Beam-energy dependence of the azimuthal anisotropic flow from RHIC

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Abstract: 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 the harmonic number ($n$), transverse momentum ($p_T$), pseudorapidity ($\eta$), collision centrality 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.

I. INTRODUCTION

A major aim of the heavy-ion experimental program at the Relativistic Heavy Ion Collider (RHIC) is to study the properties of the quark-gluon plasma (QGP) created in ion-ion collisions. Recently, several studies have highlighted the use of anisotropic flow measurements to investigate the transport properties of the QGP [1–7]. An essential question in many of these studies has been the role of initial-state fluctuations and their impact on the uncertainties associated with the extraction of $\eta/s$ for the QGP [8, 9].

In this work, we present a new measurement for the anisotropic flow coefficients, $v_n(n > 1)$ [10–12], and the rapidity-even dipolar flow coefficient, $v_{1\text{even}}$ [13, 14], with an eye toward providing a new constraint which could assist the distinction between different initial-state models and therefore, facilitate a more accurate extraction of the specific shear viscosity, $\eta/s$ [15, 16].

The anisotropic flow is described by the coefficients, $v_n$, obtained from a Fourier expansion of the azimuthal angle ($\phi$) distribution of the particles emitted in the collisions [17]:

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

where $\Psi_n$ denotes the azimuthal angle of the $n^{th}$-order event plane; the coefficients, $v_1$, $v_2$ and $v_3$ define directed, elliptic, and triangular flow, respectively. The flow coefficients, $v_n$, are linked 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 a and b are particles with $p_T^a$ and $p_T^b$, respectively, and $\delta_{NF}$ is the non-flow (NF) term, which involves potential short-range contributions from resonance decays, Bose-Einstein correlation, near-side jets, and long-range contributions from the global momentum conservation (GMC) [18–20]. The short-range non-flow contributions can be reduced by applying a pseudorapidity gap, $\Delta \eta$, between $\eta^a$ and $\eta^b$. However, the impacts of the GMC must be explicitly considered. For the current analysis, a simultaneous fitting method [13], outlined below, was used to account for the GMC.

II. MEASUREMENTS

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

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

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where \((dN/d\Delta \phi)_{same}\) denotes the normalized azimuthal distribution of particle pairs from the same event and \((dN/d\Delta \phi)_{mixed}\) denotes 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 gap requirement \(|\Delta \eta| > 0.7\) was applied to track pairs to reduce the non-flow contributions associated with the short-range correlations.

The two-particle Fourier coefficients, \(v_{n,n}\), are extracted from the correlation function as:

\[
v_{n,n} = \frac{\sum_{\Delta \phi} C_r(\Delta \phi, \Delta \eta) \cos(n \Delta \phi)}{\sum_{\Delta \phi} C_r(\Delta \phi, \Delta \eta)}.
\]

and then the two-particle Fourier coefficients, \(v_{n,n}\), are 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:

\[
v_{1,1}(p_T^a, p_T^b) = v_{1\text{even}}(p_T^a)v_{1\text{even}}(p_T^b) - Cp_r(p_T^a)p_r(p_T^b).
\]

Here, \(C \propto 1/(\langle Mult \rangle(p_T^a))\) takes into account the non-flow correlations caused by a global momentum conservation \([20, 21]\) and \(\langle Mult \rangle\) is the mean multiplicity. For a particular centrality selection, the left-hand side of Eq. 5 describes the \(N \times N\) matrix which we fit with the right-hand side using \(N + 1\) parameters; \(N\) values of \(v_{1\text{even}}(p_T)\) and one additional parameter \(C\), accounting for the momentum conservation \([22]\).

Figure 1 [13] shows the result of this fitting method for 0–5% central Au+Au collisions at \(\sqrt{s_{NN}} = 200\) GeV. The dashed curve (produced with Eq. 5) in each panel represents the effectiveness of the simultaneous fits, as well as the data constraining power. That is, \(v_{1,1}(p_T^b)\) grows from negative to positive values as the selection range for \(p_T^a\) is increased.

### III. RESULTS

Representative set of STAR measurements for \(v_{1\text{even}}\) and \(v_n(n \geq 2)\) for Au+Au collisions at several different collision energies are summarized in Figs. 2 [3] [4] and 6.

The extracted values of \(v_{1\text{even}}(p_T)\) for 0-10%, 10-20% and 20-30% centrality selections are shown in Fig. 2 the solid line in panel (a) indicates the hydrodynamic calculations \([21]\), that in good agreement with our measurements, the inset displays the results of the associated momentum conservation coefficient, \(C\), obtained for several centralities at \(\sqrt{s_{NN}} = 200\) GeV. The \(v_{1\text{even}}(p_T)\) values show 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 slowly shifts with \(\sqrt{s_{NN}}\). They also indicate that \(v_{1\text{even}}\) increases as the collisions become more peripheral, as might be expected from the centrality dependence of \(v_1\).

Figure 2 shows the \(p_T\) dependence of the \(v_n(n \geq 2)\) measurements for 0-40% centrality selection for a representative set of beam energies. Fig. 2 shows the \(v_n\) dependence on \(p_T\) and the harmonic number, \(n\), with similar trends for each beam energy.

The centrality dependence of \(v_n(n \geq 2)\) is indicated in Fig. 4 for the same representative set of beam energies. Our measurements indicate a soft centrality dependence for the higher-order flow harmonics,
which all decrease with decreasing the $\sqrt{s_{NN}}$. These $v_n$ patterns may be related to the dependence of the viscous effects in the created medium, which lead to attenuation of $v_n$ magnitude.

Figure 5 gives the excitation functions for the $p_T$-integrated $v_2$, $v_3$ and $v_4$ for $0-40\%$ central Au+Au collisions. They indicate monotonic trend for $v_n$ with $\sqrt{s_{NN}}$, as might be expected for a temperature increase with $\sqrt{s_{NN}}$.
FIG. 5. The $v_n(\sqrt{s_{NN}})$ for charged particles with $0.2 < p_T < 4$ GeV/c and 0-40% central Au+Au collisions. The shaded bands represent the systematic uncertainty. The dashed line at $v_n = 0$ is to guide the eye.

IV. CONCLUSION

In summary, we have presented 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 obtain the Fourier coefficients, $v_n(n > 1)$, and the rapidity-even dipolar flow coefficient, $v_{1\text{even}}^\text{even}$. The rapidity-even dipolar flow measurements indicate the characteristic patterns of an evolution from negative $v_{1\text{even}}^\text{even}(p_T)$ for $p_T < 1$ GeV/c to positive $v_{1\text{even}}^\text{even}(p_T)$ 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 $v_n(n > 1)$ measurements show a rich set of dependences on harmonic number $n$, $p_T$ and centrality for several collision energies. This set of measurements may provide additional constraints to test different initial-state models and to aid accuracy extraction of the temperature dependence of the specific shear viscosity.

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