Beam energy and system dependence of rapidity-even dipolar flow

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Abstract. New measurements of rapidity-even dipolar flow, $v_{ve}^{even}$, are presented for several transverse momenta, $p_T$, and centrality intervals in Au+Au collisions at $\sqrt{s_{NN}} = 200$, 39 and 19.6 GeV, U+U collisions at $\sqrt{s_{NN}} = 193$ GeV, and Cu+Au, Cu+Cu, d+Au and p+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The $v_{ve}^{even}$ shows characteristic dependencies on $p_T$, centrality, collision system and $\sqrt{s_{NN}}$, consistent with the expectation from a hydrodynamic-like expansion to the dipolar fluctuation in the initial state. These measurements could serve as constraints to distinguish between different initial-state models, and aid a more reliable extraction of the specific viscosity $\eta/s$.

1 Introduction

Heavy-ion collisions (HIC) at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) are aimed at studying the properties of the strongly interacting quark-gluon plasma (QGP) created in such collisions. Recent studies have emphasized the use of anisotropic flow measurements to study the transport properties of the QGP [1–7]. A crucial question in these studies was the role of initial-state fluctuations and their influence on the uncertainties associated with the extraction of $\eta/s$ for the QGP produced in HIC [8, 9]. This work emphasizes new measurements for rapidity-even dipolar flow, $v_{ve}^{even}$, which could aid a distinction between different initial-state models and facilitate the extraction of $\eta/s$ with better constraints.

Anisotropic flow is characterized by the Fourier coefficients, $v_n$, obtained from a Fourier expansion of the azimuthal angle ($\phi$) distribution of the emitted particles [10]:

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

where $\Psi_n$ represents the $n^{th}$-order event plane, the coefficients $v_1$, $v_2$ and $v_3$ are called directed, elliptic and triangular flow, respectively. The flow coefficients $v_n$ are related to the two-particle Fourier coefficients $v_{n,n}$ as:

$$v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b) + \delta_{NF},$$

where $p_T^a$ and $p_T^b$ are the transverse momentum of particles (a) and (b), respectively, and $\delta_{NF}$ is a so-called non-flow (NF) term, which includes possible contributions from resonance decays, Bose-Einstein correlations, jets, and global momentum conservation (GMC) [11–15]. The directed flow, $v_1$,......
Figure 1. $v_{1,1}$ vs. $p_T^b$ for several selections of $p_T^a$ for 0-5% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The dashed curve shows the result of the simultaneous fit with Eq. 5.

can be separated into an odd function of pseudorapidity ($\eta$) [16] which develops along the direction of the impact parameter, and a rapidity-even component [13, 17] which results from the effects of initial-state fluctuations acting in concert with a hydrodynamic-like expansion; $v_1(\eta) = v_{1,1}^{even}(\eta) + v_{1,1}^{odd}(\eta)$, where $v_{1,1}^{odd}$ and $v_{1,1}^{even}$ are uncorrelated. The magnitude of $v_{1,1}^{even}$ is related to the fluctuations-driven dipole asymmetry $\varepsilon_1$ and $\eta/s$ [14, 17, 18].

2 Measurements

The correlation function technique was used to generate the two-particle $\Delta\phi$ correlations:

$$C_r(\Delta\phi, \Delta\eta) = \frac{(dN/d\Delta\phi)_{same}}{(dN/d\Delta\phi)_{mixed}},$$

where $(dN/d\Delta\phi)_{same}$ represent the normalized azimuthal distribution of particle pairs from the same event and $(dN/d\Delta\phi)_{mixed}$ represents the normalized azimuthal distribution for particle pairs in which each member is selected from a different event but with a similar classification for the vertex, centrality, etc. The pseudorapidity requirement $|\Delta\eta| > 0.7$ was also imposed on track pairs to minimize possible non-flow contributions associated with the short-range correlations from resonance decays, Bose-Einstein correlations and jets.

The two-particle Fourier coefficients $v_{n,1}$ are obtained from the correlation function as:

$$v_{n,1} = \frac{\sum_{\Delta\phi} C_r(\Delta\phi, \Delta\eta) \cos(n\Delta\phi)}{\sum_{\Delta\phi} C_r(\Delta\phi, \Delta\eta)},$$

and then used to extract $v_{1,1}^{even}$ via a simultaneous fit of $v_{1,1}$ as a function of $p_T^b$, for several selections of $p_T^a$ with Eq. 2:

$$v_{1,1}(p_T^a, p_T^b) = v_{1,1}^{even}(p_T^a)v_{1,1}^{even}(p_T^b) - C p_T^a p_T^b.$$  

Here, $C \propto 1/(\langle Mult \rangle p_T^2)$ takes into account the non-flow correlations induced by a global momentum conservation [14, 15] and $\langle Mult \rangle$ is the mean multiplicity.

For a given centrality selection, the left hand side of Eq. 5 represents the $N \times N$ matrix which we fit with the right hand side using $N + 1$ parameters; $N$ values of $v_{1,1}^{even}(p_T)$ and one additional parameter $C$, accounting for momentum conservation [19]. Fig. 1 shows a representative result for this fitting procedure for 0–5% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The dashed curve (obtained with Eq. 5) in each panel illustrates the effectiveness of the simultaneous fits, as well as the constraining power of the data. That is, $v_{1,1}(p_T^a)$ evolves from negative to positive values as the selection range for $p_T^a$ is increased.
3 Results

Representative $v_1^{\text{even}}$ results for Au+Au collisions at $\sqrt{s_{NN}} = 200$, 39, and 19.6 GeV and for different collision systems U+U at $\sqrt{s_{NN}} = 193$ GeV, and Cu+Au, Cu+Cu, d+Au and p+Au at $\sqrt{s_{NN}} = 200$ GeV are summarized in Figs. 2 and 3. The values of $v_1^{\text{even}}(p_T)$ extracted for different centrality selections (0-10%, 10-20% and 20-30%) are shown in Fig. 2; the solid line in panel (a) shows the characteristic pattern of a change from negative $v_1^{\text{even}}(p_T)$ at low $p_T$ to positive $v_1^{\text{even}}(p_T)$ for $p_T > 1$ GeV/c, with a crossing point that shifts with $\sqrt{s_{NN}}$. They also indicate that $v_1^{\text{even}}$ increase as the centrality become more peripheral, as might be expected from the centrality dependence of $\varepsilon_1$.

The extracted values of $v_1^{\text{even}}(p_T)$, for different collision systems are compared in Fig. 3 for different values of $\langle \text{Mult} \rangle$. Figs. 3(a), 3(b) and 3(c) indicate similar $v_1^{\text{even}}(p_T)$ magnitudes for the systems specified at each $\langle \text{Mult} \rangle$, as well as the characteristic pattern of a change from negative $v_1^{\text{even}}(p_T)$ at low $p_T$ to positive $v_1^{\text{even}}(p_T)$ for $p_T > 1$ GeV. This pattern confirms the predicted trends for rapidity-even dipolar flow [13, 14, 17] and further indicates that for the selected values of $\langle \text{Mult} \rangle$, $v_1^{\text{even}}(p_T)$ does not show a strong dependence on the collision system. This apparent system independence of $v_1^{\text{even}}(p_T)$ for the indicated $\langle \text{Mult} \rangle$ values suggests that the fluctuations-driven initial-state eccentricity

![Figure 2](https://doi.org/10.1051/epjconf/201817116002)

*Figure 2.* Extracted values of $v_1^{\text{even}}$ vs. $p_T$ for different centrality selections (0-10%, 10-20% and 20-30%) Au+Au collisions for several values of $\sqrt{s_{NN}}$ as indicated; the $v_1^{\text{even}}$ values are obtained via fits with Eq. (5). The solid line in panel (a) shows the result from a hydrodynamic calculations with $\eta/s = 0.16$ [14]. The inset in panel (a) shows a representative set of the associated values of $C$ vs. $\langle \text{Mult} \rangle^{-1}$.

![Figure 3](https://doi.org/10.1051/epjconf/201817116002)

*Figure 3.* Extracted values of $v_1^{\text{even}}$ vs. $p_T$ for different $\langle \text{Mult} \rangle$ selections for different collisions system at $\sqrt{s_{NN}} \sim 200$ GeV as indicated; the $v_1^{\text{even}}$ values are obtained via fits with Eq. (5).
$\epsilon_1$, is similar for the six collision systems. It also suggests that the viscous effects that are related to $\eta/s$ are comparable for the matter created in each of these collision systems.

4 Conclusion

In summary, we have used the two-particle correlation method to carry out new differential measurements of rapidity-even dipolar flow, $v_1^{\text{even}}$, in Au+Au collisions at different beam energies, and in U+U, Cu+Au, Cu+Cu, d+Au and p+Au collisions at $\sqrt{s_{NN}} \approx 200$ GeV. The measurements confirm the characteristic patterns of an evolution from negative $v_1^{\text{even}}(p_T)$ for $p_T > 1$ GeV/c to positive $v_1^{\text{even}}(p_T)$ for $p_T > 1$ GeV/c, expected when initial-state geometric fluctuations act in concert with the hydrodynamic-like expansion to generate rapidity-even dipolar flow. This measurements provide additional constraints which are important to discern between different initial-state models, and to aid precision extraction of the temperature dependence of the specific shear viscosity.

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References