Measurements of Correlations of Anisotropic Flow Harmonics in Pb–Pb Collisions with ALICE

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(on behalf of the ALICE Collaboration)
The magnitudes of the Flow-vector, anisotropic flow harmonics \( v_n \), have been measured in great details (centrality, \( p_T \), \( \eta \), PID)

- constraints on the initial conditions, \( \eta/s \), EoS, freeze-out conditions et al.

The fluctuations of each individual flow harmonics have been measured.
The fluctuations of each individual flow harmonic have been investigated.

- further understanding of underlying p.d.f. of $v_n$ distributions
Correlations between $\vec{V}_m$ and $\vec{V}_n$

- **Flow angle correlations**: $\psi_m$ and $\psi_n$ correlations (have been studied)

- **Flow magnitude correlations**: $v_m$ and $v_n$ correlations
  - Does $v_m$ and $v_n$ correlated? anti-correlated? or not correlated?
  - How can we investigate the relationship of $v_m$ and $v_n$ without contribution from $\psi_m$ and $\psi_n$?

- 5-particle cumulant

- $Pb-Pb$ $S_{NN} = 2.76$ TeV $|\eta| < 0.8$ $0.2 \leq p_T < 5$ GeV/c
Correlations of $v_m$ and $v_n$

A linear correlation coefficient $c(v_m, v_n)$ was proposed to study the correlations between $v_m$ and $v_n$:

$$c(v_m, v_n) = \frac{\langle (v_m - \langle v_m \rangle_{ev})(v_n - \langle v_n \rangle_{ev}) \rangle}{\sigma_{v_n} \sigma_{v_m}}_{ev}$$

• This correlation function is 1 (-1) if a and b are linearly (anti-linearly) correlated and zero in the absence of linear correlation.

• negative correlations of $c(v_2, v_3)$ and positive correlations of $c(v_2, v_4)$

• $c(v_2, v_3)$ is sensitive to initial conditions and insensitive to $\eta/s$, $c(v_2, v_4)$ is sensitive to both

• $c(v_m, v_n)$ is a new observable to constrain initial conditions and $\eta/s$.

• However, this observable cannot be accessible easily in flow measurements which relying on two- and multi-particle correlations.
New observable:

**Symmetric 2-harmonic 4-particle Cumulants, SC(m,n)**, measures the correlations of \(v_m\) and \(v_n\)

\[
\langle\langle\cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle_c
\]

\[
= \langle\langle\cos(m\varphi_1 + n\varphi_2 - m\varphi_3 - n\varphi_4)\rangle\rangle - \langle\langle\cos[m(\varphi_1 - \varphi_2)]\rangle\rangle \langle\langle\cos[n(\varphi_1 - \varphi_2)]\rangle\rangle
\]

\[
= \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle.
\]

By construction not sensitive to:

- non-flow effects, due to usage of 4-particle cumulant
- inter-correlations of various symmetry planes (\(\Psi_m\) and \(\Psi_n\) correlations)

It is non-zero if the event-by-event amplitude fluctuations of \(v_m\) and \(v_n\) are (anti-)correlated.

- more details, see Section IV in:

In previous AMPT study, it predicted a positive SC(4,2) and negative SC(3,2), the signs of SC(m,n) in the final state seem to be determined by SC(m,n)\(\epsilon\) in the initial state.
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Both the partonic and hadronic interactions contribute to the magnitudes of SC(m,n).
In previous AMPT study, it predicted a positive $\text{SC}(4,2)$ and negative $\text{SC}(3,2)$, the signs of $\text{SC}(m,n)$ in the final state seem to be determined by $\text{SC}(m,n)_\varepsilon$ in the initial state.

Both the partonic and hadronic interactions contribute to the magnitudes of $\text{SC}(m,n)$.

$\text{SC}(m,n)$, a new observable to constrain initial conditions and the properties of the system.
Analysis Details

❖ Detectors used:
- **Inner Tracking System** (trigger, tracking and vertexing)
- **Time Projection Chamber** (tracking, centrality determination)
- **V0 detectors** (trigger, centrality determination)

❖ Data sample:
- **Pb-Pb at** $\sqrt{s_{NN}} = 2.76$ TeV
  - $\sim 12$ M events analyzed
- **Tracks used:**
  - $-0.8 < \eta < 0.8$
  - $0.2 < p_T < 5.0$ GeV/c
The positive values of SC(4,2) and negative SC(3,2) are observed for all centralities.

- suggests a correlation between $v_2$ and $v_4$, and an anti-correlations between $v_2$ and $v_3$.
- indicates finding $v_2 > \langle v_2 \rangle$ in an event enhances the probability of finding $v_4 > \langle v_4 \rangle$ and finding $v_3 < \langle v_3 \rangle$ in that event.
Non-flow contributions?

- SC(m,n) calculations from HIJING
- It is found that $\langle v_m^2 v_n^2 \rangle > 0$ and $\langle v_m^2 \rangle \langle v_n^2 \rangle > 0$ in HIJING, but SC(m,n) are compatible with zero
  - suggests SC measurements are nearly insensitive to non-flow effects.
- non-zero values of SC measurements cannot be explained by non-flow effects, thus confirms the existence of (anti-)correlations between $v_m$ and $v_n$ harmonics.
Contributions from the initial state?

Comparisons to MC-Glauber model calculations

- $\text{SC}(m,n)_\varepsilon$ from MC-Glauber model using weights of wounded nucleon (WN) and binary collisions (BC) weights are scaled and compared to data.

- Increasing trend from central to peripheral collisions with different signature has been observed for $\text{SC}(4, 2)_\varepsilon$ and $\text{SC}(3, 2)_\varepsilon$, the centrality dependence of corresponding measurements cannot be captured well.

- Correlations in the initial conditions are not the only contribution to SC measurements.
vn harmonics and hydrodynamics

H. Niemi, arXiv: 1505.02677

<table>
<thead>
<tr>
<th>Tmin/MeV</th>
<th>(η/s)min</th>
<th>η/s(100 MeV)</th>
<th>η/s(500 MeV)</th>
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<td>0.24</td>
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<tr>
<td>param2</td>
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<tr>
<td>param4</td>
<td>180</td>
<td>0.12</td>
<td>0.76</td>
</tr>
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</table>

Various settings of η/s in hydro calculations have been investigated
- standard flow measurements are not very sensitive to η/s(T) at least for central- and mid-central collisions.

IC: perturbative QCD + saturation model
(also known as EKRT)

ALICE: PRL107, 032301
Comparison of SC measurements to hydrodynamic calculations

- Although hydro describes the $v_n$ fairly well, there is no a single centrality for which a given $\eta/s$ parameterization describes simultaneously SC(4,2) and SC(3,2).
- SC measurements provide stronger constrains on the $\eta/s$ in hydro than standard $v_n$ measurements alone.
Better sensitivity to $\eta/s$

Comparison of SC measurements to hydrodynamic calculations

- Although hydro describes the $v_n$ fairly well, there is no a single centrality for which a given $\eta/s$ parameterization describes simultaneously SC(4,2) and SC(3,2).
- SC measurements provide stronger constrains on the $\eta/s$ in hydro than standard $v_n$ measurements alone.
Assuming $v_n \propto \varepsilon_n$ in the central collisions, the SC(m,n) after scaling might be able to describe SC(m,n) measurements.

Comparison to MC-Glauber calculations (initial conditions)

- the one with Binary Collisions weight (BC) quantitatively describes SC for 0-10%, while Wounded Nucleon (WN) fails completely.
Conclusion

We have measured for the first time the new multi-particle observables $SC(m,n)$ which quantify the relationship between event-by-event fluctuations of two different flow harmonics.

- $v_2$ and $v_4$ are correlated, $v_2$ and $v_3$ are anti-correlated in all centralities, the centrality dependence can’t be described quantitively by existed calculations.
- $SC(m,n)$ measurements are more sensitive to input values of $\eta/s$ than the individual flow harmonics, discriminate the inputs to hydro model with different parameterizations of $\eta/s$.
- In fluctuation-dominated regime the MC-Glauber initial conditions with binary collisions weights are favored over wounded nucleon weights by data.

SC(m,n), better sensitivity to initial conditions and $\eta/s$, provide new parameters to improve the theoretical calculations.
Backup
### Y. Zhou, NPA 931 (2014) 949-953

#### ALICE Preliminary

**Pb-Pb** $\sqrt{s_{NN}} = 2.76$ TeV

<table>
<thead>
<tr>
<th>Centrality: 0-5%</th>
<th>Centrality: 20-30%</th>
<th>Centrality: 40-50%</th>
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<tbody>
<tr>
<td>$v_2[2,</td>
<td>\Delta\eta</td>
<td>&gt;0.8]/v_2[2,</td>
</tr>
</tbody>
</table>

**ALI-PREL-68224**

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**JHEP 11 (2013) 183**

**ATLAS, PRC 90, 024905 (2014)**
$V_n, V_m$ correlations via ESE

- SC observables are not influenced by non-flow, as shown in slide 8, not the case for the study using 2-particle correlations.
- SC measurements provide a compact quantitative measure of these correlations, without needing knowledge of the functional relation between $v_m$ and $v_n$.
- Finally, our SC observables can easily be obtained from hydrodynamical calculations.
## Systematic uncertainty

<table>
<thead>
<tr>
<th>SC(3,2)</th>
<th>systematic uncertainty</th>
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<tbody>
<tr>
<td>non-uniform acceptance</td>
<td>&lt; 1%</td>
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<tr>
<td>reconstruction inefficiency</td>
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<tr>
<td>vertex $z$ range</td>
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<td><strong>Total</strong></td>
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