Multi-particle cumulant J/ψ v_2 measurement at forward rapidity in Pb-Pb at $\sqrt{s_{\rm NN}} = 5.36$ TeV with ALICE

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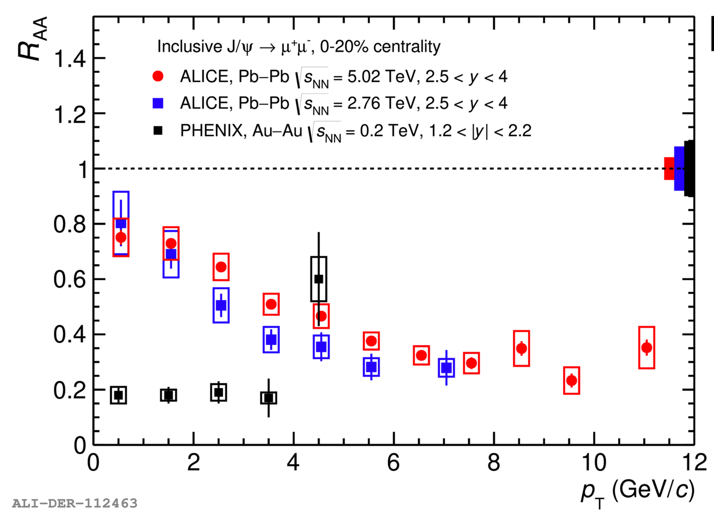
1 – Physics motivations

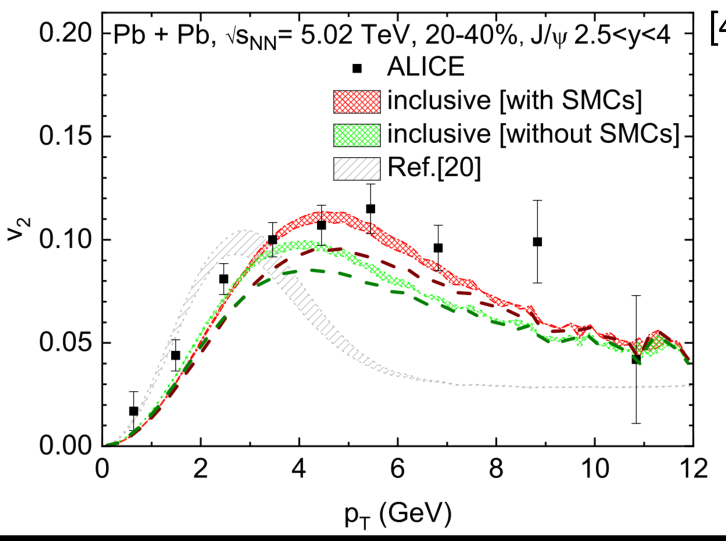
Charmonia as hard probes in quark-gluon plasma (QGP)

- **Charm quarks** in Pb-Pb collisions are created at very early times.
- **Charmonium production**: Requires a charm-anticharm quark pair: the condition $2M_c > \Lambda_{QCD}$ allows to use perturbative QCD [1].
- **Charmonium hadronization:** Effectively described by Non-relativistic QCD approach (NRQCD), with an attractive potential calculated via lattice QCD.
- **Charmonium suppression**: In a strongly interacting medium as QGP, charmonium states can be dissociated by a color screening mechanism [2].
- **QGP medium effects** can be studied with the **nuclear modification factor** $R_{\rm AA}$:

$$R_{\rm AA}(p_{\rm T}) = \frac{dN^{\rm AA}}{dp_{\rm T}}/[\langle T_{\rm AA}\rangle \cdot \frac{d\sigma^{\rm pp}}{dp_{\rm T}}] \quad \text{with} \quad \langle T_{\rm AA}\rangle = \langle N_{coll}\rangle/\sigma^{\rm pp}_{\rm inel}$$

- $R^{J/\psi}_{\rm AA}$ shows a significant **suppression** at **high** $p_{\rm T}$ **and (re)generation** at **low** $p_{\rm T}$ [3].
- The recombined **states** are expected to **exhibit** some **collective behaviour** from the interaction with the expanding QGP (see flow observable in section 2).
- New recombination model with Space Momentum Correlation (**SMC**) describes well ALICE Run 2 data [4].
- In LHC Run 2, the v_2 measurement could be influenced by non-flow contributions at high-$p_{\rm T}$.
- A measurement of the elliptic flow of J/ψ employing the **multi-cumulant method** should **mitigate non-flow** effects, offering new insights to better understand the charm behaviour at mid-high $p_{\rm T}$.





2 – Flow observable

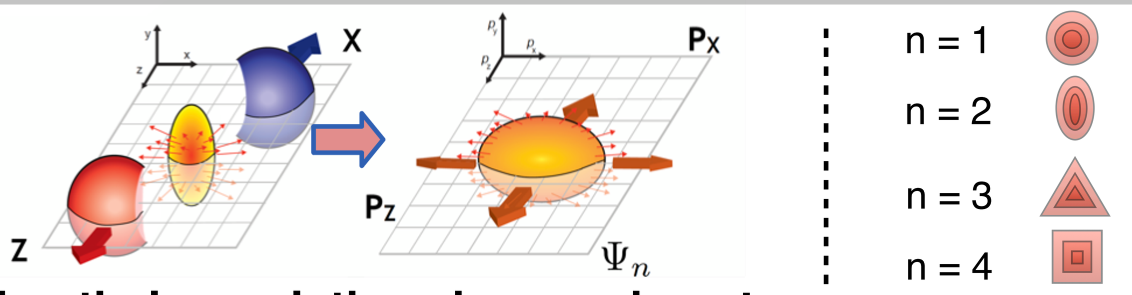
Azimuthal anisotropy

- As the QGP expands, the **initial spatial anisotropy** transforms into **momentum** space **anisotropies** [6]. This is manifested as an azimuthal dependence in the distribution of particles and it can be described with **Fourier series** [7].

$$\frac{dN}{d\varphi} = 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \psi_n)]$$

Where, $v_n = \langle \cos[n(\varphi - \psi_n)]\rangle$

- n is the harmonic order.
- φ is the particle's azimuthal angle
- ψ_n is the symmetry plane angle



Azimuthal correlations in experiment

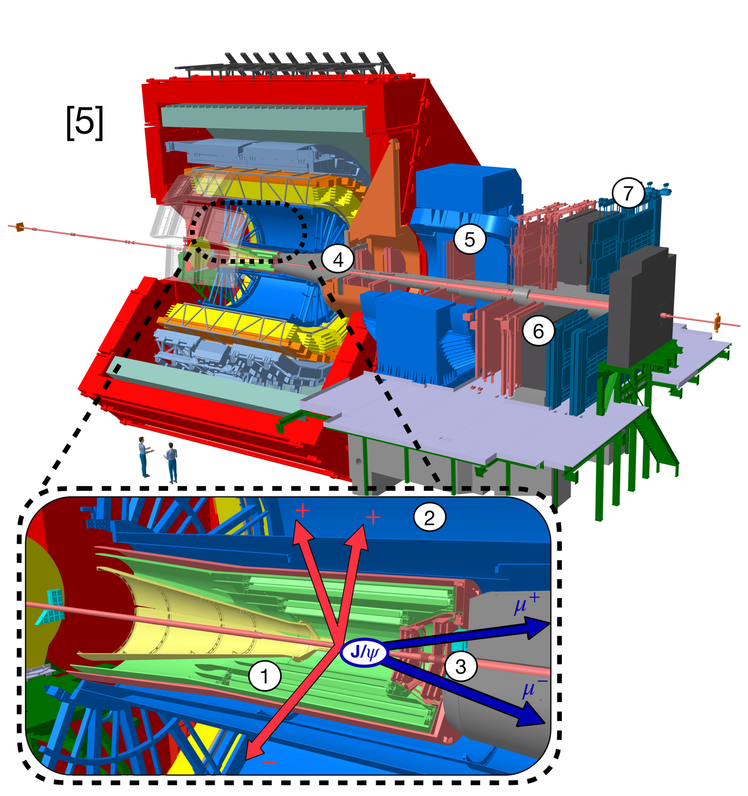
- The $v_n\{m\}$ **observable** can be determined by doing **correlations** among m particles [8]. In reality, **non-flow** contributions such as jets, di-jets, or decay resonances introduce a shift δ_m in the measurement of $v_n\{m\}$.

$$v_n\{2\}^2 = \langle \cos n(\varphi_1 - \varphi_2)\rangle = \langle v_n^2 + \delta_2\rangle \longleftrightarrow v_n\{4\}^4 = -\langle v_n^4 + \delta_4\rangle$$

- Where $\langle \ldots \rangle$ is the average over all tracks from all events
- Non-flow scales with multiplicity $\longrightarrow \delta_2 \propto 1/M$ and $\delta_4 \propto 1/M^3$.

3 – ALICE experimental setup in run 3

[5]



Muon spectrometer

- Quarkonium studied in the $\mu^+\mu^-$ decay channel.
- Acceptance coverage at forward rapidity: $2.5 < y < 4$
- Quarkonia can be detected down to $p_{\rm T} = 0$.

- **Front absorber** ④
  - Installed between ITS and MCH, reducing initial flux of hadrons by a factor of 100.
- **MCH** ⑤
  - Muon tracking system.
  - 5 stations made up of 10 chambers.
- **Muon filter** ⑥
  - Located between MCH and MID, stopping low $p_{\rm T}$ muons and filtering punch-through hadrons
- **MID** ⑦
  - Particle identification of muons.
  - 2 stations made up of 2 chambers.

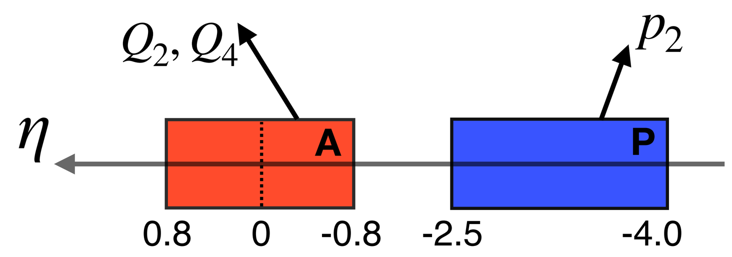
Central barrel

- **ITS** ① + **TPC** ②
  - **Vertex** reconstruction.
  - Detectors measuring charged particles at **mid-rapidity** $(-0.9 < \eta < 0.9)$.
- **FT0C** ③
  - Determines the **centrality** of the collision.

4 – Analysis strategy and signal extraction

Multi-particle cumulant with a constant η-gap [9]

- To suppress non-flow correlations, a pseudo-rapidity gap is applied.
- **A region →Multiplicity** M_A**:** Charged particles at mid-rapidity (ITS + TPC)
- **P region →Multiplicity** M_P **:** Dimuons at forward-rapidity (MCH + MID)



Reference flow (REF):

- **Charged particles** vectors:

$$Q_n = \sum_{i=1}^{M_A} e^{(in\varphi_i)},$$

- **REF** Correlators:

$$\langle 2\rangle = \frac{|Q_2|^2 - M_A}{M_A(M_A-1)}, \quad \langle 4\rangle = \frac{|Q_2|^4 + |Q_4|^2 - 2\cdot\Re[Q_4 Q_2^* Q_2^*]}{M_A(M_A-1)(M_A-2)(M_A-3)} - 2\cdot\frac{2(M_A-2)|Q_4|^2 - M_A(M_A-3)}{M_A(M_A-1)(M_A-2)(M_A-3)}$$

- **REF** Cumulants:

$$c_2\{2\} = \langle 2\rangle, \quad c_2\{4\} = \langle 4\rangle - 2\cdot\langle 2\rangle^2$$

Particle of interest flow (POI)

- **Dimuon vectors:**

$$p_2 = \sum_{i=1}^{M_p} e^{(i2\phi_i^{\mu\mu})}$$

- **POI** Correlators:

$$\langle 2'\rangle = \frac{p_2 Q_2^*}{M_p M_A}, \quad \langle 4'\rangle = \frac{p_2Q_2Q_2^*Q_2^* - p_2Q_2Q_4^*}{(M_pM_A)(M_A-1)(M_A-2)} + \frac{-2\cdot M_A p_2 Q_2^* + 2\cdot p_2 Q_2^*}{(M_pM_A)(M_A-1)(M_A-2)}$$

- **POI** Cumulants:

$$d_2^{\mu\mu}\{2\} = \langle 2'\rangle, \quad d_2^{\mu\mu}\{4\} = \langle 4'\rangle - 2\cdot\langle 2'\rangle\cdot\langle 2\rangle$$

Elliptic flow of dimuons

- $v_2^{\mu\mu}\{m\}$ as function of $M_{\mu\mu}$ for m=2, 4 are determined by computing a **ratio of REF and POI cumulants.**

$$v_2^{\mu\mu}\{2\} = -\frac{d_2^{\mu\mu}\{2\}}{\sqrt{c_2\{2\}}}, \quad v_2^{\mu\mu}\{4\} = -\frac{d_2^{\mu\mu}\{4\}}{(-c_2\{4\})^{3/4}}$$

- Each point of $v_2^{\mu\mu}\{m\}$ corresponds to the average value $\langle v_2\rangle$ of all dimuons pairs in one bin of $M_{\mu\mu}$.

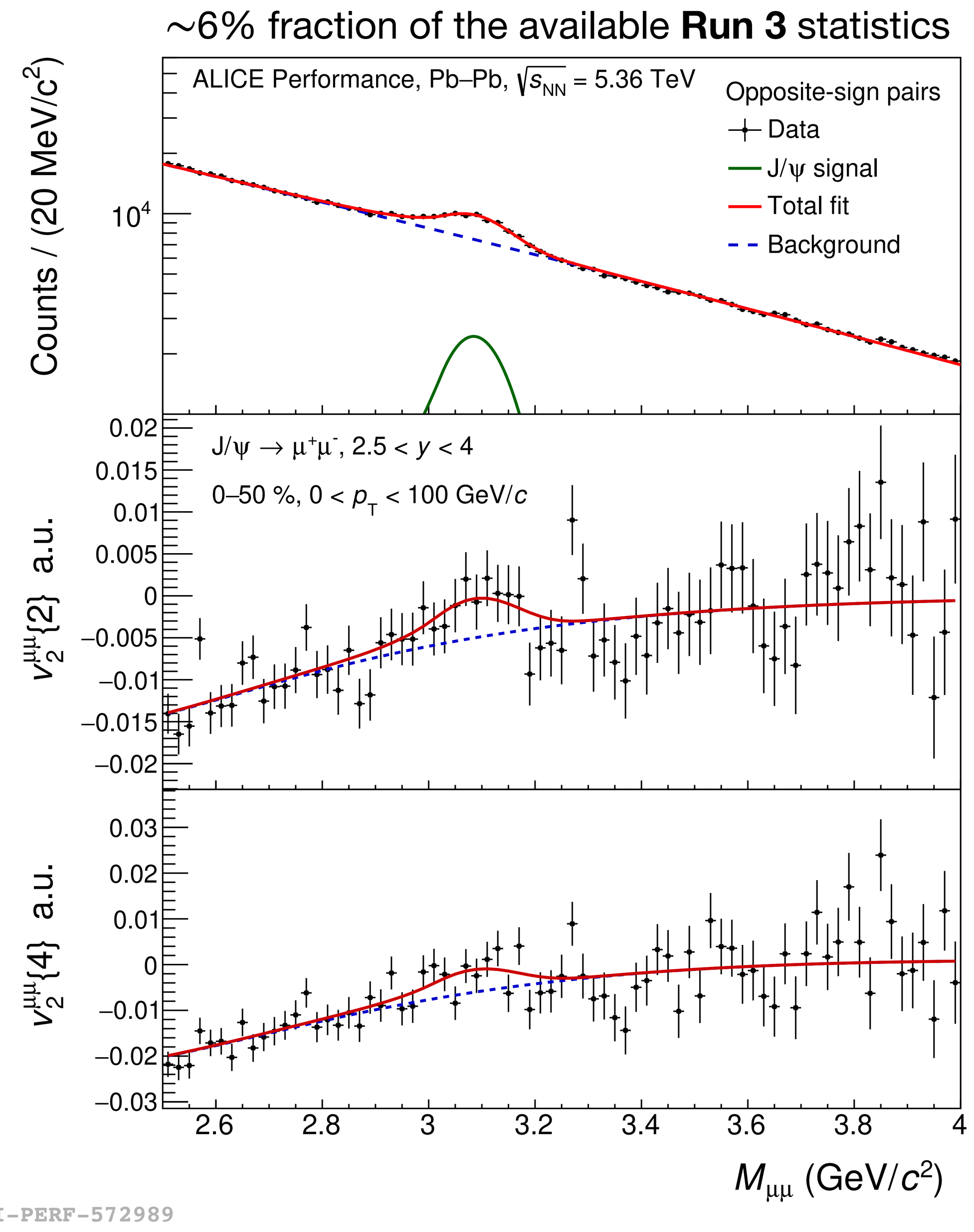
J/ψ yield and elliptic flow signal extraction

- First, the raw J/ψ **yield** is extracted by fitting the dimuon invariant mass spectrum, where the **signal to background ratio** $\alpha = S/(S+B)$ is calculated.
- The mean value of $v_2^{J/\psi}$ is obtained with a **global fit**, using the following formula [10]:

$$v_2 = v_2^{sig}\alpha + v_2^{bkg}(1-\alpha)$$

- The v_2^{bkg} is parametrised by a empirical functional form and v_2^{sig} is extracted by fitting $v_2^{\mu\mu}\{m\}$.

~6% fraction of the available **Run 3** statistics



5–Prospects: $v_2^{J/\psi}$ and $\sigma/\langle v_2^{J/\psi}\rangle$

Elliptic flow $p_{\rm T}$ -dependence

- Finally, fitting systematically the **elliptic flow of dimuons** $(v_2^{\mu\mu})$ for different $p_{\rm T}$ ranges, we can measure the **flow of** J/ψ $(v_2^{J/\psi})$ as a function of $p_{\rm T}$.
- **Non-flow effects** for $v_2^{J/\psi}\{4\}$ are expected to be smaller than those for $v_2^{J/\psi}\{2\}$ (non-flow contribution scales differently with multiplicity).
- The measurement of $v_2^{J/\psi}\{4\}$ should allow to **discriminate** between different **models** the behaviour of charm in the **mid-high** $p_{\rm T}$ **region**.

Fluctuation ratio

- The difference between $v_2^{\mu\mu}\{2\}$ and $v_2^{\mu\mu}\{4\}$ might arise from **event-by-event fluctuations** in the initial position **of nucleons** [11]. Assuming **Gaussian fluctuations** for flow harmonics, we have:

$$v_2\{2\}^2 \approx \langle v_2\rangle^2 + \sigma^2, \quad v_2\{4\}^2 \approx \langle v_2\rangle^2 - \sigma^2, \frac{\sigma}{\langle v_2\rangle} = \sqrt{\frac{v_2\{2\}^2 - v_2\{4\}^2}{v_2\{2\}^2 + v_2\{4\}^2}}$$

- If the ratio $\sigma/\langle v_2^{J/\psi}\rangle$ does not show a $p_{\rm T}$ dependence, the observed fluctuations are likely due to variations in the initial-state geometry [11]. This measurement could provide valuable insights to learn more about the flow of J/ψ.

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