PROCEEDINGS OF SCIENCE

Beam energy dependence of the anisotropic flow coefficients v$_n$

Niseem Magdy* **(For the STAR Collaboration)**
Department of Chemistry, Stony Brook University, Stony Brook, NY, 11794-3400, USA
E-mail: niseemm@gmail.com

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 (η), 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.

Critical Point and Onset of Deconfinement
, 7-11 August 2017
The Wang Center, Stony Brook University, Stony Brook, NY

*Speaker.

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 η/s for the QGP [8,9]. This work presents new measurements for the anisotropic flow coefficients, $\mathrm{v}_{n>1}$, and the rapidity-even dipolar flow coefficient, v_1^{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 η/s [10, 11].

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

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

where Ψ_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, $\mathrm{v}_{n,n}$, as:

$$\mathrm{v_{n,n}}(p_\mathrm{T}^a, p_\mathrm{T}^b) = \mathrm{v_n}(p_\mathrm{T}^a)\mathrm{v_n}(p_\mathrm{T}^b) + \delta_\mathrm{NF}, \tag{1.2}$$

where a and b are particles selected with p_T^a and p_T^b respectively, and δ_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:

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

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 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, $\mathrm{v}_{n,n}$, are obtained from the correlation function as:

$$\mathrm{v_{n,n}} = \frac{\sum_{\Delta\phi} C_r(\Delta\phi,\Delta\eta)\cos(n\Delta\phi)}{\sum_{\Delta\phi} C_r(\Delta\phi,\Delta\eta)}, \tag{2.2}$$

and then used to extract v_1^{even} via a simultaneous fit of $\mathrm{v}_{1,1}$ as a function of p_T^{b}, for several selections of p_T^a with Eq. 1.2:

$$\mathrm{v}_{1,1}(p_{\mathrm{T}}^a, p_{\mathrm{T}}^b) = \mathrm{v}_1^{\mathrm{even}}(p_{\mathrm{T}}^a)\mathrm{v}_1^{\mathrm{even}}(p_{\mathrm{T}}^b) - C p_{\mathrm{T}}^a p_{\mathrm{T}}^b. \quad (2.3)$$

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 [15, 16] and $\langle Mult \rangle$ 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 $\mathrm{v}_1^{even}(p_{\mathrm{T}})$ and one additional parameter C, accounting for the momentum conservation [17].

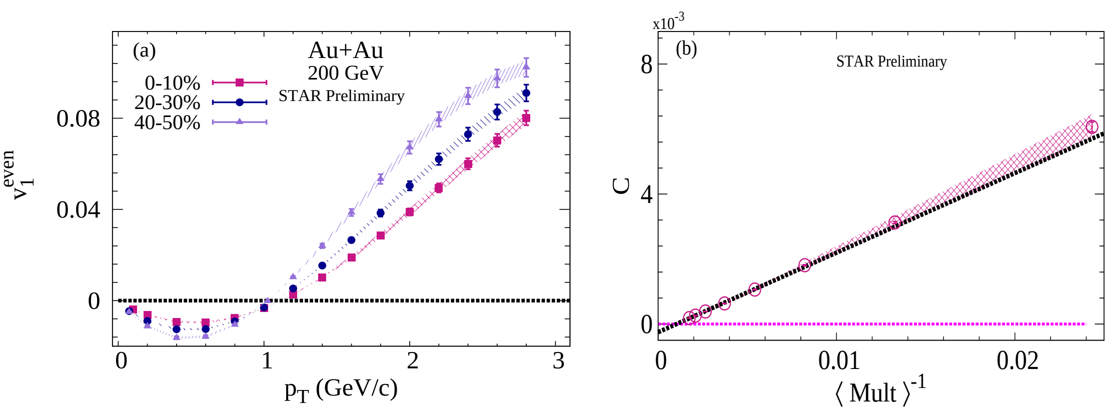

Figure 1: (a) The extracted values of v_1^{even} vs. p_T for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. (b) A representative set of the associated values of C vs. $\langle Mult \rangle^{-1}$ from the same fits. The shaded bands represent the systematic uncertainty.

3. Results

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

The values of $\mathrm{v}_1^{even}(p_{\mathrm{T}})$ 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 $\mathrm{v}_1^{even}(p_{\mathrm{T}})$ at low p_{T} to positive $\mathrm{v}_1^{even}(p_{\mathrm{T}})$ for $p_T > 1$ GeV/c. They also show the expected increase of v_1^{even} as collisions become more peripheral, in line with the expected centrality dependence of the dipole asymmetry ε_1, where $\varepsilon_1 \equiv |\langle r^3 e^{i\phi} \rangle|/r^3$ [18, 19]. Fig. 1(b) shows the results for the associated momentum conservation coefficients, C; they indicate the expected linear dependence on $\langle Mult \rangle^{-1}$.

Figure 2 and 3 show p_T and η differential $\mathrm{v_{n\geq 2}}$ 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 $\mathrm{v_{n\geq 2}}$ but with a much weaker η dependence.

The centrality dependence of $\mathrm{v}_{n\geq 2}$ 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

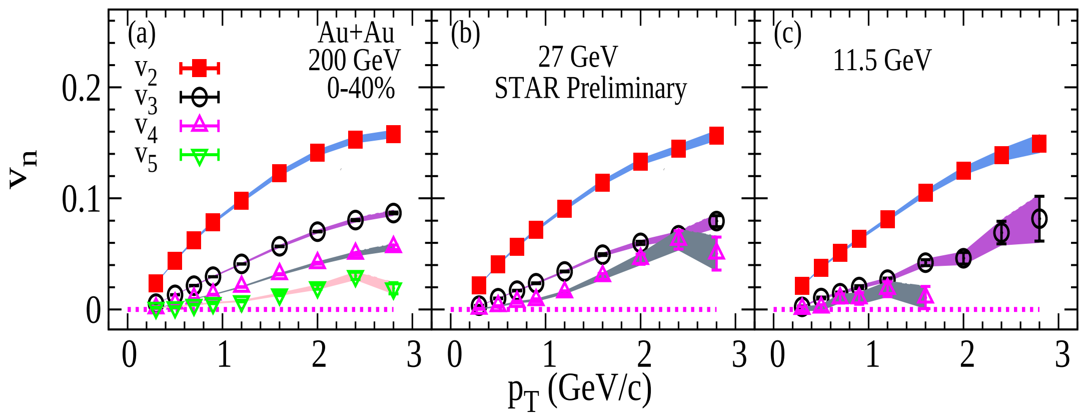

Figure 2: Examples of $v_n(p_T)$ as a function of p_T for charged particles in 0-40% central Au+Au collisions. The shaded bands represent the systematic uncertainty.

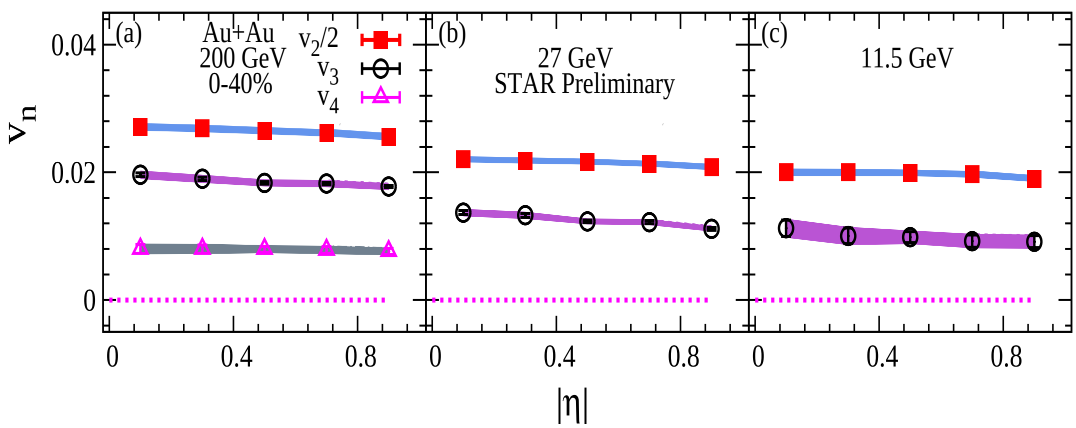

Figure 3: Examples of $v_n(|\eta|)$ as a function of $|\eta|$ for charged particles in 0-40% central Au+Au collisions. The shaded bands represent the systematic uncertainty.

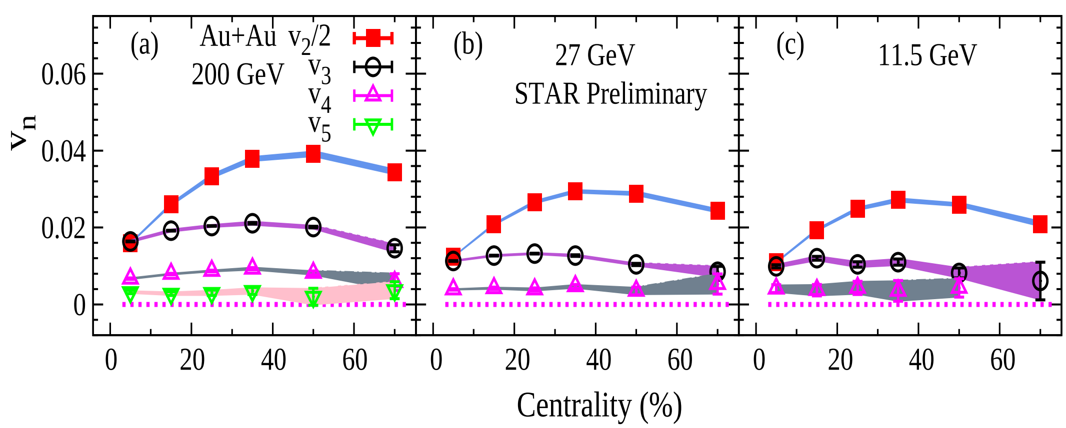

Figure 4: Examples of v_n(Centrality%) as a function of Au+Au collision centrality for charged particles with $0.2 < p_T < 4$ GeV/c. The shaded bands represent the systematic uncertainty.

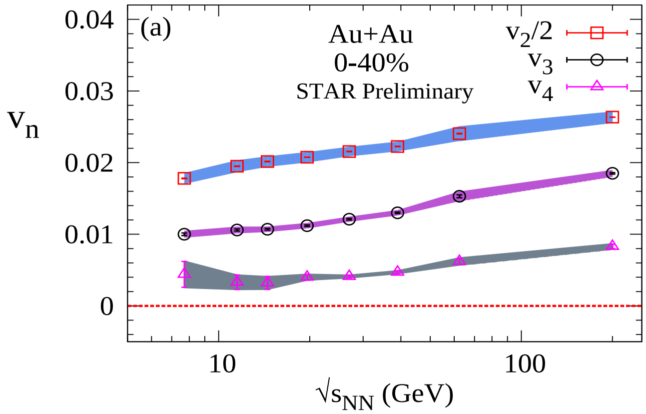

Figure 5: Examples of $\mathrm{v}_n(\sqrt{s_{\mathrm{NN}}})$ for charged particles with $0.2 < p_T < 4$ GeV/c and 0-40% central Au+Au collisions. The shaded bands represent the systematic uncertainty.

with decreasing values of $\sqrt{s_{\mathrm{NN}}}$. 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 $\sqrt{s_{\mathrm{NN}}}$, as might be expected for a temperature increase with $\sqrt{s_{\mathrm{NN}}}$.

4. Conclusion

In summary, we have performed a comprehensive set of STAR anisotropic flow measurements for Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 7.7$-200 GeV. The measurements use the two-particle correlation method to extract the Fourier coefficients, $\mathrm{v}_{n>1}$, 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 $\mathrm{v}_1^{even}(p_{\mathrm{T}})$ for $p_{\mathrm{T}} < 1$ GeV/c to positive $\mathrm{v}_1^{even}(p_{\mathrm{T}})$ for $p_{\mathrm{T}} > 1$ GeV/c, expected when initial-state geometric fluctuations act along with the hydrodynamic-like expansion to generate rapidity-even dipolar flow. The $\mathrm{v}_{n>1}$ 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.

Acknowledgments

This research is supported by the US Department of Energy under contract DE-FG02-87ER40331.

References

[1] D. Teaney, *The Effects of viscosity on spectra, elliptic flow, and HBT radii*, *Phys.Rev.* **C68** (2003) 034913, [nucl-th/0301099].

[2] R. A. Lacey and A. Taranenko, *What do elliptic flow measurements tell us about the matter created in the little bang at RHIC?*, *PoS* **CFRNC2006** (2006) 021, [nucl-ex/0610029].

[3] B. Schenke, S. Jeon and C. Gale, *Anisotropic flow in* $\sqrt{s} = 2.76$ *TeV Pb+Pb collisions at the LHC*, *Phys.Lett.* **B702** (2011) 59–63, [1102.0575].

[4] H. Song, S. A. Bass and U. Heinz, *Elliptic flow in 200 A GeV Au+Au collisions and 2.76 A TeV Pb+Pb collisions: insights from viscous hydrodynamics + hadron cascade hybrid model*, *Phys.Rev.* **C83** (2011) 054912, [1103.2380].

[5] H. Niemi, G. Denicol, P. Huovinen, E. Molnar and D. Rischke, *Influence of a temperature-dependent shear viscosity on the azimuthal asymmetries of transverse momentum spectra in ultrarelativistic heavy-ion collisions*, *Phys.Rev.* **C86** (2012) 014909, [1203.2452].

[6] G.-Y. Qin, H. Petersen, S. A. Bass and B. Muller, *Translation of collision geometry fluctuations into momentum anisotropies in relativistic heavy-ion collisions*, *Phys.Rev.* **C82** (2010) 064903, [1009.1847].

[7] STAR collaboration, N. Magdy, *Viscous Damping of Anisotropic Flow in 7.7–200 GeV Au+Au Collisions*, *J. Phys. Conf. Ser.* **779** (2017) 012060.

[8] B. Alver and G. Roland, *Collision geometry fluctuations and triangular flow in heavy-ion collisions*, *Phys. Rev.* **C81** (2010) 054905, [1003.0194].

[9] R. A. Lacey, D. Reynolds, A. Taranenko, N. N. Ajitanand, J. M. Alexander, F.-H. Liu et al., *Acoustic scaling of anisotropic flow in shape-engineered events: implications for extraction of the specific shear viscosity of the quark gluon plasma*, *J. Phys.* **G43** (2016) 10LT01, [1311.1728].

[10] J. Auvinen, I. Karpenko, J. E. Bernhard and S. A. Bass, *Investigating the collision energy dependence of* η/s *in RHIC beam energy scan using Bayesian statistics*, 1706.03666.

[11] J. Auvinen, I. Karpenko, J. E. Bernhard and S. A. Bass, *Revealing the collision energy dependence of* η/s *in RHIC-BES Au+Au collisions using Bayesian statistics*, *Nucl. Phys.* **A967** (2017) 784–787, [1704.04643].

[12] A. M. Poskanzer and S. A. Voloshin, *Methods for analyzing anisotropic flow in relativistic nuclear collisions*, *Phys. Rev.* **C58** (1998) 1671–1678, [nucl-ex/9805001].

[13] R. A. Lacey, *The Role of elliptic flow correlations in the discovery of the sQGP at RHIC*, *Nucl. Phys.* **A774** (2006) 199–214, [nucl-ex/0510029].

[14] N. Borghini, P. M. Dinh and J.-Y. Ollitrault, *Are flow measurements at SPS reliable?*, *Phys. Rev.* **C62** (2000) 034902, [nucl-th/0004026].

[15] ATLAS collaboration, G. Aad et al., *Measurement of the azimuthal anisotropy for charged particle production in* $\sqrt{s_{NN}} = 2.76$ *TeV lead-lead collisions with the ATLAS detector*, *Phys. Rev.* **C86** (2012) 014907, [1203.3087].

[16] E. Retinskaya, M. Luzum and J.-Y. Ollitrault, *Directed flow at midrapidity in* $\sqrt{s_{NN}} = 2.76$ *TeV Pb+Pb collisions*, *Phys. Rev. Lett.* **108** (2012) 252302, [1203.0931].

[17] J. Jia, S. K. Radhakrishnan and S. Mohapatra, *A study of the anisotropy associated with dipole asymmetry in heavy ion collisions*, *J. Phys.* **G40** (2013) 105108, [1203.3410].

[18] D. Teaney and L. Yan, *Triangularity and Dipole Asymmetry in Heavy Ion Collisions*, *Phys. Rev.* **C83** (2011) 064904, [1010.1876].

[19] P. Bozek, *Event-by-event viscous hydrodynamics for Cu+Au collisions at* $\sqrt{s_{NN}}$*=200 GeV*, *Phys. Lett.* **B717** (2012) 287–290, [1208.1887].