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Measurements of anisotropic flow and flow fluctuations in Xe–Xe and Pb–Pb collisions with ALICE

Jacopo Margutti (for the ALICE Collaboration)

Utrecht University, PO Box 80125, 3508 TC Utrecht (Netherlands)

Abstract

Anisotropic flow is a key observable to characterise the system created in heavy-ion collisions, as it is sensitive to the system's initial state, transport properties, the equation of state and freeze-out conditions. In these proceedings we present the anisotropic flow coefficients of inclusive charged particles in Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ and 5.02 TeV, and in Xe–Xe collisions at $\sqrt{s_{\rm NN}} = 5.44$ TeV. The results are reported for a wide range of particle transverse momentum within the pseudo-rapidity range $|\eta| < 0.8$ at different collision centralities. The energy and system dependence are found to place strong constraints on the temperature dependence of η/s and the modeling of the initial state, respectively. We also present detailed studies of flow fluctuations in heavy-ion collisions, in order to precisely characterise the underlying flow probability density function. We find evidence of non-Bessel-Gaussian fluctuations and discuss the origin of this observation.

Keywords: LHC, ALICE, anisotropic flow, flow fluctuations, Pb–Pb, Xe–Xe,

1. Introduction

The study of anisotropic flow, i.e. anisotropies in the azimuthal distribution of final-state particles, has contributed significantly to the characterisation of the system created in heavy-ion collisions. The significant magnitude of anisotropic flow at low transverse momenta has been interpreted as evidence of the formation of a strongly-coupled system, which behaves as a fluid with very low specific shear viscosity to entropy ratio (η/s) [1]. Initial-state spatial ansisotropies are converted into final-state momentum ones by the collective, hydrodynamic-like expansion of the system. Anisotropic flow is quantified by the Fourier coefficients $v_{\rm n}$ of a series decomposition of the distribution in azimuthal angle φ of final-state particles [2]

$$\frac{{\rm d}N}{{\rm d}\varphi} \propto 1 + 2\sum_{\rm n=1}^{+\infty} v_{\rm n} \cos\left[{\rm n}(\varphi - \Psi_{\rm n})\right], \quad (1)$$

where $\Psi_{\rm n}$ corresponds to the symmetry plane angle of order n. The typical almond-like shape of the overlapping area between the colliding nuclei results in elliptic flow (v_2) being the dominant flow coefficient, while

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higher order harmonics can originate from initial-state fluctuations. For low transverse momenta ($p_T \lesssim 3$ GeV/c), anisotropic flow is sensitive to the transport parameters (such as specific shear and bulk viscosity) and the QCD equation of state, being determined by the collective expansion of the system. In this contribution, we investigate the transverse momentum, centrality and collision energy dependence of anisotropic flow in Pb–Pb collisions. Using the multi-particle cumulant method, we analyse in great detail the fluctuations of elliptic flow in such collision system. We also report the first measurements of anisotropic flow in Xe–Xe collisions. We then contrast them with measurements in Pb–Pb collisions, in order to study the dependence of anisotropic flow on the system size and transverse particle density.

2. Analysis details

The data samples used for these measurements were recorded with the ALICE detector [3] during the LHC Run2 and Run1 data taking periods. In particular, Pb–Pb collisions were recorded at a centre of mass energy per nucleon ($\sqrt{s_{NN}}$) of 5.02 and 2.76 TeV, while Xe–Xe collisions were recorded at $\sqrt{s_{NN}}$ = 5.44 TeV. A minimum-bias trigger was used. About 78.4×10^6 (12.6×10^6) minimum-bias events in the centrality range 0–80%, corresponding to an integrated luminosity of 12.7 μb^{-1} (2.0 μb^{-1}), passed offline selection criteria for the Pb–Pb data sample at $\sqrt{s_{NN}}$ = 5.02 (2.76) TeV. Concerning Xe–Xe collisions, the resulting event sample consists of about 1×10^6 minimum-bias events in the centrality range 0–70%. Charged tracks with transverse momentum $0.2 < p_T < 50$ GeV/c and pseudorapidity $|\eta| < 0.8$, reconstructed using combined information from the Inner Tracking System (ITS) and Time Projection Chamber (TPC), are used. Anisotropic flow coefficients are measured using the multi-particle Q-cumulant [4] and scalar product [5] methods. Non-uniform acceptance and inefficiencies are corrected for with track weights in the Q-vector construction. A detailed description of the event and track selection, and the analysis methods can be found in [6, 7].

3. Results

The p_T-dependence of flow coefficients v_n (n = 2, . . . 6) in Pb–Pb collisions is shown in Fig. 1, for the centrality intervals 5-10%, 30-40% and 60-70%, and p_T range $0.2 < p_T < 50$ GeV/c. No significant difference between the two collision energies ($\sqrt{s_{NN}}$ = 5.02 and 2.76 TeV) is observed. We note that all flow coefficients follow a simple power-law scaling of the form $v_n(p_T) \sim p_T^{n/3}$ for $p_T < 3$ GeV/c and within each centrality interval. In ideal hydrodynamics, which is expected to approximately hold in this p_T range, $v_n(p_T)$ for massive particles should follow a power-law function $v_n(p_T) \sim p_T^n$ in the region of p_T/M up to order one, where M is the particle's mass [8]. Therefore, the observed power-law dependence is unexpected and surprising. The ratios of v_2 estimated with different multi-particle cumulants are shown in Fig. 2, top left. The ratios $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{4\}$ are observed to be below unity, which can be interpreted as evidence of non-Gaussian elliptic flow fluctuations [9]. A small but finite centrality dependence is observed, with the ratios decreasing from central to peripheral collisions. This behavior can be interpreted as initial-state fluctuations being progressively more normally distributed as the number of colliding nucleons increases, consistent with the central limit theorem. A measurement of the standardised skewness γ_1^{exp} [11] is also reported for Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (Fig. 2, top right). Measurements of elliptic flow fluctuations are observed to be consistent with previous ATLAS results [10] and hydrodynamic model calculations [11]. The full elliptic flow probability density function in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, extracted from fits of multi-particle cumulants assuming an Elliptic-Power distribution [12, 13], can be found in [6]. The first measurements of p_T-integrated flow coefficients v_n (n = 2, . . . 4) in Xe–Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV are shown in Fig. 2, bottom left. The ratio $v_2\{4\}/v_2\{2\}$, which is sensitive to elliptic flow fluctuations, is observed to be qualitatively described by initial state and hydrodynamic model predictions [15], with differences of about 10%. Compared to Pb–Pb collisions (Fig. 2, bottom right), we observe v_2 to be larger in central collisions and smaller in semi-central and peripheral collisions. The first observation can be interpreted as an evidence for nuclear deformations in Xe–Xe collisions and larger initial-state fluctuations; the second one, as smaller radial flow and/or larger viscous effects in Xe–Xe collisions. An investigation of the transverse particle density scaling in the two collision systems can be found in [7].

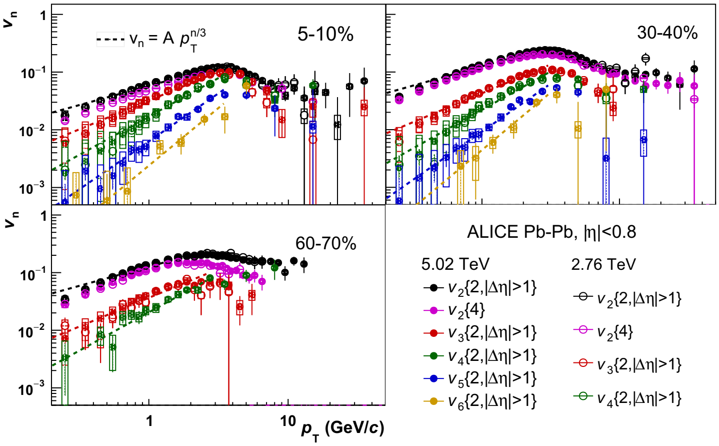

Fig. 1: Anisotropic flow coefficients $v_n(p_T)$ of inclusive charged particles in different centrality classes, measured with two-particle (denoted with $|\Delta\eta| > 1$) and four-particle cumulant methods [4]. Measurements for Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 (2.76) TeV are shown by solid (open) markers. Dashed lines are fits with a power-law function $v_n(p_T) = A\, p_T^{n/3}$, with A as free parameter, within the p_T range $0.2 < p_T < 3$ GeV/c.

4. Summary

In this contribution, a comprehensive set of measurements of anisotropic flow of inclusive charged particles in Pb–Pb and Xe–Xe collisions are reported. In particular, the collision energy, transverse momentum and centrality dependence of anisotropic flow in Pb–Pb collisions is investigated. Most notably, a simple power law scaling of the form $v_n(p_T) \sim p_T^{n/3}$ is observed at low p_T ($0.2 < p_T < 3$ GeV/c) and for harmonics $n = 2 - 6$. Elliptic flow fluctuations in Pb–Pb collisions are also investigated in great detail. A fine-splitting of multi-particle cumulants is observed and can be interpreted as evidence of non-Gaussian elliptic flow fluctuations. A direct measurement of the skewness of elliptic flow fluctuations is also reported. Finally, the first measurements of anisotropic flow in Xe–Xe collisions, which provide evidences for nuclear deformation in the Xe nuclei, are presented. Comparison with different model calculations suggests that these measurements have the potential to constrain initial-state fluctuations and transport parameters of the medium.

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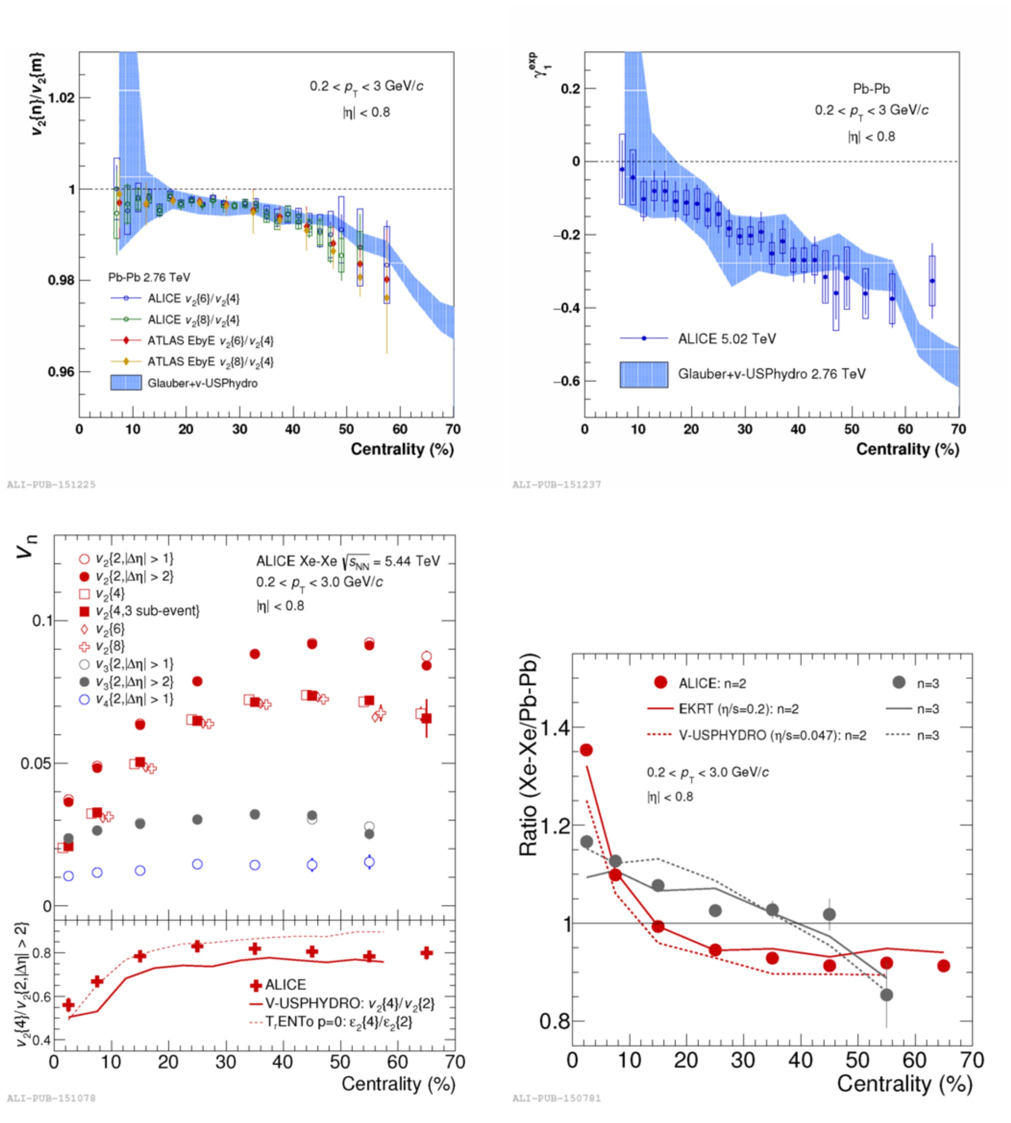

Fig. 2: Top left: Ratios of elliptic flow coefficients v_2 between measurements with different multi-particle cumulant methods, as a function of centrality, for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Hydrodynamic calculations [11] and ATLAS measurements [10] are shown for comparison. Top right: Skewness of elliptic flow γ_1^{exp} as a function of centrality, for Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, together with hydrodynamic calculations [11]. Bottom left: p_T-integrated flow coefficients v_n (n = 2, . . . 4) as a function of centrality in Xe–Xe collisions at $\sqrt{s_{NN}} = 5.44$ TeV, together with the ratio $v_2\{4\}/v_2\{2\}$. Hydrodynamic calculations [15] are shown for comparison. Bottom right: ratios of v_2 and v_3 in Pb–Pb and Xe–Xe collisions, as a function of centrality, together with hydrodynamic calculations [14, 15].