Implications for small-system collectivity from wide-range soft physics measurements in p+A collisions by PHENIX

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Motivation

p+Au

d+Au

$^3$He+Au

p+A collisions -> Cold Nuclear Effect & Important handle for collectivity

Phys. Rev. Lett. 113, 112301 (2014), figure courtesy of B. Schenke
Motivation

See more at session ‘Collectivity in small systems’ 11:10am 15th by Sylvia Morrow

Mid-rapidity, Initial geometry

v₂ in p/d/³He+Au

v₃ in p/d/³He+Au

Extend collectivity study to different kinetic ranges in p+A
Do we have more soft observables?

A wide range of longitudinal observables are needed to understand soft processes in p+A

Question: How is the flow related to longitudinal particle production?

• Longitudinal dynamics

Question: How do fluctuations contribute to the collectivity?

• Flow fluctuations

Question: In what degrees of freedom does the particle flow collectively in p+A?

• Flow for identified particles

A Coherent Picture in p+A!
Small system measurements in PHENIX

- **Midrapidity**: DC, PC, TOF -> tracking and PID
- **Forward**: BBC, FVTX -> triggering, event selection, correlations with midrapidity particles, event plane determination
- **Muon arm**: FVTX, Muon Tracking, Muon ID -> heavy flavor tracking and identification
Longitudinal dynamics
$v_2(\eta)$ vs $dN_{ch}/d\eta$ in Geometry Control Scan

- **green:** $v_2(\eta)$
- **blue:** scaled $dN_{ch}/d\eta$
- **Curve:** $v_2$ 3D hydro

- **p+Au** scales well, but **d+Au** does not at backward rapidity
- 3D hydrodynamics quantitatively describes the data in **p+Au**

The event plane is measured in $-3.9 < \eta < -3.1$
\(v_2(\eta)\) at different centrality bins in \(p+Au\)

- \(v_2(\eta)\) is enhanced at backward rapidity where the multiplicities are higher.
- Peripheral events exhibit more non-flow effect.

Wide rapidity range
Longitudinal dynamics

- Larger flow in backward region than in forward region
- Flow and longitudinal particle productions do not scale well in p+A
- Non-flow effects are important
Flow fluctuations
Multi-particle correlations in p+Au


- Adding $\eta$ gap suppresses non-flow
- Multi-particle correlation suppresses non-flow quite effectively

Why is $v_2(4)$ in p+Au complex?

$v_2(4) = (-c_2(4))^{1/4}$

$c_2(4)$ positive $\leftrightarrow$ $v_2(4)$ complex
Multi-particle correlations in d+Au

- $v_2\{2\}$ observed
- $v_2\{2, |\Delta \eta| > 2\}$
- $v_2\{4\}$
- $v_2\{6\}$

- Real $v_2\{4\}$ observed
- $v_2\{4\} \approx v_2\{6\}$, strong indication of collectivity


Why are they different?
Flow fluctuation from multi-particle correlations

- \( v_2^2 [\eta \text{ gap}]^2 \approx v_2^2 + \sigma_{v_2}^2 \)
- \( v_2^4 \approx v_2^2 - \sigma_{v_2}^2 \)
- If fluctuation \( \sigma_{v_2} > \text{mean } v_2 \), \( c_2^4 \) is positive
- Implies collectivity in p+Au is dominated by fluctuations, while d+Au is not
- AMPT (A Multi-phase transport model) describes the sign

\[ \text{Phys. Rev. Lett. 120, 062302 (2018)} \]
Multi-particle correlations in p+A

$p+A$ at RHIC energy has more contributions from fluctuations than LHC energy.

$v_2^4$ in $p+Au$ is complex.

$v_2^4$ in $p+Pb$ is positive.

- $p+A$ at RHIC energy has more contributions from fluctuations than LHC energy.
Flow fluctuations

- Small variance limit breaks in p+Au but not d+Au

- Flow fluctuations are the main source of collectivity in p+Au forward/backward rapidities
Flow for identified particles
$v_2(p_T)$ KET scaling for identified $\pi^\pm$ and protons

- Approximate quark number scaling, similar to A+A collisions
- The scaling in larger systems holds better generally
$v_2(p_T)$ for heavy flavor muons

- First measurement of heavy flavor $v_2$ in small collision systems at RHIC
- Heavy quarks flow even in small collision systems!
$R_{pAu}$ for direct photons

- Central $p+Au$ collisions shows direct photon $R_{pAu} > 1$
- Data suggests thermal photon yields
Flow for identified particles

• Identified particles flow in a wide range in p+A at RHIC
• Thermal photons yields indicates the existence of QGP
• Flow shows quark number degrees of freedom in p+A
Summary and Conclusions

• Flow and longitudinal particle productions do not scale well in p +A and non-flow effects are important

• Small variance limit breaks in p+A and fluctuations are the main source of collectivity

• Identified particles flow in a wide range in p+A at RHIC

• Flow shows quark number degrees of freedom in p+A

• Hydrodynamics describes (nearly) all the observables

• Any model should describe all the observables simultaneously
Back Up
Motivation

At RHIC, two important control experiments are done:

- Geometry Control Scan -> Change the projectiles and/or targets
- Beam Energy Scan on d+Au -> Ranges from 20 GeV to 200 GeV


Hydrodynamics does a good job describing these; Some other models also work

At RHIC, two important control experiments are done:

- Geometry Control Scan -> Change the projectiles and/or targets
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Complete sets of GCS

At RHIC, two important control experiments are done:

- Geometry Control Scan -> see Sylvia’s presentation tomorrow
- Beam Energy Scan on d+Au -> ranges from 20 GeV to 200 GeV

\[ \eta/s = 0.08 \text{ in both models} \]

hydrodynamical models provide a simultaneous and quantitative description of the data in all three systems.

arxiv:1805.02973
$v_2(p_T)$ for identified $\pi^\pm$ and protons

$\text{arXiv:1710.09736, accepted by Phys. Rev. C}$

System Size Increases

- $v_2(\pi^\pm) > v_2(\text{proton})$ at $p_T < 1.5$ GeV/c, reversed at higher $p_T$
- The hydro model describes the low-$p_T$ mass-ordering in $v_2(p_T)$ well
\[ v_2(\eta) \] vs \( dN_{ch}/d\eta \) in Geometry Control Scan

- \( d+Au \) scales well, but \( p+Au \) does not at backward rapidity, non-flow becomes more significant
- 3D hydrodynamics quantitatively describes the data in \( p+Au \)

The event plane is measured in \(-3.9 < \eta < -3.1\)
\( v_2(\eta) \) vs \( dN_{\text{ch}}/d\eta \) in Beam Energy Scan

*Phys. Rev. C 96, 064905 (2017)*

- Scaling holds, except at lower energy backward rapidity
- \( v_2(\eta) \) contains non-flow
- Flow & non-flow anti-correlation?

See more at session ‘Phase diagram and search for the critical point’ 10:20am 16th by Darren McGlinchey

Energy Decreases

Wide rapidity range

The event plane is measured in \(-3.0 < \eta < -1.0\)
Analysis methods for Flow

Two – particle correlation method

Pairs: \[ \frac{dN}{d\Delta \phi} \propto 1 + \sum_n 2v_n^a v_n^b \cos(n\Delta \phi) \] 2PC method

Event plane method:

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

Multi-particle correlation method:

\[ \langle 2 \rangle \equiv \left< e^{in(\phi_1 - \phi_2)} \right> \equiv \frac{1}{P_{M,2}} \sum_{i,j} e^{in(\phi_i - \phi_j)} \]

\[ \langle 4 \rangle \equiv \left< e^{in(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \right> \equiv \frac{1}{P_{M,4}} \sum_{i,j,k,l} e^{in(\phi_i + \phi_j - \phi_k - \phi_l)} \]
v_2(p_T) and v_3(p_T) for hadrons

\[ v_2^{p+Au} < v_2^{d+Au} \approx v_2^{3\text{He}+Au}, \]
\[ v_3^{p+Au} \approx v_3^{d+Au} < v_3^{3\text{He}+Au}. \]

- Hydrodynamics can efficiently translate the initial geometric \( \varepsilon_n \)'s into \( v_n \)'s.
- Rule out initial moment correlation picture where we expect:

\[ v_n^{p+Au} > v_n^{d+Au} > v_n^{3\text{He}+Au}, \]
Eccentricity distribution

- High skewness in p+Au, deviates from Gaussian
- Additional flow fluctuation in p+Au must take place

200 GeV
$v_2(p_T)$ in different centrality bins
dN_{ch}/d\eta vs centrality in p+Au

- Wounded Quark Model: Heavy-Ion collisions consists of independent quark-quark collisions
- Assuming a common quark source

\[ \frac{dN_{ch}}{d\eta} \text{ in BES} \]


d_{N_{ch}}/d\eta vs v_2(\eta) in small systems

- Hydro describes the shape well, although deviation in the very backward region
- All the small system d_{N_{ch}}/d\eta scales with N_{part}

(34)
$v_2(\eta)$ and $dN_{ch}/d\eta$ in models

- Bozek model is a hydrodynamics model
- The trend in data is well captured by AMPT/Hydro model

Energy Decreases

Multi-particle correlation in Pb+Pb and p+Pb
$v_2(\eta)$ and $v_2(\text{centrality})$ for hadrons