Azimuthal harmonics in small and large collision systems at RHIC top energies

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arXiv:1901.08155v1 [nucl-ex] 23 Jan 2019
The first ($v_1^{\text{even}}$), second ($v_2$) and third ($v_3$) harmonic coefficients of the azimuthal particle distribution at mid-rapidity, are extracted for charged hadrons and studied as a function of transverse momentum ($p_T$) and mean charged particle multiplicity density $\langle N_{\text{ch}} \rangle$ in $U+U$, $Au+Au$, $Cu+Au$, $Cu+Cu$, $d+Au$ and $p+Au$ collisions at $\sqrt{s_{NN}}=193$ GeV, $\sqrt{s_{NN}}=200$ GeV with the STAR Detector. For the same $\langle N_{\text{ch}} \rangle$, the $v_1^{\text{even}}$, $v_2$ and $v_3$ coefficients are observed to be independent of collision system,
while \( v_2 \) exhibits such a scaling only when normalized by the initial-state eccentricity \((e)\). The data also show that \(\ln(v_2/e)\) scales linearly with \(N_{ch}^{-1/3}\). These measurements provide insight into initial-geometry fluctuations and the role of viscous hydrodynamic attenuation on \(v_n\) from small to large collision systems.

PACS numbers: 25.75.-q, 25.75.Gz, 25.75.Ld

An important goal of the experimental program at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), is to provide qualitative experimental data which can (i) give insight on the dynamical evolution of the quark-gluon plasma (QGP) created in heavy ion collisions, and (ii) serve as important constraints for the extraction of the associated transport coefficients. The azimuthal anisotropy of particle emission in the transverse plane, known as anisotropic flow, is a key observable because it reflects the viscous hydrodynamic response to the initial spatial distribution in energy density (both from intrinsic geometry and fluctuations), produced in the early stages of the collision \([1–15]\).

Experimentally, anisotropic flow manifests as an azimuthal asymmetry of the measured single-particle distribution, quantified by the complex flow coefficients \([9, 13, 16]\):

\[
V_n \equiv v_n e^{i n \Psi_n} = \{e^{i n \phi}\}_j,
\]

where \(\phi\) denotes the azimuthal angle around the beam direction, of a particle emitted in the collision and \(\{\}_j\) denotes the average over all particles emitted in the event. The weighted average \(\langle |V_n|^2 \rangle^{1/2} = v_n\) (which accounts for multiplicity variations) and \(\Psi_n\) denote the magnitude and azimuthal direction of the \(n\)th-order harmonic flow vector that fluctuates from event to event. The first three coefficients, \(v_1\), \(v_2\), and \(v_3\), are termed directed, elliptic, and triangular flow, respectively. The fluctuations-driven component of \(v_1\), termed \(v_1^{\text{even}}\), is proportional to the dipole asymmetry of the collision system \([17, 18]\).

The \(v_n\) coefficients are also related to the Fourier coefficients \(v_{nn}\), which characterize the amplitude of the two-particle correlations in relative azimuthal angle \(\Delta \phi = \phi_a - \phi_b\) \([19, 20]\) for the particles a and b, which comprise the pairs:

\[
\frac{dN_{\text{pairs}}}{d\Delta \phi} \propto 1 + 2 \sum_{n=1}^{\infty} v_{nn} \cos(n \Delta \phi),
\]

\[
v_{nn}(p_T^a, p_T^b) = v_n(p_T^e) v_n(p_T^e) + \delta_{NF},
\]

where \(\delta_{NF}\) signify the contributions of short-range non-flow correlations due to resonance decays, Bose-Einstein correlations and jet-like decays, as well as long-range contributions, which result from global momentum conservation \([18, 20–22]\).

The initial anisotropic density profile \(\rho_c(r, \phi)\) in the transverse (\(\perp\)) plane, which drives anisotropic flow, can be similarly characterized by complex eccentricity coefficients \([17, 23–26]\):

\[
\varepsilon_n \equiv \varepsilon_n e^{i n \Phi_n} = -\int \frac{d^2 r_1}{d^2 r_2} e^{i n \varphi} \rho_c(r_1, \varphi) - \frac{\varphi}{d\varphi} \rho_c(r_2, \varphi),
\]

where \(\Phi_n\) is the angle of the so-called \(n\)th-order participant plane; \(m = n\) for \(n \geq 2\) and \(m = 3\) for \(n = 1\) \([17]\). Theoretical investigations show that \(v_n \propto \varepsilon_n\) for elliptic and triangular flow \((n = 2, 3)\) \([26–29]\), and the temperature \((T)\) dependent specific shear viscosity \(\eta/s(T)\), of the created medium, reduces the ratio \(v_n/\varepsilon_n\). Thus, the comparison of viscous hydrodynamical model calculations to this ratio is commonly employed to estimate \(\eta/s(T)\) and its average \((\langle \eta/s(T) \rangle)\), over the system’s evolution \([5, 8, 10, 12, 14, 26, 30–34]\). The viscous attenuation of \(v_n/\varepsilon_n\) can also be understood within an acoustic model framework, akin to that for viscous relativistic hydrodynamics \([35–41]\):

\[
\ln(v_n/\varepsilon_n) \propto -n^2 \langle \eta/s(T) \rangle \langle N_{ch} \rangle^{-1/3},
\]

where \(\langle N_{ch} \rangle\) is the charged particle multiplicity density and \((N_{ch})^{-1/3}\) is a proxy for the dimensionless size of the system \([35, 36, 42]\).

Recent measurements at both RHIC and the Large Hadron Collider (LHC), have indicated sizable \(v_2\) and \(v_3\) values in high multiplicity \(p + p\) \([43, 44]\), \(d + \text{Au}\) \([45, 46]\) and \(p + \text{Pb}\) collisions \([47–49]\), reminiscent of those observed in peripheral \(A + A\) collisions. These measurements have generated considerable debate on whether the final-state collective effects, which dominate the mechanism for anisotropic flow in \(A + A\) collisions, also drive the anisotropy measured in high-multiplicity \(p + p\) and \(p + \text{A}\) \((d + \text{A})\) collisions \([50–52]\). The related question of whether the properties of the medium produced in the small \(p + p\), \(p + A\) and \(d + A\) systems are similar to those produced in the larger \(A + A\) systems is also not fully settled.

In this letter we present and compare a comprehensive set of \(v_1^{\text{even}}\), \(v_2\) and \(v_3\) measurements for \(U + U\) \((\sqrt{s_{NN}} = 193 \text{ GeV})\), \(A u + A u\), \(C u + C u\), \(C u + A u\), \(d + A u\), and \(p + A u\) collisions at \(\sqrt{s_{NN}} = 200 \text{ GeV}\), that should prove invaluable for the interpretation of collectivity in small systems, and in ongoing efforts to constrain theoretical models and obtain a robust extraction of \(\eta/s(T)\).

The data for the six colliding systems presented in this work, were collected with the STAR detector at RHIC using a minimum-bias trigger. Charged-particle tracks, measured in the full azimuth and pseudorapidity range \(|\eta| < 1.0\) of the Time Projection Chamber (TPC) \([53]\).
were used to reconstruct the collision vertices. Events were selected with vertex positions ±30 cm from the nominal center of the TPC (in the beam direction). Collision centrality and the associated \( \langle N_{ch} \rangle \) was determined from the measured event-by-event multiplicity with the aid of a tuned Monte Carlo Glauber calculation [54]. Analyzed tracks were required to have a distance of closest approach to the primary vertex of less than 3 cm, and have at least 15 TPC space points used in their reconstruction. To remove split tracks, the ratio of the number of fit points to a maximum possible number of TPC space points was required to be larger than 0.52. Analyzed tracks were restricted to \( 0.2 < p_T < 4 \) GeV/c.

Two-particle \( \Delta \phi \) correlation functions \( (C_\ell) \) were generated to extract the flow coefficients:

\[
C_\ell(\Delta \phi, \Delta \eta) = \frac{(dN/d\Delta \phi)_{\text{same}}}{(dN/d\Delta \phi)_{\text{mixed}}},
\]

where \((dN/d\Delta \phi)_{\text{same}}\) represents the distribution of track pairs, in relative azimuthal angle \( \Delta \phi \), taken from the same event. \((dN/d\Delta \phi)_{\text{mixed}}\) represents the \( \Delta \phi \) distribution for track pairs in which each member is selected from different events in the same \( \langle N_{ch} \rangle \) and vertex position classes. The pseudorapidity requirement \( |\Delta \eta| > 0.7 \) was imposed for all track pairs to suppress short-range non-flow contributions [55]. A further check for the dominance of flow correlations was obtained by measuring the second-order four-particle cumulant \( c_2\{4\} \):

\[
c_2\{4\} = \langle \langle 4 \rangle \rangle - 2 \langle (2) \rangle^2,
\]

where \( \langle \langle \rangle \rangle \) represents the averaging first over particles in an event and then over all events within a given event class. The three sub-events method [56] was used for these evaluations with sub-events for \( \eta_1 < -0.35, |\eta_2| < 0.35 \) and \( \eta_3 > 0.35 \).

Figures 1(a-e) show the correlation functions obtained for U+U, Au+Au, Cu+Au, Cu+Cu, d+Au and p+Au collisions for \( \langle N_{ch} \rangle = 21 \pm 3 \). They indicate patently similar correlation patterns with a visible enhancement of near-side (\( \Delta \phi \sim 0 \)) pairs, reminiscent of the so-called “ridge” observed in high multiplicity \( p+p \) [43, 44], \( d+Au \) [45, 46] and \( p+Pb \) collisions [47, 49]. The corresponding values for \( c_2\{4\} \) vs. \( \langle N_{ch} \rangle \), shown in Fig. 1 (g), indicate negative values which suggests the absence of significant short-range non-flow contributions, and the dominance of flow correlations to \( C_\ell \) [57, 58]. Note that the paucity of central \( p+Au \) events precluded the extraction of \( c_2\{4\} \) from these events.

Similar sets of correlation functions were generated as a function of \( p_T \) and \( \langle N_{ch} \rangle \) to allow a study of \( v_1^{\text{even}}, v_2 \) and \( v_3 \) (for each collision system) for different dimensionless sizes and eccentricities. Monte Carlo quark Glauber (MC-qGlauber) calculations [35] were used to compute \( \varepsilon_n \) as a function of collision centrality or \( \langle N_{ch} \rangle \) for all collision systems, from the two-dimensional profile of the density of quark participants in the transverse plane (c.f Eq. 3). The model takes account of the finite size of the nucleon, the winding profile of the nucleon, the distribution of quarks inside the nucleon, and quark cross sections which reproduce the NN inelastic cross section at \( \sqrt{s_{NN}} = 200 \) GeV.

The \( v_{nn} \) coefficients were obtained from the correlation function as:

\[
v_{nn} = \frac{\sum_{\Delta \phi} C_\ell(\Delta \phi, \Delta \eta) \cos(n \Delta \phi)}{\sum_{\Delta \phi} C_\ell(\Delta \phi, \Delta \eta)},
\]

and then used to extract \( v_n \) for \( n > 1 \),

\[
v_{nn}(p_T^a, p_T^b) = v_{11}\langle p_T^a \rangle v_{11}\langle p_T^b \rangle,\]

and the \( v_1^{\text{even}} \) component of \( v_{11} \),

\[
v_{11}(p_T^a, p_T^b) = v_1^{\text{even}}\langle p_T^a \rangle v_1^{\text{even}}\langle p_T^b \rangle - K p_T^a p_T^b,
\]

where \( K \propto 1/\langle (N_{ch})\langle p_T^2 \rangle \rangle \) takes account of the long-range non-flow correlations induced by global momentum conservation [21, 22, 55]. A simultaneous fit of \( v_{11}(p_T^b) \) for several selections of \( p_T^a \) (c.f. Eq. 9) was used to facilitate the extraction of \( v_1^{\text{even}} \) [55].
The systematic uncertainties associated with the $v_n$ extractions were estimated through studies of the influence of the choice of the cuts for z-vertex position, track selection, efficiency correction, $\Delta \eta$ and the fitting procedure. The uncertainty associated with $\Delta v_p$ differs from those for $\langle T \rangle$ values shown in Figs. 1(c), (f) for each system. That is, they show data collapse onto a single curve for $v_2/\varepsilon_2$ vs. $p_T$ for U+U, Au+Au, Cu+Au and Cu+Cu systems. Fig. 2(l) also indicates an approximate collapse of the scaled results for $p+Au$ and $d+Au$ onto the curve for the eccentricity-scaled A+A data. This pattern is suggestive of a dominant collective flow contribution to the measured anisotropy in high multiplicity $p+A(d+A)$ collisions [36]. However, a quantitative estimate of a possible long-range non-flow contribution is required to fully establish the degree of this apparent scaling.

The $(N_{ch})$ dependence of $v_1^{even}$, $v_2$ and $v_3$ are compared for all six collision systems in Figs. 3(a) - 3(c); they are in good agreement with the $v_2$ data reported for U+U and Au+Au collisions in Ref. [59]. The inset in Fig. 3(a) compares the associated values of $K$ vs. $(N_{ch})^{-1}$ (c.f. Eq. 9) for each system.

For $(N_{ch}) \gtrsim 170$, the $v_n$ values all show a decrease with increasing values of $(N_{ch})$, consistent with the expected decrease of $\varepsilon_n$ as collisions become more central. The apparent decrease in the values of $v_2$ for $(N_{ch}) \lesssim 170$ corroborates the dominant role of size-driven viscous attenuation of the flow harmonics for these multiplicities. Note that $\varepsilon_2$ increases for $(N_{ch})<170$. Figures 3(a) and 3(b) indicate system-independent magnitudes and trends for $v_1^{even}$ and $v_3$ analogous to the $p_T$-dependent results shown in Fig. 2.

The $v_2$ comparisons shown in Fig. 3(c), accentuate the system-dependent patterns observed in Figs. 2(g), 2(h)
and 2(i). Here, the sizable uncertainties for the p+Au and d+Au data points for \(<N_{ch}>=21\) reflect the systematic uncertainty estimates for residual non-flow contributions which are smaller for these \(p_T\)-integrated measurements. The striking system-dependent patterns shown in Fig. 3(c) can be attributed to the strong dependence of \(\varepsilon_2\) on system size for a fixed value of \(<N_{ch}\>). This shape dependence, which weakens for low \(<N_{ch}\)>, is confirmed via the plot of \(v_2/\varepsilon_2 vs. \langle N_{ch}\rangle^{-1/3}\) shown in Fig. 4. A similar plot, reflecting the \(n^2\) dependence of viscous attenuation \([35, 36]\), was obtained for \(v_3/\varepsilon_3 vs. \langle N_{ch}\rangle^{-1/3}\). The inset in Fig. 4 indicates a marked similarity between the slopes of the eccentricity-scaled \(v_2\) for U+U, Au+Au, Cu+Cu, and Cu+Cu collisions. The eccentricity-scaled results for d+Au and p+Au also follow the data trend for these heavier collision species with larger systematic uncertainty. Hydrodynamic simulations for Au+Au collisions \([60]\) exhibit similar scaling trends within the same range of \(<N_{ch}\>\).

In summary, we have used the two-particle correlation method to carry out a comprehensive set of measurements of \(v_1^{\text{even}}, v_2, \) and \(v_3\) as a function of \(p_T\) and \(<N_{ch}\>\) in U+U (\(\sqrt{s_{NN}}=193\text{ GeV}\)) and Au+Au, Cu+Au, Cu+Cu, d+Au, and p+Au collisions at \(\sqrt{s_{NN}}=200\text{ GeV}\). The detailed comparisons of the measurements highlight the sensitivity of \(v_n\) to the magnitude of the initial-state eccentricity, system size and the final-state interactions in the expanding matter. The wealth of the A+A measurements lead to data collapse of \(\ln(v_n/\varepsilon_n) vs. \langle N_{ch}\rangle^{-1/3}\) onto a single curve. Similarly scaled results for d+Au and p+Au (for \(<N_{ch}\) ~ 21) are also observed with larger uncertainty. The combined measurements and their scaling properties provide a new set of constraints which could prove invaluable for the interpretation of collectivity in small systems and for detailed theoretical extraction of the temperature-dependent \(\varepsilon\).

ACKNOWLEDGMENTS

We thank the RHIC Operations Group and RCF at BNL, the NERSC Center at LBNL, and the Open Science Grid consortium for providing resources and support. This work was supported in part by the Office of Nuclear Physics within the U.S. DOE Office of Science, the U.S. National Science Foundation, the Ministry of Education and Science of the Russian Federation, National Natural Science Foundation of China, Chinese Academy of Science, the Ministry of Science and Technology of China and the Chinese Ministry of Education, the National Research Foundation of Korea, GA and MSMT of the Czech Republic, Department of Atomic Energy and Department of Science and Technology of the Government of India; the National Science Centre of Poland, National Research Foundation, the Ministry of Science, Education and Sports of the Republic of Croatia, RosAtom of Russia and German Bundesministerium fur Bildung, Wissenschaft, Forschung and Technologie (BMBF) and the Helmholtz Association.

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