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Investigating collectivity in small systems

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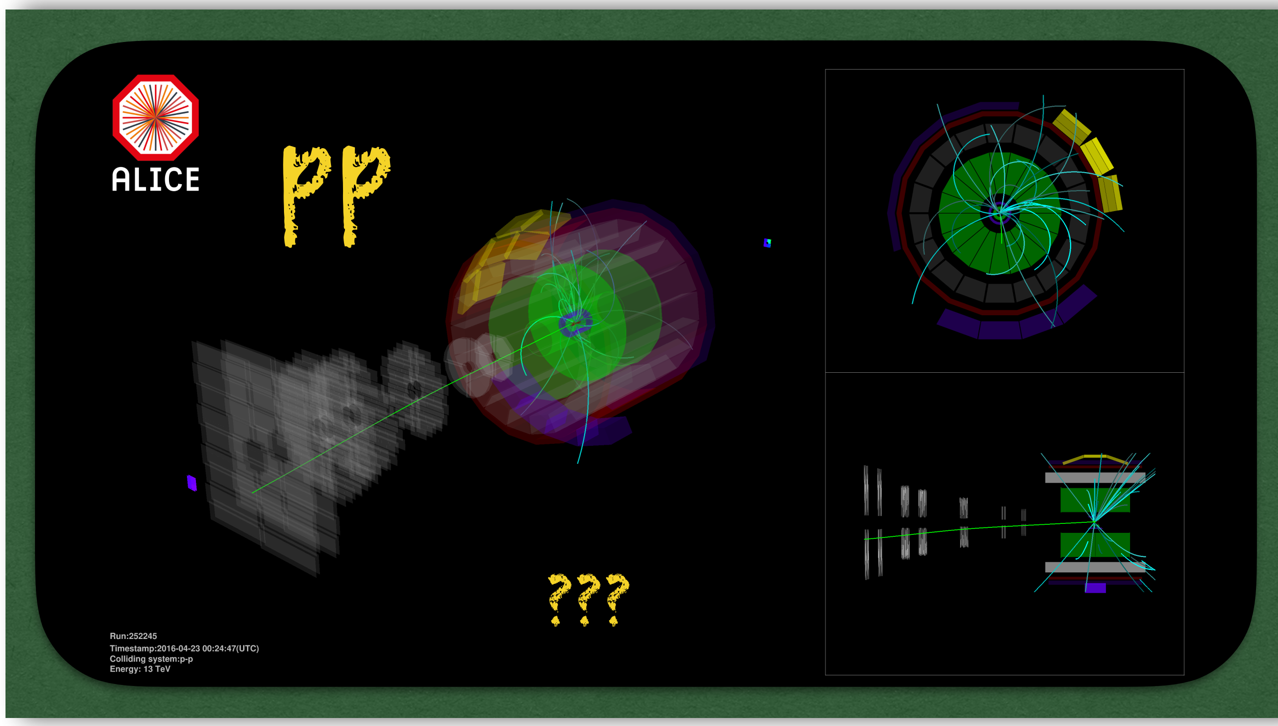
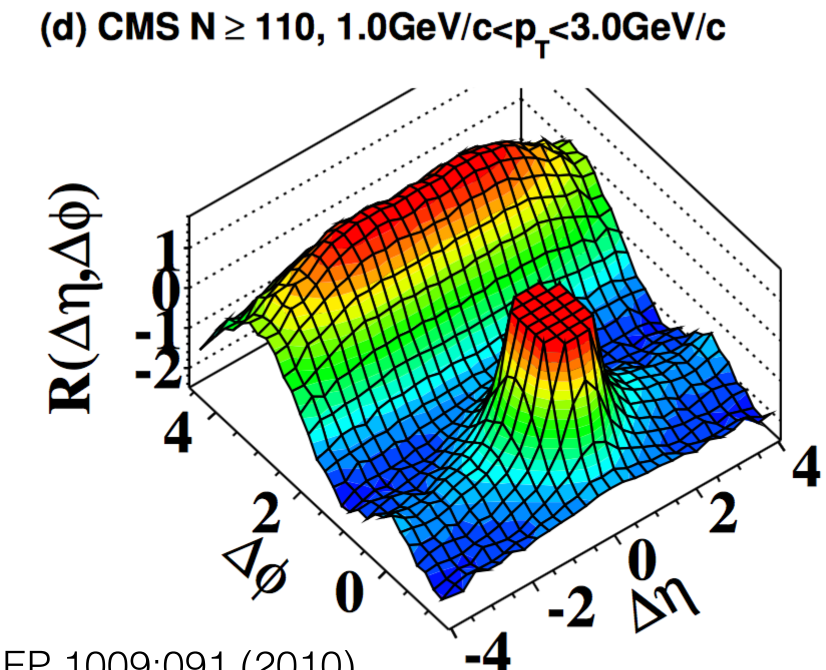
Niels Bohr Institute, University of Copenhagen

Workshop on Collectivity in Small Collision Systems

May 9, 2017

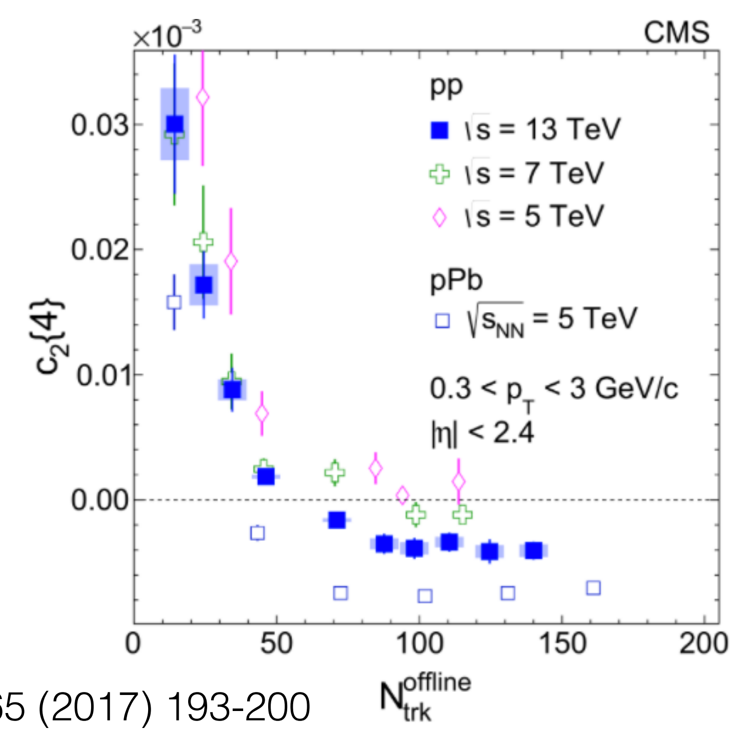
Is flow produced in pp collisions?





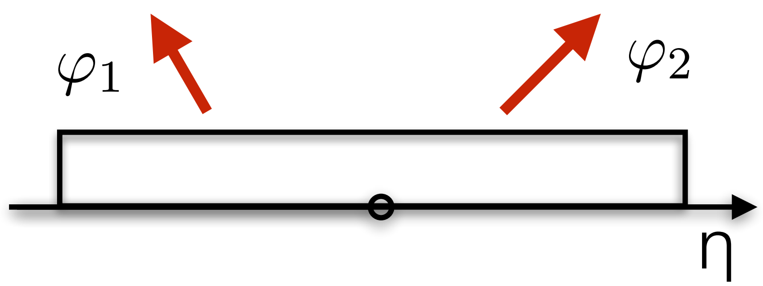
CMS, JHEP 1009:091 (2010)

- Measurements using azimuthal correlations have shown many (surprising) results:
  - **Ridge** structure in 2-particle correlations at high multiplicity pp collisions
  - **Negative $c_2\{4\}$** at high multiplicity pp collisions seen by CMS



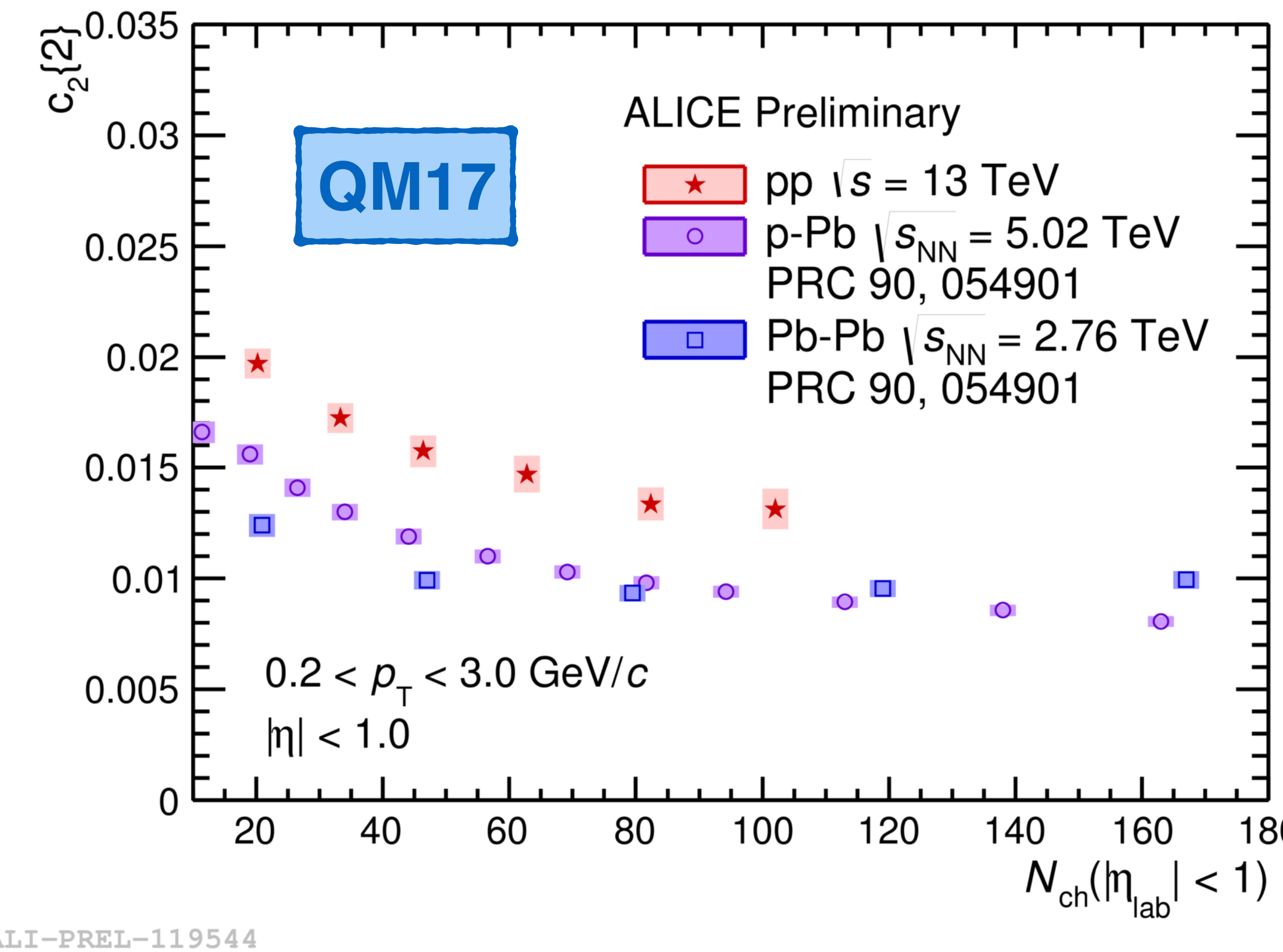
CMS, PLB 765 (2017) 193-200

2-particle cumulant

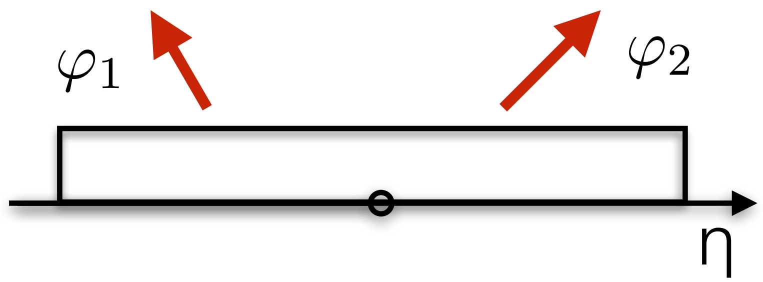


$$c_n\{2\} = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$$

- Cumulants are an important tool in the investigation of collectivity in small systems
- $c_2\{2\}$ is clearly higher in pp collisions than in p-Pb or Pb-Pb



2-particle cumulant

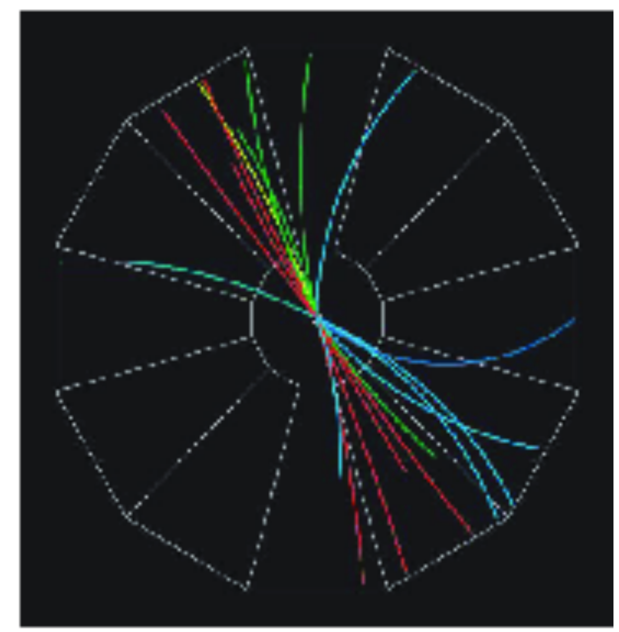


$$c_n\{2\} = \langle\langle \cos \mathrm{n}(\varphi_1 - \varphi_2) \rangle\rangle$$

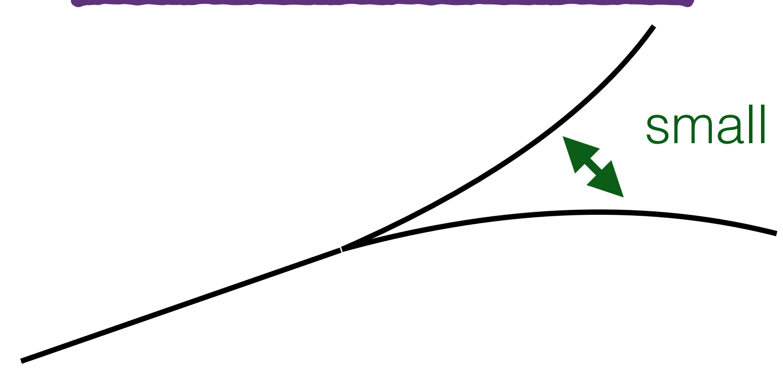
- Cumulants are an important tool in the investigation of collectivity in small systems

- Measurements are influenced by non-flow effects, especially in small systems

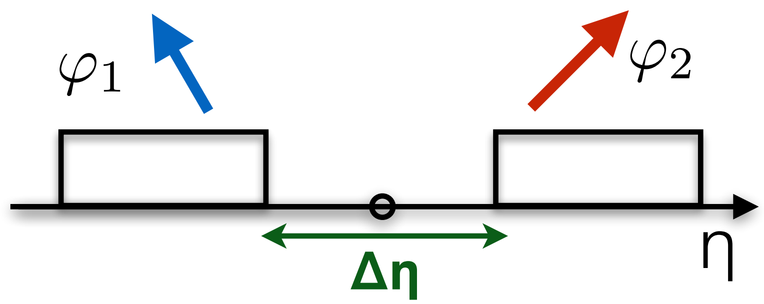
jets



resonance decays

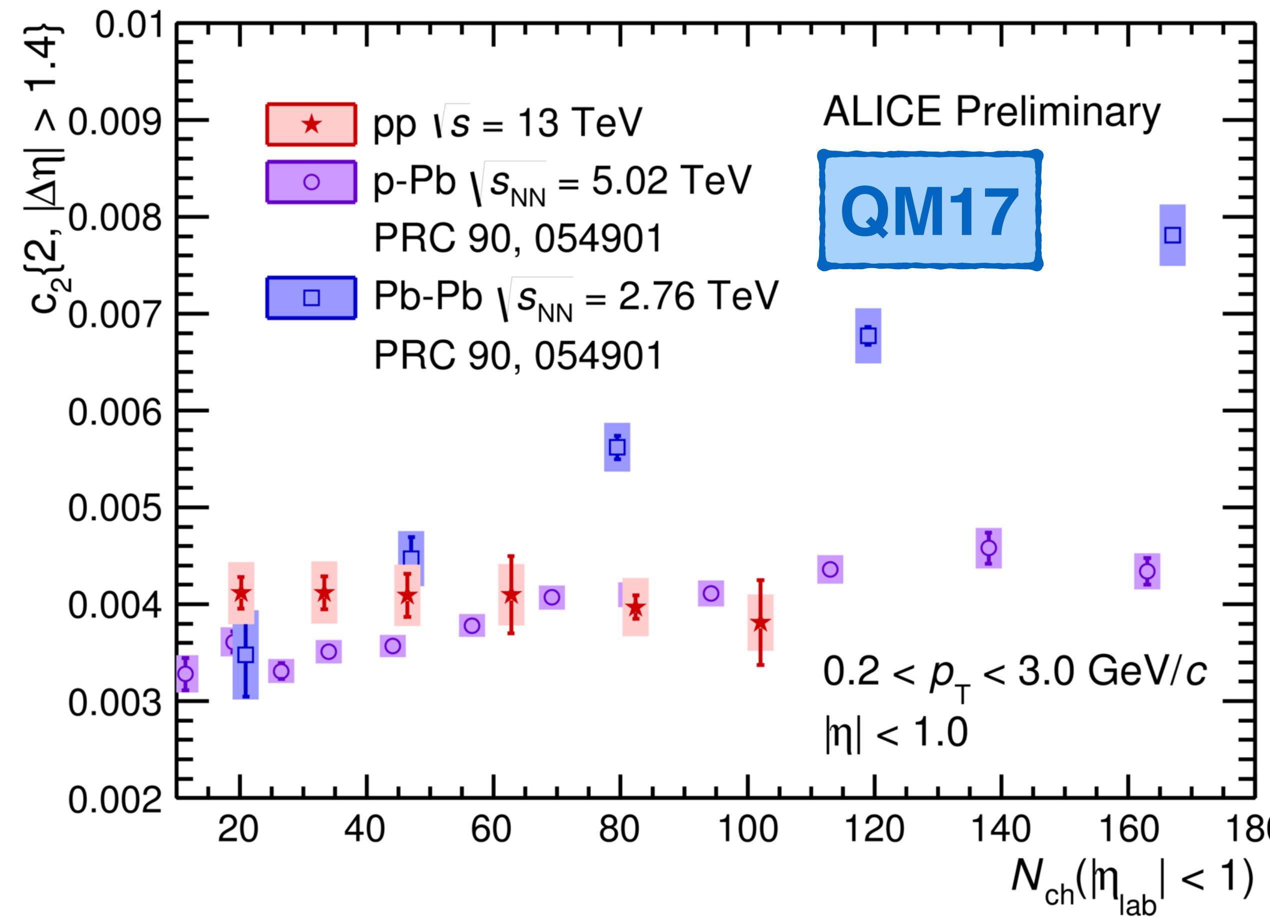


2-particle cumulant



$$c_n\{2, |\Delta\eta|\} = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$$

- Cumulants are an important tool in the investigation of collectivity in small systems
- Measurements are influenced by non-flow effects, especially in small systems
- Splitting the acceptance into different η regions helps to avoid particles from few-body correlations, aka non-flow effects
- Overall decrease of $c_2\{2, |\Delta\eta|\}$
- Shows weak or no dependence on multiplicity in pp collisions



ALI-PREL-119552

4-particle cumulant

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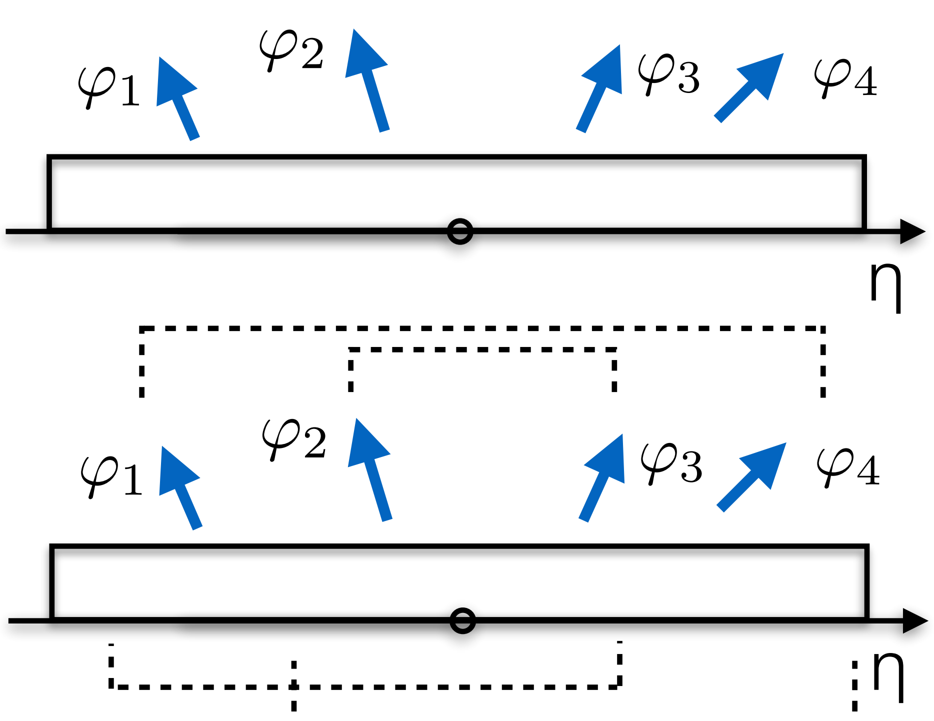
- Lower order correlation (including non-flow) are removed from multi-particle cumulants



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

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

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

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

4-particle cumulant

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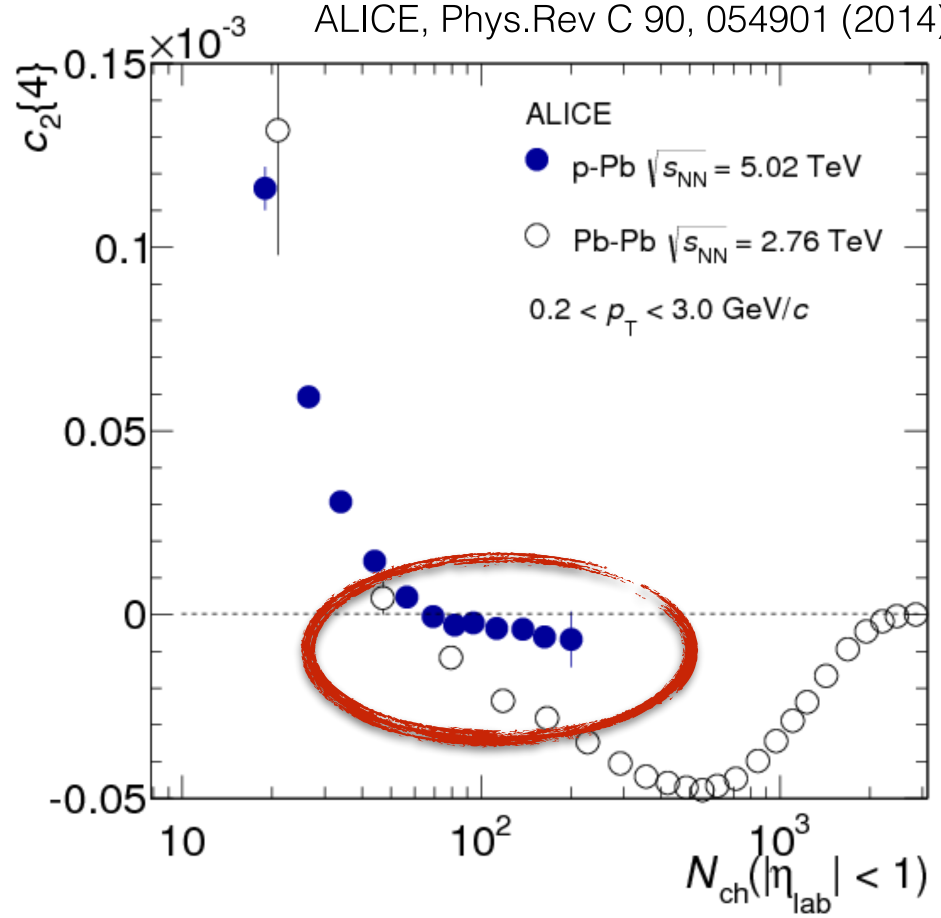
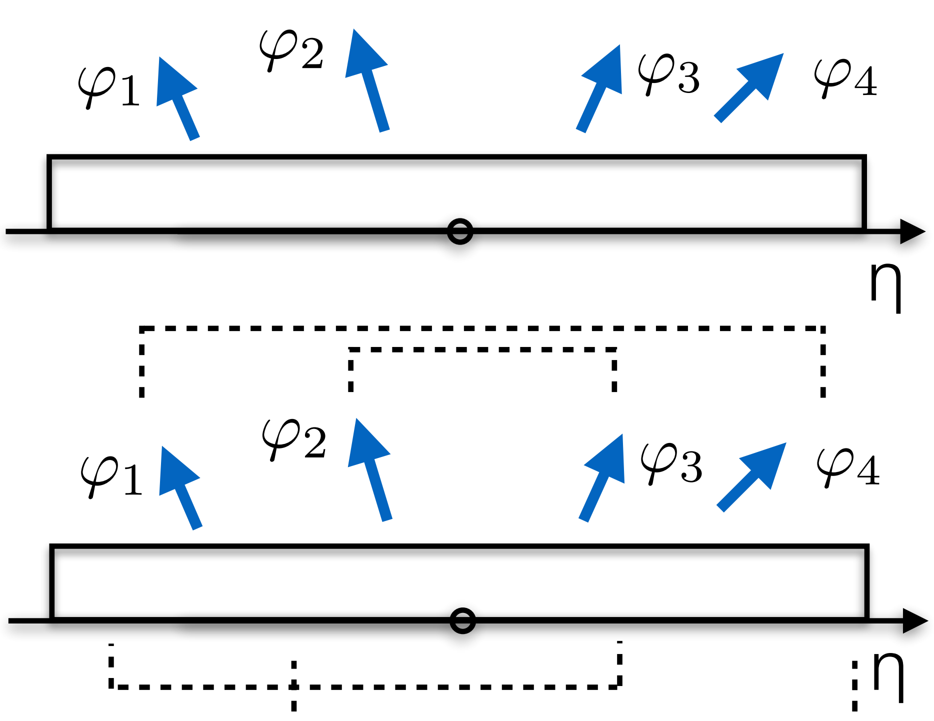
- Lower order correlation (including non-flow) are removed from multi-particle cumulants
- Negative sign of $c_n[4\}$ might indicate collectivity

ALICE, Phys.Rev C 90, 054901 (2014)





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

$$\langle\langle 2\rangle\rangle^2 = \langle\langle \cos n(\varphi_2-\varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_1-\varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2 = \langle\langle \cos n(\varphi_1-\varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2-\varphi_4)\rangle\rangle$$

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

4-particle cumulant

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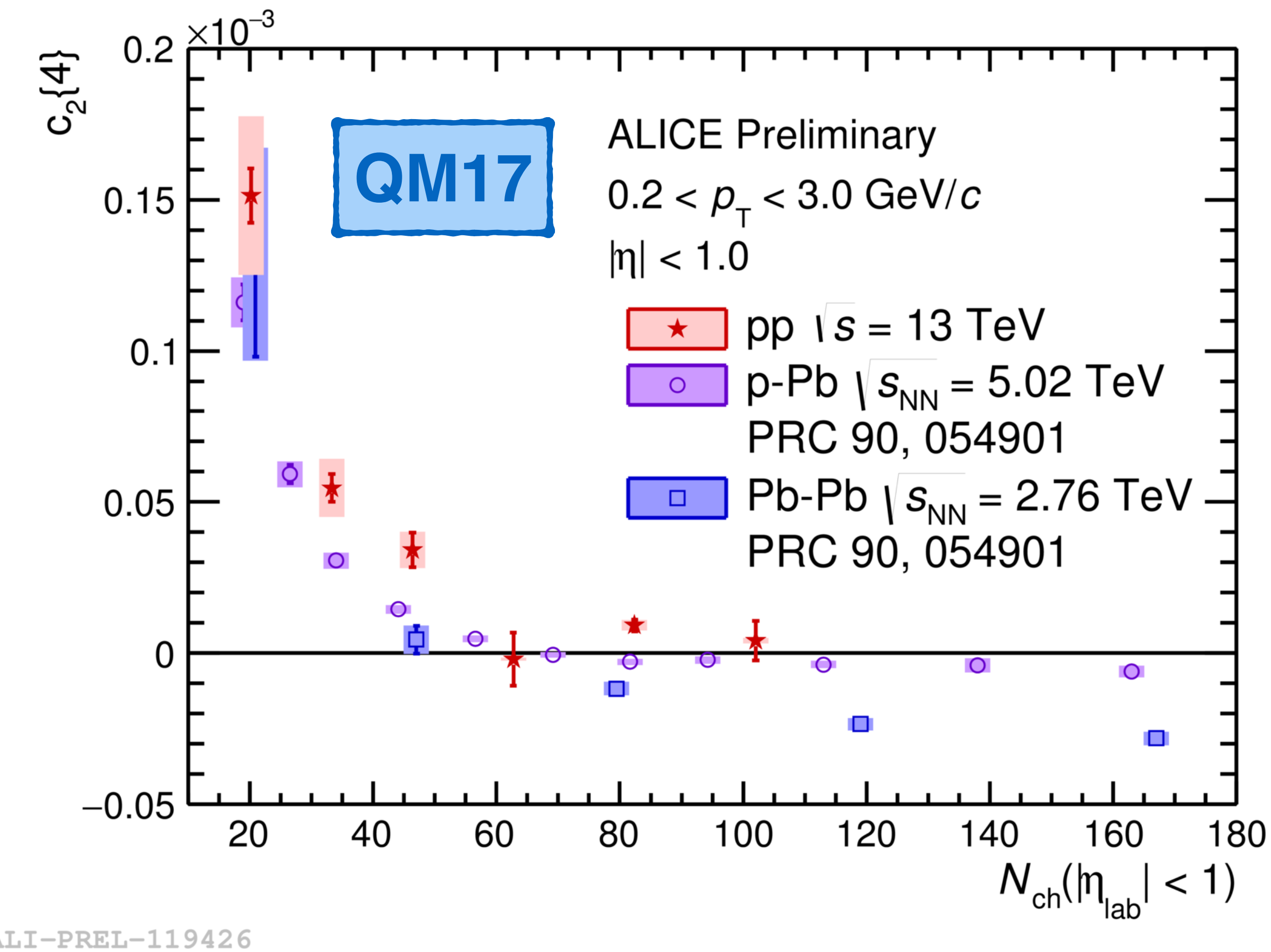
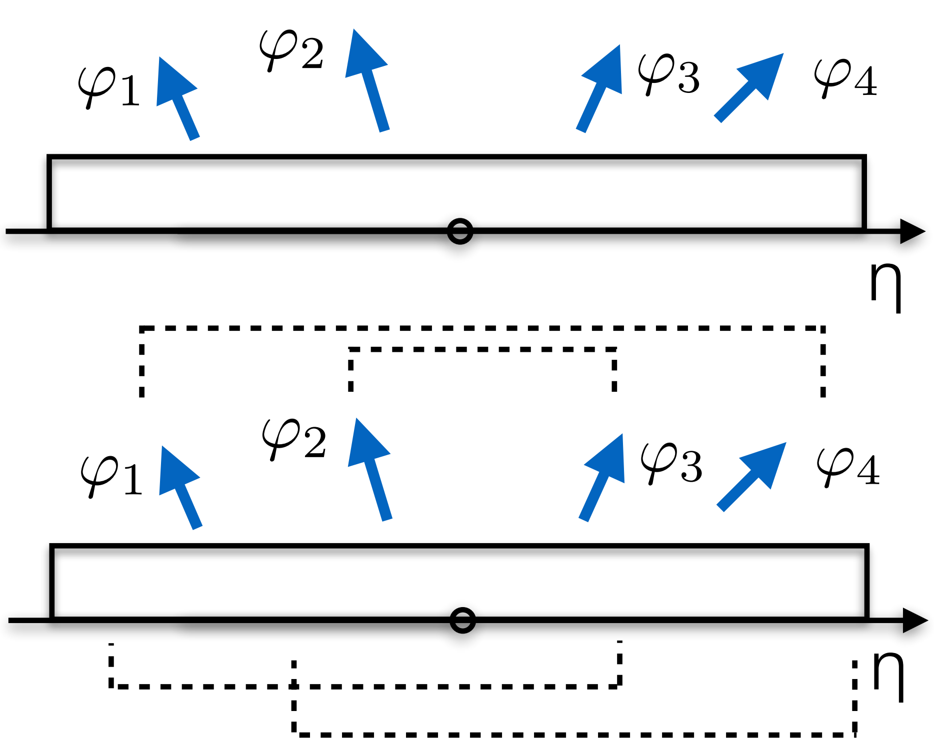
- Lower order correlation (including non-flow) are removed from multi-particle cumulants
- Negative sign of $c_2[4\}$ might indicate collectivity
  - Clear negative $c_2\{4\}$ observed in Pb-Pb and p-Pb collisions
  - No hint of collectivity in pp collisions





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

$$\langle\langle 2\rangle\rangle^2 = \langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2 = \langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

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

4-particle cumulant with |Δη| gap

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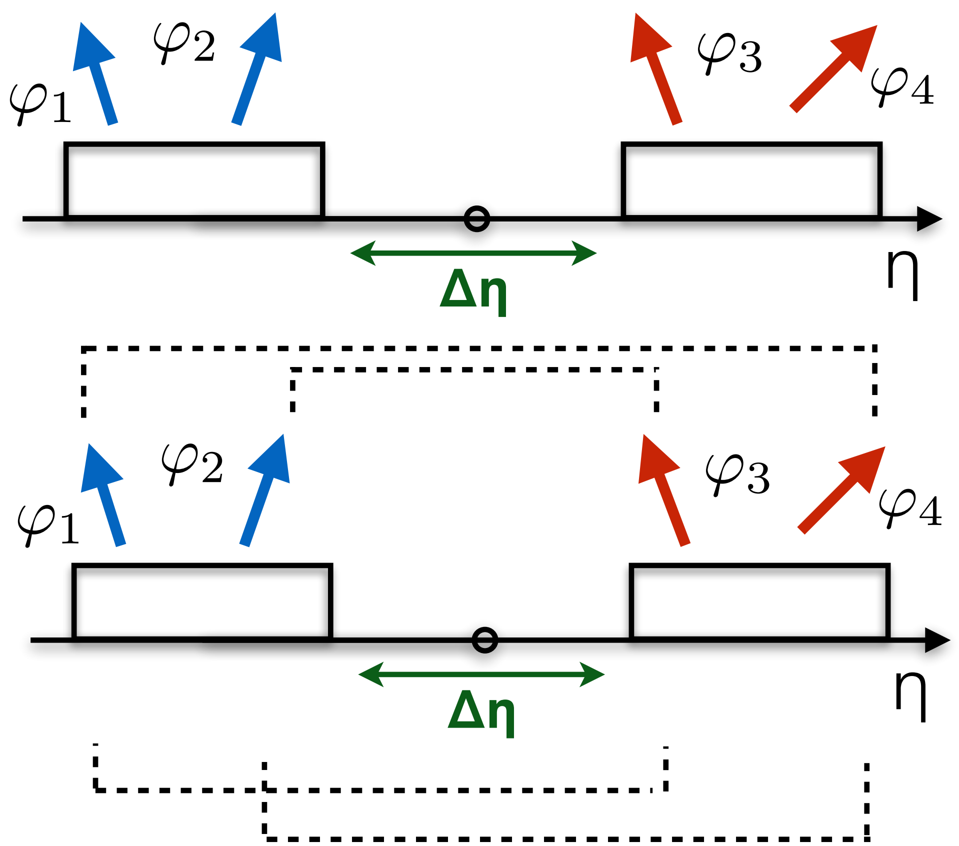


- We can **further suppress non-flow** in multi-particle cumulants using |Δη| gap

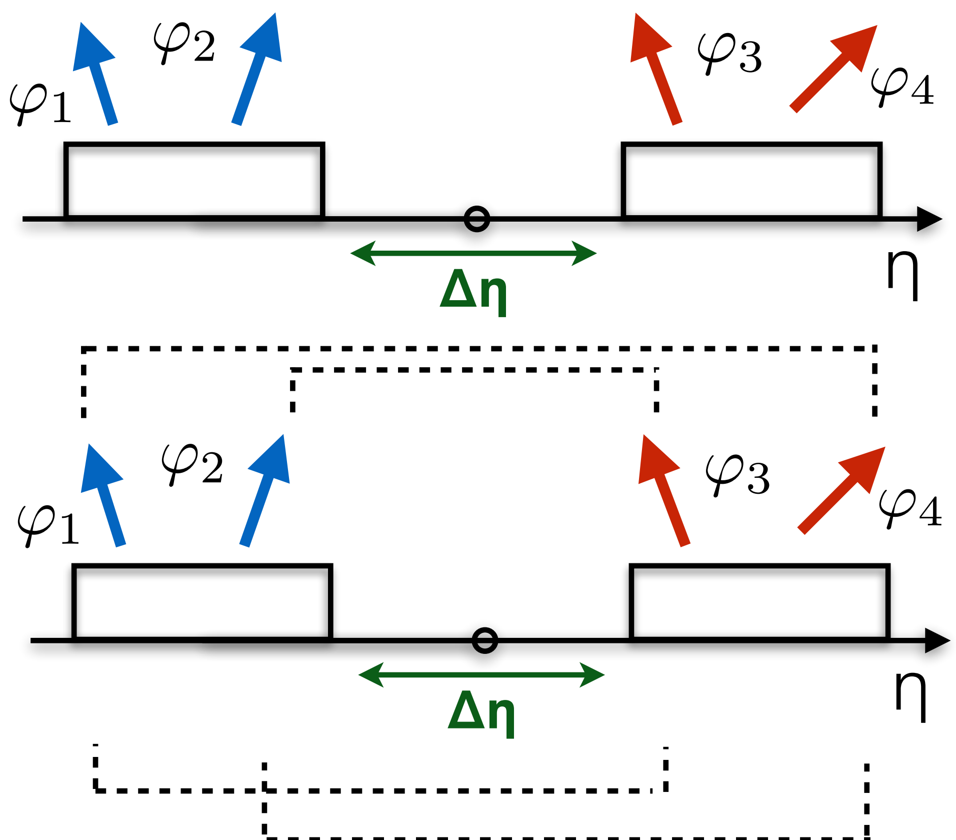
$$\langle\langle 4\rangle\rangle_{|\Delta\eta|} = \langle\langle \cos \mathrm{n}(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

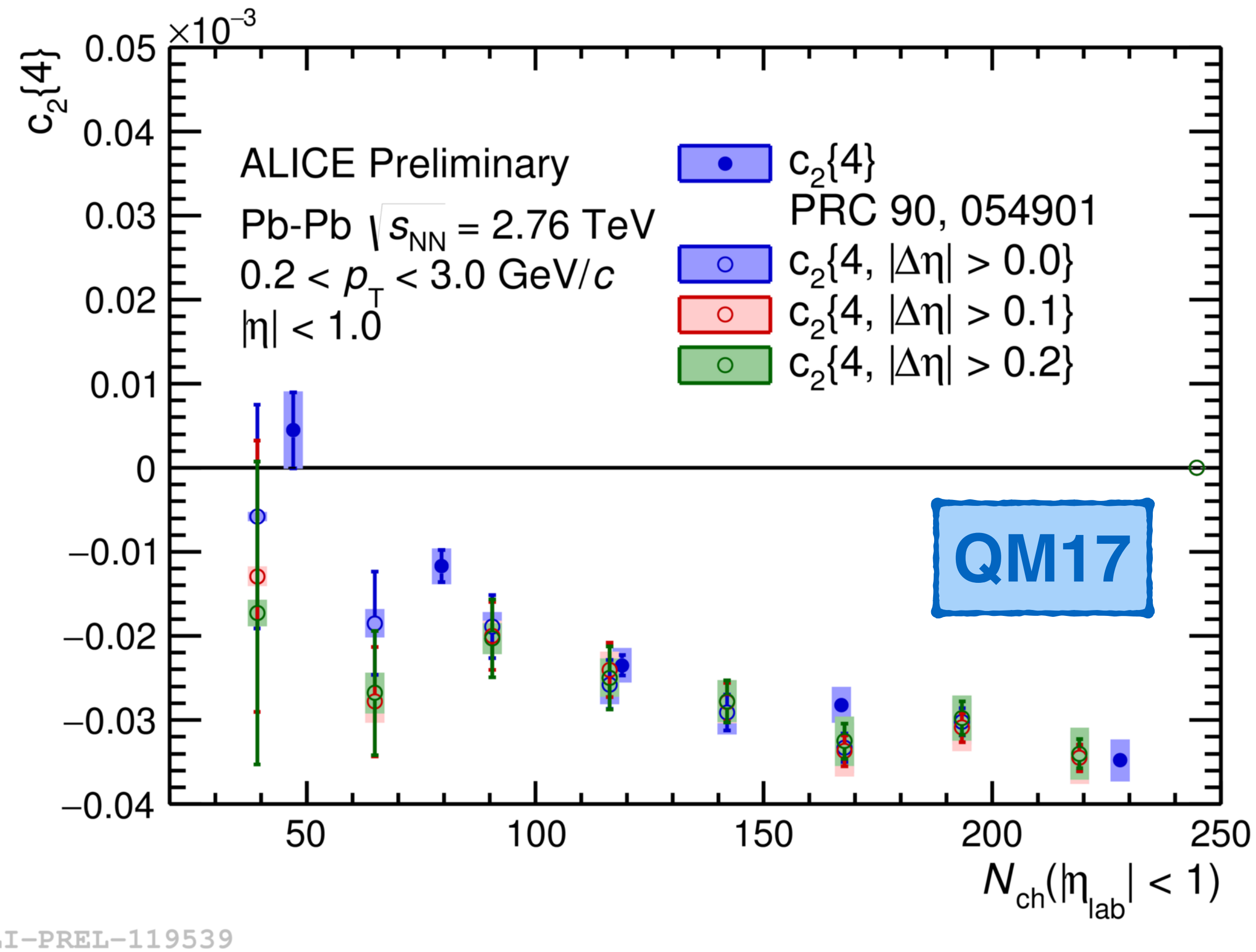
$$\langle\langle 2\rangle\rangle^2_{|\Delta\eta|} = \langle\langle \cos \mathrm{n}(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos \mathrm{n}(\varphi_2 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{|\Delta\eta|} = \langle\langle \cos \mathrm{n}(\varphi_1 - \varphi_4)\rangle\rangle\langle\langle \cos \mathrm{n}(\varphi_2 - \varphi_3)\rangle\rangle$$

$$c_n\{4\}_{|\Delta\eta|} = \langle\langle 4\rangle\rangle_{|\Delta\eta|} - 2\cdot\langle\langle 2\rangle\rangle^2_{|\Delta\eta|}$$

4-particle cumulant with |Δη| gap





- We can **further suppress non-flow** in multi-particle cumulants using |Δη| gap
- 4-particle cumulant with |Δη| gap in **Pb-Pb**
  - Measurements are compatible
  - Flow dominated system

$$\langle\langle 4\rangle\rangle_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

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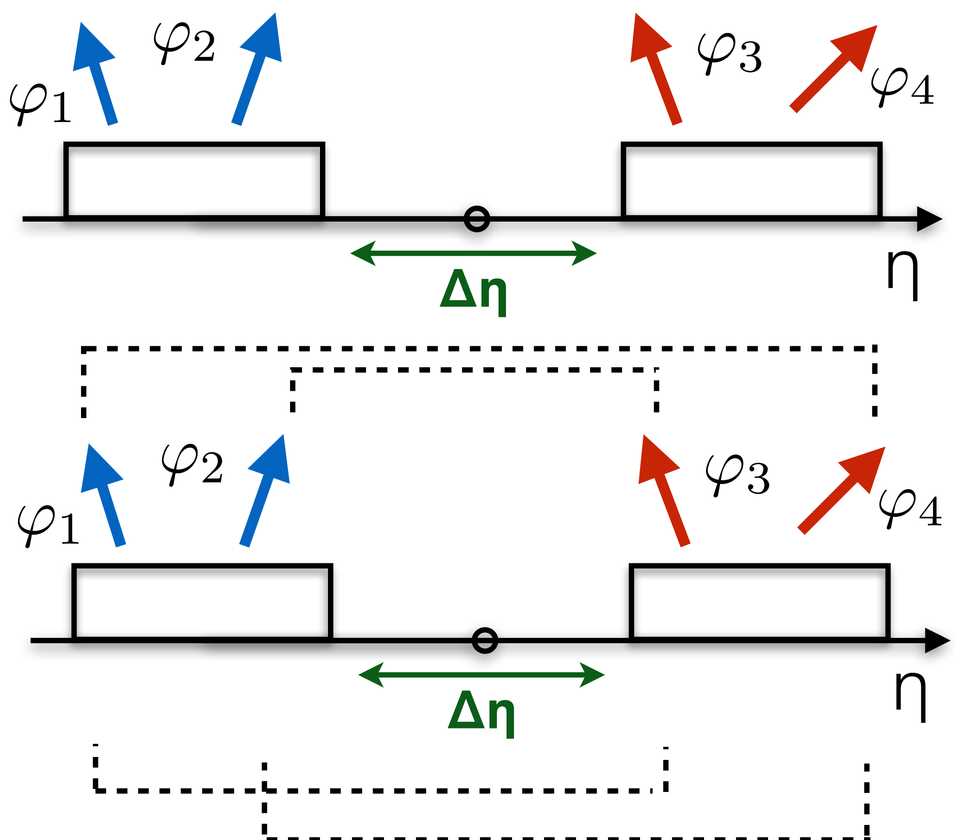
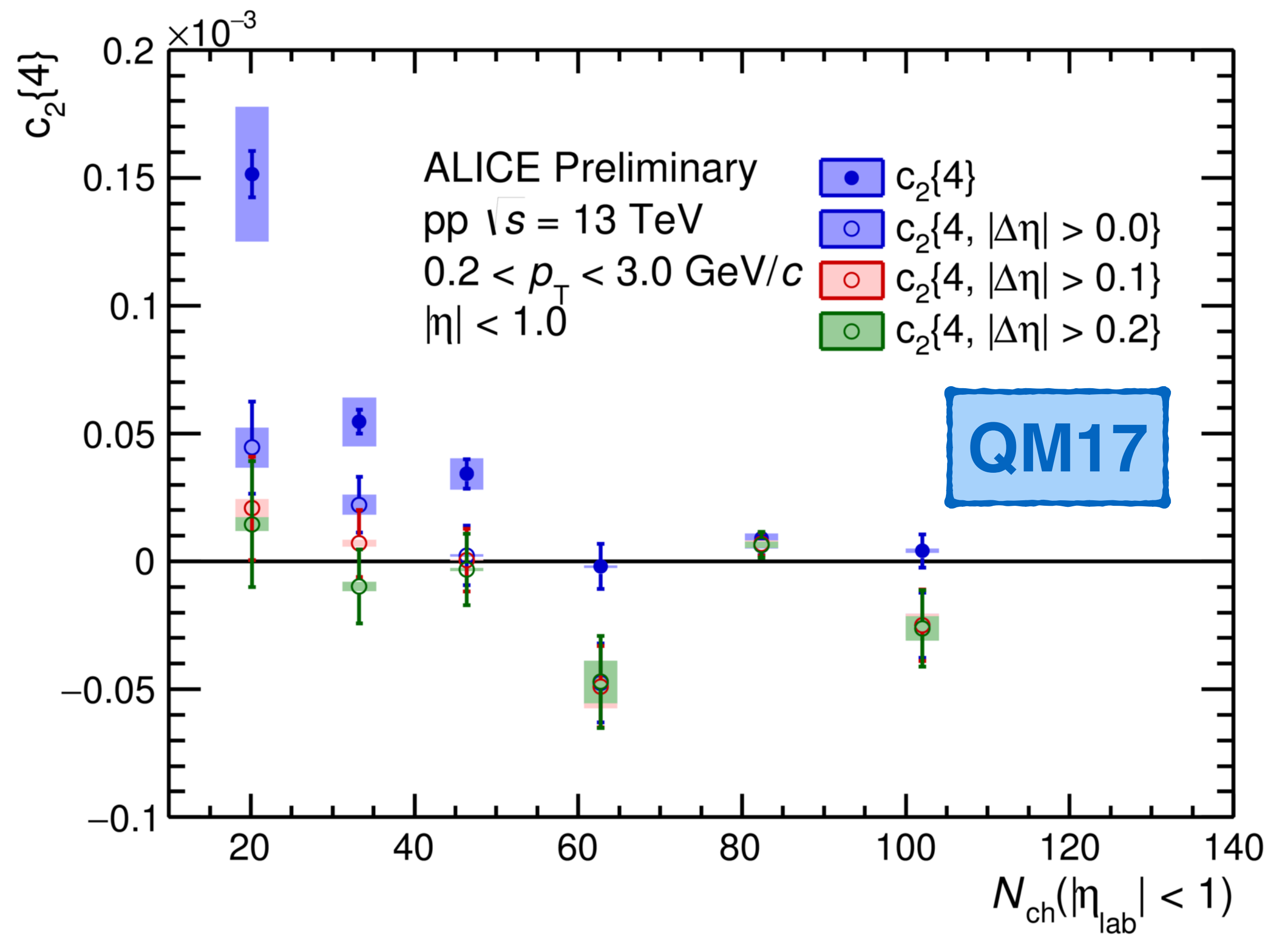
$$c_n\{4\}_{|\Delta\eta|} = \langle\langle 4\rangle\rangle_{|\Delta\eta|} - 2\cdot\langle\langle 2\rangle\rangle^2_{|\Delta\eta|}$$

4-particle cumulant with |Δη| gap





ALI-PREL-119434

- We can **further suppress non-flow** in multi-particle cumulants using |Δη| gap
- 4-particle cumulant with |Δη| gap in **pp**

$$\langle\langle 4\rangle\rangle_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

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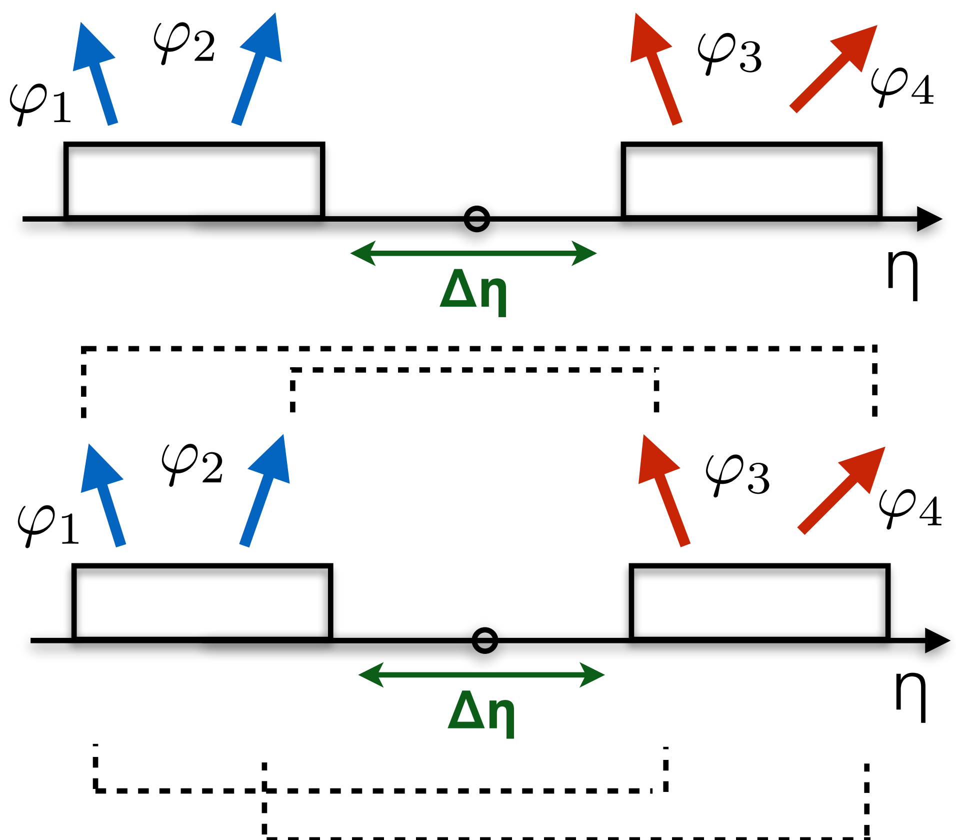
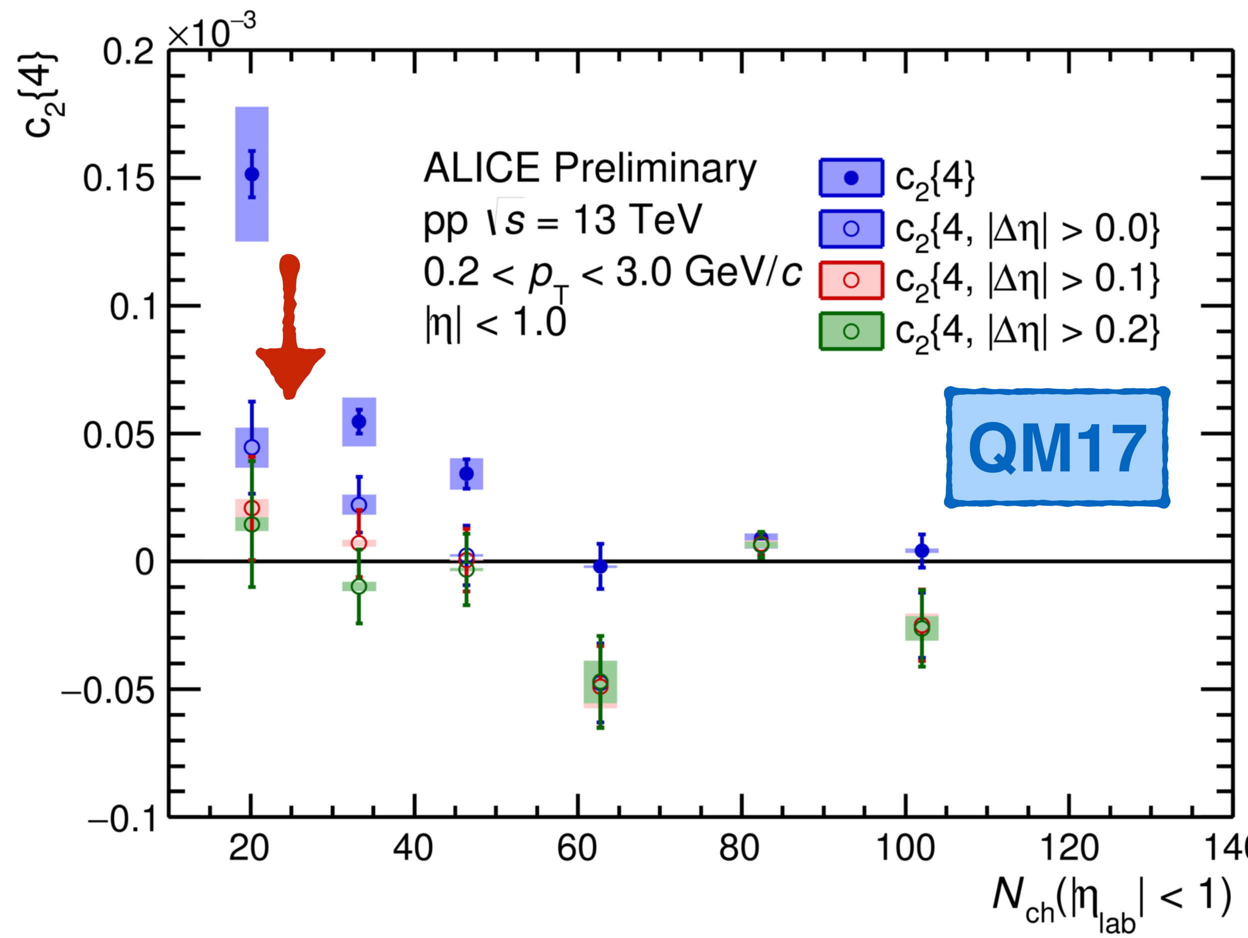
$$c_n\{4\}_{|\Delta\eta|} = \langle\langle 4\rangle\rangle_{|\Delta\eta|} - 2\cdot\langle\langle 2\rangle\rangle^2_{|\Delta\eta|}$$

4-particle cumulant with |Δη| gap





ALI-PREL-119434

- We can **further suppress non-flow** in multi-particle cumulants using |Δη| gap
- 4-particle cumulant with |Δη| gap in **pp**
  - $c_2\{4, |\Delta\eta|\}$ is lower than $c_2\{4\}$

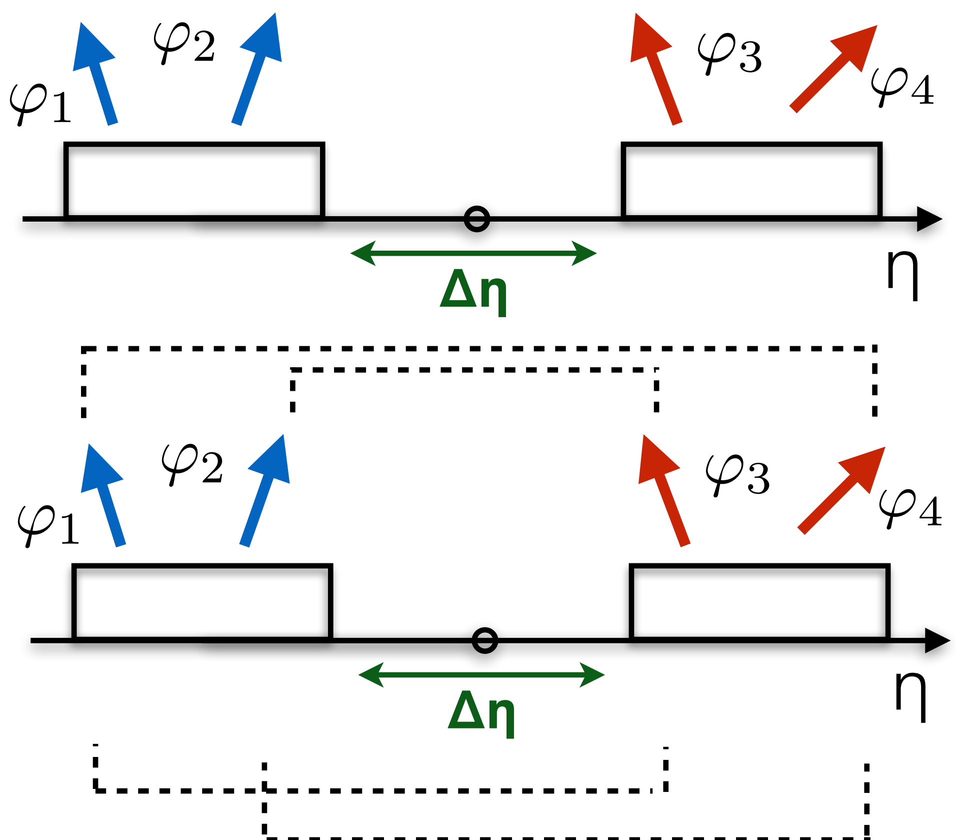
$$\langle\langle 4\rangle\rangle_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

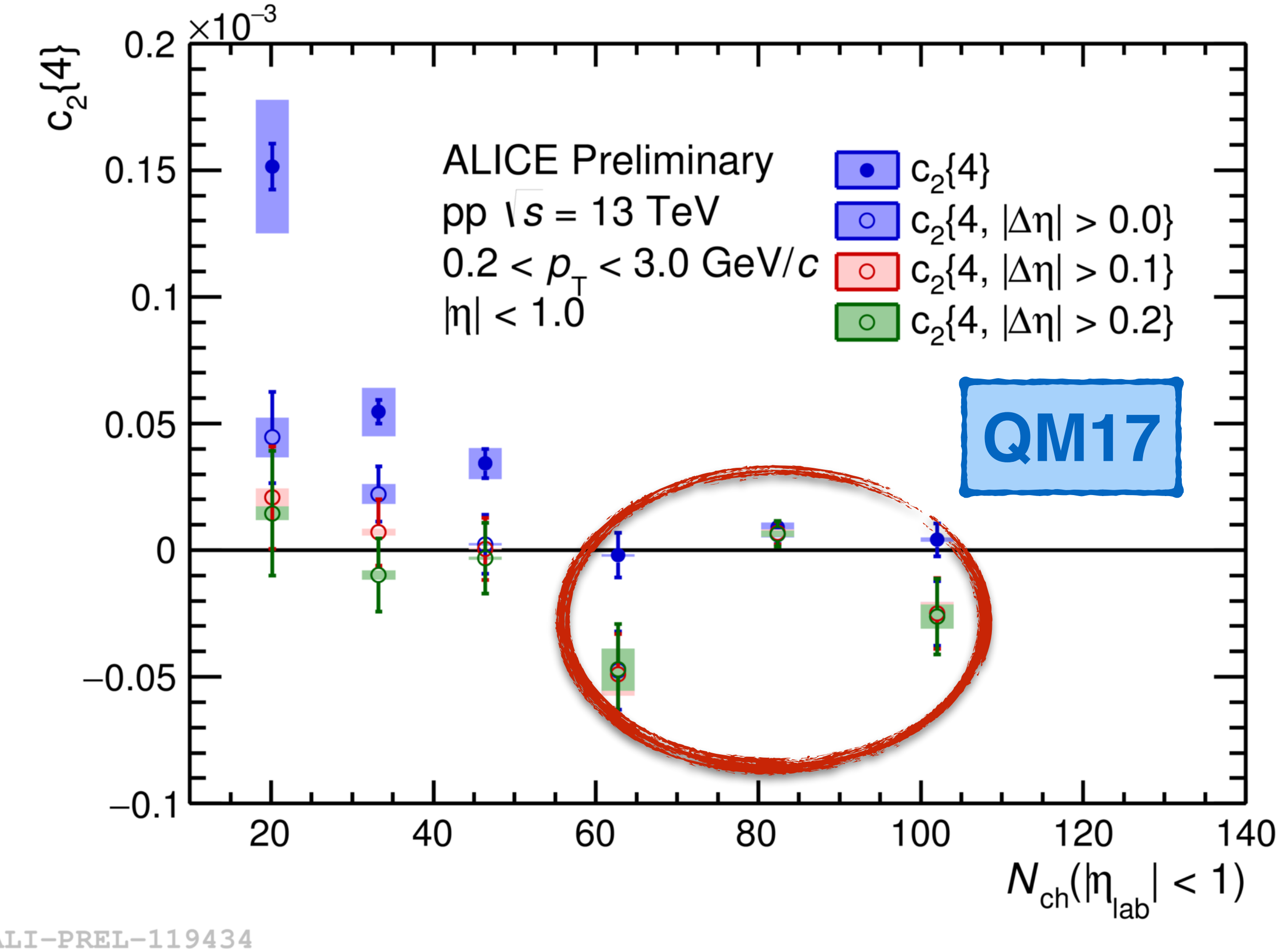
$$\langle\langle 2\rangle\rangle^2_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle$$

$$c_n\{4\}_{|\Delta\eta|} = \langle\langle 4\rangle\rangle_{|\Delta\eta|} - 2\cdot\langle\langle 2\rangle\rangle^2_{|\Delta\eta|}$$

4-particle cumulant with |Δη| gap





- We can **further suppress non-flow** in multi-particle cumulants using |Δη| gap
- 4-particle cumulant with |Δη| gap in **pp**
  - $c_2\{4, |\Delta\eta|\}$ is lower than $c_2\{4\}$
  - Still no significant negative sign observed in pp collisions

$$\langle\langle 4\rangle\rangle_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{|\Delta\eta|} = \langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle$$

$$c_n\{4\}_{|\Delta\eta|} = \langle\langle 4\rangle\rangle_{|\Delta\eta|} - 2\cdot\langle\langle 2\rangle\rangle^2_{|\Delta\eta|}$$

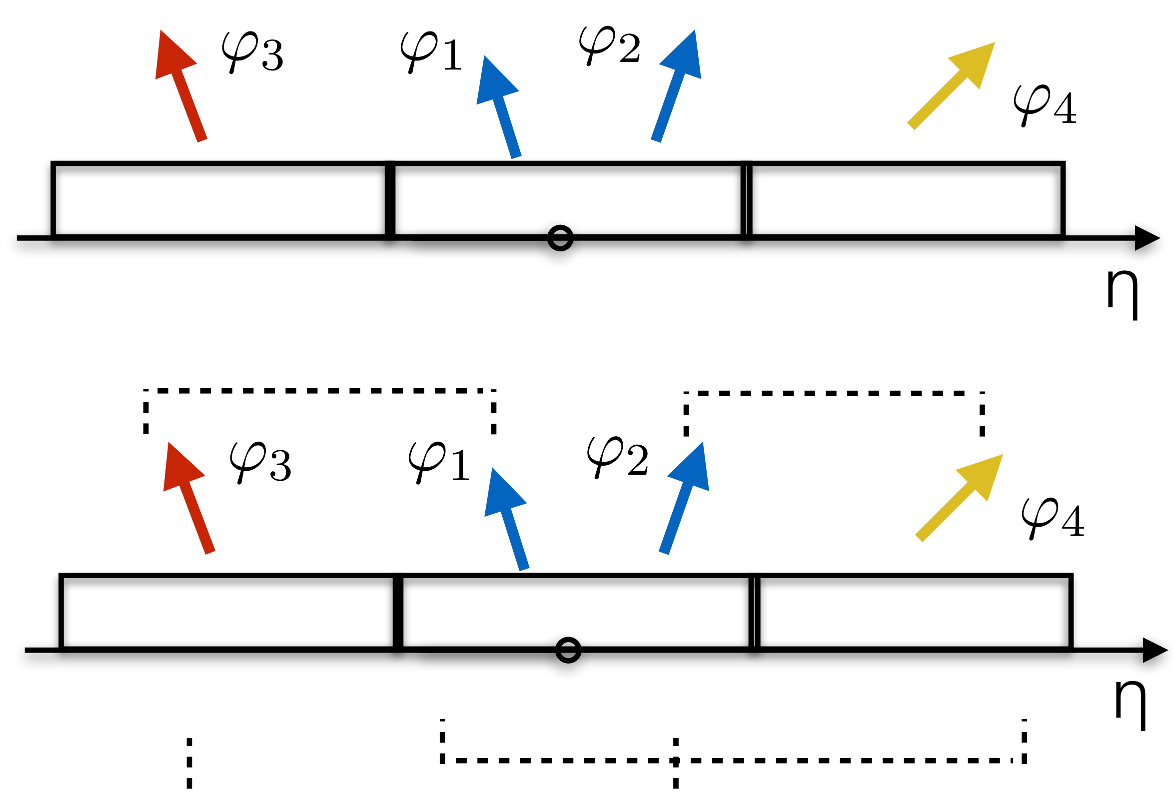
4-particle cumulant (3-subevent method)

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

$$\langle\langle 2 \rangle\rangle^2_{3\mathrm{sub}} = \langle\langle \cos \mathrm{n}(\varphi_1 - \varphi_3) \rangle\rangle \langle\langle \cos \mathrm{n}(\varphi_2 - \varphi_4) \rangle\rangle$$

$$\langle\langle 2 \rangle\rangle^2_{3\mathrm{sub}} = \langle\langle \cos \mathrm{n}(\varphi_1 - \varphi_4) \rangle\rangle \langle\langle \cos \mathrm{n}(\varphi_2 - \varphi_3) \rangle\rangle$$

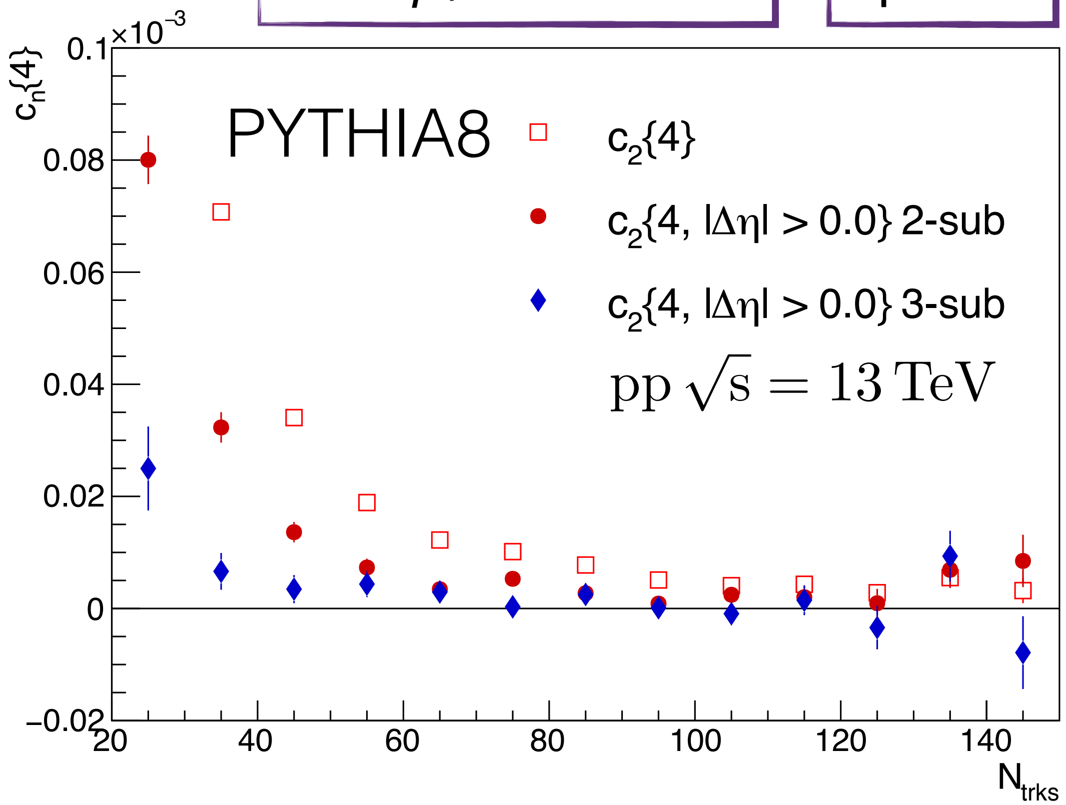
$$c_n\{4\}_{3\mathrm{sub}} = \langle\langle 4 \rangle\rangle_{3\mathrm{sub}} - 2 \cdot \langle\langle 2 \rangle\rangle^2_{3\mathrm{sub}}$$



- Method inspired by *arXiv: 1701.038301 [nucl-th]*, is implemented in Generic Framework and tested with PYTHIA8 simulations

4-particle cumulant (3-subevent method)

$0.3 < p_T < 3.0$ GeV/c | $|\eta| < 2.5$

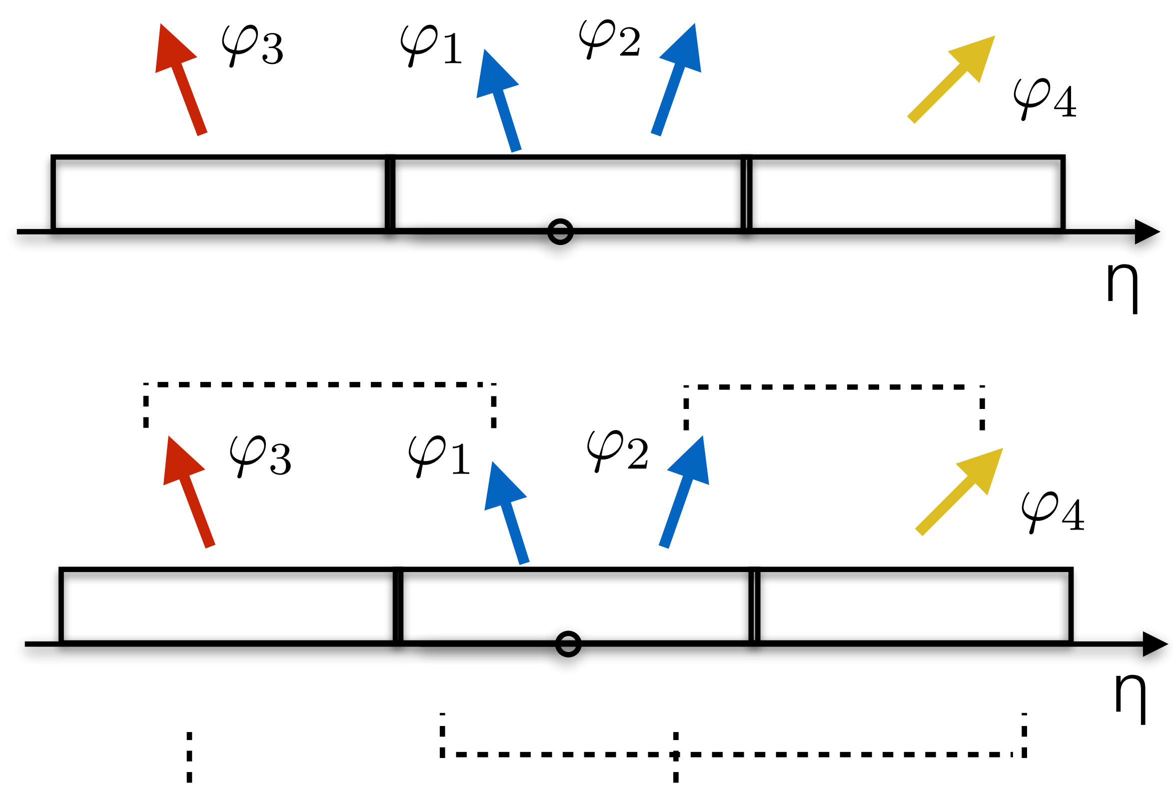


$$\langle\langle 4\rangle\rangle_{3\mathrm{sub}} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{3\mathrm{sub}} = \langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{3\mathrm{sub}} = \langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle$$

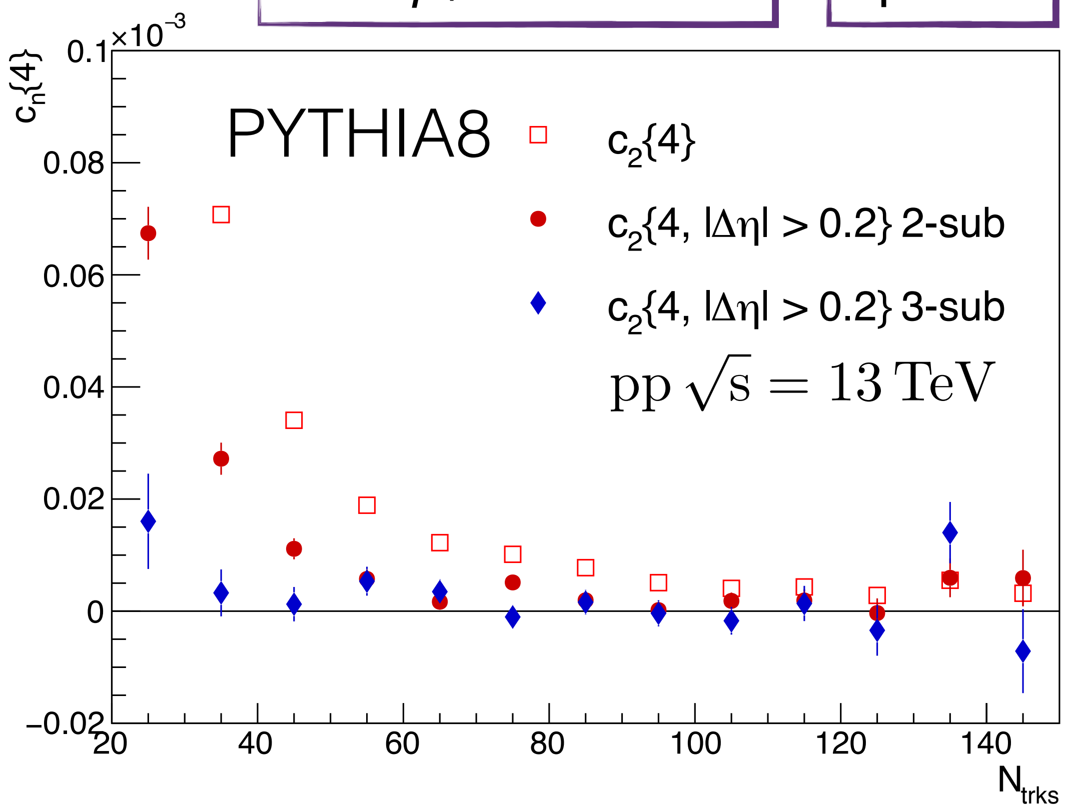
$$c_n\{4\}_{3\mathrm{sub}} = \langle\langle 4\rangle\rangle_{3\mathrm{sub}} - 2\cdot\langle\langle 2\rangle\rangle^2_{3\mathrm{sub}}$$



- Method inspired by *arXiv: 1701.038301 [nucl-th]*, is implemented in Generic Framework and tested with PYTHIA8 simulations
- Splitting the acceptance into 3 subevents shows the ability to further suppress non-flow

4-particle cumulant (3-subevent method)

$0.3 < p_T < 3.0$ GeV/c | $|\eta| < 2.5$



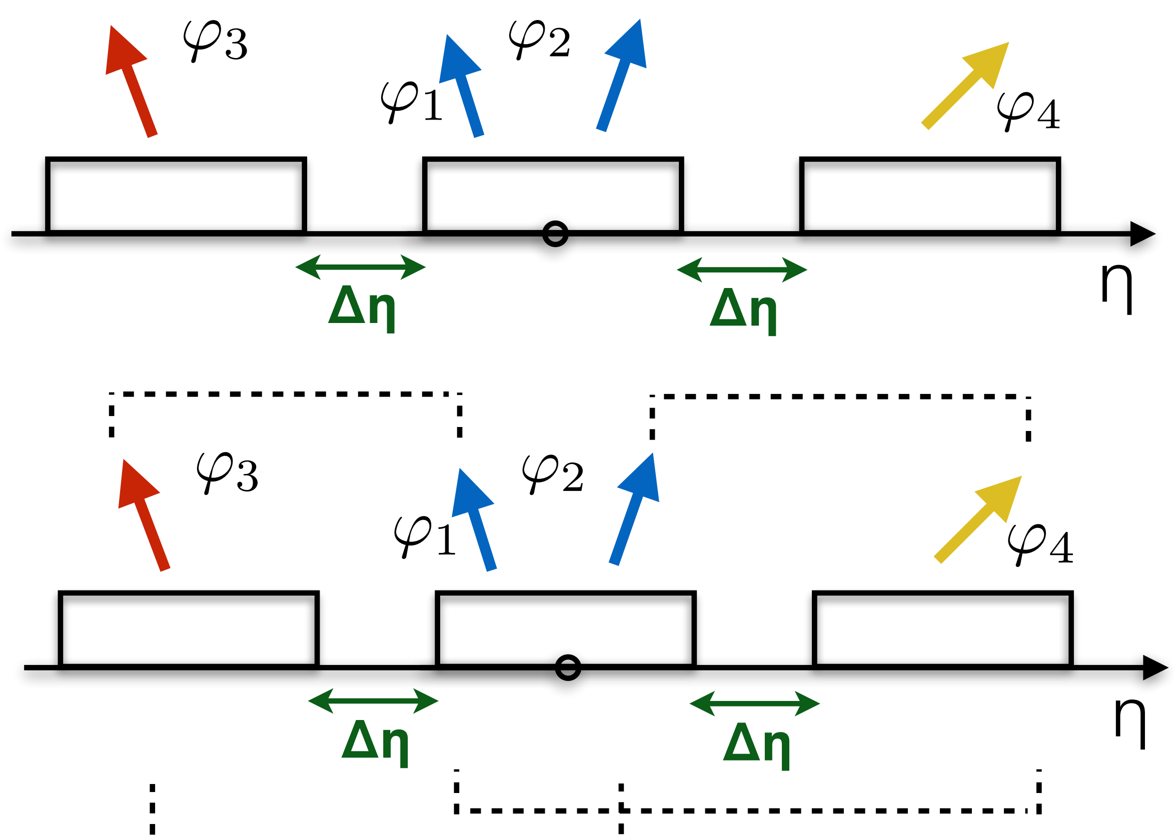
$$\langle\langle 4\rangle\rangle_{3\mathrm{sub}} = \langle\langle \cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{3\mathrm{sub}} = \langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

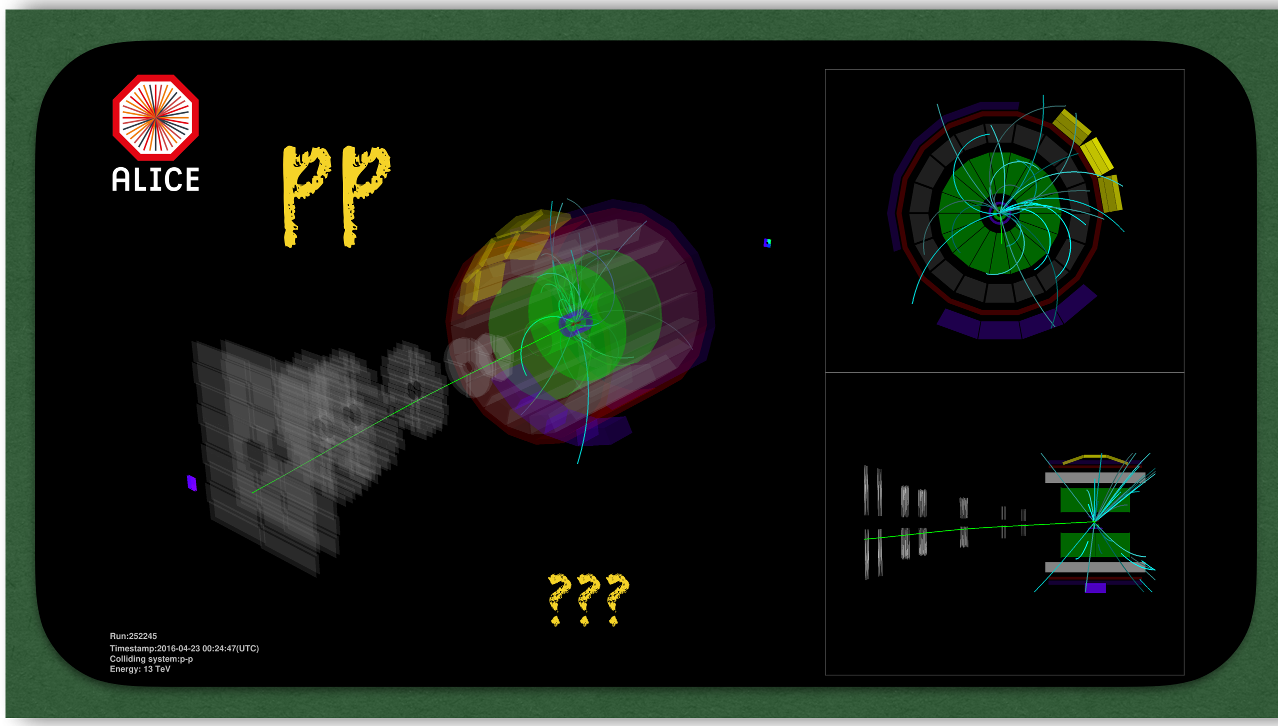
$$\langle\langle 2\rangle\rangle^2_{3\mathrm{sub}} = \langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle$$

$$c_n\{4\}_{3\mathrm{sub}} = \langle\langle 4\rangle\rangle_{3\mathrm{sub}} - 2\cdot\langle\langle 2\rangle\rangle^2_{3\mathrm{sub}}$$

- Method inspired by *arXiv: 1701.038301 [nucl-th]*, is implemented in Generic Framework and tested with PYTHIA8 simulations
- Splitting the acceptance into 3 subevents shows the ability to further suppress non-flow
- Further decrease of $c_2\{4, |\Delta\eta| > 0.2\}$ is seen w.r.t. $c_2\{4, |\Delta\eta| > 0.0\}$

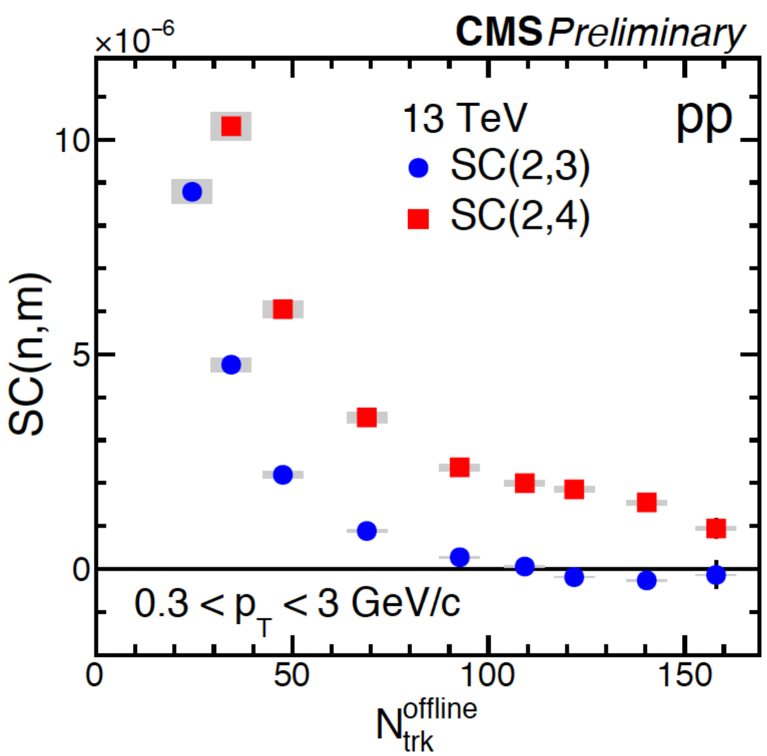


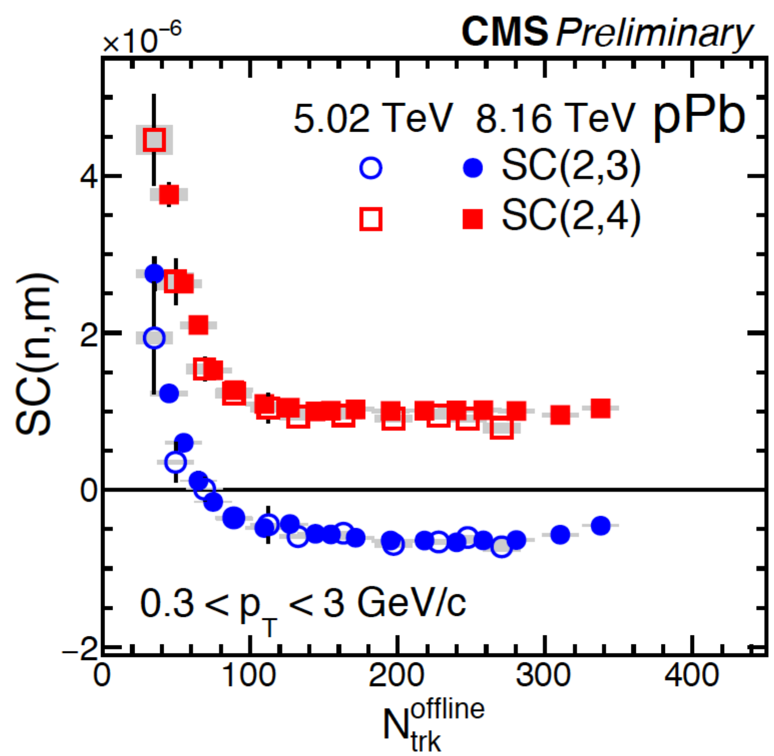
Symmetric Cumulants in small systems

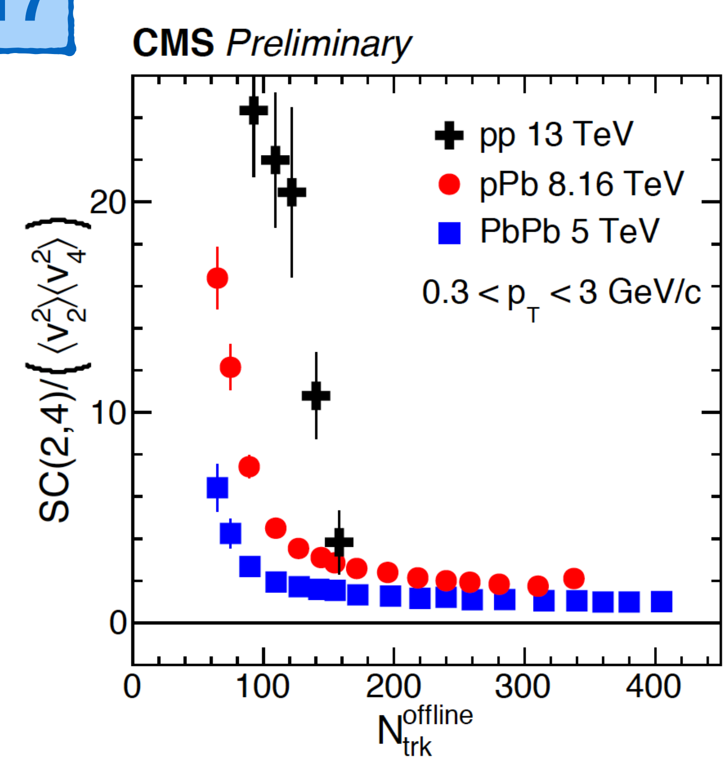


- First measurements of SC(m,n) in small systems were reported at QM17 by CMS
- However, **are SC(m,n) measurements free of non-flow contamination, especially in small systems?**

QM17







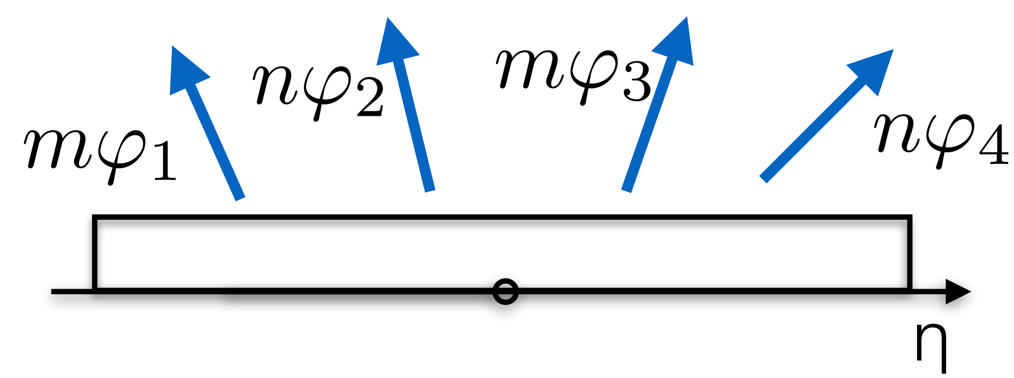
Katarina Gajdosova

Standard SC(3,2), SC(4,2)

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

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

$$SC(m,n) = \langle\langle 4\rangle\rangle - \langle\langle 2\rangle\rangle\langle\langle 2\rangle\rangle$$



Standard SC(3,2), SC(4,2)

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

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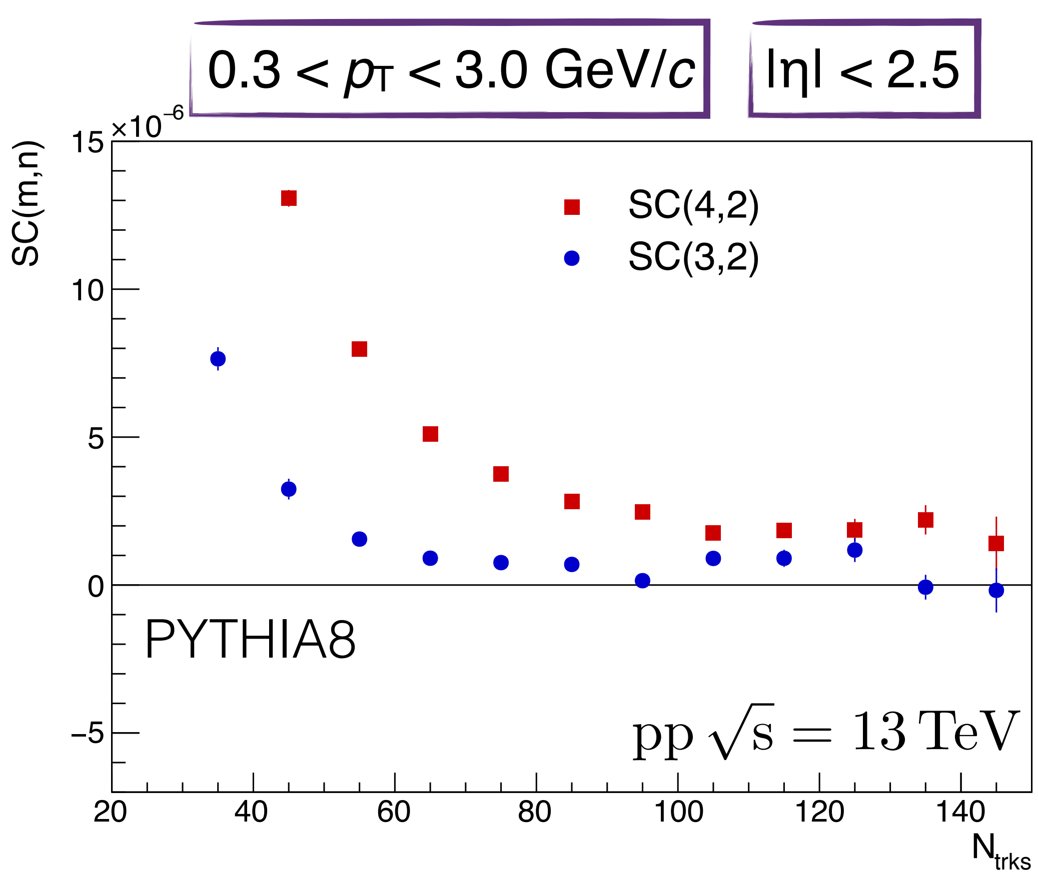
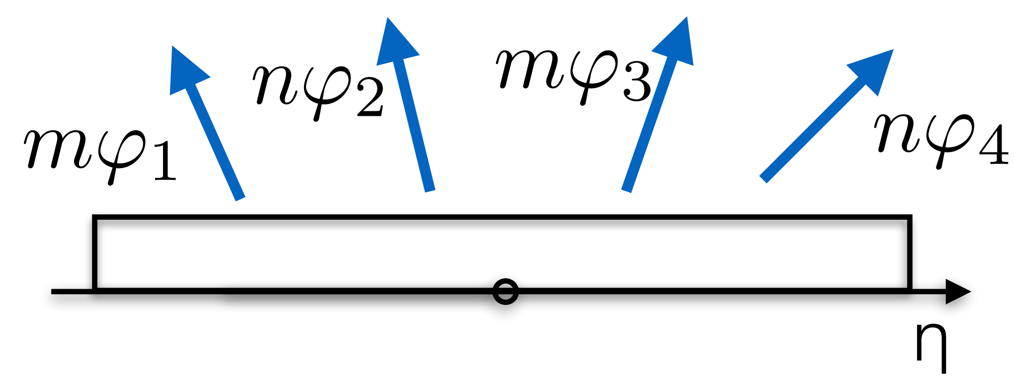
$$SC(m,n) = \langle\langle 4\rangle\rangle - \langle\langle 2\rangle\rangle\langle\langle 2\rangle\rangle$$





- Positive correlation is seen in PYTHIA between v_2 and v_3 and v_2 and v_4

Standard SC(3,2), SC(4,2)

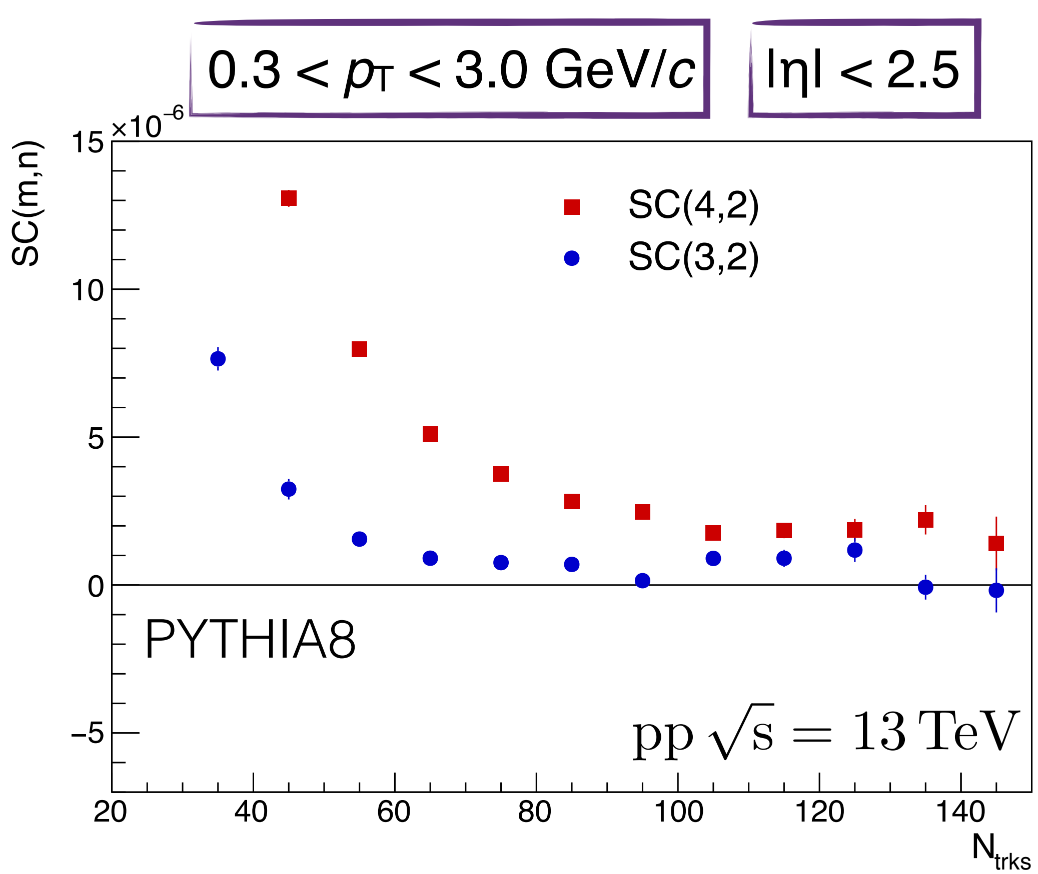
- We have seen that 4-particle cumulant still suffered from non-flow effects in pp collisions

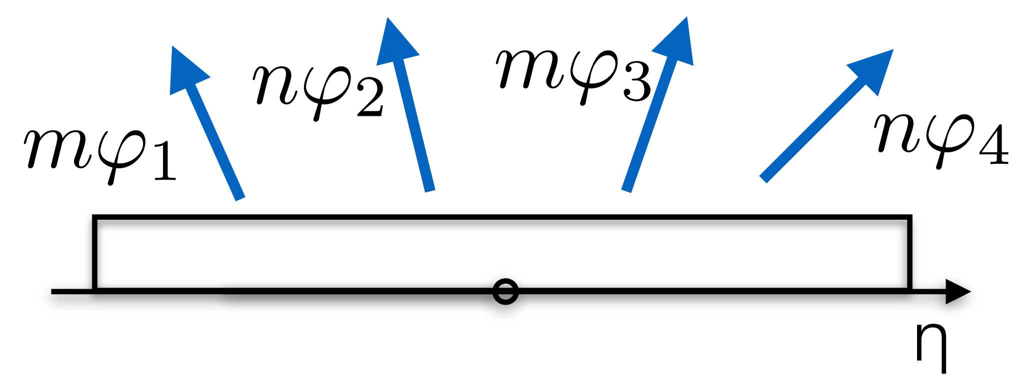
- **SC(m,n)** works on **similar principle**, therefore it **might be contaminated by non-flow**

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

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

$$SC(m,n) = \langle\langle 4\rangle\rangle - \langle\langle 2\rangle\rangle\langle\langle 2\rangle\rangle$$





- Positive correlation is seen in PYTHIA between v_2 and v_3 and v_2 and v_4

SC(3,2), SC(4,2) with |Δη| gap

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

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

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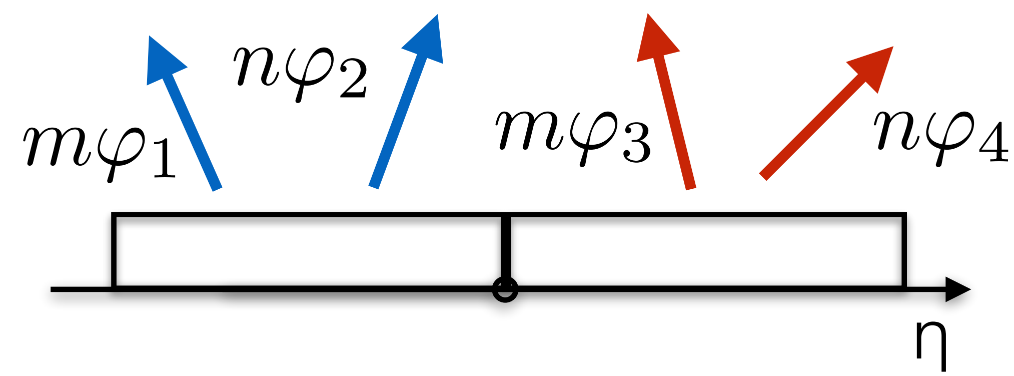

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SC(3,2), SC(4,2) with |Δη| gap

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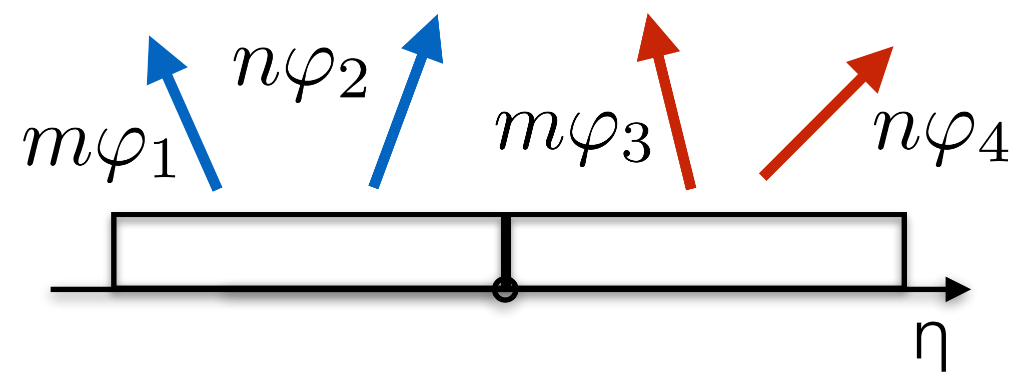

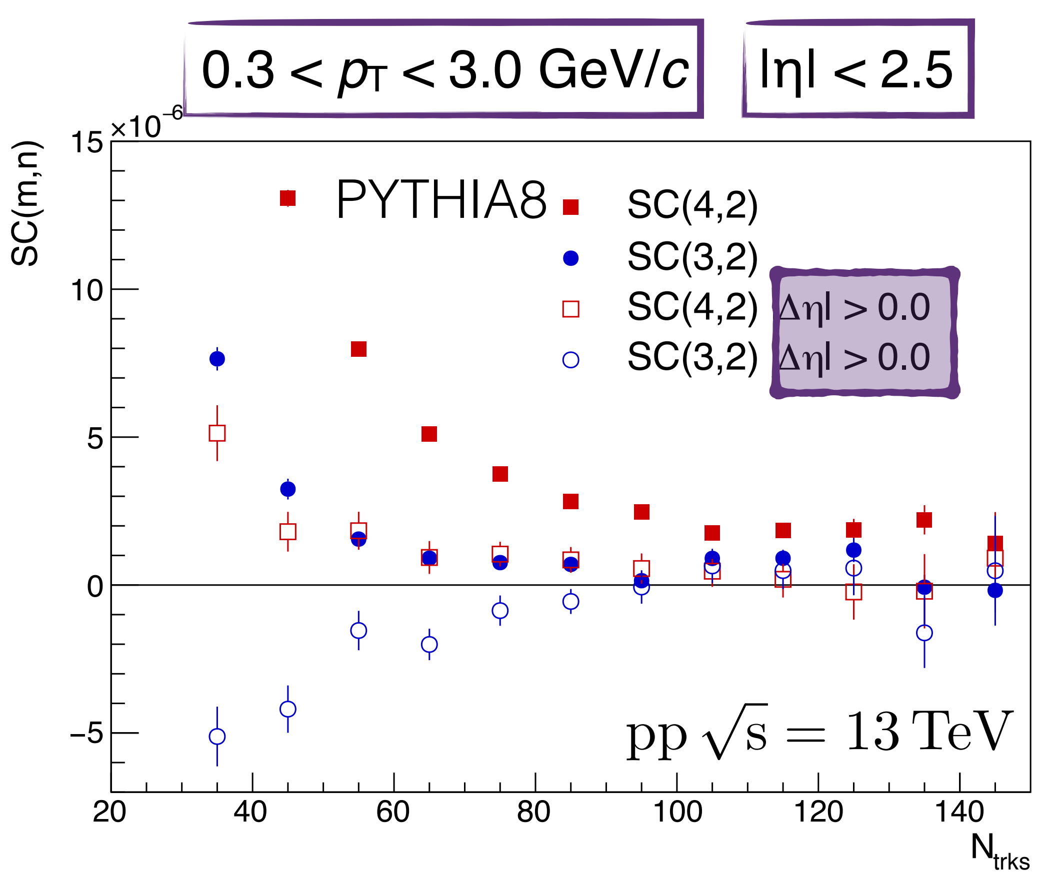

- We apply |Δη| gap (or 2-subevent method) to 2- and 4-particle correlations in the calculation of SC(m,n)
- Magnitudes of both SC(4,2) and SC(3,2) significantly decrease
- Moreover, SC(3,2) turns to be negative at low multiplicity ?

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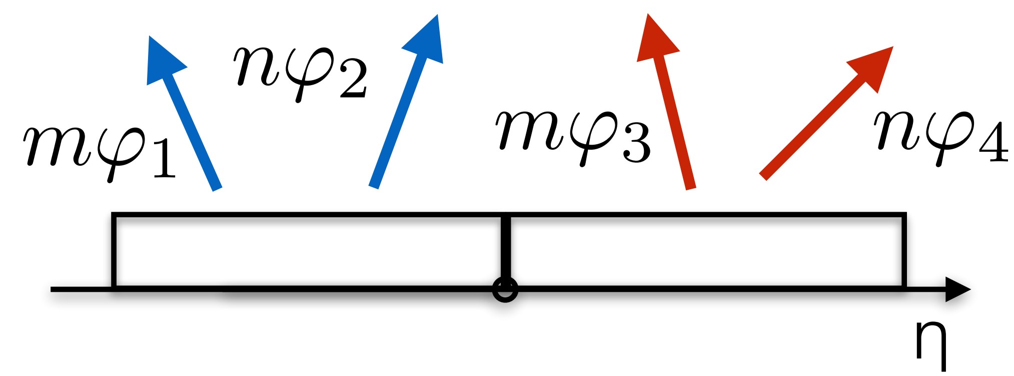

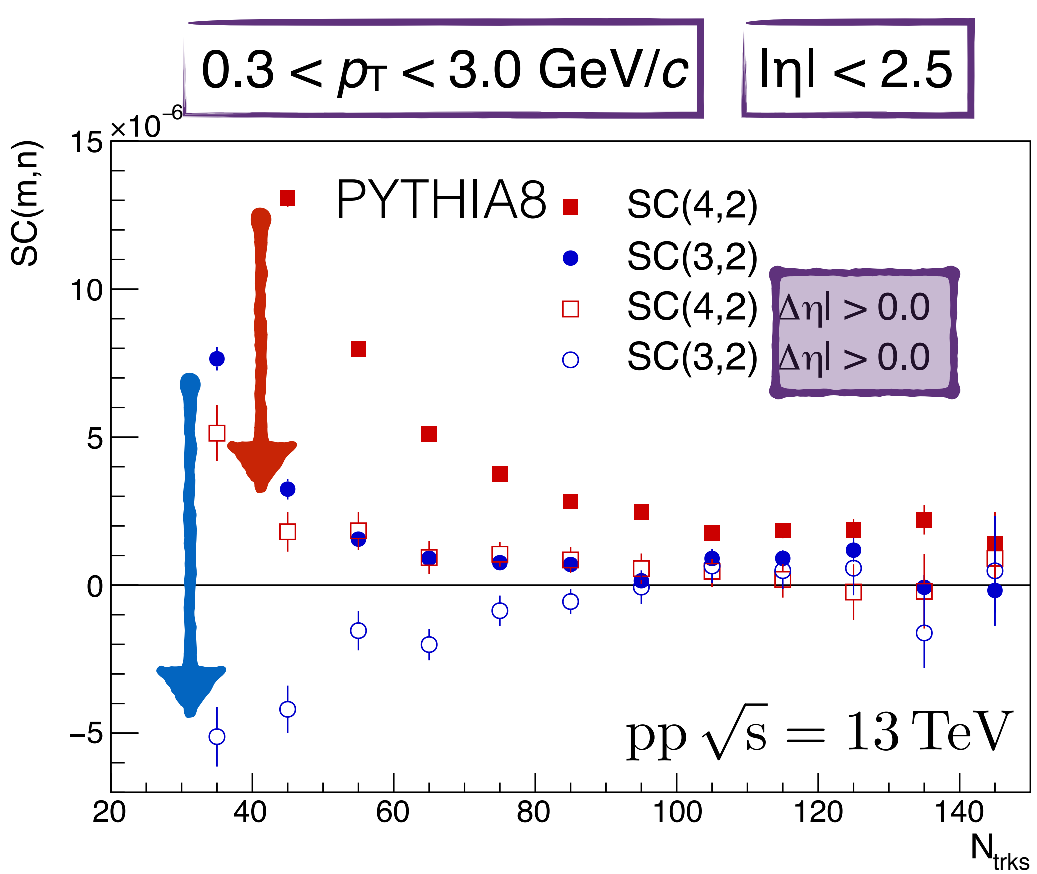

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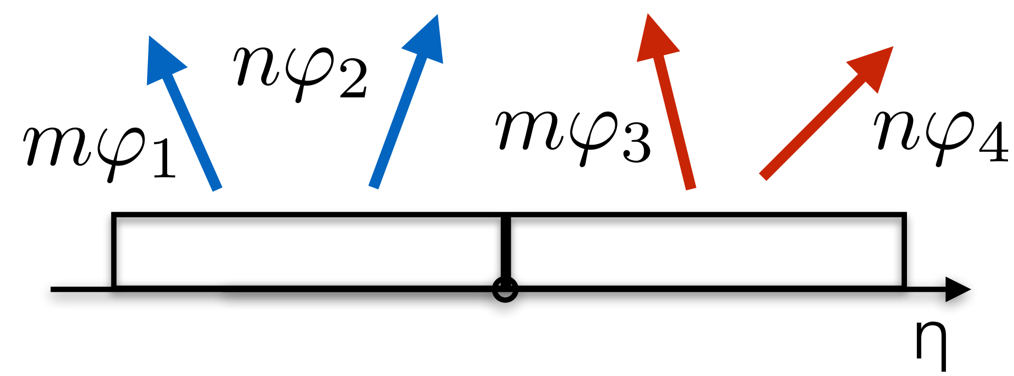

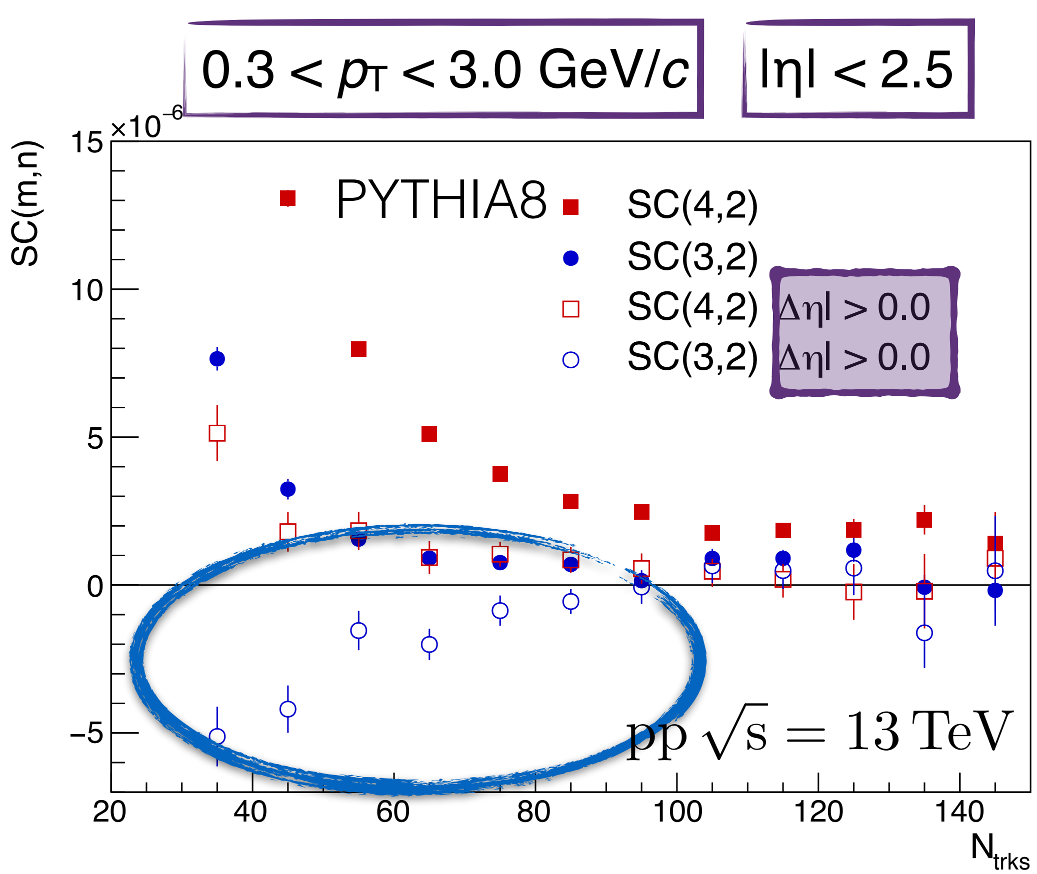

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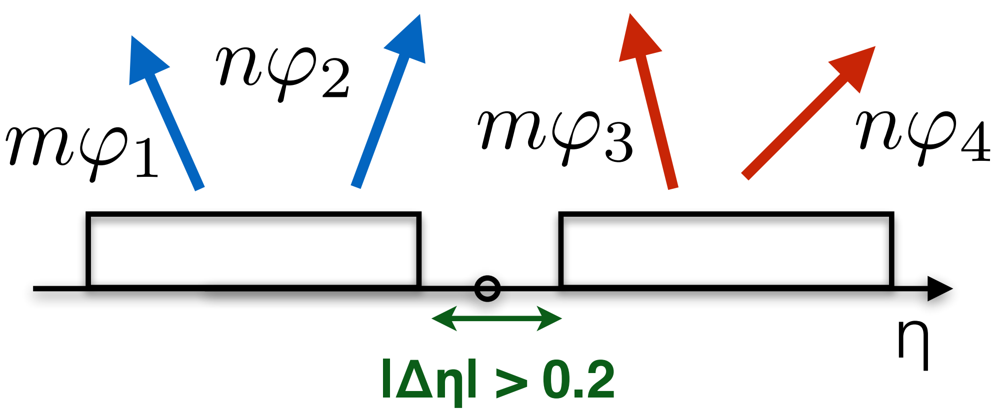

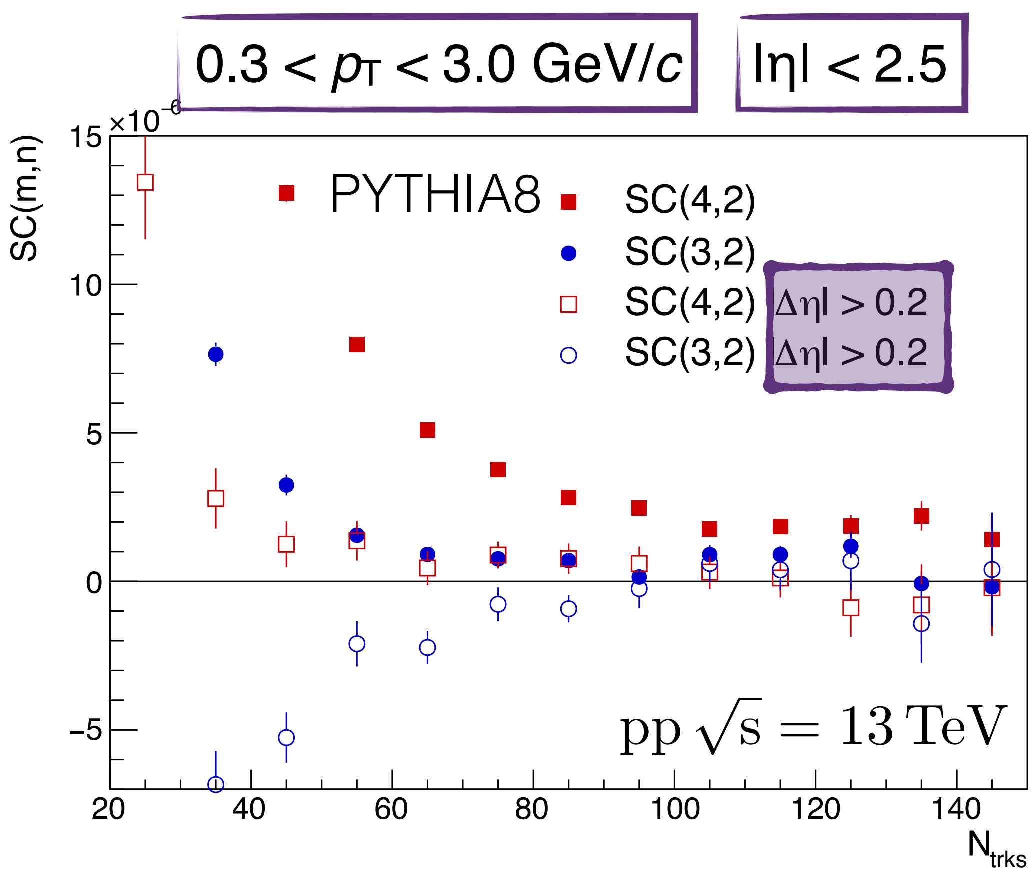

- We apply |Δη| gap (or 2-subevent method) to 2- and 4-particle correlations in the calculation of SC(m,n)

- **Magnitudes** of both SC(4,2) and SC(3,2) **significantly decrease**

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SC(3,2), SC(4,2) with 3-subevent

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

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A.

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

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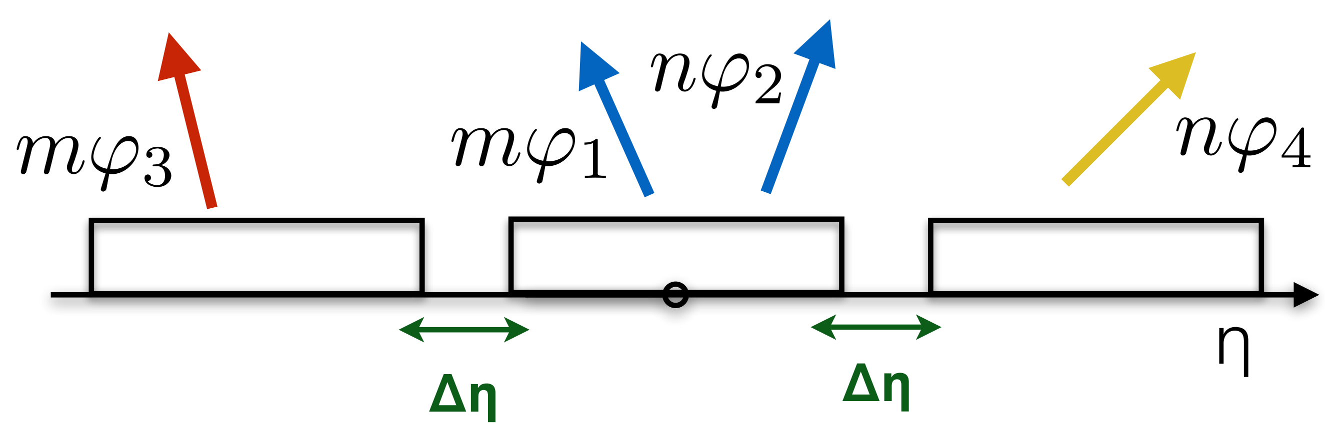
$$SC(m,n)_A = \langle\langle 4\rangle\rangle_{m,n,-m,-n} - 2\cdot\langle\langle 2\rangle\rangle_{m,-m}\langle\langle 2\rangle\rangle_{n,-n}$$

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



SC(3,2), SC(4,2) with 3-subevent

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

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B.

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

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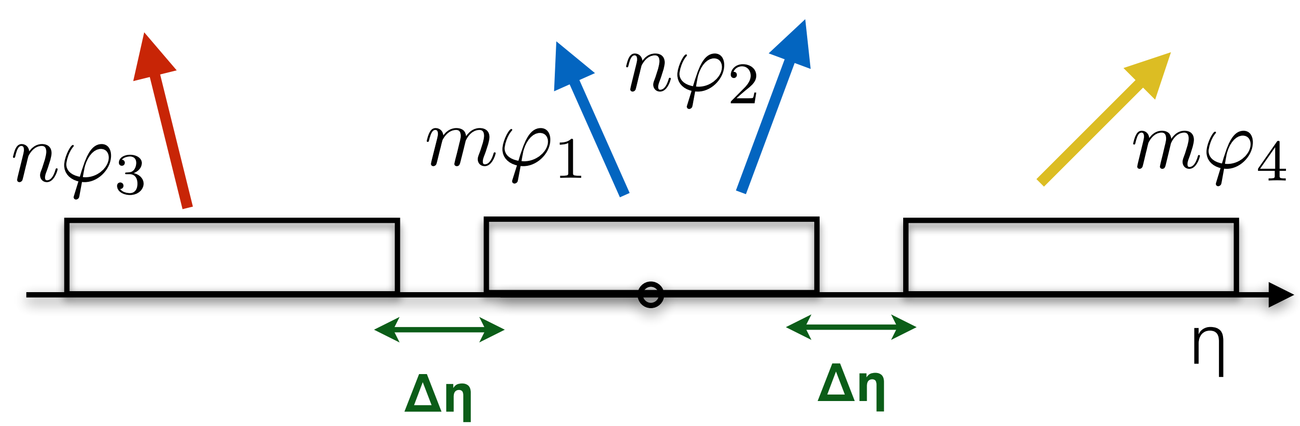

SC(3,2), SC(4,2) with 3-subevent

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

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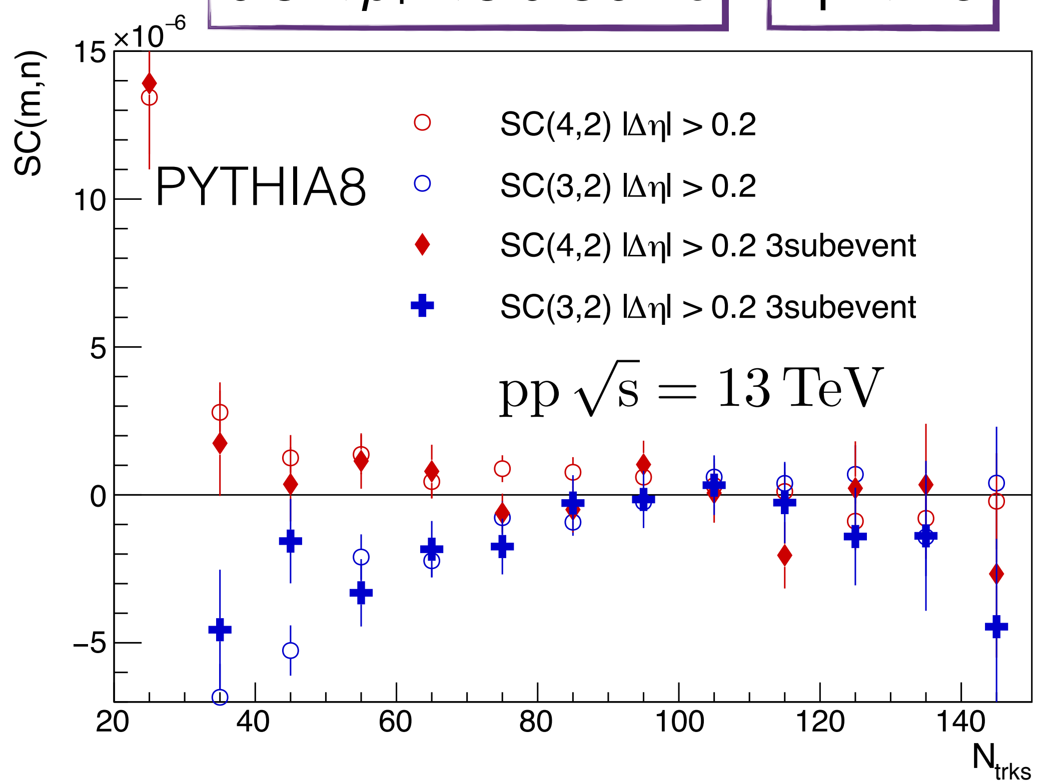
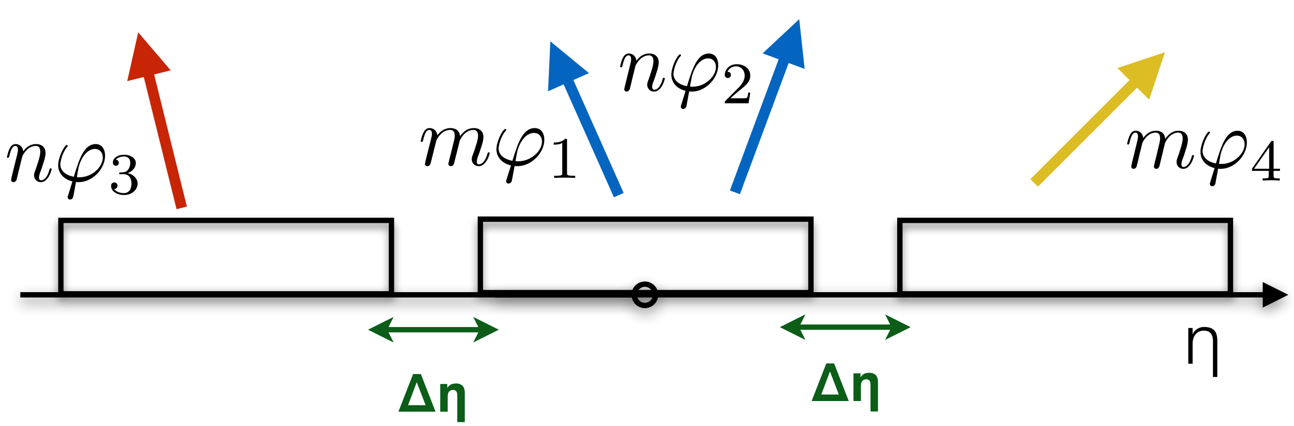
$$SC(m,n)_B = \langle\langle 4\rangle\rangle_{m,n,-n,-m} - 2\cdot\langle\langle 2\rangle\rangle_{n,-n}\langle\langle 2\rangle\rangle_{m,-m}$$

$0.3 < p_T < 3.0$ GeV/c | $|\eta| < 2.5$





- We calculate SC(m,n) with 3-subevent method
- There is no significant difference between 2- or 3-subevent method

Summary

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- Measurements of 2- and 4-particle cumulants in pp, p-Pb and Pb-Pb collisions were presented
  - While negative sign of $c_2\{4\}$ was observed in Pb-Pb and p-Pb collisions for $N_{trk} > 60$, **no definitive flow-like signature** was observed in pp collisions
  - **Further suppression of non-flow did not reveal** a definitive **negative sign** in $c_2\{4, |\Delta\eta|\}$ measurements
- Simulation study of Symmetric Cumulants with 2- and 3-subevent method was shown
  - Clear **decrease of magnitude** of the measurements when using 2- or 3-subevent method
  - **SC(3,2) changed sign** after the suppression of non-flow contribution
- It is important to perform the measurements of $c_n\{4\}$ and SC(m,n) with subevent method to avoid large non-flow contamination

Katarina Gajdosova