Quarkonium production from fixed target to collider energies: status and prospects

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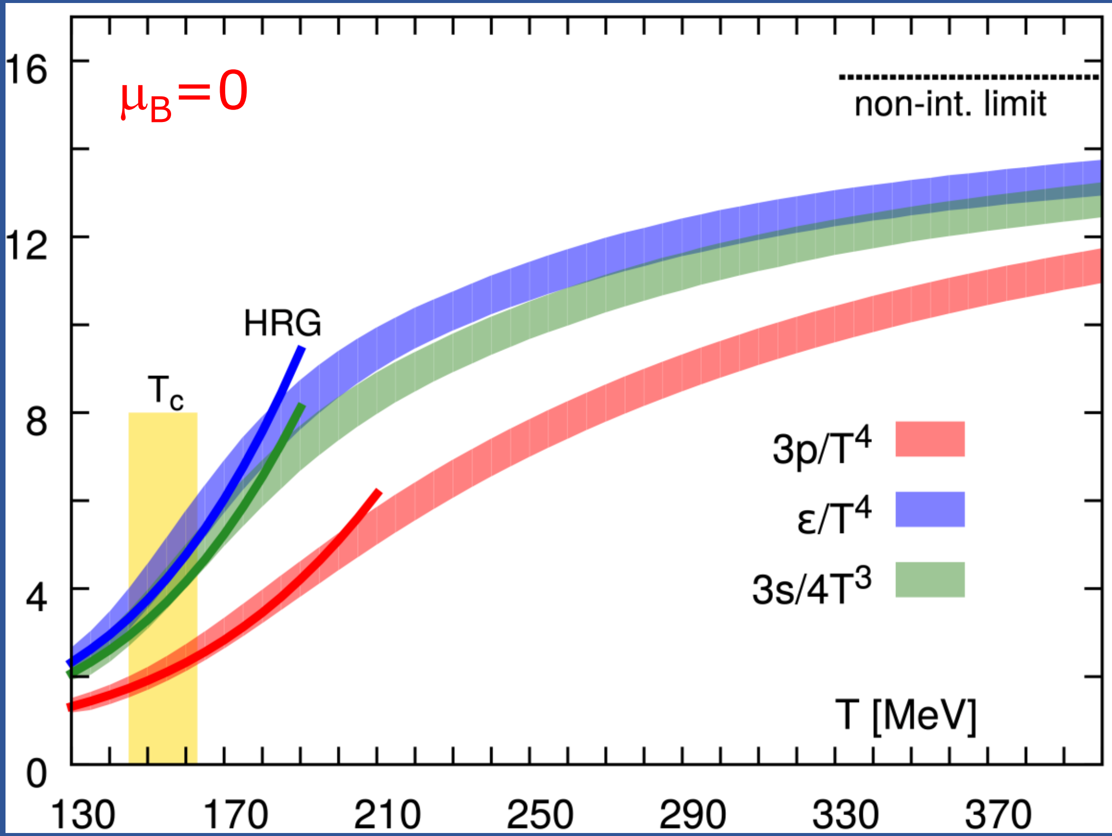
INFN Torino (Italy)

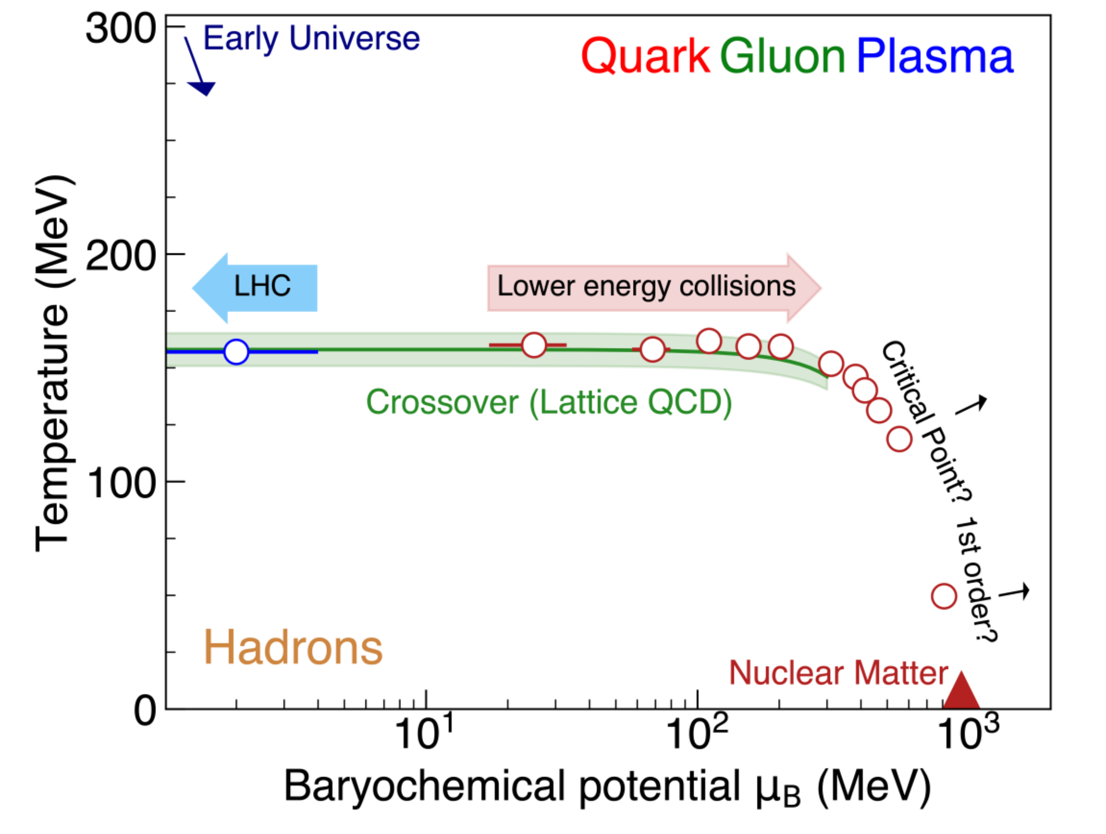
India+ lectures on Heavy-Ion Collision experiments
May 4, 2023

- ❑ Quarkonia and QGP: a short intro (see also RongRong presentation on April 13!)
- ❑ Old and new discoveries: from SPS to LHC
- ❑ Focus on excited quarkonia: the case of ψ(2S)
- ❑ Prospects for future measurements

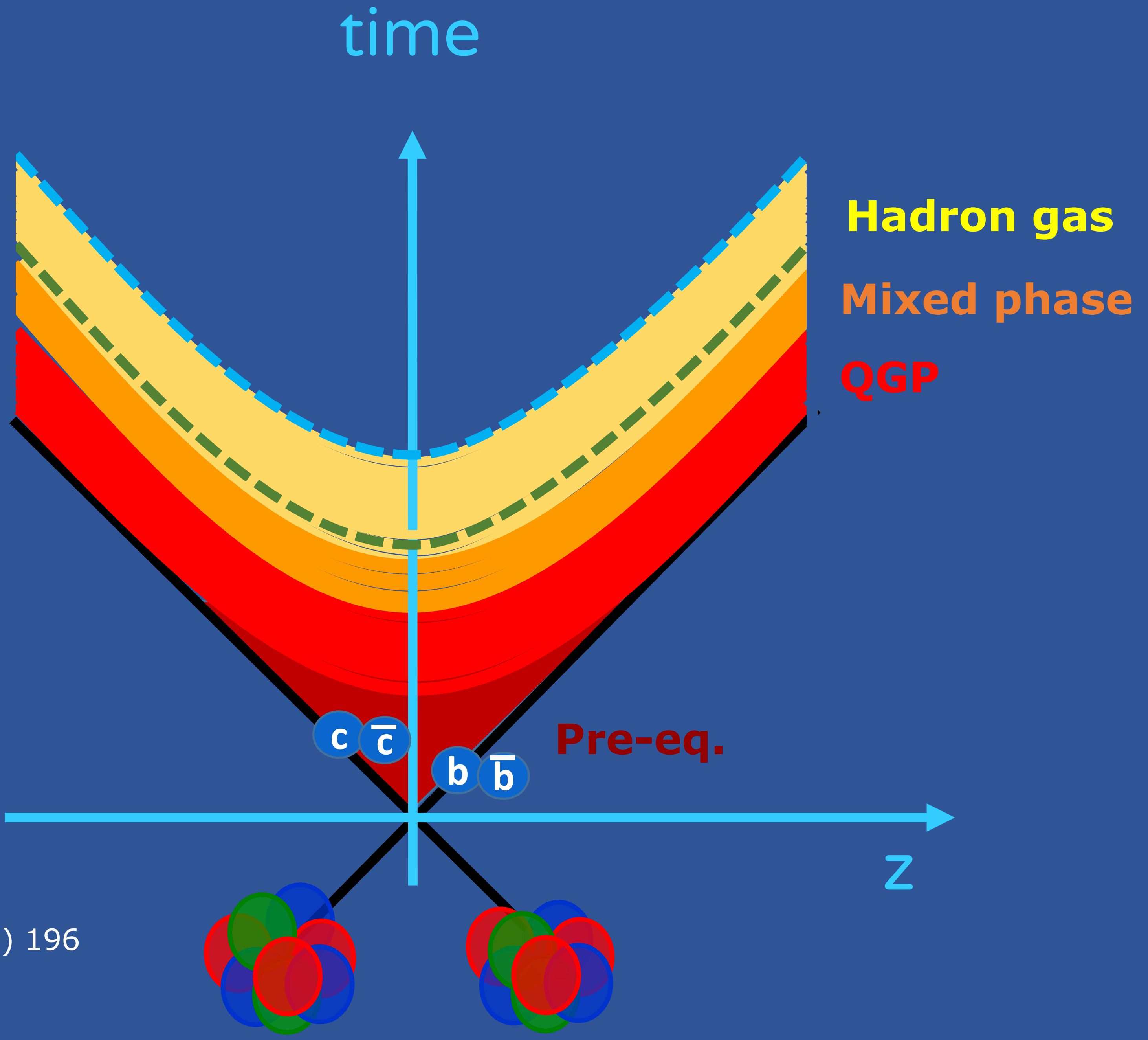
Discovering and analyzing the properties of the quark-gluon plasma (QGP)

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





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



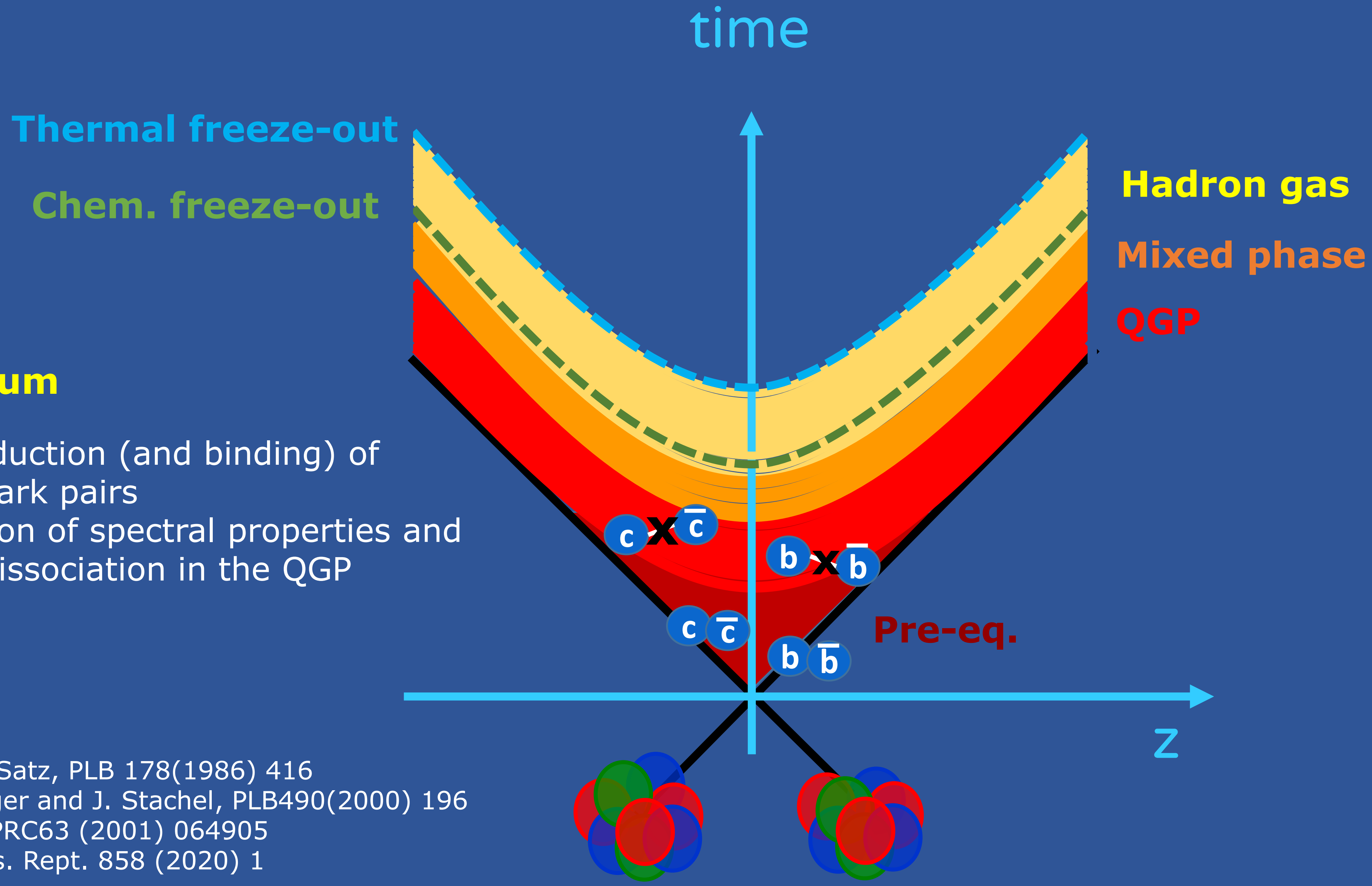
Quarkonium

- 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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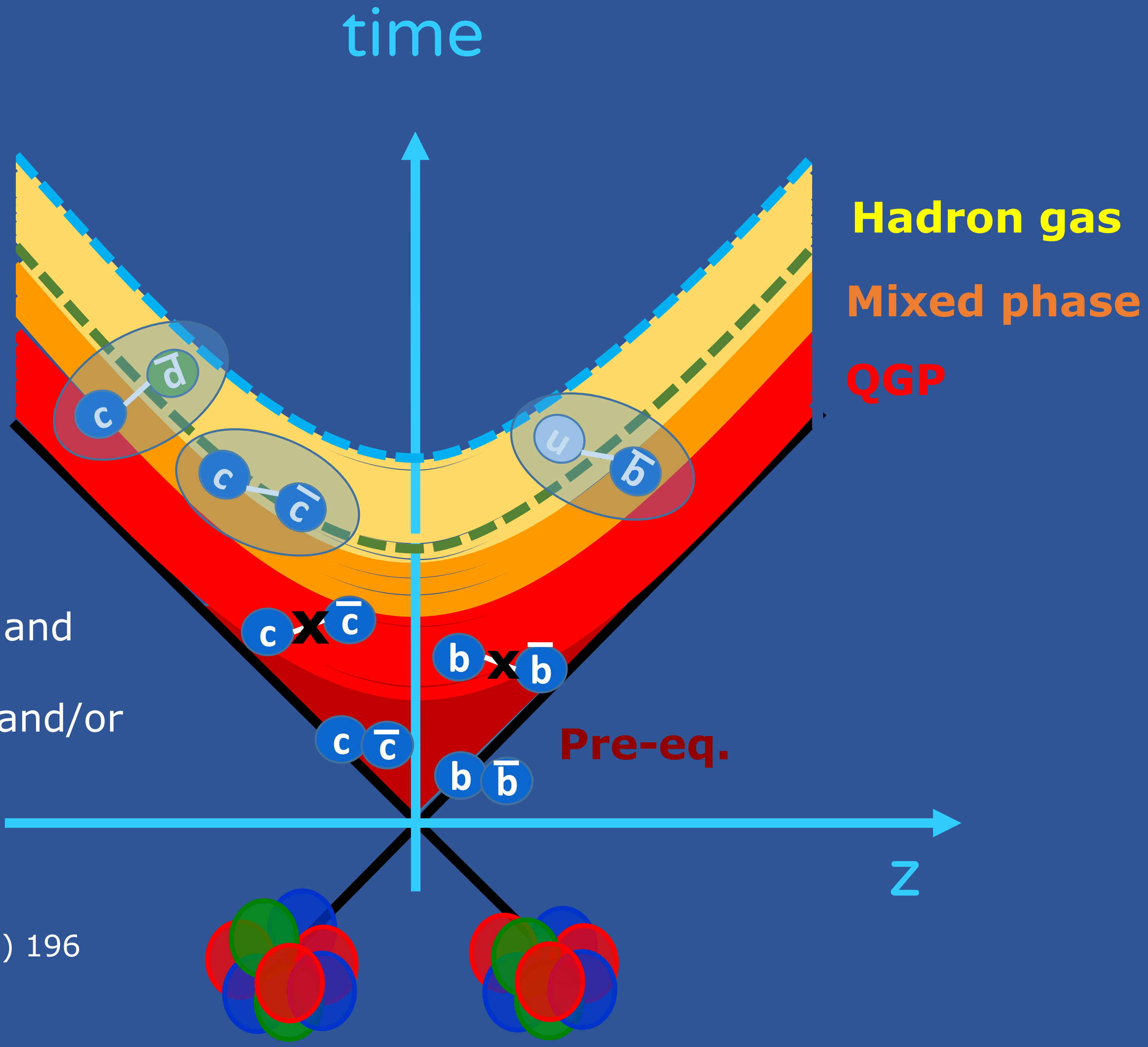
A. Rothkopf, Phys. Rept. 858 (2020) 1

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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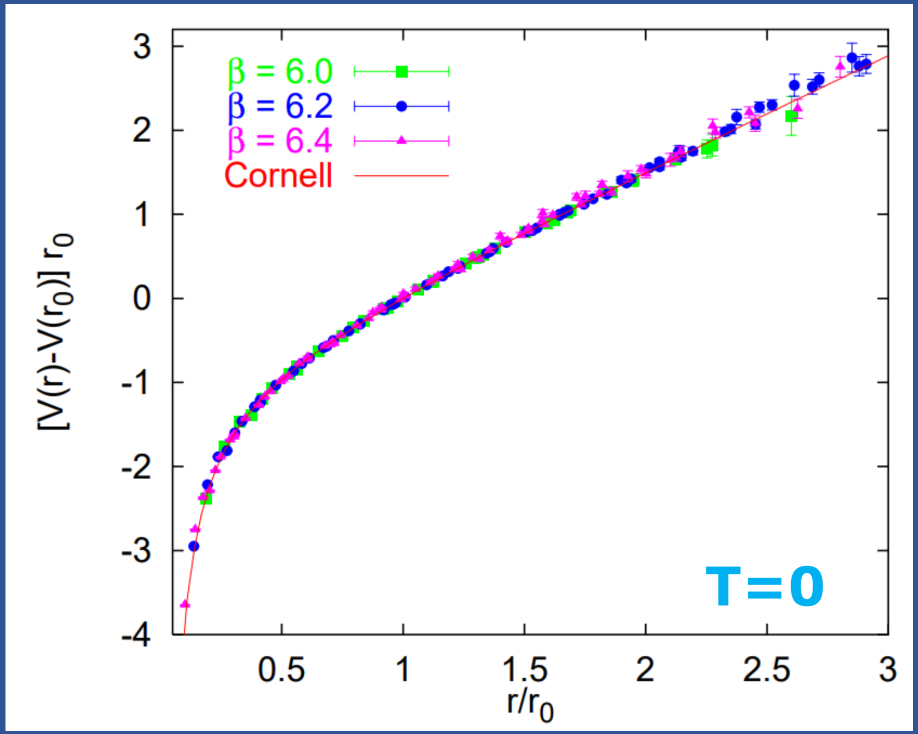
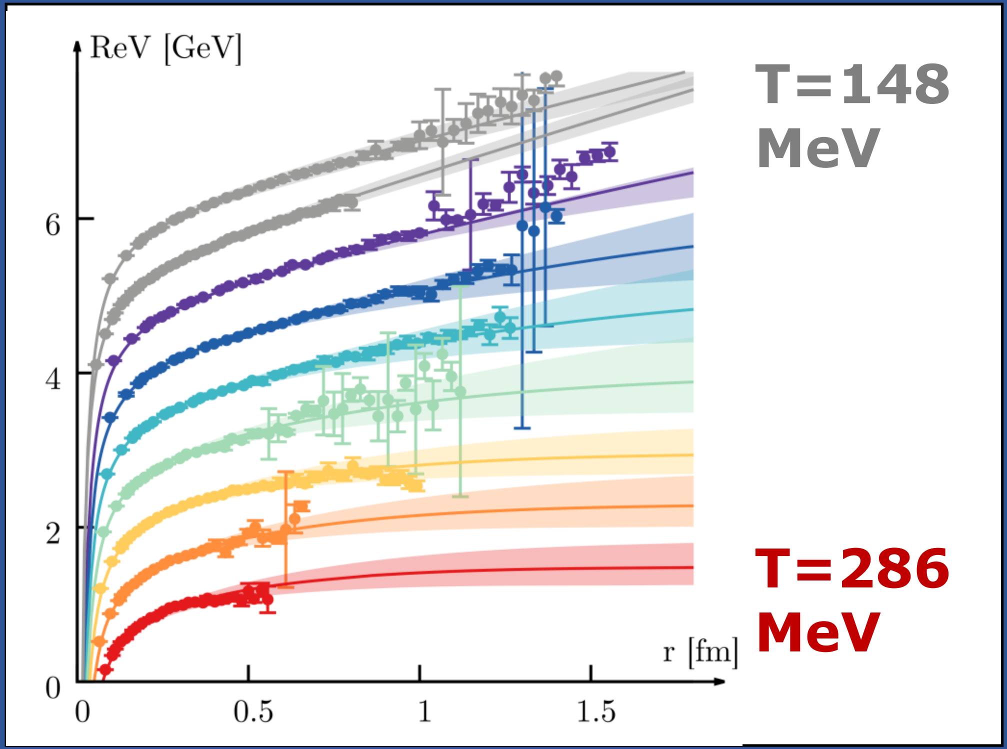
A. Rothkopf, Phys. Rept. 858 (2020) 1

Modification of spectral properties and dissociation

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



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

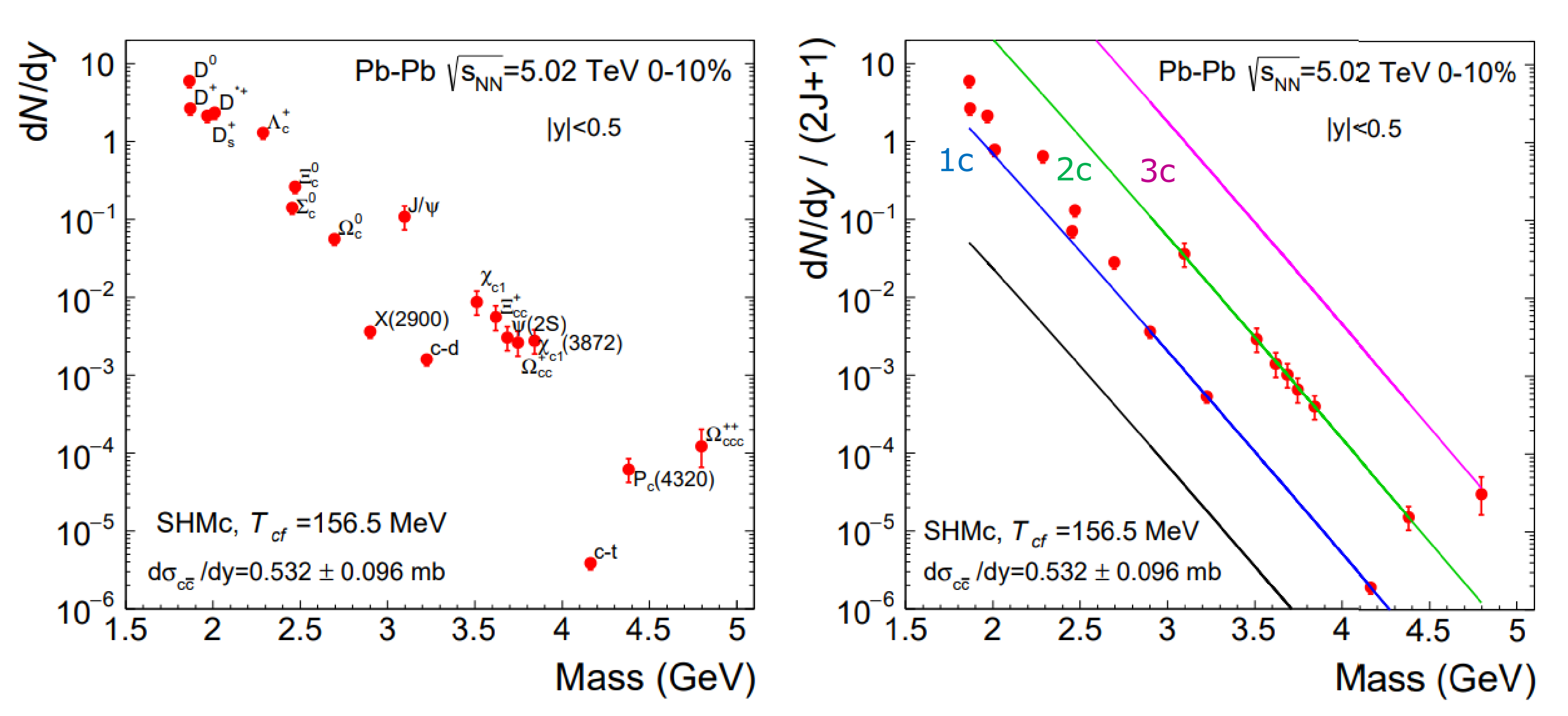


Potential models provide a faithful reproduction of available lattice data

- 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

(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



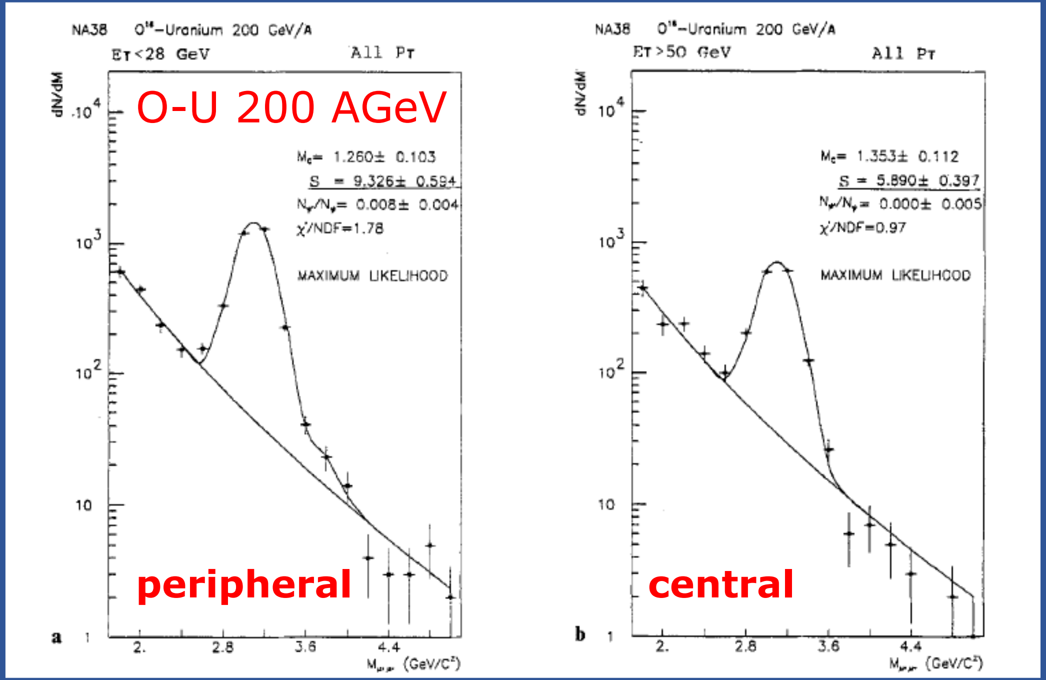
Allows **quantitative predictions** for charmed hadron yields, including quarkonia

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

J/ψ: the discoveries

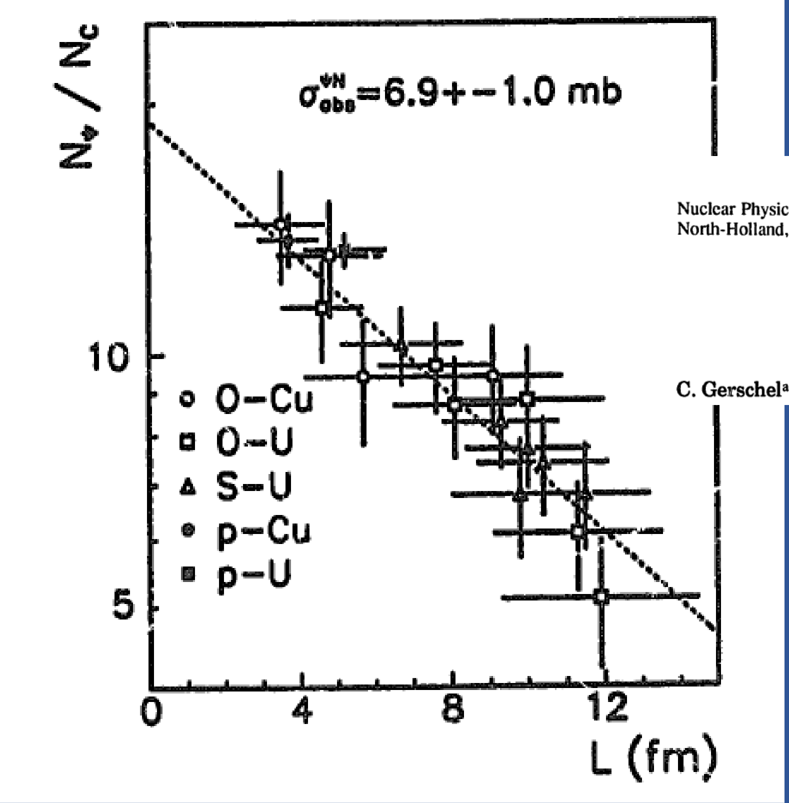
The (first) discovery of the J/ψ suppression (1986)

NA38, Z. Phys. 38(1988) 117



Centrality–dependent ratio
J/ψ / continuum
→ **Evidence for suppression**

Reference process?



C. Gerschel et al., PLB207 (1988)253

Nuclear Physics A544 (1992) 513c–516c
North-Holland, Amsterdam

NUCLEAR PHYSICS A

Comparison of J/ψ-Suppression in Photon, Hadron and Nucleus-Nucleus Collisions : Where is the Quark-Gluon Plasma ?

C. Gerschel[a] and J. Hüfner[b]

p-A collision results imply **significant dissociation cross sections in CNM**

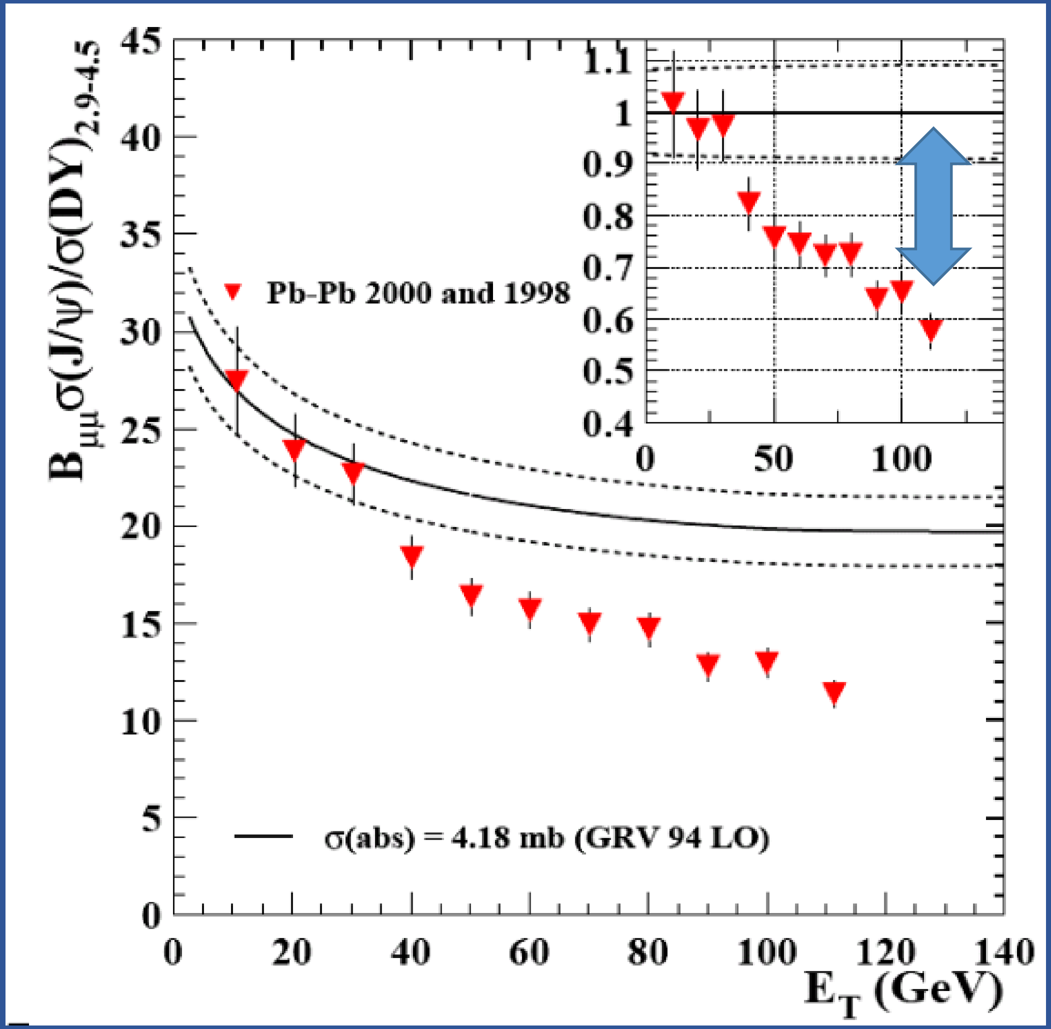
→ Crucial ingredient in the interpretation of the data
→ Stimulated an intense experimental program at both CERN and FNAL

The (real) discovery of the J/ψ suppression (2000)

Reference process
Drell-Yan

Possibly seeing an effect due to disappearance of J/ψ from χ_c and ψ(2S) decays

Role of excited states can be crucial!

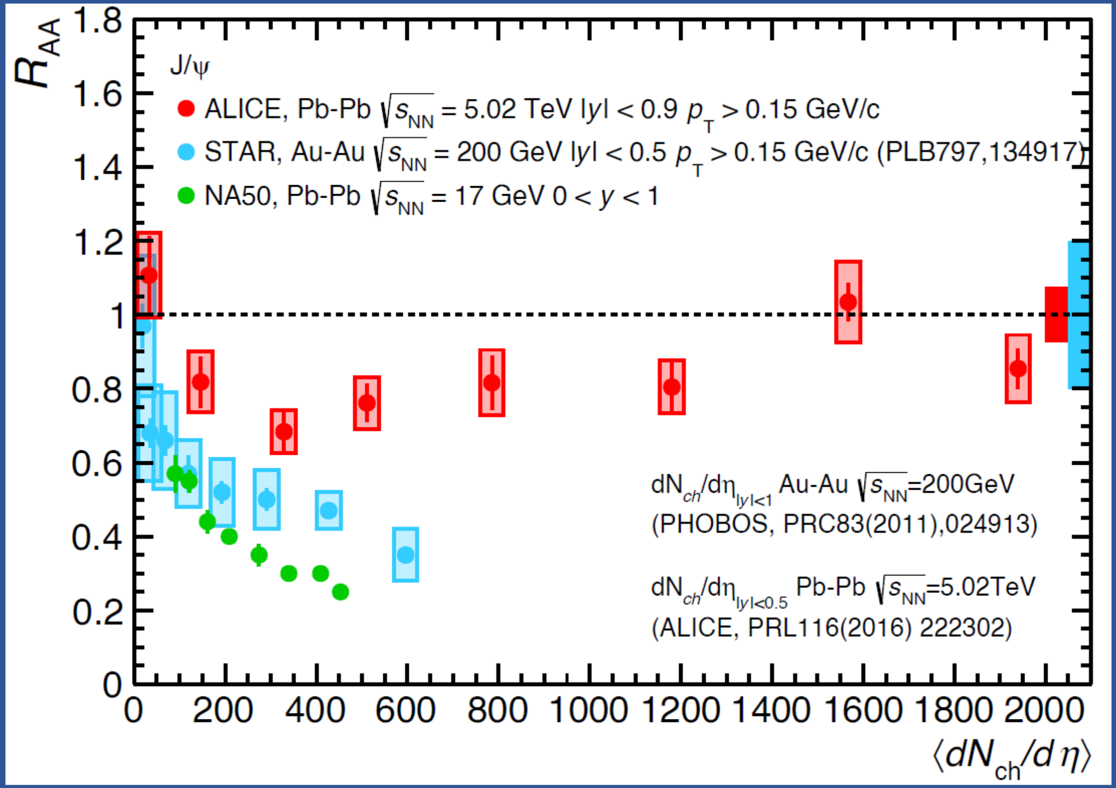


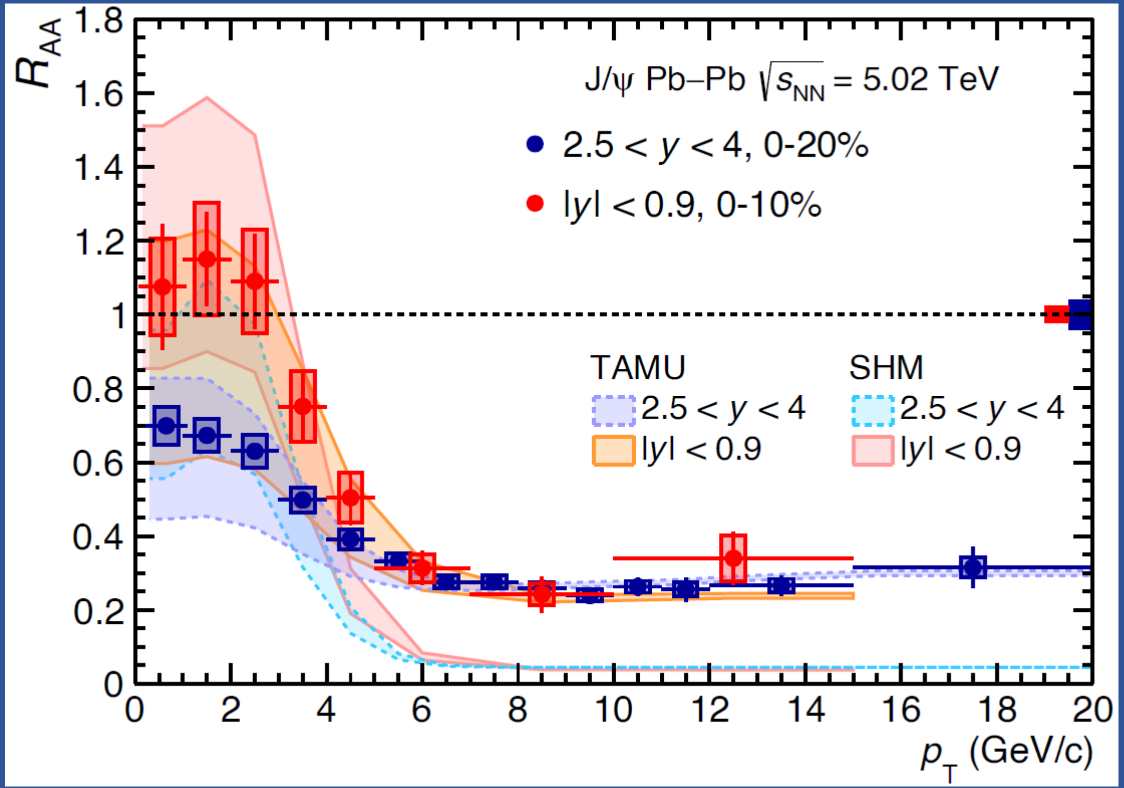
30-40%
extra suppression

Cold nuclear matter reference
from p-A collisions

The discovery of J/ψ regeneration (2010)

ALICE, arXiv:2211.04384





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

} Signature of (re)generation

Demonstrates deconfinement!

Coloured partons can move over distances much larger than the hadronic scale

What do models tell us ?

Transport

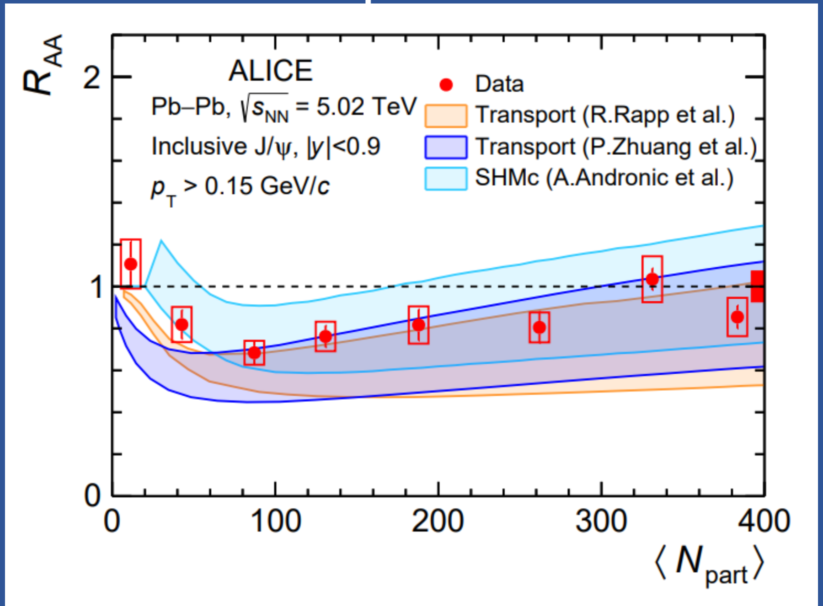
X. Du and R. Rapp, NPA 943(2015) 14P.7
P. Zhou et al., PRC89 (2014) 054911

- 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

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

ALICE, arXiv:2303.13361



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

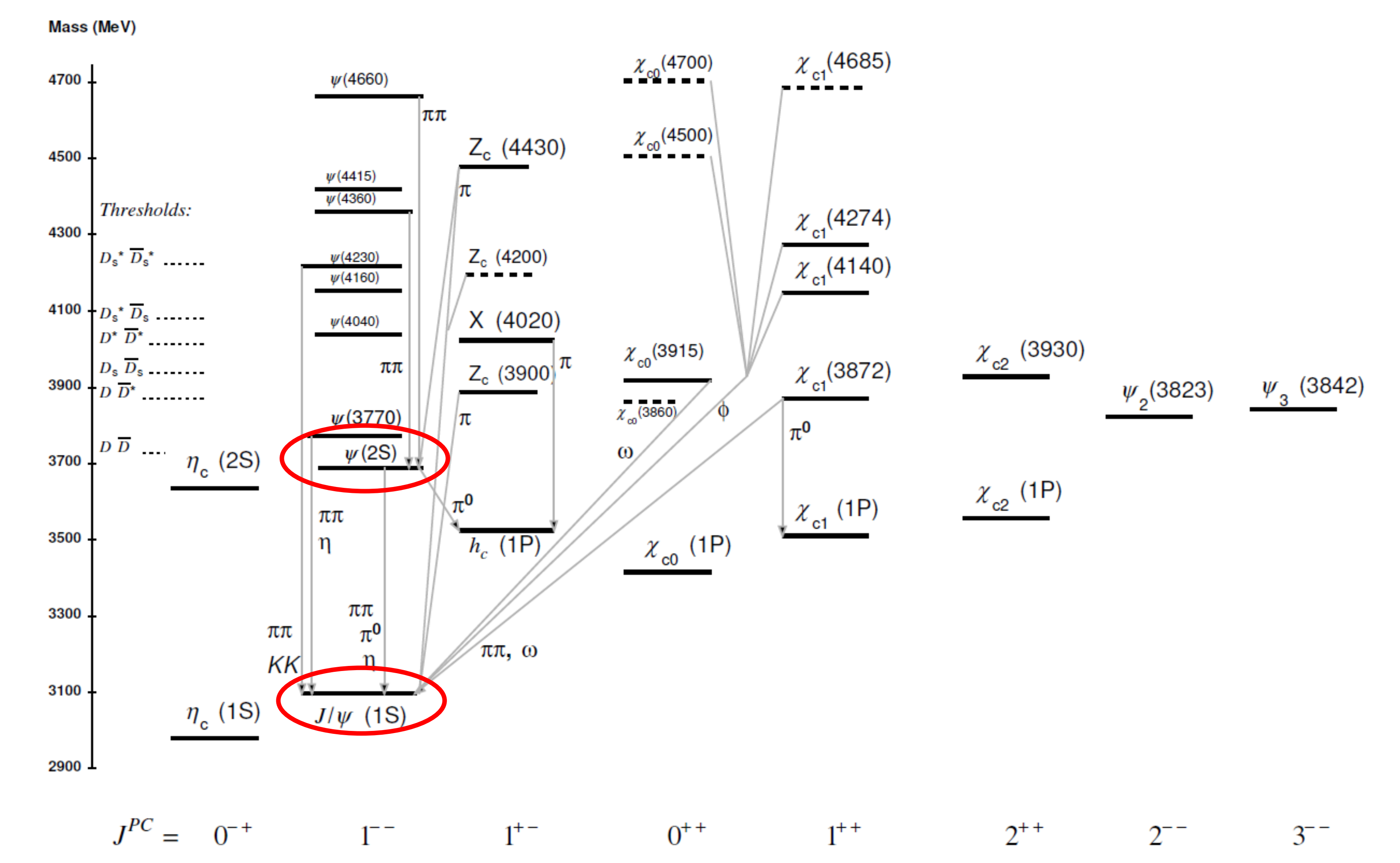
Other approaches include "comover" models

E. Ferreiro, PLB 731 (2014) 57

$\psi(2S)$: the younger son of J/ψ

ψ(2S) vs J/ψ

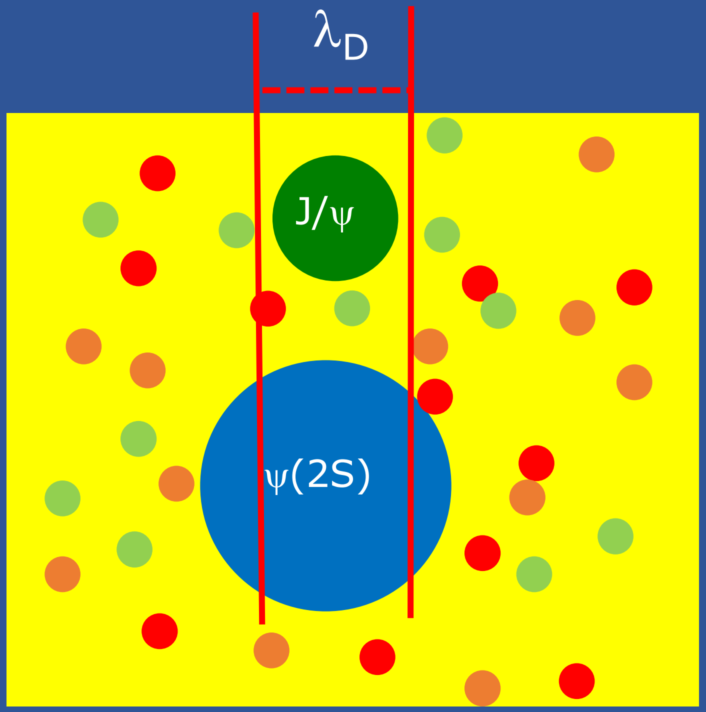
- Binding energy ~$(2m_D - m_\psi)$ → **ψ(2S) ~ 60 MeV, J/ψ ~ 640 MeV**



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

$\psi(2S)$ vs J/ψ

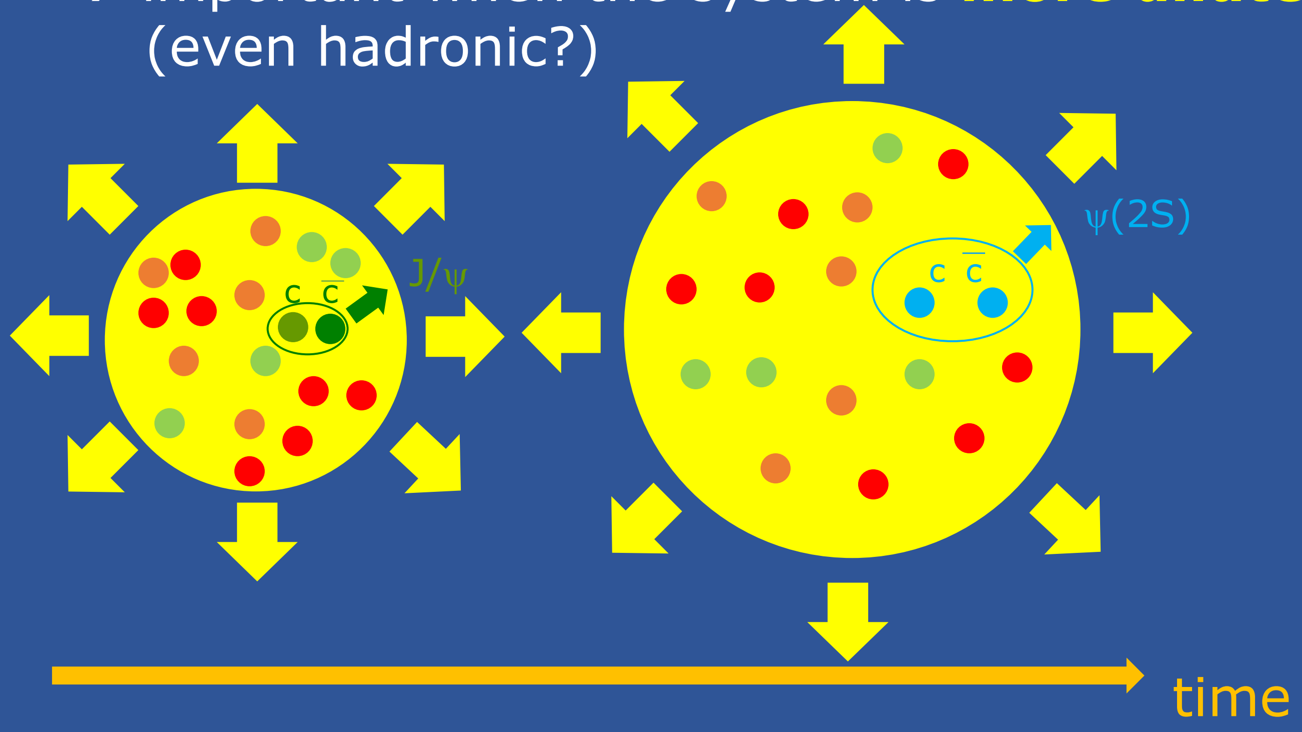
- Binding energy $\sim(2m_D - m_\psi)$ → **$\psi(2S) \sim 60$ MeV, $J/\psi \sim 640$ MeV**



Important for a quantitative test of models!

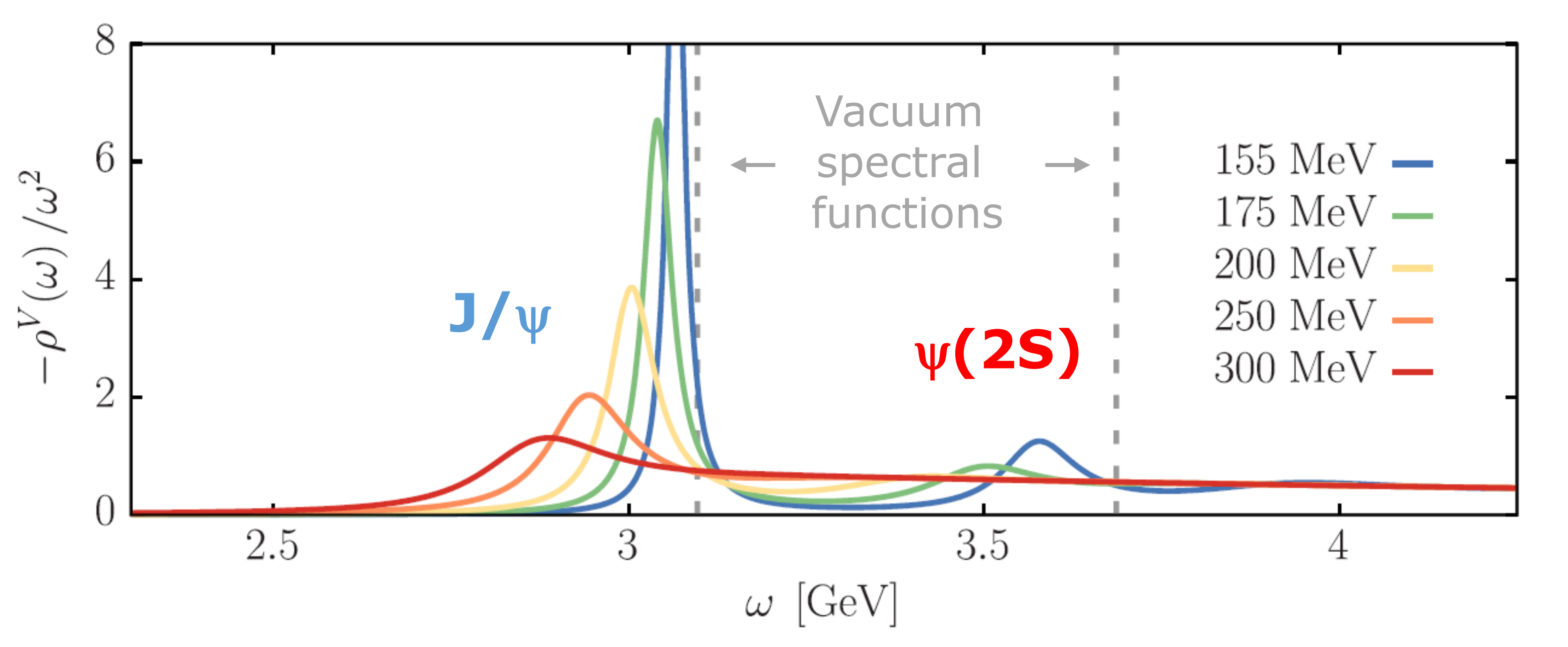
- Expect **much stronger dissociation effects** for the weakly bound $\psi(2S)$ state

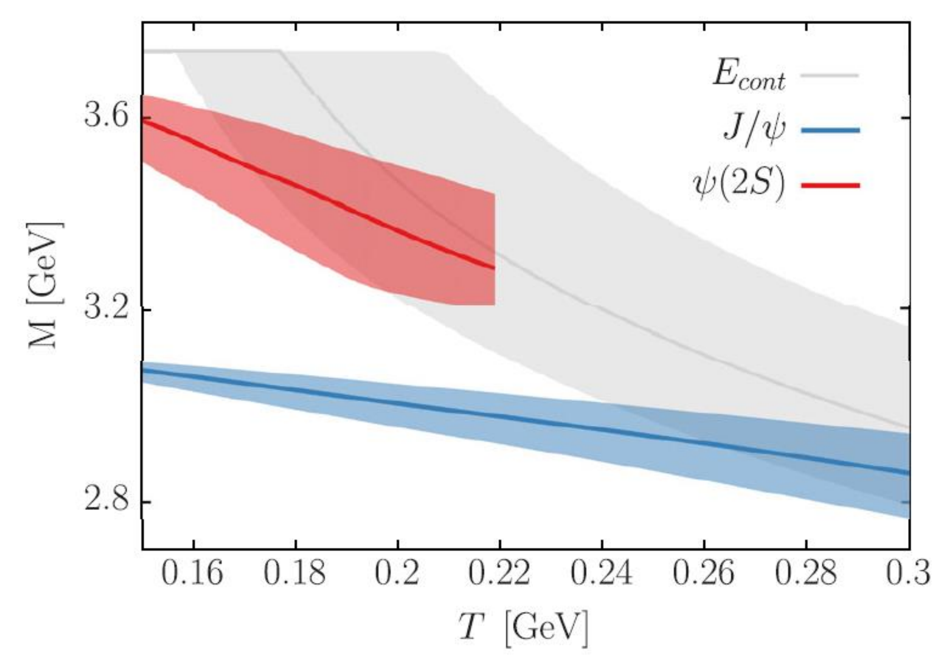
- Effect of re-combination on $\psi(2S)$ more subtle
  → important when the system is **more diluted** (even hadronic?)

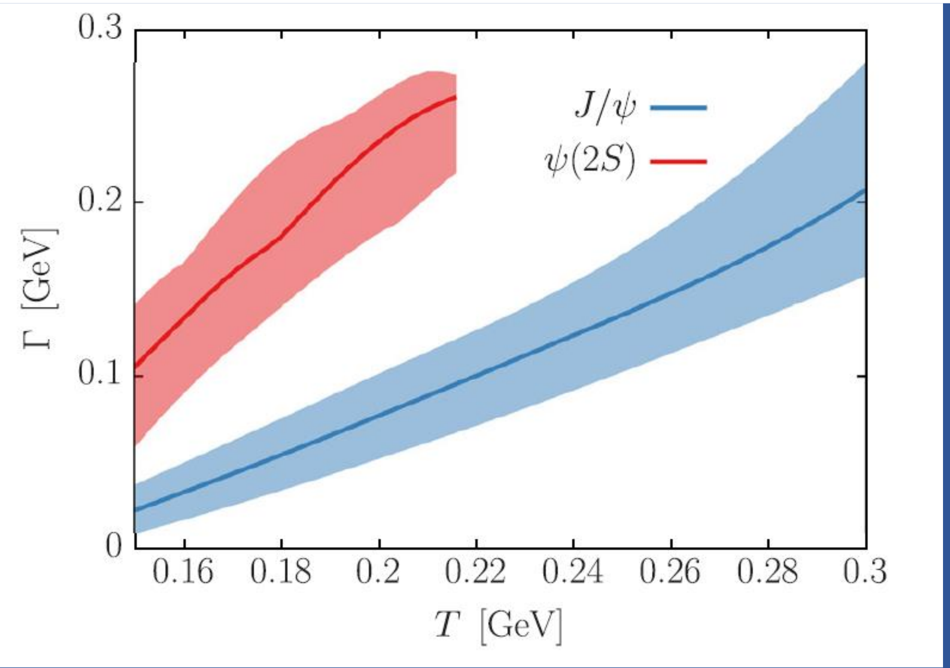


Modification of spectral properties and dissociation

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





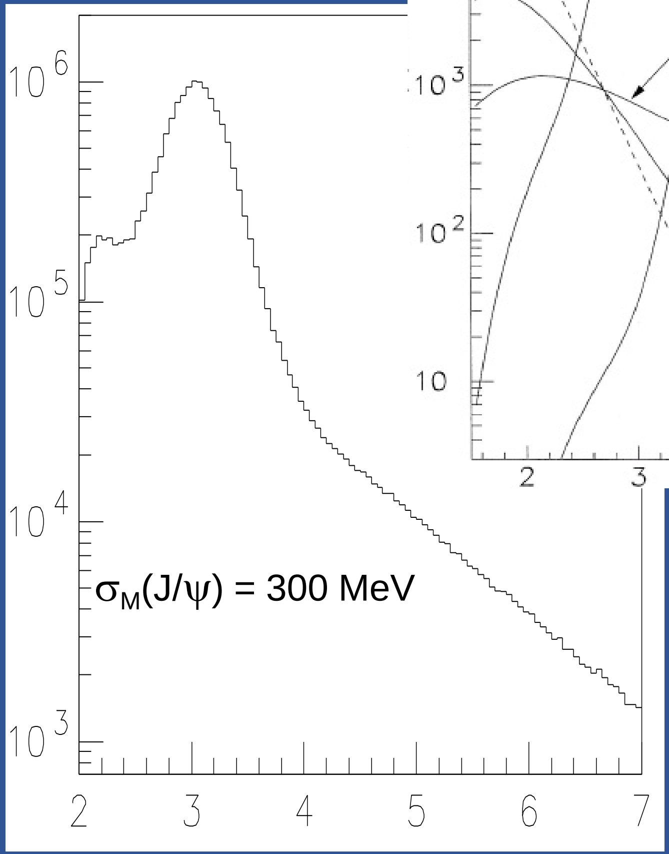


- ❑ Strong effects on the **mass AND width** of the charmonium states, with distinctive **differences between J/ψ and ψ(2S)**
- ❑ As intuitively expected, the more deeply the state is bound, the less is susceptible to medium effects

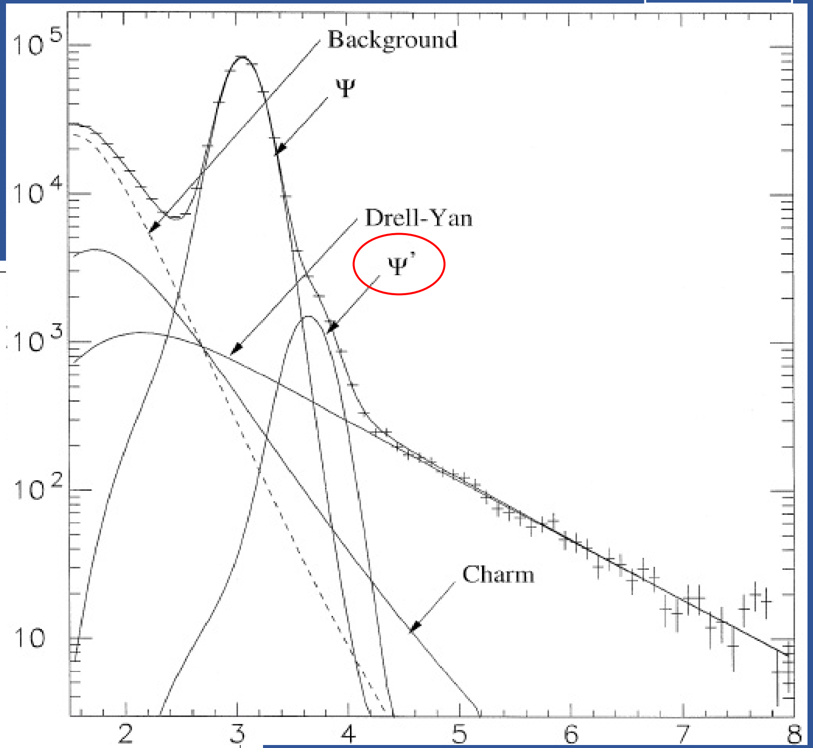
Accessing the ψ(2S)

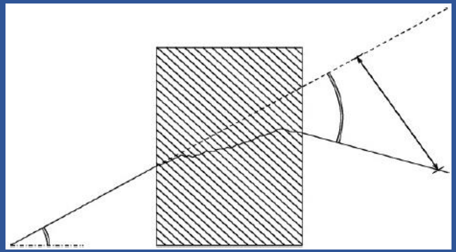
Mass resolution is a must!

E605

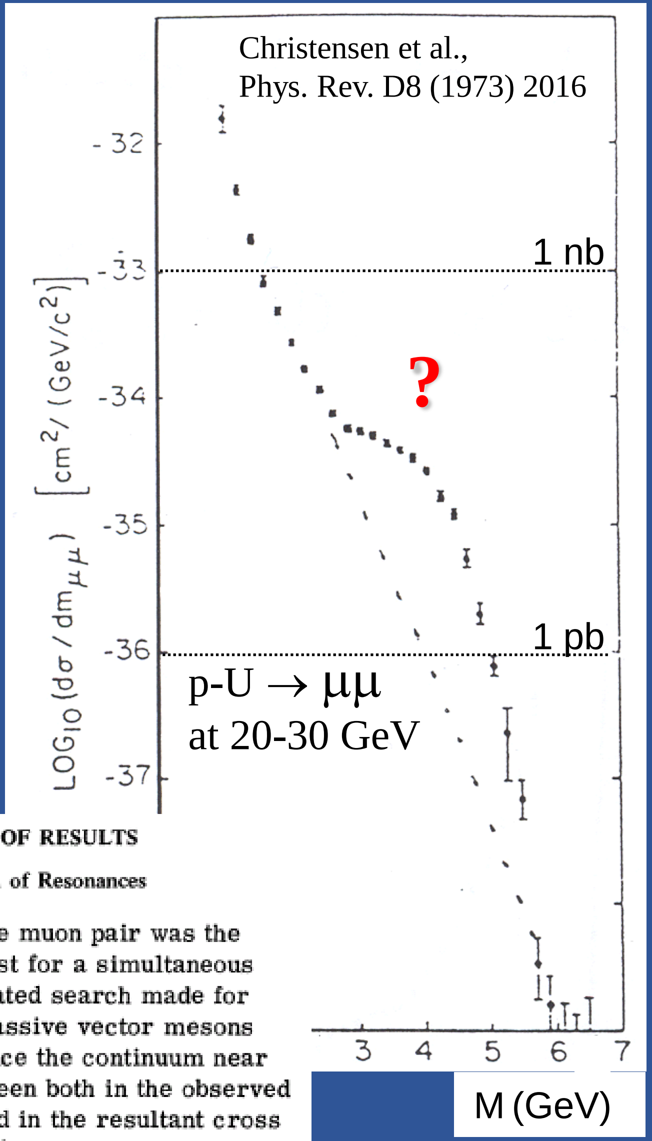


NA51





A textbook case

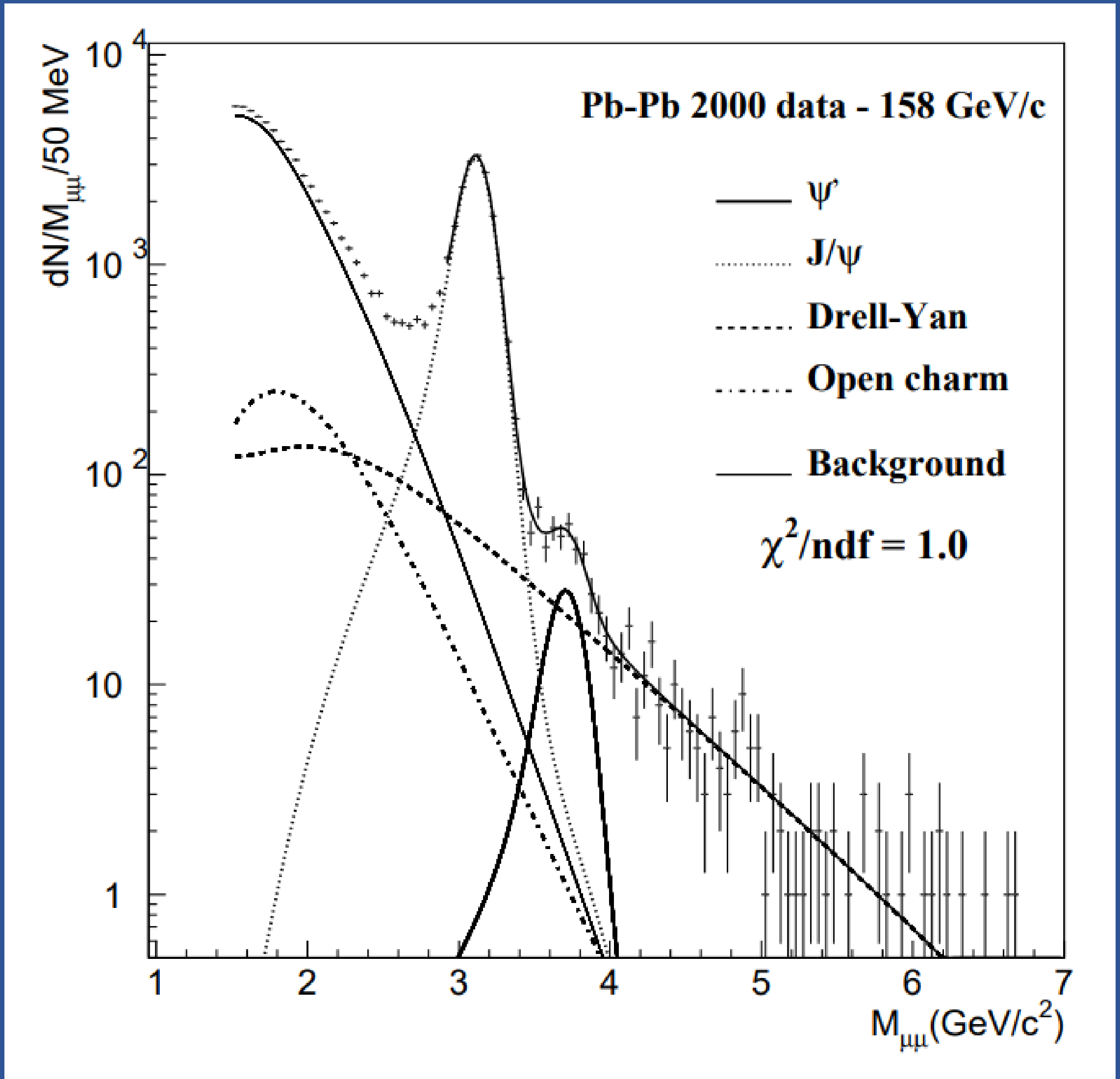


V. DISCUSSION OF RESULTS

A. Nonobservation of Resonances

The invariant mass of the muon pair was the variable of primary interest for a simultaneous and, of course, highly related search made for "resonant" states. Any massive vector mesons would be expected to enhance the continuum near the resonance mass. As seen both in the observed mass spectrum (Fig. 4) and in the resultant cross sections $d\sigma/dq$ (Figs. 6–10) there is no forcing evidence of any resonant structure.

Extracting the ψ(2S) signal



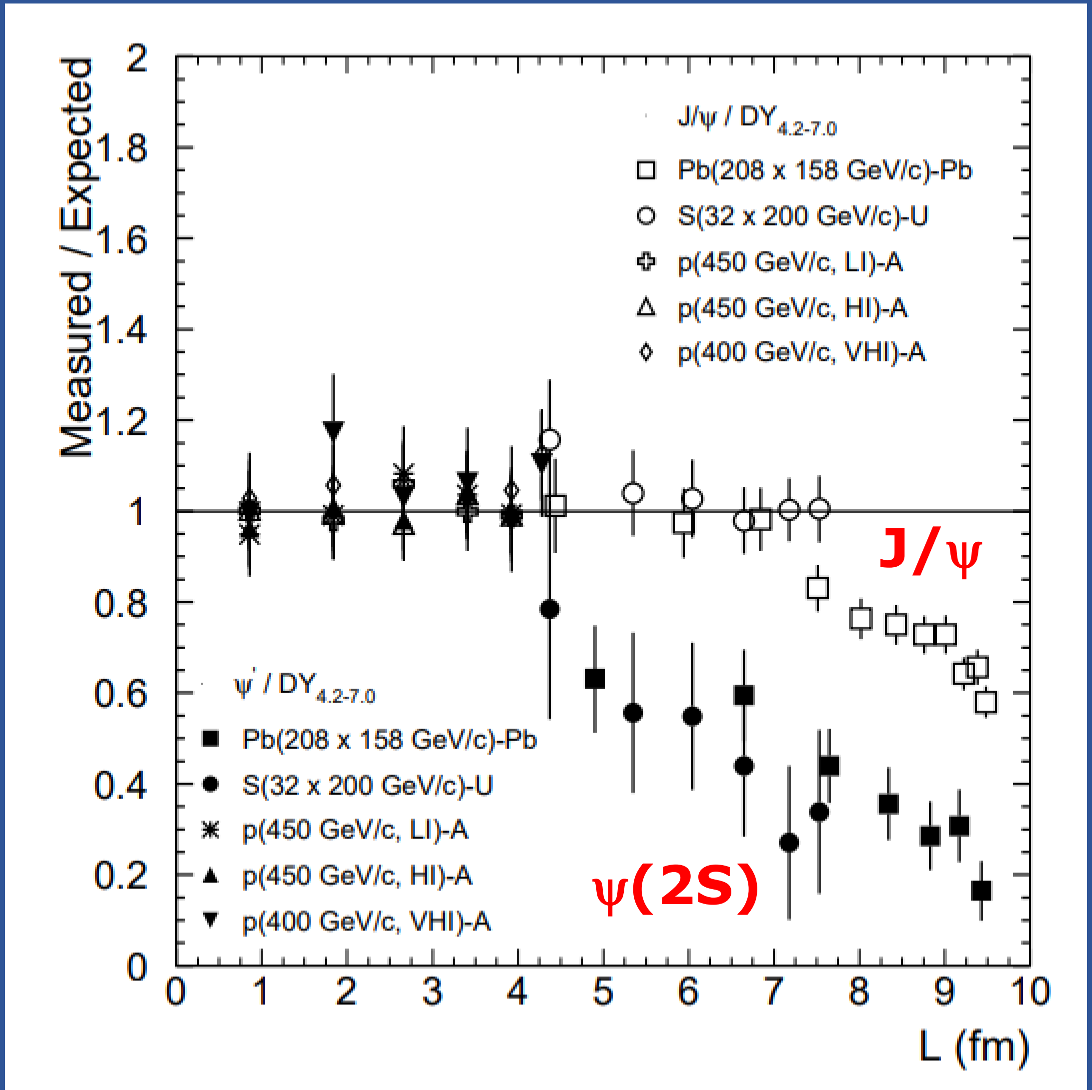
- Extraction of ψ(2S) signal is delicate

- **Yield** is ~2 order of magnitude lower than J/ψ
- **Signal/background** quite small
- Several contribution to the invariant mass spectrum in the ψ(2S) mass range

- Multi-step fit
  - Fix **combinatorial background** from like-sign dimuons
  - Fix **Drell-Yan** in the high-mass region
  - Fit **open charm** in $2.2<M<2.5$ GeV/c^2

  - (Finally) fit resonance contributions
  - **Tie ψ(2S) to J/ψ**
    - $m_{\psi(2S)} = m_{J/\psi} + (m_{\psi(2S)} - m_{J/\psi})_{PDG}$
    - $\sigma_{\psi(2S)} = \sigma_{J/\psi} \times (\sigma_{\psi(2S)} / \sigma_{J/\psi})_{MC}$

ψ(2S) in Pb-Pb collisions: fixed-target energy



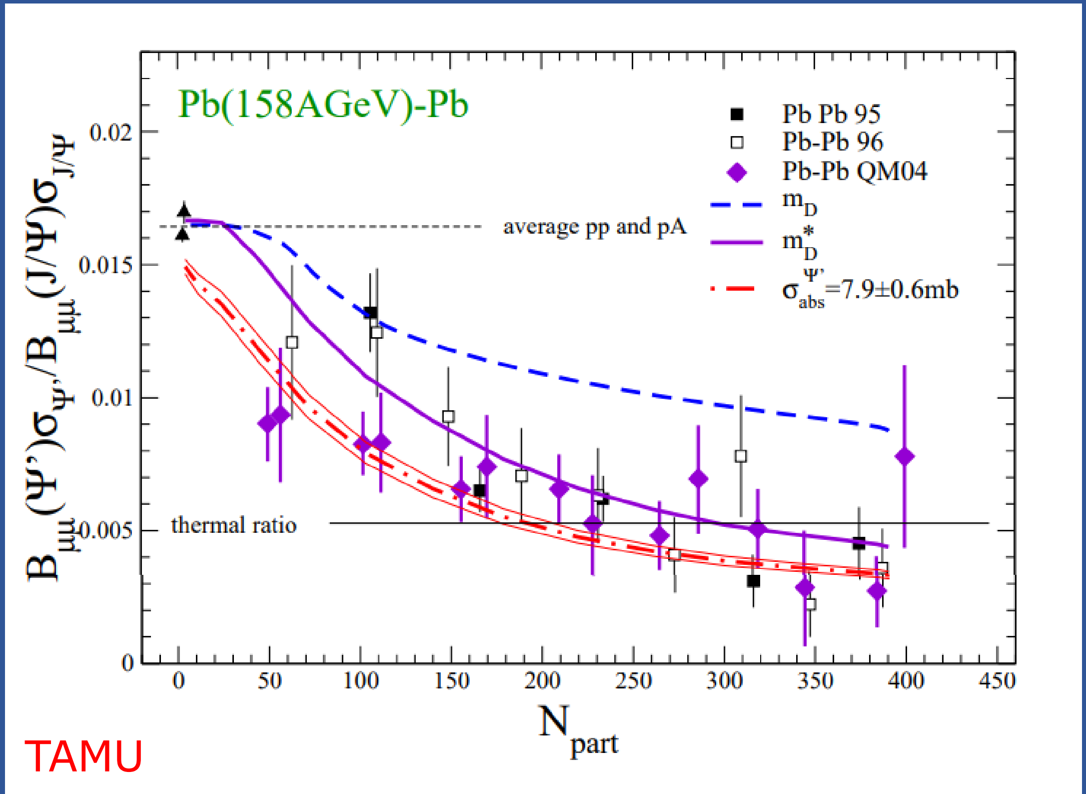
- ❑ After correcting for cold nuclear matter effects
- ❑ ψ(2S) "hot-matter" suppression
  - ❑ is **stronger than the J/ψ** one
  - ❑ **sets in at lower energy densities**
    → 1.5 GeV/fm^3 wrt ~2.5 GeV/fm^3 for the J/ψ
  - ❑ is already present in light-ion collisions (S-U)

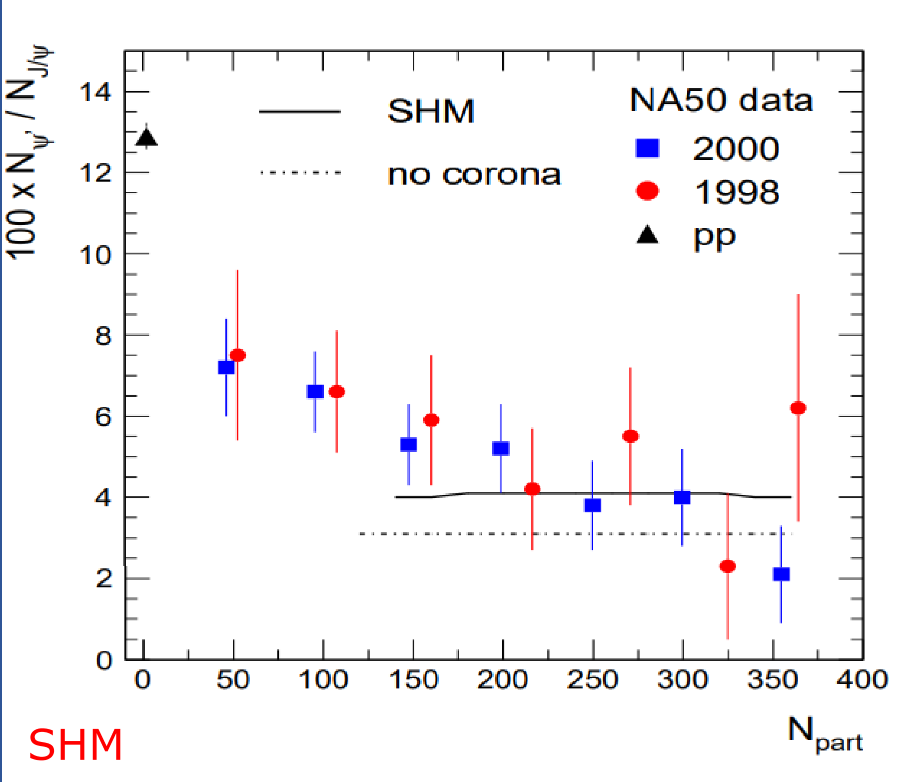
The (first) discovery of sequential suppression

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

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)





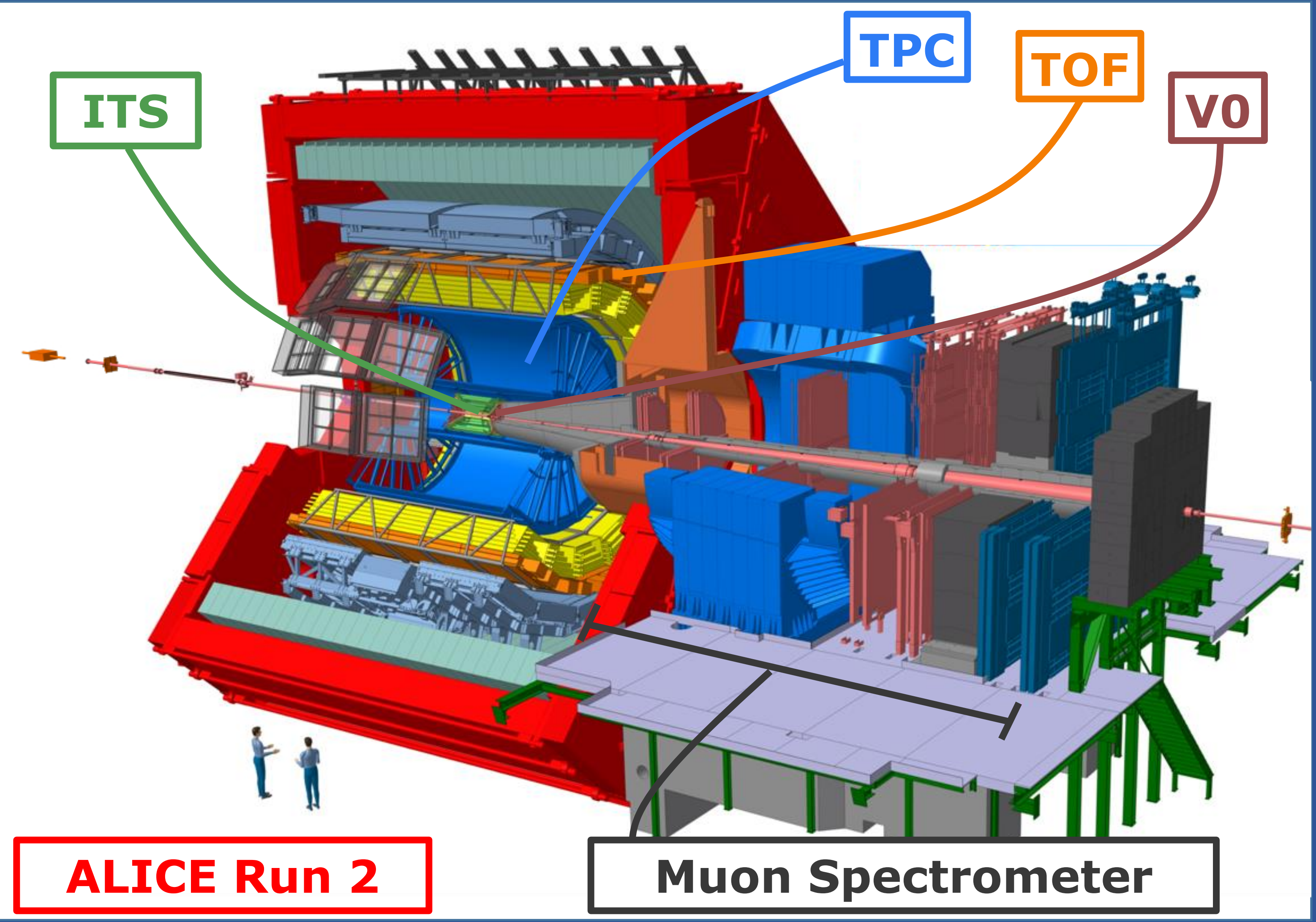
from
Rapp and Van Hees, arXiv:0903.1096

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**

A Large Ion Collider Experiment



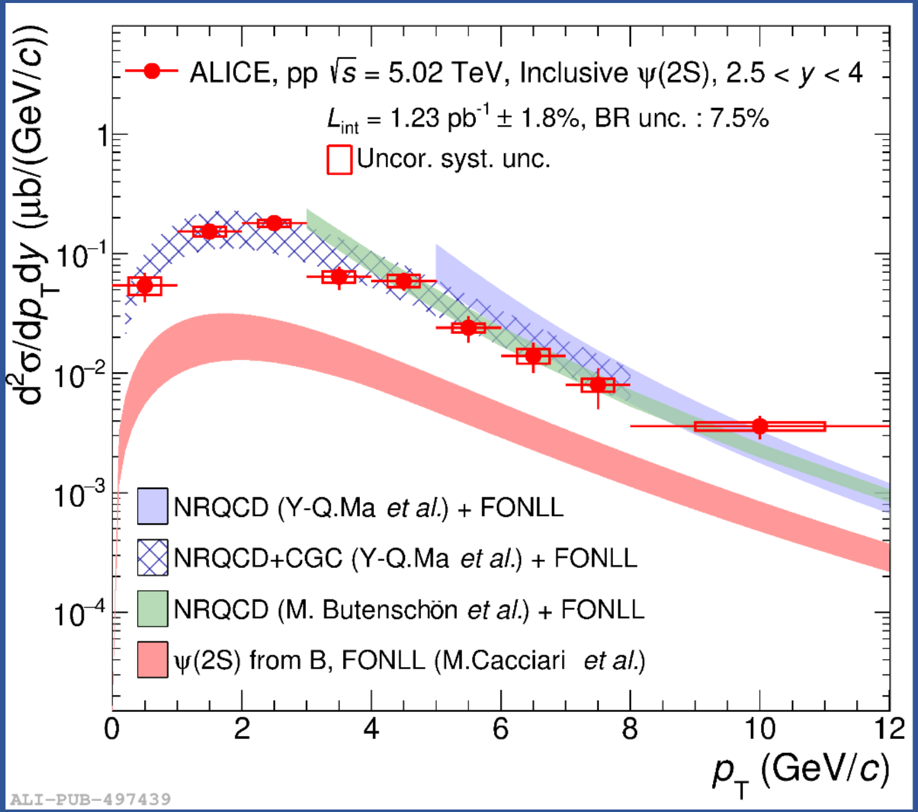
- **Inclusive quarkonium**
  - Central barrel (ee, $|y|<0.9$)
  - Muon spectrometer ($\mu\mu$, $2.5<y<4$)
  - Coverage **down to zero p_T**

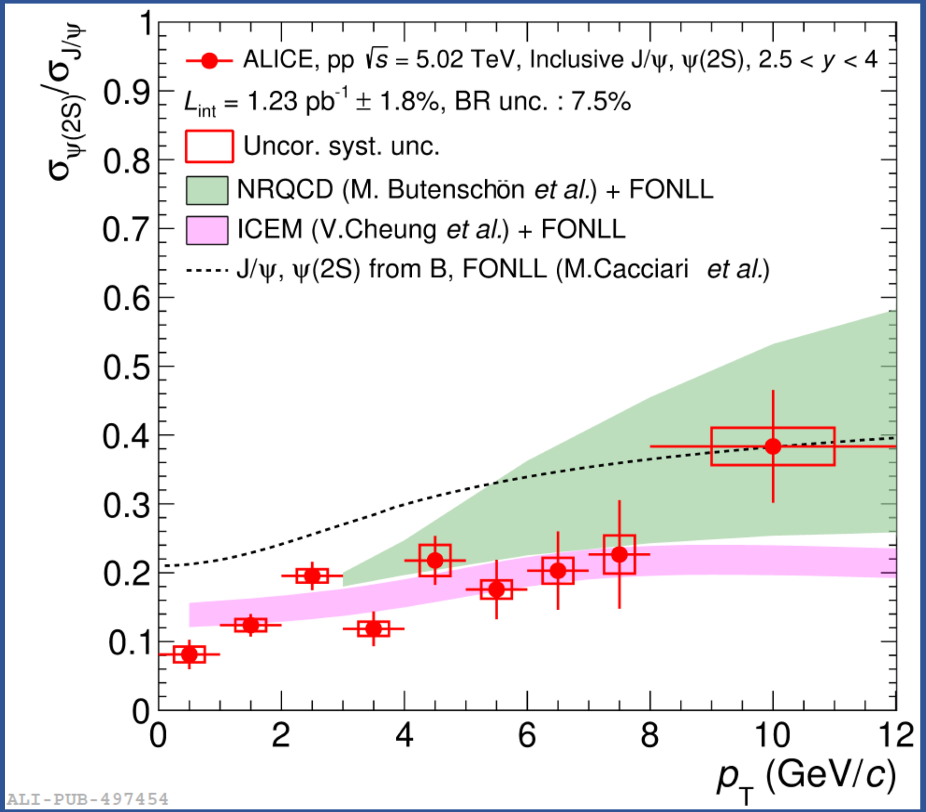
- ψ(2S) results were obtained at **forward rapidity**

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

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

Reference pp measurements



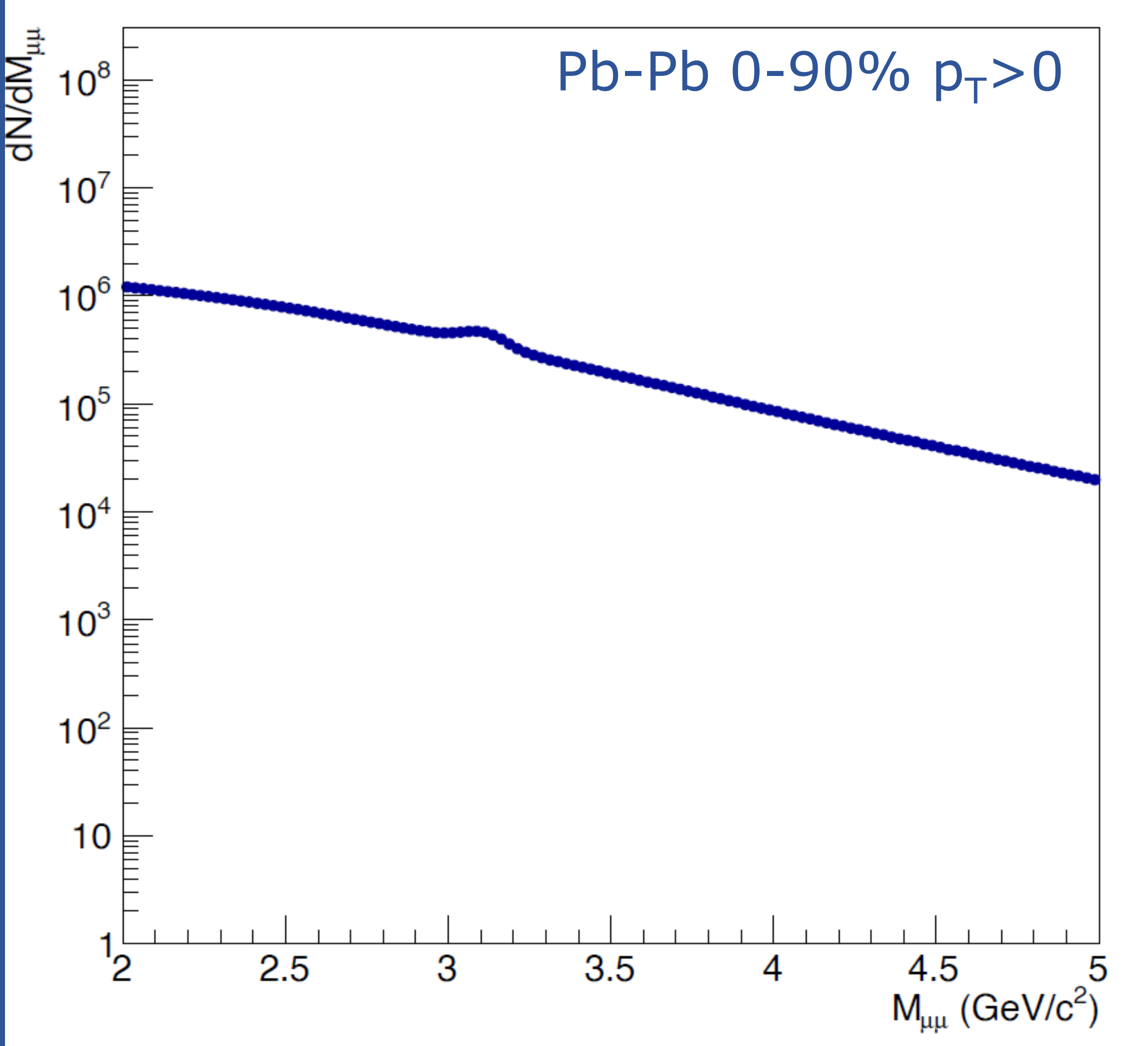


ALICE, arXiv:2109.15240

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

Extracting the ψ(2S) signal in ALICE



- S/B on the "raw" spectrum is extremely low (~ 10^{-3})

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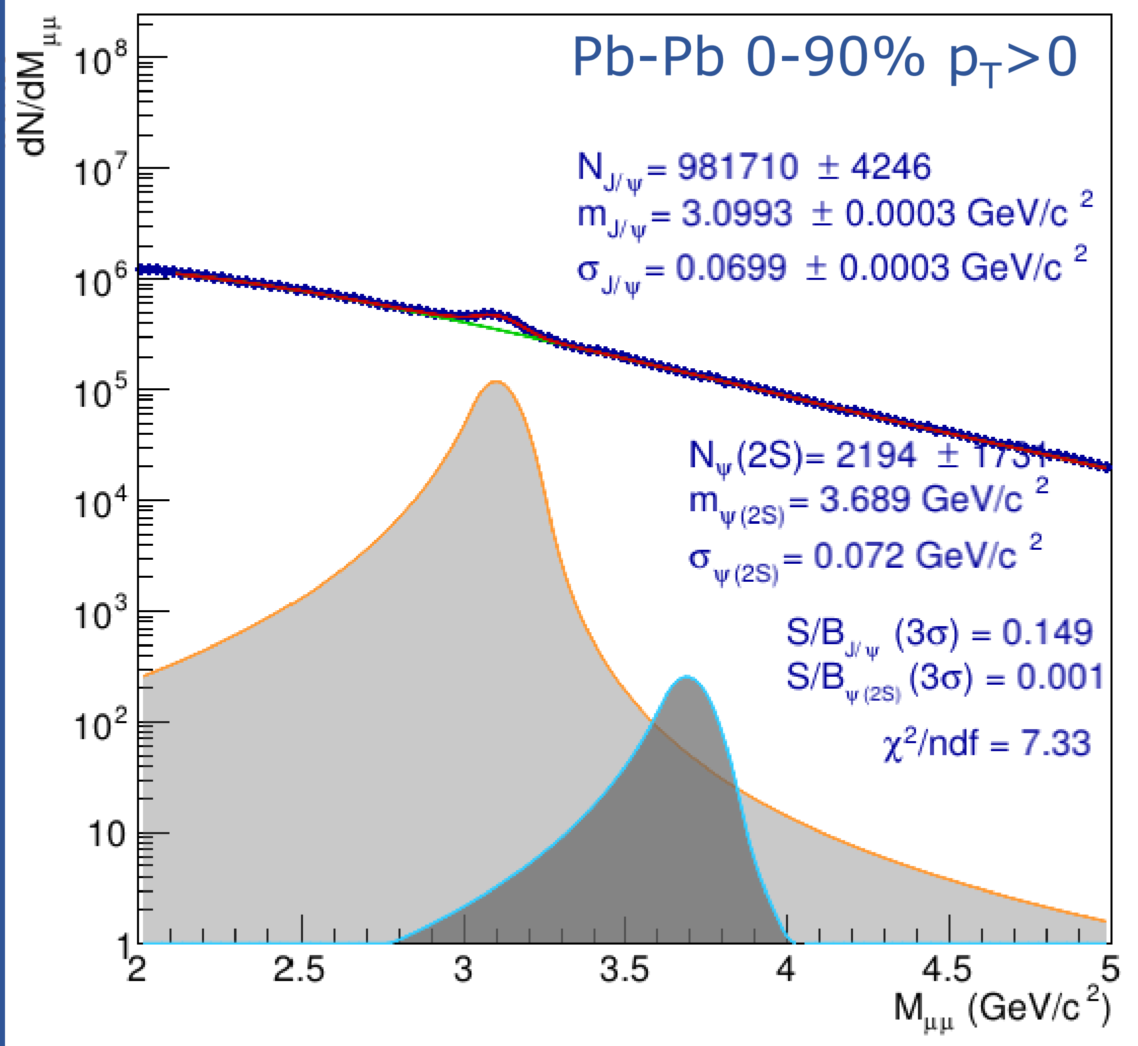
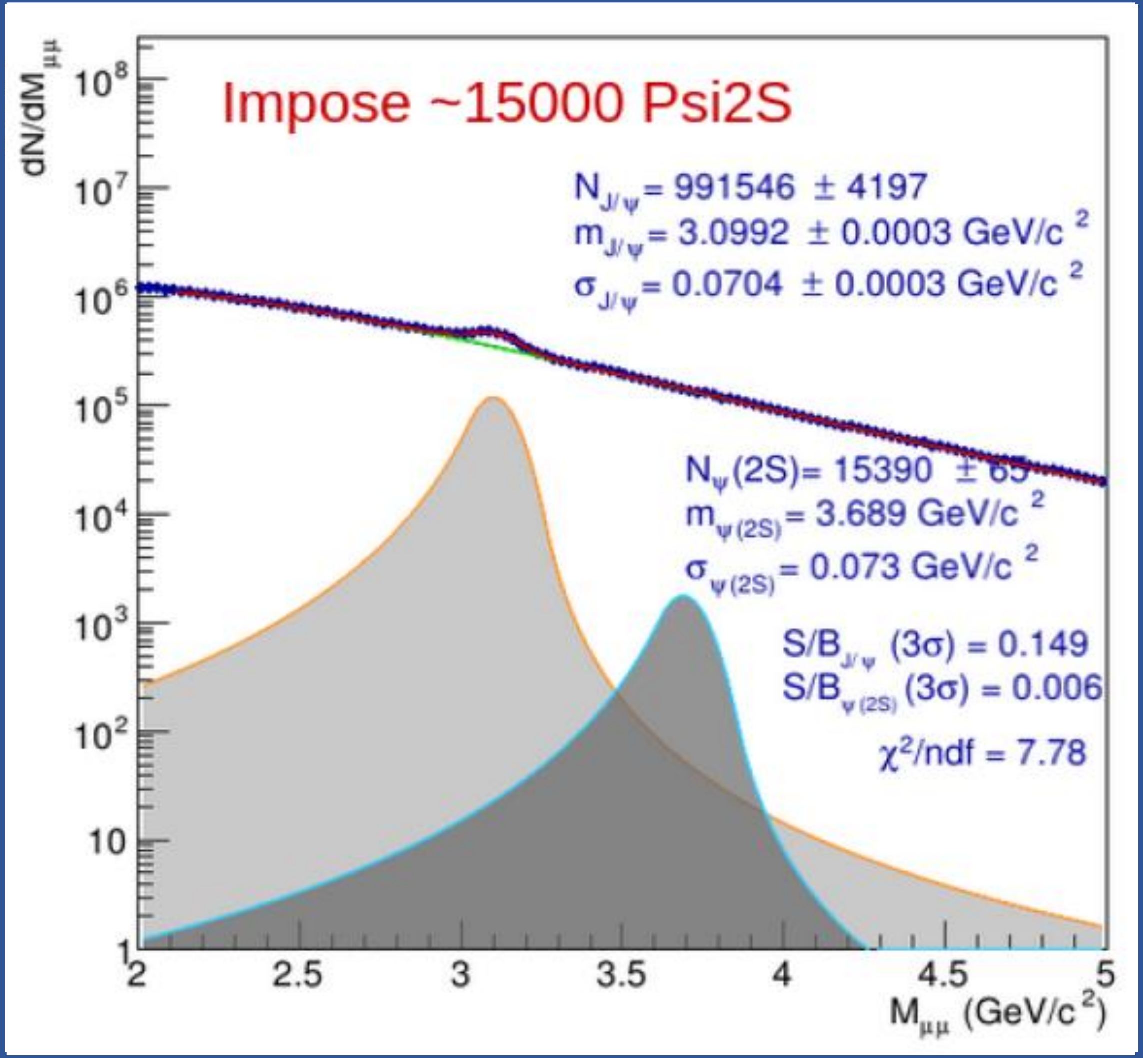


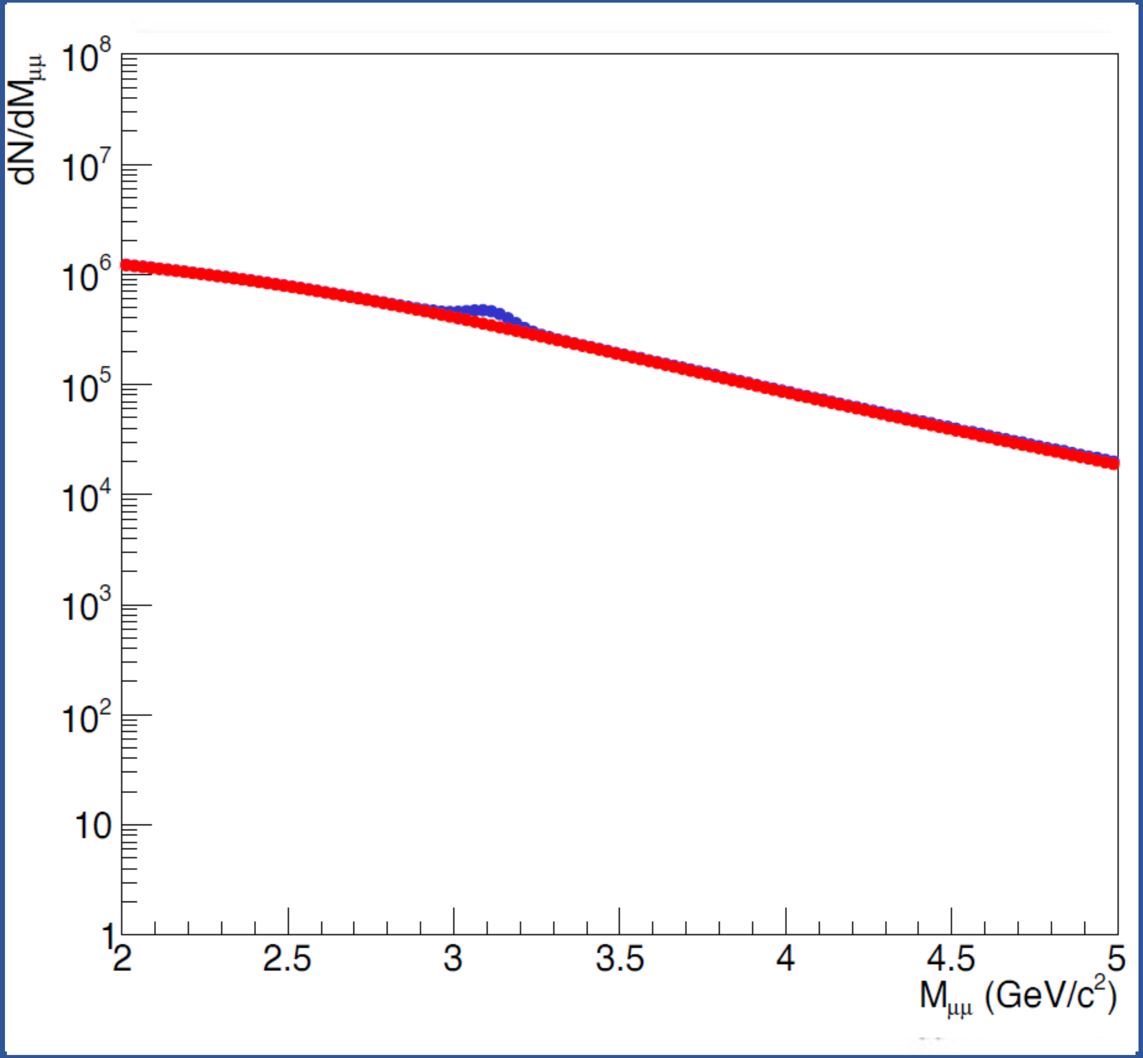
- S/B on the "raw" spectrum is extremely low (~ 10^{-3})
- A "direct" fit converges, but χ^2/ndf large

Extracting the $\psi(2S)$ signal in ALICE



- S/B on the "raw" spectrum is extremely low ($\sim 10^{-3}$)
- A "direct" fit converges, but χ^2/ndf large
- A ~6 times larger $\psi(2S)$ signal could be imposed with a similar fit quality

Extracting the ψ(2S) signal in ALICE



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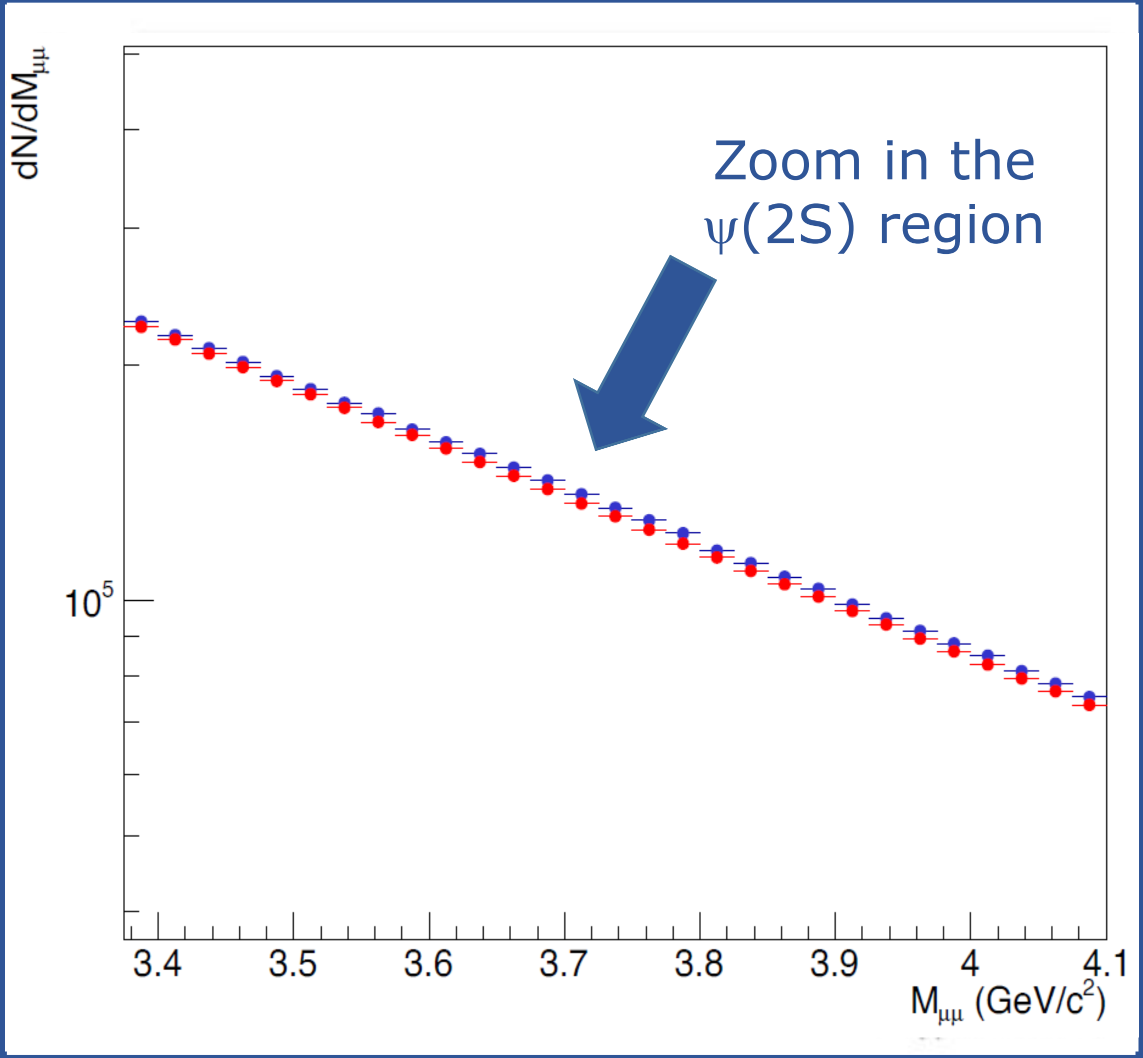
- Chosen solution
  → use mixed-event technique to subtract (most) background

Extracting the ψ(2S) signal in ALICE



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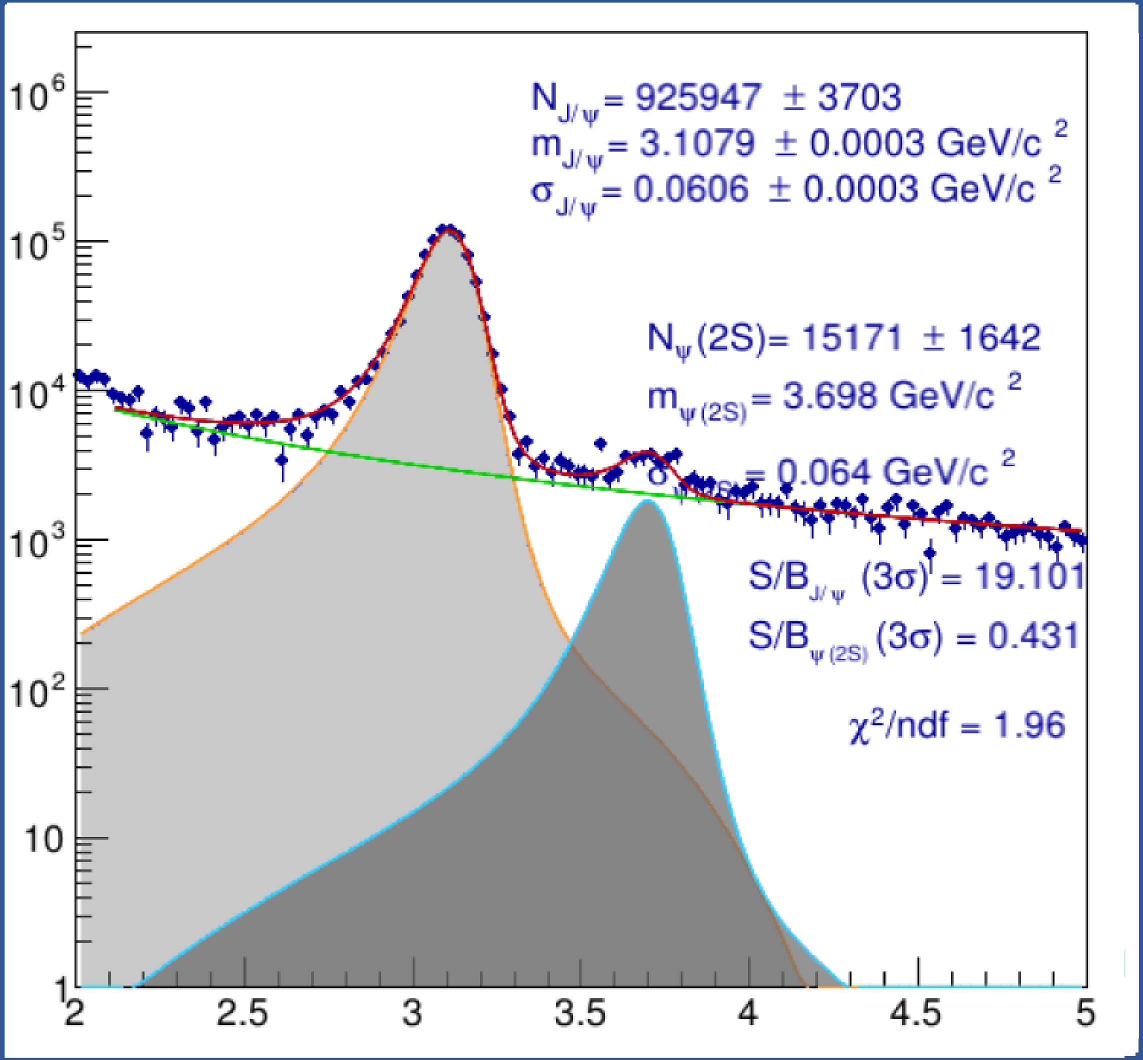

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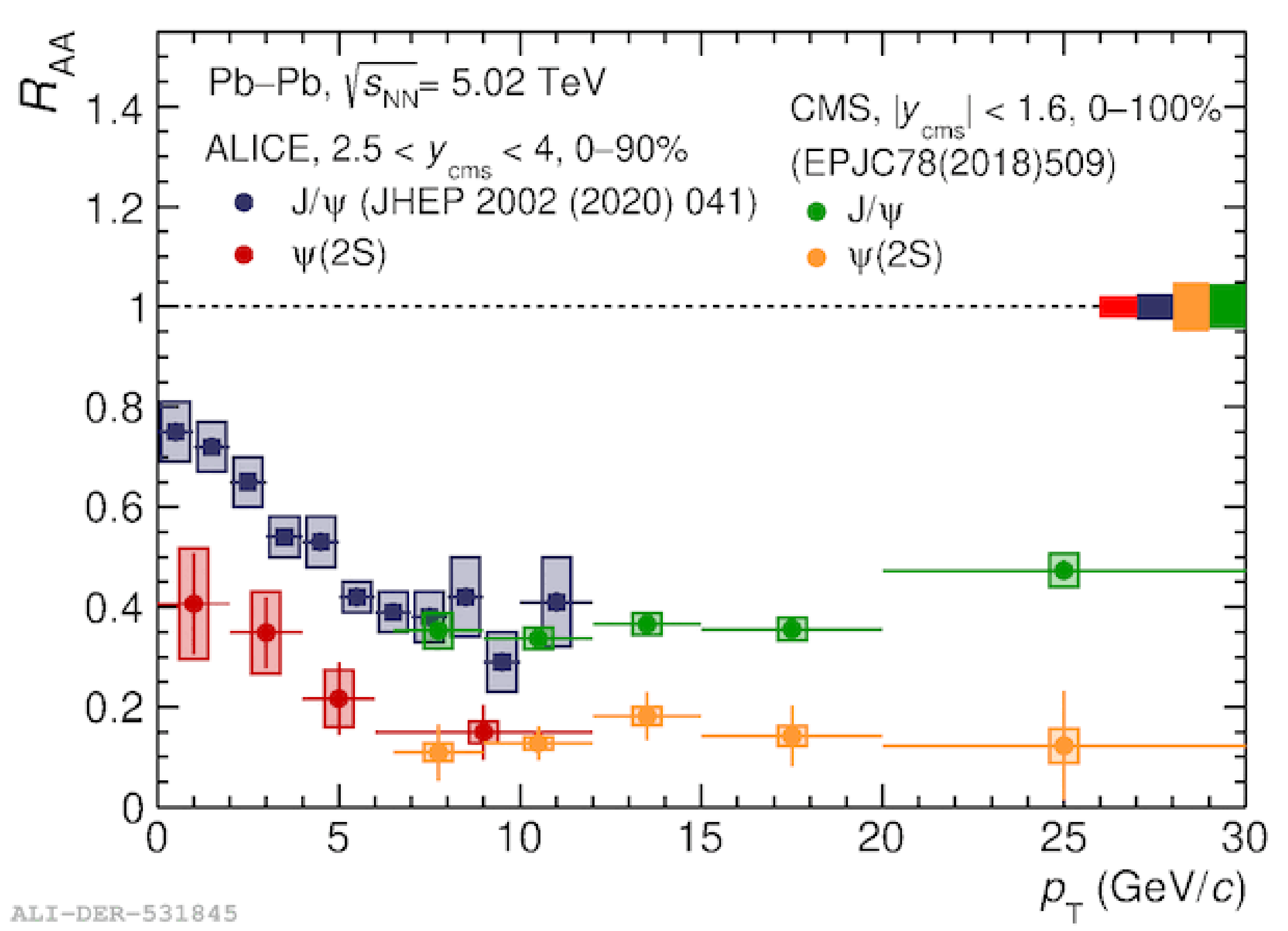
- Chosen solution
  → use mixed-event technique to subtract (most) background

- Fit background-subtracted spectrum
  → S/B improves by a factor ~400
  → χ^2/ndf becomes acceptable

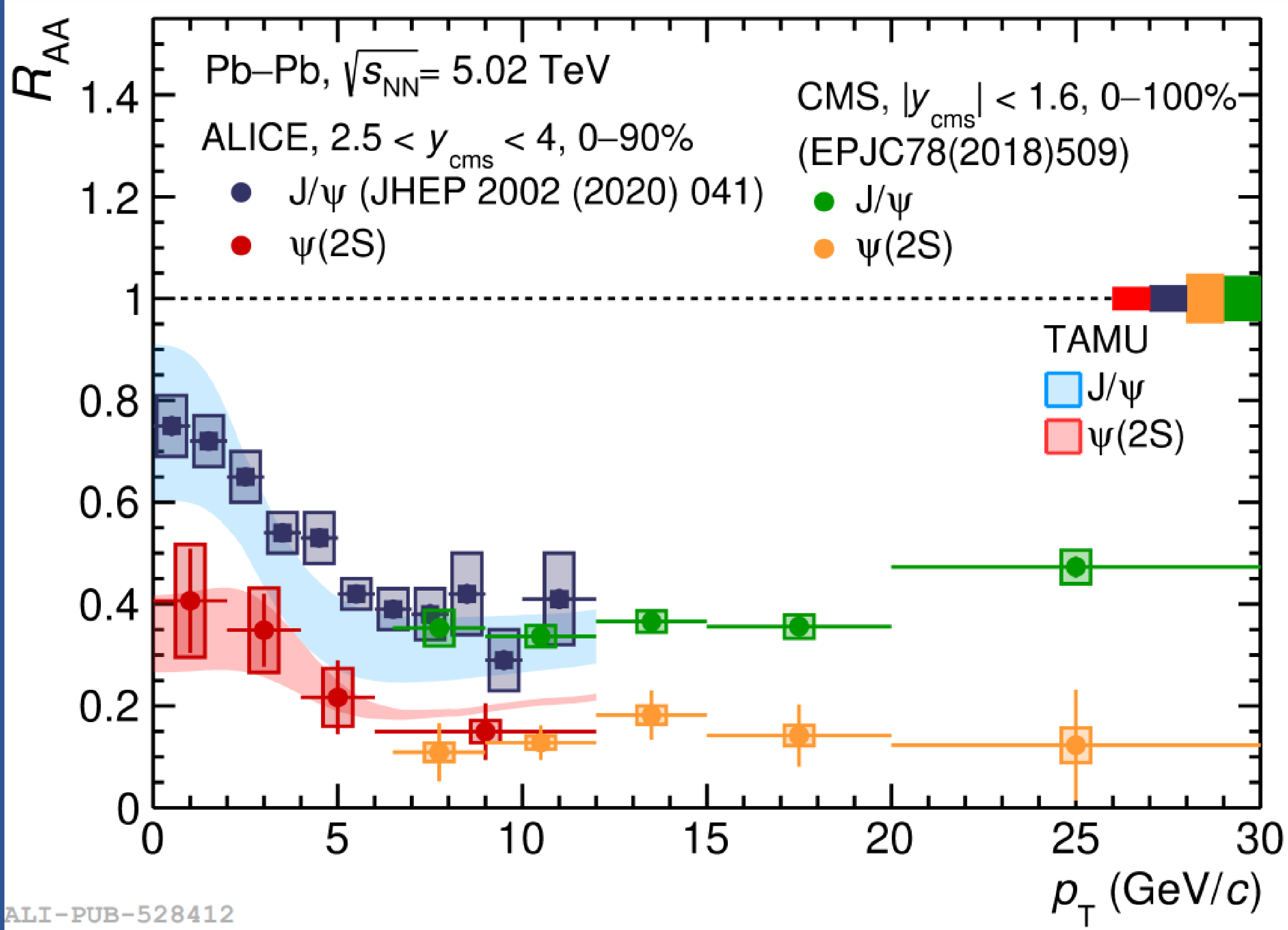
p_T dependence of the nuclear modification factor



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

- 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

p_T dependence of the nuclear modification factor



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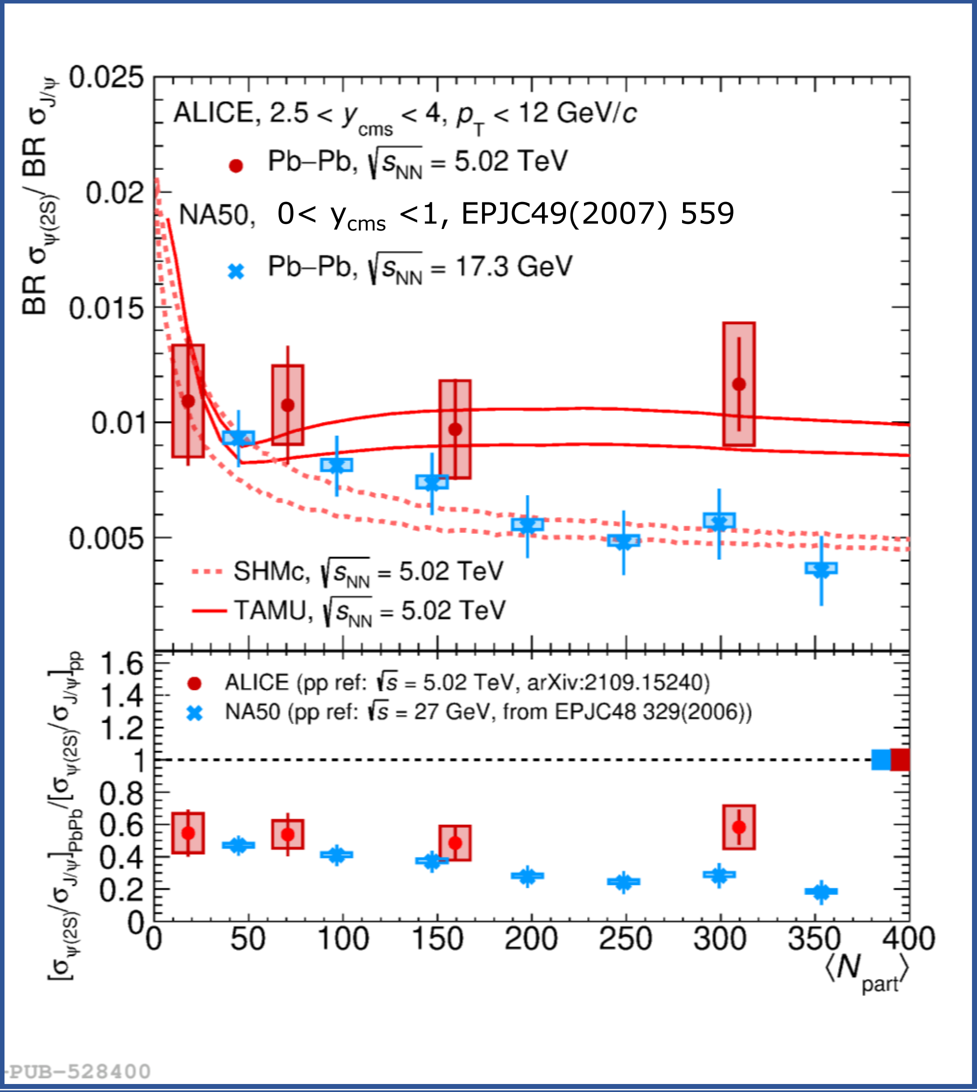
ALICE, arXiv:2210.08893

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

ALICE, arXiv:2210.08893

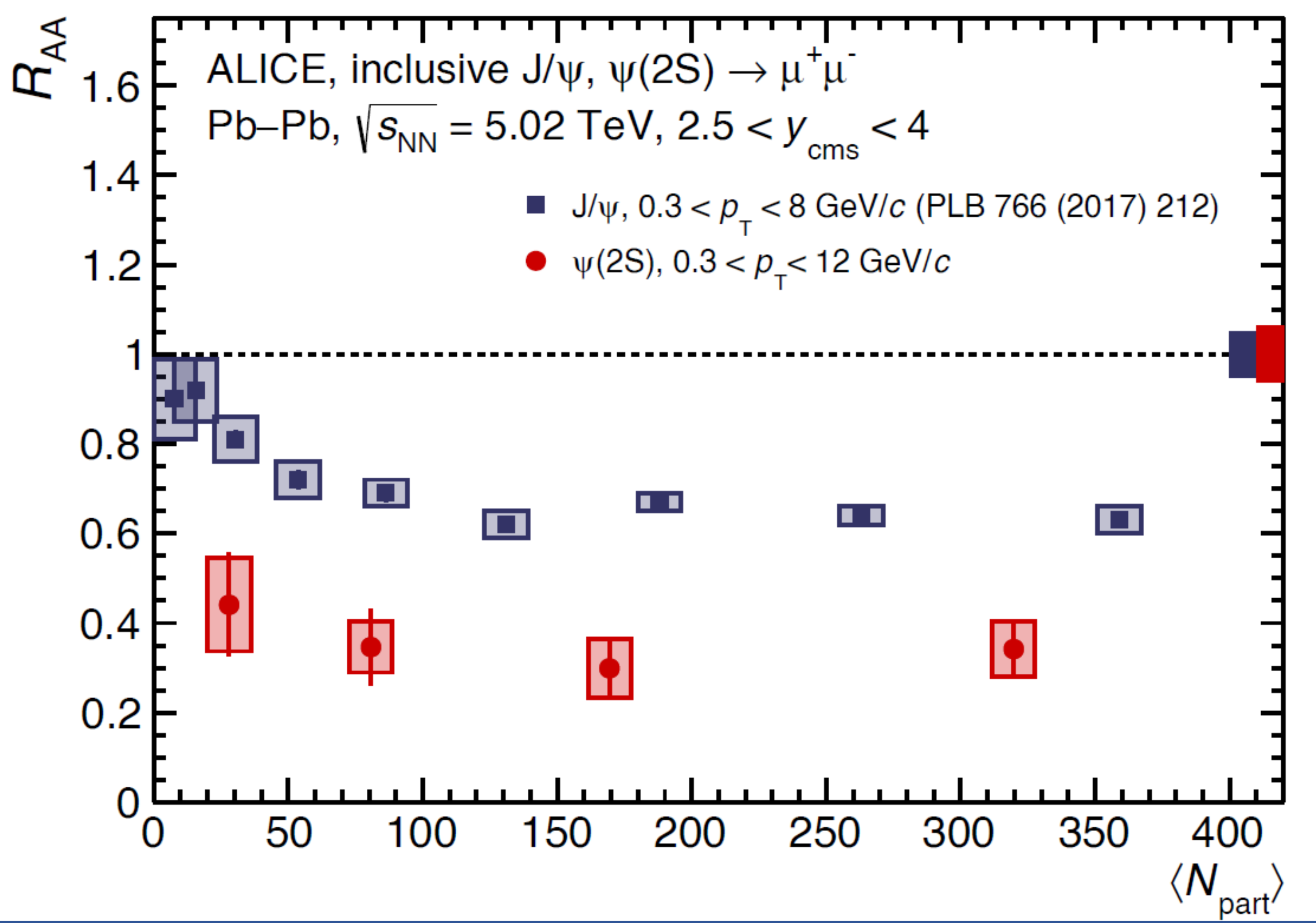


- Flat centrality dependence of ALICE ψ(2S)-to-J/ψ (double) ratio
- NA50 results show a slightly more pronounced centrality dependence
- **Indication of larger ψ(2S)-to-J/ψ (double) ratio in ALICE than in NA50 in central events**
- The **TAMU model reproduces the cross section ratios** over centrality,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

ALICE, arXiv:2210.08893

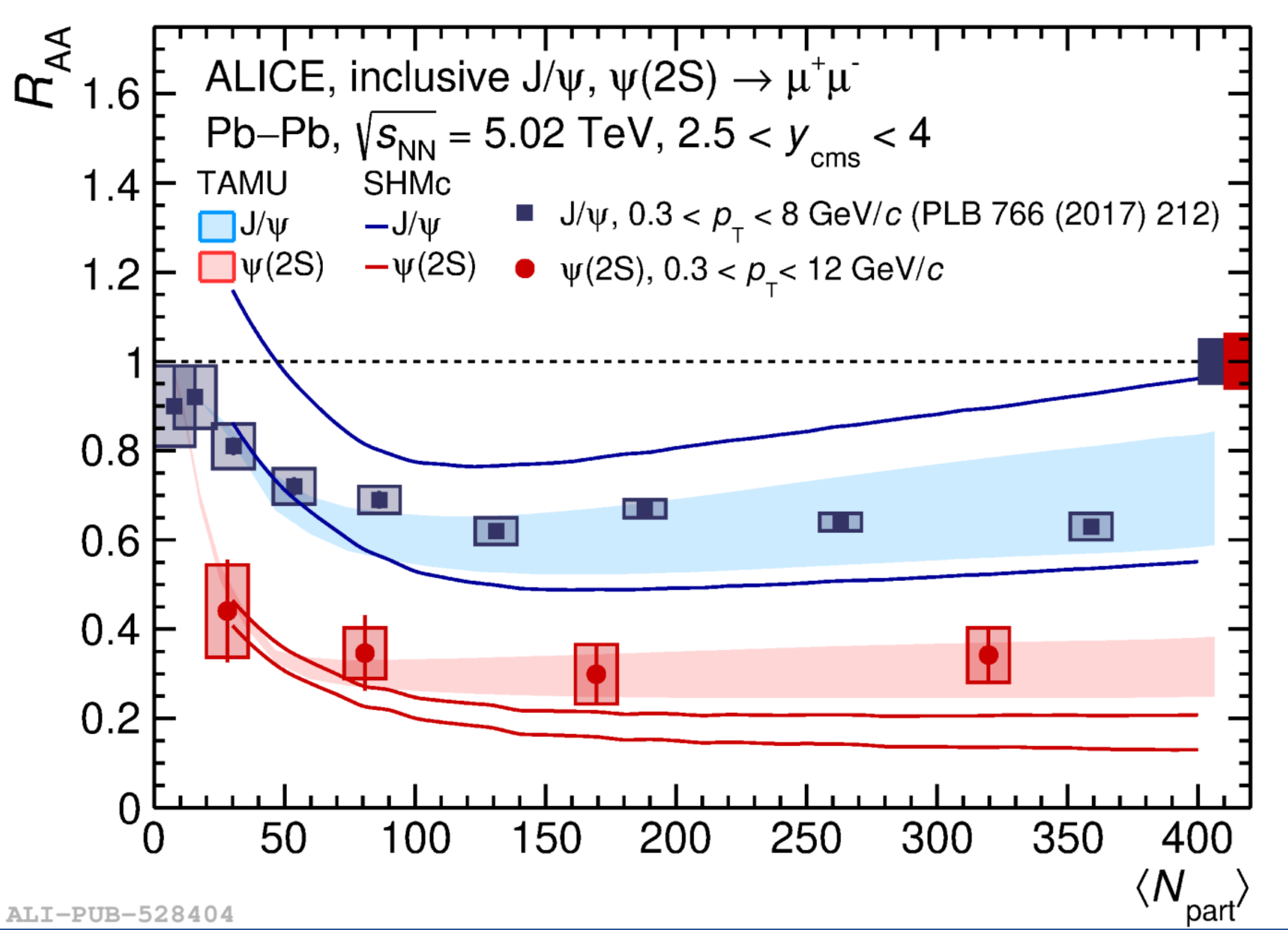


- ❑ Stronger suppression for $\psi(2S)$ compared to J/ψ
- ❑ **Flat centrality dependence of $\psi(2S)$ R_{AA} within uncertainties,** consistent with $R_{AA} \sim 0.3 - 0.4$

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

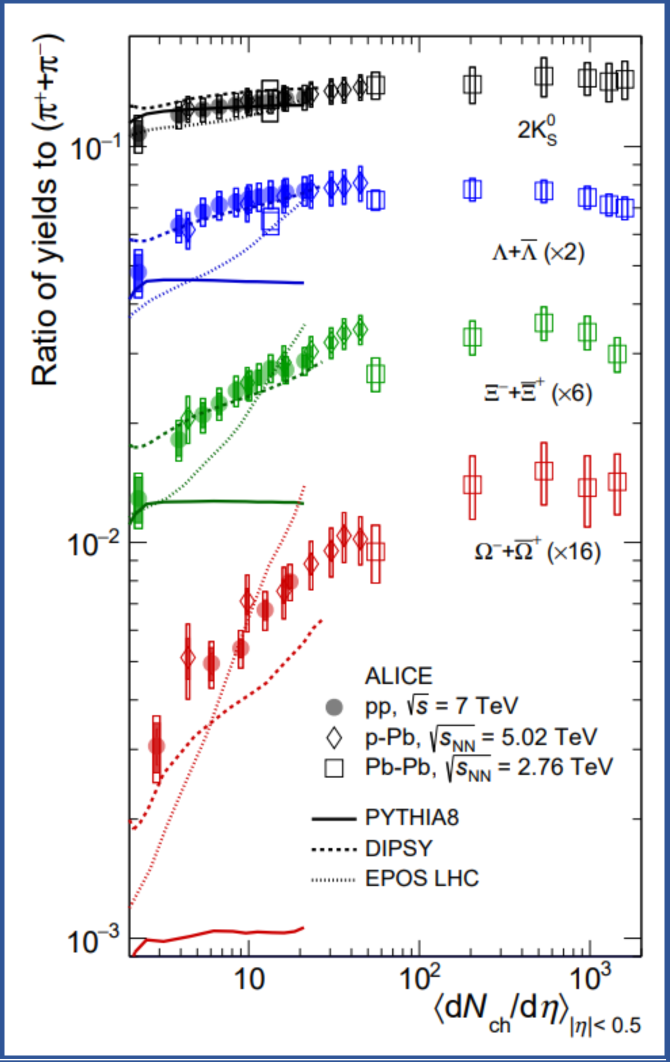


From heavy to small systems

- **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

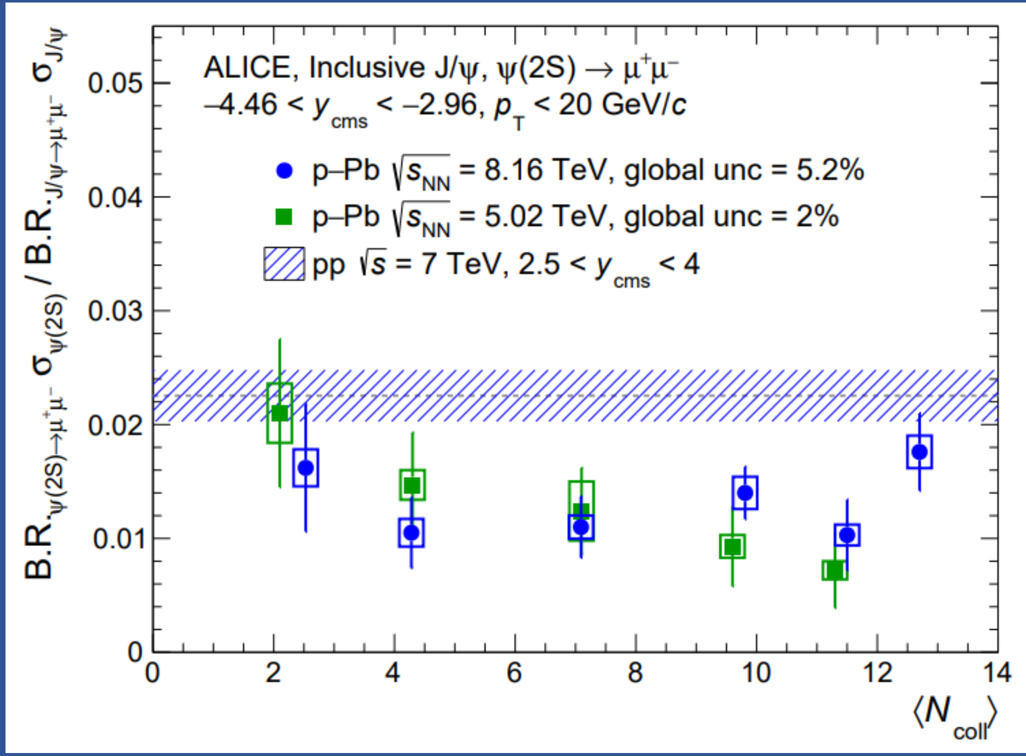


ALICE, Nat. Phys. 13 (2017) 535-539

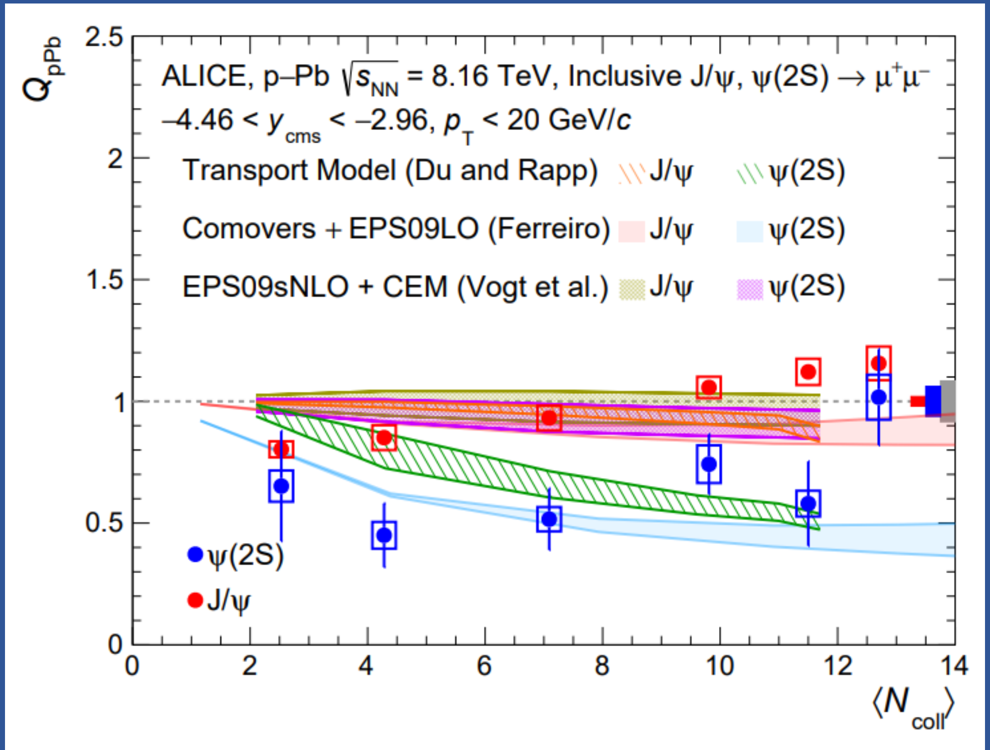
ψ(2S) production in p-Pb collisions

- The ratio between ψ(2S) and J/ψ yields is significantly lower in Pb-Pb compared to pp

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

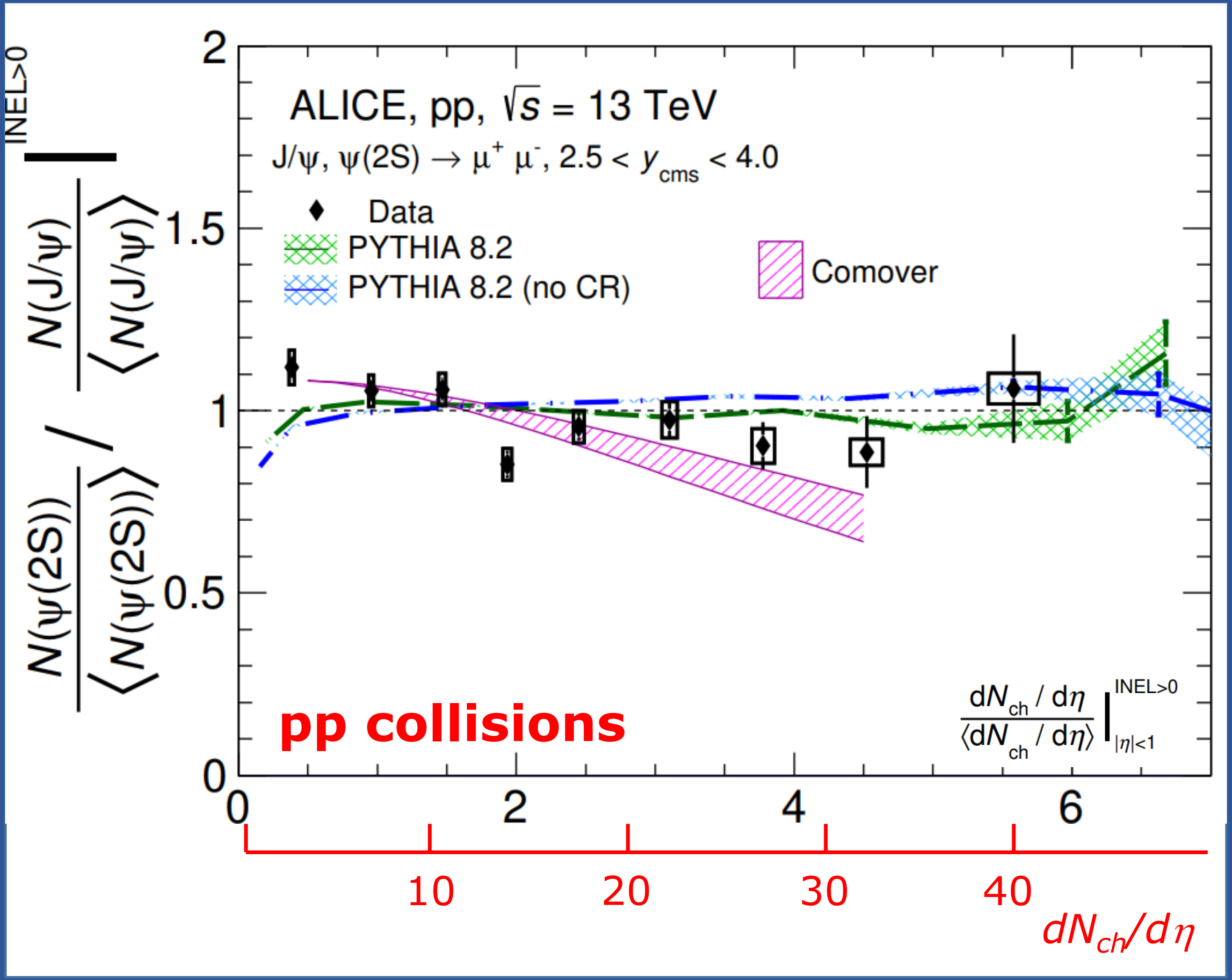


ALICE, JHEP 02 (2021) 002



→ **Evidence for final-state effects** on the ψ(2S) →Transport model includes **short-lived QGP** in p-Pb

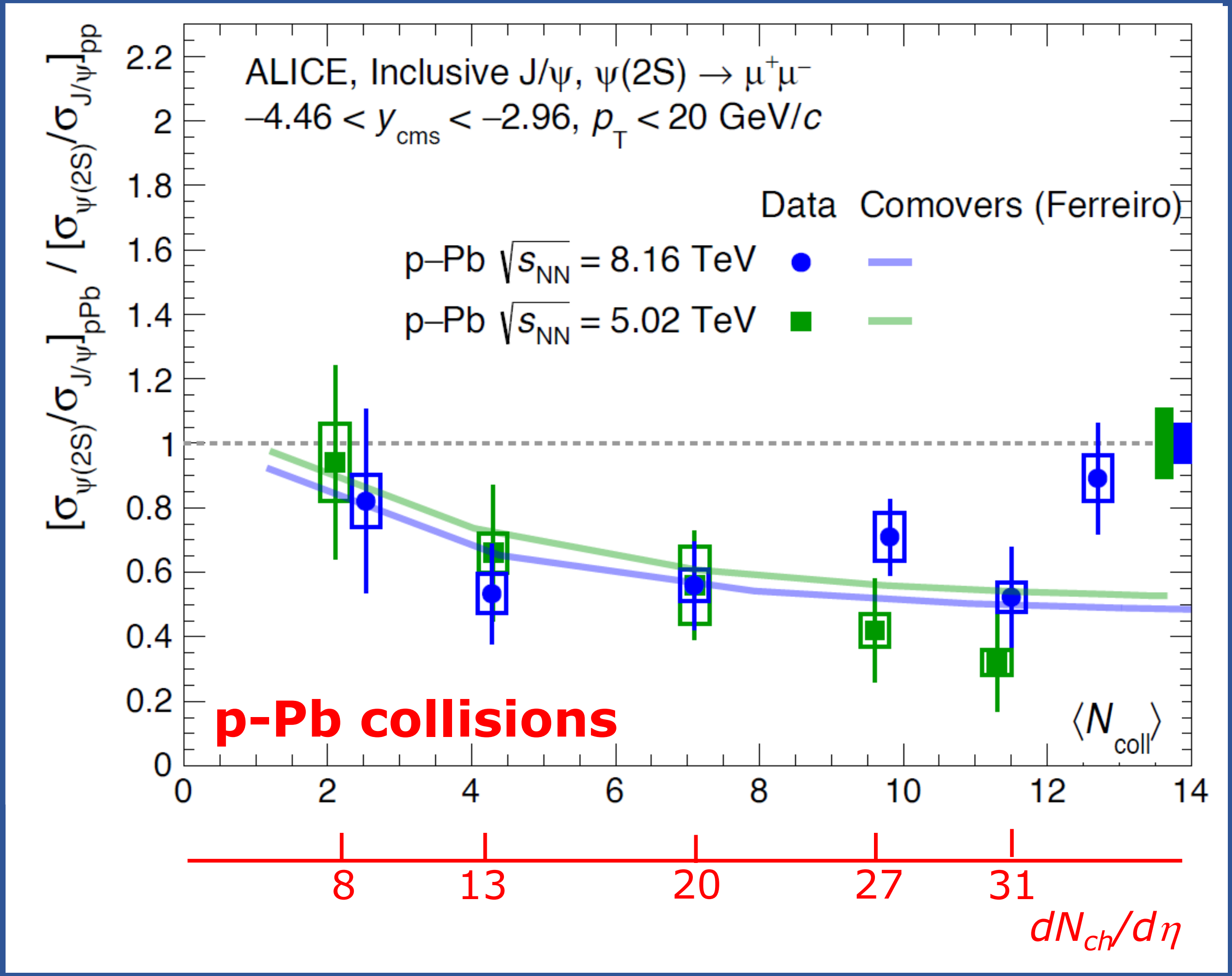
ψ(2S) in high-multiplicity pp collisions



Adapted from ALICE, arXiv:2204.10253

- **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)

ψ(2S) in high-multiplicity pp collisions



Adapted from ALICE, JHEP 02 (2021) 002

- **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 $dN_{ch}/d\eta=35$ ($\langle dN_{ch}/d\eta\rangle^{INEL>0}_{\eta<1} = 7.07^{+0.10}_{-0.08}$)

- 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

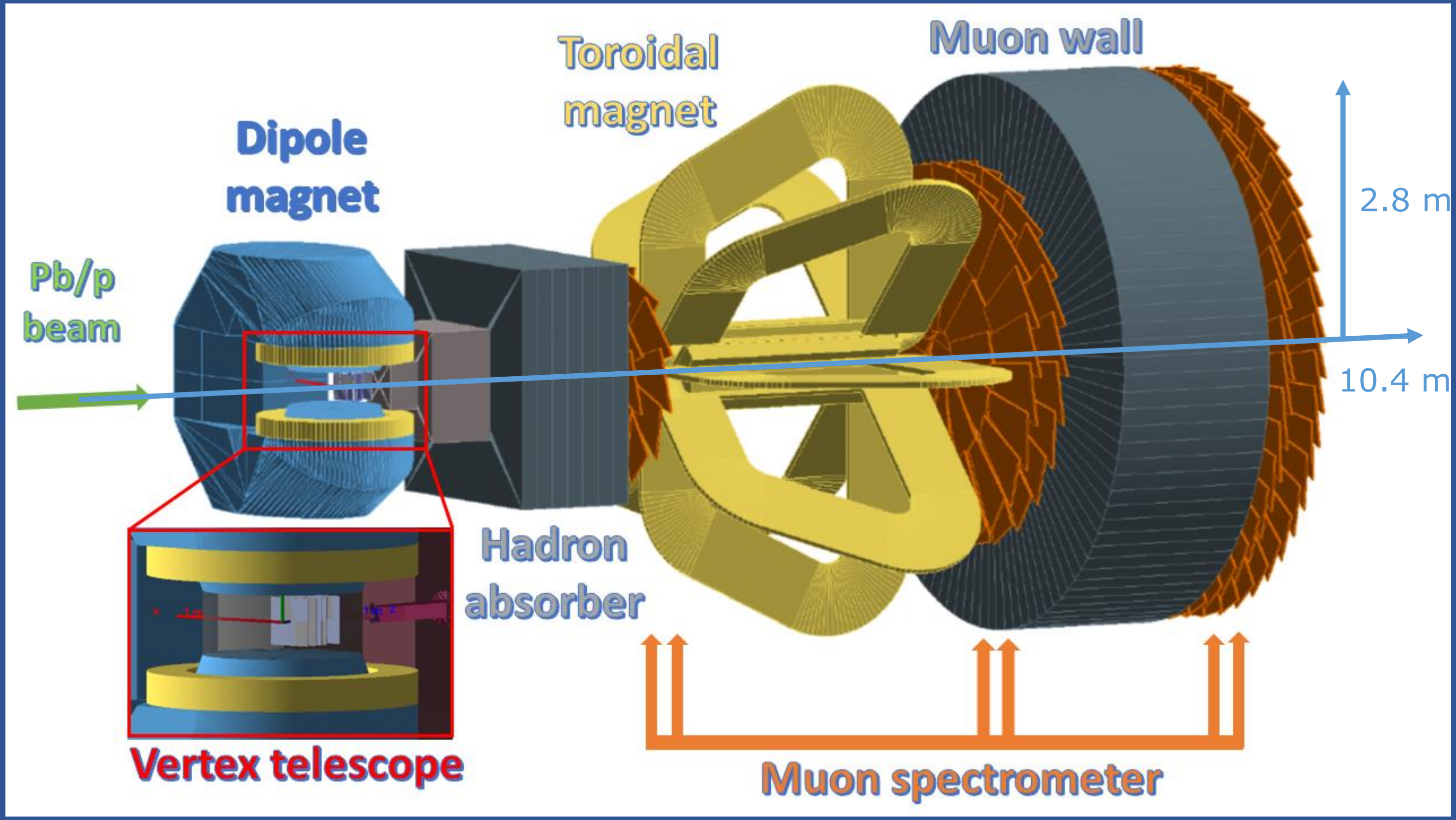
→ **40% decrease in p-Pb** at $\langle N_{coll}\rangle \sim 11.5$, corresponding to $dN_{ch}/d\eta \sim 30$
(from ALICE, EPJC 79 (2019) 307)

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

Future measurements

Fixed-target energies: NA60+

- **NO measurements** exist below top SPS energy ($\sqrt{s_{NN}}$=17 GeV)
- (Is there an) **onset for charmonium suppression** at low energy ?



NA60+ aims at measurements of hard and e.m. probes from $\sqrt{s_{NN}}$= 5 to 17 GeV (energy scan)

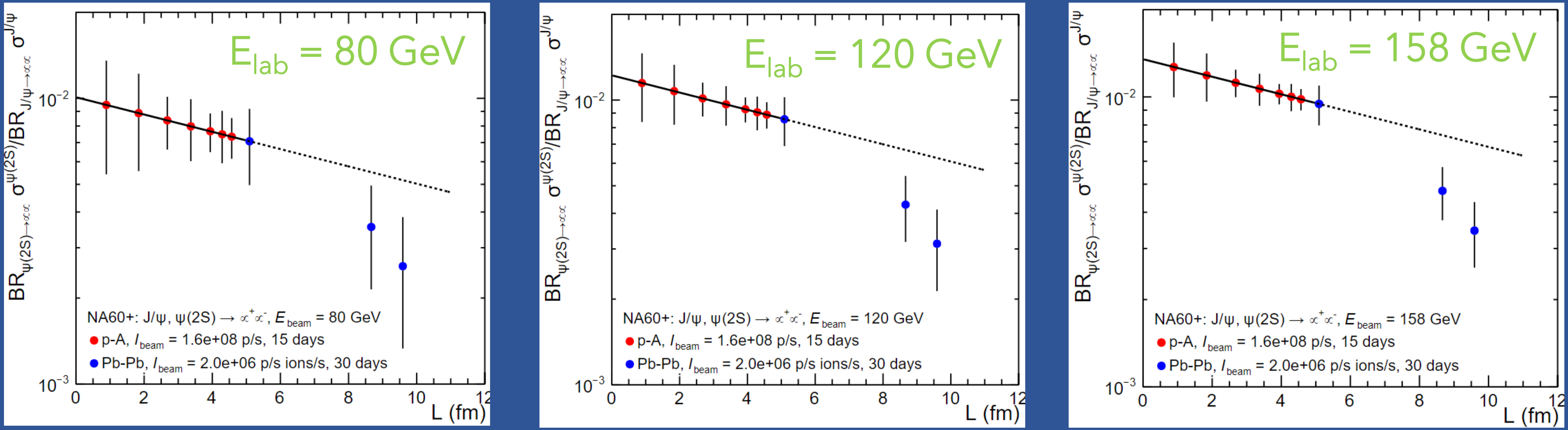
Letter of Intent recently submitted
arxiv:2212.14452

Fixed-target energies: NA60+

Good charmonium resolution (~30 MeV for the J/ψ) will help ψ(2S) measurements

Expectations based on

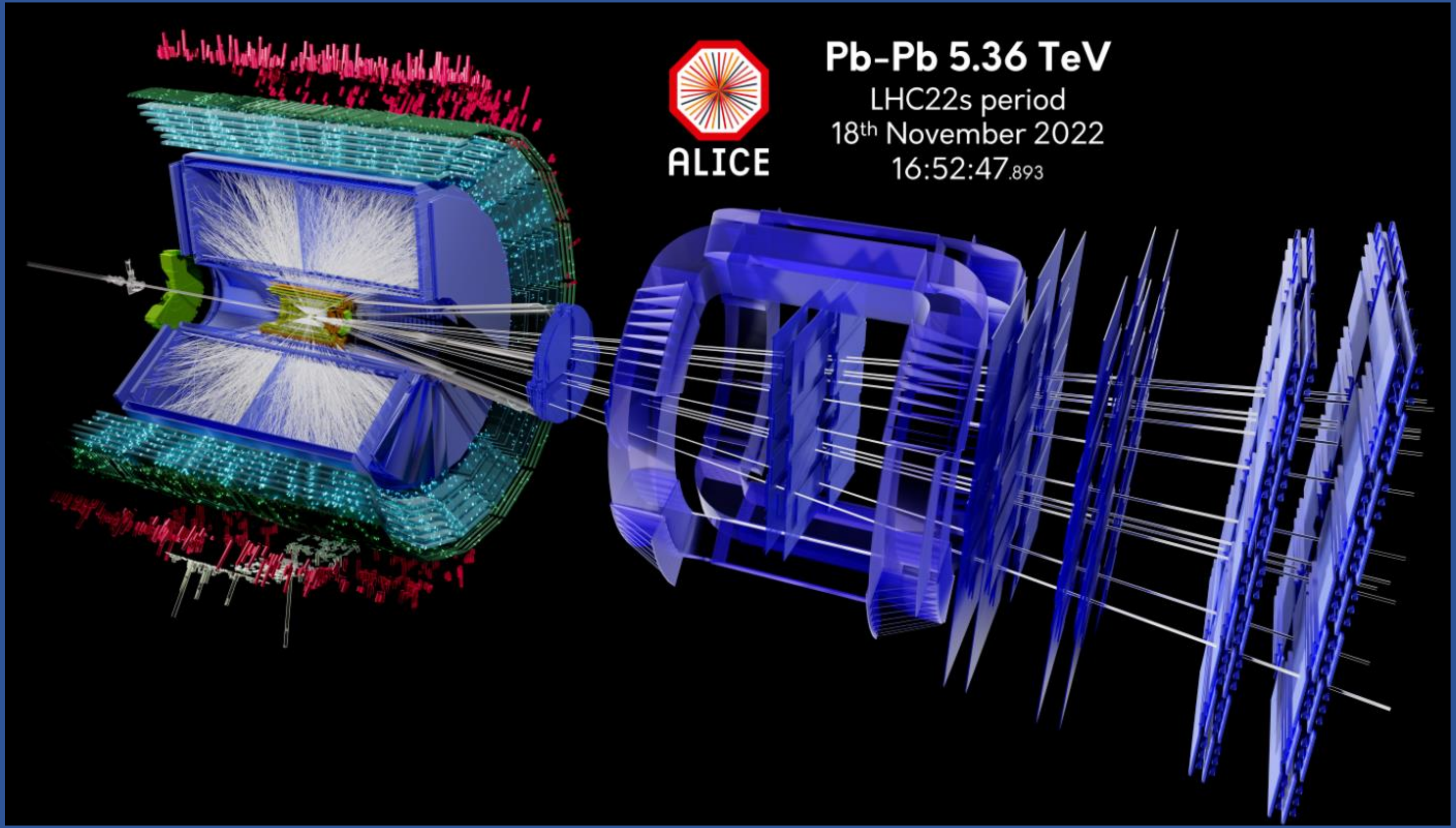
- 30 days PbPb, I_{beam} = 1e7 ions/spill (assuming stronger suppression for ψ(2S) than J/ψ)
- 15 days pA, I_{beam} = 8e8 p/spill



- ❑ **ψ(2S)/ψ measurement looks feasible down to E_{lab} = 120 GeV**
- ❑ Lower E_{lab} would require larger beam intensites/longer running times

Prospects for ALICE future measurements

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

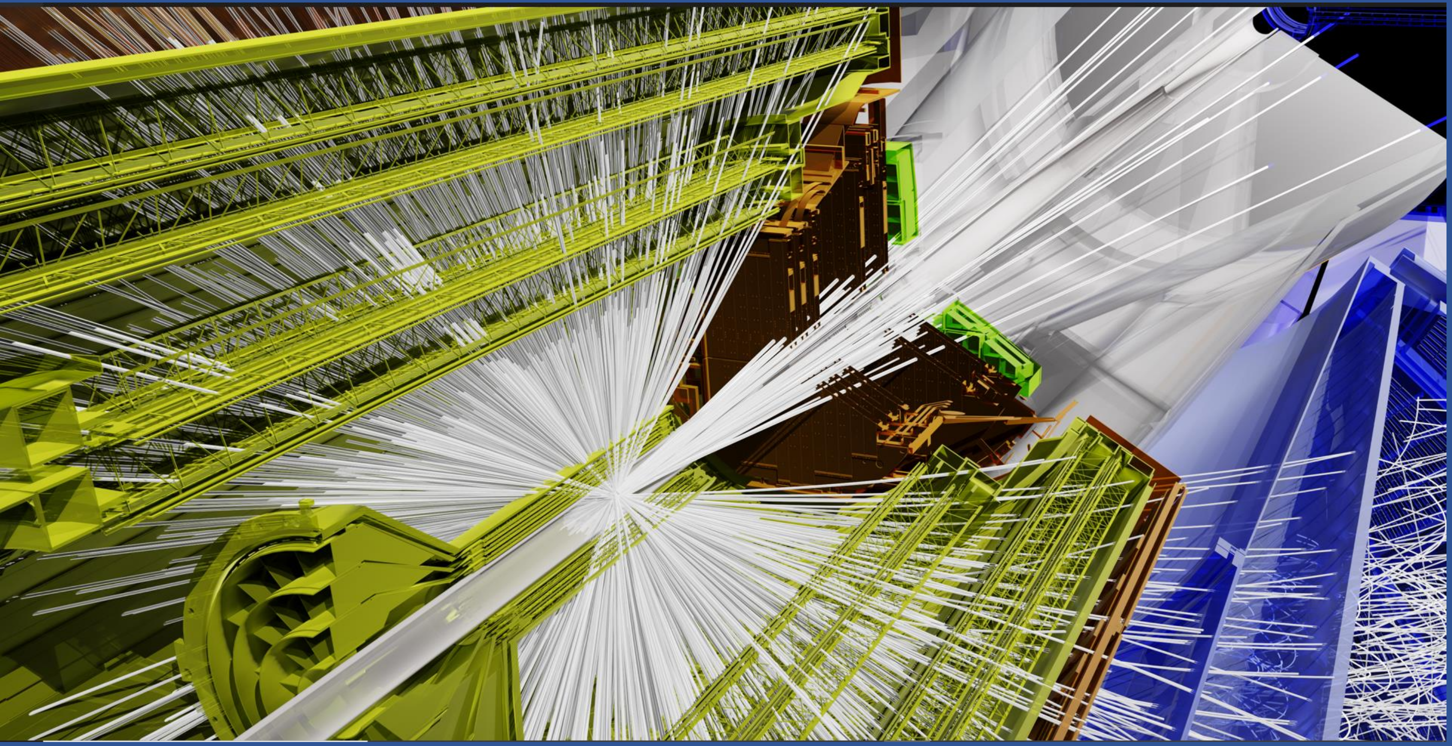


- Excellent opportunities for Run 3
- Target Pb-Pb integrated luminosity (Run 3 + 4) → L_{int} ~ 13 nb^{-1}
- Improved tracking precision by a factor 3 (6) in xy (z) direction at midrapidity (new **Inner Tracker**)

Prospects for future measurements

- ❑ Many ψ(2S) results are still statistically limited after Run 2

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***

Conclusions

- Heavy quarkonium → among the most interesting tools for QGP studies

- After early discoveries at SPS energy (anomalous J/ψ suppression), RHIC and LHC have validated a picture where **competing suppression and regeneration** effects can describe the data

- Excited quarkonium states represent a further important tool (due to their different radius and binding energies)

- Strong(er) **suppression of ψ(2S)** at fixed-target energy (NA50)

- ALICE results show for the first time an indication of **ψ(2S) regeneration**

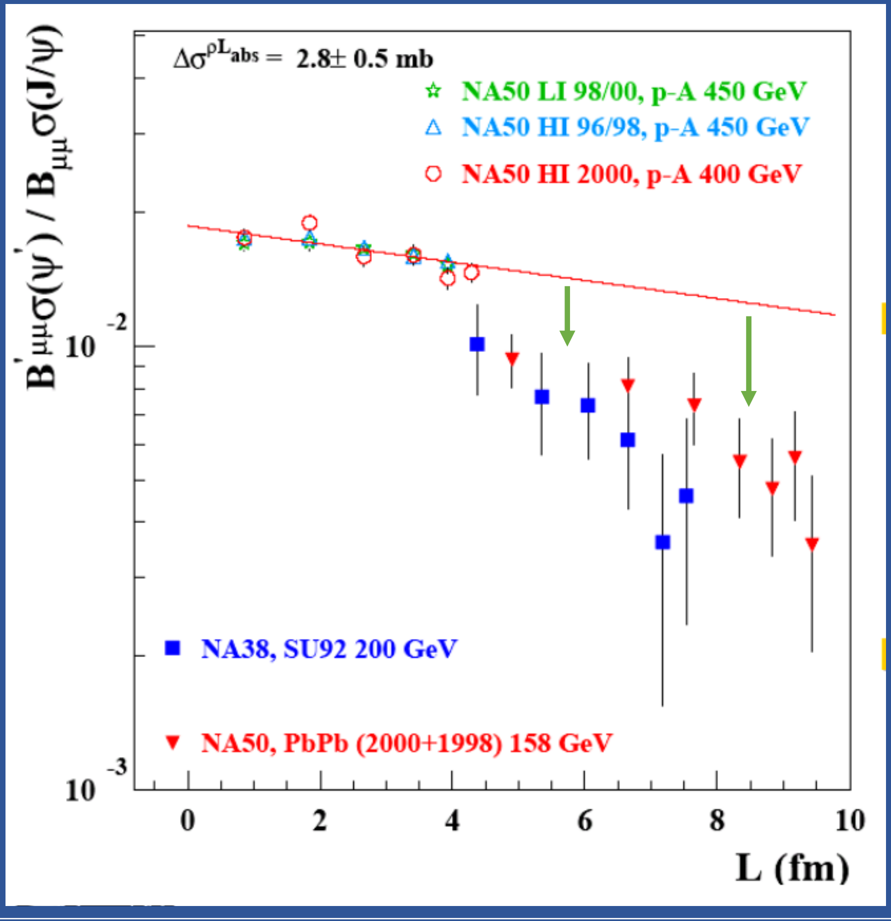
- Next frontiers
  - Fixed-target → Go to **low SPS energy**, looking for onset of suppression
  - Collider → Dramatically increase available statistics, to allow **precision studies**

Backup

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



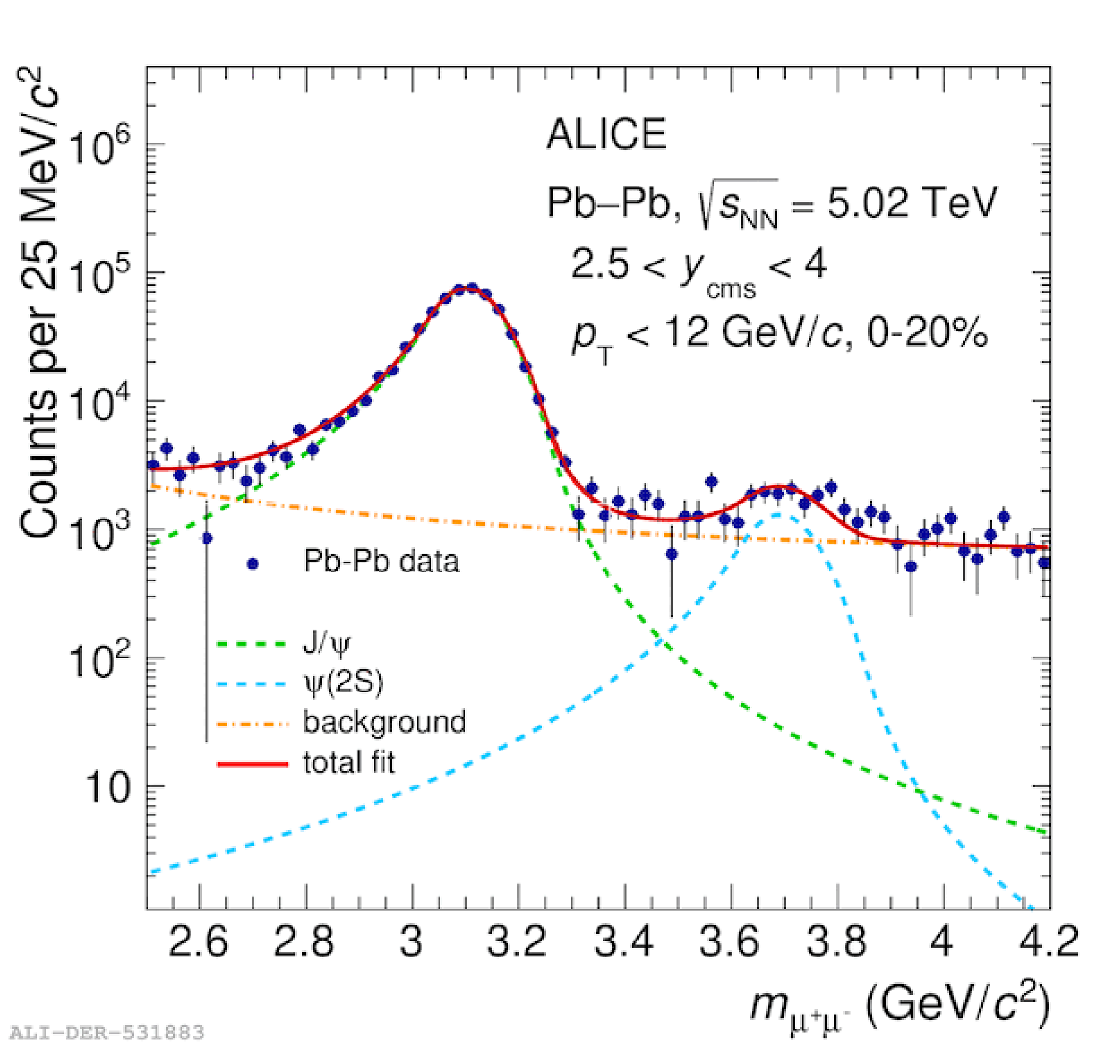
- **Stronger relative dissociation of ψ(2S) wrt J/ψ** already in p-A collisions

- 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

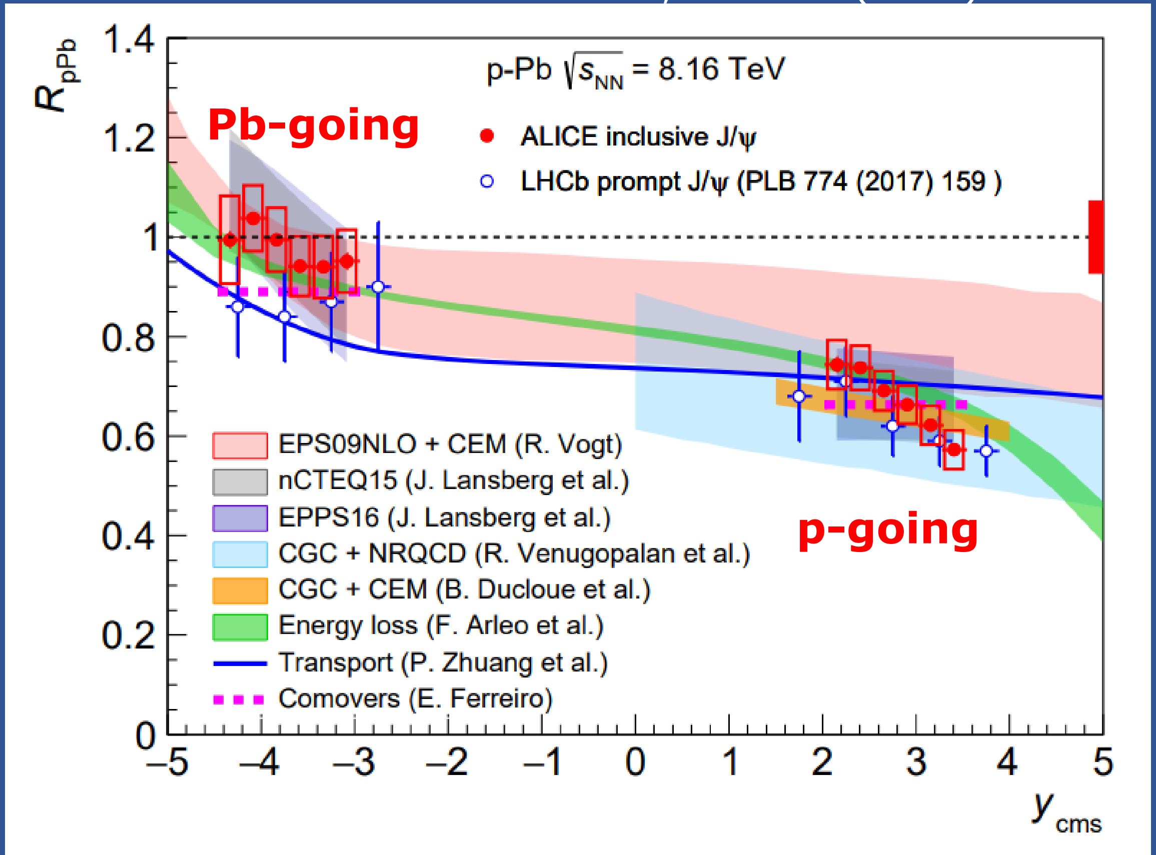
ψ(2S) signal extraction in Pb-Pb

- 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

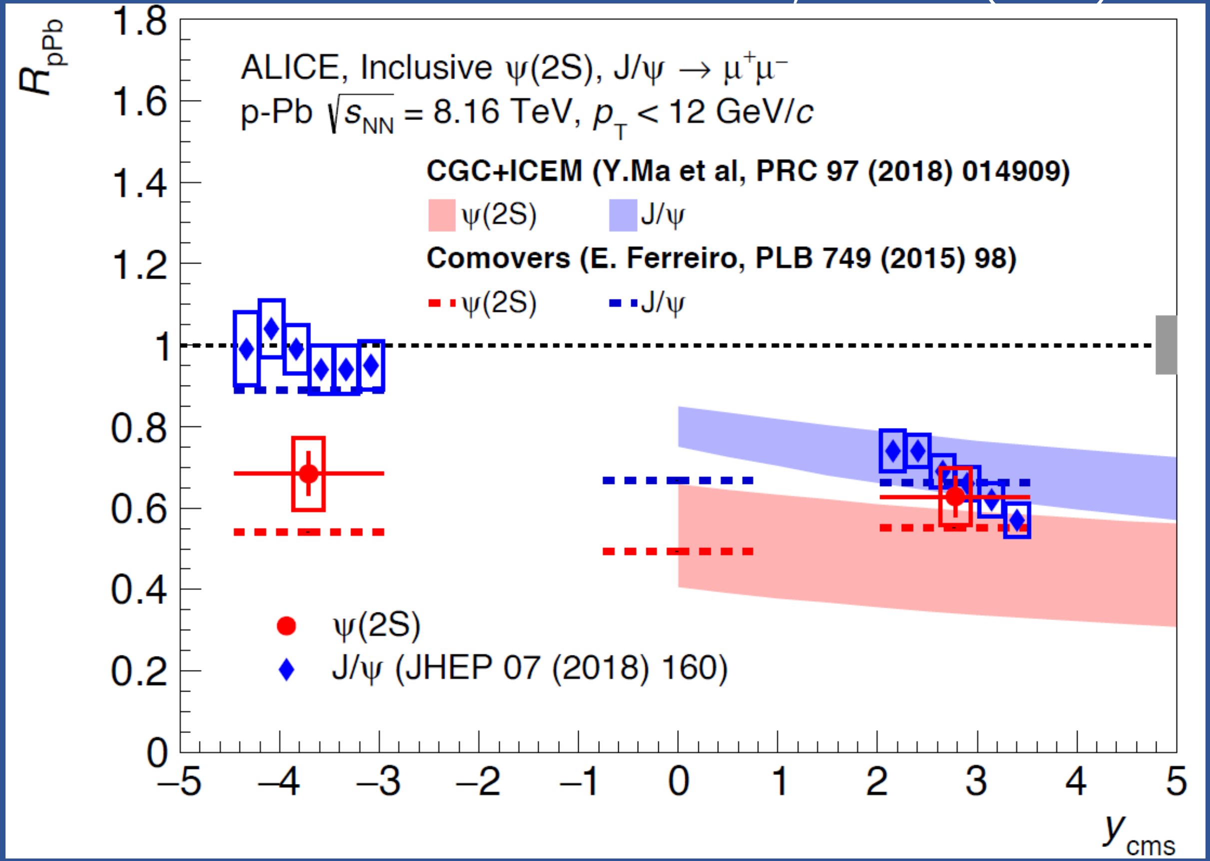


ψ(2S) production in p-Pb collisions

ALICE, JHEP 07 (2018) 160



ALICE, JHEP 07 (2020) 237

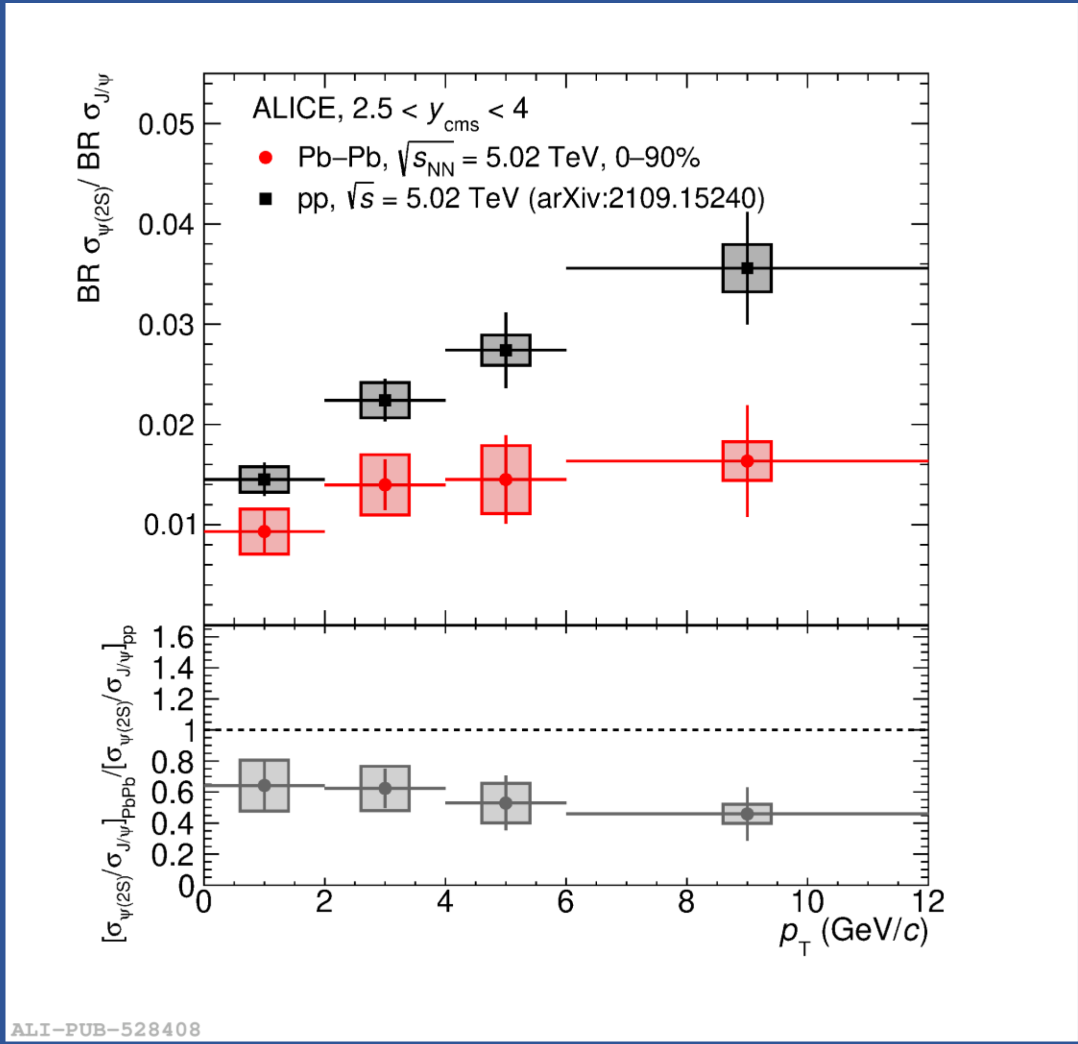


- **J/ψ R_{pPb}** compatible with effects of **nuclear shadowing** (initial state)

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

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

p_T dependence of the inclusive cross section ratios



N.B.: not corrected for branching ratios

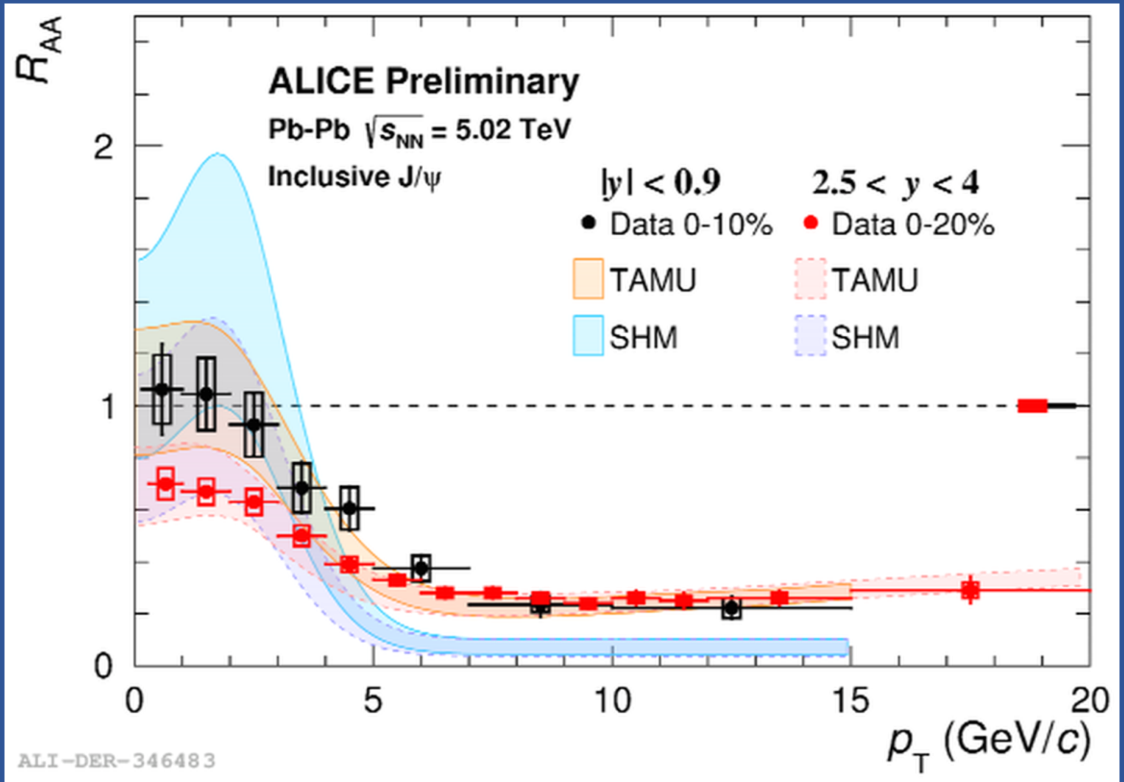
Ratio $\dfrac{BR_{\psi(2S)\rightarrow\mu\mu}\,\sigma_{\psi(2S)}}{BR_{J/\psi\rightarrow\mu\mu}\sigma_{J/\psi}}$

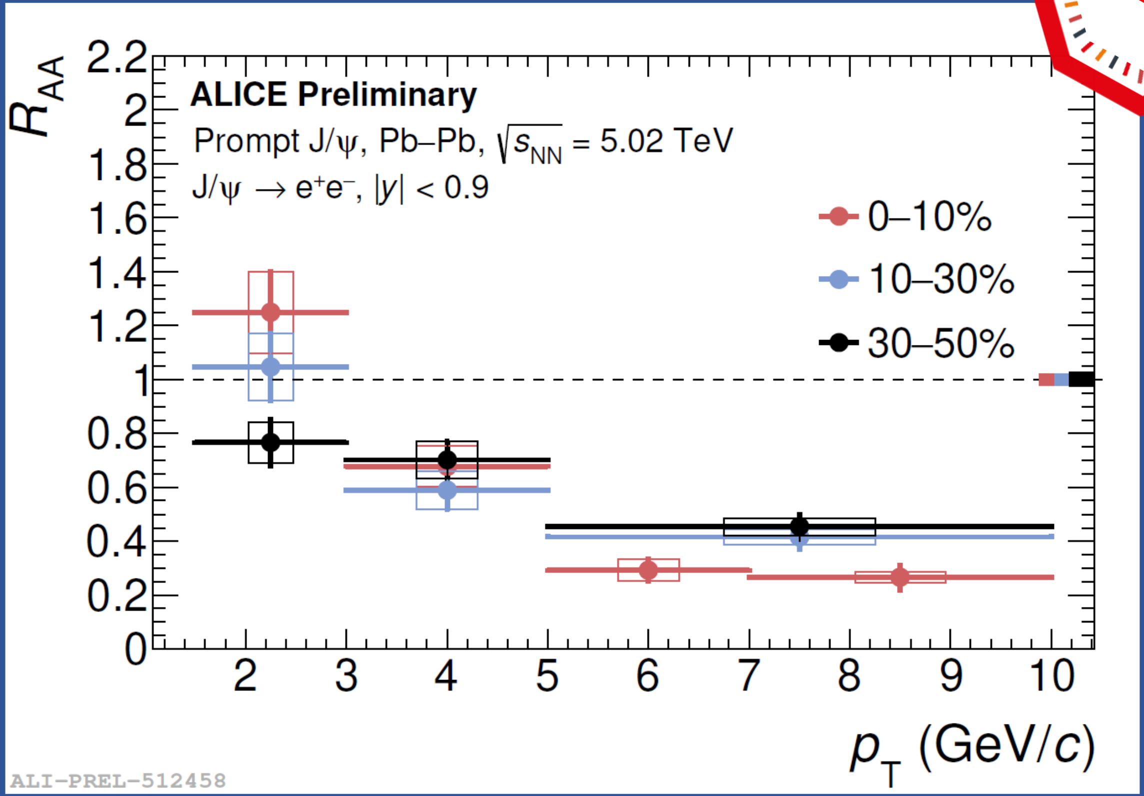
Double ratio $\dfrac{\left[\dfrac{\sigma_{\psi(2S)}}{\sigma_{J/\Psi}}\right]_{Pb-Pb}}{\left[\dfrac{\sigma_{\psi(2S)}}{\sigma_{J/\Psi}}\right]_{pp}}$

- **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

Inclusive and prompt J/ψ production in Pb-Pb



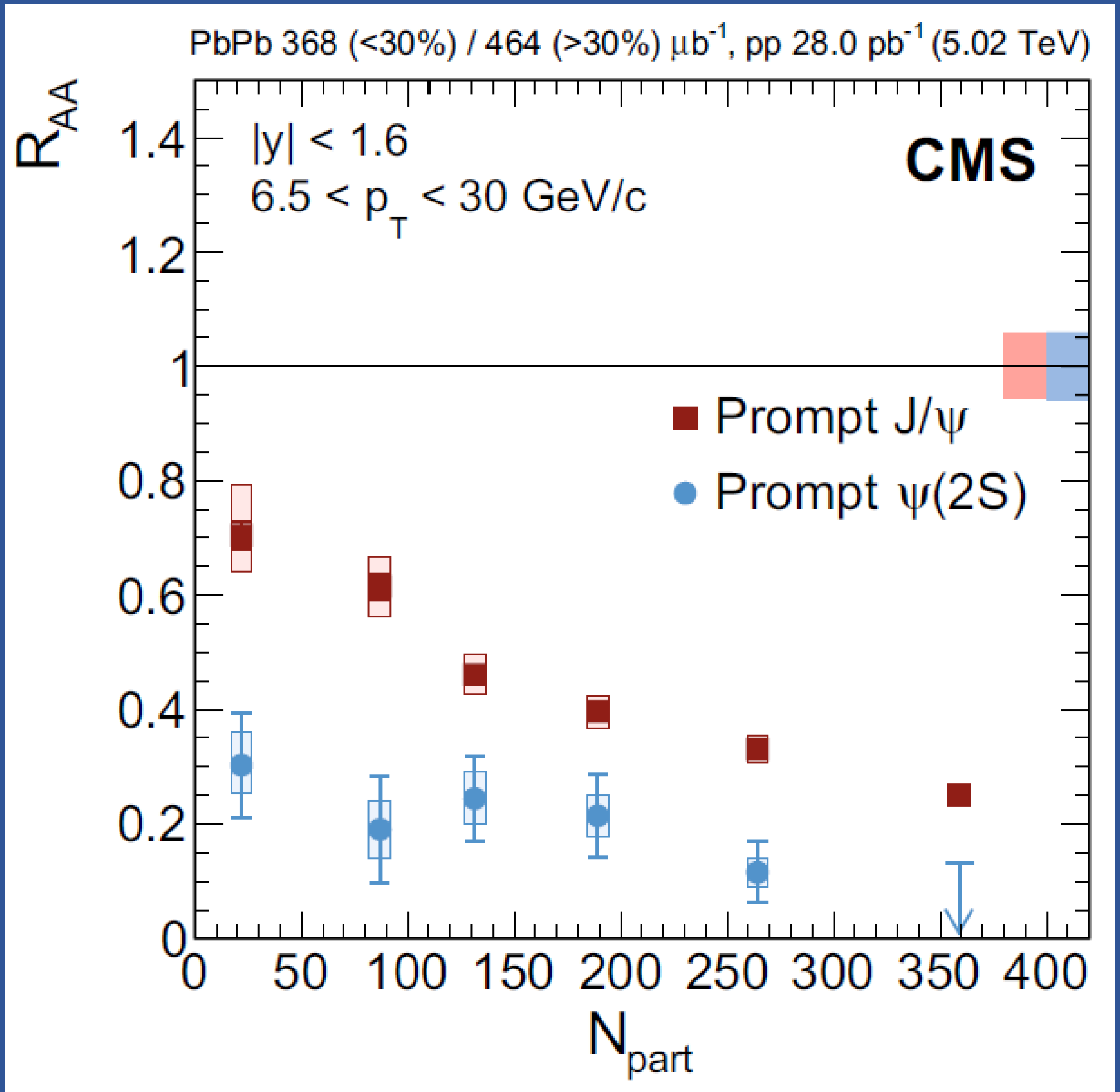


- ❑ Rise of inclusive J/ψ R_{AA} at low p_T, stronger effect at y=0 → decisive signature of recombination
- ❑ Models include regeneration either at the freeze-out (SHMc) or during the medium evolution (TAMU)
  → Both in agreement with data at low p_T

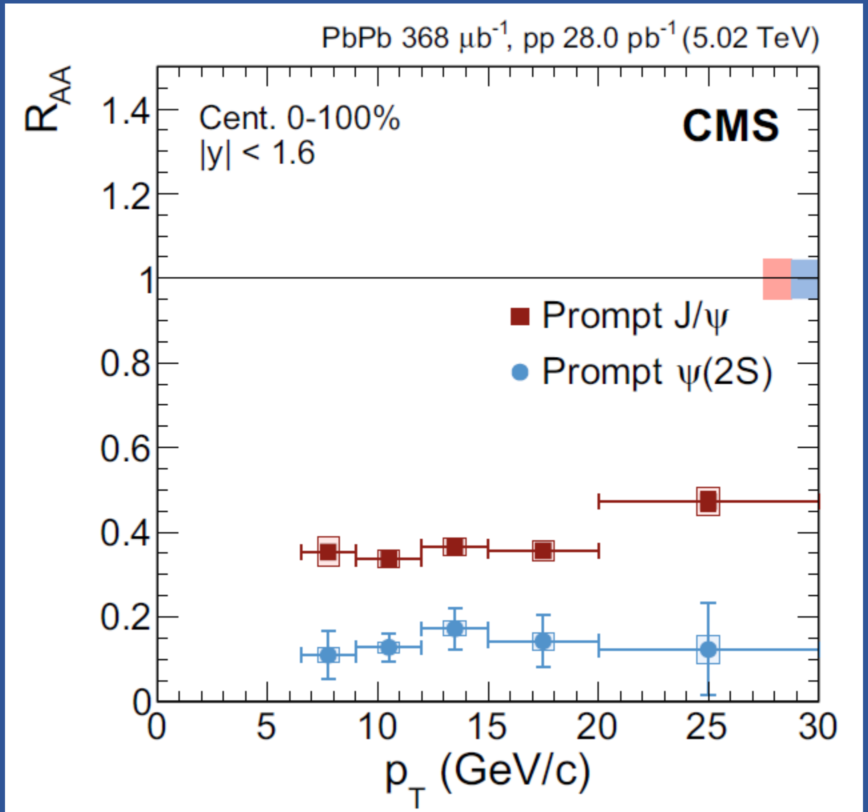
- ❑ Effect confirmed when looking at prompt J/ψ production at midrapidity, clear centrality dependence

Pb-Pb results at LHC energy, high p_T

CMS, EPJC 78 (2018) 509

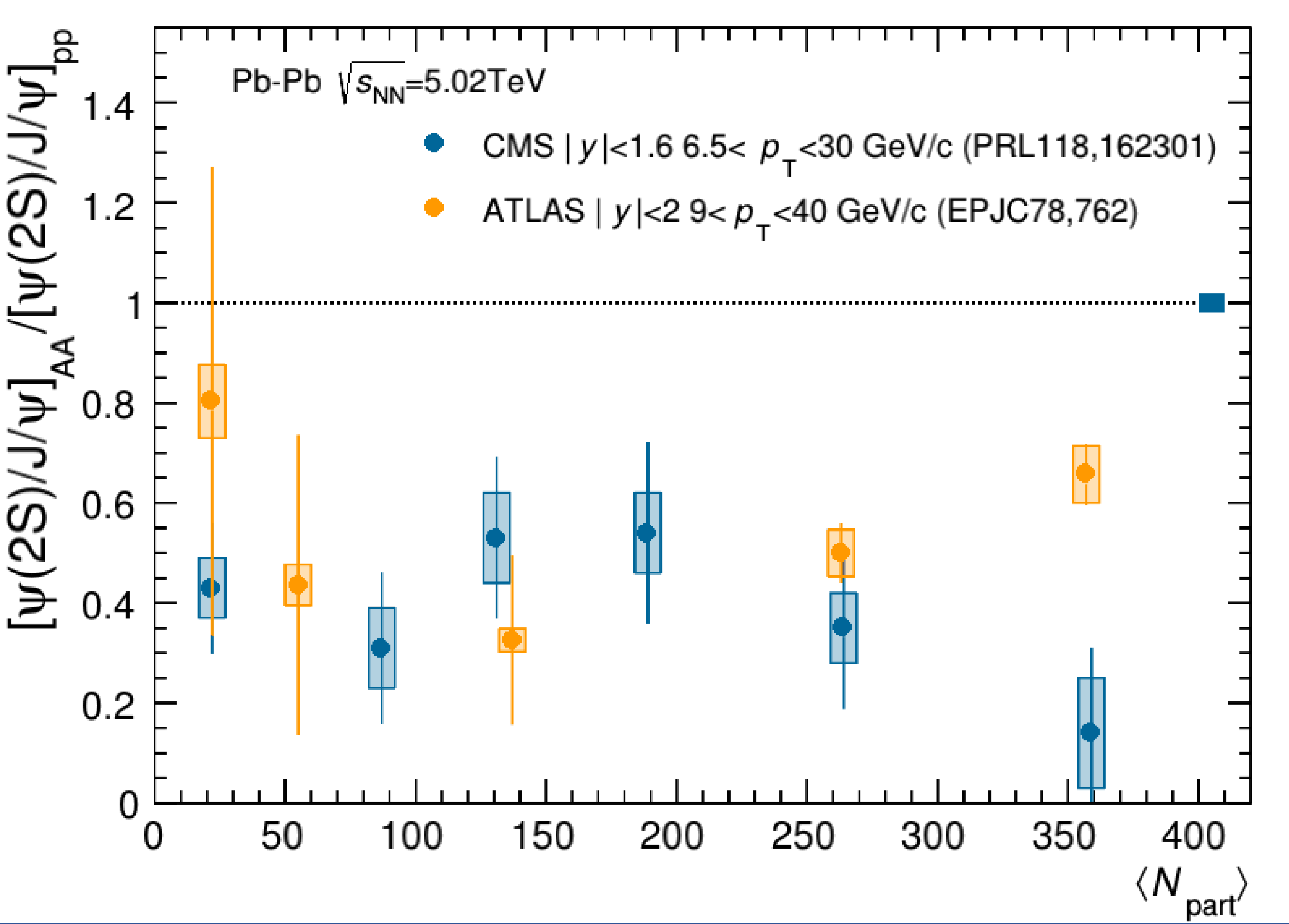


- Strong ψ(2S) suppression, larger than the J/ψ one (factor ~2), observed by **CMS**



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

Pb-Pb results at LHC energy, high p_T

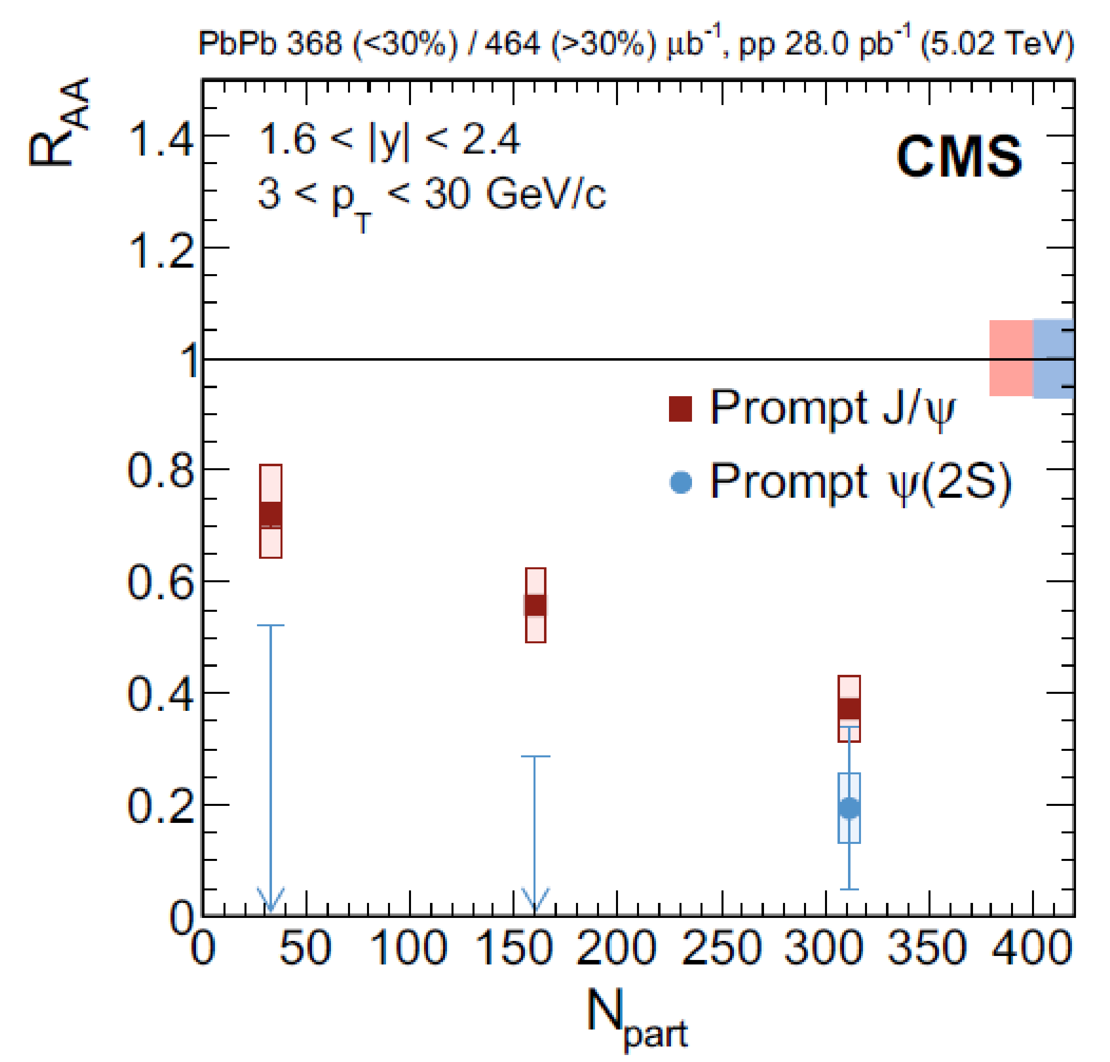


- ❑ Strong prompt ψ(2S) suppression also observed by **ATLAS**
- ❑ Slightly different kinematic coverage, but apparent tension in central events between ATLAS and CMS

Pb-Pb results at LHC energy, intermediate p_T

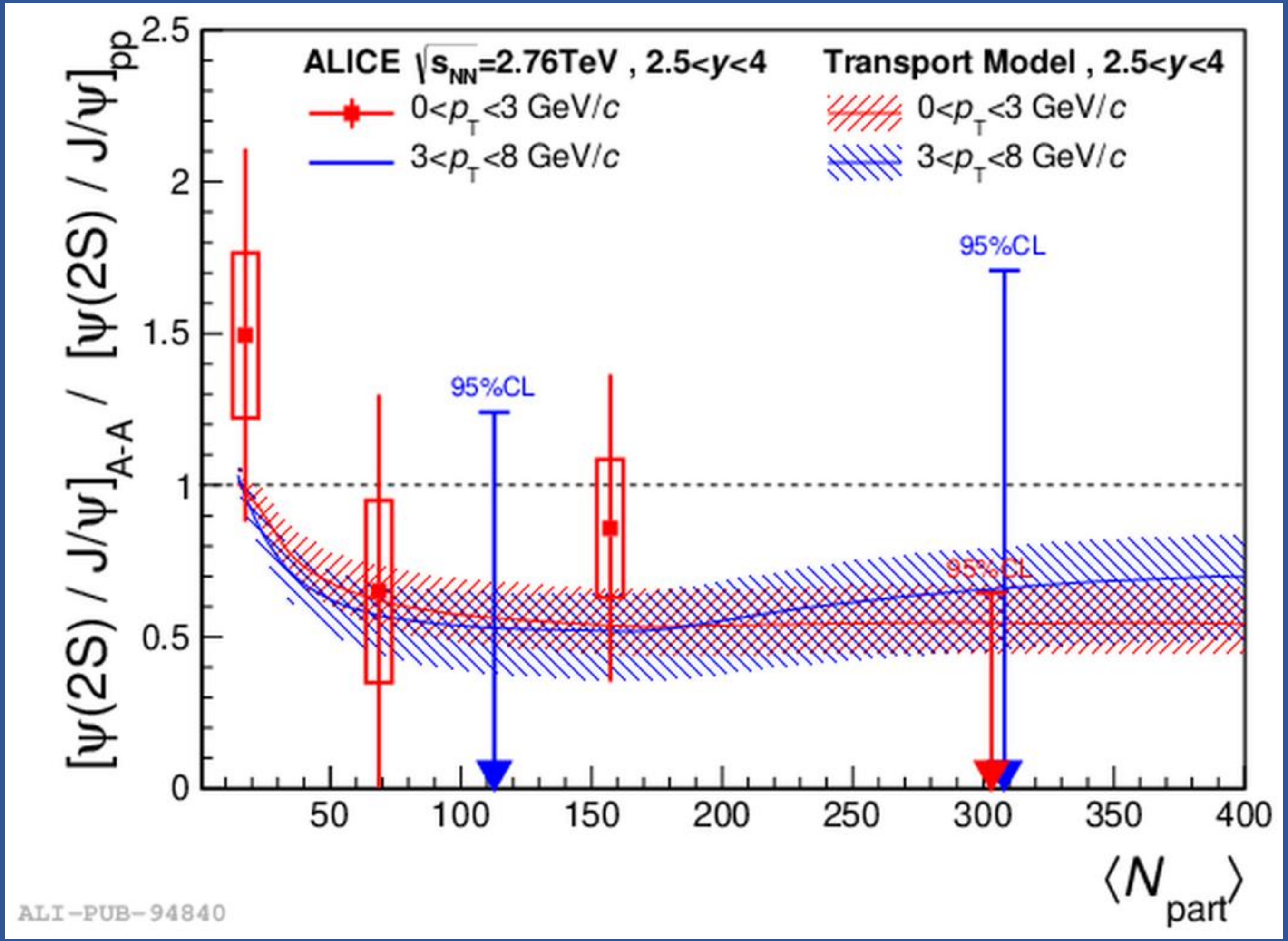
- Extending the ψ(2S) study towards lower p_T ($3<p_T<30$ GeV/c), **recombination effects** might become sizeable

- 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

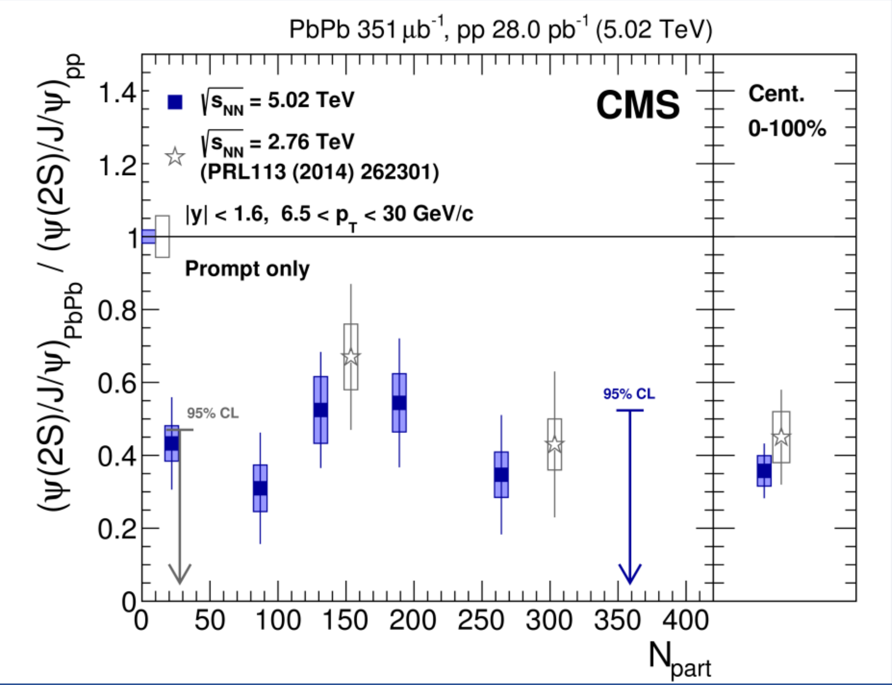
  → Run 1 L_{int} ~ 70 μb^{-1}

- ❑ 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

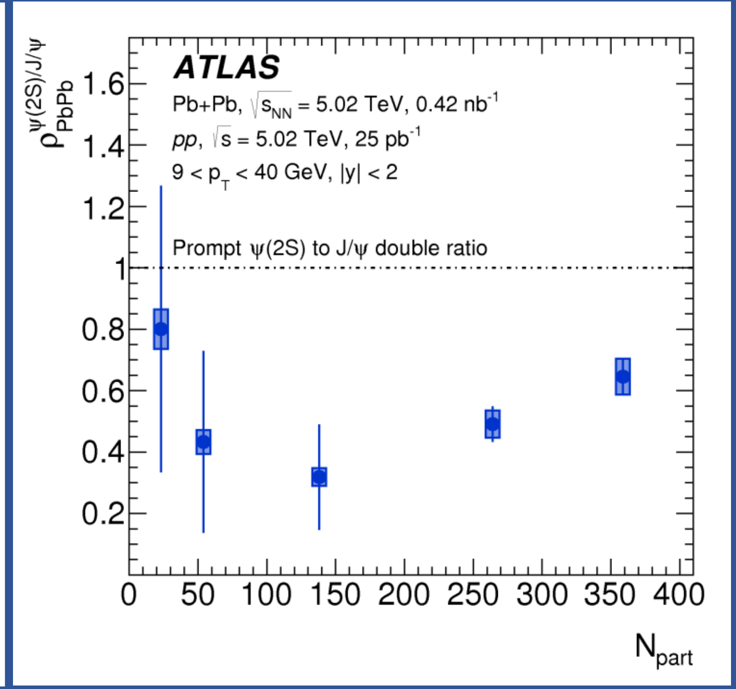
ALICE, JHEP 05 (2016) 179

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

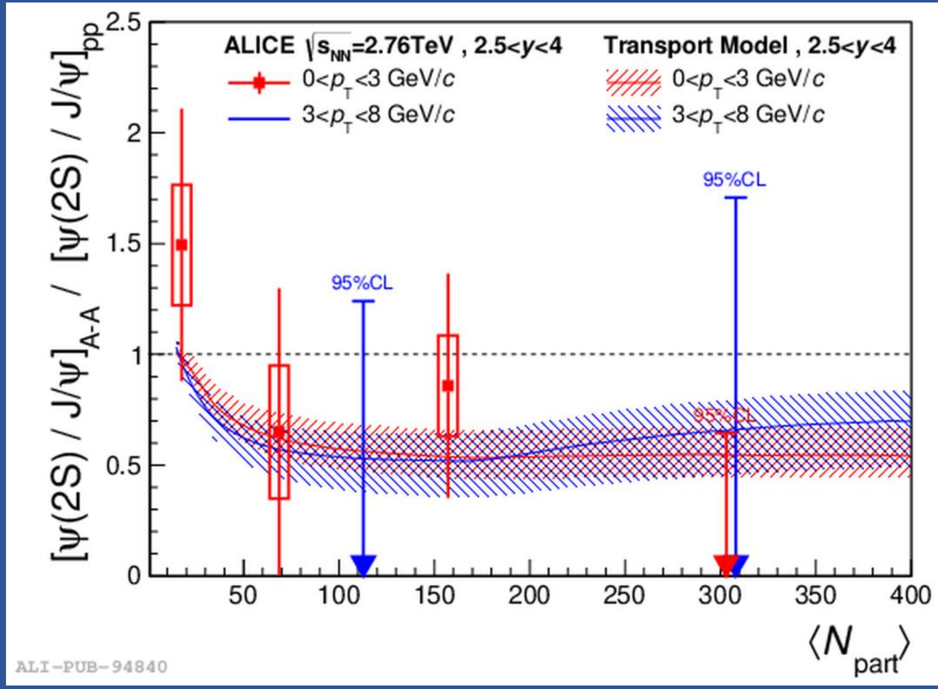
Pb-Pb results at LHC energies



CMS, PRL 118 (2017) 162301

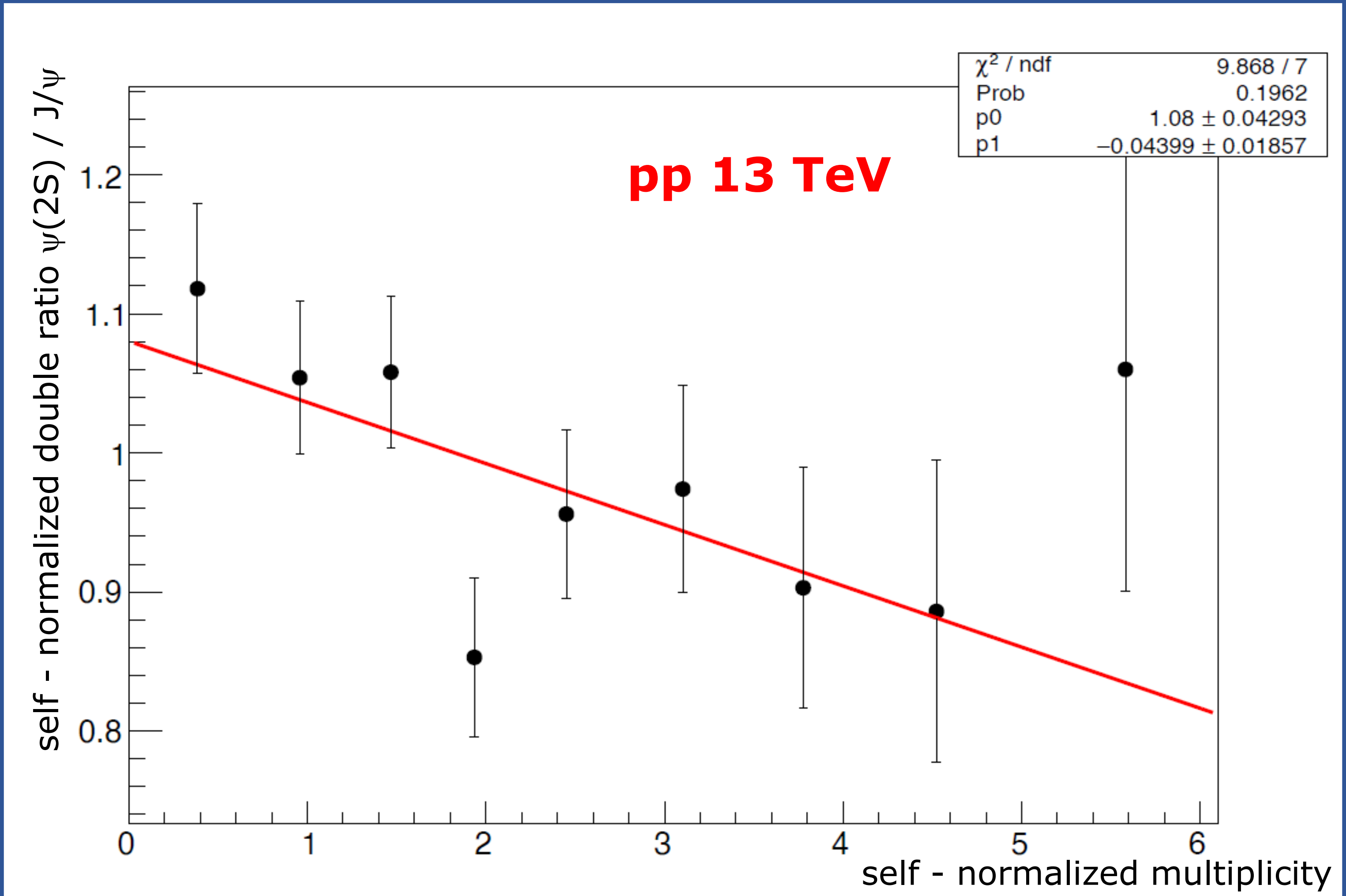


ATLAS, EPJC78 (2018) 762

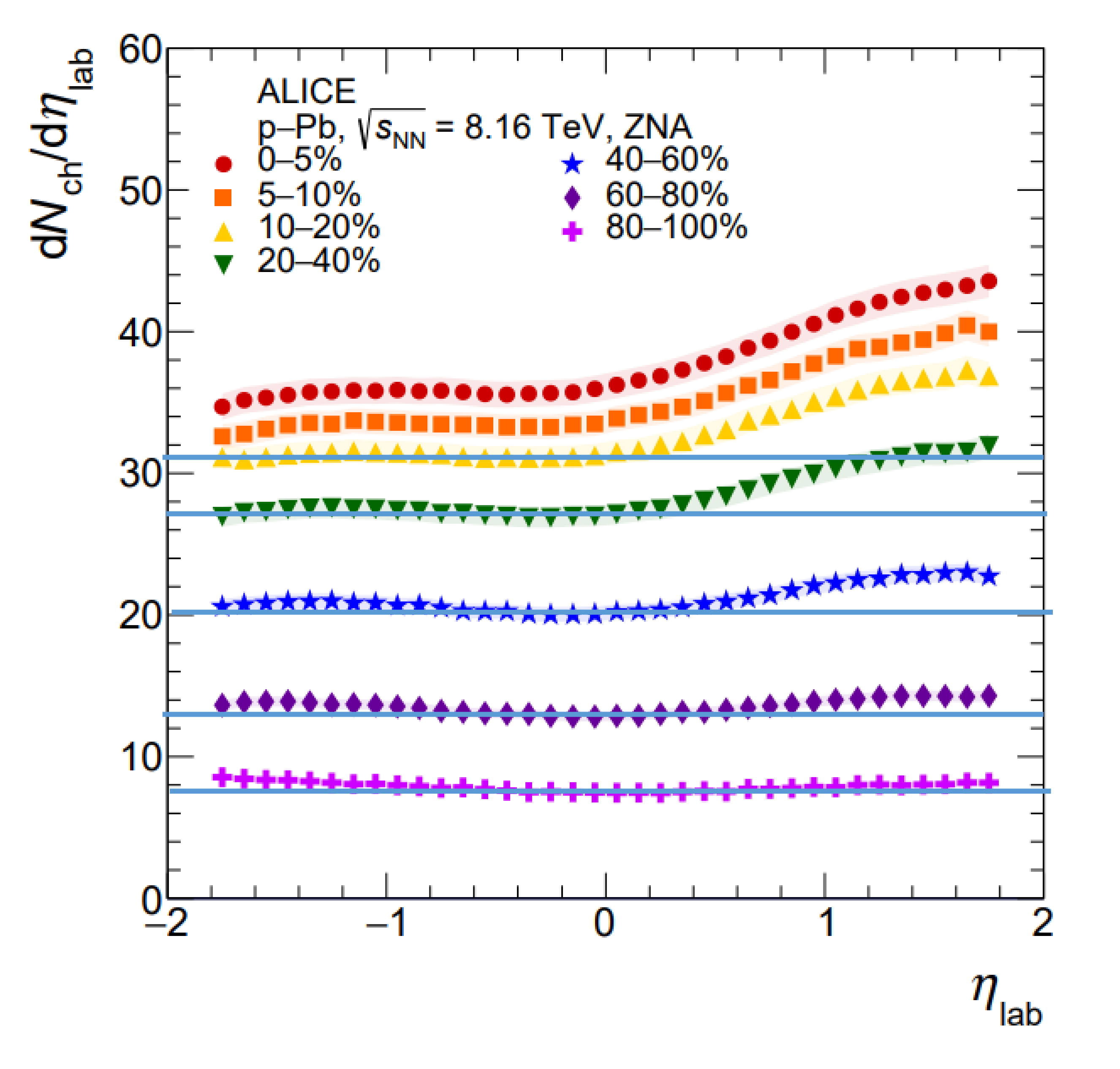


ALICE, JHEP 05 (2016) 179

- ❑ 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
0.8
0.9
1
1.1
1.2
0
1
2
3
4
5
6


ALICE
p–Pb, $\sqrt{s_{NN}}$ = 8.16 TeV, ZNA
0–5%
5–10%
10–20%
20–40%
40–60%
60–80%
80–100%
$dN_{ch}/d\eta_{lab}$
η_{lab}
60
50
40
30
20
10
0
–2
–1
0
1
2