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Measurements of Anisotropic Flow in Xe–Xe Collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV Using the ALICE Detector †

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Abstract: These proceedings summarise the first measurements of anisotropic flow coefficients v_{n}, $2 \leq \mathrm{n} \leq 4$, for inclusive charged particles at mid-rapidity in Xe–Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44$ TeV. The results are compared with those from Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, in order to test the initial state (IS) models and transport properties. The resulting differences in v_2 and v_3 between the two systems are consistent with two different hydrodynamical models. Moreover, it is expected that the ratios between v_{n} and their corresponding eccentricities for $\mathrm{n} = 2, 3$ scale with transverse density. This is observed for some IS models, except for some deviations in central collisions. These results assist in constraining the initial state as well as the hydrodynamical propagation of the system.

Keywords: flow; anisotropic flow; heavy-ion collisions; system size dependence; xenon collisions

1. Introduction

These proceedings mainly summarise the contents of Ref. [1]. In relativistic heavy-ion collisions, it is believed that a quark-gluon plasma (QGP) is formed, which is a hot and dense state of matter, behaving as a nearly perfect fluid. As a consequence, when the medium cools, it will undergo hydrodynamic expansion, driven by the pressure gradient. For an anisotropic initial state—which can be due to either an off-centre impact, or to fluctuations affecting the shape—the final state will therefore be anisotropic, resulting in an anisotropic momentum distribution of the resulting particles. This is known as *anisotropic flow*, which is characterised by the flow coefficients v_{n}, obtained from the Fourier expansion

$$\frac{dN}{d\varphi} \propto 1 + \sum_{\mathrm{n}=1}^{\infty} 2v_{\mathrm{n}} \cos\left(\mathrm{n}\left(\varphi - \Psi_{\mathrm{n}}\right)\right), \tag{1}$$

where φ is the azimuthal angle, n is the flow harmonic, and Ψ_{n} is the associated symmetry plane angle.

This observable is sensitive to the initial state (IS) model used, and to a lesser extent to the shear viscosity over entropy ratio (η/s) of the medium. To constrain these models and parameters, it is useful to make measurements across various collision systems of different sizes. In particular, it is assumed that the relation [2]

$$v_{\mathrm{n}} \approx \kappa_{\mathrm{n}} \varepsilon_{\mathrm{n}} \tag{2}$$

holds for $\mathrm{n} = 2$ or 3, where ε_{n} is the eccentricity, and the proportionality constant κ_{n} scales with the transverse charged particle density of the system.

Previously, the LHC has collided Pb ions in their heavy-ion programme, but in 2017 this was extended by running a short Xe–Xe run at 5.44 TeV. This made it possible to test the relation described in Equation (2) across system size and for different nuclear deformations (^{129}Xe is deformed whereas ^{208}Pb is spherical). Therefore, this study aims at measuring v_2, v_3, and v_4 in Xe–Xe collisions and comparing the results with those from Pb–Pb collisions and test theoretical predictions.

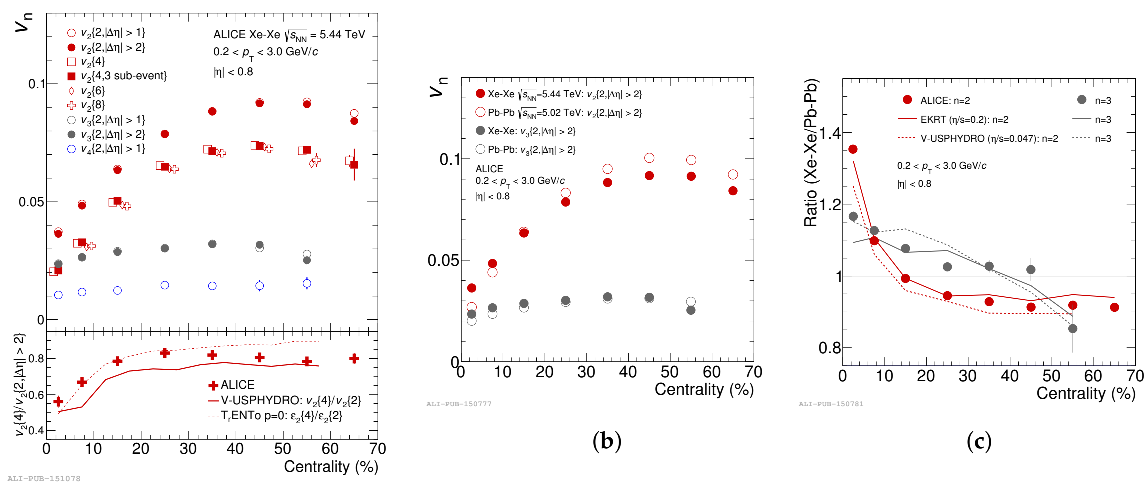
2. Analysis Methods

This study uses data from Xe–Xe collisions at 5.44 TeV from 2017 and Pb–Pb collisions at 5.02 TeV from 2015, taken by the ALICE detector. Information about the experiment and its subdetectors can be found elsewhere [3]. Here, charged-particle tracks reconstructed by the Time-Projection Chamber (TPC) are used, with pseudorapidity range $|\eta| < 0.8$. The Inner Tracking System (ITS) is used to improve spatial and momentum resolution. Centrality is determined by using the V0 detectors. Only tracks in the transverse momentum region $0.2 < p_{\mathrm{T}} < 10$ GeV/c are used in the analysis.

Flow is measured using multi-particle cumulants from the generic framework [4]. To suppress non-flow in two-particle cumulants, correlations are taken between tracks separated by an η gap larger than 1 in the TPC, or by using the scalar product method to provide an η gap larger than 2 and increase the statistics [5]. In the latter, tracks from the ITS and TPC are correlated with $\mathbf{Q}_{\mathrm{n}}$ vectors, $\mathbf{Q}_{\mathrm{n}} = \sum_{k=1}^{M} \mathrm{e}^{\mathrm{i}n\varphi_k}$, where M is the particle multiplicity, constructed from the V0 counters (these are located at $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$, respectively). Further details are provided in Ref. [1].

3. Results

Measurements of v_2, v_3, and v_4 in Xe–Xe collisions, using two- and multiparticle cumulants, are shown in the top panel of Figure 1a. The ratio $v_2\{4\}/v_2\{2\}$ is sensitive to flow fluctuations, and hence to the IS. Therefore, to test the IS model and hydrodynamic description, this ratio is compared to a hydrodynamic calculation, using V-USPHYDRO with $\eta/s = 0.047$ [6], as shown in the lower panel of Figure 1a. The IS is modelled by T$_{\mathrm{R}}$ENTo [7].



(a) (b) (c)

Figure 1. (**a**) Upper panel: $v_{\mathrm{n}}\{m\}$, $2 \leq \mathrm{n} \leq 4$, as a function of centrality in Xe–Xe collisions at 5.44 TeV, for various orders m and pseudorapidity gaps. Lower panel: Comparison of the ratio $v_2\{4\}/v_2\{2, |\Delta\eta > 2|\}$ with a hydrodynamic calculation where a T$_{\mathrm{R}}$ENTo IS model has been propagated using V-USPHYDRO [6,7]. The results are also compared with $\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from the IS model. (**b**) Comparison of $v_{\mathrm{n}}\{2, |\Delta\eta > 2|\}$, $\mathrm{n} = 2, 3$, between Xe–Xe and Pb–Pb collisions as a function of centrality. (**c**) Ratios between flow coefficients in Xe–Xe and analogous ones in Pb–Pb as a function of centrality, compared to hydrodynamic calculations from EKRT ($\eta/s = 0.2$) and V-USPHYDRO ($\eta/s = 0.47$) [6,8], respectively.

The results are also compared with the eccentricity ratio $\varepsilon_2\{4\}/\varepsilon_2\{2\}$ from the IS model. Both of these predictions follow the same trend as the data, although both deviate somewhat from the data in parts of the centrality range.

In Figure 1b, $v_2\{2, |\Delta\eta > 2|\}$ and $v_3\{2, |\Delta\eta > 2|\}$ are compared between Xe–Xe collisions at 5.44 TeV, and Pb–Pb collisions at 5.02 TeV, as a function of centrality. In Figure 1c, the ratios between the results from these two systems are compared with two different hydrodynamic calculations, EKRT using $\eta/s = 0.2$ and V-USPHYDRO using $\eta/s = 0.47$ [6,8]. Both of these models take into account the nuclear deformation in Xe, as described in Ref. [1]. Following Equation (2), the ratio $v_{\rm n}\{2, |\Delta\eta > 2|\}/\varepsilon_{\rm n}\{2\}$ provides an estimate of $\kappa_{\rm n}$, which for $\rm n = 2$ and $\rm n = 3$ is expected to scale with transverse charged particle density, $1/S\, {\rm d}N_{\rm ch}/{\rm d}\eta$, where S is the transverse area and ${\rm d}N_{\rm ch}/{\rm d}\eta$ is the charged particle density of the system. The ${\rm d}N_{\rm ch}/{\rm d}\eta$ are provided from other studies [9,10]. In Figure 2, this scaling is tested for a few different IS models: MC Glauber with nucleons and 3, 5, and 7 constituent quarks ($q = 3, 5, 7$) [11], respectively, as sources; MC KLN [12]; and the T$_{\rm R}$ENTo model [7]. MC Glauber with $q = 5$ or $q = 7$, as well as T$_{\rm R}$ENTo, generally yield good scaling, although there is a sharp decrease in the ratio at high transverse density. MC Glauber with nucleons as sources, as well as MC KLN, scale poorly across the systems.

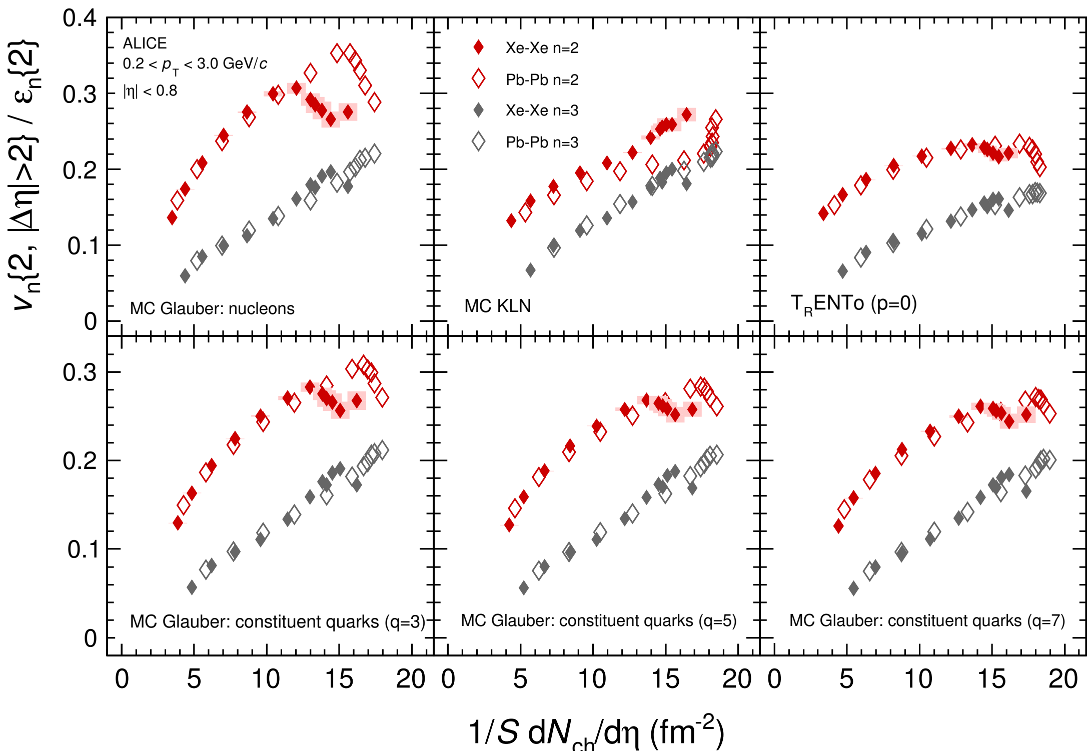


Figure 2. $v_{\rm n}\{2, |\Delta\eta > 2|\}/\varepsilon_{\rm n}\{2\}$ as a function of transverse density in Xe–Xe and Pb–Pb for $\rm n = 2$ and $\rm n = 3$, for various IS models. (**Top left**) MC Glauber using nucleons as sources [11]. (**Top centre**) MC KLN [12]. (**Top right**) T$_{\rm R}$ENTo [7]. (**Bottom**) MC Glauber using 3, 5, and 7 constituent quarks as sources [11], respectively.

4. Discussion

The fact that both the hydrodynamic prediction of $v_2\{4\}/v_2\{2, |\Delta\eta > 2|\}$ and the corresponding eccentricity ratio agree reasonably well with the data in Figure 1a indicates that Equation (2) holds approximately and that flow fluctuations are preserved in the hydrodynamic expansion. Moreover, it seems T$_{\rm R}$ENTo models the IS fairly well.

Figure 1c indicates that both EKRT and V-USPHYDRO are able to model differences in IS and medium response between Pb and Xe fairly well. The lower v_2 in Xe at mid-central collisions is expected to be due to a larger viscous damping in Xe [6,8], since ε_2 should be quite similar for the two systems. The peak in central collisions is mostly due to the deformation of the Xe nucleus, enhancing flow at central collisions. Since the Xe nucleus is smaller, it is expected to be more affected by flow fluctuations, which is the most likely reason for the larger v_3 (and v_2) in central Xe collisions.

The sharp decrease in $v_2\{2, |\Delta\eta > 2|\}/\varepsilon_2\{2\}$ at high transverse density seen in most models for Pb–Pb in Figure 2 may indicate some shortcomings in the modelling of the IS in ultra-central collisions [1]. The requirement to use $q \geq 5$ in MC Glauber for good scaling shows that one needs to use several constituent quarks as sources, i.e., take into account nuclear substructure, for this approach to work properly (also indicated in Ref. [13]). Moreover, MC KLN can be ruled out from this study, whereas also these results favour $\mathrm{T_R}$ENTo.

5. Conclusions

Measurements of v_2, v_3, and v_4 in Xe–Xe collisions have given valuable information about the initial state and hydrodynamic propagation in heavy ion collisions. These results indicate that flow fluctuations are preserved through the hydrodynamic propagation. Moreover, both EKRT and V-USPHYDRO can describe differences between Xe–Xe and Pb–Pb collisions. These models show that the Xe nucleus is deformed. Finally, the data favour the $\mathrm{T_R}$ENTo IS model and MC Glauber with multiple quarks as sources, but rule out MC KLN and MC Glauber with nucleons as sources.

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Conflicts of Interest: The author declares no conflict of interest.

References

1. ALICE Collaboration. Anisotropic flow in Xe–Xe collisions at $\sqrt{s_{\mathrm{NN}}} = 5.44\,\mathrm{TeV}$. *Phys. Lett. B* **2018**, *784*, 82–95, doi:10.1016/j.physletb.2018.06.059.
2. Holopainen, H.; Niemi, H.; Eskola, K.J. Event-by-event hydrodynamics and elliptic flow from fluctuating initial state. *Phys. Rev. C* **2011**, *83*, 034901, doi:10.1103/PhysRevC.83.034901.
3. ALICE Collaboration. The ALICE experiment at the CERN LHC. *JINST* **2008**, *3*, S08002, doi:10.1088/1748-0221/3/08/S08002.
4. Bilandzic, A.; Christensen, C.H.; Gulbrandsen, K.; Hansen, A.; Zhou, Y. Generic framework for anisotropic flow analyses with multiparticle azimuthal correlations. *Phys. Rev. C* **2014**, *89*, 064904, doi:10.1103/PhysRevC.89.064904.
5. STAR Collaboration. Elliptic flow from two and four particle correlations in Au + Au collisions at $\sqrt{s_{\mathrm{NN}}} = 130\,\mathrm{GeV}$. *Phys. Rev. C* **2002**, *66*, 034904, doi:10.1103/PhysRevC.66.034904.
6. Giacalone, G.; Noronha-Hostler, J.; Luzum, M.; Ollitrault, J.-Y. Hydrodynamic predictions for 5.44 TeV Xe + Xe collisions. *Phys. Rev. C* **2018**, *97*, 034904, doi:10.1103/PhysRevC.97.034904.
7. Moreland, J.T.; Bernhard, J.E.; Bass, S.A. Alternative ansatz to wounded nucleon and binary collision scaling in high-energy nuclear collisions. *Phys. Rev. C* **2015**, *92*, 011901, doi:10.1103/PhysRevC.92.011901.
8. Eskola, K.J.; Niemi, H.; Paatelainen, R.; Tuominen, K. Predictions for multiplicities and flow harmonics in 5.44 TeV Xe + Xe collisions at the CERN Large Hadron Collider. *Phys. Rev. C* **2018**, *97:3*, 034911, doi:10.1103/PhysRevC.97.034911.
9. ALICE Collaboration. Centrality and pseudorapidity dependence of the charged-particle multiplicity density in Xe–Xe collisions at 5.44 TeV. *arXiv* **2018**, arXiv:1805.04432.
10. ALICE Collaboration. Centrality dependence of the charged-particle multiplicity density at midrapidity in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$. *Phys. Rev. Lett.* **2016**, *116*, 222302, doi:10.1103/PhysRevLett.116.222302.
11. Loizides, C. Glauber modeling of high-energy nuclear collisions at the subnucleon level. *Phys. Rev. C* **2016**, *94*, 024914, doi:10.1103/PhysRevC.94.024914.

12. Drescher, H.-J.; Nara, Y. Eccentricity fluctuations from the color glass condensate at RHIC and LHC. *Phys. Rev. C* **2007**, *76*, 041903, doi:10.1103/PhysRevC.76.041903.
13. ATLAS Collaboration. Measurement of long-range multiparticle azimuthal correlations with the subevent cumulant method in pp and p + Pb collisions with the ATLAS detector at the CERN Large Hadron Collider. *Phys. Rev. C* **2018**, *97*, 024904, doi:10.1103/PhysRevC.97.024904.