Beam energy dependence of the anisotropic flow coefficients $v_n$

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Recent STAR measurements of the anisotropic flow coefficients, $v_n$, are presented for Au+Au collisions spanning the beam energy range $\sqrt{s_{NN}} = 7.7 - 200$ GeV. The measurements indicate dependences on harmonic number, $n$, transverse momentum ($p_T$), pseudorapidity ($\eta$), collision centrality (cent) and beam energy ($\sqrt{s_{NN}}$) which could serve as important constraints to test different initial-state models and to aid precision extraction of the temperature dependence of the specific shear viscosity.

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1. Introduction

A major goal of the heavy-ion experimental program at the Relativistic Heavy Ion Collider (RHIC) is to study the properties of the strongly interacting quark-gluon plasma (QGP) created in ion-ion collisions. Recently, many studies have emphasized the use of anisotropic flow measurements to study the transport properties of the QGP [1–7]. An important question in many of these studies has been the role of initial-state fluctuations and their influence on the uncertainties associated with the extraction of $\eta/s$ for the QGP [8, 9]. This work presents new measurements for the anisotropic flow coefficients, $v_{n>1}$, and the rapidity-even dipolar flow coefficient, $v_{1}^{\text{even}}$, with an eye toward developing new constraints which could aid a distinction between different initial-state models and hence, facilitate a more precise extraction of the specific shear viscosity $\eta/s$ [10, 11].

Anisotropic flow is characterized by the Fourier coefficients, $v_n$, obtained from a Fourier expansion of the azimuthal angle ($\phi$) distribution of the particles emitted in the collisions [12]:

$$\frac{dN}{d\phi} \propto 1 + 2 \sum_{n=1}^\infty v_n \cos(n(\phi - \Psi_n)), \quad (1.1)$$

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

$$v_{n,n}(p_T^a, p_T^b) = v_n(p_T^a)v_n(p_T^b) + \delta_{\text{NF}}, \quad (1.2)$$

where $a$ and $b$ are particles selected with $p_T^a$ and $p_T^b$ respectively, and $\delta_{\text{NF}}$ is a so-called non-flow (NF) term, which includes possible short-range contributions from resonance decays, Bose-Einstein correlations and near-side jets, and long-range contributions from the global momentum conservation (GMC) [13–15]. The short-range contributions can be reduced by employing a pseudorapidity gap, $\Delta \eta$. However, the effects of GMC must be explicitly considered. For the current analysis, a simultaneous fitting procedure, outlined below, was used to account for GMC.

2. Measurements

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

$$C_r(\Delta \phi, \Delta \eta) = \frac{(dN/d\Delta \phi)_{\text{same}}}{(dN/d\Delta \phi)_{\text{mixed}}}, \quad (2.1)$$

where $(dN/d\Delta \phi)_{\text{same}}$ represent the normalized azimuthal distribution of particle pairs from the same event and $(dN/d\Delta \phi)_{\text{mixed}}$ 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 collision vertex location, centrality, etc. The pseudorapidity requirement $|\Delta \eta| > 0.7$ was also imposed on track pairs to minimize non-flow contributions associated with the short-range correlations.

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

$$v_{n,n} = \frac{\sum_{\Delta \phi} C_r(\Delta \phi, \Delta \eta) \cos(n\Delta \phi)}{\sum_{\Delta \phi} C_r(\Delta \phi, \Delta \eta)}, \quad (2.2)$$
and then used to extract $v_1^{\text{even}}$ via a simultaneous fit of $v_{1,1}$ as a function of $p_T^b$, for several selections of $p_T^a$ with Eq. (2.2):

$$v_{1,1}(p_T^a, p_T^b) = v_1^{\text{even}}(p_T^a) + v_1^{\text{even}}(p_T^b) - C p_T^a p_T^b.$$  (2.3)

Here, $C \propto 1/(\langle \text{Mult} \rangle \langle p_T^2 \rangle)$ takes into account the non-flow correlations induced by a global momentum conservation [15, 16] and $\langle \text{Mult} \rangle$ is the corrected mean multiplicity. For a given centrality selection, the left hand side of Eq. 2.3 represents the $N \times N$ matrix which we fit with the right hand side using $N+1$ parameters; $N$ values of $v_1^{\text{even}}(p_T^a)$ and one additional parameter $C$, accounting for the momentum conservation [17].

![Figure 1](https://example.com/figure1.png)

**Figure 1:** (a) The extracted values of $v_1^{\text{even}}$ vs. $p_T$ for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. (b) A representative set of the associated values of $C$ vs. $\langle \text{Mult} \rangle^{-1}$ from the same fits. The shaded bands represent the systematic uncertainty.

### 3. Results

Representative results for $v_1^{\text{even}}$ and $v_{n \geq 2}$ for Au+Au collisions at several different collision energies are summarized in Figs. 1, 2, 3, 4 and 5.

The values of $v_1^{\text{even}}(p_T)$ extracted for different centrality selections (0-10%, 20-30% and 40-50%) are shown in Fig. 1(a). They indicate 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. They also show the expected increase of $v_1^{\text{even}}$ as collisions become more peripheral, in line with the expected centrality dependence of the dipole asymmetry $\varepsilon_1$, where $\varepsilon_1 \equiv |(r^3/\rho^3)|/r^3$ [18, 19]. Fig. 1(b) shows the results for the associated momentum conservation coefficients, $C$; they indicate the expected linear dependence on $\langle \text{Mult} \rangle^{-1}$.

Figure 2 and 3 show $p_T$ and $\eta$ differential $v_{n \geq 2}$ measurements for the centrality selection 0-40%, for a representative set of beam energies. Fig. 2 indicates a sizable dependence of the magnitude of $v_n$ on $p_T$ and the harmonic number, $n$, with similar trends for each beam energy. Figure 3 shows a similarly strong $n$ dependence for $v_{n \geq 2}$ but with a much weaker $\eta$ dependence.

The centrality dependence of $v_{n \geq 2}$ is shown in Fig. 4 for the same representative set of beam energies. They indicate a weak centrality dependence for the higher harmonics, which all decrease...
Figure 2: Examples of $v_n(p_T)$ as a function of $p_T$ for charged particles in 0-40% central Au+Au collisions. The shaded bands represent the systematic uncertainty.

Figure 3: Examples of $v_n(|\eta|)$ as a function of $|\eta|$ for charged particles in 0-40% central Au+Au collisions. The shaded bands represent the systematic uncertainty.

Figure 4: Examples of $v_n$(Centrality%) as a function of Au+Au collision centrality for charged particles with $0.2 < p_T < 4$ GeV/c. The shaded bands represent the systematic uncertainty.
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with decreasing values of $\sqrt{s_{NN}}$. These patterns may be related to the detailed dependence of the viscous effects in the created medium, which serve to attenuate the magnitude of $v_n$.

Figure 5 shows the excitation functions for the $p_T$-integrated $v_{2,3,4}$ for $0 - 40\%$ central Au+Au collisions. They indicate an essentially monotonic trend for $v_2$, $v_3$ and $v_4$ with $\sqrt{s_{NN}}$, as might be expected for a temperature increase with $\sqrt{s_{NN}}$.

4. Conclusion

In summary, we have performed a comprehensive set of STAR anisotropic flow measurements for Au+Au collisions at $\sqrt{s_{NN}} = 7.7-200$ GeV. The measurements use the two-particle correlation method to extract the Fourier coefficients, $v_{n>1}$, and the rapidity-even dipolar flow coefficient, $v_{1}^{even}$. The rapidity-even dipolar flow measurements indicate 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 along with the hydrodynamic-like expansion to generate rapidity-even dipolar flow. The $v_{n>1}$ measurements indicate a rich set of dependences on harmonic number $n$, $p_T$, $|\eta|$ and centrality for versus the beam energy. These new measurements may provide additional constraints to test different initial-state models, and to aid precision extraction of the temperature dependence of the specific shear viscosity.

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