Measurements of Elliptic and Triangular Flow in High-Multiplicity ^{3}He + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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We present the first measurement of elliptic (v_2) and triangular (v_3) flow in high-multiplicity $^3\mathrm{He}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}}=200$ GeV. Two-particle correlations, where the particles have a large separation in pseudorapidity, are compared in $^3\mathrm{He}+\mathrm{Au}$ and in $p+p$ collisions and indicate that collective effects dominate the second and third Fourier components for the correlations observed in the $^3\mathrm{He}+\mathrm{Au}$ system. The collective behavior is quantified in terms of elliptic v_2 and triangular v_3 anisotropy coefficients measured with respect to their corresponding event planes. The v_2 values are comparable to those previously measured in $d+\mathrm{Au}$ collisions at the same nucleon-nucleon center-of-mass energy. Comparisons with various theoretical predictions are made, including to models where the hot spots created by the impact of the three ^{3}He nucleons on the Au nucleus expand hydrodynamically to generate the triangular flow. The agreement of these models with data may indicate the formation of low-viscosity quark-gluon plasma even in these small collision systems.

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The study of high-energy heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider has produced abundant evidence for the formation of quark-gluon plasma (QGP). Observation of strong elliptic and triangular flow in these $A+A$ collisions indicates that the QGP has a very small viscosity and behaves like a nearly perfect fluid [1–3]. Recently, measurements at the Large Hadron Collider in very high multiplicity events from collisions of $p+p$ and $p+\mathrm{Pb}$ have revealed similar particle emission patterns [4–8]. Such features have also been detected in $d+\mathrm{Au}$ collisions at RHIC [9–11]. Explanations of the data in terms of the formation of small droplets of QGP, which then expand hydrodynamically [12], compete with alternatives involving novel initial-state effects (e.g., glasma models [13]). RHIC is uniquely suited to test these competing theories by its ability to engineer the size and shape of the initial reaction zone through collisions of $p+\mathrm{Au}$, $d+\mathrm{Au}$, and $^3\mathrm{He}+\mathrm{Au}$, as proposed in Ref. [14]. In the case when small QGP droplets are formed, the latter two systems should have the strongest elliptic and triangular flow patterns, respectively.

The azimuthal anisotropy of produced particles can be quantified by the Fourier coefficients v_n in the expansion of the particles' distribution as $dN/d\phi \propto 1+\sum_{n=1} 2v_n \cos(n(\phi-\Psi_n))$ [15], where n is the order of the harmonic, ϕ is the azimuthal angle of particles of a given type, and Ψ_n is the azimuthal angle of the nth-order event plane. In this Letter, the elliptic (v_2) and triangular (v_3) flow for inclusive charged hadrons produced at midrapidity $|\eta|<0.35$ in high-multiplicity $^3\mathrm{He}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}}=200$ GeV are measured in the PHENIX experiment with respect to Ψ_2 and Ψ_3 event planes. The signatures of collective motion beyond known nonflow correlation effects (e.g., jets, resonances, etc.) are also examined by comparing long-range correlations between $^3\mathrm{He}+\mathrm{Au}$ and $p+p$ collisions.

A full description of the PHENIX experimental setup is given in Ref. [16]. Charged particles are reconstructed in the two PHENIX central-arm tracking systems comprising drift chambers (DC) and multiwire proportional pad chambers (PC) [17]. Each arm covers $\pi/2$ in azimuth and $|\eta|<0.35$. The DC tracks are matched to hits in the outermost PC layer (PC3), reducing the contribution of tracks originating from decays and photon conversions.

The observed event-plane angles Ψ_n^{Obs} are measured in different pseudorapidity ranges by the beam-beam counters [18] (BBC) and forward-silicon-vertex [19] (FVTX) detectors. The PHENIX experiment has two BBCs, each comprising 64 quartz Čerenkov radiators read out by photomultiplier tubes (PMTs), subtending pseudorapidity ($3.0<|\eta|<3.9$). The FVTX [19] detector comprises two identical end cap assemblies, located symmetrically in the north and south directions. Charged particles can be detected with a high efficiency (>95%) using a cluster of ministrip hits. The event planes are measured by the BBC in the Au-going (south) direction (BBC-S), which covers $-3.9<\eta<-3.0$, and by the reconstructed clusters in the FVTX in the Au-going (south) end cap (FVTX-S), which covers $-3.0<\eta<-1.0$.

The $^3\mathrm{He}+\mathrm{Au}$ data for this analysis were obtained in the 2014 run of the PHENIX experiment and include 1.6 billion minimum-bias (MB) triggered events and 480 million high-multiplicity (HM) triggered events. The MB trigger is defined as a coincidence between the north and south BBCs requiring one or more photomultiplier tubes firing in each,

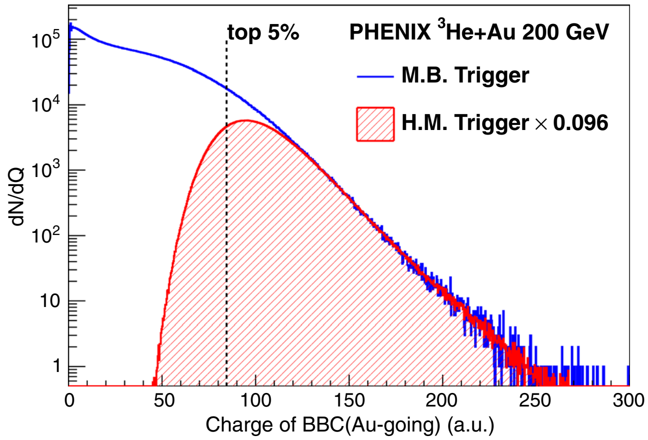

FIG. 1 (color online). The BBC-S charge distribution in minimum bias ^{3}He + Au events and in high-multiplicity triggered events, scaled appropriately. The dashed line indicates the threshold selecting the 0%–5% most central events.

capturing 88 ± 4% of the total inelastic ^{3}He + Au cross section. The HM trigger is based on the MB trigger, but additionally requires more than 48 photomultiplier tubes firing in the BBC-S.

The event centrality class in ^{3}He + Au collisions is determined as a percentile of the total charge $\sum Q^{\text{BBC-S}}$ measured in the BBC-S [18,20–22]. The distribution of BBC-S PMT charge sum is shown in Fig. 1 for both MB and HM triggered events. The distribution for HM events has been scaled down by the relative online trigger prescale factor. For the MB sample, a threshold on the BBC-S charge sum shown in Fig. 1 is applied to select the top 5% central ^{3}He + Au collisions. In total, 400 million events have been used for the measurement of v_2 and v_3 including both HM and MB triggered events having BBC-S charge sum above the threshold.

Events with high BBC-S sum charge have been simulated with a Monte Carlo Glauber model [23,24], following the procedure detailed in Ref. [18]. The average number of binary collisions (N_{coll}), participants (N_{part}), and initial-state eccentricities (ε_2, ε_3) were found to be consistent, within uncertainties, between the MB with the 0%–5% central selection and the HM events being used here. Note that in this Glauber calculation, the spatial distribution from each participant is smeared with a two-dimensional Gaussian, $\sigma_r = 0.4$ fm [18]. The simulation results for central ^{3}He + Au and d + Au are listed in Table I with the d + Au values from Ref. [18].

TABLE I. Monte Carlo Glauber characterization results.

System	N_{part}	N_{coll}	ε_2	ε_3
0%–5% ^{3}He+Au	25.0±1.6	26.1±2.0	0.50±0.02	0.28±0.02
0%–5% d + Au	17.3±1.2	18.1±1.2	0.54±0.04	0.19±0.01

To estimate the contribution to the flow measurements from elementary processes, such as jets and resonance decay, we first examine azimuthal correlations in minimum bias $p + p$ and central ^{3}He + Au events across a long range in pseudorapidity, with $|\Delta\eta| \sim 3.5$ between tracks in the PHENIX central arm at a given p_T and charge measured in the BBC PMTs. We use the BBCs for these correlation functions because the detector configuration and performance is uniform over many years, which enables us to combine data for $p + p$ collisions at $\sqrt{s} = 200$ GeV from running in 2005, 2006, 2008, and 2009. This results in 2.7 billion total minimum bias $p + p$ events.

Using track-BBC pairs, we construct the distribution over relative azimuth, and from that the normalized correlation function:

$$S(\Delta\phi, p_T) = \frac{d(w_{\text{PMT}} N^{\text{track}(p_T)\text{-PMT}}_{\text{Same event}})}{d\Delta\phi}, \quad (1)$$

$$C(\Delta\phi, p_T) = \frac{S(\Delta\phi, p_T)}{M(\Delta\phi, p_T)} \frac{\int_0^{2\pi} M(\Delta\phi, p_T) d\Delta\phi}{\int_0^{2\pi} S(\Delta\phi, p_T) d\Delta\phi}. \quad (2)$$

The weighting w_{PMT} for each pair is taken as the PMT charge. The signal distribution S is over pairs in the same event; the mixed distribution M is over pairs from different events in the same event centrality and z vertex bin, and serves to correct for any nonuniformity in acceptance over $\Delta\phi$.

Figure 2 shows the correlation functions $C(\Delta\phi, p_T)$ for different p_T bins, for HM ^{3}He + Au collisions using BBC-S, as shown in panels (a)–(c), and minimum-bias $p + p$ collisions using both BBCs, as shown in panels (d)–(f). We analyze these shapes by fitting each $C(\Delta\phi, p_T)$ to a four-term Fourier cosine expansion, $f(\Delta\phi) = 1 + \sum_{n=1}^{4} 2c_n(p_T)\cos(n\Delta\phi)$. The sum function and each individual cosine component are plotted in Fig. 2 for each distribution. Central ^{3}He + Au collisions show a clearly visible enhancement of near-side pairs, producing a local maximum in the distribution at $\Delta\phi \sim 0$. In contrast, $p + p$ collisions can be described almost completely by the dipole term $\cos(\Delta\phi)$, as expected generically from back-to-back jets and transverse momentum conservation.

As in our d + Au analysis [10], we estimate quantitatively the correlation strength that would be observed in a class of ^{3}He + Au collisions purely from elementary processes, such as in $p + p$ collisions. Approximating the ^{3}He + Au collisions as superpositions of some number N of $p + p$ collisions, we would then expect the correlation strengths c_n from the superposition to be the same as in $p + p$, but diluted by a factor of $1/N$. We then approximate this dilution factor as simply the ratio of total charge observed in the BBC-S detector in $p + p$ versus ^{3}He + Au:

$$c_n^{\text{HeAu elementary}}(p_T) \simeq c_n^{p+p}(p_T) \frac{(\sum Q^{\text{BBC-S}})_{p+p}}{(\sum Q^{\text{BBC-S}})_{\text{HeAu}}} \quad (3)$$

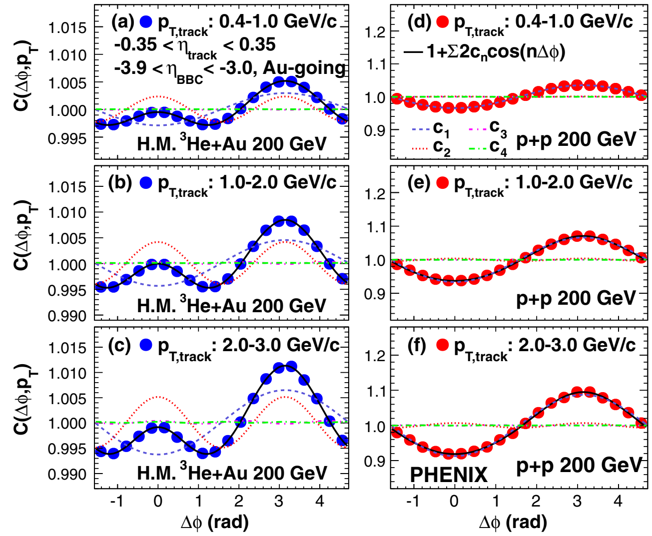

FIG. 2 (color online). The azimuthal correlation functions $C(\Delta\phi, p_T)$, as defined in Eq. (2), for track-BBC pairs with different track p_T selections in (a)–(c) HM ^{3}He + Au collisions and (d)–(f) minimum bias $p+p$ collisions both at $\sqrt{s_{NN}} = 200$ GeV. The track p_T bins are (a),(d) 0.4–1.0, (b),(e) 1.0–2.0, and (c),(f) 2.0–3.0 GeV/c. Each correlation function is fit with a four-term Fourier cosine expansion; the individual components $n = 1$ to $n = 4$ are drawn on each panel, together with the fit function sum.

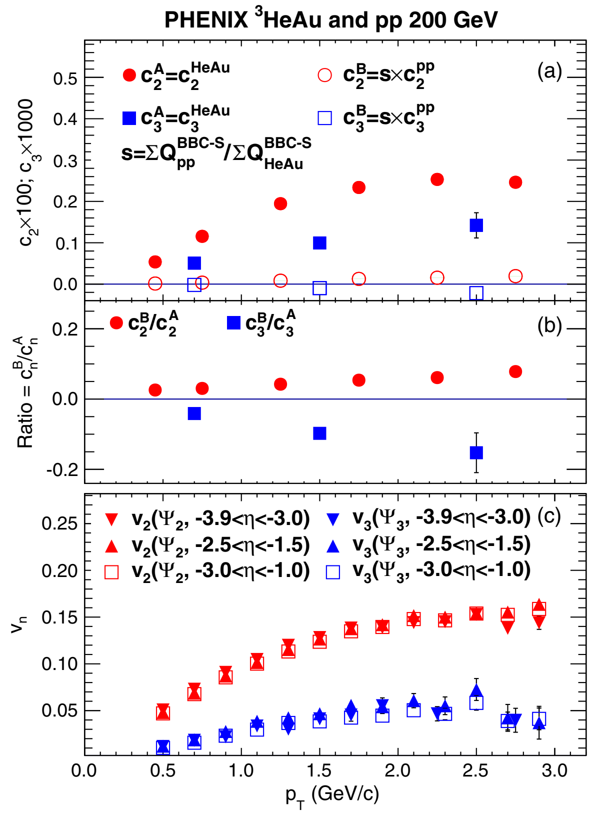

FIG. 3 (color online). (a) The $c_n(p_T)$ coefficients for track-BBC pairs from high multiplicity ^{3}He + Au collisions (filled, denoted "c^A") and $c_n(p_T)$ for pairs in minimum bias $p+p$ collisions times the dilution factor $(\sum Q^{\text{BBC-S}})_{p+p}/(\sum Q^{\text{BBC-S}})_{\text{HeAu}}$ (open, denoted "c^B"). (b) The ratio c^B/c^A is shown with statistical error bars. (c) Comparison of extracted values of v_2 and v_3 for midrapidity tracks in central ^{3}He + Au using event plane measurements with detectors in different pseudorapidity intervals (see text).

with a numerical value of $1/(20.6 \pm 0.4)$. Figure 3(a) shows the c_n's from the ^{3}He + Au correlation functions and from the $p+p$ with the dilution factor applied. The c_2^{pp} is found to be positive and the c_3^{pp} to be negative. This indicates that the correlation of elementary processes contributes positively to the v_2 but negatively to the v_3. The ratios in Fig. 3(b) show that the relative correlation strength in ^{3}He + Au from elementary processes grows with p_T, as might be expected from jet processes, for example, but does not exceed 7% (15%) for c_2 (c_3).

We now quantify the strength of collective behavior through the v_n coefficients. The v_n coefficients for charged hadrons at midrapidity are measured in central ^{3}He + Au events via the event-plane method [25] as $v_n(p_T) = \langle \cos n(\phi^{\text{Particle}}(p_T) - \Psi_n^{\text{Obs}}) \rangle / \text{Res}(\Psi_n^{\text{Obs}})$, where the average is over particles in the same p_T bin and events of the same centrality. The nth-order event-plane direction Ψ_n^{Obs} is determined in each event with the BBC-S or FVTX-S detectors. The Ψ_n^{Obs} are corrected for each detector with a standard event-plane flattening technique [25–28] to remove the effect of any small, residual nonuniformities in the detector response. As a cross-check, we use event planes from both the full FVTX-S covering $-3.0 < \eta < -1.0$ and a subsection covering $-2.5 < \eta < -1.5$. The choice of the latter is to avoid edge effects and still retain good FVTX-S acceptance.

We calculate the resolutions $\text{Res}(\Psi_n^{\text{Obs}})$ for each detector at each n using the standard three-event-plane method [10,25], combining two event planes with the nth order event plane determined from central-arm tracks, restricted to low p_T ($0.2 < p_T < 2.0$ GeV/c) to minimize contribution from jet fragments. In the case of the $n = 2$ event plane, the resolution is also estimated using the first-order event plane measured with spectator neutrons in the shower-maximum detector of the zero-degree calorimeter [28,29] on the Au-going side ($\eta < -6.5$). The values for the resolution obtained in both methods are found to be consistent within uncertainties.

The event plane resolutions for each detector and order are shown in Table II. The v_2 and v_3 measured using the

TABLE II. The resolution of nth-order event-plane angles measured by the BBC-S and FVTX-S detectors.

Subsystem	$\text{Res}(\Psi_2^{\text{Obs}})$	$\text{Res}(\Psi_3^{\text{Obs}})$
BBC-S ($-3.9 < \eta < -3.0$)	0.110	0.034
FVTX-S ($-2.5 < \eta < -1.5$)	0.232	0.052
FVTX-S ($-3.0 < \eta < -1.0$)	0.274	0.070

three event planes described above are shown in Fig. 3(c), and are consistent between detectors to within 5%(15%) for $v_2(v_3)$ over the whole p_T range.

The main sources of systematic uncertainty for the v_n measurements are (1) track backgrounds from weak decays and photon conversions, (2) multiple $^3\mathrm{He}+\mathrm{Au}$ collisions in a bunch crossing (pileup), (3) biases in event plane determination, (4) the effect of detector alignment and performance on the v_n measurement, and (5) elementary process or nonflow correlations; we assign the following values to account for these systematic uncertainties. (1) We estimate the track background contribution by reducing the spatial matching windows in PC3 from 3σ to 2σ and find a change of less than 2%(5%) fractionally in $v_2(v_3)$. (2) We expect the v_n from pileup events to be modestly reduced. Conservatively assuming that pileup events that contaminate the sample at the level of 4%–5% have a negligible v_n, this results in a $^{+0}_{-5}$% systematic uncertainty. (3) Event plane effects are estimated from v_n measurements using different event plane detectors as shown in Fig. 3(c). They are no more than 5%(15%) for $v_2(v_3)$. (4) The difference of v_n for charged hadrons measured by the east and west DC arms are found to be less than 2%(15%) for $v_2(v_3)$. (5) The contribution from nonflow correlations at each p_T is estimated from Fig. 3(b), reaching a maximum of 7% (15%) for $v_2(v_3)$. We do not attempt to correct for this contribution and instead treat it as a systematic uncertainty. All of these contributions are summed in quadrature.

The final v_n results are determined using the event plane measured in the FVTX-S covering $-3.0 < \eta < -1.0$, and these are shown in Fig. 4, with the systematic uncertainties as described above. We observe sizable v_2 and v_3 anisotropies that both rise as a function of p_T. It is notable that the $v_2(p_T)$ values for central $^3\mathrm{He}+\mathrm{Au}$ collisions are very similar within uncertainties with those reported earlier in central $d+\mathrm{Au}$ collisions [10]. In scenarios where these anisotropies reflect the initial geometry, this similarity would be expected as the initial eccentricities ε_2 for central $d+\mathrm{Au}$ and $^3\mathrm{He}+\mathrm{Au}$ are essentially identical, as shown in Table I. The same calculations indicate a much larger ε_3 in $^3\mathrm{He}+\mathrm{Au}$ compared with $d+\mathrm{Au}$ collisions. However, the $d+\mathrm{Au}$ data used in [10] were taken in 2008, without a central trigger and before the FVTX was installed, and did not allow extraction of a statistically significant v_3 in $d+\mathrm{Au}$.

We now compare the experimental data with theory predictions in the literature. Four such predictions shown in Fig. 4 employ viscous hydrodynamics with η/s at or near the conjectured lower bound $1/4\pi$ [30]. The Glauber + Hydro [31] (IP-Glasma + Hydro [32]) utilize Glauber (IP-Glasma) initial conditions, and both overpredict the magnitude of the v_2 and v_3 data. Improved agreement may be achieved by utilizing a larger value of η/s or by the inclusion of a transition from QGP to a hadronic cascade, which has much larger viscous effects and thus decreases the overall flow. The SONIC calculation [14] employs Glauber initial conditions, viscous hydrodynamics, and then at $T = 170$ MeV, a transition to a hadronic cascade. The SUPERSONIC calculation [33] additionally includes preequilibrium dynamics that boosts the initial velocity fields at the earliest times. The impact of preequilibrium is modest on the v_2 values and both calculations agree with the data within uncertainties. The effect of preequilibrium on v_3 is significantly larger as the triangular flow takes longer to develop [14]. The SUPERSONIC prediction agrees well with the experimental data for $p_T < 1.5$ GeV/c, and then the data trend towards the SONIC prediction at higher p_T.

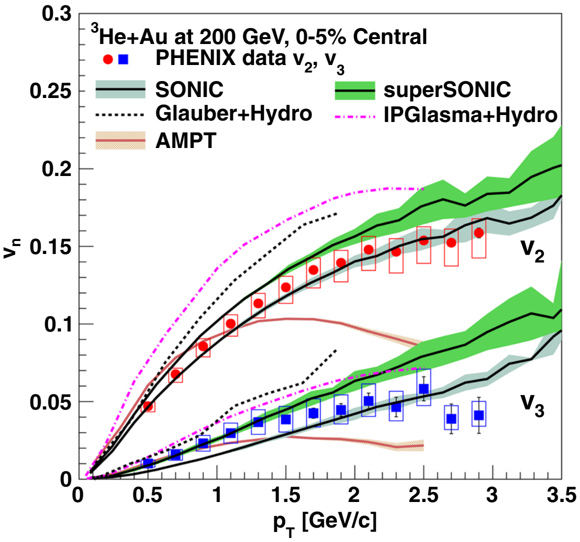

FIG. 4 (color online). Results for v_2 (circles) and v_3 (squares) as a function of p_T for inclusive charged hadrons at midrapidity in 0%–5% central $^3\mathrm{He}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV; error bars are statistical and shaded bars are systematic uncertainties as described in the text. Also shown are various theoretical calculations, see text for details and references.

Lastly, we compare to calculations utilizing the a-multiphase-transport (AMPT) model [34], which incorporates both partonic and hadronic scattering, and has recently been compared with anisotropies in central $p+\mathrm{Pb}$ and $d+\mathrm{Au}$ collisions [35,36]. AMPT results for $^3\mathrm{He}+\mathrm{Au}$ agree reasonably with the experimental v_2 and v_3 data for $p_T < 1$ GeV and then significantly underpredict the data. Possible underlying causes of the anisotropies within the AMPT model are discussed in Ref. [37].

We have presented first results on azimuthal anisotropies v_2 and v_3 in central $^3\mathrm{He}+\mathrm{Au}$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Calculations including hydrodynamic expansion of the initial hot spots created in $^3\mathrm{He}+\mathrm{Au}$ collisions qualitatively describe the data. Further comparison with different theoretical models should be informative in terms of the contributions from the initial geometry and each time stage in the medium evolution including preequilibrium. Forthcoming results from $p+\mathrm{Au}$ collisions at RHIC will provide a full suite of geometries with highly asymmetric collisions to constrain the origin of the observed anisotropies.

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