OUTLOOK — COLLECTIVITY ASPECTS

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2nd International Conference on the Initial Stages in High-Energy Nuclear Collisions
December 7, 2014
What is collectivity?

- My definition of collectivity: correlated motion between large numbers of particles
- Hydrodynamics $\implies$ collectivity
- Collectivity $\not\implies$ hydrodynamics
- Either way, points to interesting physics
Part 1: Where do we see collectivity?
Two-particle correlations

\[ \sim \frac{dN_{\text{pairs}}}{d\Delta \eta d\Delta \phi} \]

(CMS, arXiv:1305.0609)
Results based on 1 fb

Long-Range Correlations in 7 TeV Data

Figure 7

Figure 7: 2-D two-particle correlation functions for 7 TeV pp collisions

Where is collectivity?

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(d) CMS \( N \geq 110, 1.0 \text{GeV/c} < p_T < 3.0 \text{GeV/c} \)

\( p+p \)

(CMS, arXiv:1009.4122)

**Where is collectivity?**

Long-range pair correlations

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**Two-particle correlations**

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- **Pb+Pb**
- **p+p**
- **p+Pb (high multiplicity)**
- **(d) CMS \(N \geq 110, 1.0\text{GeV/c} < p_T < 3.0\text{GeV/c} \)**

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Striking long-range pair correlations are seen in small collisions systems.

Natural in a hydro picture.

Also explainable with intrinsic pair correlations from the initial state (without collectivity).

To determine collectivity, look at multiparticle correlations.
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To determine collectivity, look at multiparticle correlations.
Collectivity?

Two-particle correlation

Multi-particle (>2) cumulants:

\[
\langle \langle 6 \rangle \rangle = \langle \langle e^{in(\phi_1 + \phi_2 + \phi_3 + \phi_4 + \phi_5)} \rangle \rangle
\]

\[
c_n \langle 6 \rangle = \langle \langle 6 \rangle \rangle - 9 \cdot \langle \langle 4 \rangle \rangle \langle \langle 2 \rangle \rangle + 12 \cdot \langle \langle 2 \rangle \rangle^3
\]

Insensitive to non-flow effect

In hydrodynamics:

\[
v_2 \langle 2 \rangle > v_2 \langle 4 \rangle \approx v_2 \langle 6 \rangle \approx v_2 \langle 8 \rangle \approx v_2 \langle \infty \rangle
\]
Collectivity!

\[ v_2^2 \{2\} > v_2^2 \{4\} \approx v_2^2 \{6\} \approx v_2^2 \{8\} \approx v_2^2 \{\text{LYZ, } \infty\} \]

Evidence of the collective nature of correlations in pPb!

(Zenyu Chen, Wednesday)
Cumulants imply true collectivity

\[ v_2^\{m\} \text{ FROM CONNECTED DIAGRAMS: FINAL RESULT} \]

- Hierarchy of \( v_2^\{m\} \).
- **Complex** \( v_2^{\{4k\}}, k \in \mathbb{Z}; \) including \( v_2^\{4\} \) and \( v_2^\{8\} \)
- Experiment: high multiplicity pA
  \( c_2^\{4\} < 0 \; \rightarrow \; v_2^\{4\} \in \mathcal{R} \)
- **Theory: connected graph only**
  \( c_2^\{4\} > 0 \; \rightarrow \; v_2^\{4\} \in \mathcal{C} \)
- In order to describe high \( k_\perp \) with IS effects, one needs disconnected graphs with azimuthal anisotropy
- Similar conclusion is valid for dense-dense limit and “glasma” graph

\[ v_2^\text{con} \{ \langle k_t \gg Q_s \rangle \} \]

A. Dumitru, L. McLerran, V. S. 1410.4844
V. S. in progress

(Vladimir Skokov, Thursday)
Multiparticle cumulants strongly imply collectivity in pA, AA

- At least 8 particles at a time are correlated; likely more
- \[\implies\] shouldn’t consider pair correlation in isolation
Collectivity implies a momentum structure to the pair correlation. If pair distribution is dominated by single particle distribution:

\[ V_{n\Delta}(p_T^a, p_T^b) \equiv \langle V_n^a V_n^{b*} \rangle \]

\[ \implies V_{n\Delta}(p_T^a, p_T^a) \geq 0 \]

\[ V_{n\Delta}(p_T^a, p_T^b)^2 \leq V_{n\Delta}(p_T^a, p_T^a)V_{n\Delta}(p_T^b, p_T^b) \]

- If inequalities broken \( \implies \) unmistakable signal of intrinsic pair correlation ("non-flow")
- If first inequality satisfied, can define ratio

\[ r_n \equiv \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a)V_{n\Delta}(p_T^b, p_T^b)}} \]

2nd inequality ensures \(-1 \leq r_n \leq 1\) when dominated by collectivity
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Collectivity implies a momentum structure to the pair correlation. If pair distribution is dominated by single particle distribution:

\[
V_{n\Delta}(p^a_T, p^b_T) \equiv \langle V_n^a V_n^{b*} \rangle
\]

\[
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Collectivity from pair correlation

$r_n$ gives rigorous signal of pair correlation at low multiplicity, high $p_T$

\[ \Psi_n(p_T) \] fluctuations in pPb and PbPb

Effect in pPb is comparable to peripheral PbPb

(Wei Li, Thursday)
Part 2: What generates collectivity?
**Remark:**

It’s difficult to prove a theory is correct. The best one can do is try to disprove it, and failing that, look for other explanations that might be just as successful and more compelling.
Killing hydro

Is hydrodynamics valid in such small systems? Maybe.

(Niemi & Denicol, arXiv:1404.7327)
Killing hydro

Pure hydro must have $r_n < 1$; expect $r_n \sim 1$, increasing with multiplicity.

$\frac{p_T^{\text{trig}}}{p_T^{\text{assoc}}}$

$220 < N_{\text{trk}}^{\text{offline}} < 260$

120 < $N_{\text{trk}}^{\text{offline}}$ < 150

Kozlov et al. hydro model qualitatively describes data

(S. Devetak, QM2014)
Mass ordering is also a generic expectation from hydro. The $v_2$ of $\pi$ and $p$ in $d+Au$ is observed in both $d+Au$ and $p+Pb$ consistent with hydrodynamic flow. (Shengli Huang, Wednesday)
Hadron pairs widely separated in $p_T$ are correlated

\( v_n^2 \)

Evidence for Flow in $p+A$ Collisions

\[
\begin{align*}
\sqrt{s_{\text{NN}}} &= 5.02 \text{ TeV} \\
L_{\text{int}} &= 28 \text{ nb}^{-1} \\
220 &\leq N_{\text{ch}}^{\text{rec}} < 260 \\
1 &< p_T^b < 3 \text{ GeV, } |\Delta R| > 2
\end{align*}
\]

- $n=2$
- $n=3$
- $n=4$
- $n=5$

CMS, $220 \leq N_{\text{trk}}^{\text{off}} < 260$

- $v_2$, $N_{\text{trk}}^{\text{off}} < 20 \text{ sub.}$
- $v_3$, $N_{\text{trk}}^{\text{off}} < 20 \text{ sub.}$

hep-ex/1409.1792

(Angerami, Wednesday)
Quantitative hydro predictions for p-Pb systems have been successful.

\[
\text{\textit{ATLAS}} \\
p+Pb, \sqrt{s_{NN}} = 5.02 \text{ TeV, } L_{\text{int}} = 1 \mu\text{b}^{-1}
\]

\[
0.3 < p_T < 5 \text{ GeV} \\
|\eta| < 2.5
\]

Quantitative hydro predictions for p-Pb systems have been successful. 

\[ C(q, k_{\perp}) = 1 + \lambda e^{-R_0^2 q^2 - R_o^2 q_s^2 - R_l^2 q_l^2} \]

Subsequently it has become clear that most (all?) relevant high-mult. p-Pb data can be described by hydrodynamic calculations.
The correct interpretation is still an open question. Interesting features that should be kept in mind when considering possible mechanisms for observed correlations:

1. $v_n\{4\} \approx v_n\{6\} \approx v_n\{8\} \approx v_n\{LYZ\} > 0$

2. Pair correlations almost factorized in $\rho_T$ ($r_n \approx 1$)

3. Dependence of correlations on multiplicity, system size

4. Correlation between particles of very different $\eta$, $\rho_T$

If all current data really admit multiple interpretations, more data may be needed.
Part 3: What can we learn from flow measurements?
WHAT CAN FLOW MEASUREMENTS TELL US?

MEDIUM PROPERTIES

QGP PROPERTIES

Event plane correlations at LHC

\[
\langle \cos(k_1 \Psi_1 + \cdots + nk_n \Psi_n) \rangle_{SP} \equiv \frac{\langle v_1^{k_1} \cdots v_n^{k_n} \cos(k_1 \Psi_1 + \cdots + nk_n \Psi_n) \rangle_{ev}}{\sqrt{\langle v_1^{2k_1} \rangle_{ev} \cdots \langle v_n^{2k_n} \rangle_{ev}}}.
\]

(Paatelainen, Wednesday)

\(\kappa\) Hydro Response Parameter

Assuming \(\kappa'\) does not vary with centrality

viscous hydro calc. of \(v/\varepsilon\) for \(\eta/s=0.19\)

(Poskanzer, Thursday)
Properties of initial state from flow measurements

(Retinskaya, ML, Ollitrault, arXiv:1401.3241; IS2013 proceedings)
WHAT CAN FLOW MEASUREMENTS TELL US?

INITIAL STATE PROPERTIES

PROPERTIES OF INITIAL STATE FROM FLOW MEASUREMENTS

EbyE distributions of $\delta v_2$ and $\delta \varepsilon_2$ at LHC

- constraint for initial state, not a viscous effect!

(Schenke, Venugopalan, PRL 113 (2014) 102301)

(Paatelainen, Wednesday) (Venugopalan, Wednesday)

(Paatelainen, Wednesday)

(Venugopalan, Wednesday)
$r_n$ insensitive to viscosity, sensitive to granularity

(Kozlov, ML, Denicol, Jeon, Gale, arXiv:1405.3976)
Conclusions

- Strong evidence of collectivity seen in p-A collisions (slightly weaker in d-A, and much weaker in p-p)
- Source of collectivity still under investigation, but strong constraints exist in data.
- My opinion: hydro looks most promising at present for high-multiplicity p-Pb.
- When hydro is applicable — e.g. in A-A collisions — information can be obtained about initial state despite strong final state effects