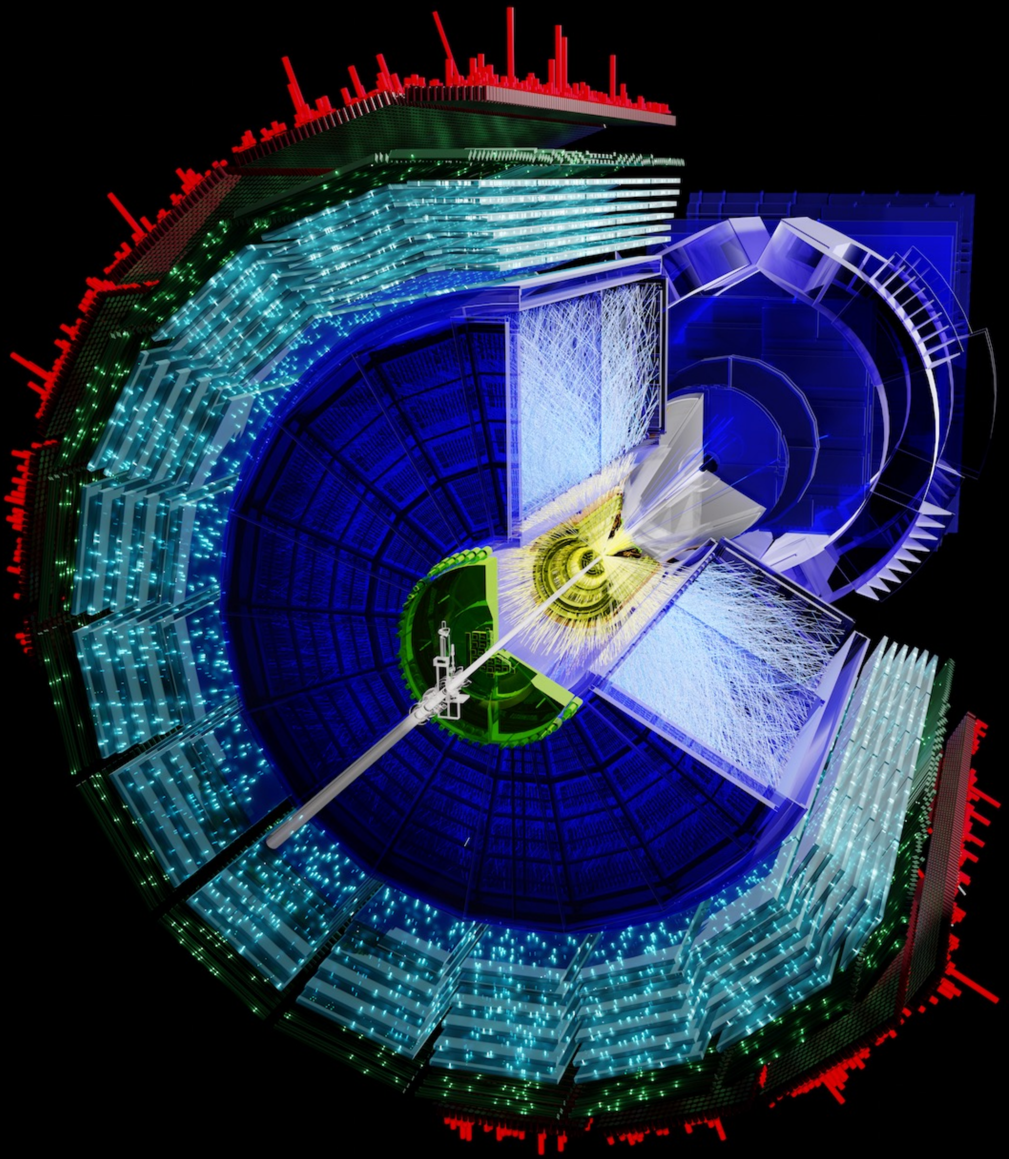


Quarkonium production and collectivity in heavy-ion collisions with ALICE

Luca Micheletti
On behalf of the ALICE experiment

09/07/2025

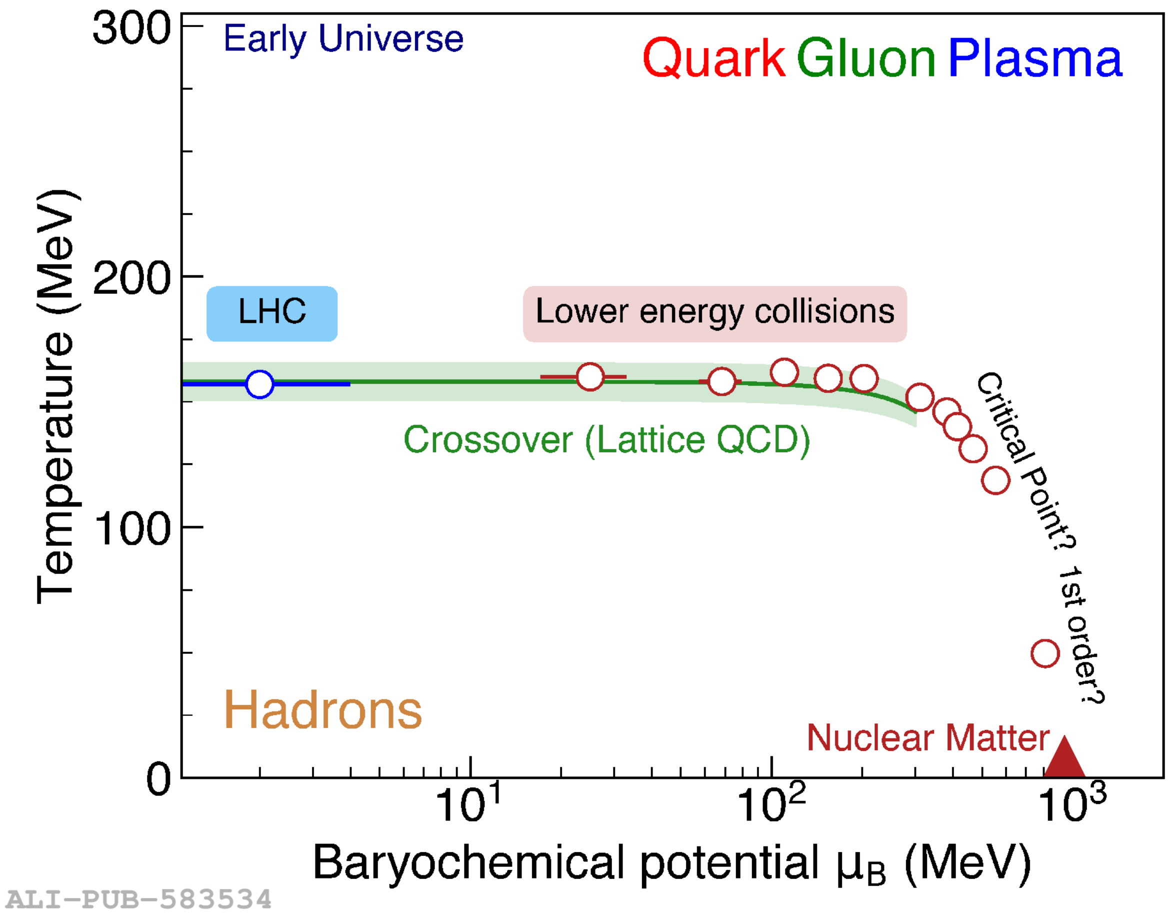
EPS-HEP 2025

ALICE

INFN TORINO

Physics motivations

Quark-gluon plasma (QGP): state of matter in which **quarks** and **gluons** are no more confined into hadrons



- **QGP phase diagram**: illustrates the phase transition in terms of **temperature ($\mathbf{T}$)** and **baryochemical potential ($\boldsymbol{\mu}_\mathbf{B}$)**
- From lattice QCD calculations:
  - Critical energy density (ε_c) ~ 0.5 GeV/c^3
  - Critical temperature (T_c) ~ 150 MeV

Eur. Phys. J. C 84 (2024) 813, ALICE

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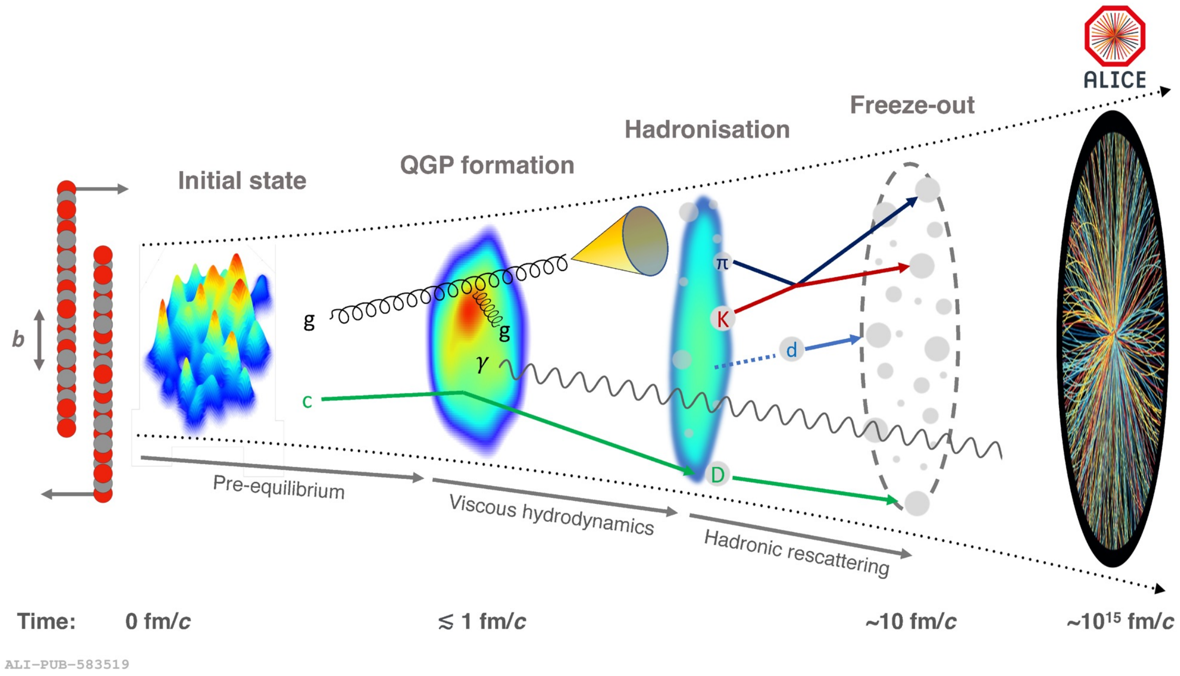


Eur. Phys. J. C 84 (2024) 813, ALICE

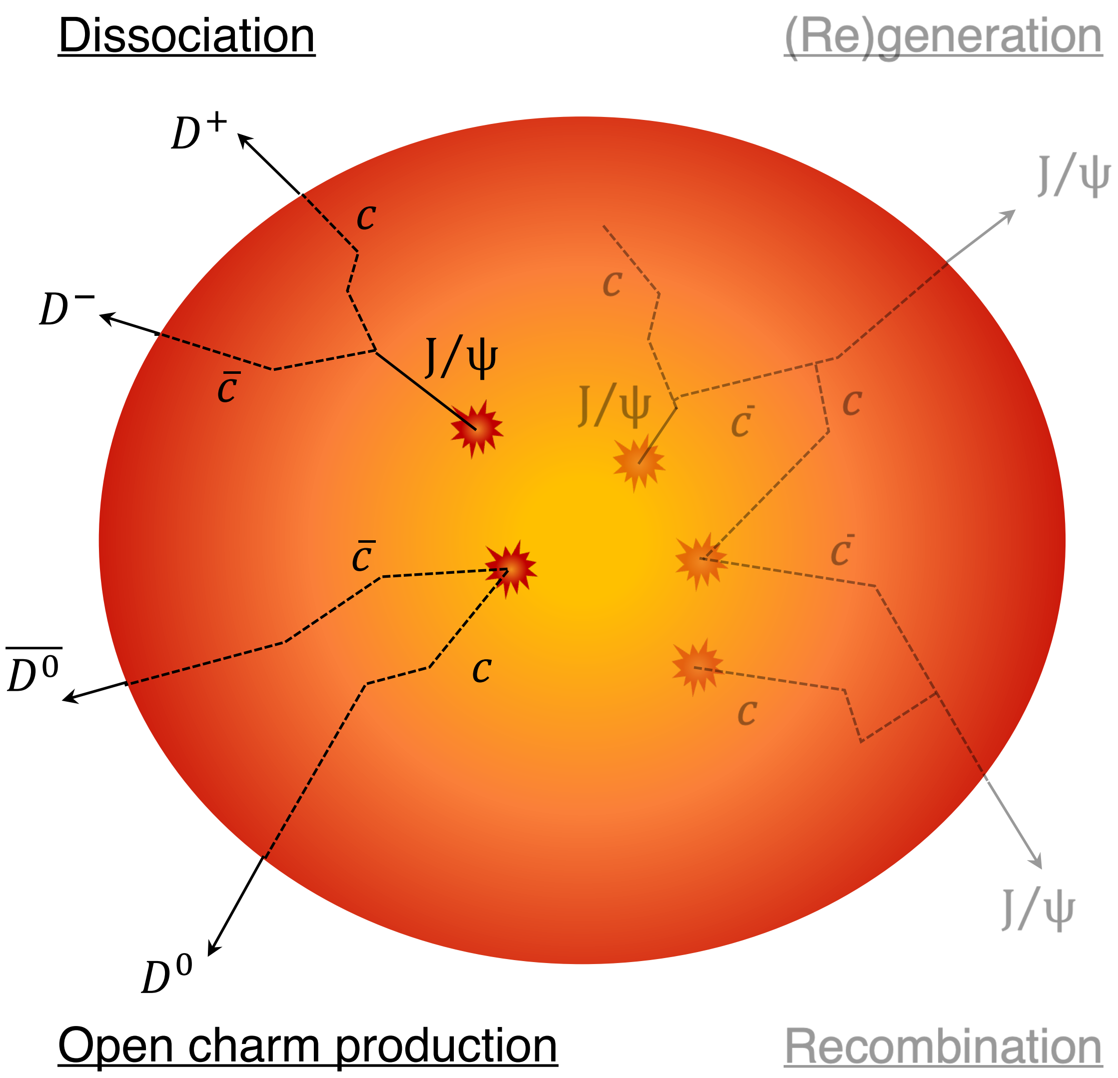
- **QGP phase diagram**: illustrates the phase transition in terms of **temperature** ($\mathbf{T}$) and **baryochemical potential** (μ_B)
- From lattice QCD calculations:
  - **Critical energy density** (ε_c) ~ 0.5 GeV/c³
  - **Critical temperature** (T_c) ~ 150 MeV
- QGP rapid evolution / expansion ($\tau_{QGP} \sim 10$ fm/c)

❑ Quarkonia ($c\bar{c}$ & $b\bar{b}$):
  - **Heavy quarks** produced in the first stages of the collision ($\tau_{HQ} \sim 0.05 - 0.1$ fm/c)
  - Cross section can be computed within the **factorization approach (NRQCD)**

Phys.Rev.D51:1125-1171,1995, Bodwin et al.

Quarkonia ideal probe to investigate QGP!

Quarkonia & QGP



Quarkonium suppression

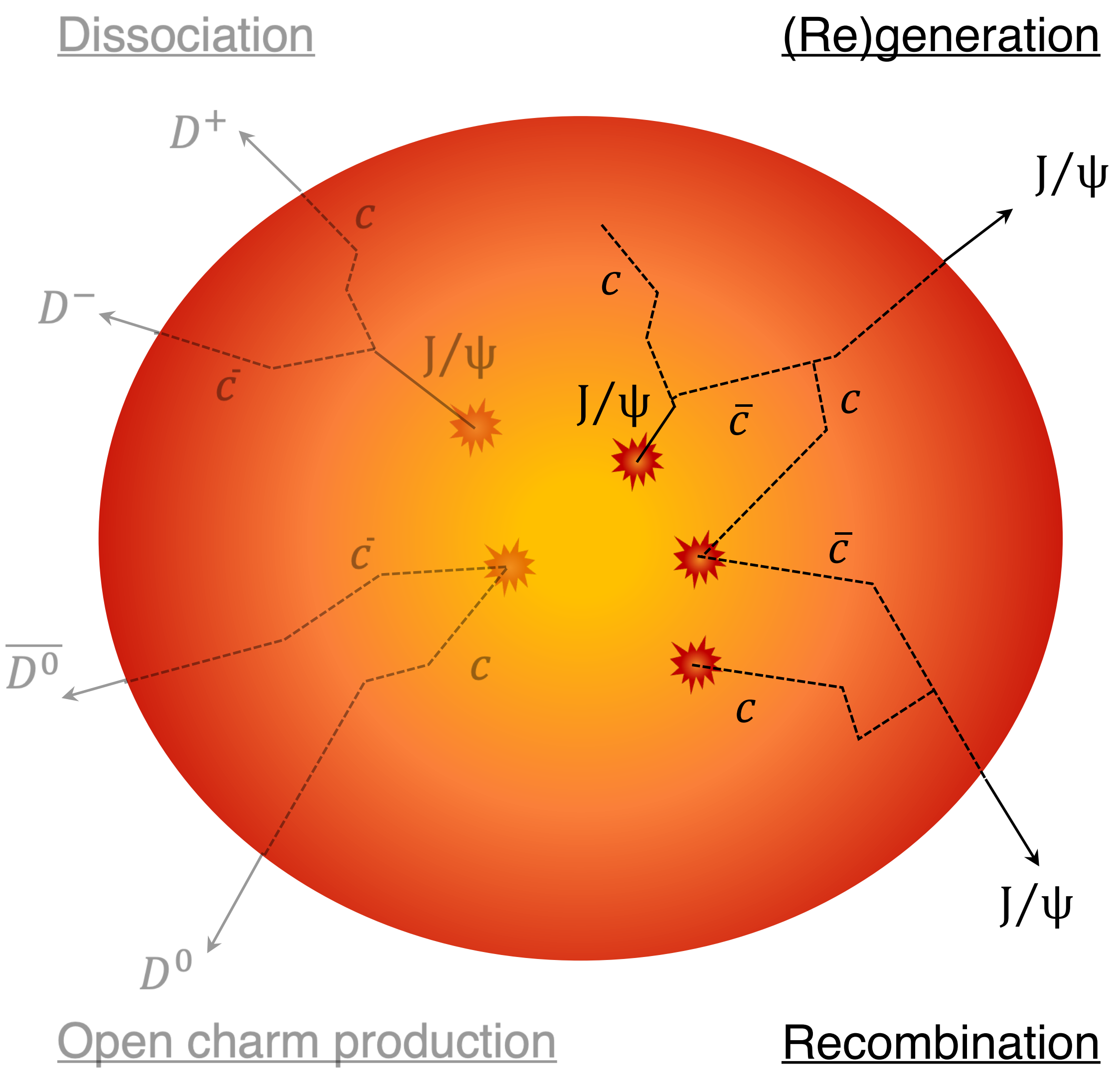
- In a strongly interacting medium quarkonium states can be dissociated by a **color screening mechanism**

  - PLB 178 (1986) 416, T. Matsui, H. Satz
  - PR 858 (2020) 1-117, A. Rothkopf
  - PRD 109 (2024) 7, 074504 A. Bazavov et al.

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

	charmonia			bottomonia		
	J/ψ	χ_c	ψ(2S)	ϒ(1S)	ϒ(2S)	ϒ(3S)
Mass (GeV)	3.10	3.53	3.68	9.46	10.02	10.36
E_B (GeV)	0.64	0.20	0.05	1.10	0.54	0.20

Quarkonia & QGP



(Re)generation / recombination

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

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

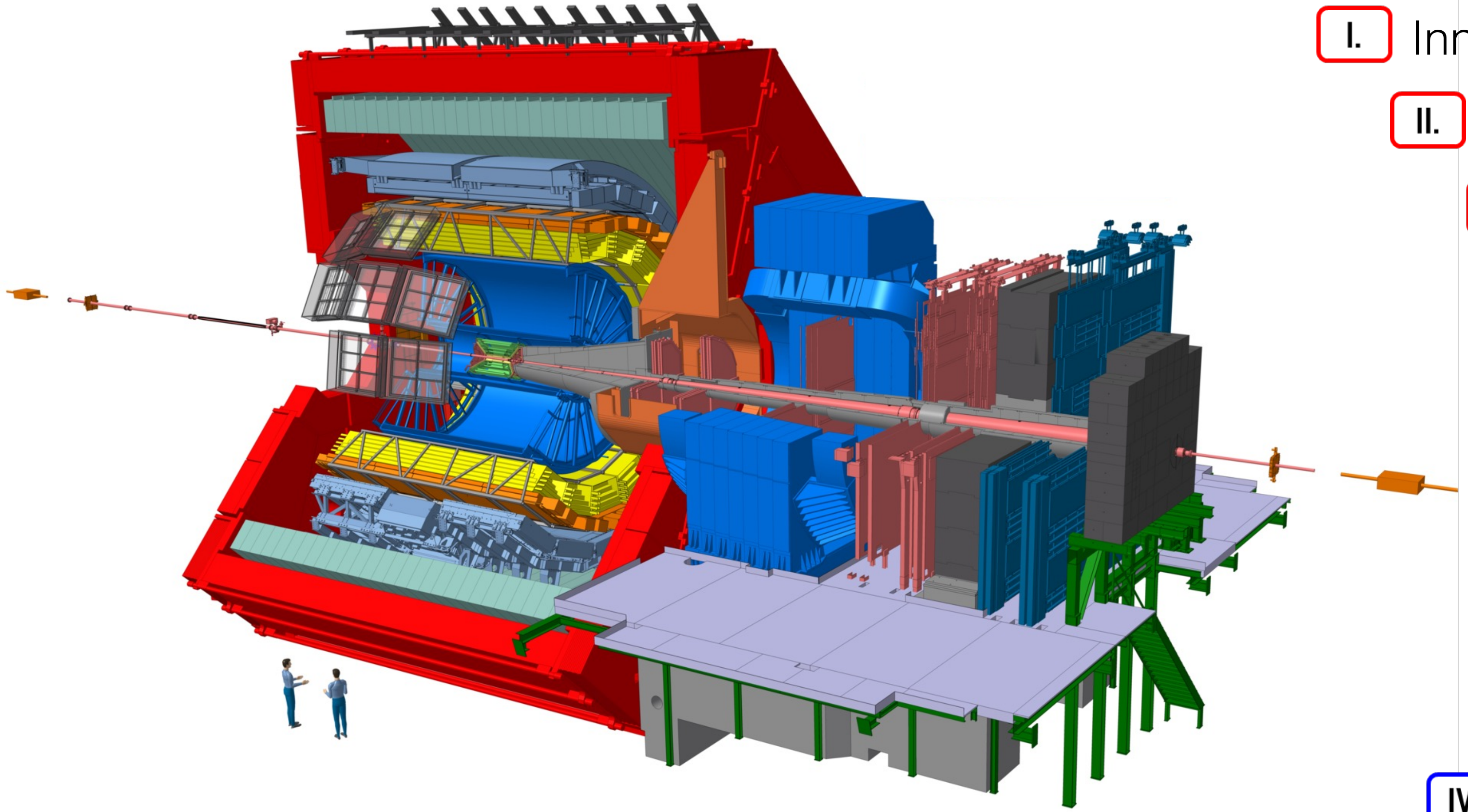
PRC 63 (2001) 054905, R. Thews et al.

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

	RHIC $\sqrt{s_{\mathrm{NN}}} = 200$ GeV	LHC $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV
$\mathrm{N_{c\bar{c}}}$/event	10	115
$\mathrm{N_{b\bar{b}}}$/event	0.05	3

A Large Ion Collider Experiment

■ Trigger ■ Vertexing ■ Tracking ■ PID



Central Barrel ($|y| < 0.9$)

- I. Inner Tracking System (**ITS**) ■ ■
- II. Time Projection Chamber (**TPC**) ■ ■
- III. Time-Of-Flight detector (**TOF**) ■
- IV. V0 detectors ■

Muon Spectrometer ($2.5 < y < 4$)

- I. Front absorber
- II. Dipole magnet
- III. Muon Chambers (**MCH**) ■
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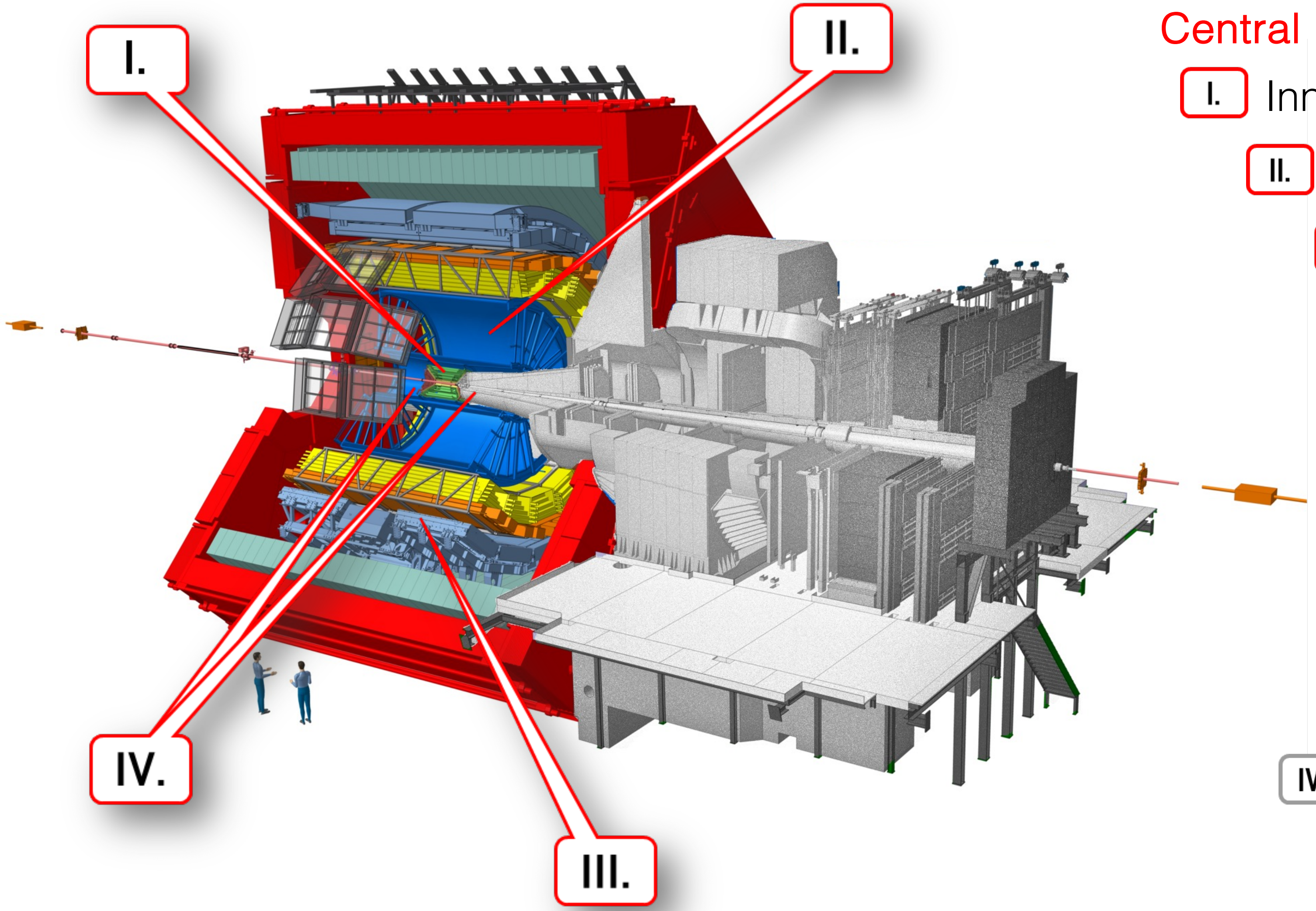
A Large Ion Collider Experiment

Trigger | Vertexing | Tracking | PID



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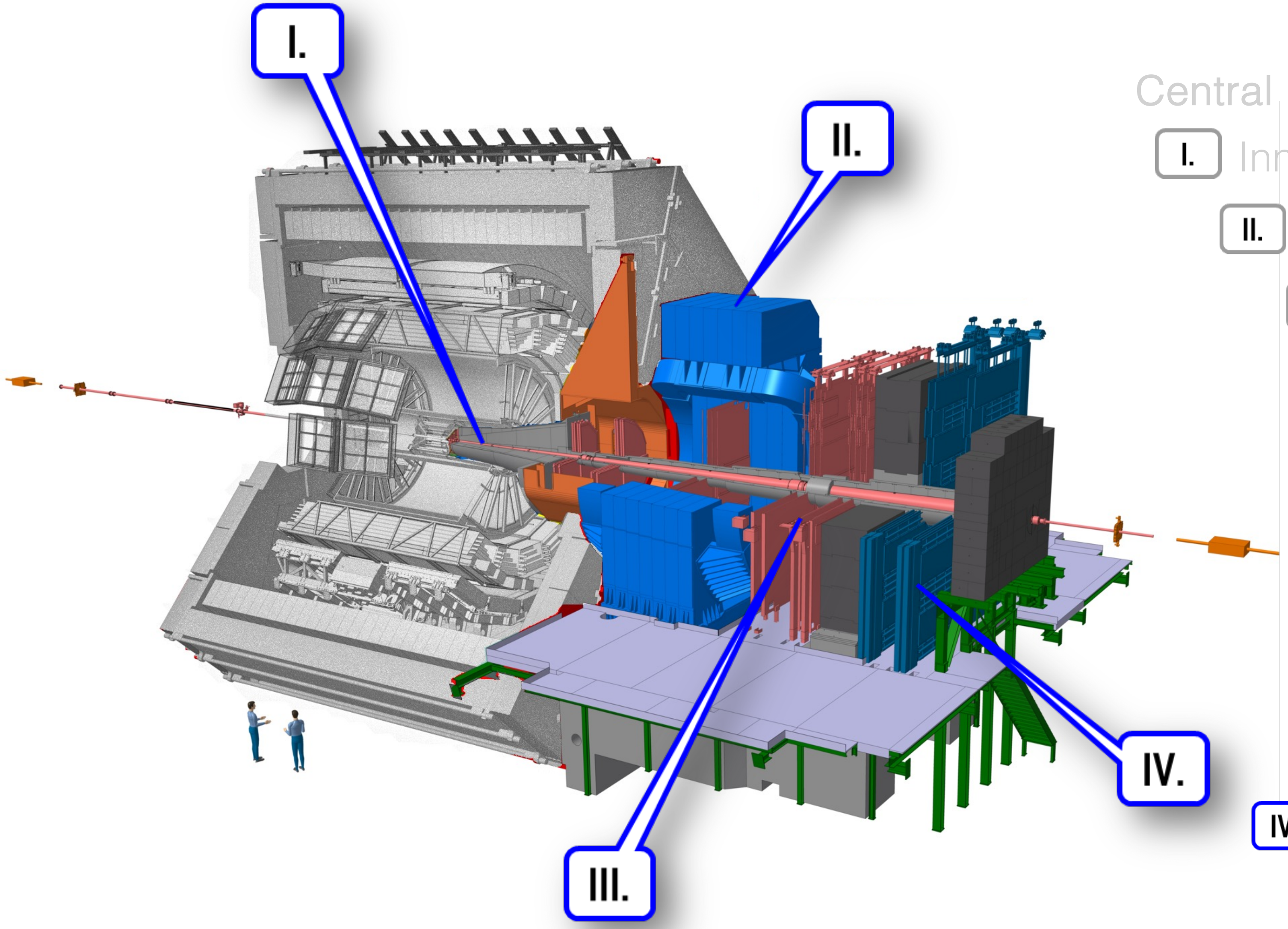
A Large Ion Collider Experiment

ALICE

Trigger Vertexing Tracking PID



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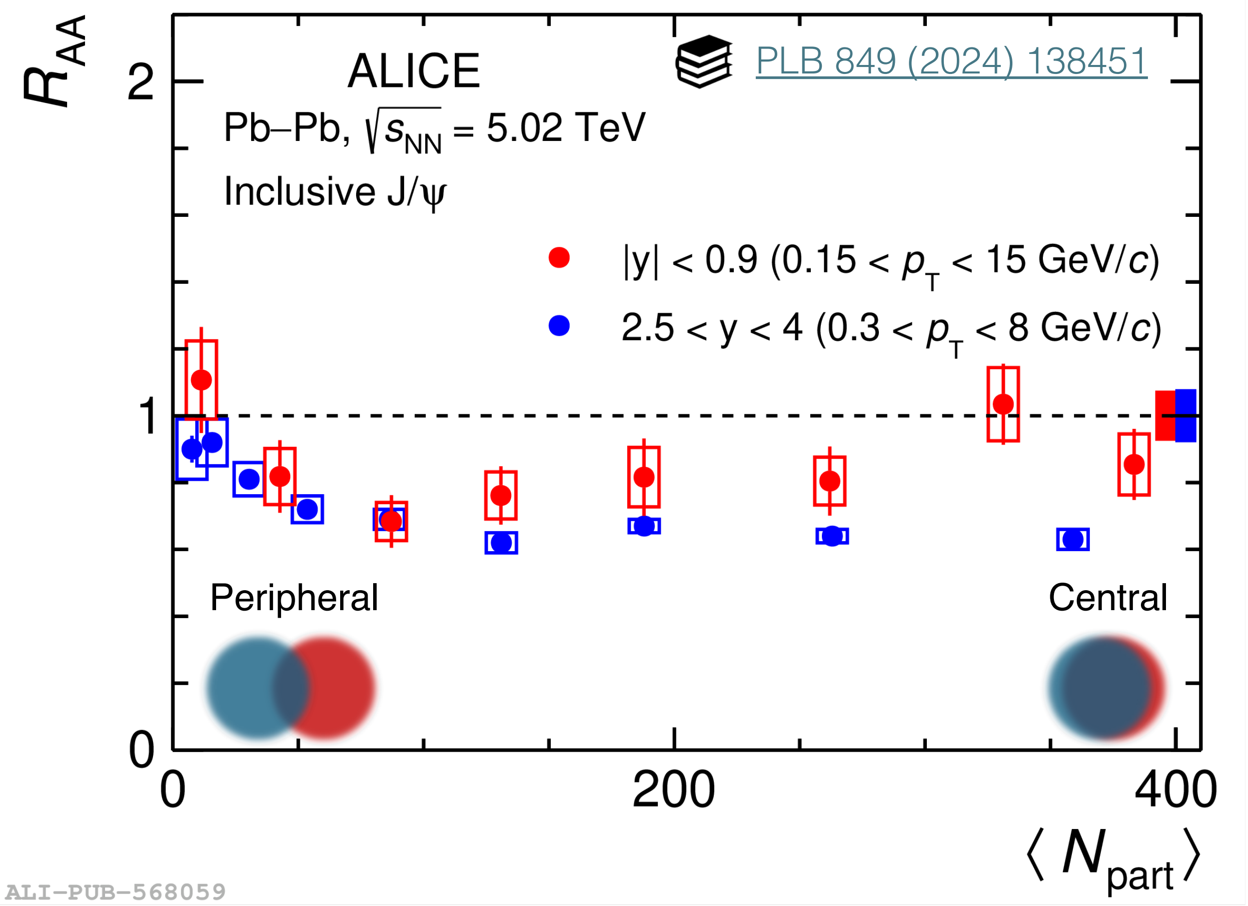
J/ψ production in Pb–Pb collisions

<u>Nuclear modification factor</u>

$$R_{AA} = \frac{(d^2N/dp_T\,dy)_{AA}}{\langle T_{AA}\rangle\,(d^2\sigma/dp_T\,dy)_{pp}}$$

- **Stronger J/ψ suppression** in central collisions at forward rapidity w.r.t. to midrapidity



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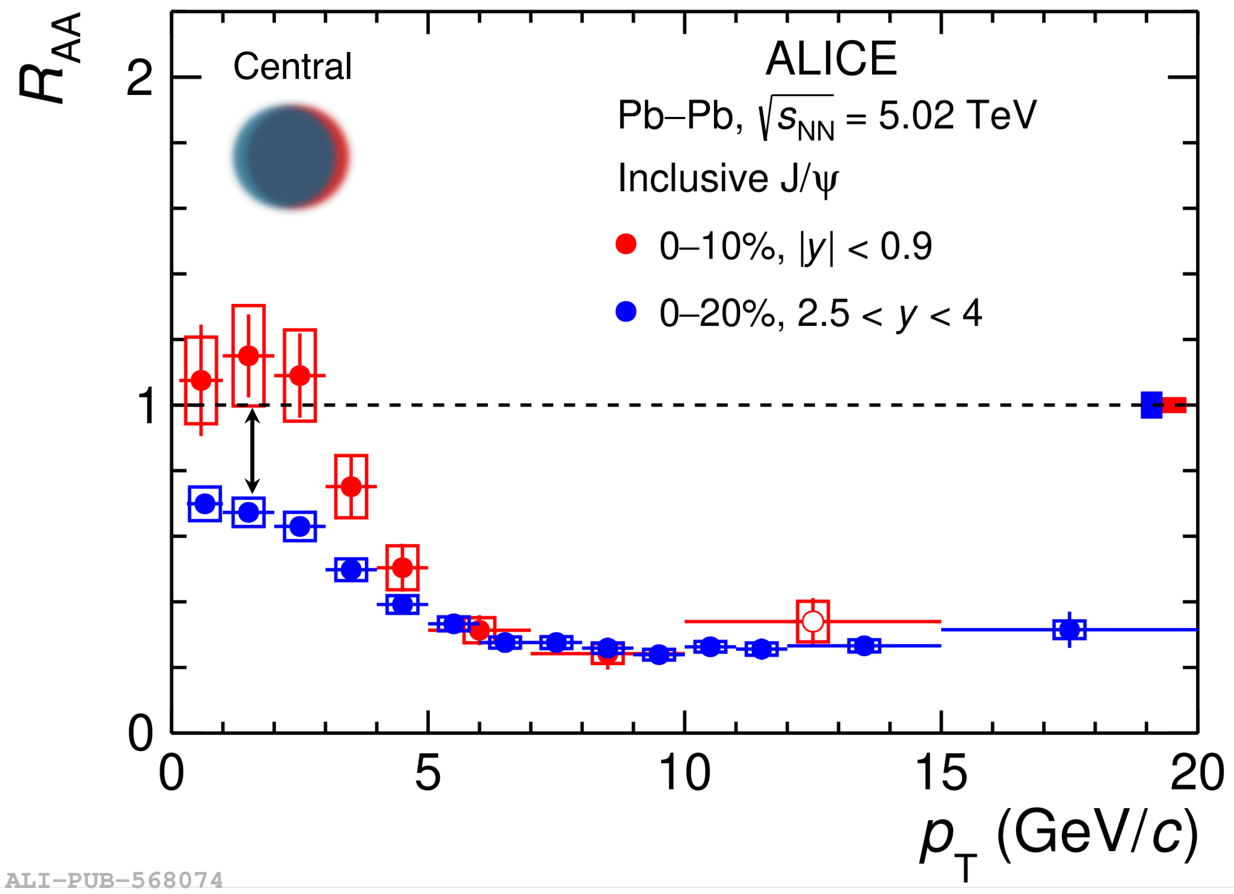
- **Stronger at midrapidity** due to the higher density of charm quarks



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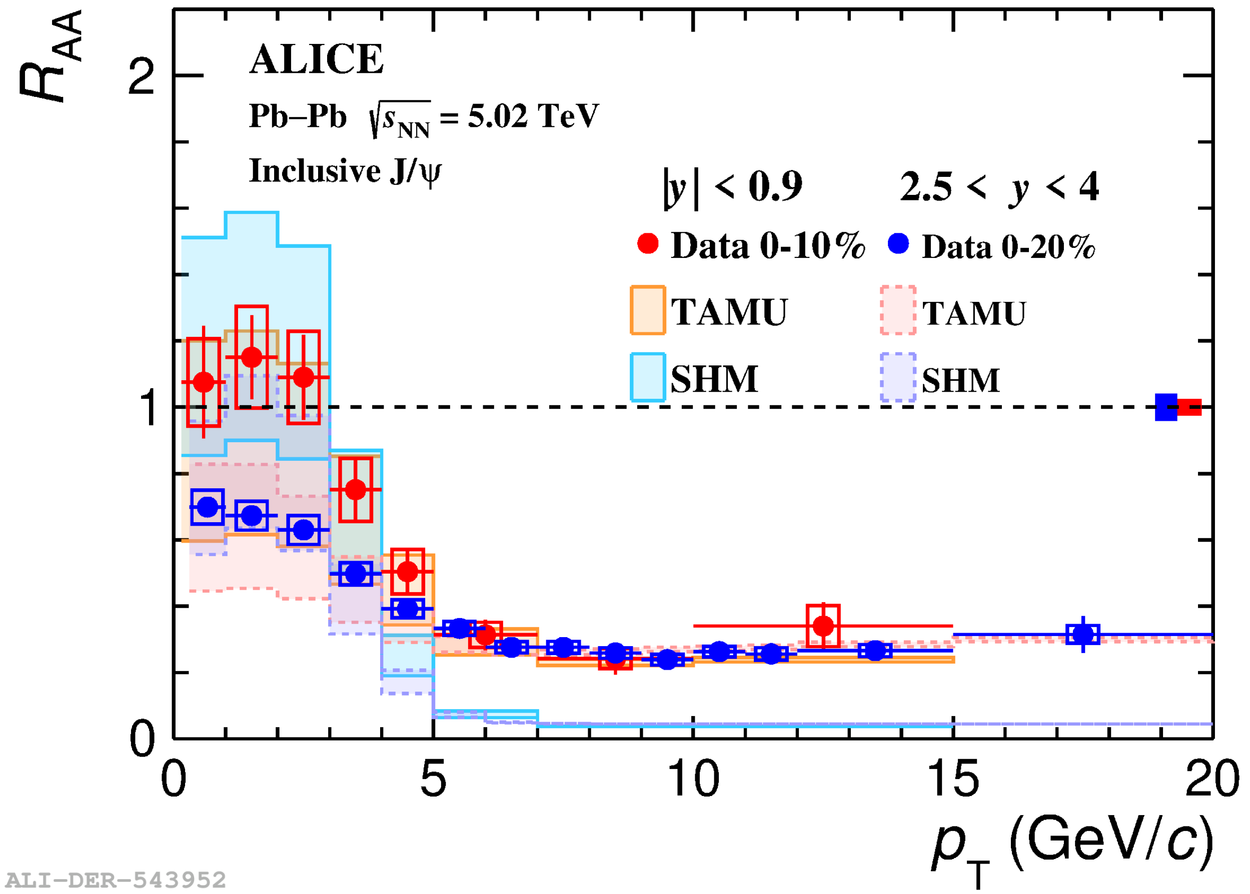
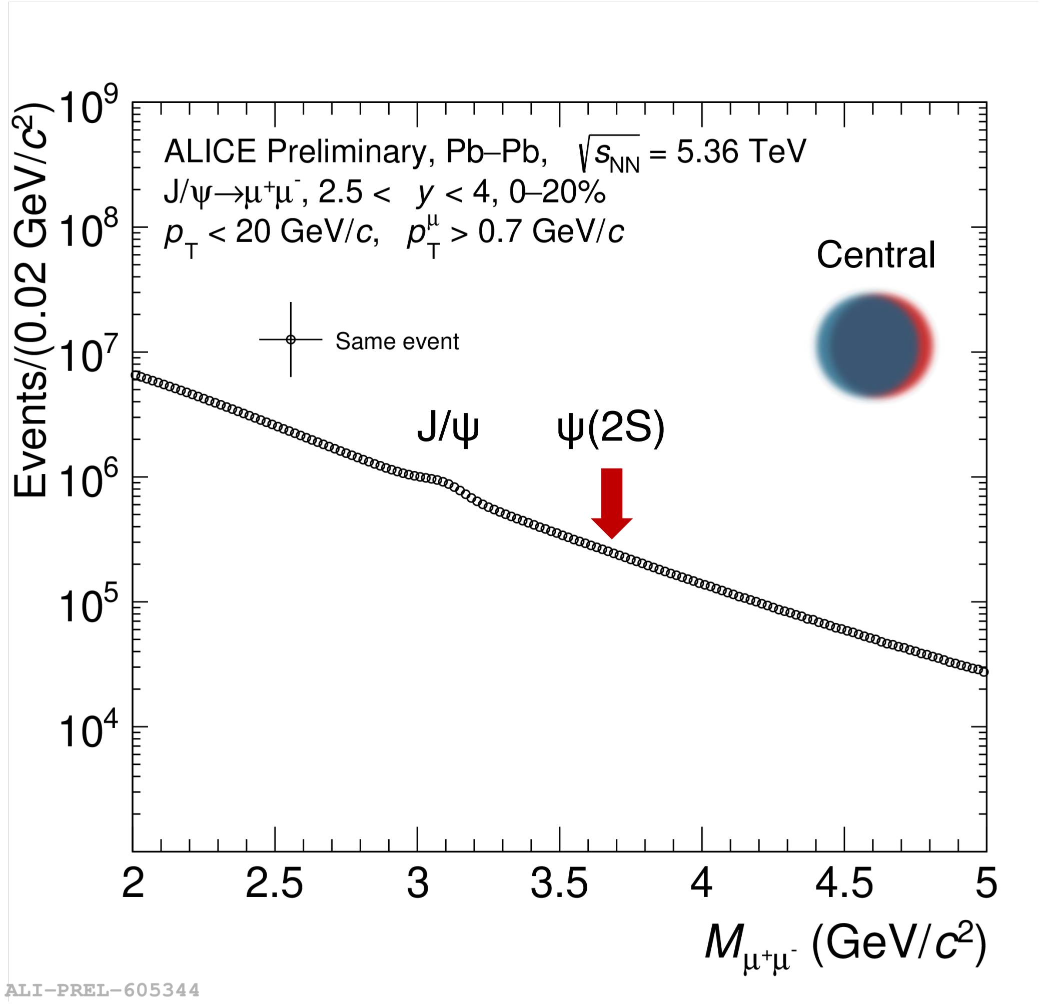
Statistical Hadronization Model (SHM)
quarkonia production at the **phase boundary**

Transport models (TAMU)
countinuous **dissociation / recombination** of quarkonia in the QGP



PLB 797 (2019) 134836, A. Andronic et al.
PLB 664:253-257,2008, R. Rapp et al.

ψ(2S) production in Pb–Pb collisions



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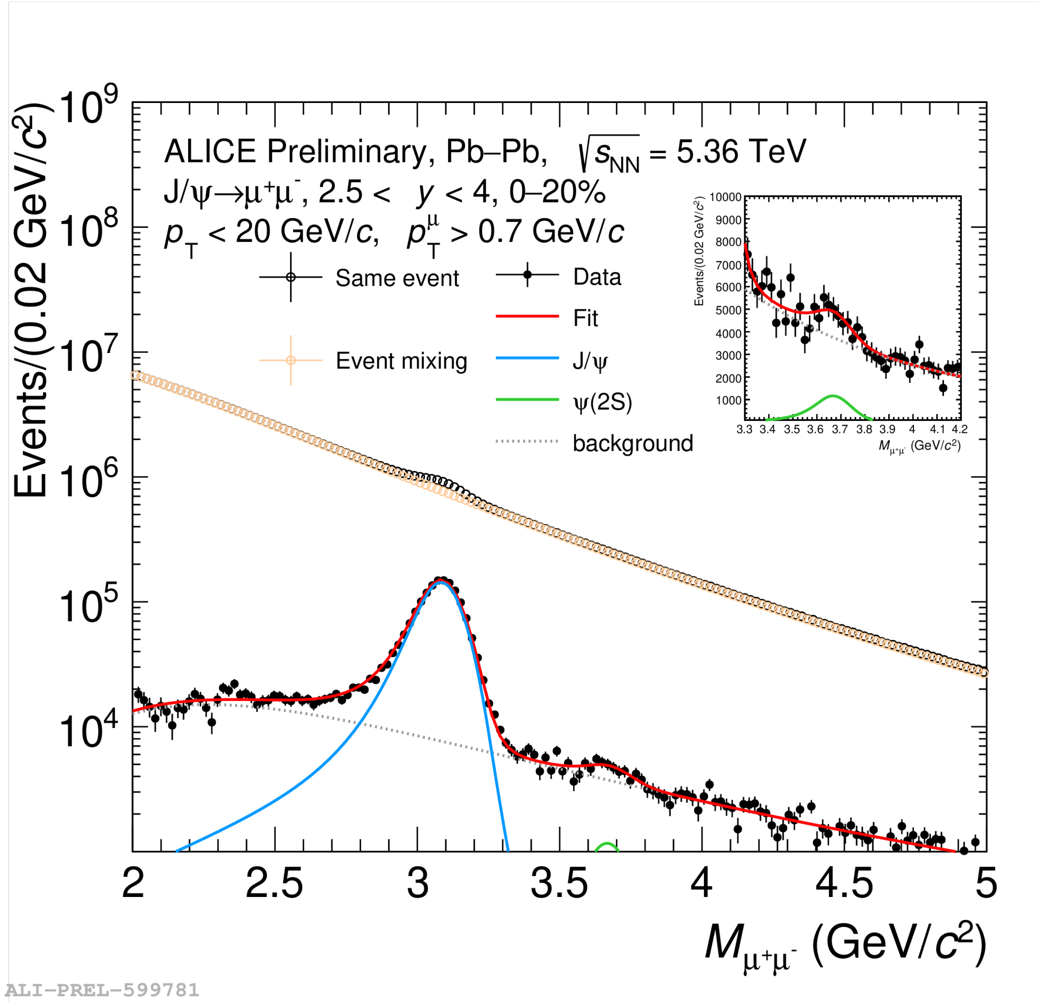

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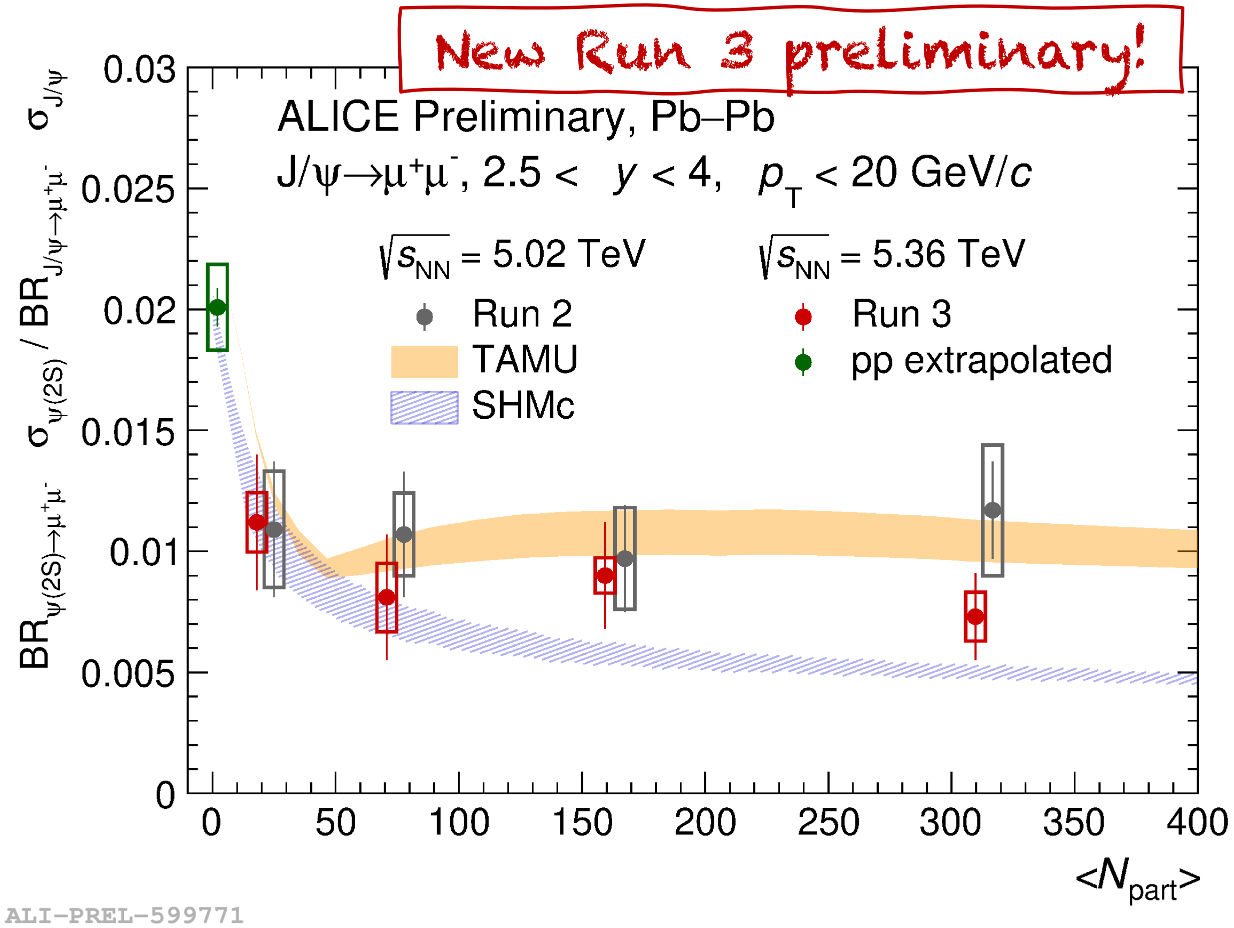

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PRL 132 (2024) 042301

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

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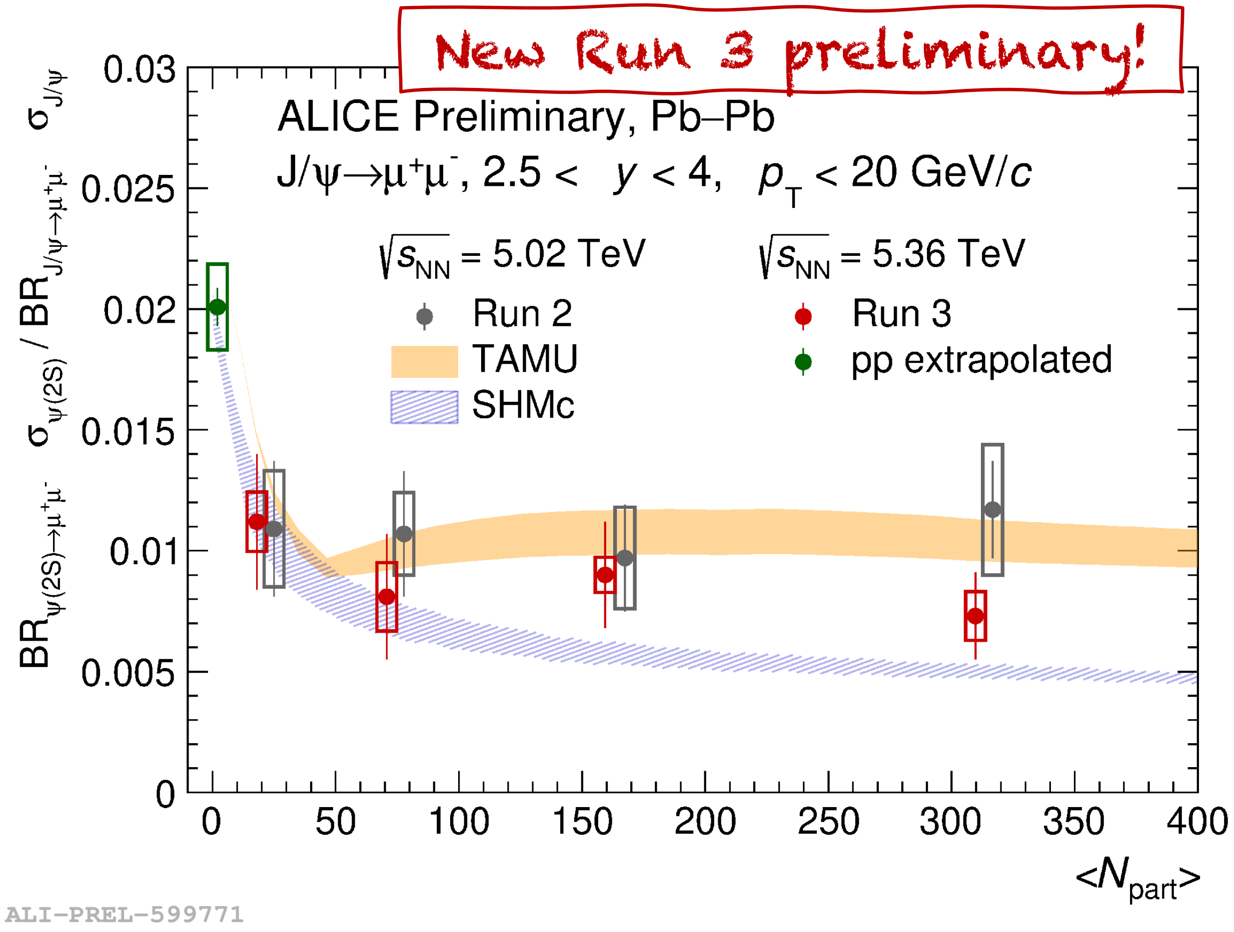
ALICE



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Different observable to study quarkonium suppression / (re)generation mechanisms?

PRL 132 (2024) 042301

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

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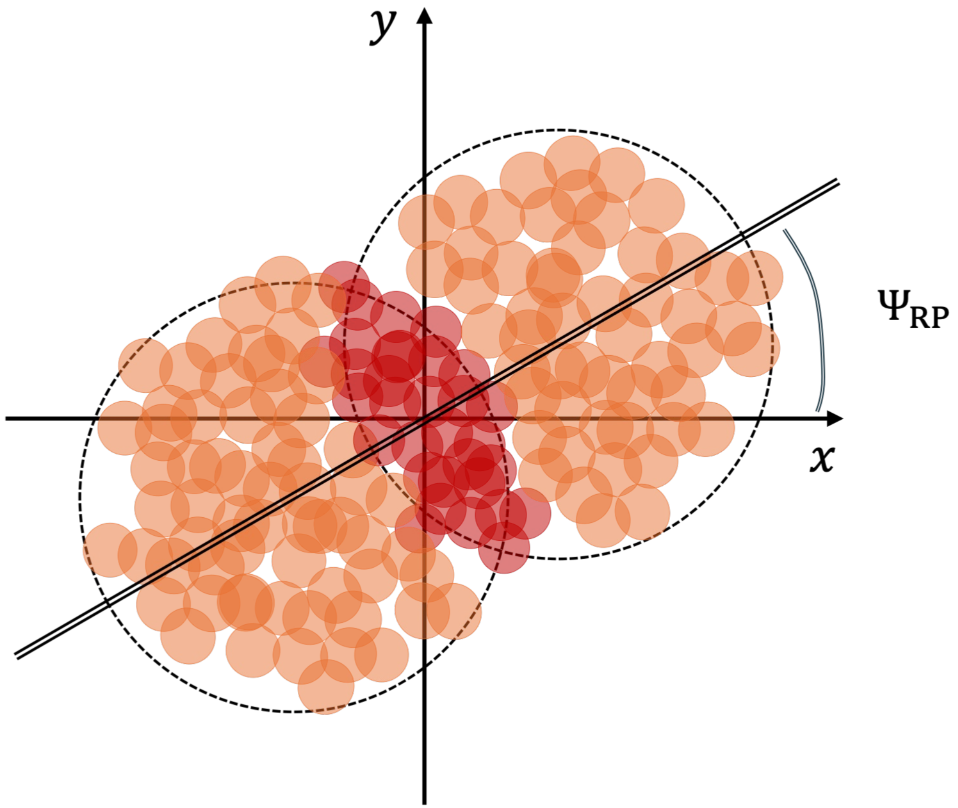
Collectivity



Elliptic flow

- Anisotropic shape of the fireball in non-central collisions (“**almond**” **shape**)
- Ψ_{RP}: Reaction Plane angle

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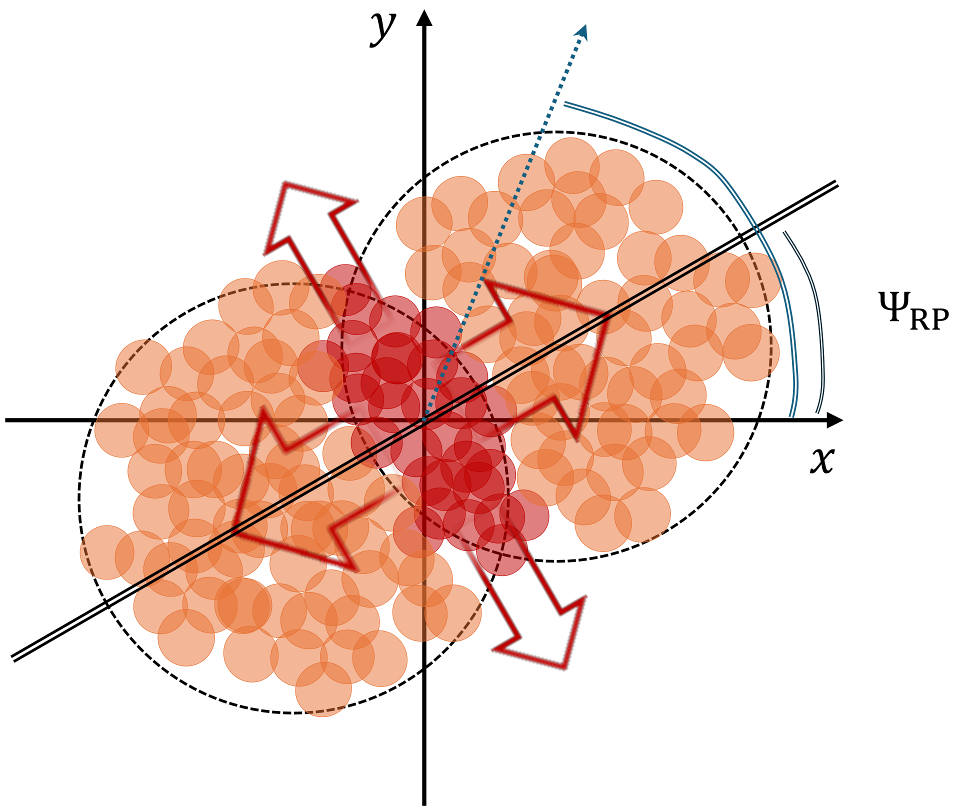

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- **Initial geometric anisotropy** convert to a **momentum anisotropy** of the measured particles

$$\frac{dN}{d\varphi} \propto \left(1 + 2\sum_{n=1}^{\infty} \boldsymbol{v_n}(cos[n(\varphi - \Psi_{RP})])\right)$$

$$\boldsymbol{v_n} = \langle cos[n(\varphi - \Psi_{RP})] \rangle$$

❑ $\boldsymbol{v_2}$ ~ elliptic modulation of the particle distribution in the **transverse plane** (x, y)

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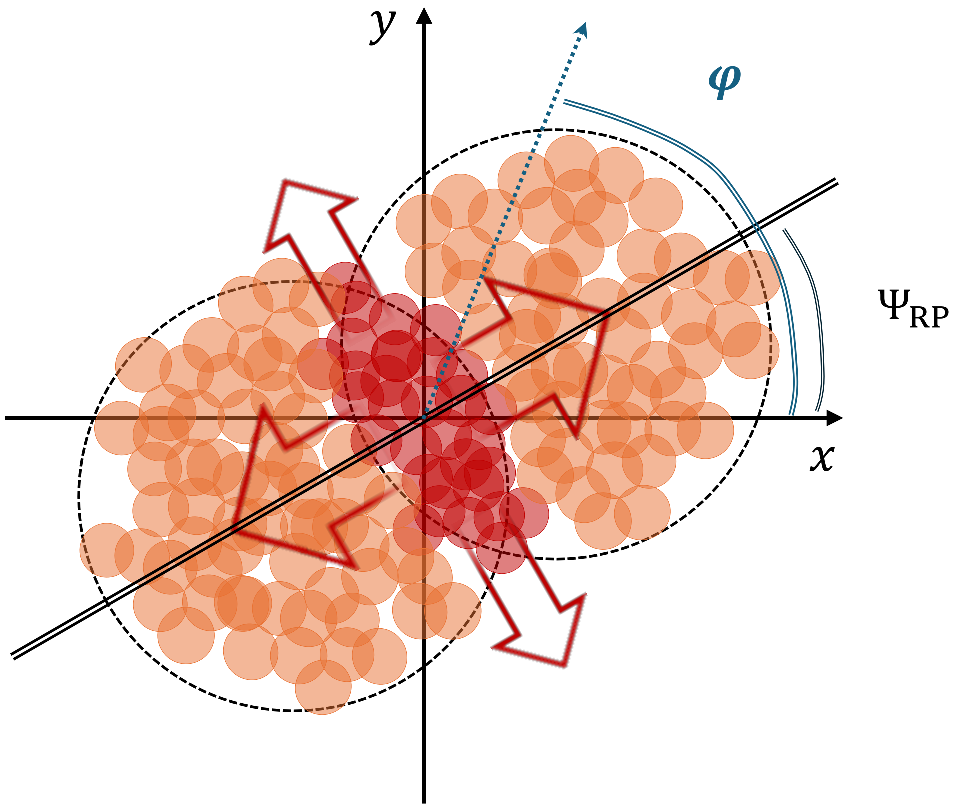

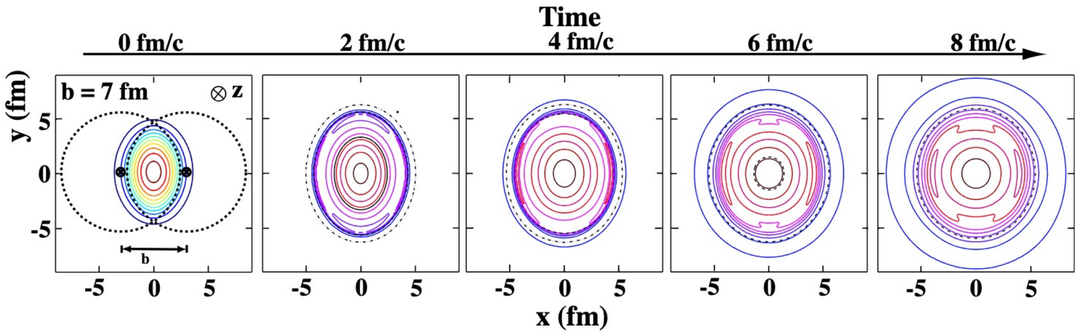

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❑ $\boldsymbol{v_2}$ originates in the **first stages after the collision**
  - Sensitive to the **equation of state** of the system
  - Sensitive to quark **thermalization** in the medium

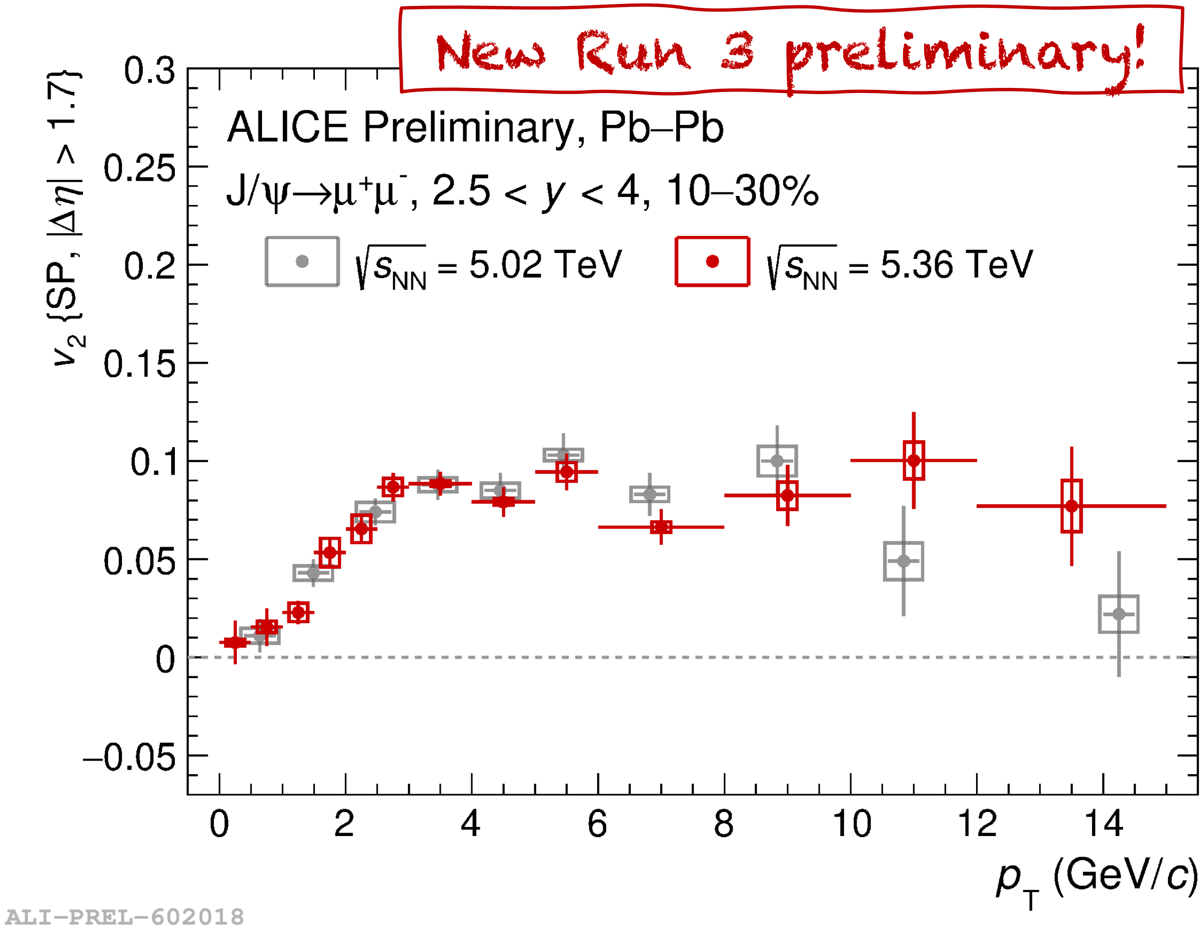
New J.Phys.13:055008,2011, R. Snellings

Collectivity: quarkonia

ALICE

J/ψ elliptic flow

- Improved granularity in Run 3 w.r.t. Run 2
- Run 3 results consistent with Run 2



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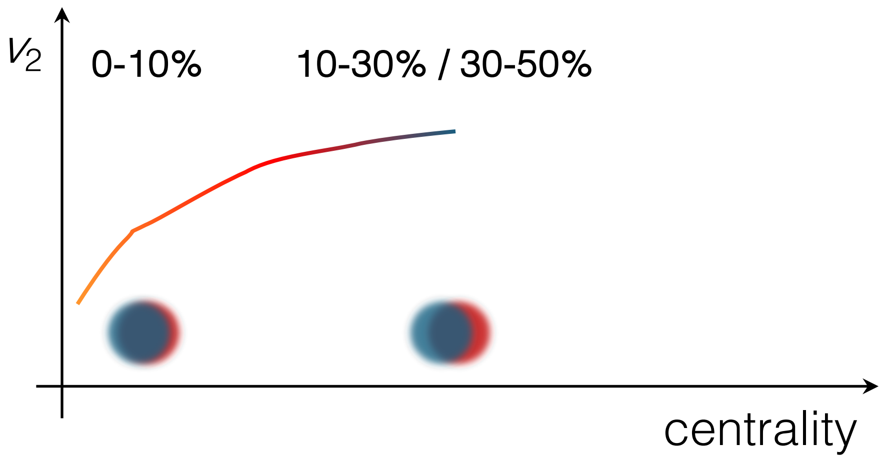

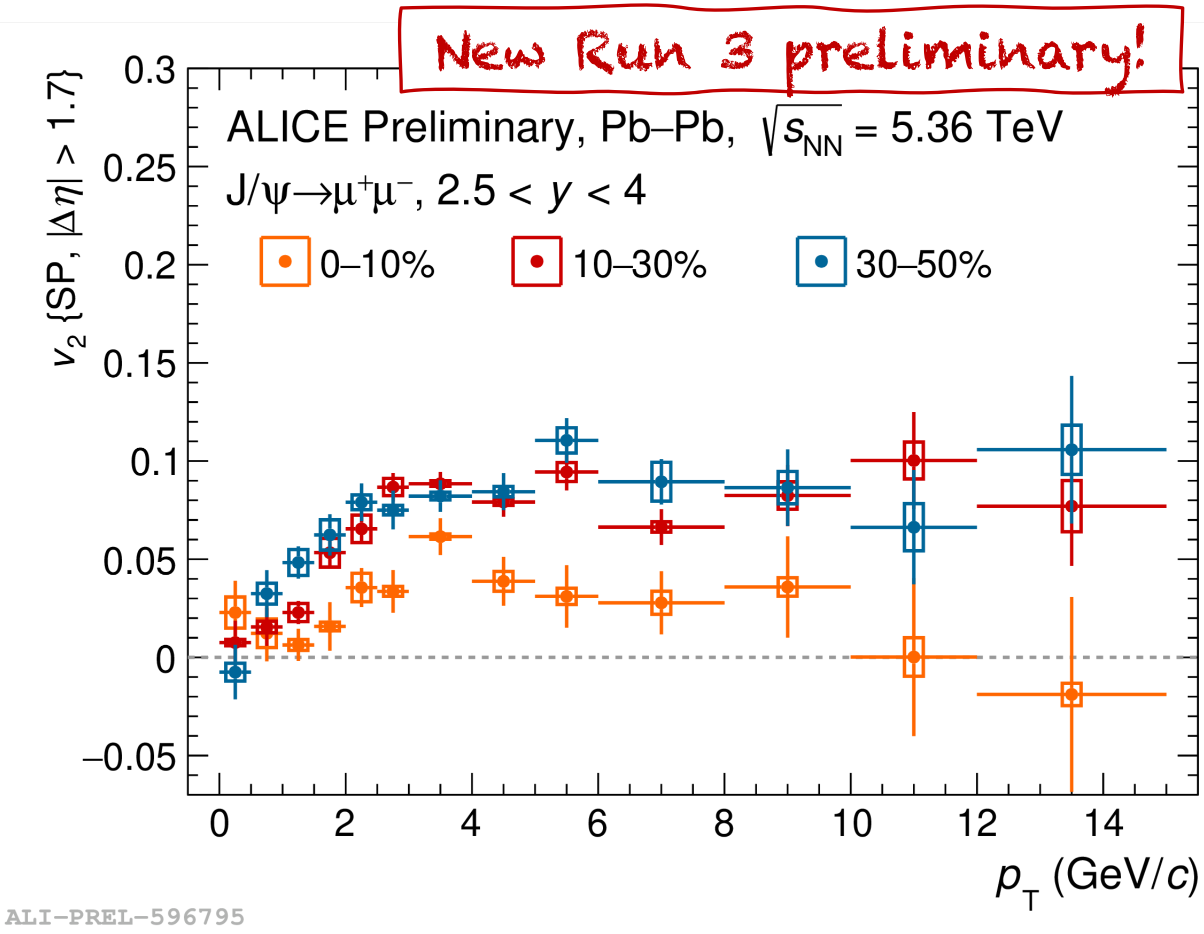

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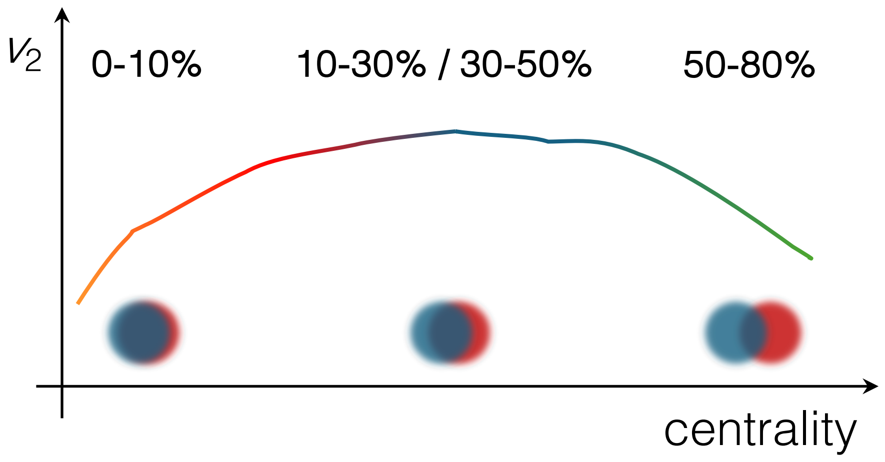

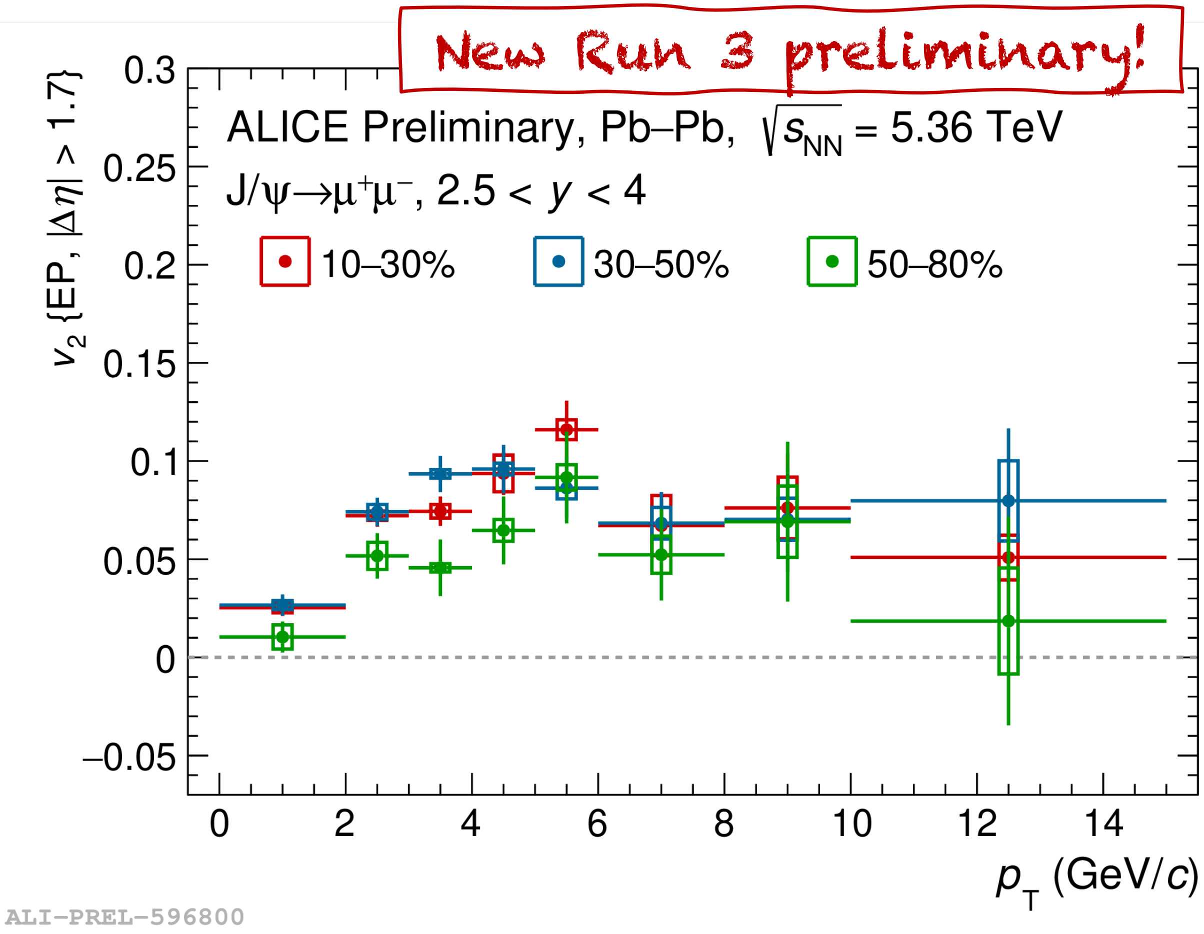

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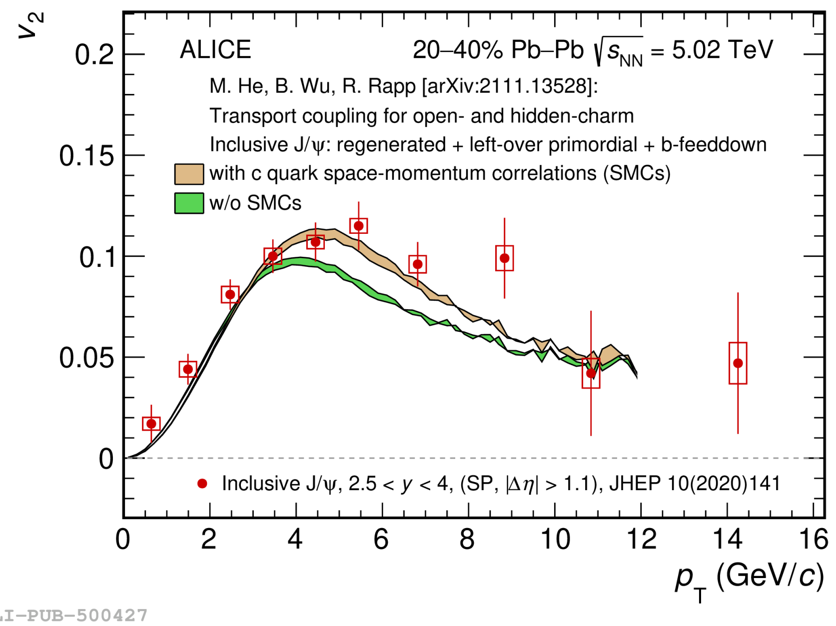

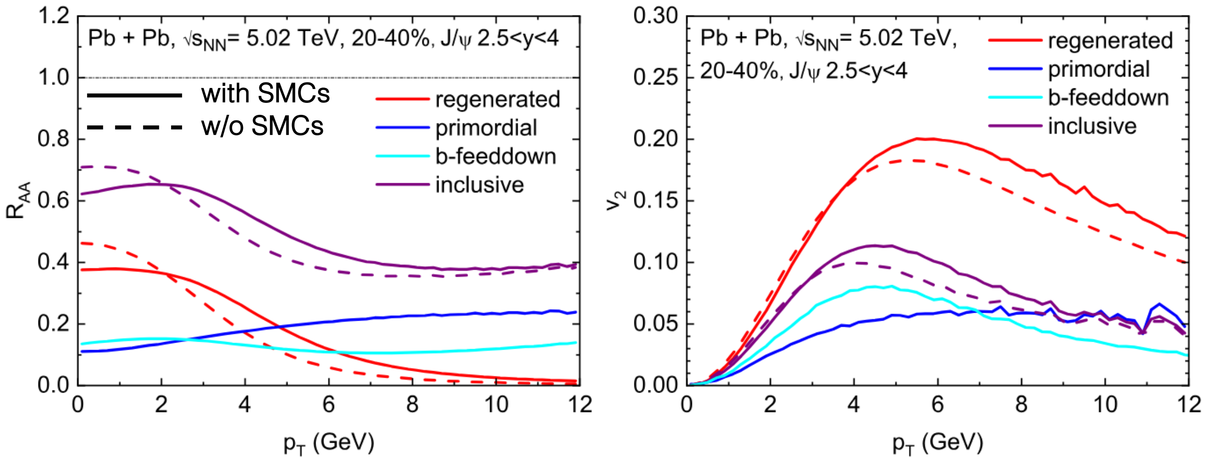

PRL 128, 162301 (2022), M. He, B. Wu, R. Rapp

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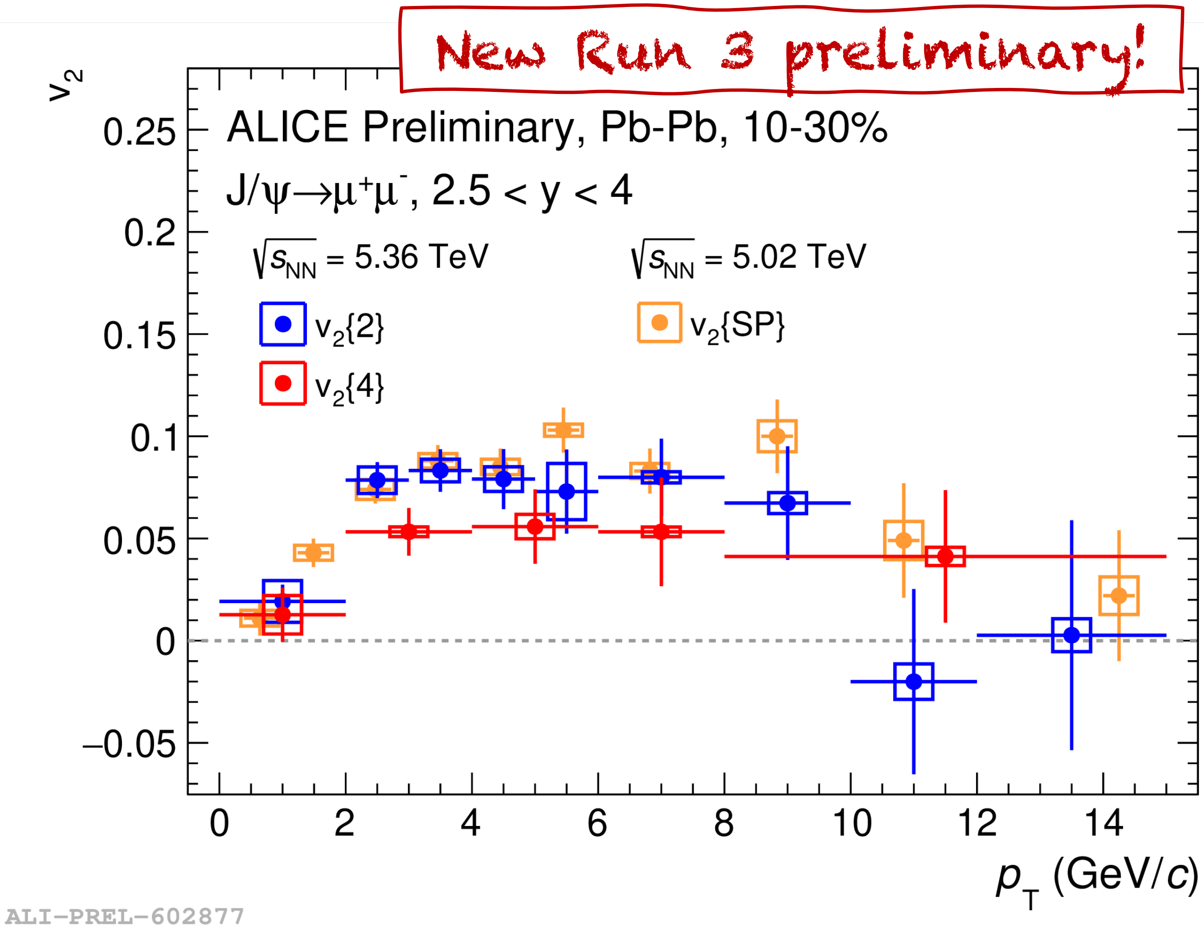
❑ Multiparticle correlations v_2:
  - 2/4 particle correlations ($v_2\{2\}$, $v_2\{4\}$)
  - $v_2\{4\} < v_2\{2\} \Rightarrow$ flow fluctuation (?)
  - Initial state geometry variation (?)

- Flow fluctuation ratio (σ/v_2) accessible (assuming gaussian fluctuations)



$$\frac{\sigma}{\langle v_2 \rangle} = \sqrt{\frac{v_2\{SP\}^2 - v_2\{4\}^2}{v_2\{SP\}^2 + v_2\{4\}^2}} \qquad \begin{cases} v_2\{SP\}^2 \sim \langle v_2 \rangle^2 + \sigma^2 \\ v_2\{4\}^2 \sim \langle v_2 \rangle^2 - \sigma^2 \end{cases}$$

Collectivity: quarkonia

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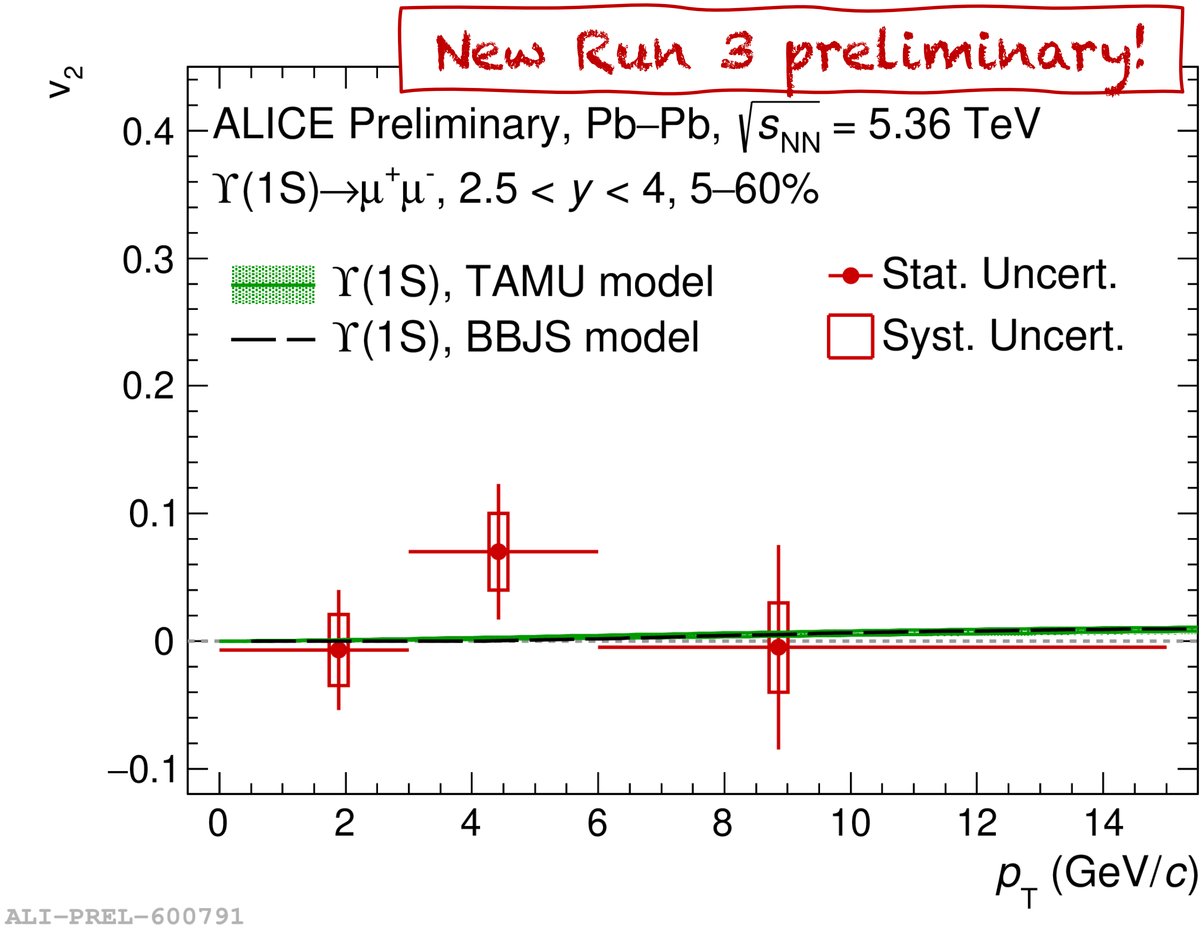


ϒ(1S) elliptic flow

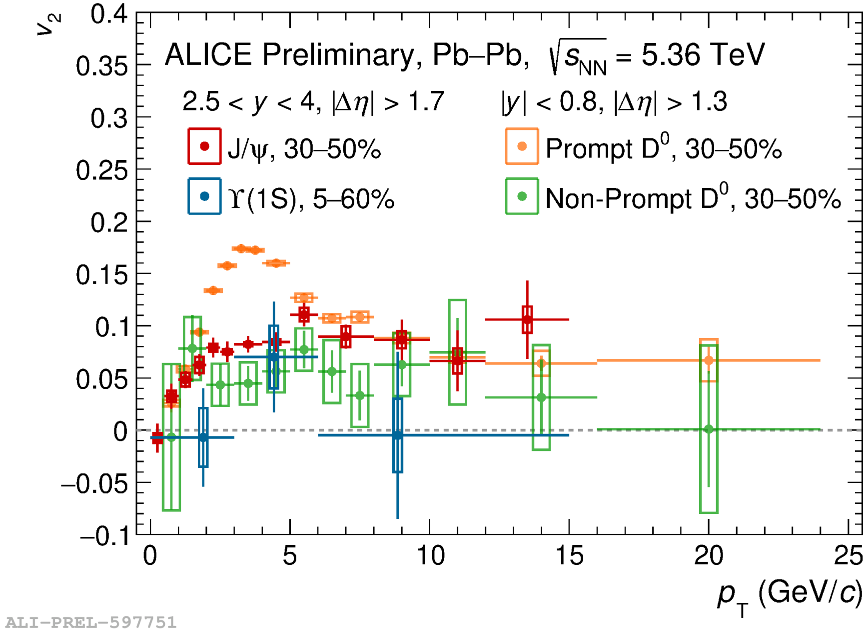
- v_2 compatible with **zero**
- No evidence of **(re)generation** in Pb−Pb

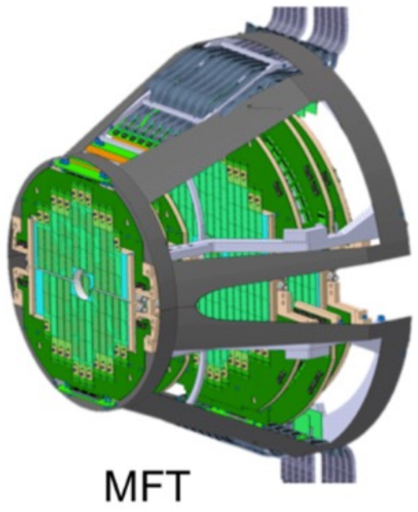
Summary and perspectives

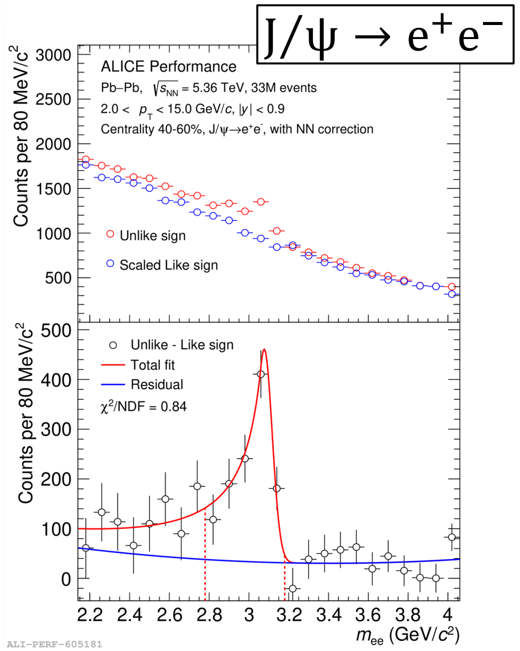
Charmonia production & flow in Pb–Pb collisions

- **Suppression** and **(re)generation** mechanisms explain Run 2 / Run 3 measurements
- Flow measurements support **charm quarks thermalization** in the QGP
- At LHC energies no evidence of bottomonia (re)generation (**Υ(1S)** v_2 ~ 0)

! Marcello Di Costanzo, T04, Wed 17:00







Future perspectives

- ❑ Larger luminosity collected (2023+2024 Pb–Pb):
  - Fwd. Rapidity factor ~4 increase
  - Midrapididty factor ~100 increase
- ❑ **prompt / non-prompt charmonia** separation at fwd thanks the **Muon Forward Tracker (MFT)** installed in Run 3

! Emilie Barreau, T05, Tue 17:50