PHENIX results on collectivity in small systems

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Abstract. Recent results from small collision systems at RHIC and LHC indicate that many of the signatures of collective behavior observed in AA collisions are also present in small systems in high-multiplicity events. Using the extraordinary versatility of RHIC in selecting different colliding species, the PHENIX experiment has collected data in p+Al, p+Au, d+Au, and $^3$He+Au at a nucleon-nucleon center-of-mass energy of 200 GeV and conducted a comprehensive set of anisotropic flow measurements. These geometry-controlled experiments provide a unique testing ground for theoretical models that produce azimuthal particle correlations based on initial and/or final state effects. In this paper, we present measurements of elliptic and triangular flow for inclusive charged particles, and $v_2(p_T)$ measurements for identified pions, and protons. Detailed model comparisons and the implications for the origin of collectivity in p/d/$^3$He+Au collisions are discussed.

1. Introduction
Collective behavior, such as the azimuthal momentum anisotropy of the particles produced in collisions between large nuclei, such as Au+Au, is considered to be evidence for the formation of a strongly interacting, nearly-perfect fluid [1]. However, in recent years, similar phenomena have been observed in various small systems (e.g., p/d/$^3$He+Au collisions at RHIC [2, 3, 4, 5], and in pp and p+Pb collisions at the LHC [6, 7, 8, 9]. Many explanations have been proposed to explain the anisotropy signals in small systems. One explanation is that the initial-state geometry is translated into final-state flow under the gradient pressure. We can test this by changing the projectile/target of the collision system and see if the final-state flow strength corresponds to the initial-state geometric eccentricity. We should also see a mass ordering of $v_2(p_T)$ for identified final-state hadrons.

2. Methods
The PHENIX collaboration has measured the $v_2(p_T)$ of charged particles and identified pions, kaons, and protons in p+Au, d+Au, and $^3$He+Au collisions and $v_3(p_T)$ of charged in d+Au and $^3$He+Au collisions [2, 4, 5, 10]. The $v_2$ values are measured with the event-plane method. The event plane is determined using the south section (in the direction of the Au beam) of the forward vertex detector (FVTX), which is a silicon detector comprised of two identical end-cap assemblies symmetrically arranged in the longitudinal direction around the interaction region. The pseudorapiditidy coverage of the FVTX is $1 < |\eta| < 3$. The pions, kaons, and protons are identified by measuring their mass using time-of-flight measurements from the two Time-of-flight detectors located in the East and West arms of PHENIX in conjuhnction with the momentum and path-lenth measurements from the tracking detectors.
3. Results

3.1. Measurements of \(v_2(p_T)\) and \(v_3(p_T)\) of charged hadrons in geometry-controlled experiments

Figure 1 shows the transverse momentum dependence of \(v_2\) for charged hadrons in central \(p+Au\), \(d+Au\), and \(^3\)He+Au collisions [2] and the theory predictions from the SONIC hydrodynamics model [2]. From this figure, we see that the values of \(v_2(p_T)\) in \(d+Au\) and \(^3\)He+Au collisions are larger than those measured in \(p+Au\) collisions, which corresponds to the ordering of the initial geometric eccentricity \(\epsilon_2(p+Au) < \epsilon_2(^3\text{He}+Au) \approx \epsilon_2(d+Au)\). The SONIC model [11] describes the data well. It uses the Glauber model to set-up the initial energy density of the system, which then evolves with QGP equation of state. Table 1 shows the average spatial eccentricities for \(p+Au\), \(d+Au\) and \(^3\)He+Au collisions calculated from a Monte Carlo Glauber model for the top 5% central collisions in each system.

![Figure 1](image1.png)

**Figure 1.** Measurement of \(v_2\) for charged hadrons produced at mid-rapidity in central \(p+Au\), \(d+Au\), and \(^3\)He+Au collisions [2] in comparison to SONIC predictions.

![Figure 2](image2.png)

**Figure 2.** Transverse momentum dependence of \(v_2\) and \(v_3\) for charged hadrons produced at mid-rapidity in central \(d+Au\), and \(^3\)He+Au collisions.

| Spatial eccentricity | \(p+Au\) | \(d+Au\) | \(^3\)He+Au |
|----------------------|----------|----------|-------------|
| \(\langle\epsilon_2\rangle\) | 0.23±0.01 | 0.54±0.04 | 0.50±0.02 |
| \(\langle\epsilon_3\rangle\) | 0.16±0.01 | 0.18±0.01 | 0.28±0.02 |

Table 1. Average spatial eccentricities for \(p+Au\), \(d+Au\) and \(^3\)He+Au calculated from a Monte Carlo Glauber model for 0-5% central collisions.

Figure 2 shows both \(v_2(p_T)\) and \(v_3(p_T)\) in \(d+Au\) and \(^3\)He+Au collisions. The \(v_2\) values are similar in these two systems, while the \(v_3\) values are definitely different, as expected from the geometry.

Figure 3 shows the comparison of \(v_2\) and \(v_3\) to the iEBE-VISHNU hydrodynamics model [12]. The \(v_2\) and \(v_3\) are well described simultaneously with the same model parameters. Since the presentation at the conference, the PHENIX collaboration has submitted for publication the
measurements of $v_3(p_T)$ in p+Au and d+Au collisions [13]. The measurement in d+Au has significantly reduced systematic uncertainty in comparison to the preliminary results presented here. With the complete set of $v_2$ and $v_3$ measurements in three small systems with distinct initial geometry, the geometric origin of the observed azimuthal anisotropies is further established.

3.2. Measurements of $v_2(p_T)$ for identified particles in central p/d/3He+Au collisions

Mass-ordering is expected in the $v_2(p_T)$ distributions of identified particles, if the particles emerge from a common velocity field. Figure 4 shows $v_2(p_T)$ for identified pions and protons in 0%-5% central p+Au, d+Au, and 3He+Au collisions [10]. We can see a clear separation between the pion and proton $v_2$ values in the d+Au and 3He+Au systems, with the pion $v_2$ values being larger than those of the protons for $p_T < 1.5$ GeV/c, and the order being reversed at higher $p_T$. In the p+Au system, the splitting between pion and proton $v_2$ is smaller.

Figure 4 also compares the measured $v_2(p_T)$ with hydrodynamic calculations using the iEBE-VISHNU model. This model includes event-by-event fluctuating initial conditions via Monte Carlo Galuber simulation and then viscous hydrodynamics starting at $t_0 = 0.6$ fm/c. The hydrodynamic evolution utilizes an $\eta/s = 0.08$ and ends at $T = 155$ MeV. After that point, hadronization occurs and hadronic rescattering is implemented using URQMD. This model shows good agreement with the measurements at low $p_T$, but does not describe the mass-dependence of the measured $v_2$ values at high $p_T$. This figure also shows the theory curves with no hadronic rescattering. For $p_T < 1.5$ GeV, there is little change in the model calculations with or without hadronic rescattering. This means that the mass splitting at low $p_T$ in the hydrodynamic models mostly comes from the early-stage interactions.

Figure 5 compares the experimental data to the theory calculations from a-multiphase-transport model (AMPT) [14]. AMPT uses Monte Carlo Glauber initial conditions, and it models the evolution of the system by a succession of partonic scattering, spatial coalescence, and late-stage hadronic scattering as implemented in ART. The results shown in Fig. 5 are calculated from the AMPT time evolution with a partonic cross section $\sigma_{part} = 1.5$ mb. Also shown are the results with the hadronic rescattering turned off. We observed that the full AMPT describes the mass-splitting in all three collision systems for $p_T < 1.5$ GeV/c. At higher $p_T$, the $v_2$ from the theory becomes lower than the data points. The splitting of pion and proton $v_2$ at higher $p_T$ comes from the implementation of recombination model for hadronization. The comparison of the calculations with and without hadronic rescattering reveals that in AMPT the mass-splitting between $v_2$ of pions and protons at low $p_T$ comes mainly from the hadronic rescattering stage, which is different than the results from iEBE-VISHNU. These differences in the role of the
Figure 4. Transverse momentum dependence of $v_2$ for identified pions and protons within $|\eta| < 0.35$ in 0%-5% central p+Au, d+Au, and $^3$He+Au collisions. The measurements are compared to hydrodynamic calculations using the iEBE-VISHNU hydrodynamic model, illustrating the effect of hadronic rescattering on the mass-dependent $v_2$ values.

Figure 5. Same as Figure 4, but also shown are $v_2$ transport model calculations using AMPT.

hadronic rescattering may be due to differences in the hadronic cascade implementation and are worth investigating further.

Figure 6 shows the ratio of pion to proton $v_2(p_T)$ in all collision systems, together with the theory curves. In the ratio, many systematic uncertainties are canceled and thus we can see more clearly that the data in the three systems exhibit a similar trend, where pion $v_2$ is larger than the proton $v_2$ for $p_T < 1.5$ GeV/c, with the order reversed at higher $p_T$. Linear fit of the ratio within the $p_T$ range from 0.5 GeV/c to 3.0 GeV/c gives nonzero values for all three systems: $-0.22 \pm 0.07$ in p+Au collisions, $-0.40 \pm 0.07$ in d+Au collisions, and $-0.34 \pm 0.03$ in $^3$He+Au collisions. While both the hydrodynamics models and AMPT describe the ratio at low $p_T$, only AMPT successfully describes the ratio for $p_T > 1.5$ GeV/c, which emphasizes the importance of hadronization by recombination.
Figure 6. Ratio of pion $v_2$ over proton $v_2$ in central 0%-5% (a) p+Au, (b) d+Au, (c) $^3$He+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Theoretical calculations from SUPERSONIC and AMPT are also shown.

4. Summary
We have shown $v_2(p_T)$ of inclusive charged hadrons for p+Au, d+Au,$^3$He+Au collisions and $v_3(p_T)$ of inclusive hadrons produced in d+Au and $^3$He+Au collisions. These measurements support the idea that the final-state flow observed in small systems arises from the initial-state geometry. We have also measured $v_2(p_T)$ for identified pions and proton in p+Au, d+Au, $^3$He+Au collisions. We observe mass-splitting in all three systems, with the heavier particles having smaller $v_2$ at a given $p_T$ in the range $p_T < 1.5$ GeV/c, and the reverse order at higher $p_T$. These observations are qualitatively similar to previously measured effects in A+A collisions.

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