Investigating the flow-like correlations and the new possibility

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10th International Workshop on Multiple Partonic Interactions at the LHC

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Flow correlation

“Investigating the flow-like correlations and the new possibility”

What is flow correlation?
What have we learned?
Anisotropic flow in AA collisions

\[ \mathbf{V}_m = v_m e^{-i m \Psi_m} \]
\[ \mathbf{V}_n = v_n e^{-i n \Psi_n} \]

- \( v_2, v_3 \) and \( v_4 \) are nicely described by hydrodynamic predictions
- QGP: a state of **perfect liquid**
  - liquid: described by hydrodynamics
  - perfect: \( \eta/s \) is closed to the quantum limit \( 1/4\pi \)
$V_n$ and $V_m$ correlations in AA collisions

Since 2014

General question:
• what are the correlations between $v_n$ and $v_m$?
• what are the correlations between $\Psi_n$ and $\Psi_m$?
• will these correlations provide new information?
• new observables to answer the above questions!

$V_m = v_m e^{-im\Psi_m}$

$V_n = v_n e^{-in\Psi_n}$
Correlations between $v_m$ and $v_n$

Symmetric cumulants: $SC(m, n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$

- Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations
  - Although hydro describes $v_n$ fairly well, there is not a single centrality for which a given $\eta/s$ parameterization describes simultaneously SC and NSC.
  - SC and NSC measurements provide stronger constraints on the $\eta/s$ in hydro than standard $v_n$ measurements alone.

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ALICE, PRL117, 182301 (2016)
Symmetry plane correlations

- Agreement between ALICE and ATLAS (different eta coverage)
- Results are compatible with hydrodynamic calculations using IP-Glasma & $\eta/s=0.095$

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$\rho_{4,22} = \frac{v_{4,22}}{v_{4\{2\}}} \approx \langle \cos(4\Psi_4 - 4\Psi_2) \rangle$

$\rho_{5,32} = \frac{v_{5,32}}{v_{5\{2\}}} \approx \langle \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2) \rangle$

$\rho_{6,222} = \frac{v_{6,222}}{v_{6\{2\}}} \approx \langle \cos(6\Psi_6 - 6\Psi_2) \rangle$

$\rho_{6,33} = \frac{v_{6,33}}{v_{6\{2\}}} \approx \langle \cos(6\Psi_6 - 6\Psi_3) \rangle$

ALICE, PLB773 (2017) 68

ATLAS Collaboration, PRC90, 024905 (2014)

IP-Glasma:
S. McDonald et al., arXiv: 1609.02958
**$v_n$ of identified particles**

- **ALICE, JHEP 1809 (2018) 006**

  - **PID $v_2$ measurements in Pb-Pb at 5.02 TeV**
  - **Mass dependence at low $p_T$**, described by hydrodynamic model VISHNU / iEBE-VISHNU (not shown here)
  - **Baryon meson grouping** (recombination or coalescence?) at intermediated $p_T$
    - Rough NCQ scaling, at the level no better than 20%
Global Bayesian Analysis

Model Parameters - System Properties
- initial state
- temperature-dependent viscosities
- hydro to micro switching temperature

Physics Model:
- Trento
- iEeE-VISHNU

Experimental Data
- ALICE flow & spectra

Data:
- ALICE $v_2$, $v_3$ & $v_4$ flow cumulants
- identified & charged particle yields
- identified particle mean $p_T$
- 2 beam energies:
  2.76 & 5.02 TeV

the entire success of the analysis depends on the quality of the exp. data!

S. Bass, QM2017 using Pb-Pb data only

You Zhou (NBI) @ MPI, Perugia
Constrain the initial conditions and $\eta/s(T)$

- Theory can be further constrained by combined Pb-Pb & Xe-Xe fits
  - Initial conditions by the same initial state model; common $\eta/s(T)$ and $\zeta/s(T)$
  - Theory can be further constrained by sensitive observables

S. Bass, QM2017 using Pb-Pb data only

- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

Temperature-dependent viscosities:
“Investigating the **flow-like correlations** and the new possibility”

What is **flow-like** correlation?

what have we learned?
2- and multi-particle cumulants

- **2-particle correlations**
  - comparable $v_n\{2\}$ at low $N_{ch}$
  - weak $N_{ch}$ dependence
  - ordering $v_2 > v_3 > v_4$

- **Multi-particle cumulants**
  - $v_2\{4\}_{3\text{-sub}} \sim v_2\{6\} \sim v_2\{8\}$
  - Can not be reproduced by a model w/o flow generation
  - **Evidence of collectivity?**
Symmetric cumulants

- Symmetric cumulants consistent between all three systems in the \( <N_{ch}> \) range covered by pp collisions
- For the p-Pb and Pb-Pb collisions, SC(3,2) and SC(4,2) show significant decrease / increase with \( <N_{ch}> \)
- Future quantitative theoretical descriptions are still missing at the moment.
Asymmetric cumulants

Very nice results on non-linear response of flow to initial eccentricity

However, the normalization factor is different from commonly used definition (note: different moments have different information)
Identified particle $v_2$ in p-Pb

- $v_2$ of identified particles in Pb-Pb
  - at low $p_T$: mass ordering, described by hydrodynamic calculations (VISHNU)
  - at intermediate $p_T$: approximate baryon/meson grouping

- $v_2$ of identified particles in p-Pb
  - at low $p_T$: most particle species follow mass ordering $\rightarrow$ hydrodynamic flow?
  - at intermediate $p_T$: baryon $v_2 >$ meson $v_2$ $\rightarrow$ partonic collectivity? Indication of QGP?
Global Bayesian Analysis with pA & AA

J. Moreland etc, arXiv:1806.04802
Seems extracted initial conditions agree with EKRT/IP-Glasma,

- note: hydro calculation with IP-Glasma could not describe small system data
- Why? Too large uncertainty of extraction or any issue in hydro part?

\[ dS/dy \sim \sqrt{T_A T_B} \]
Extracted $\eta/s$ of QGP in pA & AA

- $\eta/s$ in pA seems follow a similar trend as in AA
  - Description of hydrodynamic flow works in pA?
  - It might “work” for pp with even larger $\eta/s$, what is the implication?

J. Moreland etc, arXiv:1806.04802
Do we understand?

- We see similarities in large and small systems
  - Flow-like correlation observed in data -> Hydro-flow in small systems?
  - Do we really understand what we see?
Multi-particle correlations: not described quantitatively by any model

- Initial state model -> overestimated data by a factor of 10!
- hydro calculations -> wrong sign of $c_2\{4\}！$
New attempts in hydro

- Further tuning of initial state models
  - Negative $c_2\varepsilon\{4\}$, still positive $c_2\{4\}$ for $v_2$
  - Even include pre-equilibrium effects, free-streaming + hydrodynamics or free-streaming + kinetic theory + hydrodynamics, one still can not get negative $c_2\{4\}$
  - Still a long way to go

W. Zhao etc, in preparation
Mass ordering is not an evidence of hydrodynamic flow!

- Also reproduced by initial stage effects (e.g. CGC+Lund), or final stage effects: parton escape (AMPT), hadronic rescatterings (UrQMD), rope & shoving (PYTHIA)
Baryon-meson grouping is observed in p-Pb
- NCQ scaling, if valid, is only approximate (similar as in Pb-Pb)
- can not be reproduced by any existing models, call for theoretical explanation!
Future experimental investigations

- Complete studies of $V_n$ and $V_m$ correlations including higher order cumulants of $SC(m^k,n^l)$, $SC(m,n,k)$, non-linear flow modes
- Factorization ratio (vs $p_T$ and $\eta$) with multi-particle correlations
- Precise $v_2\{4\}$ measurement: suppress non-flow and constrain model quantitatively

New theoretical investigations

- Improve current models
- Deep Learning
Deep learning

- Using Deep learning to identify flow and non-flow events? Similar to the “cat or dog” question
  
  - After training by many images of dog and cat with labels, the well-trained network can nicely discriminate the dog and cat images

H. Huang, C. Liu etc, private communication
Using Deep learning to identify flow and non-flow events? Maybe just a cat or dog question

- After training by many images of flow and non-flow with labels, the well-trained network can nicely discriminate the flow and non-flow images.

H. Huang, C. Liu etc, priviate communication
High accuracy of identification

Flow event (model B)  Non-flow event (model C)

<table>
<thead>
<tr>
<th>Averaging size</th>
<th>100</th>
<th>50</th>
<th>20</th>
<th>10</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow event (model A)</td>
<td>100.0%</td>
<td>99.7%</td>
<td>96.1%</td>
<td>89.0%</td>
<td>80.0%</td>
</tr>
<tr>
<td>Flow event (model B)</td>
<td>100.0%</td>
<td>100.0%</td>
<td>99.7%</td>
<td>97.0%</td>
<td>91.1%</td>
</tr>
<tr>
<td>non-flow event (model C)</td>
<td>100.0%</td>
<td>100.0%</td>
<td>99.6%</td>
<td>97.1%</td>
<td>91.3%</td>
</tr>
</tbody>
</table>

❖ High accuracy of flow vs non-flow event identification
• Future possibility of application in data analysis (whether we can select flow events in data)
Flow-like correlations has been observed in small collision systems and could be reproduced qualitatively or even semi-quantitatively by theoretical models.

- **Data: indications of collectivity in small collision systems**
- Its origin? Studies from both EXP (more sensitive observables) and TH (initial? final? Initial & final?) are necessary

LHC Run3 program as well as new theoretical efforts provide new possibilities!
backup
Baryon-meson grouping is observed in p-Pb
• can not be reproduced by any existing models, call for theoretical explanation!
• NCQ scaling, if valid, is only approximate (similar as in Pb-Pb)
\( v_n \) also quantitatively described by hydrodynamics using EKRT, AMPT, Trento initial conditions (but not MC-Glauber, nor MC-KLN) with different \( \eta/s(T) \)
You Zhou (NBI) @ MPI, Perugia

Pb-Pb & Xe-Xe collisions

• 2.76 TeV
• 5.02 TeV (2018)
• 5.44 TeV

Little Bang
Hot QGP

Pb-Pb & Xe-Xe collisions

• 2.76 TeV
• 5.02 TeV
• 5.44 TeV
• 8.16 TeV
• 900 GeV
• 2.76 TeV
• 5.02 TeV
• 7 TeV
• 8 TeV
• 13 TeV (2018)

p-Pb collisions

• 5.02 TeV
• 8.16 TeV

Is there flow?
What is its origin?

pp collisions

pp collisions

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