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

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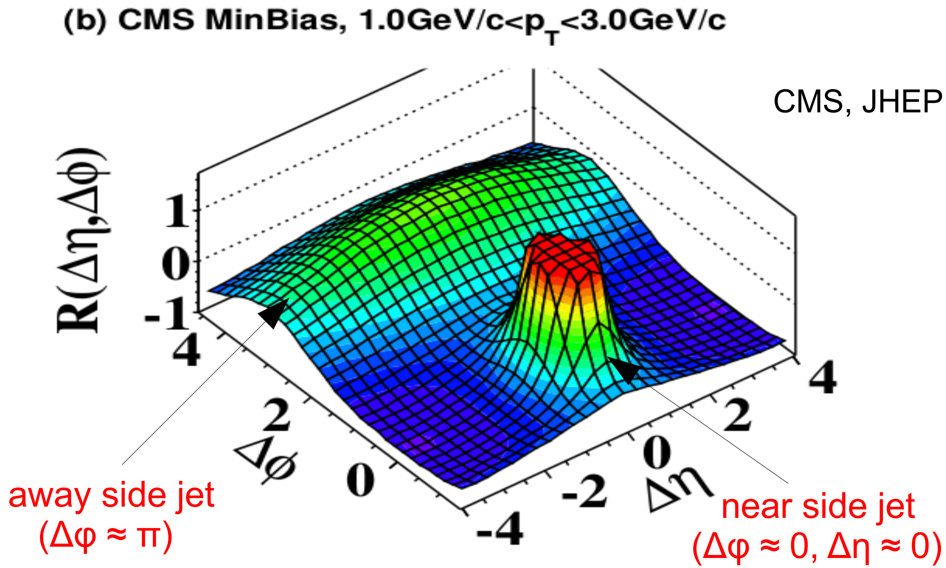
V. Gonzalez, C. Pruneau

14th International Workshop on Multiple Parton Interactions at the LHC

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

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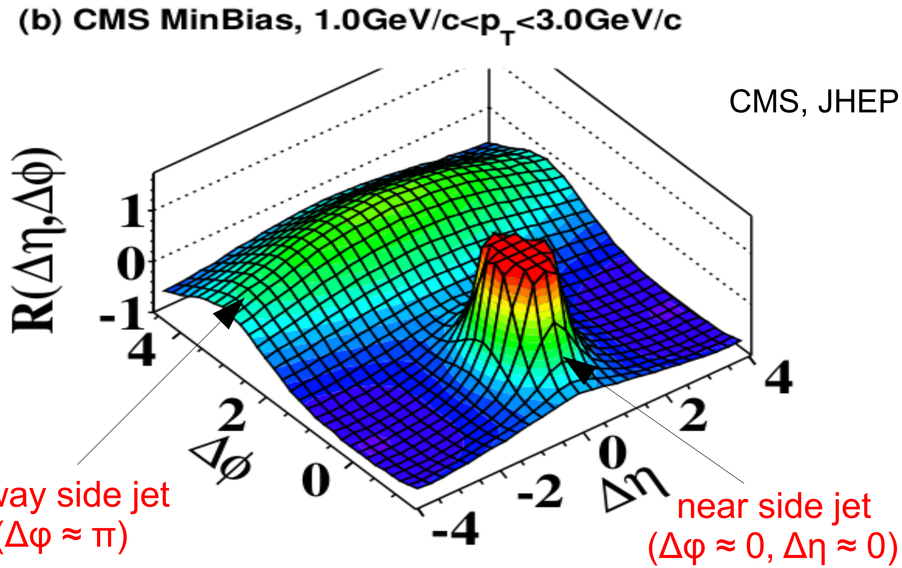
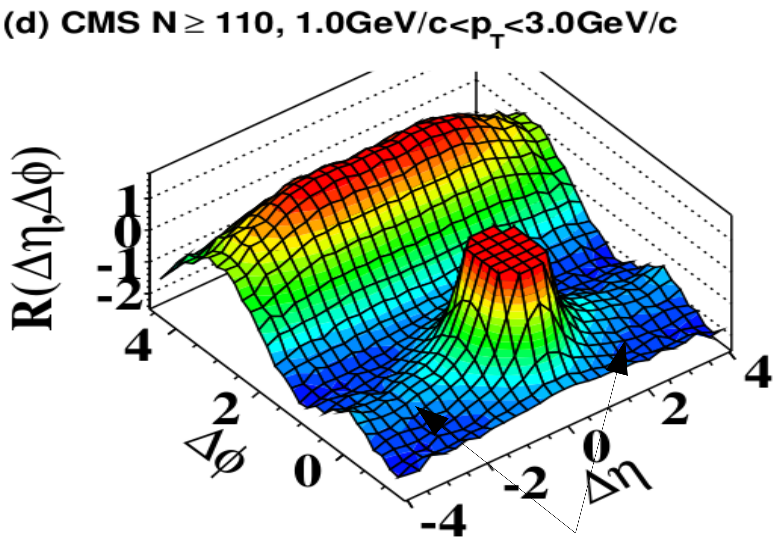


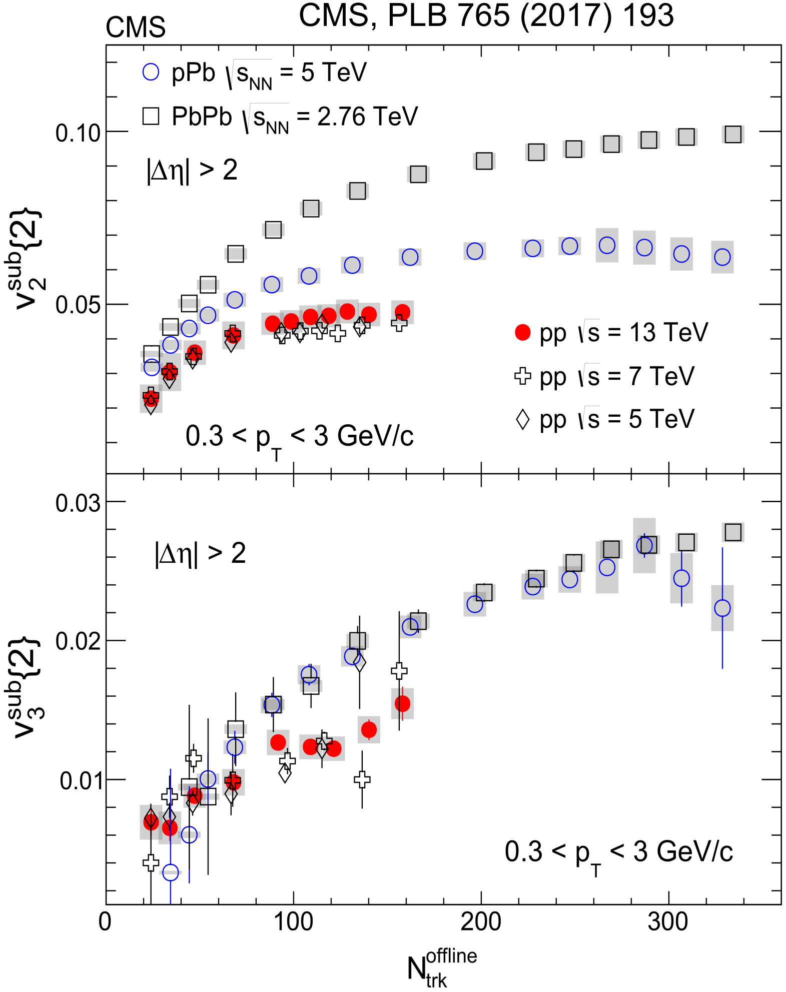


- Minimum bias pp
  - Non-flow contributions
    - Near side jet peak (+ resonances, HBT effects)
    - Recoil jet in away side
- High multiplicity pp
  - Near side ridge, typical of collective systems
    - Decomposed into Fourier harmonics v_n

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

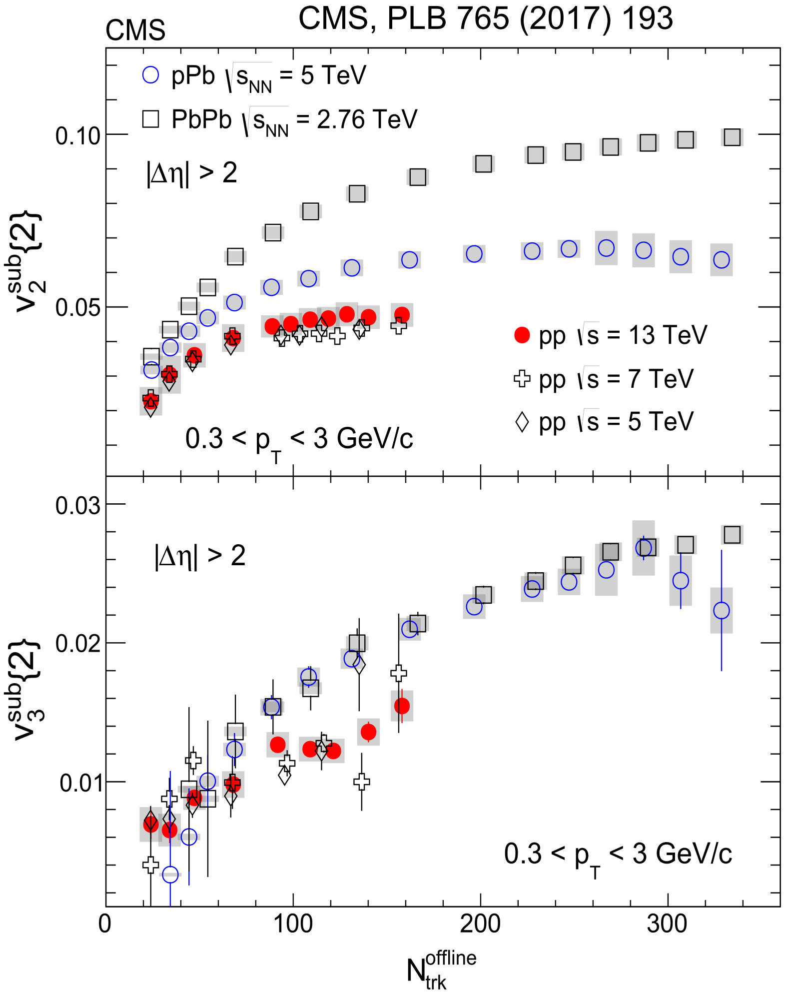
v_n coefficients

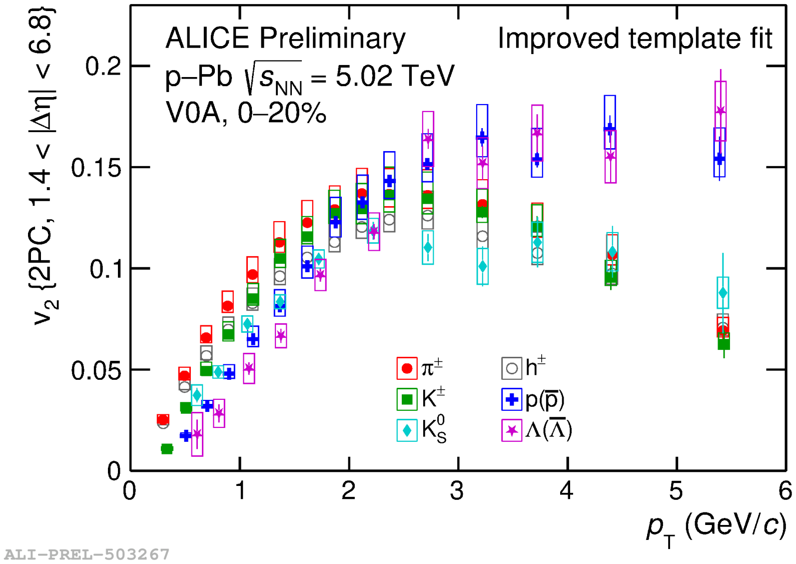
CMS, PLB 765 (2017) 193



- v_n dependence on collision system but not on energy

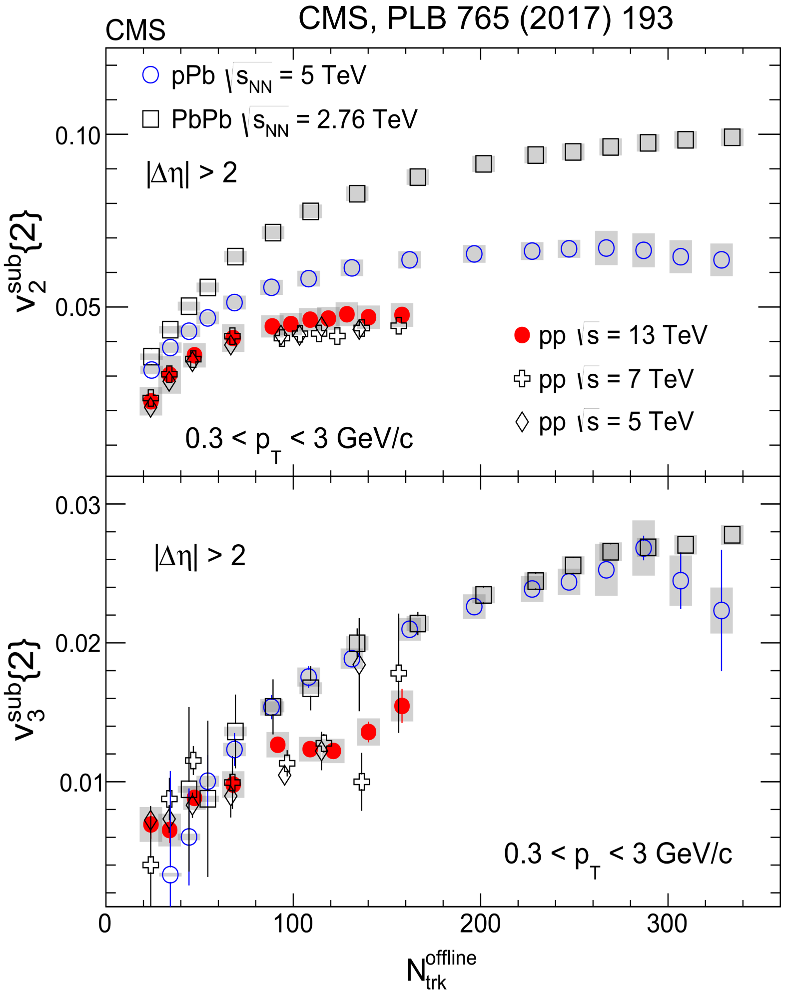
v_n coefficients

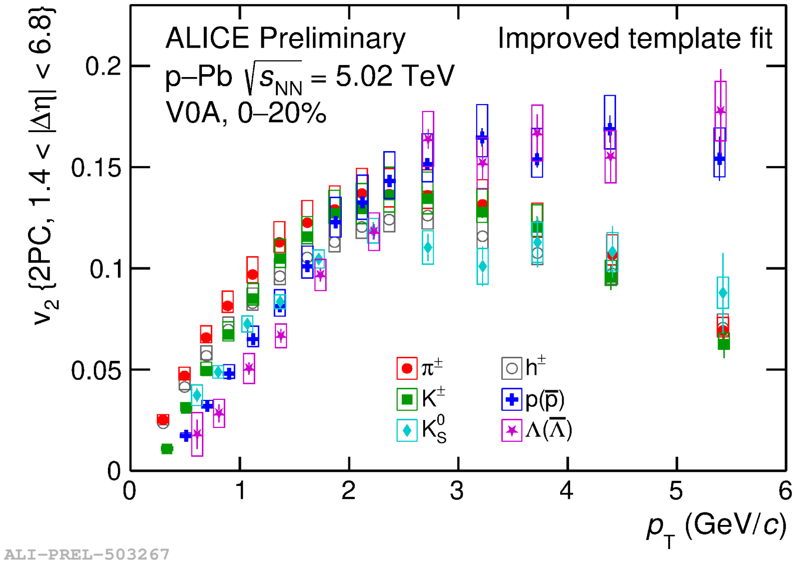




- v_n dependence on collision system but not on energy
- Mass ordering observed in high multiplicity p-Pb and pp collisions
  - Test particle type dependence at high p_T

v_n coefficients



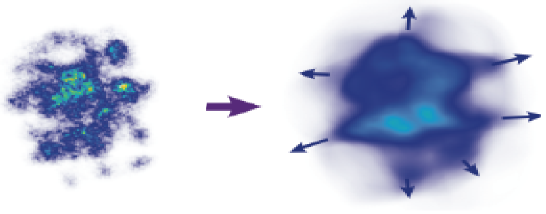


- v_n dependence on collision system but not on energy
- Mass ordering observed in high multiplicity p-Pb and pp collisions
  - Test particle type dependence at high p_T

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



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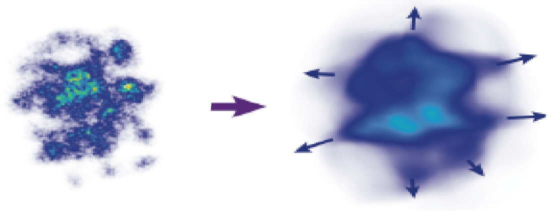
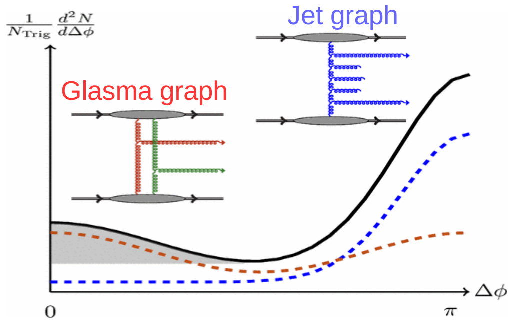


- Initial state effects
  - Initial momentum anisotropies from initial interactions
    - Color Glass Condensate (CGC) Glasma
    - Color-field domains



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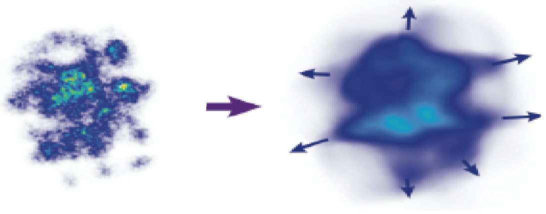

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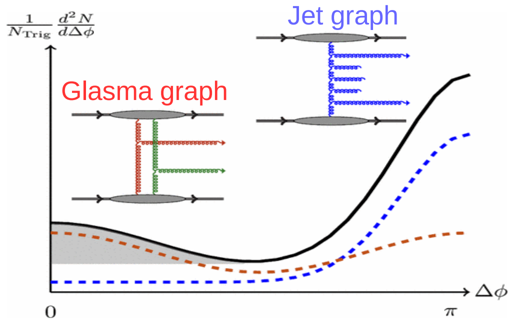
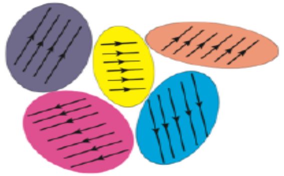
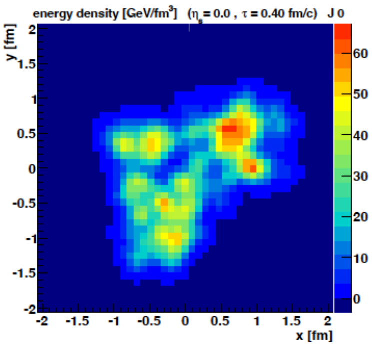




How to disentangle different regimes?

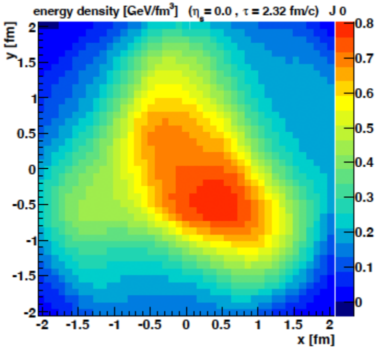
Our approach: macroscopic vs microscopic models

K. Werner, arXiv: 2306.10277



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

Transport equation



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

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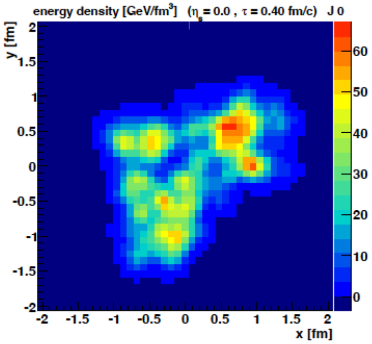

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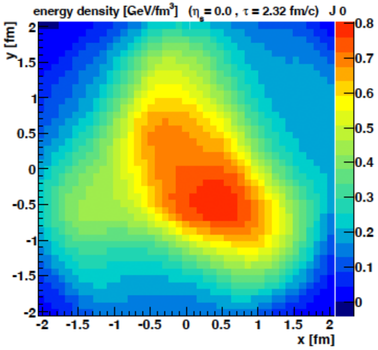
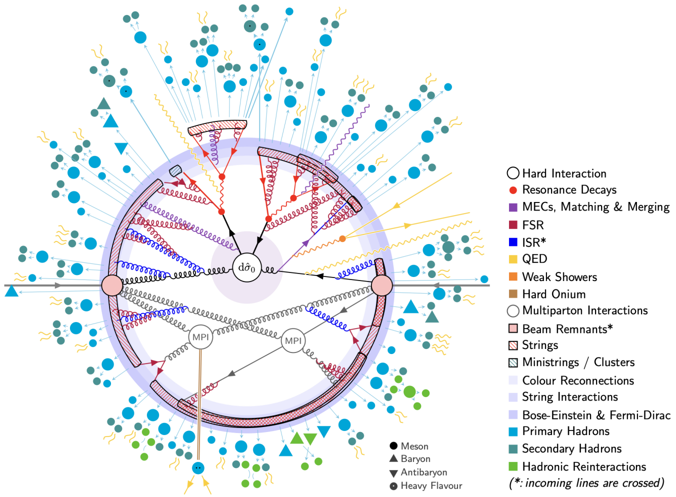


C. Bierlich et al., arXiv: 2203.11601



- Macroscopic model: 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: flow

- Scalar product (SP) method

S. Voloshin et al., arXiv:0809.2949

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

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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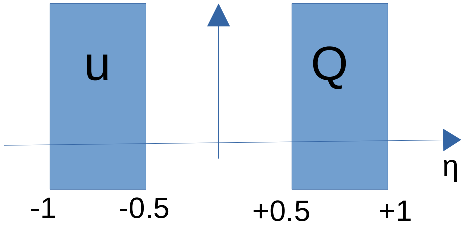

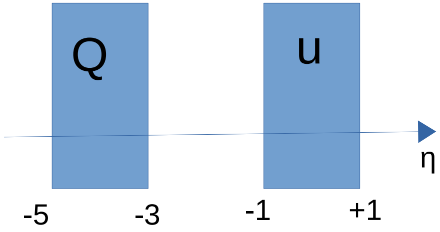

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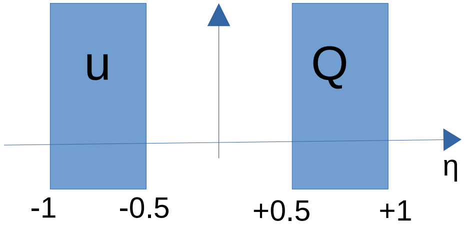

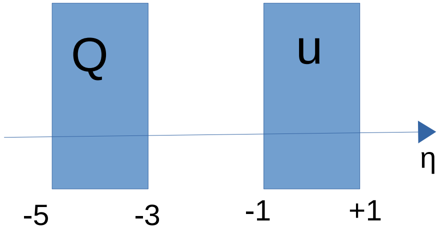

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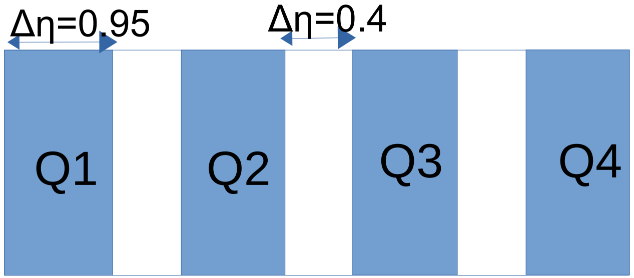
- Cumulants
  - 2- and 4-particle azimuthal correlations for an event

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

  - 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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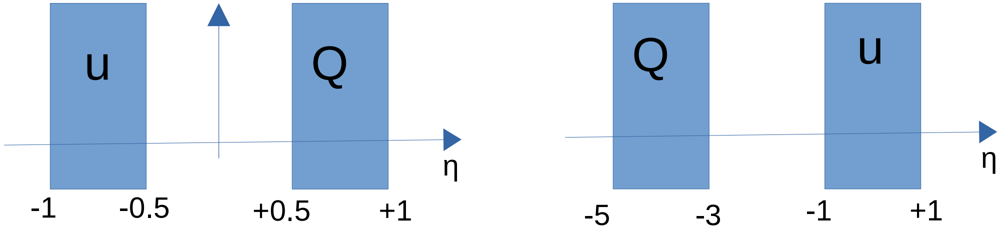

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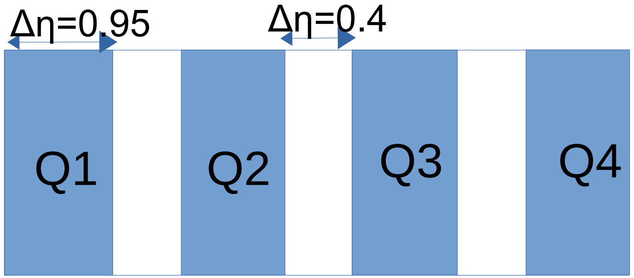

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- Methods have different sensitivity to non-flow and fluctuations

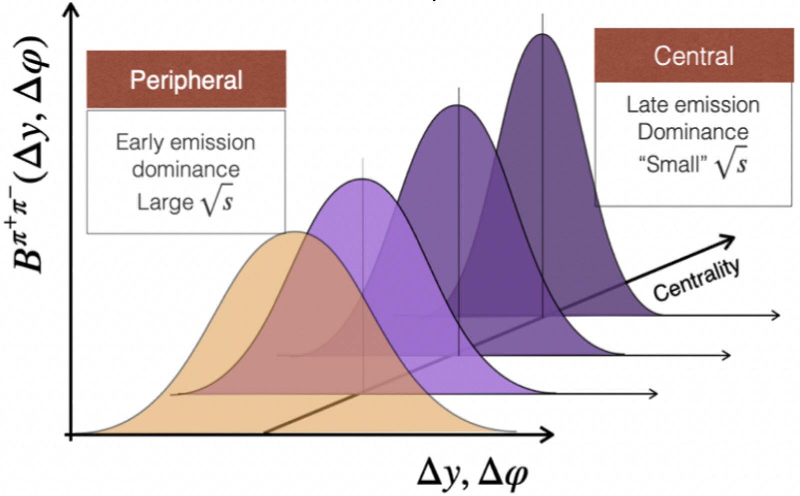
Experimental methods: Balance function

Balance function gives insight into charged particle production

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

$$\rho_1(\eta, \varphi) = \frac{\mathrm{d}^2 N}{\mathrm{d}\eta\, \mathrm{d}\varphi} \qquad \rho_2(\Delta\eta, \Delta\varphi) = \frac{\mathrm{d}^2 N}{\mathrm{d}\Delta\eta\, \mathrm{d}\Delta\varphi}$$

C. Pruneau et al., arXiv:2209.10420



Cumulant based method

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

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

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

- Integrals provide information about each balancing charge
- Possibility to probe particle production mechanisms for different models

v_n in pp and p-Pb collisions

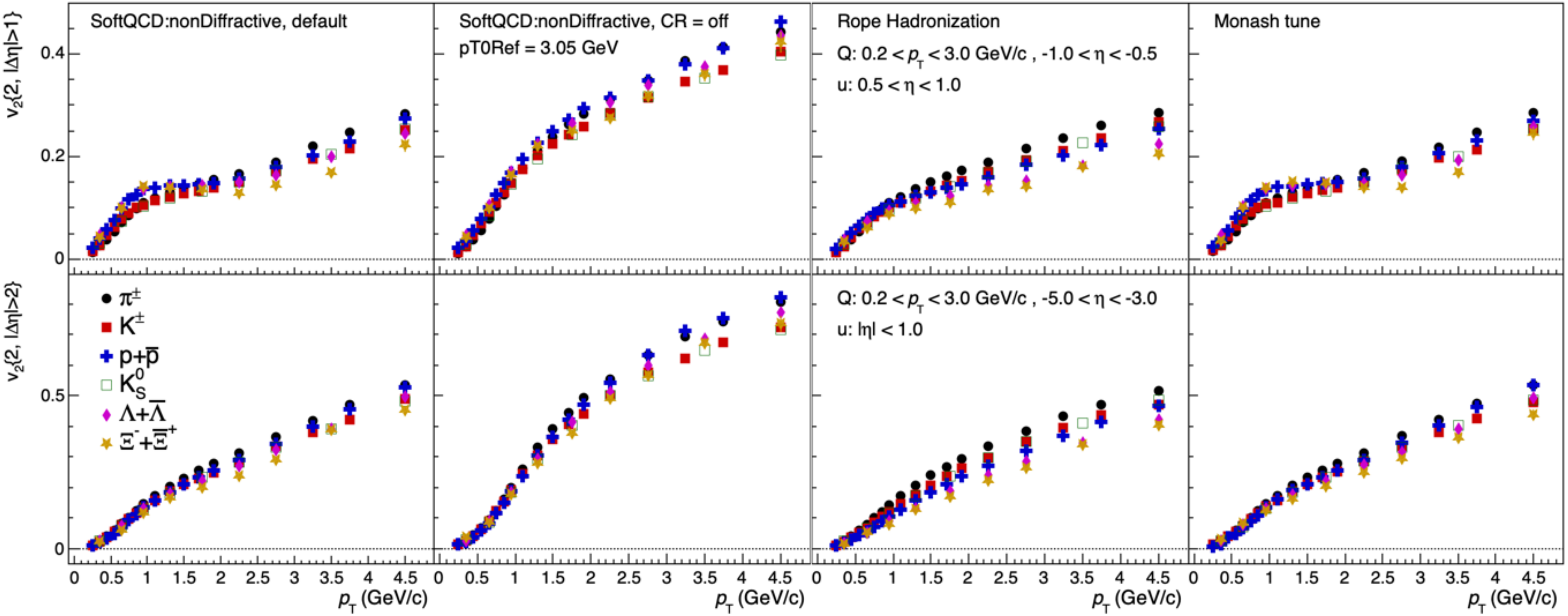
- PYTHIA 8
  - pp collisions @ 13.6 TeV
    - Default
    - Default – no CR
    - Rope hadronization   https://gitlab.com/Pythia8/releases/-/issues/80
    - Monash tune
  - p-Pb collisions @ 5.02 TeV
    - Angantyr

- EPOS4
  - pp collisions @ 13.6 TeV
    - core+corona+hadronic afterburner (full simulation)
    - core+corona
    - core

PYTHIA 8 pp collisions: PID v_2

|Δη|>1

|Δη|>2

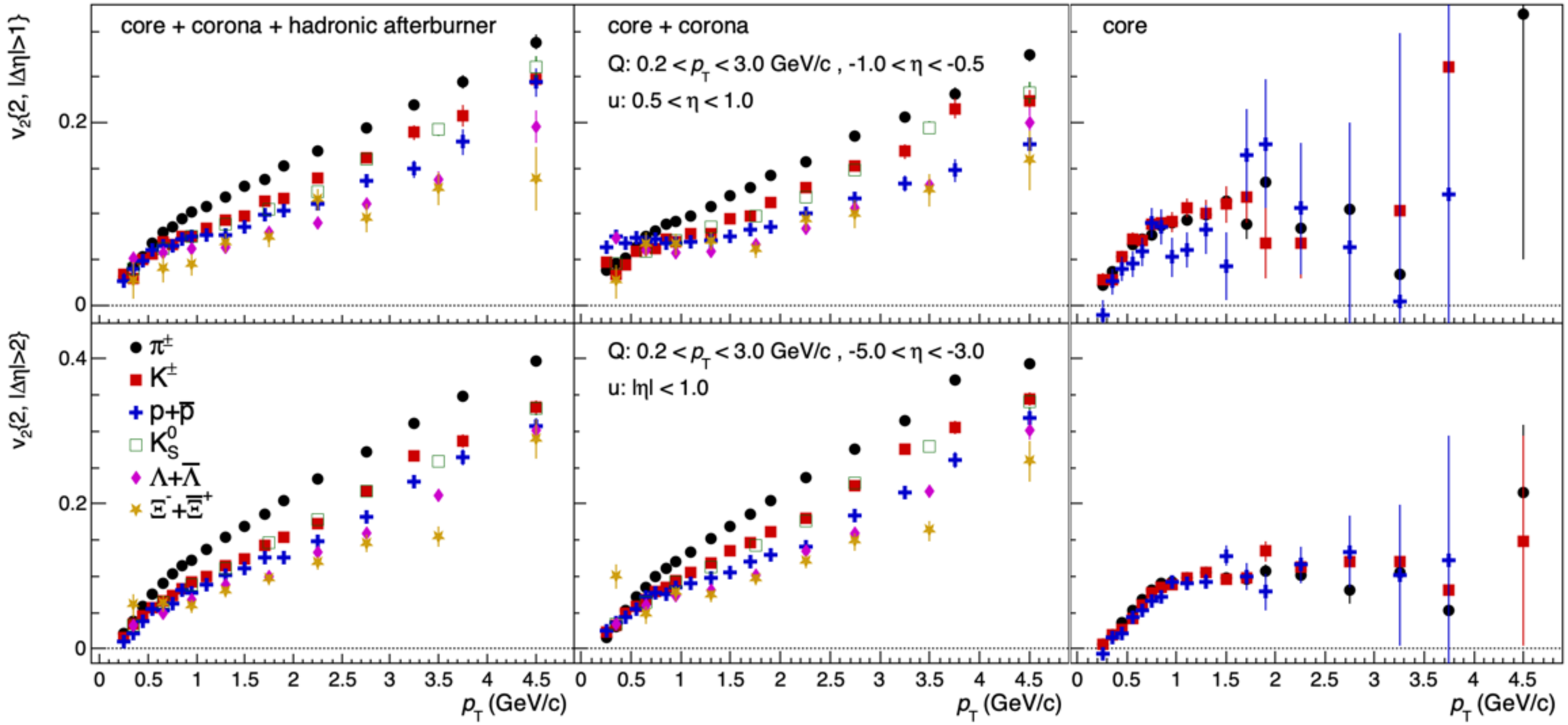


- Mass ordering broken for |Δη|>1
- Small mass ordering for |Δη|>2
  - More pronounced for rope hadronization
- No particle type grouping
- Hint of crossing between proton and pion v_2 for |Δη|>2
  - Not for rope hadronization

EPOS4 pp collisions: PID v_2

|Δη|>1

|Δη|>2

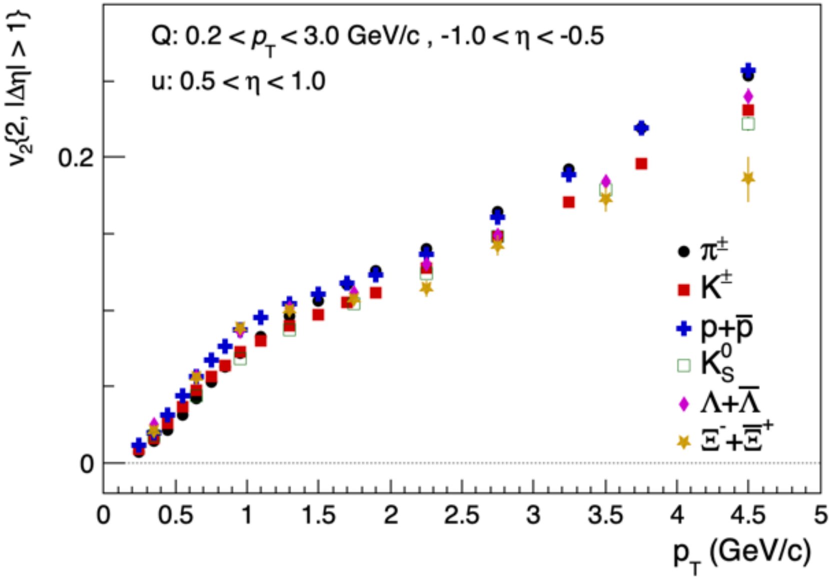


- Mass ordering for both |Δη| gaps
  - Mass ordering influenced by UrQMD for p_T<1.0 GeV/c
- No particle type grouping

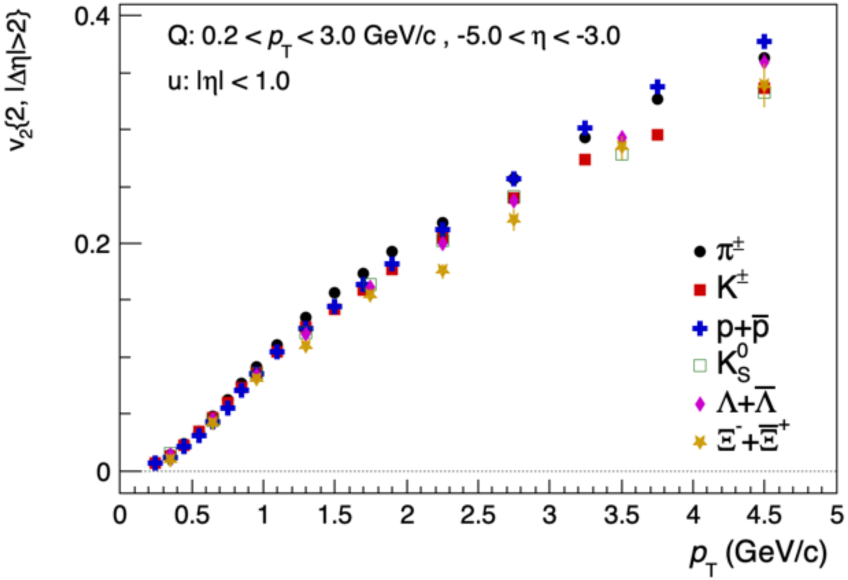
- Different trends than in PYTHIA 8

PYTHIA 8 p-Pb collisions: PID v_2

|Δη|>1



|Δη|>2

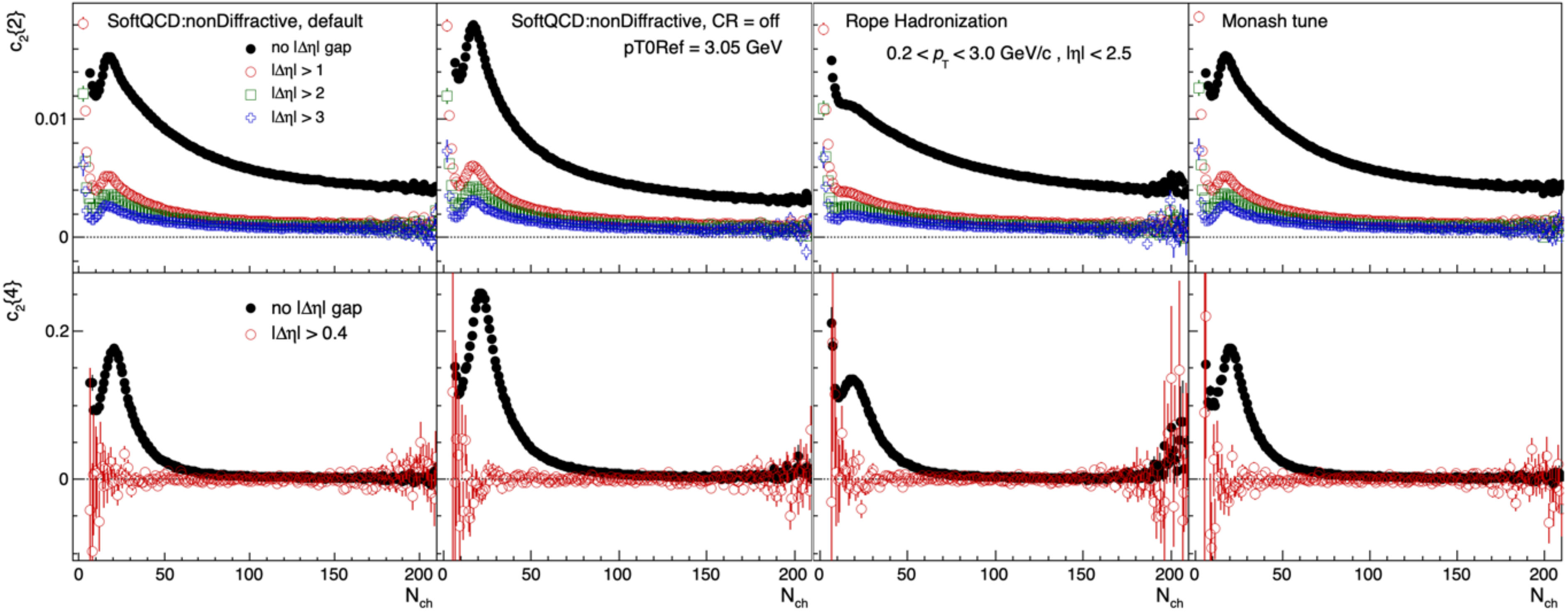


- Mass ordering broken for |Δη|>1
- Small mass ordering for |Δη|>2
- Crossing between proton and pion v_2 for |Δη|>2
- No particle type grouping

PYTHIA 8 pp collisions: $c_2\{2\}$ and $c_2\{4\}$

$c_2\{2\}$

$c_2\{4\}$



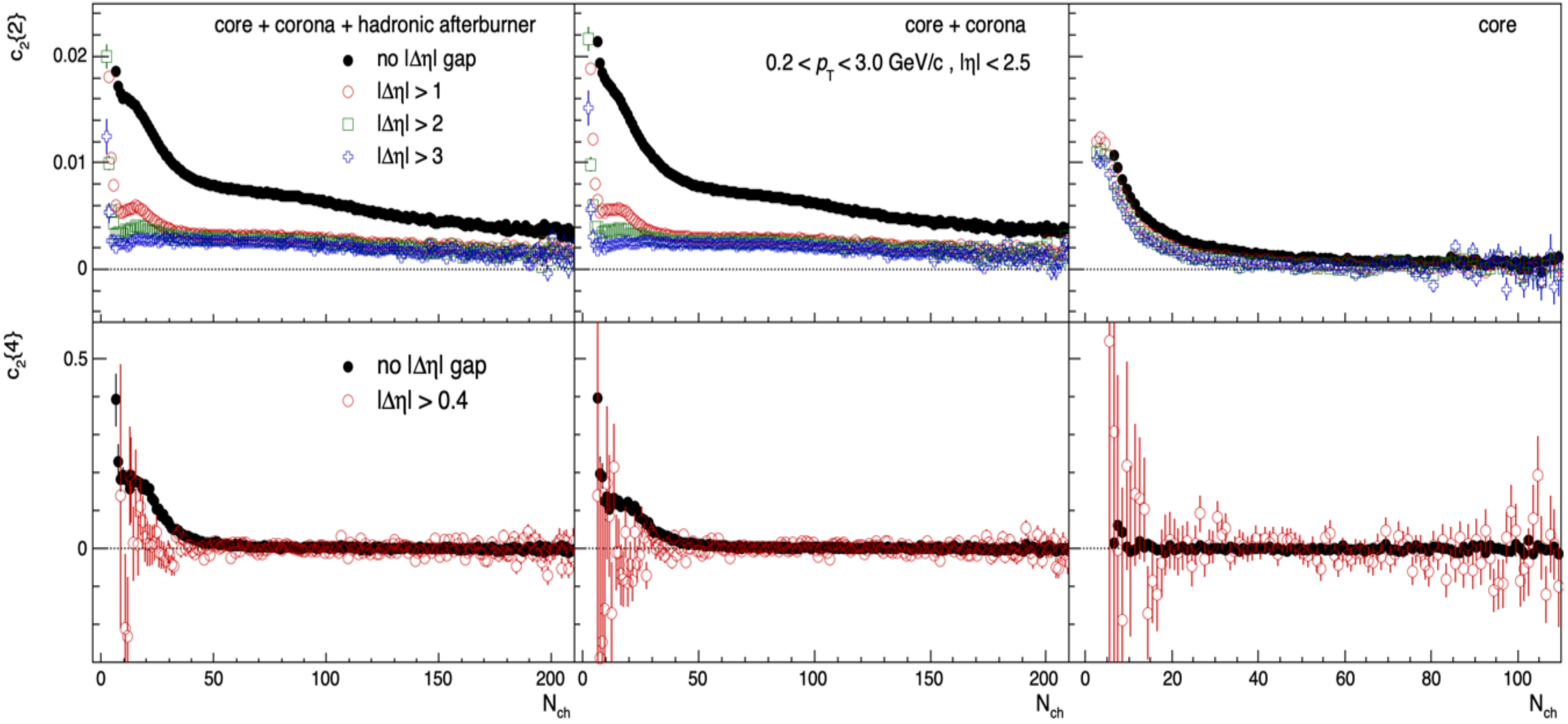
- $c_2\{2\} > 0$ at high multiplicities
  - Small dependence on |Δη| gap for $c_2\{2\}$
- $c_2\{4\} \sim 0 \rightarrow$ expected for Gaussian fluctuations

- Similar qualitatively trends for all configurations

EPOS4 pp collisions: $c_2\{2\}$ and $c_2\{4\}$

$c_2\{2\}$

$c_2\{4\}$

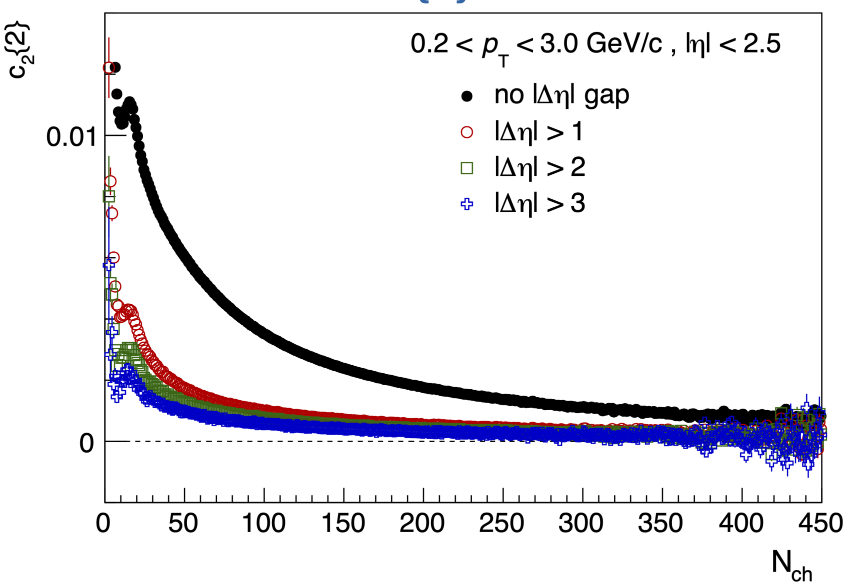


- $c_2\{2\} > 0$ at high multiplicities (except core)
  - Small dependence on |Δη| gap for $c_2\{2\}$
- $c_2\{4\} \sim 0$ → expected for Gaussian fluctuations

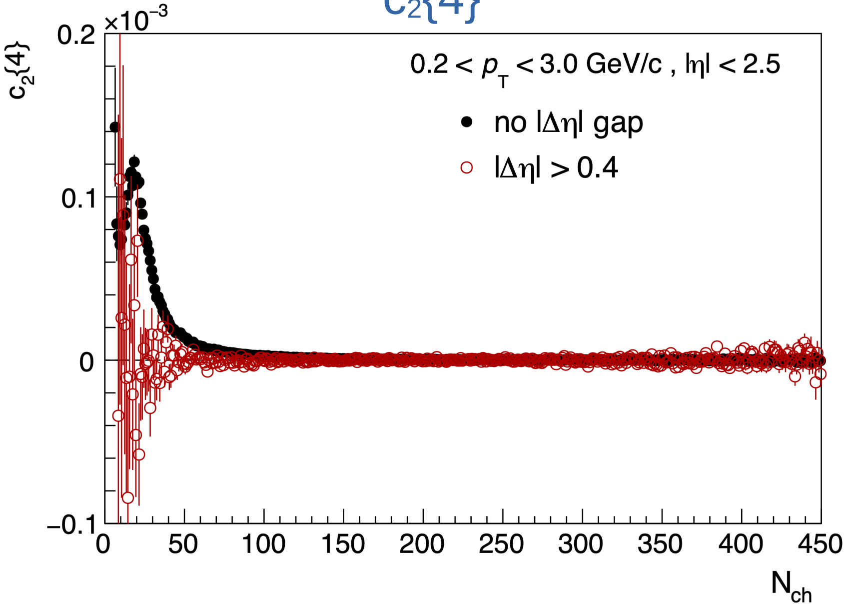
- Different trends between core+corona and core
- Different trends than in PYTHIA 8
  - More pronounced at low multiplicities

PYTHIA 8 p-Pb collisions: $c_2\{2\}$ and $c_2\{4\}$

$c_2\{2\}$



$c_2\{4\}$



- Similar trends as in pp collisions
- $c_2\{2\} > 0$ at high multiplicities
  - Small dependence on |Δη| gap for $c_2\{2\}$
- $c_2\{4\} \sim 0 \rightarrow$ expected for Gaussian fluctuations

Balance function in pp collisions

- PYTHIA 8
  - Rope hadronization
  - Monash tune

https://gitlab.com/Pythia8/releases/-/issues/80

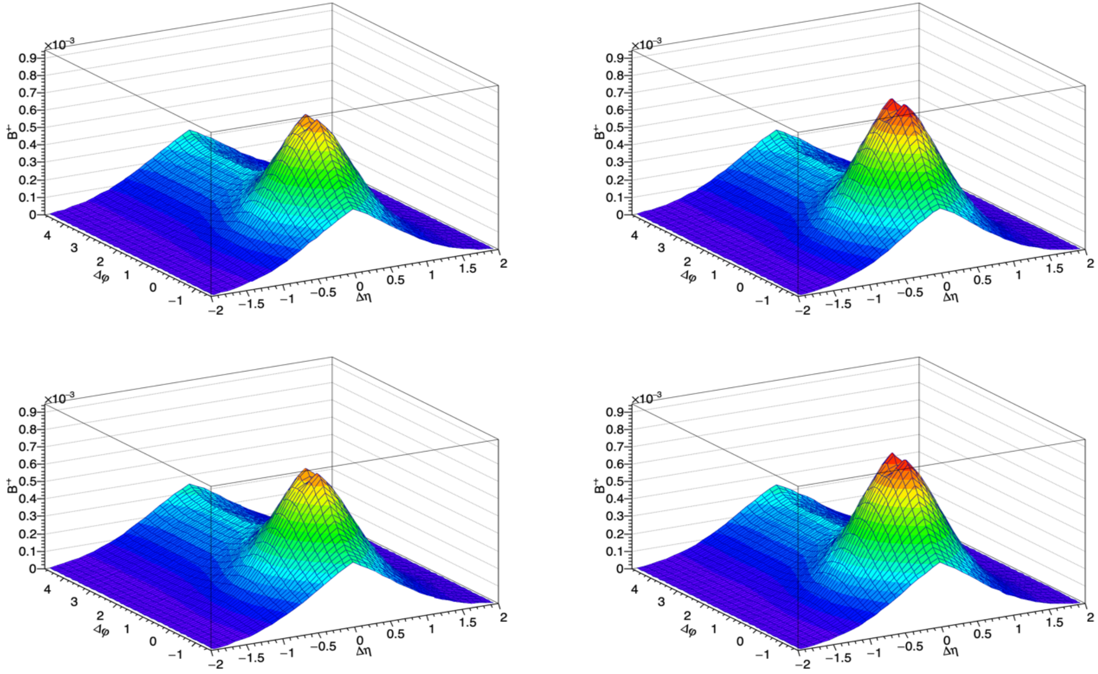
- EPOS4
  - core+corona+hadronic afterburner (full simulation)

Balance function

"Rope hadronization" "Monash tune"

B+-

B-+



Integral value B^{+-} : 0.469 0.490

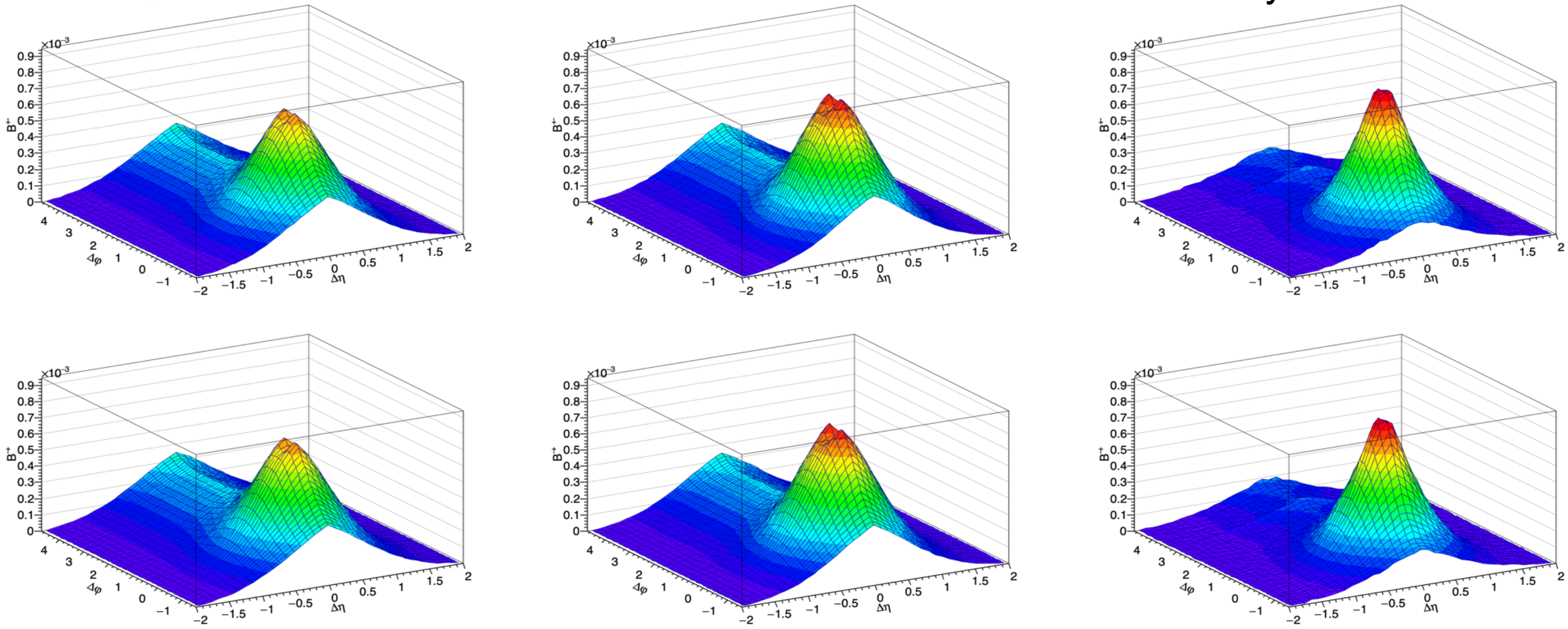
Integral value B^{-+} : 0.474 0.486

Balance function

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

B+-

B-+

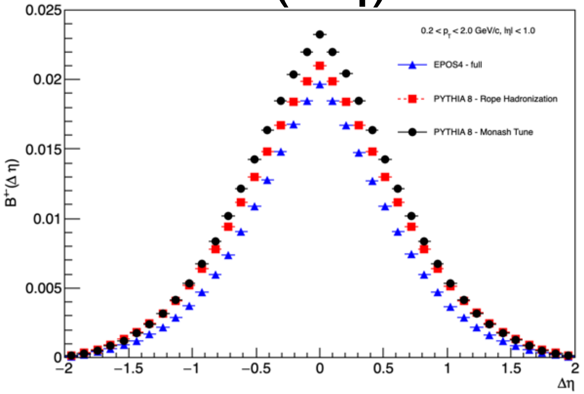


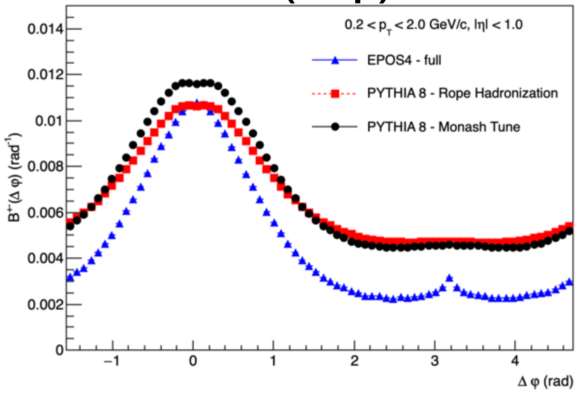
	"Rope hadronization"	"Monash tune"	"Full hydro+UrQMD"
Integral value B^{+-} :	0.469	0.490	0.344
Integral value B^{-+} :	0.474	0.486	0.336

Balance function projections

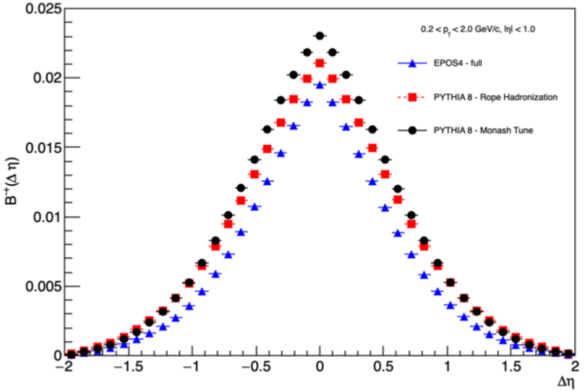
B(Δη) B(Δϕ)

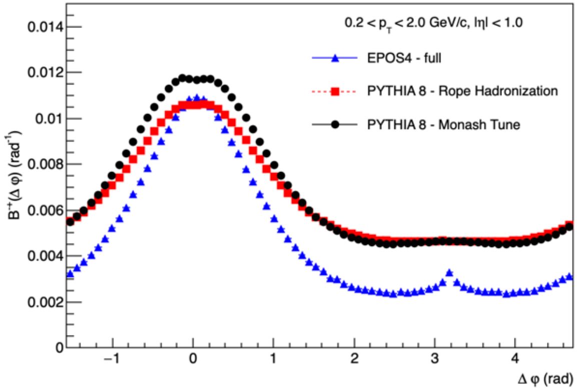
B^{+-}





B^{-+}





Projections show different trends in away side ridge

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

- PID v2: mass ordering for large $|\Delta\eta|$ gap
  - No particle type grouping

- Balance function: different trends in away side