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?

ALICE

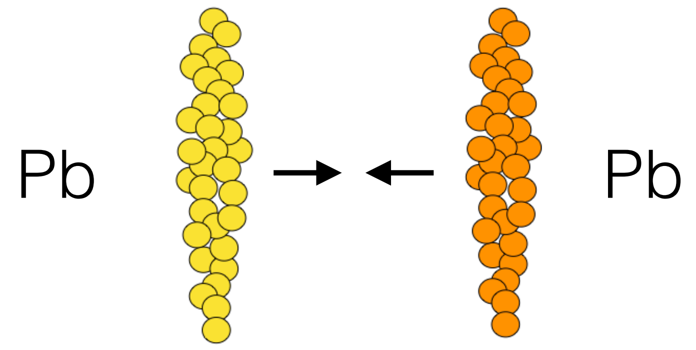
Niels Bohr Institutet

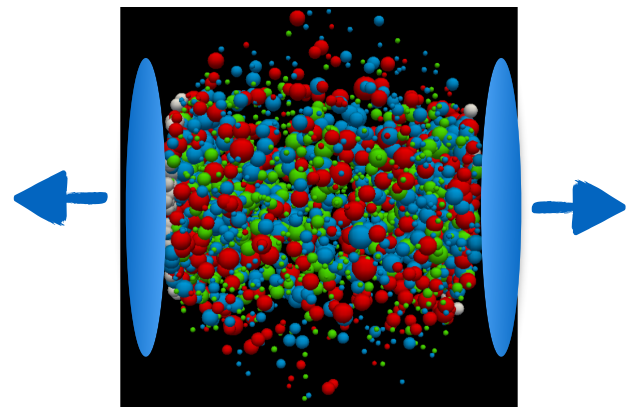
Katarina Gajdosova
on behalf of the ALICE Collaboration
Niels Bohr Institute, Copenhagen

Venezia 2018 Quark Matter

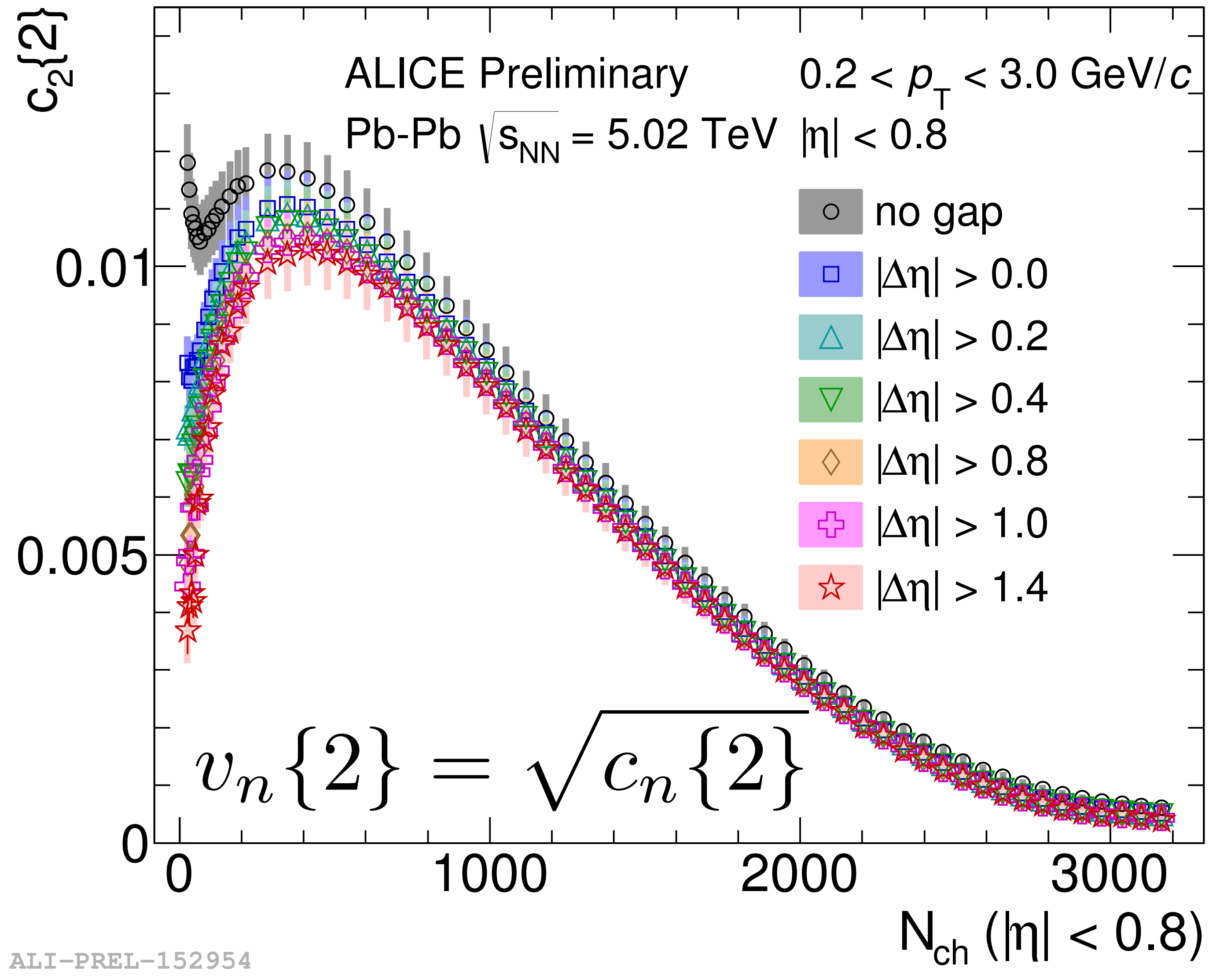
What is collectivity: long-range correlations

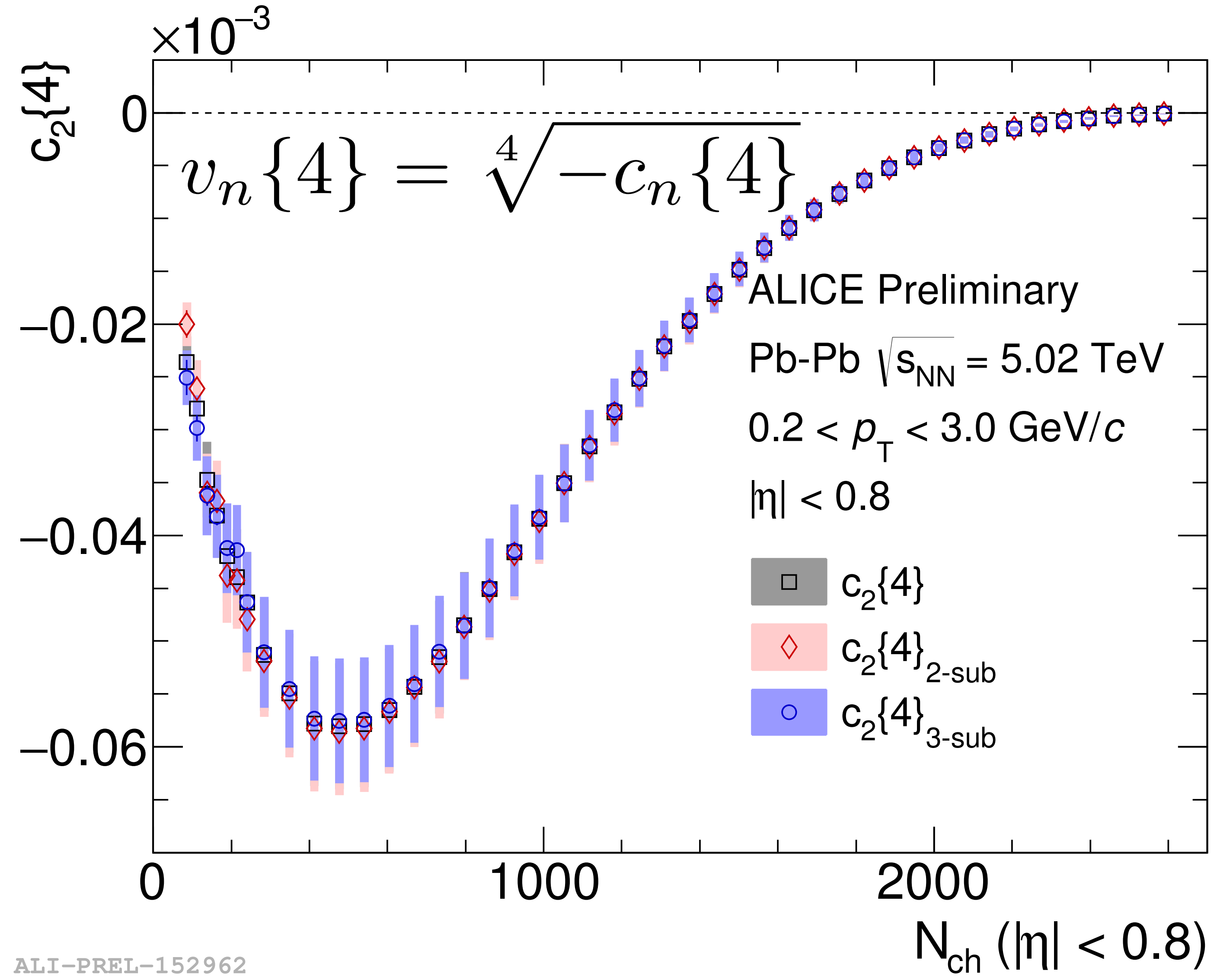
Collectivity: **long-range** multi-particle correlations

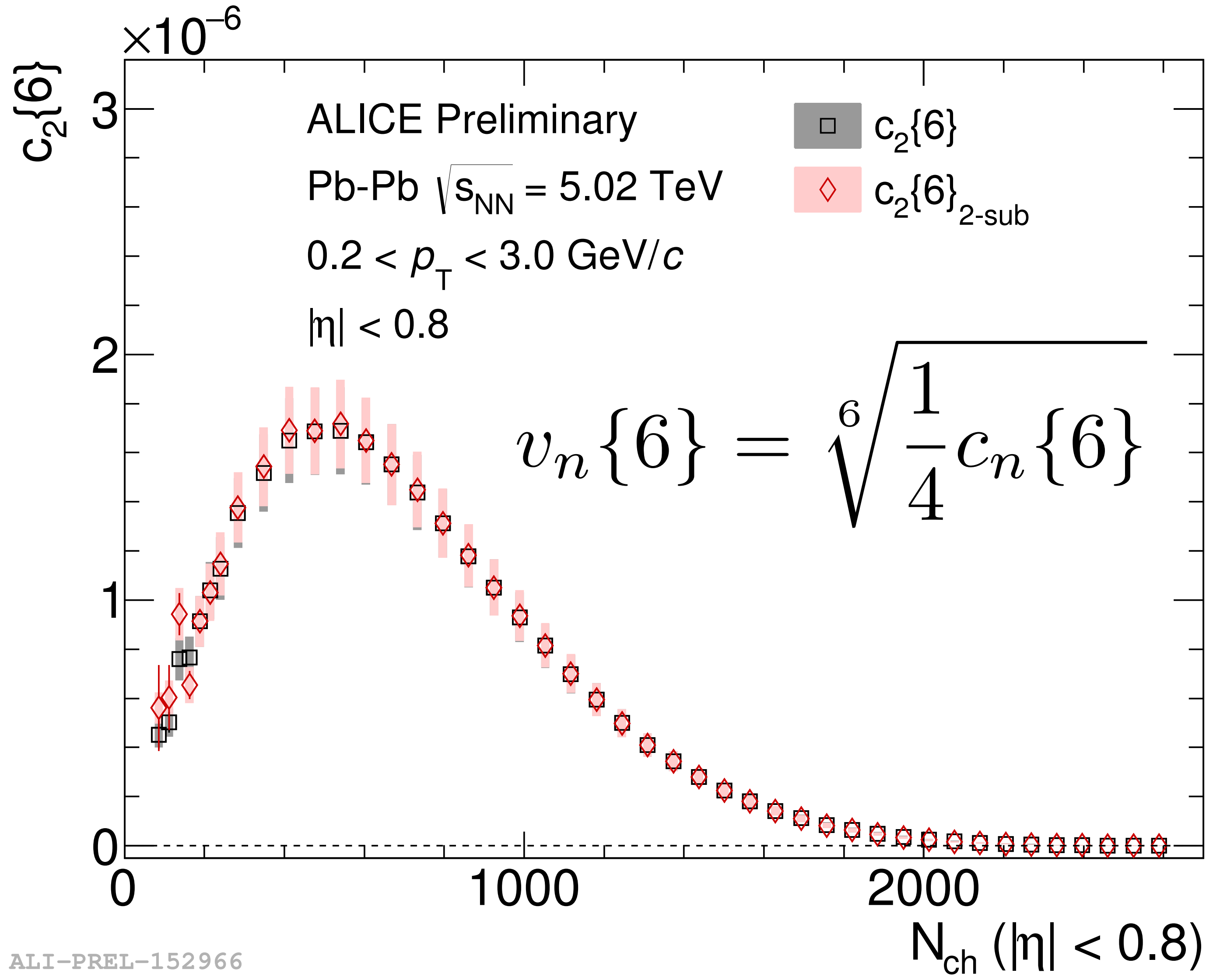


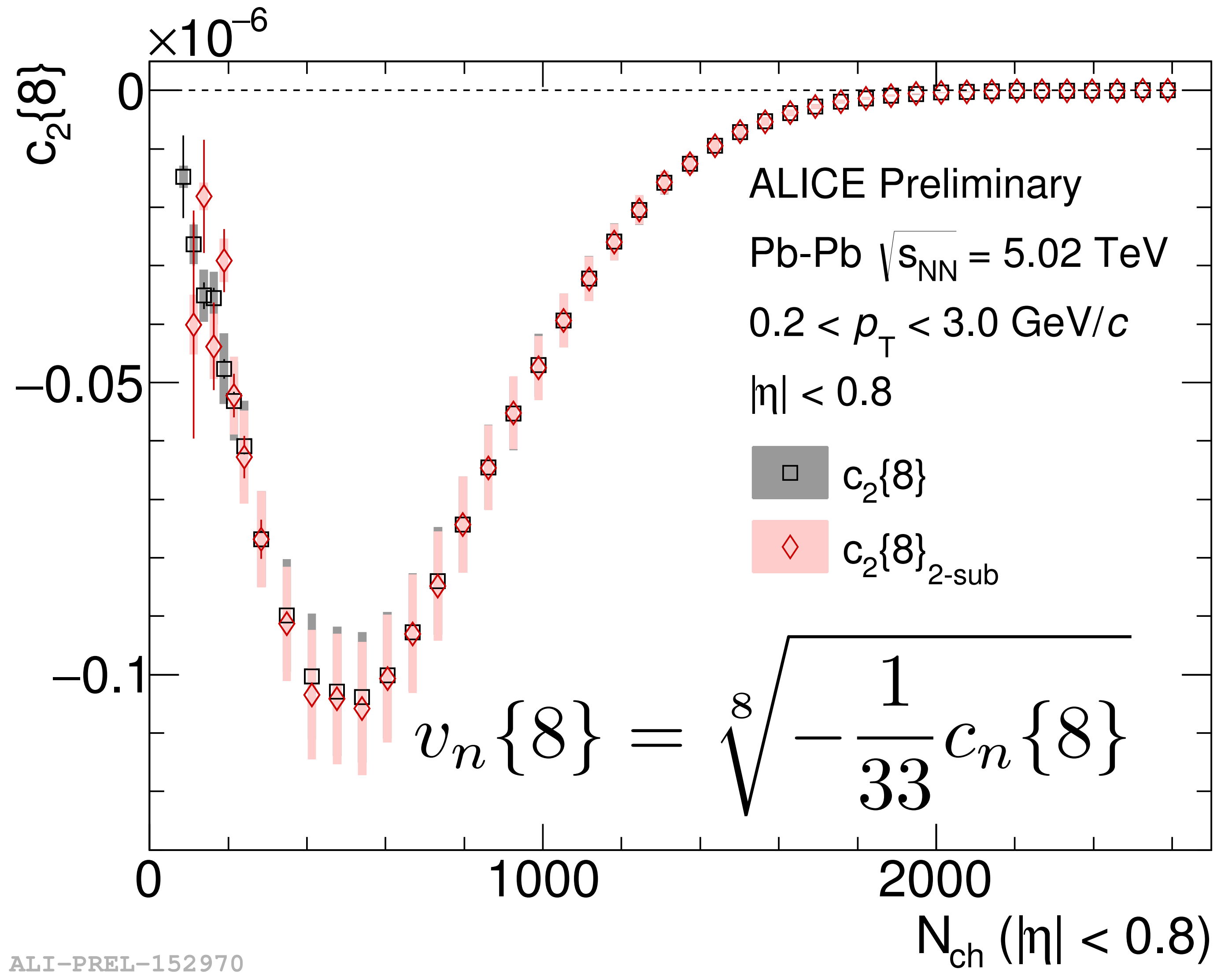


- **Correlations are long-range**: saturation of the v_2 with $|\Delta\eta|$ separation



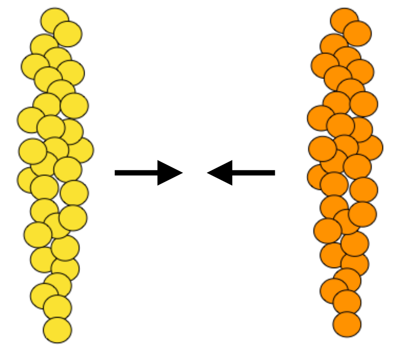


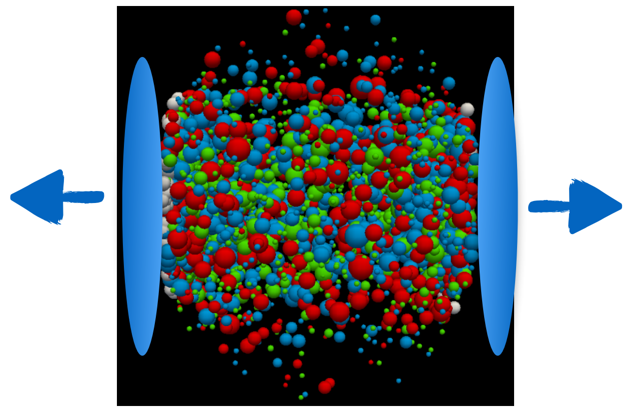




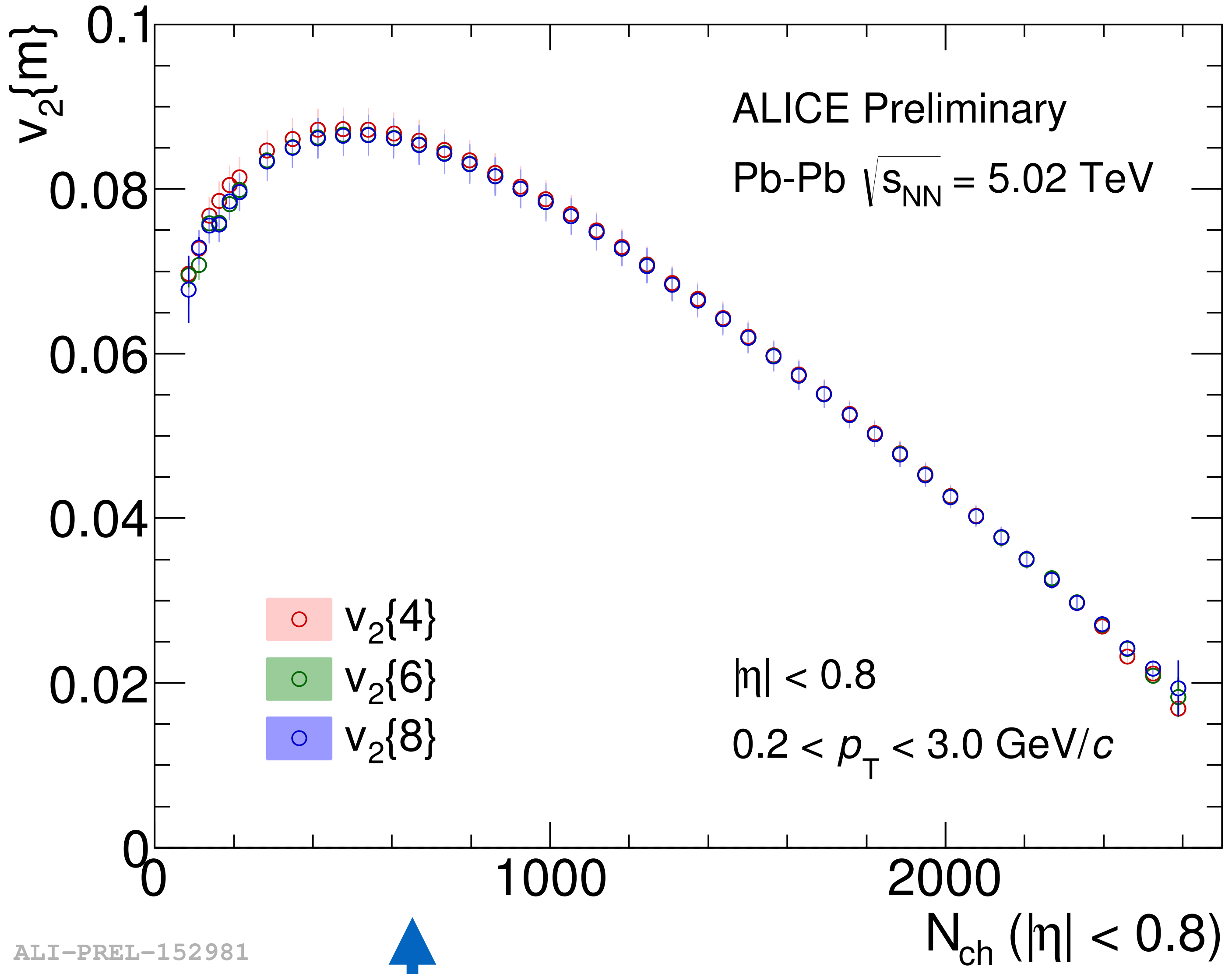
What is collectivity: multi-particle correlations

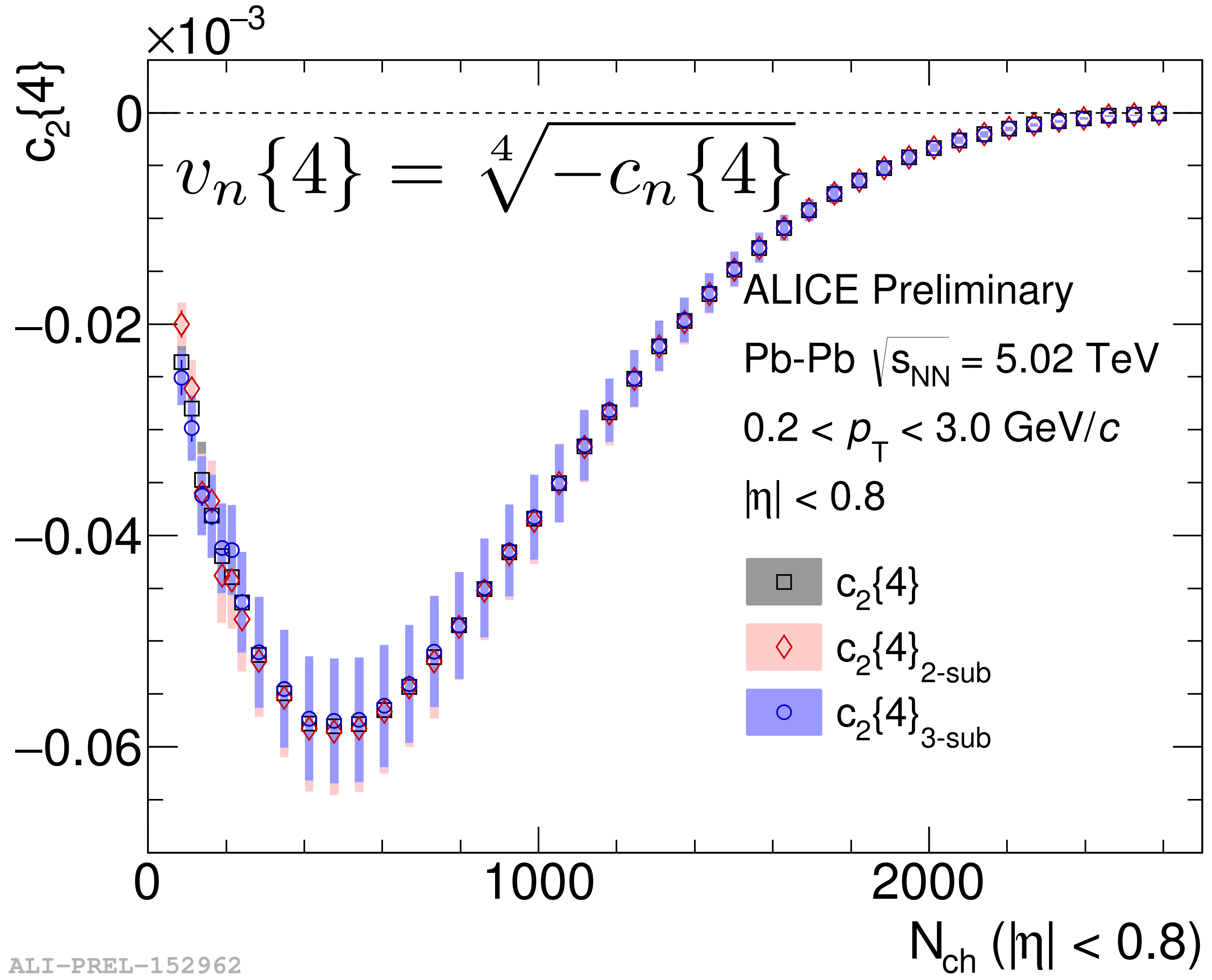
Collectivity: long-range **multi-particle** correlations

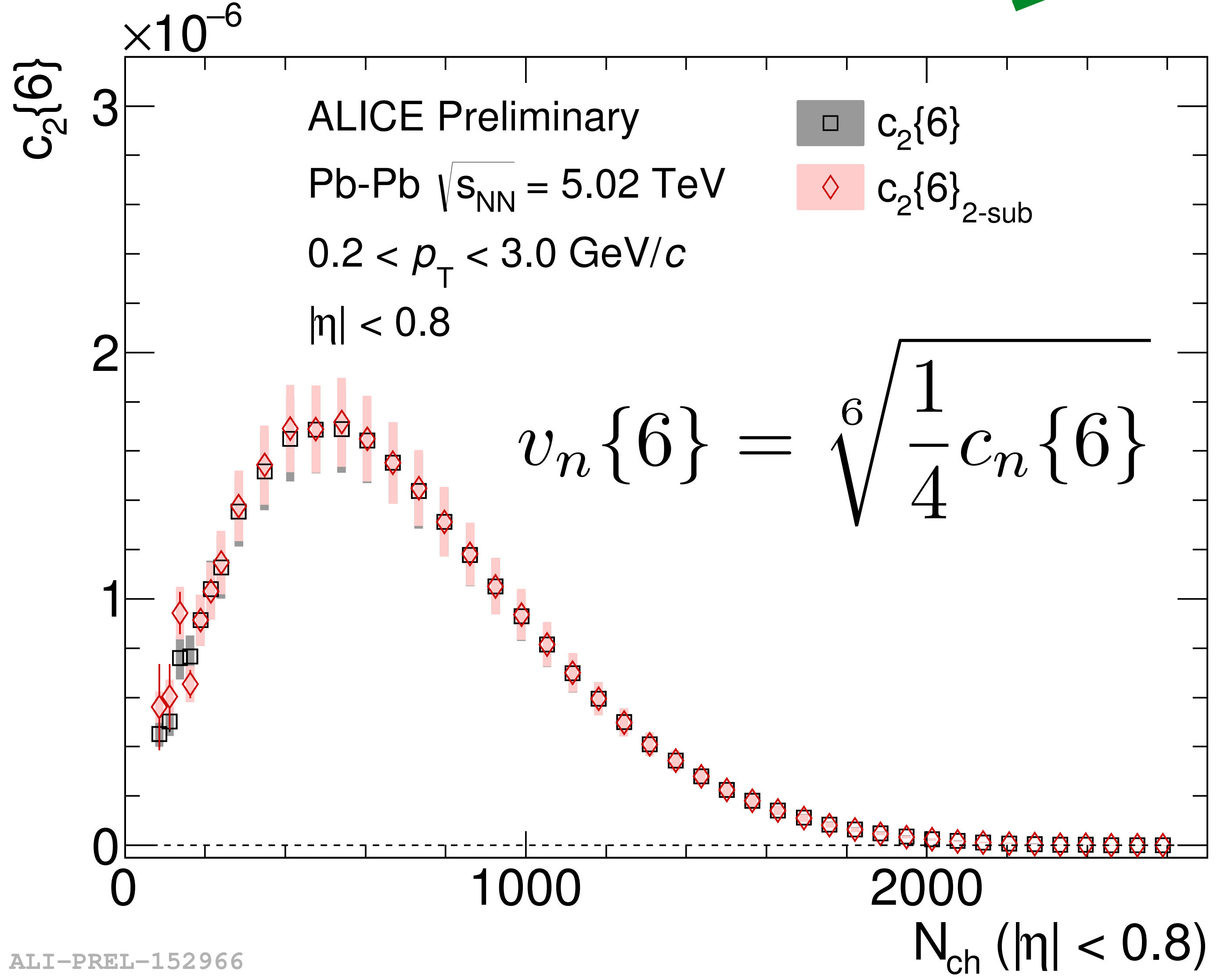


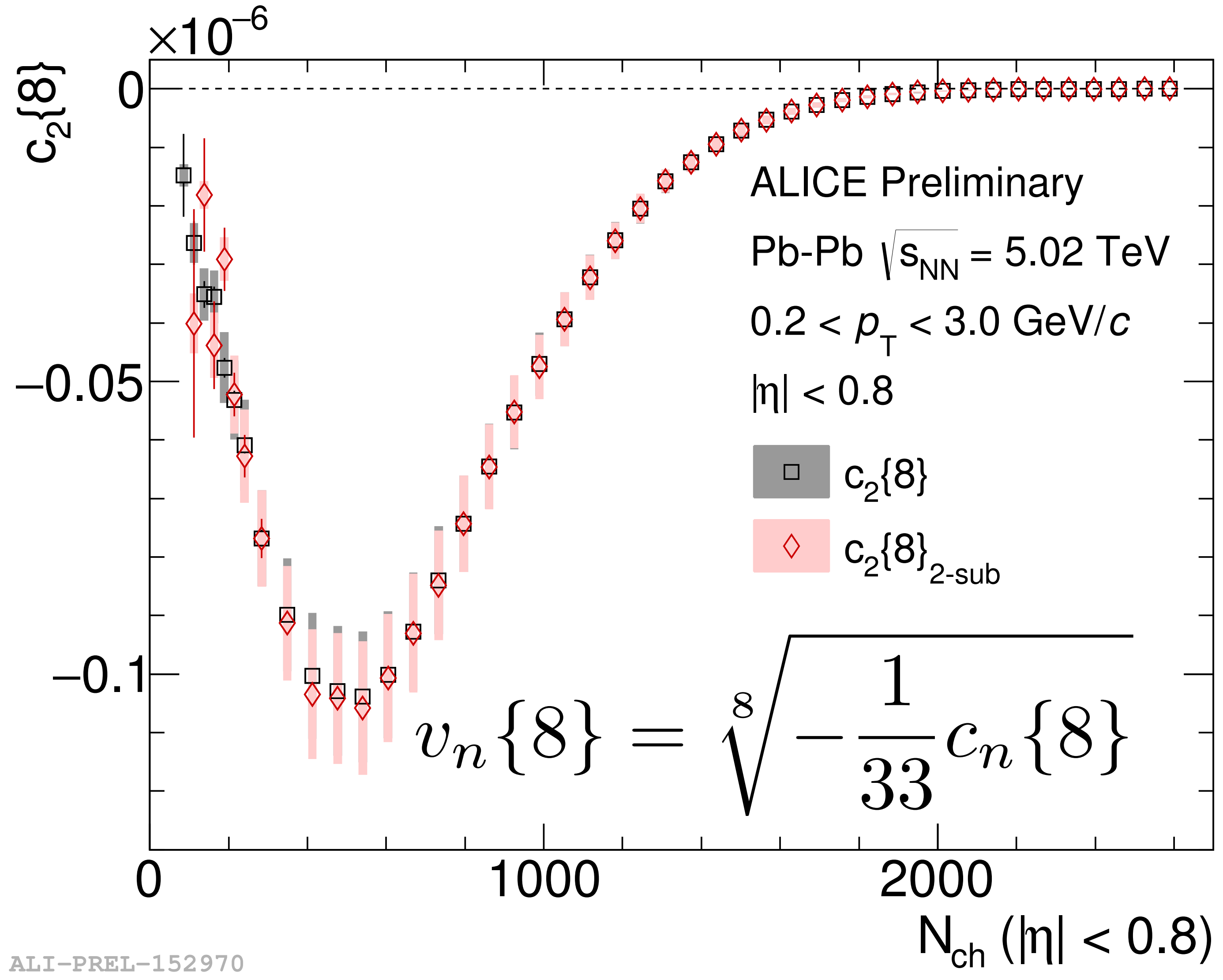


- **Correlations are long-range**: saturation of the v_2 with $|\Delta\eta|$ separation
- **Correlations among many particles**
  - $v_2\{4\} \sim v_2\{6\} \sim v_2\{8\}$

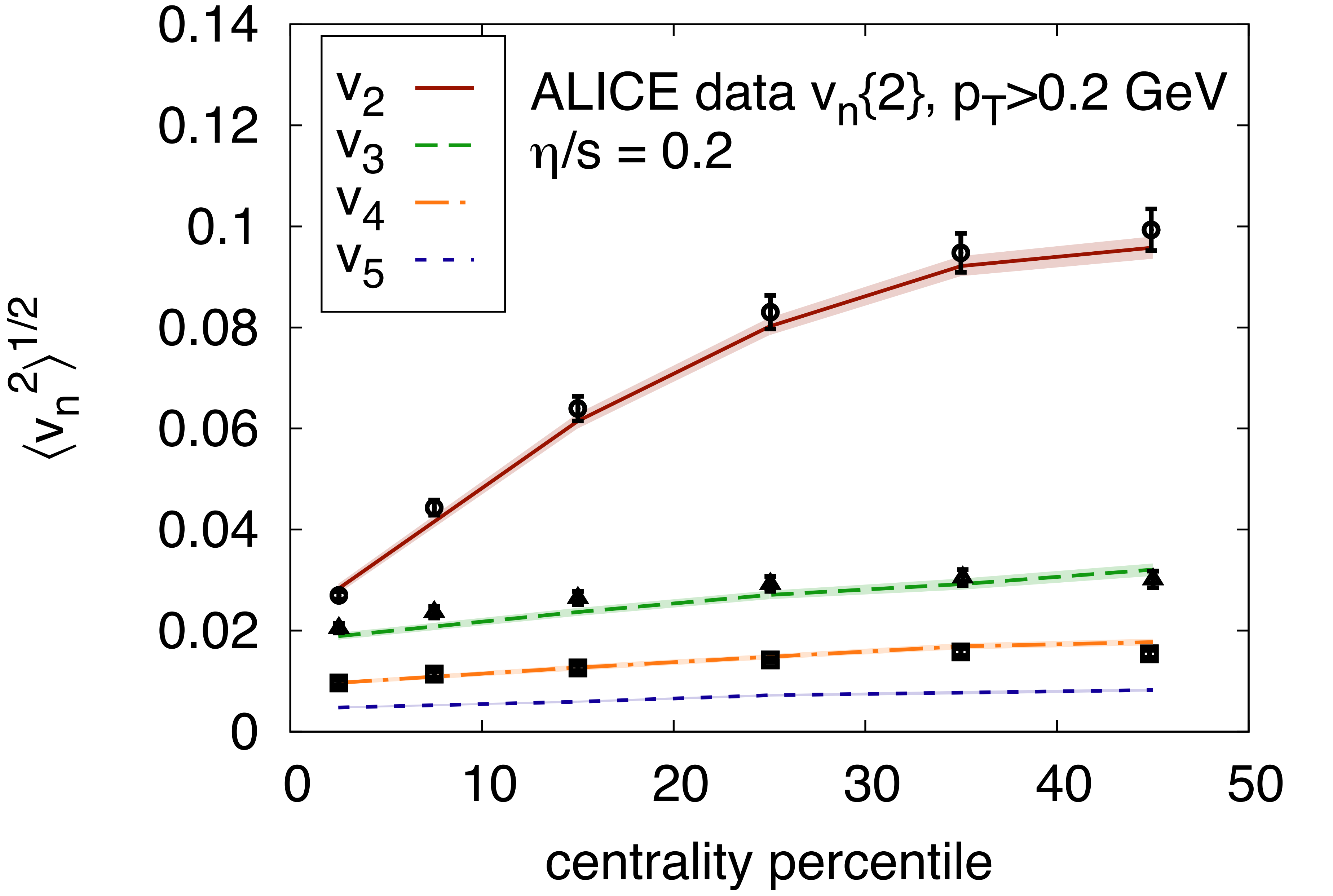


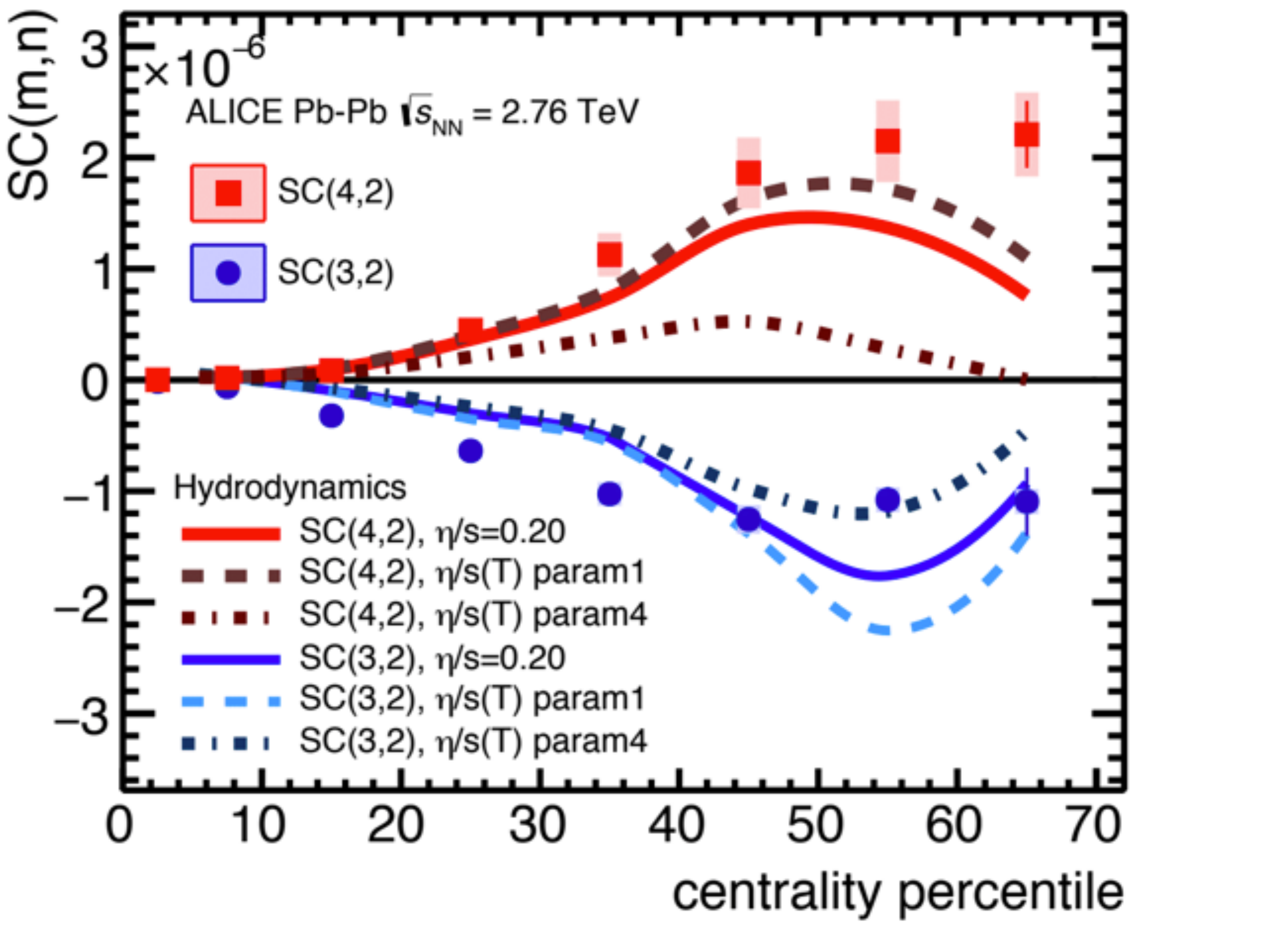






Origin of collectivity in Pb-Pb collisions





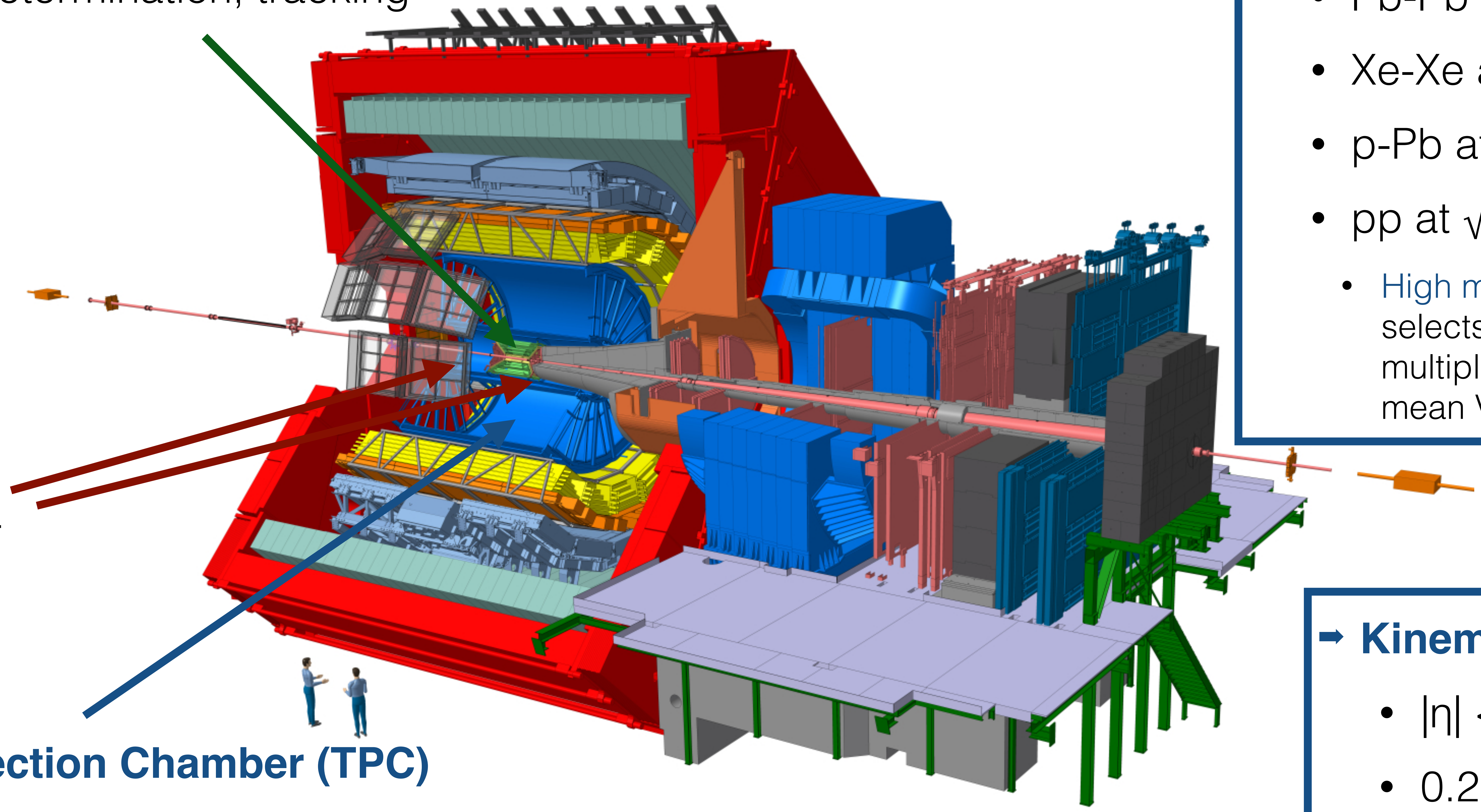
- Measurements of v_n consistent with hydrodynamical model calculations
- Symmetric Cumulants provide further constraints on the initial conditions and transport coefficients
- $v_n\{m\}$ together with SC(m,n) provide a better handle of the model parameters than each of them independently

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

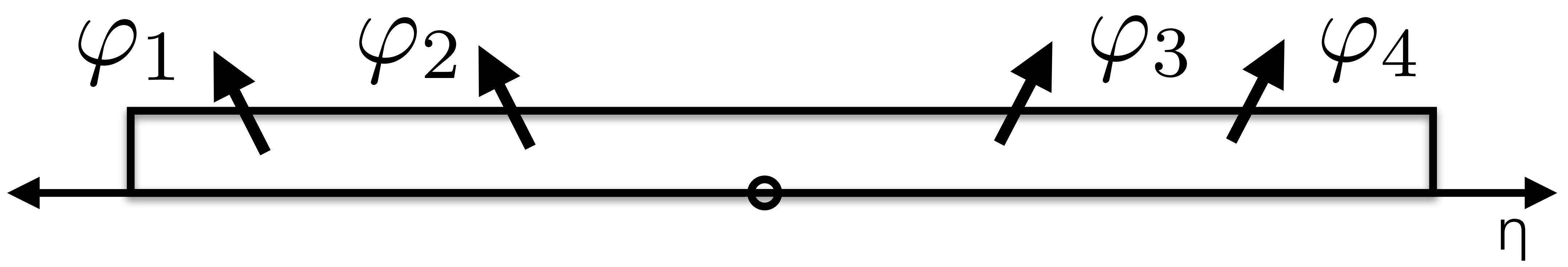
Suppression of non-flow effects

- 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

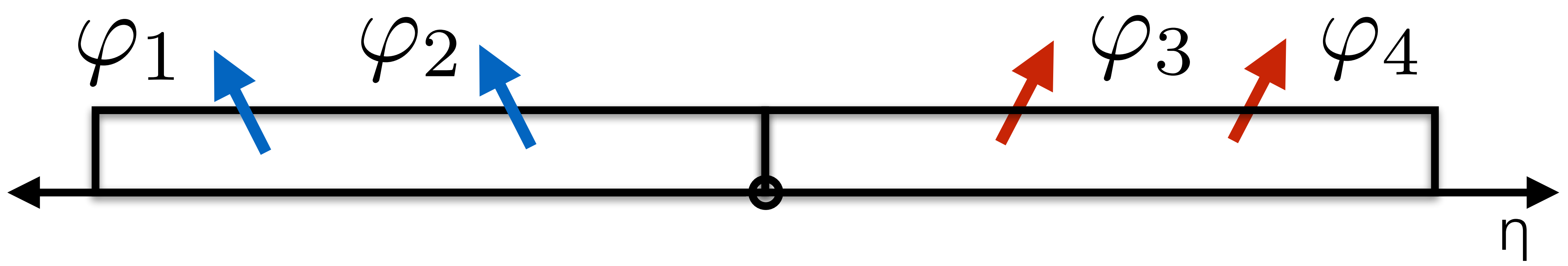
standard method



$$\langle\langle 4 \rangle\rangle = \langle\langle \cos \mathrm{n}(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle\rangle$$

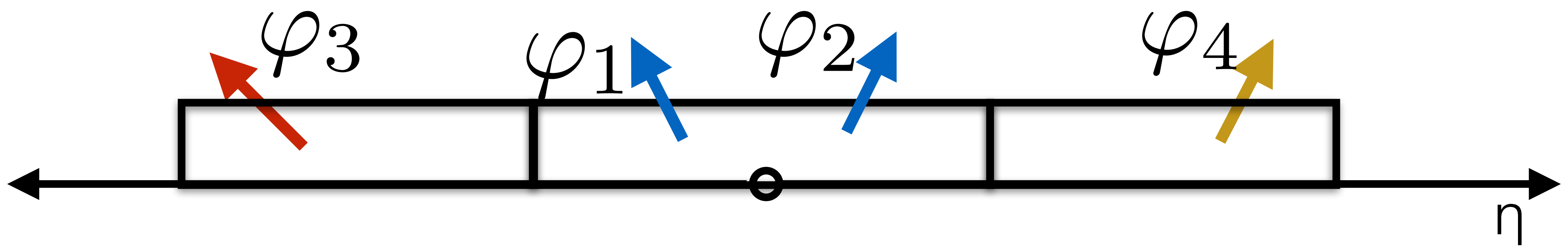
Example: 4-particle correlation

2-subevent method



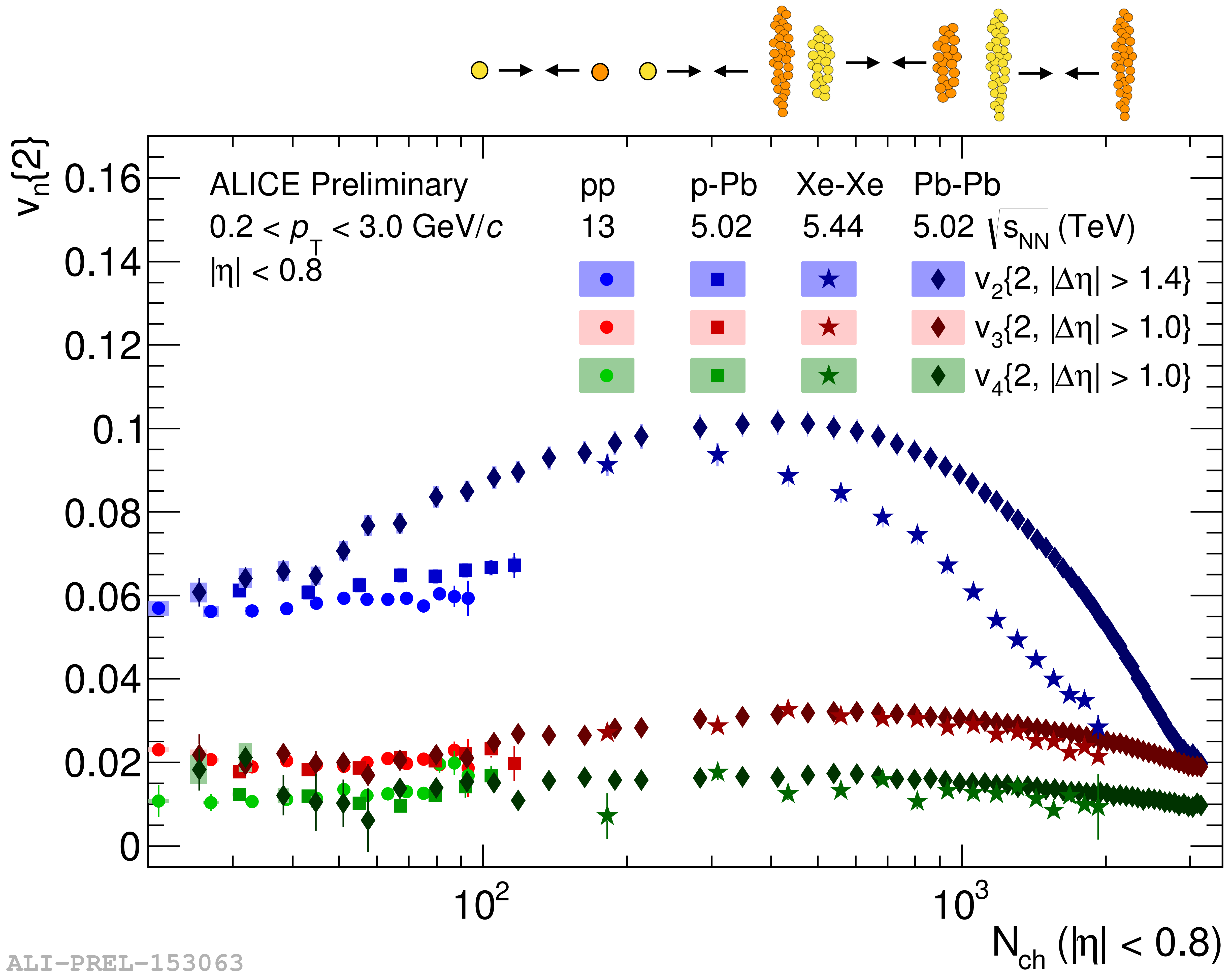
$$\langle\langle 4 \rangle\rangle_{2-sub} = \langle\langle \cos \mathrm{n}(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4) \rangle\rangle$$

3-subevent method



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

$v_n\{2\}$: all systems



Cannot be explained solely by non-flow

➡ **Heavy-ion collisions**:

- Clear multiplicity dependence of v_2 showing response to collision geometry
- Ordering $v_2 > v_3 > v_4$

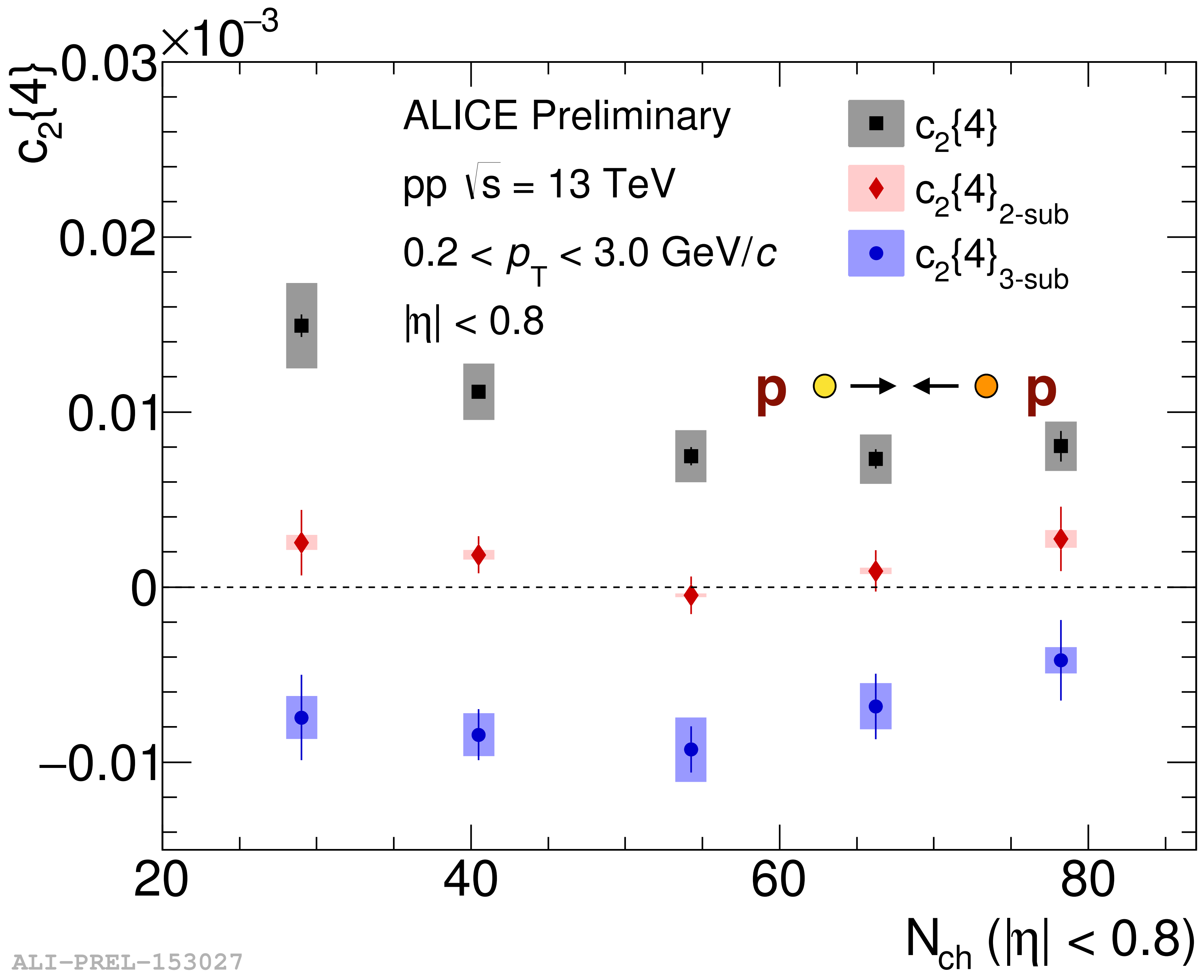
➡ **Small systems**:

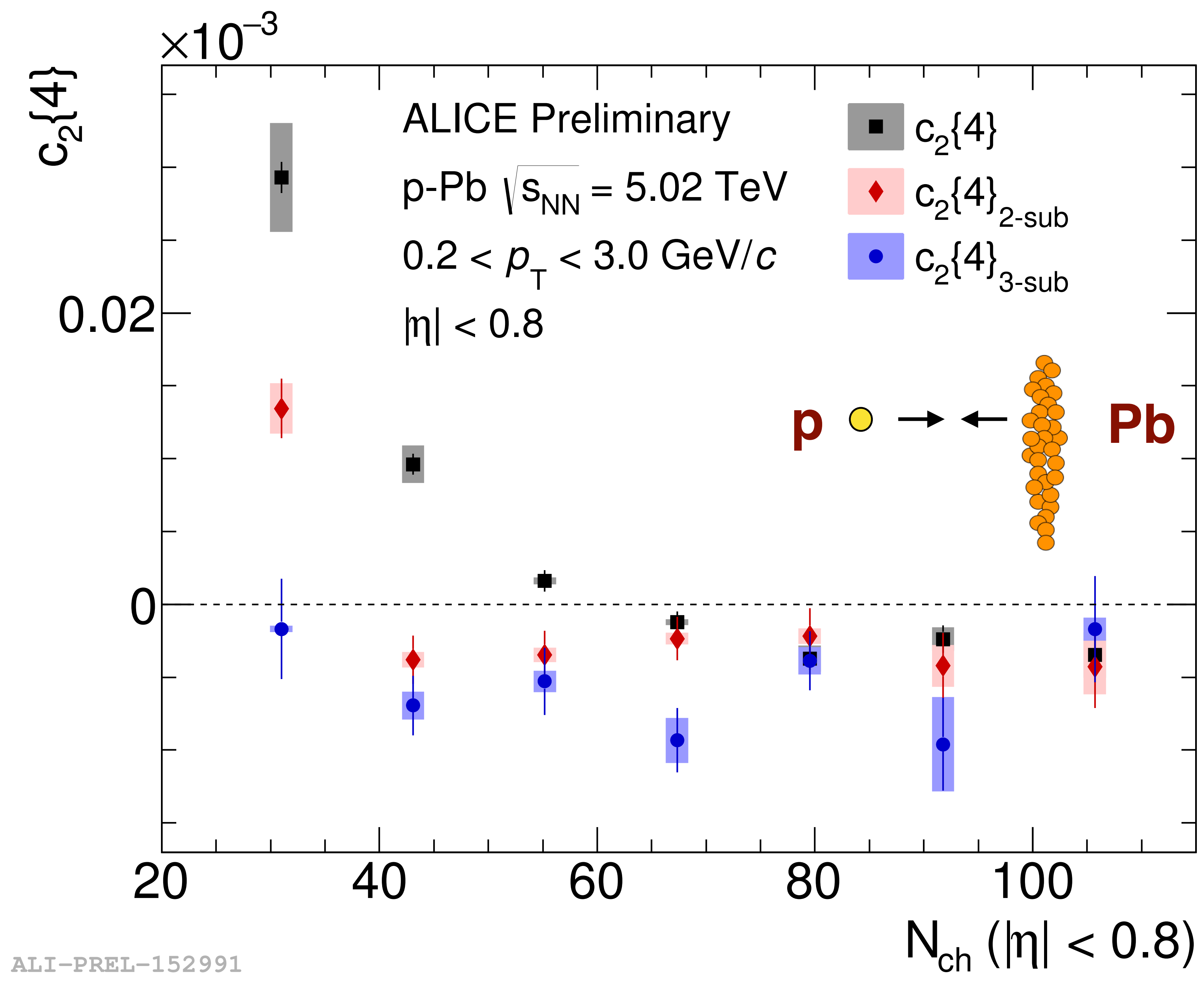
- Comparable values with Pb-Pb at low N_{ch}
- Weak multiplicity dependence
- Ordering $v_2 > v_3 > v_4$

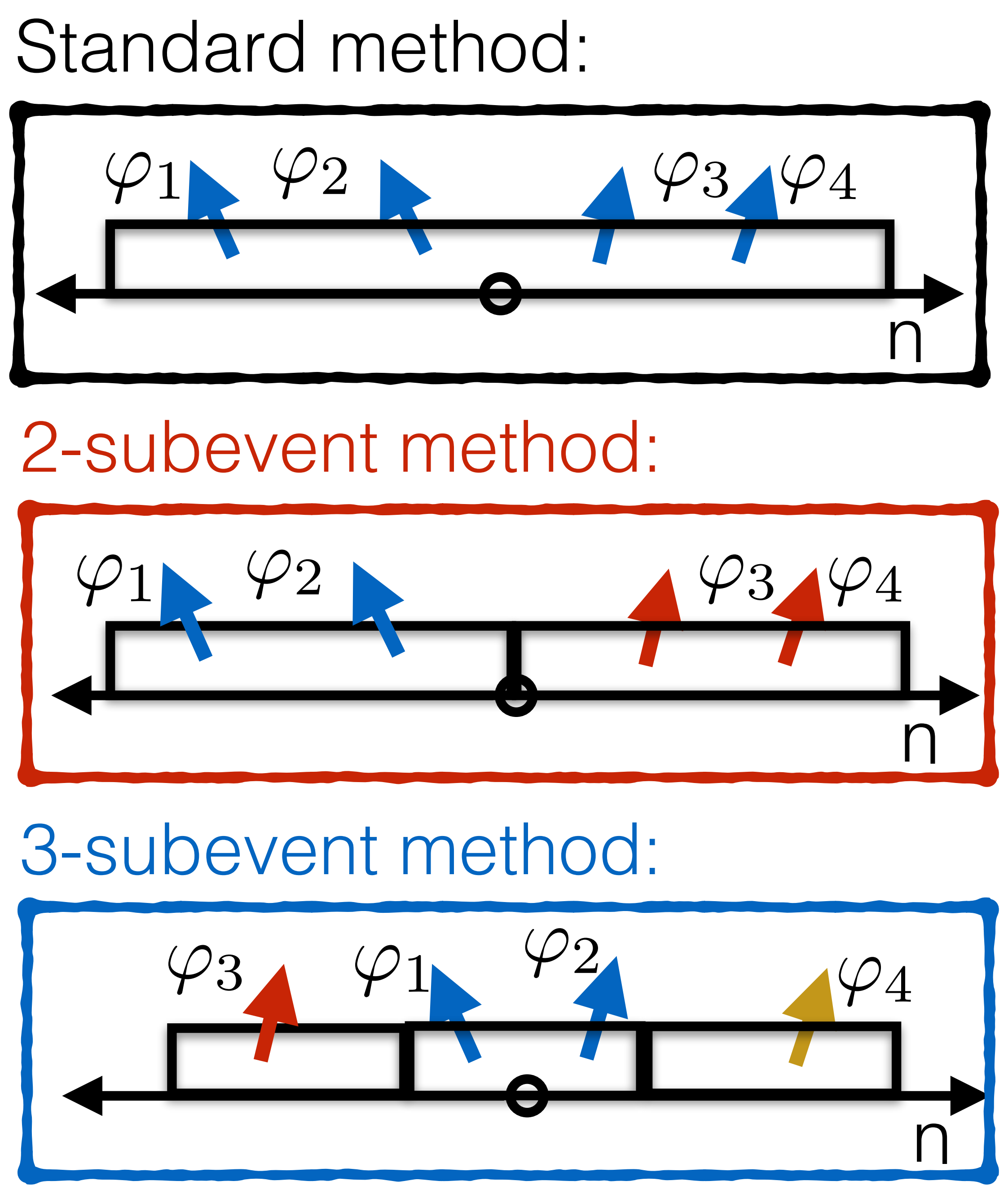
REMINDER: **Collectivity**: long-range multi-particle correlations

Collectivity can be better probed with multi-particle cumulants

$c_2\{4\}$: small systems

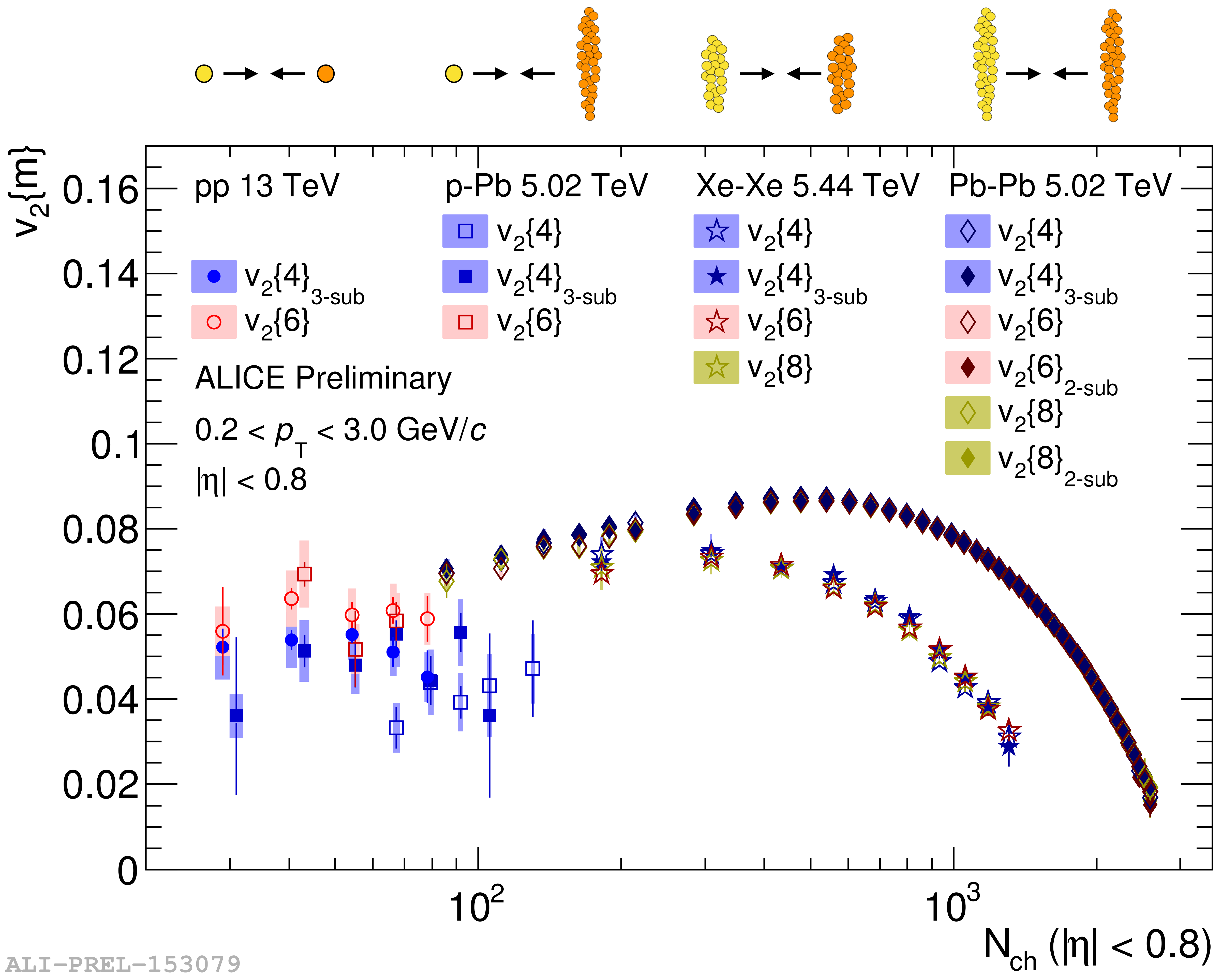






- Subevent method further suppresses non-flow in multi-particle cumulants in **pp collisions**
  - **Negative $c_2\{4\}_{3\text{-sub}}$** -> **real value** for **$v_2\{4\}_{3\text{-sub}}$**
- Non-flow can be largely suppressed also in **p-Pb collisions**
- No significant further decrease of $v_2\{4\}_{3\text{-sub}}$ with $|\Delta\eta| > 0.2$ between subevents

$v_2\{m\}$ (m>2): all systems



Multi-particle cumulants show
evidence of long-range multi-particle correlations

➡ **Heavy-ion collisions:**

- Long-range: signal doesn't change anymore with subevent method

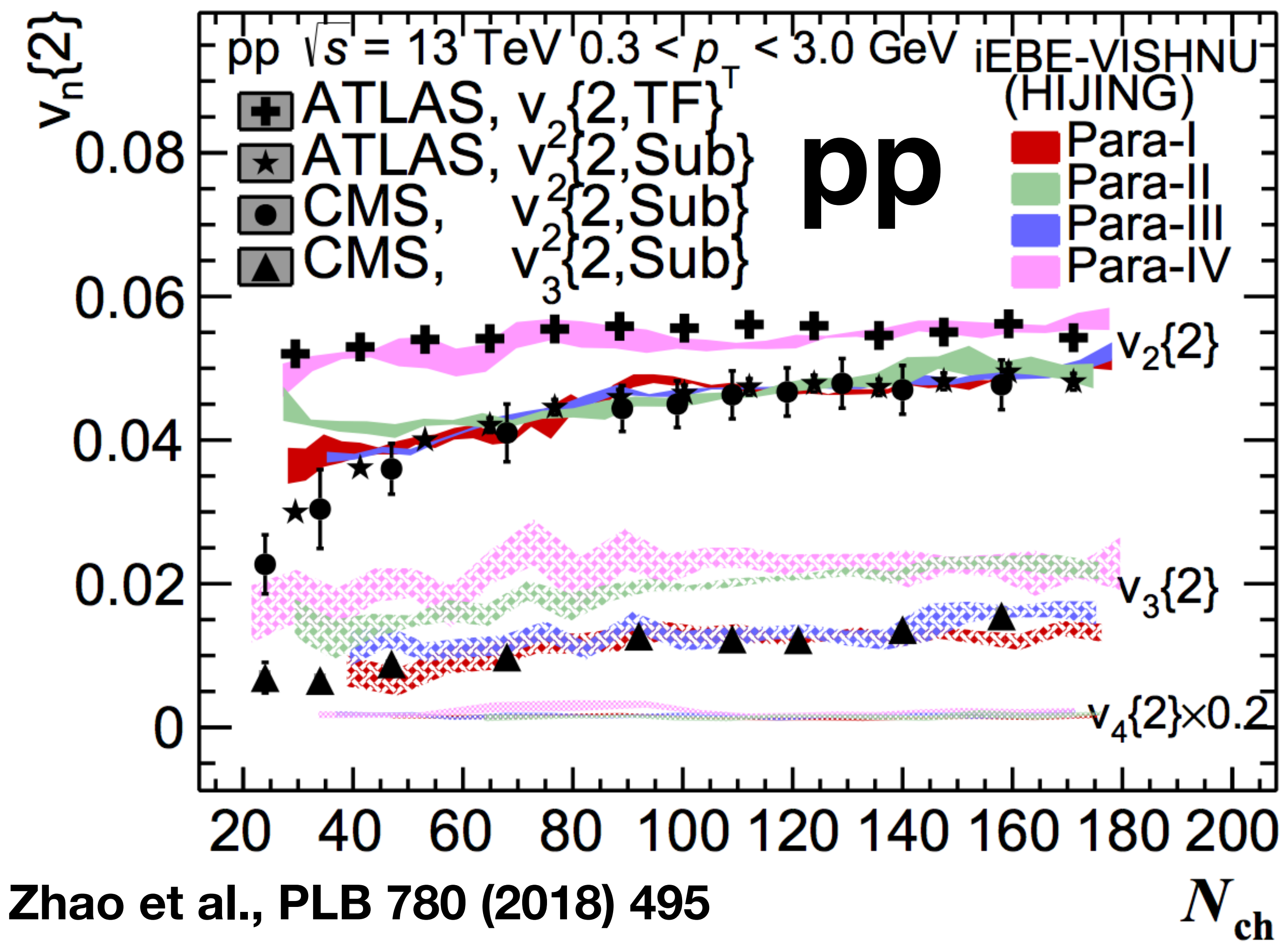
  $v_2\{4\} \sim v_2\{4\}_{3\text{-sub}}$
  $v_2\{6\} \sim v_2\{6\}_{2\text{-sub}}$
  $v_2\{8\} \sim v_2\{8\}_{2\text{-sub}}$

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

➡ **Small systems:**

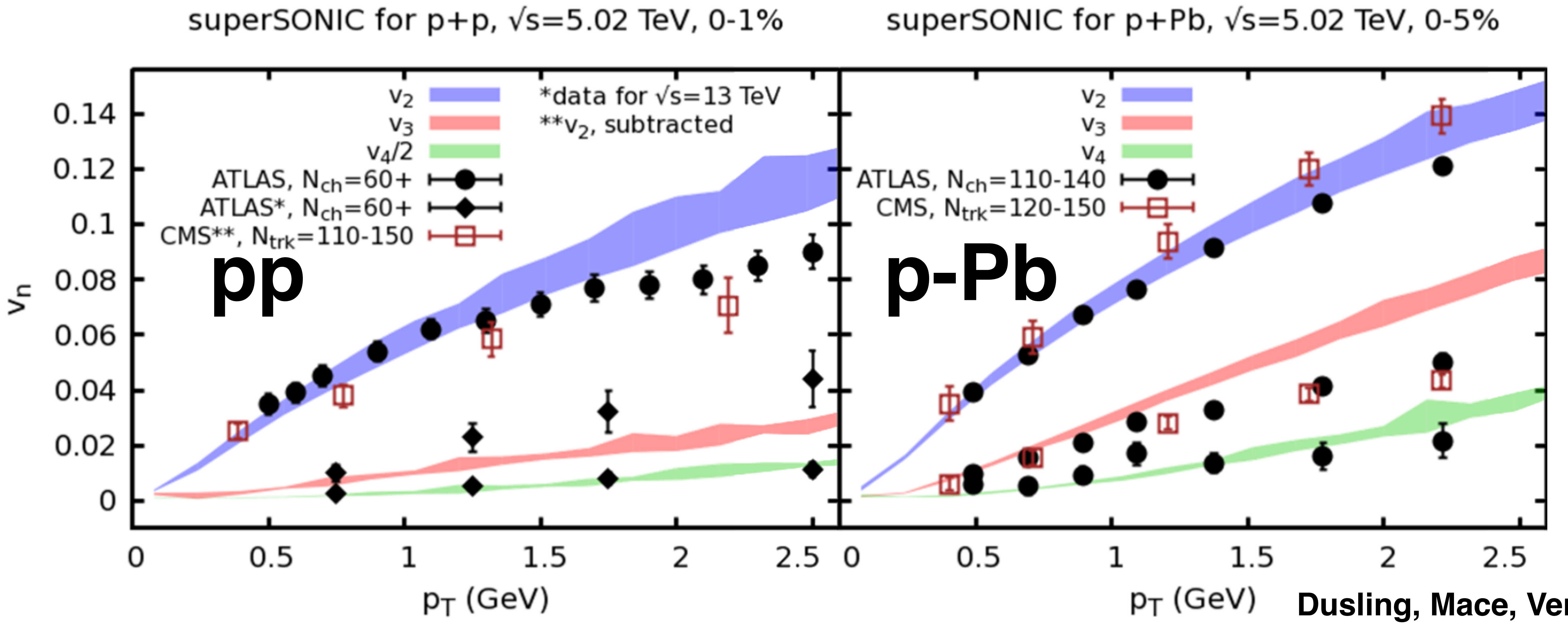
- Real $v_2\{4\}_{3\text{-sub}}$ (extracted for the first time in pp collisions with ALICE)
- $v_2\{4\}_{3\text{-sub}} \sim v_2\{6\}$ (Improved agreement could be done with subevent method in $v_2\{6\}$)

Origin of collectivity in small collision systems

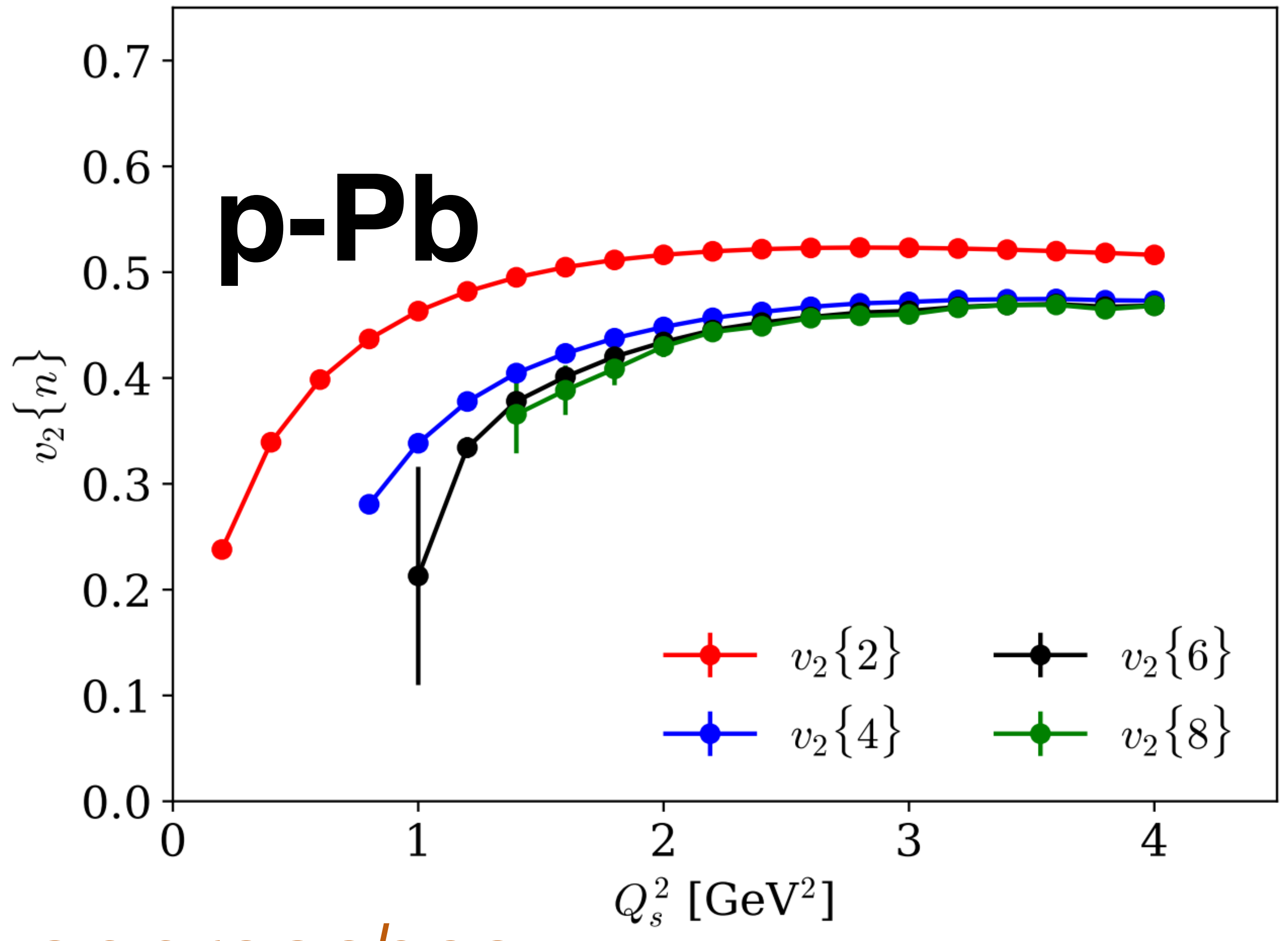


W. Zhao et al., PLB 780 (2018) 495

Weller, Romatschke, PLB 774 (2017) 351



Dusling, Mace, Venugopalan, arXiv:1705.00745

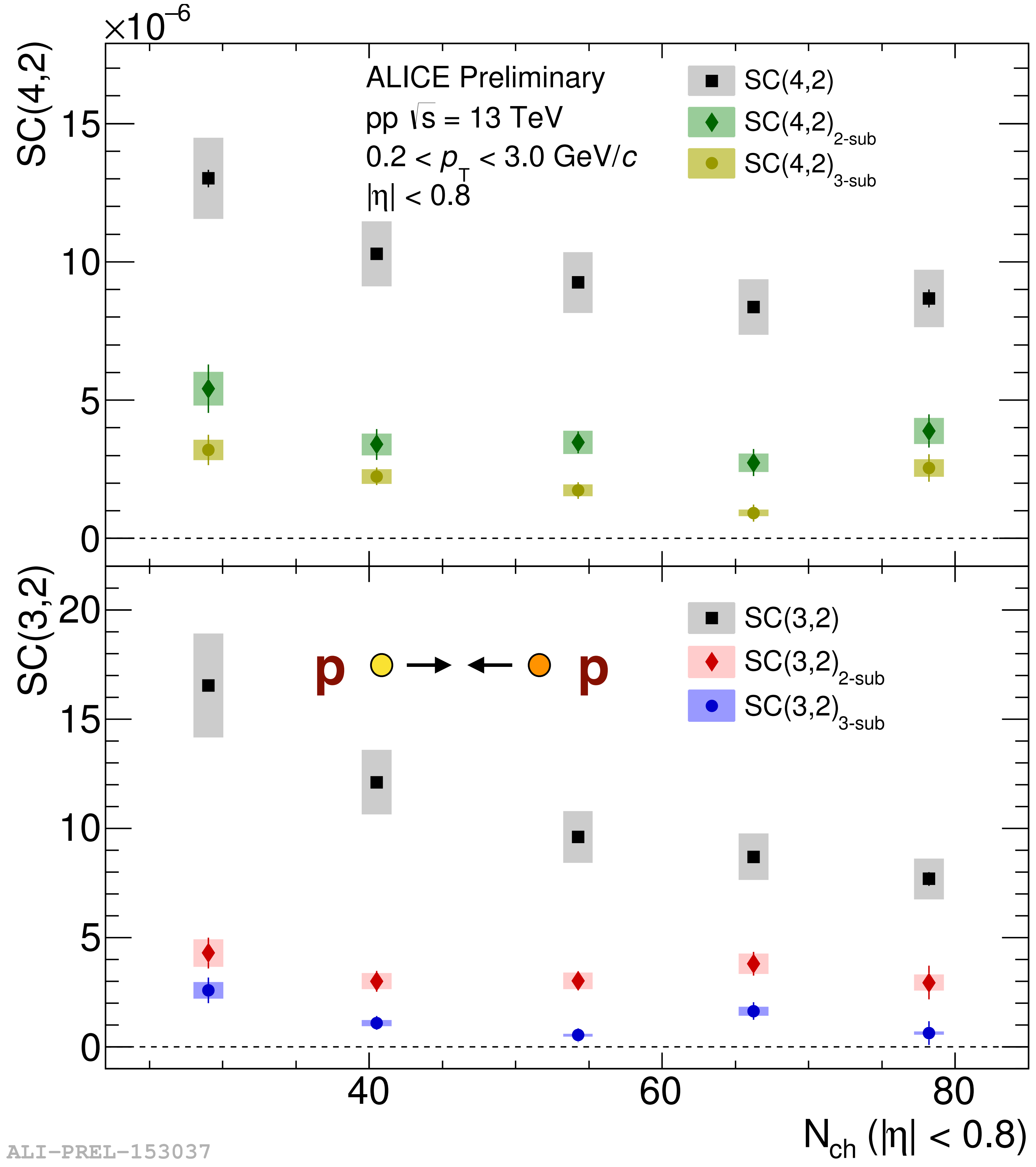


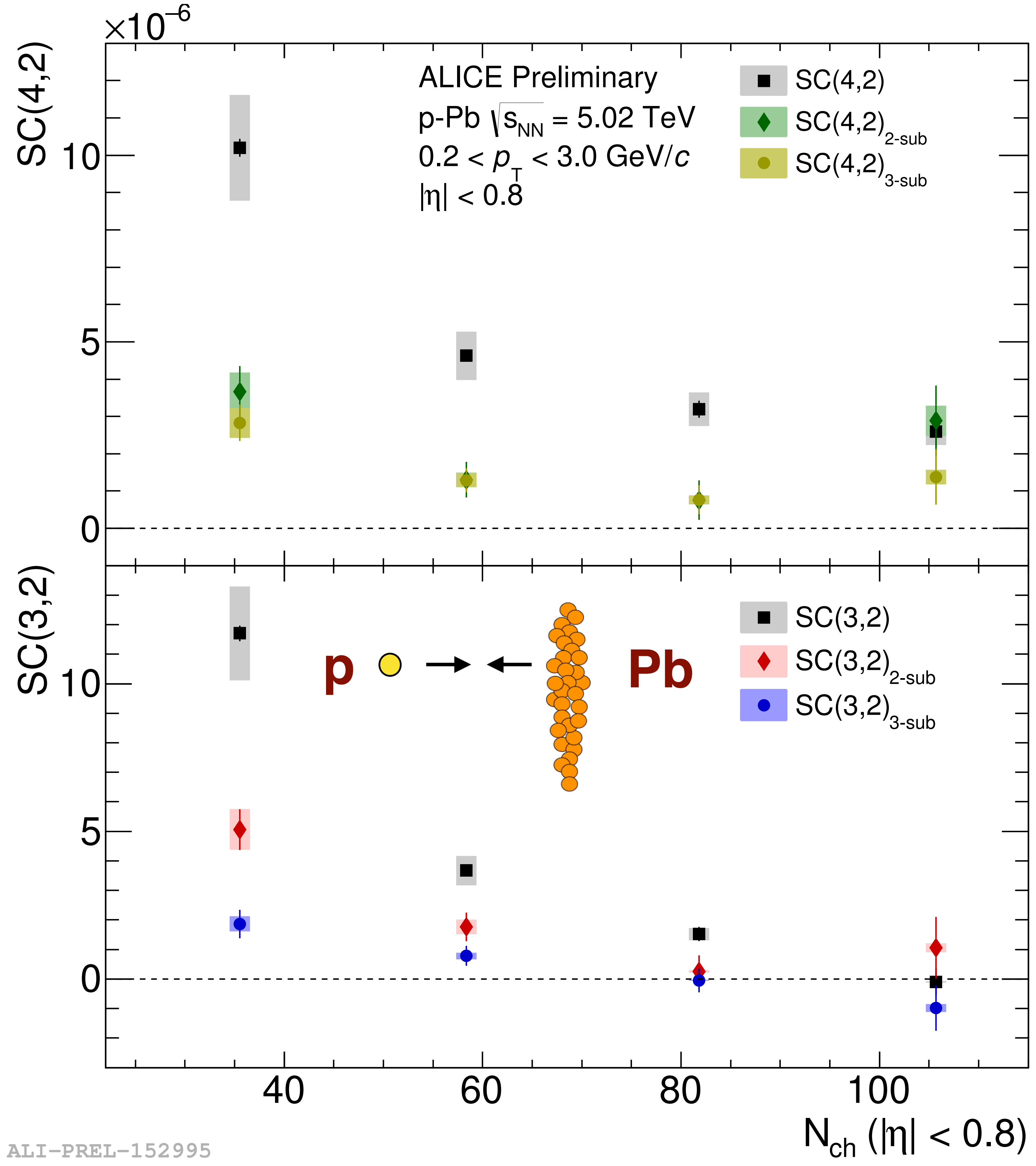
- **2-particle correlations**: described by final state models (including hydrodynamics, parton escape, hadron interactions) and rope and shoving
- **Multi-particle correlations**: not described quantitatively by any model so far
  - Initial state model -> overestimated magnitude

$v_n\{m\}$ measurements alone cannot distinguish between initial and final state approaches

SC(m,n): suppression of non-flow effects

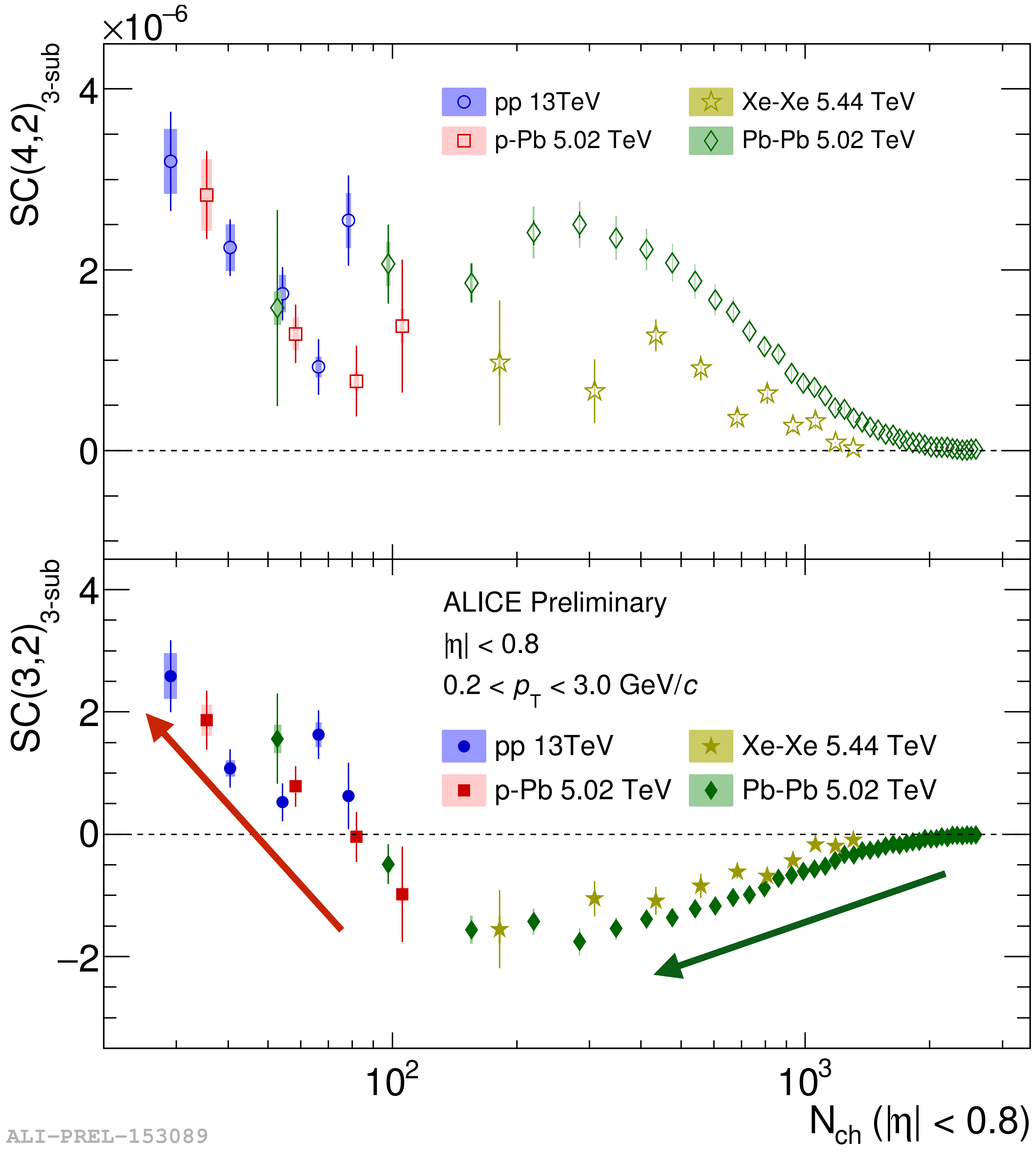
- Constraining initial conditions in small systems, which are currently not well known, is crucial to improve the understanding of the measurements
  - Observable sensitive to initial conditions is necessary: Symmetric Cumulants



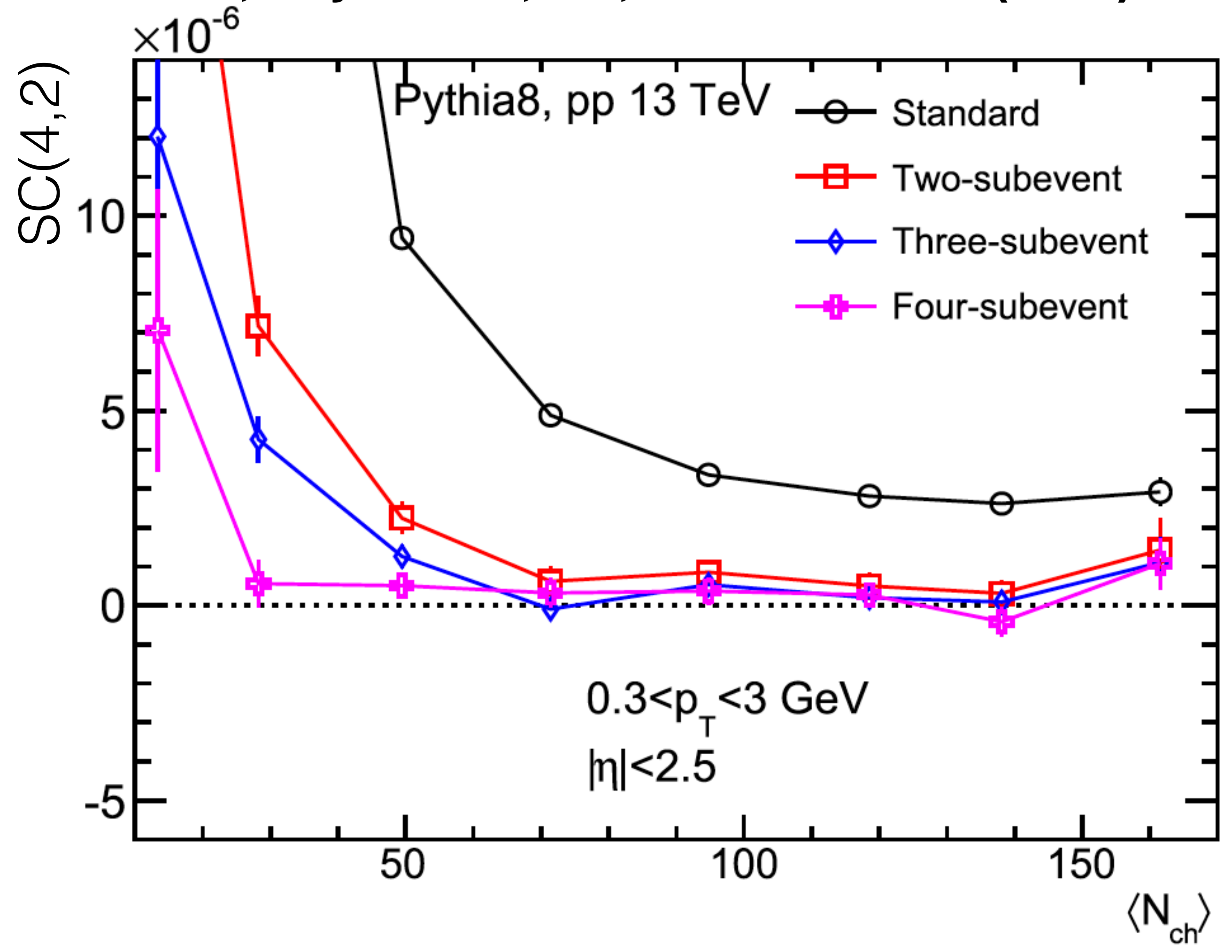


- Clear suppression of non-flow effects in Symmetric Cumulants
- SC(m,n) > $SC(m,n)_{2\text{-sub}}$ > **$SC(m,n)_{3\text{-sub}}$**

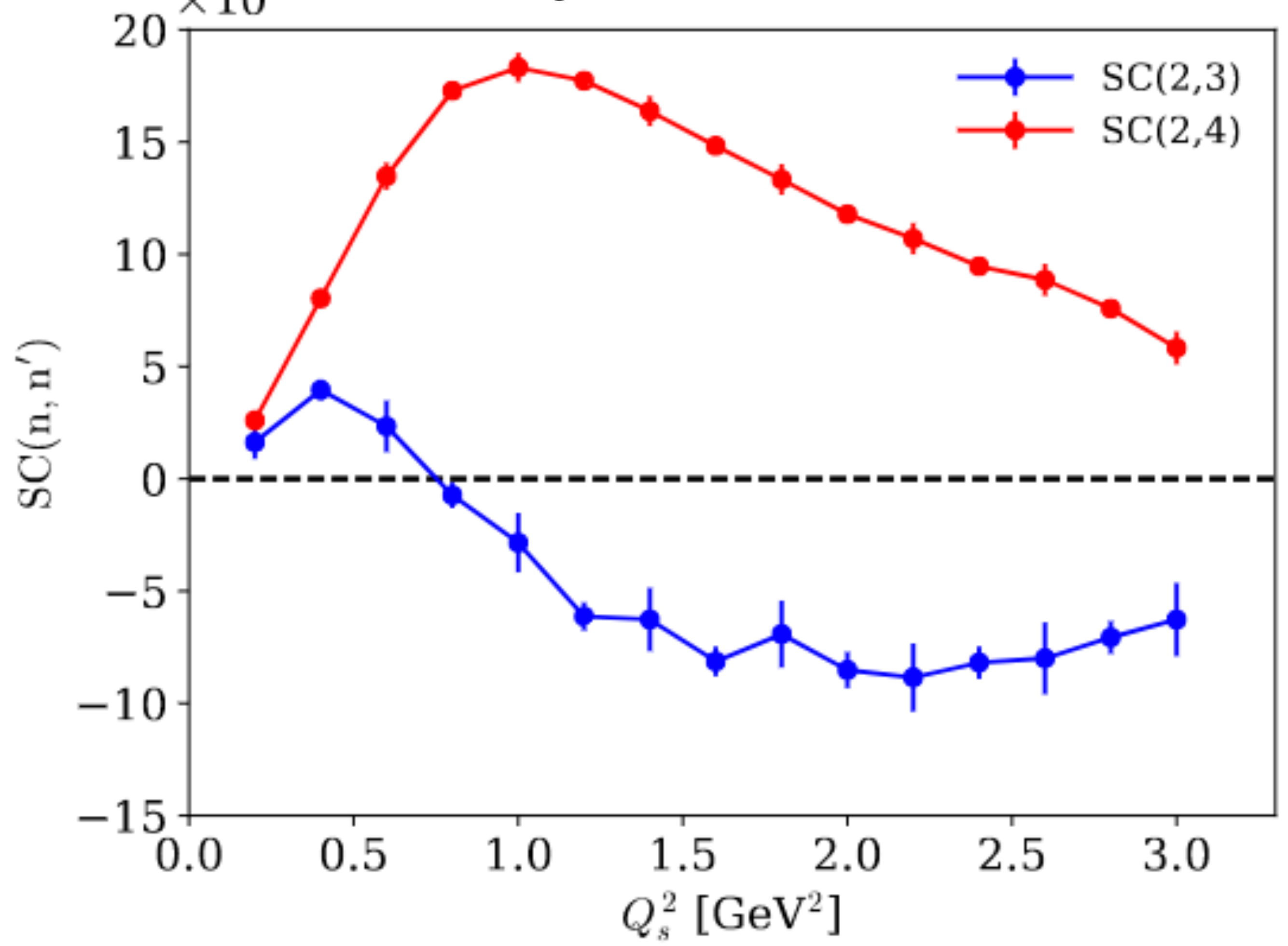
SC(m,n)$_{3\text{-sub}}$: all systems



Huo, Gajdosova, Jia, Zhou PLB 777 (2018) 201



Dusling et al. PRL 120, 042002 (2018)



- **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

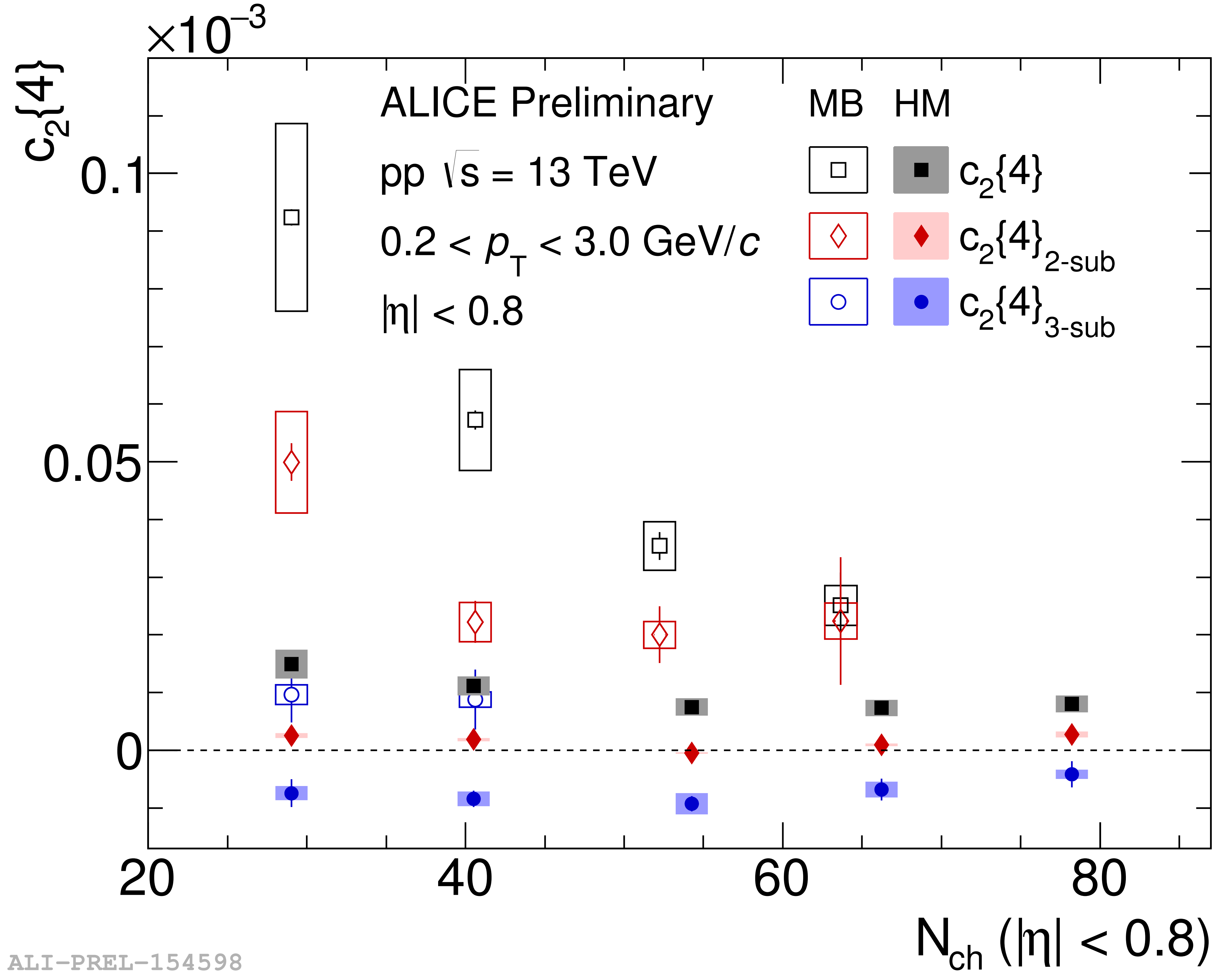
Backup

Trigger selection

- Minimum-bias trigger:
  - Suppression of non-flow with subevent method
  - The sign of $c_2\{4\}$ remains positive
- High multiplicity trigger selection:

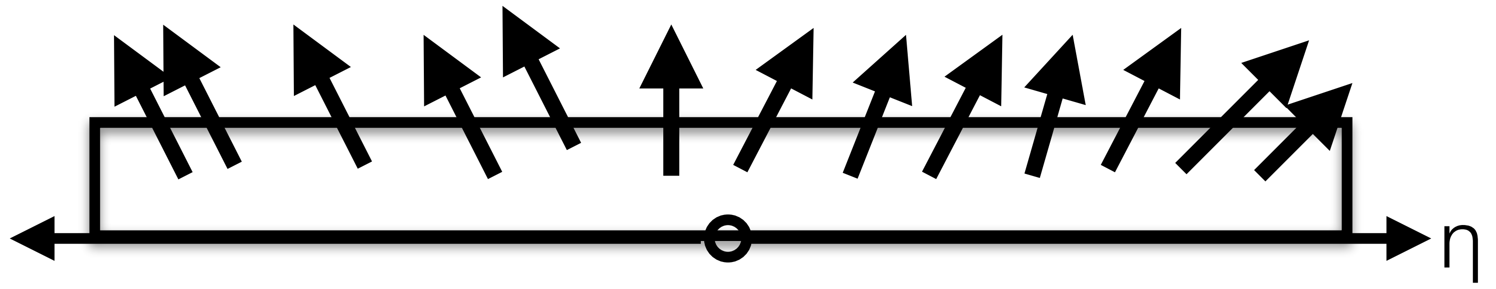
$$\frac{V0M}{\langle V0M \rangle} > 4$$

  - Additional event selection allows to obtain negative $c_2\{4\}_{3\text{-sub}}$



How do we calculate observables

m-particle correlation — step 1



$$\langle\langle 2\rangle\rangle_n = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$$

$$\langle\langle 4\rangle\rangle_n = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

$$\langle\langle 6\rangle\rangle_n = \langle\langle \cos n(\varphi_1 + \varphi_2 + \varphi_3 - \varphi_4 - \varphi_5 - \varphi_6)\rangle\rangle$$

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

step 2 — m-particle cumulant

$$c_n\{2\} = \langle\langle 2\rangle\rangle_n$$

$$c_n\{4\} = \langle\langle 4\rangle\rangle_n - 2\cdot\langle\langle 2\rangle\rangle_n^2$$

$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\cdot\langle\langle 2\rangle\rangle\cdot\langle\langle 4\rangle\rangle + 12\cdot\langle\langle 2\rangle\rangle^3$$

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

flow coefficients — step 3

$$v_n\{2\} = \sqrt{c_n\{2\}} \qquad v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$$

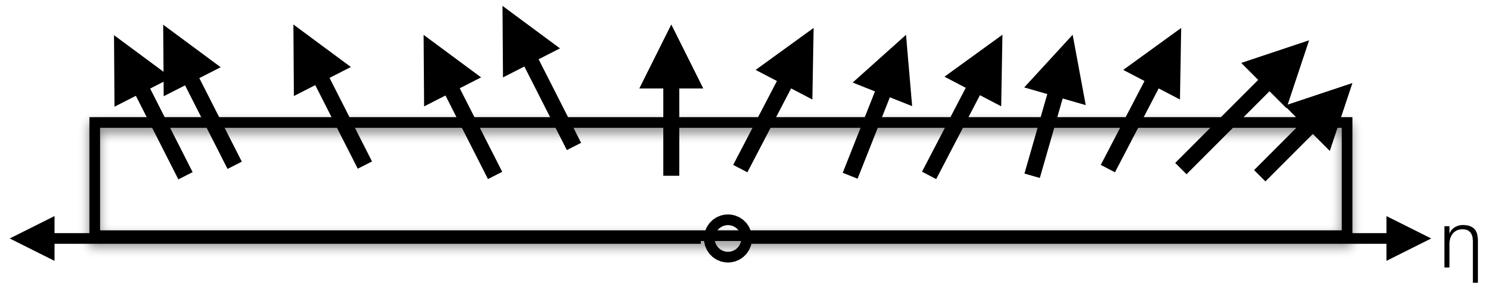
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}} \qquad v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}}$$

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

m-particle correlation **step 1**



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

- **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)

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

Two-particle correlation

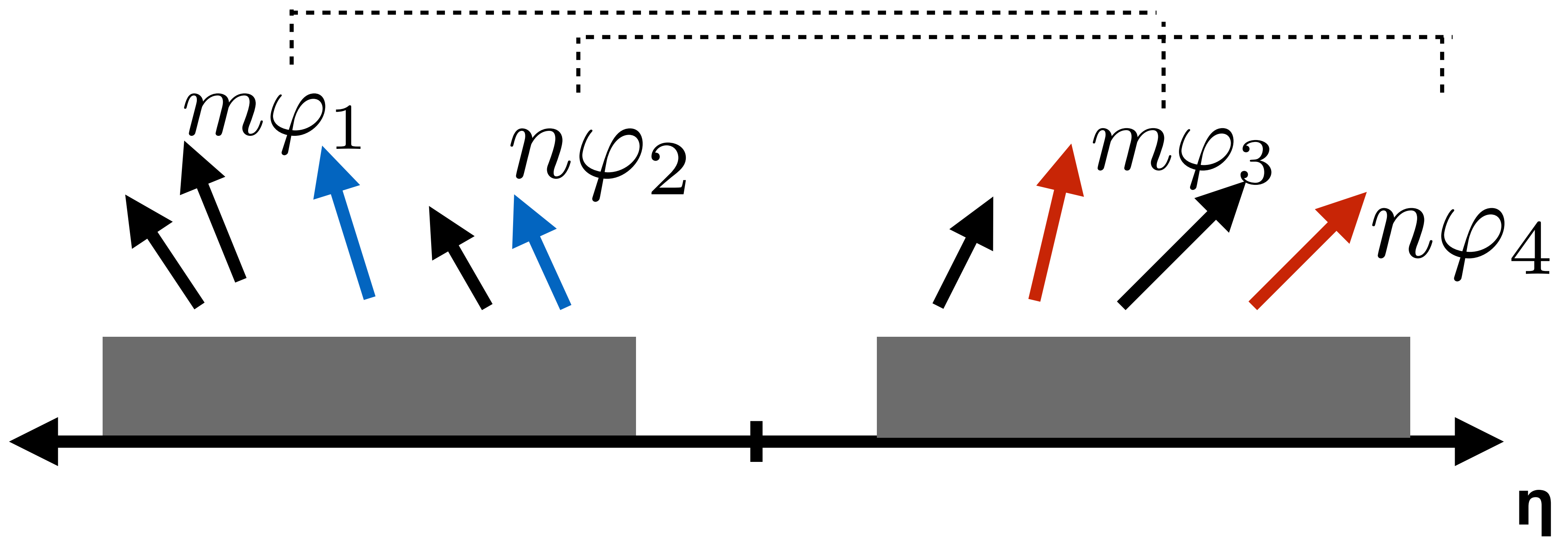
$$\mathrm{Two}\,(n_1, n_2) = \frac{Q_{n_1,1}Q_{n_2,1} - Q_{n_1+n_2,2}}{Q_{0,1}^2 - Q_{0,2}}$$

Four-particle correlation

$$\mathrm{Four}(\mathrm{n}_1, \mathrm{n}_2, \mathrm{n}_3, \mathrm{n}_4) = \frac{\begin{array}{l} Q_{n_1,1}Q_{n_2,1}Q_{n_3,1}Q_{n_4,1} - Q_{n_1+n_2,2}Q_{n_3,1}Q_{n_4,1} - Q_{n_2,1}Q_{n_1+n_3,2}Q_{n_4,1} \\ - Q_{n_1,1}Q_{n_2+n_3,2}Q_{n_4,1} + 2Q_{n_1+n_2+n_3,3}Q_{n_4,1} - Q_{n_2,1}Q_{n_3,1}Q_{n_1+n_4,2} \\ + Q_{n_2+n_3,2}Q_{n_1+n_4,2} - Q_{n_1,1}Q_{n_3,1}Q_{n_2+n_4,2} + Q_{n_1+n_3,2}Q_{n_2+n_4,2} \\ + 2Q_{n_3,1}Q_{n_1+n_2+n_4,3} - Q_{n_1,1}Q_{n_2,1}Q_{n_3+n_4,2} + Q_{n_1+n_2,2}Q_{n_3+n_4,2} \\ + 2Q_{n_2,1}Q_{n_1+n_3+n_4,3} + 2Q_{n_1,1}Q_{n_2+n_3+n_4,3} - 6Q_{n_1+n_2+n_3+n_4,4}, \end{array}}{Q_{0,1}^4 - 6Q_{0,1}^2 Q_{0,2} + 3Q_{0,2}^2 + 8Q_{0,1}Q_{0,3} - 6Q_{0,4}}$$

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**
- Method developed very recently by both ATLAS and ALICE (WPCF 2017, Phys.Lett. B777 (2018) 201-206)



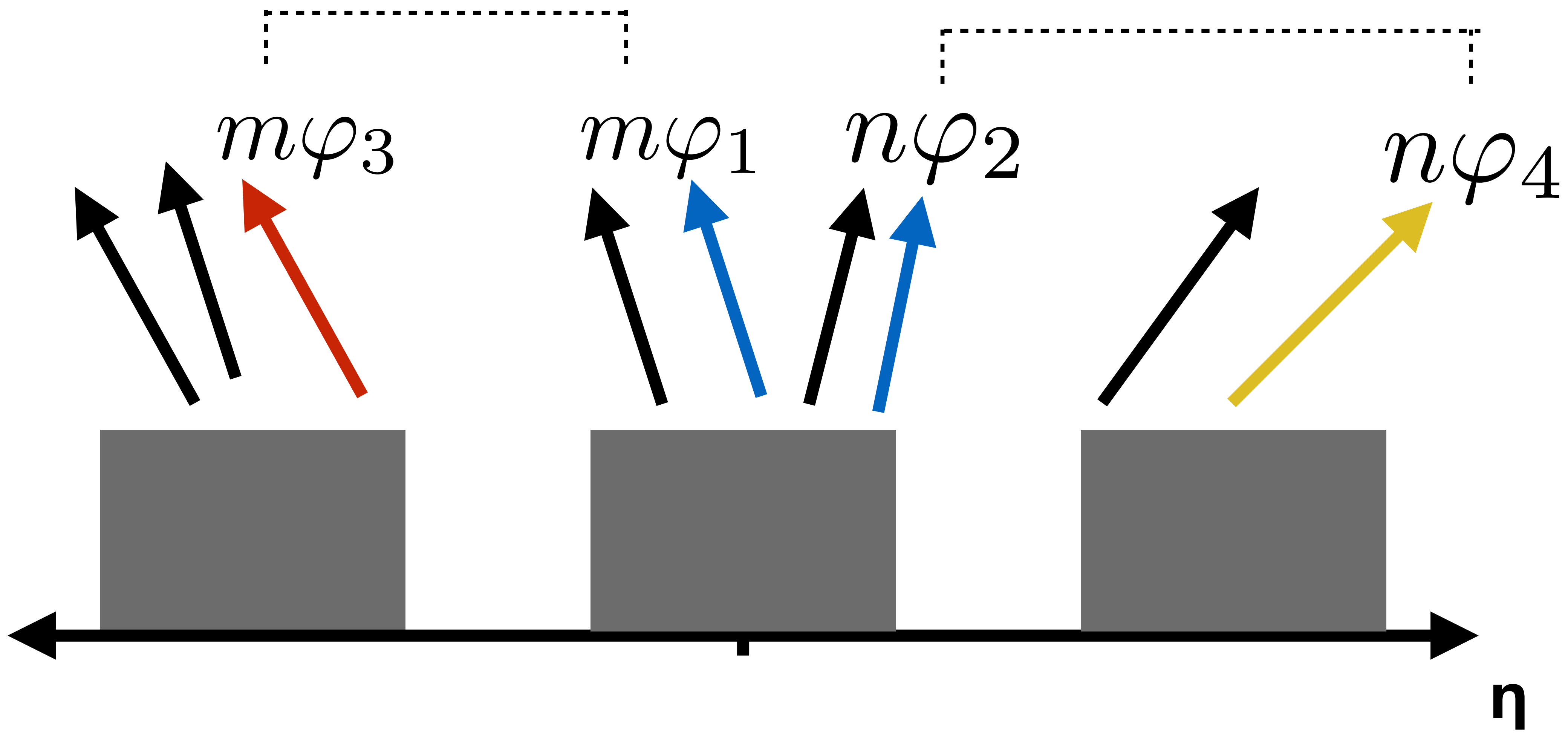
$$\langle\langle 4\rangle\rangle_{\text{2-sub}} = \langle\langle\cos\left(\mathrm{m}\varphi_1 + \mathrm{n}\varphi_2 - \mathrm{m}\varphi_3 - \mathrm{n}\varphi_4\right)\rangle\rangle$$

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

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

3-subevent method in the backup

3-subevent method in SC(m,n)

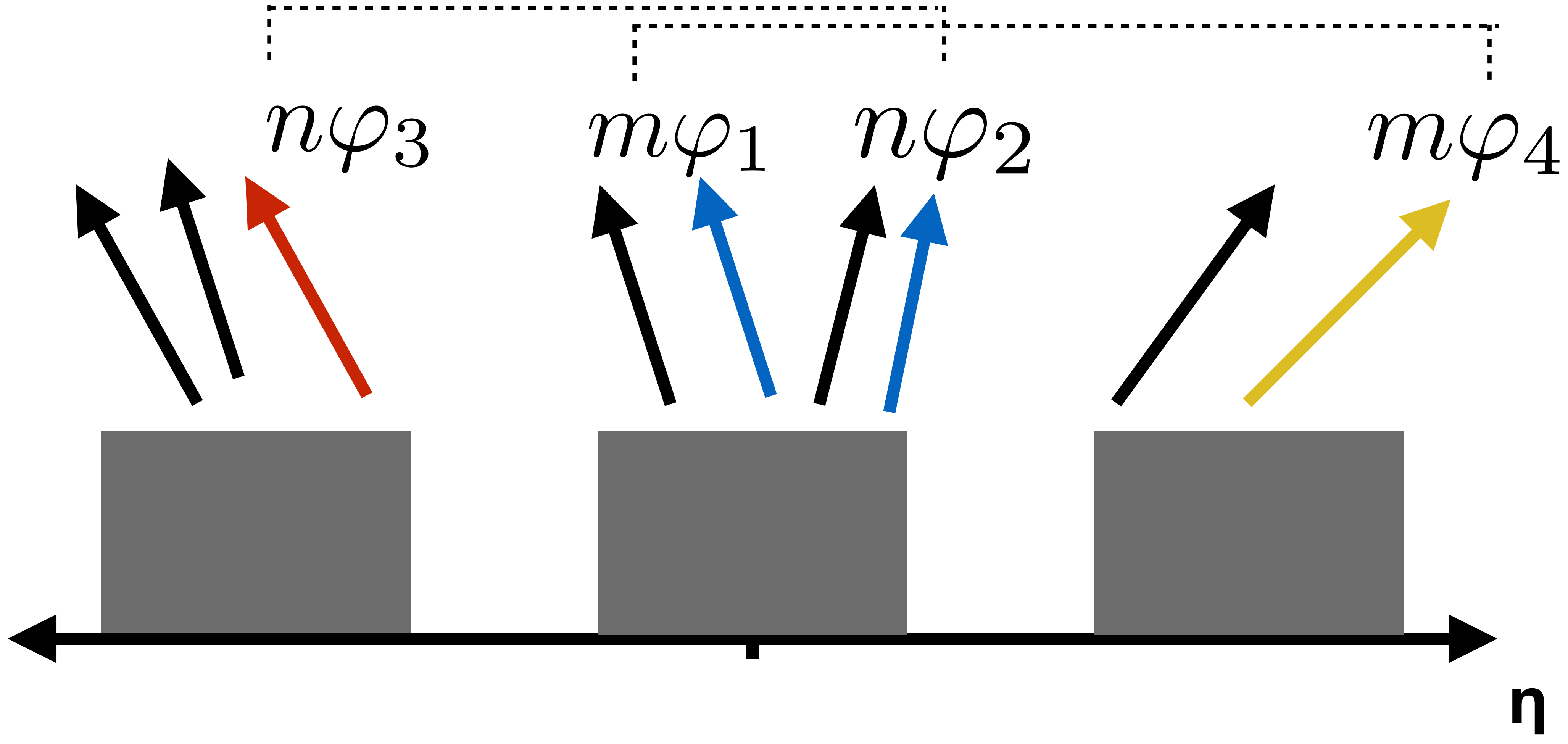


A.

$$\langle\langle 4\rangle\rangle_{m,n,-m,-n} = \langle\langle\cos\left(\mathrm{m}\varphi_1 + \mathrm{n}\varphi_2 - \mathrm{m}\varphi_3 - \mathrm{n}\varphi_4\right)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle_{m,-m}\langle\langle 2\rangle\rangle_{n,-n} = \langle\langle\cos\mathrm{m}(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle\cos\mathrm{n}(\varphi_2 - \varphi_4)\rangle\rangle$$

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



B.

$$\langle\langle 4\rangle\rangle_{m,n,-n,-m} = \langle\langle\cos\left(\mathrm{m}\varphi_1 + \mathrm{n}\varphi_2 - \mathrm{n}\varphi_3 - \mathrm{m}\varphi_4\right)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle_{n,-n}\langle\langle 2\rangle\rangle_{m,-m} = \langle\langle\cos\mathrm{n}(\varphi_2 - \varphi_3)\rangle\rangle\langle\langle\cos\mathrm{m}(\varphi_1 - \varphi_4)\rangle\rangle$$

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

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