

Viscous Damping of Anisotropic Flow in 7.7 – 200 GeV Au+Au Collisions

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Abstract. Recent STAR measurements of the anisotropic flow coefficients v_n ($2 \leq n \leq 5$) in Au+Au collisions at RHIC, are presented for the full span of energies (7.7 – 200 GeV) employed in beam energy scan I (BES-I). The measurements which can provide strong constraints for the baryon chemical potential (μ_B) and temperature (T) dependence of the specific shear viscosity η/s , indicate sizable dependencies on harmonic number n , p_T and centrality, with similar patterns [but different magnitudes] across the beam energies studied. An excitation function for the viscous coefficient, extracted via specific ratios of v_n for a fixed centrality, indicates a non-monotonic pattern which could be related to the onset of critical reaction dynamics in the BES-I energy range.

1. Introduction

Studies of the properties of the strongly interacting medium produced in heavy ion collisions is a major theme of current heavy ion research. Ongoing programs are underway at RHIC [1], SPS [2] and LHC [3], and new programs are slated for the future FAIR [4] and NICA [5] facilities. These programs are at the forefront of experimental efforts designed to map the QCD phase diagram and delineate the thermodynamic and transport properties of each QCD phase. The viscous coefficient, which is directly related to the specific shear viscosity of the QCD matter produced in heavy-ion collisions, can be probed via measurements of anisotropic flow [6, 7, 8, 9]. Initial works focused on the first and second flow harmonics, termed directed and elliptic flow respectively, as well as higher-order even harmonics [10]. Studies of the third harmonic [11, 12] received attention subsequent to the realization that event-by-event fluctuations [11, 12, 13, 14, 15] lead to non-zero magnitudes for the odd harmonics.

In this work, v_n [for $2 \leq n \leq 5$] measurements for Au+Au collisions, obtained in BES-I with the STAR detector, are presented and used to extract an excitation function for the viscous coefficient. Such an excitation function can give important insight on the temperature dependence of the specific viscosity $\eta/s(T)$, as well as an indication for a possible non-monotonic pattern which could signal critical reaction dynamics [16, 17].

2. Measurements

The two-particle azimuthal correlation function technique is employed for the present measurements. The correlation function $C(\Delta\phi, \Delta\eta)$ is given as,

$$C(\Delta\phi, \Delta\eta) = \frac{(dN/d\Delta\phi)_{Same}}{(dN/d\Delta\phi)_{Mix}}, \quad (1)$$

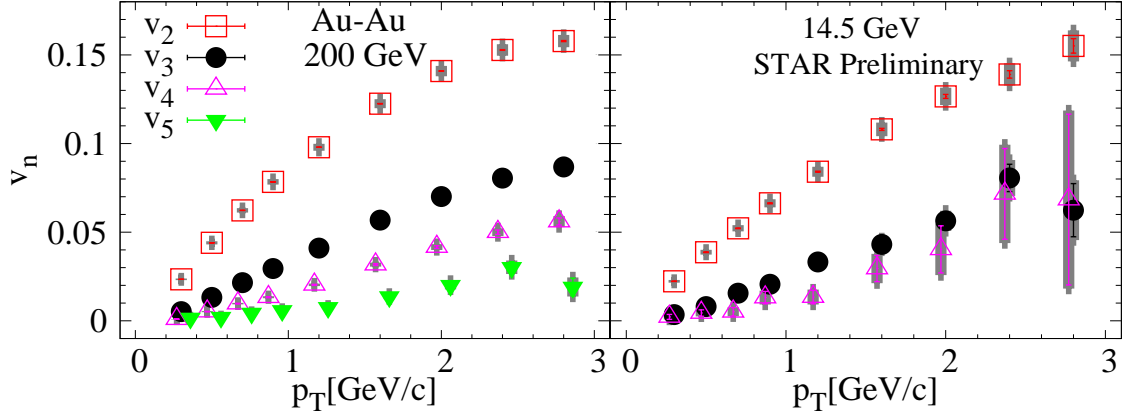


Figure 1. Illustrative examples of $v_n(p_T)$ for 0-40% central Au+Au collisions at two beam energies as indicated.

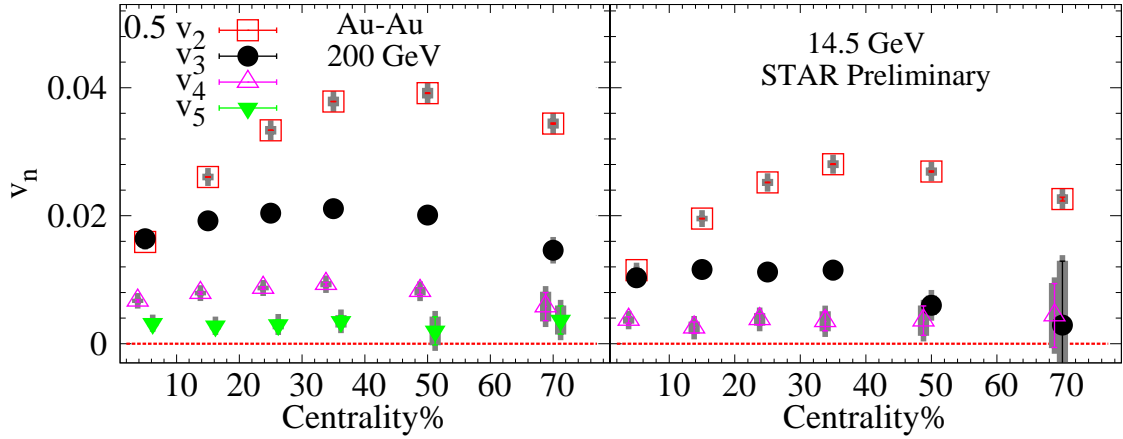


Figure 2. Centrality dependence of the p_T -integrated v_n values for Au+Au collisions for two beam energies as indicated.

where $(dN/d\Delta\phi)_{Same}$ and $(dN/d\Delta\phi)_{Mix}$ are the distributions for charged hadron pairs from the *same* and *mixed* events respectively; $\Delta\phi$ and $\Delta\eta$ are the azimuthal angle difference and the pseudorapidity difference between charged hadron pairs. The condition $\Delta\eta > 0.7$ was used to minimize the influence of the non-flow contributions. On average the relative contributions were found to be less than 3%.

The values for v_n are obtained via Fourier analysis the correlation function (cf. Eq.(1)) in conjunction with the factorization assumption;

$$v_n^2 = \left(\sum_{\Delta\phi} C(\Delta\phi, \Delta\eta) \cos(n\Delta\phi) \right) / \left(\sum_{\Delta\phi} C(\Delta\phi, \Delta\eta) \right). \quad (2)$$

$$v_n(p_T) = v_n^2(p_T, p_T^{ref}) / \sqrt{v_n^2(p_T^{ref}, p_T^{ref})}, \quad (3)$$

where p_T^{ref} is the transverse momentum of the reference particle. The factorization assumption Eq.(3) was tested via several evaluations of $v_n(p_T)$ for different selections for p_T^{ref} .

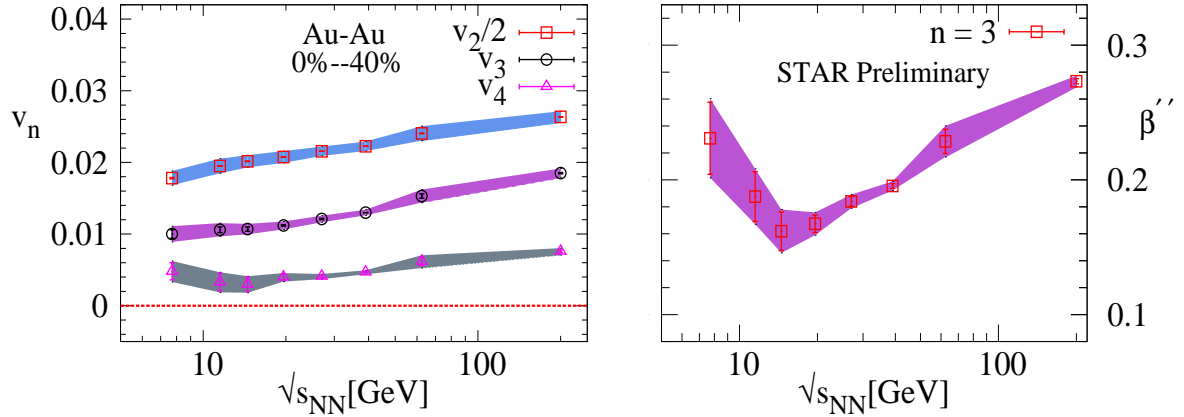


Figure 3. $\sqrt{s_{\text{NN}}}$ dependence of the p_T -integrated v_n (left panel) and the viscous coefficient $\beta'' \propto \eta/s$ (right panel). Results are shown for 0-40% central Au+Au collisions; the shaded lines are the systematic uncertainty.

Figures 1 and 2 show representative examples of the p_T (0-40% central) and centrality dependence of v_n for $\sqrt{s_{\text{NN}}} = 200$ and 14.5 GeV. These figures indicate a sizable dependence of the magnitude of v_n on p_T and the harmonic number n , with similar trends for the two beam energies shown. Similar patterns, albeit with different magnitudes, were observed for the other beam energies. Fig. 2 further suggests a weak centrality dependence for the higher harmonics, which all decrease with decreasing values of $\sqrt{s_{\text{NN}}}$. 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 .

3. Extraction of the viscous coefficient

For a given beam energy, the viscous coefficient β'' which is related to η/s , can be estimated via the acoustic ansatz for anisotropic flow [19, 20, 21]. That is,

$$\frac{v_n(p_T, \text{cent})}{\epsilon_n(\text{cent})} \propto \exp(-n^2 \beta'), \quad \beta' \propto \frac{(\eta/s)}{RT}, \quad (4)$$

where RT and ϵ_n are the dimensionless size and the eccentricities of the collision zone respectively. For a given centrality, ϵ_n changes very slowly, if at all, with beam energy. Therefore, Eq. 4 can be further simplified as;

$$\frac{v_n^{1/n}}{v_{n'}^{1/n'}} \propto \exp(-(n - n')\beta'). \quad (5)$$

or

$$\ln(v_n^{1/n}/v_{n'}^{1/n'}) = -(n - n')\beta' + \ln(c), \quad (6)$$

where c is a constant and $n \neq n'$. Since the dimensionless size $RT \propto (dN/d\eta)^{1/3}$ [22], Eq. 6 reduces to;

$$\beta'' = (dN/d\eta)^{1/3} \ln(v_n^{1/n}/v_{n'}^{1/n'}) = -a(n - n')\eta/s + (dN/d\eta)^{1/3} \ln(c). \quad (7)$$

where a is a constant and $n' = 2$. Note that the viscous coefficient β'' is linearly related to η/s .

Estimates for β'' were made as a function of $\sqrt{s_{\text{NN}}}$ to obtain constraints for its (T, μ_B) dependence, as well as to search for a possible non-monotonic pattern in its excitation function. Such a pattern could result from abrupt changes in the transport coefficients and relaxation rates due to anomalies in the expansion dynamics resulting from critical reaction dynamics [16, 17, 18].

The left panel of Fig. 3 shows the beam energy dependence of the p_T -integrated v_n for 0–40% central Au+Au collisions. It indicates an essentially monotonic trend for v_2, v_3 and v_4 with $\sqrt{s_{\text{NN}}}$ as might be expected for a temperature increase as $\sqrt{s_{\text{NN}}}$ increases. In contrast, the excitation function for $\beta'' \propto \eta/s$, shown in the right panel of Fig. 3, indicates a non-monotonic trend over the same beam energy range. A similar trend has been indicated in hydrodynamical calculations [23].

4. Conclusion

In summary, we have presented a comprehensive set of STAR v_n measurements for Au+Au collisions spanning the BES-I beam energy scan. The measurements indicate a rich set of dependencies on harmonic number n , p_T and centrality across the beam energies studied, which can provide strong model constraints for detailed extraction of the μ_B and T dependence of the specific shear viscosity. An excitation function for the viscous coefficient, obtained from ratios of v_n for different values of n , indicates a non-monotonic pattern which could be related to the onset of critical reaction dynamics in the BES-I energy range.

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