Signatures of collectivity in small systems

Wei Li (Rice University)
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What is collectivity?

*a group of entities that share a common property*
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_a group of entities that share a common property_

Collectivity  Emergent phenomena of a many-body _interacting_ system
What is collectivity?

a group of entities that share a common property

Collectivity  Emergent phenomena of a many-body interacting system

What is the mechanism driving the collectivity?
Emergent phenomena in pA and AA

**Long-range**

**Collective**

PLB 724 (2013) 213

PRL 115 (2015) 012301
Emergent phenomena in pA and AA

Long-range ➞ Initial stage

Collective

PLB 724 (2013) 213

PRL 115 (2015) 012301
Emergent phenomena in pA and AA

Long-range → Initial stage

Collective → Interactions

(b) CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $220 < N_{\text{offline}} < 260$

$1 < p_T^{\text{trig}} < 3$ GeV/c
$1 < p_T^{\text{assoc}} < 3$ GeV/c

$\frac{1}{N_{\text{trig}}} \frac{d^2N}{d\Delta\eta d\Delta\phi}$

$\Delta\phi$ (radians)

$\Delta\eta$

$V_2$

$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\infty\}$

CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $L_{\text{int}} = 35$ nb$^{-1}$

$0.3 < p_T < 3.0$ GeV/c; $|\eta| < 2.4$

PLB 724 (2013) 213

PRL 115 (2015) 012301
Emergent phenomena in pA and AA

Long-range → Initial stage

Collective → Interactions

Two scenarios

Initial spatial $\varepsilon_s$ + final interactions (hydro., transport)

V.S.

Initial momentum $\varepsilon_p$ from initial interactions (CGC glasma, etc.)
“Perfect” fluid paradigm in AA systems

Long-range collectivity in AA (large)
✧ Described by nearly ideal ($\eta/s \rightarrow 0$) hydrodynamics
“Perfect” fluid paradigm in AA systems

Long-range collectivity in AA (large)

✧ Described by nearly ideal ($\eta/s \rightarrow 0$) hydrodynamics
✧ Connection to initial geometry well established

![Graphical representation of hydrodynamics and collectivity](attachment:image.png)

IJMP E25 (2016) 1630002

PRL 110 (2013), 012302

20-25% $\varepsilon_2$ IP-Glasma
$v^2$ IP-Glasma+MUSIC
$v^2$ ATLAS

PbPb 2.76 TeV

on event-by-event basis!
“Perfect” fluid paradigm in AA systems

Long-range collectivity in AA (large)

认真学习/index.html 新版” PQCD 

Described by nearly ideal ($\eta/s \rightarrow 0$) hydrodynamics

Connection to initial geometry well established

PbPb $\sqrt{s_{NN}} = 2.76$ TeV

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

on event-by-event basis!
Collectivity diminishing as $L$ decreases
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$Kn = \lambda_{mfp}/L \sim 1$

No QGP fluid expected in “small” systems (pp, pA)!
Collectivity diminishing as $L$ decreases

No QGP fluid expected in "small" systems (pp, pA)!

But what if making it denser (reducing $\lambda_{mfp}$)?
Collectivity diminishing as $L$ decreases

Kn = $\frac{\lambda_{mfp}}{L} \sim 1$

No QGP fluid expected in “small” systems (pp, pA)!

But what if making it denser (reducing $\lambda_{mfp}$)?

⇒ a smaller but hotter QGP fluid?!
The “ridge” in pp

pp 7 TeV, $N_{\text{trk}} \geq 110$

1 < $p_T$ < 3 GeV/c

Mini-QGP fluid (L ~ 1 fm) in pp?
The “ridge” tsunami in pPb at the LHC

CMS

ALICE

ATLAS

LHCb
The “ridge” tsunami in pPb at the LHC

What is the origin of “ridge” in small systems?
How small a QCD fluid can be?

Smallness is relative
How small a QCD fluid can be?

Smallness is relative

“Absolute smallness” only w.r.t. a fundamental scale

Smallest scale of QED fluid
How small a QCD fluid can be?

Smallness is relative

“Absolute smallness” only w.r.t. a fundamental scale

Smallest scale of QED fluid

Is there a fundamental scale in QCD?

- Not obvious with point-like partons \( (\lambda_{\text{mfp}} \sim 1/T) \)
- “Quasi-particles” of sQGP?
How small a QCD fluid can be?

\[ \varepsilon \sim \frac{N_{trk}}{V} \]

Weakly-coupled regime reachable in principle, but not in practice

HM pp and pA well in the “fluid” regime

Endrodi et al., 0710.4197
Evidence of collectivity ("big" and "small")

Striking similarities between "big" and "small"
Evidence of collectivity ("big" and "small")

\[ \langle p_T \rangle \text{ (GeV/c)} \]

ALICE, p-Pb $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

Uncertainties: stat.(bars), sys.(boxes)

EPJC76 (2016) 245
Evidence of collectivity ("big" and "small")

Faster increase in \( \langle p_T \rangle \) for heavier species

(\( \Delta \langle p_T \rangle \sim m \langle \beta_T \rangle \))
Evidence of collectivity ("big" and "small")

Simultaneous Blast-Wave fits to $K_0^s$, $\Lambda$ and $\Xi^-$
Evidence of collectivity ("big" and "small")

Simultaneous Blast-Wave fits to $K_0^s$, $\Lambda$ and $\Xi^-$

Stronger velocity boost for smaller system
Evidence of collectivity ("big" and "small")

Larger mass splitting of $v_2$ in pPb

CMS

PbPb $\sqrt{s_{NN}} = 2.76$ TeV

CMS

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

Larger mass splitting of $v_2$ in pPb
Evidence of collectivity ("big" and "small")

Larger mass splitting of $v_2$ in pPb

At a similar $N_{\text{trk}}$,

smaller hydro. system more explosive!?

Shuryak, Zahed, PRC 88, 044915 (2013)
Clear evidence of collectivity observed, similar for both “small” and “large” systems

- Multi-particle correlation $v_n\{m\}$
- Mass dependence of spectra and $v_n$
- HBT radii v.s. $k_T$ and $N_{\text{trk}}$
- …
Clear evidence of collectivity observed, similar for both “small” and “large” systems

- Multi-particle correlation $v_n\{m\}$
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Is it hydrodynamics in small systems?

- Data consistent with “hydro-like” scenario
- Not obvious “small” and “large” fluids behave differently

→ Accept or discard QGP fluid paradigm altogether
Clear evidence of collectivity observed, similar for both “small” and “large” systems

✓ Multi-particle correlation $v_n\{m\}$
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✓ ...

Is it hydrodynamics in small systems?

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Connection to geometry in small systems?
“Smallness” is not the limitation

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

Glauber geometry dominates
“Smallness” is not the limitation

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But if $A_1 \ (A_2) = 1$

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But if $A_1 (A_2) = 1$

Models of initial states in pA collisions

- Glauber-like
- IP-glasma
- eccentric proton
- pomerons

In pA, the unknown is the “Shape”

Glauber geometry dominates
“Smallness” is not the limitation

Shape of a proton relevant for describing $v_n$ in pA

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

CMS $v_2$ data, $185 \leq N^\text{offline}_{\text{trk}} < 220$

IP-glasma, $b=0$, $\eta/s=0.18$ (Very preliminary)

Initial energy density (IP-glasma)

- **Eccentric**
- **Round**

$p_T$ (GeV/c) vs. $v_2^{(2, |\Delta\eta|>2)}$

- **Eccentric proton**
- **Round proton**
“Smallness” is not the limitation

Shape of a proton relevant for describing $v_n$ in pA

What is the image of a proton in yoctoseconds?

Mantysaari, Schenke, arXiv:1603.04349
“Smallness” is not the limitation

Shape of a proton relevant for describing $v_n$ in pA

What is the image of a proton in yoctoseconds?

exciting opportunity, well connected to EIC physics
IS of small system: (I) \( v_n \) in pp

Ridge and \( v_n \) in pp

\[ v_3 > 0 \text{ in pp} \] – the “shape” of a proton must fluctuate
**IS of small system: (I) $v_n$ in pp**

Ridge and $v_n$ in pp

$v_3 > 0$ in pp – the “shape” of a proton must fluctuate

Strongly constrained by pp + pPb data
IS of small system: (II) cumulant $v_n\{m\}$

Fluctuation-driven $\varepsilon_n$

Yan, Ollitrault, PRL 112, 082301 (2014)

Cumulants

$\varepsilon_{2\{m\}}$

($m = 2, 4, 6, 8 \ldots$)
IS of small system: (II) cumulant $v_n\{m\}$

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Yan, Ollitrault, PRL 112, 082301 (2014)

Cumulants

$\varepsilon_2\{m\}$ → Hydro. $v_2\{m\}$

($m = 2, 4, 6, 8 \ldots$)
IS of small system: (II) cumulant $v_n\{m\}$

**Fluctuation-driven $\varepsilon_n$**

Yan, Ollitrault, PRL 112, 082301 (2014)

Cumulants

$\varepsilon_2\{m\} \quad \text{Hydro.} \quad v_2\{m\}$

($m = 2, 4, 6, 8 \ldots$)

$P(\varepsilon) = 2\alpha\varepsilon(1 - \varepsilon^2)^{\alpha - 1}$

CMS pPb $v_{SN} = 5.02$ TeV

$0.3 < p_T < 3.0$ GeV/c; $|h| < 2.4$

PRL 115, 012301 (2015)
**IS of small system: (II) cumulant \( v_n \{ m \} \)**

**Fluctuation-driven \( \varepsilon_n \)**

Yan, Ollitrault, PRL 112, 082301 (2014)

\[
P(\varepsilon) = 2\alpha \varepsilon (1 - \varepsilon^2)^{\alpha-1}
\]

Cumulants

\( \varepsilon_2 \{ m \} \quad \xrightarrow{Hydro.} \quad v_2 \{ m \} \)

\( (m = 2, 4, 6, 8 \ldots) \)

**PRL 115, 012301 (2015)**

Hydrodynamic model is very testable!
IS of small system: (II) cumulant $v_n\{m\}$

Fluc.-driven $\varepsilon_n$ determined by # of sources ($N_s$)

\[
\frac{v_n\{4\}}{v_n\{2\}} = \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}} = \left(\frac{2}{1 + N_s / 2}\right)^{1/4}
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Yan, Ollitrault, PRL 112, 082301 (2014)
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Yan, Ollitrault, PRL 112, 082301 (2014)

See experimental talks for new results later!
IS of small system: (III) $v_n$ correlations

$v_2 - v_3$ correlation in AA from initial-state geometry
IS of small system: (III) $v_n$ correlations

Uli’s prediction, EIC users meeting 2016

Is it there in pp/pA systems?
Flow factorization breaking/PCA

\[ V_{n\Delta}(p_T^a, \eta^a; p_T^b, \eta^b) \neq v_n(p_T^a, \eta^a) \times v_n(p_T^b, \eta^b) \]

(two-particle) \quad (single-particle)

IS of small system: (IV) factorization
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Flow factorization breaking/PCA

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(two-particle)  (single-particle)

– caused by “lumpiness” of the initial state
IS of small system: (IV) factorization

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PRC 90, 044906 (2014), PRC92, 034911 (2015)
IS of small system: (IV) factorization

Flow factorization breaking/PCA

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PRC 90, 044906 (2014), PRC92, 034911 (2015)
Summary

Clear evidence of *long-range, collective* phenomena in HM QCD systems

- Initial spatial $\varepsilon_s$ + final interactions
- OR
- Initial momentum $\varepsilon_p$ from initial interactions
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In AA, consistent with “hydro-like” – “*perfect fluid*”
Summary

Clear evidence of *long-range, collective* phenomena in HM QCD systems

Initial spatial $\varepsilon_s$ + final interactions  OR  Initial momentum $\varepsilon_p$ from initial interactions

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

QCD fluid in pp/pA? Connection to initial geometry is the key ingredient to be established in the future
Summary

Clear evidence of *long-range, collective* phenomena in HM QCD systems

- Initial spatial $\varepsilon_s$ + final interactions
- OR
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In AA, consistent with “hydro-like” – “**perfect fluid**”

QCD fluid in pp/pA? Connection to initial geometry is the key ingredient to be established in the future

Unique opportunity in pp/pA of probing fluctuations of proton substructure – *Test of fundamental QCD*

→ Potential connection to future EIC program!
Backup
Jet quenching in small systems (?)

If ridge is flow $\Rightarrow$ strongly interacting
$\Rightarrow$ presence of jet quenching?

In small system at fixed $N_{\text{trk}}$

$$\Delta E \sim \alpha_s(T) \hat{q}(T) L^2$$

Who wins?

Roughly balanced

$$s \sim T^3 \quad s \sim \frac{N_{\text{trk}}}{\pi L^2}$$
Jet quenching in small systems (?)

If ridge is flow → strongly interacting
→ presence of jet quenching?

Sizable suppression predicted for $p_T \sim 10$-$20$ GeV/c
Misconception of IP-glasma model

N. B. fluctuation of each N-N energy deposit

AA data NOT sensitive to subnucleonic structure

“Lumpiness” of proton can be probed by pA (or pp)
Connection to Geometry
NCQ scaling in pPb system!

Baryon/meson crossing

Flow developed at partonic level!? 

Expected or surprising in pPb? 

Amazing scaling in AA discovered 10 yrs ago in quest of explanations, esp. in light of pPb data
Ridge in pPb persists up to at least several GeV/c

Sizeable $v_2 \sim 5\%$ (after a large subtraction)

Multiplicity correlations to test collectivity of high $p_T$ particles
CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV
Preliminary

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

Systematic uncertainties