Anisotropic flow of identified particles in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV measured with ALICE at the LHC

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Abstract. The anisotropic flow (v_n) of identified particles is an important observable to probe the freeze-out properties, the parton energy loss and the transport coefficients of the system created in heavy-ion collisions. We report on the anisotropic flow measurements for a number of identified particles such as charged pions, kaons and (anti-)protons, as well as K_s^0 , $\Lambda(\bar{\Lambda})$, ϕ , $\Xi^-(\bar{\Xi}^+)$, and $\Omega^-(\bar{\Omega}^+)$. The measurements are performed in the rapidity range $|\eta| < 0.5$, over a wide range of transverse momenta, $0.2 < p_T < 6$ GeV/c, for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV recorded by ALICE at the LHC. We will present the mass ordering as a function of transverse momentum for several collision centralities compared with results at lower energies. While in the low p_T region hydrodynamical computations describe the experimental data points fairly well, at intermediate momenta the quark number (n_q) scaling indicates that it holds at an approximate level of 20–30%. Finally, focusing on the low momentum region ALICE has recently observed a similar mass ordering behaviour of v_2 in p–Pb systems. We will present this intriguing result which may be connected to a collective effect similar to that observed in Pb–Pb collisions.

1 Introduction

Anisotropic flow [1] studies can probe the nature of matter produced in heavy-ion collisions. These studies allow to investigate collective effects among produced particles. Anisotropic flow is described by the coefficients v_n in the Fourier expansion of the azimuthal particle distribution with respect to the symmetry plane via the formula

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos[\phi - \Psi_n], \quad (1)$$

where ϕ is the azimuthal angle and Ψ_n the flow angle associated to each harmonic. Anisotropic flow of identified hadrons is sensitive to the partonic degrees of freedom in the early stages of the evolution of a heavy-ion collision [2]. It is sensitive to the properties of the deconfined QCD matter created and to the details of the hadronization mechanism. Herein, we report on the elliptic, v_2 , and triangular, v_3 , flow of identified particles measured by ALICE [3] in Pb–Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV. Results are compared with that obtained at RHIC at the highest energy. The scaling properties of v_2 with the number of constituent quarks, n_q , are studied. Moreover, focusing on the low momentum region we also report recent ALICE results for v_2 in p–Pb systems and we discuss possible analogies with the collective phenomena observed in Pb–Pb.

2 Analysis details

For the analyses presented here a sample of about 10 million minimum bias Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV collected by ALICE in 2010 and a sample of 100 million p–Pb minimum bias events collected in 2013 at $\sqrt{s_{NN}} = 5.02$ TeV were used.

The collision centrality (or multiplicity for p–Pb case) is determined using the forward VZERO scintillator arrays both in Pb–Pb and p–Pb systems. Particle tracking is done by means of the Time Projection Chamber (TPC) and the Inner Tracking System (ITS) with full azimuthal coverage for $|\eta| < 0.8$. Identification of pions, kaons and (anti-)protons is performed with a combination of the time-of-flight and the energy loss measured by the Time Of Flight (TOF) and TPC detectors, respectively. By combining their information it is possible to reach a particle species separation greater than 2σ for π , K and p up to 6 GeV/c [5], as reported in Fig. 1. Then, the selection for each species is tuned to assure a purity greater than 90% for $p_T < 4$ and 6 GeV/c for kaons and pions/protons, respectively. Particle identification can be also extended to very high p_T for pions and protons using a TPC standalone approach in the relativistic rise region of dE/dx [6]. K_s^0 , $\Lambda/\bar{\Lambda}$, $\Xi^-/\bar{\Xi}^+$, and $\Omega^-/\bar{\Omega}^+$ particles are reconstructed via their weak decay channels ($K_s^0 \rightarrow \pi\pi$, $\Lambda(\bar{\Lambda}) \rightarrow p(\bar{p})\pi$, $\Xi \rightarrow \Lambda\pi$, and $\Omega \rightarrow \Lambda K$) using topological cuts to suppress the combinatorial background. In the case of ϕ meson decay via K^+K^- channel, the combinatorial background is suppressed by identifying kaons with the TPC and TOF.

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Figure 1. Separation power of hadron identification in the ITS, TPC, TOF and HMPID as a function of p_T at midrapidity in Pb–Pb collisions [5]. The left panel shows the separation between pions and kaons, while the right one the separation between kaons and protons.

Figure 2. Invariant mass distributions [4] in the 10–20% centrality interval of Pb–Pb collisions for reconstructed decaying particles: (a) K_S^0 , (b) $\Lambda + \bar{\Lambda}$, (c) ϕ , (d) $\Xi^- + \bar{\Xi}^+$, and (e) $\Omega^- + \bar{\Omega}^+$.

Invariant mass distributions are reported in Fig. 2 after the selection cuts are applied. In order to remove the contribution of the residual background visible in Fig. 2 the two components (signal and background) were disentangled by fitting v_2 as a function of the invariant mass using the expression

$$v_2^{tot}(m_{inv}) = v_2^{sign} \frac{S}{S+B}(m_{inv}) + v_2^{back} \frac{B}{S+B}(m_{inv}), \quad (2)$$

where S and B are the fractions of the signal and the background, respectively, in a given invariant mass bin. Anisotropic flow is measured using the scalar product and event plane methods with large rapidity separation (1 or 2 units) between correlated particles [4]. Different configurations and different η gaps were used to verify that non-flow effects are really suppressed when using the VZERO scintillators to define the sample of reference particles.

Figure 4. The p_T -differential v_2 for different particle species [4] (a), (b), (e), (f), measured with the scalar product method with a pseudo-rapidity gap $|\Delta\eta| > 0.9$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, compared to theoretical hydrodynamical calculations coupled to a hadronic cascade model [7–9]. The panels (c), (d), (g) and (h), show the dependence of the ratio of the experimental points to a fit over the theoretical calculations as a function of p_T . The left and right plots present the comparison for the 10–20% and 40–50% centrality intervals, respectively.

3 Results

3.1 Elliptic flow

Figure 3 presents the p_T -differential v_2 for all identified particles measured in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The results are grouped by particle species in different panels, to illustrate the evolution of v_2 as a function of centrality for $\pi^\pm$, $K^\pm$, K_S^0 , $p + \bar{p}$, ϕ , $\Lambda + \bar{\Lambda}$, $\Xi^- + \bar{\Xi}^+$ and $\Omega^- + \bar{\Omega}^+$. The error bars correspond to statistical uncertainties, while the shaded colour boxes around each point indicate the systematic uncertainties. A clear mass ordering is seen for all species below $p_T \sim 2.5$ GeV/c, where the ordering changes and the v_2 behaviour shows a clear difference between baryons and mesons. At low transverse momenta, p_T , the ϕ -meson elliptic flow is similar to that of (anti-)proton. This can be explained by a similar effect of radial flow for particles with similar mass.

In Fig. 4, the experimental points for two centrality intervals, the 10–20% in the left column and the 40–50% interval in the right column, are compared to hydrodynamical calculations coupled to a hadronic cascade model (VISHNU) [7–9]. The usage of such a hybrid approach provides the possibility of investigating the influence of

Figure 3. The p_T -differential v_2 for different particle species grouped by centrality class of Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [4].

the hadronic stage on the development of elliptic flow for the different particle species. It also provides an excellent testing ground for the particles that are argued to have small hadronic cross section (ϕ , Ξ) and are thus expected not to be affected by this stage. VISHNU uses the MC-KLN model to describe the initial conditions, an initial time $\tau_0 = 0.9$ fm/c after which the hydrodynamical evolution begins and a value of the shared viscosity to entropy ratio $\eta/s = 0.16$, almost two times the lower bound of $1/4\pi$ [10] (for $\hbar = k_B = 1$). These theoretical calculations are represented in Fig. 4 by the different curves, with the line colour matching that of the experimental measurement for each species. For more central collisions the measured v_2 for the $\pi^\pm$ is systematically above the theoretical calculations for $p_T < 2$ GeV/c, whereas the kaon measurement is described fairly well in the same range. For heavier particles the model calculations appear to underestimate significantly the elliptic flow for protons, but

overestimate v_2 of $\Xi^- + \Xi^+$. This multi-strange baryon is thought to have small hadronic cross sections and thus could be unaffected from the hadronic rescattering in the late stages of the collision. Furthermore, for $\Lambda + \bar{\Lambda}$, the model does not preserve the mass ordering, observed in the experiment, and overestimates v_2 . This could indicate that the implementation of the hadronic cascade phase and the hadronic cross-sections within the model needs further improvements. For peripheral collisions, the model calculations agree better with the results for $\pi^\pm$, kaons and $\Lambda + \bar{\Lambda}$.

Figure 5 presents the elliptic flow of identified particles scaled with the constituent number of quarks, n_q (2 for mesons and 3 for baryons) as a function of transverse momentum per n_q . In the intermediate p_T region (3–6 GeV/c) this representation serves as a test of the hadron production via quark coalescence. To quantify the deviation, the p_T/n_q dependence of v_2/n_q for p and $\bar{p}$ is fitted

with a seventh order polynomial function and the ratio of $(v_2/n_q)/(v_2/n_q)_{\text{Fit p}}$ for each particle species is calculated. The corresponding p_T/n_q dependence of this double ratio is presented in Fig. 6 for the various centrality intervals as in Fig. 5. In the double ratio representation it is clearly shown that for $p_T/n_q > 1$ GeV/c and for all centrality intervals the data points exhibit deviations from a perfect scaling at the level of $\pm 20\text{--}30\%$ with respect to the reference ratio. The same conclusion can be also extracted from Figs. 7 and 8 where p_T/n_q is replaced by $KE_T/n_q = (m_T - m_0)/n_q$. In this latter representation, introduced to extend the scaling also to low values of transverse momentum, the data points show significant deviations for $KE_T/n_q < 0.6 - 0.8$ GeV/c².

Figure 5. Identified particle $v_2(p_T)$ scaling with the constituent number of quarks [4], n_q , vs. transverse momentum, p_T , per n_q for 10–20% (top) and 40–50% (bottom) centrality classes.

The energy dependence of charged hadrons v_2 can be accessed through the comparison of ALICE and RHIC results as reported in Fig. 9. The v_2 from STAR is calculated using the two-particle cumulant analysis (i.e. $v_2\{2\}$) [11], while PHENIX reconstructed v_2 using the event plane method with a pseudo-rapidity gap of $|\Delta\eta| > 1.0$ [12]. These two measurements have different sensitivity to non-flow effects, which makes their quantitative comparison difficult. At LHC energies pion and kaon v_2 is slightly above the RHIC results, while anti-proton v_2 shows the effect of the stronger radial flow, as expected from hydrodynamical model calculations [7–9].

Figure 6. $v_2(p_T)$ scaling with the constituent number of quarks [4], n_q , vs. transverse momentum, p_T , per n_q : ratio with respect to the proton fit for 10–20% (top) and 40–50% (bottom) centrality classes.

Recent hydrodynamic simulations [14, 15] predict that the flow angle and the fluctuations may affect in a different way particles with different p_T . In order to verify it a new observable can be defined $v_2[2]$ which is the flow coefficient obtained using a sample of reference particles selected in the same p_T interval of the particles under investigation [13]. The ratio of $v_2\{2\}$ and $v_2[2]$ can be then quantitatively compared with the different theoretical predictions to add further constraints on the initial state and η/s . In Fig. 10 $v_2[2]$ and $v_2\{2\}$ are reported for different centrality classes. A significant deviation for $p_T > 2$ GeV/c in most central collisions is clearly visible and it qualitatively agrees with the prediction from hydrodynamical models [14, 16]. Models based on MC-KLN initial conditions works better both for $v_2[2]$ and $v_2\{2\}$ up to high p_T . It has to be noted that for ALICE data an estimate of non-flow effects, not present in the theoretical predictions, is currently under investigation.

3.2 Triangular flow and higher harmonics

Higher order harmonics allow to add more constraints to the models and in particular to the initial conditions. Differently from the second order v_2 , v_n (with $n > 2$) does not have any contribution from the initial geometry of the two colliding nuclei and it is determined by the fluctuations in the initial state. In Fig. 11 we report the comparison

Figure 7. Identified particle $v_2(p_T)$ scaling with the constituent number of quarks [4], n_q , vs. transverse kinetic energy, KE_T , per n_q for 10–20% (top) and 40–50% (bottom) centrality classes.

between the ALICE v_3 measurement and hydrodynamical predictions obtained with the same parameters used to get agreement for v_2 . As clearly visible in Fig. 11, the same models tuned on v_2 provide very different predictions for v_3 .

Moreover, v_3 exhibits a similar particle mass dependence as v_2 and the value of p_T at which all the species cross looks similar to that in the elliptic flow case.

For the case of non-identified particles it is possible to compare the experimental results also with the IP-Glasma model [16] and a very good agreement was found for a value of $\eta/s = 0.16$ for all the harmonics (Fig. 12). In Fig. 12 it is also shown that there is not any significant difference when comparing $v_n[2]$ and $v_n\{2\}$.

3.3 The second Fourier coefficient v_2 in p–Pb

Finally, focusing on the low momentum region ALICE has recently observed a mass scaling behaviour of v_2 also in p–Pb systems [17]. In Fig. 13 we report the v_2 measured in high multiplicity p–Pb collisions (0–20%) after the subtraction of correlations measured in the 60–100% multiplicity class. Such a subtraction allows to remove a significant fraction of correlations due to jets.

Qualitatively, a similar picture as observed in Pb–Pb is also observed in p–Pb central collisions, with a clear mass scaling for protons and pions and a crossing point at

Figure 8. $v_2(p_T)$ scaling with the constituent number of quarks, n_q [4], vs. transverse kinetic energy, KE_T , per n_q : ratio with respect the proton fit for 10–20% (top) and 40–50% (bottom) centrality classes.

$p_T \sim 2 \text{ GeV}/c$. A mass ordering effect at low transverse momenta is consistent with expectations from hydrodynamic model calculations assuming a collectively expanding system. At 3–4 GeV/c, v_2^p is slightly larger than v_2^π , albeit with low significance. The question if collective phenomena are also present in p–Pb collisions is one of the most intriguing aspect in this field in the LHC era.

4 Summary

The second Fourier coefficient $v_2(p_T)$ of identified particles is measured for Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ by the ALICE detector. Viscous hydrodynamic models describe the main features of elliptic flow of all measured species. In particular the mass splitting is qualitatively well described by hydrodynamical models with the exception of the sorting of the Λ and p cases. These suggest a more accurate tuning of the hadronic rescattering parameters is still needed. Compared with the measurements at the highest RHIC energies, we observed a larger mass splitting, most evident in the proton flow. Such an observation is consistent with a radial flow at LHC larger than at RHIC. In the intermediate momentum region, where coalescence processes may play a role in the hadron production, p_T/n_q scaling of v_2 exhibits deviations from a perfect scaling at the level of $\pm 20\text{--}30\%$. In the low momentum region, $(m_T - m_0)/n_q < 0.6\text{--}0.8 \text{ GeV}/c^2$, KE_T/n_q scaling of

Figure 9. The comparison of the p_T -differential v_2 for π^+ , K and $p+\bar{p}$ for the 10–20% centrality class of Pb–Pb [4] and Au–Au collisions at the LHC and RHIC, respectively. The RHIC points are extracted from [11] (STAR) and [12] (PHENIX).

Figure 10. $v_2\{2\}$ and $v_2[2]$ (with $\Delta\eta > 0.8$) for centrality 0–5%, 20–30%, 40–50% and various hydrodynamic calculations. Statistical uncertainty only. The systematic uncertainty, which is not shown here, is smaller than the marker size.

v_2 is also broken, especially for the most central collisions. The third harmonic v_3 of π , K, and p has a similar mass dependence and crossing point as that of v_2 . In general high order harmonics allow to better constrain the model and in particular the value of η/s assumed. A value of η/s close to 0.16 (two times the lower bound of $1/4\pi$) allows to find the best agreement of the models with the data for all the harmonics considered. In addition it was shown

how the observation of flow angle and magnitude fluctuations may help to constrain initial conditions and viscosity in the models although more studies in this direction are needed. Finally, intriguing results were observed in p–Pb high multiplicity events revealing similar feature for v_2 as in Pb–Pb. The question if collective phenomena are observed also in p–Pb system is currently one of the more debated topic in this field.

Figure 12. $v_n\{2\}$ and $v_n[2]$ (with $\Delta\eta > 0.8$) for centrality 0–5%, 20–30%, 40–50% and various hydrodynamic calculations. Statistical uncertainty only. The systematic uncertainty, which is not shown here, is smaller than the marker size.

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Figure 11. Triangular flow of identified particles measured by ALICE for two centrality classes (no η gap). The comparison with the hydrodynamical models, which agree for v_2 , is also reported.

Figure 13. The Fourier coefficient $v_2\{2PC, \text{sub}\}$ for hadrons (black squares), pions (red triangles), kaons (green stars) and protons (blue circles) as a function of p_T from the correlation in the 0–20% multiplicity class after the subtraction of the correlations from the 60–100% multiplicity class [17]. The data is plotted at the average- p_T for each considered p_T interval and particle species under study. Error bars show statistical uncertainties while shaded areas denote systematic uncertainties.

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