Recent results on collective effects in small systems from PHENIX at RHIC

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Collectivity in Heavy Ion Collisions

STAR & PHOBOS found a ridge in h-h in Au+Au

Decompose $C(\Delta \phi)$ into Fourier components, $c_n$

\[
c_n(p_{T1}, p_{T2}) = v_n(p_{T1})v_n(p_{T2})
\]

STAR PRC 80 (2009) 064912
PHOBOS PRL 104 (2010) 062301

Luzum PLB 696 (2011) 499
ALICE PLB 708 (2012) 249

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A+A $v_n$ at LHC and RHIC

- Similar anisotropies at LHC and RHIC

- $v_n$ well described by the same hydrodynamic model

- Similar underlying physics processes
Collectivity in p+Pb at LHC

CMS, ATLAS and ALICE see a ridge in 5 TeV p+Pb

CMS PLB 718 (2013) 795
ATLAS PRL 110 (2013) 182302
ALICE PLB 719 (2013) 29
Small Systems → Initial State Geometry

This talk: 200 GeV d+Au, $^3$He+Au and p+Au at PHENIX

Image from B. Schenke
d+Au
d+Au: Long-range Correlation Measurement

\[ |\Delta \eta| \in [2.75, 4.05] \]

Ridge in d+Au confirmed at RHIC

PRL 114 192301 (2015)
Reach higher $p_T$ with $\pi^0$-MPC

- Ridge stronger in central d+Au
  - similar behavior to low $p_T$ h-MPC

Measurement out to 8 GeV/c
Reach higher $p_T$ with $\pi^0$-MPC

Measurement out to 8 GeV/c

Study energy loss in $d+A$?

Reach higher $p_T$ with $\pi^0$-MPC

Measurement out to 8 GeV/c

Study energy loss in $d+A$?
Mass ordering, similar to what is seen in A+A

\[
n_2 = \frac{\langle \cos 2(\phi - \Psi_{EP}) \rangle}{\text{Res}(\Psi_{EP})}
\]

PRL 114 192301 (2015)
$^3$He+Au and p+Au
Detector Upgrades

High Multiplicity Trigger

Almost all central events are recorded
$^3\text{He}+\text{Au}: \text{Event-plane Measurement}$

$v_3 > 0$ seen in $^3\text{He}+\text{Au}$, as expected from initial collision geometry

PRL 115 (2015) 142301
$^3\text{He}+\text{Au}: \text{Event-plane Measurement}$

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

PHENIX data $v_2$, $v_3$

SONIC, superSONIC, Glauber+Hydro, IPGPlasma+Hydro, AMPT

$PRL \ 115 (2015) \ 142301$
Identified particle $v_2$ in $^3\text{He}+\text{Au}$

Mass-ordering

Meson-baryon splitting

Follows $n_q$-scaling, much like $A+A$
\[ \frac{\nu_n}{\left(\epsilon_n \sqrt[3]{N_{Part}}\right)} \] scaling

Does not work as well in small collision systems, especially \( v_3 \)

Higher-order anisotropy damps quickly in small collision systems
$^3\text{He}+\text{Au}, \ p+\text{Au}: \text{Long-range Correlation Measurements}$

PRL 115 (2015) 142301

$|\Delta \eta| \in [2.75, 4.05]$
$v_2$ in p+Au, d+Au, $^3$He+Au

$v_2$ follows $\epsilon_2$ ordering

$$\epsilon_2^{d+Au} \sim \epsilon_2^{^3He+Au}$$

$$\epsilon_2^{d+Au} > \epsilon_2^{p+Au}$$
Theory comparisons

\[ \eta/s = 0.12 \]

\[ \eta \]
Conclusions

• Initial state geometric effects
  – $\varepsilon_2$ ordering of $v_2$ in $p+Au$, $d+Au$, $^3He+Au$
  – $v_3$ in $^3He+Au$

• Hydrodynamic modeling

• Mass ordering of $v_2$ in $d+Au$, $^3He+Au$ at low $p_T$
  – $n_q$-scaling of $v_2$ in $^3He+Au$

• Faster damping $v_3$ in $^3He+Au$

• Extend $p_T$ out to 8GeV/c in $d+Au$ using $\pi^0$-MPC
d+Au: Central Arm
Correlation Measurement

PHENIX, 200 GeV, d+Au, 0-5%, $\Delta\eta \in [0.48, 0.7]$

ATLAS, 5.02 TeV, p+Pb, 0-2%, $\Delta\eta \in [2, 5]$

Suggests ridge-like behavior in d+Au at RHIC

PHENIX PRL 111 212301 (2013)
ATLAS PRL 110 182302 (2012)
Estimating non-flow

\[ c_n^{d+Au} = c_n^{Non-Elem.} + c_n^{Elem.} \]

\[ c_n^{Elem.} \approx c_n^{p+p} \frac{\sum E_T^{p+p}}{\sum E_T^{d+Au}} \]
High multiplicity trigger in $^3$He+Au

Almost all central events are recorded

10 $\times$ enhancement of high multiplicity events

PRL 115 (2015) 142301
$^3$He+Au, p+Au: Long-range Correlation Measurements

$v_2$ follows $\epsilon_2$ ordering

PRL 115 (2015) 142301
AMPT Comparison

Orjuela-Koop et. al. PRC 92 (2015) 054903
\[ \frac{V_2}{\varepsilon_2} \]

\[ \langle p_T \rangle \approx 1.4 \text{ GeV/c} \]

Data points represent different experiments and conditions:
- \( d+Au, \varepsilon_2 \) (point-like centers) \( (\sqrt{s}=200 \text{ GeV}) \)
- \( Au+Au, \varepsilon_2 \) (point-like centers) \( (\sqrt{s}=200 \text{ GeV}) \)
- \( \varepsilon_2 \) (Gaussian smearing \( \sigma = 0.4 \))
- \( \varepsilon_2 \) (disks, \( R = 1 \text{ fm} \))
- CMS Pb+Pb \( \frac{v_2}{\varepsilon_2} \) (\( \sqrt{s}=2.76 \text{ TeV} \))
- CMS Pb+Pb \( \frac{v_2}{\varepsilon_2} \) (\( \sqrt{s}=2.76 \text{ TeV} \))
- ATLAS p+Pb (\( \sqrt{s}=5 \text{ TeV} \))
- ALICE p+Pb (\( \sqrt{s}=5 \text{ TeV} \))
Collectivity in p+p
Abstract

• Collisions of simple systems, such as p+p, or p+Nucleus have been used as benchmarks for our understanding of Heavy Ion Collisions, since it was assumed they would be free of the effects from hot nuclear matter.

Recently long range correlations and anisotropies of momentum spectra have been seen in such collisions, challenging this assumption. Such phenomena have been understood to be the result of the collective motion, which can best be described by hydrodynamics, whose initial conditions are set by the geometry of the colliding systems, together with their fluctuations. This talk will discuss the recent results from the PHENIX experiment at RHIC using a variety of colliding species (p+Au, d+Au, He3+Au) which give a better understanding of the origin of the observed correlations and anisotropies, thus providing insight as to whether a Quark Gluon Plasma is formed in these simple system