Collective flow from AA, pA to pp

— Toward a unified paradigm

Wei Li
Rice University

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Collective phenomena

a central theme in the study of strongly correlated, interacting many-body systems

QGP
Ultra-cold Fermi gas

Neutron stars

small
large

Complex frontier – “Emergence”
Collective phenomena

a central theme in the study of strongly correlated, interacting many-body systems

QGP  Ultra-cold Fermi gas  Neutron stars

small  large

Complex frontier – “Emergence”

The key question:

- What is the underlying mechanism to drive?
- Can be understood from fundamental forces?
Emergent phenomena in pp, pA and AA

Novel azimuthal correlations

ATLAS  $p+Pb$
$\sqrt{s_{NN}}=5.02$ TeV, 28 nb$^{-1}$

$0.5<p_{T}^{a,b}<5$ GeV
$N_{\text{ch}}^{\text{rec}}>220$

$\eta, \Delta \phi$

$C(\Delta \eta, \Delta \phi)$

Preliminary ATLAS
$\sqrt{s_{NN}}=5.02$ TeV, 22 $\mu$b$^{-1}$

$2<p_{T}^{a,b}<3$ GeV
(25-30)$%$

$0.5<p_{T}^{a,b}<5.0$ GeV
$N_{\text{ch}}^{\text{rec}} \geq 120$

$\eta, \phi$

$C(\Delta \eta, \Delta \phi)$

PbPb

$Pb+Pb$

0.98

$0.5<p_{T}^{a,b}<5$ GeV
$N_{\text{ch}}^{\text{rec}}>220$

$0.98$

$\cos(2\Delta \phi)$

Pp

$N_{\text{ch}}^{\text{rec}}\geq120$

$0.98$

$0.5<p_{T}^{a,b}<5.0$ GeV

$0.98$

$\eta, \phi$

$C(\Delta \eta, \Delta \phi)$

Pp

$N_{\text{ch}}^{\text{rec}}\geq120$

$0.98$

$\eta, \phi$

$C(\Delta \eta, \Delta \phi)$
Emergent phenomena in pp, pA and AA

Novel azimuthal correlations

\( \Delta \eta, \Delta \phi \)

\( C(\Delta \eta, \Delta \phi) \)

\( \cos(2\Delta \phi) \)

✿ Long-range in \( \eta \)
Emergent phenomena in pp, pA and AA

Novel azimuthal correlations

![Graph showing v2(2Δφ) vs. N_{trk}](image)

- Long-range in η
- Collective
  - v2{4} ≈ v2{6} ≈ v2{8} ≈ v2{∞}
  - Independent of N_{trk}
  - Mass ordering...

**ATLAS** p+Pb
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV, } 28 \text{ nb}^{-1} \]
\[ 0.5<p_T^{a,b}<5 \text{ GeV} \]
\[ N_{\text{ch}}^{\text{rec}} = 220 \]

**PRL 115 (2015) 012301**

**CMS**
\[ \sqrt{s_{NN}} = 5.02 \text{ TeV, } L_{\text{int}} = 35 \text{ nb}^{-1} \]
\[ 0.3 < p_T < 3.0 \text{ GeV/c; } |η| < 2.4 \]

**ALICE**
\[ p-\text{Pb} \quad \sqrt{s_{NN}} = 5.02 \text{ TeV} \]
\[ (0-20\%) - (60-100\%) \]
\[ v_2(2\text{PC, sub}) \]
\[ p_T \text{ (GeV/c)} \]

**PLB726 (2013) 164**
Emergent phenomena in pp, pA and AA

Novel azimuthal correlations

\[ \cos(2\Delta\phi) \]

\[ \Delta \eta \]

\[ \eta \]

\[ \Delta \phi \]

\[ v_2 \]

\[ pPb \]

\[ ATLAS \]

\[ p+Pb \]

\[ \sqrt{s_{NN}}=5.02 \text{ TeV}, 28 \text{ nb}^{-1} \]

\[ 0.5<p_T^{a,b}<5 \text{ GeV} \]

\[ N_{\text{rec}}=220 \]

\[ \text{CMS} \]

\[ CMS \text{ pPb} \]

\[ \sqrt{s_{NN}}=5.02 \text{ TeV}, L_{\text{int}}=35 \text{ nb}^{-1} \]

\[ 0.3<p_T<3.0 \text{ GeV/c}; |\eta|<2.4 \]

\[ v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\} \]

\[ \text{Collective} \quad \Rightarrow \quad \text{Interactions} \]

\[ \text{Long-range in } \eta \]

\[ \text{Independent of } N_{\text{trk}} \]

\[ \text{Mass ordering} \]

\[ \ldots \]
Emergent phenomena in pp, pA and AA

Long-range anisotropy in $\eta$

Rooted in initial/early stage

$$\tau_O \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right)$$

arXiv:1509.07939
Emergent phenomena in pp, pA and AA

Long-range anisotropy in $\eta$

Rooted in initial/early stage

$$\tau_O \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right) \sim 0.1 \text{ fm/c}$$

arXiv:1509.07939
Emergent phenomena in pp, pA and AA

Long-range anisotropy in $\eta$

Rooted in initial/early stage

$$\tau_O \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right) \sim 0.1 \text{ fm/c}$$

Initial spatial $\varepsilon_s$

Initial momenta $\varepsilon_p$

arXiv:1509.07939
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$$\tau_O \leq \tau_{F.O.} \exp \left( -\frac{1}{2} |y_a - y_b| \right) \sim 0.1 \text{ fm/c}$$

Initial spatial $\varepsilon_s$ + final interactions

Initial momenta $\varepsilon_p \sim q_z^{-1}$

arXiv:1509.07939
Emergent phenomena in pp, pA and AA

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$$\tau_O \leq \tau_{F.O.} \exp\left(-\frac{1}{2}|y_a - y_b|\right) \sim 0.1 \text{ fm/c}$$

Scenario #1

Hydrodynamics

Parton transport, escape

Initial spatial $\varepsilon_s$ + final interactions

Initial momenta $\varepsilon_p$
Emergent phenomena in pp, pA and AA

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Parton transport, escape

Initial spatial $\epsilon_s$ + final interactions

Initial momenta $\epsilon_p$ by initial interactions
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Scenario #1

Initial spatial $\varepsilon_s$ + final interactions

Hydrodynamics
Parton transport, escape

Scenario #2

Initial momenta $\varepsilon_p$ by initial interactions

CGC Glasma
Color-field domains, etc.

arXiv:1509.07939
Perfect-liquid paradigm of AA collisions

Initial state: \( \epsilon(x, y, \eta^s) \)

Event-by-event

Pre-equilibrium

Hydrodynamics
\[ \partial_\mu T^{\mu\nu} = 0 + (\eta, \zeta, \ldots) \]

Freeze-out; Hadronic transport

Final state: \( f(p_T, \eta, \phi) \)
Perfect-liquid paradigm of AA collisions

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\[ \varepsilon(x, y, \eta^s) \]

Event-by-event

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Hydrodynamics
\[ \partial_\mu T^{\mu\nu} = 0 + (\eta, \zeta, ...) \]

Freeze-out;
Hadronic transport

Final state:
\[ f(p_T, \eta, \phi) \]

Fourier bases:
\[ f(p_T, \eta, \phi) = N(p_T, \eta) \sum_{n=-\infty}^{+\infty} \tilde{V}_n(p_T, \eta) e^{-in\phi} \]
Perfect-liquid paradigm of AA collisions

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\[ \varepsilon(x, y, \eta^s) \]

Event-by-event

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\[ \partial_\mu T^{\mu\nu} = 0 + (\eta, \zeta, ...) \]

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Radial flow
Perfect-liquid paradigm of AA collisions

Initial state:
\[ \varepsilon(x, y, \eta^s) \]

Event-by-event
- Pre-equilibrium
- Hydrodynamics
\[ \partial_\mu T^{\mu\nu} = 0 + (\eta, \zeta, ...) \]
- Freeze-out; Hadron transport

Final state:
\[ f(p_T, \eta, \phi) \]

Fourier bases:
\[ f(p_T, \eta, \phi) = N(p_T, \eta) \sum_{n=-\infty}^{+\infty} \tilde{V}_n(p_T, \eta) e^{-in\phi} \]

Radial flow
- \( \tilde{V}_n = v_n e^{in\psi_n} \)

Anisotropy flow
Perfect-liquid paradigm of AA collisions

**Initial state:**

\[ \varepsilon(x, y, \eta^s) \]

- Fourier bases:

\[ f(p_T, \eta, \phi) = N(p_T, \eta) \sum_{n=-\infty}^{+\infty} \vec{V}_n(p_T, \eta) e^{-in\phi} \]

- Radial flow

\[ \vec{V}_n = v_n e^{in\psi_n} \]

**Graph:**

- ATLAS Preliminary
- Pb+Pb, 5 \( \mu b^{-1} \)
- \( |\vec{s}_{NN}| = 5.02 \text{ TeV} \)
- \( |\eta| < 2.5 \)
Perfect-liquid paradigm of AA collisions

A precision era with still open questions:

- Details of dynamics in $3+1D$:
  - Initial state in 3D – $\varepsilon(x,y,\eta^s)$
  - Transport properties – $\eta/s(T)$, $\zeta/s(T)$, …
Perfect-liquid paradigm of AA collisions

A precision era with still open questions:

- Details of dynamics in \( 3+1 \text{D} \):
  - Initial state in 3D – \( \varepsilon(x,y,\eta^s) \)
  - Transport properties – \( \eta/s(T), \zeta/s(T), \ldots \)

- Do small systems fit into the paradigm?
Perfect-liquid paradigm of AA collisions

A precision era with still open questions:

- Details of dynamics in $3+1D$:
  - Initial state in $3D$ – $\varepsilon(x,y,\eta^s)$
  - Transport properties – $\eta/s(T)$, $\zeta/s(T)$, ...

- Do small systems fit into the paradigm?

Toward extracting full final-state information

$$\text{pdf}(N(p_{T},\eta), \vec{V}_1(p_{T},\eta), \vec{V}_2(p_{T},\eta), ...)$$
Perfect-liquid paradigm of AA collisions

A precision era with still open questions:

- Details of dynamics in 3+1D:
  - Initial state in 3D – $\varepsilon(x,y,\eta^s)$
  - Transport properties – $\eta/s(T)$, $\zeta/s(T)$, …

- Do small systems fit into the paradigm?

Practically, “New” flow observables:

1. $\{\vec{V}_n, \vec{V}_m\}$ — Mixed-order harmonics correlations
2. $\{\vec{V}_n(p_{T,1},\eta_1), \vec{V}_n(p_{T,2},\eta_2)\}$, $\{N(p_{T,1},\eta_1), N(p_{T,2},\eta_2)\}$ — Details of initial states
Correlations of harmonics \((V_n, V_m)\)

\[ v_n - v_m \text{ correlations} \]

\[ SC(n, m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \]

\[ \rightarrow \quad SC(2, 3) < 0, \quad SC(2, 4) > 0 \]
Correlations of harmonics \((V_n, V_m)\)

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As

\[ v_2 = K_2 \varepsilon_2 \]

\[ v_3 = K_3 \varepsilon_3 \]

SC(2,3) directly probes the initial state

– fluctuation granularities
Correlations of harmonics \((V_n, V_m)\)

\[
V_n - V_m \text{ correlations}
\]

\[
SC(n, m) = \left< v_n^2 v_m^2 \right> - \left< v_n^2 \right> \left< v_m^2 \right>
\]

\[
\rightarrow \quad SC(2,3) < 0, \quad SC(2,4) > 0
\]

As

\[
v_2 = K_2 \epsilon_2
\]

\[
v_3 = K_3 \epsilon_3
\]

SC(2,3) directly probes the initial state

– fluctuation granularities
Correlations of harmonics \((V_n, V_m)\)

Moving to higher-order harmonics

\[ V_4 \neq K_4 \epsilon_4 \]
\[ V_5 \neq K_5 \epsilon_5 \]
\[ \vdots \]

Linear responses to initial geometry do not hold for \(n \geq 4\)
Correlations of harmonics \((V_n, V_m)\)

Moving to higher-order harmonics

\[ V_4 \neq K_4 \epsilon_4 \]
\[ V_5 \neq K_5 \epsilon_5 \]

Linear responses to initial geometry do not hold for \(n \geq 4\)

Because of mixing with lower orders \((v_2, v_3)\)

\[ \vec{V}_4 = \vec{V}_{4L} + \chi_{422} (\vec{V}_2)^2 \]
\[ \vec{V}_5 = \vec{V}_{5L} + \chi_{523} \vec{V}_2 \vec{V}_3 \]
\[ \vec{V}_6 = \vec{V}_{6L} + \chi_{6222} (\vec{V}_2)^3 + \chi_{633} (\vec{V}_3)^2 \]
\[ \vec{V}_7 = \vec{V}_{7L} + \chi_{7223} (\vec{V}_2)^2 \vec{V}_3 \]

\[ \vdots \]
Correlations of harmonics \((V_n, V_m)\)

Moving to higher-order harmonics

\[ v_4 \neq K_4 \varepsilon_4 \]
\[ v_5 \neq K_5 \varepsilon_5 \]
\[ \vdots \]

Because of mixing with lower orders \((v_2, v_3)\)

\[ \mathbf{V}_4 = \mathbf{V}_{4L} + \chi_{422} \left( \mathbf{V}_2 \right)^2 \]
\[ \mathbf{V}_5 = \mathbf{V}_{5L} + \chi_{523} \mathbf{V}_2 \mathbf{V}_3 \]
\[ \mathbf{V}_6 = \mathbf{V}_{6L} + \chi_{6222} \left( \mathbf{V}_2 \right)^3 + \chi_{633} \left( \mathbf{V}_3 \right)^2 \]
\[ \mathbf{V}_7 = \mathbf{V}_{7L} + \chi_{7223} \left( \mathbf{V}_2 \right)^2 \mathbf{V}_3 \]
\[ \vdots \]

**Leading terms:** not exactly \( \propto \varepsilon_n \)
Correlations of harmonics \( (V_n, V_m) \)

Moving to higher-order harmonics

\[
V_4 \neq K_4 \mathcal{E}_4 \\
V_5 \neq K_5 \mathcal{E}_5 \\
\vdots
\]

Because of mixing with lower orders \((v_2, v_3)\)

\[
\begin{align*}
\vec{V}_4 &= \vec{V}_{4L} + \chi_{422} \left( \vec{V}_2 \right)^2 \\
\vec{V}_5 &= \vec{V}_{5L} + \chi_{523} \vec{V}_2 \vec{V}_3 \\
\vec{V}_6 &= \vec{V}_{6L} + \chi_{6222} \left( \vec{V}_2 \right)^3 + \chi_{633} \left( \vec{V}_3 \right)^2 \\
\vec{V}_7 &= \vec{V}_{7L} + \chi_{7223} \left( \vec{V}_2 \right)^2 \vec{V}_3 \\
\end{align*}
\]

**Nonlinear terms:** sensitive to final-state dynamics

**Leading terms:** not exactly \( \propto \mathcal{E}_n \)
Correlations of harmonics \((V_n, V_m)\)

Moving to higher-order harmonics

\[ V_4 \neq K_4 \varepsilon_4 \]
\[ V_5 \neq K_5 \varepsilon_5 \]
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Because of mixing with lower orders \((v_2, v_3)\)

\[ V_4 = V_{4L} + \chi_{422} (V_2)^2 \]
\[ V_5 = V_{5L} + \chi_{523} V_2 V_3 \]
\[ V_6 = V_{6L} + \chi_{6222} (V_2)^3 + \chi_{633} (V_3)^2 \]
\[ V_7 = V_{7L} + \chi_{7223} (V_2)^2 V_3 \]
\[ \vdots \]

Leading terms: not exactly \(\propto \varepsilon_n\)

Nonlinear terms: sensitive to final-state dynamics

Orthogonal
Correlations of harmonics ($V_n$, $V_m$)

Non-linear response coefficients

\[ \chi_{422} = \frac{\langle \bar{V}_4 (\bar{V}_2^*)^2 \rangle}{\langle |\bar{V}_2|^4 \rangle} \]

\[ \chi_{523} = \frac{\langle \bar{V}_5 \bar{V}_2^* \bar{V}_3^* \rangle}{\langle |\bar{V}_2|^2 |\bar{V}_3|^2 \rangle} \]

\[ \chi_{7223} = \frac{\langle \bar{V}_7 (\bar{V}_2^*)^2 \bar{V}_3^* \rangle}{\langle |\bar{V}_2|^4 |\bar{V}_3|^2 \rangle} \]

CMS Preliminary, 0.3 < $p_T$ < 3.0 GeV/c, $|\eta| < 2.4$

New constraints to freeze-out dynamics
Evolution of the QGP in 3+1D

Longitudinal dynamics not fully explored yet

- How is the initial entropy deposited in 3D space? How it fluctuates event-by-event?
- What is the role of longitudinal pressure?
Initial states in 3D

Torqued QGP fireball
(Bozek et.al., arXiv:1011.3354)
Initial states in 3D

Torqued QGP fireball

(Bozek et.al., arXiv:1011.3354)
**Initial states in 3D**

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**Granularity of gluon fields**
(Schenke, Schlichting, arXiv:1605.07158)
Initial states in 3D

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Granularity of gluon fields
(Schenke, Schlichting, arXiv:1605.07158)

\[ \left\langle \tilde{\varepsilon}_n(\eta_1^s)\tilde{\varepsilon}_n^*(\eta_2^s) \right\rangle \rightarrow \left\langle \tilde{V}_n(\eta_1)\tilde{V}_n^*(\eta_2) \right\rangle \]

– rapidity-correlated flow fluctuations
Rapidity-correlated flow fluctuations

\[ r_n \equiv \frac{\langle \vec{V}_n(-\eta^a)\vec{V}_n^*(\eta^b) \rangle}{\langle \vec{V}_n(\eta^a)\vec{V}_n^*(\eta^b) \rangle} \sim \langle \cos n \left[ \Psi_n(\eta^a) - \Psi_n(-\eta^a) \right] \rangle \quad \text{"Event-plane decorrelations"} \]

\[ r_2(\eta^a,\eta^b) \]

PbPb \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

PRC92 (2015), 034911

CMS, 0-5%

AMPT IS + 3D Hydro.

Torque IS

3D-glasma IS, \( \alpha_s = 0.025 \)

4.4 < \( \eta_b \) < 5
Rapidity-correlated flow fluctuations

\[ \left| V_n(-\eta^a)V_n^*(\eta^b) \right| \sim \left| \cos n\left[ \Psi_n(\eta^a) - \Psi_n(-\eta^a) \right] \right| \]

“Event-plane decorrelations”

Transverse dynamics is approx. **boost invariant**, but **NOT** for the initial states (3D)
Rapidity-correlated flow fluctuations

\[ r_n = \frac{\langle \mathbf{V}_n(-\eta^a) \mathbf{V}^*_n(\eta^b) \rangle}{\langle \mathbf{V}_n(\eta^a) \mathbf{V}^*_n(\eta^b) \rangle} \int \langle \cos n [\Psi_n(\eta^a) - \Psi_n(-\eta^a)] \rangle \]

"Event-plane decorrelations"

Transverse dynamics is approx. **boost invariant**, but **NOT** for the initial states (3D)
Rapidity-correlated flow fluctuations

Minimize $\varepsilon_n$ fluct. and single out EP twist

$$R_n \equiv \frac{\left\langle \vec{V}_n(-\eta^a)\vec{V}_n(-\eta^b)\vec{V}_n^*(\eta^a)\vec{V}_n^*(\eta^b) \right\rangle}{\left\langle \vec{V}_n(-\eta^a)\vec{V}_n(\eta^b)\vec{V}_n^*(-\eta^a)\vec{V}_n^*(\eta^b) \right\rangle} \approx \left\langle \cos 2n \left[ \Psi_n(\eta^a) - \Psi_n(-\eta^a) \right] \right\rangle$$
Rapidity-correlated flow fluctuations

Minimize $\varepsilon_n$ fluct. and single out EP twist

$$R_n \equiv \frac{\langle \vec{V}_n(-\eta^a)\vec{V}_n(-\eta^b)\vec{V}_n^*(-\eta^a)\vec{V}_n^*(-\eta^b) \rangle}{\langle \vec{V}_n(-\eta^a)\vec{V}_n(\eta^b)\vec{V}_n^*(-\eta^a)\vec{V}_n^*(\eta^b) \rangle} \approx \langle \cos[2n(\Psi_n(\eta^a) - \Psi_n(-\eta^a))] \rangle$$

**ATLAS** Preliminary

<table>
<thead>
<tr>
<th>$r_2$ vs $\eta^a$</th>
<th>$R_2$ vs $\eta^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb+Pb 0-5%</td>
<td>Pb+Pb 0-5%</td>
</tr>
<tr>
<td>2.76 TeV</td>
<td>2.76 TeV</td>
</tr>
<tr>
<td>5.02 TeV</td>
<td>5.02 TeV</td>
</tr>
</tbody>
</table>

EP twist accounts for ~50% of $r_2$
Rapidity-correlated flow fluctuations

$v_2(\eta)$ proposed as a means of probing $\eta/s(T)$

Crucial to understand the contribution of rapidity-correlated initial-state effects
How small a QGP fluid can be?

Hydrodynamics applies when:

\[ L \gg \lambda_{m.f.p.} \]

where \( \lambda_{m.f.p.} \sim \frac{1}{g^4 T} \)
How small a QGP fluid can be?

Hydrodynamics applies when:

\[ L >> \lambda_{m.f.p.} \]

where \( \lambda_{m.f.p.} \sim \frac{1}{g^4T} \)

- For \( g \sim 1 \),

\[ LT >> 1 \]
How small a QGP fluid can be?

Hydrodynamics applies when:

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where \( \lambda_{m.f.p.} \sim \frac{1}{g^4 T} \)

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- In the limit of \( g \to \infty \), \( LT \sim 1 \)

QGP fluid in pp
How small a QGP fluid can be?

Hydrodynamics applies when:

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where \( \lambda_{m.f.p.} \sim \frac{1}{g^4 T} \)

- For \( g \sim 1 \), \( LT \gg 1 \) OR \( LT \sim 1 \)

**Experimental condition**

\[ N_{trk} \sim (LT)^3 \]

\( \left( \frac{N_{trk}}{L^3} \sim s \sim T^3 \right) \)

P. Chesler

QGP fluid in pp
How small a QGP fluid can be?

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where \( \lambda_{m.f.p.} \sim \frac{1}{g^4 T} \)

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- In the limit of \( g \to \infty \)

Experimental condition

\[ N_{trk} \sim (LT)^3 \]

\[ (N_{trk}/L^3 \sim s \sim T^3) \]

What is the smallest size for a QGP fluid?
How small a QGP fluid can be?

Hydrodynamics applies when:

\[ L \gg \lambda_{m.f.p.} \]

where \( \lambda_{m.f.p.} \sim \frac{1}{g^4 T} \)

- For \( g \sim 1 \), \( LT \gg 1 \)
- In the limit of \( g \to \infty \), \( LT \sim 1 \)

**Experimental condition**

\( N_{trk} \sim (LT)^3 \)

\( (N_{trk}/L^3 \sim s \sim T^3) \)

Multiplicity or entropy

What is the smallest size for a QGP fluid?
Collective flow in small systems (?)

Key features of collectivity seen in HM pp

- **pp**
  - $v_2(2, |\Delta\eta|>2)$
  - $h^\pm$
  - $K_S^0$
  - $\Lambda/\bar{\Lambda}$

- **pPb**

- **PbPb**

| System   | Energy | $v_2(2, |\Delta\eta|>2)$ |
|----------|--------|--------------------------|
| $\sqrt{s} = 13$ TeV | $v_2(4)$ |
| $\sqrt{s_{NN}} = 5$ TeV | $v_2(6)$ |
| $\sqrt{s_{NN}} = 2.76$ TeV | $v_2(8)$ |

| System   | Energy | $v_2(2, |\Delta\eta|>2)$ |
|----------|--------|--------------------------|
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| $\sqrt{s_{NN}} = 2.76$ TeV | $v_2(8)$ |

- $0.3 < p_T < 3.0$ GeV

- $105 \leq N_{\text{offline}}^{\text{trk}} < 150$
- $10 \leq N_{\text{offline}}^{\text{trk}} < 20$
- $120 \leq N_{\text{offline}}^{\text{trk}} < 150$
- $120 \leq N_{\text{offline}}^{\text{trk}} < 150$

- CMS
Collective flow in small systems (?)

Initial interaction models confronting the data!
(scenario #2)

CGC + Lund (PYTHIA)

Schenke et. al, PRL 117, 162301 (2016)

How about $v_2\{m\}$?

CMS pp $\sqrt{s} = 13$ TeV

$pp$

$0\leq N^{\text{offline}}_{\text{trk}} < 150$ - $(10 \leq N^{\text{offline}}_{\text{trk}} < 20)$

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$h^+$
$K^0_S$
$\Lambda/\bar{\Lambda}$
Collective flow in small systems (?)

Initial interaction models confronting the data!
(scenario #2)

CGC + Lund (PYTHIA)

Schenke et. al, PRL 117, 162301 (2016)

How about $v_2\{m\}$?

Connection to **initial-state geometry** is the key to further differentiate the two scenarios!
Geometry-controlled small systems

“Smallness” is not the limitation

For $A_1 (A_2) \geq 2$, all hydro. models agree

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

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Geometry-controlled small systems

“Smallness” is not the limitation

For $A_1 (A_2) \geq 2$, all hydro. models agree

We know how to do hydro. in small systems!
Geometry “uncontrolled” in pA and pp

But if $A_1 (A_2) = 1$

$pPb \sqrt{s_{NN}} = 5.02$ TeV

- CMS data, $120 \leq N_{\text{trk}} < 150$
- ATLAS data, $110 \leq N_{\text{trk}} < 140$

$v^{\text{sub}}_2 (2, |\Delta|>2)$

- superSONIC (preflow), Glauber + $\eta/s=0.16$
- Bozek et al, Glauber + $\eta/s=0.08$
- IP-glasma (round, $b=0$) + $\eta/s=0.18$
Geometry “uncontrolled” in pA and pp

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$v_{2}^{\text{sub}[\{2, |\eta|>2\}]}$ vs $p_T$ (GeV/c)

- CMS data, $120 \leq N_{\text{trk}} < 150$
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- superSONIC (preflow), Glauber $+ \eta/s=0.16$
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$pPb \sqrt{s_{NN}} = 5.02$ TeV

Geometry “uncontrolled” in pA and pp

Glauber-like

IP-glasma
Geometry “uncontrolled” in pA and pp

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$v_{2, \Delta \eta|>2}$

*superSONIC (preflow), Glauber + $\eta/s=0.16$*
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*IP-glasma (eccentric, b=0) + $\eta/s=0.18$*

(very preliminary)
Geometry “uncontrolled” in pA and pp

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(unique preliminary)

CMS data, $120 \leq N_{\text{trk}} < 150$
ATLAS data, $110 \leq N_{\text{trk}} < 140$

Unique opportunities for probing subnucleonic quantum fluctuations in yoctoseconds!
New insights to IS fluc. of pp and pA

SC\((n,m)\) = \(\langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle\) in small systems

2016 pPb data!
New insights to IS fluc. of pp and pA

\[ SC(n,m) = \langle v_n^2 v_m^2 \rangle - \langle v_n^2 \rangle \langle v_m^2 \rangle \] in small systems

2016 pPb data!

Anti-correlation of \( v_2 \) and \( v_3 \) in pPb, same as PbPb
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Anti-correlation of \( v_2 \) and \( v_3 \) in pPb, same as PbPb

- Naturally explained by initial geometry
- A new challenge to initial interaction models?
New insights to IS fluc. of pp and pA

Normalized by $\langle v_n^2 \rangle \langle v_n^2 \rangle$

Constraining the IS with “new” flow observables
New insights to IS fluc. of pp and pA

Normalized by $\left\langle v_n^2 \right\rangle \left\langle v_m^2 \right\rangle$

Constraining the IS with “new” flow observables toward a **unified paradigm of pp, pA, AA**
Still open questions in small systems

Does collectivity turn off at low $N_{\text{trk}}$?

Template fit

Low-$N_{\text{trk}}$ subtraction

ATLAS

CMS

$\sqrt{s} = 13$ TeV

$0.5 < p_T < 5$ GeV

$0.3 < p_T < 3$ GeV
Still open questions in small systems

Does collectivity turn off at low $N_{\text{trk}}$?

If hydro., $v_2$ should go down toward low $N_{\text{trk}}$
Still open questions in small systems

Does collectivity turn off at low $N_{\text{trk}}$?

If hydro., $v_2$ should go down toward low $N_{\text{trk}}$

Summary and outlook

Clear evidence of *long-range, collective* phenomena *universal* in all *high-multiplicity* hadronic collisions

- Initial spatial $\varepsilon_s$ + final interactions
- OR
- Initial momentum $\varepsilon_p$ via initial interactions
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Clear evidence of long-range, collective phenomena universal in all high-multiplicity hadronic collisions.

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In AA, consistent with “hydro-like” – “perfect fluid”
Summary and outlook

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\textbf{QCD fluid in pp/pA?} Connection to \textbf{initial geometry} is the key to be established – “\textit{New}” flow observables!

$\rightarrow$ \textit{Unique probes of subnucleonic fluctuations!}
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Open issue: collectivity ever turning off at low $N_{trk}$?

Universal collective behavior should even extend to high-multiplicity ep, eA (EIC), UPC, e$^+$e$^-$
Backup
\[ \frac{v_n \{4\}}{v_n \{2\}} = \frac{\varepsilon_n \{4\}}{\varepsilon_n \{2\}} = \left( \frac{2}{1 + N_s / 2} \right)^{1/4} \]
Higher-order cumulants

\[ \varepsilon_{2\{m\}} \rightarrow \nu_{2\{m\}} \]

(m = 2, 4, 6, 8 …)

Very testable prediction from hydrodynamics
Blast-Wave fits to $K_0^s$, $\Lambda$ and $\Xi^-$

$\langle \beta_T \rangle$ larger as $N_{trk}$ increases
\[ |<3 \eta| 1<| \]

Extrapolated
Res(\( \psi_2^{1<|1<3} \))
Global Sys = +35% (19.6 GeV) = -48%

(a) \( \sqrt{s_{NN}} = 200 \text{ GeV} \) 0-5%
(b) \( \sqrt{s_{NN}} = 62.4 \text{ GeV} \) 0-5%
(c) \( \sqrt{s_{NN}} = 39 \text{ GeV} \) 0-10%
(d) \( \sqrt{s_{NN}} = 19.6 \text{ GeV} \) 0-20%
Jet quenching in small system?

multiparticle $v_2$ at high $p_T$

$L_{\text{int}} \sim 186 \text{ nb}^{-1}$ collected in 2016