Investigating collective effects in small collision systems using PYTHIA8 and EPOS 4 simulations

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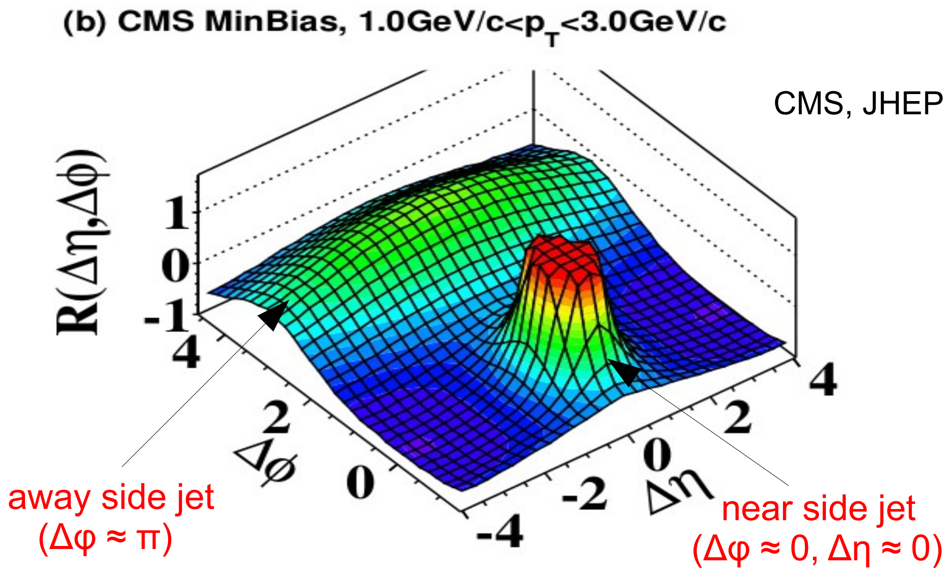
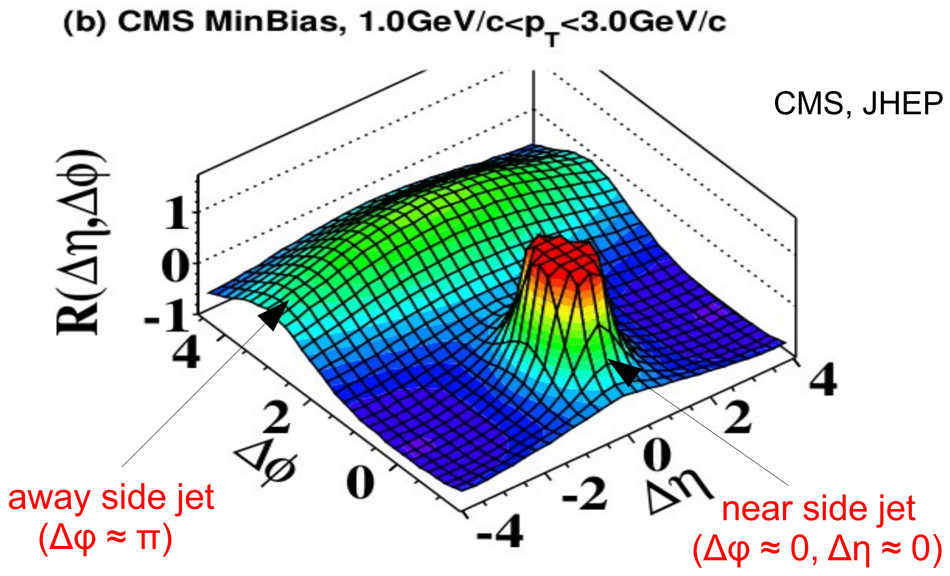
Ridge in pp: first observation



CMS, JHEP 1009 (2010) 091

- Minimum bias pp
  - Non-flow contributions
    - Near side jet peak (+ resonances, HBT effects)
    - Recoil jet in away side

Ridge in pp: first observation



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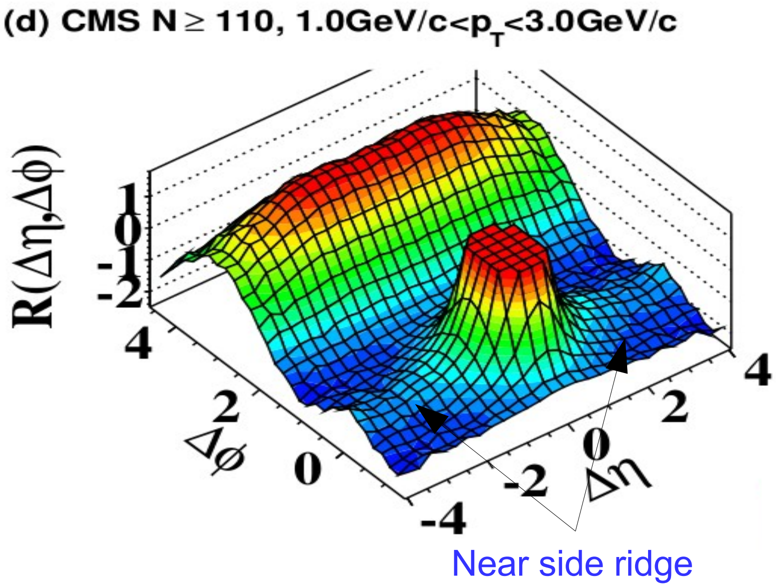
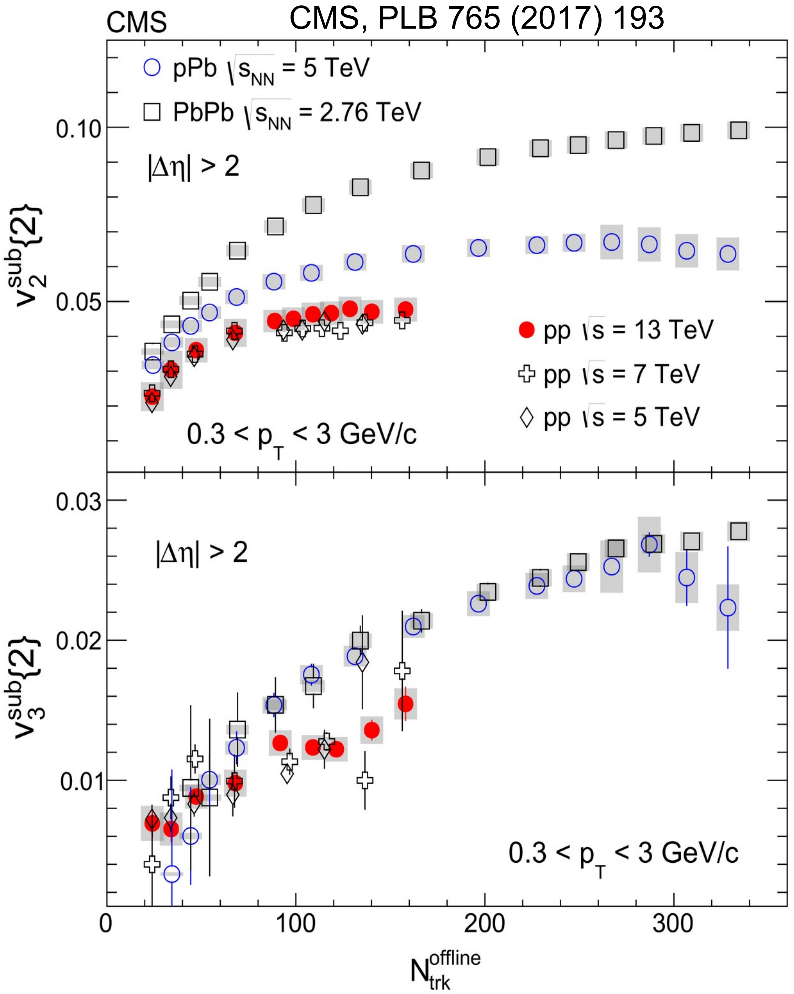


- Minimum bias pp
  - Non-flow contributions
    - Near side jet peak (+ resonances, HBT effects)
    - Recoil jet in away side
- High multiplicity pp
  - Near side ridge, typical of collective systems
    - Decomposed into Fourier harmonics v_n

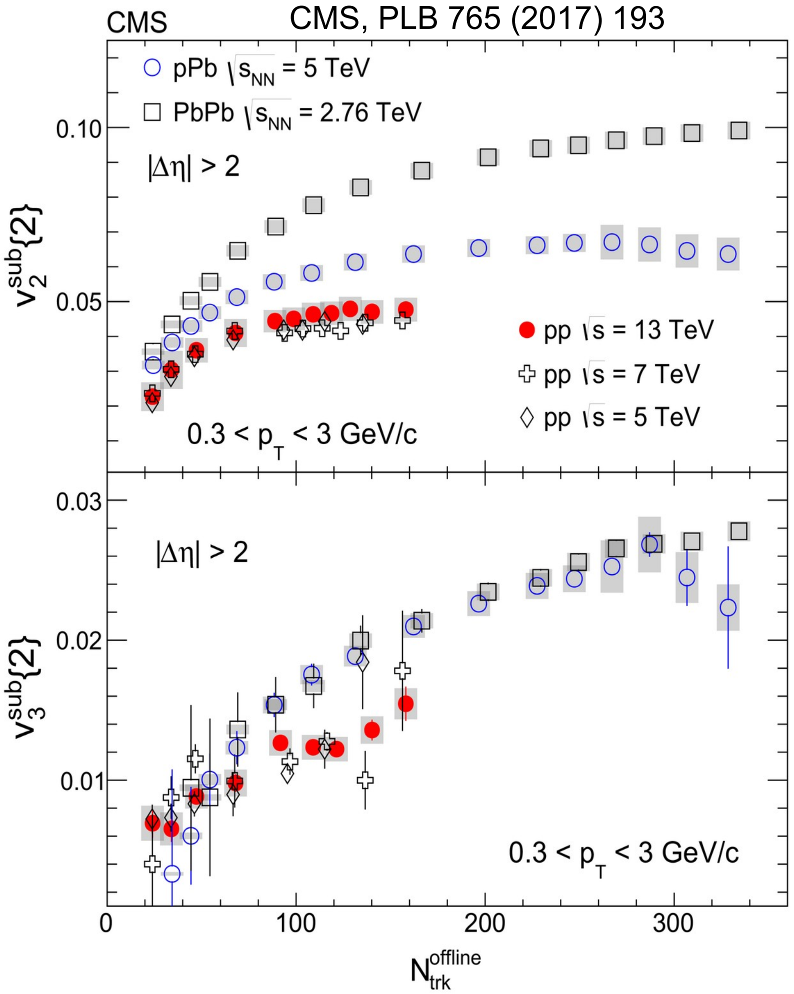
$$1+\sum_{n=1}^{\infty} 2 v_n \cos\left(n\left(\varphi-\Psi_n\right)\right)$$

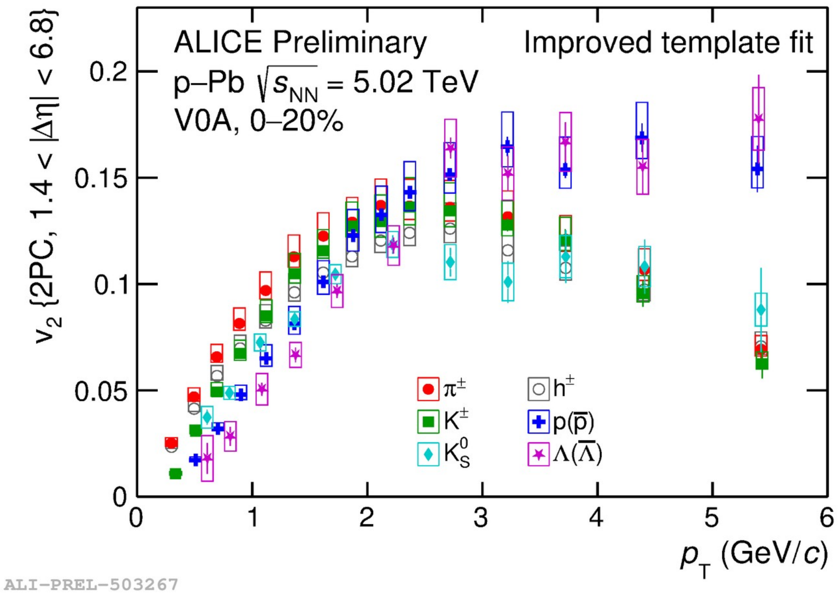
v_n coefficients



- v_n dependence on collision system but not on energy

v_n coefficients

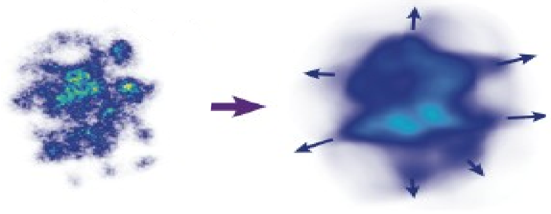




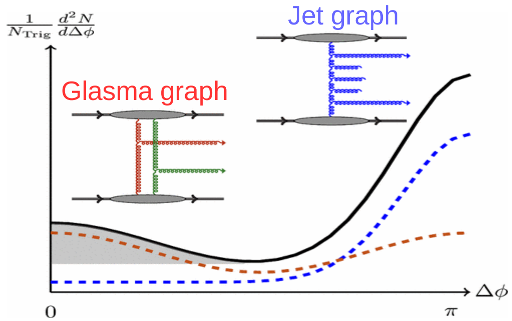
- v_n dependence on collision system but not on energy
- Mass ordering observed in high multiplicity p-Pb and pp collisions
  - Test particle type dependence at high p_T

Sources of collectivity

- Final state effects
  - Initial spatial eccentricities converted into momentum anisotropies via final state interactions
    - Hydrodynamics
    - Parton transport
    - Parton escape



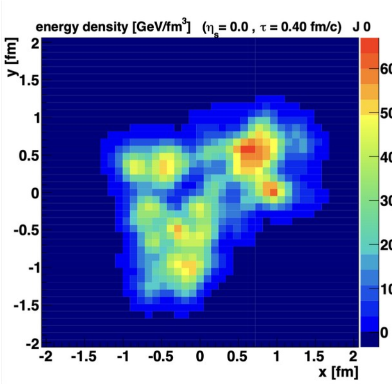
- Initial state effects
  - Initial momentum anisotropies from initial interactions
    - Color Glass Condensate (CGC) Glasma
    - Color-field domains
    - Numerical solutions



How to disentangle different regimes?

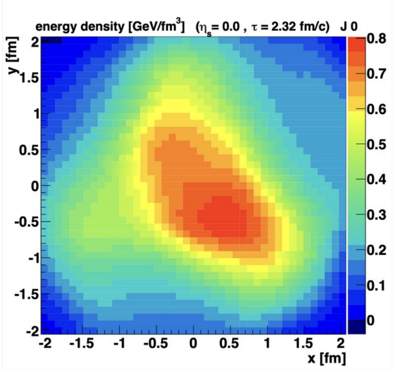
Our approach: macroscopic vs microscopic models

K. Werner, arXiv: 2306.10277



$$\partial_\mu T^{\mu\nu} = 0$$

Transport equation



- Macroscopic model: EPOS 4
  - Core–corona model with statistical hadronization
  - Collective effects from hydrodynamical evolution of the medium

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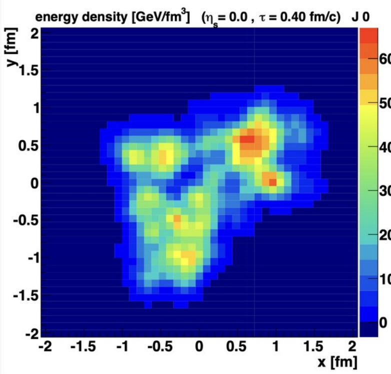

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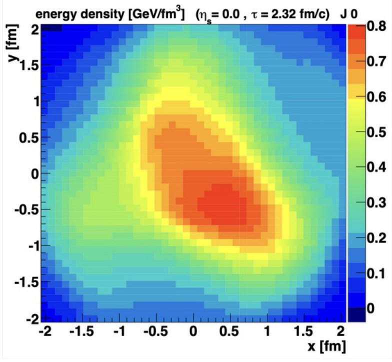
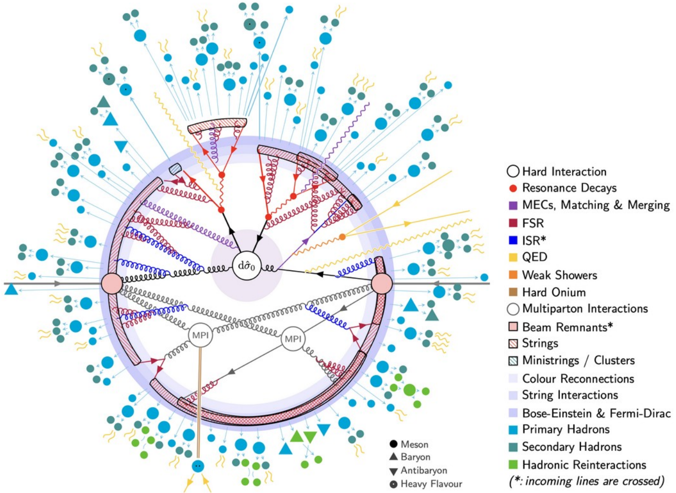


C. Bierlich et al., arXiv: 2203.11601



- Macroscopic model: EPOS 4
  - Core–corona model with statistical hadronization
  - Collective effects from hydrodynamical evolution of the medium
- Microscopic model: PYTHIA8
  - QCD strings with LUND fragmentation
  - Collective effects from new processes
    - Color reconnection, rope hadronization, ...

Experimental methods

- Scalar product (SP) method

S. Voloshin et al., arXiv:0809.2949

$$v_n\{SP\} = \frac{\langle\langle \mathbf{u}_{n,k} \mathbf{Q}_n^{*}/M\rangle\rangle}{\sqrt{\langle \mathbf{Q}_n^{*a}\mathbf{Q}_n^{*b}/(M^a M^b)\rangle}}$$

Particles of Interest (POI)

$$u_{n,x} = \cos(n\varphi)$$
$$u_{n,y} = \sin(n\varphi)$$

Reference Particles (RPs)

$$Q_{n,x} = \sum_i \cos(n\varphi_i)$$
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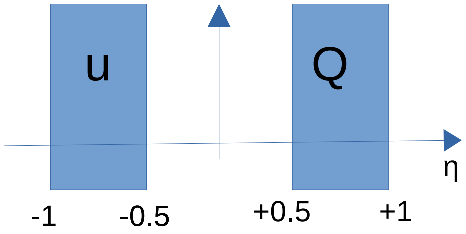

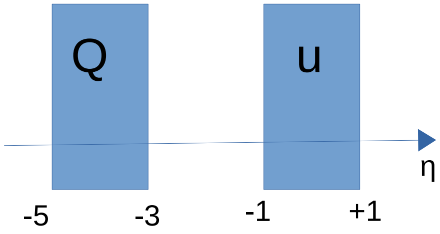

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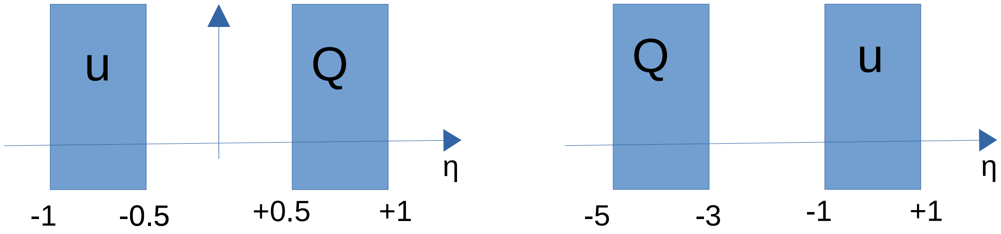

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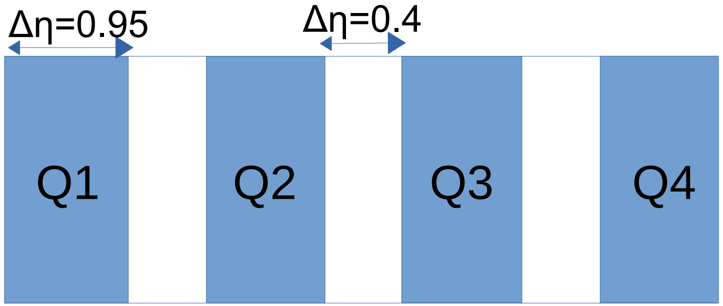
- Cumulants
  - 2- and 4-particle azimuthal correlations for an event

$$\langle 2\rangle \equiv \langle \cos(n(\varphi_i - \varphi_j))\rangle, i \neq j$$
$$\langle 4\rangle \equiv \langle \cos(n(\varphi_i + \varphi_j - \varphi_k - \varphi_l))\rangle, i \neq j \neq k \neq l$$

  - Averaging over all events → 2nd and 4th order cumulants

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



A. Bilandzic et al., PRC 83, 044913 (2011)
J. Jia et al., PRC 96, 034906 (2017)

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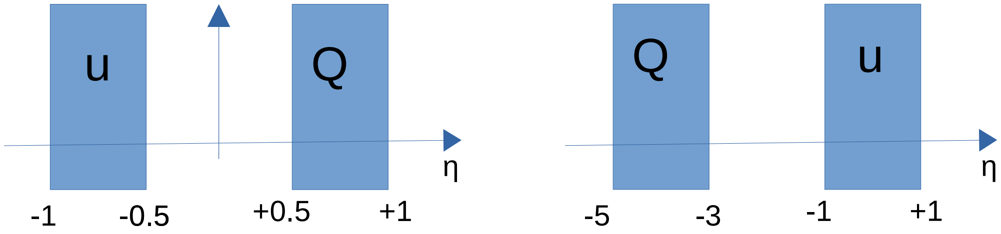

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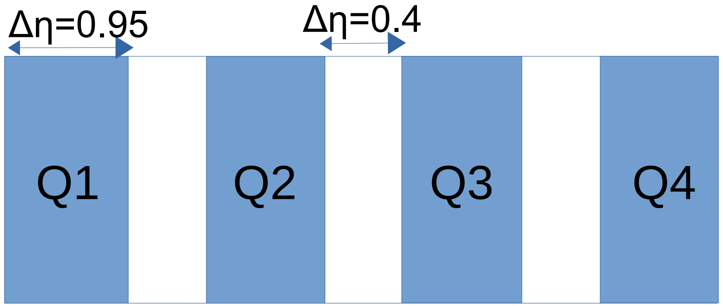

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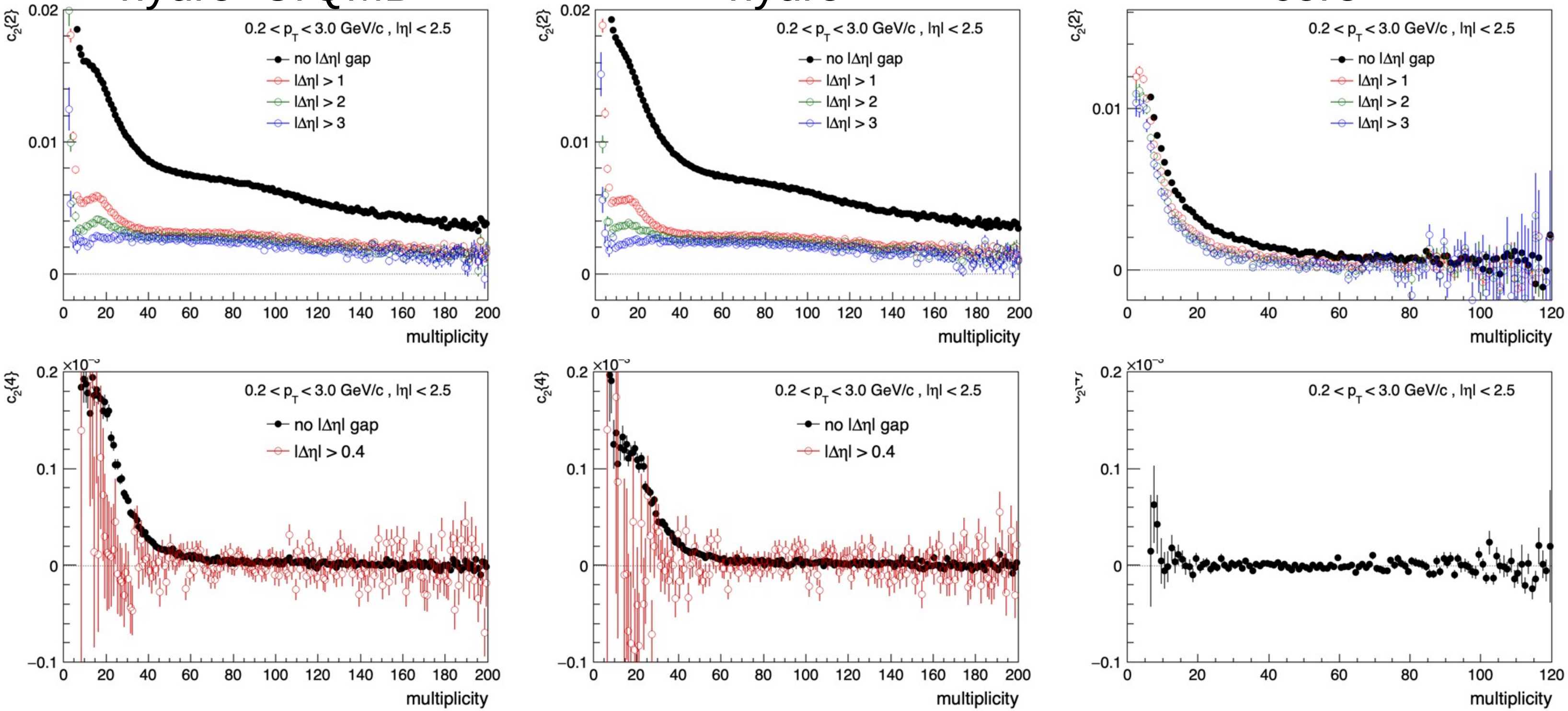
- Methods have different sensitivity to non-flow and fluctuations

$c_2\{2\}$ and $c_2\{4\}$ in EPOS4: minimum bias pp @ 13.6 TeV

hydro+UrQMD | hydro | core



- Small differences when using UrQMD
- Different behavior for hydro and core

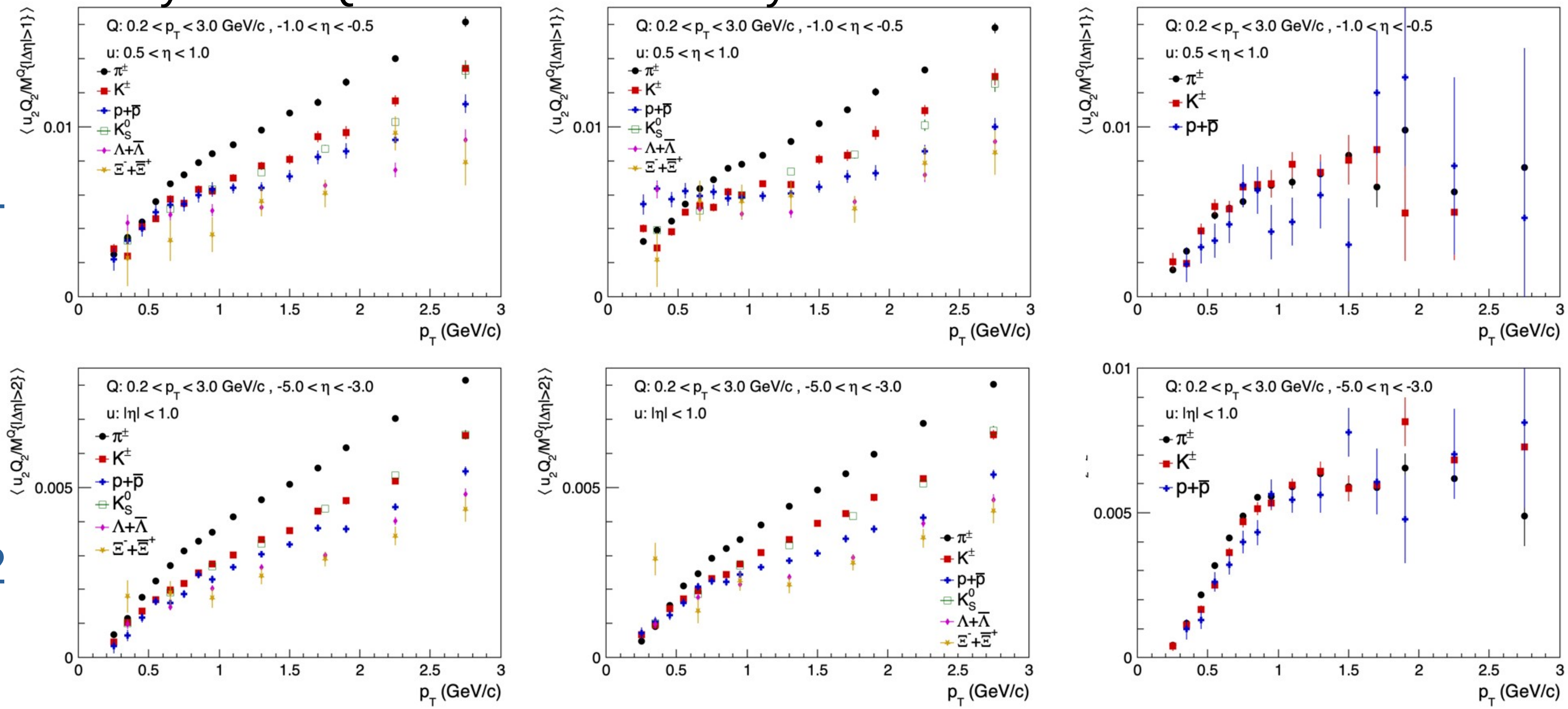
- $c_2\{2\} > 0$ and $c_2\{4\} \sim 0$ at high multiplicities
  - Small dependence on $|\Delta\eta|$ gap for $c_2\{2\}$
  - $c_2\{4\} \sim 0 \rightarrow$ expected for Gaussian fluctuations

PID u_2Q_2 in EPOS4: minimum bias pp @ 13.6 TeV

hydro+UrQMD | hydro | core

|Δη| > 1

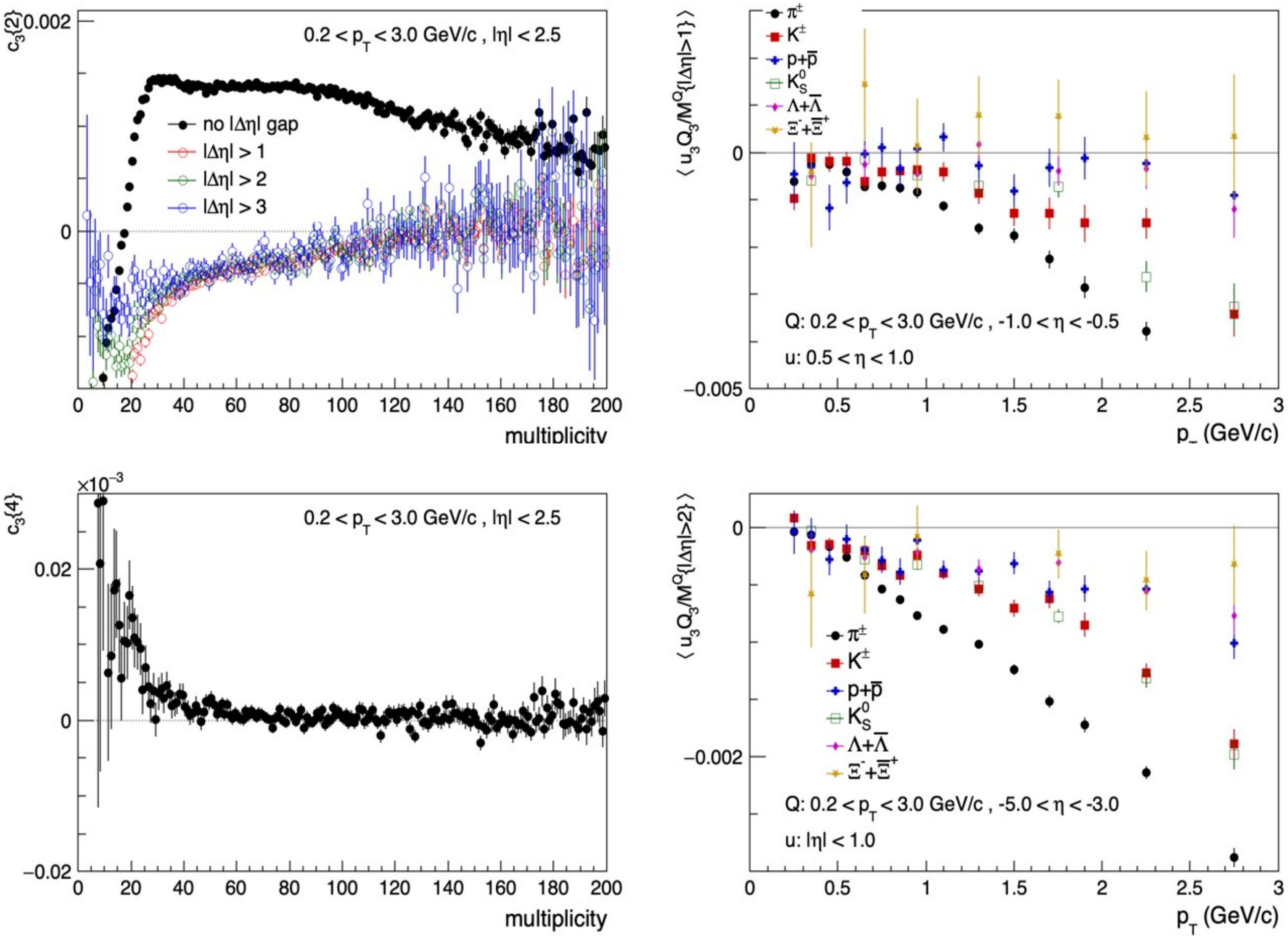
|Δη| > 2



- Differences when using UrQMD
  - More pronounced for small |Δη| gap at low p_T
- Different behavior for hydro and core

- Mass ordering in all cases
  - More pronounced for large |Δη| gap
- Hint of crossing between proton and pion u_2Q_2 for core
  - Currently limited by the available data sample

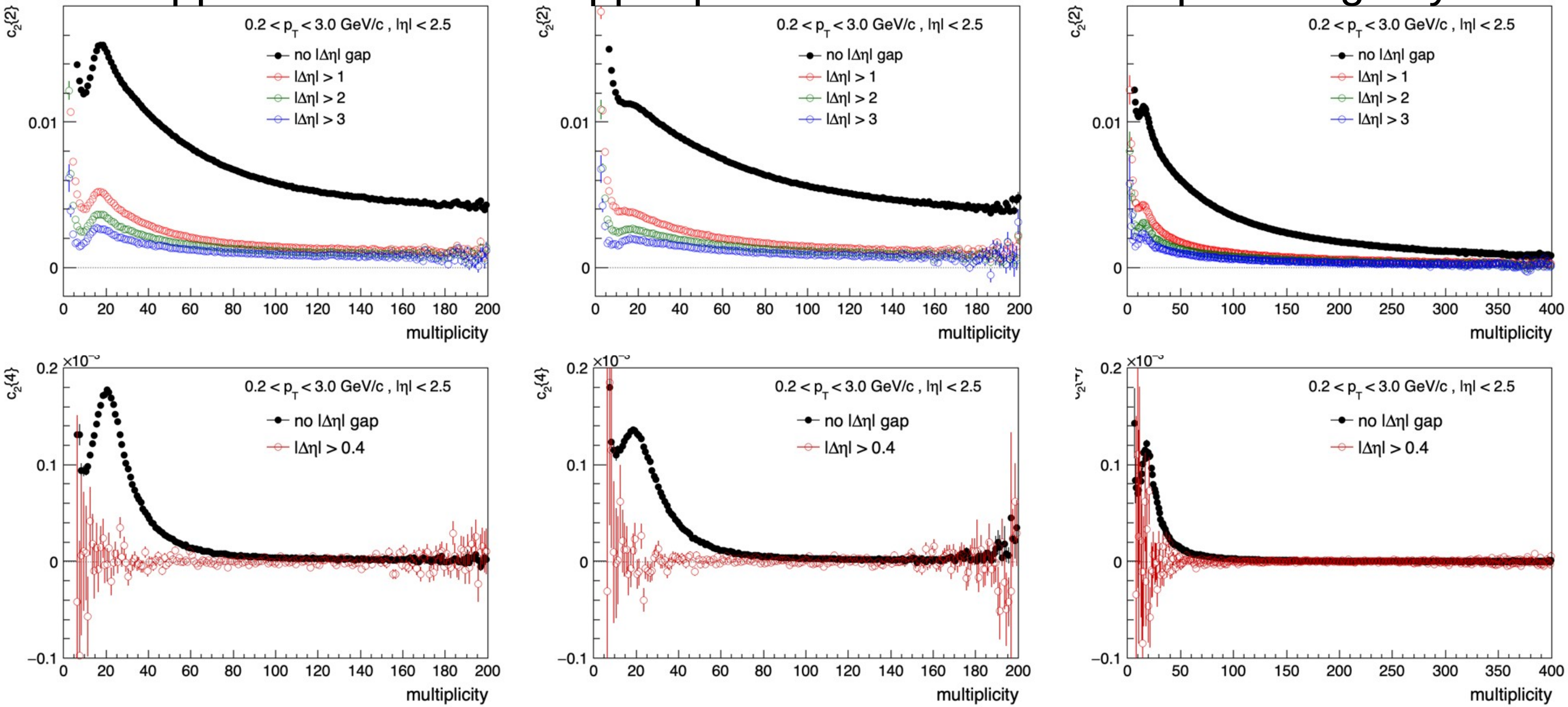
“v_3” in EPOS4 (hydro+UrQMD): minimum bias pp @ 13.6 TeV



- $c_3\{2, |\Delta\eta|\}$ ~ 0 and $c_3\{4\}$ ~ 0 at high multiplicities
  - Small dependence on |Δη| gap for $c_3\{2\}$
- “Mass ordering” more pronounced for large |Δη| gap

$c_2\{2\}$ and $c_2\{4\}$ in PYTHIA 8.309: minimum bias pp @ 13.6 TeV and p-Pb @ 5.02 TeV

pp default | pp rope hadronization | p-Pb Angantyr



- Small differences between pp default and rope hadronizaton
- Similar trends in pp and p-Pb default

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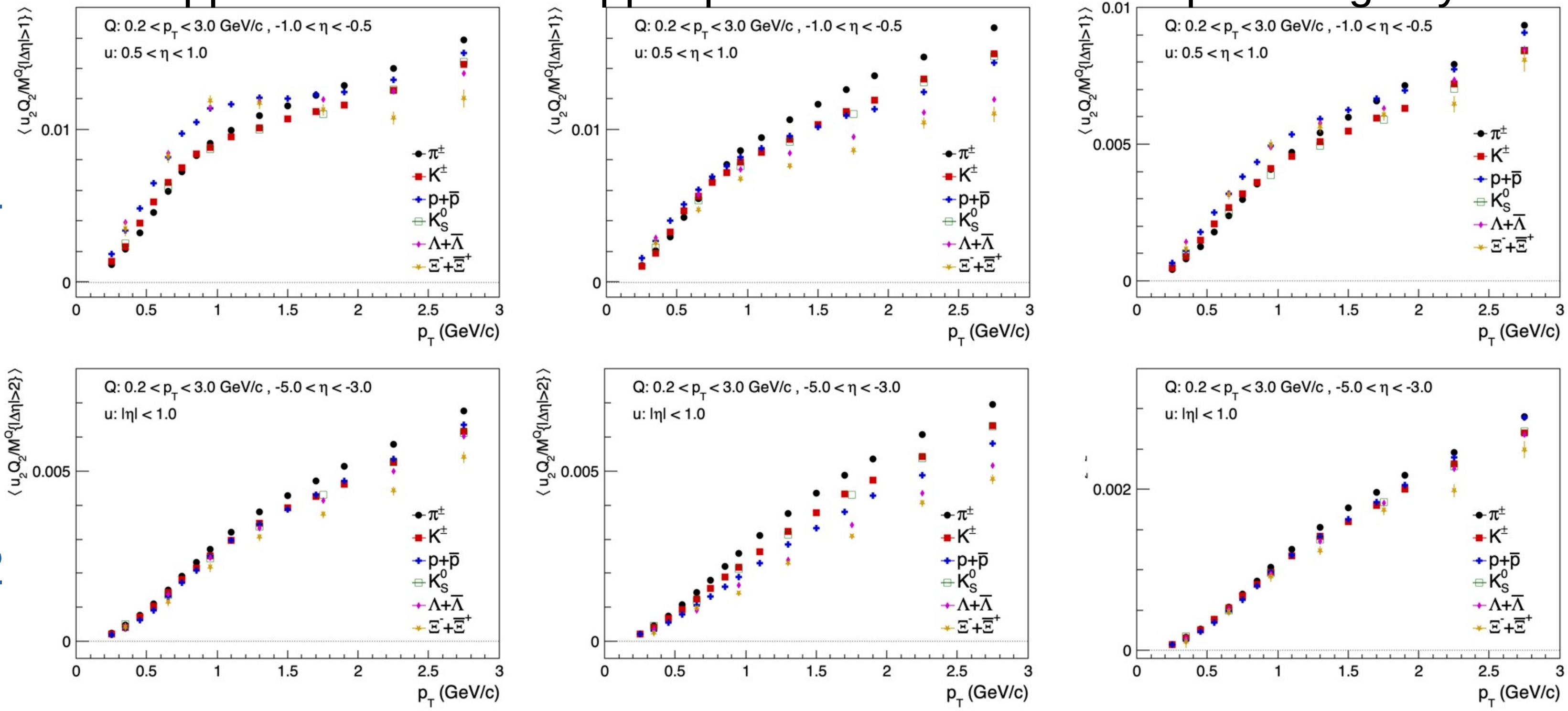
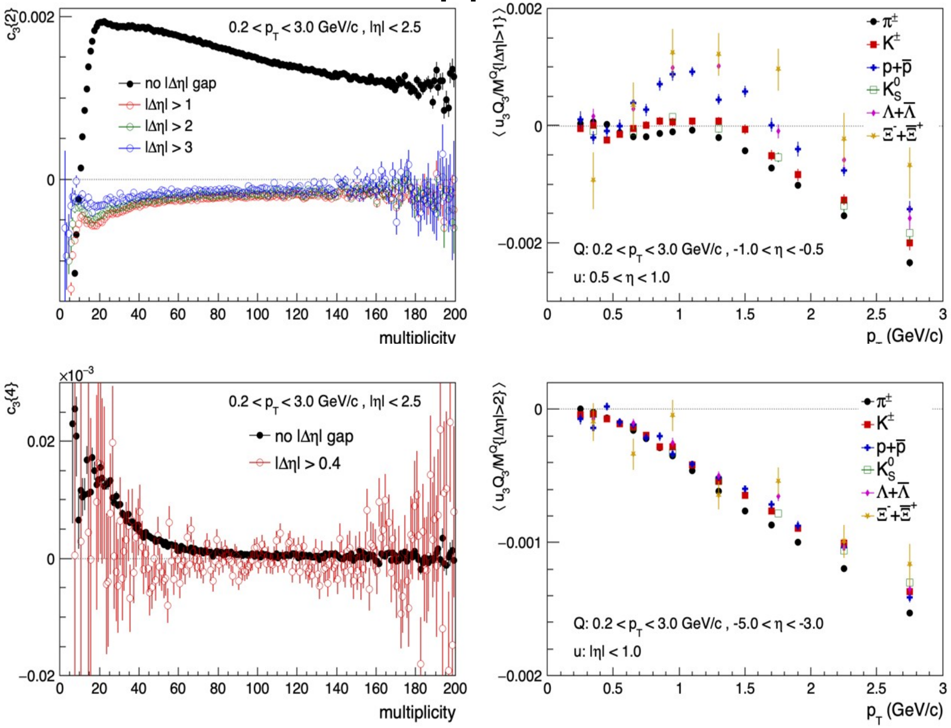


- Differences between pp default and rope hadronizaton
- Similar trends in pp and p-Pb default

- Small mass ordering for large |Δη| gap
  - More pronounced for rope hadronization
- Crossing between proton and pion u_2Q_2 for large |Δη| gap in p-Pb
  - No particle type grouping

“v_3” in PYTHIA 8.309 (default): minimum bias pp @ 13.6 TeV and p-Pb @ 5.02 TeV

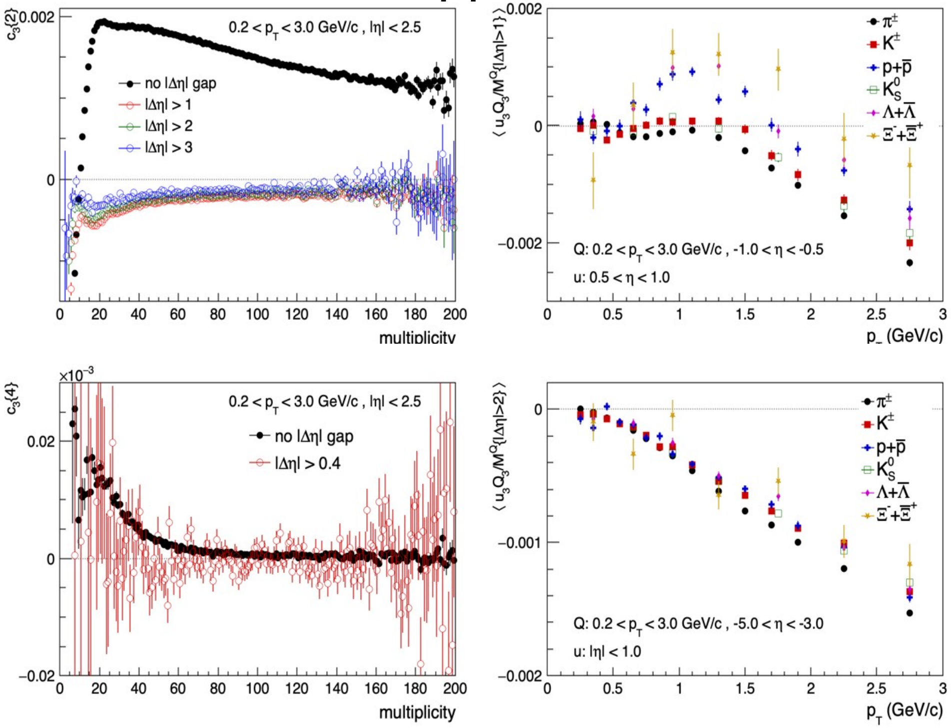
pp



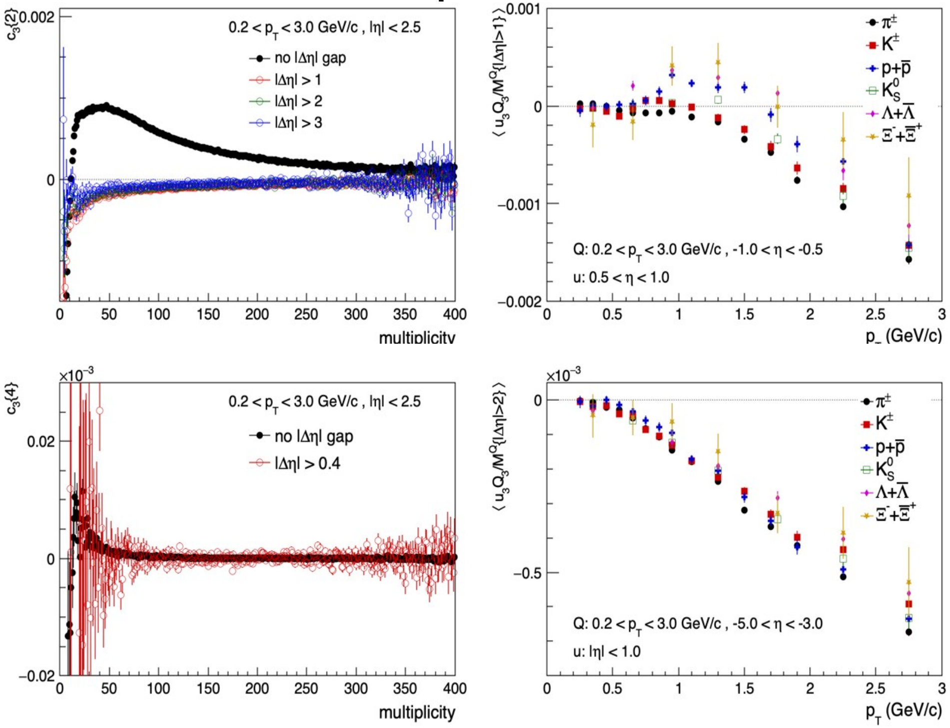
- $c_3\{2, |\Delta\eta|\} < 0$ and $c_3\{4\} \sim 0$ at high multiplicities
  - Small dependence on $|\Delta\eta|$ gap for $c_3\{2\}$
- “Mass ordering” more pronounced for small $|\Delta\eta|$ gap

“v_3” in PYTHIA 8.309 (default): minimum bias pp @ 13.6 TeV and p-Pb @ 5.02 TeV

pp



p-Pb



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- $c_3\{2, |\Delta\eta|\} \sim 0$ and $c_3\{4\} \sim 0$ at high multiplicities
  - Small dependence on $|\Delta\eta|$ gap for $c_3\{2\}$
- “Mass ordering” more pronounced for small $|\Delta\eta|$ gap

Summary

- Investigate collective effects in EPOS4 and PYTHIA 8 simulations
  - Different trends for various settings
- $c_2\{2\}$ decreasing with increasing multiplicity and $|\Delta\eta|$ gap
  - Small dependence on $|\Delta\eta|$ gap
- $c_2\{4\} \sim 0$ at high multiplicities
  - Expected for Gaussian fluctuations
- Mass ordering for u_2Q_2 when a large $|\Delta\eta|$ gap is employed
  - Crossing between pions and protons u_2Q_2 in PYTHIA 8 Angantyr p-Pb simulations
    - No particle type grouping