Origin of collectivity in QCD systems

by

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Collectivity: defining paradigm of nuclear phenomenology.

Quadrupole correlations in many-body system.

**Effective description:** ‘ellipsoidal’ surface.

\[ R(\Theta, \Phi) = R_0 \left[ 1 + \beta Y_{2,0}(\Theta, \Phi) \right] \]

Huge densities of gluons at small x.

**Effective description:**

\[ \rho^a(x^-, x_\perp) A_{1,2}^{\mu}(x) \]

Color Glass Condensate.

\[ \vec{F} = -\vec{\nabla}P \]
OBSERVATIONS OF COLLECTIVITY

No evidence so far in e⁺e⁻ and e⁻p collisions.

Experimentally ubiquitous. (pp?)

Indicators: c₂{2,4}.

[ZEUS Collaboration, 1912.07431]
[Badea et al., 1906.00489]
ORIGIN OF COLLECTIVITY: SCATTERING (FINAL STATE)

Anisotropy from anisotropy:

\[ \vec{F} = -\nabla P \]

more generic. If there are interactions ("Hydro"):

\[ V_n \propto \mathcal{E}_n \]

[PHENIX Collaboration, 1805.02973]
Revamping the question: collectivity = hydrodynamics?

"Qualifying" the QGP.  [Kurkela, Wiedemann, Wu, 1905.05139]

Generating collectivity is actually easy.  [Kurkela, Mazeliauskas, Törnkvist, 2104.08179]
 [Roch, Borghini, 2012.02138]
 [Borghini, Feld, Kersting 1804.05729]

FRONTIER:
Thermalization → “Hydrodynamization”
Towards off-equilibrium hydrodynamics.
Microscopic details less important.

[Romatschke, Romatschke, 1712.05815]

PHENOMENOLOGICAL PROGRAM?
Collective nucleons at high energy?

Role of sub-structure depends **dramatically** on energy deposition.

- Describes $v_n$ cumulants in pA.
- Does not describe $\rho(v^2, <pT>) < 0$.
- Not viable for Pb-Pb collisions

- Describes $\rho(v^2, <pT>) < 0$ in pA.
- Works in both p-Pb and Pb-Pb collisions.

[Bożek *1601.04513*]

[Kozlov, Luzum, Denicol, Jeon, Gale *1405.3976*]

[Bożek, Broniowski *1304.3044*]

[Mäntysaari, Schenke *1603.04349, 1607.01711*]

[Nijs, van der Schee, Gürsoy, Snellings *2010.15130, 2010.15134*]

[Schenke, Shen, Teaney, *2004.00690*]

[Bass, Bernhard, Moreland *1808.02106*]

[Bożek *1601.04513*]

[Kozlov, Luzum, Denicol, Jeon, Gale *1405.3976*]

[Bożek, Broniowski *1304.3044*]
Spectacular observations of collectivity in pPb collisions.

Do we understand any of this? Goal for the future.

model without substructure.

[Giacalone, Noronha-Hostler, Ollitrault 1702.01730]
ORIGIN OF COLLECTIVITY: INITIAL STATE

Primordial velocity field $\sqrt{u_x^2(x) + u_y^2(x)}, b = 0$

IP-Glasma, $\tau = 0.1$ fm,

$\mathcal{E}_{2p} \propto \langle T^{xx} - T^{yy} + 2iT^{xy} \rangle$

Hybrid CGC+hydro formalism.

[Altinoluk, Armesto 2004.08185]

“MOMENTUM” ANISOTROPY

[Schenke, Shen, Tribedy 2005.14682]
We only know it is relevant for very small systems \((dN/d\eta \sim 10)\).

[Schenke, Shen, Tribedy, 1908.06212]

**Observations?** One has to be creative.

**Recent realization:** system-size dependence at fixed \(dN/d\eta\).

![Diagram showing system sizes and \(<pT>\) values](image)

In IP-Glasma+MUSIC:

\[
\rho(\varepsilon_p^2, \langle p_t \rangle) > 0
\]

Thus, if \(v_2\) is driven by \(e_p\):

\[
\rho(v_2^2, [p_t]) > 0
\]

For \(dN/d\eta < 10\). Universal feature.

[Giacalone, Schenke, Shen, 2006.15721]
Collectivity of heavy mesons in pPb collisions.
Dilute-dense results yield sizable $v_2$ values.

[Zhang, Marquet, Qin, Wei, Xiao, 1901.10320]
[CMS Collaboration 1810.01473]
[ALICE Collaboration 1709.06807]

Collectivity in gamma-nucleus collisions (UPC).
A probe of the initial state. CGC?
Bridge with EIC physics.

[ATLAS Collaboration 2101.10771]
[Shi, Wang, Wei, Xiao, Zheng, 2008.03569]
SUMMARY

COLLECTIVITY: PARADigm OF NUCLEAR PHENOMENOLOGY

RESPONSE TO GEOMETRY: “HYDRO”
- Assessing the nature of the “QGP” from experiments.
- Structure of high-energy nucleons ↔ Tests of energy deposition.
- Need for theory-to-data comparisons for $c\{n>2\}$ in pA.

BEYOND THE GEOMETRY: PRIMORDIAL FLOW
- Hybrid CGC+Hydro framework – New ideas for small systems.
- Observables in pA to probe initial-state correlations $\rightarrow$ towards EIC.
THANK YOU!