PHENIX results on collective behavior in small systems from geometry-controlled experiments at
\[ \sqrt{s_{_{NN}}} = 200 \text{ GeV} \]
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Motivation

• Does initial geometry play a role?

RHIC geometry control experiments: change projectile/target

\[
\begin{align*}
\nu_2^{(3\text{HeAu})} & \sim \nu_2^{(d\text{Au})} \\
& > \nu_2^{(p\text{Au})} \sim \nu_2^{(p\text{Al})} \\
\nu_3^{(3\text{HeAu})} & > \nu_3^{(d\text{Au})}
\end{align*}
\]

Initial State Hot Spots

Collectivity in Final State

- 2\text{nd} order harmonics
- 2\text{nd} and 3\text{rd} order harmonics

Phys. Rev. Lett. 113, 112301 (2014), figure courtesy of B. Schenke
Hydrodynamics predicts:

• initial state eccentricity -> final state azimuthal correlation
  – Correlation functions in $p+Al$, $p/d/^{3}He+Au$
  – $v_{2}$ in $p+Al$, $p/d/^{3}He+Au$
  – $v_{3}$ in $d/^{3}He+Au$

• common flow velocity
  – $d+Au$ identified particle flow result shows mass ordering
  – identified particle flow in $p/^{3}He+Au$
Small system measurements in PHENIX

- The RHIC extraordinary collection of heavy ion collisions:
  - p+Al, p+Au, d+Au, $^3$He+Au, Cu+Au, Cu+Cu, Au+Au, U+U
- Geometry engineering at RHIC!
- Midrapidity: DC, PC, TOF -> tracking and PID
- Forward: BBC, MPC, FVTX -> triggering, event selection, correlations with midrapidity particles, event plane determination
High-multiplicity triggering

- High-multiplicity trigger in Beam Beam Counter

  - The trigger increases 0-5% most central events by 40 times in p+Au
    - by 15 times in d+Au
    - by 10 times in $^3$He+Au

More central collisions

Analysis methods

Two – particle correlation method

\[ \frac{dN}{d\Delta\phi} \propto 1 + \sum_{n} 2v_n^a v_n^b \cos(n\Delta\phi) \]

Event plane method:

\[ \frac{dN}{d\phi} = 1 + \sum_{n} 2v_n \cos(n(\phi - \Psi_n)) \]

- Particles of interest: tracks in mid-rapidity\(|\eta|<0.35\)
- Event plane determination:
  - Using detectors at larger pseudorapidity
  - Standard flattening and re-centering procedure applied
- Three sub-events method is used to evaluate the resolution.
Inclusive Hadrons
Correlation function in small systems


|Δη| > 2.75


arXiv:1609.02894

p+Al 200 GeV

0 - 5%
1.2 < p_T,trig < 3.0 (GeV/c)
-3.9 < η_asso < -3.0
-0.35 < η_trig < 0.35

PHENIX preliminary
Nonflow estimation in small systems

- Nonflow contribution is estimated by p+p minbias data scaled by its multiplicity.
- Cited as a systematic uncertainty instead of being subtracted.

**ArXiv:1609.02894**

Central p+Au

**Graph (a):**
- \( c_2^{\text{pAu}} \), cent:0-5%, \( <Q_{\text{bbc}}>=58.9 \)
- \( c_2^{\text{pp}} \times S, S = \frac{<Q_{\text{bbc}}^{\text{pp}}>}{<Q_{\text{bbc}}^{\text{pAu}}>}, c_2^{\text{pp}} \times S/c_2^{\text{pAu}} \)

**Graph (b):**
- Non flow at high pT
- 3He+Au: 5%
- d+Au: 10%
- p+Au: 25%
- p+Al: 33%
Charged $v_2$ Comparison between systems

- $v_2(^3\text{HeAu}) \sim v_2(\text{dAu})$
- $\varepsilon_2(^3\text{HeAu}) = 0.50$, $\varepsilon_2(\text{dAu}) = 0.54$
Charged $v_2$ Comparison between systems

- $v_2(pAu) \sim v_2(pAl)$
- $\varepsilon_2(pAu) = 0.23, \varepsilon_2(pAl) = 0.30$

Asymmetry systematics comes from nonflow effect.
Charged $v_2$ Comparison between systems

- $v_2(^3\text{HeAu}) \sim v_2(\text{dAu}) > v_2(\text{pAu}) \sim v_2(\text{pAl})$
- Geometry control works!
The $v_2/\varepsilon_2$ in p+Au is higher than that of d+Au and $^3$He+Au collisions.

$^3$He/d+Au – some events hot spots never connect and so $\varepsilon_2 \rightarrow v_2$ translation incomplete.

This behavior is within the expectation of SONIC model, which includes Glauber initial geometry and viscous hydro evolution.
Charged $v_2$ Compared to models

- SONIC model predicts the $v_2$ values in all three systems
- AMPT model can predict the three systems up to 1.5GeV/c
- IPGlasma+Hydrodynamic model underpredict the p+Au results but overpredict the d/$^3$He+Au results

arXiv:1609.02894
$v_2$ and $v_3$ in d/$^3$He+Au collisions

- $v_3$ in d+Au is systematically smaller than in $^3$He+Au
- SONIC prediction agrees with data qualitatively
$v_2$ and $v_3$ in $d/^{3}\text{He}+\text{Au}$ collisions

Model including pre-flow

- pre-flow makes the $v_2$ & $v_3$ larger
- Imply that pre-flow may not be so important at 200 GeV energy
Identified Particles
Identified particles $v_2$ in $p/d/^3\text{He}+\text{Au}$

Central $p+\text{Au}$

Central $d+\text{Au}$

Central $^3\text{He}+\text{Au}$

**$p+\text{Au}$ 200 GeV 0-5%**

**$d+\text{Au}$ 200 GeV 0-5%**

**$^3\text{He}+\text{Au}$ 200 GeV 0-5%**

$\pi^+\pi^-$

*Phys. Rev. Lett. 114, 192301, 2015*
Identified particles $v_2$ in $p/d/^{3}\text{He}+\text{Au}$

- Mass-ordering feature is observed in $p+\text{Au}$
- Less pronounced in $p+\text{Au}$ than in $d+\text{Au}$ and $^{3}\text{He}+\text{Au}$
- Consistent with hydrodynamic flow (common velocity field)

Details see Poster J17 by Weizhuang Peng
Identified particles $v_2$ between systems

- Pions and protons flow in p+Au are smaller than in d+Au and $^3$He+Au
Summary

• Ridge is seen in p+Al, p/d/³He+Au collisions
• Sizable $v_2$ is seen in p+Al/Au, smaller than d/³He+Au
• Non-zero $v_3$ is seen in d+Au, smaller than in ³He+Au
• Glauber + Hydrodynamics reproduces $v_2$ & $v_3$
• Eccentricity scaling understood
  ◦ eccentricity transferred to anisotropy incomplete
• Mass ordering observed in p+Au, less obvious than in d/³He+Au
Back Up
The familiar behavior of number of quark scaling observed in Au+Au collisions is also seen in the small $^3$He+Au system.
Details of the methods

Non flow estimation method:

\[ c_{2}^{dAu}(p_T) = c_{2}^{\text{Non-elem.}}(p_T) + c_{2}^{\text{Elem.}}(p_T) \]
\[ \approx c_{2}^{\text{Non-elem.}}(p_T) + c_{2}^{pp}(p_T) \frac{\sum E_{T}^{pp}}{\sum E_{T}^{dAu}} \]

Two particle correlation Method:

- 2-particle correlation between mid-rapidity tracks and backward (Au-going) charge particles
- Separated by 2.75 units in pseudo-rapidity

\[ M(\Delta \phi, p_T) : \text{mixed event} \]
\[ S(\Delta \phi, p_T) = \frac{d(w_{PMT} N_{\text{track}}(p_T) - \text{PMT})}{d\Delta \phi} \]
\[ C(\Delta \phi, p_T) = \frac{S(\Delta \phi, p_T) \int_{0}^{2\pi} M(\Delta \phi, p_T) d\Delta \phi}{M(\Delta \phi, p_T) \int_{0}^{2\pi} S(\Delta \phi, p_T) d\Delta \phi} \]
Charged particles: RHIC dAu and LHC pPb

- PHENIX dAu and LHC pPb results - similar $v_2$

*Phys. Rev. Lett. 114, 192301*
Initial eccentricity in Glauber models

PRL 113, 112301 (2014)
$^3$He/d+Au – some events hot spots never connect and so $\epsilon_2 \rightarrow v_2$ translation incomplete

PRL 113, 112301 (2014)