

# Characterizing the initial state and dynamical evolution in Xe-Xe and Pb-Pb collisions using multiparticle cumulants

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**Abstract.** Xenon-xenon (Xe–Xe) collisions at a center-of-mass energy per nucleon pair  $\sqrt{s_{NN}} = 5.44$  TeV provide a unique probe of nuclear deformation at the Large Hadron Collider (LHC). By comparing with lead-lead (Pb–Pb) collisions at  $\sqrt{s_{NN}} = 5.36$  TeV, the dependence of flow harmonics ( $v_n$ ) on system size and initial geometry is studied. For the first time, correlations between multiple flow harmonics ( $v_2$ ,  $v_3$ , and  $v_4$ ) using higher-order mixed harmonic cumulants are measured and compared across centrality classes between Xe-Xe and Pb-Pb collisions. The results, obtained with charged particles in  $|\eta| < 2.4$  and  $0.5 < p_T < 3.0$  GeV/c, are compared to theoretical models, offering constraints on Xe deformation and insights into the quark-gluon plasma (QGP) evolution.

## 1 Introduction

High-energy heavy-ion collisions at the Large Hadron Collider (LHC) at CERN produce a strongly interacting medium known as the quark-gluon plasma (QGP) [1, 2]. Azimuthal anisotropies in particle emission are quantified using Fourier harmonics ( $v_n$ ), which describe the azimuthal angle distribution of emitted particles with respect to the reaction plane:

$$\frac{dN}{d\phi} = \frac{1}{2\pi} \left[ 1 + 2 \sum_{n=1}^{\infty} v_n \cos n(\phi - \psi_n) \right]. \quad (1)$$

Here,  $\phi$  is the azimuthal angle, and  $\psi_n$  is the  $n$ th-order flow symmetry plane. The coefficients  $v_2$ ,  $v_3$ , and  $v_4$  are referred to as elliptic, triangular, and quadrangular flow, respectively.

Anisotropic flow fluctuations arise from event-by-event fluctuations in the initial geometry [3]. Higher-order moments  $\langle v_n^k \rangle$  offer additional constraints, capturing non-linear hydrodynamic effects beyond those probed by  $\langle v_n^2 \rangle$  or inter-harmonic second-power correlations [4–6]. These observables are sensitive to deviations from the linear relation  $v_n \propto \varepsilon_n$ , where  $\varepsilon_n$  is the corresponding initial anisotropy.

The shape of the colliding nuclei influences the overlap region and particle production. The nuclear density is modeled as:

$$\rho(r, \theta) = \frac{\rho_0}{1 + \exp[(r - R(\theta))/a_0]}, \quad (2)$$

with an angular-dependent radius:

$$R(\theta) = R_0 [1 + \beta_2 Y_{20}(\theta) + \beta_4 Y_{40}(\theta)]. \quad (3)$$

Here,  $\rho_0$  is the central density,  $a_0$  the skin depth, and  $\beta_2$  and  $\beta_4$  represent quadrupole and hexadecapole deformations. The functions  $Y_{\ell m}(\theta, \phi)$  denote the spherical harmonics of degree  $\ell$  and order  $m$ . For a spherical nucleus,  $\beta_2 = \beta_4 = 0$ .

Comparisons between Xe–Xe and Pb–Pb collisions explore how nuclear deformation and system size affect flow correlations [1]. These measurements, alongside theoretical models, help constrain the initial geometry and evolution of the QGP at the LHC.

## 2 Analysis Technique

The Q-cumulant method [7] is employed to study multi-particle correlations involving two, four, six, or eight particles. These correlations can mix different powers and orders of flow harmonics. For example, a six-particle correlation may involve  $\langle v_n^4 v_m^2 \rangle$  or  $\langle v_n^2 v_m^2 v_p^2 \rangle$ .

Mixed-harmonic cumulants (MHCs), or  $m$ -observable cumulants [8], involve six or eight particles and were first explored by the ALICE experiment [9]. By construction, they exclude contributions from correlations among fewer particles, enhancing suppression of non-flow effects. For example, the six-particle cumulant MHC involving  $v_2^4$  and  $v_3^2$  is :

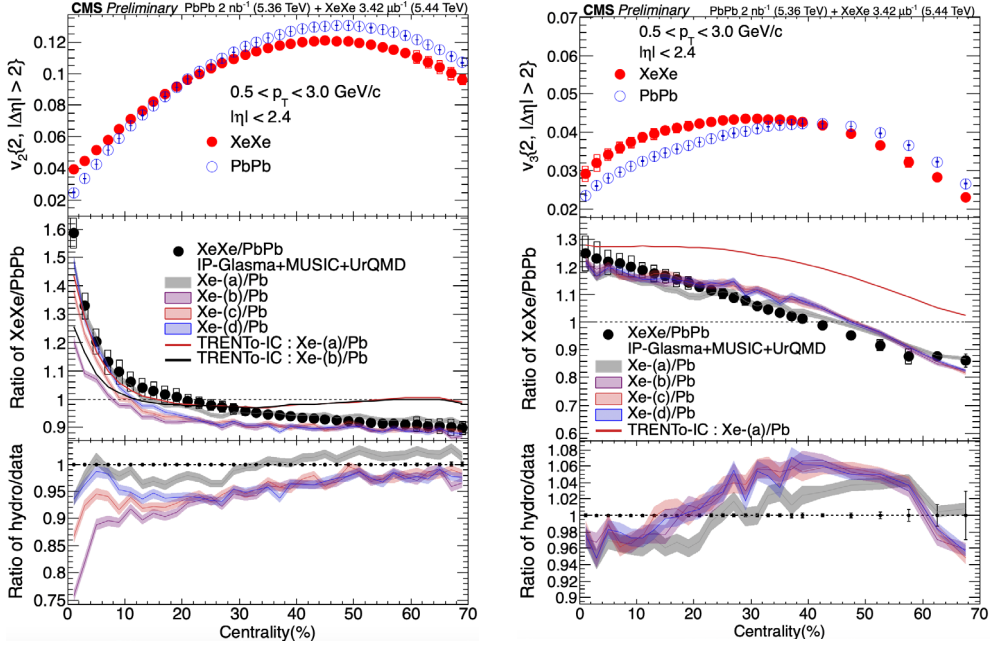
$$\text{MHC}(v_2^4, v_3^2) = \langle v_2^4 v_3^2 \rangle - 4\langle v_2^2 v_3^2 \rangle \langle v_2^2 \rangle - \langle v_2^4 \rangle \langle v_3^2 \rangle + 4\langle v_2^2 \rangle^2 \langle v_3^2 \rangle. \quad (4)$$

Similar observables have been defined using the prescription in Ref. [9]. A  $|\Delta\eta| > 2$  gap in pseudorapidity is used for all the observables in order to further reduce the effects of any remaining non-flow contributions.

## 3 Results

Figure 1 (left) shows two-particle correlation results,  $v_2\{2, |\Delta\eta| > 2\}$ , as a function of centrality for Xe-Xe and Pb-Pb collisions. The top row shows the  $v_2$  values, the middle row shows Xe-Xe/Pb-Pb ratios, and the bottom row compares hydrodynamic model predictions to data. In central collisions, Xe-Xe values are larger than Pb-Pb, possibly due to stronger initial-state geometry fluctuations and Xe nuclear deformation. Hydrodynamic predictions from IP-Glasma+MUSIC+UrQMD are shown for four Xe shape parameter sets, as detailed in Ref. [1]. The best match to data is obtained with set (a) ( $a_0 = 0.492, \beta_2 = 0.207$ ), especially for  $v_2$  in central events. TRENTo-IC model ratios, based on initial-state eccentricities, agree well with  $v_2$  in central collisions for set (a), but fail for peripheral collisions, likely due to stronger viscous damping in the smaller Xe-Xe system. Figure 1 (right) shows  $v_3\{2, |\Delta\eta| > 2\}$  as a function of centrality. The values are greater for Xe-Xe than Pb-Pb till almost 40% centrality, indicating that there are more initial-state energy density fluctuations in the smaller Xe-Xe system. For the IP-Glasma+MUSIC+UrQMD predictions, some parameter sets perform better than others for different centrality ranges.

Figure 2 shows some eight-particle normalized mixed-harmonic cumulants involving different powers of  $v_2$  and  $v_3$  (left), and  $v_2$  and  $v_4$  (right). While the TRENTo-IC and IP-Glasma IC initial-state model predictions qualitatively agree with the data for  $v_2 - v_3$  correlations, they fail for  $v_2 - v_4$  correlations when higher-order moments of  $v_4$  ( $v_4^4$  or  $v_4^6$ ) are involved, reversing the sign compared to data. The hydrodynamic model predictions correctly capture all of the trends. This points toward the nonlinear response of  $v_4$  to  $\varepsilon_2^2$  and indicates that these correlations predominantly develop dynamically during system evolution [9].



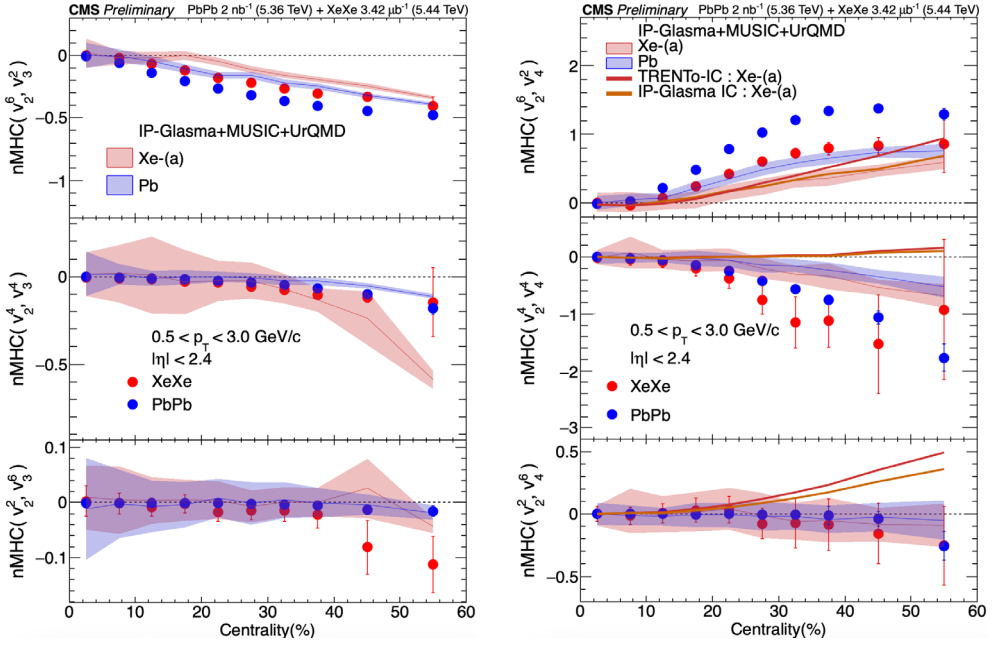
**Figure 1.** Top: Two-particle correlations  $v_n\{2, |\Delta\eta| > 2\}$  ( $n = 2$ , left, and  $n = 3$ , right) vs. centrality in Xe-Xe and Pb-Pb collisions. Middle: Xe-Xe/Pb-Pb ratios compared to TRENTo-IC and hydrodynamic model predictions. Shaded bands show IP-Glasma+MUSIC+UrQMD results for different Xe deformations. Bottom: Ratios of hydrodynamic predictions to data. The bars and the open boxes represent statistical and systematic uncertainties, respectively.

## 4 Summary

For the first time, individual flow harmonics ( $v_2, v_3, v_4$ ), two- and three-harmonic correlations, and higher-order mixed harmonic cumulants are measured and compared in Xe-Xe and Pb-Pb collisions. The IP-Glasma+MUSIC+UrQMD model with  $a_0 = 0.492$  and  $\beta_2 = 0.207$  for Xe best reproduces the data, indicating a prolate  $^{129}\text{Xe}$  nucleus, unlike the nearly spherical  $^{208}\text{Pb}$ . Cumulants involving higher-order moments of fluctuation-dependent harmonics like  $v_3$  and  $v_4$  are larger in XeXe, which is the smaller system. Initial-state models like TRENTo-IC and IP-Glasma IC capture  $v_2$ - $v_3$  correlations but fail for higher-order  $v_4$  moments due to its nonlinear hydrodynamic response to  $\varepsilon_2^2$ . Overall, the differences between data and model predictions point out the importance of properly modeling pre-equilibrium dynamics and fine-tuning QGP transport coefficients.

## References

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**Figure 2.** 8-particle normalized mixed-harmonic cumulants (nMHC) involving  $v_2$ - $v_3$  (left) and  $v_2$ - $v_4$  correlations (right) vs centrality in Xe-Xe and Pb-Pb collisions. The bars represent the statistical uncertainties.

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