Beam energy and system dependence of rapidity-even dipolar flow

Niseem Magdy (For the STAR Collaboration) 1

1 Department of Chemistry, Stony Brook University, Stony Brook, NY, 11794-3400, USA

Abstract. New measurements of rapidity-even dipolar flow, $v^\text{even}_1$, 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 $v^\text{even}_1$ 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 $\eta/s$.

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

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

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

where $\Psi_n$ 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:

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

where $p_T^a$ and $p_T^b$ are the transverse momentum of particles (a) and (b), respectively, and $\delta_{NF}$ 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, $v_1$, 

*e-mail: niseemm@gmail.com

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (http://creativecommons.org/licenses/by/4.0/).
can be separated into an odd function of pseudorapidity ($\eta$) [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; $v_1(\eta) = v_{1,\text{even}}(\eta) + v_{1,\text{odd}}(\eta)$, where $v_{1,\text{odd}}$ and $v_{1,\text{even}}$ are uncorrelated. The magnitude of $v_{1,\text{even}}$ is related to the fluctuations-driven dipole asymmetry $\epsilon_1$ and $\eta/s$ [14, 17, 18].

2 Measurements

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

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

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 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:

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

and then used to extract $v_{1,\text{even}}$ via a simultaneous fit of $v_{1,1}$ as a function of $p_T$, for several selections of $p_T^b$ with Eq. 2:

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

Here, $C \propto 1/\langle(\text{Mult})(p_T^2)\rangle$ takes into account the non-flow correlations induced by a global momentum conservation [14, 15] and $\langle\text{Mult}\rangle$ 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 $v_{1,\text{even}}(p_T^b)$ 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 $p_T^b$ is increased.
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 \( (p_T) \) extracted for different centrality selections (0-10%, 10-20% and 20-30%) are shown in Fig. 2; the solid line in panel (a) shows 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 \( \epsilon_1 \).

The extracted values of \( v_1 \) even \( (p_T) \), for different collision systems are compared in Fig. 3 for different values of \( \langle Multi \rangle \). Figs. 3(a), 3(b) and 3(c) indicate similar \( v_1 \) even \( (p_T) \) magnitudes for the systems specified at each \( \langle Multi \rangle \), 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/c. This pattern confirms the predicted trends for rapidity-even dipolar flow \([13, 14, 17]\) and further indicates that for the selected values of \( \langle Multi \rangle \), \( v_1 \) 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 \( \langle Multi \rangle \) values suggests that the fluctuations-driven initial-state eccentricity...
is similar for the six collision systems. It also suggests that the viscous effects that are related to \( \eta/s \) 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, \( v_1^{\text{even}} \), in Au+Au collisions at different beam energies, and in U+U, Cu+Au, Cu+Cu, d+Au and p+Au collisions at \( \sqrt{s_{\text{NN}}} \approx 200 \text{ GeV} \). The measurements confirm the characteristic patterns of an evolution from negative \( v_1^{\text{even}}(p_T) \) for \( p_T > 1 \text{ GeV/c} \) to positive \( v_1^{\text{even}}(p_T) \) for \( p_T > 1 \text{ GeV/c} \), 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

This research is supported by the US Department of Energy under contract DE-FG02-87ER40331.A008.

References

[1] D. Teaney, Phys.Rev. C68, 034913 (2003), nucl-th/0301099
[2] R.A. Lacey, A. Taranenko, PoS CFRNC2006, 021 (2006), nucl-ex/0610029
[3] B. Schenke, S. Jeon, C. Gale, Phys.Lett. B702, 59 (2011), 1102.0575
[4] H. Song, S.A. Bass, U. Heinz, Phys.Rev. C83, 054912 (2011), 1103.2380
[5] H. Niemi, G. Denicol, P. Huovinen, E. Molnar, D. Rischke, Phys.Rev. C86, 014909 (2012), 1203.2452
[6] G.Y. Qin, H. Petersen, S.A. Bass, B. Muller, Phys.Rev. C82, 064903 (2010), 1009.1847
[7] N. Magdy (STAR), J. Phys. Conf. Ser. 779, 012060 (2017)
[8] B. Alver, G. Roland, Phys. Rev. C81, 054905 (2010), [Erratum: Phys. Rev.C82,039903(2010)], 1003.0194
[9] R.A. Lacey, D. Reynolds, A. Taranenko, N.N. Ajitanand, J.M. Alexander, F.H. Liu, Y. Gu, A. Mwai, J. Phys. G43, 10LT01 (2016), 1311.1728
[10] A.M. Poskanzer, S.A. Voloshin, Phys. Rev. C58, 1671 (1998), nucl-ex/9805001
[11] R.A. Lacey, Nucl. Phys. A774, 199 (2006), nucl-ex/0510029
[12] N. Borghini, P.M. Dinh, J.Y. Ollitrault, Phys. Rev. C62, 034902 (2000), nucl-th/0004026
[13] M. Luzum, J.Y. Ollitrault, Phys. Rev. Lett. 106, 102301 (2011), 1011.6361
[14] E. Retinskaya, M. Luzum, J.Y. Ollitrault, Phys. Rev. Lett. 106, 102302 (2012), 1203.0931
[15] G. Aad et al. (ATLAS), Phys. Rev. C86, 014907 (2012), 1203.3087
[16] P. Danielewicz, R. Lacey, W.G. Lynch, Science 298, 1592 (2002), nucl-th/0208016
[17] D. Teaney, L. Yan, Phys. Rev. C83, 064904 (2011), 1010.1876
[18] F.G. Gardim, F. Grassi, Y. Hama, M. Luzum, J.Y. Ollitrault, Phys. Rev. C83, 064901 (2011), 1103.4605
[19] J. Jia, S.K. Radhakrishnan, S. Mohapatra, J. Phys. G40, 105108 (2013), 1203.3410