Investigating collective effects in small collision systems using PYTHIA 8 and EPOS4 simulations

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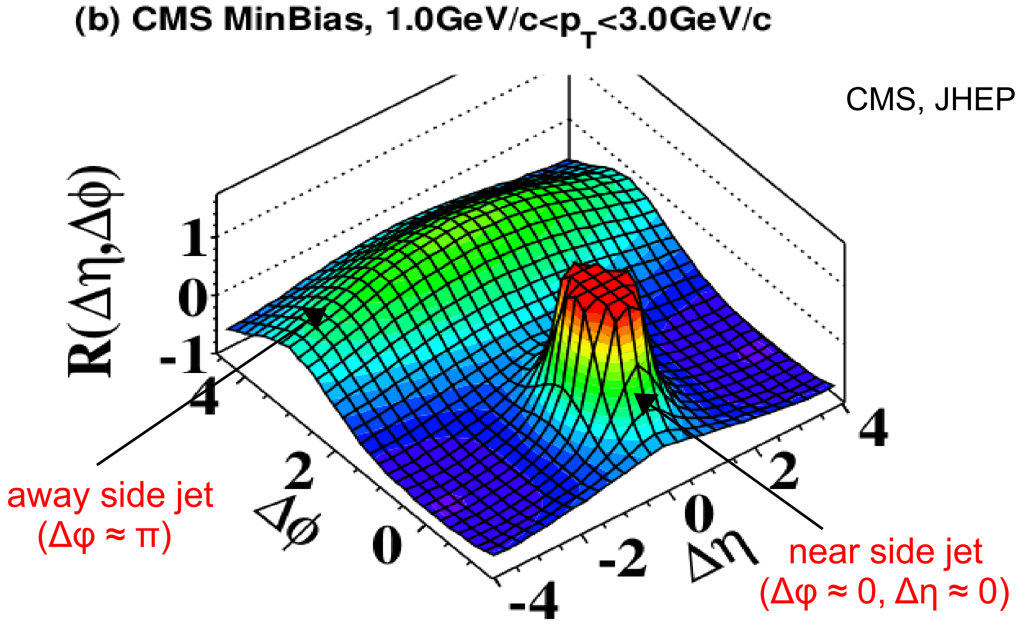
Outline

- Introducing experimental methods of flow analysis using cumulant and scalar product
- Determination of v_2 and $c_2\{2\}$, $c_2\{4\}$ for EPOS4 and PYTHIA 8 and comparing results
- Comparison of balance function analysis of both event generators

Ridge in pp: first observation



CMS, JHEP 1009 (2010) 091

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

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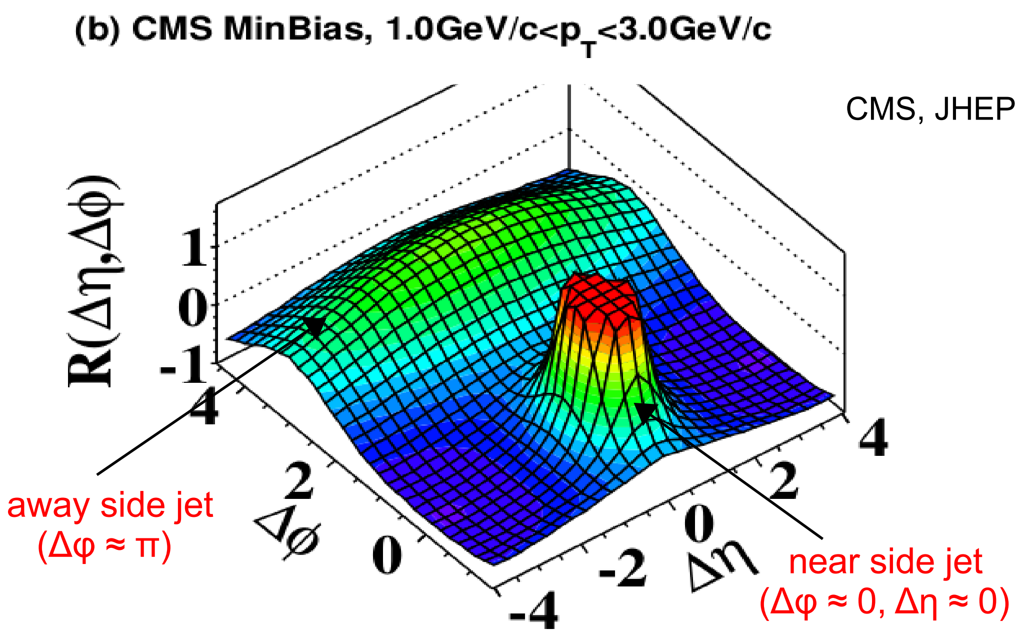

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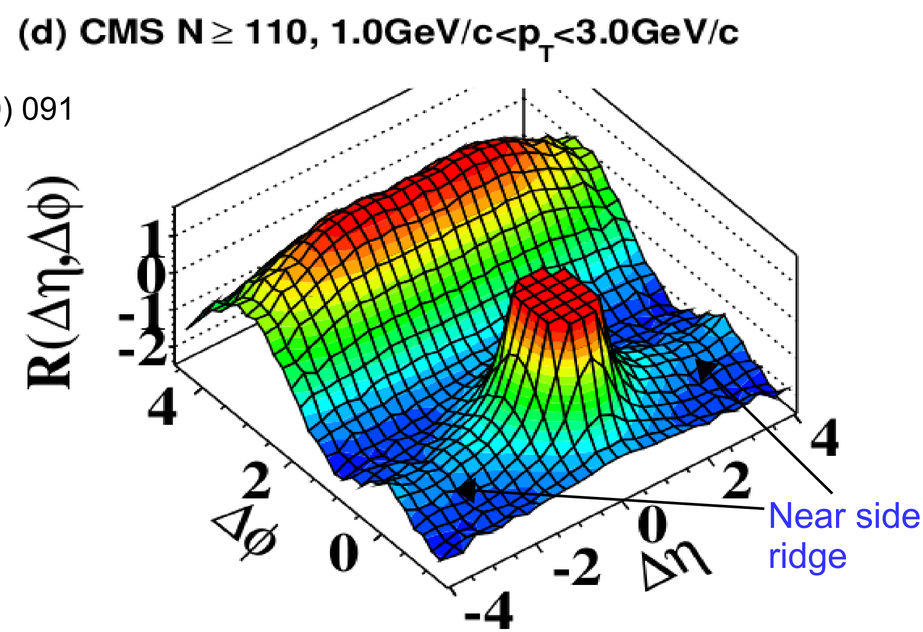

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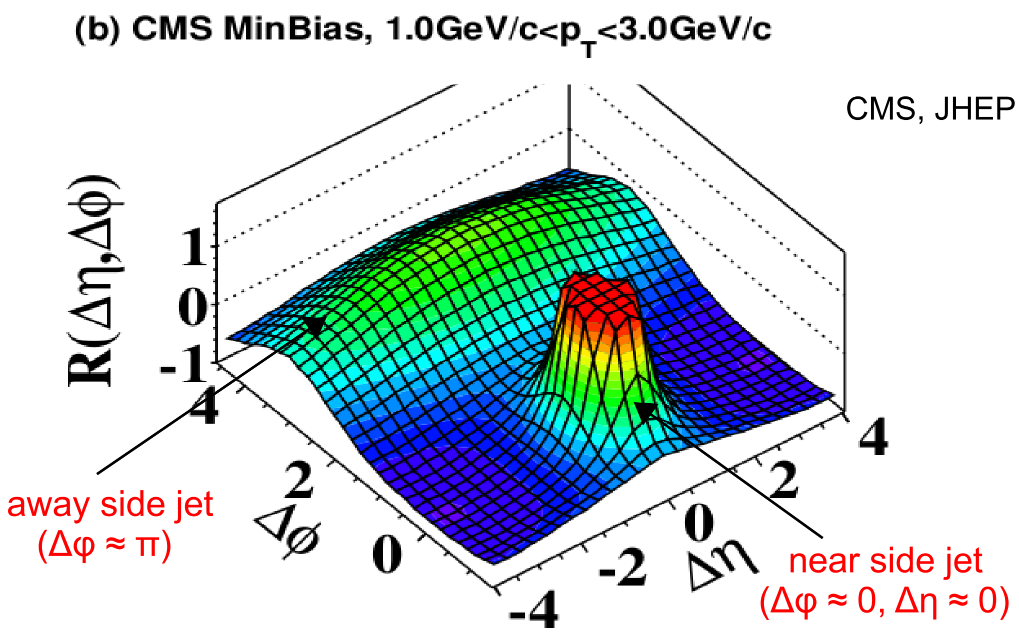
- High multiplicity pp
  - Near side ridge, typical of collective systems
    - Decomposed into Fourier harmonics

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

Ridge in pp: first observation



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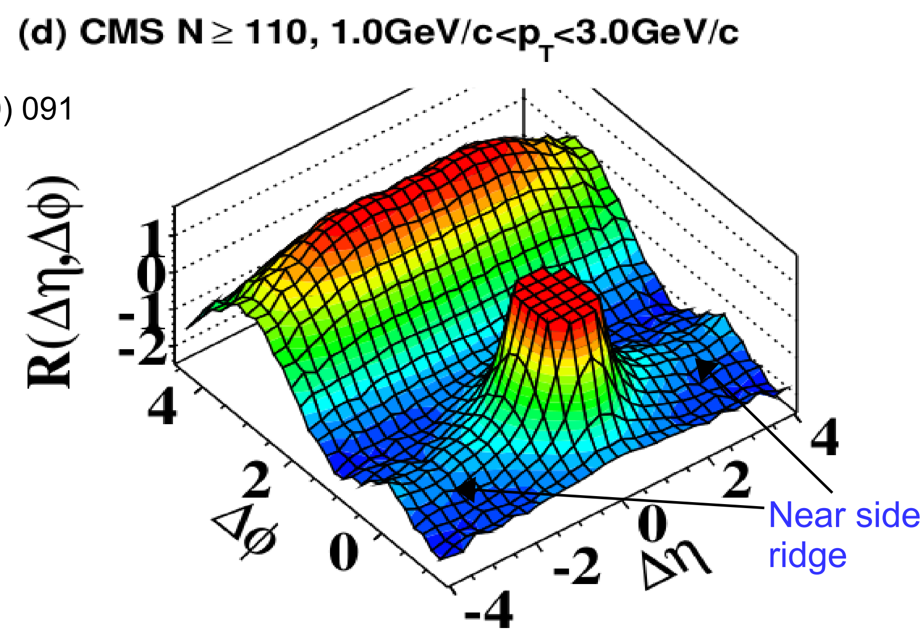

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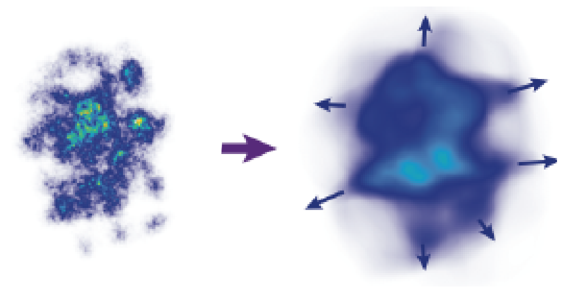
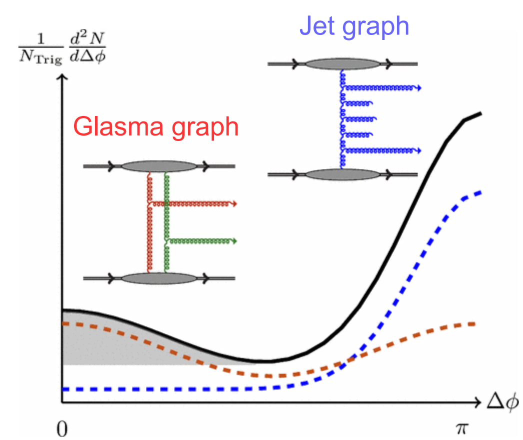
$$1+\sum_{n=1}^{\infty} 2 v_n \cos\left(n\left(\varphi-\Psi_n\right)\right)$$

What is the origin of these collective effects?

Sources of collectivity

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





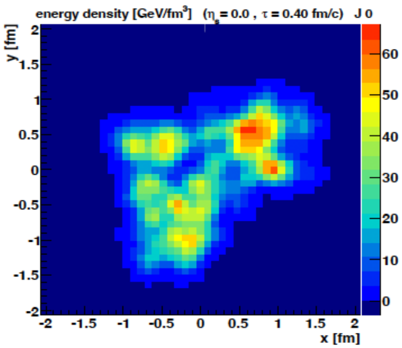
- Initial state effects
  - Initial momentum anisotropies from initial interactions
    - Color Glass Condensate (CGC) Glasma
    - Color-field domains
    - Numerical solutions

How to disentangle different regimes?

Our approach: macroscopic vs microscopic models

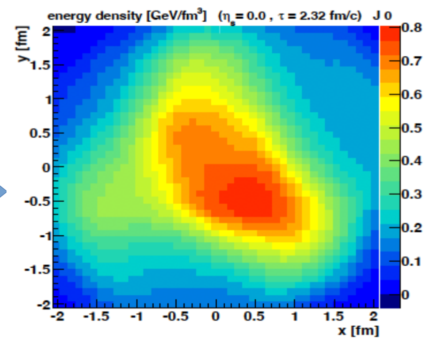
C. Bierlich et al., arXiv: 2203.11601

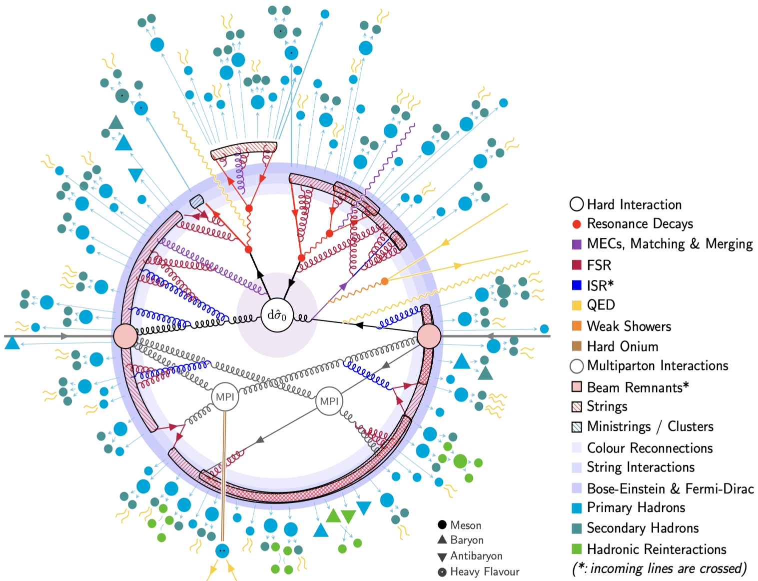
K. Werner, arXiv: 2306.10277



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

Transport equation





- Macroscopic model: EPOS4
  - Core–corona model with statistical hadronization
  - Collective effects from hydrodynamical evolution of the medium
- Microscopic model: PYTHIA 8
  - QCD strings with LUND fragmentation
  - Collective effects from new processes
    - Color reconnection, rope hadronization, ...

Experimental methods

- Scalar product (SP) method

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

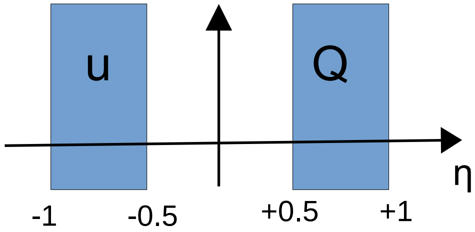
Particles of Interest (POI)

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

Reference Particles (RPs)

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

S. Voloshin et al., arXiv:0809.2949



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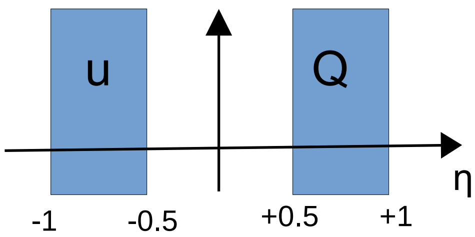
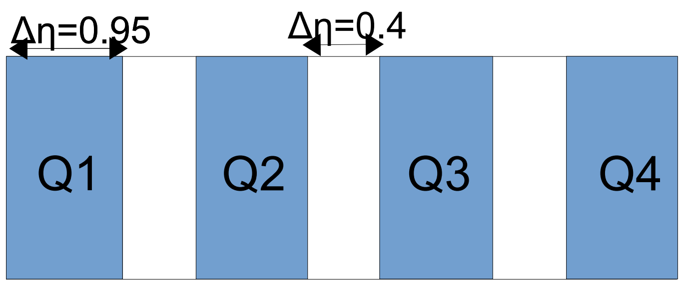


- Cumulant method
  - 2- and 4-particle azimuthal correlations for an event
  - Averaging over all events → 2nd and 4th order cumulants

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



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

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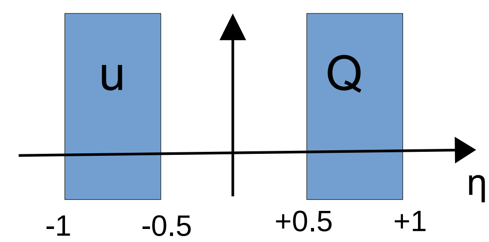

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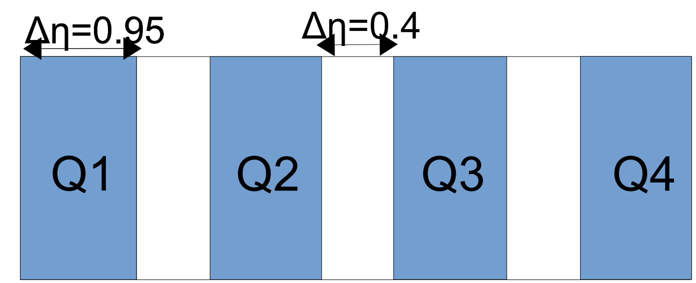
$$c_n\{4\} = \langle\langle 4 \rangle\rangle - 2\langle\langle 2 \rangle\rangle^2 = -v_n^4$$



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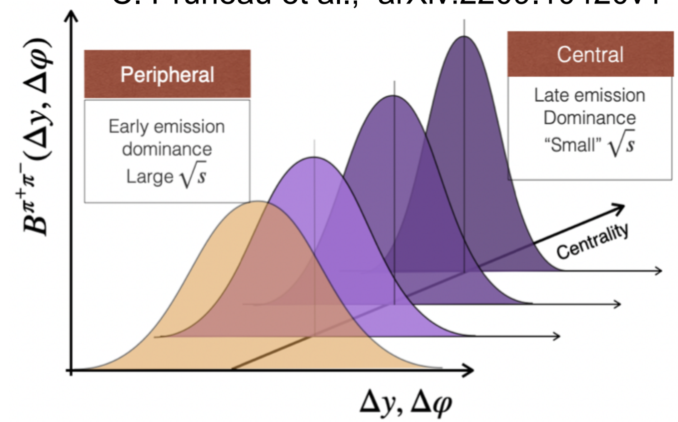
- Balance function

$$A_2^{\alpha|\beta}(y_1, y_2) = \frac{\rho_2^{\alpha\beta}(y_1, y_2)}{\rho_1^{\beta}(y_2)} - \rho_1^{\alpha}(y_1)$$

$$B^{\alpha|\bar{\beta}}(y_1|y_2) = A_2^{\alpha|\bar{\beta}}(y_1|y_2) - A_2^{\bar{\alpha}|\bar{\beta}}(y_1|y_2)$$
$$B^{\bar{\alpha}|\beta}(y_1|y_2) = A_2^{\bar{\alpha}|\beta}(y_1|y_2) - A_2^{\alpha|\beta}(y_1|y_2)$$

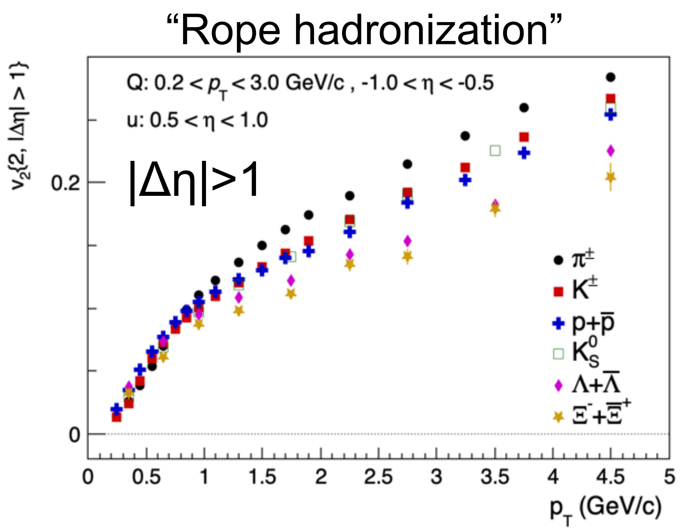
C. Pruneau et al., arXiv:2209.10420v1

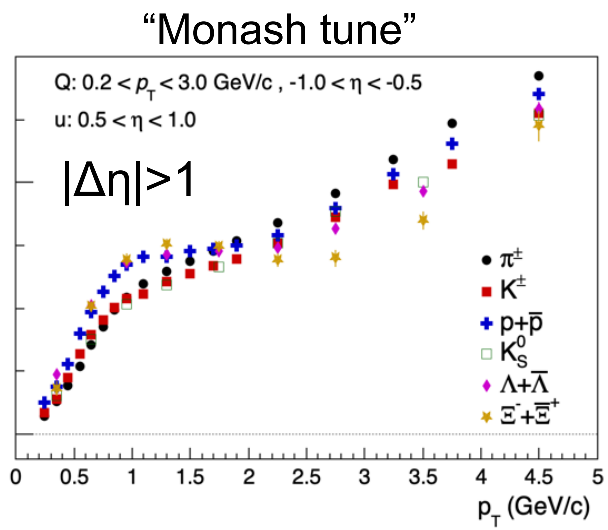


v_n in pp collisions @ 13.6 TeV

- PYTHIA 8
  - Rope hadronization https://gitlab.com/Pythia8/releases/-/issues/80
  - Monash tune
- EPOS4
  - Full simulation (core+corona+hadronic afterburner)

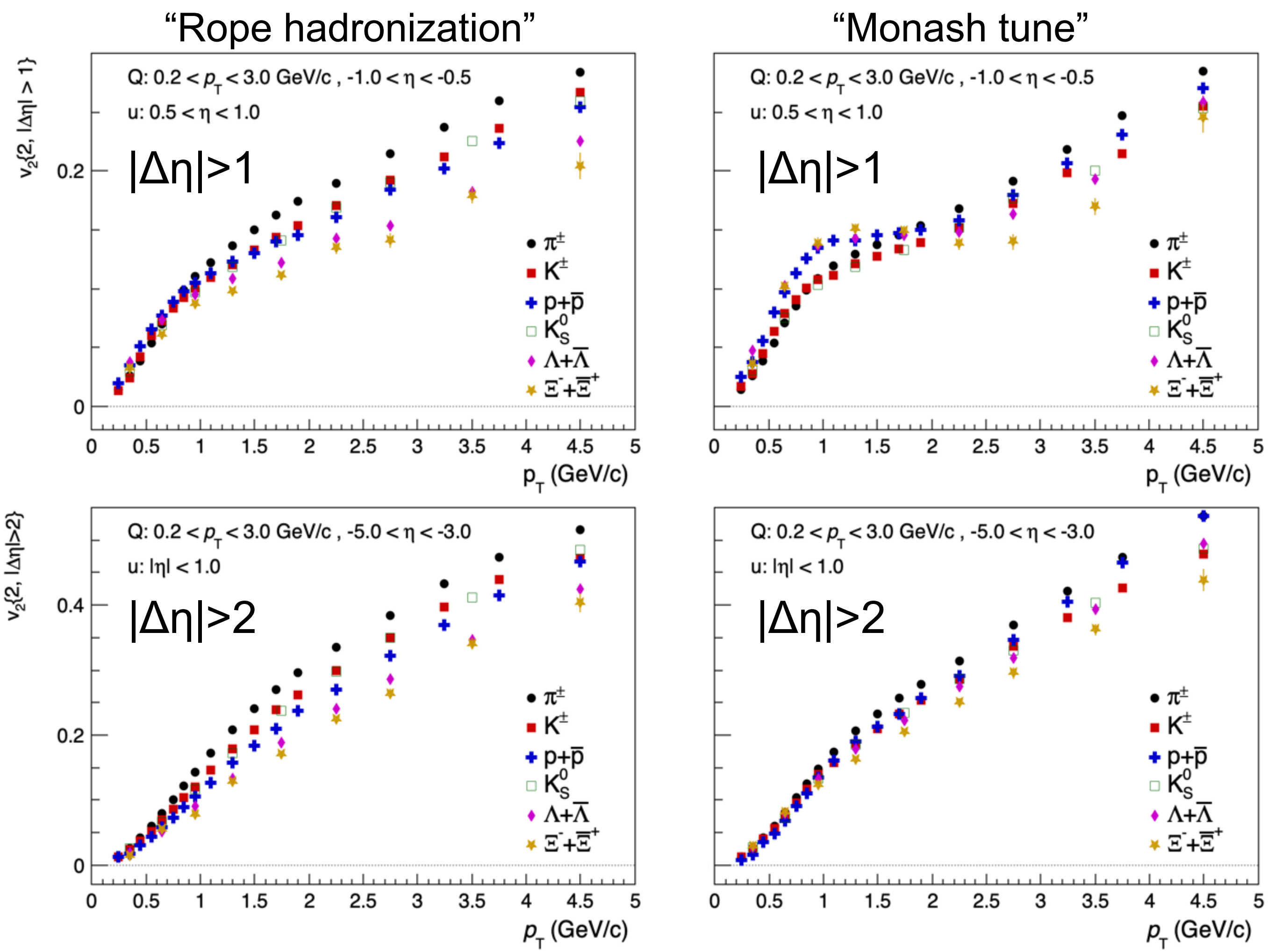
PID v_2





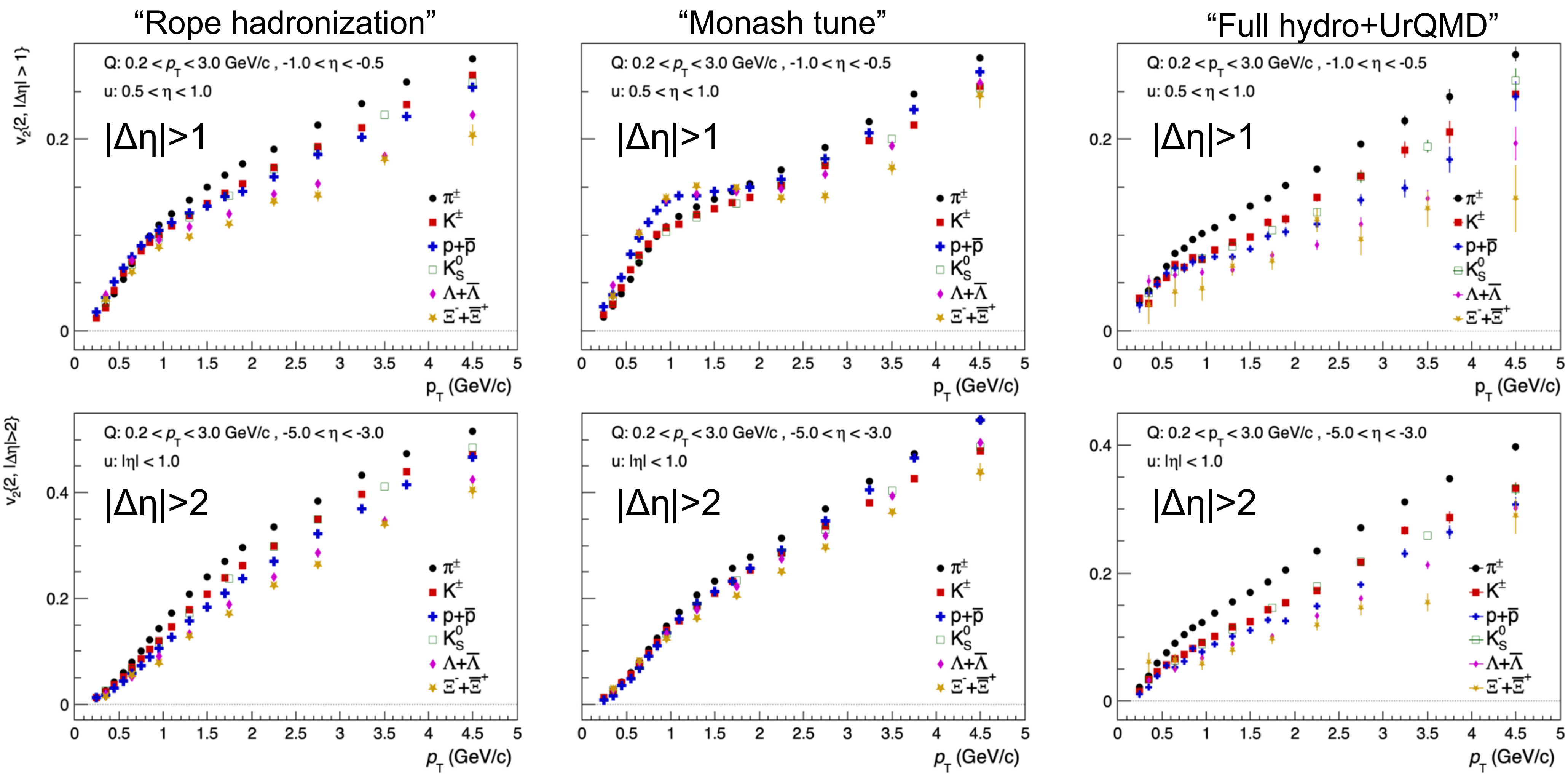
- PYTHIA 8
    - Mass ordering broken for |Δη|>1

PID v_2



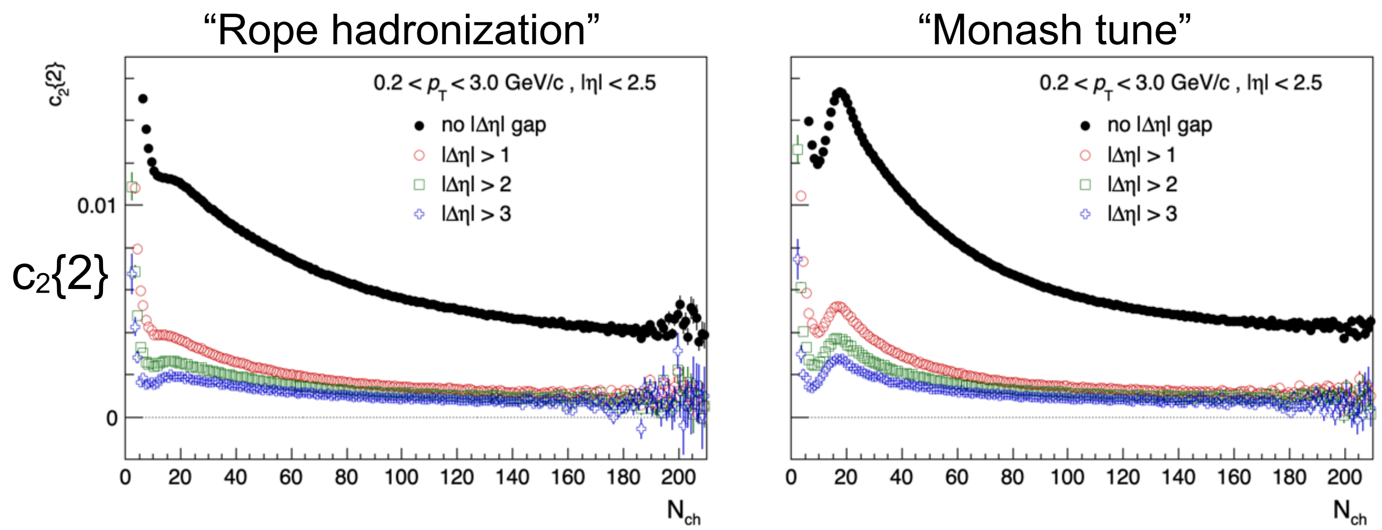
- PYTHIA 8
  - Mass ordering broken for |Δη|>1
  - Small mass ordering for |Δη|>2
    - More pronounced for rope hadronization
  - No particle type grouping

PID v_2



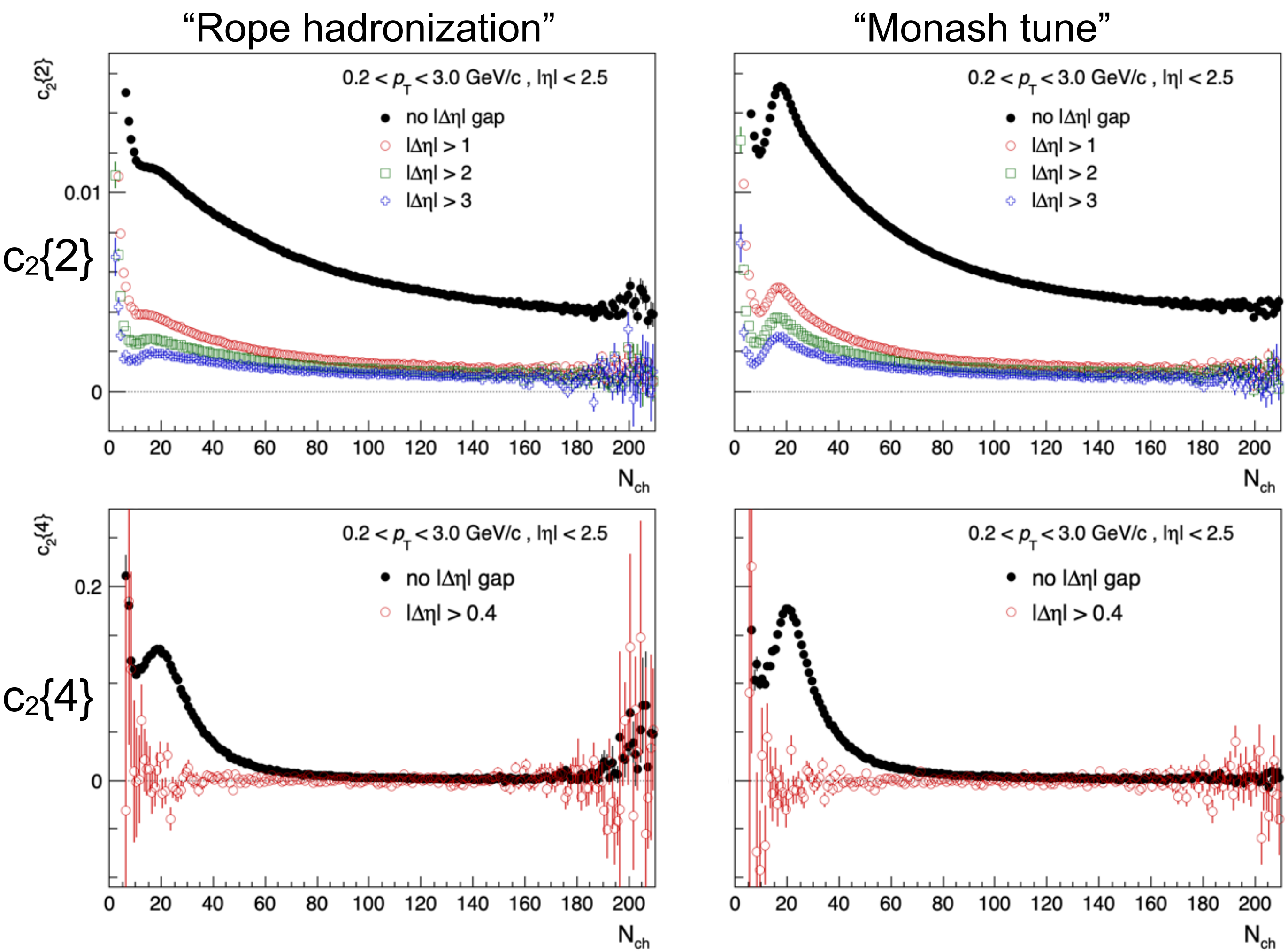
- PYTHIA 8
  - Mass ordering broken for |Δη|>1
  - Small mass ordering for |Δη|>2
    - More pronounced for rope hadronization
  - No particle type grouping
- EPOS4
  - Different trends than in PYTHIA
    - Influenced by core and hadronic afterburner (see backup)

$c_2\{2\}$ and $c_2\{4\}$



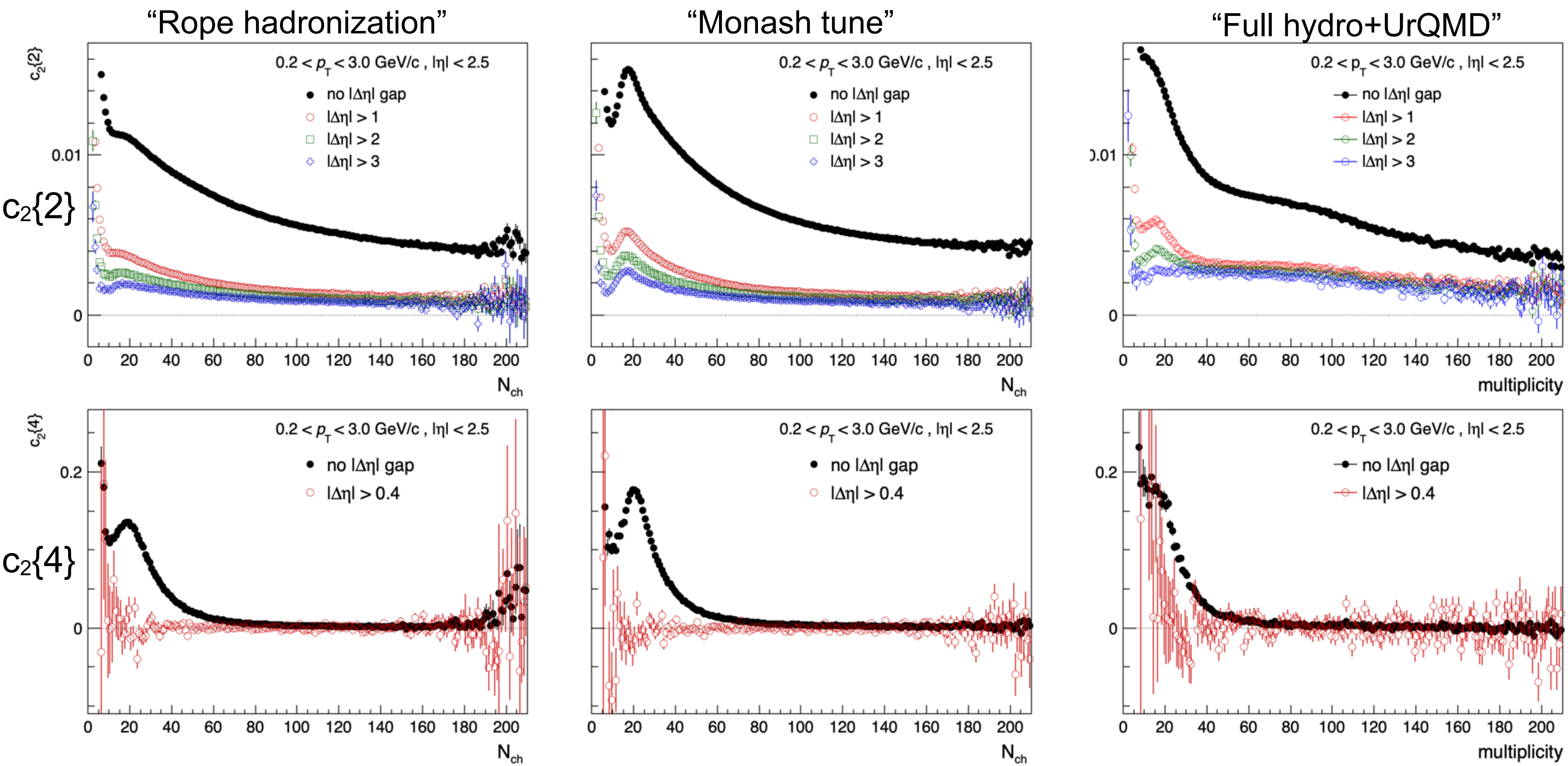
- $c_2\{2\}$ > 0 at high multiplicities
  - Small dependence on |Δη| gap

$c_2\{2\}$ and $c_2\{4\}$



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

$c_2\{2\}$ and $c_2\{4\}$



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

- Different trends in EPOS than in PYTHIA
  - More pronounced at low multiplicities

Balance Function in pp collisions @ 13.6 TeV

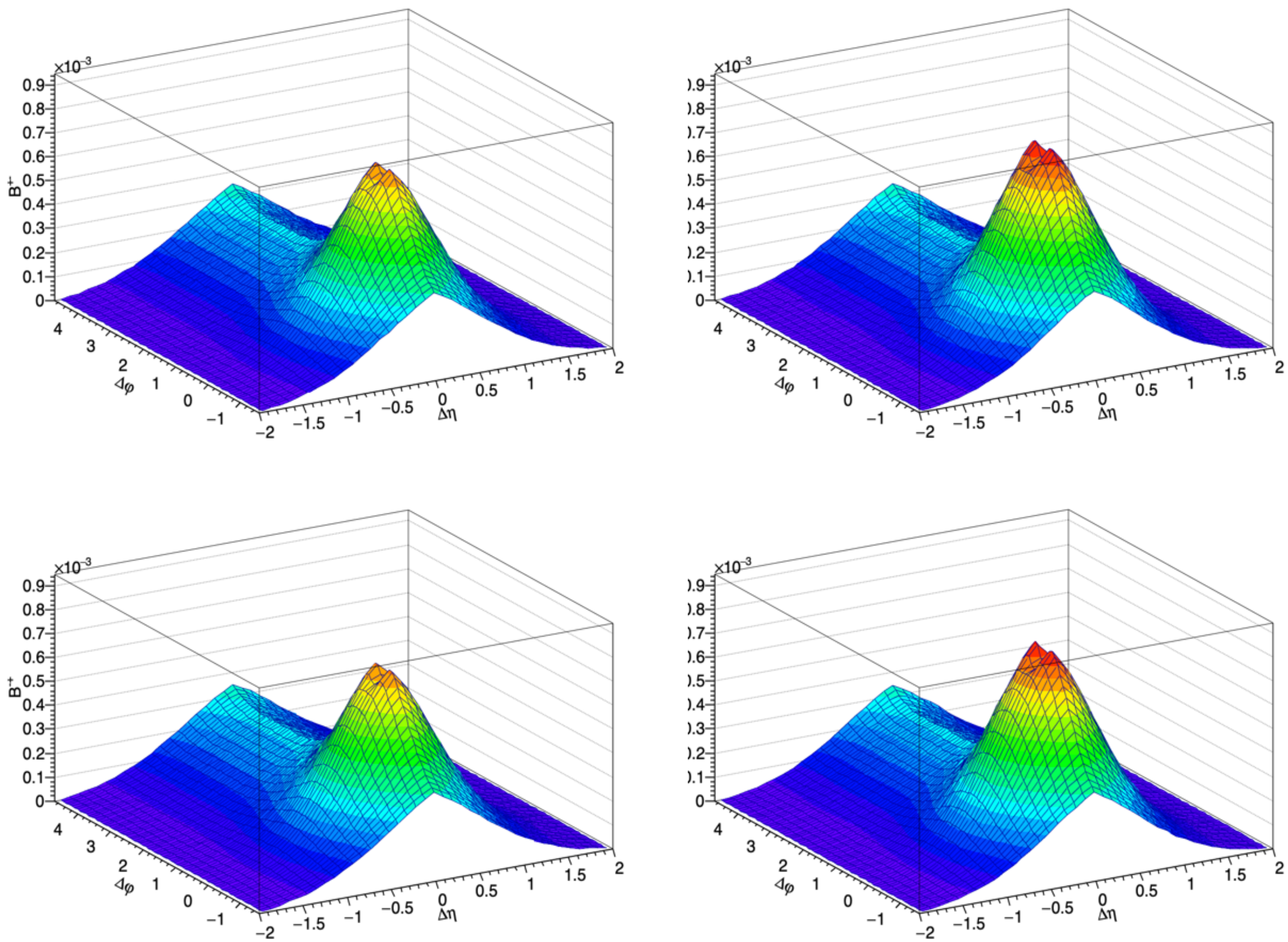
- PYTHIA 8
  - Rope hadronization https://gitlab.com/Pythia8/releases/-/issues/80
  - Monash tune
- EPOS4
  - Full simulation (core+corona+hadronic afterburner)

Balance Function

"Rope hadronization" | "Monash tune"

B^{+-}

B^{-+}



Integral definition:

$$I^{\alpha\bar{\beta}} = \frac{\langle N_2^{\alpha\bar{\beta}} \rangle}{\langle N_1^{\bar{\beta}} \rangle} - \frac{\langle N_2^{\bar{\alpha}\bar{\beta}} \rangle}{\langle N_1^{\bar{\beta}} \rangle}$$

$$I^{\bar{\alpha}\beta} = \frac{\langle N_2^{\bar{\alpha}\beta} \rangle}{\langle N_1^{\beta} \rangle} - \frac{\langle N_2^{\alpha\beta} \rangle}{\langle N_1^{\beta} \rangle}$$

Integral value B^{+-} : 0.469 0.490

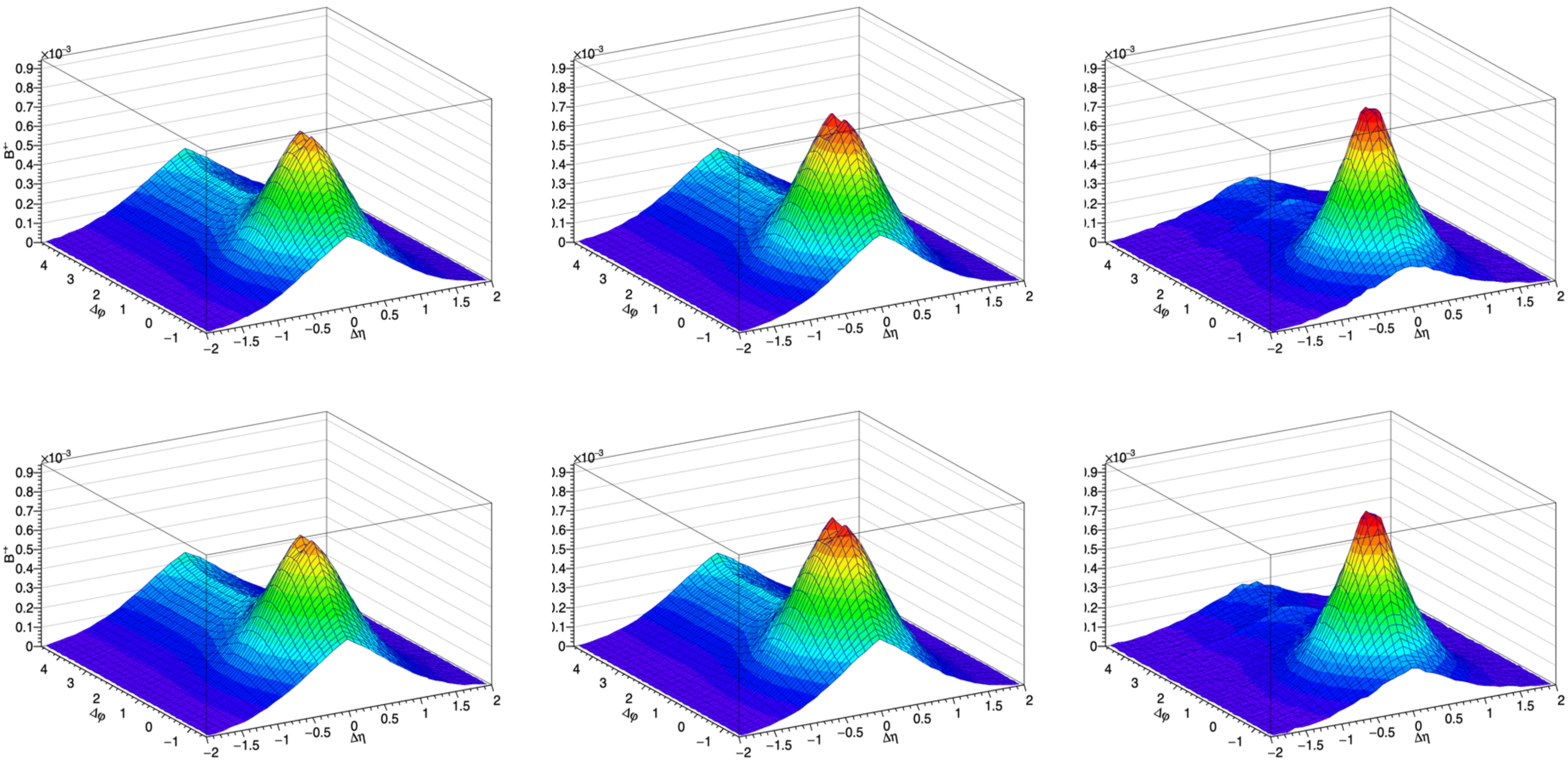
Integral value B^{-+} : 0.474 0.486

Balance Function

	"Rope hadronization"	"Monash tune"	"Full hydro+UrQMD"

B^{+-}

B^{-+}

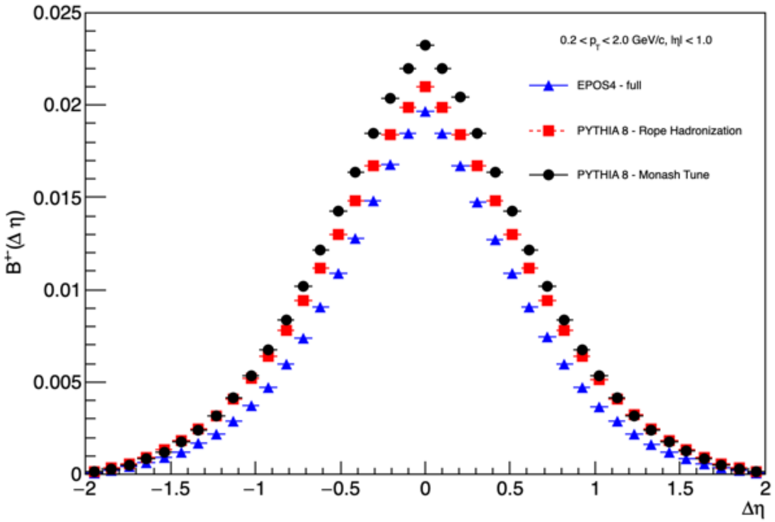


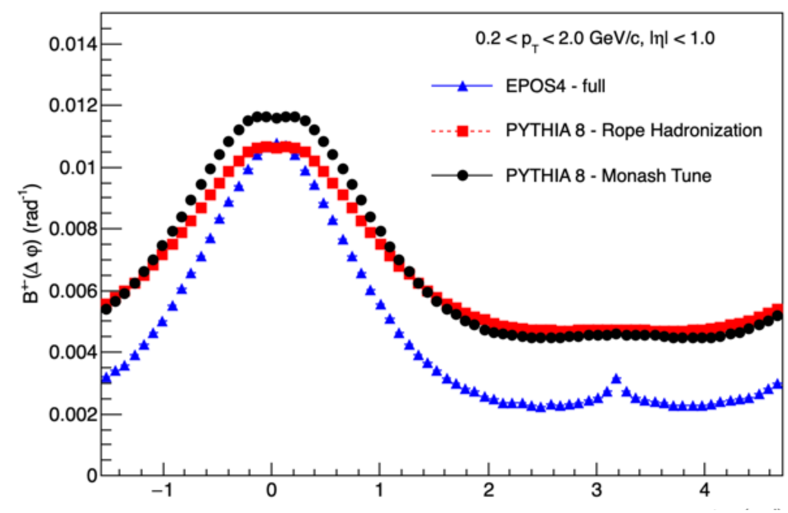
	"Rope hadronization"	"Monash tune"	"Full hydro+UrQMD"
Integral value B^{+-} :	0.469	0.490	0.344
Integral value B^{-+} :	0.474	0.486	0.336

Balance Function

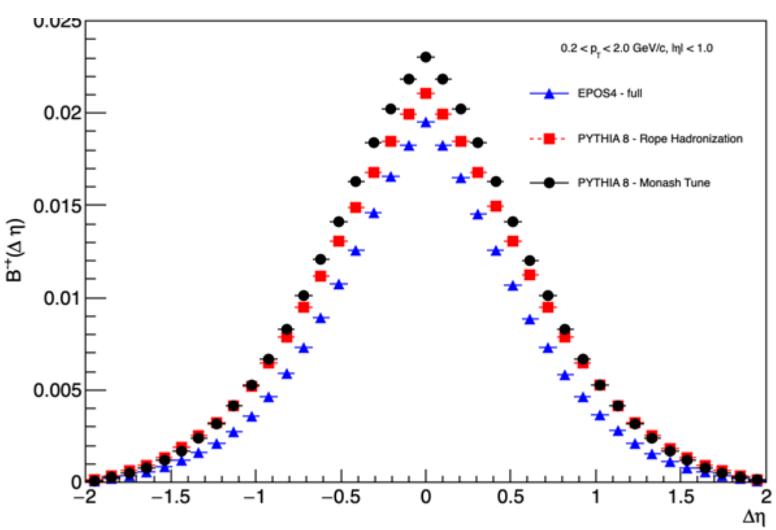
B(Δη) | B(Δϕ)

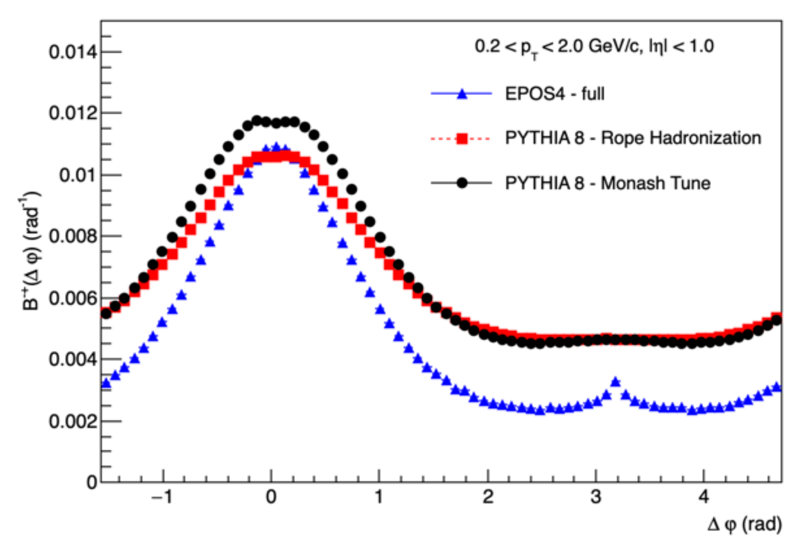
B+-





B-+





Different trends in EPOS than in PYTHIA

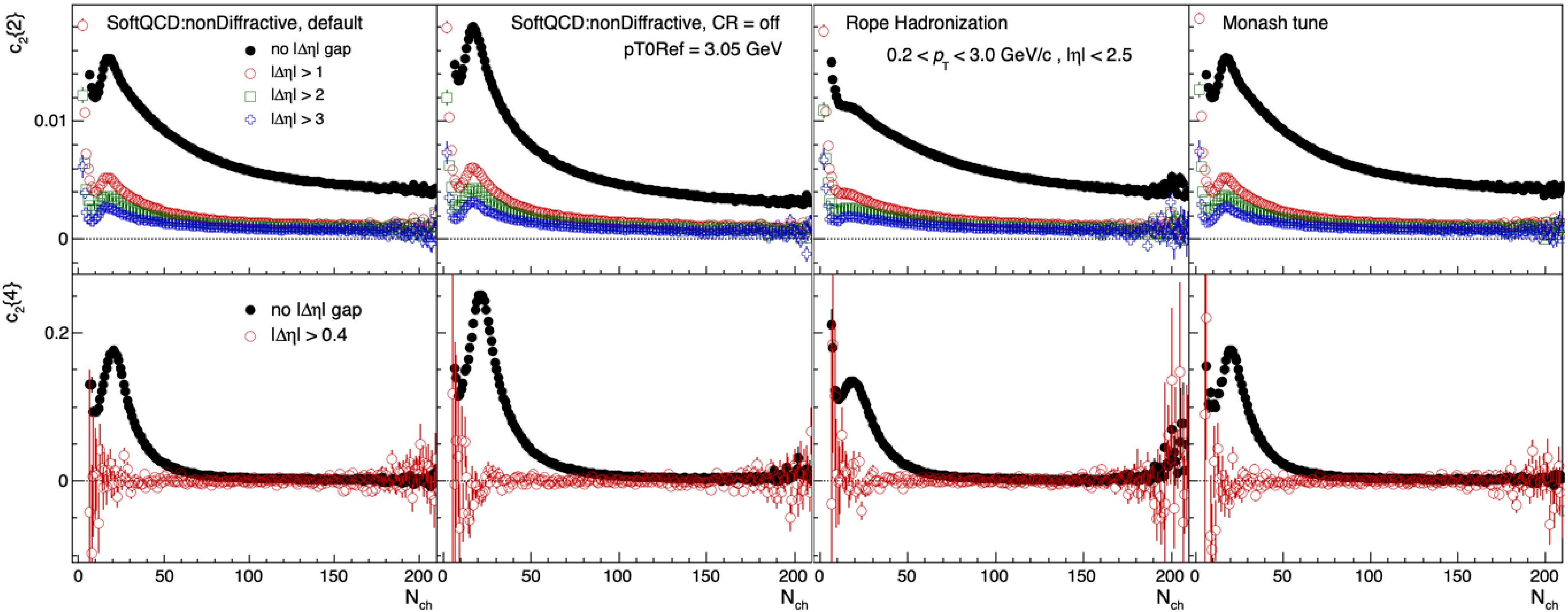
Summary

- Investigate collective effects in EPOS4 and PYTHIA 8
  - 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
- PID v_2: mass ordering for large $|\Delta\eta|$ gap
  - No particle type grouping
- Balance function: different trends in away side

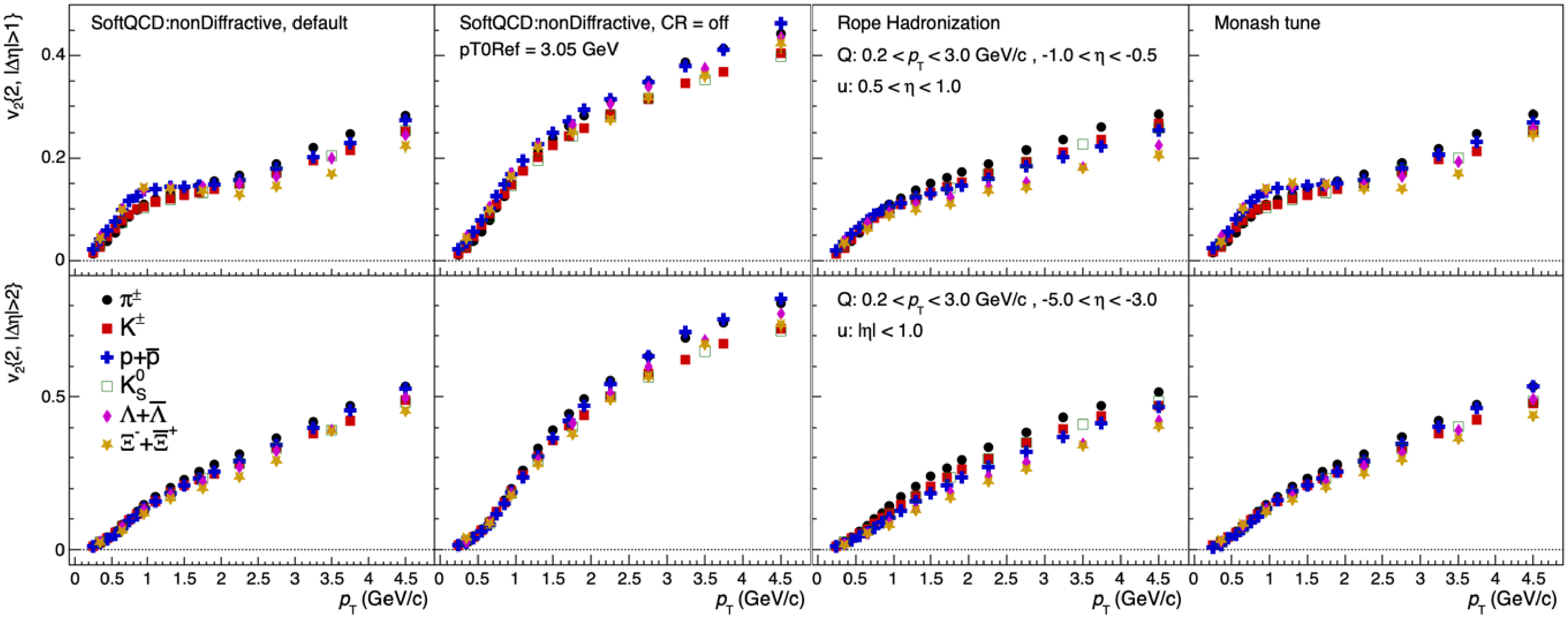
Thank you!

Backup

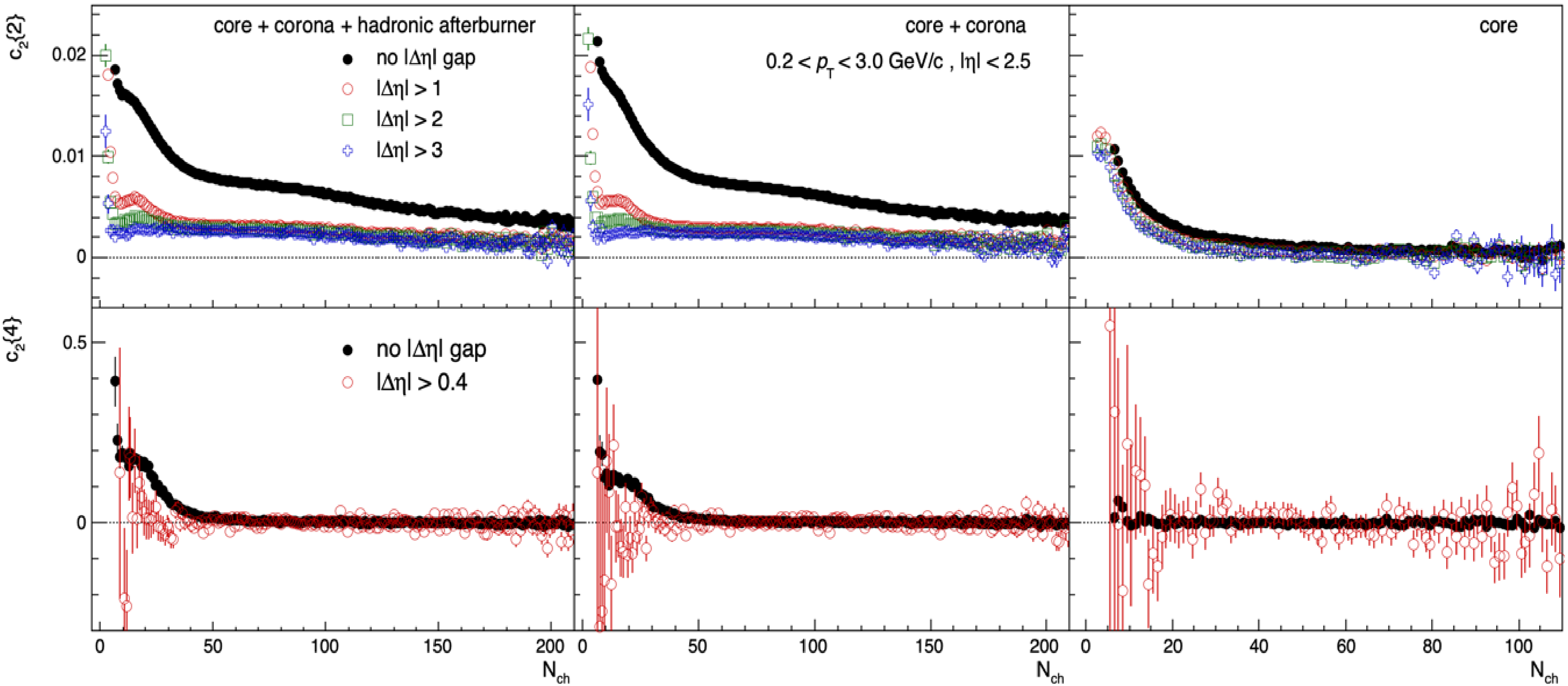
$c_2\{2\}$ and $c_2\{4\}$ in PYTHIA 8



PID v_2 in PYTHIA 8



$c_2\{2\}$ and $c_2\{4\}$ in EPOS4



PID v_2 in EPOS4