Quarkonium collectivity in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.36 TeV with ALICE

EuNPC2025, 23/09/2025

Rebecca Cerri*
On behalf of the ALICE Collaboration

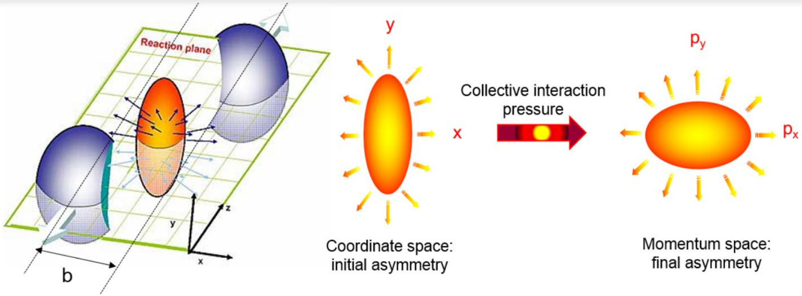
*University and INFN of Turin, Italy

Anisotropic Flow in heavy-ion collisions

- ➢ Collective medium behavior studied via particle azimuthal distributions with respect to the reaction plane

In non-central collisions:

- The initial **geometrical anisotropy** translates into a **particle momentum anisotropy**



Eur. Phys. J. Plus 131, 70 (2016)

- ➢ Anisotropic flow is described via Fourier expansion of particle distributions

$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3\mathbf{p}} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{t}\mathrm{d}p_\mathrm{t}\mathrm{d}y}\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_\mathrm{RP})]\right)$$

the Fourier coefficients: $v_n(p_\mathrm{t}, y) = \langle\cos[n(\varphi - \Psi_\mathrm{RP})]\rangle$

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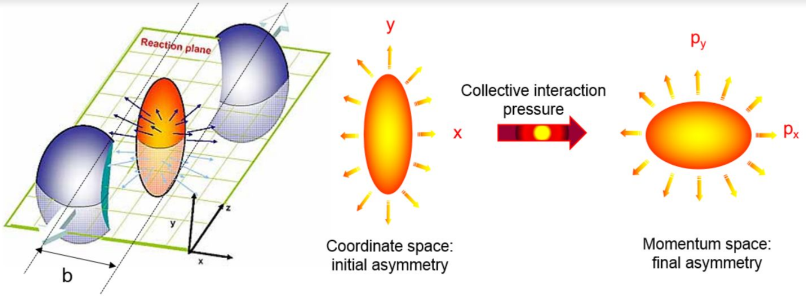

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Final stage flow observables:

- Directed flow (v_1): sensitive to pre-equilibrium phase
- Elliptic flow (v_2): early-stage expansion, thermalization
- Triangular flow (v_3): fluctuation in initial geometry

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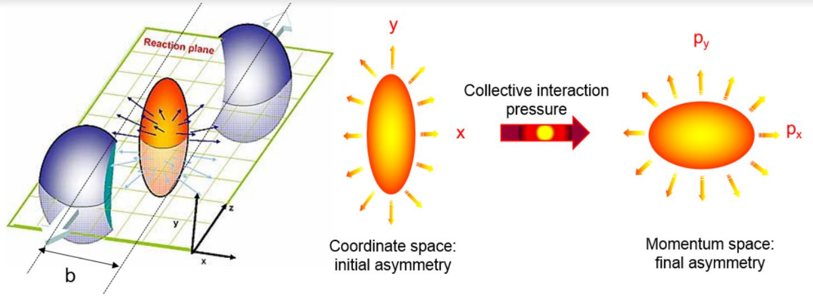

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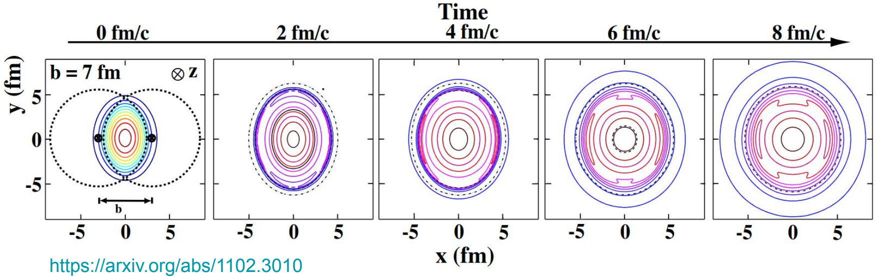
In-medium and collective effects on quarkonium

Quarkonium elliptic flow (v_2) in heavy-ion collisions:

Low p_T: hydrodynamic expansion with pressure gradients

- ➔ Regenerated **J/ψ** inherits the flow of charm quarks in the medium
- ➔ **ϒ(1S)** acquires a minor flow component via regeneration



https://arxiv.org/abs/1102.3010

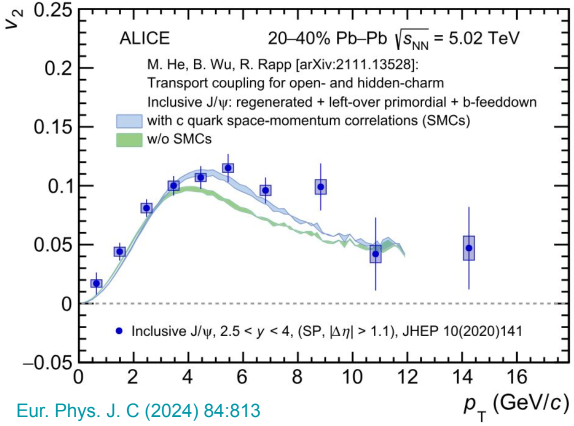
High p_T: effect resulting from in-medium path-length variations

- ➔ Open HF and quarkonium exhibit converging flow at large p_T

$\langle L_{in}\rangle \approx \langle L_{out}\rangle$ Induced $v_2 \approx 0$

$\langle L_{in}\rangle < \langle L_{out}\rangle$ Induced $v_2 > 0$

Previous v_2 results



Eur. Phys. J. C (2024) 84:813

Forward **J/ψ** flow in Pb−Pb collision (Run 2):

- Results are consistent with transport models, supporting charm quark thermalization

Low p_T**:** follows hydrodynamic description,

Regeneration contributes to **J/ψ** from low to intermediate p_T

High p_T**:** path-length dependent effects

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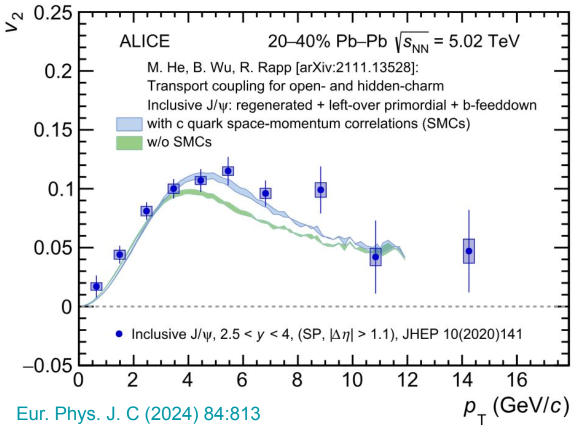

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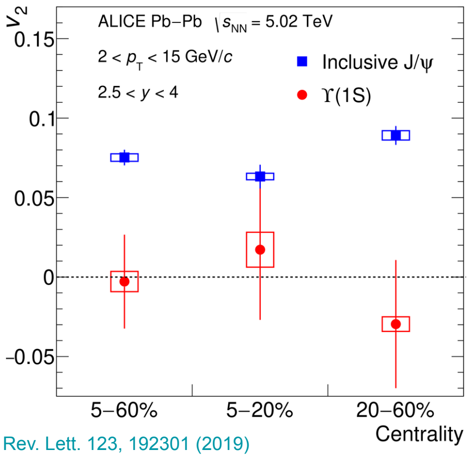

Phys. Rev. Lett. 123, 192301 (2019)

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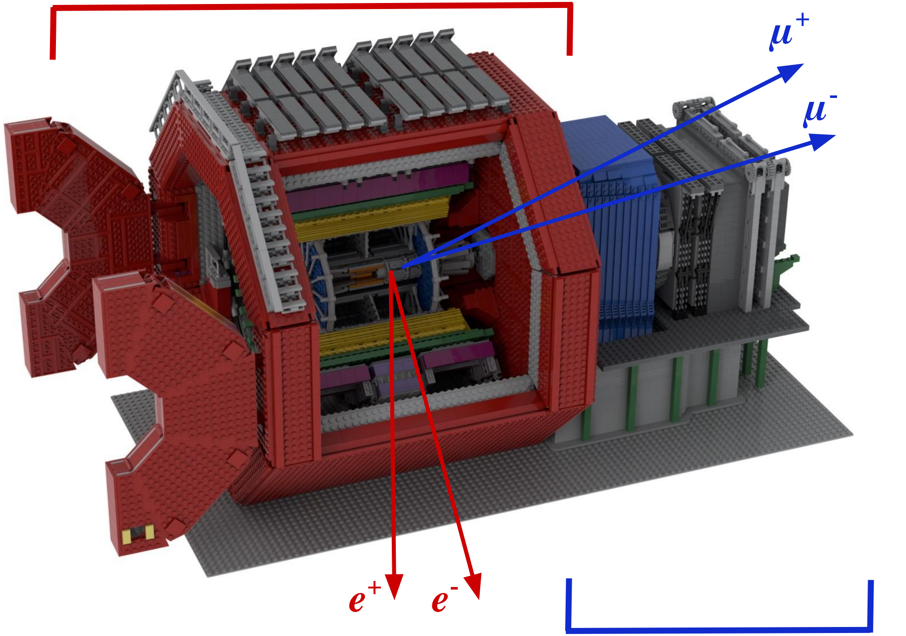
Forward **ϒ(1S)** flow in Pb–Pb collision (Run 2):

- Observed flow is consistent with 0, regeneration contribution negligible
- Early-stage dissociation is the dominant effect

ALICE: quarkonium measurement in Run 3

Central barrel, Midrapidity: $|y| < 0.9$



Muon spectrometer, Forward rapidity: $2.5 < y < 4$

Quarkonium studied through its dielectron decay channel (e^+, e^-)

- Inner Tracking System (ITS): tracking, vertexing, multiplicity
- Time Projection Chamber (TPC): tracking, PID, event-plane
- Fast Interaction Triggers (FITs): centrality, event-plane

Quarkonium studied through its dimuon decay channel (μ^+, μ^-)

- Muon tracking
- Muon identification

Overview of Preliminary Results from Run 3

1. **J/ψ** flow measurement at forward rapidity in Pb–Pb collision

2. **ϒ(1S)** flow measurement at forward rapidity in Pb–Pb collision

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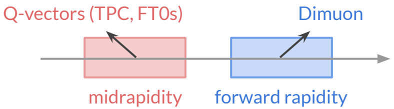
Forward $v_2^{J/\psi}$ vs. p_T in Pb–Pb collision (Run 3)



Event Plane (EP) Method

$$v_2\{EP\} = \frac{\langle \cos(2(\phi - \Psi_2)) \rangle}{R_2\{EP\}}$$

Scalar Product (SP) Method

$$v_2\{SP\} = \frac{\langle \mathbf{u}_2 \, Q_2^{\mathrm{TPC}*} \rangle}{R_2\{SP\}}$$

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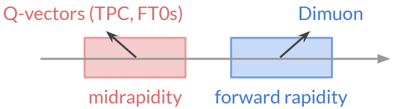

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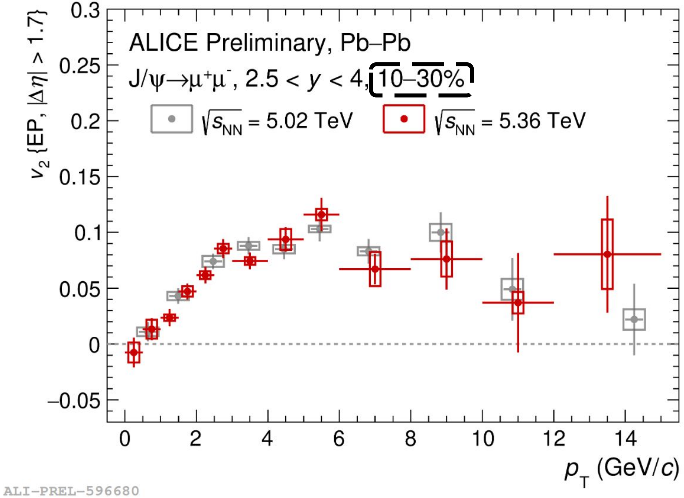

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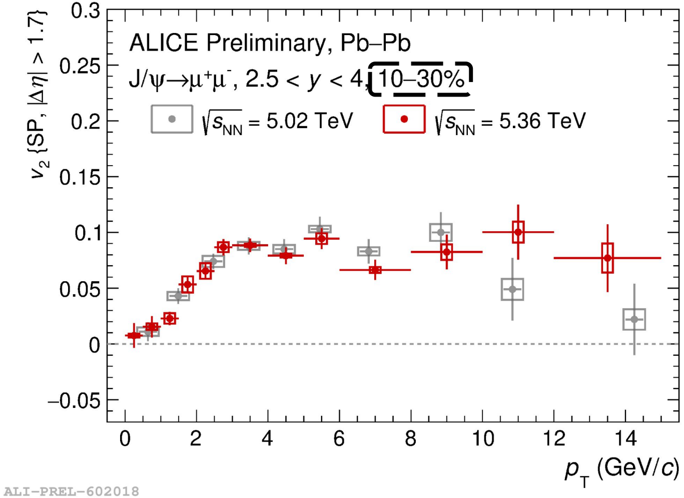

Run 3 results (SP & EP) are compatible with Run 2:

- Finer binning at low p_T (up to 3 GeV/c)
- Positive v_2 at low p_T, consistent with regeneration

Forward $v_2^{J/\psi}$ vs. p_T in Pb–Pb collision (Run 3)

Additional centrality classes studied:

Event Plane (EP) Method

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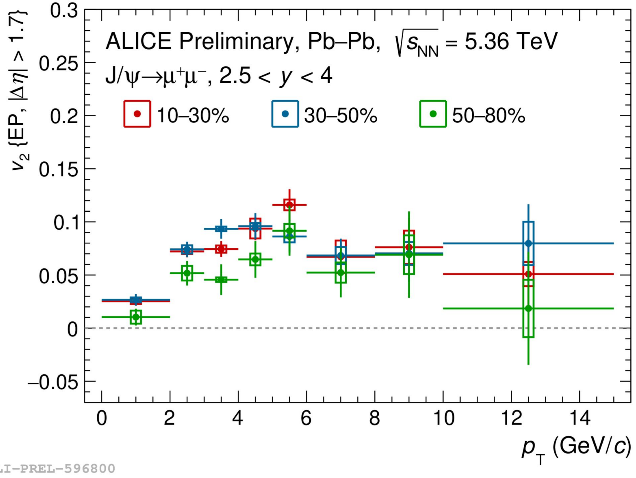

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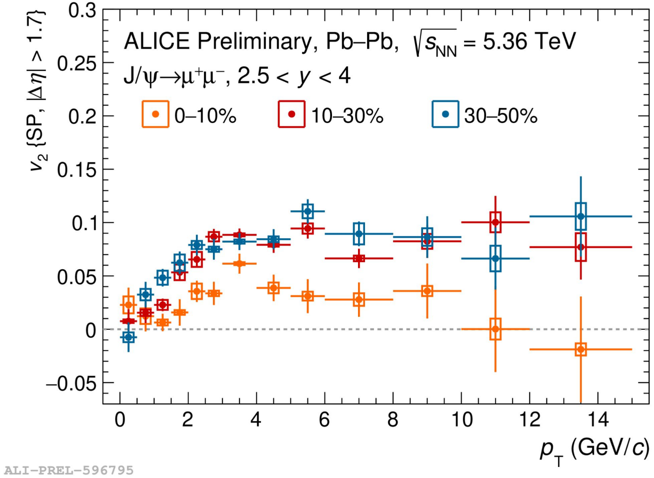
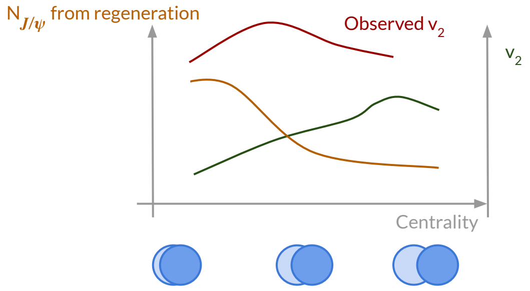


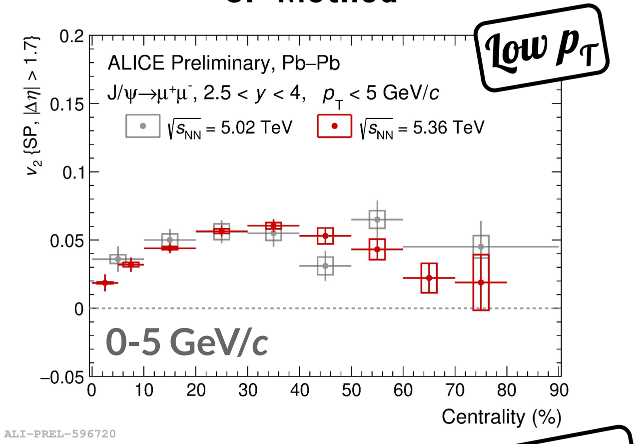
First measurement in ALICE within **50-80%** centrality!

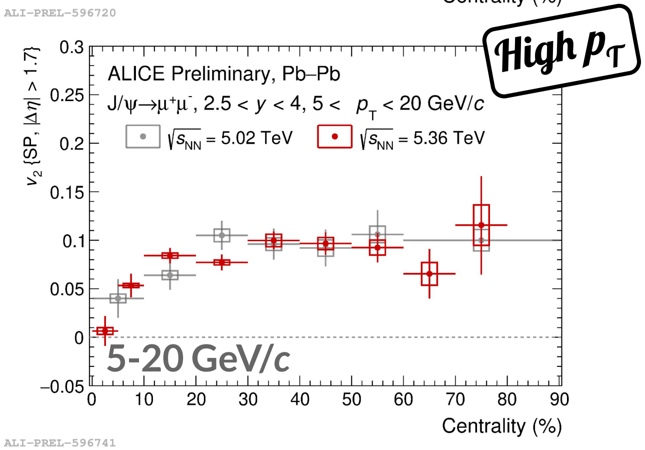
Forward $v_2^{J/\psi}$ vs. centrality in Pb–Pb collision (Run 3)



Results compatible with Run 2

SP Method





Low p_T

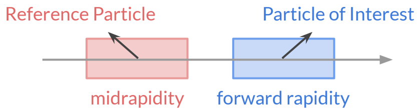
- *Smooth progression from central to peripheral*
- Peak around 30%, slightly more central relative to light flavors

High p_T

- *Clear increase from zero at central collisions*
- Path-length dependence of E-loss levels off toward peripheral

Forward $v_2\{2,4\}^{J/\psi}$ in Pb–Pb collision (Run 3)

Correlate charged particles at midrapidity with J/ψ at forward rapidity



Multi-particle correlation method (cumulants)

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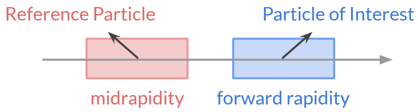

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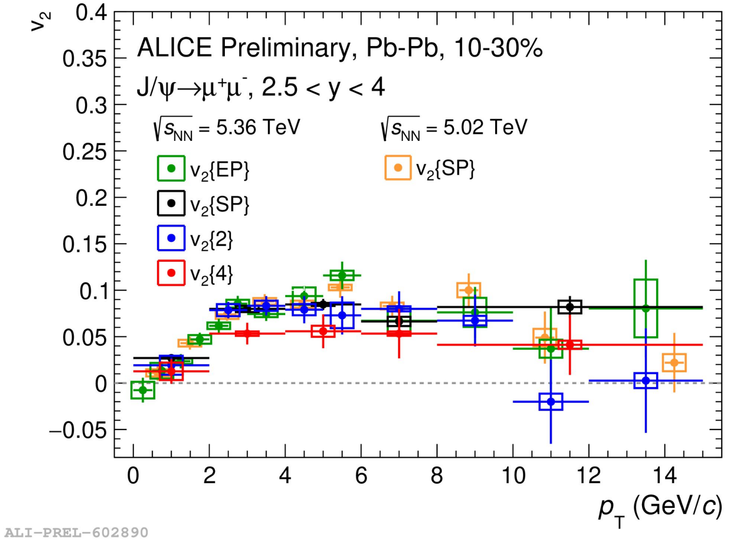


$v_2\{2\}$: Elliptic flow from 2-particle correlation

$v_2\{4\}$: Elliptic flow from 4-particle correlation

First forward-rapidity J/ψ v_2 measurement with cumulants in Pb–Pb collisions!

- $v_2\{2\}$ compatible with SP, EP and Run 2 within current uncertainties
- Indication that $v_2\{4\} < v_2\{2\}$, possible flow fluctuations?

Flow fluctuation measurement (Run 3)

Assuming Gaussian fluctuations of the flow, the approximations for v_2 are:

$$v_2\{SP\} \approx \langle v_2 \rangle + \sigma \qquad v_2\{4\} \approx \langle v_2 \rangle - \sigma$$

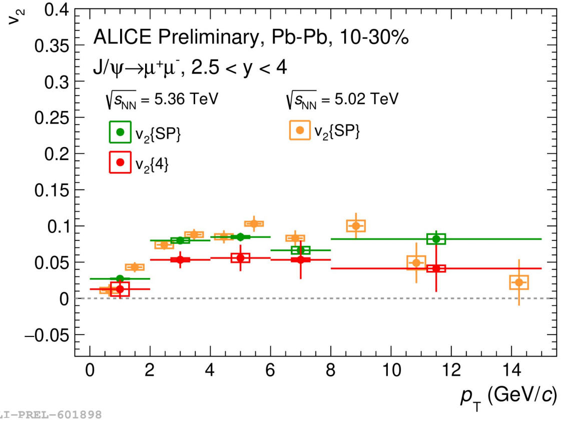
the fluctuation ratio can be expressed as:

$$\frac{\sigma}{\langle v_2 \rangle} \approx \frac{v_2\{SP\} - v_2\{4\}}{v_2\{SP\} + v_2\{4\}}$$

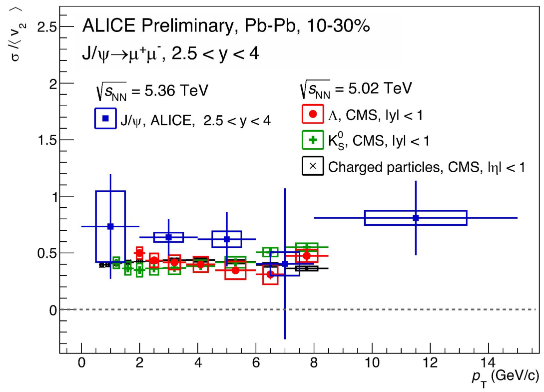
Fluctuation ratio independent of p_T

⇩

v_2 fluctuations likely reflect variations in the initial-state geometry from event to event



- v_2 {SP} > v_2 {4} with a significance of ~ 2.6σ



First measurement of J/ψ flow fluctuation ratio!

- Result compatible with light flavors

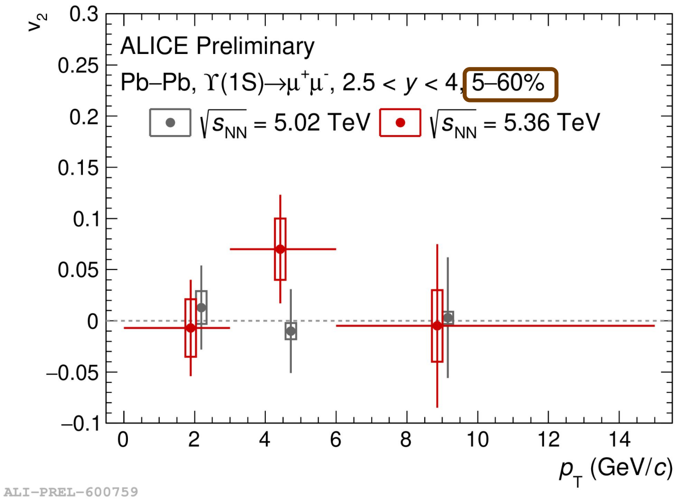
Overview of Preliminary Results from Run 3

1. **J/ψ** flow measurement at forward rapidity in Pb–Pb collision

2. **ϒ(1S)** flow measurement at forward rapidity in Pb–Pb collision

Forward $v_2^{\Upsilon(1S)}$ vs. p_T in Pb–Pb collision (Run 3)

EP Method



- Run 3 result compatible with Run 2

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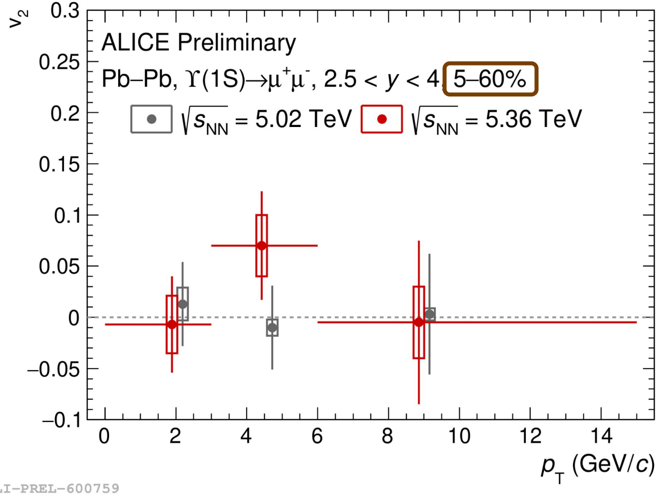


Model Comparison (TAMU & BBJS)

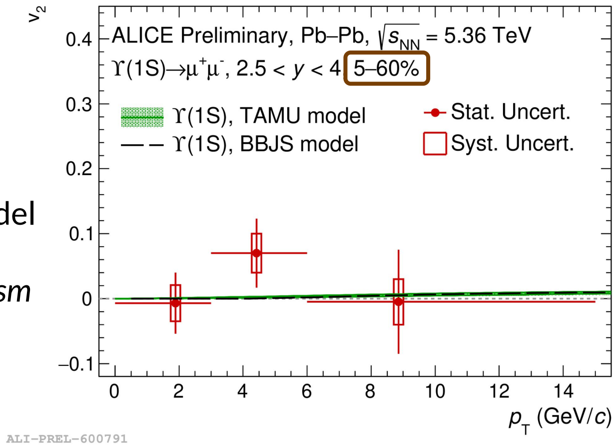
TAMU:

- Langevin-based transport model with ideal hydro.
  Including regeneration mechanism

BBJS:

- PYTHIA + (3+1d) quasiparticle aniso-hydro.
  No regeneration

EP Method



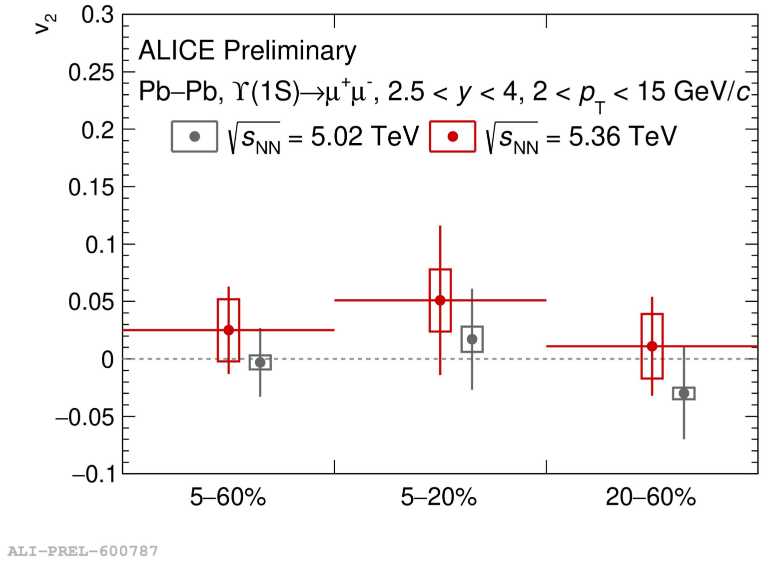
X. Du, R. Rapp, and M. He, Phys. Rev. C 96, 054901 (2017)

P. P. Bhaduri, N. Borghini, A. Jaiswal, and M. Strickland, Phys. Rev. C 100, 051901 (2019)

- Run 3 result compatible with Run 2

- Test for regeneration mechanism
- Indistinguishable within current uncertainties

Forward $v_2^{\Upsilon(1S)}$ vs. centrality in Pb–Pb collision (Run 3)



- Run 3 result compatible with Run 2
- Significant suppression of v_2 across different centrality ranges

Results compatible with 0 within uncertainties:
indicating b quarks may not be thermalized?

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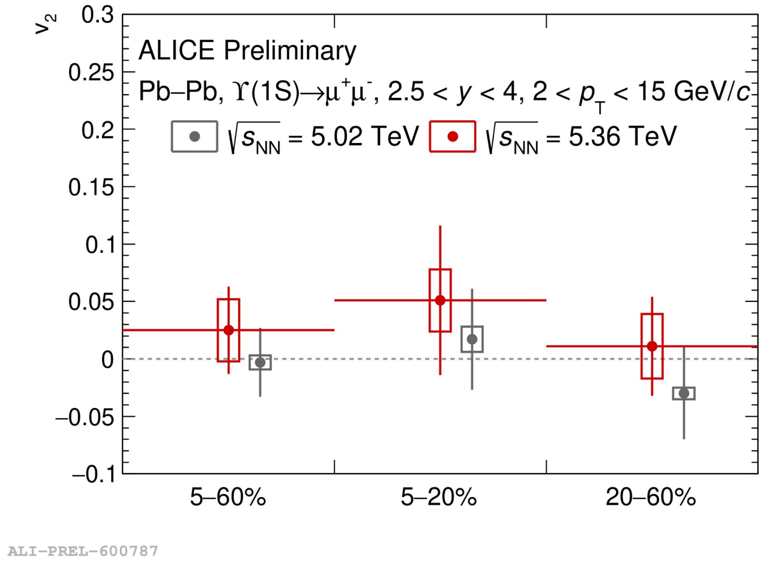

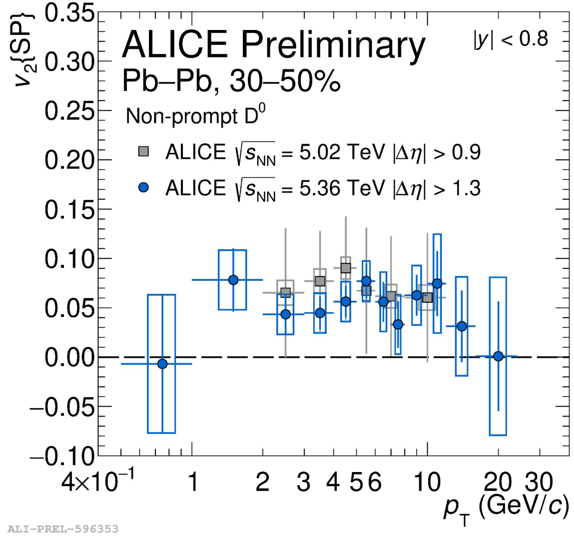

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Results compatible with 0 within uncertainties: indicating b quarks may not be thermalized?

When associated with light flavors, beauty hadrons exhibit a positive v_2

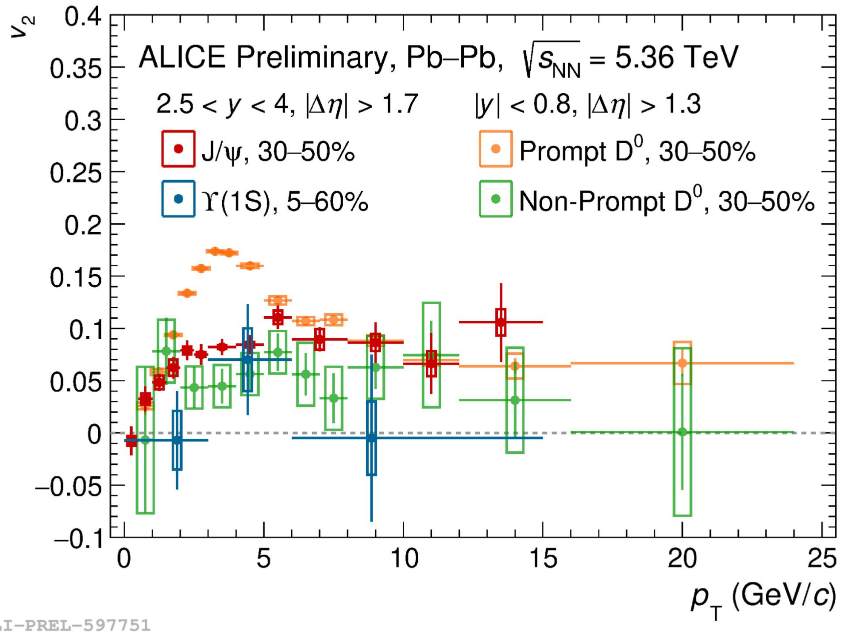
$v_2^{\Upsilon(1S)} \leq v_2^{\text{non-prompt } D^0} < v_2^{J/\psi} < v_2^{\text{prompt } D^0}$

Low to intermediate p_T:
- Ordering between prompt/non-prompt D^0, **J/ψ** and **ϒ(1S)**

High p_T:
- Convergence - Energy-loss

- Prompt vs. non-prompt D meson flow comparison indicates different thermalization for c and b quarks
- No decisive evidence for **ϒ(1S)** flow, results are compatible with 0 within uncertainties.

Quarkonium + Open-HF



Conclusions

New Run 3 measurements on quarkonium flow in Pb–Pb:

- **J/ψ** flow at forward rapidity
    - **First Run 3 results with SP/EP/cumulants!**
    - Consistent with Run 2, finer p_T binning
    - First $v_2\{2, 4\}$ via cumulants
    - First flow fluctuation ratio

- **ϒ(1S)** flow at forward rapidity
    - **First Run 3 measurement!**
    - Compatible with Run 2 within current uncertainties
    - Compared with different theoretical models

Future plans:

- Increase the datasets by adding new data from 2024 and beyond

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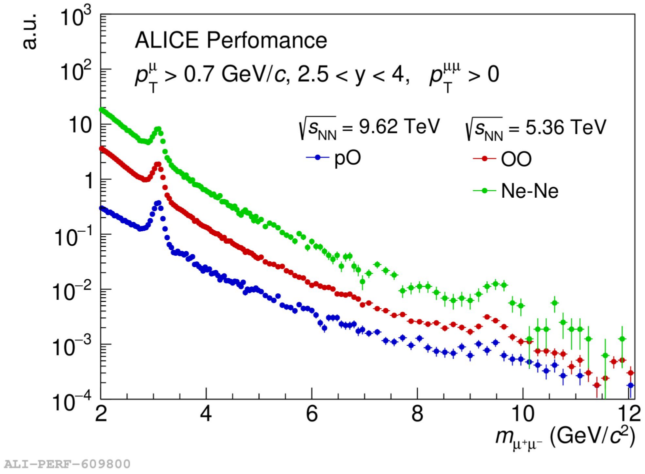
NEW

Light Ion runs

Dimuon distribution in pO, OO and Ne-Ne collisions!



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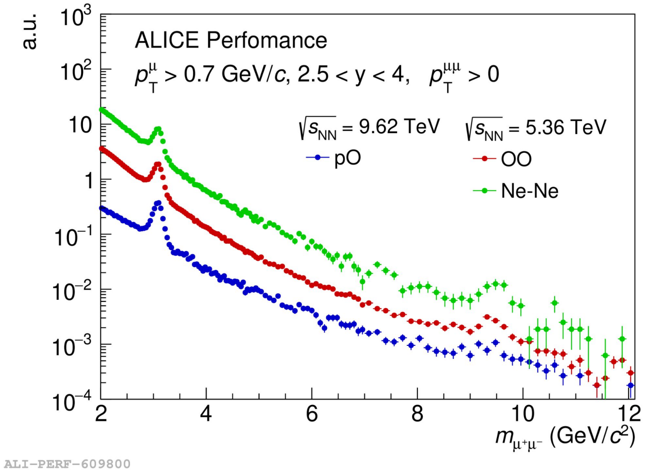
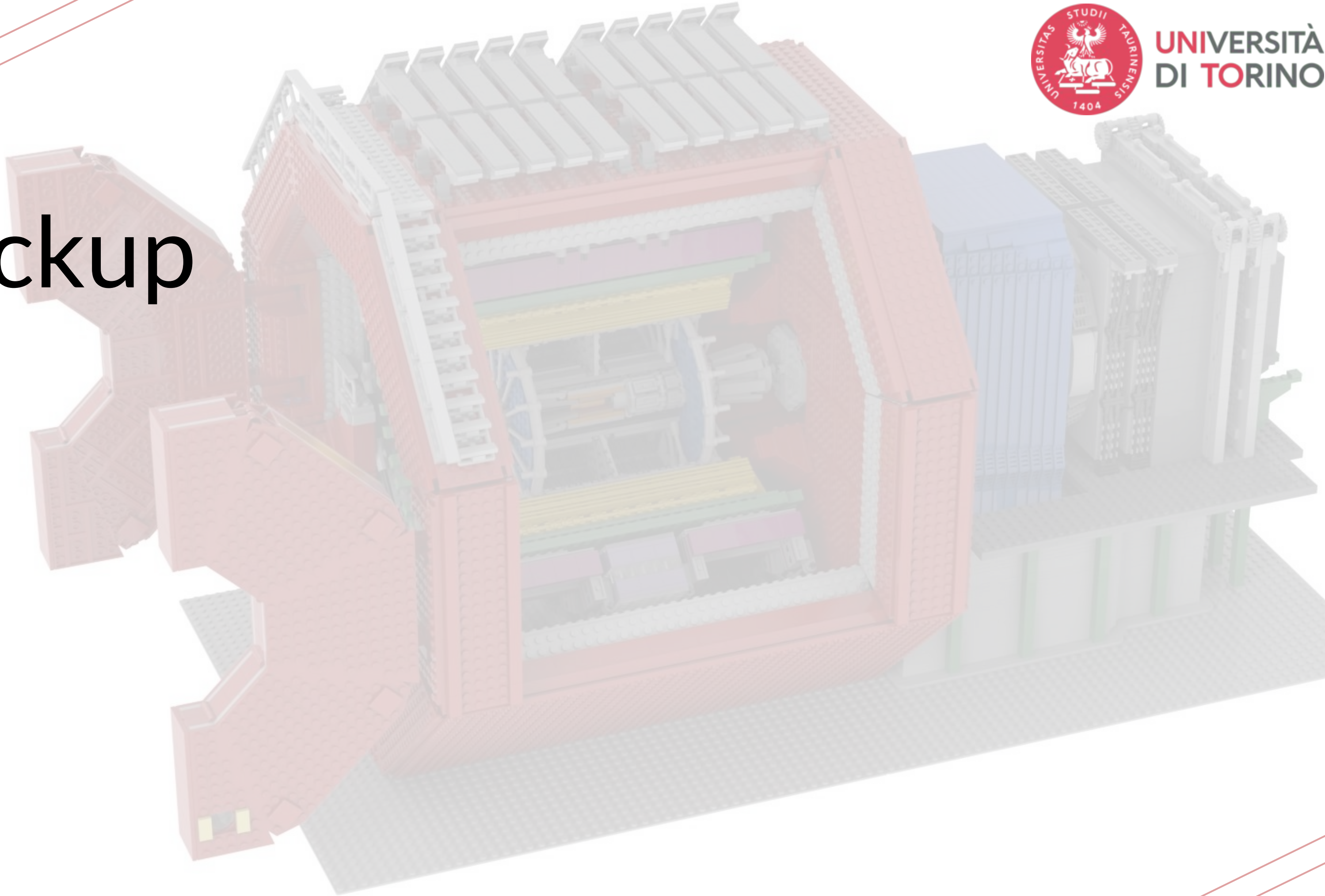


Thank you!

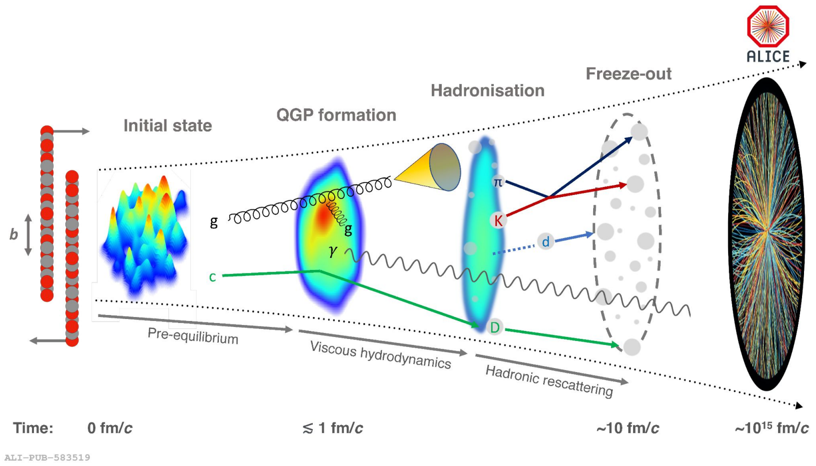
Backup



Heavy-quarks & quarkonium in heavy-ion collisions

Heavy-quarks (charm, beauty):

- Produced in the **initial hard parton scatterings**, before QGP formation (~ ½ m_Q ~ 0.1 fm/c)
- Production described by pQCD, since their mass scale ($\gg \Lambda_{QCD}$)
- Thermalization time (~ fireball life-time)



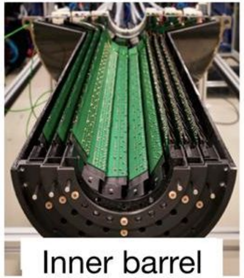
Evolution into bound states:

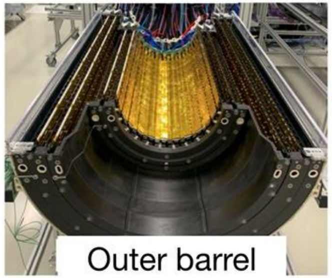
- **Quarkonia** (charmonia $c\bar{c}$, bottomonia $b\bar{b}$)
  → In-medium modifications
  - Color-screening
  - Dynamic dissociation
  - Collisional & radiative energy loss
  - Regeneration

- **Open heavy-flavors** (D and B mesons)
  → Transport properties
  → Thermalization degree
  → Hadronization

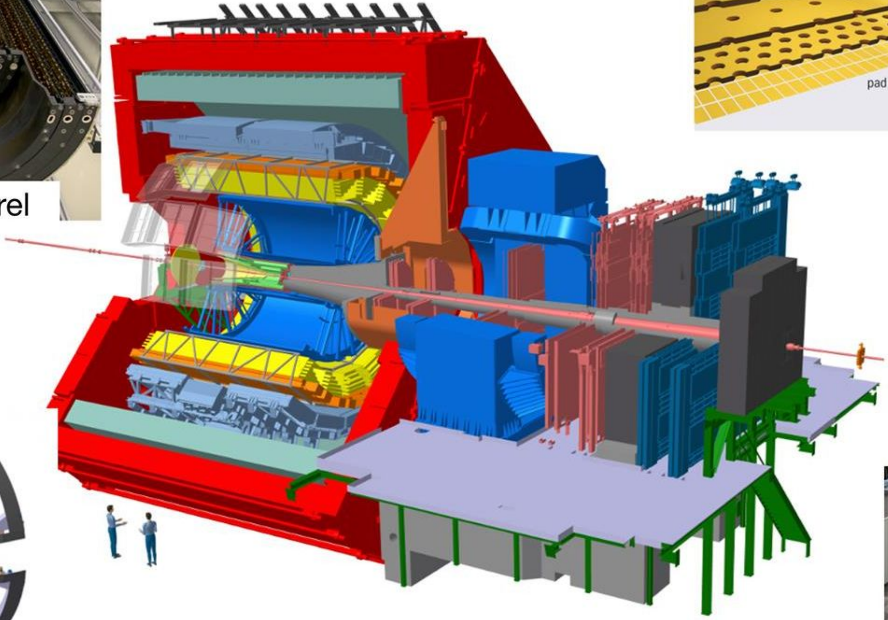
ALICE upgrades in LS2

New ITS

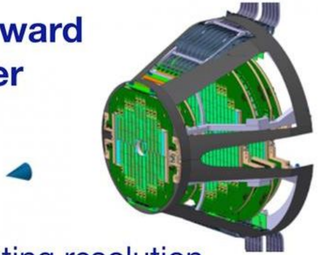




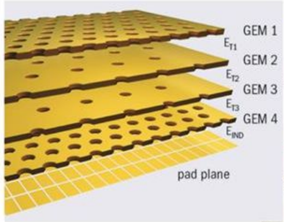
Full pixel detector
Improved read-out rate,
spatial resolution



Muon Forward Tracker



Improved pointing resolution
for muons

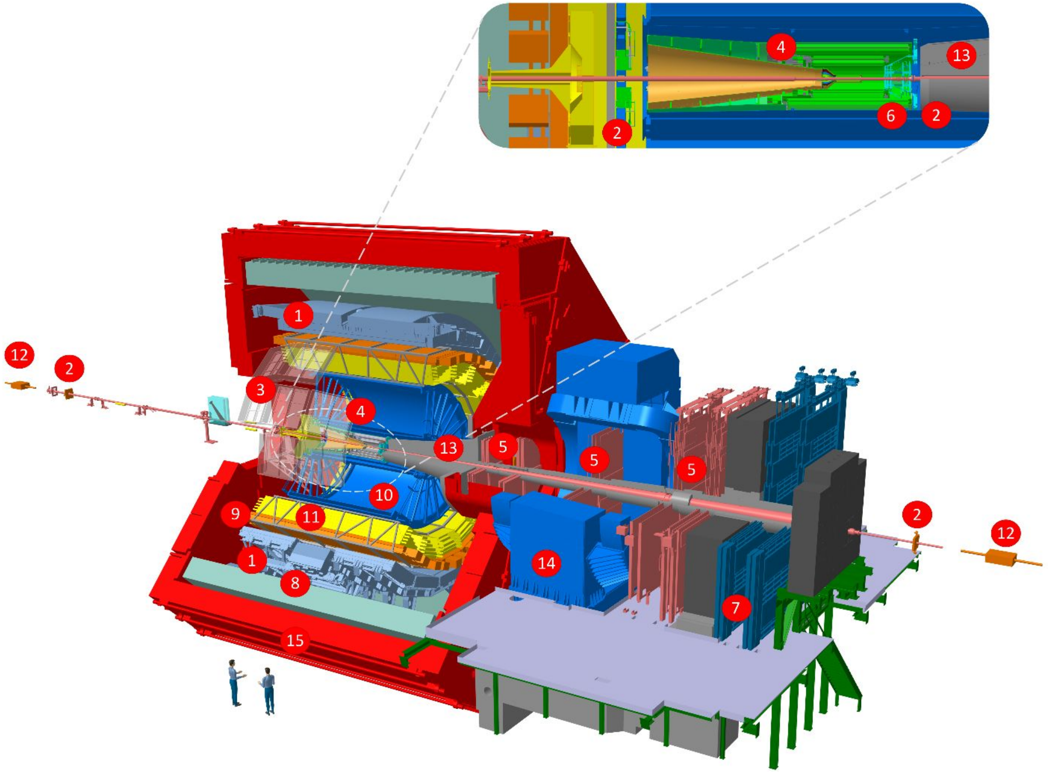


TPC: GEM readout

Continuous readout
Higher rates

Upgraded readout and online processing

ALICE upgrades in LS2



1. **EMCAL |** Electromagnetic Calorimeter
2. **FIT |** Fast Interaction Trigger
3. **HMPID|** High Momentum Particle Identification Detector
4. **ITS|** Inner Tracking System
5. **MCH|** Muon Tracking Chambers
6. **MFT|** Muon Forward Tracker
7. **MID|** Muon Identifier
8. **PHOS/CPV|** Photon Spectrometer
9. **TOF|** Time Of Flight
10. **TPC|** Time Projection Chamber
11. **TRD|** Transition Radiation Detector
12. **ZDC|** Zero Degree Calorimeter
13. **Absorber**
14. **Dipole Magnet**
15. **L3 Magnet**

Event Plane & Scalar Product Methods

$$v_2\{EP\} = \frac{\langle \cos(2(\phi - \Psi_2^A)) \rangle}{R_2\{EP\}}$$

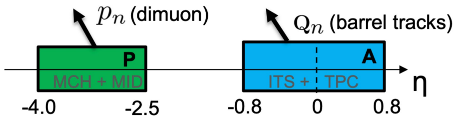
$$R_2\{EP\} = \sqrt{\frac{\langle \cos\left(2[\psi_2^A - \psi_2^C]\right)\rangle \langle \cos\left(2[\psi_2^A - \psi_2^B]\right)\rangle}{\langle \cos\left(2[\psi_2^B - \psi_2^C]\right)\rangle}}$$

$$v_2\{SP\} = \frac{\langle \mathbf{u}_2 \, Q_2^{A*} \rangle}{R_2\{SP\}}$$

$$R_2\{SP\} = \sqrt{\frac{\langle Q_2^A Q_2^{B*} \rangle \langle Q_2^A Q_2^{C*} \rangle}{\langle Q_2^B Q_2^{C*} \rangle}}$$

Three sub detector (A: TPC, B: FT0A and C: FT0C) for the Event Plane and Q_2 vectors calculation

Multi-particle correlation method: cumulants



$$Q_{n;k} = \sum_{i=1}^{M} w_i^k e^{(in\phi_i)}$$

$$S_{p,k} \equiv \left[\sum_{i=1}^{M} w_i^k\right]^p \qquad \mathcal{M}_{abcd\cdots} \equiv \sum_{i,j,k,l,\ldots=1}^{M}{}' w_i^a w_j^b w_k^c w_l^d \cdots$$

Differential Flow

$$\langle\langle 2' \rangle\rangle = \frac{\sum_{i=1}^{N} (\mathcal{M}'_{01})_i \langle 2' \rangle_i}{\sum_{i=1}^{N} (\mathcal{M}'_{01})_i} \qquad \langle\langle 4' \rangle\rangle = \frac{\sum_{i=1}^{N} (\mathcal{M}'_{0111})_i \langle 4' \rangle_i}{\sum_{i=1}^{N} (\mathcal{M}'_{0111})_i}$$

$$\mathcal{M}'_{01} \equiv \sum_{i=1}^{m_p} \sum_{i,j=1}^{M}{}' w_j \qquad \mathcal{M}'_{0111} \equiv \sum_{i=1}^{m_p} \sum_{j,k,l=1}^{M}{}' w_j w_k w_l$$

$$d_n^{\mu\mu}\{2\} = \langle\langle 2' \rangle\rangle$$

$$d_n^{\mu\mu}\{4\} = \langle\langle 4' \rangle\rangle - 2 \cdot \langle\langle 2' \rangle\rangle \, \langle\langle 2 \rangle\rangle$$

$$v_n^{\mu\mu}\{2\} = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}$$

$$v_n^{\mu\mu}\{4\} = -\frac{d_n^{\mu\mu}\{4\}}{(-c_n\{4\})^{3/4}}$$

Reference Flow

$$\langle\langle 2 \rangle\rangle = \frac{\sum_{i=1}^{N} (\mathcal{M}_{11})_i \langle 2 \rangle_i}{\sum_{i=1}^{N} (\mathcal{M}_{11})_i} \qquad \langle\langle 4 \rangle\rangle = \frac{\sum_{i=1}^{N} (\mathcal{M}_{1111})_i \langle 4 \rangle_i}{\sum_{i=1}^{N} (\mathcal{M}_{1111})_i}$$

$$\mathcal{M}_{11} \equiv \sum_{i,j=1}^{M}{}' w_i w_j \qquad \mathcal{M}_{1111} \equiv \sum_{i,j,k,l=1}^{M}{}' w_i w_j w_k w_l$$

$$c_n\{2\} = \langle\langle 2 \rangle\rangle$$

$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2 \cdot \langle\langle 2 \rangle\rangle^2$$

$$v_n^{\mathrm{REF}}\{2\} = \sqrt{c_n\{2\}}$$

$$v_n^{\mathrm{REF}}\{4\} = \sqrt[4]{-c_n\{4\}}$$

$v_2^{J/\psi}$ extraction method: two-step fitting

Step 1

Fit dimuon invariant mass distribution

- *Signal*: described with empirical functions (CB2, NA60)
- *Background*: either fixed by event-mixing or by empirical function (VWG...)
- *Calculated alpha factor*:

$$\alpha(m_{\mu\mu}) = \frac{S(m_{\mu\mu})}{S(m_{\mu\mu})+B(m_{\mu\mu})}$$

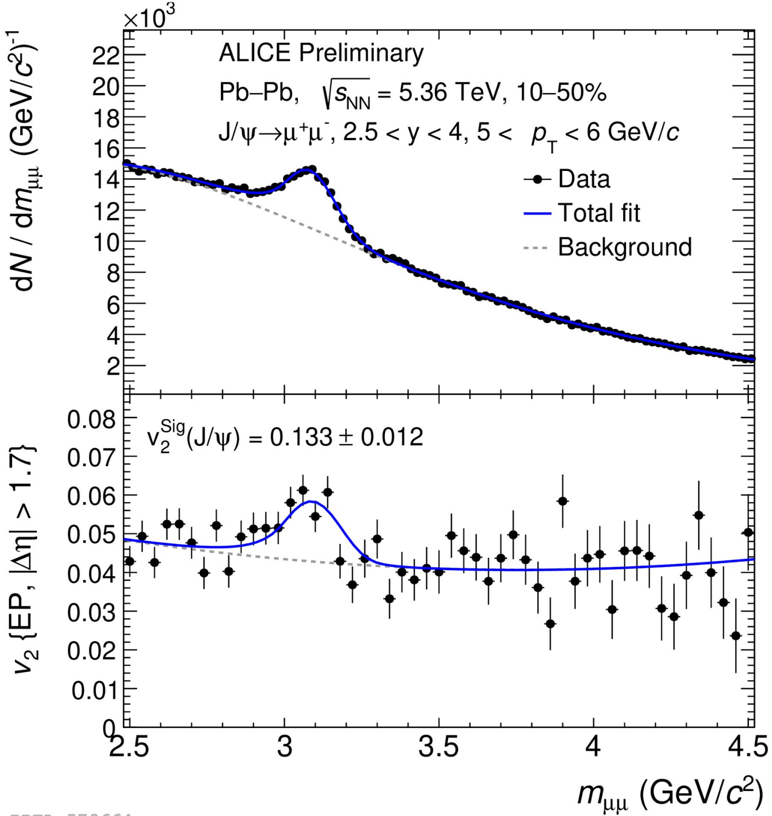
Step 2

Fit dimuon v_2 distribution

- *The fitting function*:

$$v_2^{\mu\mu}(m_{\mu\mu}) = \alpha(m_{\mu\mu})v_2^{J/\psi} + (1-\alpha(m_{\mu\mu}))\, v_2^{\mathrm{Bkg}}$$

- *Background flow* can be:
  - Modeled by empirical functions (Chebyshev, Pol2)
  - Fixed using event-mixing



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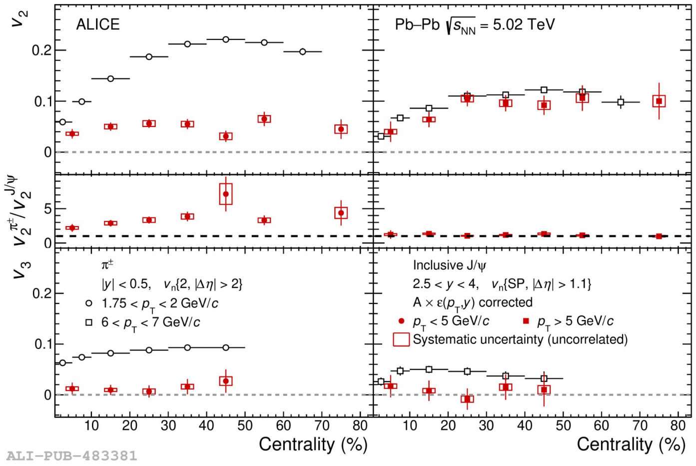
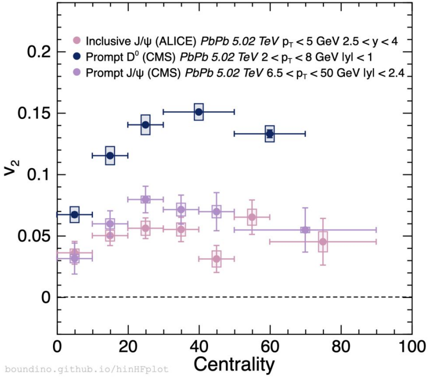
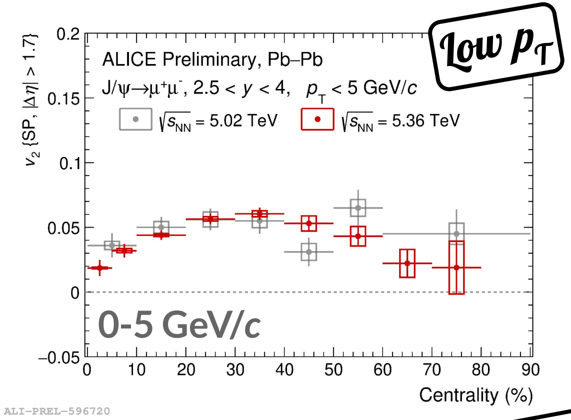
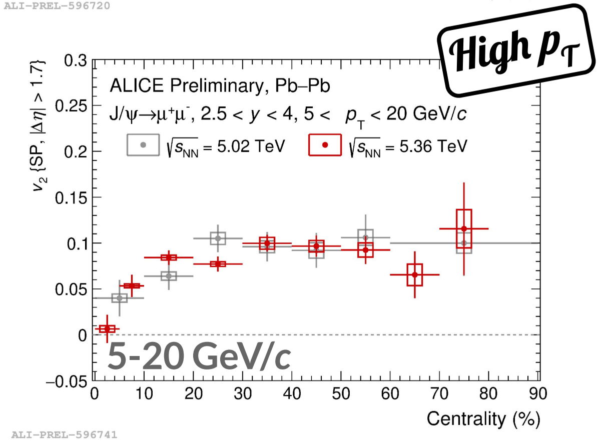
Forward $v_2^{J/\psi}$ vs. centrality in Pb–Pb collision (Run 3)









In the low p_T region:

- Peak around 30%, slightly more central relative to light quarks
- D meson flow peaked around 40%
- Pion flow peaked around 40–50%