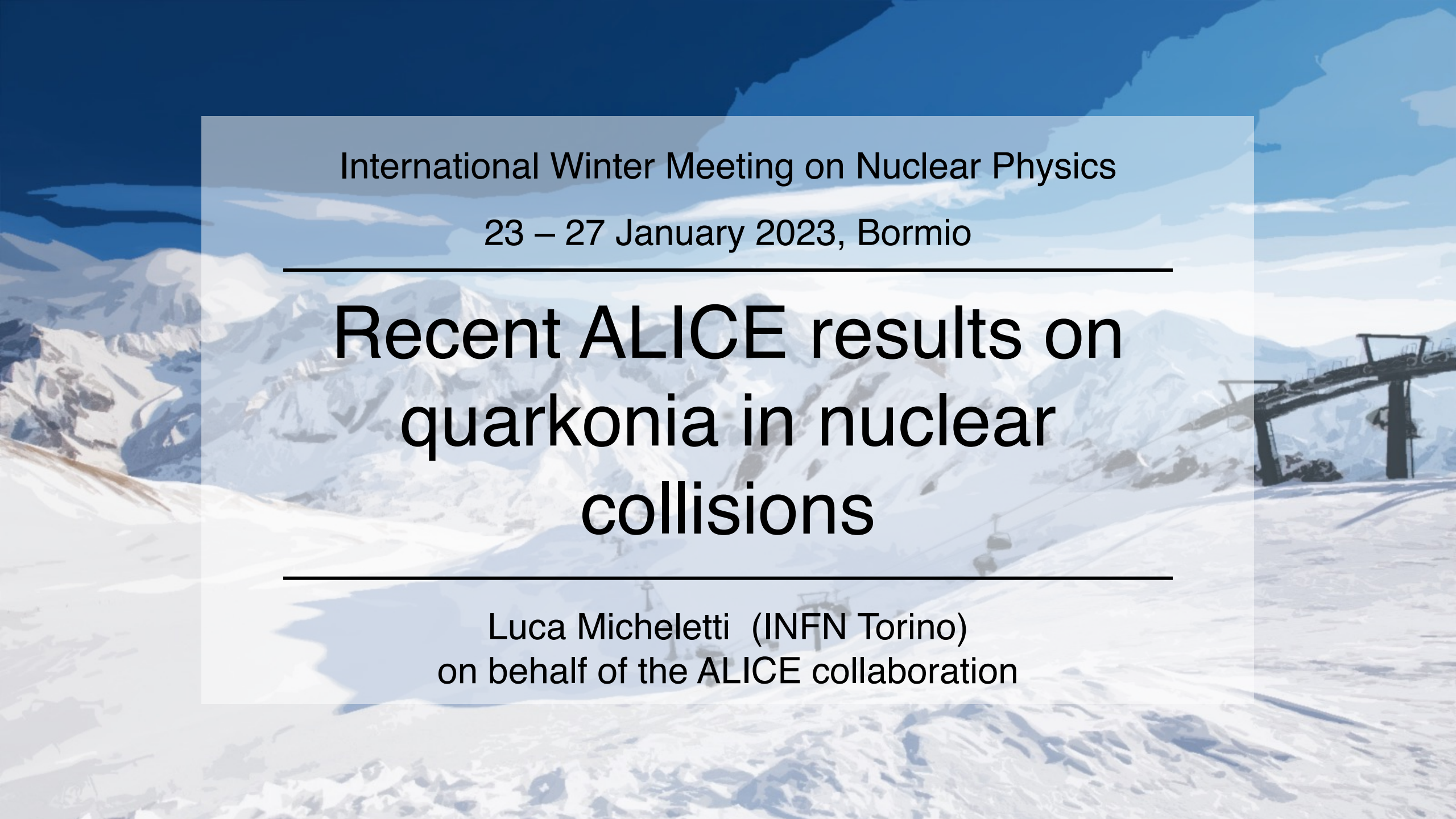


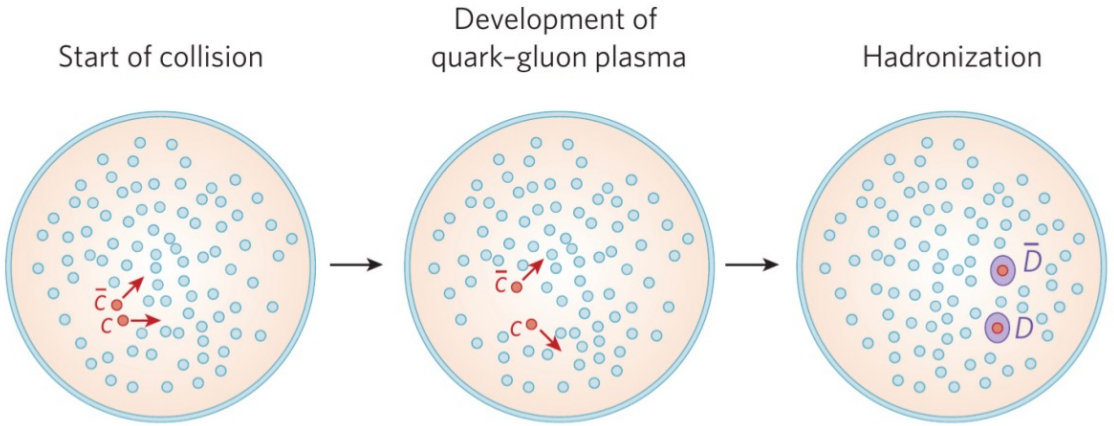
International Winter Meeting on Nuclear Physics

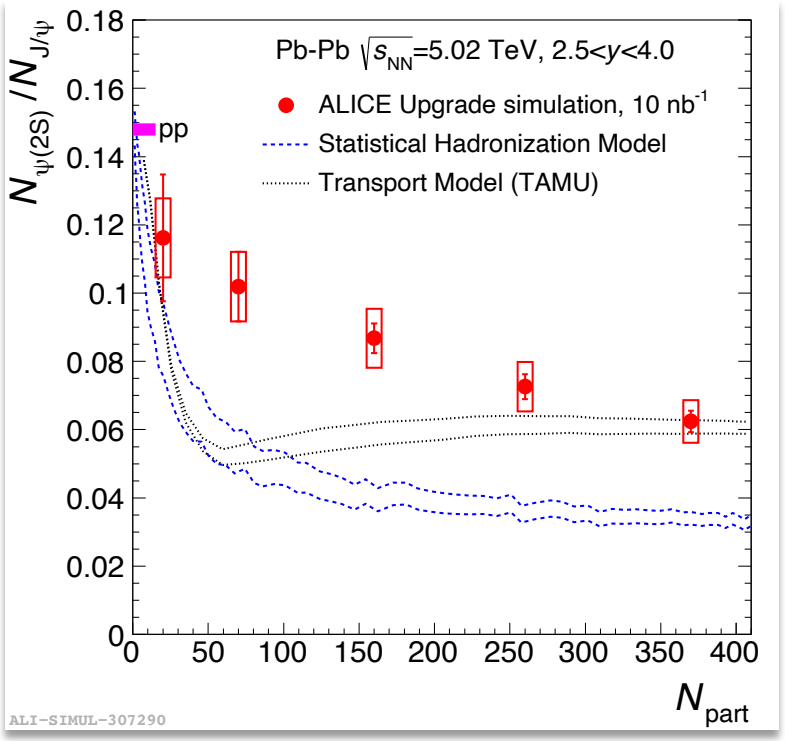
23 – 27 January 2023, Bormio

Recent ALICE results on quarkonia in nuclear collisions

Luca Micheletti (INFN Torino)
on behalf of the ALICE collaboration

Physics motivations





Quarkonium suppression

- In a strongly interacting medium quarkonium states can be dissociated by a **color screening mechanism**

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

  PR 858 (2020) 1-117, A. Rothkopf

- **Sequential melting** of the quarkonium states according to the binding energy

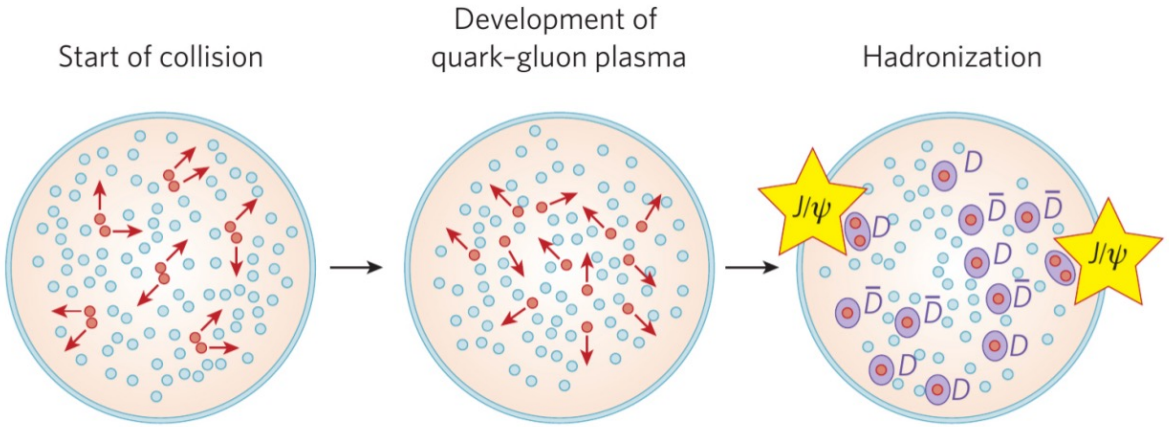
➢ **SHM**: quarkonia formed at hadronization

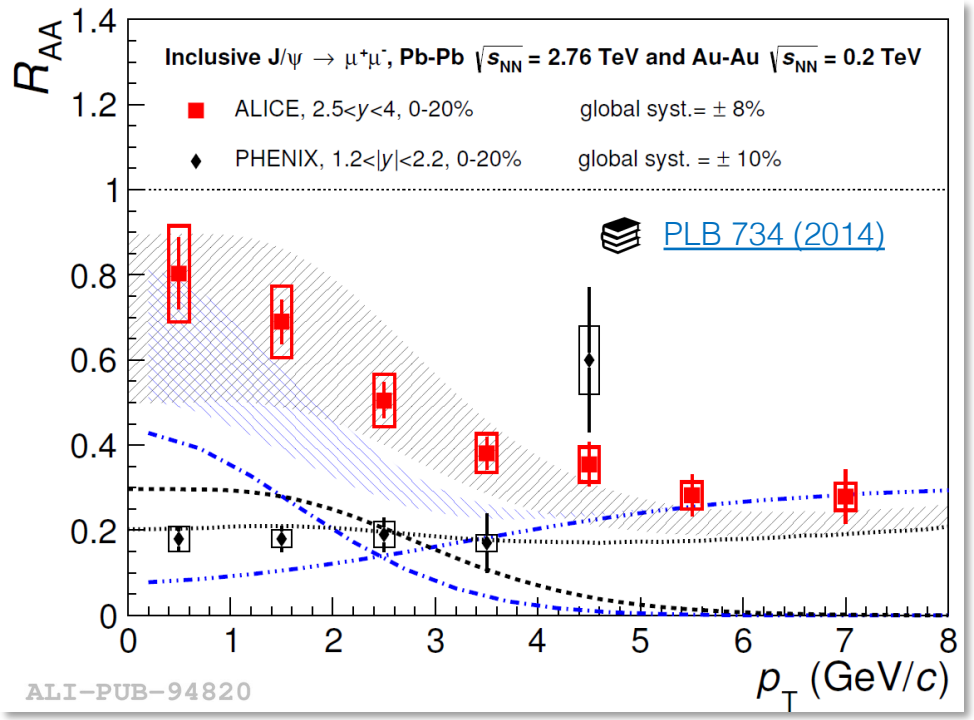
PLB 797 (2019) 134836, A.Andronic et al.

➢ **TAMU**: dissociation/recombination of quarkonia in the QGP phase

NPA 943 (2015) 147–158, X. Du, R. Rapp

Physics motivations





(Re)generation

- The aboundance of heavy quarks produced in HICs at LHC energies determines the statistical **(re)combination** of uncorrelated $\mathrm{Q\bar{Q}}$

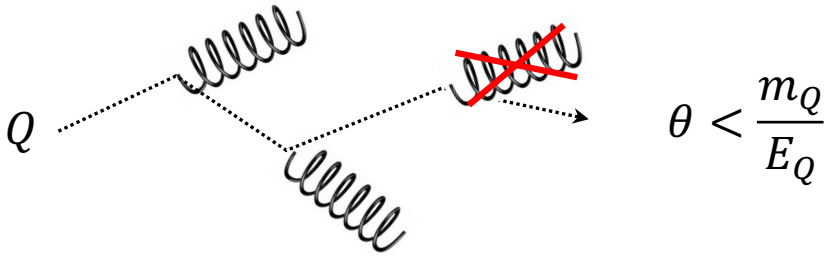
  PLB 490 (2000) 196-202, P. Braun-Munzinger, J. Stachel

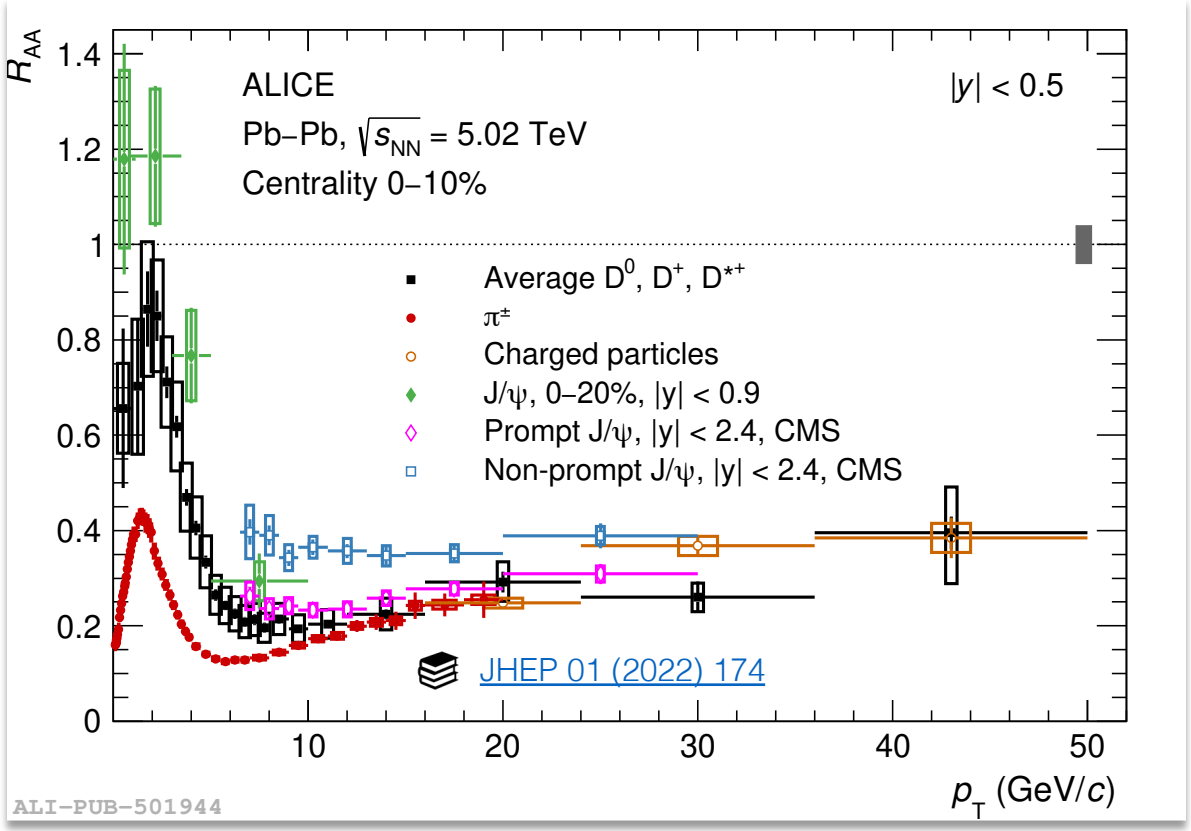
  PRC 63 (2001) 054905, R. Thews et al.

- The larger low-p_{T} $\mathrm{J/\psi}$ production at LHC w.r.t. RHIC is interpreted as a consequence of (re)generation

$$\sqrt{s_{\mathrm{NN}}} = 5.02\ \mathrm{TeV} \quad \begin{cases} \boldsymbol{N_{\mathrm{c\bar{c}}}/\mathrm{event} \sim 115} \\ N_{\mathrm{b\bar{b}}}/\mathrm{event} \sim 3 \end{cases}$$

Physics motivations





Heavy quarks energy loss in the QGP

- Sizeable charmonium fraction from beauty hadron decays ($J/\psi \leftarrow b$)
- Heavy quarks energy loss (radiative and collisional) in the QGP due to their early production via hard scattering
- Reduced radiative losses for beauty quarks due to the **dead cone effect**

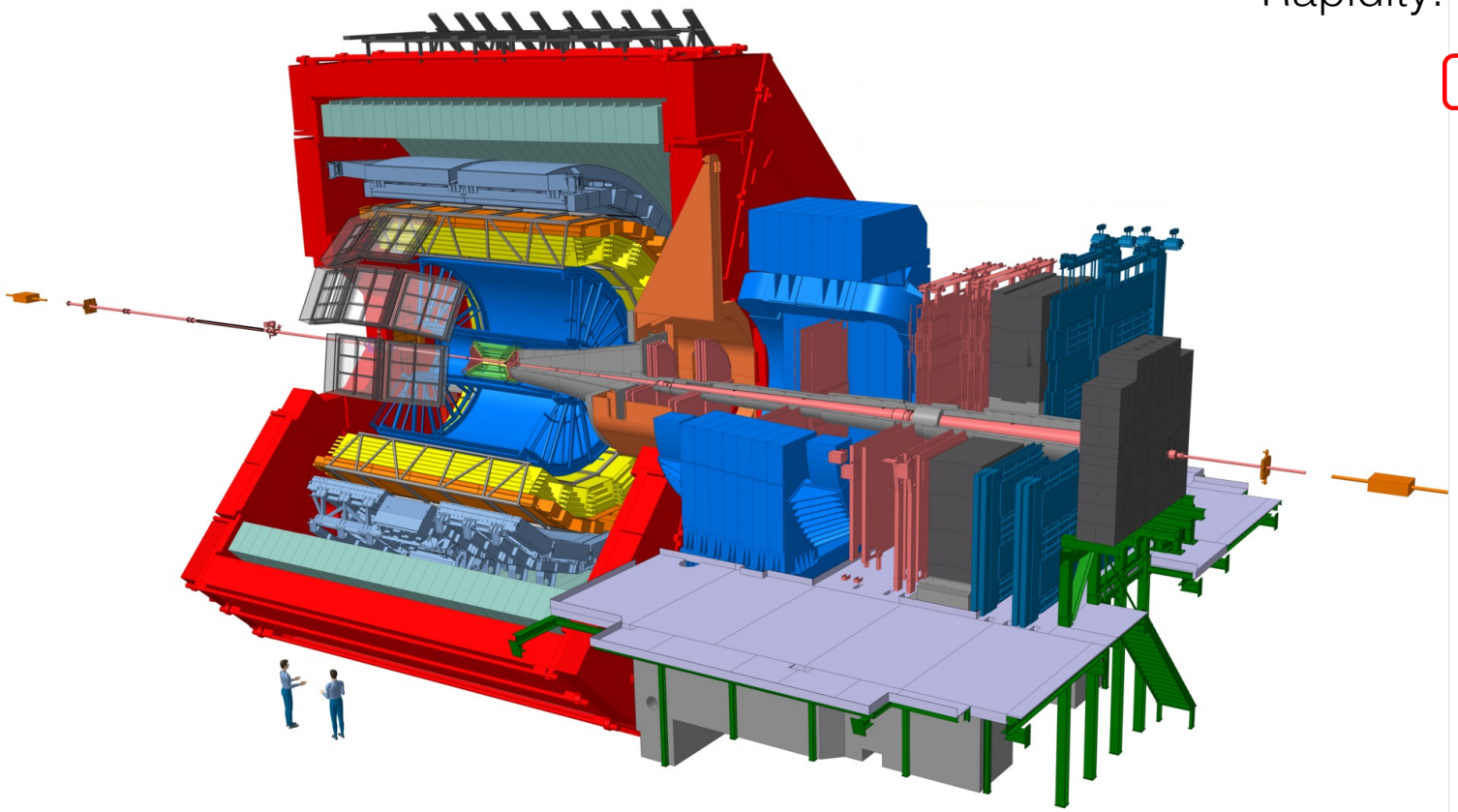
  Nature 605 (2022) 440-446, ALICE collaboration

- Hierarchy expected for the R_{AA} of light and heavy-flavor hadrons

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \cdot \frac{(dN/dy)_{AA}}{(dN/dy)_{pp}}$$

The ALICE experiment in Run2

ALICE is designed for the study of heavy-ion collisions



Central Barrel

- Rapidity: $|y| < 0.9$

I. Inner Tracking System

II. Time Projection Chamber

III. Time of Flight

IV. V0 detectors

Muon Spectrometer

- Rapidity: $2.5 < y < 4$

I. Front absorber

II. Dipole magnet

III. Tracking system

IV. Trigger system

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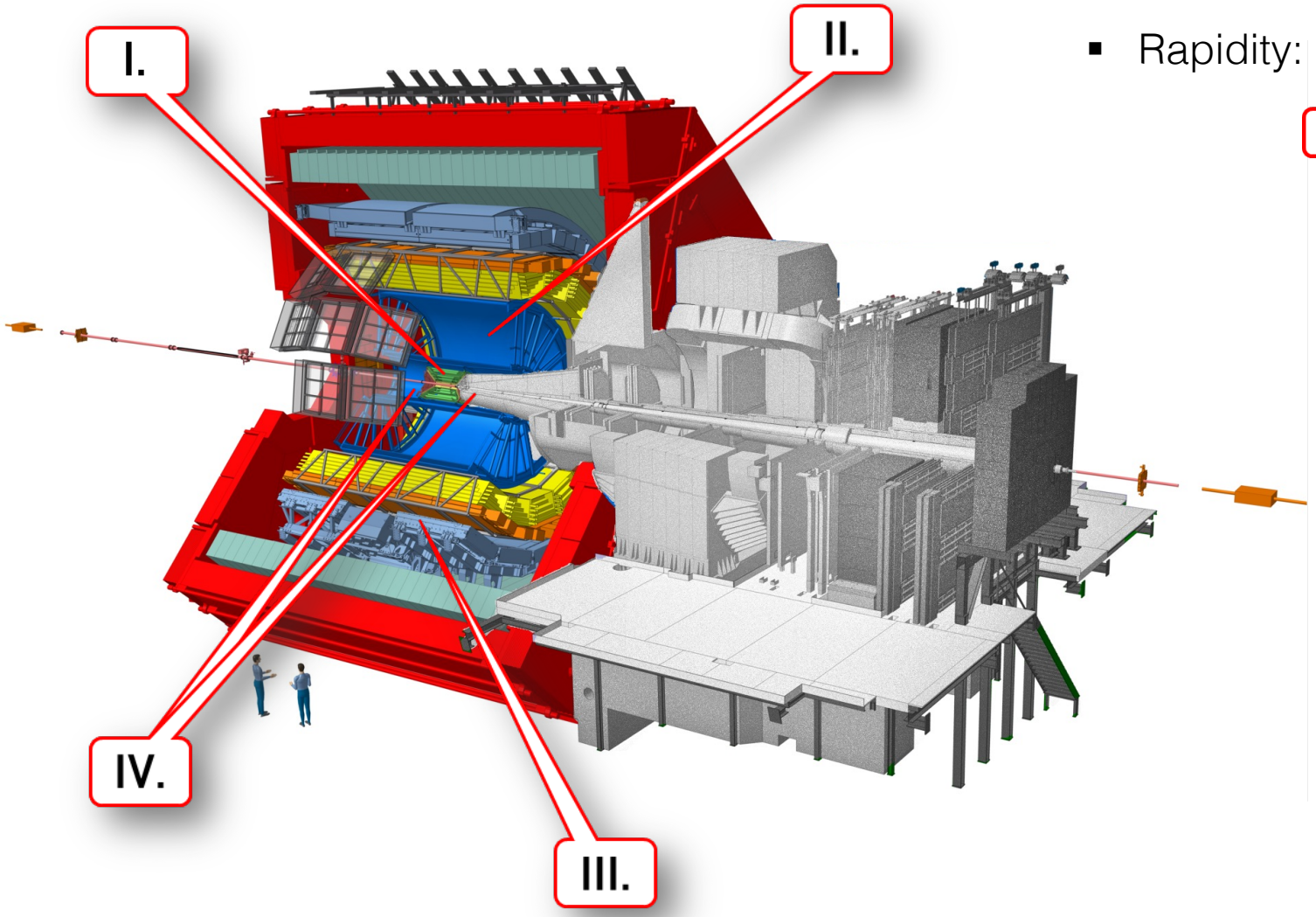

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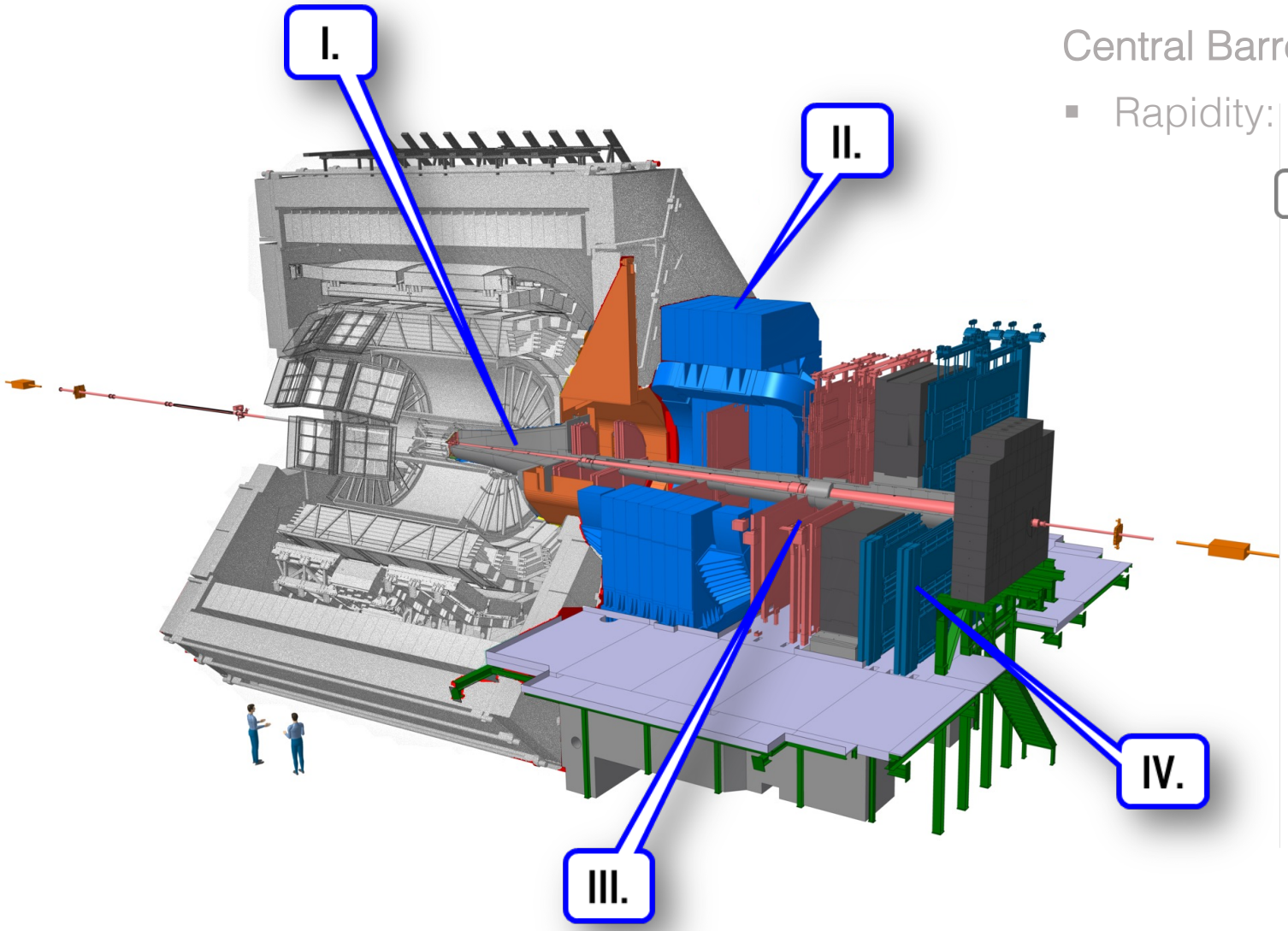

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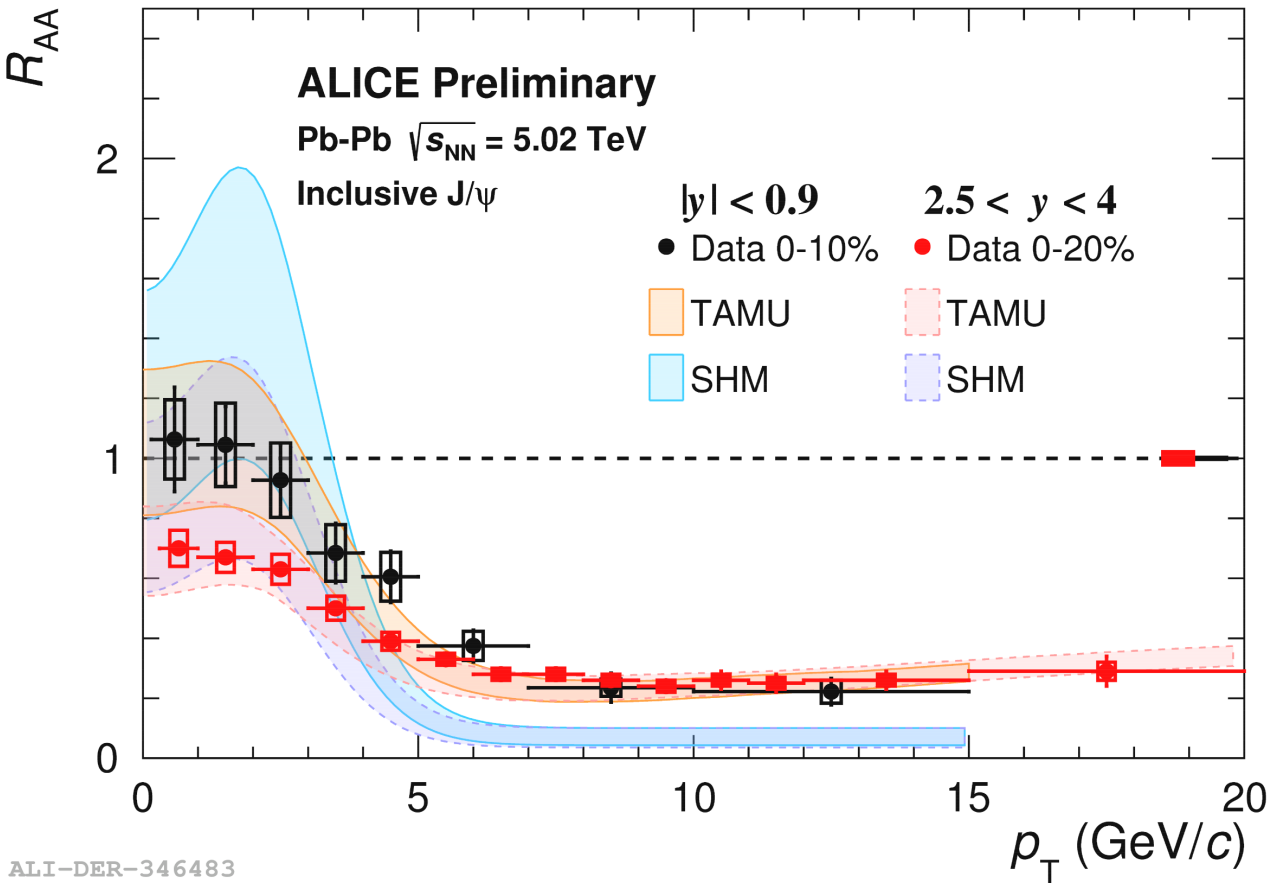
Inclusive J/ψ production

- Inclusive (prompt + non-prompt) J/ψ nuclear modification factor at mid and forward rapidity for central collisions vs p_{T}

- $R_{\mathrm{AA}}^{|y|<0.9} > R_{\mathrm{AA}}^{2.5<y<4}$ at low $\mathrm{p_T}$ due to the rapidity dependence of the regeneration

- Models including regeneration at the phase boundary (SHM) or in the QGP (TAMU) are in good agreement with data



PLB 797 (2019) 134836, A.Andronic et al., (SHM)

NPA 943 (2015) 147–158, X. Du, R. Rapp, (TAMU)

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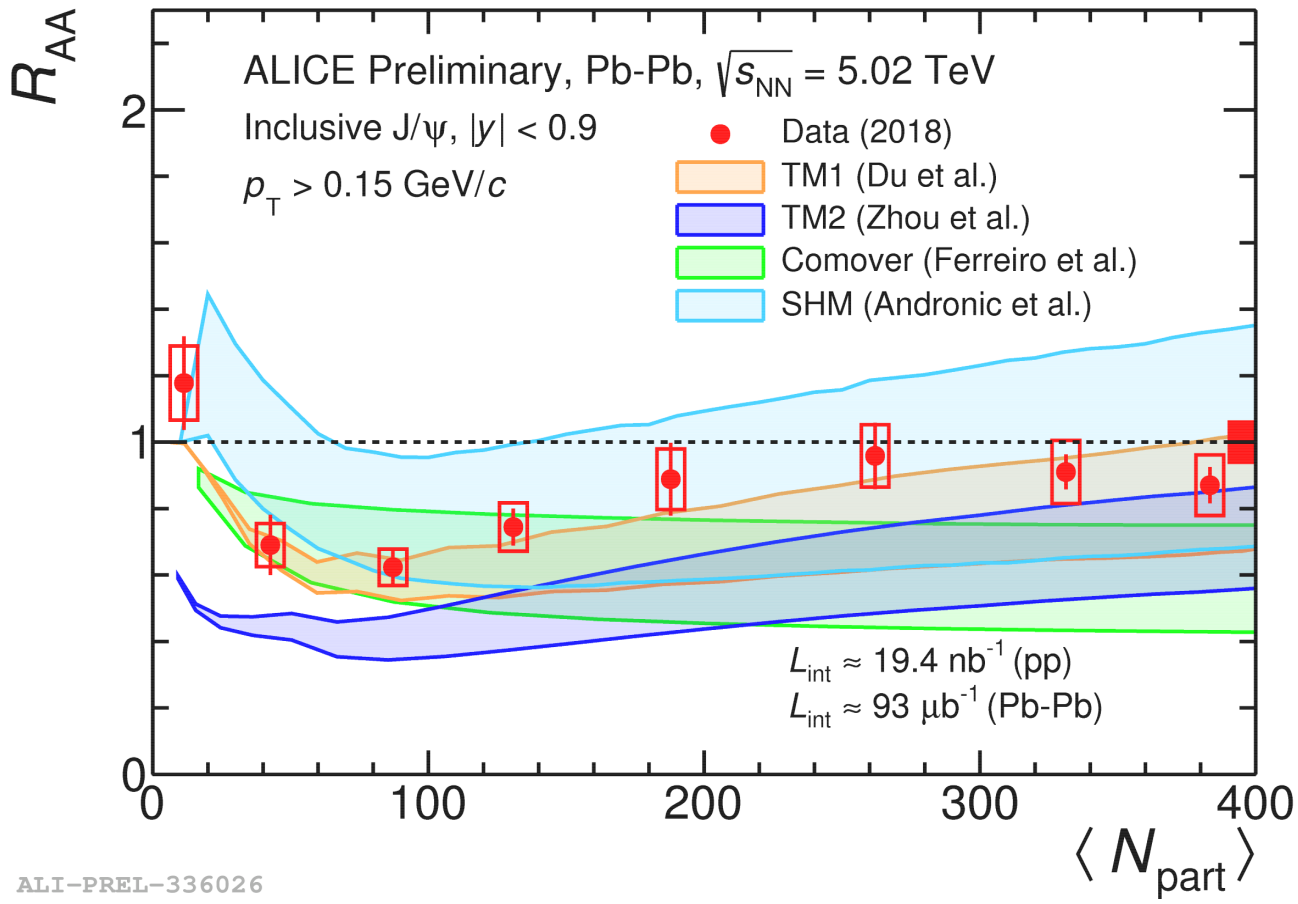
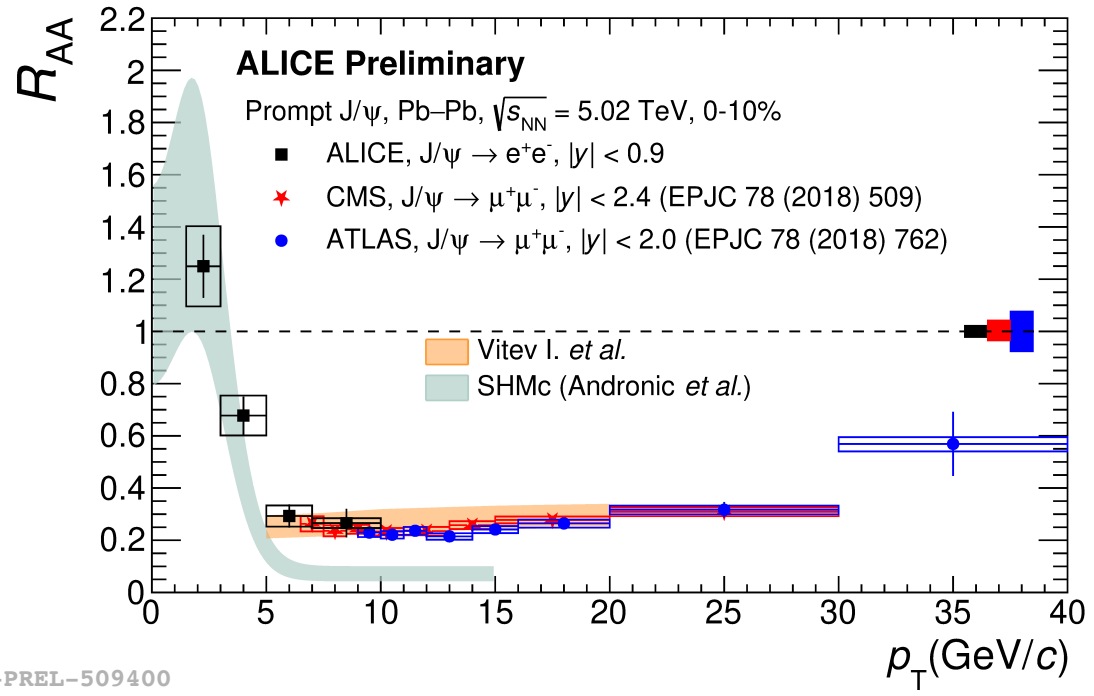
- Inclusive nuclear modification factor at mid rapidity vs centrality

  - Models qualitatively in agreement with data, but uncertainties hide the effect of the different J/ψ production phenomenology

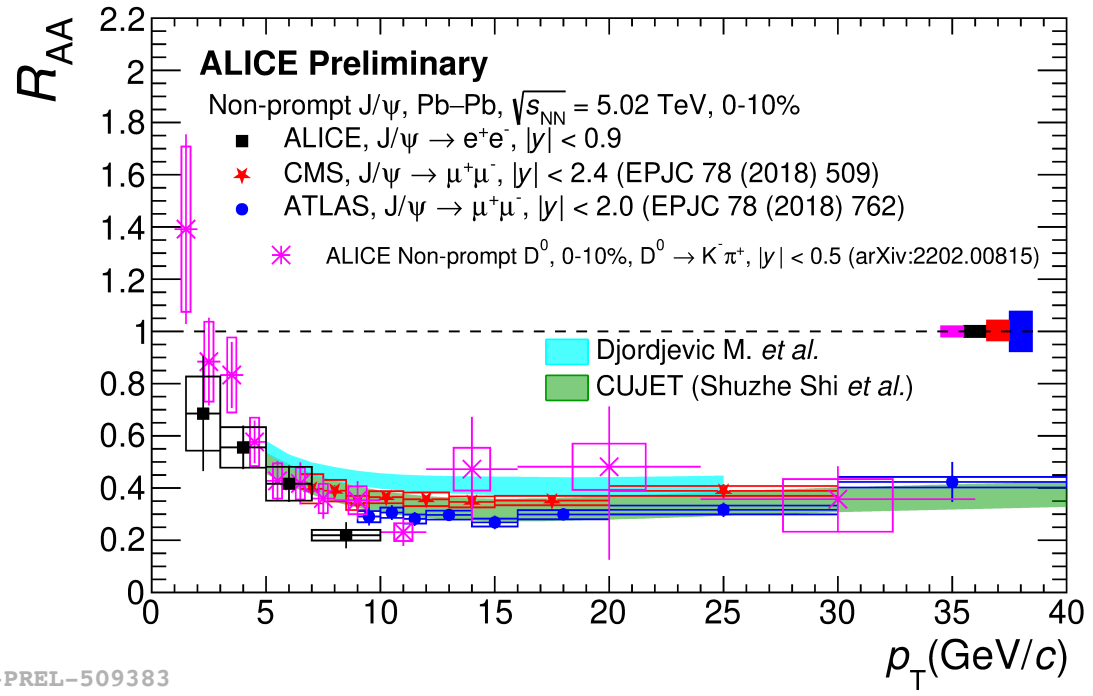


NPA 943 (2015) 147–158
PRC 89,054911 (2014)
PLB 731 (2014) 57
PLB 797 (2019) 134836

Prompt and non-prompt J/ψ production



ALI-PREL-509400



ALI-PREL-509383

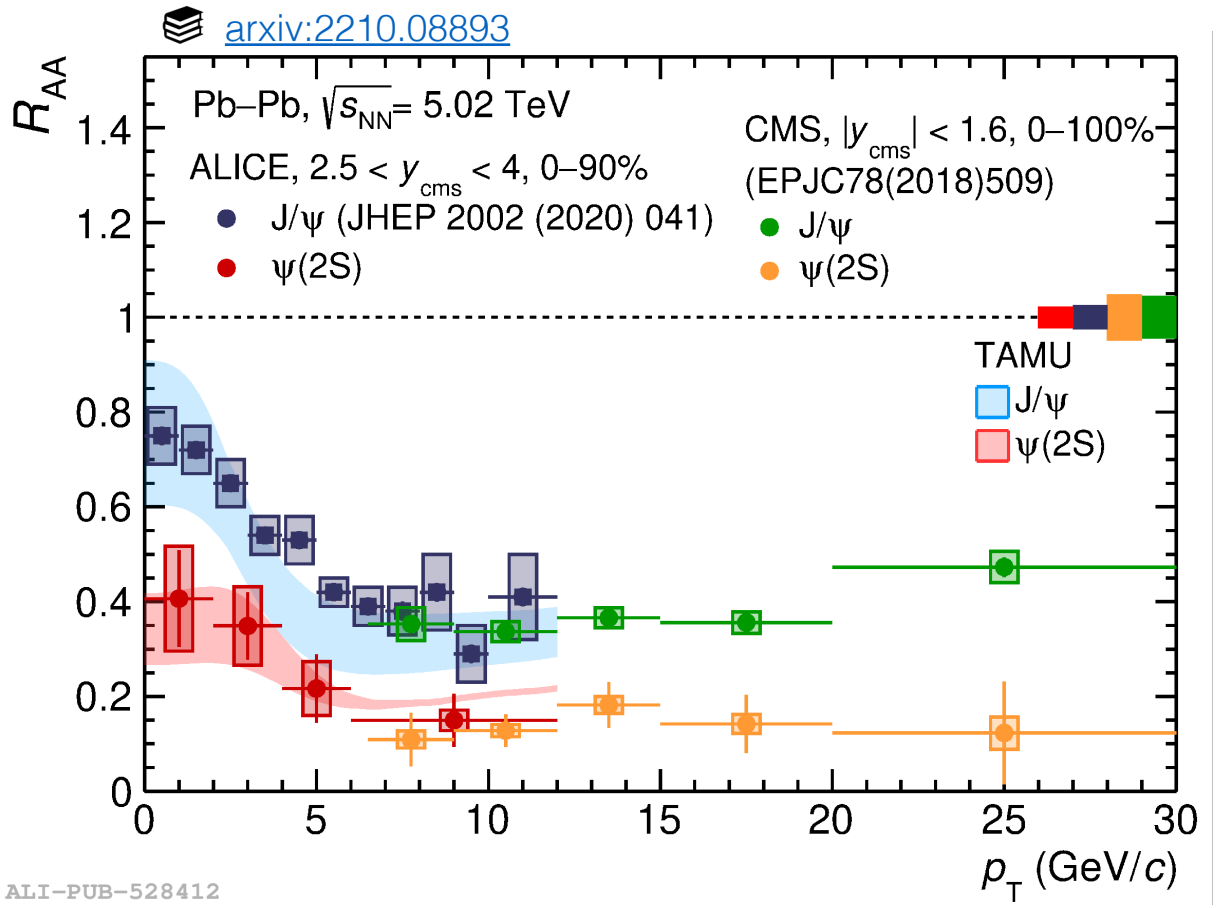
- SHM agrees with data for p_T < 5 GeV/c, model by Vitev et al. agrees for p_T > 5 GeV/c (energy loss of charmonia in the QGP)
  - JHEP 10 (2019) 111, I. Vitev et al.
  - Nature 561 (2018) 7723, A. Andronic et al.
- Good agreement among LHC experiments

- Good agreement with models including **collisional** and **radiative energy loss**
  - PRC 105, L021901 (2022) , M. Djordjevic et al.
  - CPC 43 (2019) no.4, 044101, S. Shuzhe et al.
- Similar trend for non-prompt J/ψ and D^0

ψ(2S) production in Pb-Pb collisions

- Inclusive $\psi(2S)$ nuclear modification factor at forward rapidity vs p_{T}

- $\psi(2S)$ more suppressed than J/ψ
- Lower suppression at low- p_{T} w.r.t. high- p_{T} as a possible hint of **regeneration**
- Nice continuity among **ALICE** and **CMS**
- **TAMU** model well in agreement with data



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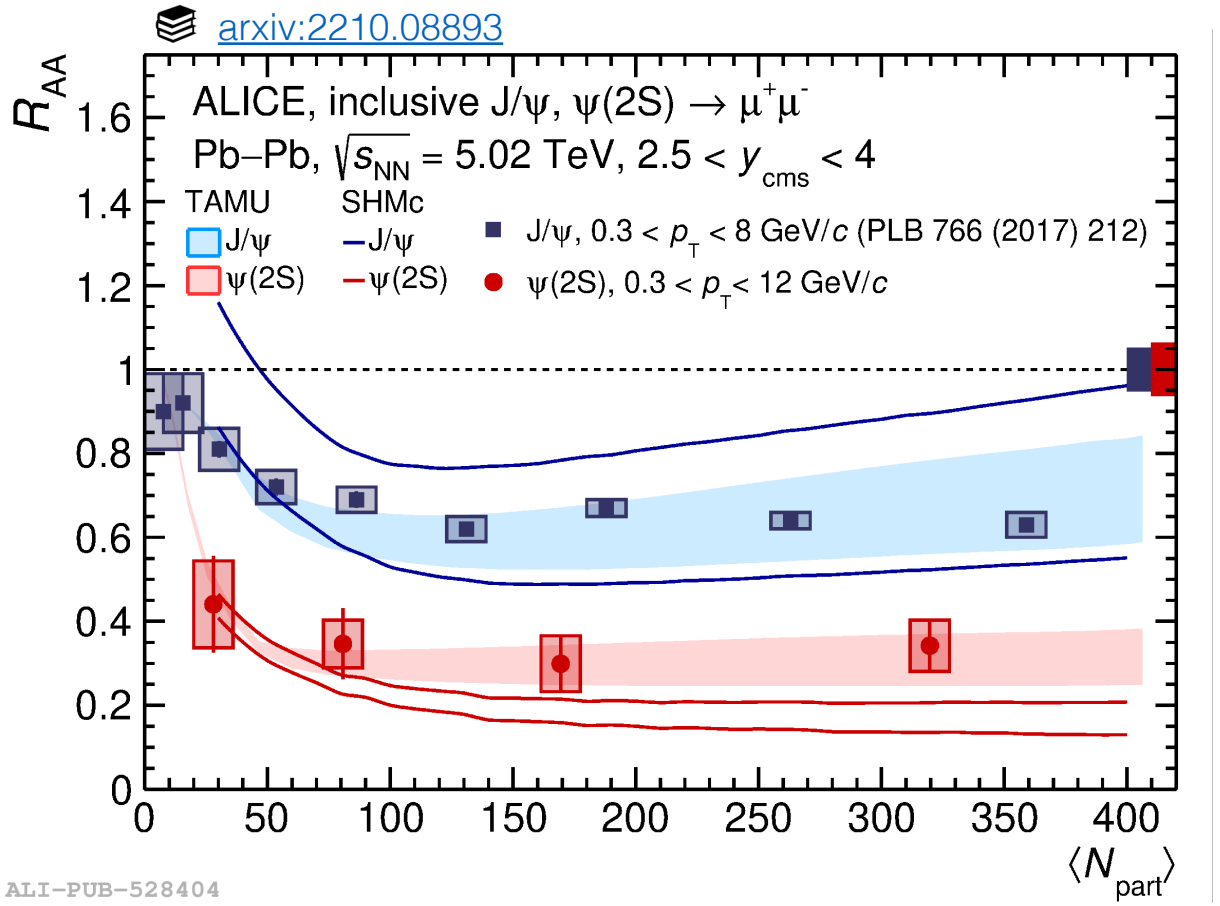
- Inclusive $\psi(2S)$ nuclear modification factor at forward rapidity vs centrality
  - $\psi(2S)$ R_{AA} flat vs centrality within uncertainties
  - **TAMU** model well in agreement with data, while **SHM** tends to underestimate the R_{AA} in central events



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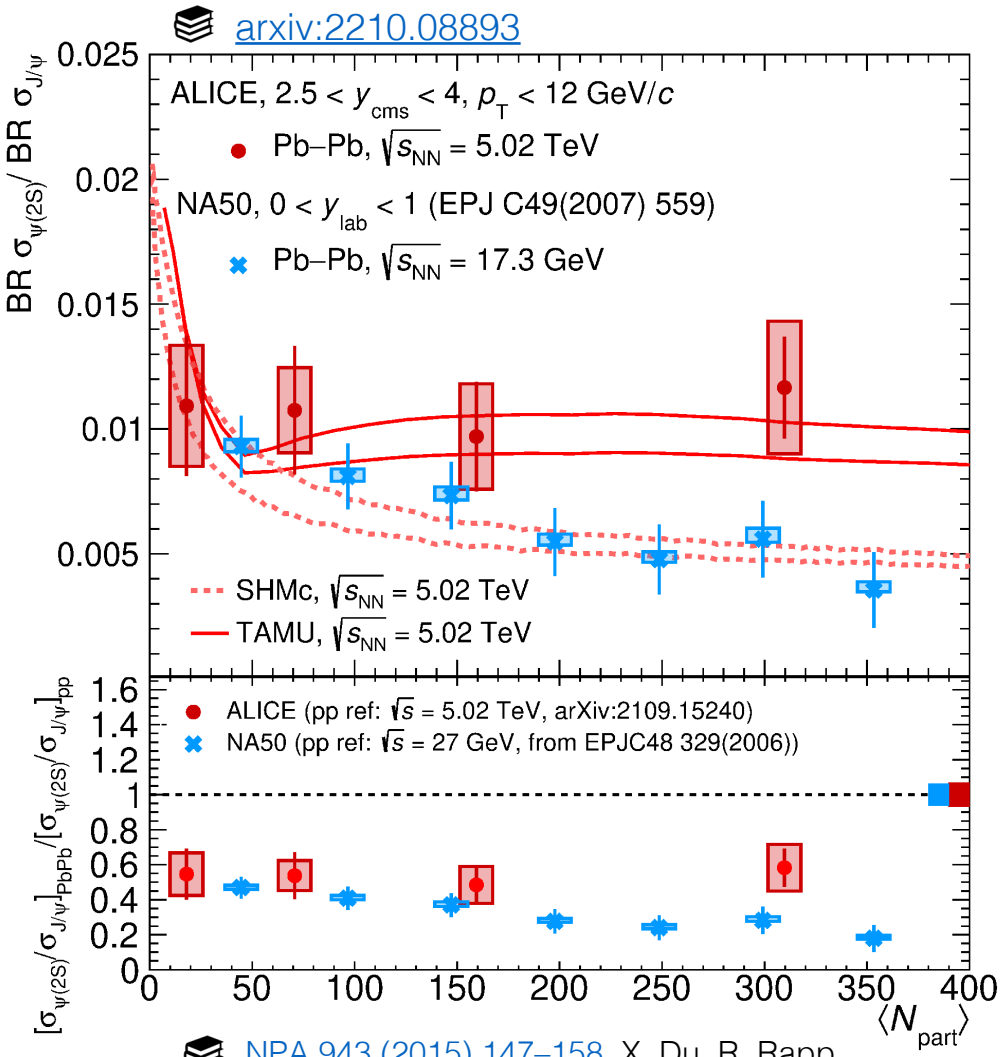
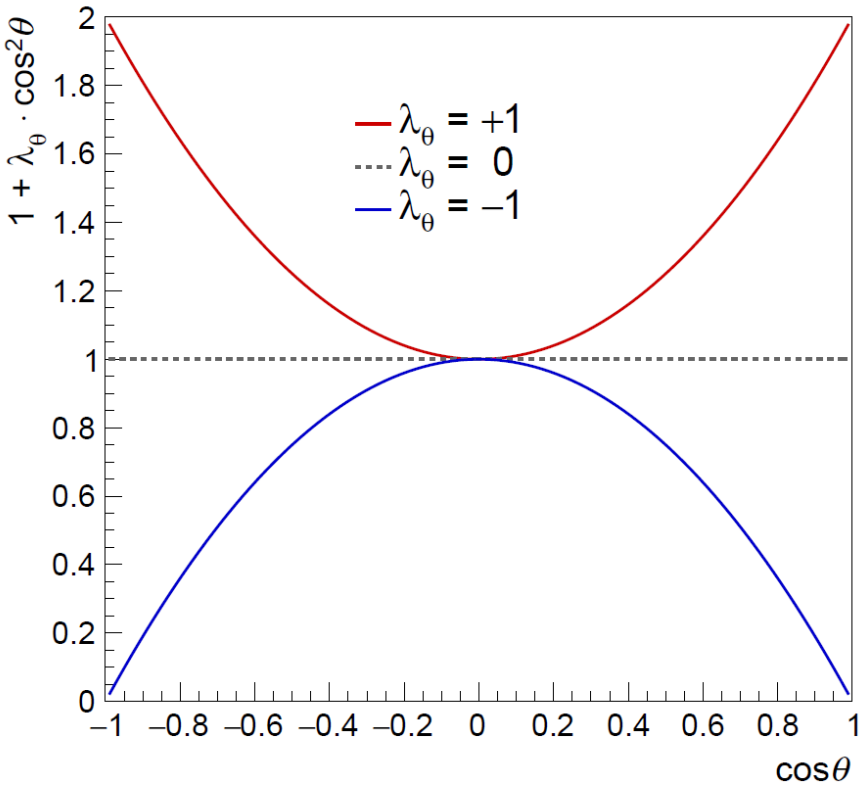
  - **TAMU** model well in agreement with data, while **SHM** tends to underestimate the R_{AA} in central events
- Inclusive $\psi(2S)$-to-J/ψ (double) ratio vs centrality
  - Larger ratio at LHC than at SPS in central events



J/ψ polarization in Pb-Pb collisions

- Polarization refers to the particle spin alignment with respect to a chosen direction
- For a vector meson (ν) the total angular momentum (J, J_z) state can be expressed as:



- $|\nu: J, J_z\rangle = b_{+1}|1,+1\rangle + b_0|1,0\rangle + b_{-1}|1,-1\rangle$

Spin-alignment ⇔ decay products angular distribution

EPJC 69 (657-673), 2010, Faccioli et al.

Dilepton decay angular distribution

- $W(\cos\theta, \phi) \propto \frac{1}{3+\lambda_\theta} \cdot (1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi)$

❑ Polarization parameters

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (0,0,0)$ ⟹ No polarization

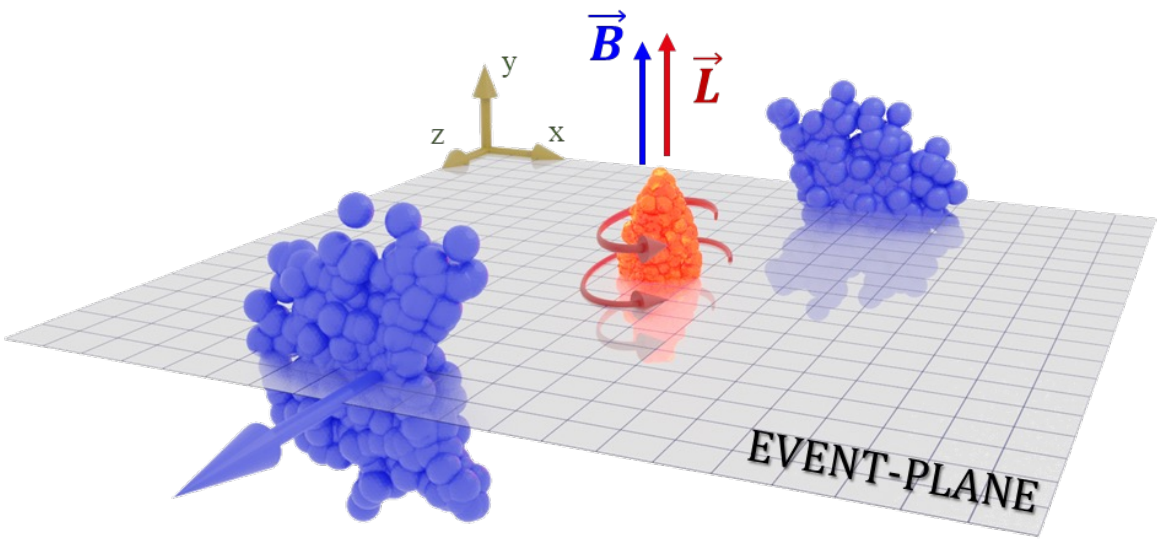
$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (+1,0,0)$ ⟹ Transverse polarization

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi}) = (-1,0,0)$ ⟹ Longitudinal polarization

J/ψ polarization in Pb-Pb collisions

Possibility to investigate the role of $\vec{L}$ and $\vec{B}$ with an ad hoc reference frame

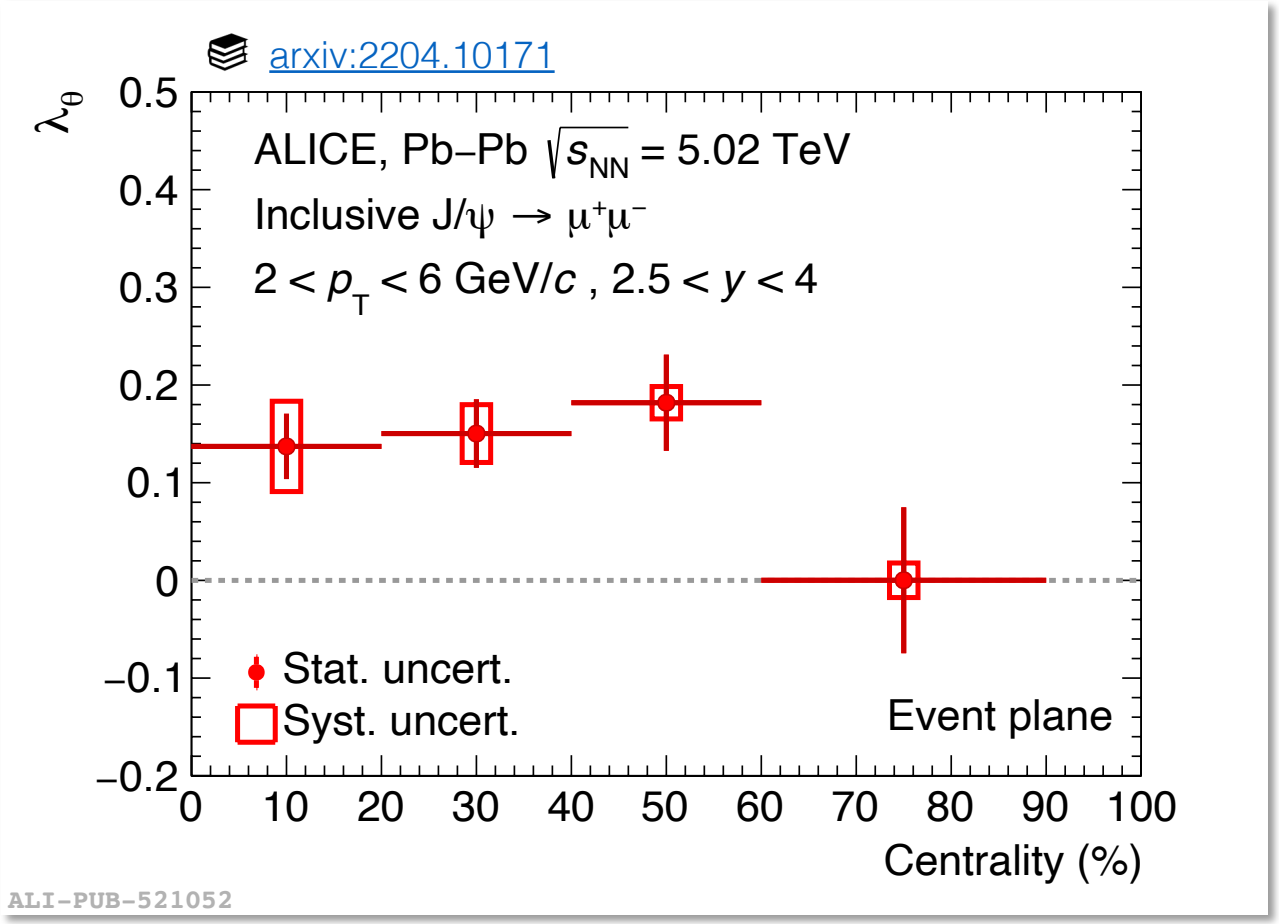
- **Large angular momentum** due to the medium rotation is predicted — PRC 77 (2008) 024906, Becattini et al.
- **Huge magnetic field** ($|\vec{B}| \sim 10^{14}$ T) is expected to be short-living — NPA 803 (2008), Kharzeev et al.



- Event Plane based frame (EP): axis orthogonal to the event plane in the collision center of mass frame
  - Event Plane normal to $\vec{B}$ and $\vec{L}$
  - Significant spin alignment observed for light vector mesons (K^{*0}, ϕ)

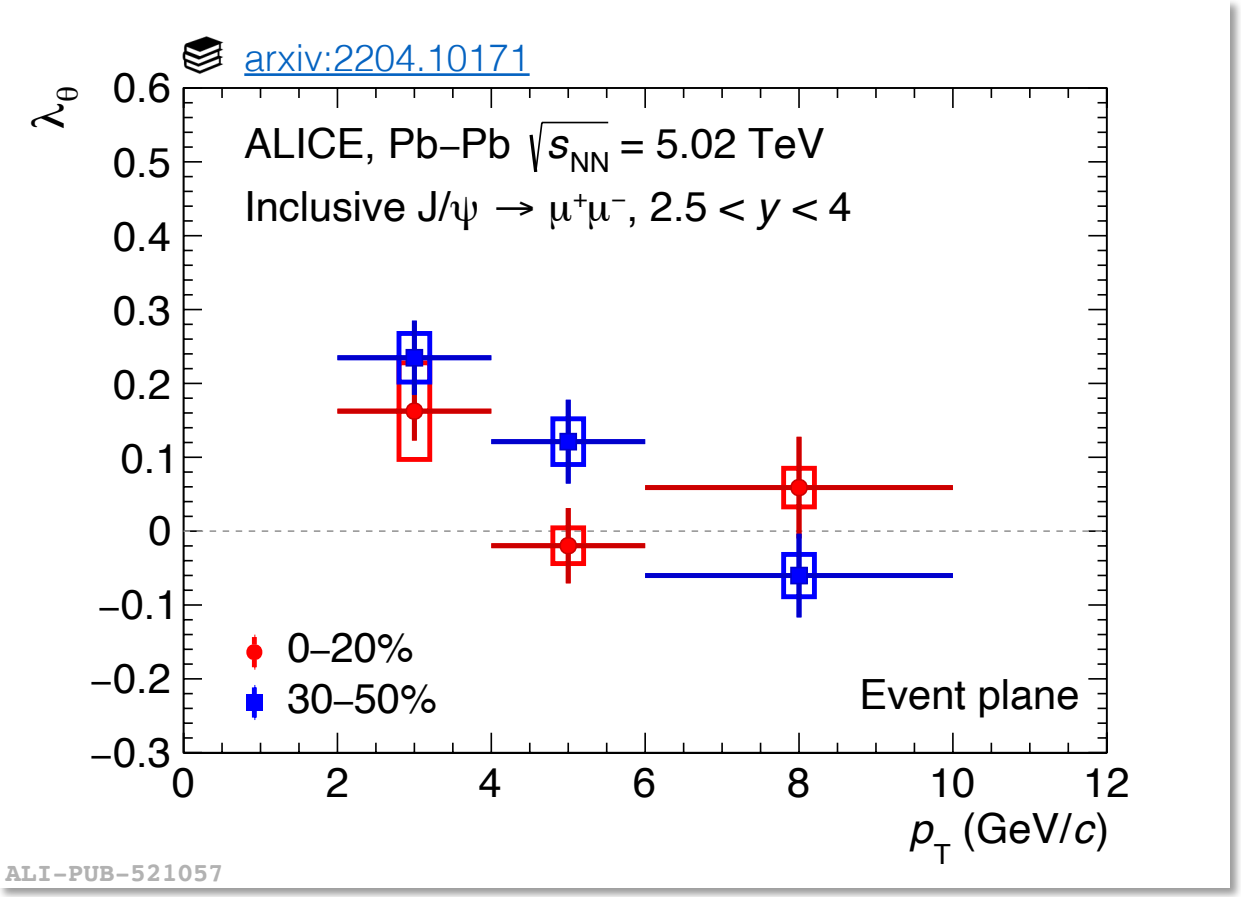
    PRL 125 (2020) 012301
  - Heavy quark pair production occurs early in the collision ($t \sim 0.1$ fm/c)

J/ψ polarization in Pb-Pb collisions



- First measurement of quarkonium polarization with respect to the Event Plane
  - Centrality dependence:
    Small but significant (3.5σ) polarization observed in 40-60% and $2 < p_T < 6$ GeV/c

J/ψ polarization in Pb-Pb collisions



- First measurement of quarkonium polarization with respect to the Event Plane
  - p_T dependence:
    30-50%: significant deviation (3.9σ) at low transverse momentum ($2 < p_T < 4$ GeV/c)

- Similarly to light flavors (K^{*0}, ϕ) maximum polarization for semicentral collisions at low p_T

  PRL 125 (2020) 012301

  BUT

- Not clear which contribution (**vorticity** and / or **magnetic field**) is the dominant one
- The same explanation for light vector mesons can be extended to charmonia?

  arXiv:2205.15689, Xin-Li Sheng et al.

Summary and conclusions

- Inclusive J/ψ and $\psi(2S)$ nuclear modification factor vs p_{T} and centrality
  - $\psi(2S)$ more suppressed than J/ψ
  - Transport model (**TAMU**) describes well the magnitude and the trend of the $\mathrm{R_{AA}}$
  - **SHM** is qualitatively in agreement with data but tends to underestimate the $\psi(2S)$ $\mathrm{R_{AA}}$ in central events

- Prompt J/ψ nuclear modification factor vs p_{T}
  - Results are described at low-p_{T} by model including regeneration (SHMc), dissociation at high-p_{T} and energy loss in the QGP (Vitev et al.)

- Non-prompt J/ψ nuclear modification factor vs p_{T}
  - Models including **radiative** and **collisional energy loss** are in fair agreement with data at high-p_{T}

- J/ψ polarization with respect to the event-plane
  - Significant polarization observed for the first time **BUT** a full theoretical description is missing