Droplets of quark gluon plasma: PHENIX results on small systems at RHIC

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Abstract. In these proceedings we discuss PHENIX results on small systems at RHIC, specifically those relating to collectivity and flow. We discuss the small systems geometry scan, which comprises collisions of \( p + Au \), \( d + Au \), and \( \text{^3He} + Au \) at \( \sqrt{s_{NN}} = 200 \) GeV and is designed to exploit differences in intrinsic geometry. We also discuss the small systems beam energy scan, which comprises \( d + Au \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV, 62.4 GeV, 39 GeV, and 19.6 GeV and is designed to explore differences in system size and lifetime while keeping the geometry fixed. We find the data in nearly all cases are well-described by hydrodynamical calculations involving a QGP phase, suggestion formation of QGP droplets in a wide variety of collisions.

1. Small systems geometry scan

In 2014, a small systems geometry scan at the relativistic heavy ion collider (RHIC) was proposed [1] to exploit intrinsic geometry of \( p + Au \), \( d + Au \), and \( \text{^3He} + Au \) collisions. This ambitious program made use of the versatility and flexibility of the RHIC accelerator complex.

In \( p + Au \) collisions, there is no intrinsic geometry, so the \( n \)-th harmonic eccentricities \( \varepsilon_n \) come from nucleonic and subnucleonic fluctuations only. In \( d + Au \) collisions, there is intrinsic ellipticity due to the configuration of the nucleus (viz. two nucleons in the projectile nucleus), but no intrinsic triangularity—therefore, the ellipticity \( \varepsilon_2 \) has contributions both from fluctuations and intrinsic geometry while the triangularity \( \varepsilon_3 \) is generated by fluctuations only. In \( \text{^3He} + Au \) collisions, the shape of the projectile nucleus contributes both intrinsic triangularity (viz. three nucleons) and intrinsic ellipticity—there’s more phase space available for configurations that are elongated than for configurations resembling an equilateral triangle, both in terms of the \( \text{^3He} \) wave function and in the fact that the plane of the \( \text{^3He} \) can be inclined relative to the transverse plane of the collision. It is critical to understand that fluctuations contribute to all \( \varepsilon_n \) in all systems, but intrinsic geometry contributes to only some \( \varepsilon_n \) in only some collision systems.

Different models will lead to different relative contributions from fluctuations and intrinsic geometry. However, based simply on the presence or absence of contributions from intrinsic geometry, we expect the following qualitative hierarchy:

- \( \varepsilon_2(p + Au) < \varepsilon_2(d + Au) \approx \varepsilon_2(\text{^3He} + Au) \);
- \( \varepsilon_3(p + Au) \approx \varepsilon_3(d + Au) < \varepsilon_3(\text{^3He} + Au) \).

This hierarchy is generally seen in various theoretical calculations of the \( \varepsilon_n \) in these small systems, as shown in Table 1. The hierarchy is more consistent for \( \varepsilon_2 \) than for \( \varepsilon_3 \); in some cases, the \( \varepsilon_3 \) values of \( d + Au \) and \( \text{^3He} + Au \) tend stand further apart from \( p + Au \).
### Table 1. Eccentricity values from various calculations with descriptions and references given in the first row.

|          | PHOBOS MC Glauber [1, 2] | Multiplicity fluctuations [2, 3] | Mult. & gluon fluctuations [2, 3] | IP-Glasma Nucleons $t = 0$ [2, 4, 5] | IP-Glasma 3 quarks $t = 0$ [2, 4, 5] |
|----------|--------------------------|---------------------------------|----------------------------------|--------------------------------------|--------------------------------------|
| $\varepsilon_2 (p+Au)$ | 0.23 | 0.32 | 0.38 | 0.10 | 0.50 |
| $\varepsilon_2 (d+Au)$ | 0.54 | 0.48 | 0.51 | 0.58 | 0.73 |
| $\varepsilon_2 (^3\text{He}+Au)$ | 0.50 | 0.50 | 0.52 | 0.55 | 0.64 |
| $\varepsilon_3 (p+Au)$ | 0.16 | 0.24 | 0.30 | 0.09 | 0.32 |
| $\varepsilon_3 (d+Au)$ | 0.18 | 0.28 | 0.31 | 0.28 | 0.40 |
| $\varepsilon_3 (^3\text{He}+Au)$ | 0.28 | 0.32 | 0.35 | 0.34 | 0.46 |

The completion of that geometry scan culminates in the publication of event plane method $v_2$ and $v_3$ in $p+Au$, $d+Au$, and $^3\text{He}+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV in Nature Physics [6].

Eschewing theoretical comparisons for the moment, Figure 1 shows $v_2$ ($v_3$) in the left (right) panel in $p+Au$ (red points), $d+Au$ (blue points), and $^3\text{He}+Au$ (black point) collisions at $\sqrt{s_{NN}} = 200$ GeV. Indeed, we see the same hierarchy as the $\varepsilon_n$ discussed above:

- $v_2 (p+Au) < v_2 (d+Au) \approx v_2 (^3\text{He}+Au)$;
- $v_3 (p+Au) \approx v_3 (d+Au) < v_3 (^3\text{He}+Au)$.

![Figure 1](image_url)

**Figure 1.** $v_2$ (left panel) and $v_3$ (right panel) in $p+Au$ (red circles), $d+Au$ (blue squares), and $^3\text{He}+Au$ (black diamonds) collisions at $\sqrt{s_{NN}} = 200$ GeV [6]. The data exhibit a geometrical hierarchy as discussed in the text.

We now consider some theoretical comparisons. Figures 2, 3, and 4 show the $v_2$ (solid circles) and $v_3$ (solid diamonds, top and middle; sold triangle, bottom) in $p+Au$ (left panels), $d+Au$ (middle panels), and $^3\text{He}+Au$ (right panels) at $\sqrt{s_{NN}} = 200$ GeV.

Two hydrodynamical calculations are shown in Figure 2: the SONIC model [1] (solid red lines) and iEBE-VISHNU [7] (dashed blue lines). Both sets of theory curves describe the data...
extremely well. Figure 3 shows the theoretical calculations in the color glass condensate effective
time formalism [8]; the curves completely fail to describe the data, which seems to fully
rule out the possibility for explaining the data with initial state effects alone. It is noteworthy
that both the overall curves and specifically the peaks appear to decrease with increasing system
size, which is suggestive of an intuitive scaling in which the strength of the correlation is inversely
proportional to the number of color domains, as suggested in Ref. [6].

![Figure 2](image1)

**Figure 2.** $v_2$ (black circles) and $v_3$ (black diamonds) as a function of $p_T$ in $p+Au$ (left), $d+Au$
(middle), and $^3He+Au$ (right) collisions at $\sqrt{s_{NN}} = 200$ GeV and comparison to hydrodynamical
calculations [6].

![Figure 3](image2)

**Figure 3.** $v_2$ (black circles) and $v_3$ (black diamonds) as a function of $p_T$ in $p+Au$ (left), $d+Au$
(middle), and $^3He+Au$ (right) collisions at $\sqrt{s_{NN}} = 200$ GeV [6] and comparison to an initial
state calculation [8].

This does not, however, rule out any role for initial state effects. Recent efforts [9] have sought
to include effects both from the initial state and from the hydrodynamical evolution—these are
shown in Figure 4. They are generally in quite reasonable agreement with the data, especially
when taking the uncertainties into account. Nevertheless, they do not describe the data quite as
well as hydrodynamics alone, which could indicate a relatively small role for initial state effects, or the need for a rather different set of fluid parameters.

**Figure 4.** $v_2$ (red circles) and $v_3$ (blue triangles) as a function of $p_T$ in $p+Au$ (left), $d+Au$ (middle), and $^3He+Au$ (right) collisions at $\sqrt{s_{NN}} = 200$ GeV [6] and a comparison to a combined initial state and hydrodynamical calculation [9].

Longitudinal dynamics were also explored via measurements of $dN_{ch}/d\eta$ and $v_2(\eta)$ [10]. Figure 5 shows $v_2$ as a function of $\eta$ in green points in $p+Al$, $p+Au$, $d+Au$, and $^3He+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV. Also shown as blue points is $dN_{ch}/d\eta$ in each system, scaled down to meet the forward rapidity points. The $v_2$ and $dN_{ch}/d\eta$ follow the same trend at central and forward rapidity. At backward rapidity, we see a very large increase in the $v_2$ in $p+Al$, and a similar but smaller increase in the $v_2$ in $p+Au$; this increase is absent in $d+Au$ and $^3He+Au$. This increase is due to the prevalence of non-flow when the particles are near ($\Delta\eta < 1$) the event plane detector ($-3.9 < \eta < -3.1$). The relative strength of this rise is inversely proportional to the size of the collision system, which is expected based on combinatoric dilution of few-particle correlations. Also shown are calculations in a 3D hydrodynamic model [11] for $p+Au$, $d+Au$, and $^3He+Au$. The theory curves describe the $p+Au$ and $d+Au$ very well; contrariwise, the theory has less forward/backward asymmetry than the experimental data in the $^3He+Au$ case.

2. $d+Au$ beam energy scan

In 2016, RHIC performed a beam energy scan (BES) of $d+Au$ collisions, colliding at $\sqrt{s_{NN}} = 200$ GeV, 62.4 GeV, 39 GeV, and 19.6 GeV. The collision geometry is fixed by colliding the same species, and the system size and lifetime are varied by changing the collision energy [12].

Figure 6 shows event plane method $v_2$ as a function of $p_T$ in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV (left), 62.4 GeV (left middle), 39 GeV (right middle), and 19.6 GeV (right) [13]. Hydrodynamical calculations [12] describe the 200 GeV and predict the 62.4 GeV well. On the other hand, the 39 GeV and 19.6 GeV data are under-predicted. In the large systems BES, it has been shown [14, 15] that adjusting the equation of state and accounting for conserved charges (e.g. baryon number) is very important in getting accurate calculations. It seems likely that this is the case in the small systems BES as well.

Figure 7 shows multiparticle cumulant $v_2$ as a function of multiplicity in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV (left), 62.4 GeV (left middle), 39 GeV (right middle), and 19.6 GeV (right) [16]. The $v_2(4)$ is real-valued in all collision systems. In the 200 GeV case, there is sufficient statistical precision to measure $v_2(6)$ as well, which is consistent with the $v_2(4)$, as seen in large systems and in $p+Pb$ at the LHC.
Figure 5. $v_2(\eta)$ (green squares) and $dN_{ch}/d\eta$ (blue circles, scaled downward to match $v_2(\eta)$) in $p+Al$ (left), $p+Au$ (left middle), $d+Au$ (right middle), and $^{3}\text{He}+Au$ (right) collisions at $\sqrt{s_{NN}}=200$ GeV [10]. Also shown are 3D hydrodynamics calculations for $p+Au$, $d+Au$, and $^{3}\text{He}+Au$ [11].

Figure 6. $v_2(p_T)$ (black circles) in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV (left), 62.4 GeV (left middle), 39 GeV (right middle), and 19.6 GeV (right) [13]. Also shown are hydrodynamical calculations [12].

Figure 7. $v_2\{2\}$ (red circles) and $v_2\{4\}$ (blue squares) as a function of multiplicity in $d+Au$ collisions at $\sqrt{s_{NN}}=200$ GeV (left), 62.4 GeV (left middle), 39 GeV (right middle), and 19.6 GeV (right); also shown for 200 GeV collisions is $v_2\{6\}$ (black crosses) [16].
3. Summary

In these proceedings we have shown the marquee results from the RHIC small systems program. The multiparticle cumulant $v_2$ measurements show signatures of collectivity at all four collision energies in the $d+Au$ BES, which is a necessary (but insufficient) condition to demonstrate QGP formation. The $v_2(p_T)$ measurements in the $d+Au$ BES show the success of hydrodynamical theory with a QGP phase at both 200 GeV and 62.4 GeV, and invite additional calculations specifically tuned for lower collision energies. The $v_2(\eta)$ and $dN_{ch}/d\eta$ in $p+Al$, $p+Au$, $d+Au$, and $^3He+Au$ demonstrate the importance of longitudinal dynamics in small systems and the need for three-dimensional hydrodynamical calculations. Lastly, the $v_3(p_T)$ and $v_3(p_T)$ in $p+Au$, $d+Au$, and $^3He+Au$ demonstrate a geometrical ordering, and show excellent agreement with predictions and descriptions from hydrodynamical calculations. Taken together, there is strong evidence for QGP droplet formation in small systems at RHIC.

4. References

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