Collectivity in small systems

- The *deconfined* quark-gluon plasma formed in nucleus-nucleus collisions at RHIC and the LHC is best described as a *fluid*.
- *But* the phenomena leading to this conclusion have then been observed, to some extent, in proton-nucleus, and even high-multiplicity proton-proton collisions.
- *Are the underlying mechanisms identical in all systems?*
- *Can we describe small systems as fluids?*
Collectivity in small systems

- Roberta Arnaldi (Torino, Italy), ALICE experiment
- Wei Li (Rice University, USA), CMS experiment
- Piotr Bożek (Cracow, Poland), hydrodynamics
- Dénes Molnár (Purdue University, USA), kinetic theory
- Wilke van der Schee (MIT, USA), strong coupling&holography
- Sören Schlichting (Brookhaven, USA), Yang-Mills dynamics
- Jean-Yves Ollitrault (Saclay, France).
Round table: Collectivity in Small Systems

Experimental Overview

Wei Li (Rice University)
Why colliding ultra-relativistic heavy ions?

“In high-energy physics we have concentrated on experiments in which we distribute a higher and higher amount of energy into a region with smaller and smaller dimensions.

In order to study the question of ‘vacuum’, we must turn to a different direction; we should investigate some ‘bulk’ phenomena by distributing high energy over a relatively large volume.”

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(AA)

Standard paradigm of a heavy-ion collision

Discovery of a high temperature, thermalized medium with quark and gluon degree of freedom
Surprisingly, the QGP behaves as a fluid, described by nearly ideal hydrodynamics (very little friction).
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Initial-state asymmetry:

Reaction plane

$\phi$ - defines $\psi_R$

(direction of the impact parameter)
Surprisingly, the QGP behaves as a fluid, described by nearly ideal hydrodynamics (very little friction).

Initial-state asymmetry:

Reaction plane: $z$

Initial-state asymmetry: $\phi$

$\psi_R$, (direction of the impact parameter)

Final-state anisotropy:

$dN/d\Delta\phi$

$4v_2$

$\sim 1 + 2v_2 \cos[2(\phi-\psi_R)]$

“elliptic flow”
Surprisingly, the QGP behaves as a fluid, described by nearly ideal hydrodynamics (very little friction).

Initial-state asymmetry:

Final-state anisotropy:

\[ dN/d\Delta\phi \sim 1 + 2v_2 \cos[2(\phi - \Psi_R)] \]

"elliptic flow"
Flow, two-particle correlations, ridge ...

\[ \eta = -\ln(\tan(\theta/2)) \]

\[ \Delta \eta \]

\[ \Delta \phi \]

\[ \eta = 2 \ (\theta \approx 15^\circ) \]

\[ \eta = 1 \ (\theta \approx 45^\circ) \]

\[ \eta = 0 \ (\theta = 90^\circ) \]
Flow, two-particle correlations, ridge …

\[ \eta = -\ln(t) \]

PbPb 2.76 TeV

35-40%

\[ 1 < p_T^a, p_T^b < 3 \text{ GeV/c} \]
Flow, two-particle correlations, ridge …

\[ \eta = -\ln(t) \]

\[ \Delta \phi \]

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

\[ 1 < p_T^a, p_T^b < 3 \text{ GeV}/c \]

PbPb 2.76 TeV

35-40%
Flow, two-particle correlations, ridge …

pp 7 TeV, MinBias

PbPb 2.76 TeV 35-40%

R(Δη, Δφ)

Δφ

Δη

1 < p_T^a, p_T^b < 3 GeV/c

cos(2ΔΦ)
Flow, two-particle correlations, ridge …

pp 7 TeV, MinBias

PbPb 2.76 TeV 35-40%

R(Δη, Δφ)

Nothing at ΔΦ ~ 0, |Δη|>2 (Near-side)

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

1 < p_T^a, p_T^b < 3 GeV/c
Breaking news in 2010!

High-multiplicity pp events

pp 7 TeV, MinBias $<N_{trk} \sim 15>$

pp 7 TeV, $N_{trk} > 110$

Nothing at $\Delta \Phi \sim 0$, $|\Delta \eta| > 2$
(Near-side)

1 < $p_T^a$, $p_T^b$ < 3 GeV/c

CMS, JHEP 09 (2010) 091
Breaking news in 2010!

High-multiplicity pp events

pp 7 TeV, MinBias $\langle N_{\text{trk}} \sim 15 \rangle$

$1 < p_T^a, p_T^b < 3$ GeV/c

Near-side ridge

CMS, JHEP 09 (2010) 091
Breaking news in 2010!

High-multiplicity pp events

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

Not a pileup!

$10^{-6} - 10^{-5}$ prob.

$1 < p_T^a, p_T^b < 3 \text{ GeV/c}$

Near-side ridge

CMS, JHEP 09 (2010) 091
“Ridge” tsunami in pPb at the LHC

Collective phenomena and QGP fluid in small systems (L ~ 1fm)??!
“Ridge” tsunami in pPb at the LHC

Collective phenomena and QGP fluid in small systems (L ~ 1fm)?
How small a QGP fluid can be?

Hydrodynamic applies when:

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

Too small and dilute?

\[ L \sim 10 \text{ fm} \]

\[ L \sim 1 \text{ fm} \]
How small a QGP fluid can be?

Hydrodynamic applies when:

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

What if making it denser by increasing \( N_{\text{trk}} \)?
Summary of current status

Almost all signatures of “flow” phenomena now commonly observed in all hadronic systems (pp, pA, AA), at sufficiently high multiplicities.

Some questions:

✧ Is QGP fluid created in small systems like pp?
✧ Is there a smallest scale of QCD fluid-like system?
✧ What’s still needed (experimentally) to reach a definitive conclusion?
✧ If everything flows, do we learn anything new about QGP from small systems?
Elliptic and triangular flow in p-Pb

Hydro consistent with data

\[ v_2, v_3 \text{ consistent with hydro} \]

(Glauber MC, EPOS3)

\[ v_{2,3} \text{ - hydro response to initial deformation} \]
Elliptic and triangular flow in p-AU, d-Au, $^3$He-Au

(small) deformed projectile

deuteron projectile (PB 1112.09)
intrinsic deformation dominates over fluctuations

- hierarchy of $v_2$ and $v_3$ consistent with fireball geometry

large eccentricity - large flow component

collective response to geometry
1. Elliptic and triangular flow
2. Hierarchy of $v_2$ and $v_3$ in p-A, d-A, He-A
collective response to geometry (final state effect)
3. Flow from higher cumulants
4. Interferometry radii

right magnitude and $k_\perp$ dependence of HBT radii
indication of space-momentum correlations

5. Factorization at intermediate $p_\perp$ and large $\Delta \eta$
particles at intermediate $p_\perp$, large $\eta$, correlated to geometry
6. Mass splitting of $v_2$
7. Mass hierarchy of spectra $(<p_\perp>)$
Validy of hydrodynamics? 

$K < 1$

H. Niemi, G. Denicol 1404.7327

large gradients in the evolution

pressure asymmetry

Heller, Janik, Witaszczyk 1103.3452, solution converges to hydro

1. **Hydrodynamics works with** $P_L \ll P_\perp$

2. **Pressure asymmetry** $P_L \ll P_\perp$ irrelevant

PB, I. Wyskiel-Piekarska 1011.6210; J. Vredevoogt, S. Pratt 0810.4325, pressure asymmetry irrelevant for flow
Collective expansion observed in pA

- Is it hydrodynamics?

Requires dominance of hydrodynamic modes
- estimate for a system size $R$ (Spalinski 1607.06381)

$$RT > 2\pi \sqrt{2T} \tau_\pi \eta/s \simeq 1 - 3$$

in numerical AdS/CFT: $RT > 1$, (Chesler 1601.01583)

Hydrodynamics works down to $N_{ch} = 10 - 30$ (ATLAS, CMS)

Success of hydrodynamics not accidental!

Break down of hydrodynamics difficult to observe (non-flow, jets . . .)
Initial state effects

Soeren Schlichting (BNL)
Multi-particle production in QCD naturally leads to momentum space correlations

-> multi-parton correlations in hadronic wave functions

Effects are sizable in small systems (p+p/A)

Calculations based on initial state correlations can describe two-particle correlations in wide range of semi-hard $p_T$ and $N_{trk}$

-> $d^2N/d\Delta \Phi$, $<p_T>$ & $v_2(p_T)$ mass ordering, ...

(c.f. talk by Schlichting on Tuesday)

**Challenges:** Extend calculations to lower $p_T$
(di-jet,hadronization, ...)

Compute multi-particle correlations (n>2)
**Initial state vs. final state effects**

Sizable correlations exist between particles produced in the initial state of hadronic collisions (p+p/A; p/d/He3+A). How much they contribute to final state observables depends on to what extent they are modified by final state effects.

**Qualitative picture:**

![Graph showing azimuthal correlation strength vs. event multiplicity (N_{trk}).](image)

- **Challenges:**
  - Develop theoretical framework including initial state & final state effects.
  - Identify observables to distinguish different regimes? (mini-) jet-quenching?
HYDRO IN SMALL SYSTEMS?

When is hydro applicable?

• Not far-from-equilibrium (shock)

• Not when pressure is negative (unstable)
  • But viscous/anisotropic hydro can apply if pressure ~ 0 (!!)

• Not in small system: $L \gg \frac{1}{T}$ (perhaps $L \gg \frac{1}{\pi T}$?): $VT^3 \gg 1$

• Shocks: hydro applies within $0.3/T$
TWO COMPUTATIONS FOR SMALL SYSTEMS

A fluctuation in a thermal bath:

- Hydro works within 0.2 fm/c, for system of size 0.5 fm.

A full-blown off-center `p-p collision’:

- Hydro found to work in a system with $R \sim 1/T$

WS, Holographic thermalization with radial flow (2012)
Paul Chesler, How big are the smallest drops of quark-gluon plasma? (2016)
AN ESTIMATE

For p-Pb and p-p collisions only few particles produced

• Naïve estimate: \( s \approx 16T^3 \) gives \( \frac{N_{ch}}{V} \approx \frac{Vs}{7.5} \approx 2.1VT^3 \)

• When \( R > \frac{1}{T} \) (or \( 1/\pi T \)) then \( \frac{dN_{ch}}{dy} > 2.1 \) (0.7??)

• Note that \( R \) increases faster than \( \frac{1}{T} \) (\( \tau \) versus \( \tau^{1/3} \))
  • Hydro works better at later times
  • Flow requires time to develop, i.e. 2.1 is `optimistic’ estimate
Can we learn something on the medium produced in p-A collisions looking at a different (and hard) probe?

suppression of loosely bound $\psi(2S)$ is stronger than the $J/\psi$ one, both at RHIC and LHC in dA, pA

→ unexpected since time spent by cc in the nucleus is shorter than charmonium formation time

→ CNM as shadowing and energy loss, almost identical for $J/\psi$ and $\psi(2S)$, do not account for the different suppression

→ only models including already in pA QGP + hadron resonance gas or comovers describe the stronger $\psi(2S)$ suppression
Re: hydro/kinetic theory applied to systems of $\mathcal{O}(1 \text{ fm})$ size with sub-fermi structures...

**one intriguing question:** how/when quantum mechanics (wave physics) enters - e.g., cannot localize both in $x$ and $p$

$\Rightarrow$ inherent momentum anisotropies e.g. DM, Wang & Greene 1404.4119

Also, if these systems are opaque enough for hydro, there should be **energy loss (jet quenching) signatures**. E.g., $p+Pb$ @ 5.02 TeV (top 3.4% cent): DM & Sun at QM2015