



# Probing the Origin of Finite $V_{2\Delta}$ in Low-Multiplicity pp Collisions using string shoving model

(Based on: arXiv:2606.09760)

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ICN, UNAM

# Outline

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- Introduction
- Motivation
- Methodology
- Results and discussion
- Summary and Outlook

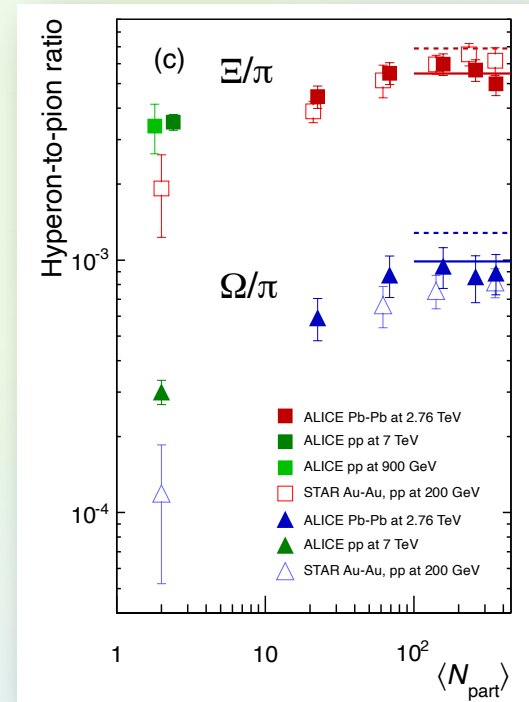
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- What is **Quark-Gluon Plasma** (QGP)?
  - Thermalized state of quarks and gluons
  - Has collectivity
- Was present in the early universe
- Can be formed in heavy-ion collisions
- QGP signatures:

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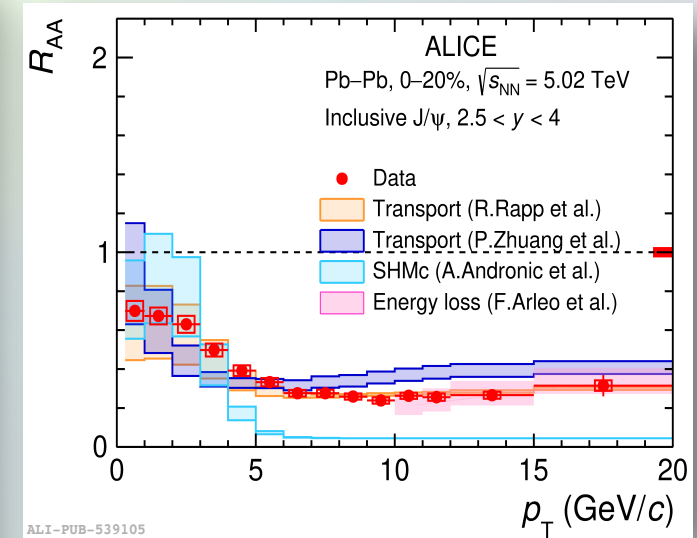
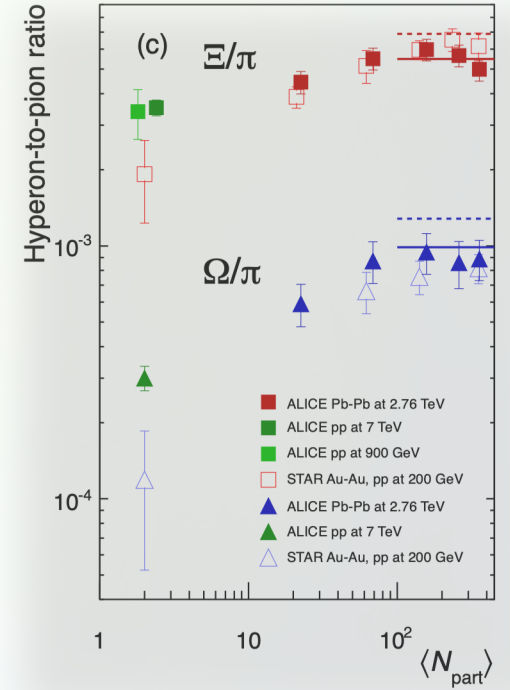
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[ALICE Collaboration, Phys. Lett. B 728, 216 (2014)]

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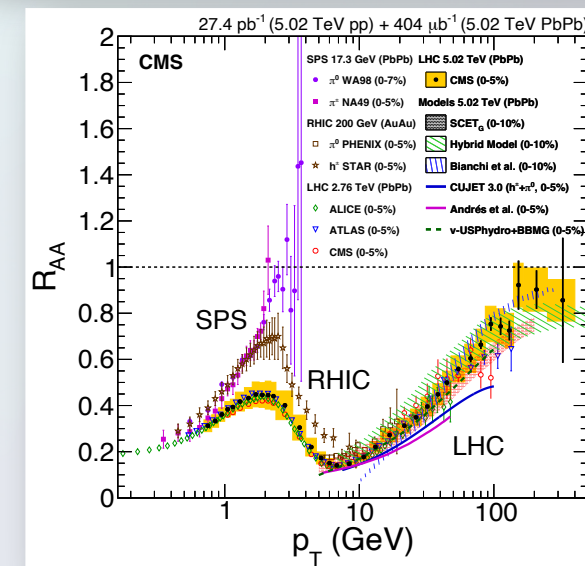
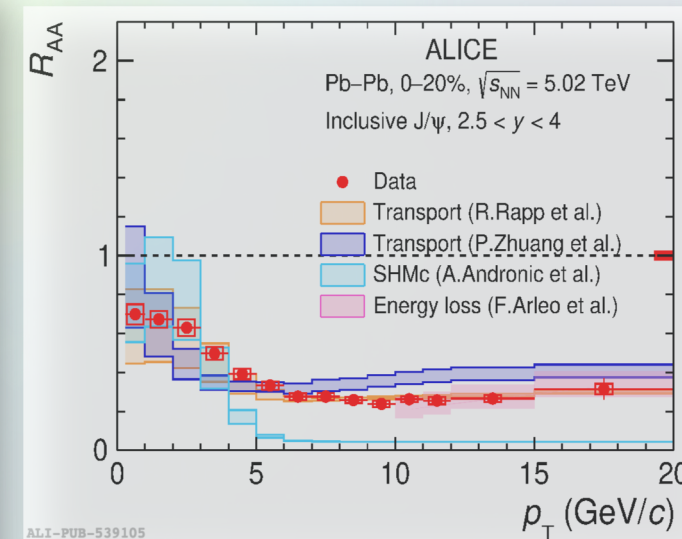
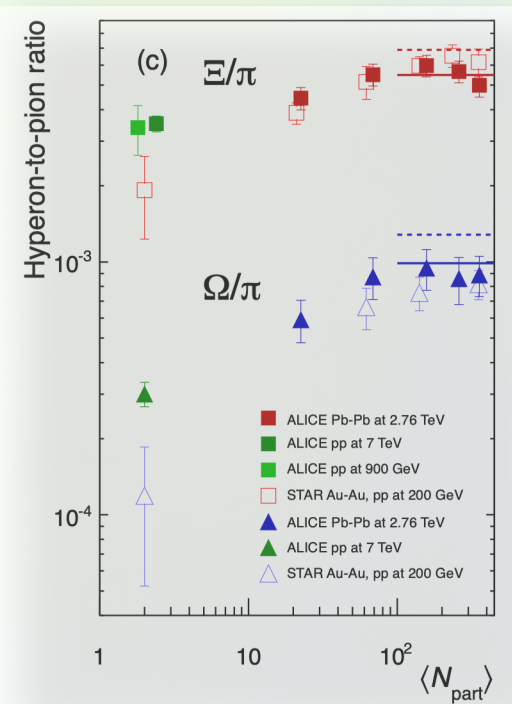
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[CMS Collaboration, JHEP **07**, 076 (2011)]

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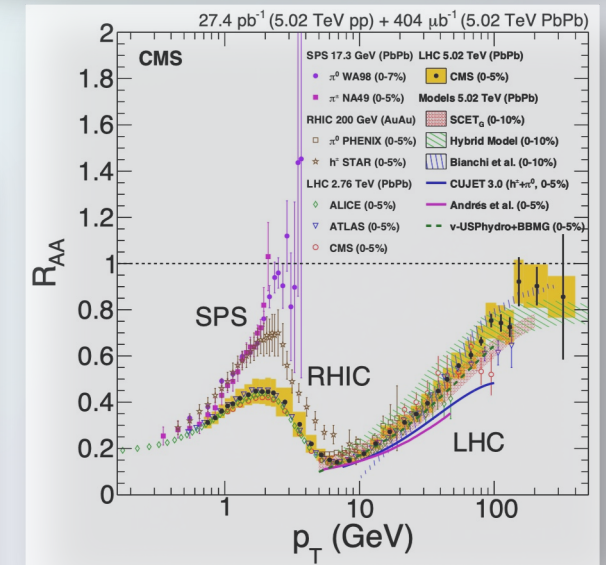
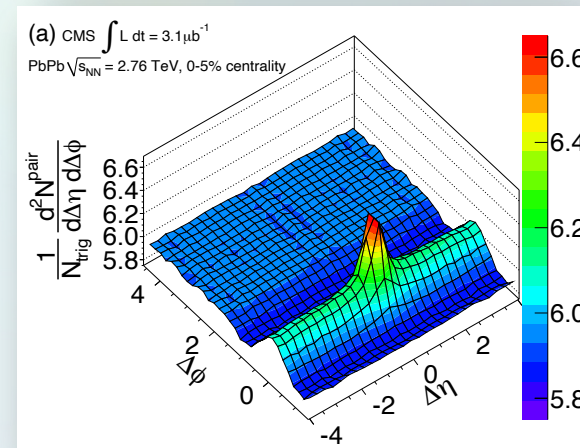
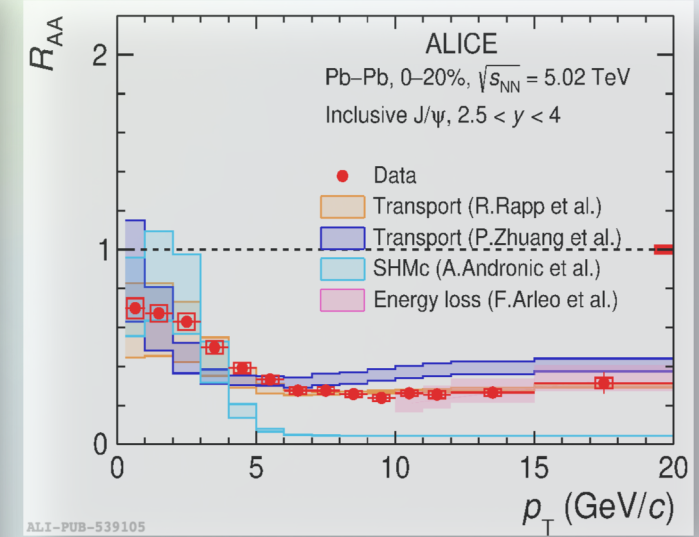
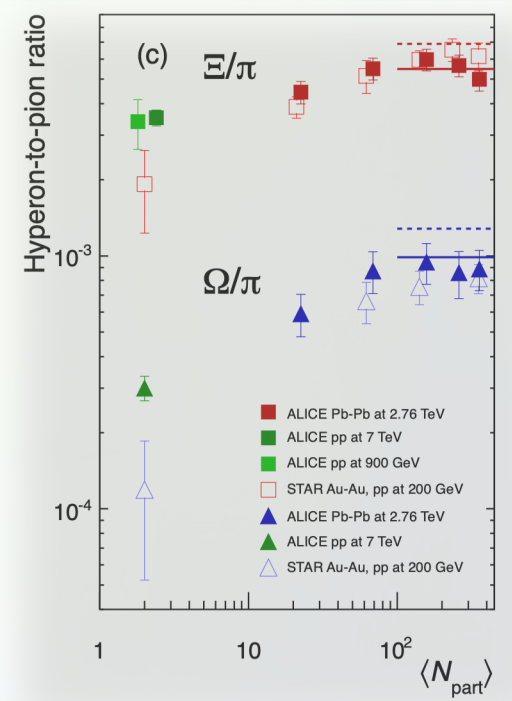
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  - Collective flow

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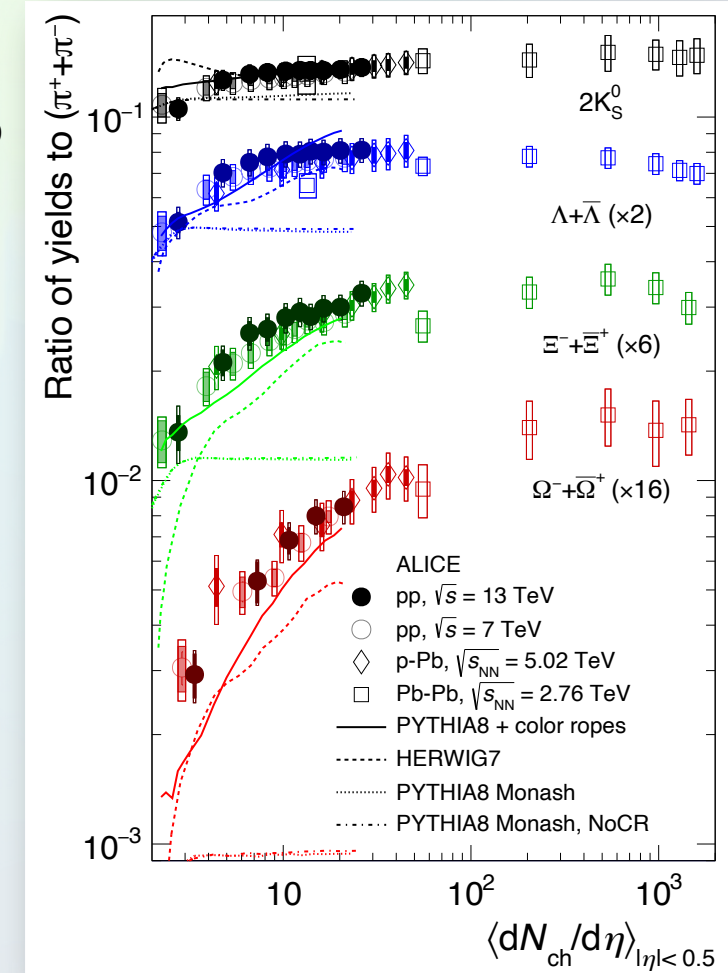
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- Recent studies show the possible formation of QGP droplets in high multiplicity pp collisions

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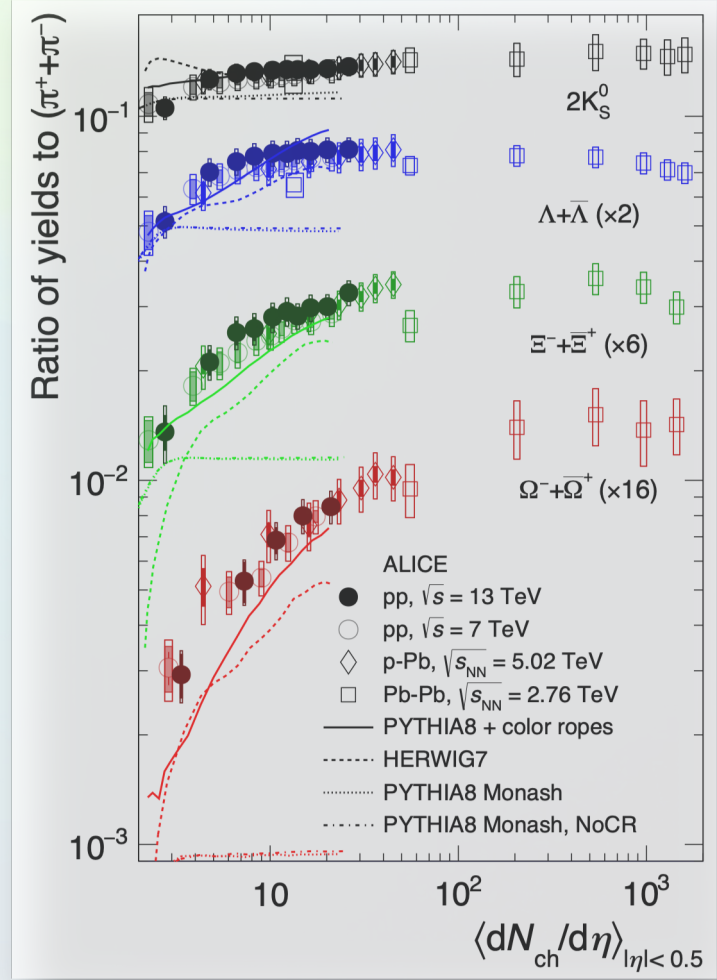
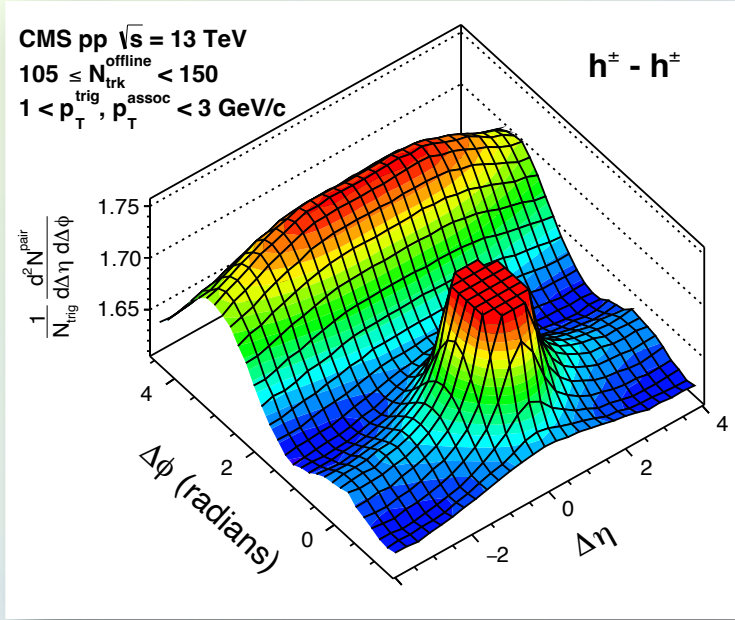
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- Recent studies show the possible formation of QGP droplets in high multiplicity pp collisions
- Hint of strangeness enhancement



[ALICE Collaboration, Eur. Phys. J. C 80, 693 (2020)]

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- Ridge-like structure: hint of collective flow

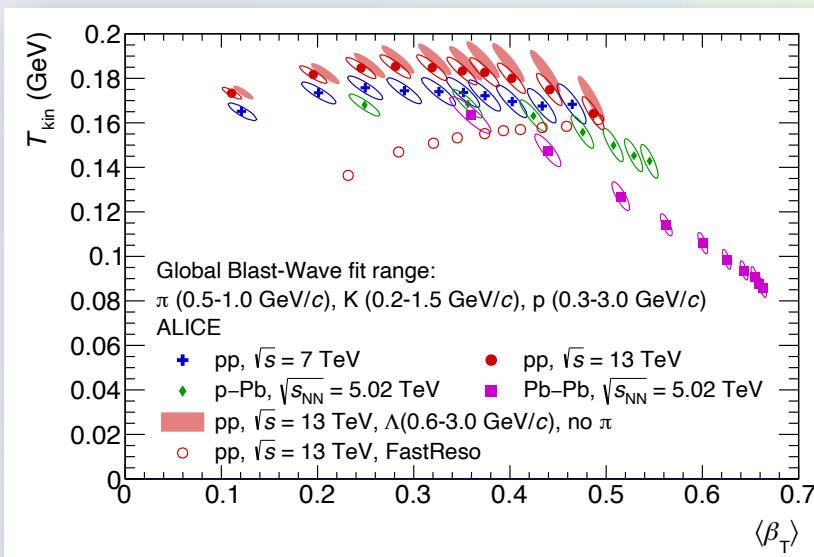


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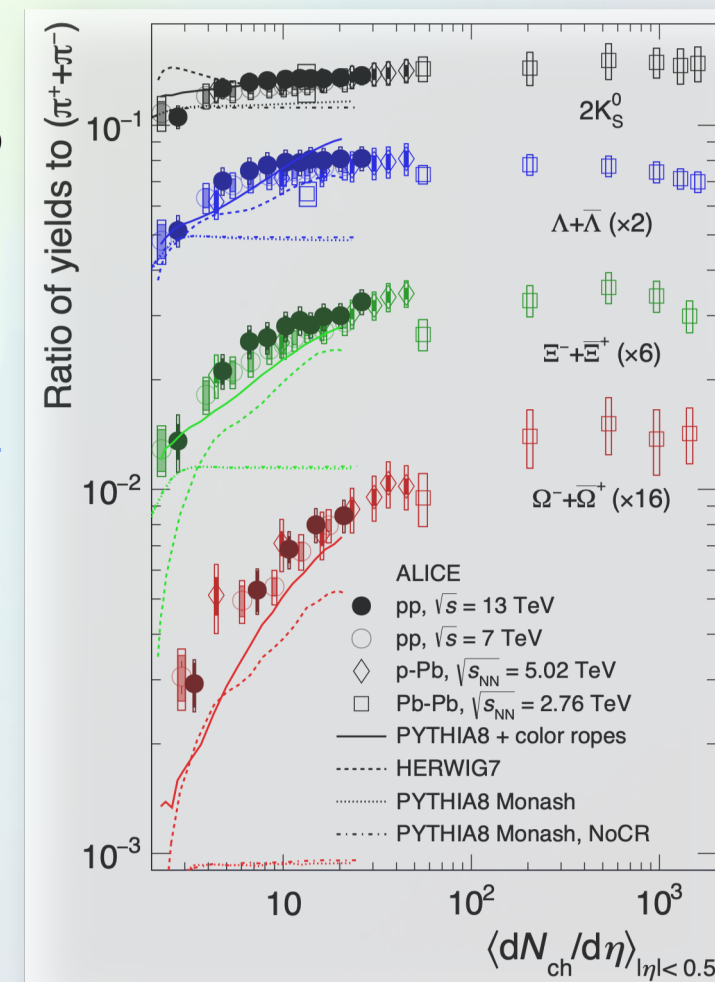
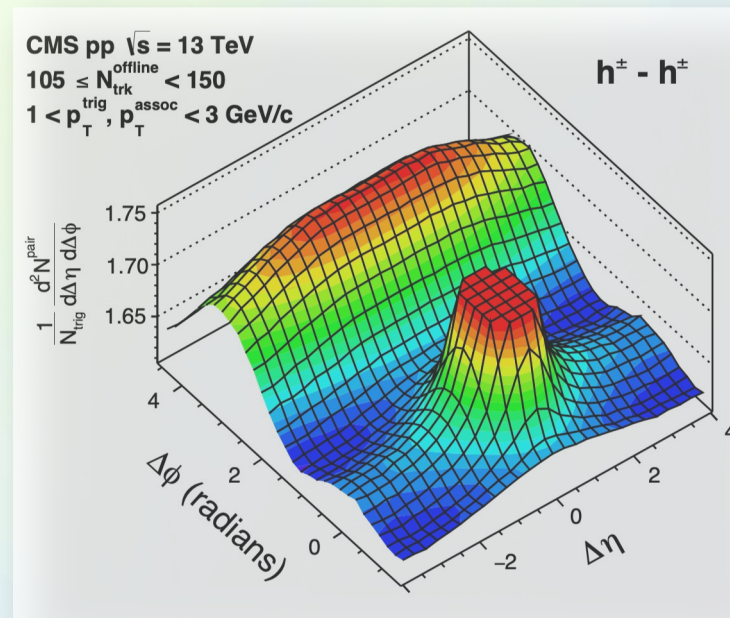
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- Kinetic freezeout temperature and radial velocity comparable to that of peripheral heavy-ion collisions



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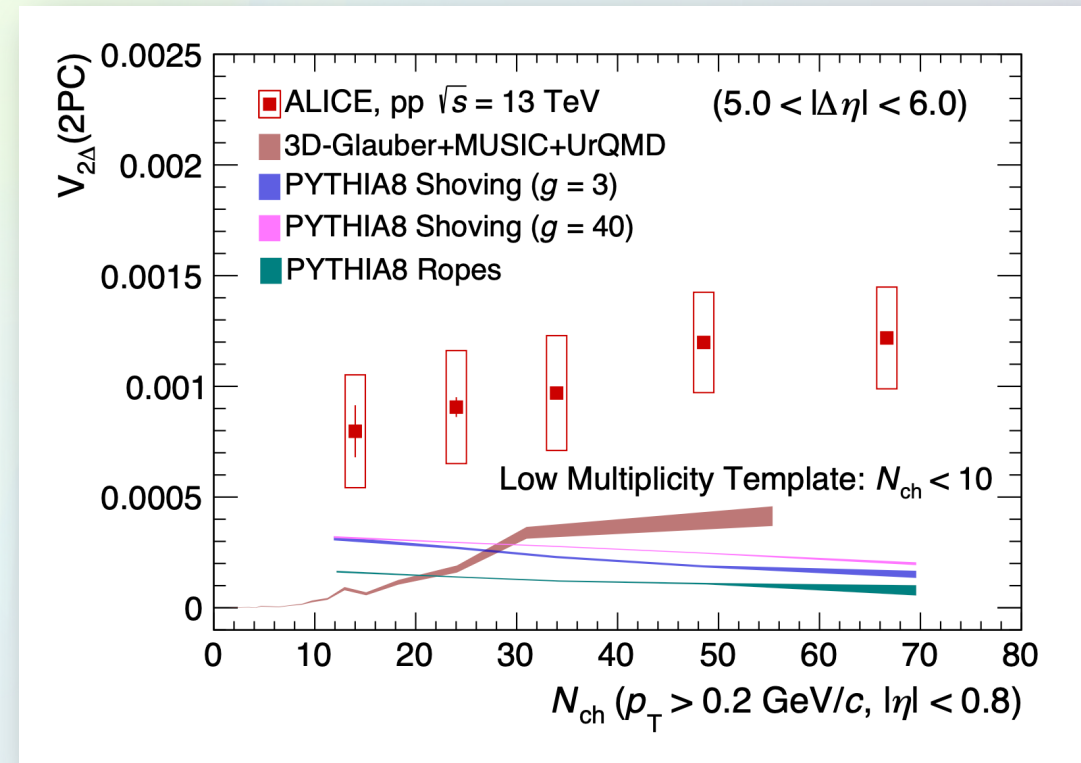
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# Motivation

- Observation of collective-like effects (ridges, flow) observed in high-multiplicity pp
- Traditional View: Low-multiplicity pp = jet-dominated, incoherent parton scattering
- First measurement of ultra-long-range correlations ( $|\Delta\eta| > 5.0$ ) in low-multiplicity pp

## What Are Ultra-Long-Range Correlations?

- Two-particle correlations across large pseudorapidity gaps
- Enhanced correlation at  $\Delta\phi \sim 0$  (near-side)
- Long-range in  $\eta$  suggests collective, non-jet origin



[ALICE Collaboration, arXiv:2504.02359]

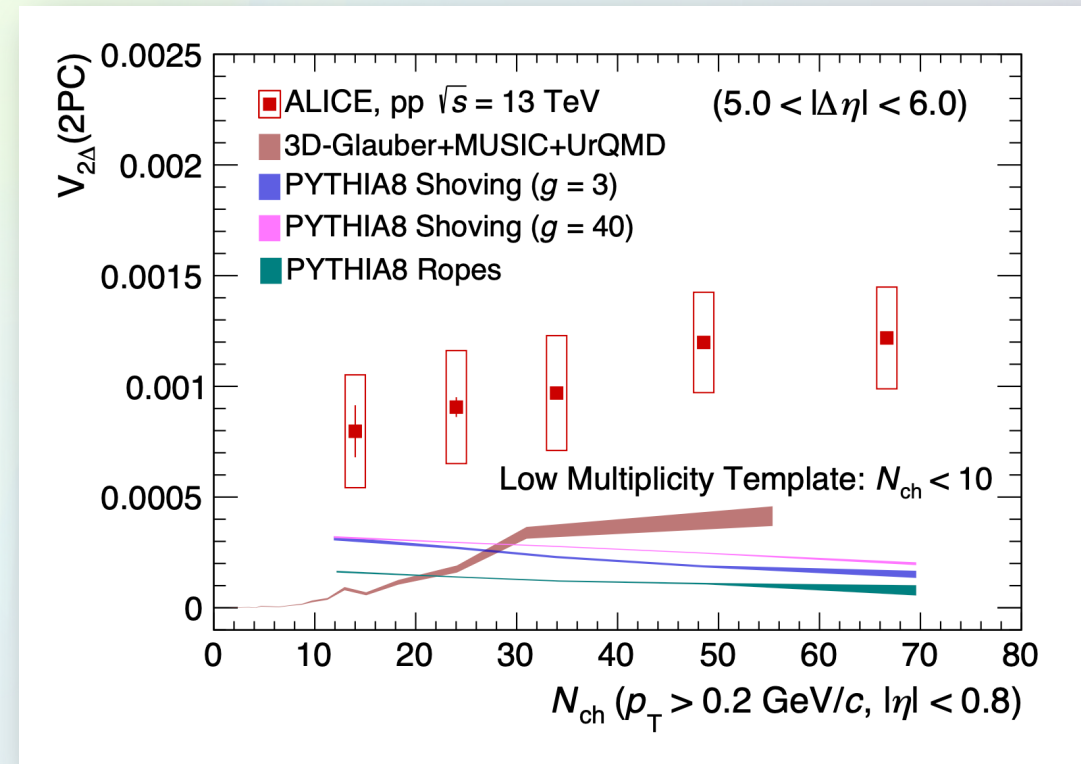
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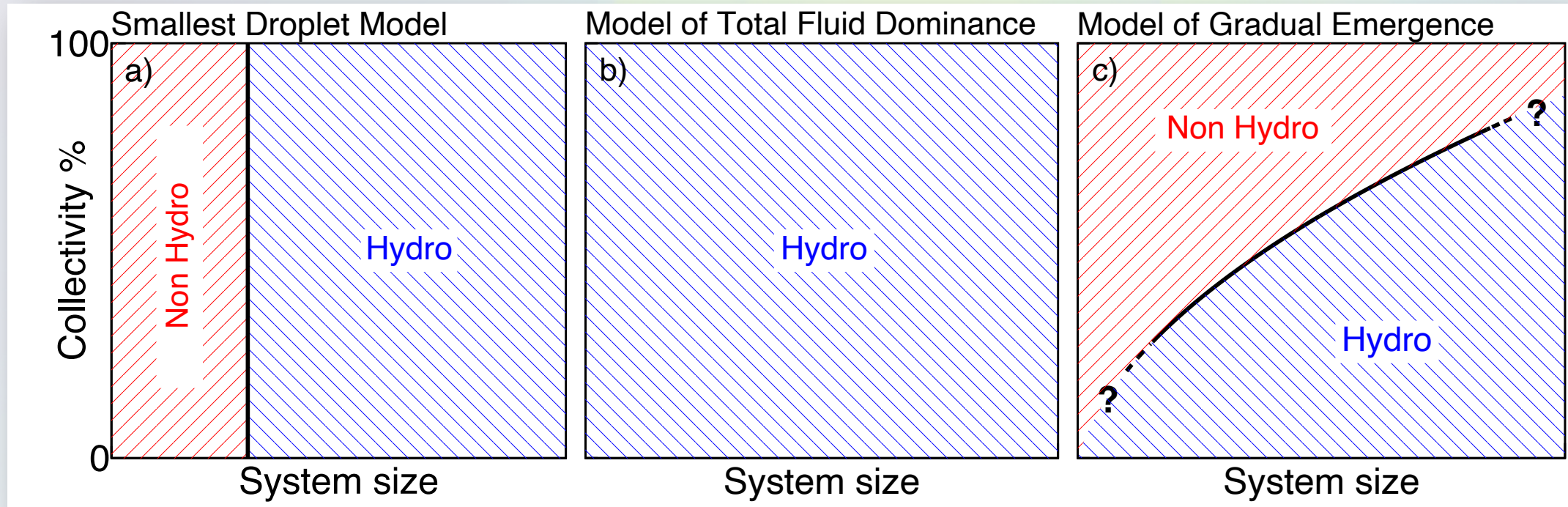
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- Non-zero  $V_{2\Delta}$  even at lowest multiplicities
- $3.1\sigma$  in lowest  $N_{ch}$  class ( $\langle N_{ch} \rangle \approx 10$ )
- $V_{2\Delta}$  increases with multiplicity
- ALICE results doesn't match with Hydro and PYTHIA results
- PYTHIA shows decreasing trend with  $N_{ch}$



[ALICE Collaboration, arXiv:2504.02359]

# Motivation



[J. F. Grosse-Oetringhaus and U. A. Wiedemann, arXiv:2407.07484]

- Sudden or gradual onset of hydro?
- What is the threshold of QGP-like effects?

# Methodology

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- To isolate long-range effects and suppress short-range jet correlations, only pairs with  $5.0 < |\Delta\eta| < 6.0$  are analyzed
- To remove trivial yield variations and focus on the shape of the modulation, the distribution is normalized to unit area
- The raw correlation contains both "flow" (collective) and "non-flow" (jets, resonances) contributions
- The method assumes a low-multiplicity event class (e.g.,  $N_{ch} = 0-10$ ) contains minimal flow and acts as a template for the non-flow shape

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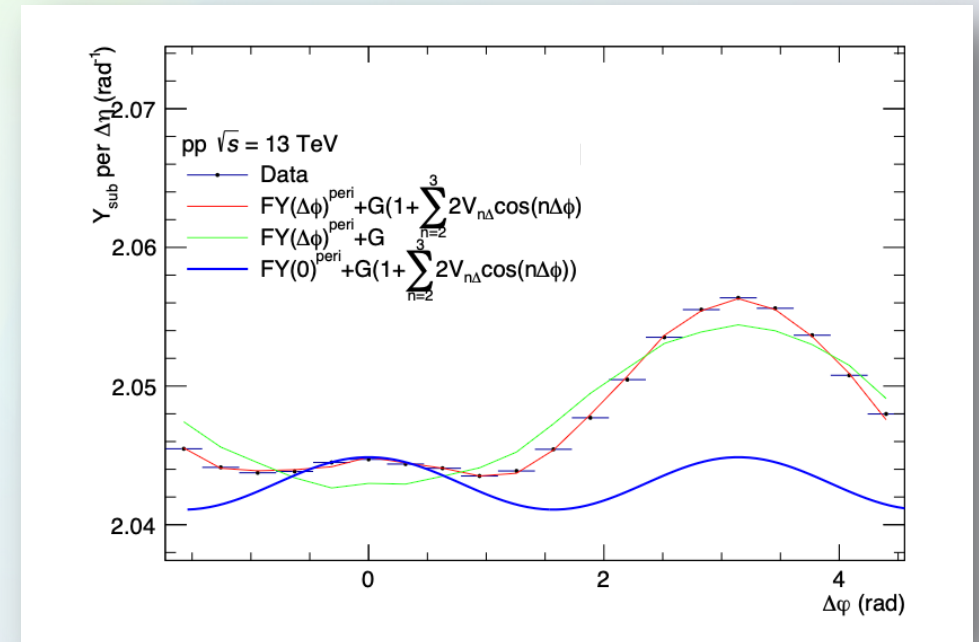
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- Employ the template fit method:

$$Y(\Delta\phi) = FY^{\text{LM}}(\Delta\phi) + G \left[ 1 + \sum 2V_{n\Delta} \cos(n\Delta\phi) \right]$$

$$Y(\Delta\phi) = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta\phi} = \int_{|\Delta\eta| > 5.0/6.5} \left( \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta\eta d\Delta\phi} \right) d\Delta\eta.$$

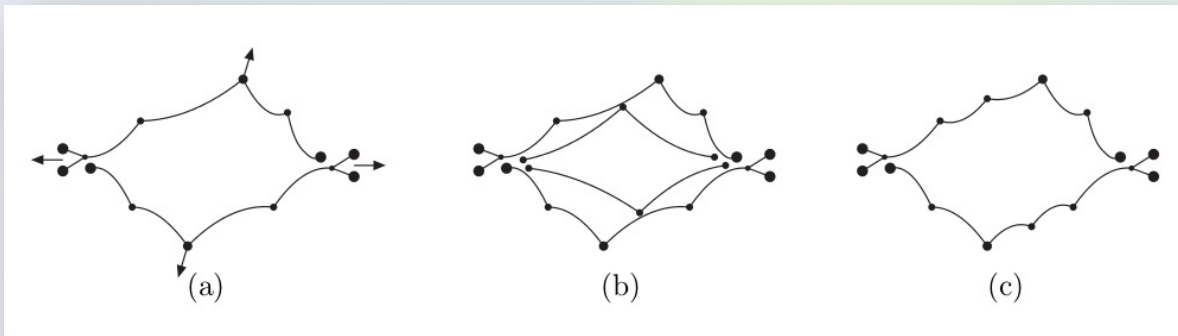


[ALICE Collaboration, arXiv:2504.02359]

# PYTHIA8

## Color Reconnection:

- After MPI (multiple parton interactions), colored partons form many string pieces
- CR reconnects color lines so that: total string length is minimized, effective string tension increases
- leads to harder  $p_T$  spectra and flow-like patterns
- Enhanced baryon/meson ratios
- Improvements in tuning for LHC pp data

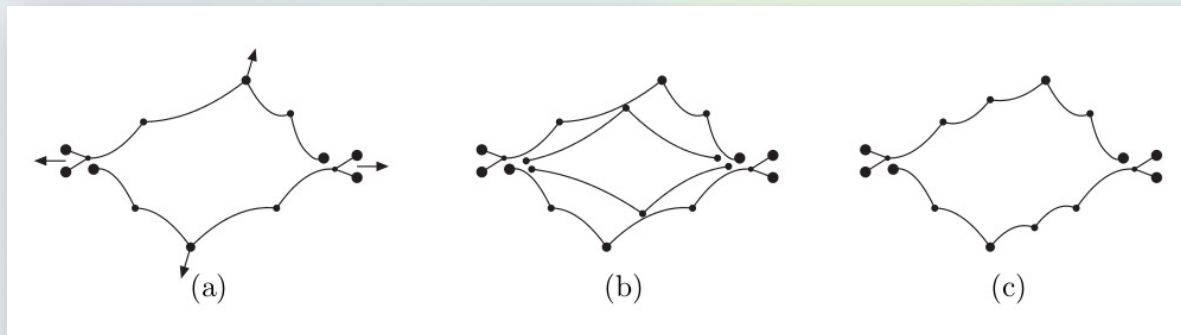


[A. Ortiz Velasquez, et. al., Phys. Rev. Lett. 111, 042001 (2013)]

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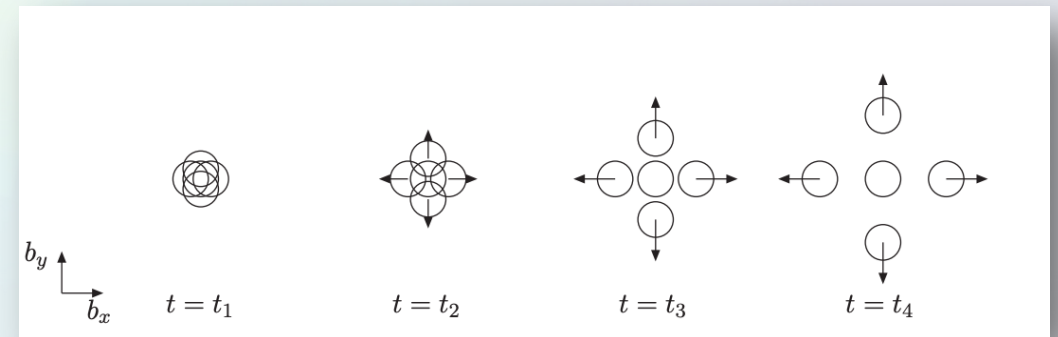
[A. Ortiz Velasquez, et. al., Phys. Rev. Lett. 111, 042001 (2013)]

## String shoving:

- Overlapping color strings repel each other due to their transverse energy density  $\rightarrow$  creates collective transverse push

$$f(d_{\perp}) = \frac{g_A \kappa d_{\perp}}{R^2} \exp\left(-\frac{d_{\perp}^2}{4R^2}\right)$$

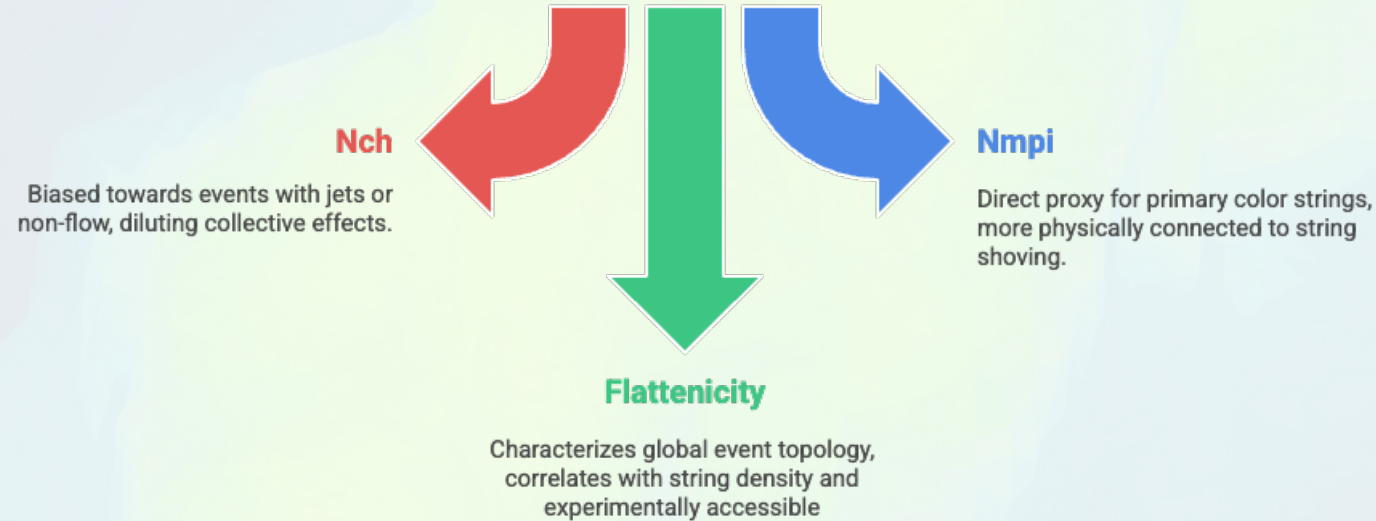
$$\Delta p_{\perp} = \int dt \int dx f(d_{\perp}(t))$$



[C. Bierlich, et. al., Phys. Lett. B 779, 58 (2018)]

# Event classifiers

Which event classifier should be used?

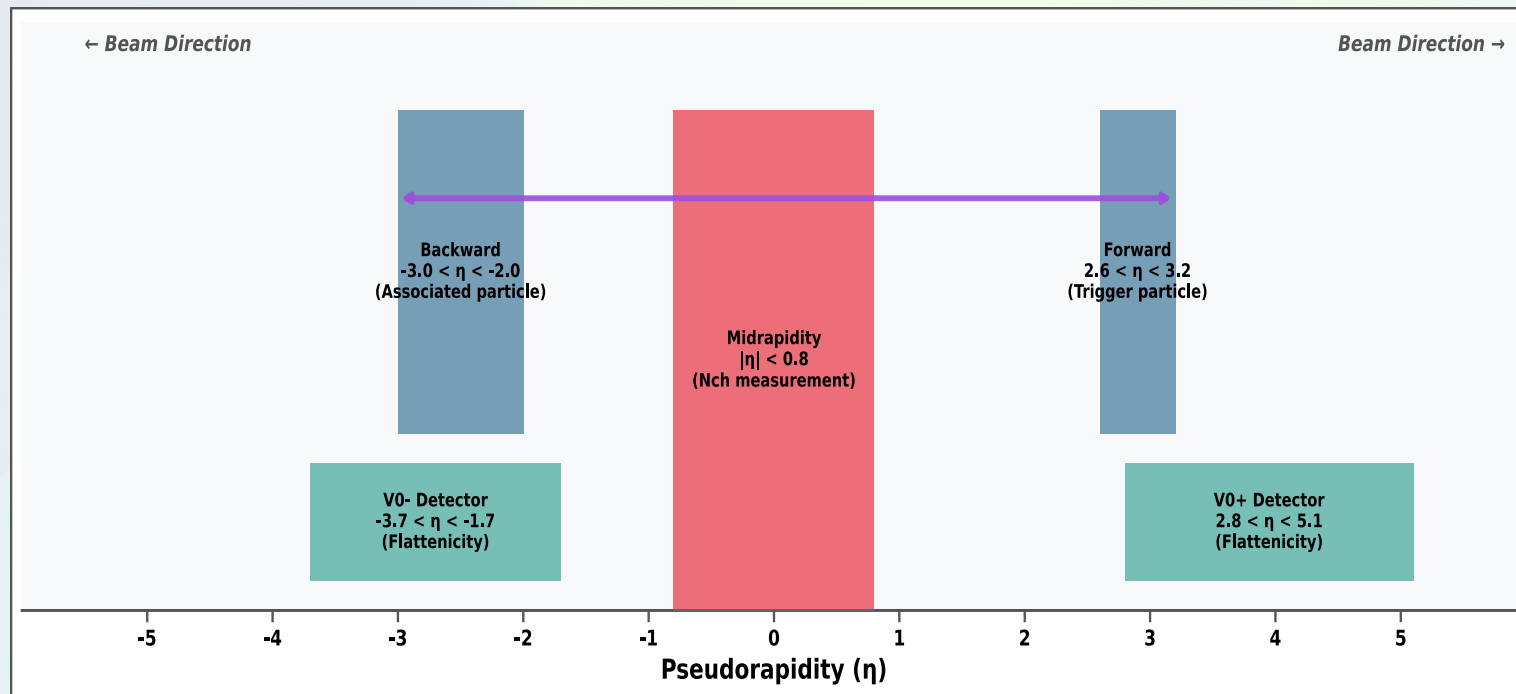


- $N_{mpi}$  is the number of multiple independent parton-parton scatterings occur within a single pp collision
- Flattenicity is introduced to characterize the global topology of pp collisions, with a specific design goal to isolate events dominated by MPI

$$\rho_{nch} = \frac{\sqrt{\sum_i (N_{ch}^{cell,i} - \langle N_{ch}^{cell} \rangle)^2 / N_{cell}^2}}{\langle N_{ch}^{cell} \rangle},$$

[A. Ortiz, A. Khuntia, O. Vazquez-Rueda, et. al., Phys. Rev. D 107, 076012 (2023)]

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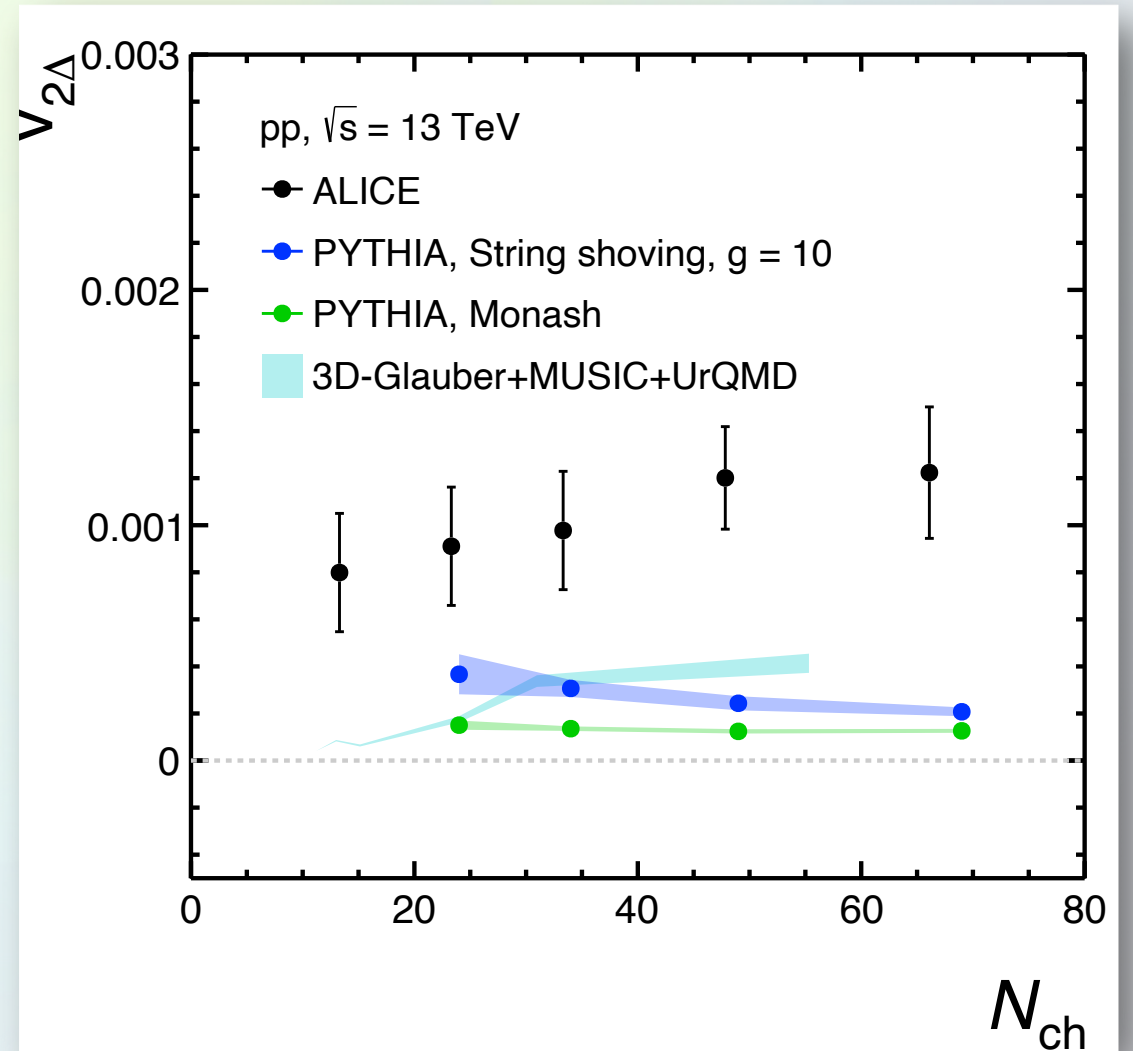
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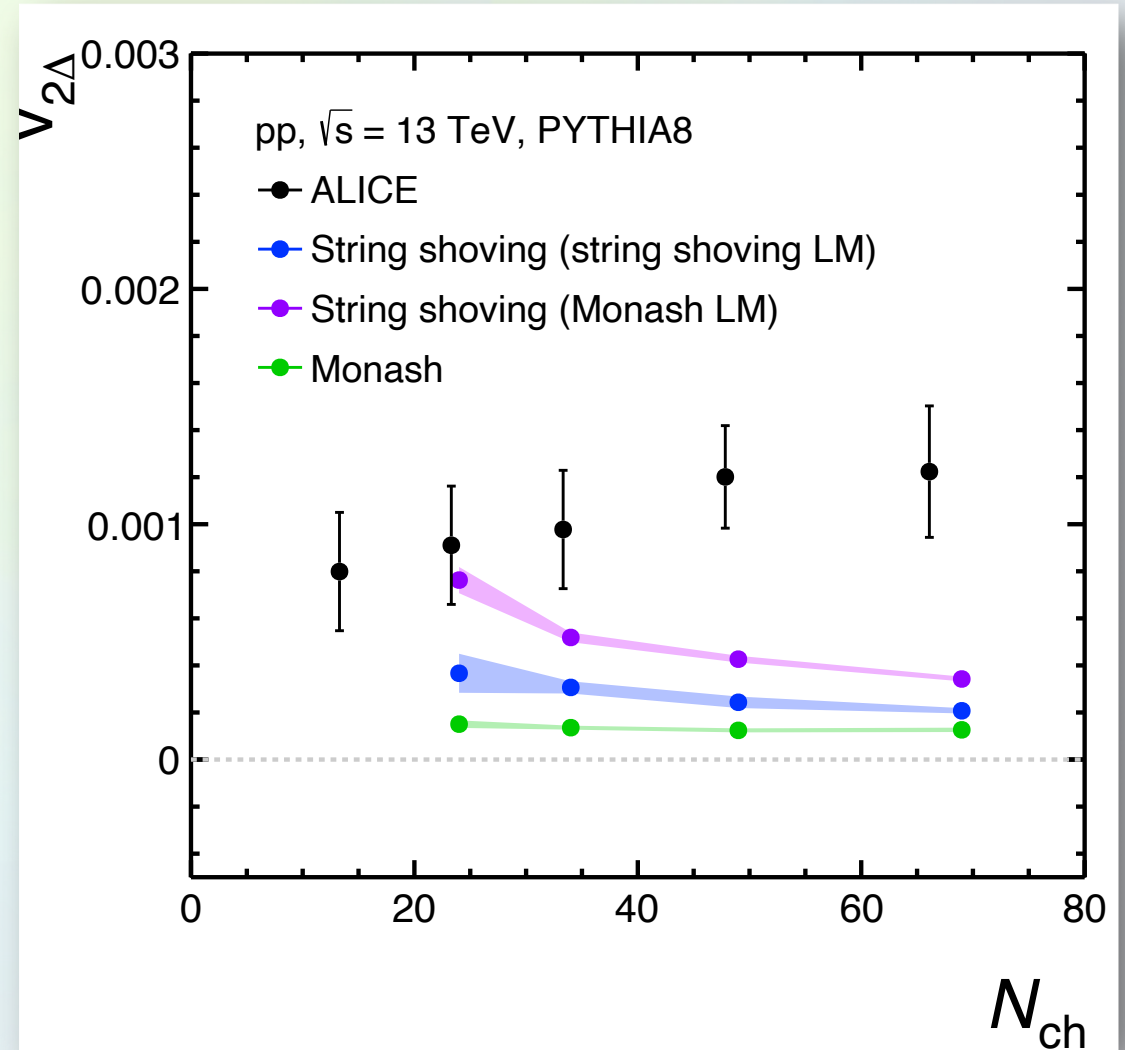
# Results

- PYTHIA Monash: nearly zero  $V_{2\Delta}$  (baseline non-flow)
- PYTHIA string shoving: finite  $V_{2\Delta}$ , but decreases with  $N_{ch}$
- ALICE data: slight increase or flat trend within uncertainties
- Hydrodynamics: increases with  $N_{ch}$  but still underestimates data

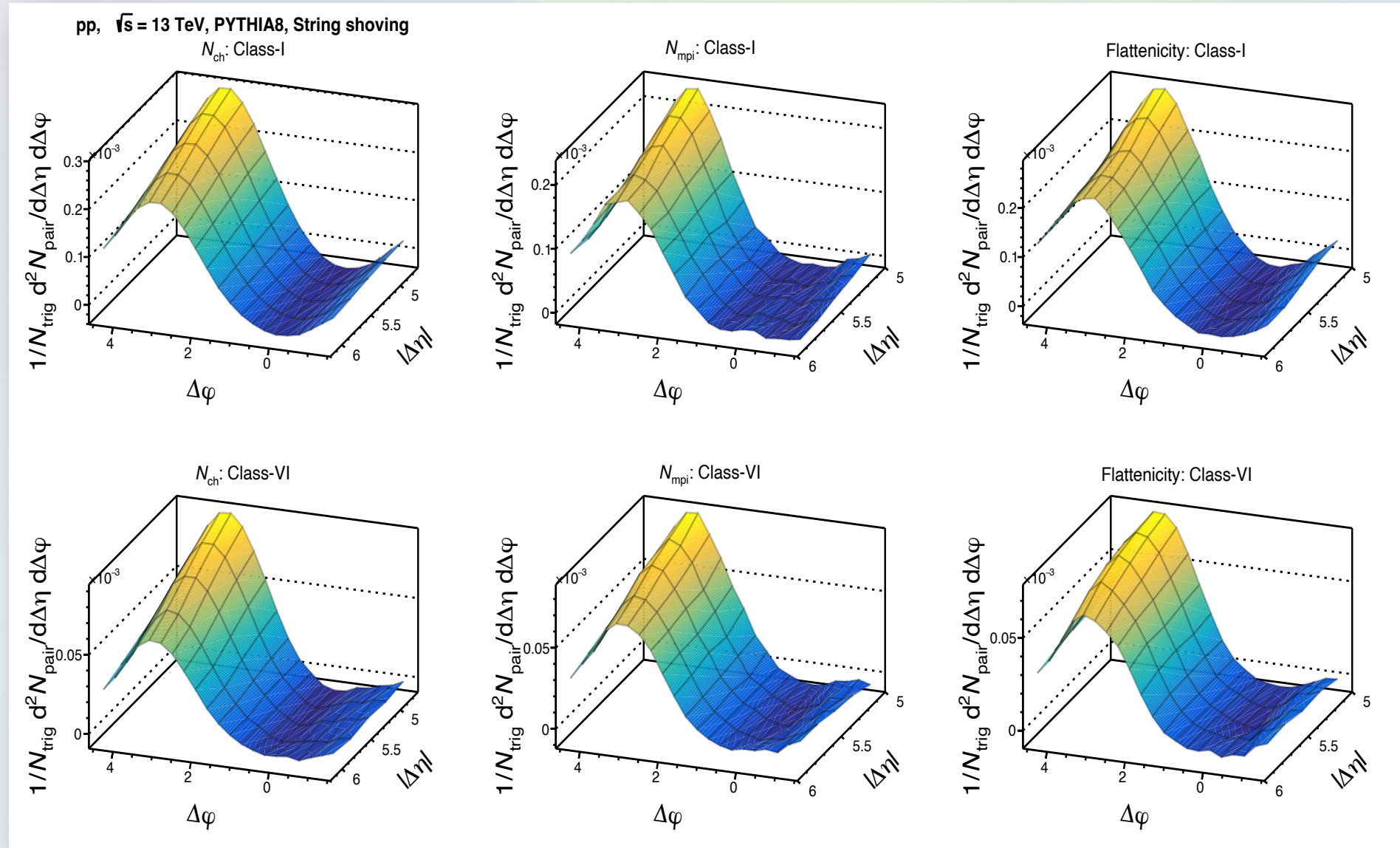


# Results

- Using lowest- $N_{ch}$  template from string shoving  $\rightarrow$  underestimates  $V_{2\Delta}$  (over-subtraction)
- Using Monash lowest- $N_{ch}$  template  $\rightarrow$  larger  $V_{2\Delta}$ , closer to ALICE at lower multiplicities
- Low- $N_{ch}$  class in string shoving already contains some flow-like signal, causing significant bias

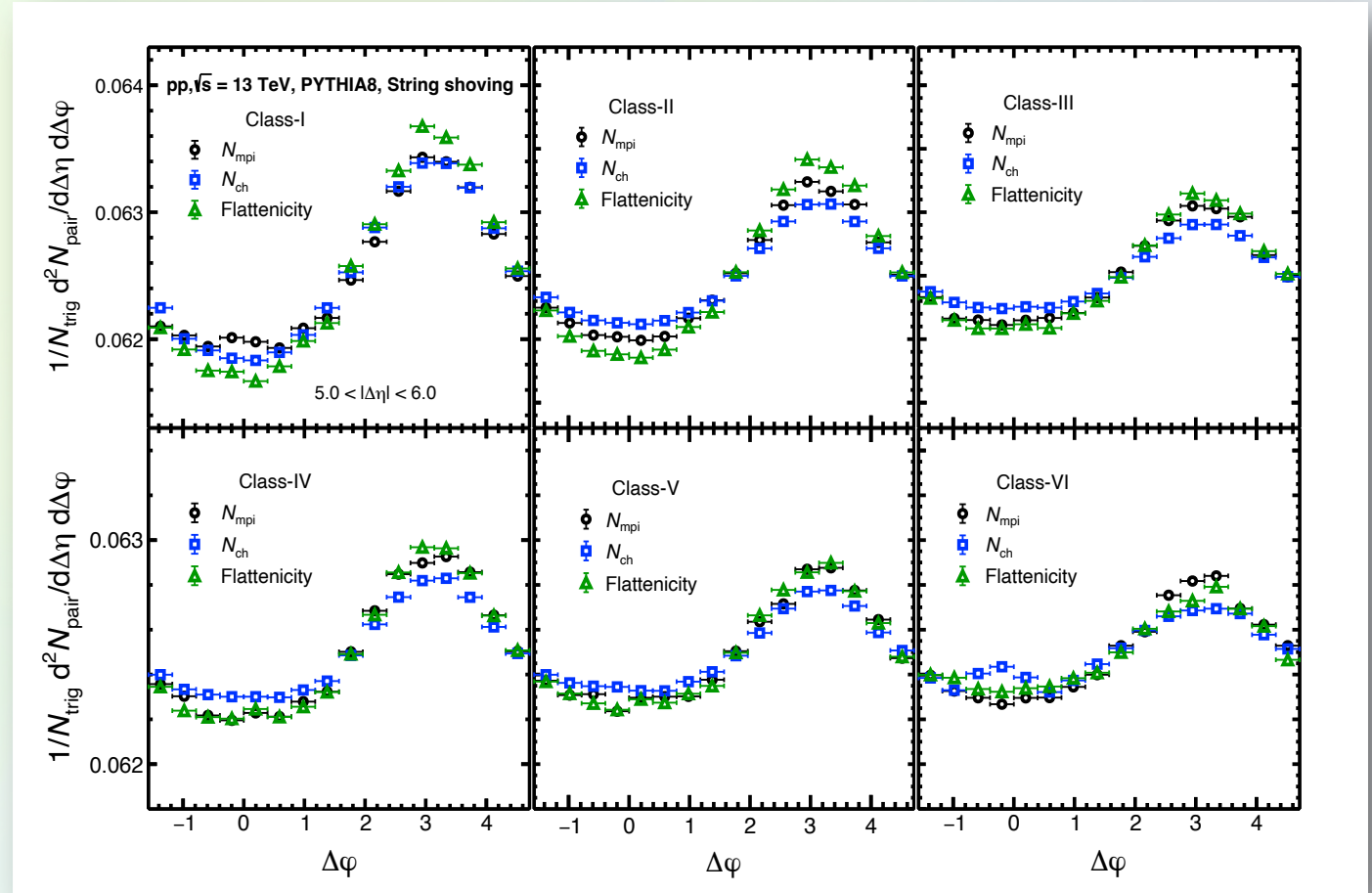


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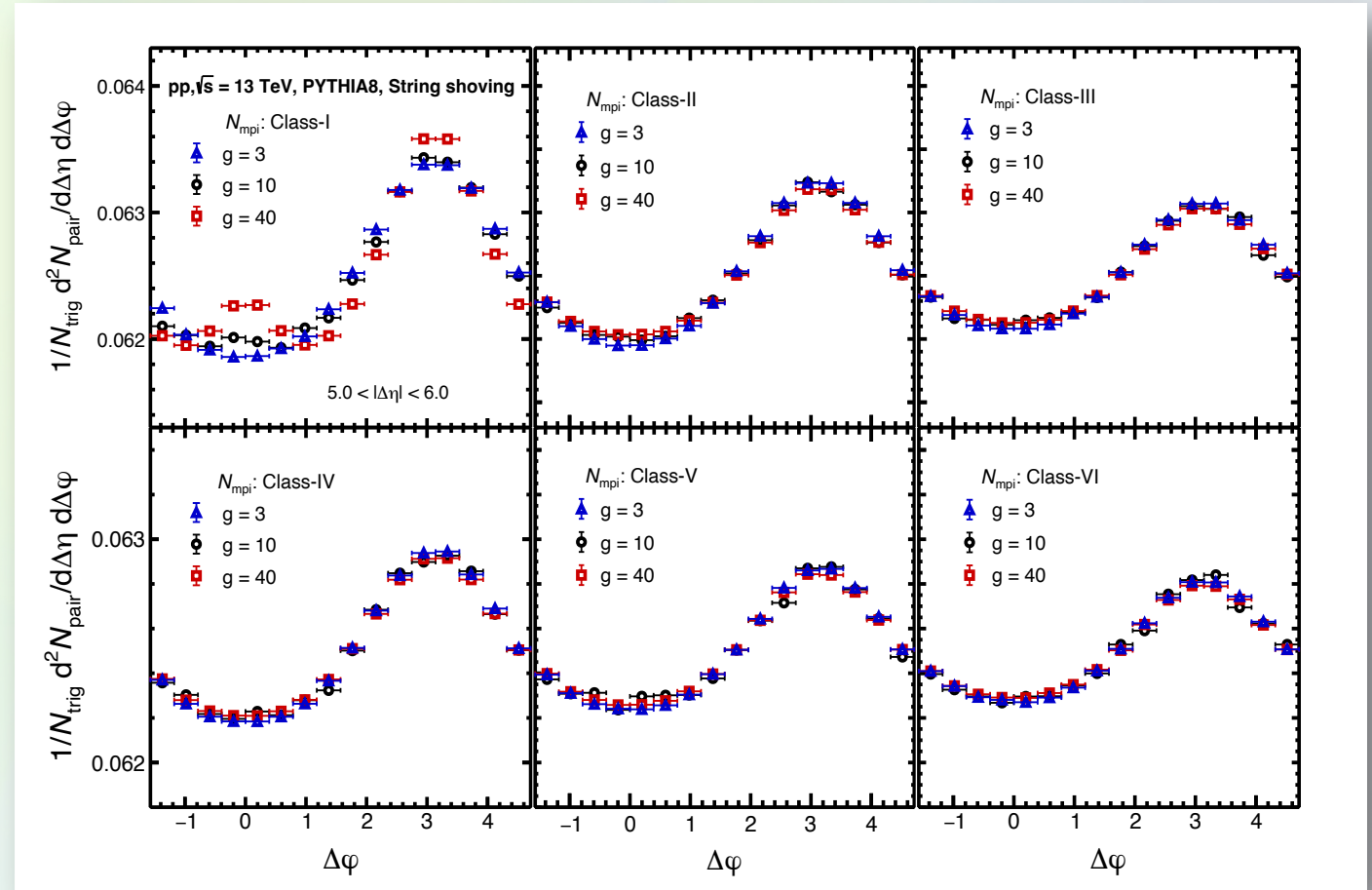
# Results

- $N_{mpi}$  estimator is a clean proxy of string density
- But, a single jet can produce high  $N_{ch}$   $\rightarrow$  misclassified as “high activity”
- Distorts correlation structure by mixing: Jetty events with MPI-rich isotropic events
- Low-flattenicity (jet-like)  $\rightarrow$  no ridge structure
- High-flattenicity (isotropic)  $\rightarrow$  mild collective behavior



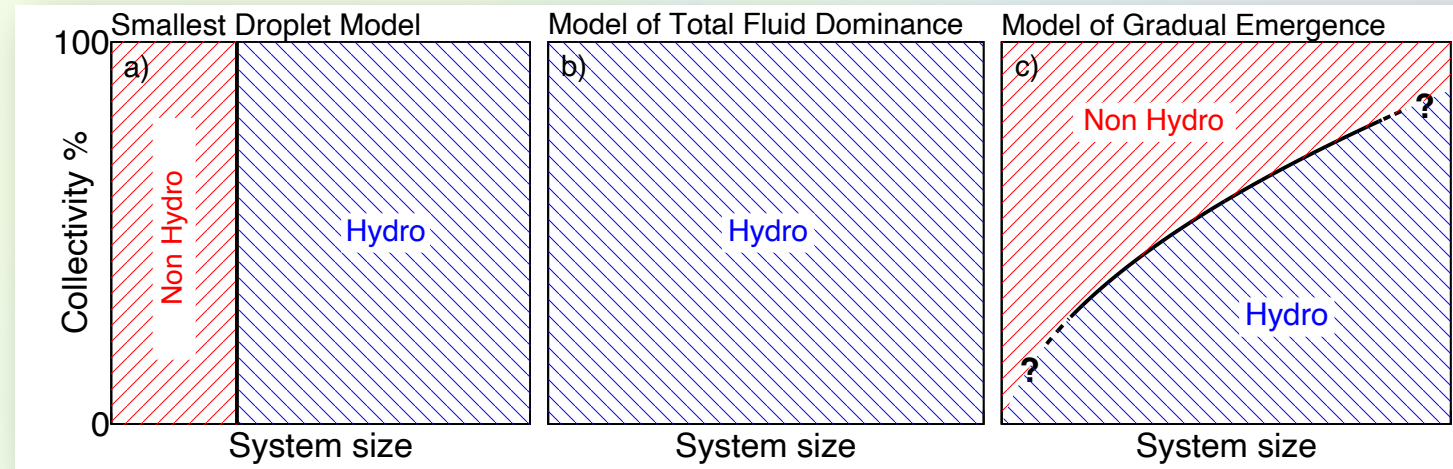
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- Strongest  $V_{2\Delta}$  appears for  $N_{mpi} = 1$  (dijet events)
- Reason: few strings  $\rightarrow$  large initial spatial anisotropy
- At high  $N_{mpi}$  (dense string environment): Pushes cancel out, Anisotropy gets diluted,  $V_{2\Delta}$  decreases
- Shoving works best in sparse environments



# Summary and Outlook

- Confronting the  $V_{2\Delta}$  signal from ultra-long range correlation studies with observables like flattenicity and MPI with PYTHIA8
- String shoving provides partial explanation for ultra-long-range correlations, but fails to reproduce increasing  $V_{2\Delta}$  with  $N_{ch}$



[J. F. Grosse-Oetringhaus and U. A. Wiedemann, arXiv:2407.07484]

- $N_{ch}$  is a biased estimator; flattenicity and  $N_{mpi}$  are more meaningful
- Long-range collectivity emerges from a combination of: Initial-state string interactions (small systems, low activity) and Final-state hydrodynamics (higher multiplicities)
- More dynamic modeling is needed beyond static string repulsion in PYTHIA8

Thank you!