$\Psi(2S)$ production in Pb-Pb collisions measured by ALICE at the LHC

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on behalf of the ALICE collaboration

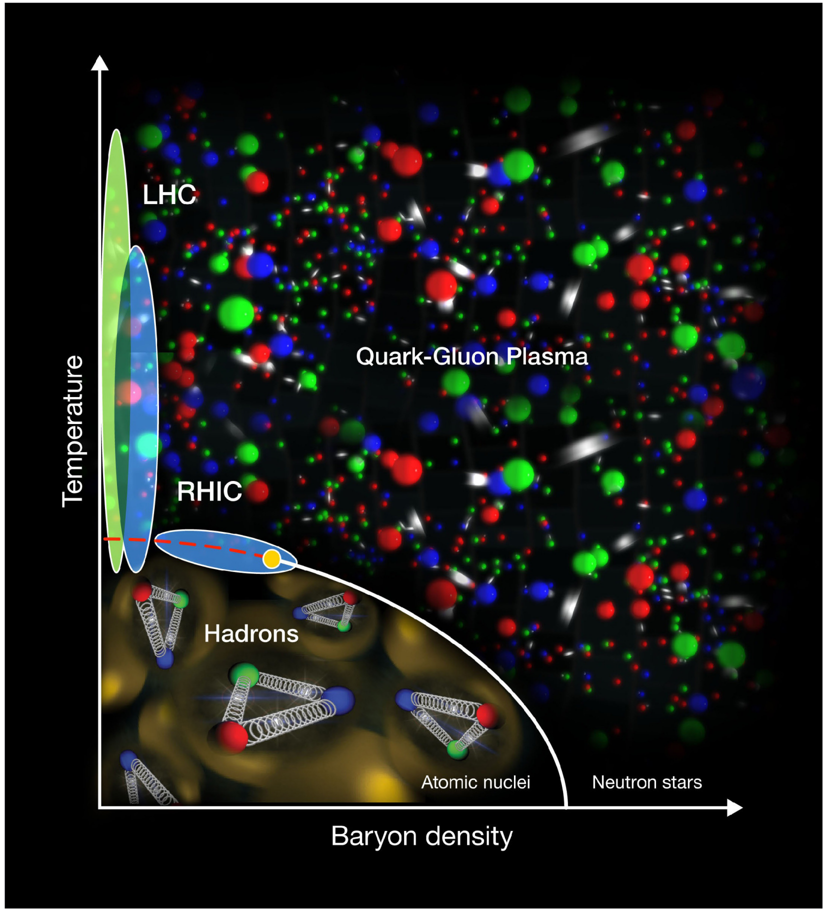
Introduction – The QGP

- Quark-gluon plasma (QGP) is a state of matter predicted by QCD where quark and gluons are deconfined

- Transition temperature :
  $T_C \approx 157$ MeV with zero net baryonic number
  (Bazavov et al. *Phys. Lett. B 795 (2019) 15–21*)

- It is the state of matter at the early stages of the universe

- It is possible to recreate the QGP by doing relativistic heavy-ion collisions, but only during a short period of time (≈10 fm/*c* at LHC) and in a very small volume (≈ 5.10^3 fm^3 per unity of rapidity at LHC)
  (ALICE, *Phys.Lett. B696 (2011) 328-337*)



Introduction - Charmonia

- Charmonia (J/ψ, ψ(2S),…) are bound states of a $c - \bar{c}$ pair
- Because of the large mass of charm quarks, they are produced in hard collisions, face all the medium evolution and are affected by it
  ➔Measurement of charmonium production can provide information on the QGP properties
- Theory predicts that charmonia are dissociated in a QGP because of the colour screening and dynamical dissociation
  ➔quarkonium suppression
  ([Matsui & Satz, *Phys. Lett. B 178 (1986) 416*](); [Rothkopf, *Phys. Rept. 858 (2020) 1-117*]())
- If there are enough charm-anticharm pairs, and if thermalized in QGP or at hadronisation
  ➔quarkonium (re)combination
  ([Braun-Munzinger & Stachel, *Phys. Lett. B 490 (2000) 196*](); [Thews, Schroedter, & Rafelski Phys. Rev. C 63 (2001) 054905]())

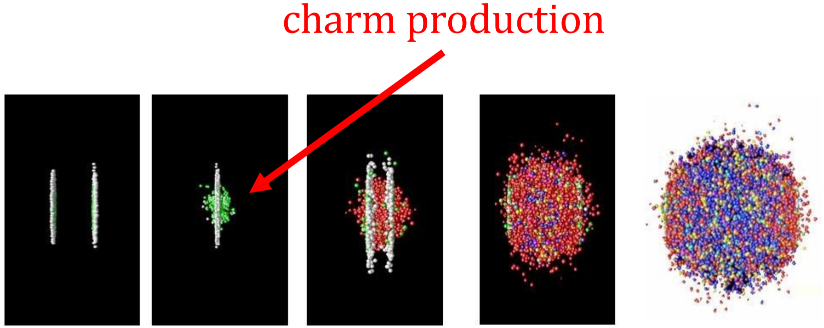


Illustration of a A-A collision

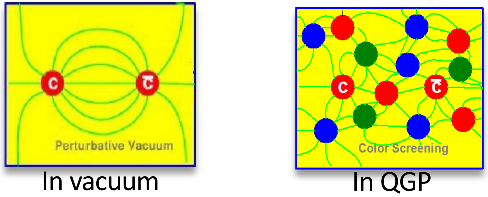


Illustration of colour screening

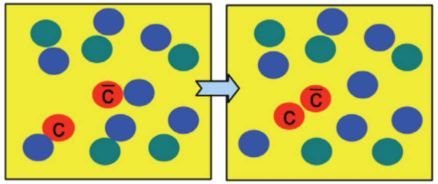


Illustration of (re)combination

Introduction - Charmonia

- J/ψ and ψ(2S) have a factor 10 difference in binding energy (~640 and ~50 MeV, respectively)
  (Satz, *J. Phys. G. (2006) 32 R25*)

  ➔ψ(2S) is expected to be dissociated at lower temperature in QGP than the J/ψ

- J/ψ and ψ(2S) differ by a factor ~2 in size (~0.5 and ~0.9 fm, respectively)

  ➔ψ(2S) and J/ψ recombination processes might differ, the larger ψ(2S) being produced later in the evolution of the system

- Studying both J/ψ and ψ(2S) can provide insightful information to test the recombination models

- Other relevant talks for charmonia in QGP :
  - Pengzhong Lu : *Measurements of J/ψ production in Pb–Pb collisions at 5.02 TeV* (Tuesday 28th, 11:10)
  - Andrea Ferrero : *Quarkonium polarization in pp and Pb–Pb collisions* (Thusday 30th, 9:00)
  - Ionut Arsene : *J/ψ photoproduction in Pb–Pb collisions with nuclear overlap* (Wednesday 29th, 9:00)

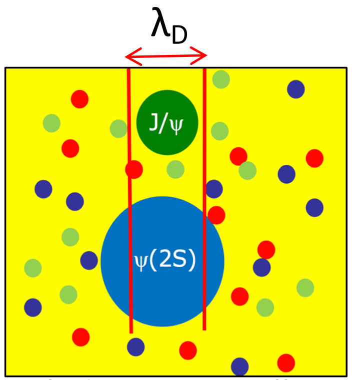


Illustration of colour screening affecting J/ψ and ψ(2S) differently

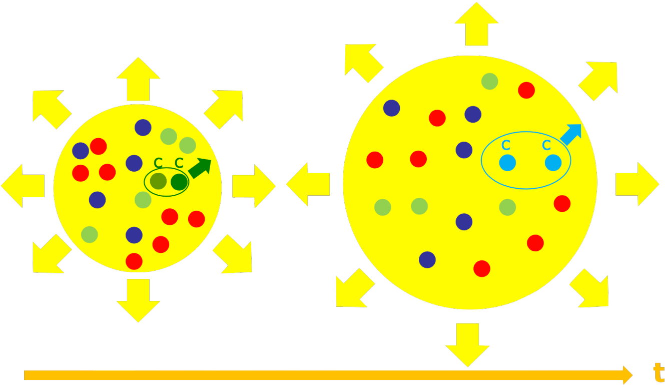


Illustration of recombination happening at different times in the QGP evolution for J/ψ and ψ(2S)

ALICE apparatus

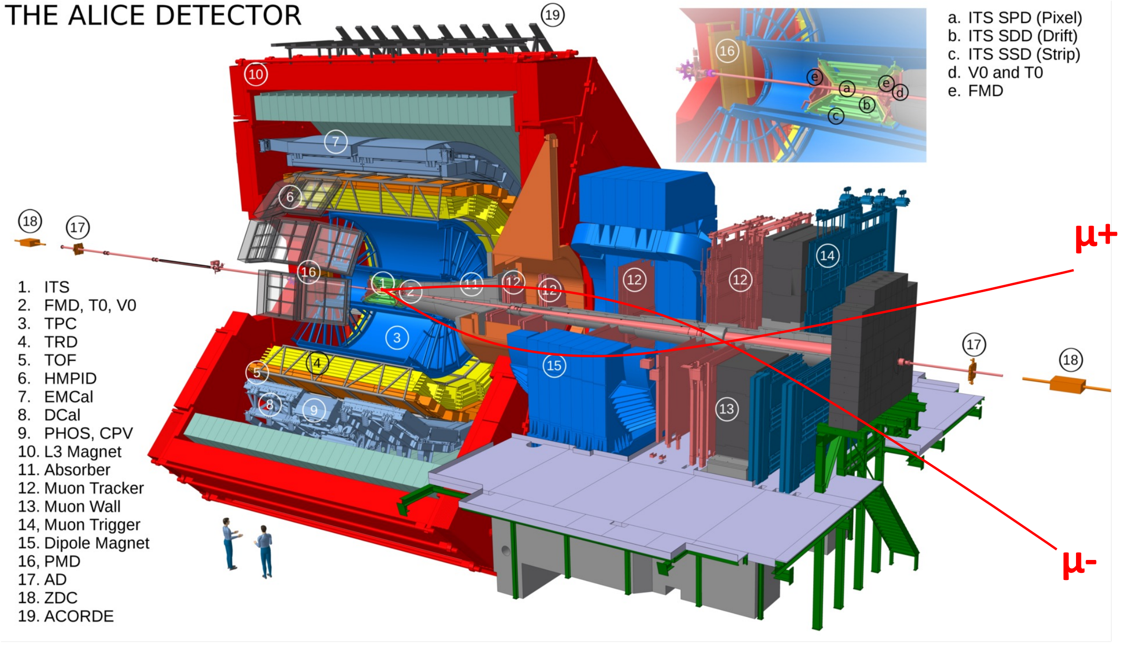


Illustration of ALICE Detector during Run 2

- Muon Arm : J/ψ, ψ(2S), **Υ**(nS) → $\mu^+\mu^-$
- Acceptance : 2.5<y<4.0
- Down to p_T = 0
- Inclusive charmonia only

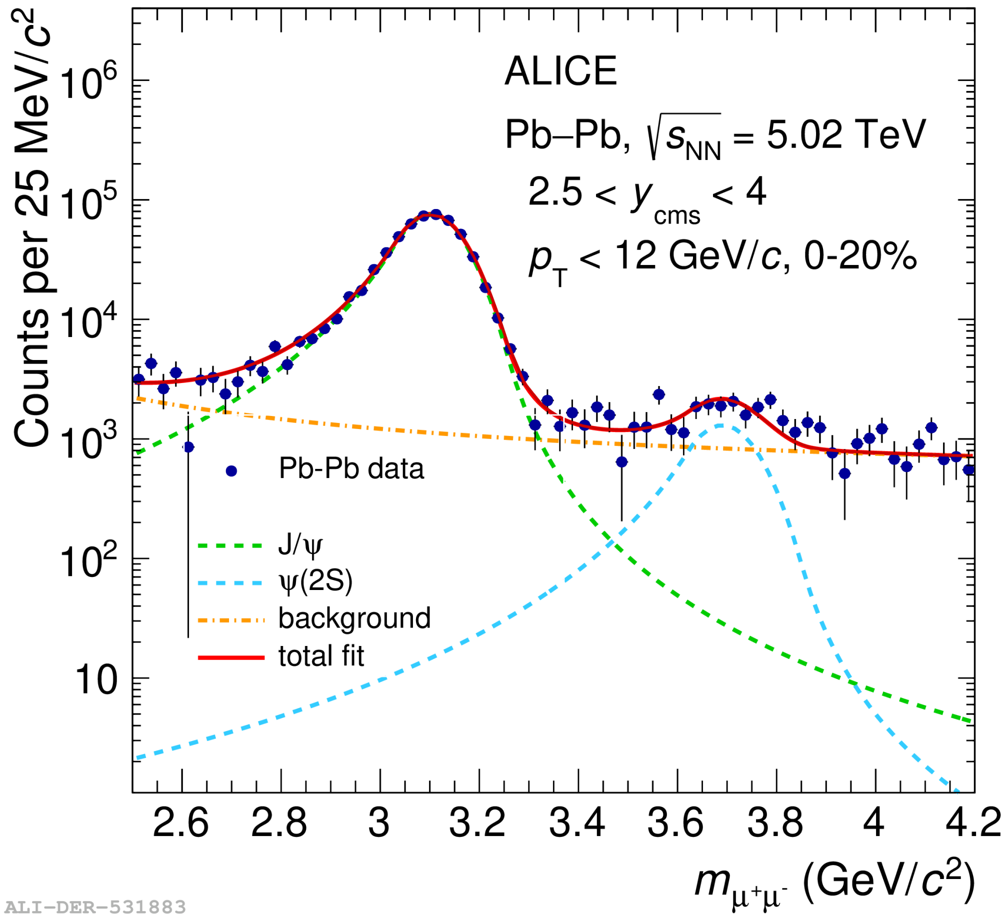
- 5 stations of tracking chambers
- 2 stations of trigger chambers
- Dipole Magnet
- Absorbers

- ITS used for vertex determination
- V0 hodoscopes used as trigger (in coincidence with Muon Trigger)
- V0 also used for centrality determination
- V0 and ZDC used for background rejection

New ψ(2S) measurements in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

Signal extraction procedure

- Data collected in 2015 and 2018, corresponding to an integrated luminosity of $L_{int} \sim 750\ \mu b^{-1}$
- ψ(2S) yield extracted by χ^2 minimization fits to the opposite sign dimuon invariant mass spectrum
- For the whole dataset, $N_{\psi(2S)} \approx 1.3\ .10^4$ and $N_{J/\psi} \approx 9.2\ .10^5$



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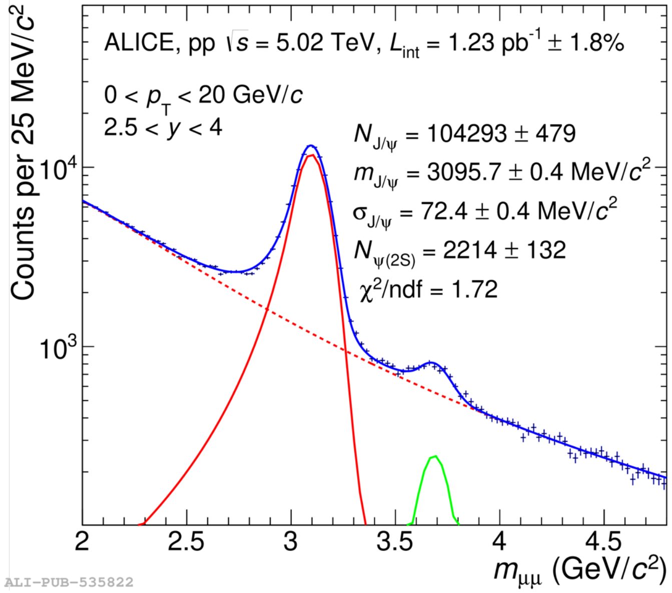
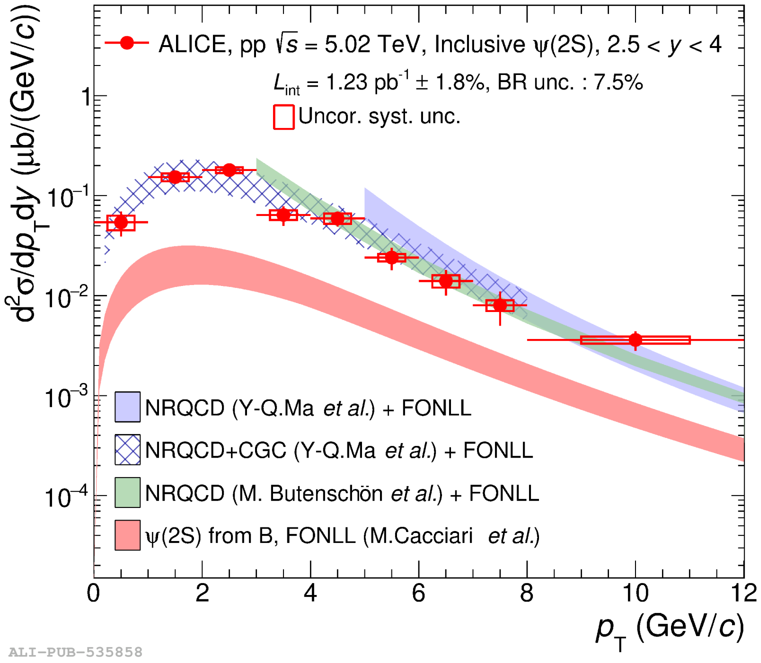
pp cross-section at $\sqrt{s} = 5.02$ TeV





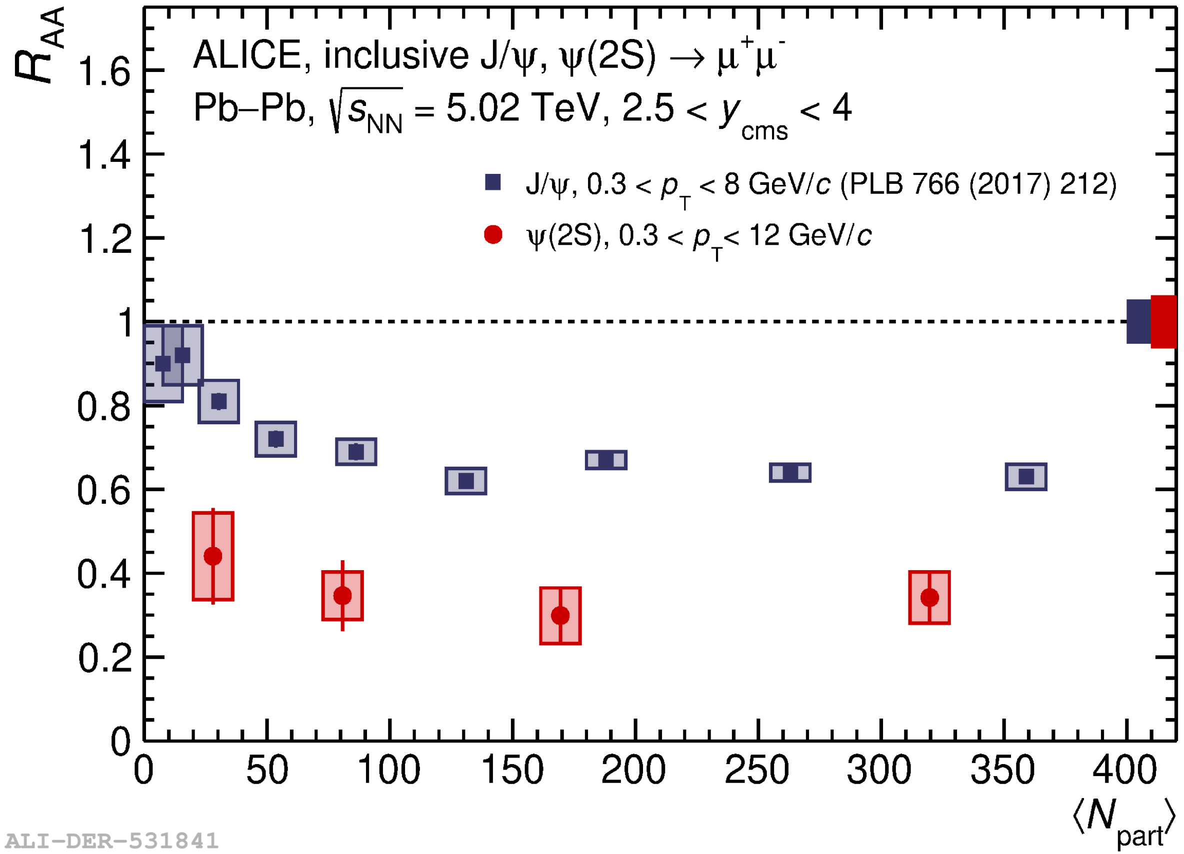
NRQCD : Butenschön et al, *Phys. Rev. Lett. 106 (2011) 022003*
NRQCD : Ma et al, *Phys. Rev. Lett. 106 (2011) 042002*
NRQCD + CGC : Ma et al, *Phys. Rev. Lett. 113 (2014) 192301*
FONLL : Cacciari et al, *JHEP 10 (2012) 137*

- pp data collected in 2017, for a total luminosity $L_{\text{int}} \sim 1230$ nb^{-1}
- Integrated cross section (p_T < 12 GeV/c) : $\sigma^{pp}_{\psi(2S)}$ = 0.87 ± 0.06 (stat) ± 0.10 (syst) μb

(ALICE, *Eur. Phys. J. C 83 (2023) 1, 61*)

R_{AA} vs centrality

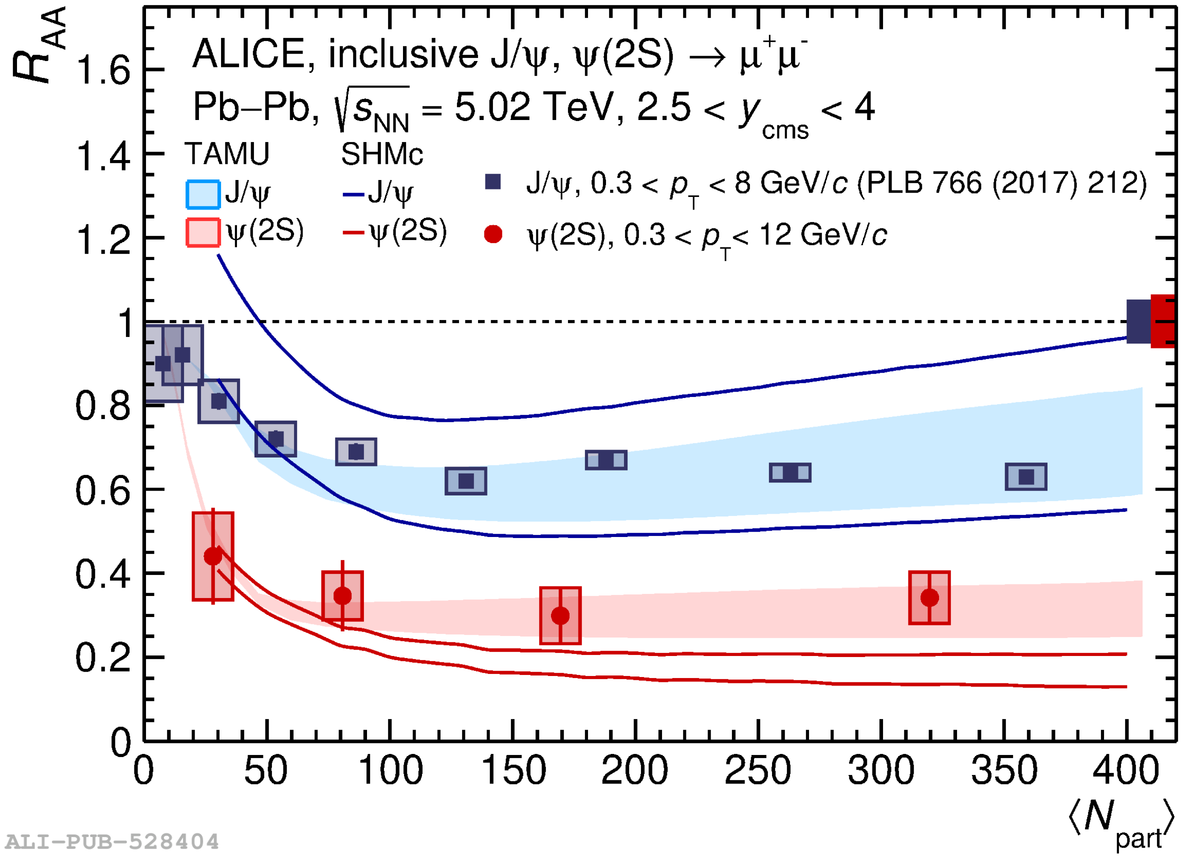
arXiv:2210.08893v2



- Nuclear modification factor : $R_{AA} = \frac{dN_{PbPb}}{\langle T_{AA}\rangle \cdot d\sigma_{pp}}$
- If $R_{AA} \neq 1$, then initial and/or final state effects are present
- A larger suppression of the ψ(2S) with respect to the J/ψ is observed
- No centrality dependence is observed for the ψ(2S) R_{AA} within uncertainties

R_{AA} vs centrality

arXiv:2210.08893v2



- **Statistical Hadronization Model (SHMc) :** (Andronic et al., *Phys. Lett. B797 (2019) 134836*)
  - No binding of charmonia in the QGP phase
  - Charmonium production occurs at phase boundary by the statistical hadronization of charm quarks
- **Transport Model (TAMU) :** (Du and Rapp, *Nucl. Phys. A 943 (2015) 147-158*)
  - Continuous charmonium dissociation and regeneration in the QGP, described by a rate equation

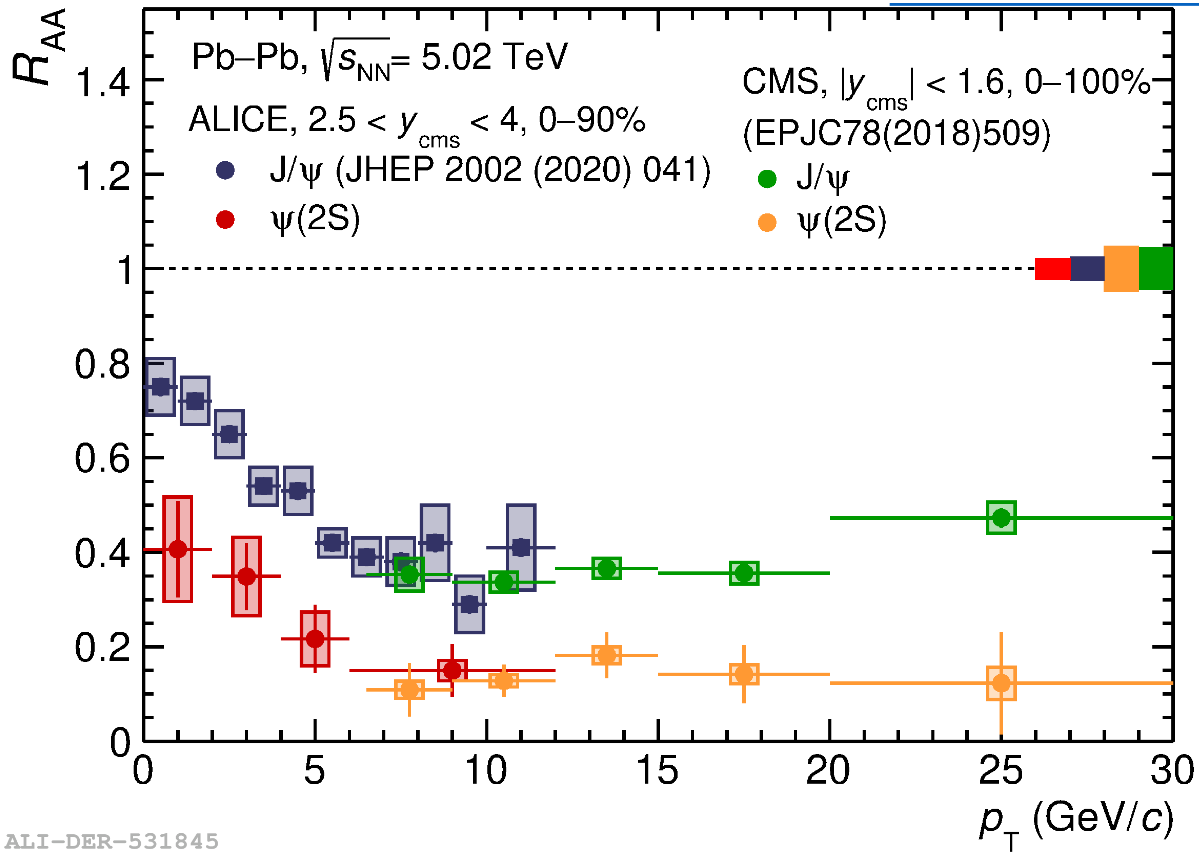
- TAMU shows a good agreement with the R_{AA} for both J/ψ and ψ(2S), within uncertainties

- The SHMc model reproduces the J/ψ R_{AA} centrality dependence within uncertainties
- It underestimates the ψ(2S) one in central collisions.

R_{AA} vs p_T

[arXiv:2210.08893v2](https://arxiv.org/abs/2210.08893v2)

- The ψ(2S) R_{AA} increases at low p_T, similarly to the J/ψ one
- Results are compatible with CMS measurements in the common p_T region (but different *y* coverage)
  (CMS, *Eur. Phys. J. C 78 no. 6 (2018) 509*)
- The strong suppression of the ψ(2S) persists up to p_T = 30 GeV/*c*



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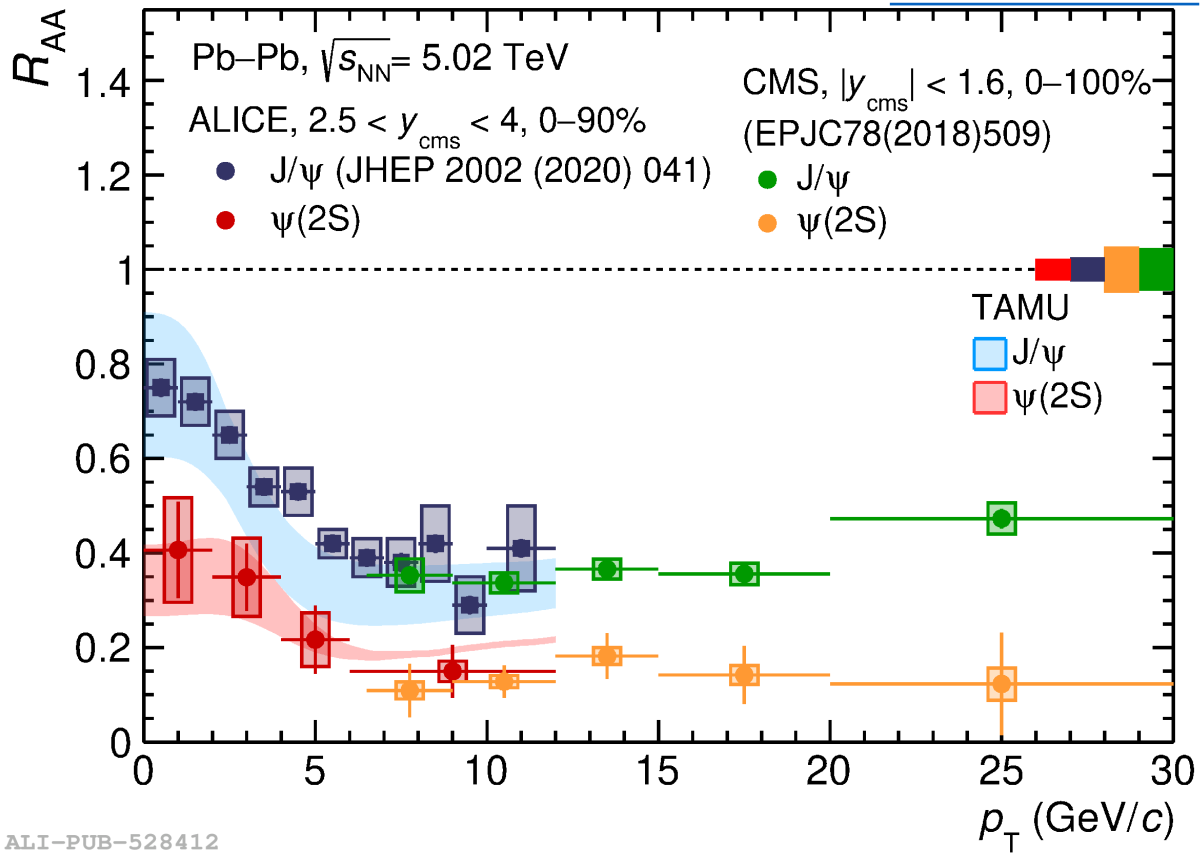
  (CMS, *Eur. Phys. J. C 78 no. 6 (2018) 509*)
- The strong suppression of the ψ(2S) persists up to p_T = 30 GeV/c
- TAMU model is able to reproduce the p_T dependence of the R_{AA} for both J/ψ and ψ(2S)
  ➔ **Results agree with models including recombination of $c - \bar{c}$ quarks**

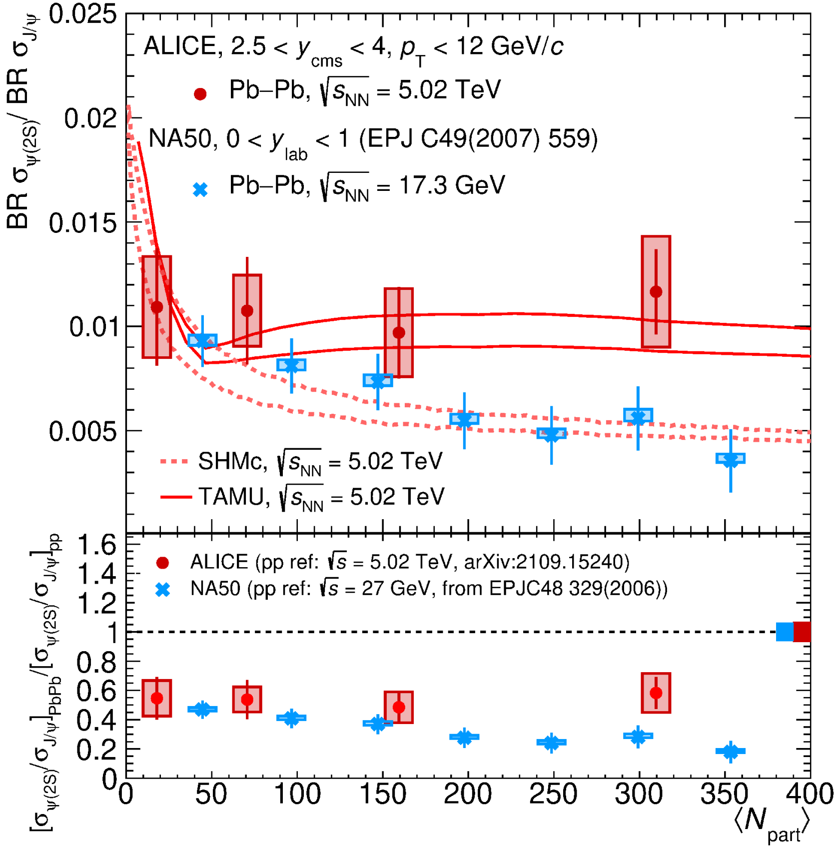


ALI-PUB-528412

Single and double ratio vs centrality

- Single Ratio: $\sigma^{PbPb}_{\psi(2S)} / \sigma^{PbPb}_{J/\psi}$
- All uncertainties except the one on signal extraction cancel out
- The ratio of ψ(2S) and J/ψ cross sections shows no significant centrality dependence
- The TAMU model reproduces the cross-section ratios over centrality
- The SHMc model tends to underestimate the data in central Pb–Pb collisions
- NA50 results reach smaller ψ(2S)-to-J/ψ single and double ratios values for central events
- The double ratio shows that the ψ(2S) suppression in Pb–Pb w.r.t pp is larger than the J/ψ one by a factor ~2

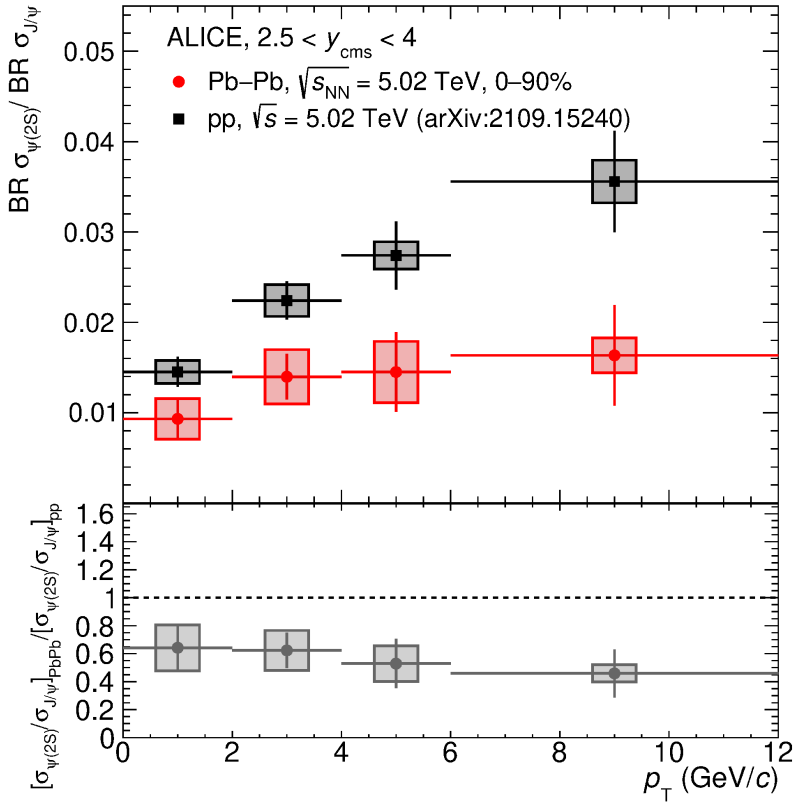
arXiv:2210.08893v2



Single and double ratio vs p_T

arXiv:2210.08893v2

- Both the Pb–Pb and pp ψ(2S)-to-J/ψ ratios increase as a function of p_T
- The Pb–Pb ratio tends to show a milder rise as a function of p_T than the pp one
- The double ratio values tend to decrease with p_T, down to a value of ~0.5, indicating a corresponding possible increase of the relative suppression of the ψ(2S)



Conclusions

- The inclusive nuclear modification factor of the ψ(2S) in Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV and forward rapidity has been measured down to p_T = 0
  ➔See arXiv:2210.08893v2 for the publication

- The centrality and p_T dependence of the R_{AA} have been studied and show :
  - No centrality dependence of the ψ(2S) R_{AA} within uncertainties
  - An increase of the ψ(2S) suppression at high p_T with respect to low p_T, similar to the J/ψ one

- The (double) ratio of ψ(2S) and J/ψ cross sections show :
  - A relative suppression by a factor ~2 of the ψ(2S) with respect to the J/ψ
  - No centrality dependence within the uncertainties, hint of a decrease of the double ratio with increasing p_T

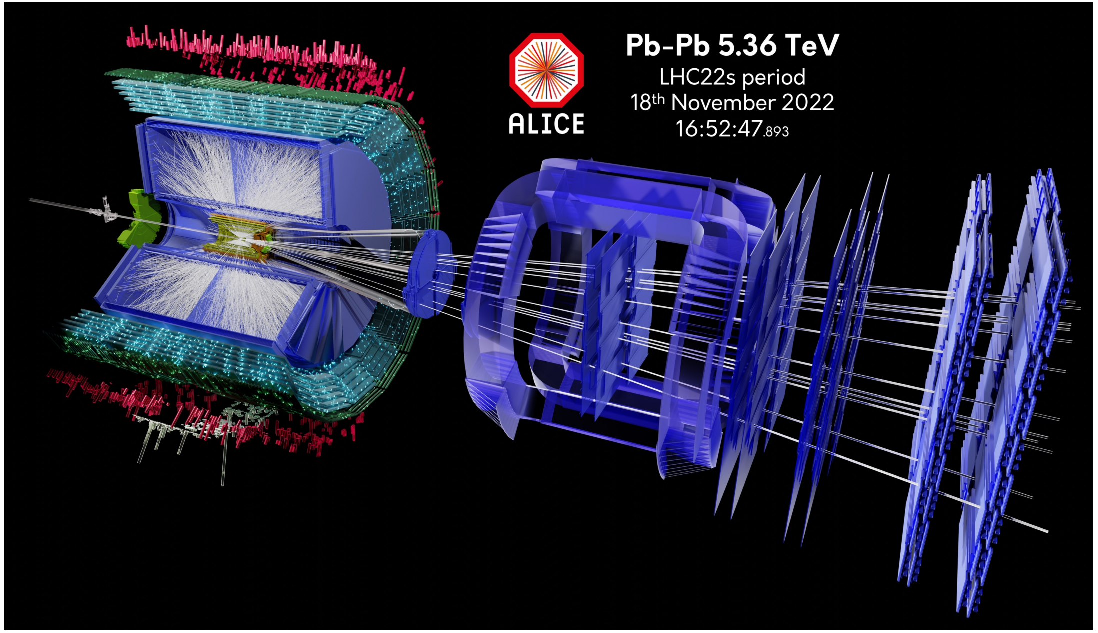
- These results show a fair agreement with Transport Model and SHMc calculations, both including J/ψ and ψ(2S) regeneration
- TAMU model calculations are better able to reprocuce the ψ(2S) results in central collisions

Perspectives

- Run 3 at the LHC is ongoing :
  - pp collisions being recorded at this moment
  - Pb-Pb collisions scheduled for the end of the year

- The new Muon Forward Tracker (MFT) installed allows now to distinguish between prompt and non-prompt charmonia at forward rapidity

- New exciting results coming soon!



ALICE event display of a Pb-Pb collision during Run 3

THANK YOU FOR YOUR ATTENTION!

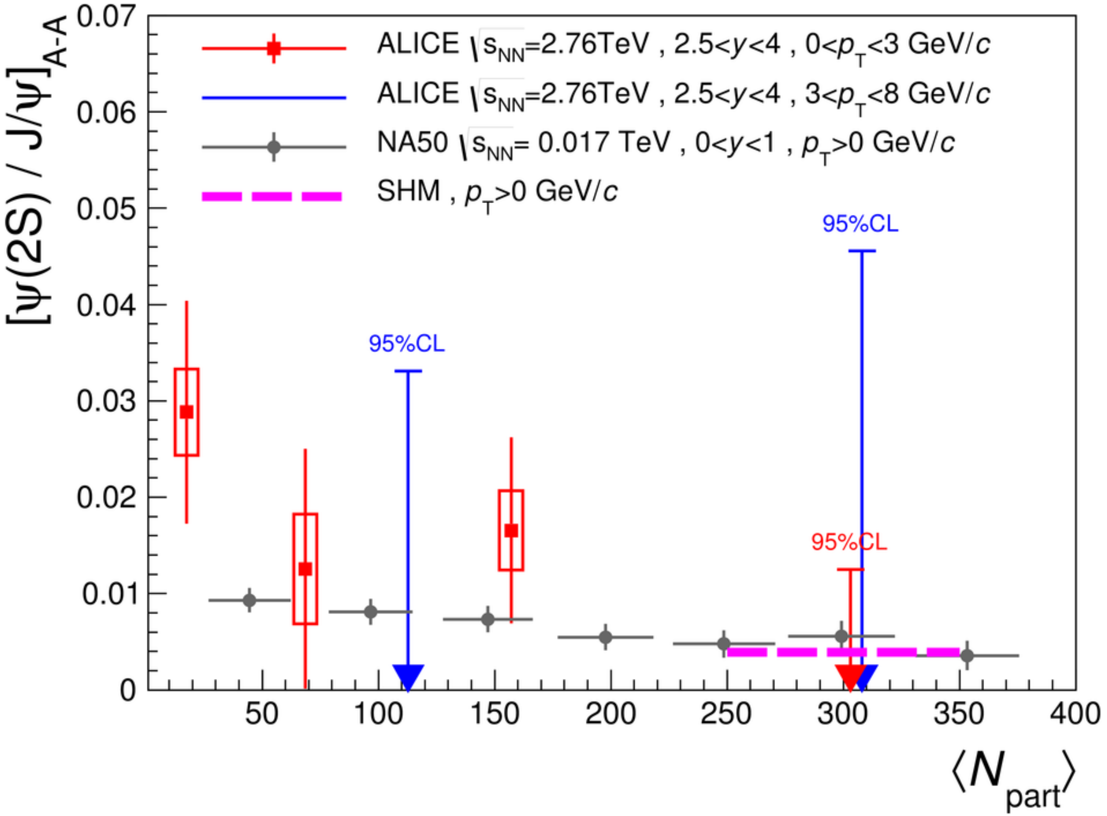
Questions?

Previous Results – ψ(2S) in Pb–Pb

- Single Ratio: $\sigma^{PbPb}_{\psi(2S)} / \sigma^{PbPb}_{J/\psi}$

- The previous published ALICE result at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV does not allow any firm conclusion, due to the large uncertainties (ALICE, *JHEP 05 (2016) 179* ; NA50, *Eur. Phys. J. C49 (2007) 559–567*)

- With the data collected in Run 2 at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, a significant improvement on the ψ(2S) measurement is possible



Event and Track Selection

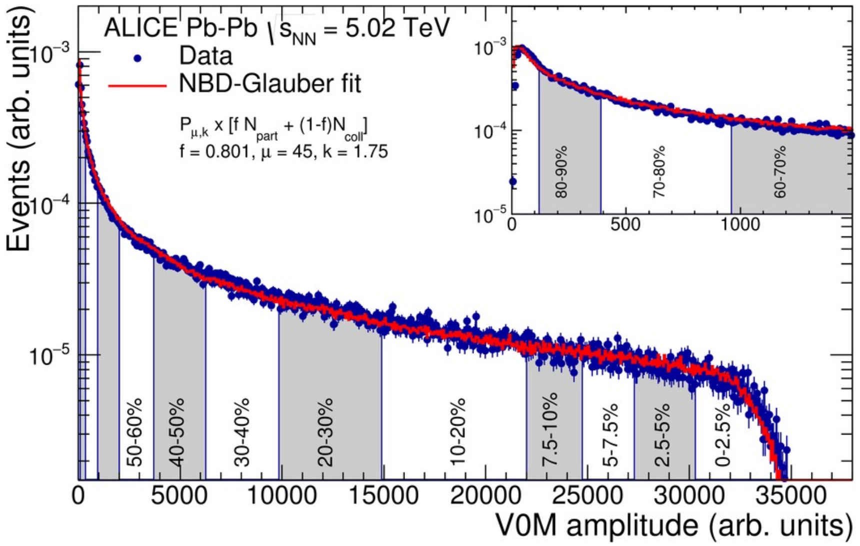
- Results from Run 2, 2015 + 2018 combined
- Integrated Luminosity ≈ 750 μb^{-1}

- Muon pair selection :
  - Pseudo rapidity on each muon $-4.0<\eta<-2.5$
  - Radial transverse position at the end of the absorber $17.6<R_{abs}<89.5$cm
  - Rapidity of the dimuon $2.5<y<4.0$
  - Muons of opposite sign
  - Matching tracks between tracking chambers and trigger

- Event selection
  - Beam gas and electromagnetic interactions rejected using V0 and ZDC
  - SPD used for vertex determination

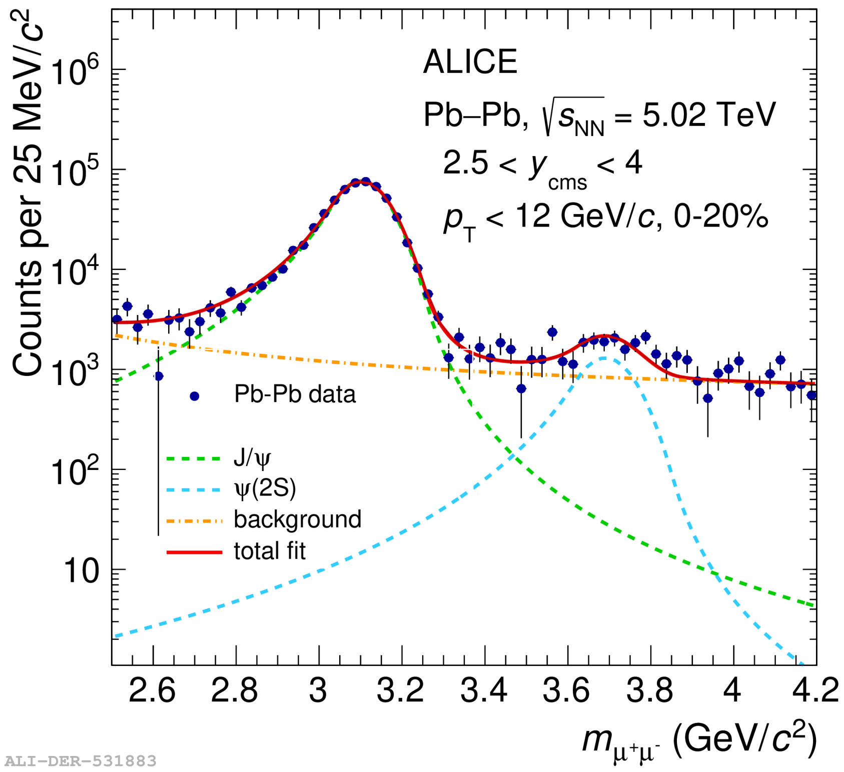
- Centrality estimated on a Glauber model fit of the V0 amplitude (PRL. 116 (2016) 222302)

ALICE, ALICE-PUBLIC-2015-008



Signal extraction detailed procedure

- ψ(2S) yield extracted by χ^2 minimization fits the opposite sign dimuon invariant mass spectrum using :
  - 2 signal functions
  - Several line shapes are used for the signal functions
  - Combinatorial Background substracted with mixed-event technique
  - Remaining background fitted with several empirical functions
  - The mass of the ψ(2S) is fixed to the one of the J/ψ via the mass difference of the two resonances as provided by the Particle Data Group
  - Several fit ranges



- For the whole dataset, $N_{\psi(2S)} \approx 1.3 .10^4$ and $N_{J/\psi} \approx 9.2 .10^5$

R_{AA} detailed evaluation

$$R_{AA} = \frac{N_{\psi(2S)}}{BR_{\psi(2S)\rightarrow\mu\mu} \times N_{MB} \times A\varepsilon \times \langle T_{AA} \rangle \times \sigma^{pp}_{\psi(2S)}}$$

- $N_{\psi(2S)}$: number of ψ(2S)
- $A\varepsilon$: Acceptance-efficiency, correcting the number of extracted particles by the acceptance and efficiency of the detector, calculated with Monte-Carlo simulations using the embedding technique
- $BR_{\psi(2S)\rightarrow\mu\mu}$: Branching ratio
- N_{MB}: Number of equivalent minimum bias events
- $\langle T_{AA} \rangle$: Nuclear overlap function, calculated using a Glauber model
- $\sigma^{pp}_{\psi(2S)}$: pp cross section at $\sqrt{s} = 5.02$ TeV (ALICE, *Eur. Phys. J. C 83 (2023) 1, 61*)

➔Each one of these elements is a source of systematic uncertainty. For the ψ(2S)-to-J/ψ single ratio all uncertainties except the one on signal extraction cancel each other out

Systematic uncertainties

- Values with an asterisk correspond to the systematic uncertainties correlated as a function of the given variable

	Vs centrality (%)	Vs p_T (%)
Signal extraction	16-22	12-25
Tracking efficiency	3*	3
Trigger efficiency	1.6*	1.5-2
Matching efficiency	1*	1
MC input	2*	2
Normalization factor	0.7*	0.7*
$\langle T_{AA} \rangle$	0.7-2.3	1*
Centrality estimation	0-7	0.3*
pp reference	4.7*	7.9-11.1