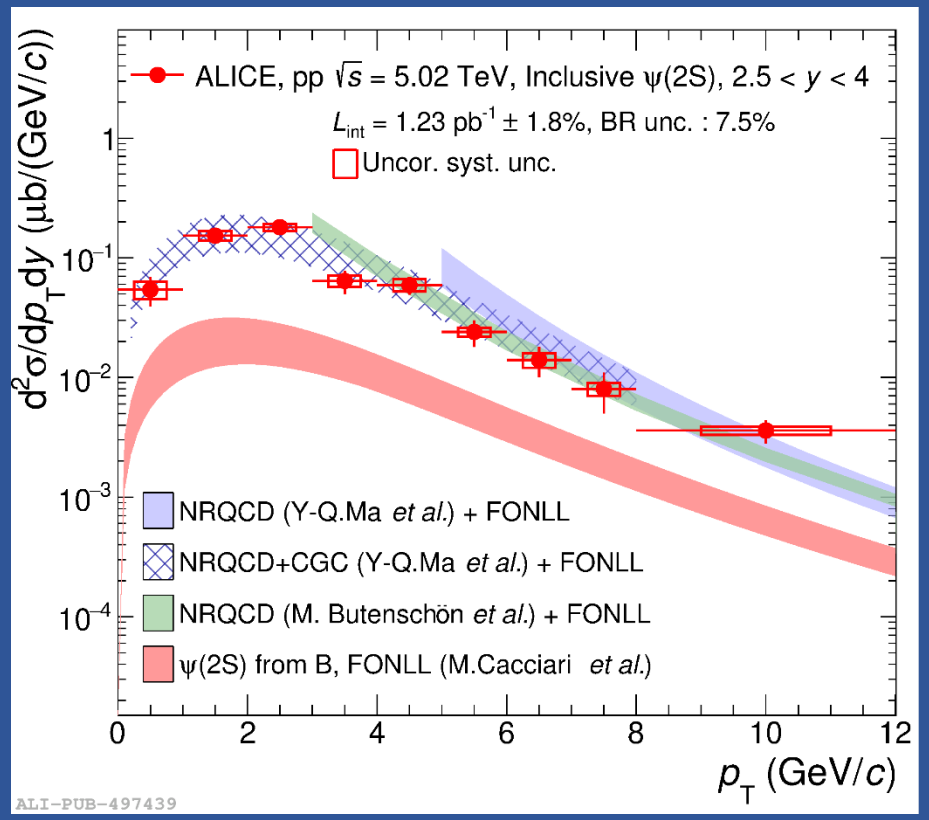
- **Inclusive quarkonium**
  - Central barrel (ee, $|y|<0.9$)
  - Muon spectrometer ($\mu\mu$, $2.5<y<4$)
  - Coverage **down to zero p_T**

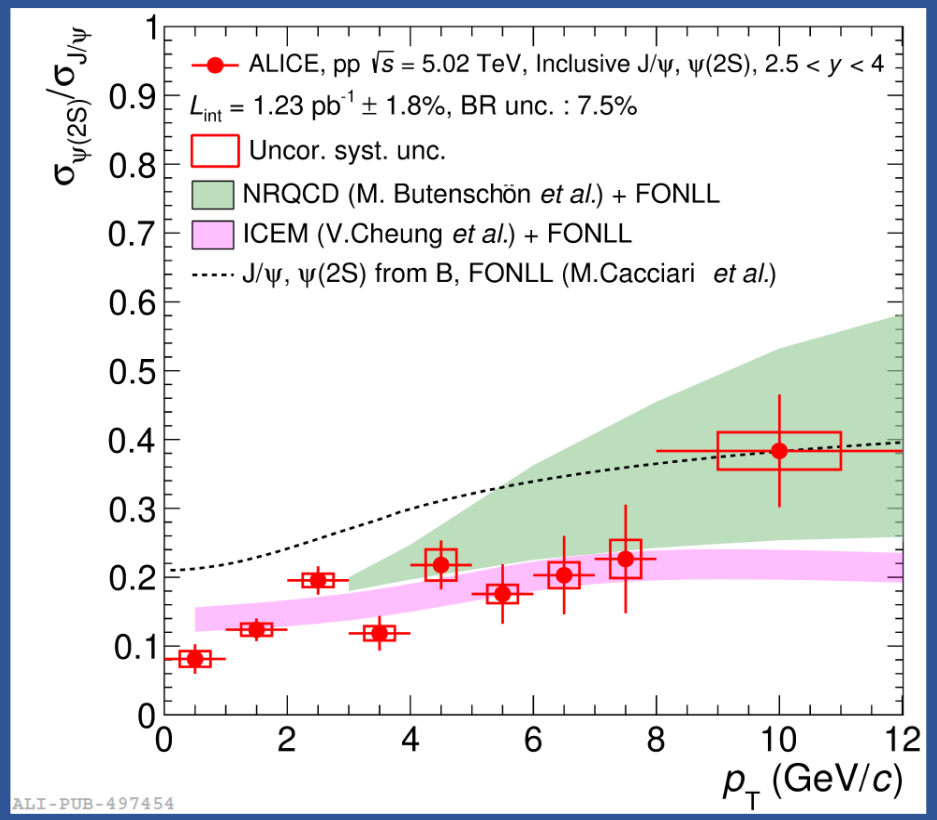
- $\psi(2S)$ results were obtained at **forward rapidity**

- (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





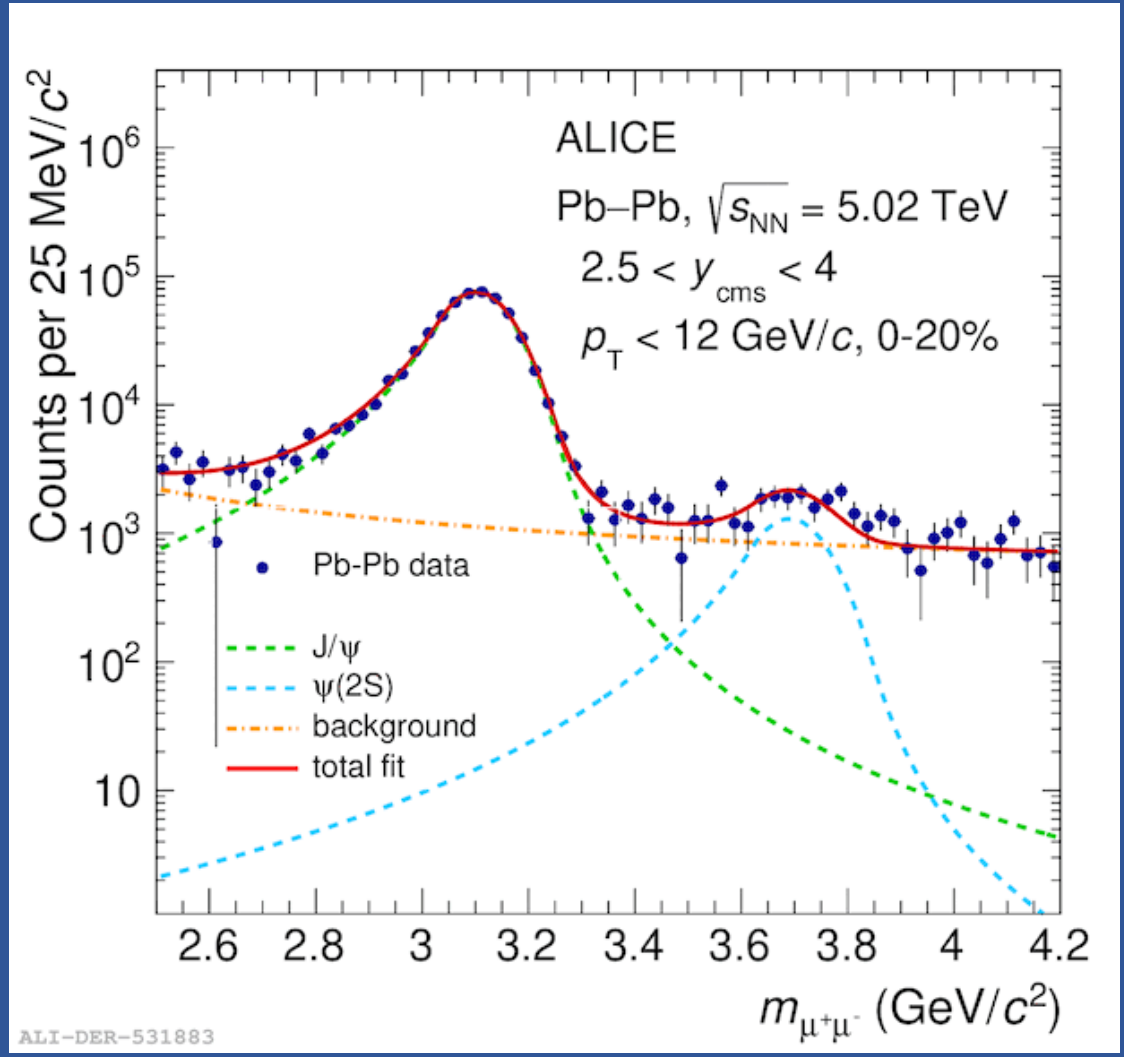
ALICE, arXiv:2109.15240

Inclusive production

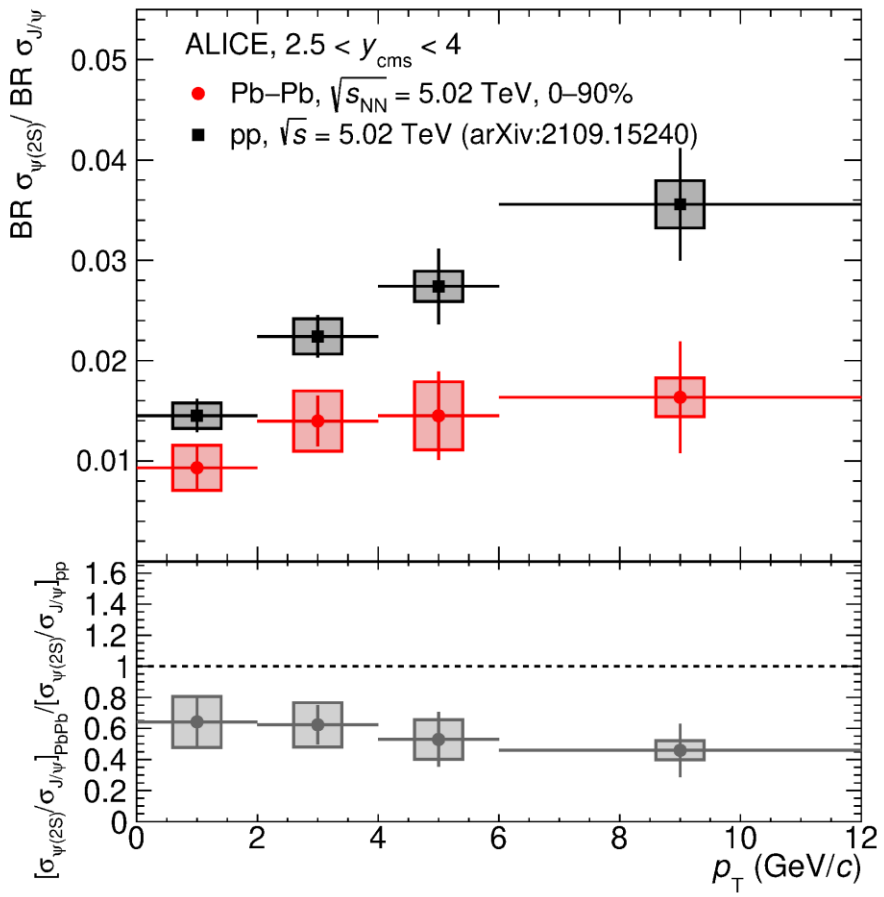
- Recent cross section measurement with 10 times more statistics than earlier publication
  → y- and p_T-differential studies of ψ(2S)
- **NRQCD+CGC+FONLL provides a good data description** down to zero p_T
- ψ(2S)-to-J/ψ ratio increases with p_T and agrees within uncertainties with theoretical models

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



N.B.: not corrected for branching ratios

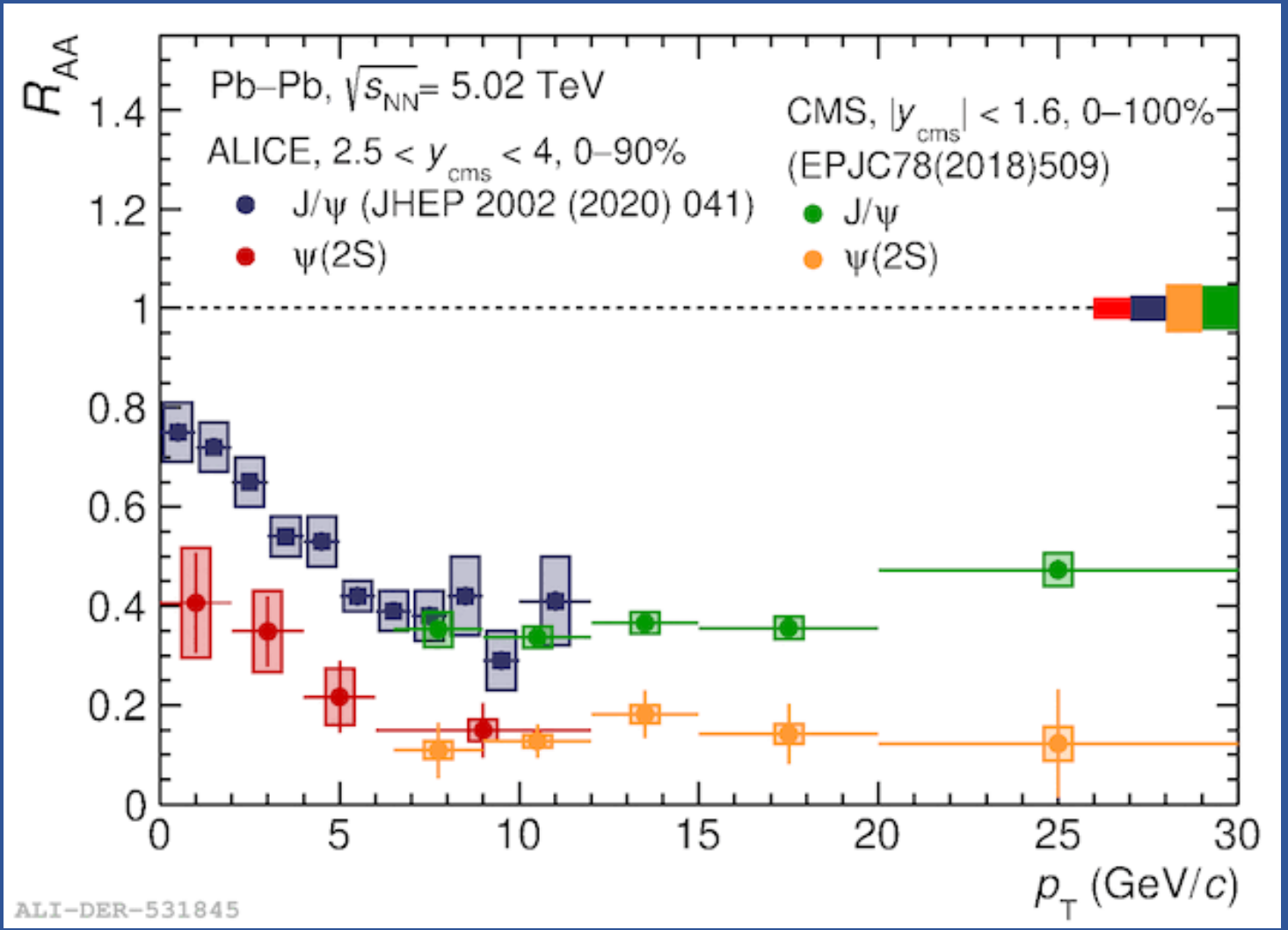
Ratio $\dfrac{BR_{\psi(2S)\to\mu\mu}\,\sigma_{\psi(2S)}}{BR_{J/\psi\to\mu\mu}\sigma_{J/\psi}}$

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

ALICE, arXiv:2210.08893

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

Two theory approaches for phenomenology

Transport

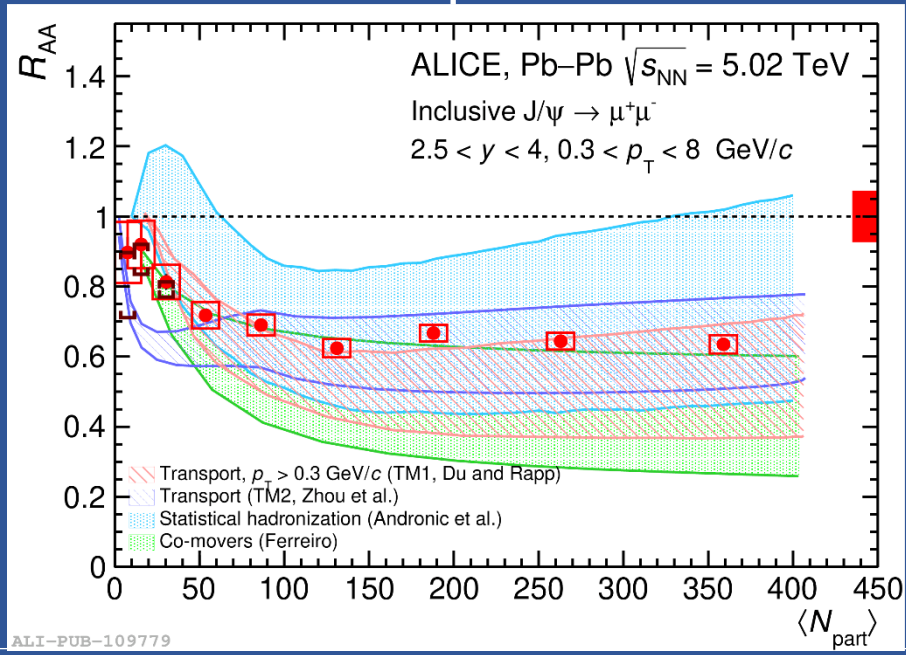
X. Du and R. Rapp, NPA 943(2015) 14P.7
P. Zhou et al., PRC89 (2014) 054911

- 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

- 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



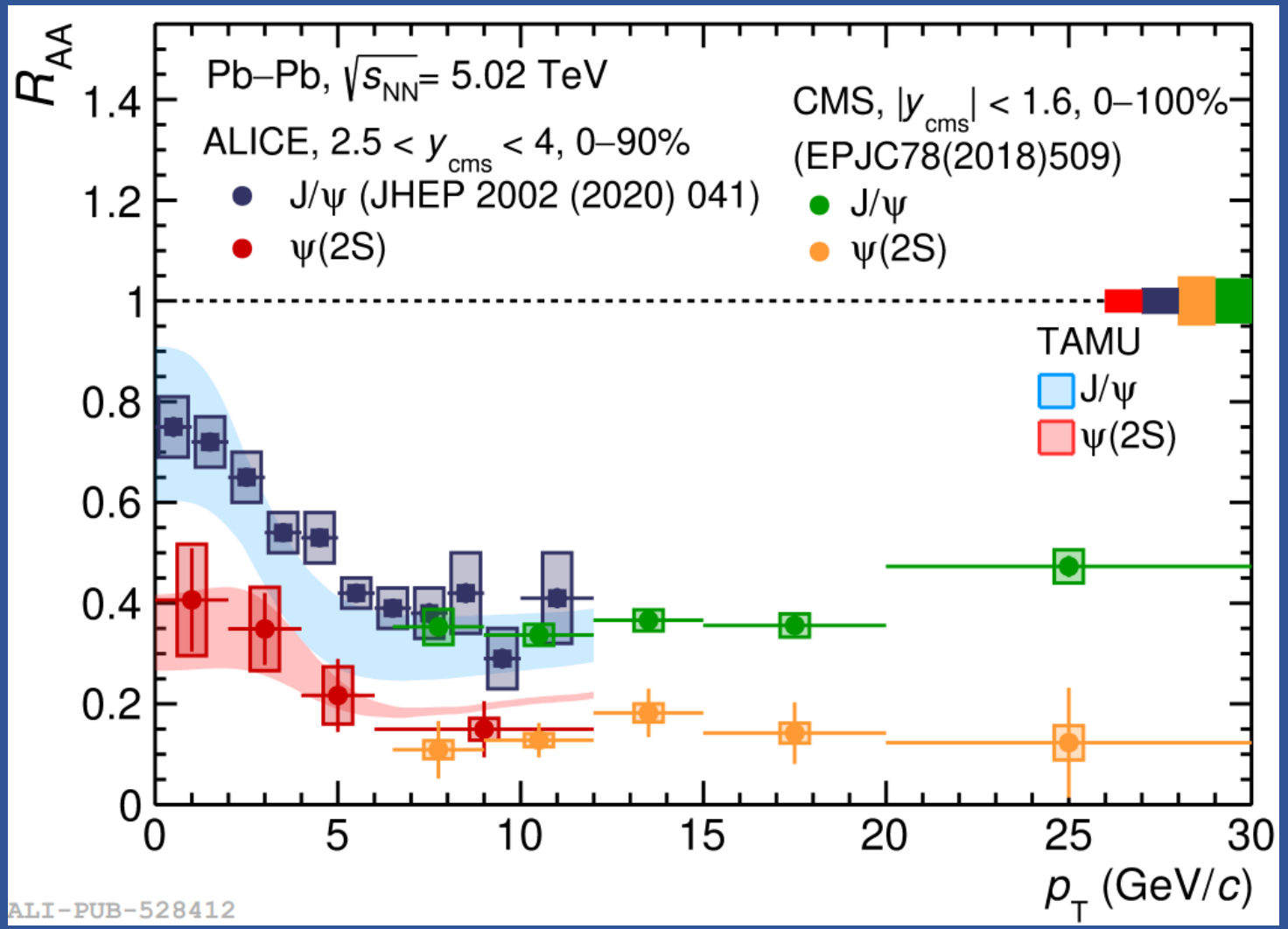
As already mentioned, both approaches fairly **reproduce LHC experimental results on the J/ψ**

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

Other approaches include "comover" models

E. Ferreiro, PLB 731 (2014) 57

p_T dependence of the nuclear modification factor



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ALICE, arXiv:2210.08893

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

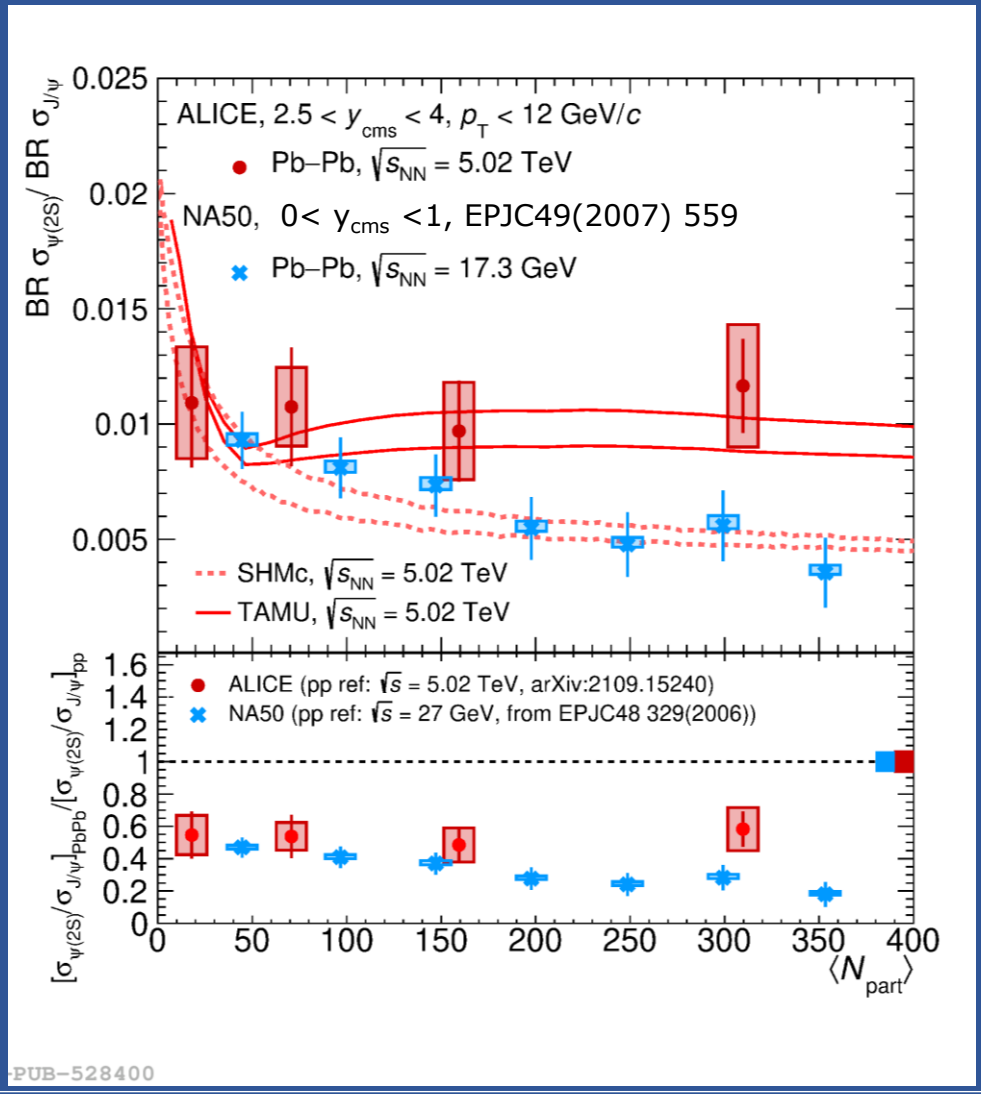
Transport model (TAMU) well reproduces J/ψ and ψ(2S) results, within uncertainties

Centrality dependence of the inclusive cross section ratios

- 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

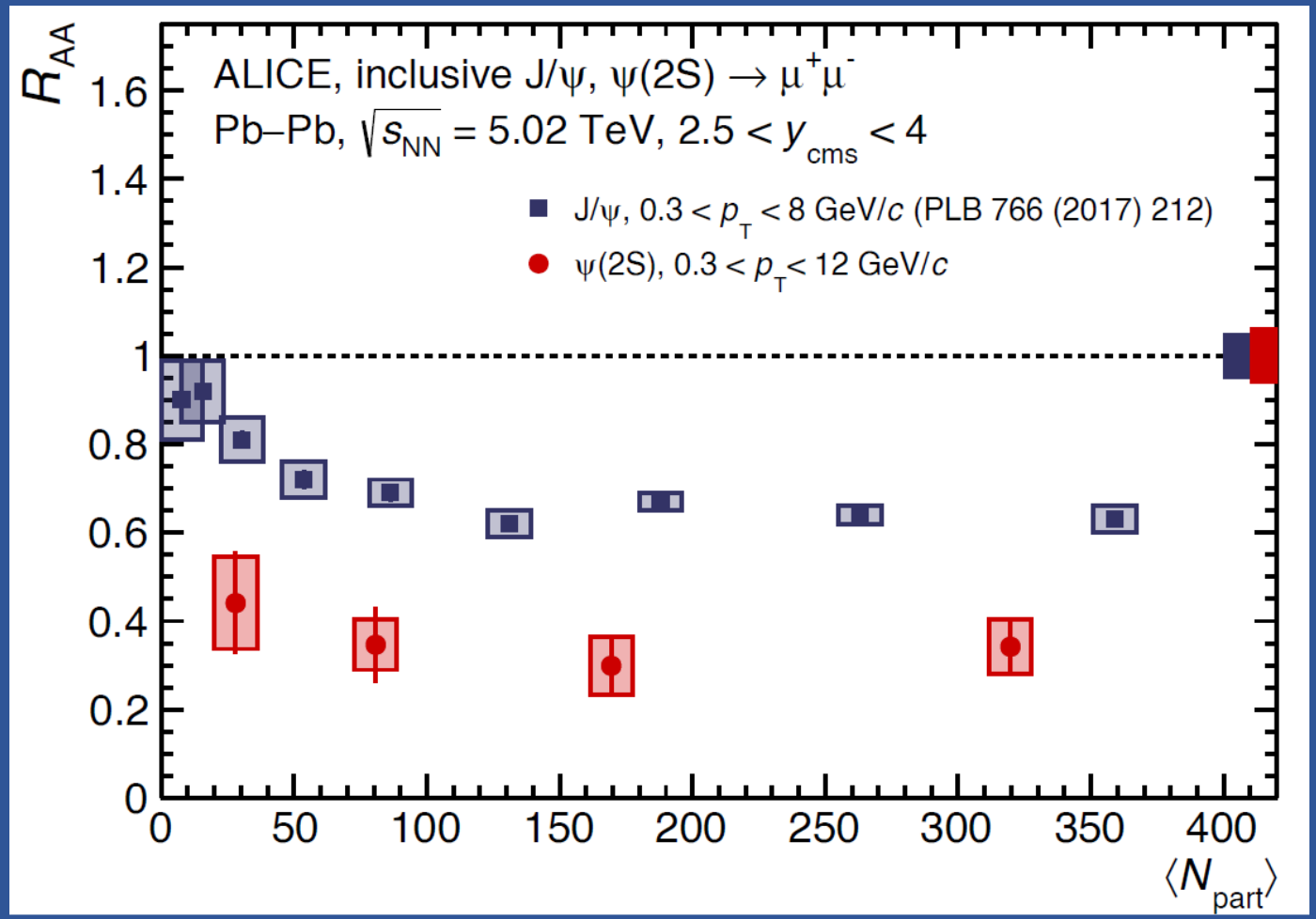
ALICE, arXiv:2210.08893



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

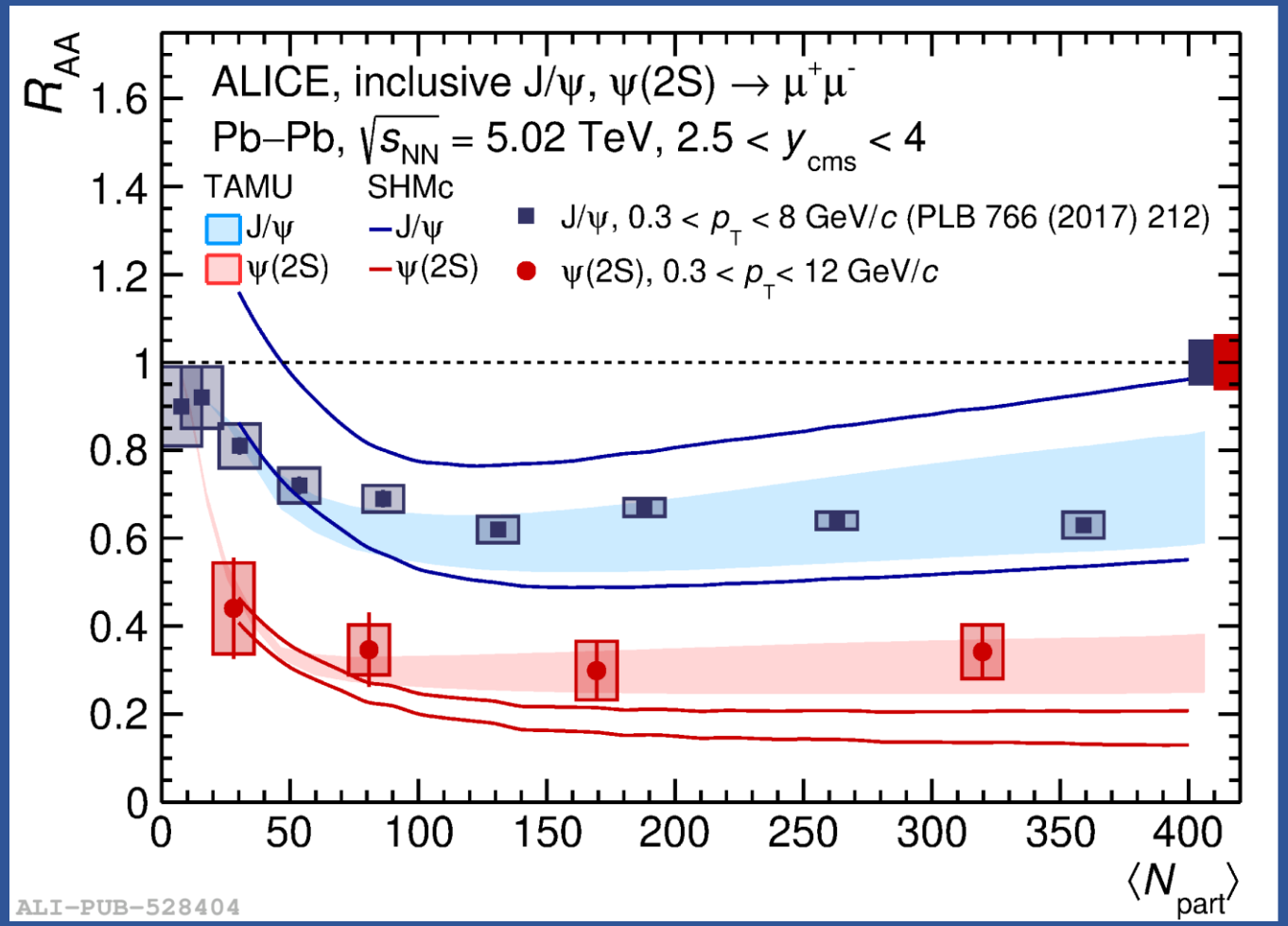
ALICE, arXiv:2210.08893



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

ALICE, arXiv:2210.08893

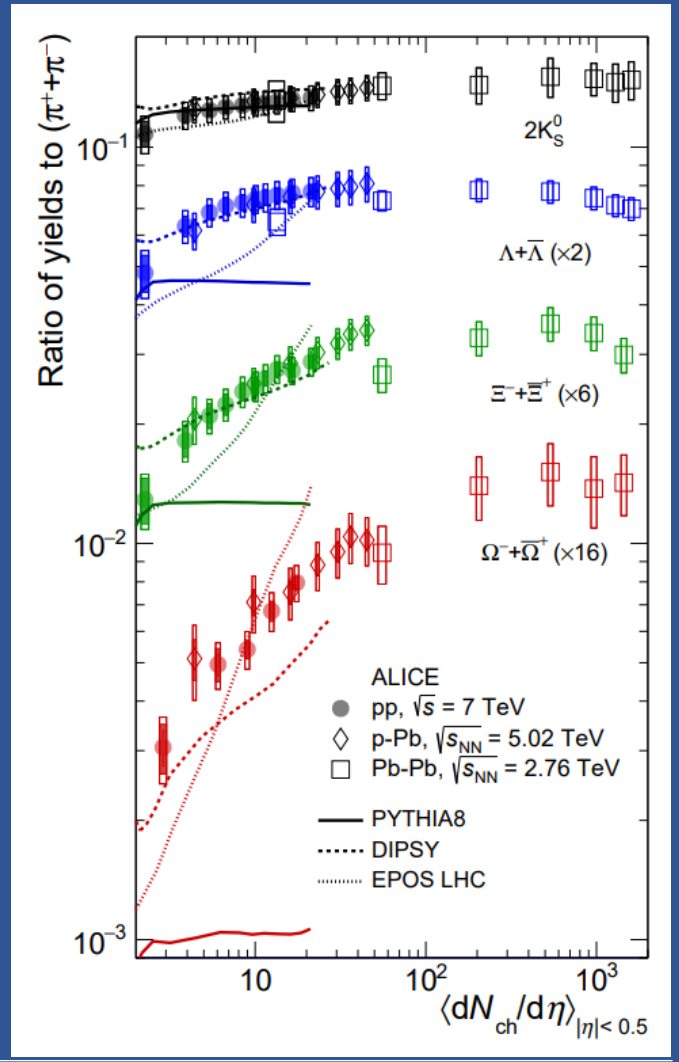


From heavy to small systems

- **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)

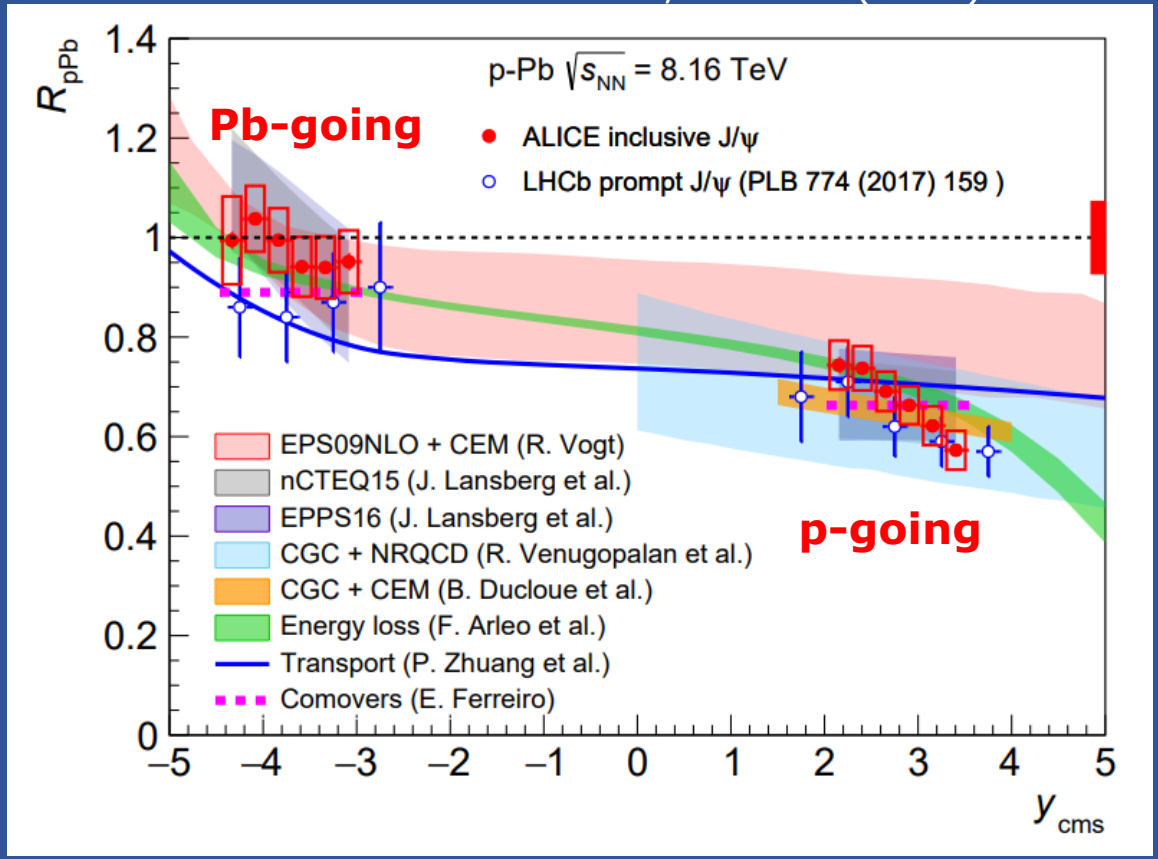
- Do we see hints for such effects also in the **charmonium sector** ?
  → ψ(2S), thanks to its relatively small binding energy, could represent a good testing ground



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

ψ(2S) production in p-Pb collisions

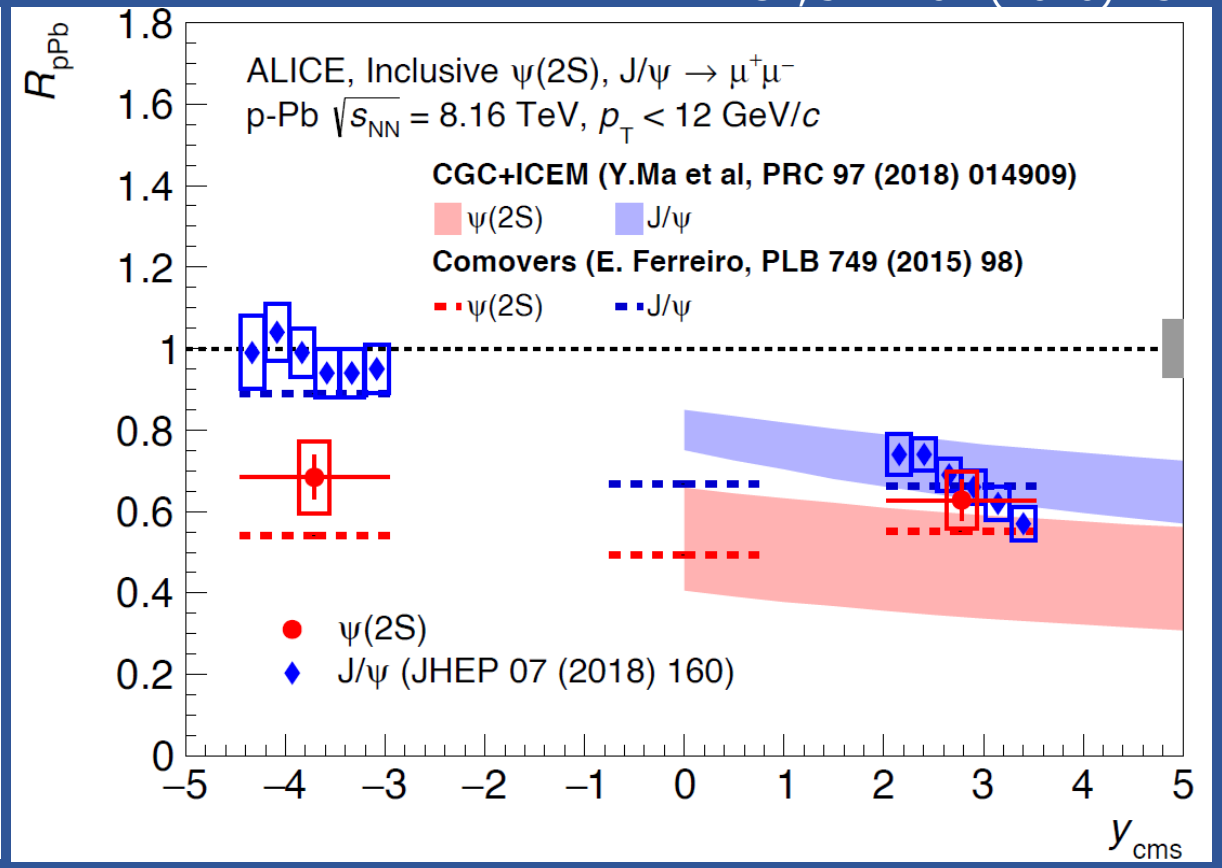
ALICE, JHEP 07 (2018) 160



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

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

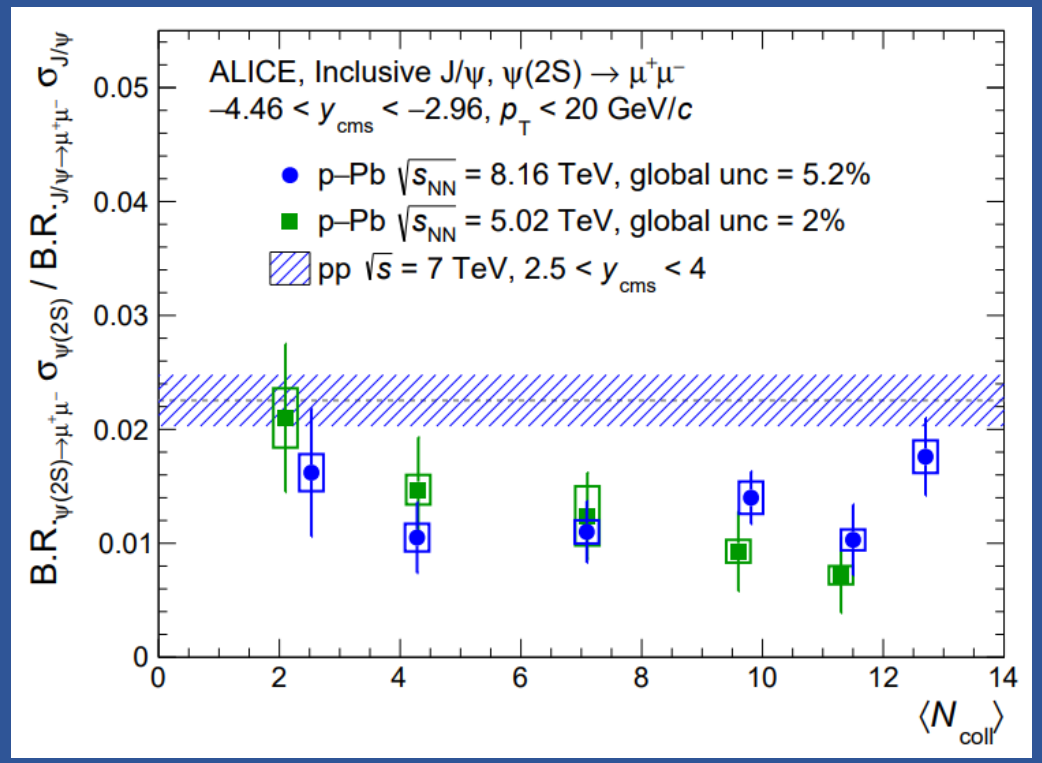
ALICE, JHEP 07 (2020) 237



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

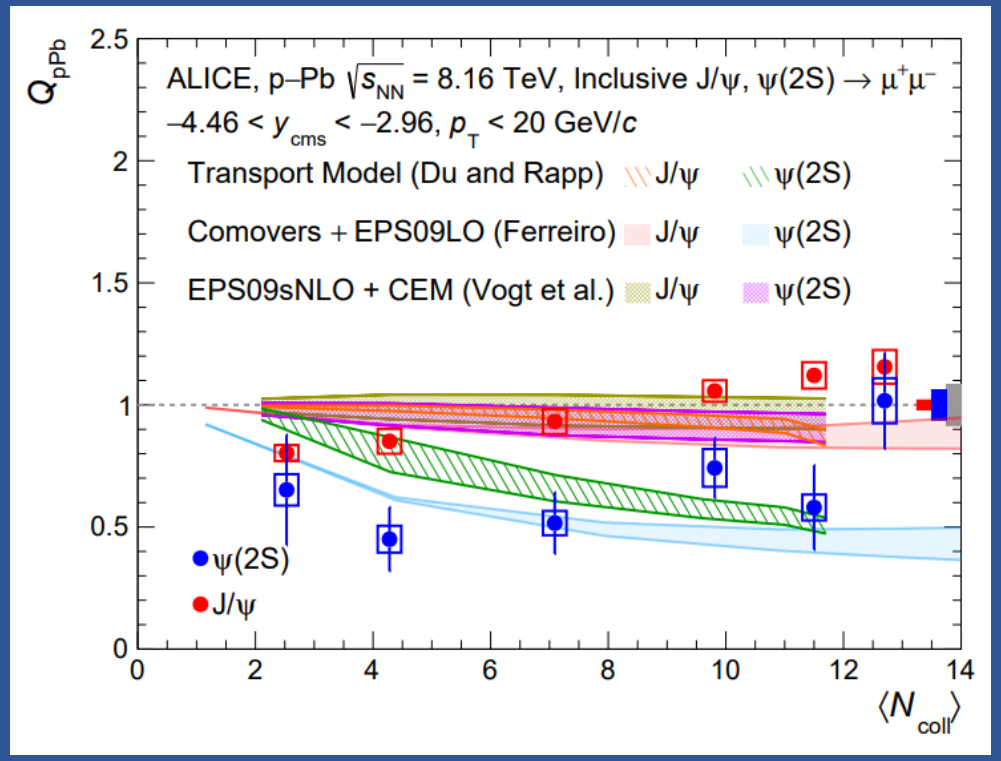
ψ(2S) production in p-Pb collisions

- 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)



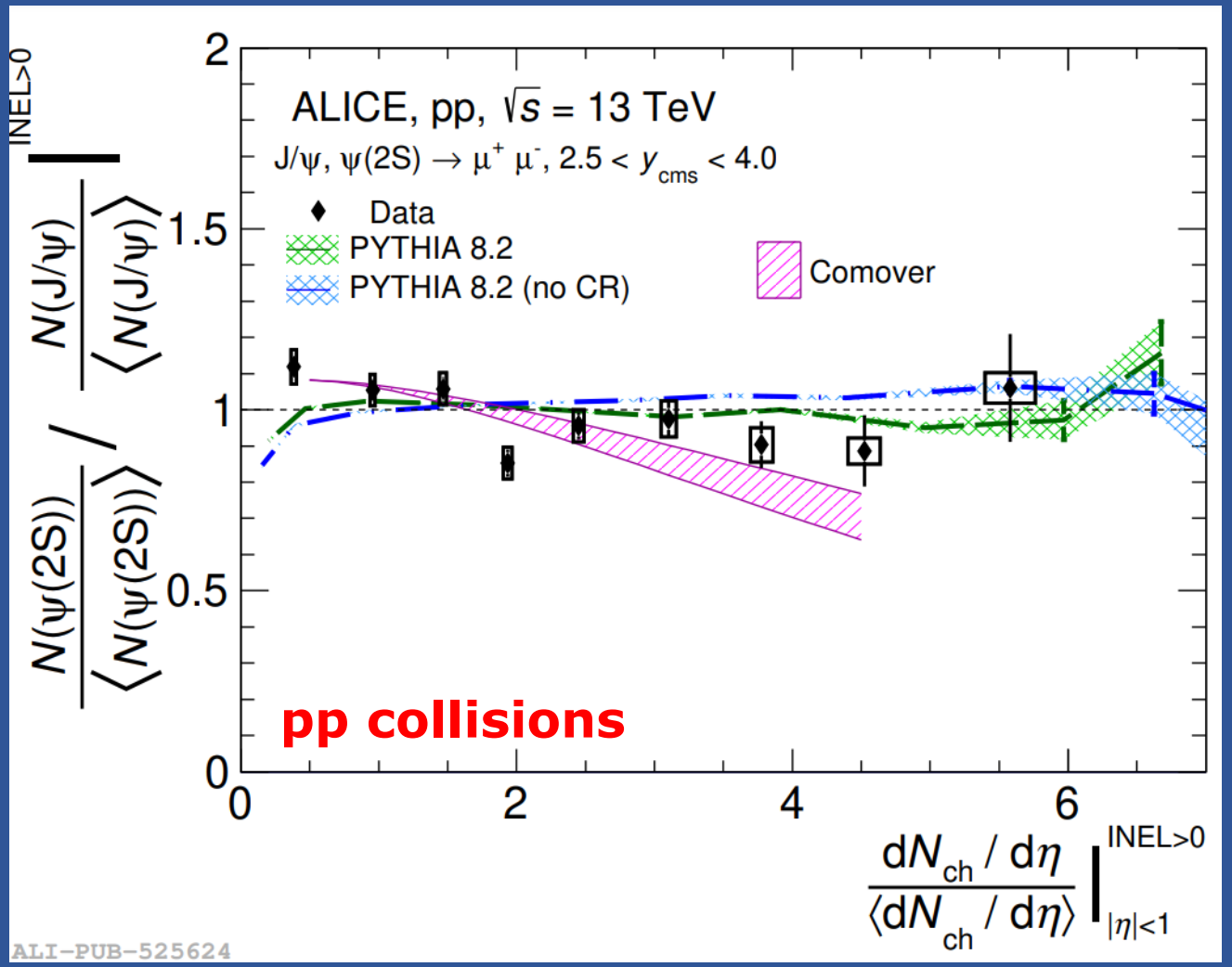
ALICE, JHEP 02 (2021) 002

- 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

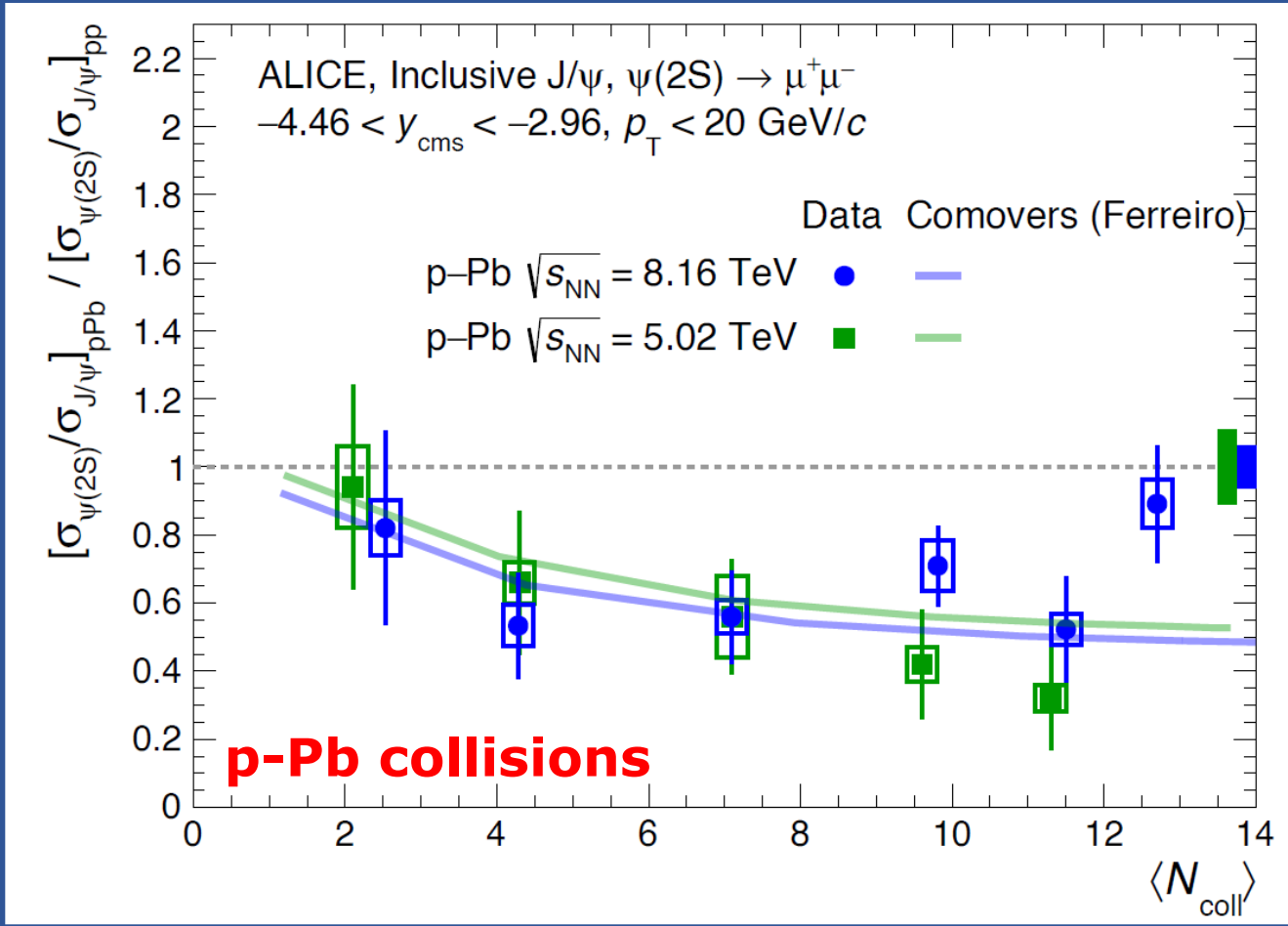
ψ(2S) in high-multiplicity pp collisions



- **Self-normalized ratios of ψ(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)

ALICE, arXiv:2204.10253

ψ(2S) in high-multiplicity pp collisions



ALICE, JHEP 02 (2021) 002

- **Self-normalized ratios of ψ(2S) and J/ψ** may exhibit a weak multiplicity dependence
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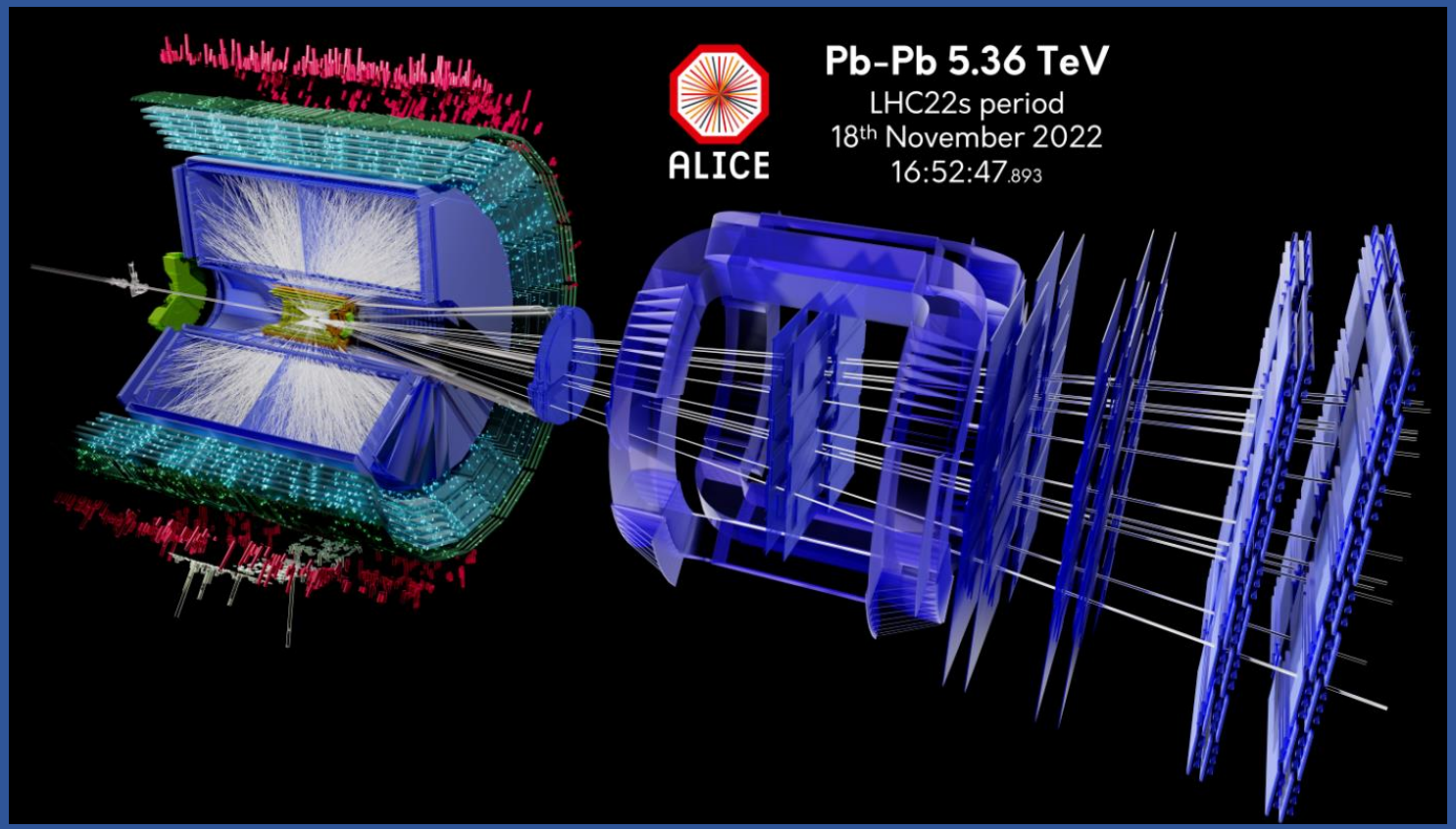
- At constant $dN_{ch}/d\eta$, the decrease of the ψ(2S)/(J/ψ) ratio is larger in p-Pb than in high multiplicity pp
- → **40% decrease in p-Pb** at $\langle N_{coll} \rangle$~11.5, corresponding to $dN_{ch}/d\eta$~30
  (from ALICE, EPJC 79 (2019) 307)
- Contrary to strangeness results, ψ(2S) yields do not scale with $dN_{ch}/d\eta$ for different collision systems

Prospects for future measurements

- Many ψ(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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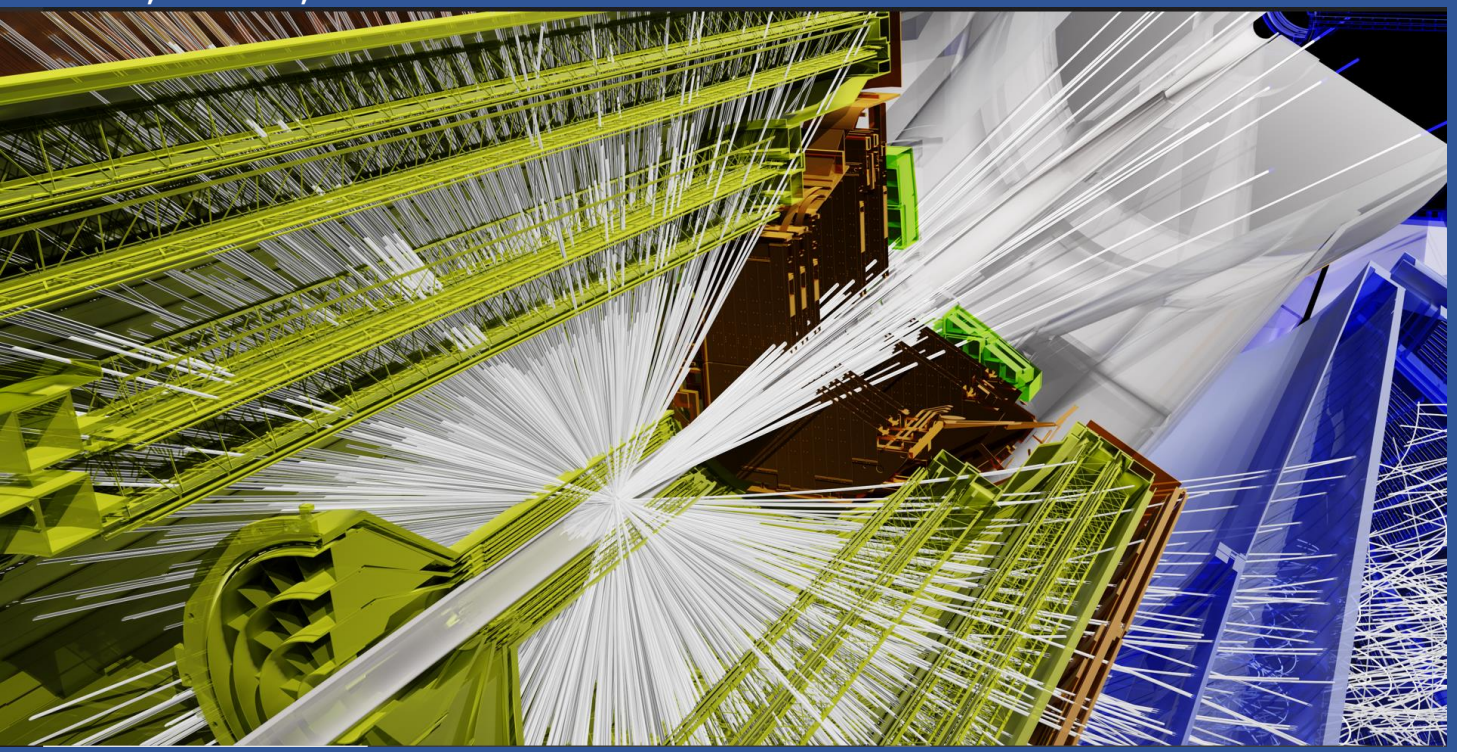
ALICE, Pb-Pb, Run 3



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- Target Pb-Pb integrated luminosity (Run 3 + 4) → $L_{int} \sim 13\ nb^{-1}$
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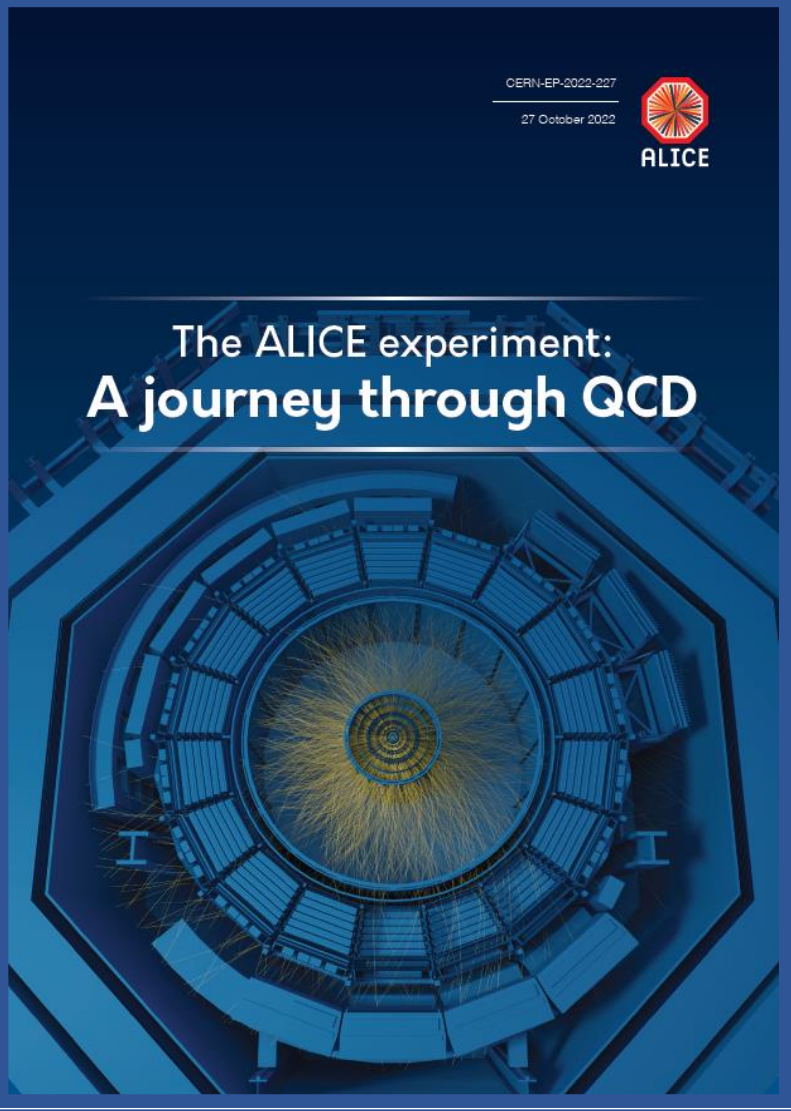
- New **Muon Forward Tracker (MFT),** enabling prompt/non-prompt separation

→ **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

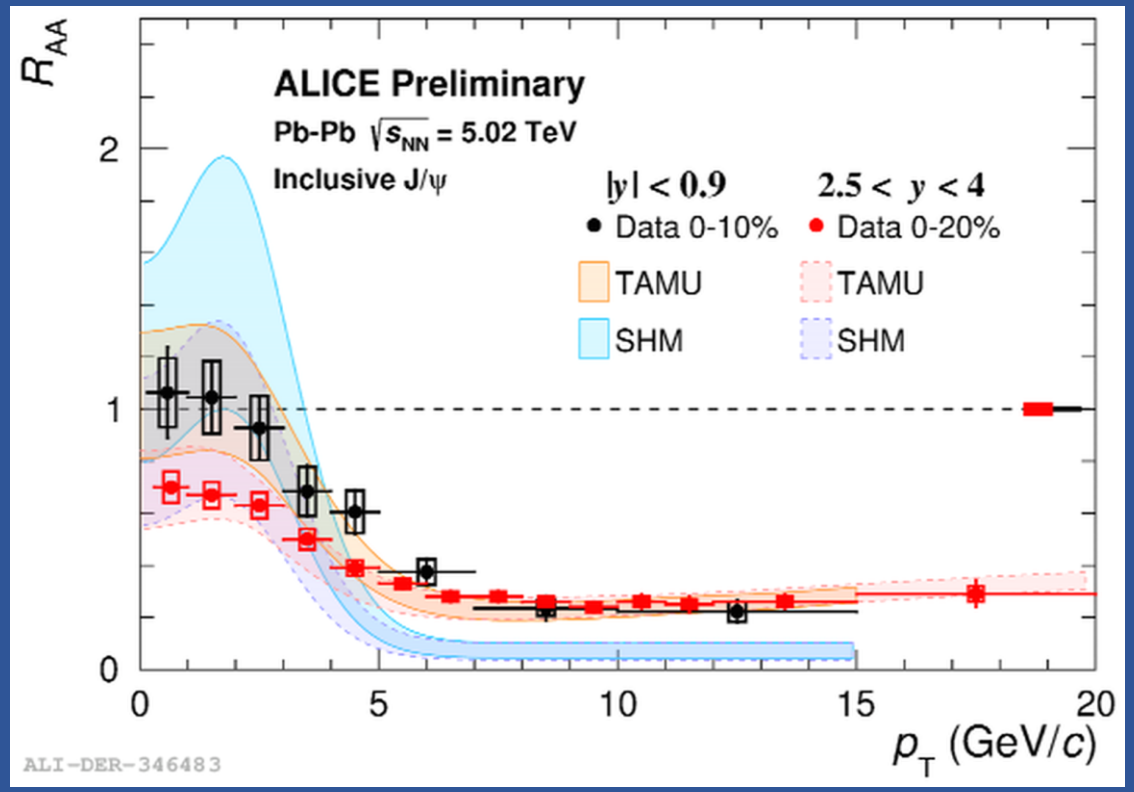
- Model predictions **fairly reproduce data**, except for SHMc in central collisions

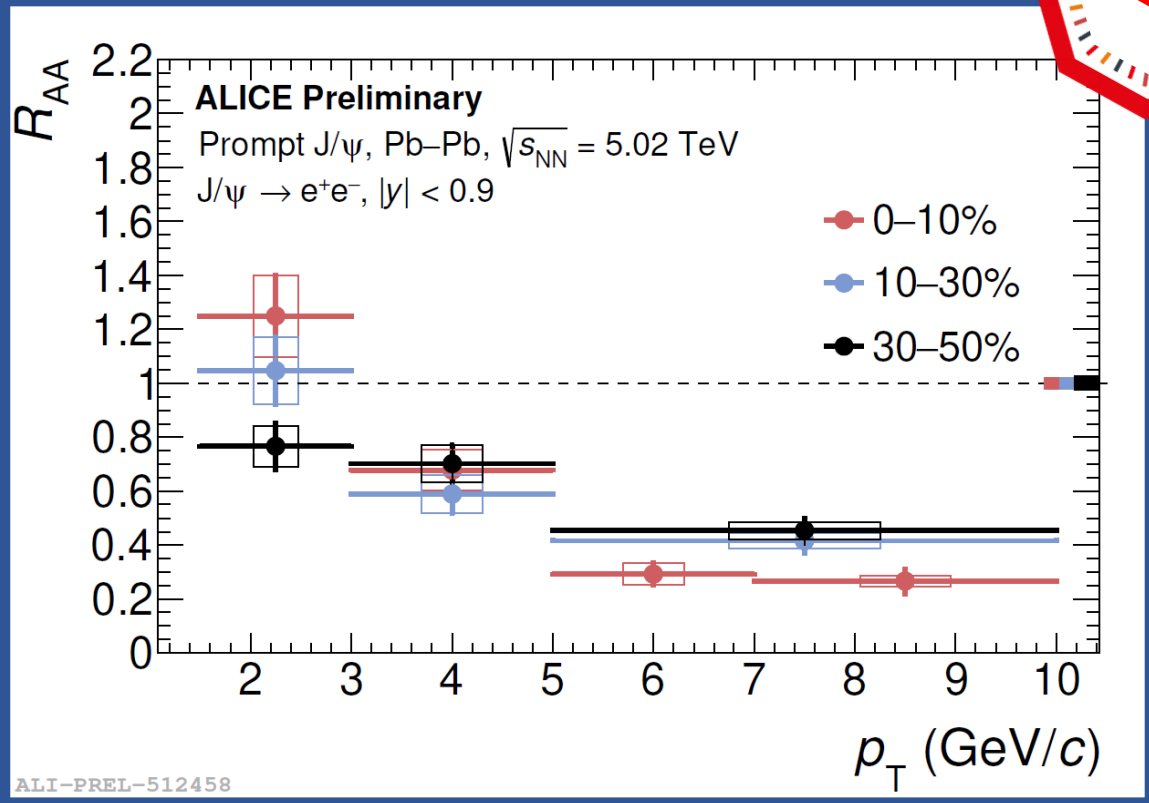
- Evidence for **final state effects on ψ(2S) in p-Pb collisions**
- **Weaker effects**, if any, in **high multiplicity pp collisions**

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

Backup

Inclusive and prompt J/ψ production in Pb-Pb

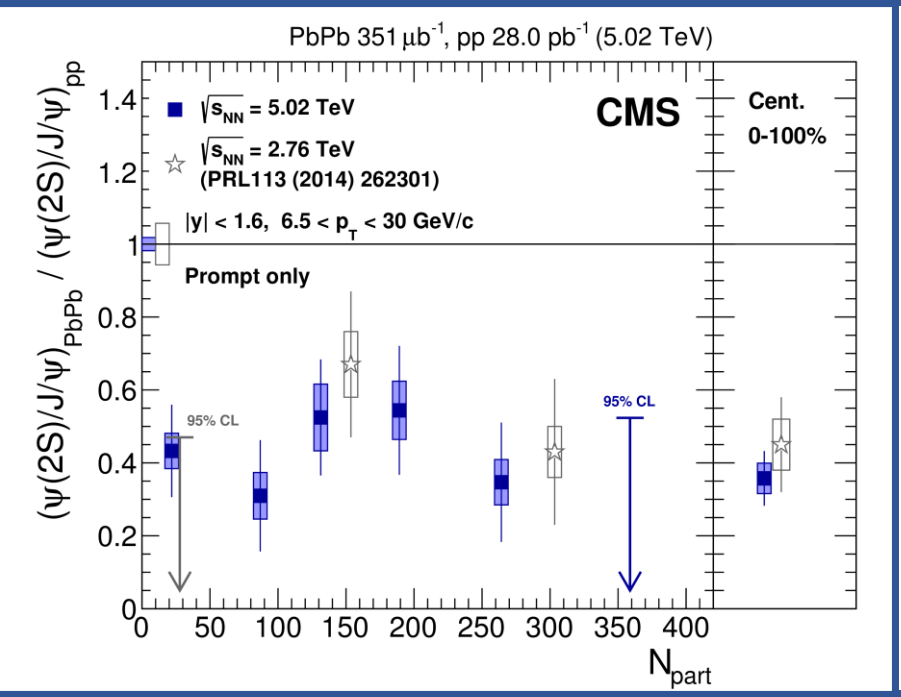


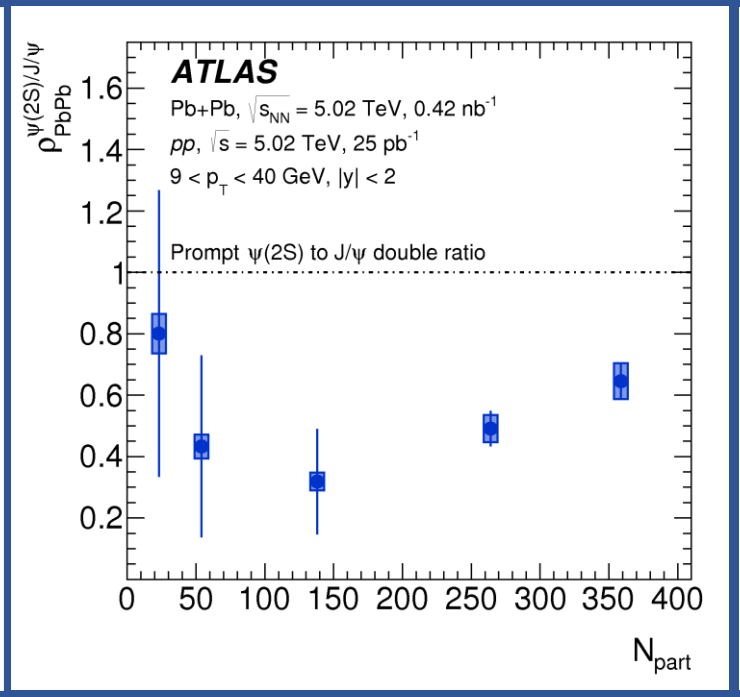


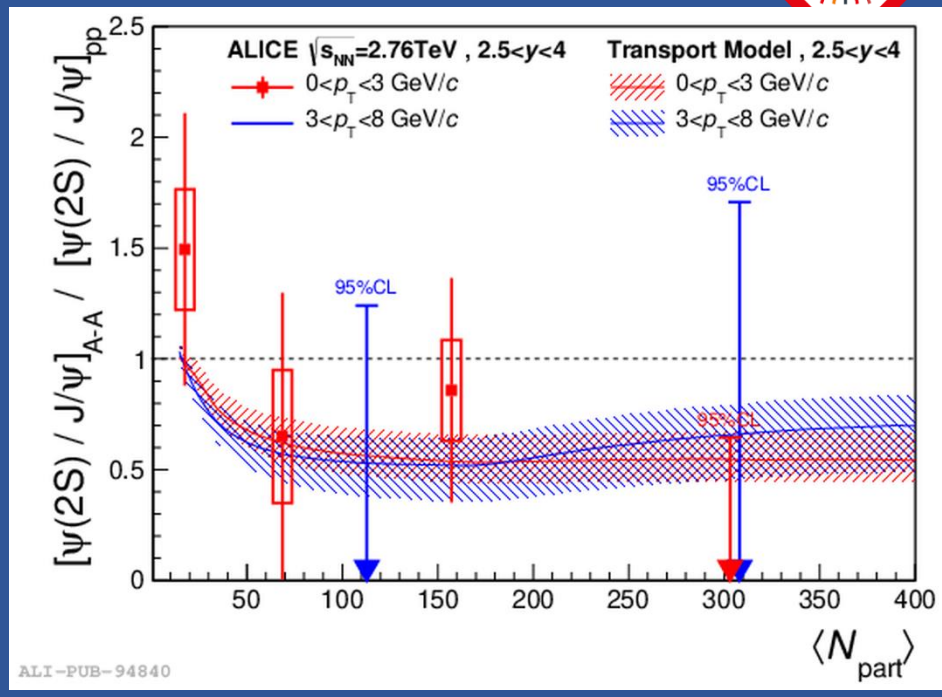
- Rise of inclusive J/ψ R_{AA} at low p_T, stronger effect at y=0 → decisive signature of recombination
- Models include regeneration either at the freeze-out (SHMc) or during the medium evolution (TAMU)
  → Both in agreement with data at low p_T

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

Pb-Pb results at LHC energies

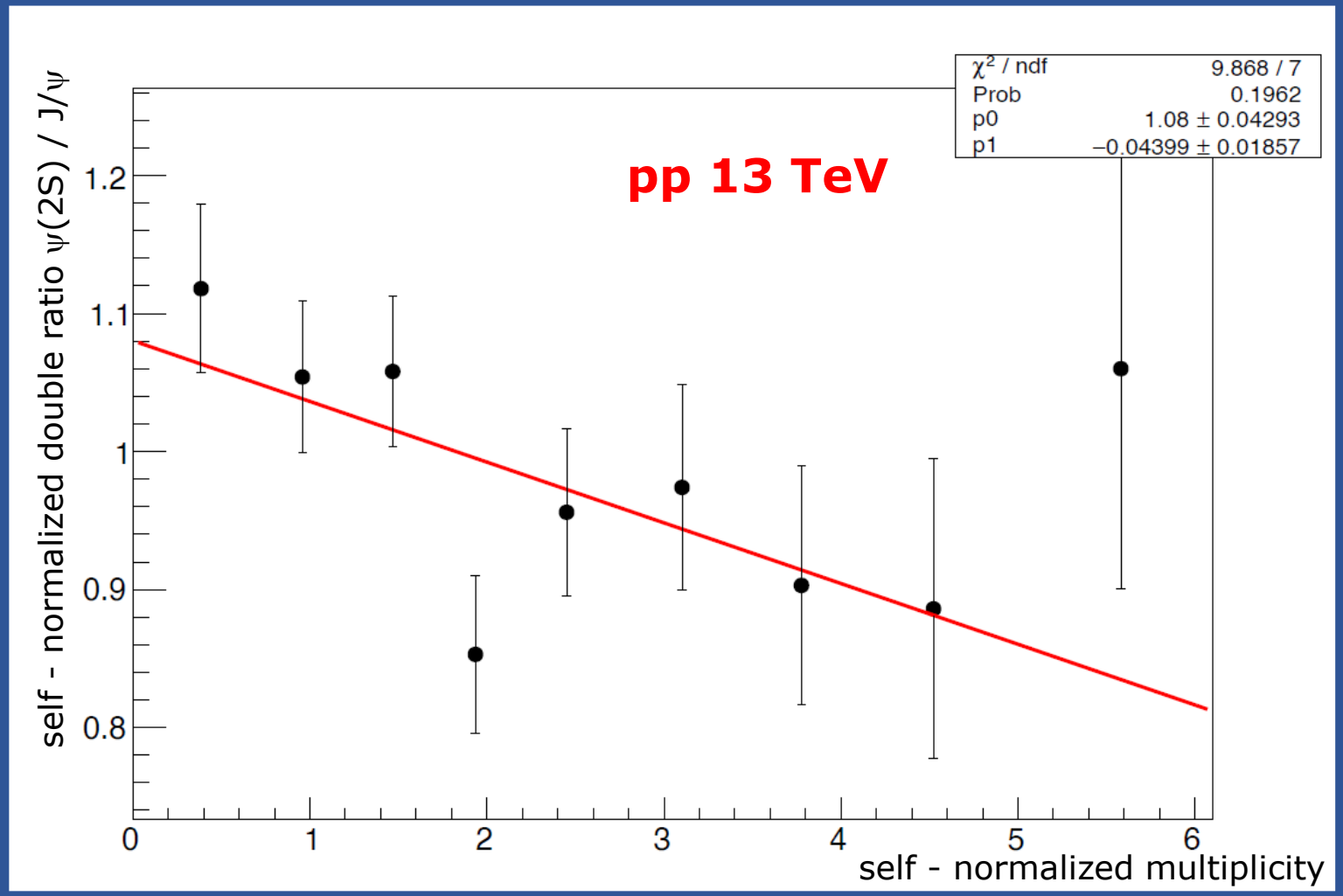






CMS, PRL 118 (2017) 162301 ATLAS, EPJC78 (2018) 762 ALICE, JHEP 05 (2016) 179

- 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


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