ALICE measurements of flow coefficients and their correlations in small (pp and p-Pb) and large (Xe-Xe and Pb-Pb) collision systems

Is there collectivity in small collision systems?

If yes, what is its origin?

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What is collectivity: long-range correlations

Collectivity: long-range multi-particle correlations

- Correlations are long-range: saturation of the $v_2$ with $|\Delta \eta|$ separation

$\nu_n \{4\} = 4c_n \{4\}$

$\nu_n \{6\} = 6\sqrt{1/4}c_n \{6\}$

$\nu_n \{8\} = \sqrt{\frac{1}{33}}c_n \{8\}$
**What is collectivity: multi-particle correlations**

**Collectivity:** long-range multi-particle correlations

- **Correlations are long-range:** saturation of the $v_2$ with $|\Delta \eta|$ separation
- **Correlations among many particles**
  - $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$
Origin of collectivity in Pb-Pb collisions

- Measurements of $v_n$ consistent with hydrodynamical model calculations
- Symmetric Cumulants provide further constraints on the initial conditions and transport coefficients
- $v_n$ together with SC(m,n) provide a better handle of the model parameters than each of them independently

*Origin of collectivity in large collision systems is well understood.*
Experimental setup and data sets

- **Inner Tracking System (ITS)**
  - vertex determination, tracking

- **V0**: trigger

- **Time Projection Chamber (TPC)**
  - tracking

**Data samples (LHC Run2):**
- Pb-Pb at $\sqrt{s_{NN}} = 5.02$ TeV
- Xe-Xe at $\sqrt{s_{NN}} = 5.44$ TeV
- p-Pb at $\sqrt{s_{NN}} = 5.02$ TeV
- pp at $\sqrt{s} = 13$ TeV
  - High multiplicity trigger selects events with V0 multiplicity 4 times larger than mean V0 multiplicity

**Kinematic cuts**
- $|\eta| < 0.8$
- $0.2 < p_T < 3.0$ GeV/c
Suppression of non-flow effects

- **Non-flow**: few particle correlations not associated to the common symmetry plane
  - Correlations between particles in jets, or from resonance decays, etc.

**Subevent method**  J. Jia, M. Zhou, A. Trzupek, PRC 96, 034906 (2017)

- Enforces a space separation between particles that are being correlated
- Extended to multi-particle cumulants

Example: 4-particle correlation

**2-subevent method**

\[
\langle\langle 4 \rangle\rangle_{-sub} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle\rangle
\]

**3-subevent method**

\[
\langle\langle 4 \rangle\rangle_{3-sub} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle\rangle
\]

**Standard method**

\[
\langle\langle 4 \rangle\rangle = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle\rangle
\]
**$v_n\{2\}$: all systems**

**Heavy-ion collisions:**
- Clear multiplicity dependence of $v_2$ showing response to collision geometry
- Ordering $v_2 > v_3 > v_4$

**Small systems:**
- Comparable values with Pb-Pb at low $N_{ch}$
- Weak multiplicity dependence
- Ordering $v_2 > v_3 > v_4$

**Collectivity:** long-range multi-particle correlations

*Collectivity can be better probed with multi-particle cumulants*
$c_2\{4\}$: small systems

- Subevent method further suppresses non-flow in multi-particle cumulants in **pp collisions**
  - **Negative** $c_2\{4\}_{3\text{-sub}}$ -> **real value** for $v_2\{4\}_{3\text{-sub}}$

- Non-flow can be largely suppressed also in **p-Pb collisions**

- No significant further decrease of $v_2\{4\}_{3\text{-sub}}$ with $|\Delta \eta| > 0.2$ between subevents
$v_2\{m\}$ (m>2): all systems

**Heavy-ion collisions:**
- **Long-range**: signal doesn’t change anymore with subevent method
  
  $v_2\{4\} \sim v_2\{4\}_{3\text{-sub}}$
  
  $v_2\{6\} \sim v_2\{6\}_{2\text{-sub}}$
  
  $v_2\{8\} \sim v_2\{8\}_{2\text{-sub}}$

- **Multi-particle**: $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$

**Small systems:**

- Real $v_2\{4\}_{3\text{-sub}}$ (extracted for the first time in pp collisions with ALICE)
- $v_2\{4\}_{3\text{-sub}} \sim v_2\{6\}$ (Improved agreement could be done with subevent method in $v_2\{6\}$)

Multi-particle cumulants show evidence of long-range multi-particle correlations
Origin of collectivity in small collision systems

- **2-particle correlations**: described by final state models (including hydrodynamics, parton escape, hadron interactions) and rope and shoving

- **Multi-particle correlations**: not described quantitatively by any model so far
  - Initial state model -> overestimated magnitude

$\nu_n[m]$ measurements alone cannot distinguish between initial and final state approaches
SC(m,n): suppression of non-flow effects

- Constraining initial conditions in small systems, which are currently not well known, is crucial to improve the understanding of the measurements
  - Observable sensitive to initial conditions is necessary: Symmetric Cumulants

- Clear suppression of non-flow effects in Symmetric Cumulants
- \( SC(m,n) > SC(m,n)_{2\text{-sub}} > SC(m,n)_{3\text{-sub}} \)
**SC(m,n)_{3-sub}: all systems**

- **Positive correlation between $v_2$ and $v_4$** in all collision systems
- **Anti-correlation between $v_2$ and $v_3$** at large multiplicities (direct link to initial eccentricity correlations)
  - A **transition** to positive correlation followed by both small and large systems
- **Not described by non-flow only models, but qualitatively predicted by model with initial state correlations**
Summary

Is there collectivity in small collision systems?  Yes

- Measurements of $v_n(m)$: long-range multi-particle correlations observed in pp and p-Pb

If yes, what is its origin?  Initial state effects, final state effects, both?

- Measurements of $SC(m,n)_{3\text{-sub}}$ provide tight constraints to future theoretical calculations

- Our measurements provide complete set of information to better understand the collectivity in small collision systems

REMINDER: Collectivity: long-range multi-particle correlations
Backup
• Minimum-bias trigger:
  • Suppression of non-flow with subevent method
  • The sign of $c_2\{4\}$ remains positive
• High multiplicity trigger selection:
  \[ \frac{V0M}{\langle V0M \rangle} > 4 \]
  • Additional event selection allows to obtain negative $c_2\{4\}_{3-sub}$
How do we calculate observables

**m-particle correlation**

- $\langle \langle 2 \rangle \rangle_n = \langle \langle \cos n(\varphi_1 - \varphi_2) \rangle \rangle$
- $\langle \langle 4 \rangle \rangle_n = \langle \langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle \rangle$
- $\langle \langle 6 \rangle \rangle_n = \langle \langle \cos n(\varphi_1 + \varphi_2 + \varphi_3 - \varphi_4 - \varphi_5 - \varphi_6) \rangle \rangle$
- $\langle \langle 8 \rangle \rangle_n = \langle \langle \cos n(\varphi_1 + \varphi_2 + \varphi_3 + \varphi_4 - \varphi_5 - \varphi_6 - \varphi_7 - \varphi_8) \rangle \rangle$

**step 1**

**m-particle cumulant**

- $c_n\{2\} = \langle \langle 2 \rangle \rangle_n$
- $c_n\{4\} = \langle \langle 4 \rangle \rangle_n - 2 \cdot \langle \langle 2 \rangle \rangle_n^2$
- $c_n\{6\} = \langle \langle 6 \rangle \rangle_n - 9 \cdot \langle \langle 2 \rangle \rangle_n \cdot \langle \langle 4 \rangle \rangle_n + 12 \cdot \langle \langle 2 \rangle \rangle_n^3$
- $c_n\{8\} = \langle \langle 8 \rangle \rangle_n - 16 \cdot \langle \langle 6 \rangle \rangle_n \langle \langle 2 \rangle \rangle_n - 18 \cdot \langle \langle 4 \rangle \rangle_n^2 + 144 \cdot \langle \langle 4 \rangle \rangle_n \langle \langle 2 \rangle \rangle_n^2 - 144 \cdot \langle \langle 2 \rangle \rangle_n^4$

**flow coefficients**

- $v_n\{2\} = \sqrt{c_n\{2\}}$
- $v_n\{4\} = \sqrt[4]{-c_n\{4\}}$
- $v_n\{6\} = \sqrt[6]{\frac{1}{4} c_n\{6\}}$
- $v_n\{8\} = \sqrt[8]{-\frac{1}{33} c_n\{8\}}$

**step 3**

**step 2.2 Symmetric Cumulants**

$SC(m, n) = \langle \langle 4 \rangle \rangle_{m,n} - \langle \langle 2 \rangle \rangle_m \langle \langle 2 \rangle \rangle_n$
Efficient method to calculate m-particle correlations

\[ \langle \langle 2 \rangle \rangle_n = \langle \langle \cos n(\varphi_1 - \varphi_2) \rangle \rangle \]
\[ \langle \langle 4 \rangle \rangle_n = \langle \langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle \rangle \]
\[ \langle \langle 6 \rangle \rangle_n = \langle \langle \cos n(\varphi_1 + \varphi_2 + \varphi_3 - \varphi_4 - \varphi_5 - \varphi_6) \rangle \rangle \]
\[ \langle \langle 8 \rangle \rangle_n = \langle \langle \cos n(\varphi_1 + \varphi_2 + \varphi_3 + \varphi_4 - \varphi_4 - \varphi_5 - \varphi_6 - \varphi_7 - \varphi_8) \rangle \rangle \]

\[ Q_{n,p} = \sum_{k=1}^{M} w_k^p e^{in\varphi_k} \]

**Generic Framework** (PRC 89, 064904 (2014))

- Universal implementation able to calculate any type and order of correlation, including corrections (which was not possible to do with Q-cumulant method)

Two-particle correlation

\[ \text{Two} (n_1, n_2) = \frac{Q_{n_1,1}Q_{n_2,1} - Q_{n_1+n_2,2}}{Q_{0,1}^2 - Q_{0,2}} \]

Four-particle correlation

\[ Q_{n_1,1}Q_{n_2,1}Q_{n_3,1}Q_{n_4,1} - Q_{n_1+n_2,2}Q_{n_3,1}Q_{n_4,1} - Q_{n_2,1}Q_{n_1+n_3,2}Q_{n_4,1} - Q_{n_1,1}Q_{n_2+n_3,2}Q_{n_4,1} + 2Q_{n_1+n_2+n_3,3}Q_{n_4,1} - Q_{n_2,1}Q_{n_3,1}Q_{n_1+n_4,2} + 2Q_{n_2+n_3,2}Q_{n_1+n_4,2} - Q_{n_1,1}Q_{n_3,1}Q_{n_2+n_4,2} + 2Q_{n_1+n_3,2}Q_{n_2+n_4,2} + 2Q_{n_1,1}Q_{n_2+n_3,4} + 2Q_{n_1,1}Q_{n_2+n_3+n_4,3} - 6Q_{n_1+n_2+n_3+n_4,4} \]
\[ Q_{0,1} - 6Q_{0,1}^2Q_{0,2} + 3Q_{0,2}^2 + 8Q_{0,1}Q_{0,3} - 6Q_{0,4} \]
Contamination with non-flow in SC(m,n)

- SC(m,n) measurements are based on 4-particle cumulant
- Clear contamination of standard $c_2[4]$ measurements -> **SC(m,n) is contaminated too**

$$\langle \langle 4 \rangle \rangle_{2\text{-sub}} = \langle \langle \cos (m \varphi_1 + n \varphi_2 - m \varphi_3 - n \varphi_4) \rangle \rangle$$
$$\langle \langle 2 \rangle \rangle_{2\text{-sub}} \langle \langle 2 \rangle \rangle_{2\text{-sub}} = \langle \langle \cos m(\varphi_1 - \varphi_3) \rangle \rangle \langle \langle \cos n(\varphi_2 - \varphi_4) \rangle \rangle$$

$$SC(m, n)_{2\text{-sub}} = \langle \langle 4 \rangle \rangle_{2\text{-sub}} - \langle \langle 2 \rangle \rangle_{2\text{-sub}} \langle \langle 2 \rangle \rangle_{2\text{-sub}}$$

3-subevent method in the backup
3-subevent method in SC(m,n)

\[ A. \]
\[
\langle \langle 4 \rangle \rangle_{m,n,-m,-n} = \langle \langle \cos (m \varphi_1 + n \varphi_2 - m \varphi_3 - n \varphi_4) \rangle \rangle \\
\langle \langle 2 \rangle \rangle_{m,-m} \langle \langle 2 \rangle \rangle_{n,-n} = \langle \langle \cos m(\varphi_1 - \varphi_3) \rangle \rangle \langle \langle \cos n(\varphi_2 - \varphi_4) \rangle \rangle
\]

\[ SC(m, n)_A = \langle \langle 4 \rangle \rangle_{m,n,-m,-n} - \langle \langle 2 \rangle \rangle_{m,-m} \langle \langle 2 \rangle \rangle_{n,-n} \]

\[ B. \]
\[
\langle \langle 4 \rangle \rangle_{m,n,-n,-m} = \langle \langle \cos (m \varphi_1 + n \varphi_2 - n \varphi_3 - m \varphi_4) \rangle \rangle \\
\langle \langle 2 \rangle \rangle_{n,-n} \langle \langle 2 \rangle \rangle_{m,-m} = \langle \langle \cos n(\varphi_2 - \varphi_3) \rangle \rangle \langle \langle \cos m(\varphi_1 - \varphi_4) \rangle \rangle
\]

\[ SC(m, n)_B = \langle \langle 4 \rangle \rangle_{m,n,-n,-m} - \langle \langle 2 \rangle \rangle_{n,-n} \langle \langle 2 \rangle \rangle_{m,-m} \]

• SC(m,n)_A and SC(m,n)_B are then combined together