PHENIX results on collectivity in small systems

Weizhuang Peng
Vanderbilt University
Motivation

- Ridge observed in small systems
- Where does the flow in small systems come from?
  - Initial geometry translated into final flow
  - Initial state momentum correlation

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Geometry scan

- $\varepsilon_2(^3{\text{He}}+{\text{Au}}) \sim \varepsilon_2({\text{d}}+{\text{Au}}) > \varepsilon_2({\text{p}}+{\text{Au}})$
- $\varepsilon_3(^3{\text{He}}+{\text{Au}}) > \varepsilon_3({\text{d}}+{\text{Au}}) \sim \varepsilon_3({\text{p}}+{\text{Au}})$

Ref: Reaching for the horizon: The 2015 long range plan for nuclear science
Experimental method

We used event plane method to calculate $v_2$
GEOMETRY SCAN
$v_2$ in p/d/$^3$He+Au

$\varepsilon_2(^3\text{HeAu}) \sim \varepsilon_2(\text{dAu}) > \varepsilon_2(\text{pAu})$

- $v_2(^3\text{HeAu}) \sim v_2(\text{dAu}) > v_2(\text{pAu})$, consistent with eccentricity
- SONIC model describes the data well
$v_3$ in $d/\text{He}+\text{Au}$

$\epsilon_3(\text{HeAu}) > \epsilon_3(\text{dAu})$

- $v_3(\text{HeAu}) > v_3(\text{dAu})$
- Initial geometry translates into final state flow

$\sqrt{s_{nn}} = 200 \text{ GeV}$

- $\text{He}+\text{Au} v_2, v_3$ (PRL 115, 142301)
- $d+\text{Au} v_2, v_3$
Theory and the combined $v_2/v_3$ data

Look for updates at QM18

| Spatial eccentricity | p+Au     | d+Au     | $^3$He+Au |
|----------------------|----------|----------|-----------|
| $\langle \varepsilon_2 \rangle$ | 0.23±0.01 | 0.54±0.04 | 0.50±0.02 |
| $\langle \varepsilon_3 \rangle$ | 0.16±0.01 | 0.18±0.01 | 0.28±0.02 |

- Simultaneous description of both $v_2$ and $v_3$ provides a unique model test: excellent agreement with hydro for all available measurements.
FLOW OF IDENTIFIED PARTICLES
Identified particle flow

Quark number scaling in Au+Au at 200 GeV

Mass ordering of $v_2$ in p+Pb at 5 TeV

What happens in small systems at RHIC energies?
Evolution of the collision

- Pre-equilibrium
- Is QGP formed?
- Hadronization
- Hadronic phase freeze out

Models compared to data
SONIC vs superSONIC: Role of pre-flow
SONIC and iEBE vs AMPT: Role of hadronization by recombination
iEBE and AMPT with vs without hadronic rescattering: Role of hadronic rescattering

What we want to learn?
Identified particle $v_2$ in p/d/$^3$He+Au

- Mass splitting observed in all three systems
- Splitting more obvious in d/$^3$He+Au than in pAu
Hydro w/o pre-equilibrium stage

- p+Au at $\sqrt{s_{NN}} = 200$ GeV 0-5%
  - $\pi^+ + \pi^-$ Data
  - $p+\bar{p}$ Data
  - $\pi^+ + \pi^-$ SONIC
  - $p+\bar{p}$ SONIC

- d+Au at $\sqrt{s_{NN}} = 200$ GeV 0-5%
  - Data

- $^3$He+Au at $\sqrt{s_{NN}} = 200$ GeV 0-5%
Both calculations predict mass splitting at low $p_T$, which is smaller in $p+Au$ than in $d+Au$ and $^3He+Au$ as seen in the data.

Pre-equilibrium flow increases $v_2$ for both pions and protons and brings the result closer to the data.
Partonic stage and hadronization

In the hydro models the mass splitting in $v_2$ at low $p_T$ arises in the partonic phase due to the common flow field.
Partonic stage and hadronization

\( p+Au \text{ at } \sqrt{s_{NN}} = 200 \text{ GeV } 0-5\% \)

\( \pi^+ + \pi^- \text{ Data} \)
\( p+\bar{p} \text{ Data} \)
\( \pi^+ + \pi^- \text{ AMPT (no rescattering)} \)
\( p+\bar{p} \text{ AMPT (no rescattering)} \)

\( pAu \)

\( d+Au \text{ at } \sqrt{s_{NN}} = 200 \text{ GeV } 0-5\% \)

\( \text{PRL 114} \)

\( \pi^+ + \pi^- \text{ AMPT (no rescattering)} \)

\( \text{dAu} \)

\( ^3\text{He}+Au \text{ at } \sqrt{s_{NN}} = 200 \text{ GeV } 0-5\% \)

\( ^3\text{HeAu} \)
Partonic stage and hadronization

\[ p+Au \] at \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 0-5%

\( \pi^+ + \pi^- \) Data
- p+\bar{p} Data
- \( \pi^+ + \pi^- \) AMPT (no rescattering)
- p+\bar{p} AMPT (no rescattering)

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No splitting at low \( p_T \)
Partonic stage and hadronization

\[ p+Au \text{ at } \sqrt{s_{NN}} = 200 \text{ GeV} \ 0-5\% \]

- \( \pi^+ + \pi^- \) Data
- \( p+\bar{p} \) Data
- \( \pi^+ + \pi^- \) AMPT (no rescattering)
- \( p+\bar{p} \) AMPT (no rescattering)

\[ p_Au \]

\[ d+Au \text{ at } \sqrt{s_{NN}} = 200 \text{ GeV} \ 0-5\% \]

\[ ^3He+Au \text{ at } \sqrt{s_{NN}} = 200 \text{ GeV} \ 0-5\% \]

No splitting at low \( p_T \)

Splitting at high \( p_T \) comes from hadronization by recombination
Hadron rescattering stage

![Graph showing V2 vs. pT for p+Au, d+Au, and 3He+Au at √s_{NN} = 200 GeV 0-5%.](image)

- **p+Au at √s_{NN} = 200 GeV 0-5% (a)**
  - π^+π^- Data
  - p+p Data
  - π^+π^- iEBE-VISHNU (no rescattering)
  - p+p iEBE-VISHNU (no rescattering)

- **d+Au at √s_{NN} = 200 GeV 0-5% (b)**
  - PHENIX PRL 114

- **3He+Au at √s_{NN} = 200 GeV 0-5% (c)**

**Legend:**
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Hadron rescattering stage

(a) $p+\text{Au}$ at $\sqrt{s_{\text{NN}}} = 200$ GeV 0-5%

(b) $d+\text{Au}$ at $\sqrt{s_{\text{NN}}} = 200$ GeV 0-5%

(c) $^3\text{He}+\text{Au}$ at $\sqrt{s_{\text{NN}}} = 200$ GeV 0-5%
Hadron rescattering stage

No influence at low $p_T$
Hadron rescattering stage

No influence at low $p_T$  
The $v_2$ at higher $p_T$ is larger
Hadron rescattering stage

- **p+Au at $\sqrt{s_{NN}} = 200$ GeV 0-5%**
  - $\pi^+ + \pi^-$ Data
  - $p+\bar{p}$ Data
  - $\pi^+ + \pi^-$ AMPT (no rescattering)
  - $p+\bar{p}$ AMPT (no rescattering)

- **d+Au at $\sqrt{s_{NN}} = 200$ GeV 0-5%**

- **$^3$He+Au at $\sqrt{s_{NN}} = 200$ GeV 0-5%**

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**PRL 114**
Hadron rescattering stage

Mass splitting at low $p_T$ can also come from hadron rescattering.
**Pion $v_2$ over proton $v_2$**

Slope: $-0.22 \pm 0.07$  
$- 0.4 \pm 0.07$  
$- 0.34 \pm 0.03$

- Data in all systems exhibit a similar trend (systematics cancel in ratio)
- Both hydro and AMPT describe the mass splitting at low $p_T$.
- Hadronization by recombination can predict the ratio right at high $p_T$. 

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**Image Description**

The image contains plots showing the ratio of pion $v_2$ to proton $v_2$ for different systems: $pAu$, $dAu$, and $^3HeAu$. Each plot compares data with simulations from various models, including SuperSonic, iEBE-VISHNU, AMPT, and AMPT (no hadron rescattering). The plots are labeled with $\sqrt{s_{NN}} = 200$ GeV and 0-5% centrality. The data points are overlaid with smooth curves representing the models. The x-axis represents the transverse momentum ($p_T$) in GeV/c, while the y-axis shows the ratio of pion $v_2$ to proton $v_2$. The plots illustrate the trend across different $p_T$ values, with the slope values provided in the caption.
Approximate scaling in all three systems
Works better in larger systems
Summary

• Initial geometry translates into final state flow
• Mass splitting in $v_2$ is observed in all three systems: p/d/$^3$He + Au collisions
• Both hydro and AMPT describe the mass splitting at low $p_T$
  • hydro - from early stages through common flow velocity
  • AMPT - from late-stage hadronic rescattering
  • Different hadronic rescattering models (UrQMD and ART) have different predictions
• Reverse mass order at high $p_T$ described by recombination
• The quark scaling motivated by recombination is observed in the three small systems, more obvious in d+Au and $^3$He+Au collisions, where the multiplicity is higher
