PHENIX results on small systems collectivity at RHIC

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Based on developments in hydro theory over the last few years, we might replace “thermalization” with “hydrodynamization”
Azimuthal anisotropy measurements

\[ \frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n \cos n\phi \quad v_n = \langle \cos n\phi \rangle \quad \varepsilon_n = \sqrt{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle} / \langle r^n \rangle \]

Hydrodynamics translates initial shape (including fluctuations) into final state distribution.
Azimuthal anisotropy measurements

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\]

- Hydrodynamics translates initial shape (including fluctuations) into final state distribution
Important discovery in 2005

PHOBOS Plenary, Quark Matter 2005 (see also Phys.Rev.C 77, 014906 (2008))

A nucleus isn’t just a sphere
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NeXSPheRIO results on elliptic flow at RHIC and connection with thermalization

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Received 1 January 2004

Worth noting that lumpy initial conditions were predicted some time in 2003
Nucleon fluctuations can produce non-zero $\varepsilon_n$ for odd $n$.

Symmetry planes $\psi_n$ can be different for different harmonics.

$$\varphi = \phi_{lab} - \psi_n$$
Fluctuations should also be translated, so measure $\frac{\sigma_{v_2}}{\langle v_2 \rangle}$

$|\eta| < 1$

Generally good agreement with models of initial geometry
Fluctuations in large systems


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Central: breakdown of small-variance limit (assumed in data and solid line)

Peripheral: non-linearity in hydro response (e.g. J. Noronha-Hostler et al Phys. Rev. C 93, 014909 (2016))
Testing hydro by controlling system geometry

Collective motion translates initial geometry into final state distributions

To determine whether small systems exhibit collectivity, we can adjust the geometry and compare across systems

We can also test predictions of hydrodynamics with a QGP phase
Testing hydro by controlling system geometry

Creation of quark–gluon plasma droplets with three distinct geometries

PHENIX Collaboration

*Nature Physics* 15, 214–220 (2019) | Cite this article
Testing hydro by controlling system geometry

Testing hydro by controlling system geometry

\[ v_2 \text{ and } v_3 \text{ ordering matches } \varepsilon_2 \text{ and } \varepsilon_3 \text{ ordering in all three systems} \]

—Collective motion of system translates the initial geometry into the final state

Testing hydro by controlling system geometry


- $v_2$ and $v_3$ vs $p_T$ predicted or described very well by hydrodynamics in all three systems
  —All predicted (except $v_2$ in $d+Au$) in J.L. Nagle et al, PRL 113, 112301 (2014)
  —$v_3$ in $p+Au$ and $d+Au$ predicted in C. Shen et al, PRC 95, 014906 (2017)
Testing hydro by controlling system geometry

Initial state effects alone do not describe the data
Testing hydro by controlling system geometry

Important to include initial state effects
—B. Schenke et al, Phys. Lett. B 803, 135322
Good agreement between STAR and PHENIX for $v_2$
Comparisons with STAR

Good agreement between STAR and PHENIX for $v_2$

Large discrepancy between STAR and PHENIX for $v_3$
Comparisons with STAR

PHENIX takes the issue seriously, so we are doing our due diligence!

The published small systems results use the event plane method, where the resolution nominally follows

\[ R(\chi) = \frac{\sqrt{\pi}}{2} \epsilon e^{-\frac{\chi^2}{2}} \left( I_0\left(\frac{\chi^2}{2}\right) + I_1\left(\frac{\chi^2}{2}\right) \right) \]

In small systems we’re in the limiting case where \( \chi \ll 1 \) so \( R \propto \chi \) (note that \( \chi = v_n \sqrt{N_{ch}} \)).

The set of PHENIX event plane resolutions do not follow the expected pattern.

The origin of this effect is the beam and angle offset relative to the detector and an additional offset of the PHENIX central carriage (all of these things vary between operational periods). The effect is qualitatively reproduced in toy simulation studies that utilize the full analysis procedure.

The three-subevent 2-particle correlation method uses event mixing, which corrects these effects quite well. Checks with the 3x2PC method show no such bias as seen in EP method for all systems, and all of these checks agree with published EP results within uncertainties.

Further checks on going as part of due diligence!
Most PHENIX results use backward rapidity detectors in combination with mid-rapidity

STAR uses mid-rapidity only (TPC, $|\eta| < 1$)
Most PHENIX results use backward rapidity detectors in combination with mid-rapidity.

- STAR uses mid-rapidity only (TPC, $|\eta| < 1$)
- PHENIX can use a backward-mid-forward combination to better mimic STAR acceptance
  - Unsubtracted STAR results match PHENIX backward-mid-forward
  - Non-flow subtracted STAR results match PHENIX backward-backward-mid
Comparisons with STAR

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- STAR uses mid-rapidity only (TPC, $|\eta| < 1$).
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  — Unsubtracted STAR results match PHENIX backward-mid-forward.
  — Non-flow subtracted STAR results match PHENIX backward-backward-mid.
- $v_3$ with both detector combinations coming soon!
### Initial eccentricities

#### Table compiled by J.L. Nagle

<table>
<thead>
<tr>
<th>System</th>
<th>Nagle Nucleons w/o NBD fluctuations</th>
<th>Welsh Nucleons w/ NBD fluctuations</th>
<th>Welsh Quarks w/ NBD and Gluon fluctuations</th>
<th>IP-Glasma w/ Nucleons t=0</th>
<th>IP-Glasma w/ 3 Quarks t=0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon_2$ p+Au</td>
<td>0.23</td>
<td>0.32</td>
<td>0.38</td>
<td>0.10</td>
<td>0.50</td>
</tr>
<tr>
<td>$\varepsilon_2$ d+Au</td>
<td>0.54</td>
<td>0.48</td>
<td>0.51</td>
<td>0.58</td>
<td>0.73</td>
</tr>
<tr>
<td>$\varepsilon_2$ $^3$He+Au</td>
<td>0.50</td>
<td>0.50</td>
<td>0.52</td>
<td>0.55</td>
<td>0.64</td>
</tr>
<tr>
<td>$\varepsilon_3$ p+Au</td>
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<td>0.24</td>
<td>0.30</td>
<td>0.09</td>
<td>0.32</td>
</tr>
<tr>
<td>$\varepsilon_3$ d+Au</td>
<td>0.18</td>
<td>0.28</td>
<td>0.31</td>
<td>0.28</td>
<td>0.40</td>
</tr>
<tr>
<td>$\varepsilon_3$ $^3$He+Au</td>
<td>0.28</td>
<td>0.32</td>
<td>0.35</td>
<td>0.34</td>
<td>0.46</td>
</tr>
</tbody>
</table>

- IP-Glasma run by S. Lim using publicly available code (thanks to B. Schenke)
Longitudinal dynamics in small systems

PHENIX Small Systems $\sqrt{s_{NN}}=200$ GeV

$p+Al$, $p+Au$, $d+Au$, $^3He+Au$

Good agreement with wounded quark model (M. Barej et al, Phys. Rev. C 97, 034901 (2018))

Good agreement with 3D hydro (P. Bozek et al, Phys. Lett. B 739, 308 (2014))
Longitudinal dynamics in small systems

Good agreement with 3D hydro for $p+Au$ and $d+Au$ (Bozek et al., PLB 739, 308 (2014))

- $v_2$ vs $\eta$ in $p+Al$, $p+Au$, $d+Au$, and $^{3}\text{He}+\text{Au}$
- Prevalence of non-flow near the EP detector ($-3.9<\eta<-3.1$)

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Longitudinal dynamics in small systems

\[ v_2 \] vs \( \eta \) in \( p+Al, p+Au, d+Au, \) and \( ^3He+Au \)

Good agreement with 3D hydro for \( p+Au \) and \( d+Au \) (Bozek et al, PLB 739, 308 (2014))

Prevalence of non-flow near the EP detector \((-3.9 < \eta < -3.1)\)
Longitudinal dynamics in small systems


- $v_2$ vs $\eta$ in $p+Al$, $p+Au$, $d+Au$, and $^3He+Au$
- Good agreement with 3D hydro for $p+Au$ and $d+Au$ (Bozek et al, PLB 739, 308 (2014))
- Prevalence of non-flow near the EP detector ($-3.9 < \eta < -3.1$)
Testing hydro by controlling system size and life time

Geometry in $d+$Au collisions dominated by deuteron shape, thus largely independent of collision energy

Spacetime volume of system in QGP phase decreases with decreasing collision energy
Hydro theory agrees with higher energies very well, underpredicts lower energies.

- Likely need different EOS for lower energies; influence of conserved charges likely more important at lower energies (see e.g. M. Martinez et al, arXiv:1911.10272, 1911.12454)
- Nonflow likelier to be an issue due to lower multiplicity at lower energies
Measurement of $v_2$ in $d+Au$ at 200 GeV and $v_2$ in $d+Au$ at all energies.

Multiparticle correlations can be a good indicator of collectivity.

Measurement of $v_2\{6\}$ in $d+Au$ at 200 GeV and $v_2\{4\}$ in $d+Au$ at all energies
Measurement of $v_2\{6\}$ in $d+Au$ at 200 GeV and $v_2\{4\}$ in $d+Au$ at all energies

Multiparticle correlations can be a good indicator of collectivity
Collective motion translates initial geometrical shape into final state azimuthal anisotropies.

Evidence of this translation is seen in small and large systems.

The $v_2$ and $v_3$ in $p+Au$, $d+Au$, and $^3He+Au$ qualitatively follow the geometrical ordering of the initial state.

The $v_2$ and $v_3$ in $p+Au$, $d+Au$, and $^3He+Au$ quantitatively agree with multiple hydrodynamical calculations.

Several internal cross-checks of published PHENIX small system results give confidence to the measurements, which have remained unchanged.

A variety of collective signatures are seen in the $d+Au$ beam energy scan.

— $v_2$ vs $p_T$ agrees with hydro at the higher two energies
— Observation of multiparticle correlations at all energies
Extra material
Components and cumulants in p+Au and d+Au at 200 GeV


\[ v_2\{4\} = (-c_2\{4\})^{1/4} \]

Negative \( c_2\{4\} \) means real \( v_2\{4\} \)
Components and cumulants in p+Au and d+Au at 200 GeV


PHENIX p+Au $|s_{NN}| = 200$ GeV
$1 < |\eta| < 3$
- $\langle 4 \rangle$
- $2\langle 2 \rangle^2$

PHENIX d+Au $|s_{NN}| = 200$ GeV
$1 < |\eta| < 3$
- $\langle 4 \rangle$
- $2\langle 2 \rangle^2$

Can we blame this on nonflow?

$v_2^{(4)} = c_2^{(4)}$

Negative $c_2^{(4)}$ means real $v_2^{(4)}$

Use of subevents further suppresses nonflow

Positive $c_2^{(4)}$ in p+Au doesn’t seem to be related to nonflow
Components and cumulants in \( p+Au \) and \( d+Au \) at 200 GeV


\[ c_2\{4\} \] is positive in \( p+Au \)

Can we blame this on nonflow?
Components and cumulants in p+Au and d+Au at 200 GeV


[Graphs and plots related to PHENIX and AMPT calculations for c2{4} and c2{4} ab|ab, c2{4} aa|bb in p+Au collisions.]

Can we blame this on nonflow?

Negative $c_2\{4\}$ means real $v_2\{4\}$

Use of subevents further suppresses nonflow

Positive $c_2\{4\}$ in p+Au doesn’t seem to be related to nonflow.
Components and cumulants in p+Au and d+Au at 200 GeV

Use of subevents further suppresses nonflow

Positive $c_2\{4\}$ in $p$+Au doesn’t seem to be related to nonflow
Cumulants are computationally expensive in hydro theory, so not as well-studied.

This particular calculation doesn’t show the strong geometry dependence seen in the data.

Important to note this is 2+1D hydro, so the kinematics can’t match the data.
Particle species dependence of “Cronin enhancement”


\[
d^{+}\text{Au} \sqrt{s_{\text{NN}}} = 200 \text{ GeV}
\]

\[
\begin{align*}
\pi^+, \pi^-, \pi^0, \\
K^+, K^-, \\
p, \bar{p}, \\
\phi
\end{align*}
\]

Protons much more strongly modified than pions
\(\phi\) mesons similar to pions
Photons in small systems

$\sqrt{s_{NN}} = 200 \text{ GeV}, |\eta| < 0.35$

$R_{p+Au}$ vs $p_T$ [GeV/c]

PHENIX preliminary
Photons in small systems

\[ \sqrt{S_{NN}} = 200 \text{ GeV}, |\eta| < 0.35 \]

- **p+Au, 0-100 %**

- **p+Au, 0-5 %**

**PHENIX preliminary**

- Thermal(-ish) photons in \( p+Au? \)

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Photons in small systems

Photon yields

\[ \approx \eta \frac{\eta}{d_{ch} dN} 10^2 10^3 10^{10} \text{ GeV/c) } T / dy \ (p \gamma dN) \]

\[ = 2760 \text{ GeV} \]

PHENIX

Common scaling for Au+Au and Pb+Pb at different energies; very different from \( N_{coll} \)-scaled \( p+p \)
Photon yields

$\gamma_{\text{dir}} + X$

Common scaling for Au+Au and Pb+Pb at different energies; very different from $N_{\text{coll}}$-scaled $p+p$

$p+Au$ and $d+Au$ in between
Comparisons with STAR


FVTX EP: $0.65 < \Delta \eta < 3.35$

MPC EP: $2.75 < \Delta \eta < 4.05$

2PC: 3-sub event method with BBC, FVTX, CA

Nonflow is kinematically suppressed in PHENIX
Nonflow is kinematically suppressed in PHENIX

- STAR measurement uses kinematic range with more nonflow
  — Subtracted result matches PHENIX

- For highest $p_T$ points, oversubtraction is an issue
Comparisons with STAR

Nonflow is kinematically suppressed in PHENIX

We can also choose a different set of detectors to better (NOT exactly) match the STAR acceptance
—Good agreement with STAR unsubtracted results in this configuration (more nonflow)