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Azimuthal correlations in Pb–Pb and Xe–Xe collisions with ALICE

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Measurements of two- and multiparticle azimuthal correlations provide valuable information on the properties of the quark–gluon plasma created in ultrarelativistic heavy-ion collisions. Further input can be achieved using the event shape engineering (ESE) technique which allows to select events corresponding to a specific initial geometry in a given centrality class. The elliptic (v_2) and triangular (v_3) flow coefficients of inclusive charged hadrons, $\pi^{\pm}$, $K^{\pm}$, p+$\overline{\mathrm{p}}$, K^0_S, Λ+$\overline{\Lambda}$, and Ξ^-+$\overline{\Xi}^+$ are measured with ESE in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV recorded by ALICE. In addition, the v_2 of $\pi^{\pm}$, $K^{\pm}$, p+$\overline{\mathrm{p}}$, K^0_S, and Λ+$\overline{\Lambda}$ from Xe–Xe collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.44 TeV is presented. The results obtained using the scalar product method are reported as a function of transverse momentum, p_{T}, within the pseudorapidity (rapidity) range $|\eta| < 0.8$ ($|y| < 0.5$) for various centrality classes. The flow coefficients exhibit a particle mass dependence for $p_{\mathrm{T}} < 3$ GeV/c and a grouping according to particle type (i.e. mesons and baryons) for $3 < p_{\mathrm{T}} < 10$ GeV/c. The v_2 of $\pi^{\pm}$, $K^{\pm}$, and p+$\overline{\mathrm{p}}$ is described by MUSIC hydrodynamic calculations for $p_{\mathrm{T}} < 1$ GeV/c. The ratios between v_{n} for shape selected and unbiased events show a weak dependence on transverse momentum for $p_{\mathrm{T}} < 3$ GeV/c and are almost flat at higher p_{T}, independent on particle species. These measurements provide new and independent constraints for the initial conditions and system properties of nuclear matter created in heavy-ion collisions.

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1. Introduction

An important observable used to study the properties of the quark–gluon plasma created in ultrarelativistic heavy-ion collisions is the anisotropic flow (i.e. the transfer of initial spatial anisotropy into a momentum anisotropy of the produced particles) [1]. Anisotropic flow is sensitive to initial-state shape, equation-of-state, transport coefficients (e.g. the shear and bulk viscosity over entropy density ratios, η/s and ζ/s, respectively), and particle production mechanisms [1, 2]. It is commonly quantified by the v_n coefficients in a Fourier decomposition of the azimuthal distribution of particles with respect to the collision symmetry plane [3]. The second (v_2) and third (v_3) order coefficients are called elliptic and triangular flow, respectively. While v_2 directly reflects the almond-shaped geometry of the interaction volume being the largest contribution to the asymmetry in non-central collisions, v_3 is generated by fluctuations in the initial distribution of nucleons in the overlap region.

In these proceedings, the effect of the initial geometry on final observables is studied using collisions between nuclei of different size and shape, and by selecting events corresponding to a specific initial geometry in a given centrality employing the event shape engineering (ESE) technique [4]. The v_2 and v_3 of inclusive charged hadrons, $\pi^{\pm}$, $K^{\pm}$, $p+\overline{p}$, K^0_S, $\Lambda+\overline{\Lambda}$, and $\Xi^-+\overline{\Xi}^+$ are measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV for shape selected and unbiased results up to p_T = 20 GeV/c, while v_2 of $\pi^{\pm}$, $K^{\pm}$, $p+\overline{p}$, K^0_S, and $\Lambda+\overline{\Lambda}$ is measured in Xe–Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV.

2. Analysis

The data samples recorded by ALICE [5] during the 2015 and 2018 Pb–Pb runs at $\sqrt{s_{NN}}$ = 5.02 TeV, and the 2017 Xe–Xe run at $\sqrt{s_{NN}}$ = 5.44 TeV, are analyzed. The Inner Tracking System (ITS) and the Time Projection Chamber (TPC) are used to reconstruct charged-particle tracks. Particle identification is performed using the specific energy loss measured in the TPC and the flight time obtained from the Time-of-Flight detector. The V0 detector, covering the pseudorapidity ranges $-3.7 < \eta < -1.7$ (V0C) and $2.8 < \eta < 5.1$ (V0A), is employed for triggering, event selection, and the determination of centrality and flow vector Q_n. Only events with a primary vertex position within ±10 cm from the nominal interaction point along the beam line are used in the analyses. Charged tracks are selected in $|\eta| < 0.8$ and $0.5 < p_T < 20.0$ GeV/c for the v_n measurements. More information can be found in Refs. [6, 7].

The magnitude of the reduced flow vector q_n, calculated from the azimuthal distribution of the energy deposition measured in the V0C, is used for event shape selection [8]. It is given by

$$q_n = \frac{|Q_n|}{\sqrt{M}}, \tag{1}$$

where $|Q_n| = \sqrt{Q_{n,x}^2 + Q_{n,y}^2}$ is the magnitude of the n-th order harmonic flow vector with $Q_{n,x} = \sum_i w_i \cos(n\varphi_i)$ and $Q_{n,y} = \sum_i w_i \sin(n\varphi_i)$ (the sum runs over all channels i of the V0C detector ($i = 1-32$), φ_i is the azimuthal angle of channel i, and w_i is the amplitude measured in channel i), and M is the multiplicity. Ten event-shape classes with the 10% lowest (highest) values of q_n denoted as 0–10% (90–100%) q_n are investigated. The flow coefficients are measured using the scalar product (SP) method with the particle of interest taken from TPC and reference particles from V0A. Non-flow contributions (i.e. correlations unrelated to the azimuthal asymmetry in the initial geometry) are suppressed due to large pseudorapidity gaps between the charged particles in the TPC and those in the V0C ($|\Delta\eta| > 0.9$) and V0A ($|\Delta\eta| > 2.0$).

3. Results

The left panel of Fig. 1 presents the $p_{\rm T}$-differential elliptic flow, $v_2(p_{\rm T})$, of inclusive charged hadrons for shape selected and unbiased events in the 5–10% central Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV. The magnitude of v_2 for the shape selected events differs from the average by up to 30%, which demonstrates the ability to experimentally select events with the desired initial spatial anisotropy. The ratios between $v_2(p_{\rm T})$ from shape selected and unbiased events show a weak transverse momentum dependence for $p_{\rm T} < 3$ GeV/c, while they are almost flat at higher $p_{\rm T}$, indicating the same source of flow fluctuations over a large momentum range independent of the magnitude of the initial anisotropy of the event.

The $v_{\rm n}(p_{\rm T})$ of inclusive charged hadrons, $\pi^{\pm}$, $K^{\pm}$, p+$\overline{\rm p}$, K^0_S, $\Lambda+\overline{\Lambda}$, and $\Xi^-+\overline{\Xi}^+$ from unbiased sample (left panels), 10% lowest $q_{\rm n}$ (middle panels), and 10% highest $q_{\rm n}$ (right panels) for the 5–10% and 30–40% centrality classes is reported in the right panel of Fig. 1. Although the measured $v_{\rm n}$ from shape selected events is larger or smaller than that from unbiased events, the $v_{\rm n}$ coefficients show the same trends in both samples. For $p_{\rm T} < 3$ GeV/c, the $v_{\rm n}$ coefficients exhibit a mass ordering (i.e. heavier particles have a smaller $v_{\rm n}$ than lighter particles at the same $p_{\rm T}$) which can be attributed to the interplay between anisotropic flow and radial flow. At intermediate $p_{\rm T}$, particles are grouped according to their number of constituent quarks with baryon $v_{\rm n}$ being larger than that of mesons. For $p_{\rm T} > 10$ GeV/c, where a weak dependence on transverse momentum is found for v_2, the $\pi^{\pm}$ v_2 is similar with that for p+$\overline{\rm p}$ within uncertainties.

The ratios between $v_{\rm n}$ $(p_{\rm T})$ from shape selected and unbiased events for the 5–10% and 30–40% centrality classes are presented in Fig. 2. The ratios of identified particles show the same trends as the ones of inclusive charged particles and have similar magnitudes within uncertainties up to $p_{\rm T}$ = 8 GeV/c and $p_{\rm T}$ = 6 GeV/c for v_2 and v_3, respectively. This agreement indicates that flow fluctuations do not depend on particle species. For v_3 selected with q_2, the 10% highest q_2 results are smaller than the 10% lowest q_2. Thus v_3 is anticorrelated with q_2. In addition, these ratios show no dependence on particle species within uncertainties.

Figure 3 compares the v_2 of $\pi^{\pm}$, $K^{\pm}$, p+$\overline{\rm p}$, K^0_S, and $\Lambda+\overline{\Lambda}$ from Xe–Xe collisions at $\sqrt{s_{\rm NN}}$ = 5.44 TeV [6] to that from Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV [7] for the 0–5%, 10–20%, and 40–50% centrality classes. For the 0–5% centrality class, the v_2 of all particle species is larger in Xe–Xe than in Pb–Pb collisions in the considered $p_{\rm T}$ range. This behaviour can be attributed to the Xe nucleus deformation and the different initial-state fluctuations. The magnitude of v_2 is similar for the 10–20% centrality class, while it is ~8% lower in Xe–Xe than in Pb–Pb collisions for the 40–50% centrality interval. The MUSIC hydrodynamic calculations [9] are in agreement with the measured $v_2(p_{\rm T})$ of $\pi^{\pm}$, $K^{\pm}$, and p+$\overline{\rm p}$ for $p_{\rm T} < 1$ GeV/c, while they overestimate the data points at higher $p_{\rm T}$ for both collision systems. However, the Xe–Xe/Pb–Pb ratios are quantitatively reproduced by the corresponding MUSIC ones up to $p_{\rm T}$ = 3 GeV/c. This points to similar differences between the data points and model for both systems.

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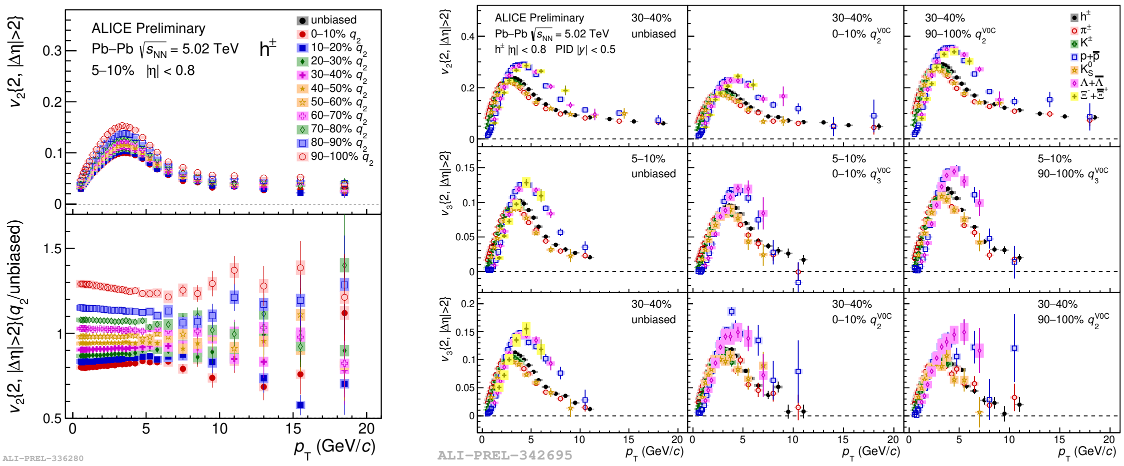

Figure 1: Left: $v_2(p_T)$ of inclusive charged hadrons for shape selected and unbiased events (top) and ratios between $v_2(p_T)$ from event shape selected and unbiased events (bottom) in the 5–10% central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV. Right: $v_n(p_T)$ of inclusive charged hadrons, $\pi^{\pm}$, $K^{\pm}$, $p+\bar{p}$, K^0_S, $\Lambda+\bar{\Lambda}$, and $\Xi^{-}+\bar{\Xi}^{+}$ in Pb–Pb collisions for the 5–10% and 30–40% centrality classes for unbiased events (left), 10% lowest q_n (middle), and 10% highest q_n (right): v_2 with q_2 (top), v_3 with q_3 (middle), and v_3 with q_2 (bottom). The event selection is based on q_n determined in the V0C. Bars (boxes) denote statistical (systematic) uncertainties.

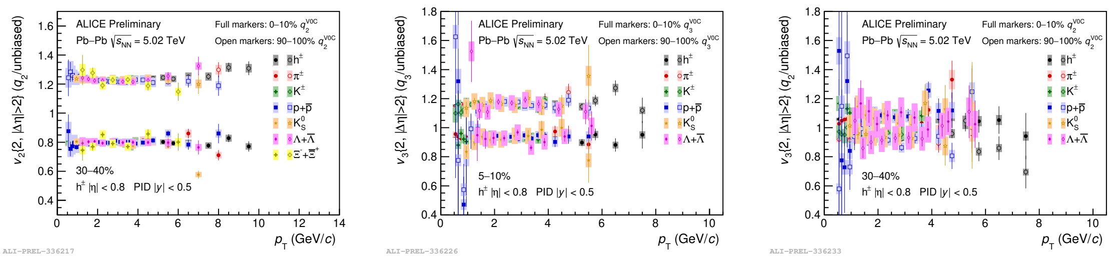

Figure 2: Ratios between v_n (p_T) from shape selected events and that from unbiased sample for inclusive charged hadrons, $\pi^{\pm}$, $K^{\pm}$, $p+\bar{p}$, K^0_S, $\Lambda+\bar{\Lambda}$, and $\Xi^{-}+\bar{\Xi}^{+}$ in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV for the 5–10% and 30–40% centrality classes: v_2 with q_2 (left), v_3 with q_3 (middle), and v_3 with q_2 (right). The event selection is based on q_n determined in the V0C. For clarity, the markers for shape selected results are slightly shifted along the horizontal axis. Bars (boxes) denote statistical (systematic) uncertainties.

4. Summary

The v_n coefficients of inclusive charged hadrons, $\pi^{\pm}$, $K^{\pm}$, $p+\bar{p}$, K^0_S, $\Lambda+\bar{\Lambda}$, and $\Xi^{-}+\bar{\Xi}^{+}$, measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV for shape selected and unbiased results, and v_2 of $\pi^{\pm}$, $K^{\pm}$, $p+\bar{p}$, K^0_S, and $\Lambda+\bar{\Lambda}$ measured in Xe–Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV have been presented. The flow coefficients exhibit a particle mass dependence for $p_T < 3$ GeV/c and a grouping according to particle type (i.e. mesons and baryons) for $3 < p_T <$ 8-10 GeV/c. The v_2 of $\pi^{\pm}$, $K^{\pm}$, and $p+\bar{p}$ are described by MUSIC hydrodynamic calculations for $p_T < 1$ GeV/c. The values of v_2 are larger

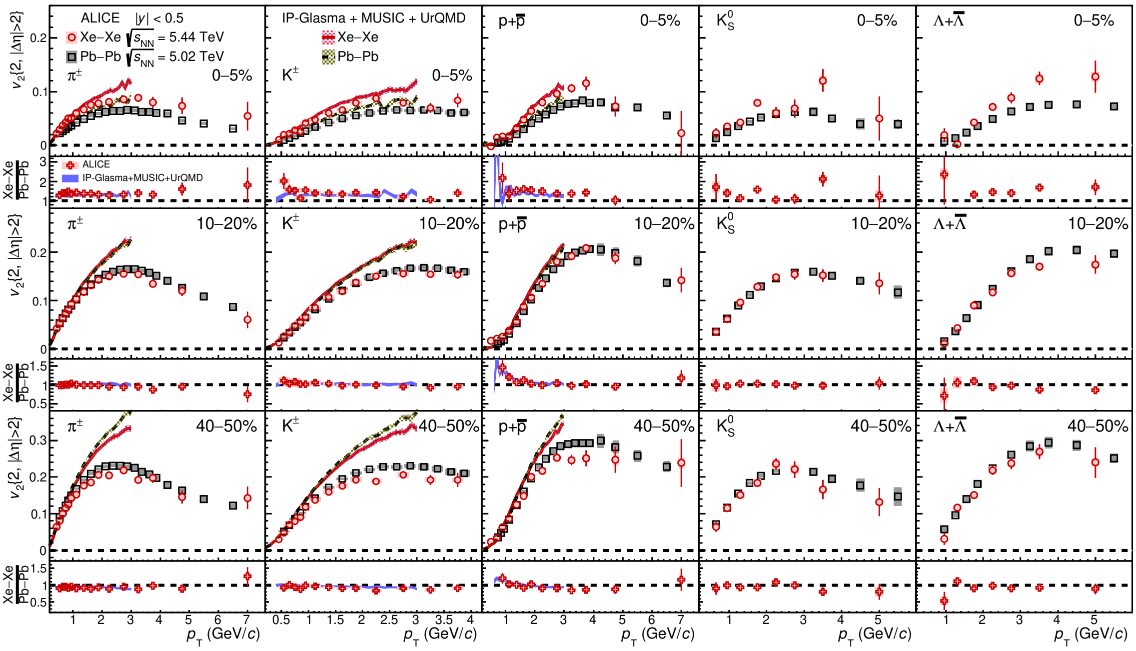

Figure 3: $v_2(p_T)$ of $\pi^{\pm}$, $K^{\pm}$, $p+\bar{p}$, K^0_S, and $\Lambda+\overline{\Lambda}$ from Xe–Xe collisions at $\sqrt{s_{NN}}$ = 5.44 TeV (red markers) compared with ALICE measurements performed in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV (black markers) and MUSIC hydrodynamic calculations (colored curves) for the 0–5% (top panels), 10–20% (middle panels), and 40–50% (bottom panels) centrality intervals. The ratios of Xe–Xe measurements to a cubic spline fit to Pb–Pb measurements are also presented for clarity. Bars (boxes) denote statistical (systematic) uncertainties.

(smaller) in central (peripheral) Xe–Xe collisions than in the corresponding Pb–Pb collisions. The ratios between v_n for shape selected and unbiased events show a weak dependence on transverse momentum for $p_T < 3$ GeV/c and are almost flat at higher p_T, independent on particle species.

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