Beam energy and system dependence of rapidity-even dipolar flow

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Abstract. New measurements of rapidity-even dipolar flow, v_1^{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_1^{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 η/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 η/s for the QGP produced in HIC [8, 9]. This work emphasizes new measurements for rapidity-even dipolar flow, v_1^{even}, which could aid a distinction between different initial-state models and facilitate the extraction of η/s with better constraints.

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

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

where Ψ_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:

$$v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b) + \delta_{NF}, \tag{2}$$

where p_T^a and p_T^b are the transvers momentum of particles (a) and (b), respectively, and δ_{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,

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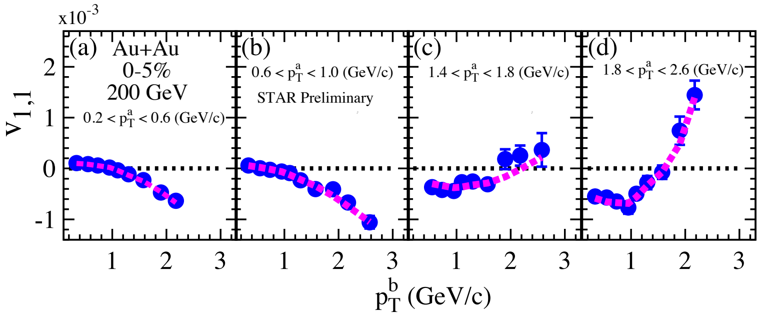

Figure 1. $v_{1,1}$ vs. p_T^b for several selections of p_T^a for 0-5% central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. The dashed curve shows the result of the simultaneous fit with Eq. 5.

can be separated into an odd function of pseudorapidity (η) [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; $v_1(\eta) = v_1^{even}(\eta) + v_1^{odd}(\eta)$, where Ψ_1^{odd} and Ψ_1^{even} are uncorrelated. The magnitude of v_1^{even} is related to the fluctuations-driven dipole asymmetry ε_1 and η/s [14, 17, 18].

2 Measurements

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

$$C_r(\Delta\phi, \Delta\eta) = \frac{(dN/d\Delta\phi)_{same}}{(dN/d\Delta\phi)_{mixed}}, \tag{3}$$

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 $v_{n,n}$ are obtained from the correlation function as:

$$v_{n,n} = \frac{\sum_{\Delta\phi} C_r(\Delta\phi, \Delta\eta)\cos(n\Delta\phi)}{\sum_{\Delta\phi} C_r(\Delta\phi, \Delta\eta)}, \tag{4}$$

and then used to extract v_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:

$$v_{1,1}(p_T^a, p_T^b) = v_1^{even}(p_T^a) v_1^{even}(p_T^b) - C p_T^a p_T^b. \tag{5}$$

Here, $C \propto 1/(\langle Mult\rangle\langle p_T^2\rangle)$ 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 $v_1^{even}(p_T)$ 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, $v_{1,1}(p_T^b)$ evolves from negative to positive values as the selection range for p_T^a is increased.

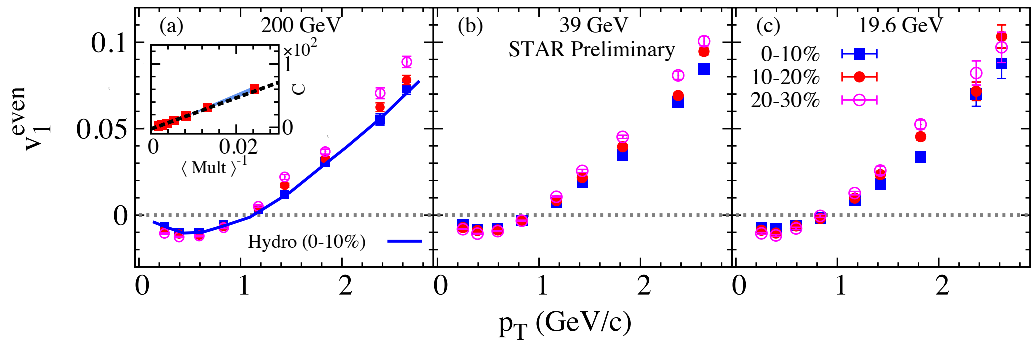

Figure 2. Extracted values of v_1^{even} vs. p_T for different centrality selections (0-10%, 10-20% and 20-30%) Au+Au collisions for several values of $\sqrt{s_{NN}}$ as indicated; the v_1^{even} values are obtained via fits with Eq. (5). The solid line in panel (a) shows the result from a hydrodynamic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

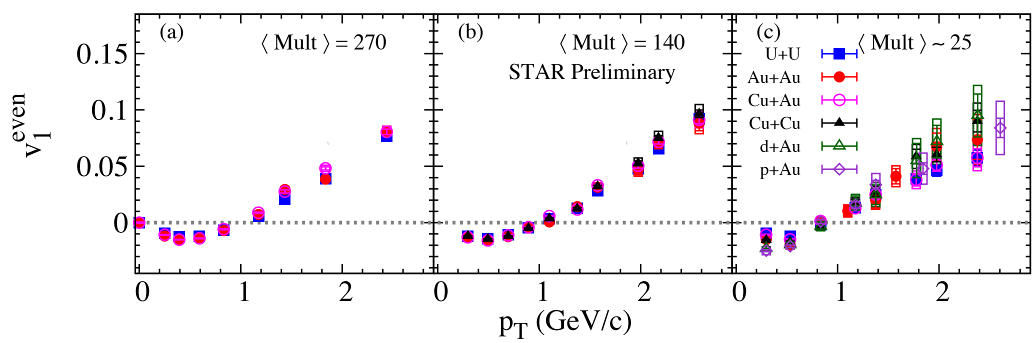

Figure 3. Extracted values of v_1^{even} vs. p_T for different $\langle Mult\rangle$ selections for different collisions system at $\sqrt{s_{NN}} \sim 200$ GeV as indicated; the v_1^{even} values are obtained via fits with Eq. (5).

3 Results

Representative v_1^{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 $v_1^{even}(p_T)$ extacted for different centrality selections (0-10%, 10-20% and 20-30%) are shown in Fig. 2; the solid line in panel (a) shows the a hydrodynamic calculations with $\eta/s = 0.16$[14], which in good agreement with our measurements, the inset shows the corresponding results for the associated momentum conservation coefficient, C, extracted for several centralities at $\sqrt{s_{NN}} = 200$ GeV. The $v_1^{even}(p_T)$ values indicate the characteristic pattern of a change from negative $v_1^{even}(p_T)$ at low p_T to positive $v_1^{even}(p_T)$ for $p_T > 1$ GeV/c, with a crossing point that shifts with $\sqrt{s_{NN}}$. They also indicate that v_1^{even} increase as the centrality become more peripheral, as might be expected from the centrality dependence of ε_1.

The extracted values of $v_1^{even}(p_T)$, for different collision systems are compared in Fig. 3 for different values of $\langle Mult\rangle$. Figs. 3(a), 3(b) and 3(c) indicate similar $v_1^{even}(p_T)$ magnitudes for the systems specified at each $\langle Mult\rangle$, as well as the characteristic pattern of a change from negative $v_1^{even}(p_T)$ at low p_T to positive $v_1^{even}(p_T)$ 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 $\langle Mult\rangle$, $v_1^{even}(p_T)$ does not show a strong dependence on the collision system. This apparent system independence of $v_1^{even}(p_T)$ for the indicated $\langle Mult\rangle$ values suggests that the fluctuations-driven initial-state eccentricity

ε_1, is similar for the six collision systems. It also suggests that the viscous effects that are related to η/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^{even}, in Au+Au collisions at different beam energies, and in U+U, Cu+Au, Cu+Cu, d+Au and p+Au collisions at $\sqrt{s_{NN}} \simeq 200$ GeV. The measurements confirm the characteristic patterns of an evolution from negative $v_1^{even}(p_T)$ for $p_T > 1$ GeV/c to positive $v_1^{even}(p_T)$ 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.

Acknowledgments

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