PHENIX flow results from the $d+$Au beam energy scan

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Abstract. The appearance of flow signatures, typically associated with the formation of a Quark Gluon Plasma, in small collision systems was a surprise to many in the community. Experimental measurements of elliptic anisotropy, now in $p/d/^{3}\text{He}+\text{Au}$ collisions at RHIC and $p+\text{Pb}$ collisions at the LHC, have been well described by both hydrodynamic models and models involving parton transport. To help investigate how these signals arise, RHIC delivered a beam energy scan of $d+$Au collision in 2016. PHENIX has measured the azimuthal anisotropy using event plane and multiparticle cumulant methods at the four collision energies and find nonzero signals at even the lowest collision energy of $\sqrt{s_{NN}}=19.6$ GeV. This presentation will discuss the results, comparisons to theoretical models, and their implications for our understanding of how these signals arise in small collision systems.

1. Introduction
Unexpected by many, azimuthal momentum anisotropies typically associated with quark gluon plasma (QGP) formation in $A+$A collisions have now been observed in $p/d/^{3}\text{He}+\text{Au}$ collisions at RHIC as well as $p+$p and $p+\text{Pb}$ collisions at the LHC. Recent measurements of $v_2$ and $v_3$ in central $p/d/^{3}\text{He}+\text{Au}$ collisions [1], shown in Fig. 1, follow the same ordering as their respective $\varepsilon_n$’s, indicating a geometric origin of the measured anisotropies. Further, hydrodynamic predictions, which include a QGP phase, provide a simultaneous and quantitative description of the data. If a small QGP droplet is formed in these small collision systems, an obvious question is what are the limitations on it’s formation? How small of a droplet can be formed? How short lived can the droplet be and still translate initial spatial anisotropy into final state particle momentum anisotropy? In order to address these questions, Ref. [2] proposed a beam energy scan of $d+$Au. A beam energy scan would amount to varying the initial temperature, as well as lifetime, of a possible QGP droplet. In 2016, this proposal was carried out at RHIC, the results of which are discussed in these proceedings.

2. RHIC $d+$Au beam energy scan
The 2016 RHIC $d+$Au beam energy scan consisted of four collision energies at $\sqrt{s_{NN}}=200, 62.4, 39, \text{ and } 19.6$ GeV. PHENIX collected data using a high multiplicity trigger in order to take nearly the full luminosity for central collisions. Details of the trigger conditions and event selection criteria can be found in Ref. [3]. The resulting event statistics are shown in Table 1 for central events, along with the mean number of participating nucleons ($\langle N_{\text{part}} \rangle$) and the average second order eccentricity ($\langle \varepsilon_2 \rangle$) as calculated from Monte Carlo Glauber.
Figure 1. The measured $v_2$ and $v_3$ as a function of $p_T$ in 0–5% central $p+Au$ (a), $d+Au$ (b), and $^3He+Au$ (c) collisions at $\sqrt{s_{NN}} = 200$ GeV [1].

Table 1. Summary of the data analyzed by PHENIX from the 2016 $d+Au$ beam energy scan.

| $\sqrt{s_{NN}}$ [GeV] | Centrality | $\langle N_{part} \rangle$ | $\langle v_2 \rangle$ | $\langle v_3 \rangle$ | $N_{events}$ [$10^6$] | $dN_{ch}/d\eta|_{\eta=0}$ |
|------------------------|------------|------------------|------------------|------------------|------------------|------------------|
| $d+Au$ 200            | (0–5%)     | 17.8±1.2         | 0.54±0.04        | 569              | 20.3±1.5         |
| $d+Au$ 62.4           | (0–5%)     | 16.3±1.0         | 0.55±0.05        | 214              | 12.4±2.4         |
| $d+Au$ 39             | (0–10%)    | 15.9±1.0         | 1.56±0.06        | 171              | 9.3±1.6          |
| $d+Au$ 19.6           | (0–20%)    | 13.6±1.0         | 0.55±0.05        | 7                | 5.8±1.1          |

The charged particle multiplicity ($dN_{ch}/d\eta$) as a function of pseudorapidity ($\eta$) for each centrality and at each energy is shown in Fig. 2. The distributions show a clear asymmetry in the particle production for central events, with more particles being produced at $\eta < 0$ (backward or Au-going) compared to $\eta > 0$ (forward or $d$-going) due to the asymmetric collision system. This asymmetry decreases from central to peripheral events, with the most peripheral bin being symmetric, as is the case in $p+p$ collisions. The charged particle production at midrapidity decreases by nearly a factor of 4 in central collisions between 200 and 19.6 GeV.

Figure 2. Charged particle multiplicity as a function of $\eta$ and event centrality for $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ (a), 62.4 (b), 39 (c), and 19.6 (d) GeV.

Also shown in Fig. 2 are calculations from A Multi-phase Transport (AMPT) model. The centrality bins in the AMPT results are determined similarly to the data, by selecting on the total number of charged particles in the region $-3.9 < \eta < -3.1$, which corresponds to acceptance of the PHENIX south beam beam counter (BBC). At 200 GeV, AMPT describes the data well at
mid and forward pseudorapidities for all centralities, but overpredicts the data at backward pseudorapidity. This may be due to a stronger bias from categorizing centrality based on multiplicity in the neighboring pseudorapidity region in AMPT than appears in the data. For the lower collision energies, AMPT overpredicts the $dN_{ch}/d\eta$ across pseudorapidity and centrality.

3. Establishing collectivity

Using the standard event plane (EP) method, the $v_2(p_T)$ of charged particles within $|\eta| < 0.35$ is measured for central $d+Au$ collisions at all four energies. Additionally, the $v_2(\eta)$, integrated over $p_T$, of charged particles is measured for central $d+Au$ collisions at $\sqrt{s_{NN}} = 200$, 62.4, and 39 GeV. The results are shown in Fig. 3. A significant, nonzero, $v_2$ signal is measured at all four collision energies. When measuring $v_2(p_T)$, the EP is measured using the PHENIX forward silicon vertex detector (FVTX) in the Au-going direction which covers $-3.0 < \eta < -1.0$, yielding a pseudorapidity gap of $0.65 < \Delta \eta < 3.35$. For $v_2(\eta)$, the EP is measured in the Au-going BBC covering $-3.9 < \eta < -3.1$. In these results, no estimate or subtraction of nonflow contributions is performed. Based on comparing the $v_2$ measured using EP’s in different regions, as well as alternative 2 particle correlation measurements (detailed in Ref. [3]), the nonflow contribution for 0–5% central $d+Au$ at 200 GeV is expected to be small for $p_T < 3$. However, at the lowest energies it is expected that the nonflow contribution increases.

Alongside the EP method, the $v_2$ is also measured using multiparticle cumulants. Figure 4 shows the $v_2(\{2\})$, with and without a minimum $\Delta \eta$ cut, $v_2(\{4\})$, and $v_2(\{6\})$ as a function of the number of tracks reconstructed in the north and south FVTX arms ($N_{\text{tracks}}$) [5]. A positive $v_2(\{2\})$, $v_2(\{4\})$, and $v_2(\{6\})$ is observed at 200 GeV. The positive $v_2(\{4\})$ and $v_2(\{6\})$ and the fact that
\textbf{Figure 4.} Multiparticle cumulants as a function of the number of offline tracks in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ (a), 62.4 (b), 39 (c), and 19.6 (d) GeV [5].

$v_2\{4\} \approx v_2\{6\}$ is a strong indication that the measured $v_2$ is truly collective, and the nonflow contributions are minimal. A positive $v_2\{4\}$ is also observed down to 19.6 GeV, again yielding evidence that the measured $v_2$ arises from a collective flow effect.

It is known that $v_2\{2\}$, without the requirement of a $\Delta \eta$ gap between pairs, is susceptible to a strong nonflow contribution. Typically, one then imposes such a gap to help remove nonflow. Also shown in Fig. 4 is $v_2\{2,|\Delta \eta| > 2\}$, where a gap of $|\Delta \eta| > 2$ is imposed. Due to the pseudorapidity coverage of the PHENIX FVTX arms used in this analysis, this imposes a requirement that one track is measured in the Au-going FVTX while the other is measured in the $d$-going FVTX. Unfortunately, due to the asymmetric collision system, this imposes different weighting of the $v_2$ values at backward and forward pseudorapidities than in the $v_2\{2\}$ or $v_2\{4\}$ without an eta gap, making direct comparisons difficult. The $v_2\{2,|\Delta \eta| > 2\}$ is effectively a direct product of the $v_2$ in the $d$ and Au-going directions, while the $v_2\{2\}$ and $v_2\{4\}$ are weighted by the respective multiplicity in each region, as shown in Fig. 2. This can explain why $v_2\{2,|\Delta \eta| > 2\}$ decreases with decreasing energy while $v_2\{4\}$ appears to increase with decreasing energy. These features are qualitatively reproduced in AMPT, which includes both $\eta$-dependent multiplicity and $v_2$, as shown in Ref. [5]. These cumulant results strongly indicate that the $v_2$ arises from multiparticle correlations from 200 down to 19.6 GeV.

\section{4. Hydrodynamic theory comparison}

Predictions for $v_2(p_T)$ from the hydrodynamic \textit{sonic} and \textit{supersonic} models are shown compared to the measured data in Fig. 3. The main difference between the calculations being that \textit{supersonic} additionally includes pre-equilibrium flow. The calculations agree with the data well at 200 and 62.4, with \textit{supersonic} giving a showing a slightly better agreement with the data, perhaps indicating the importance of the pre-equilibrium. However, at 39 and 62.4 GeV, the calculations are significantly lower than the measured data. One likely explanation for the discrepancy is that the measurement includes contributions from both flow and nonflow. As discussed above, the results at 200 and 62.4 GeV are believed to be dominated by flow, particularly at low-$p_T$. However, it is expected that the nonflow contribution will increase with decreasing collision energy and with increasing $p_T$, which would cause an increase in the measured $v_2$ signal. It is worth noting that both \textit{sonic} and \textit{supersonic} are in good agreement with the $p_T$ integrated $v_2$ at midrapidity, even at 39 GeV, as shown in Fig. 3(g).

\section{5. Microscopic transport comparison}

An alternative class of models which translates initial spatial anisotropy into final state particle momentum anisotropy include microscopic transport models. Once such model is AMPT. One
advantage of AMPT is that it is a full Monte Carlo event generator which produces final state particles, as would be detected experimentally. Because of this the same analysis procedure used in data can be applied to the AMPT output, while simultaneously knowing the true initial conditions. This allowed us to produce two distinct “measures” of the $v_2$ within AMPT. The first calculates the $v_2$ of final state particles relative to the initial parton plane (PP). This correlates final state momentum with true initial geometry only, i.e. what we think of as flow. Additionally, for the same set of events, we can calculate the $v_2$ relative to the EP, as is done in real data. Since AMPT includes particle decays and mini-jets, that means that the calculated $v_2$ relative to the EP contains correlations from both flow and nonflow. Figure 5 shows the $v_2(p_T)$ and $v_2(\eta)$ compared to AMPT calculations using both the parton and event planes. By comparing the two AMPT curves, we can gain some intuition about the effect of nonflow as a function of $p_T$, $\eta$, collision energy, and event multiplicity. As expected, the nonflow contribution appears to grow with larger $p_T$, lower collision energy, and as the $\Delta\eta$ gap relative to the EP decreases. The AMPT EP calculations provide a much more consistent description of the data, particularly at high-$p_T$.

An interesting phenomenon in $v_2(\eta)$ is also seen at 39 GeV, where the AMPT EP calculations show a lower value relative to the PP results for $\eta < -2$, indicating a more complicated coupling between flow and nonflow. For a more detailed discussion of the comparison to $v_2(\eta)$ data see Ref. [3].

Within AMPT, we can also disentangle how the various stages of the evolution contribute to the total $v_2$ signal. This can be done by turning off either or both of the partonic or hardonic interactions. The resulting calculations of $v_2(p_T)$ relative to the EP are shown in Fig. 6. For a full discussion including $v_2(\eta)$ calculations, as well as results relative to the parton plane,
Figure 6. The value of $v_2$ as a function of $p_T$ in central $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ (a), 62.4 (b), 39 (c), and 19.6 (d) GeV. The curves are calculations from AMPT under different conditions. The red curve is AMPT run with both partonic and hadronic scattering. The yellow curve is AMPT run with hadronic scattering only (H. S.). The cyan curve is AMPT run with partonic scattering only (P. S.). The purple curve is AMPT run with no scattering (N. S.). For all AMPT curves, the $v_2$ is calculated relative to the final state event plane.

see Ref. [3]. When both partonic and hadronic scattering are turned off, we find $v_2 = 0$ when calculated relative to the PP, indicating now true flow is present. However, when producing the same calculations relative to the EP, a nonzero signal is observed which increases strongly with increasing $p_T$ and decreasing collision energy, showing the signal from nonflow alone. Once partonic scattering is turned on, a larger $v_2$ signal is observed which dominates at $p_T > 1$ GeV/c. When turning on hadronic scattering, but leaving partonic scattering turned off, the hadronic stage is isolated. Here we can see that the majority of the low-$p_T$ signal in AMPT is driven by the hadronic scattering. A note of caution: the separate curves can not simply be added together to achieve the results with all scattering turned on, as turning off various pieces changes the number of particles produced, and hence the EP, as well as changing the amount of time spent in the various stages. However, it is still useful to gain some insight into the origins of $v_2$ within the microscopic transport approach as encoded within AMPT.

6. Summary

In summary, PHENIX has measured $v_2$ over a range of kinematics in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$, 62.4, 39, and 19.6 GeV using multiple techniques. These results provide further evidence that the measured $v_2$ is coupled to the initial geometry, and are consistent with hydrodynamic predictions. At $\sqrt{s_{NN}} = 200$ GeV, the measured $v_2$ appears to be dominated by contributions related to flow, while as the collision energy is lowered this contribution appears to be present, although it becomes less dominant.

References
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