Anisotropic flow of inclusive and identified particles in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with ALICE

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Abstract

Elliptic ($v_2$) and higher harmonic ($v_3$, $v_4$) flow coefficients of $\pi^\pm$, $K^\pm$, $p$, and the $\phi$-meson, measured in Pb-Pb collisions at the highest-ever center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV, are presented. The results were obtained with the scalar product method, correlating hadrons with reference particles from a different $\eta$ region. The $v_n$ exhibit a clear mass ordering for $p_T \lesssim 2$ GeV/$c$ and only approximate particle type scaling for $p_T \gtrsim 2$ GeV/$c$. Reasonable agreement with hydrodynamic calculations (IP-Glasma+MUSIC+UrQMD) is seen at $p_T \lesssim 1$ GeV/$c$.

Keywords: anisotropic flow, heavy-ion, higher harmonic, identified, relativistic hydrodynamics

1. Introduction

Heavy-ion collision experiments are used to study the properties of the quark-gluon plasma (QGP), a state of deconfined quarks and gluons created at high baryon densities or temperatures. Particles produced in collisions are boosted collectively by a common velocity field that is induced by the rapid expansion of the system. Spatial anisotropies resulting from the elliptic overlap region of the colliding nuclei in non-central collisions, and the initial inhomogeneities of the system density, are transformed, through multiple interactions between the produced particles, into an anisotropy in momentum space of the produced particles. The efficiency of this process depends on e.g. the shear ($\eta/s$) and bulk ($\zeta/s$) viscosity of the created matter, and the lifetime of the system.

Anisotropy in particle production can be quantified by a Fourier analysis of the azimuthal distribution relative to the system’s symmetry plane angles $\Psi_n$, characterized by harmonic coefficients $v_n$ [1]

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

where $\varphi$ is the azimuthal angle of the produced particles.

Flow coefficients $v_n$ are, in addition to being a probe for $\eta/s$ and $\zeta/s$, sensitive to the initial state of the system, freeze-out conditions and hadronization mechanisms.

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http://dx.doi.org/10.1016/j.nuclphysa.2017.04.025
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Fig. 1. Flow coefficients $v_2$, $v_3$ and $v_4$ of unidentified charged particles as function of $p_T$ for various centrality classes. In addition to the scalar product method, the 4-particle $Q$-cumulant [5] estimate of $v_2$, $v_2\{4\}$, is shown as well. Statistical uncertainties are shown as bars and systematic uncertainties as boxes.

2. Data analysis

The data used for this work were recorded in 2015 at a center of mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector [2] and comprise approximately $6 \times 10^7$ collisions with a vertex within $\pm 10$ cm of the nominal interaction point and collision centrality between 5-60%. Charged particle tracks are reconstructed using the Inner Tracking System (ITS) and Time Projection Chamber (TPC) at $|y| < 0.5$ for identified particles or $|\eta| < 0.8$ for unidentified particles. Centrality determination, as well as reconstruction of the $Q_{V0}$ vectors (see Eq. 2), is performed with V0 detectors, located at $2.8 < \eta < 5.1$ (V0A) and $-3.7 < \eta < -1.7$ (V0C).

Coefficients $v_n$ are measured using the scalar product method [3], written as

$$v_n[\text{SP, V0C}] = \frac{\langle \langle u_n \cdot Q_{V0C}^* \rangle \rangle}{\sqrt{\langle Q_{V0C}^* \cdot Q_{TPC}^* \rangle \langle Q_{V0A}^* \cdot Q_{V0A}^* \rangle}}$$

where $u_n = \exp(in\varphi)$ is the unit vector of a single particle of interest (the particles of which $v_n$ is measured), with azimuthal angle $\varphi$. Flow vectors $Q_n = \sum_j \exp(in\varphi_j)$ of the reference particles, where the sum runs over all $j$ tracks and * denotes the complex conjugate, are measured in the TPC or V0 detectors. Brackets $\langle \langle \cdots \rangle \rangle$ indicate an all-event average; the double brackets in the numerator of Eq. 2 mean that prior to the all-event average, an average over all $u_n \cdot Q_{V0C}^*$ within the single event is taken. The large (pseudo-)rapidity gap between $u_n$ and $Q_{V0C}^*$ reduces sensitivity to short-range correlations that are unrelated to the initial geometry, commonly referred to as non-flow.

Particle identification is performed using ionization energy loss measured in the TPC, combined with the arrival time of particles in the Time of Flight (TOF) detector. The $\phi$-meson is reconstructed in the $\phi \rightarrow K^+ K^-$ channel, using the analysis method outlined in [4].

3. Results

Figure 1 shows $p_T$-differential $v_2$, $v_3$ and $v_4$ of unidentified charged particles. For the presented centrality classes, $v_2 > v_3 > v_4$ for $p_T < 5$ GeV/$c$. The observed trends at low and intermediate $p_T$ ($< 7$ GeV/$c$) are
characteristic for the hydrodynamic expansion of the medium. The non-zero $v_2$ at high $p_T$ is attributed to path-length dependent in-medium energy loss of highly energetic partons.

The top panel of Fig. 2 shows $p_T$-differential $v_2$ of $\pi^\pm$, $K^\pm$, $p$(\overline{p}) and the $\phi$-meson for 10-20% (left) and 40-50% (right) collision centrality as function of $p_T$. Statistical uncertainties are shown as bars and systematic uncertainties as boxes.

Fig. 2. Flow coefficient $v_2$ (top), $v_3$ (middle) and $v_4$ (bottom) of $\pi^\pm$, $K^\pm$, $p$(\overline{p}) and the $\phi$-meson for 10-20% (left) and 40-50% (right) collision centrality (these two centrality intervals are used for all subsequent figures; note that for $p_T < 4$ GeV/c only $p$ are considered to exclude a contamination by secondary protons produced from detector material). For $p_T < 2$ GeV/c, $v_2$ of the different species is mass-ordered, which is indicative of strong radial flow [6]. For $3 < p_T < 8$ GeV/c, particles are grouped according to their valence quark content, which supports the hypothesis of particle production via quark coalescence [7]. Particle type scaling and mass ordering is most directly tested by $\phi$-meson $v_2$, as the $\phi$ is a meson with a mass close to proton mass. Figure 2 demonstrates that $\phi$-meson $v_2$ follows proton $v_2$ at low $p_T$, but pion $v_2$ at intermediate $p_T$. Lastly it should be noted that $p$(\overline{p}) $v_2$ is larger than $\pi^\pm$ $v_2$ for $3 \lesssim p_T \lesssim 10$ GeV/c, after which the $v_2$ converge, which suggests that partonic energy loss is flavor independent at high transverse momenta.

Higher harmonic flow coefficients ($n > 2$) are generated by inhomogeneities in the initial nucleon distribution and are thought to be more sensitive to transport coefficients than $v_2$ [8]. The middle and lower panels of Fig. 2 show that non-zero $v_3$ is observed for $\pi^\pm$, $K^\pm$, $p$(\overline{p}) up to $p_T \approx 8$ GeV/c. Statistical precision
Fig. 3. Flow coefficient $v_2$ of $\pi^\pm, K^\pm, p(\bar{p})$ and the $\phi$-meson for 10-20% (left) and 40-50% (right) collision centrality compared to predictions from relativistic hydrodynamic calculations [10]. Statistical uncertainties are shown as bars and systematic uncertainties as boxes.

4. Summary

Flow harmonics $v_2$, $v_3$ and $v_4$ of unidentified and identified particles have been measured at $\sqrt{s_{NN}} = 5.02$ TeV Pb–Pb collisions. Mass ordering is observed for $p_T < 2$ GeV/c, as well as approximate particle type scaling for $p_T > 2.5$ GeV/c. The flow coefficient $v_2$ of unidentified particles is non-zero up to high $p_T$, and $p(\bar{p})$ $v_2$ and $v_3$ are larger than $\pi^\pm$ $v_2$ and $v_3$ up to $p_T = 10$ GeV/c. The unprecedented precision of these new measurements will put strong constraints on model calculations and further the understanding of the hydrodynamic behavior of the QGP, as well as its initial state, and freeze-out conditions.

References