

Charmonium production in heavy ion collisions at forward rapidity with ALICE

Sara Garetti

Outline

- **Introduction**
  - Heavy quarks and quarkonium
  - Prompt and non-prompt charmonium
- **Physics motivation**
  - Hot nuclear matter effects on charmonium production
- **ALICE detectors in Run 3**
- **ψ(2S)-to-J/ψ ratio**
  - **in Pb-Pb**
  - **in OO**
- **Conclusion and outlook**

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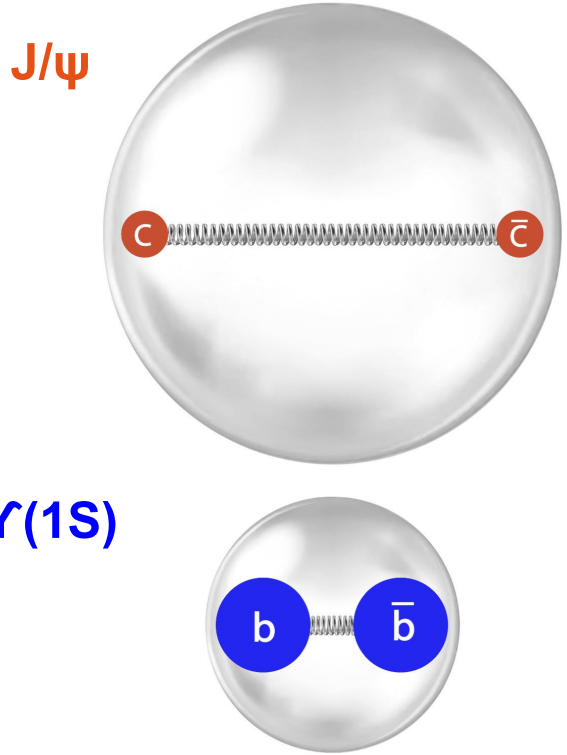
Heavy quarks and quarkonium

Heavy quarks (charm **c** and beauty **b**):

- **Produced** in **initial** hard partonic **scattering**

Quarkonium:

- **Bound states** of **heavy-quark pairs** (charmonium $c\bar{c}$, bottomonium $b\bar{b}$)
- Produced in a two-stage process:
  - heavy-quark production (pQCD, $gg \rightarrow q\bar{q}$)
  - subsequent bound-state formation (non-perturbative QCD)
- Sensitive to medium produced in heavy-ion collisions

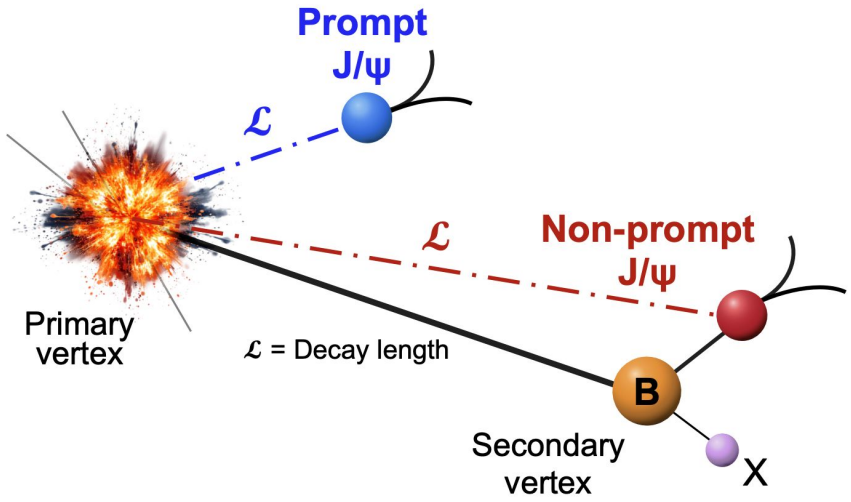


Prompt and non-prompt charmonium

Prompt charmonium:
- Formed from $c\bar{c}$ pairs produced directly in the **initial hard scattering**
- Produced through **feed down** from excited charmonium states

Non-prompt charmonium:
- Produced from the **decay** of **beauty** hadrons

Inclusive charmonium:
- Prompt + non-prompt components



Outline

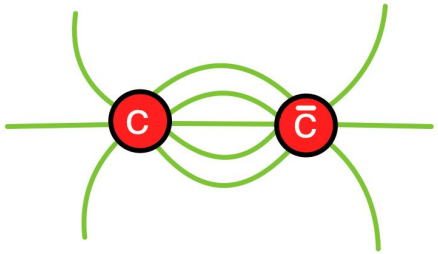
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Hot Nuclear Matter effects on charmonium production

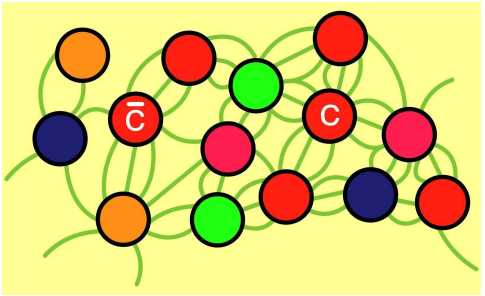
Pb–Pb collisions at LHC energies → hot nuclear matter effects:

- **quarkonium suppression** (color screening [1])
- **regeneration** (enhanced $c\bar{c}$ production [2,3]) are expected.

- Studying **ψ(2S)** and **J/ψ production** in **Pb–Pb** collisions provides insight into **QGP properties** through their **different suppression** and **recombination** dynamics.



Perturbative vacuum



Color screening in deconfined medium

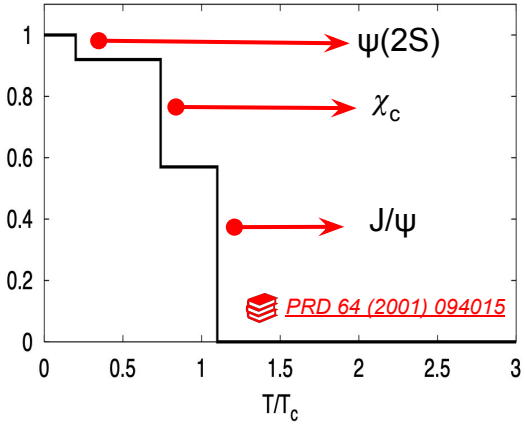
[1] T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416 *[2] P. Braun-Munzinger et al., PLB (2001) 518* *[3] R. L. Thews et al., PRC 63 (2001) 054905*

Hot Nuclear Matter effects on charmonium production

Pb–Pb collisions at LHC energies → hot nuclear matter effects:

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Quarkonium sequential suppression:

- ≠ quarkonium states → ≠ **dissociation temperatures**
- Quarkonium states with weaker binding energies dissociate first

  → **sequential suppression**

	J/ψ	χ_c	ψ(2S)
Mass (GeV/c^2)	3.10	3.53	3.68
E_B (MeV)	~ 640	~ 200	~ 60

ψ(2S) is **less tightly bound** w.r.t. **J/ψ**

ψ(2S) more **suppressed**

Hot Nuclear Matter effects on charmonium production

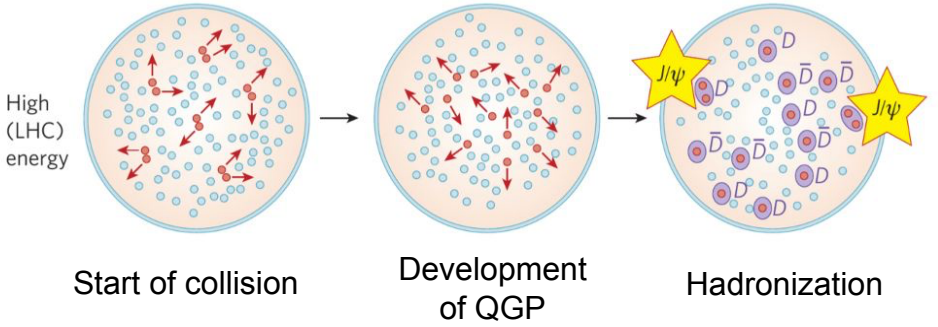
Quarkonium regeneration [2,3]**:**

- Enhanced $c\bar{c}$ pair production at LHC energies
- **Recombination** of **uncorrelated** heavy-quarks **pairs**

	RHIC	LHC
$N_{c\bar{c}}$/event	10	200
$N_{b\bar{b}}$/event	0.05	6

[4]

Studying various quarkonium states in **Pb–Pb** collisions provides insight into **QGP properties** through their **different suppression** and **recombination** effects.

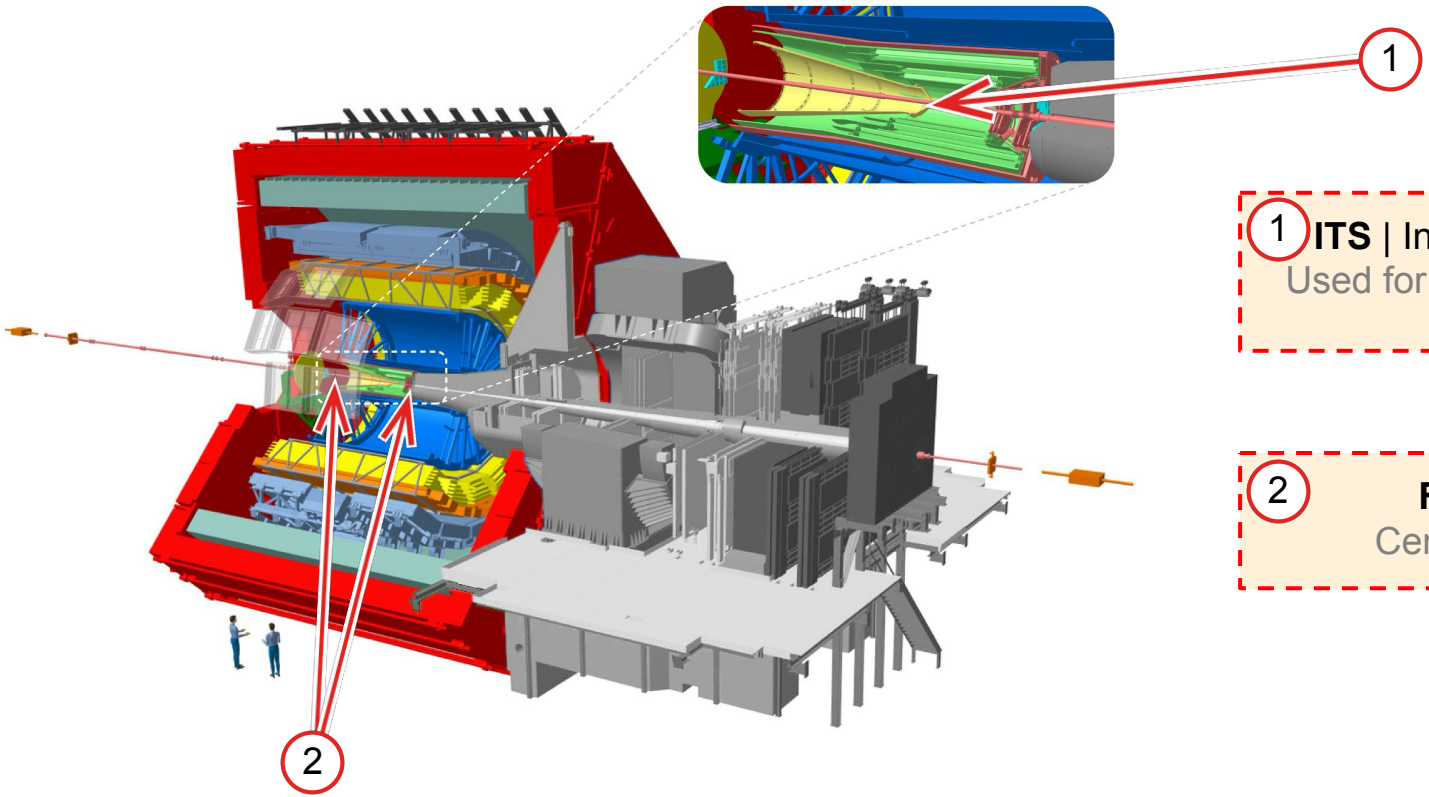


[2] P. BRAUN-MUNZINGER ET AL., PLB 518 (2001) [3] R. L. THEWS ET AL., PRC 63 (2001) 054905 [4] ALICE COLLAB. NPS 1014 (2024) 122354

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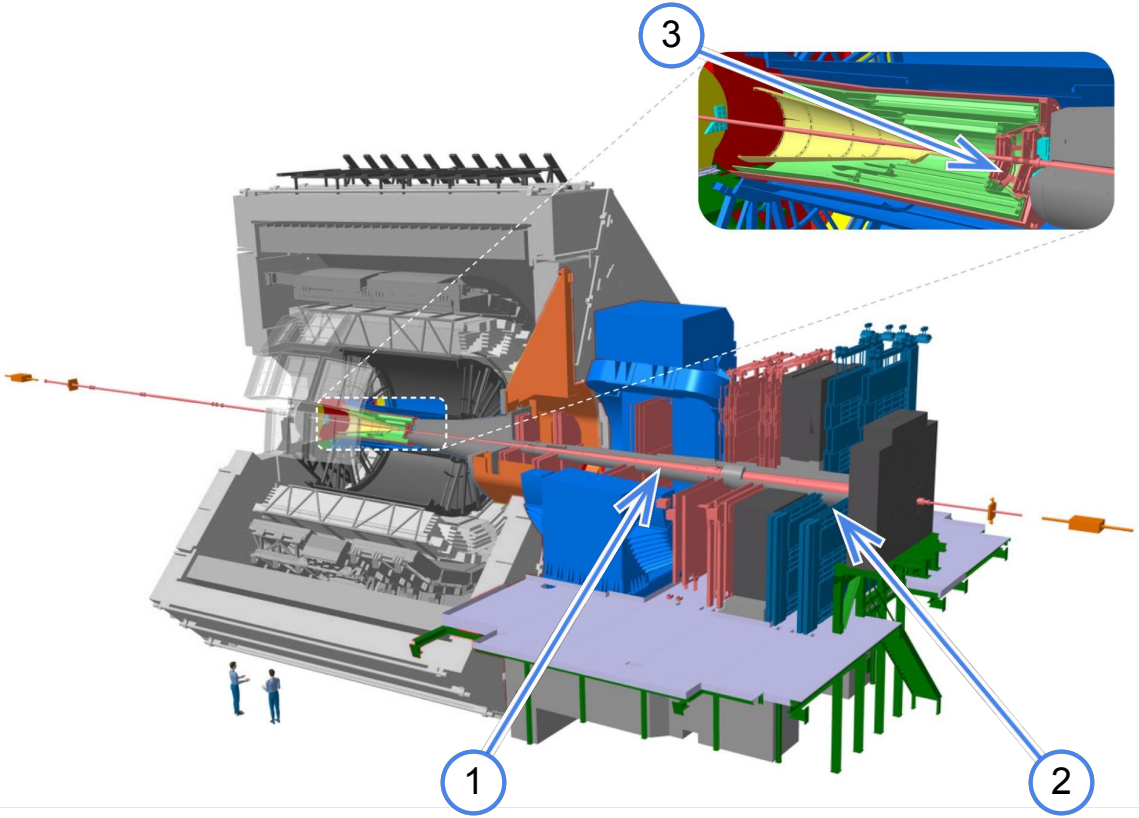
ALICE Run 3



1 **ITS** | Inner Tracking System
Used for tracking and vertexing

2 **FT0** | detectors
Centrality estimation

ALICE Run 3



1 **MCH** | Muon Chambers
Used to reconstruct muons
$-4 < \eta < -2.5$

2 **MID** | Muon IDentifier
Used to identify muons
$-4 < \eta < -2.5$

3 **MFT** | Muon Forward Tracker
Improves tracking and vertex finding (not used for this analysis)
$-3.6 < \eta < -2.5$

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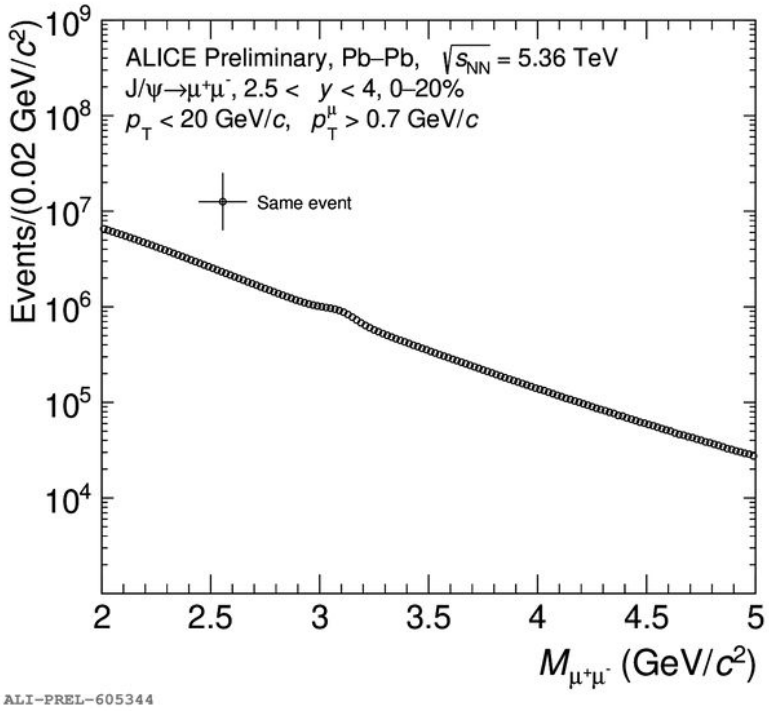
Analysis procedure

To measure the ψ(2S)-to-J/ψ ratio:

$$\frac{BR * \sigma_{\psi(2S)}}{BR * \sigma_{J/\psi}} = \frac{N_{\psi(2S)} \Big/ Ax\varepsilon_{\psi(2S)}}{N_{J/\psi} \Big/ Ax\varepsilon_{J/\psi}}$$

1) Signal extraction:

- After event selection, data processed to obtain **opposite-sign dimuon** invariant-mass spectra



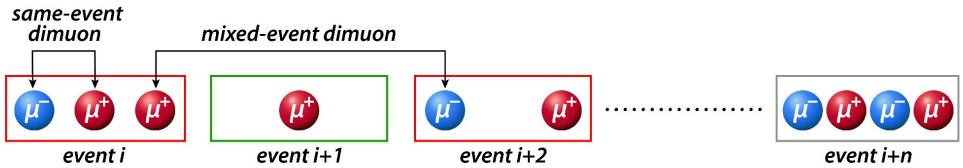
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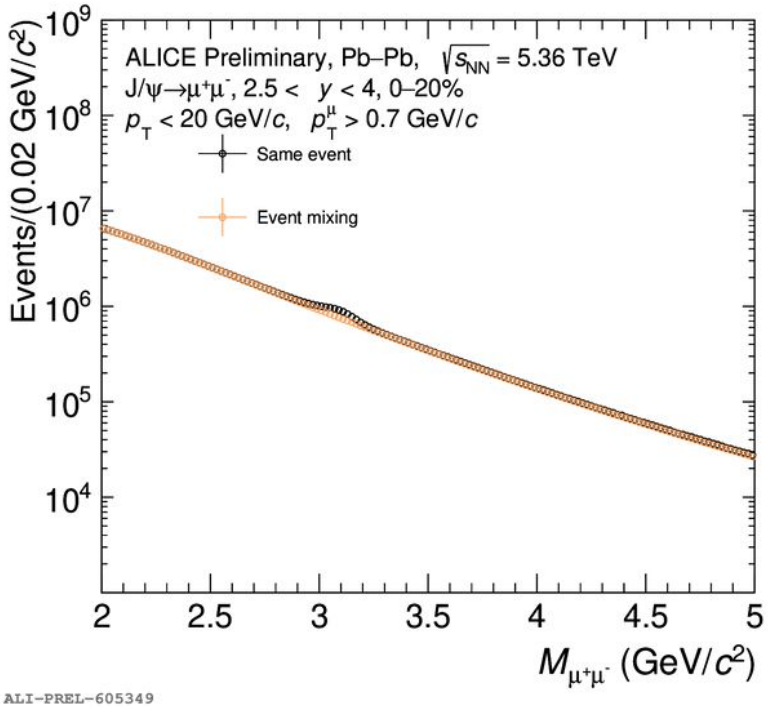
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- To reproduce **combinatorial background** shape: **mixed-events spectra normalized** (ME)





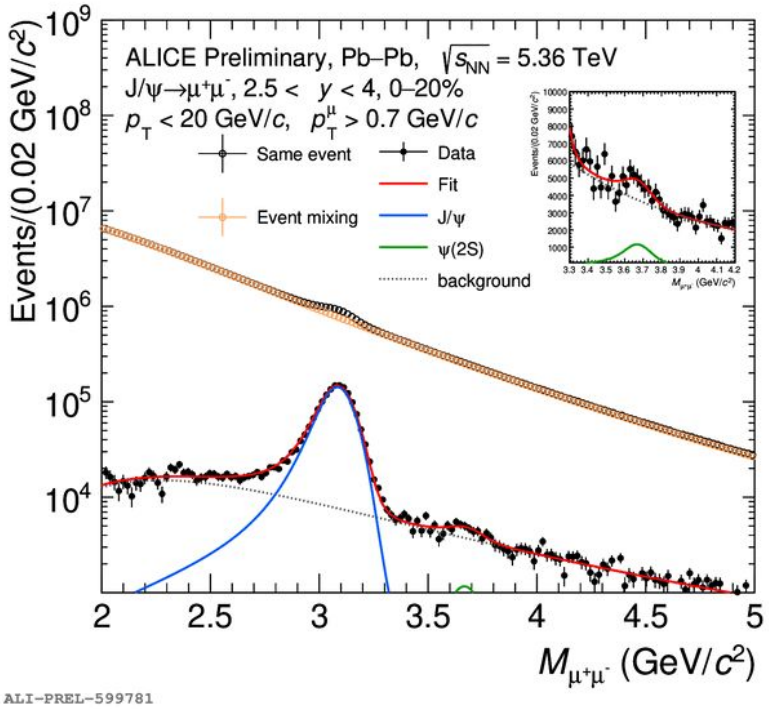
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- Determine **J/ψ** and **ψ(2S) yields** by fitting subtracted spectra using various **signal** + **background** functions



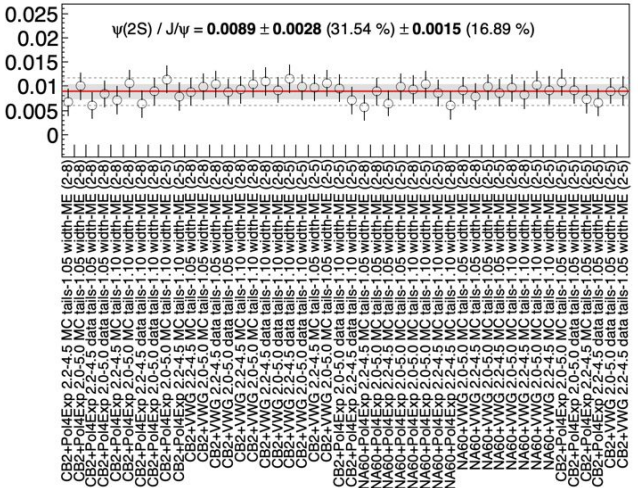
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- 48 trials
- Estimation of final yield of J/ψ and ψ(2S) → average of results
- Systematics uncertainty → RMS of the distribution

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1) **Signal extraction**

2) **Estimate** the **detectors Axε** using the **MC**:
   a) MC input kinematics tuned on real data from previous measurements
   b) Charmonium signals injected in Pythia 8

3) **Correct** the ratio $\mathbf{N_{\psi(2S)}/N_{J/\psi}}$ by **Axε** obtaining $BR\sigma_{\psi(2S)}/BR\sigma_{J/\psi}$

4) **Systematic uncertainties**:
   - Dominated by **signal extraction**

Analysis procedure

To measure the ψ(2S)-to-J/ψ ratio:

$$\frac{BR * \sigma_{\psi(2S)}}{BR * \sigma_{J/\psi}} = \frac{N_{\psi(2S)} / Ax\varepsilon_{\psi(2S)}}{N_{J/\psi} / Ax\varepsilon_{J/\psi}}$$

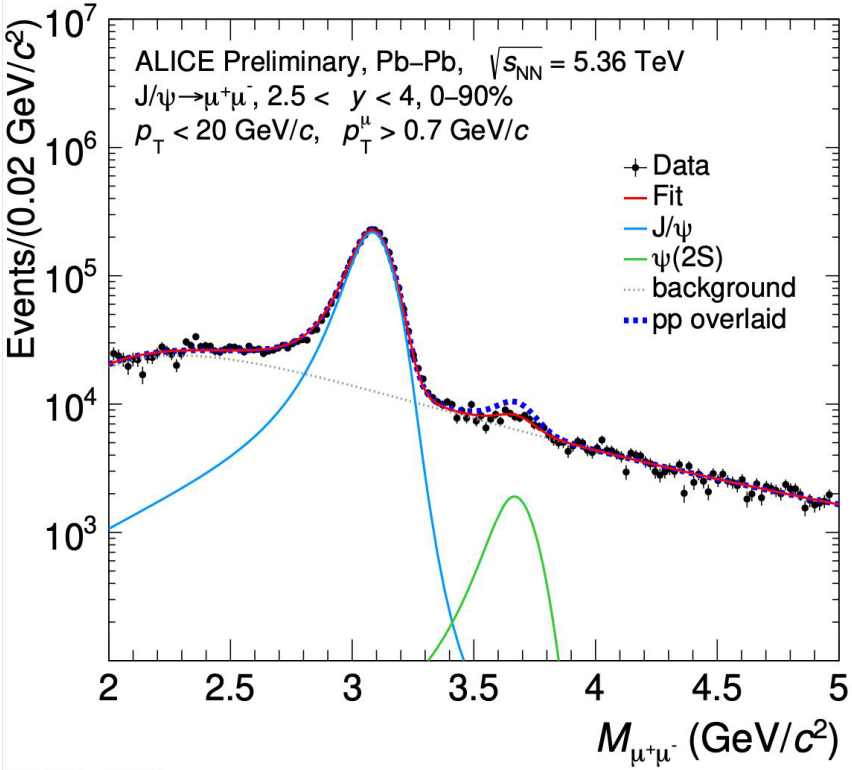
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Source	Centrality	p_T
Signal extraction	8-17 %	10-29 %
MC realism	2 %	2 %

ψ(2S)-to-J/ψ relative suppression

What should we observe without ψ(2S)-to-J/ψ relative suppression?

- **ψ(2S) rescaled** according to what we should expect **without QGP** formation (as in pp collisions)
- Extrapolated **ratio** in **pp** at energy of $\sqrt{s}$ **= 5.36 TeV [6]**
- ψ(2S) relative suppression observed to be a factor ~ 2 less than in rescaled pp collisions

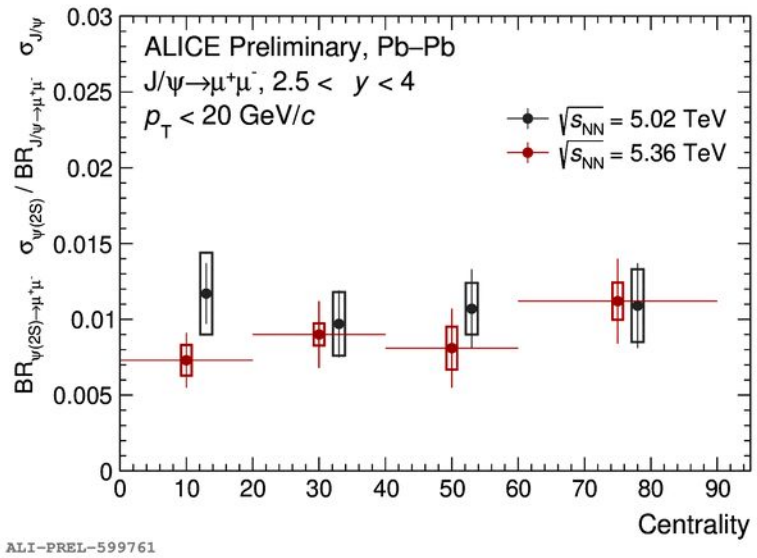


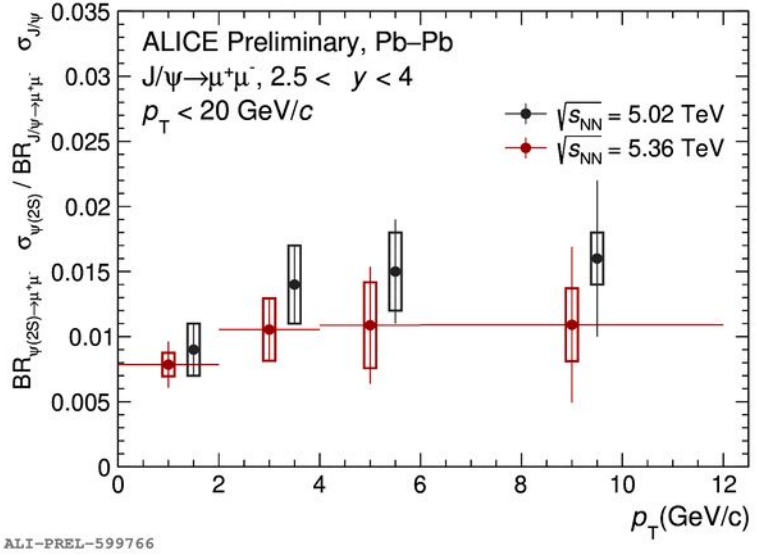
[6] ALICE COLLABORATION, EPJ 77 (2017) 392

ψ(2S)-to-J/ψ ratio as a function of centrality and p_T

Comparison with Run2:

- Run 2 points are shifted to better see the results
- **Run 3** has the **same binning as Run 2** both in p_T and centrality
- Ratio vs centrality and p_T → **no significant dependence** within the uncertainties
- **Results** obtained in **Run 3** in **good agreement** with the ones obtained in **Run 2!**

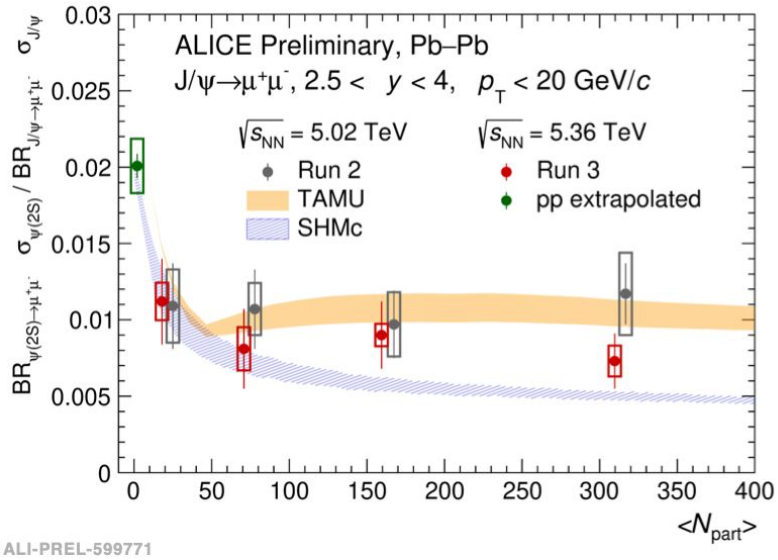


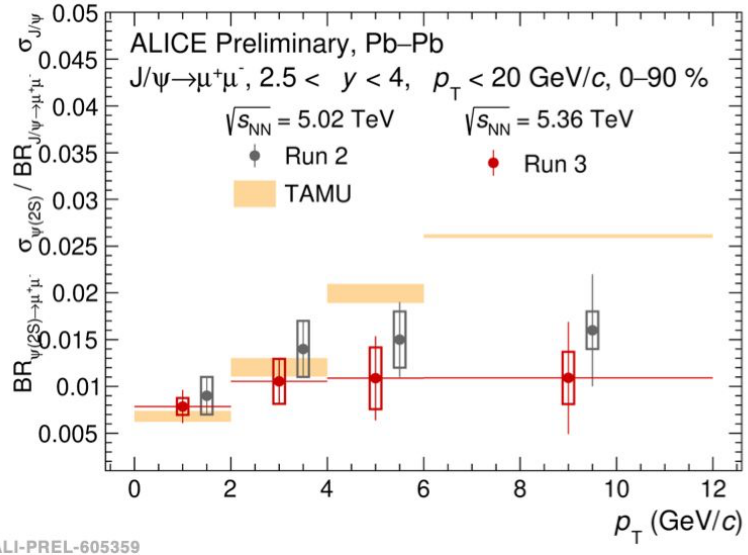


ψ(2S)-to-J/ψ ratio as a function of centrality and p_T

Comparison with:

- **TAMU model:** hierarchic suppression of charmonia in the QGP + regeneration [7]
- **SHMc:** no quarkonium survive in the QGP → charm recombination at chemical freeze-out [8]



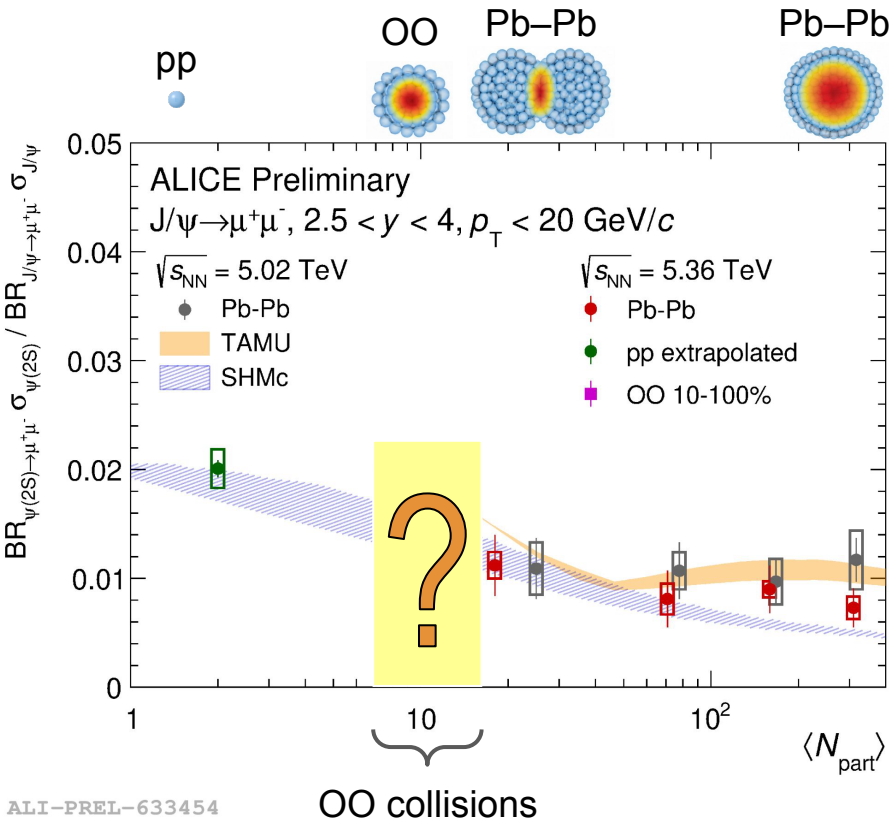


[7] R. RAPP, NPA 943 (2015) 147 [8] A. ANDRONIC, PLB 797 (2019) 134836

Physics motivation

- Theoretical models (TAMU [3], SHMc [4]) predict a steep decrease of the **ψ (2S)-to-J/ψ** ratio from pp to peripheral Pb–Pb

OO allows one to probe quarkonium behavior in a medium characterized by intermediate conditions between Pb–Pb and pp collisions



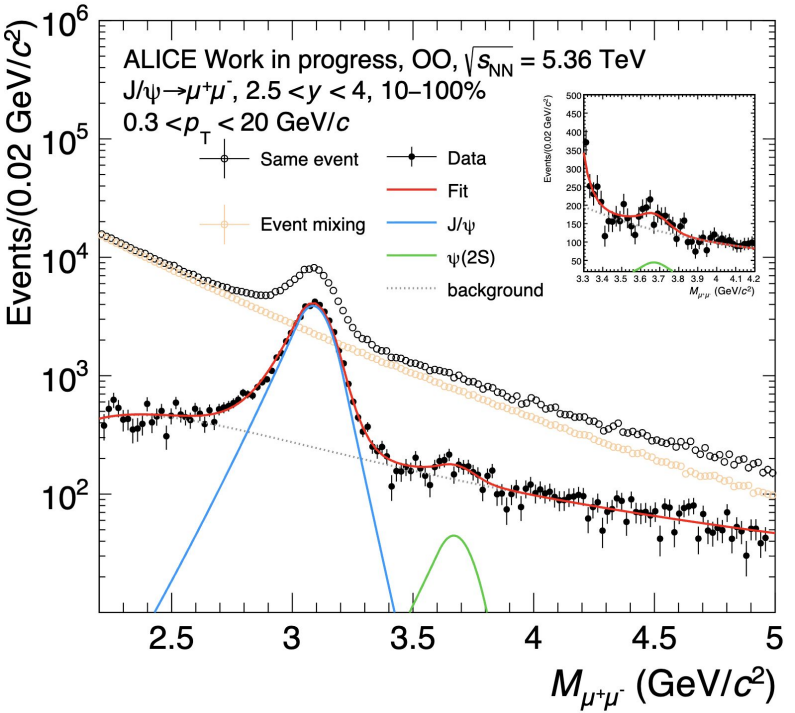
[3] R. RAPP, NPA 943 (2015) 147 [4] A. ANDRONIC, PLB 797 (2019) 134836

Measurement of the ψ(2S)-to-J/ψ ratio in OO

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Same procedure as Pb-Pb

1) **Signal extraction**:
   - **Normalize** the **mixed events** (ME) **spectra**
   - **Subtract** from **opposite-sign** invariant **mass spectra** the normalized ME spectra
   - Determine **J/ψ** and **ψ(2S) yields** by fitting subtracted spectra (48 trials) using various **signal + background** functions
2) **Estimate** the **detectors Axε** using the **MC**
3) **Correct** the ratio $\mathbf{N_{\psi(2S)}/N_{J/\psi}}$ by Axε obtaining $BR\sigma_{\psi(2S)}/BR\ \sigma_{J/\psi}$



ψ(2S)-to-J/ψ ratio

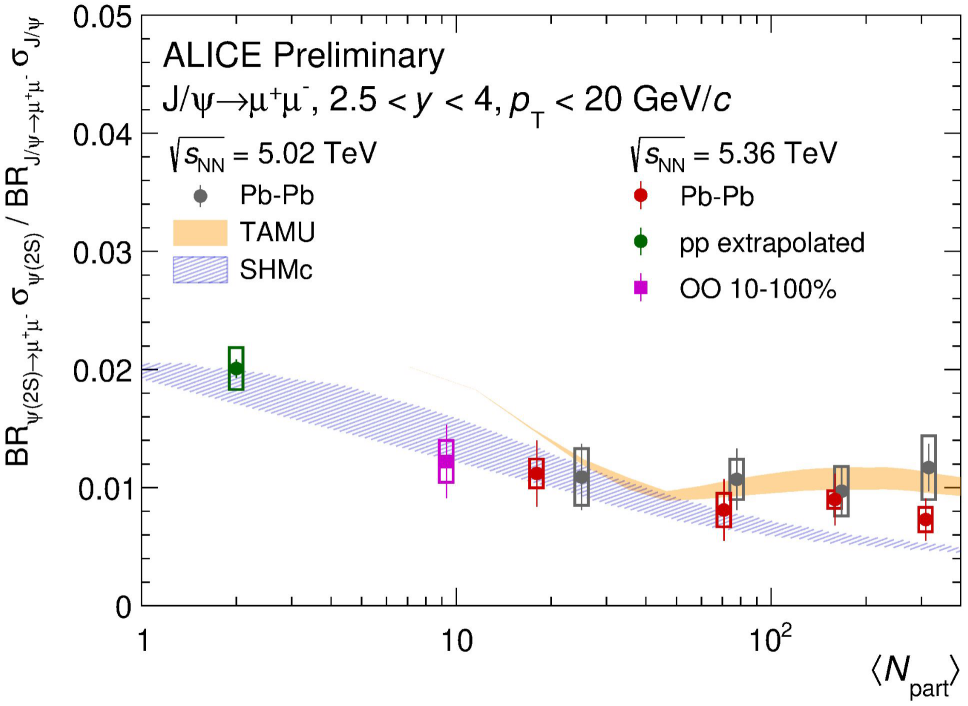
- $\langle N_{part} \rangle$ computed as:

$$< N_{part} >= \frac{\sum_i \omega_i x_i}{\sum_i \omega_i} \qquad \sigma_{N_{part}} = \frac{\sqrt{\sum_i (\omega_i^2 \sigma_i^2)}}{\sum_i \omega_i}$$

where x_i is N_{part} of the bin i and w_i the % width of the latter

- Centrality range 10-100% chosen because of fit instability due to low ψ(2S) statistics and large background including 0-10%

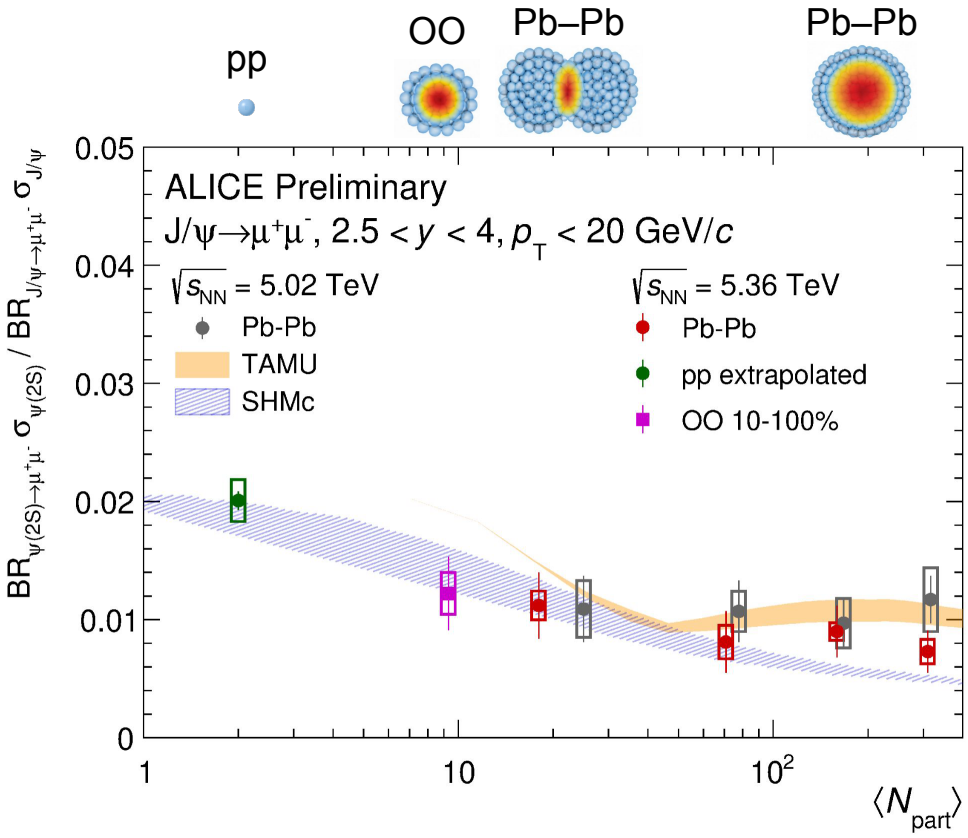
- Systematics box on x axis is arbitrary large
- Uncertainties on $\langle N_{part} \rangle$ reported like stat unc. in x (not visible)



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ψ(2S)-to-J/ψ ratio

- The ratio in OO is compatible with the one obtained for peripheral Pb-Pb collisions



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Conclusions

- **Charmonium as a QGP probe**
  - J/ψ probes the interplay of suppression and regeneration in Pb–Pb collisions at LHC energies
  - ψ(2S): more fragile and more suppressed than J/ψ, sensitive to late-stage medium effects
- **Perspectives**
  - Run 3 Pb–Pb:
    - Improved precision at low p_T and for excited states
    - Join together different years of Pb-Pb data taking
    - ψ(2S) R_{AA} extraction as well as J/ψ one is ongoing
  - OO:
    - Allows us to study intermediate conditions between pp and Pb-Pb
    - QGP suppression observed in OO studying J/ψ R_{AA}
    - ψ(2S)-to-J/ψ ratio compatible with the one observed for peripheral centrality bin in Pb-Pb

Thanks for your attention!