



Creating a small droplet of early universe in the Laboratory

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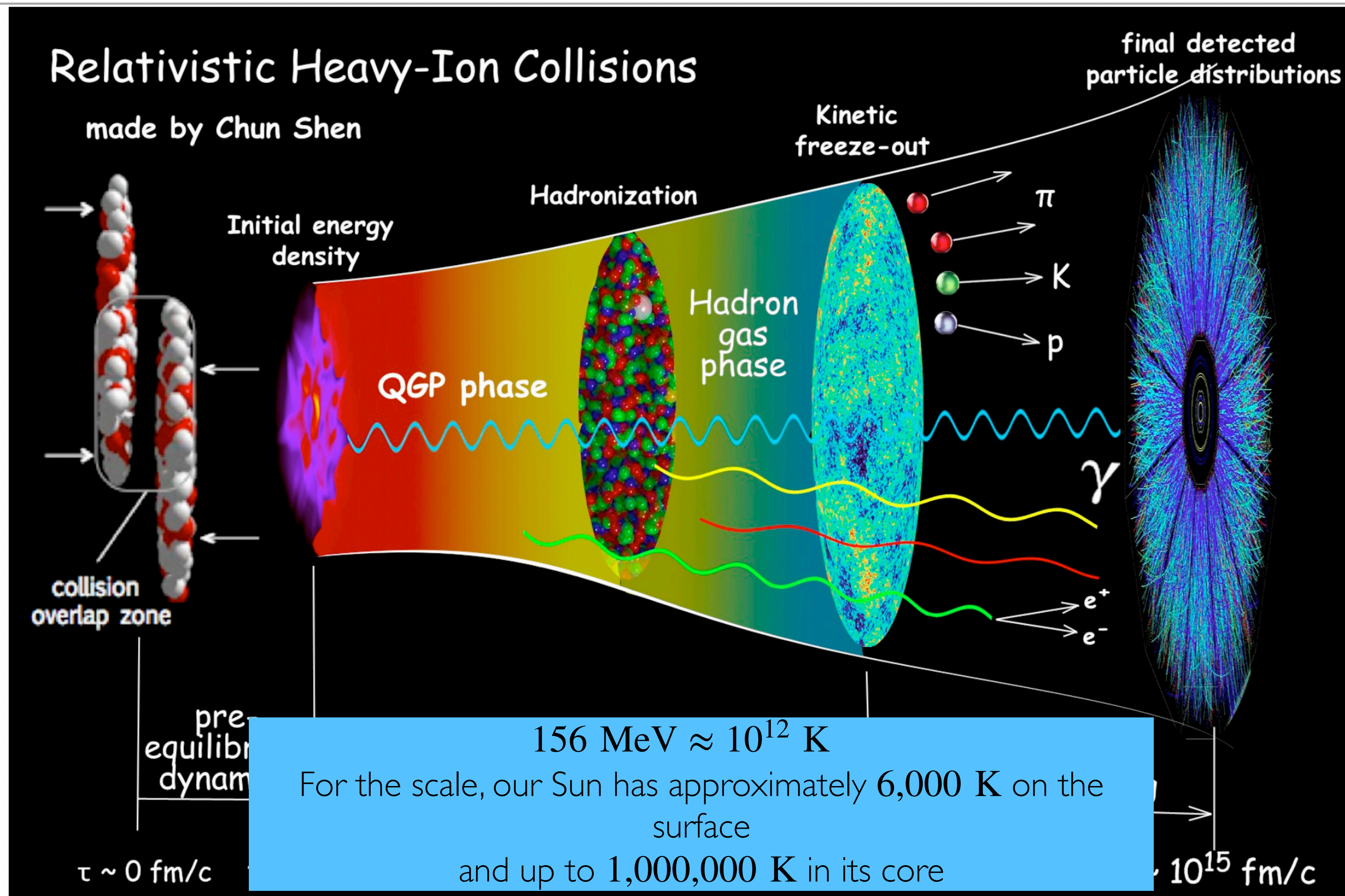


UNIVERSITY OF
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Relativistic heavy-ion collisions



QGP: **Thermalized** state of quarks and gluons with a dimension much larger than that of a nucleon (**deconfined**).



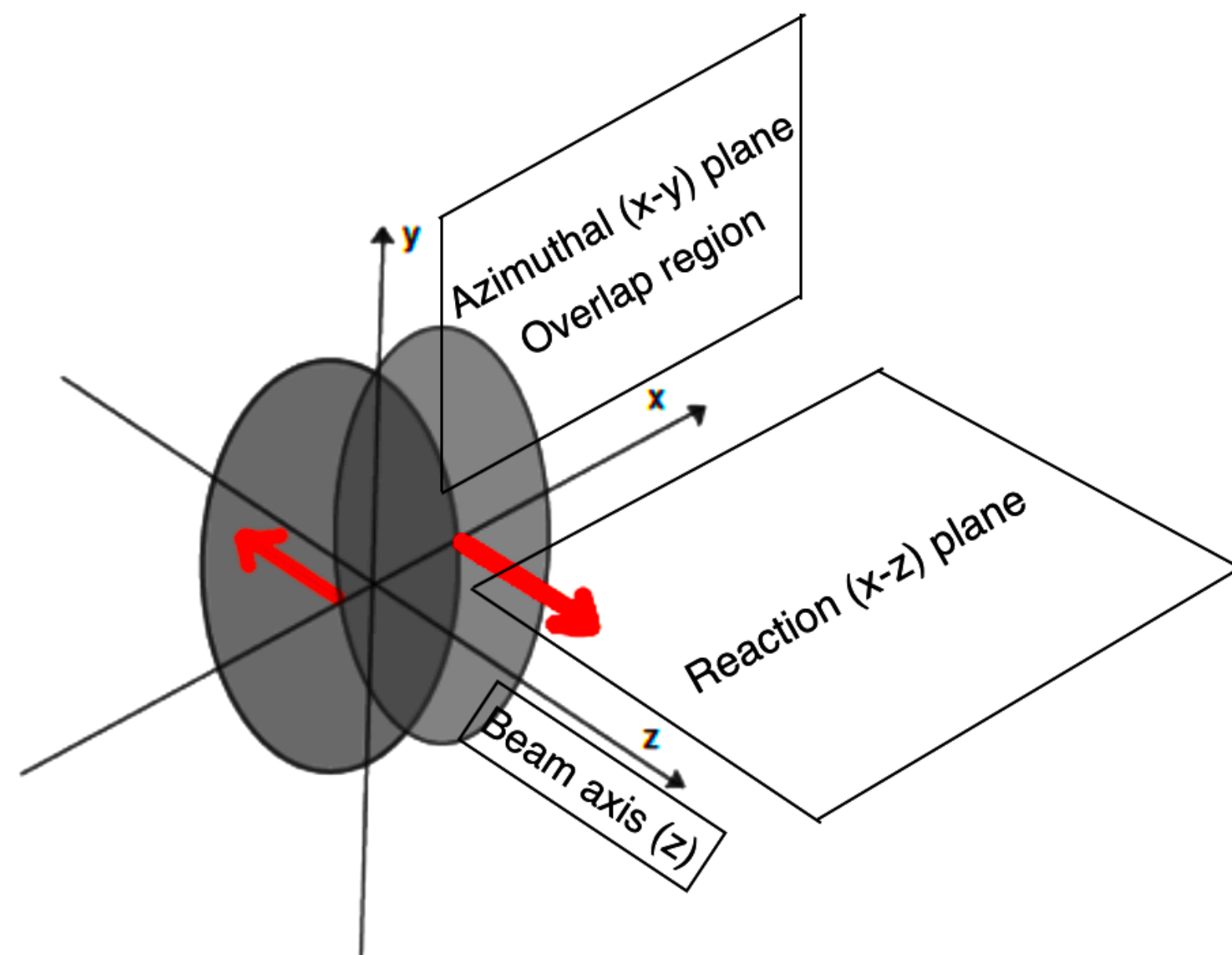
Outline

- Quark-gluon plasma (QGP—thermalized and deconfined partonic medium) formation in relativistic heavy-ion collisions— baseline for collectivity in small collision systems.
- Comparison between small systems and the heavy-ion results—what do we learn?
- Is there an on/off switch for this phenomenon??



Collectivity in heavy-ion collisions (Anatomy)

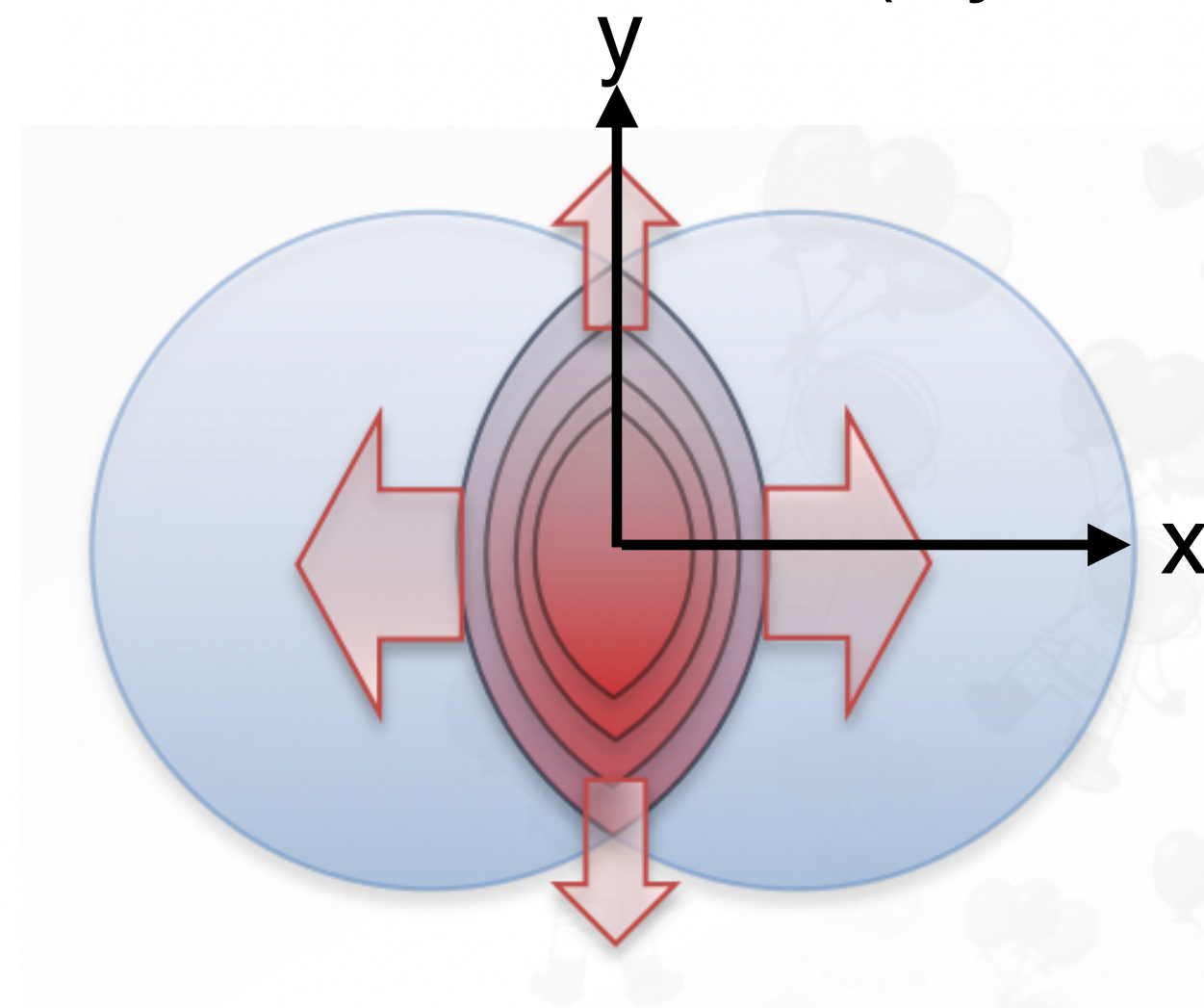
Initial state geometry + Final state interaction (Hydrodynamics description)



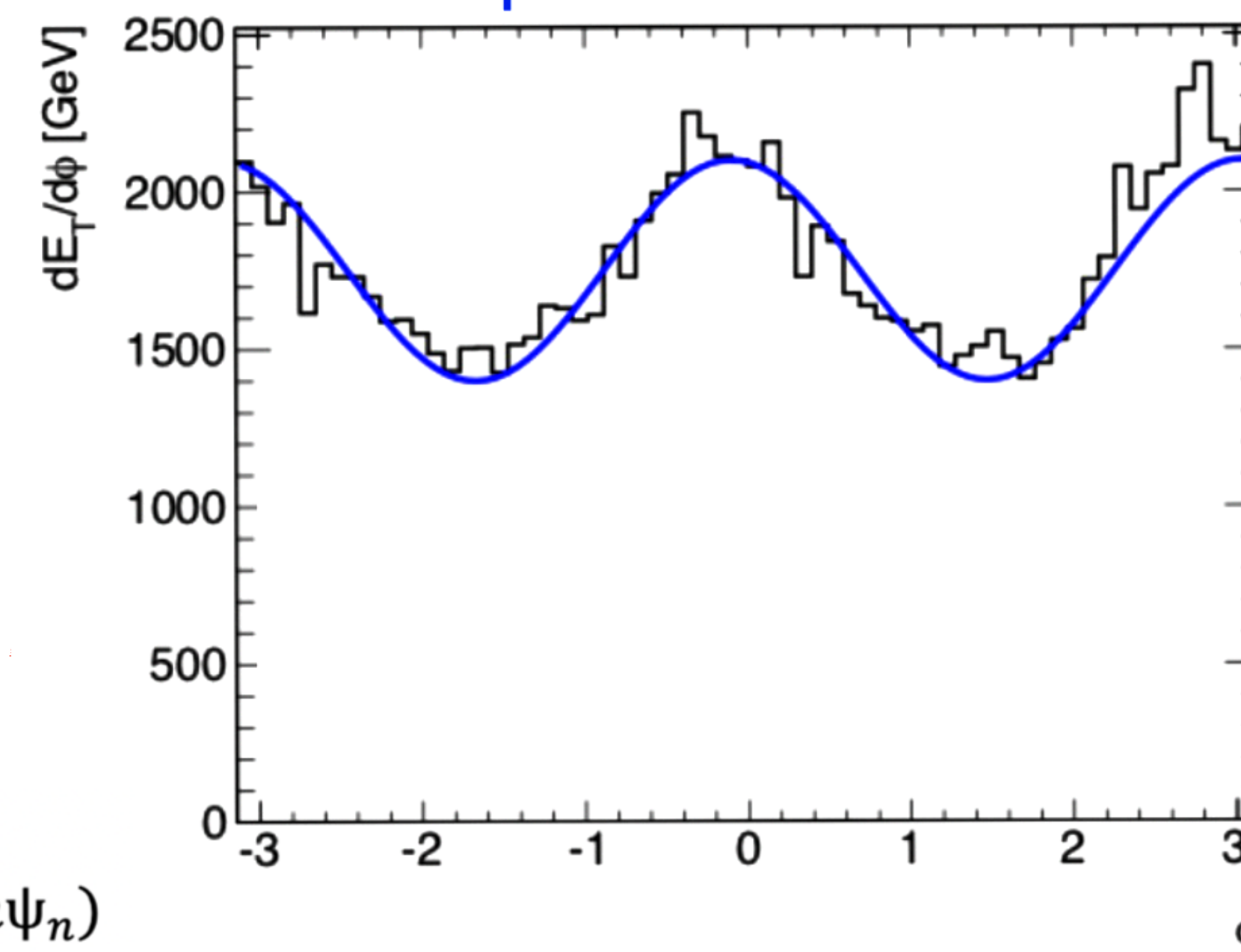
Single particle distribution: $P(\phi) \equiv$

$$\frac{dN^{\text{singlets}}}{d\phi} \propto 1 + 2 \sum_n v_n \cos(n\phi - n\psi_n)$$

$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$



Final particle distributions



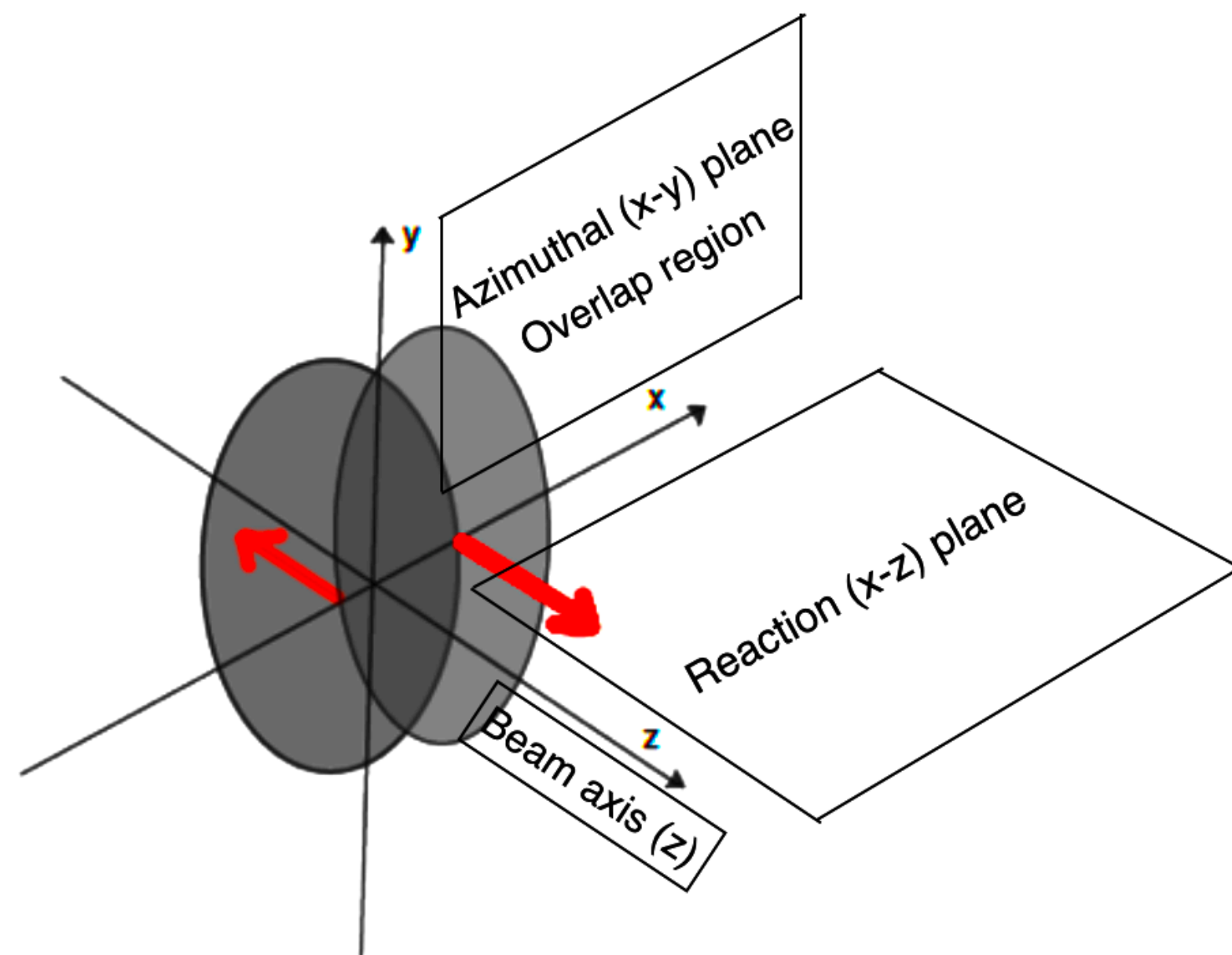
$P(\phi) \rightarrow$

Driven by system properties
(pressure+ geometry)



Collectivity in heavy-ion collisions (Anatomy)

Initial state geometry + Final state interaction (Hydrodynamics description)

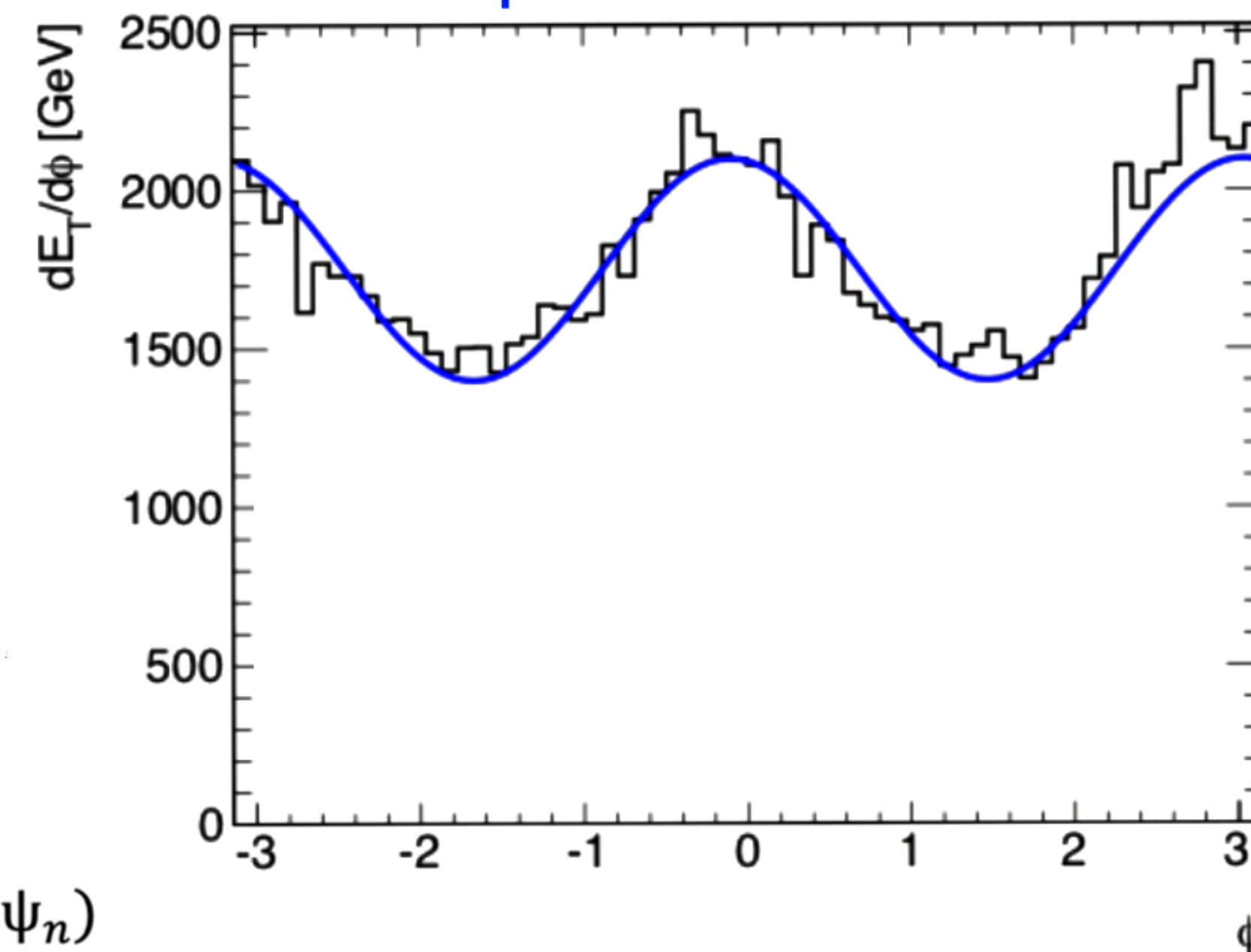


Single particle distribution: $P(\phi) \equiv$

$$\frac{dN^{\text{singels}}}{d\phi} \propto 1 + 2 \sum_n v_n \cos(n\phi - n\psi_n)$$

$$v_n = \langle \cos n(\phi - \Psi_n) \rangle$$

Final particle distributions



$P(\phi) \rightarrow$

Driven by system properties
(pressure+ geometry)

Pair distribution: $P(\phi_1) * P(\phi_2) \equiv$

$$\frac{dN^{\text{pairs}}}{d\Delta\phi} \propto 1 + 2 \sum_n V_{n\Delta} \cos(n\Delta\phi)$$

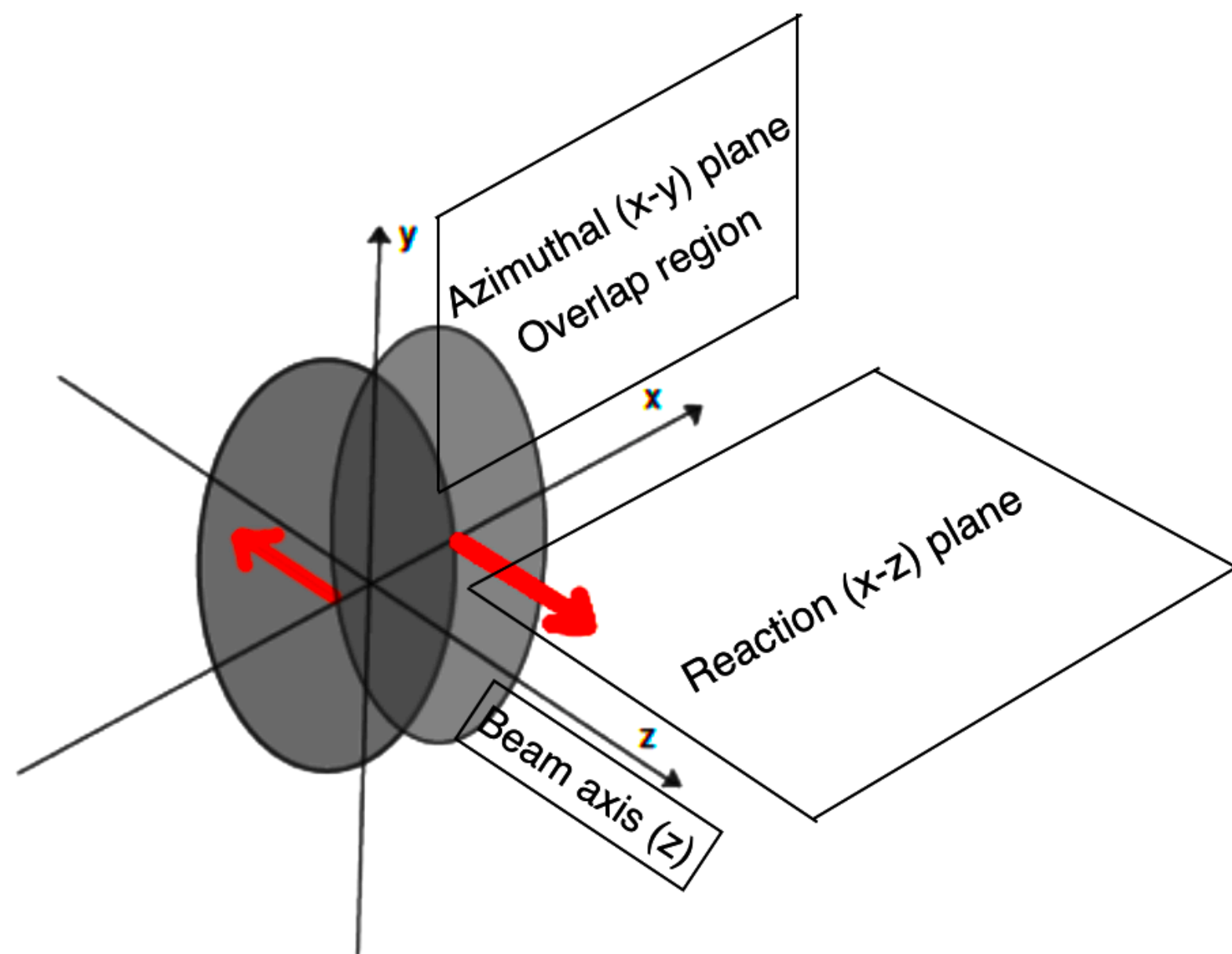
$$V_{n\Delta} = \langle \langle \cos n(\varphi_1 - \Psi_n) \cdot \cos n(\varphi_2 - \Psi_n) \rangle \rangle = \langle \langle \cos n[(\varphi_1 - \Psi_n) - (\varphi_2 - \Psi_n)] \rangle \rangle = \langle \langle \cos n(\varphi_1 - \varphi_2) \rangle \rangle$$

The pair distribution gets rid of the event plane (difficult to determine experimentally)



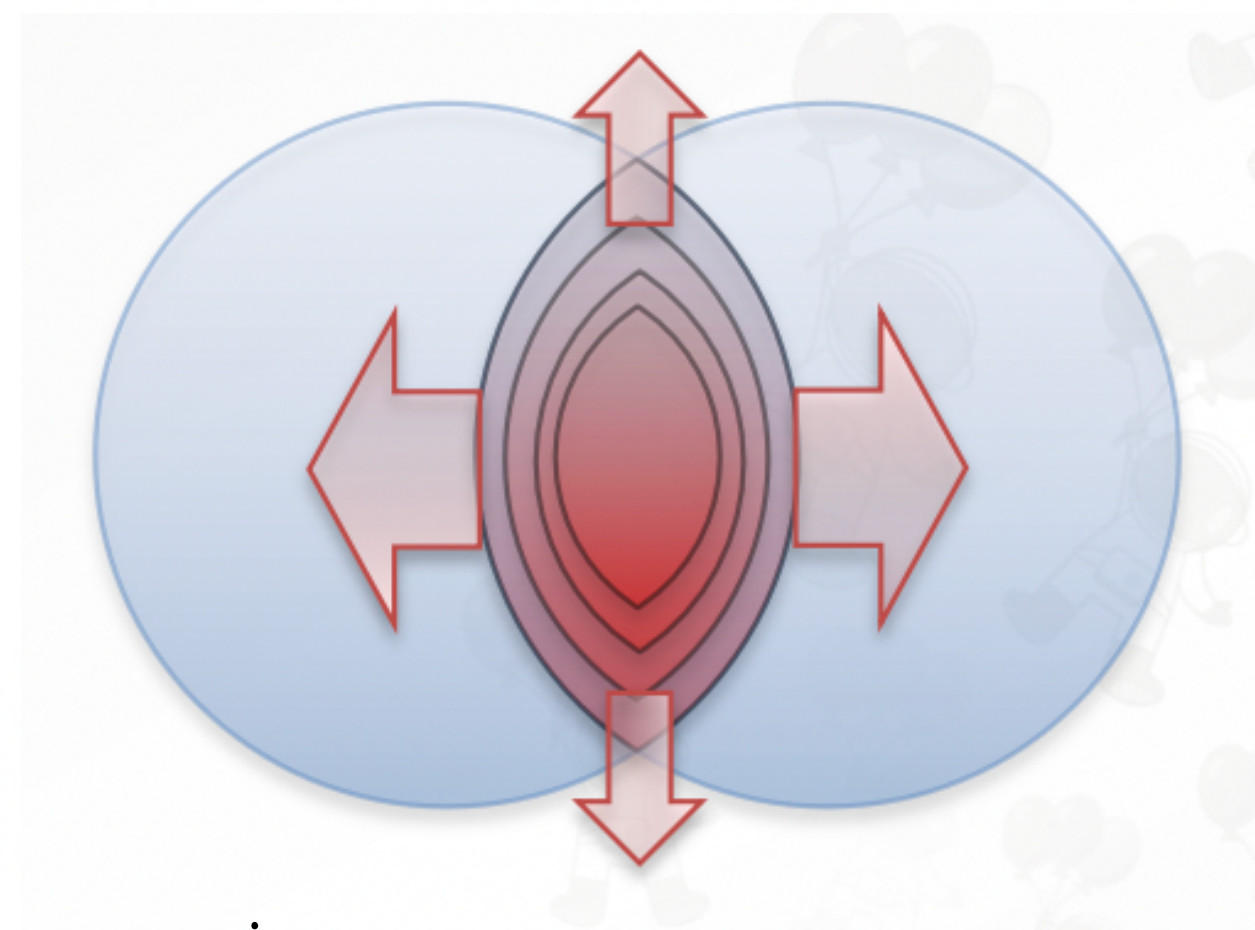
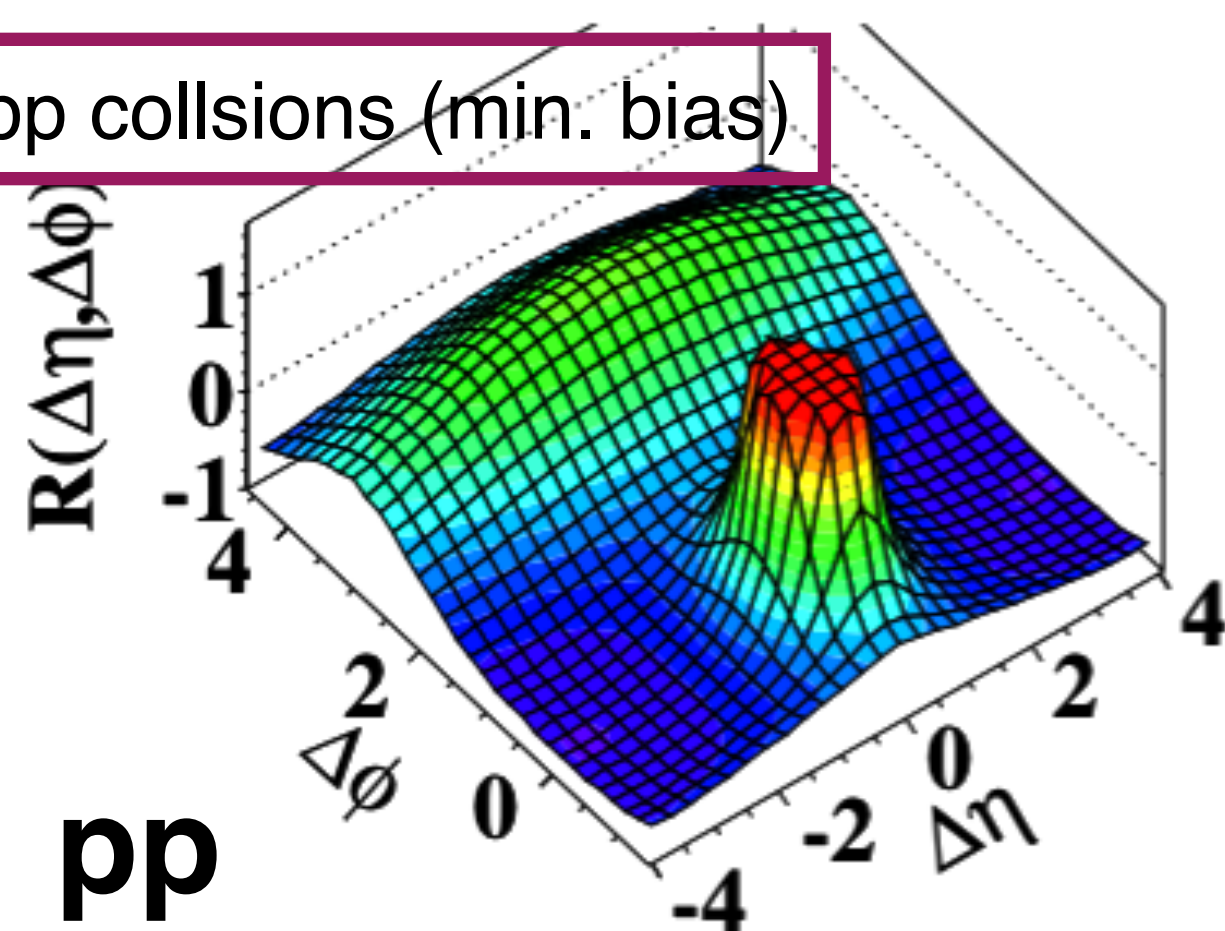
Collectivity in heavy-ion collisions (Anatomy)

Initial state geometry + Final state interaction (Hydrodynamics description)

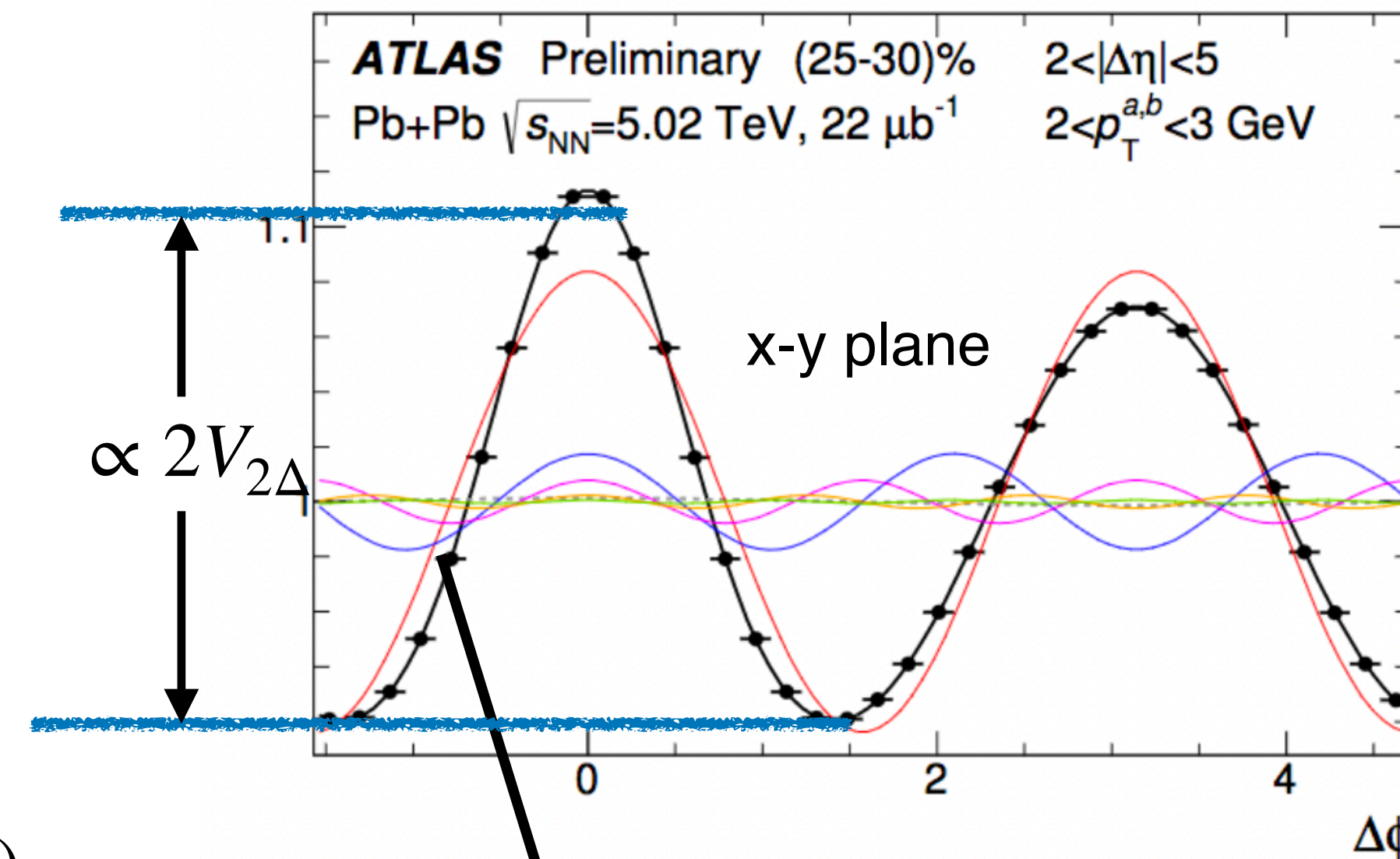


CMS MinBias, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$

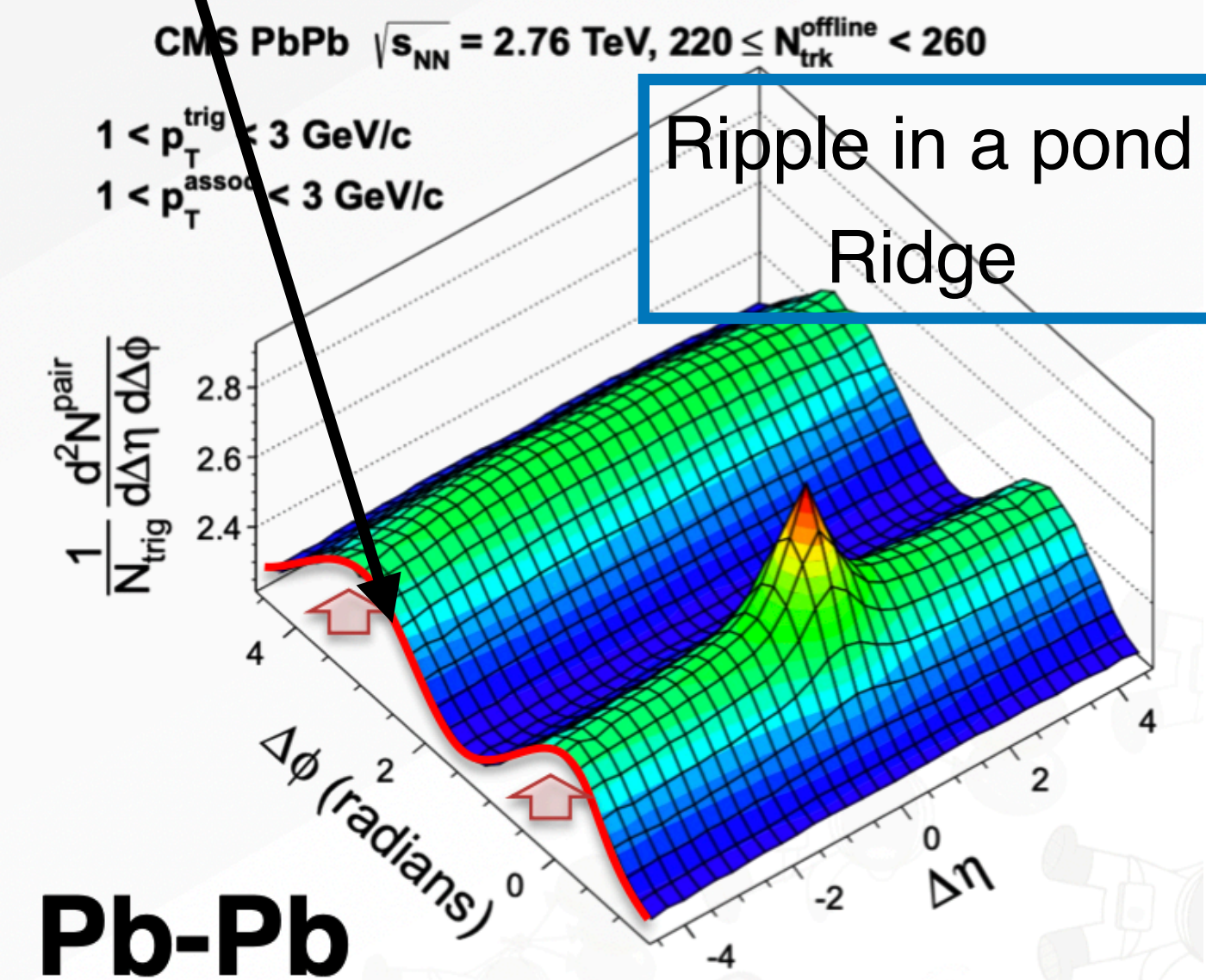
No Ridge in pp collisions (min. bias)



$$\frac{dN^{pairs}}{d\Delta\phi} \propto 1 + 2 \sum_n V_{n\Delta} \cos(n\Delta\phi)$$

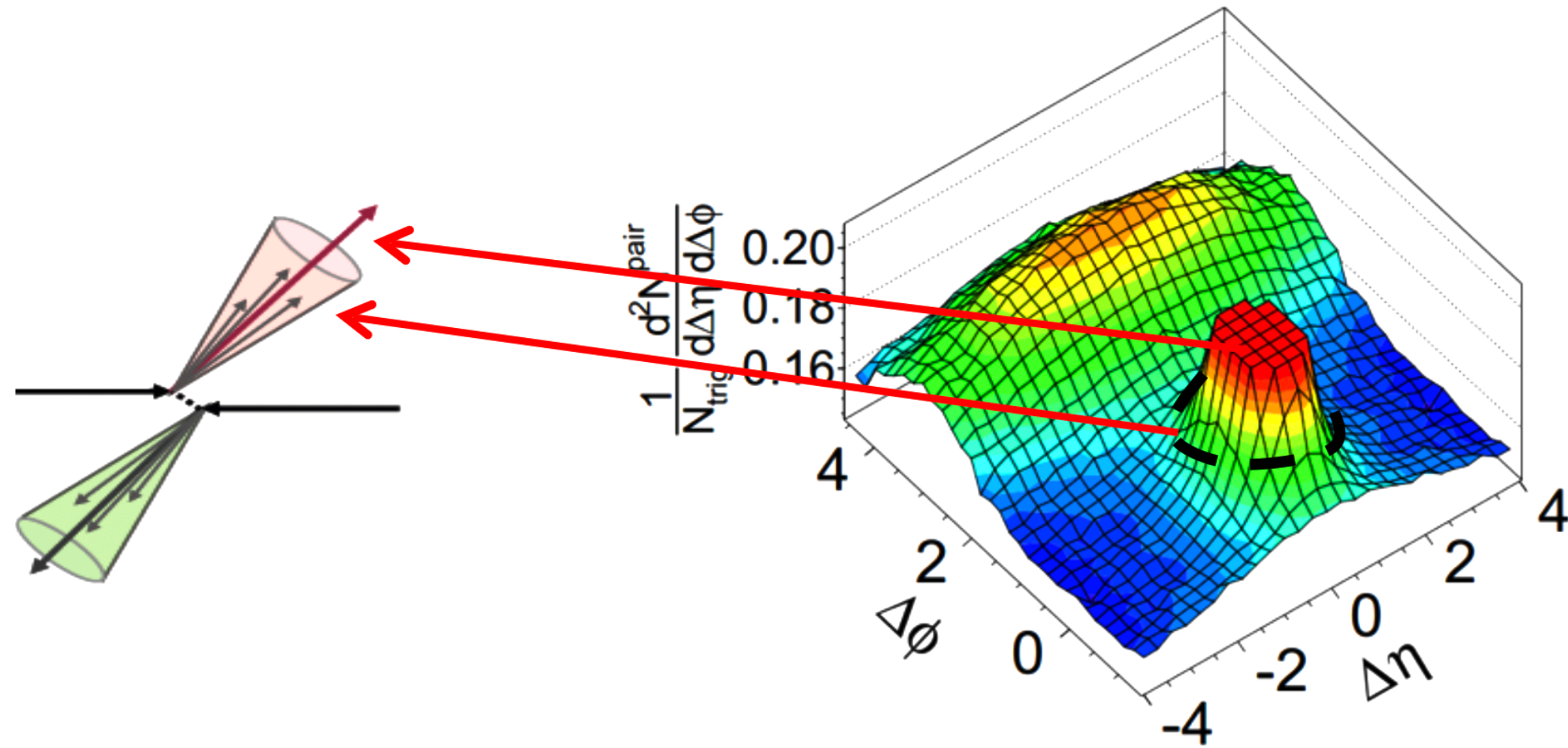


Phys. Lett. B 724 (2013) 213

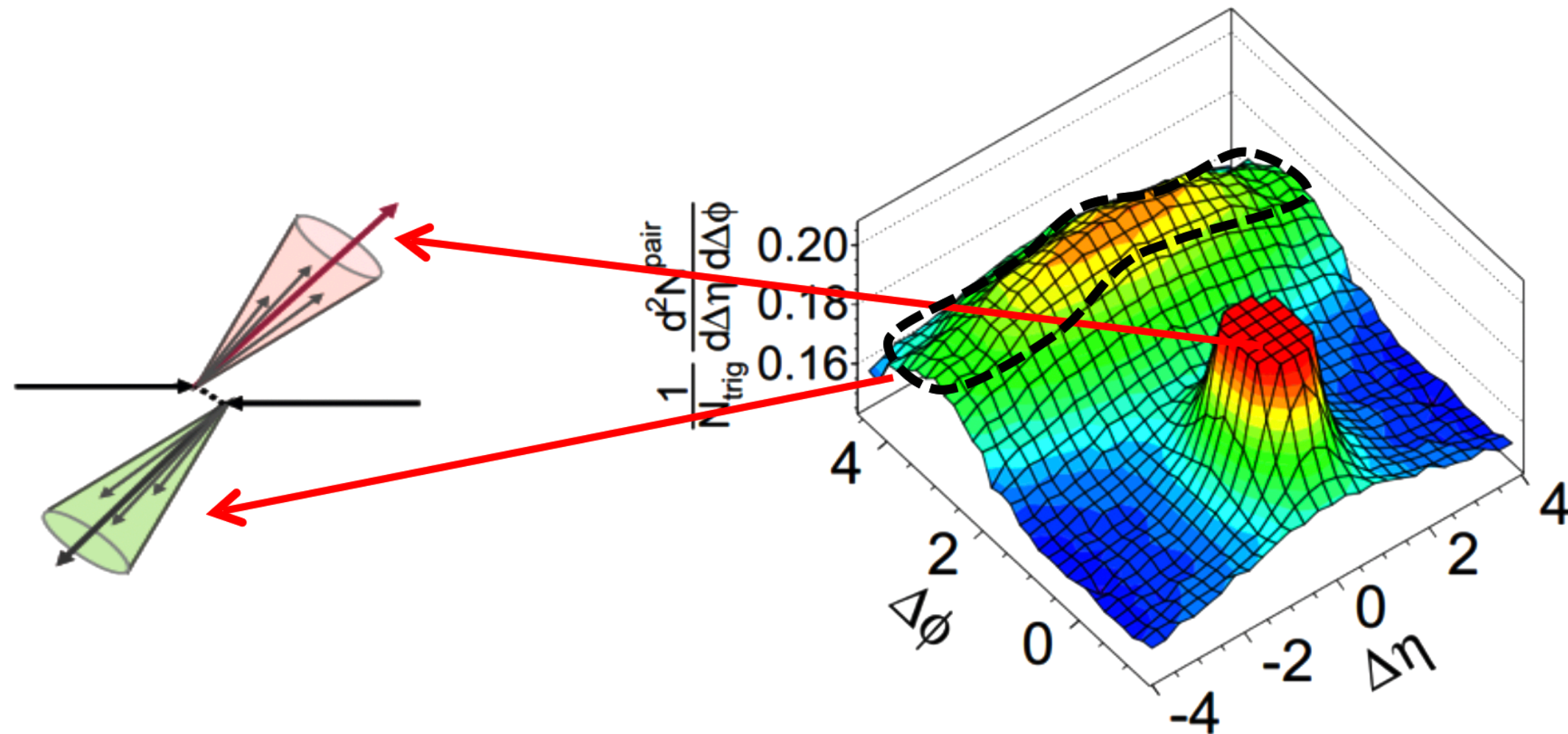




Non flow: need to be removed



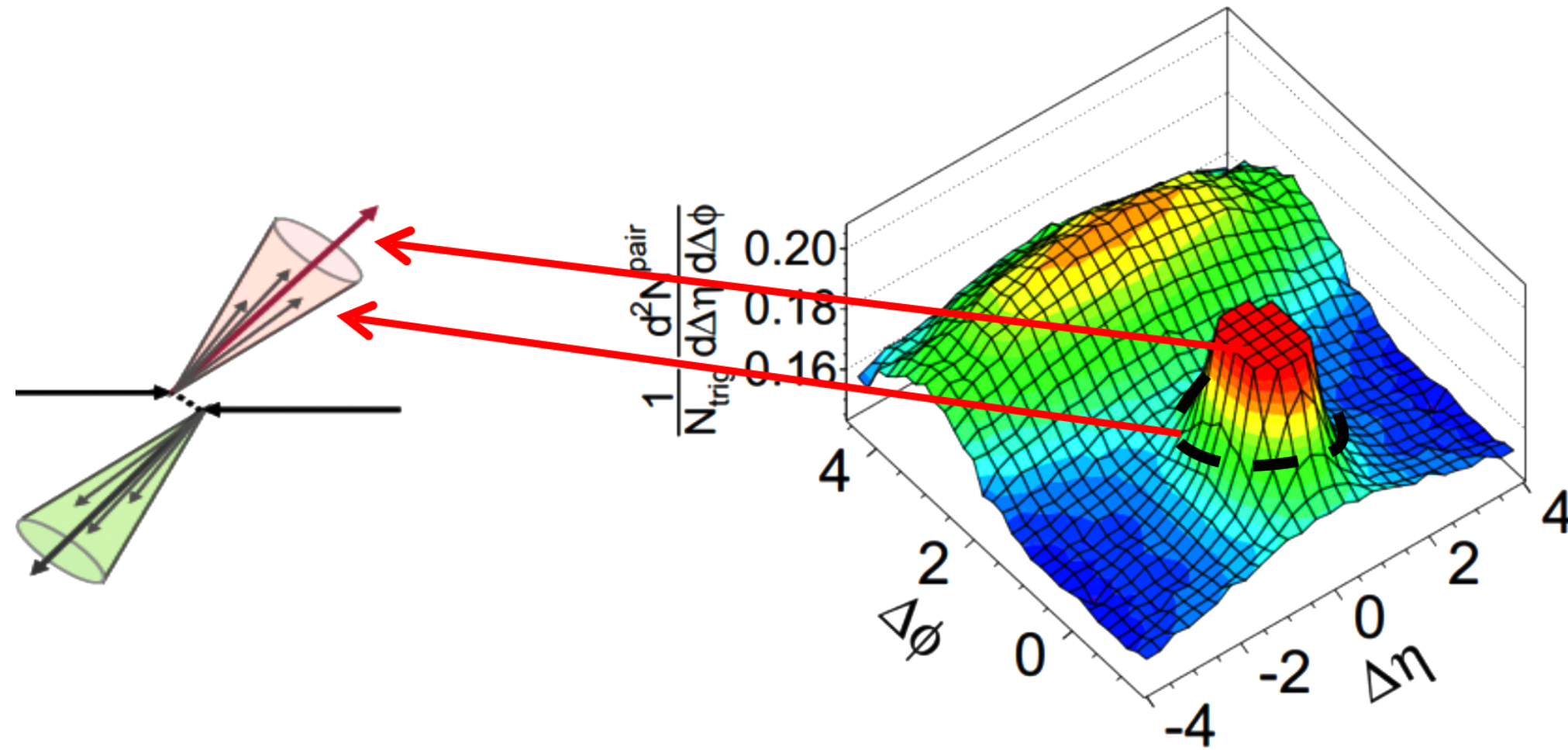
Near-side ($\Delta\phi, \Delta\eta \sim 0$) correlations from single jets



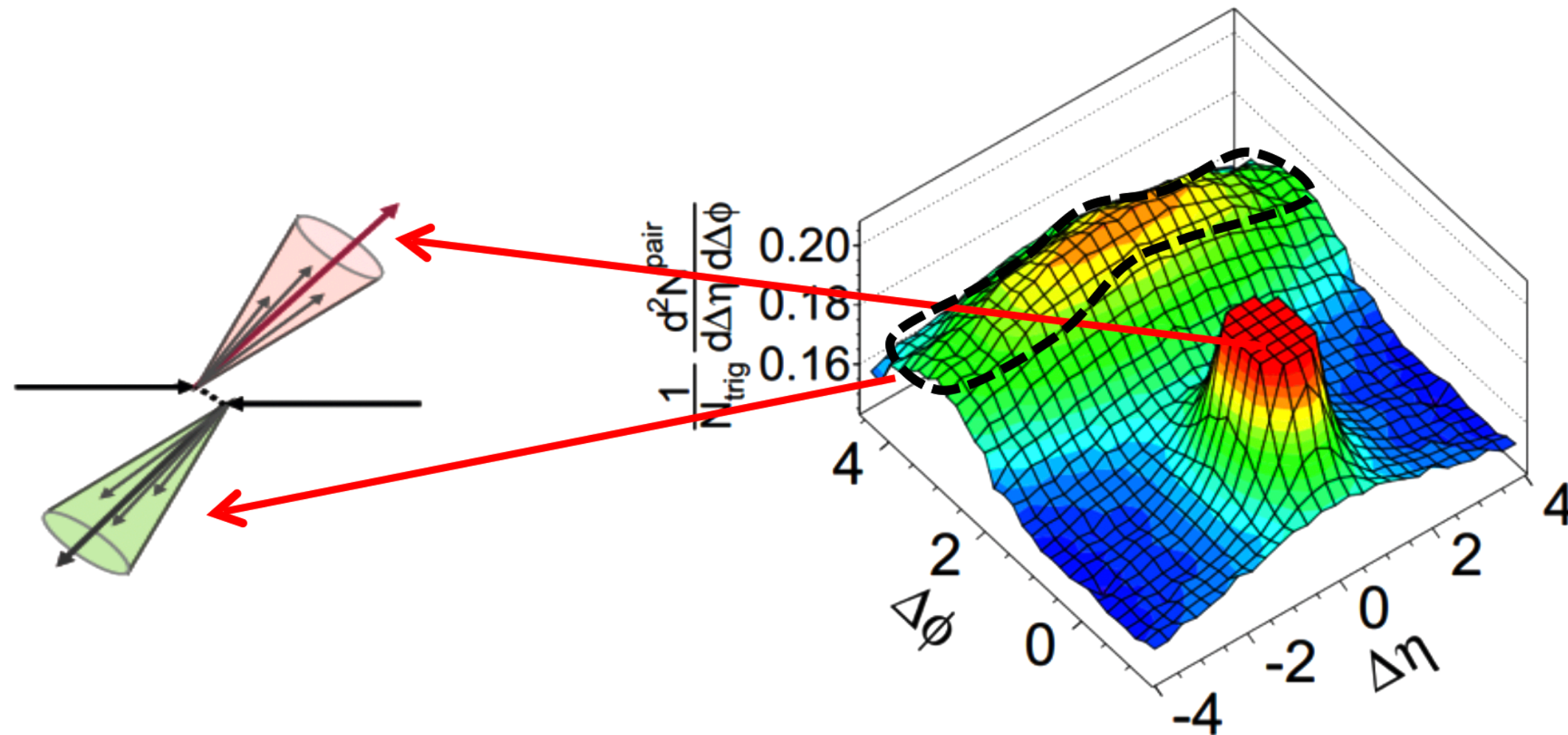
Away-side ($\Delta\phi \sim \pi$) back-to-back jet correlations:
two jets may have different rapidities: $\Delta\eta \neq 0$



Non flow: need to be removed

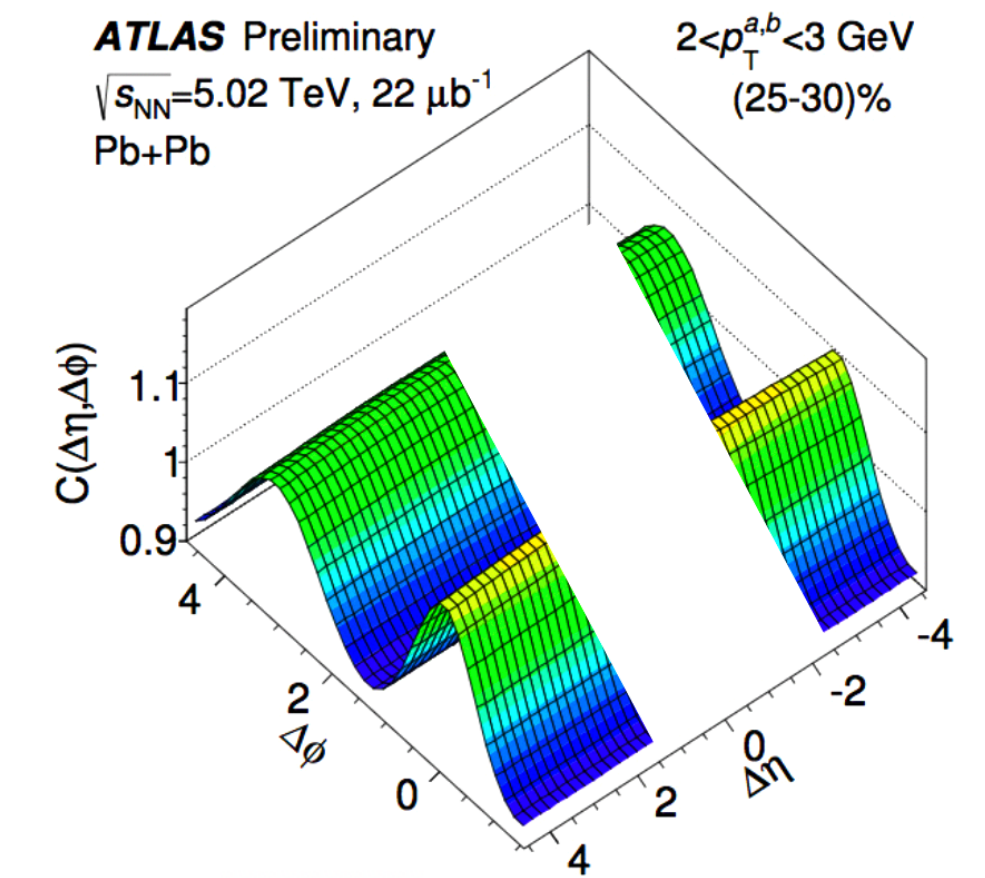


Near-side ($\Delta\phi, \Delta\eta \sim 0$) correlations from single jets



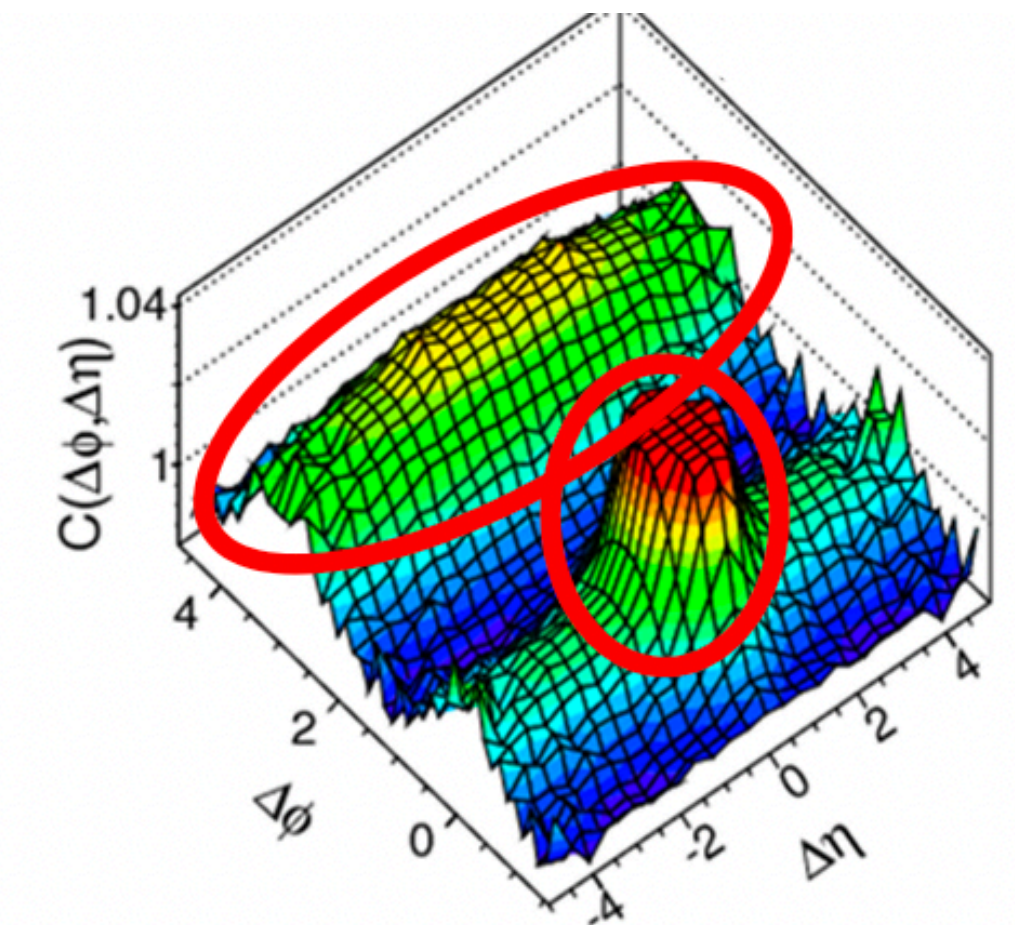
Non-flow: Jets, resonances
Short range correlations

Away-side ($\Delta\phi \sim \pi$) back-to-back jet correlations:
two jets may have different rapidities: $\Delta\eta \neq 0$



A+A

Issue— non-flow removal.

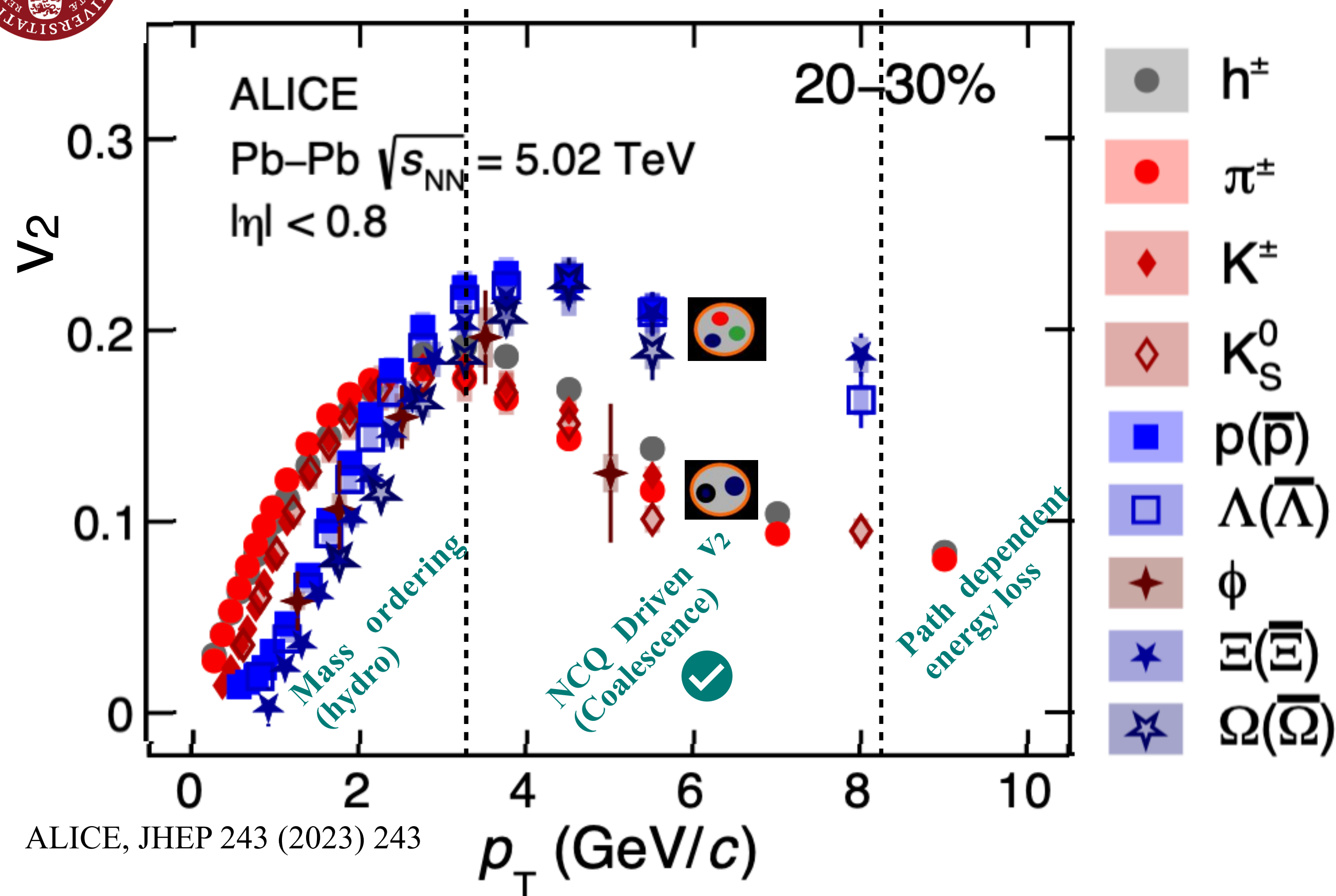


p+A

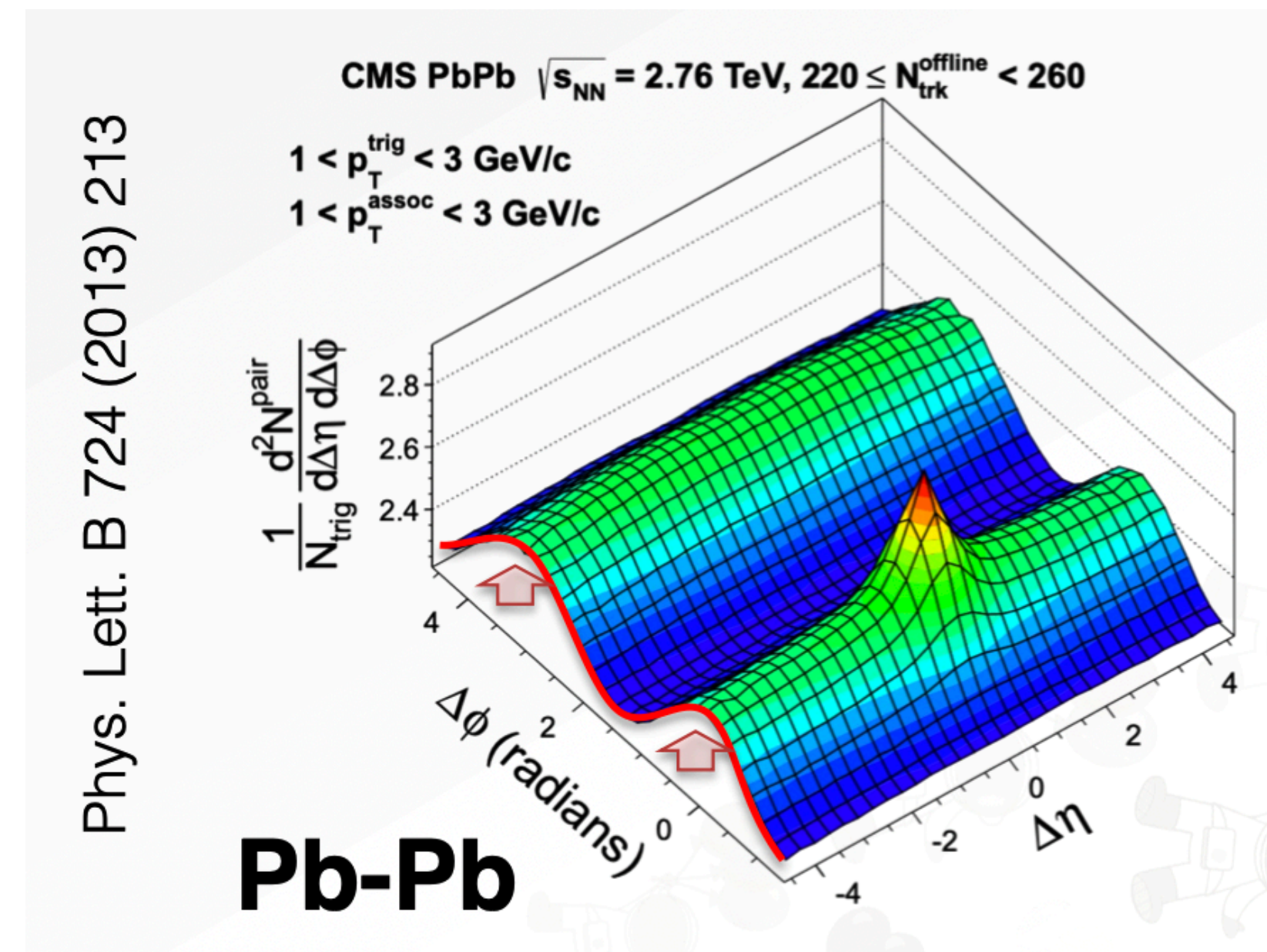
Major issue— non-flow removal.



Baseline: Collective features in heavy-ion collisions



ALICE, JHEP 243 (2023) 243



Phys. Lett. B 724 (2013) 213

Ridge: “Thermalized”
What about “deconfined”?

- low p_T ($p_T \lesssim 3$ GeV/c) — Mass ordering — Interplay between radial and elliptic flow ([Hydro: Thermalized](#)).
- [Intermediate \$p_T\$](#) ($3 < p_T \lesssim 8$ GeV/c) — NCQ driven Baryon-meson splitting and grouping — quark coalescence, sign of partonic collectivity ([Thermalized + deconfined](#)).

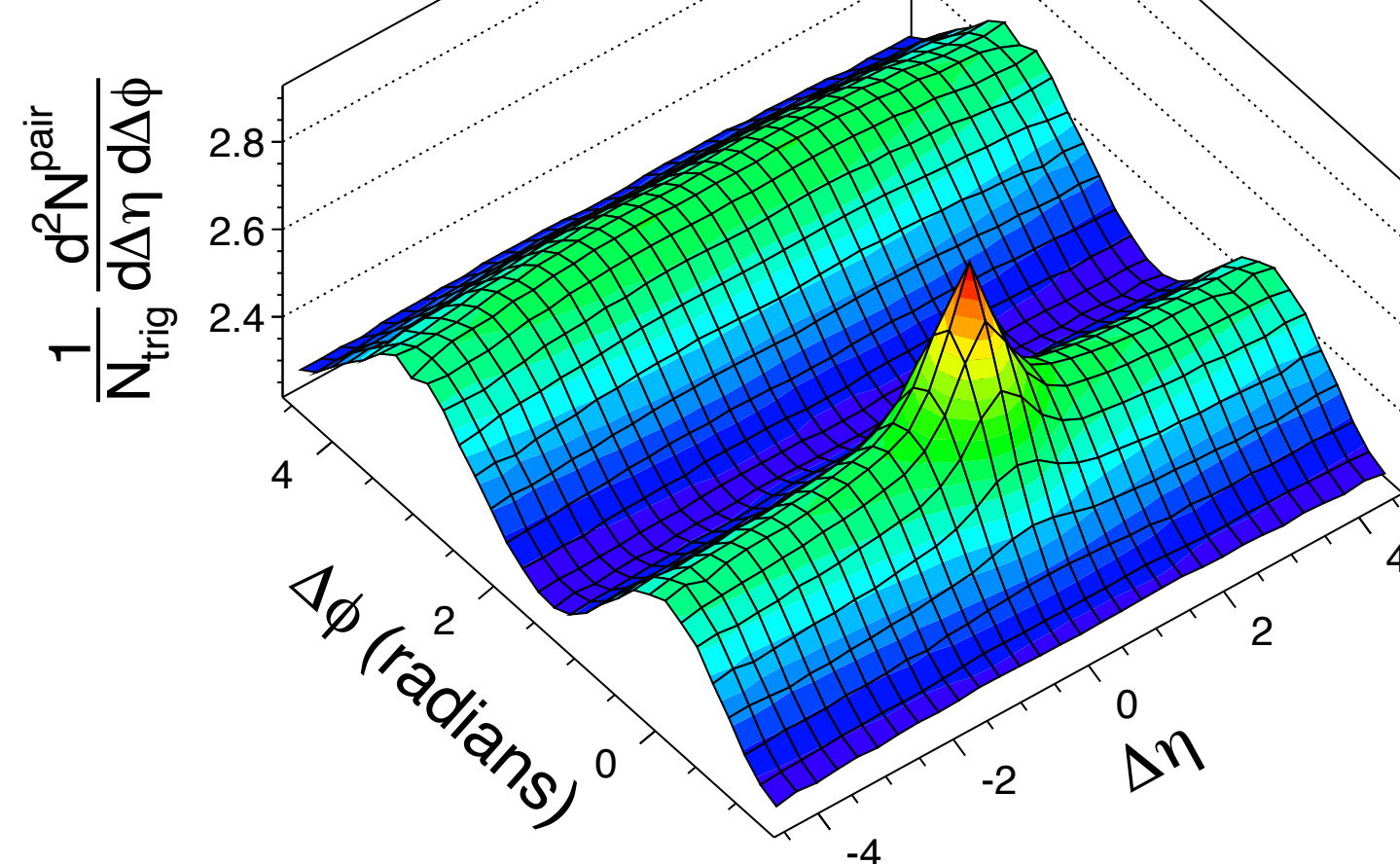
What about small (pp, p-Pb) collision systems? Just a non-QGP baseline?



Collectivity in small systems?

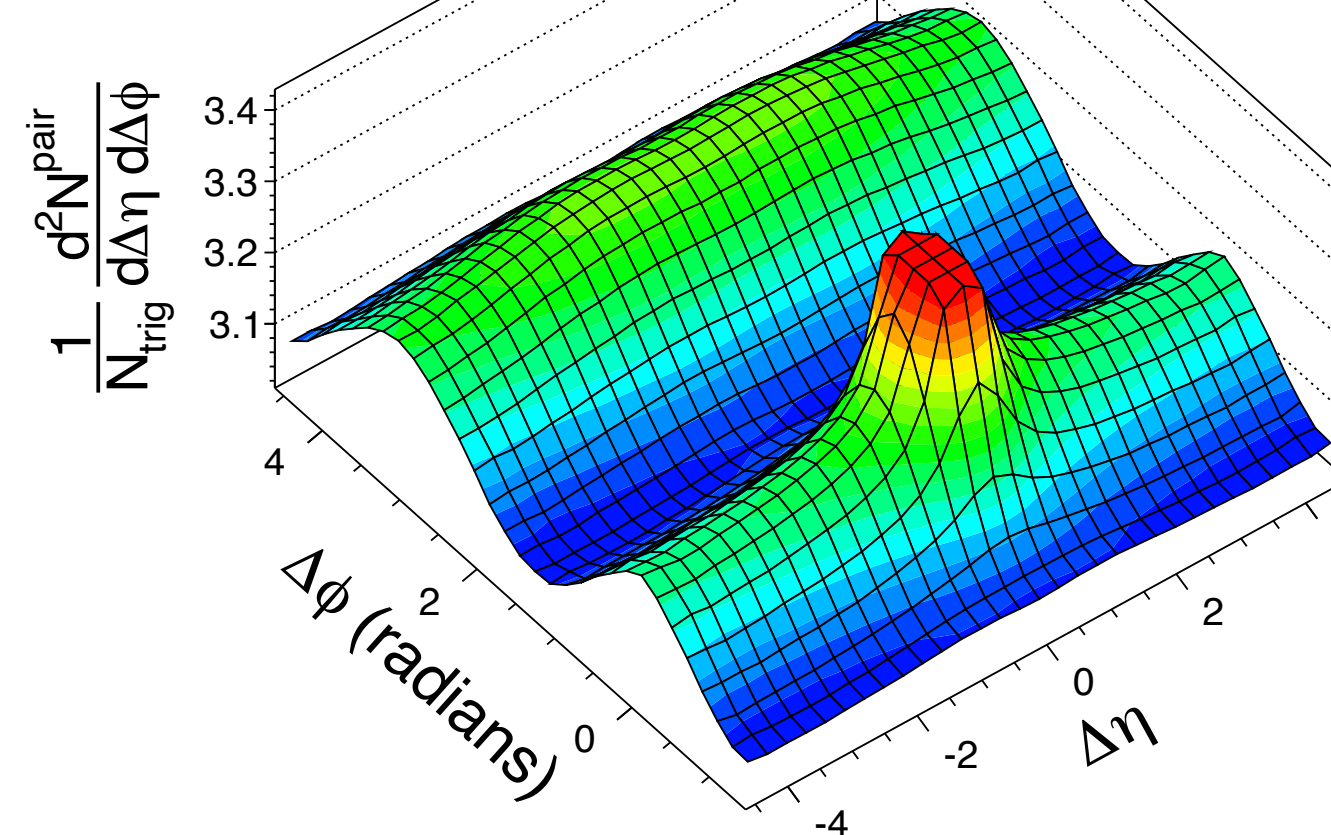
(a) CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 \leq N_{trk}^{offline} < 260$

$1 < p_T^{trig} < 3$ GeV/c
 $1 < p_T^{assoc} < 3$ GeV/c

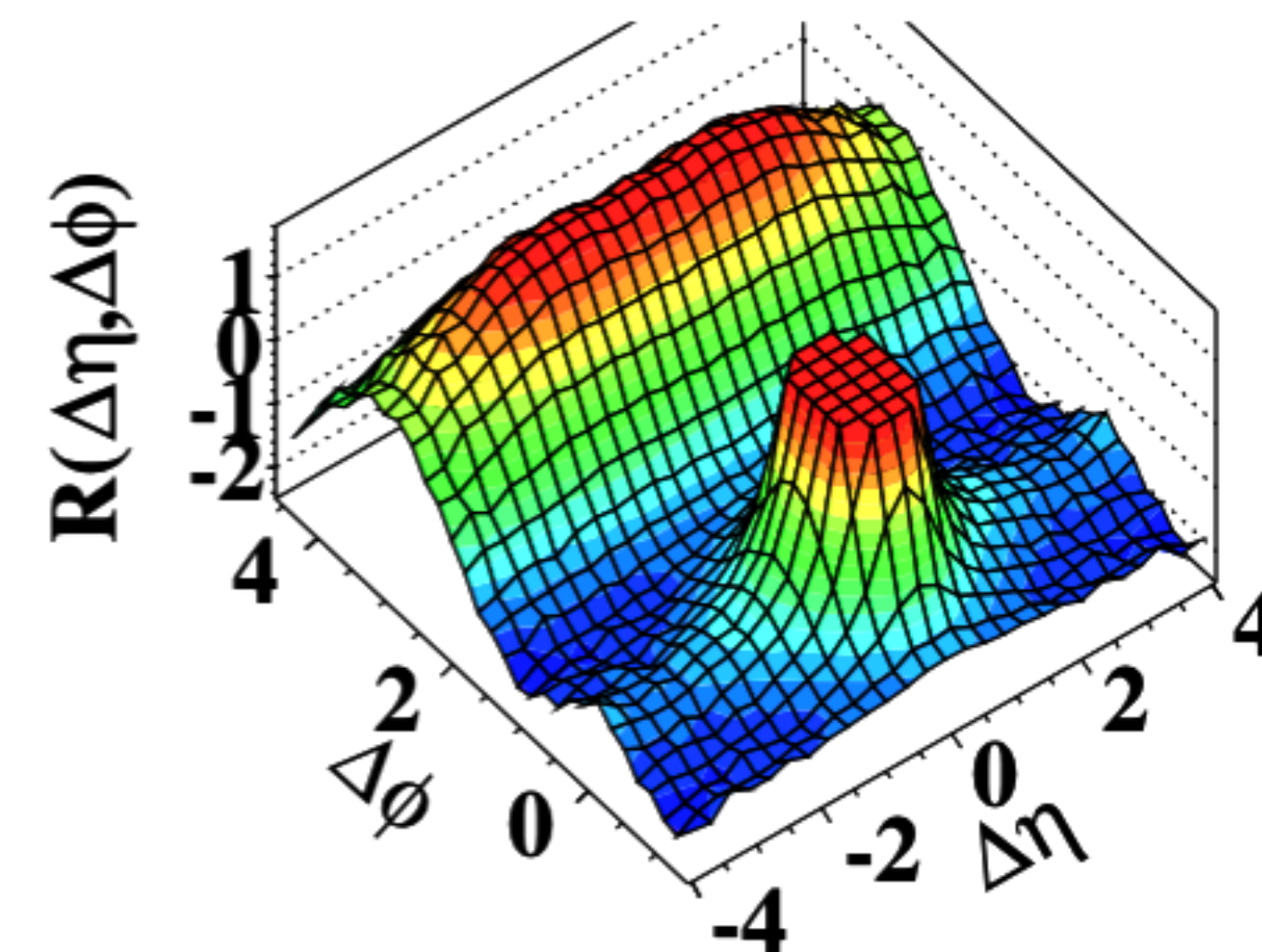


(b) CMS pPb $\sqrt{s_{NN}} = 5.02$ TeV, $220 \leq N_{trk}^{offline} < 260$

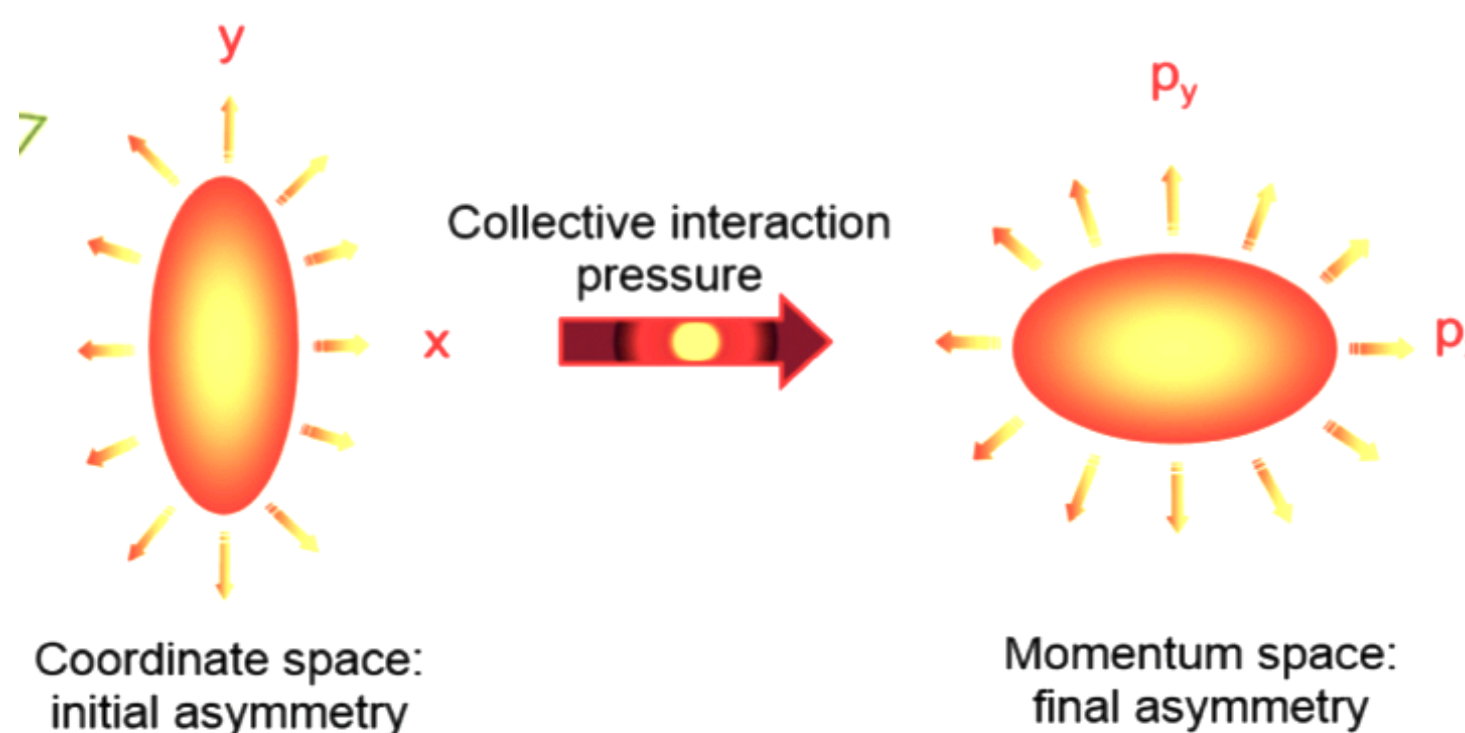
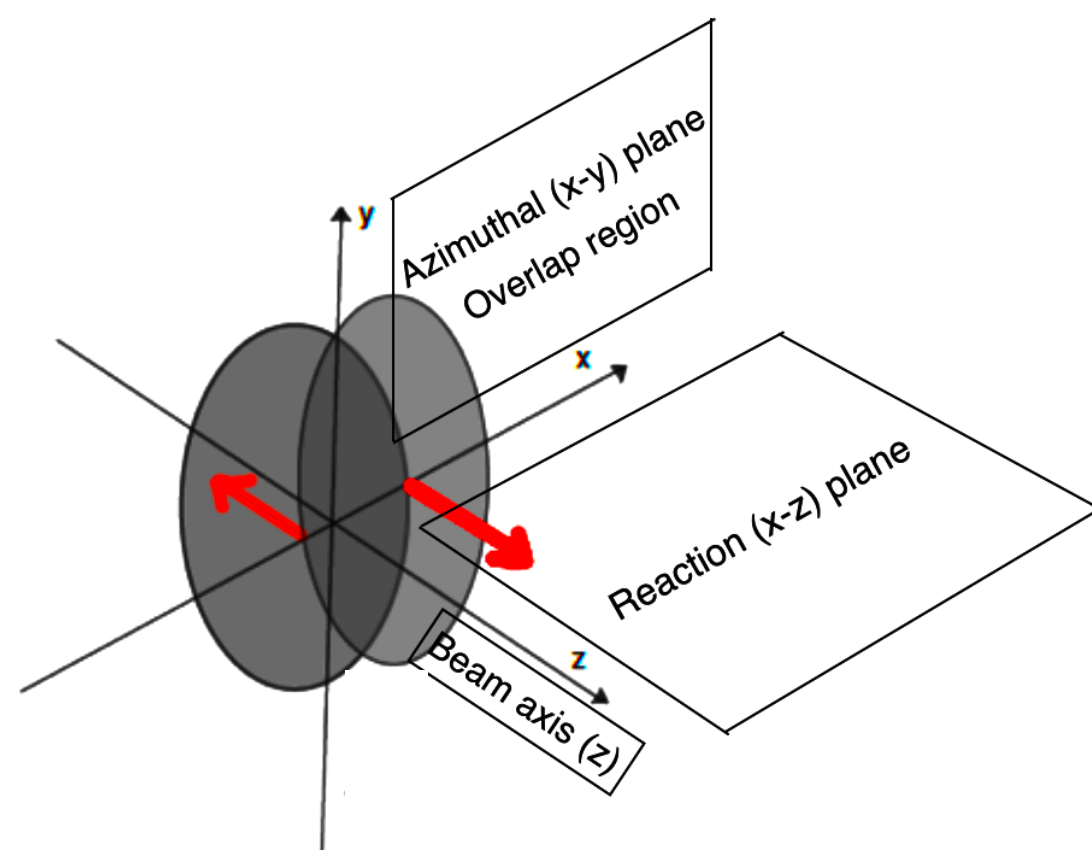
$1 < p_T^{trig} < 3$ GeV/c
 $1 < p_T^{assoc} < 3$ GeV/c



(d) CMS $N \geq 110$, $1.0 \text{ GeV/c} < p_T < 3.0 \text{ GeV/c}$

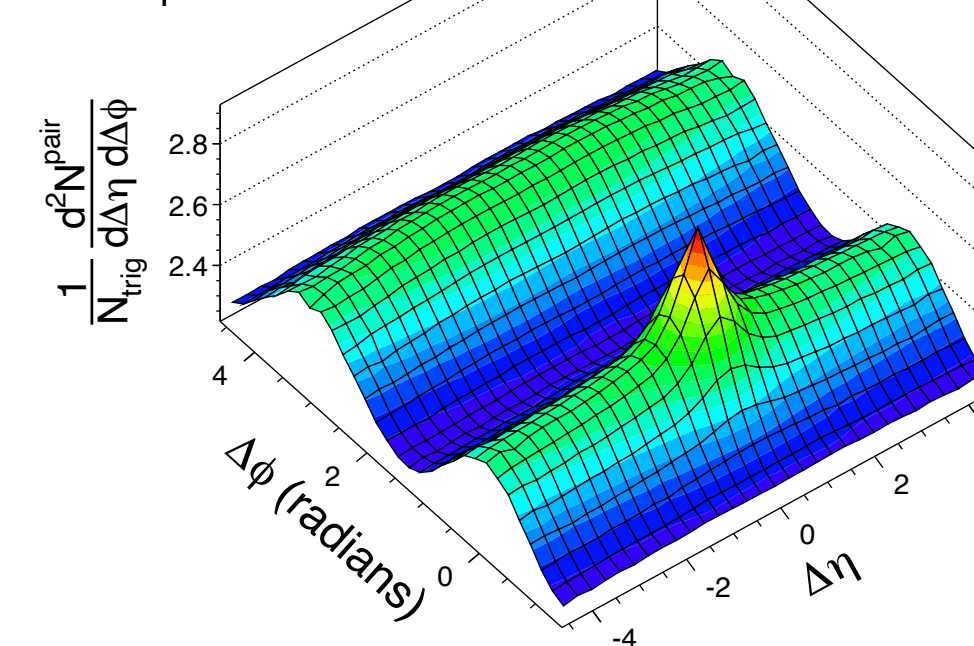


Everything flows (?) - Initial state geometry + Final state interaction (hydro description)



(a) CMS PbPb $\sqrt{s_{NN}} = 2.76$ TeV, $220 \leq N_{trk}^{offline} < 260$

$1 < p_T^{trig} < 3$ GeV/c
 $1 < p_T^{assoc} < 3$ GeV/c





Most unexpected discovery at the LHC!

World US elections 2024 UK Climate crisis Ukraine Environment **Science** Global development Football Tech Business Obituaries

Life and Physics
Science

This article is more than 14 years old

A surprise from the LHC already!

The CMS experiment at the Large Hadron Collider (LHC) announced a surprise yesterday which may dramatically change our ideas about quarks, gluons and protons

There was a special Cern seminar yesterday evening on some **new results** from the CMS experiment, one of the detectors at the Large Hadron Collider. The result is summarised in this colourful landscape.

N>110, 1.0GeV/c<p_T<3.0GeV/c

Most viewed

Trump and Harris to win votes in key final day of campaign

Live US elections live: j... rejects legal challenge against Musk's \$1bn giveaways; Harris v 'a president for all Americans'

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US presidential election updates: Poll shows Biden ahead in early voting; Trump jokes about reporters being shot

22.09.2010 →

Jon Butterworth
Wed 22 Sep 2010 12.05 CEST

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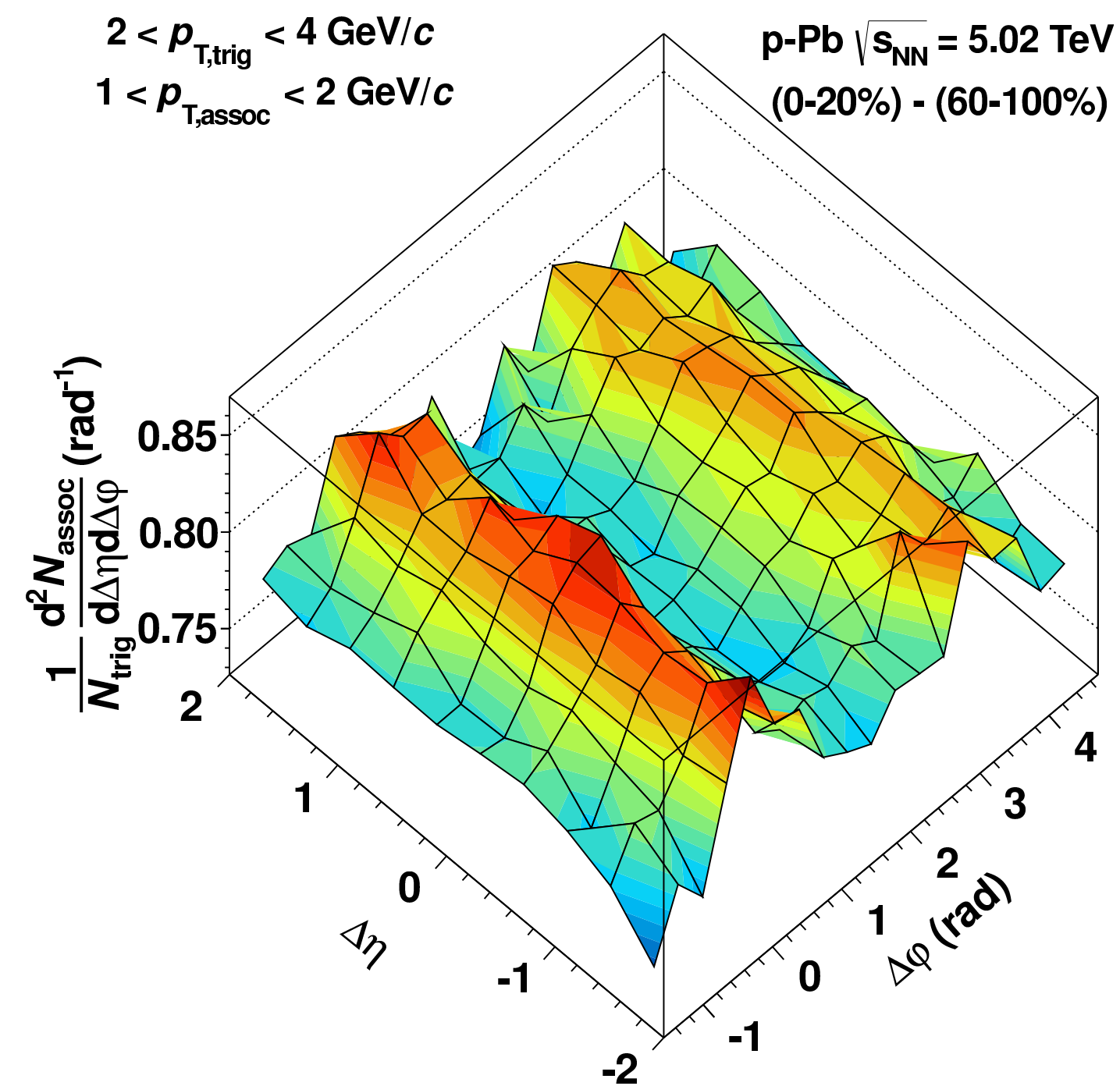
The CMS experiment at the Large Hadron Collider (LHC) announced a surprise yesterday which may dramatically change our ideas about quarks, gluons and protons

[Article link](#)

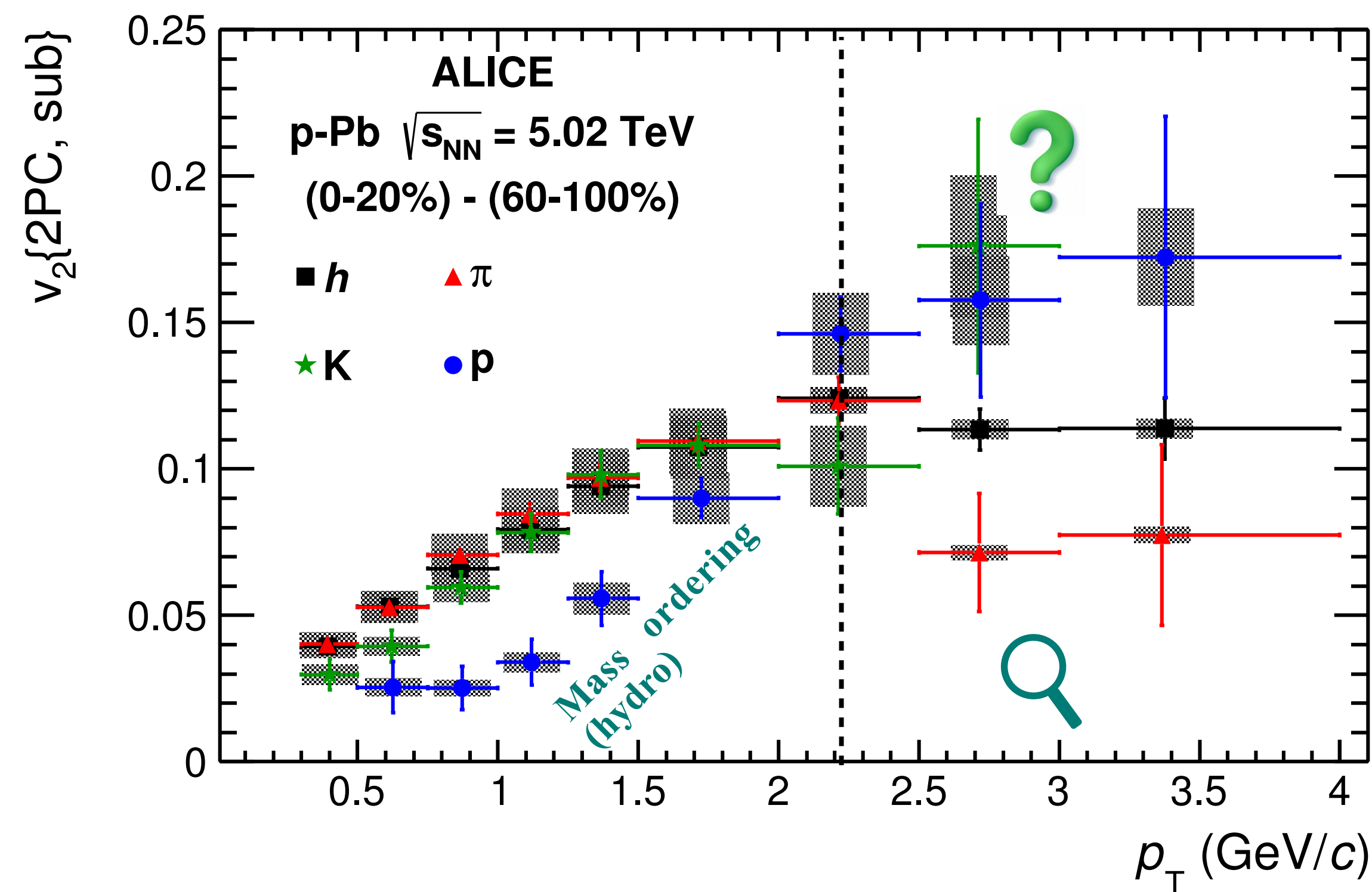
Courtesy: Jan Fiete Grosse-Oetringhaus



Similarity with heavy-ions? Partonic collectivity?



ALICE, Phys.Lett. B719 (2013) 29-41



ALICE, Phys. Lett. B 726 (2013) 164–177

- low p_{T} ($p_{\text{T}} \lesssim 2.5$ GeV/c) — Mass ordering — Interplay between radial and elliptic flow (Hydro: Thermalized).
- No evidence of jet-quenching in p-Pb.
- partonic collectivity can still be probed — probe the NCQ driven baryon-meson splitting and grouping of v_2 at intermediate p_{T} (Q).

Focus: Baryon and meson $v_2(p_{\text{T}})$ at intermediate p_{T}



The ALICE Detector

- Detectors primarily used in this analysis:

1. V0 Detector

Triggering and event classification.

2. Forward Multiplicity Detector (FMD)

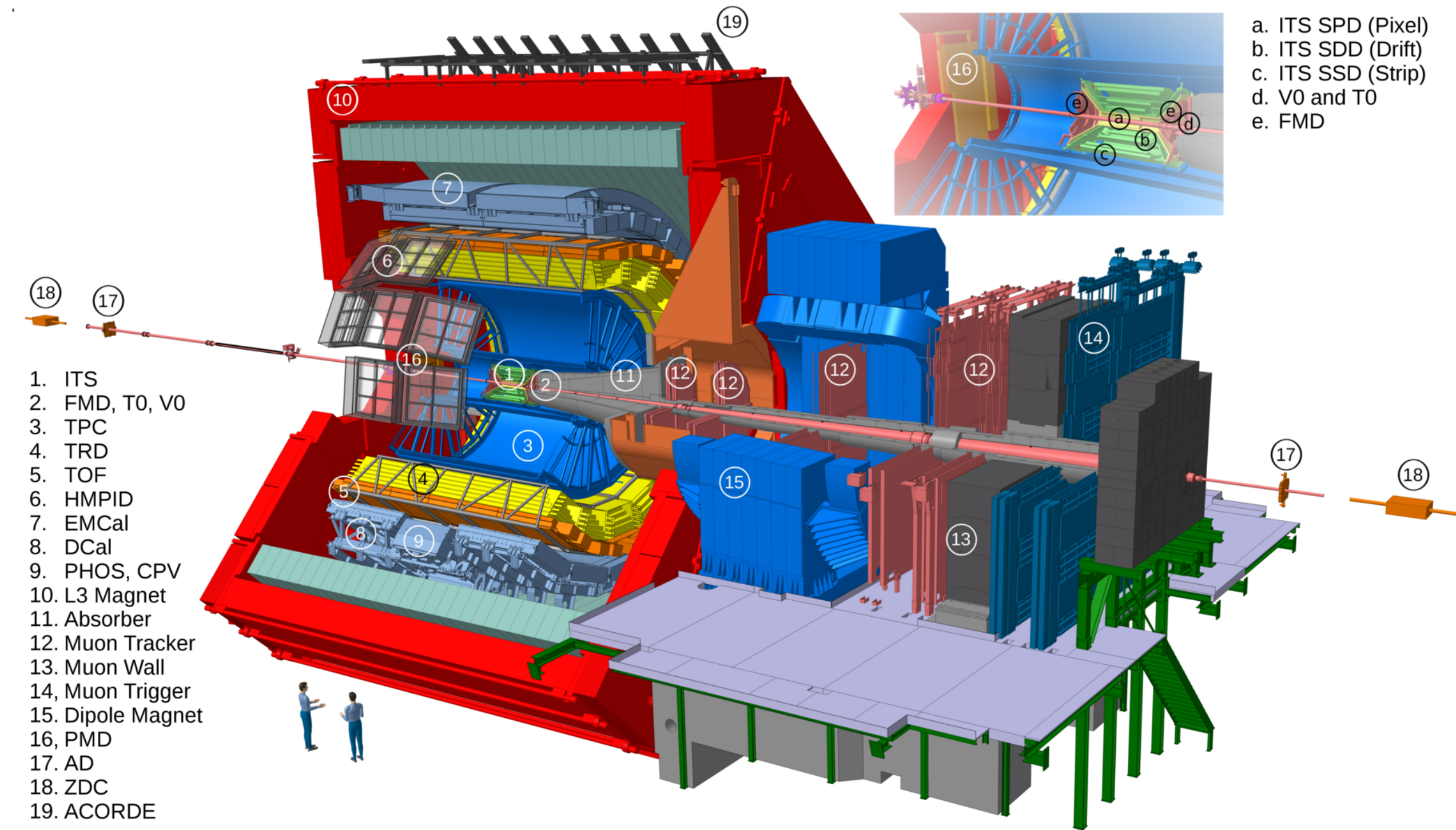
Unique coverage for long range correlation in ALICE.

3. Time-of-Flight (TOF)

Particle identification.

4. Time Projection Chamber (TPC)

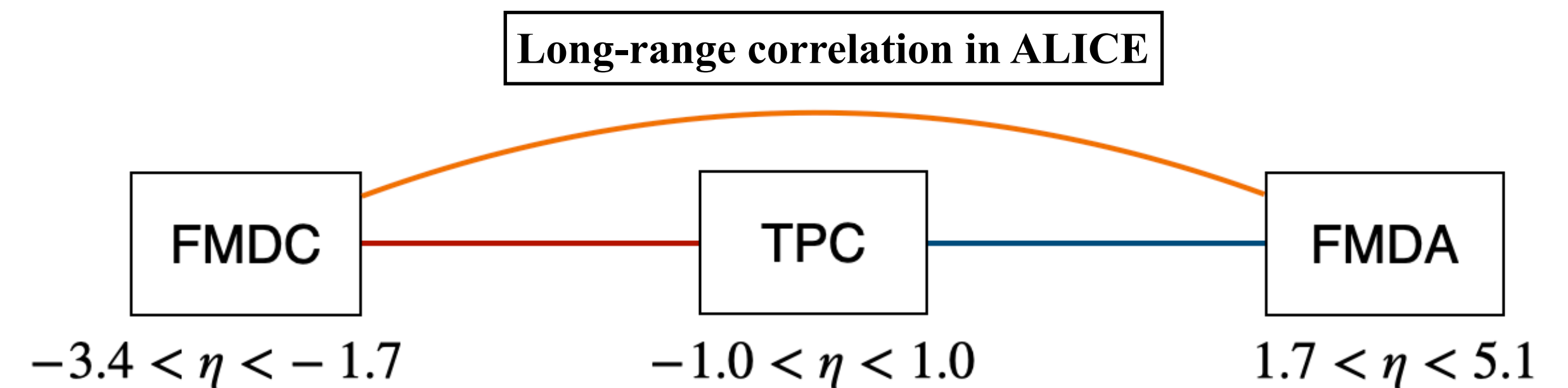
Tracking and particle identification.



- N_{ch} : Number of tracks in TPC with ($|\eta| < 0.8$, and $p_T > 0.2 \text{ GeV}/c$). Used as event classifier.

Datasets:

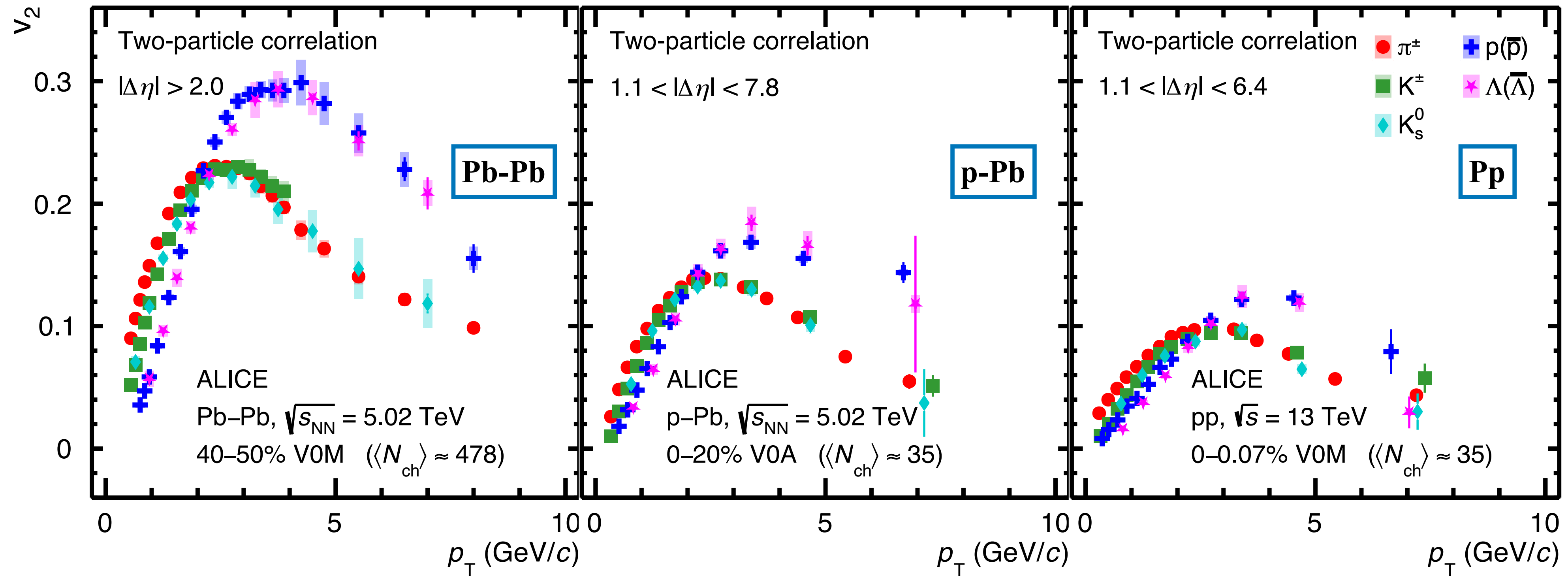
- p–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$
- pp collisions at $\sqrt{s} = 13 \text{ TeV}$





Everything flows, everywhere...

ALICE, arXiv:2411.09323 [nucl-ex], submitted in Nature Physics



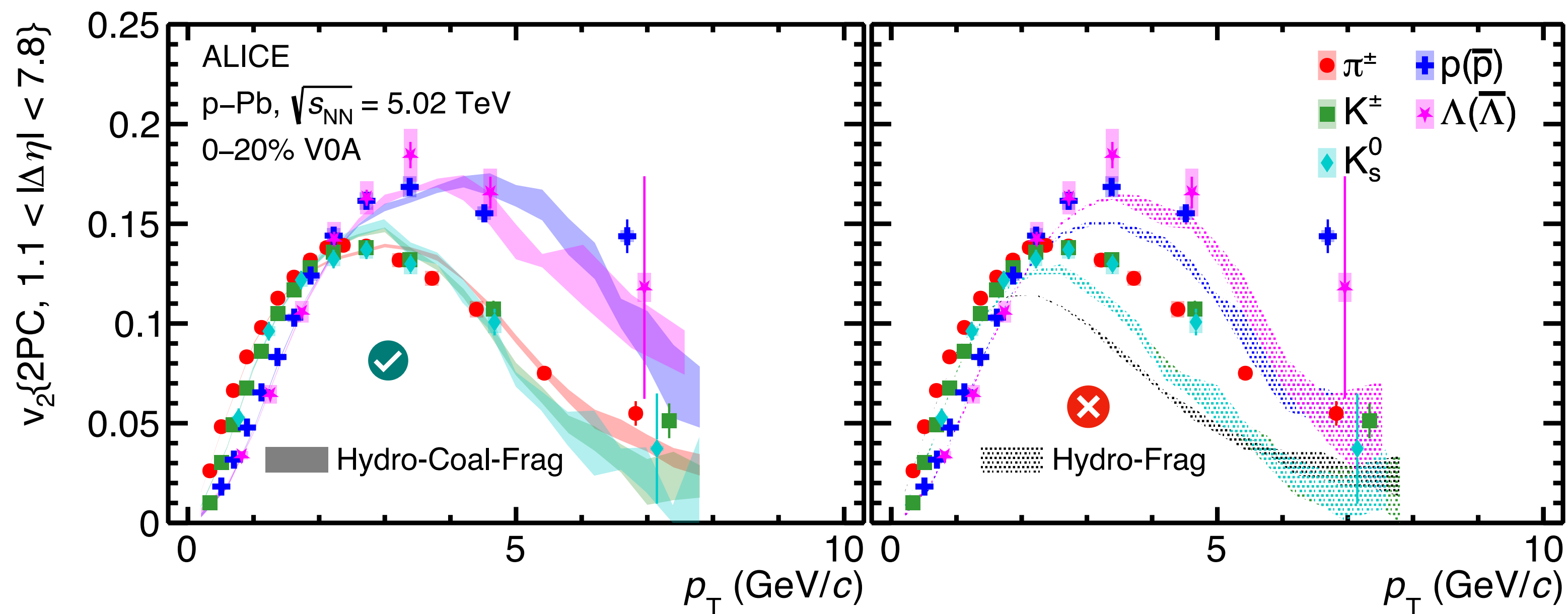
High multiplicity events in small systems: Qualitatively similar to the heavy-ion results!

- Low p_T ($p_T \lesssim 3$ GeV/c) — Mass ordering of v_2 .
- Intermediate p_T ($3 \lesssim p_T \lesssim 5$ GeV/c) — Baryon-meson grouping ($\sim 1\sigma$ confidence) + splitting ($> 5\sigma$ confidence) of v_2 — quark coalescence, evidence of partonic collectivity (✓).



Partonic collectivity in small collision systems!

High multiplicity p-Pb



Hydro: Hydrodynamics

Coal: Coalescence model of hadronization

Frag: Jet fragmentation

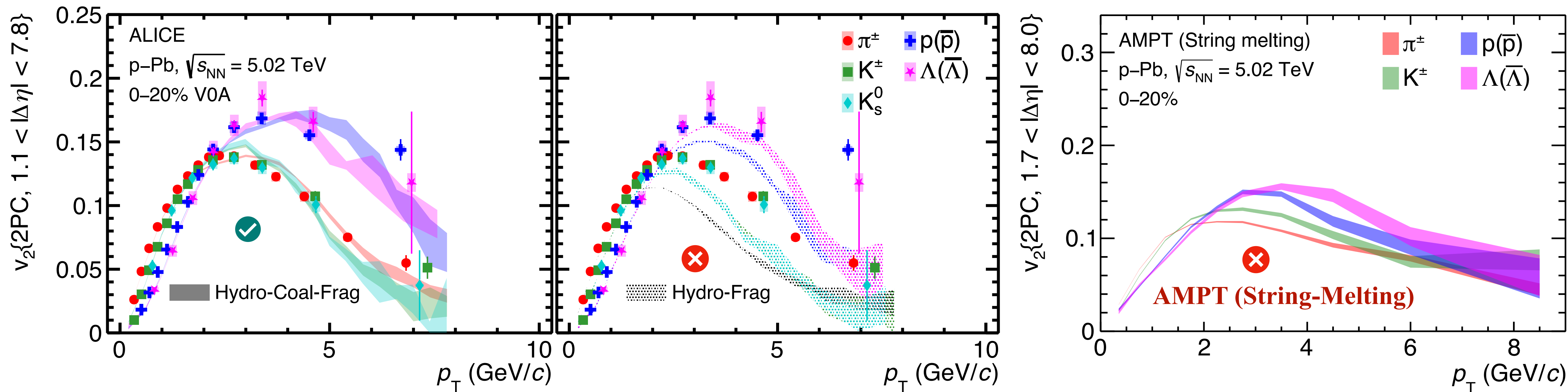
ALICE, [arXiv:2411.09323](https://arxiv.org/abs/2411.09323) [nucl-ex], submitted in Nature Physics

- Hydro+Coal+Frag explains the baryon-meson v_2 grouping and splitting. ✓
- Hydro+Frag fails to describe the pattern (despite parameters adjustments). ✗



Partonic collectivity in small collision systems!

High multiplicity p-Pb



ALICE, [arXiv:2411.09323](https://arxiv.org/abs/2411.09323) [nucl-ex], submitted in Nature Physics

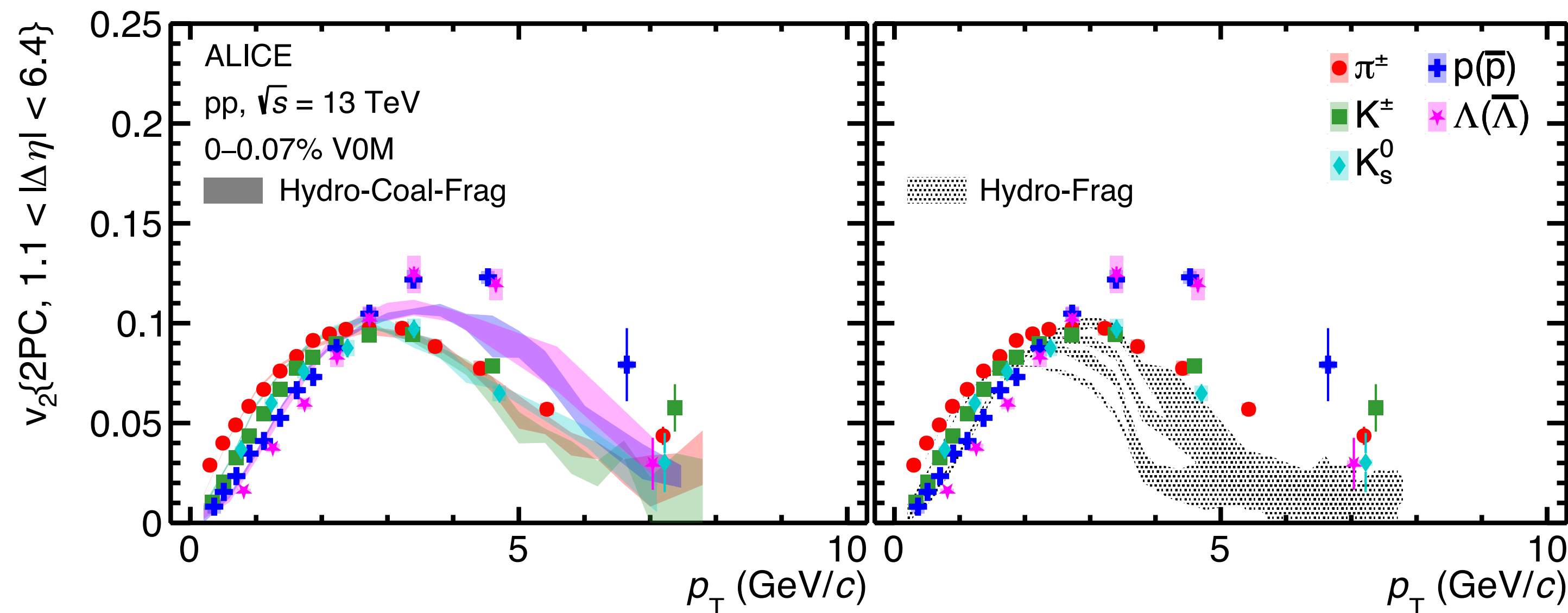
- Hydro+Coal+Frag explains the baryon-meson v_2 grouping and splitting. ✓
- Hydro+Frag fails to describe the pattern (despite parameters adjustments). ✗
- Transport model with coalescence model of hadronization (AMPT) fails to describe the data. ✗

Coalescence of flowing partons necessary to describe the pattern



Partonic collectivity in small collision systems!

High multiplicity pp



ALICE, [arXiv:2411.09323](https://arxiv.org/abs/2411.09323) [nucl-ex], submitted in Nature Physics

Hydro: Hydrodynamics

Coal: Coalescence model of hadronization

Frag: Jet fragmentation

W. Zhao et al., Phys. Rev. Lett. 125, 072301 (2020)

Absence of proper initial condition might contribute to the quantitative discrepancy between data and models.

- Hydro+Coal+Frag explains the baryon-meson v_2 grouping and splitting. ✓
- Hydro+Frag fails to describe the pattern (despite parameters adjustments). ✗
- PYTHIA String-Shoving doesn't describe the data. ✗

Coalescence of flowing quarks necessary to describe the pattern



Partonic collectivity in small collision systems!

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



CERN-EP-2024-299
13 November 2024

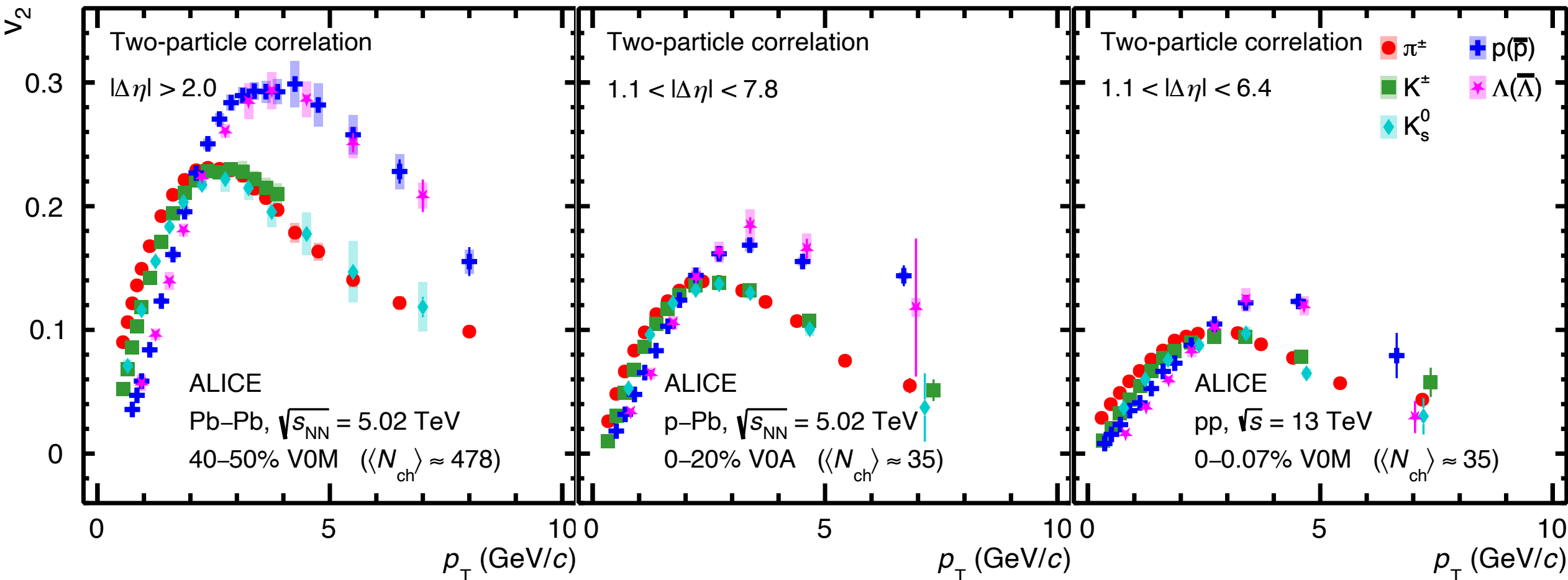
Observation of partonic flow in proton–proton and proton–nucleus collisions

ALICE Collaboration

Abstract

Quantum Chromodynamics predicts a phase transition from ordinary hadronic matter to the quark–gluon plasma (QGP) at high temperatures and energy densities, where quarks and gluons (partons) are not confined within hadrons. The QGP is generated in ultrarelativistic heavy-ion collisions. Anisotropic flow coefficients, quantifying the anisotropic azimuthal expansion of the produced matter, provide a unique tool to unravel QGP properties. Flow measurements in high-energy heavy-ion collisions show a distinctive grouping of anisotropic flow for baryons and mesons at intermediate transverse momentum, a feature associated with flow being imparted at the quark level, confirming the existence of the QGP. The observation of QGP-like features in relativistic proton–proton and proton–ion collisions has sparked debate about possible QGP formation in smaller collision systems, which remains unresolved. In this article, we demonstrate for the first time the distinctive grouping of anisotropic flow for baryons and mesons in high-multiplicity proton–lead and proton–proton collisions at the Large Hadron Collider (LHC). These results are described by a model that includes hydrodynamic flow followed by hadron formation via quark coalescence, replicating features observed in heavy-ion collisions. This observation is consistent with the formation of a partonic flowing system in proton–proton and proton–lead collisions at the LHC.

Submitted in Nature Physics



Coalescence of flowing quarks necessary to describe 3 systems

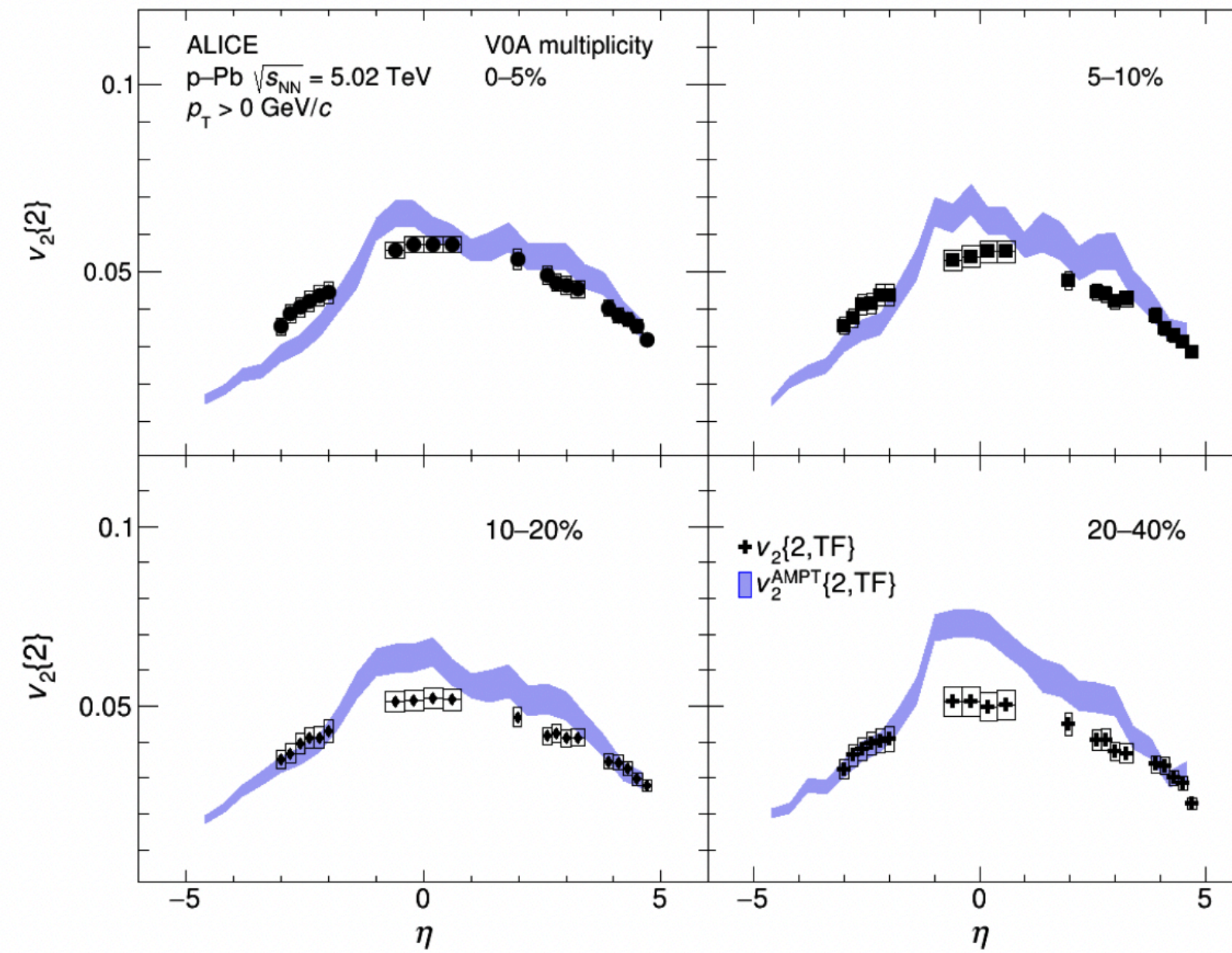
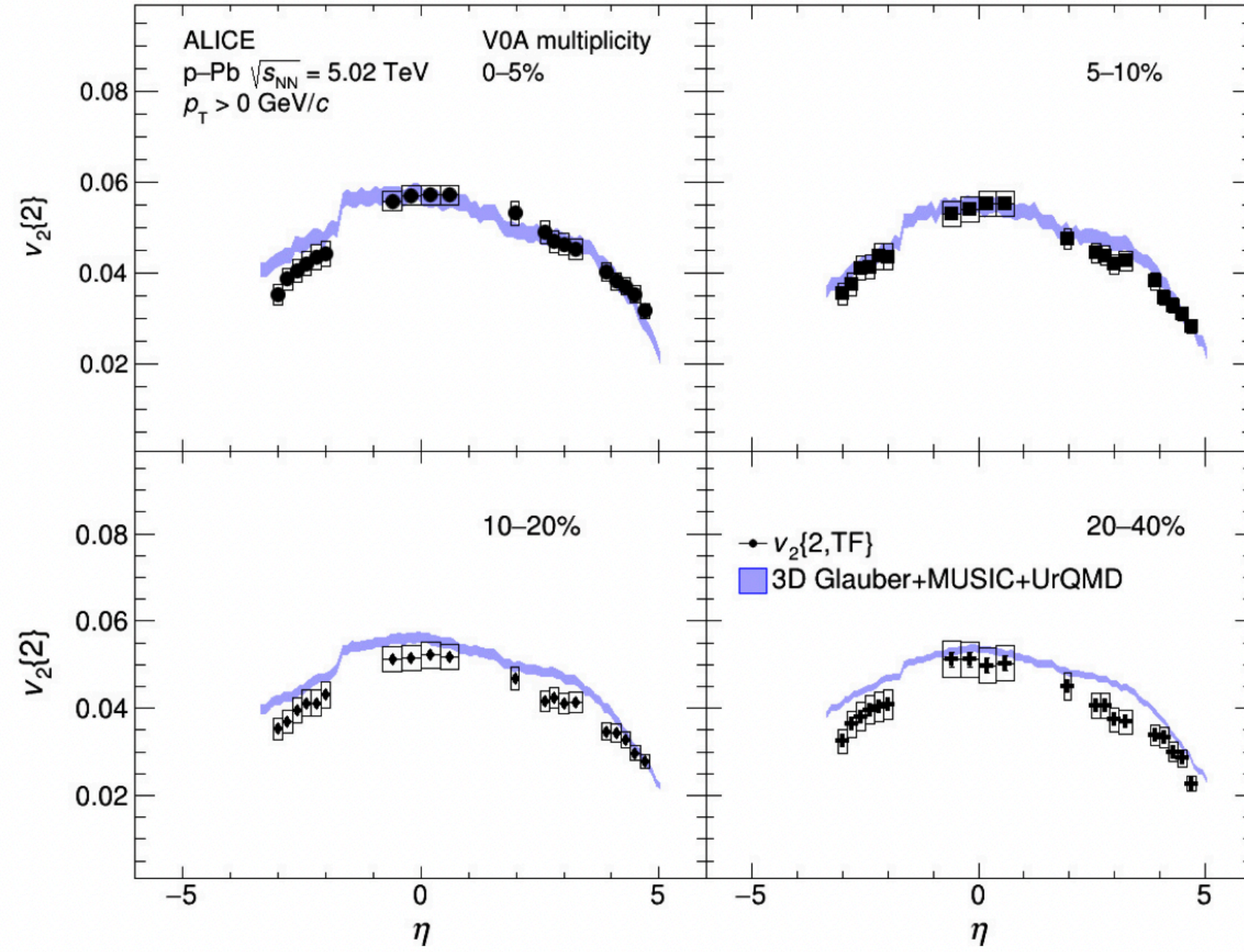
Any further similarities between small systems and heavy-ions?

ALICE, [arXiv:2411.09323](https://arxiv.org/abs/2411.09323) [nucl-ex]

arXiv:2411.09323v1 [nucl-ex] 14 Nov 2024



Similarities: High multiplicity small systems and heavy-ions

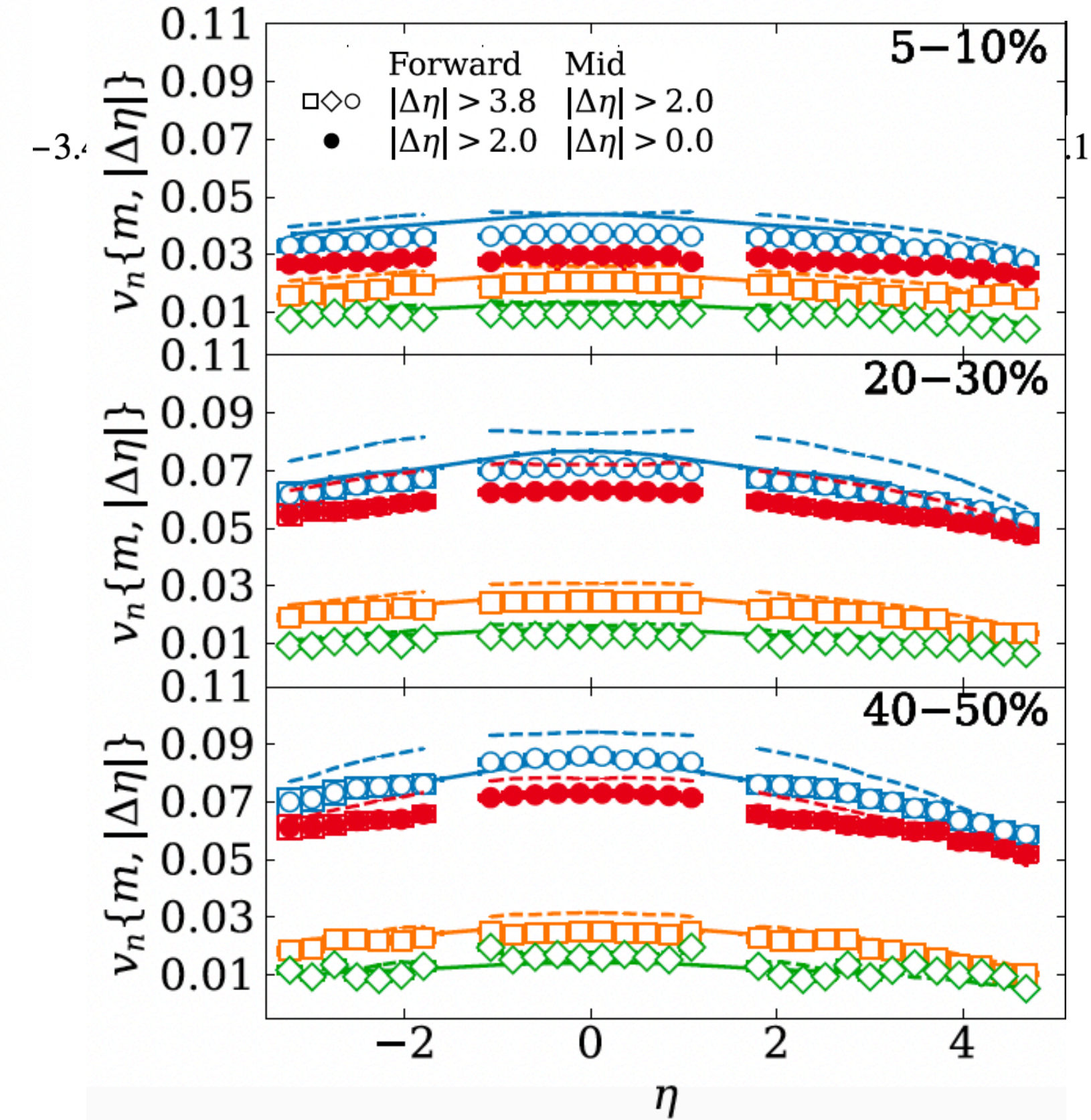


ALICE, JHEP 01 (2024) 199

$$v_n(\eta_a) = \sqrt{\frac{V_{n,n}(\eta_a, \eta_b) V_{n,n}(\eta_a, \eta_c)}{V_{n,n}(\eta_b, \eta_c)}},$$

ALICE Pb–Pb $\sqrt{s_{\text{NN}}} = 5.02 \text{ TeV}$

$\circ$ $n = 2, m = 2$ $\square$ $n = 3, m = 2$
 $\bullet$ $n = 2, m = 4$ $\diamond$ $n = 4, m = 2$
 ----- AMPT — CLVisc



- Event geometry driven final state effects — correlated across large rapidity intervals.



Similarities: High multiplicity small systems and heavy-ion collisions

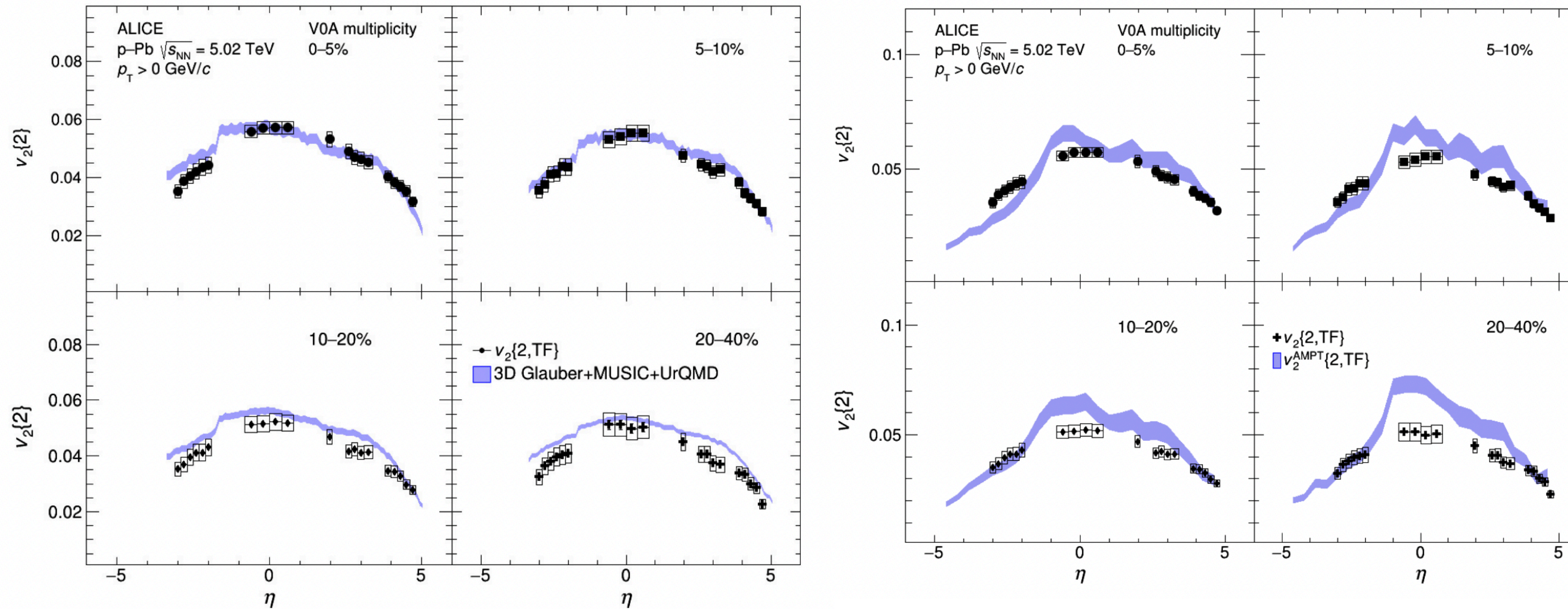


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ALICE, JHEP 01 (2024) 199

$$v_n(\eta_a) = \sqrt{\frac{V_{n,n}(\eta_a, \eta_b)V_{n,n}(\eta_a, \eta_c)}{V_{n,n}(\eta_b, \eta_c)}},$$

- Event geometry driven final state effects — correlated across large rapidity intervals.

Measurements of long-range two-particle correlation over a wide pseudorapidity range in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV



ALICE

The ALICE collaboration

E-mail: alice-publications@cern.ch

ABSTRACT: Correlations in azimuthal angle extending over a long range in pseudorapidity between particles, usually called the “ridge” phenomenon, were discovered in heavy-ion collisions, and later found in pp and p-Pb collisions. In large systems, they are thought to arise from the expansion (collective flow) of the produced particles. Extending these measurements over a wider range in pseudorapidity and final-state particle multiplicity is important to understand better the origin of these long-range correlations in small collision systems. In this Letter, measurements of the long-range correlations in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are extended to a pseudorapidity gap of $\Delta\eta \sim 8$ between particles using the ALICE forward multiplicity detectors. After suppressing non-flow correlations, e.g., from jet and resonance decays, the ridge structure is observed to persist up to a very large gap of $\Delta\eta \sim 8$ for the first time in p-Pb collisions. This shows that the collective flow-like correlations extend over an extensive pseudorapidity range also in small collision systems such as p-Pb collisions. The pseudorapidity dependence of the second-order anisotropic flow coefficient, $v_2(\eta)$, is extracted from the long-range correlations. The $v_2(\eta)$ results are presented for a wide pseudorapidity range of $-3.1 < \eta < 4.8$ in various centrality classes in p-Pb collisions. To gain a comprehensive understanding of the source of anisotropic flow in small collision systems, the $v_2(\eta)$ measurements are compared with hydrodynamic and transport model calculations. The comparison suggests that the final-state interactions play a dominant role in developing the anisotropic flow in small collision systems.

KEYWORDS: Collective Flow, Heavy Ion Experiments, Particle Correlations and Fluctuations

ARXIV EPRINT: [2308.16590](https://arxiv.org/abs/2308.16590)

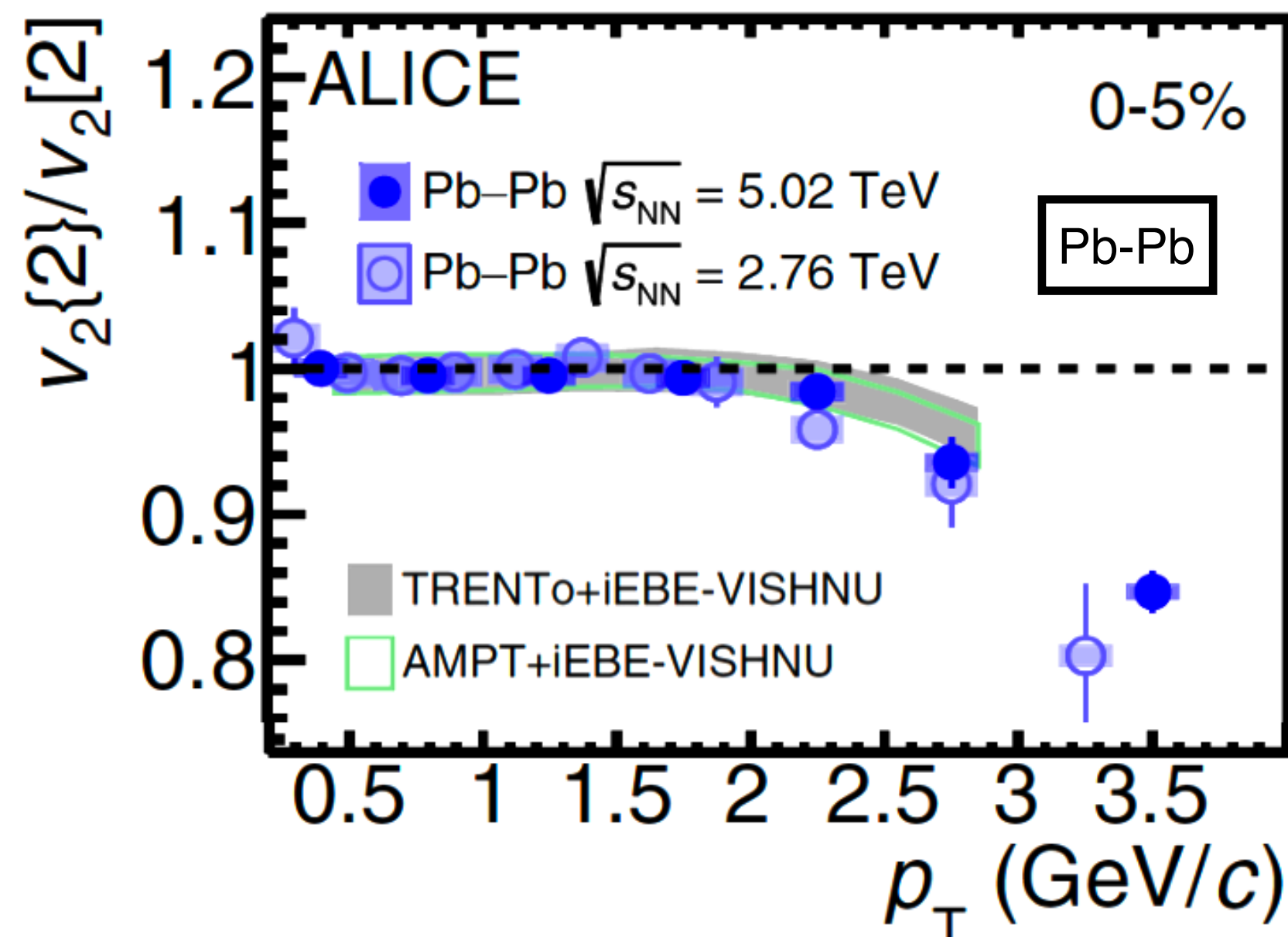
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Article funded by SCOAP³.

[https://doi.org/10.1007/JHEP01\(2024\)199](https://doi.org/10.1007/JHEP01(2024)199)

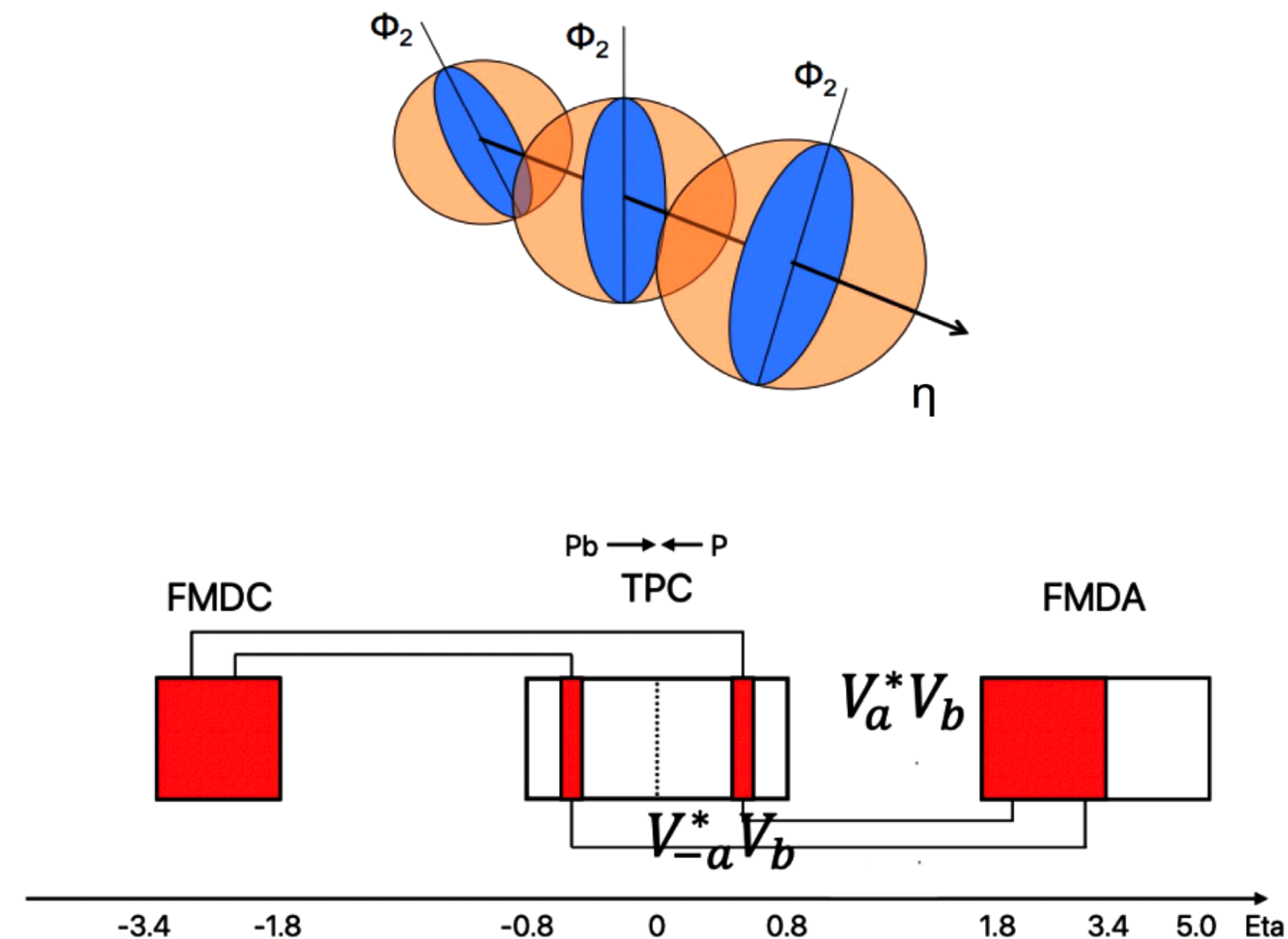
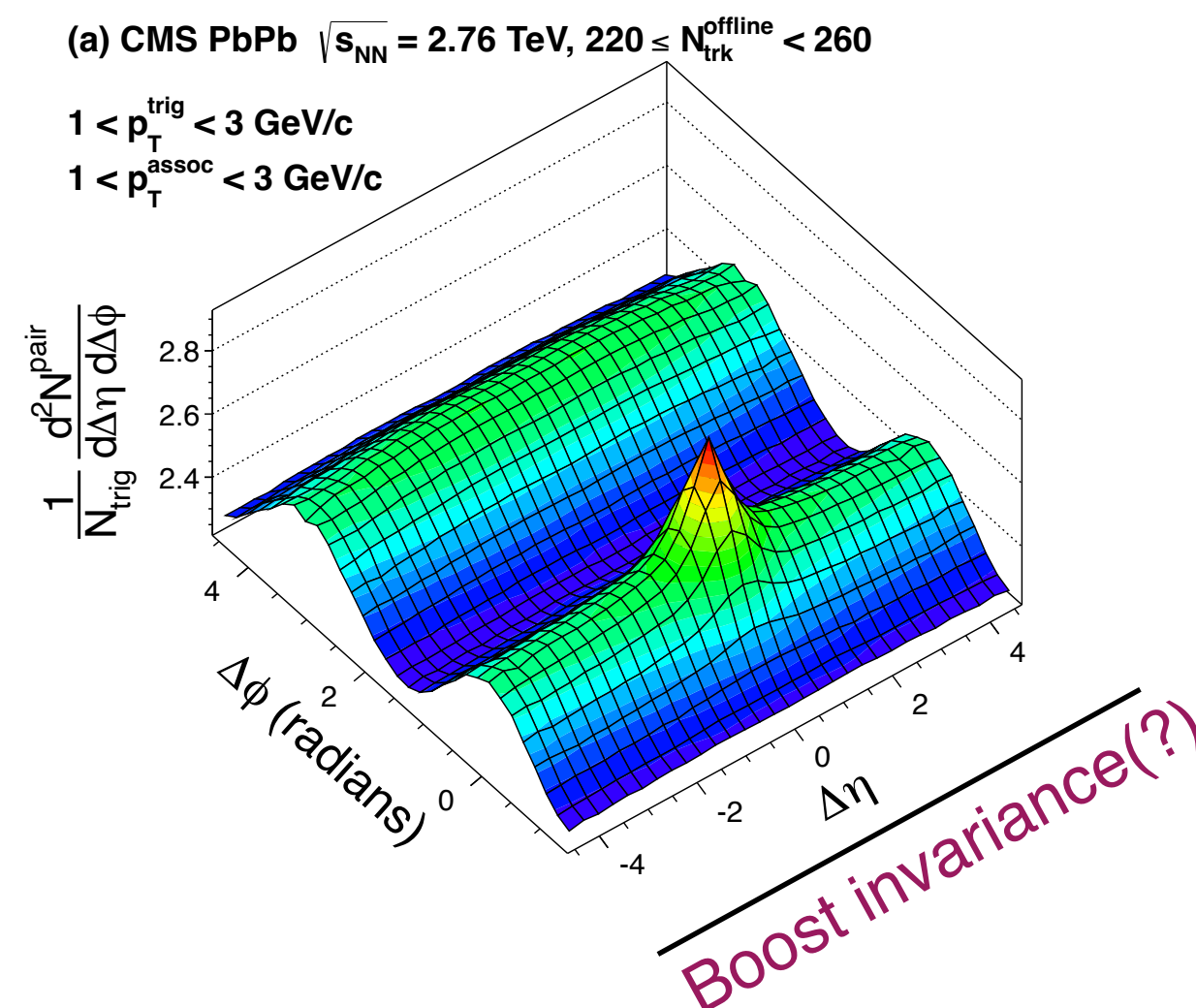


Similarities: Flow vector fluctuation- probes 3D initial conditions

Boost invariant approaches fine in heavy-ions?



ALICE, JHEP09(2017)032
ALICE, PRC Letter 107 (2023) 051901
ALICE, PRC109, 065202 (2024)



$$\frac{v_n\{2\}}{v_n[2]} = \frac{\langle v_n(p_T^a) v_n^{ref} \cos[n(\Psi_n(p_T^a) - \Psi_n)] \rangle}{\sqrt{\langle v_n(p_T^a)^2 \rangle} \sqrt{\langle (v_n^{ref})^2 \rangle}}$$

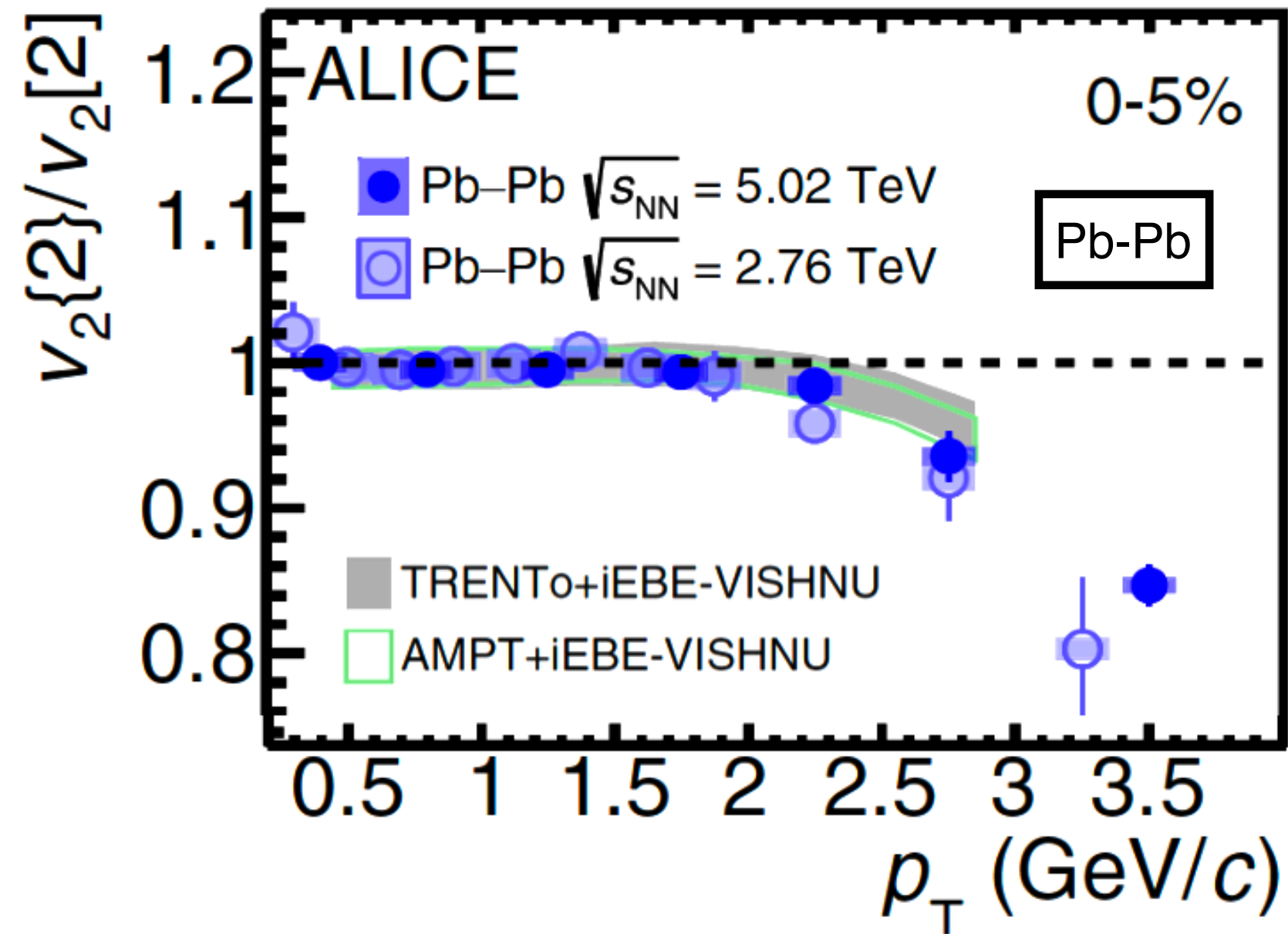
ALICE, PLB850 (2024) 138477

- Flow symmetry plane Ψ_n depends on the kinematic regions of p_T and η .
- Flow fluctuations probe the initial geometry and density variations in both transverse and longitudinal directions (3D initial condition).

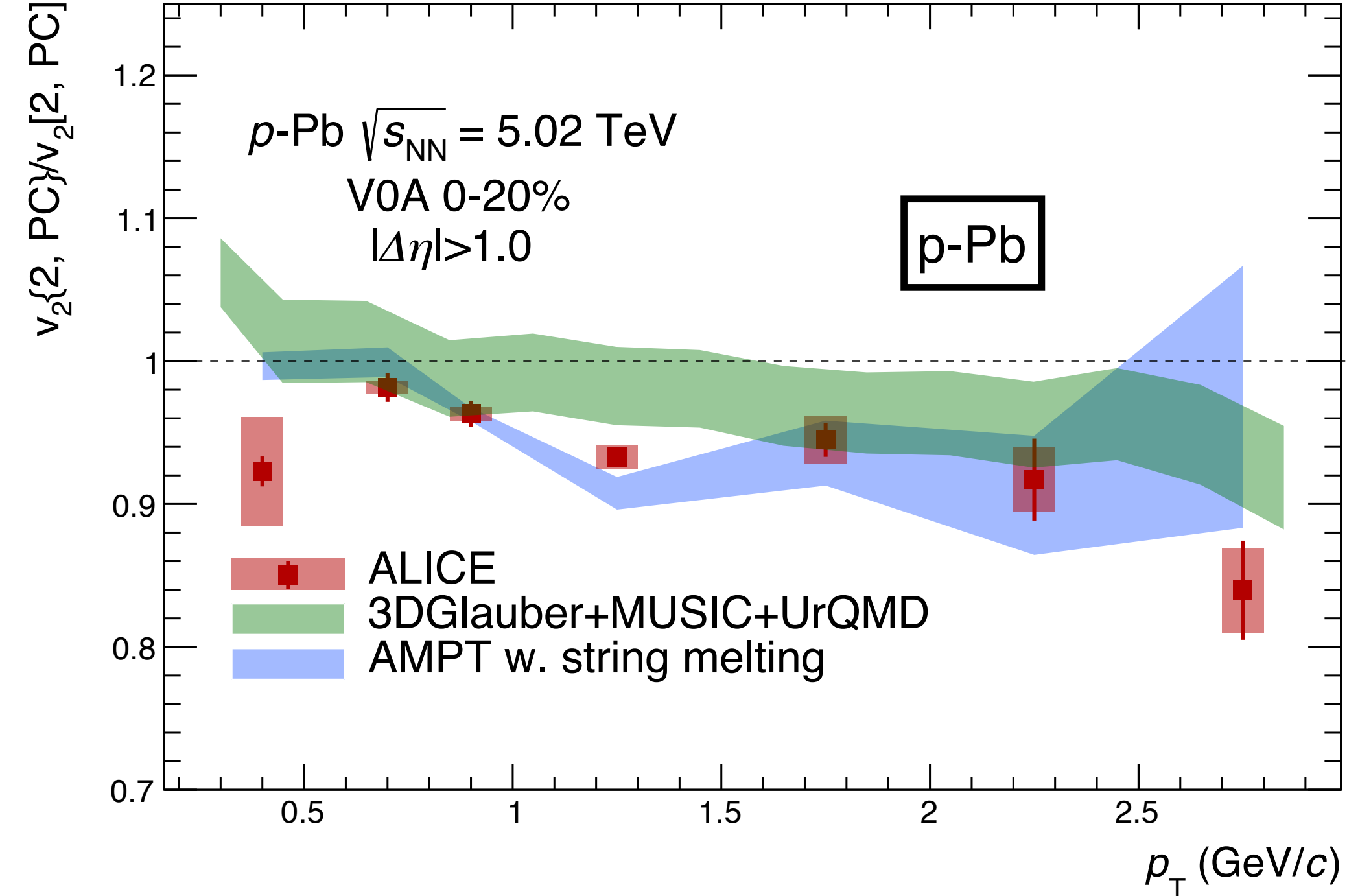
Similar flow vector fluctuations in small systems?



Similarities: Flow vector fluctuation- probes 3D initial conditions



ALICE, JHEP09(2017)032
ALICE, PRC Letter 107 (2023) 051901
ALICE, PRC109, 065202 (2024)



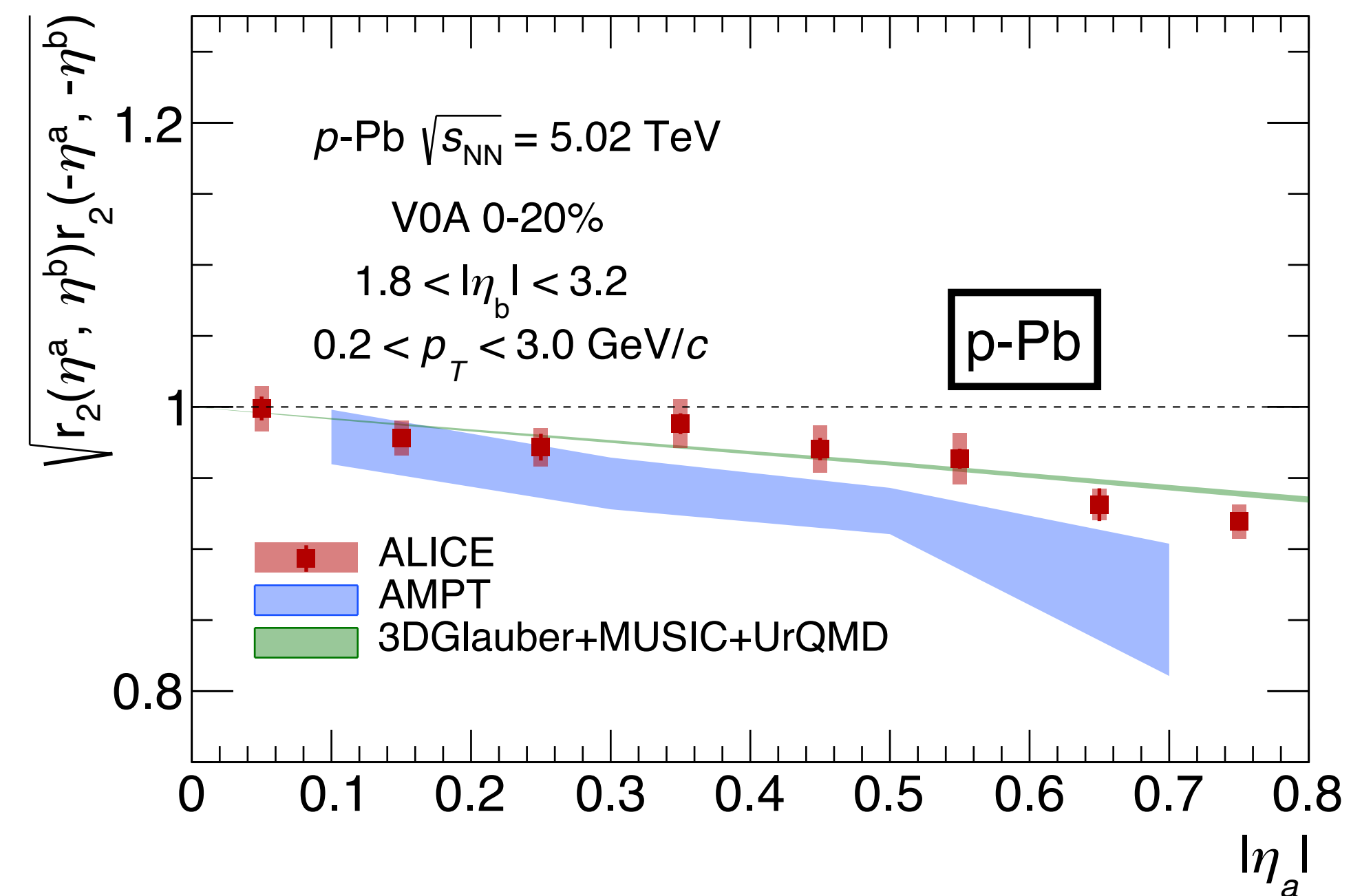
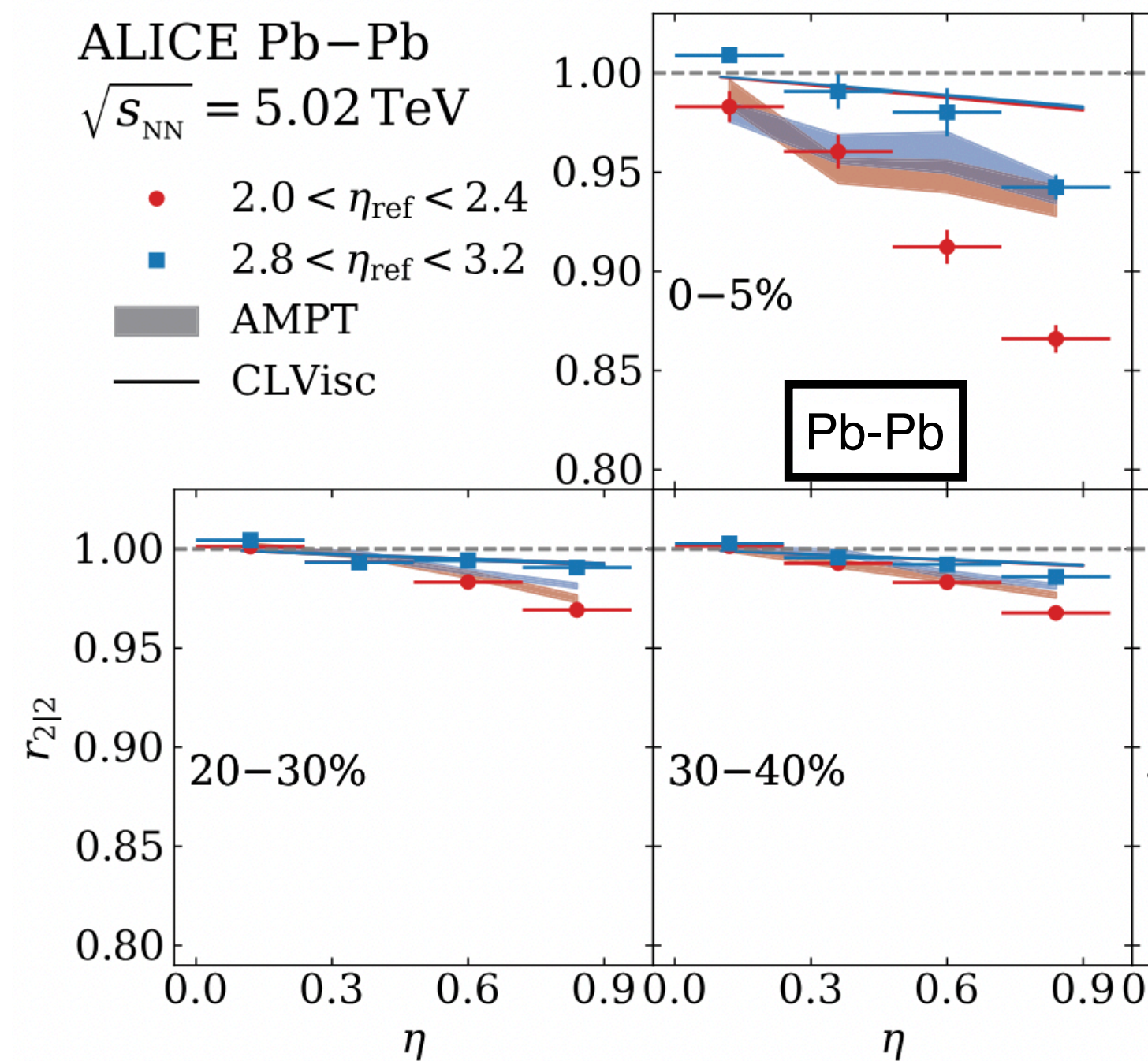
- p_T -dependent flow vector fluctuations:

$$\frac{v_n\{2\}}{v_n[2]} = \frac{\langle v_n(p_T^a) v_n^{ref} \cos[n(\Psi_n(p_T^a) - \Psi_n)] \rangle}{\sqrt{\langle v_n(p_T^a)^2 \rangle} \sqrt{\langle (v_n^{ref})^2 \rangle}}$$

- Evidence of flow vector decorrelations in p_T in p-Pb collisions (Similar to Pb-Pb).
- Small systems results can not be explained by nonflow. AMPT and 3D Hydro reasonably explains the data!



Similarities: Flow vector fluctuation- probes 3D initial conditions



ALICE, Physics Letters B, Volume 850, 2024, 138477

- η -dependent flow vector fluctuations: $r_n(\eta^a, \eta^b) = \frac{V_{n\Delta}(-\eta^a, \eta^b)}{V_{n\Delta}(\eta^a, \eta^b)} = \frac{\langle v_n(-\eta^a) v_n(\eta^b) \cos[n(\Psi_n(-\eta^a) - \Psi_n(\eta^b))] \rangle}{\langle v_n(\eta^a) v_n(\eta^b) \cos[n(\Psi_n(\eta^a) - \Psi_n(\eta^b))] \rangle}$

For asymmetric system: $\sqrt{r_n(\eta^a, \eta^b) r_n(-\eta^a, -\eta^b)}$

- Evidence of flow vector decorrelations in η in p-Pb collisions (Similar to Pb-Pb)
- Small systems results can not be explained by nonflow. AMPT and 3D Hydro qualitatively captures the trend.

Similar flow vector fluctuations in small and large systems!



Similarities: Flow vector fluctuation- probes 3D initial conditions

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



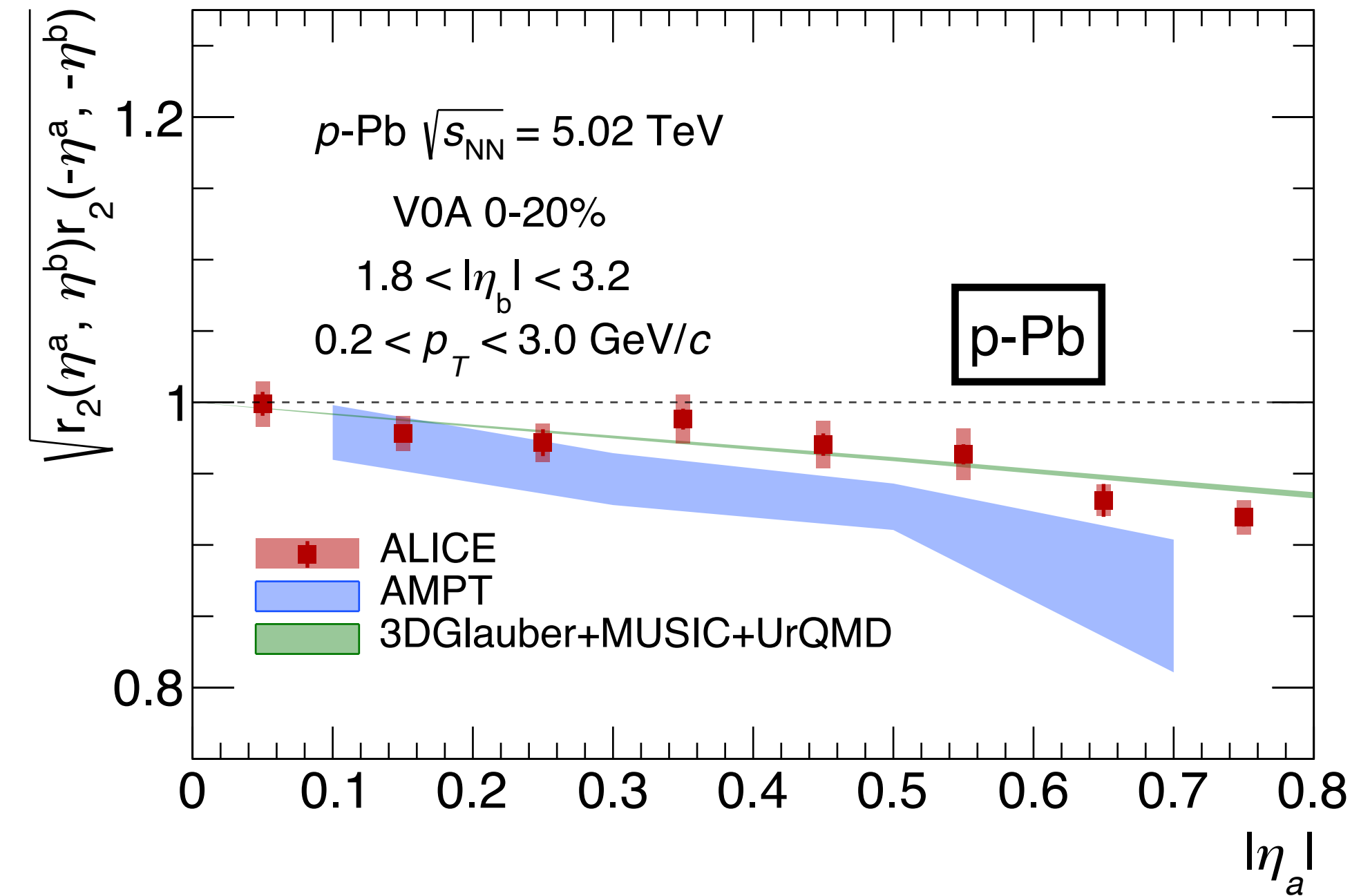
CERN-EP-2024-XX
December 16 2024

Evidence of flow vector fluctuations in $\sqrt{s_{NN}} = 5.02$ TeV p-Pb collisions

ALICE Collaboration

Abstract

Measurements of transverse momentum (p_T) and pseudorapidity (η) dependent flow vector fluctuations in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at the CERN Large Hadron Collider are presented. Utilizing long-range two-particle correlations with the template fit method, potential biases from non-flow effects such as jets and resonance decays are effectively suppressed. Significant p_T and η dependent fluctuations of the second-harmonic flow vector are observed with more than 5σ confidence in p-Pb collisions, mirroring observations in Pb-Pb collisions. These results cannot be solely attributed to non-flow effects, providing new evidence for flow vector fluctuations in small collision systems at the LHC. Comparisons with hydrodynamic model calculations from 3DGlauber+MUSIC+UrQMD and parton transport model calculations from AMPT significantly enhance the understanding of the three-dimensional initial geometry and its event-by-event fluctuations, offering critical insights into the origin of collective flow in small collision systems at the LHC.

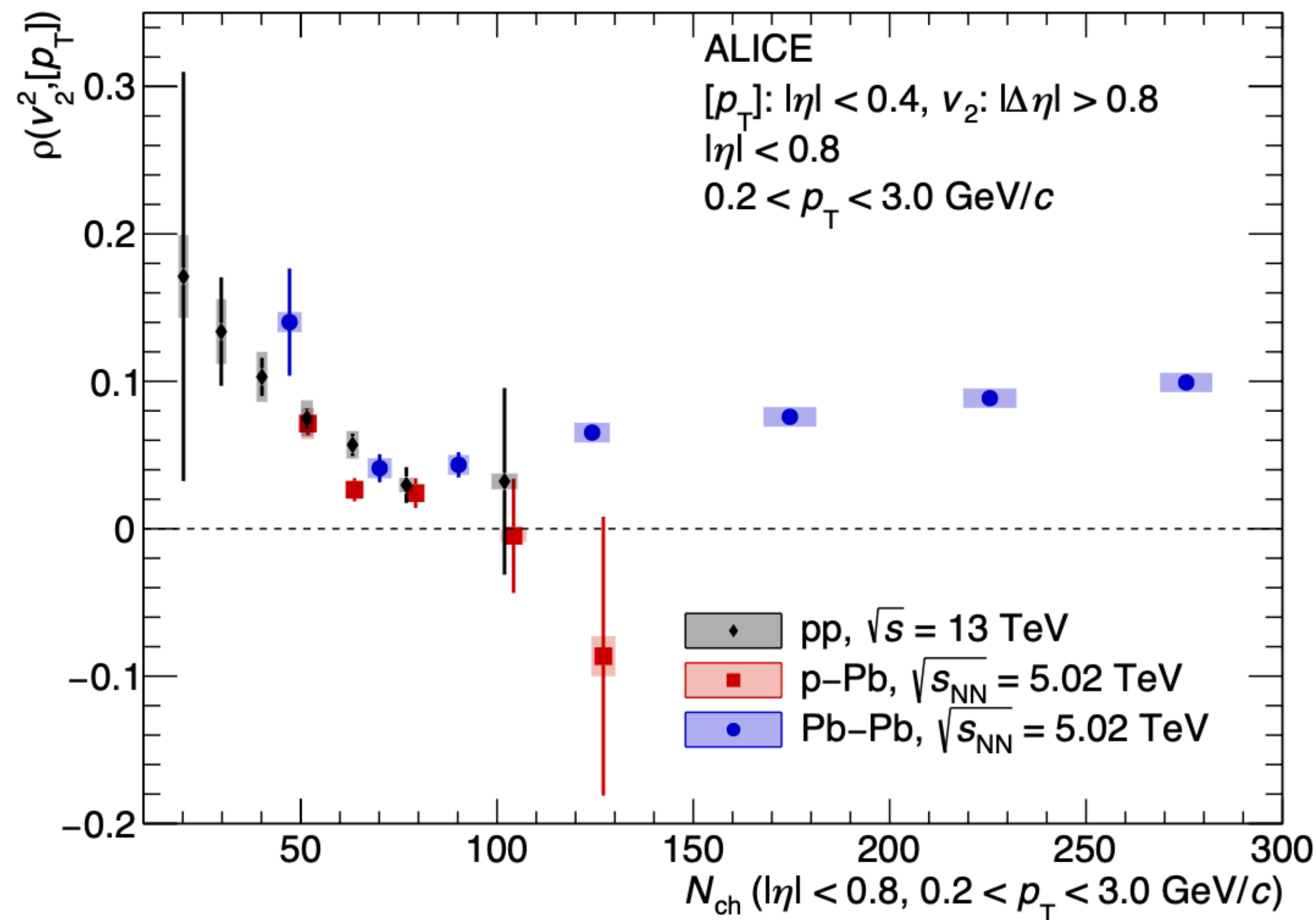


- Evidence of flow vector decorrelations in η in p-Pb collisions (Similar to Pb-Pb)
- Small systems results can not be explained by nonflow. AMPT and 3D Hydro qualitatively captures the trend.

Similar flow vector fluctuations in small and large systems!



Similarities in $\rho(v_2^2, [p_T])$: Tracing back “Initial stage” from “Final Effect”

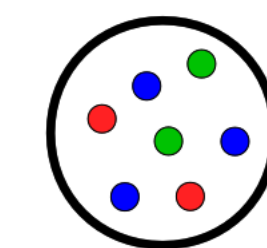


Initial State

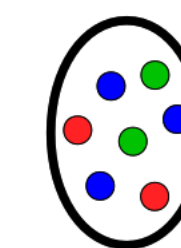
$$\epsilon_n$$

Final State

$$v_n$$



small v_2



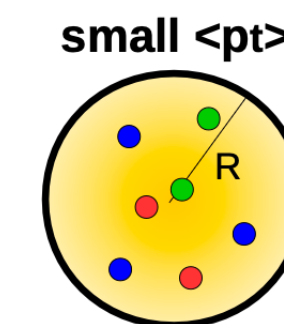
large v_2

Initial State

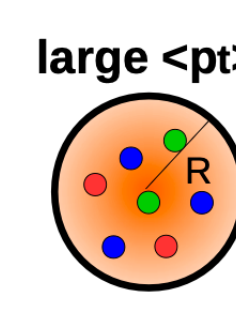
$$1/R, E$$

Final State

$$\langle p_T \rangle$$



small $\langle p_T \rangle$



large $\langle p_T \rangle$

- Pearson correlation coefficient:

$$\rho(v_n^2, [p_T]) = \frac{\text{cov}(v_n^2, [p_T])}{\sqrt{\text{var}(v_n^2)} \sqrt{\text{var}([p_T])}}$$

- Traces back “initial cause” from “final effect”:

- $(\rho(v_2^2, [p_T]))$ similar across all three systems (pp, p–Pb, and Pb–Pb) for $N_{ch} < 80$.
- Small systems results can not be explained by nonflow (PYTHIA).

Similar $\rho(v_2^2, [p_T])$ in small and large systems at comparable multiplicities!



Similarities in $\rho(v_2^2, [p_T])$: Tracing back “Initial stage” from “Final Effect”

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



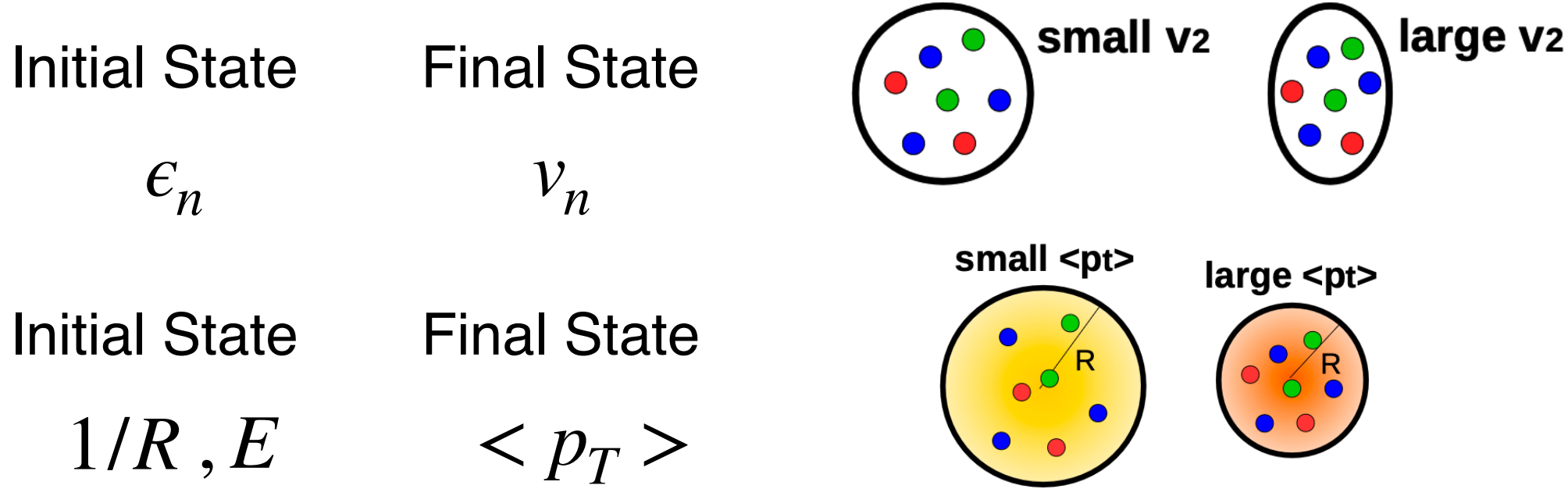
CERN-EP-XXXX-XXX
Day Month XXXX

Measurement of correlations between elliptic flow and mean transverse momentum in pp, p–Pb and Pb–Pb collisions

ALICE Collaboration*

Abstract

Measurements of correlation between elliptic flow (v_2) and the mean transverse momentum ($[p_T]$) using the modified Pearson correlation coefficient $\rho(v_2^2, [p_T])$ are reported in pp collisions at $\sqrt{s} = 13$ TeV, p–Pb and Pb–Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV recorded with the ALICE detector. In Pb–Pb collisions, the correlation initially decreases and then increases with the multiplicity. A similar decreasing trend is observed in p–Pb collisions, with a subtle indication of crossing zero. A positive correlation is also noted in pp collisions, which decreases with the multiplicity. The correlations in pp, p–Pb, and Pb–Pb collisions are consistent for multiplicities less than 70. The measurements in pp or p–Pb collisions cannot be reproduced by the non-collectivity model PYTHIA. By comparing the measurements with AMPT and IP-Glasma + MUSIC + UrQMD, it becomes evident that these measurements offer a unique theoretical understanding of collectivity in small collision systems. This includes insights into the initial state, such as geometry, initial momentum correlation from color glass condensate, and hydrodynamics evolution times.



- Pearson correlation coefficient:

$$\rho(v_n^2, [p_T]) = \frac{\text{cov}(v_n^2, [p_T])}{\sqrt{\text{var}(v_n^2)} \sqrt{\text{var}([p_T])}}$$

- Traces back “initial cause” from “final effect”:

Similar $\rho(v_2^2, [p_T])$ in small and large systems at comparable multiplicities!

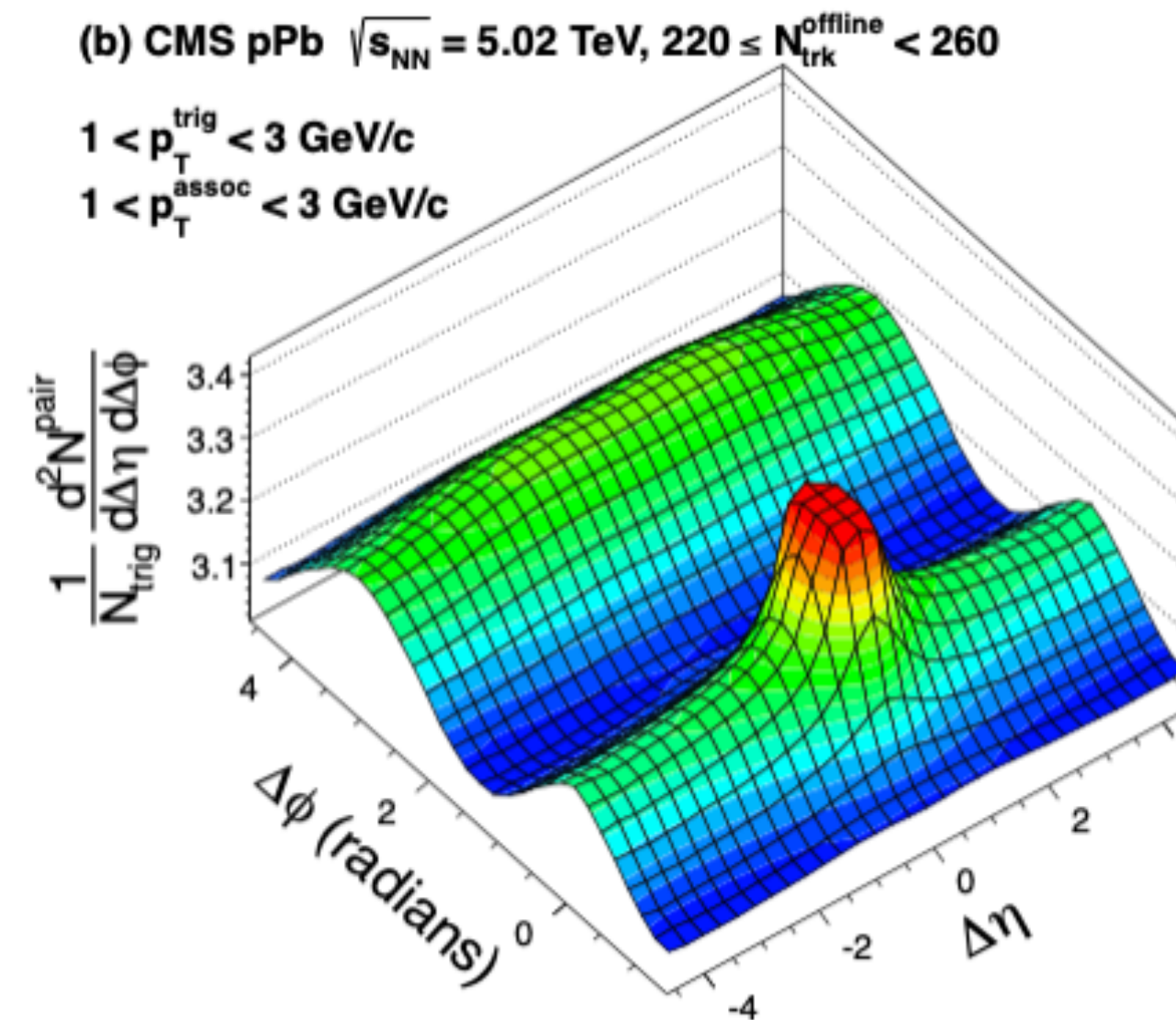
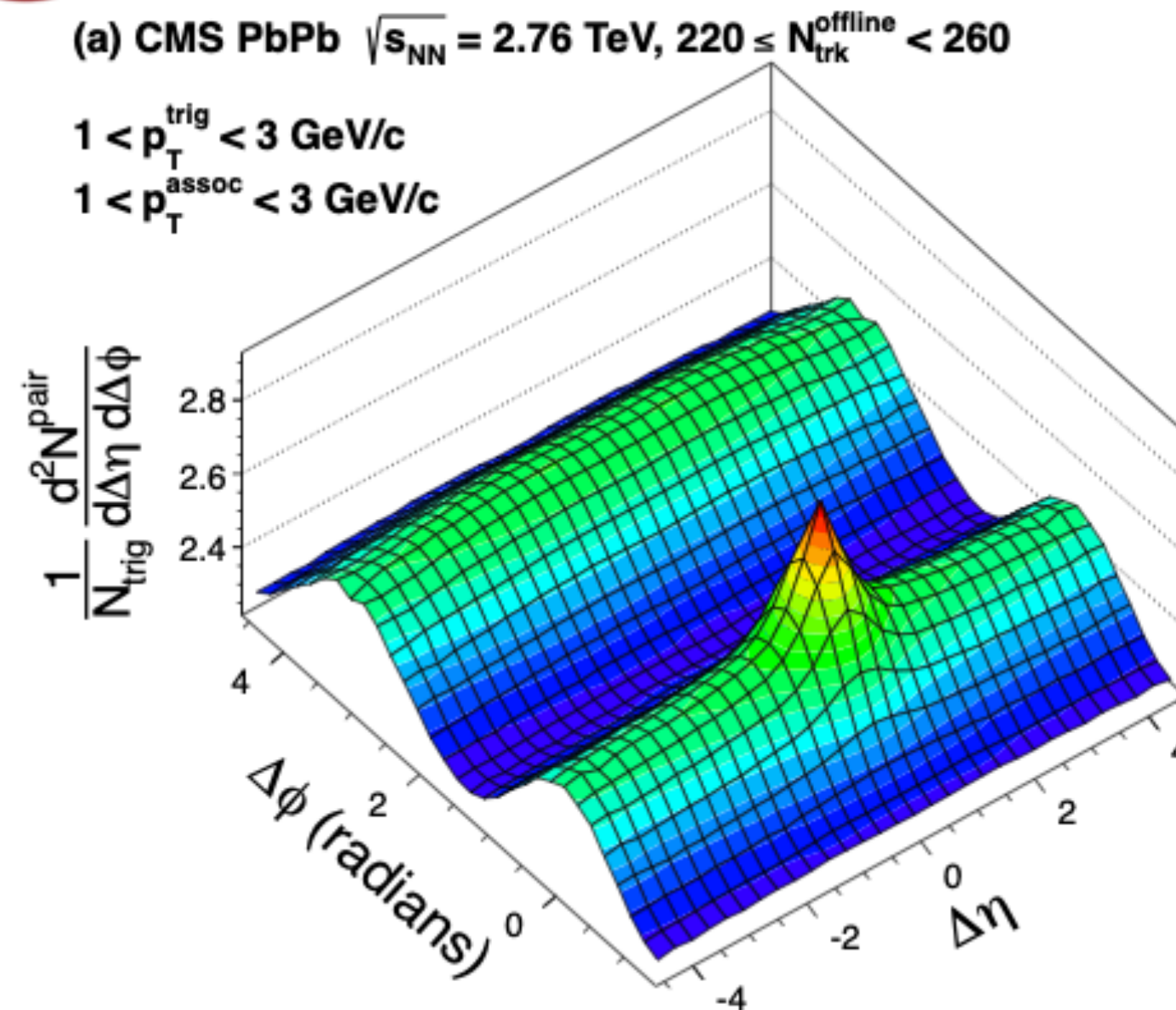


The Old Milestone

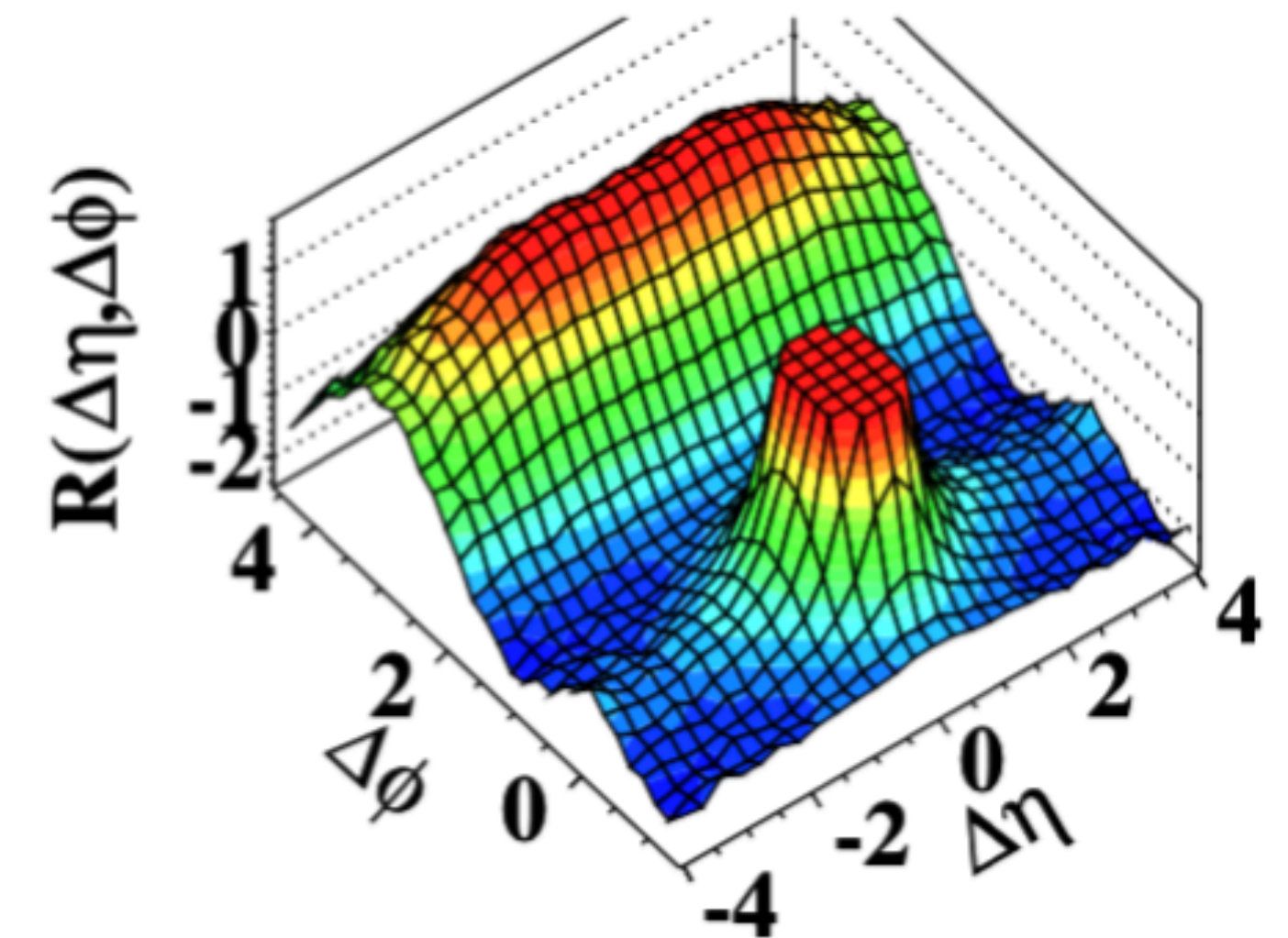
Semi-central Pb–Pb

High multiplicity p–Pb

High multiplicity pp



(d) CMS $N \geq 110$, $1.0 \text{ GeV}/c < p_T < 3.0 \text{ GeV}/c$



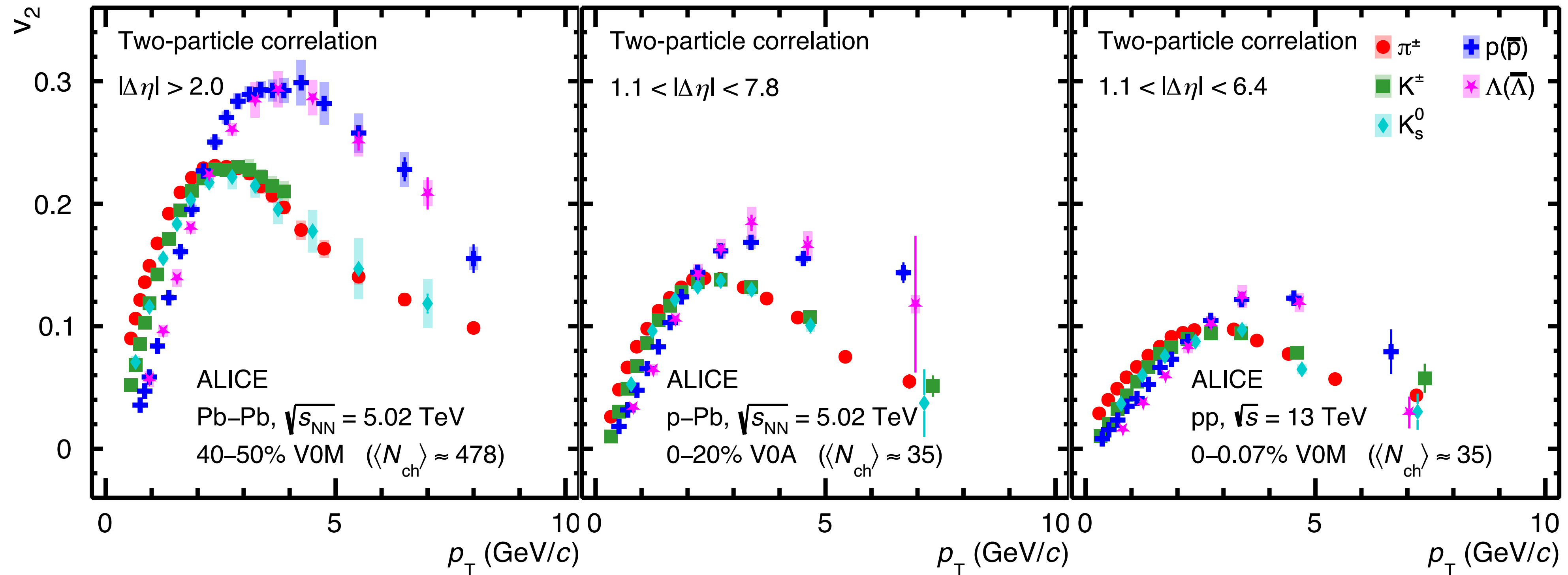
For the last 14 years: these plots appear within the first 2 slides of any talk on small systems!

High multiplicity events in small systems: Qualitatively similar to the heavy-ion results!

Is it partonic collectivity (thermalized and deconfined)?



A New Milestone...And



High multiplicity events in small systems: Qualitatively similar to the heavy-ion results!

It is partonic collectivity!

Where does it switch off? At which multiplicity?

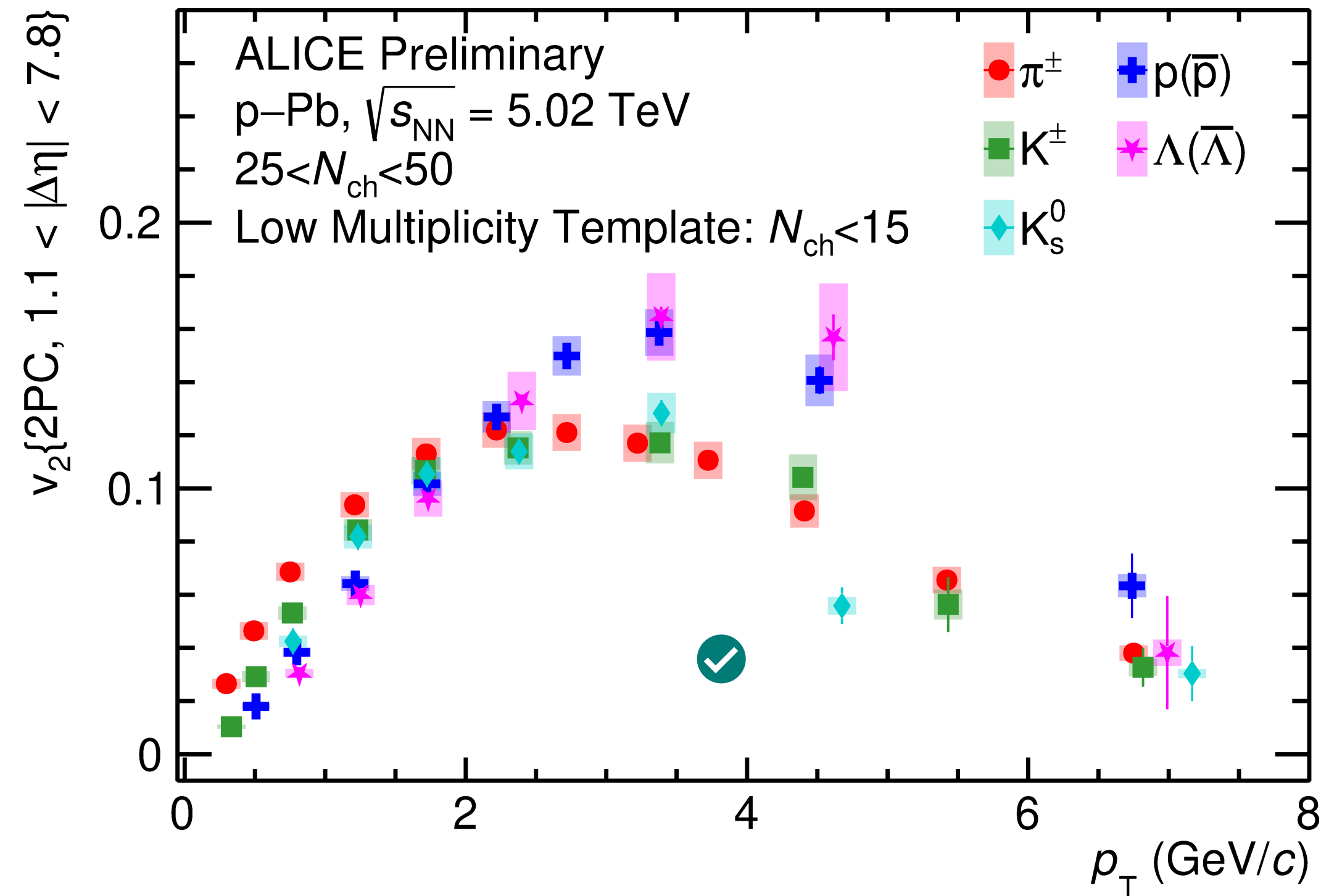
New open question



p–Pb : N_{ch} dependence of v_2 of identified particles

$25 < N_{\text{ch}} < 50$

p–Pb



ALI-PREL-573060

- $N_{\text{ch}} > 25$: Baryon-meson grouping ($\sim 1\sigma$) + splitting ($> 5\sigma$) of v_2 at intermediate p_T . ✓

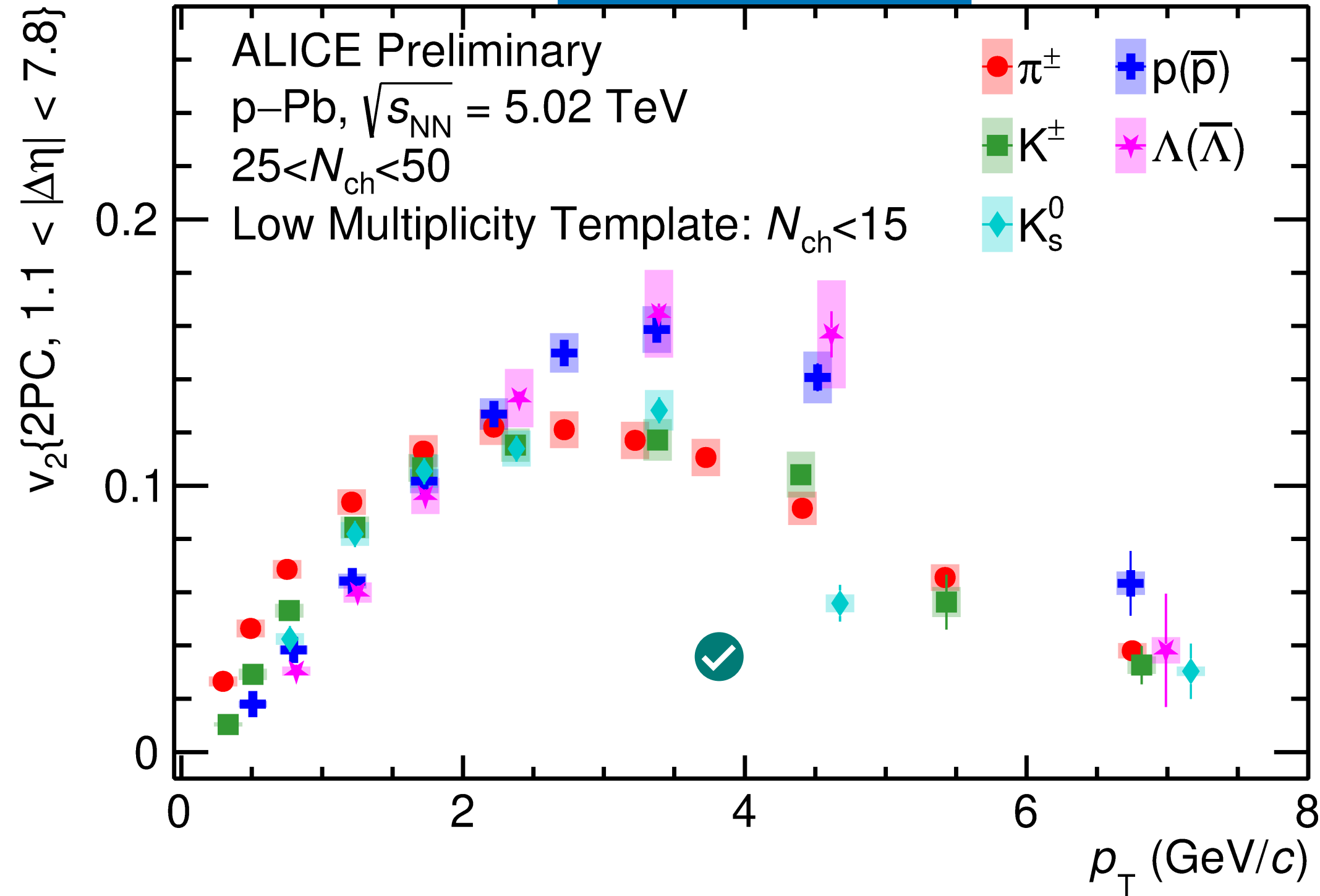


p-Pb : N_{ch} dependence of v_2 of identified particles

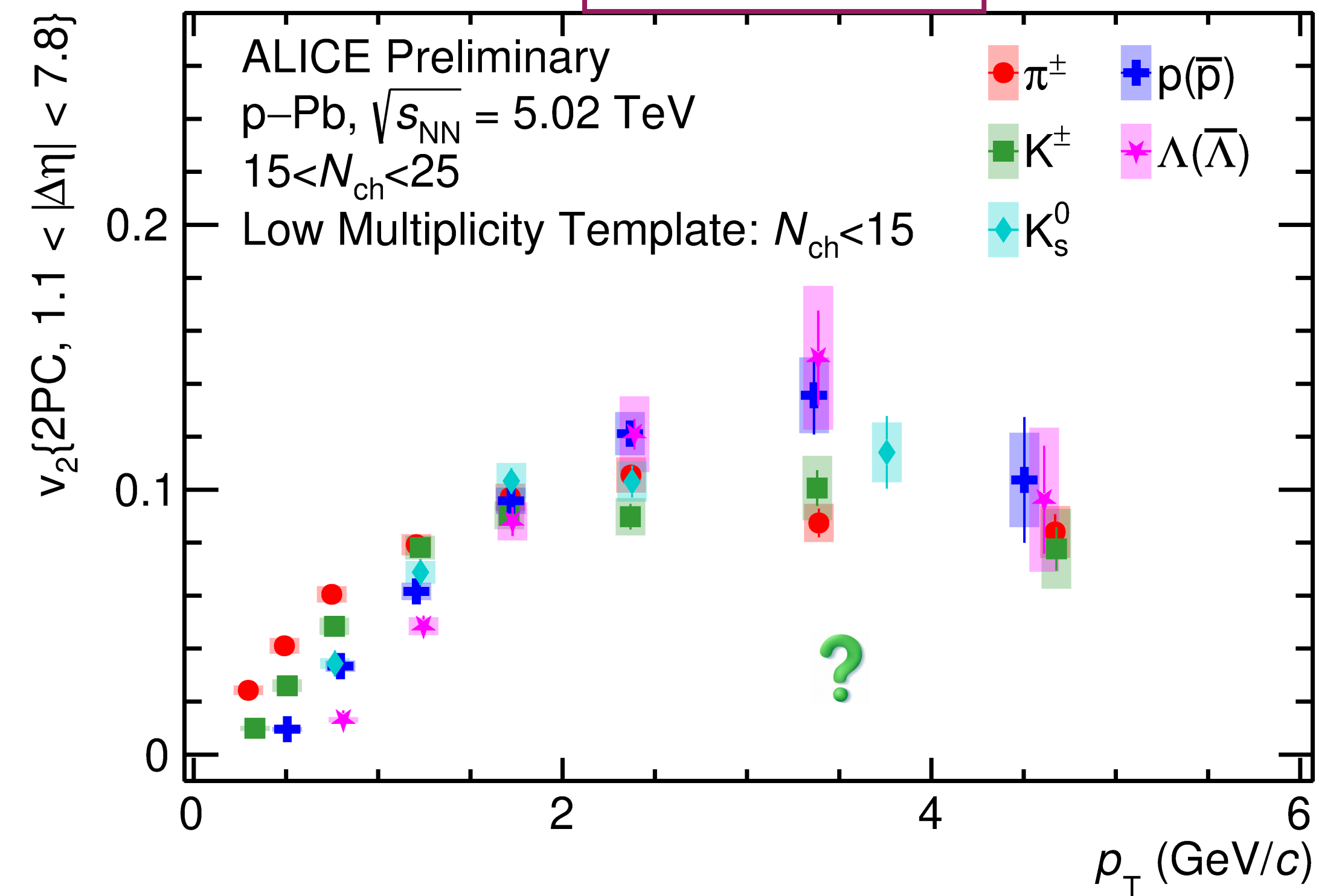
$25 < N_{ch} < 50$

p-Pb

$15 < N_{ch} < 25$



ALI-PREL-573060



ALI-PREL-573055

- $N_{ch} > 25$: Baryon-meson grouping ($\sim 1\sigma$) + splitting ($> 5\sigma$) of v_2 at intermediate p_T . ✓
- $N_{ch} < 25$: grouping and splitting (within 2σ) diluted.

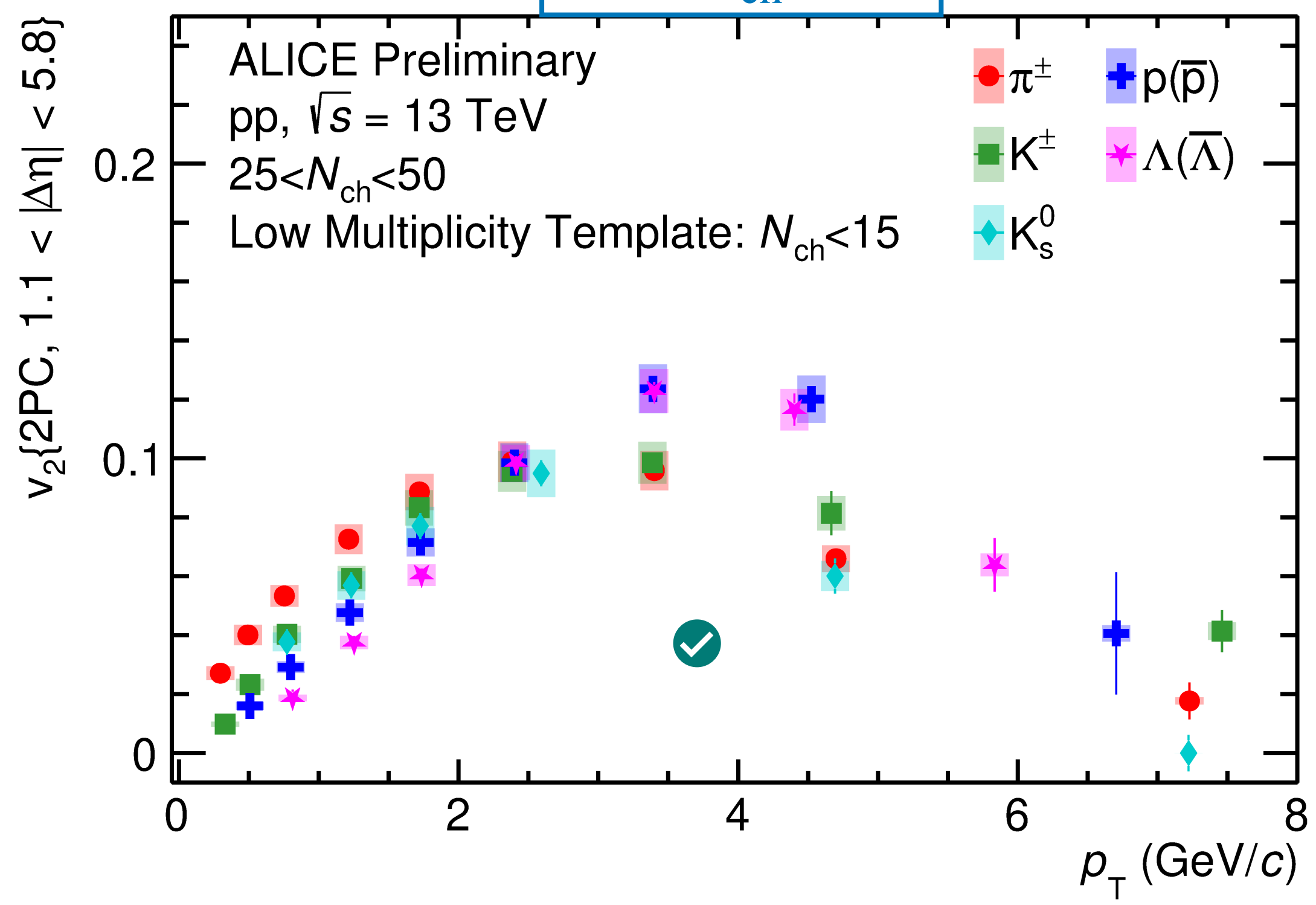


pp : N_{ch} dependence of v_2 of identified particles

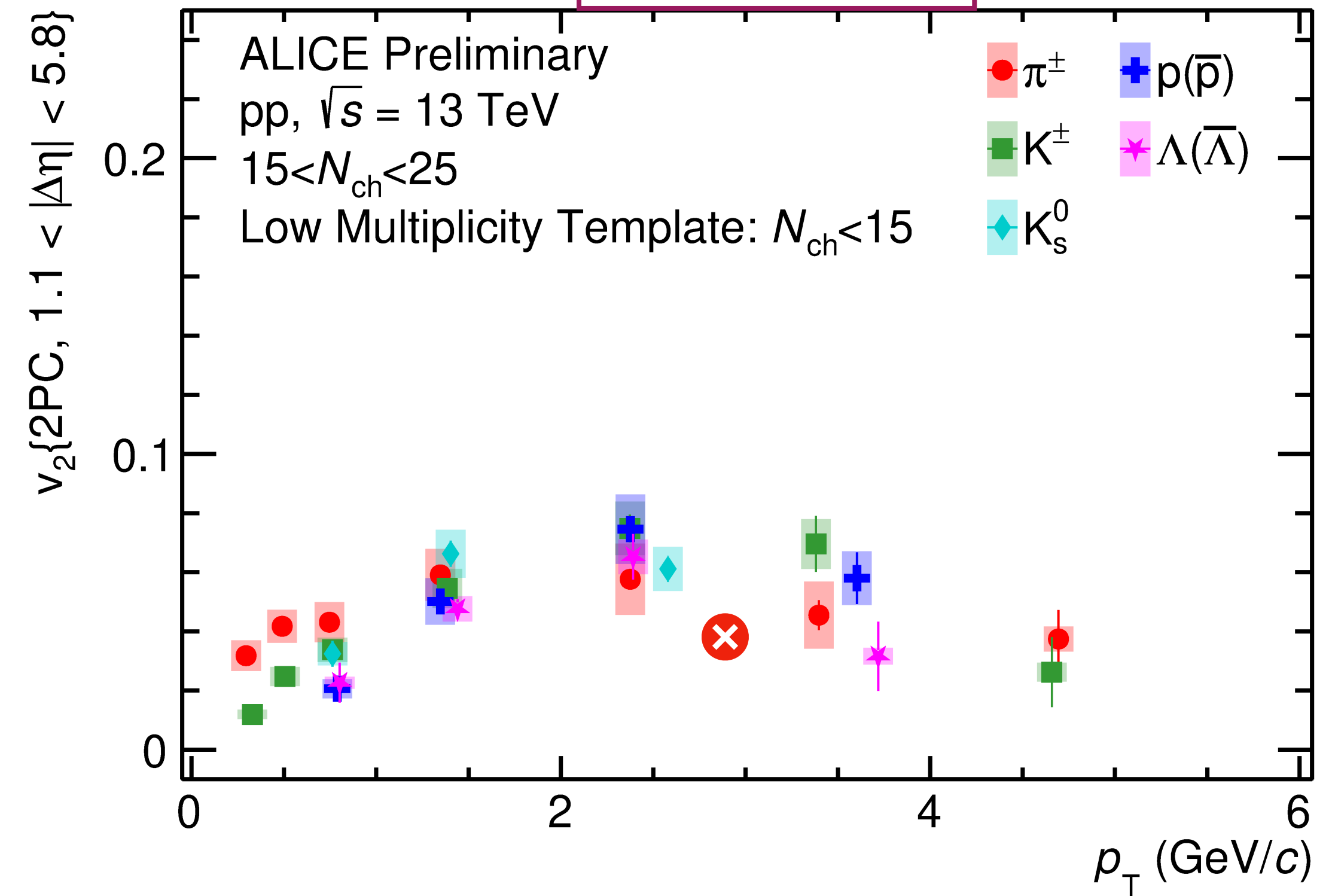
pp

$25 < N_{ch} < 50$

$15 < N_{ch} < 25$



ALI-PREL-573050



ALI-PREL-573045

- $N_{ch} > 25$: Baryon-meson grouping ($\sim 1\sigma$) + splitting ($> 5\sigma$) of v_2 at intermediate p_T . ✓
- $N_{ch} < 25$: grouping and splitting (within 2σ) diluted. ✗

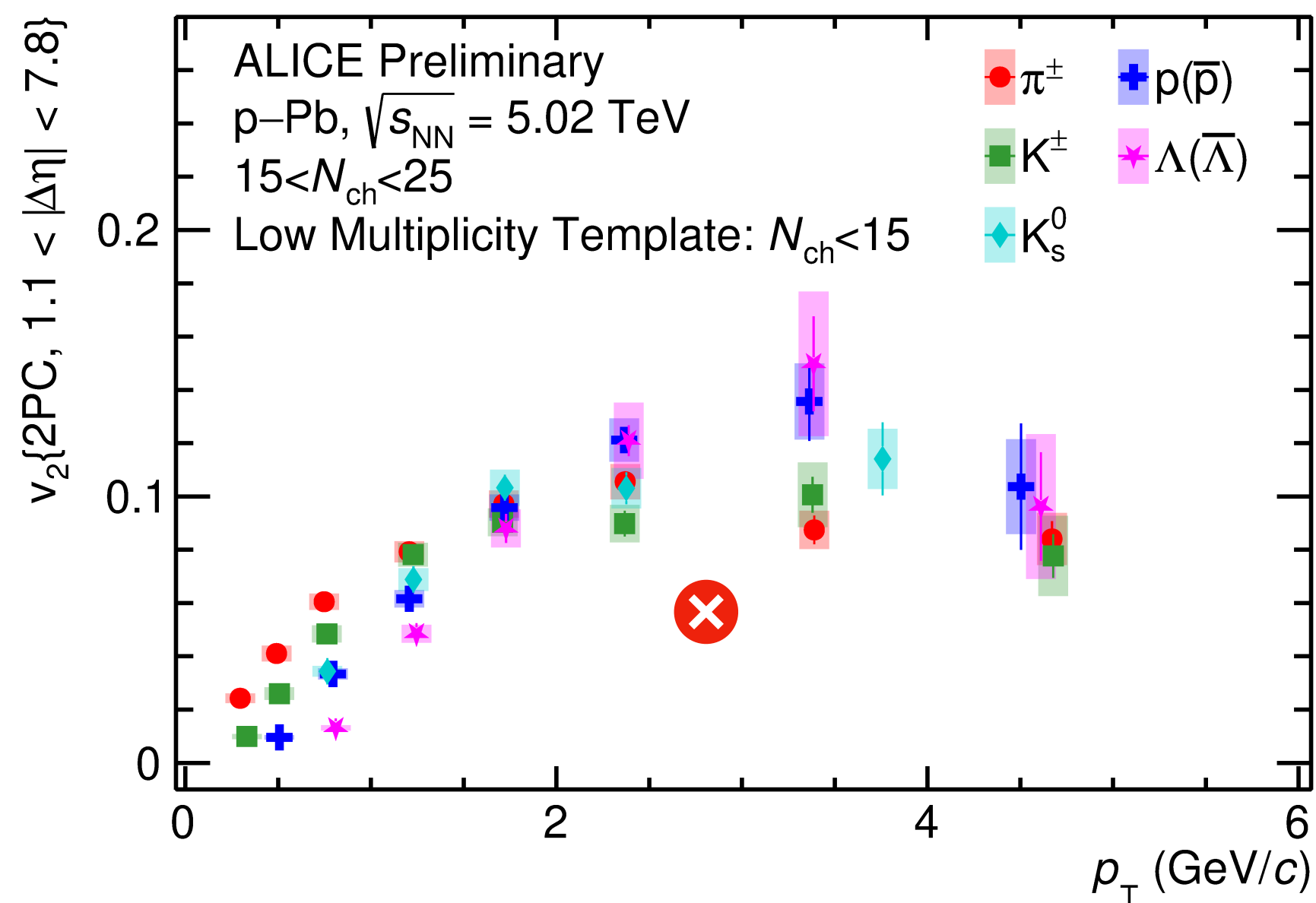
Where is the onset of collectivity?



What is the low multiplicity limit for collectivity?

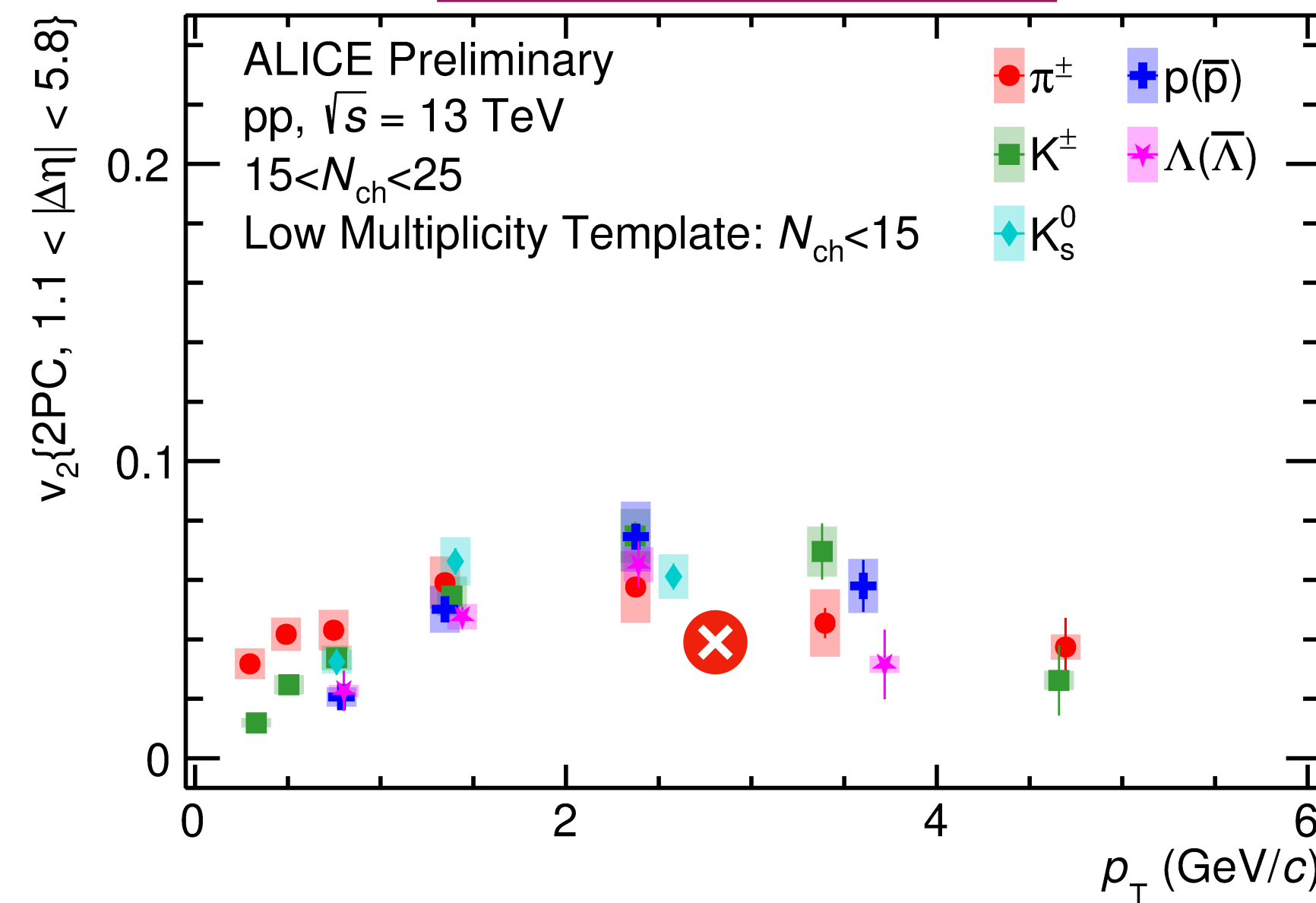
No evidence of baryon-meson grouping and splitting of v_2 at intermediate p_T .

p-Pb: $15 < N_{ch} < 25$



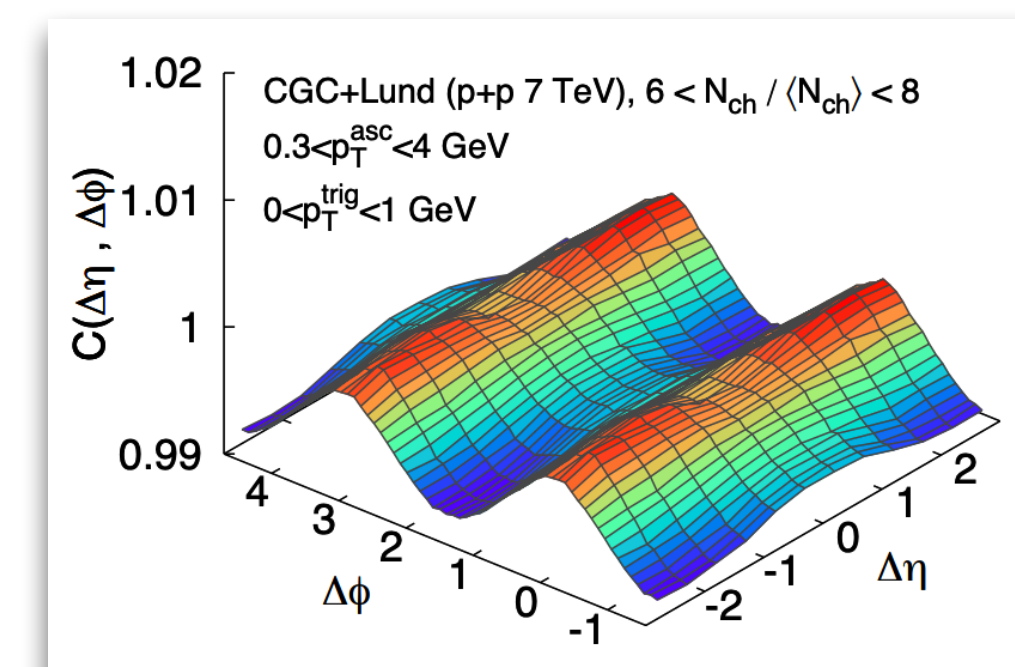
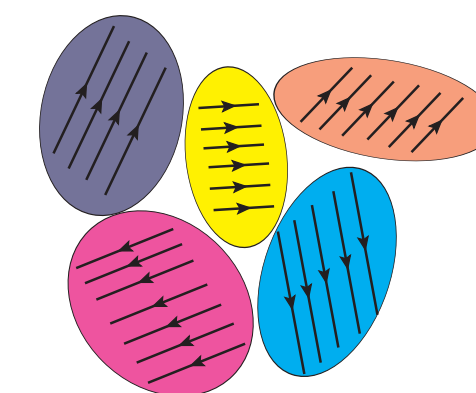
ALI-PREL-573055

pp: $15 < N_{ch} < 25$



ALI-PREL-573045

- Maybe initial state effects are dominant in these dilute systems!
- Continue the search for collectivity towards lower N_{ch} in p-Pb and pp collisions— with unidentified particles...

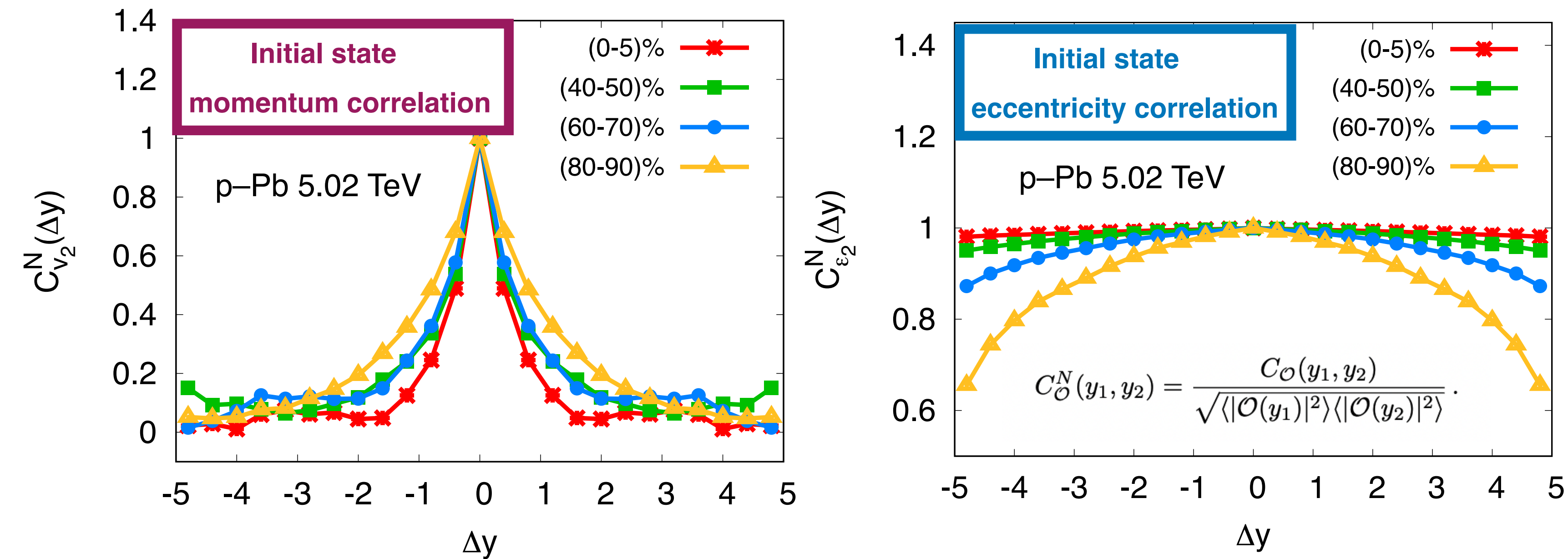


A Dumitru et al, Phys. Lett. B 697:21-25,2011



Initial state effects might be short range...

THE 3D IP-GLASMA MODEL



B. Schenke, S. Schlichting, P. Singh; Phys. Rev. D 105, 094023 (2022)

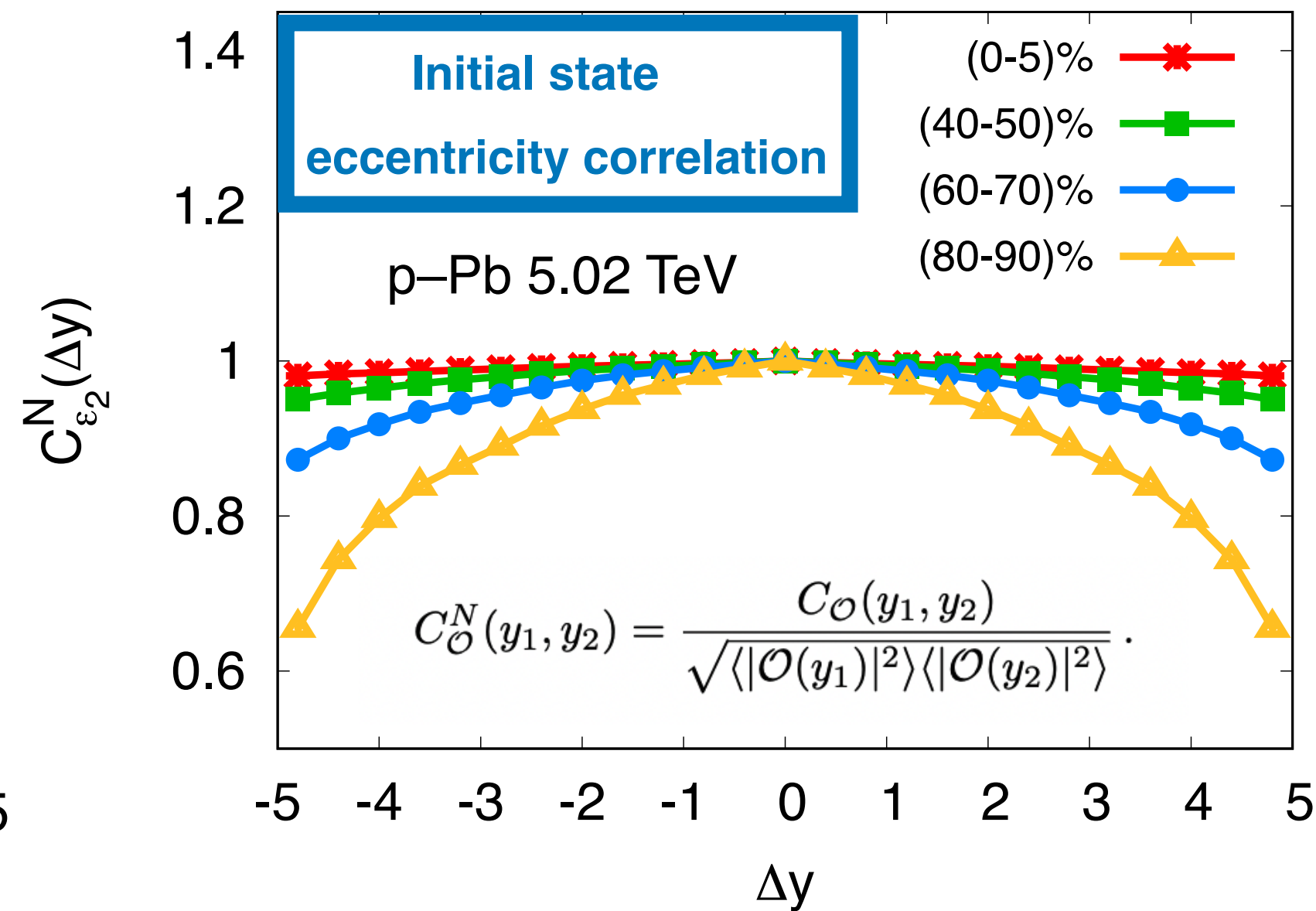
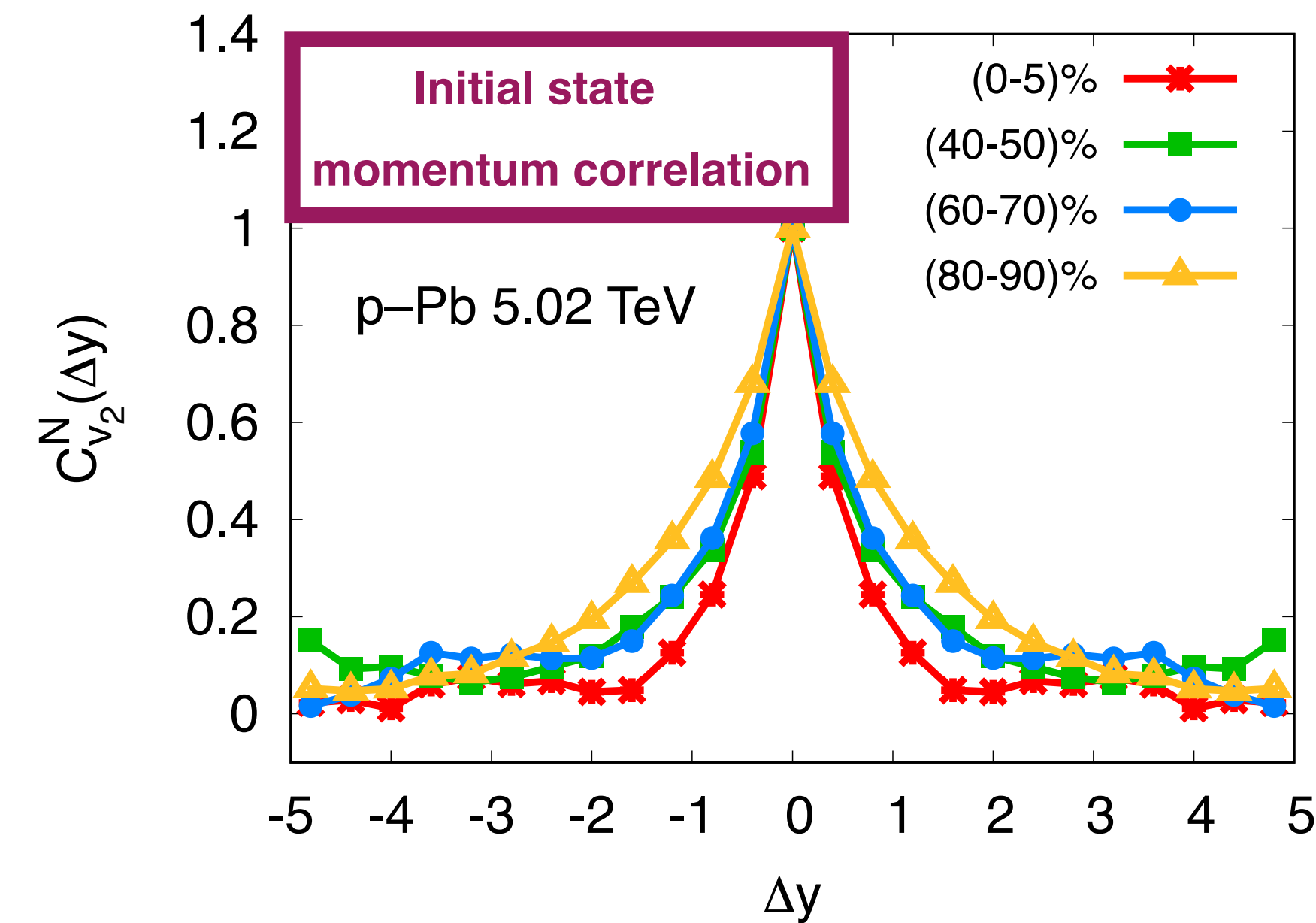
- Initial state momentum correlations — relatively short-range (still has finite contribution for $|\Delta\eta| < 3.0$).
- Event geometry (transverse) — correlated across large rapidity intervals.

How to disentangle Initial and Final state effects?



Initial state effects might be short range...

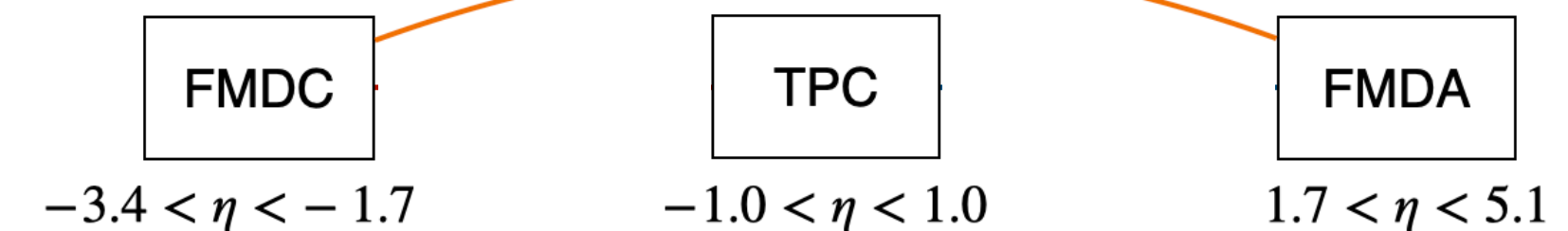
THE 3D IP-GLASMA MODEL



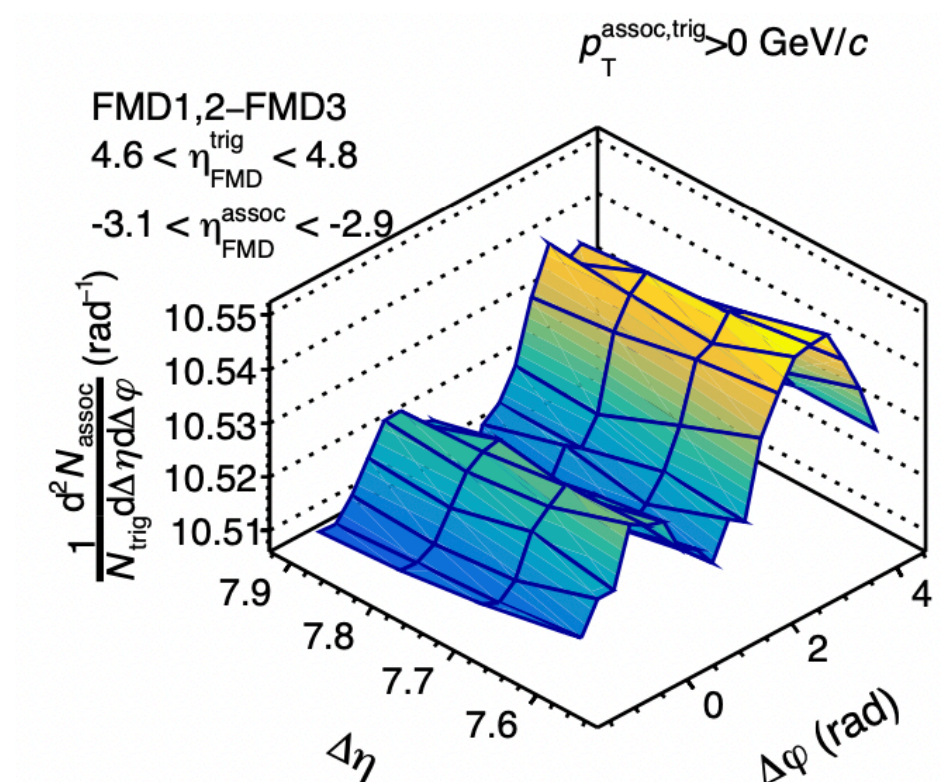
B. Schenke, S. Schlichting, P. Singh; Phys. Rev. D 105, 094023 (2022)

- Initial state momentum correlations — relatively short-range (still has finite contribution for $|\Delta\eta| < 3.0$).
- Event geometry (transverse) — correlated across large rapidity intervals.

Ultra Long-range correlation in ALICE



FMDA—FMDC correlation ($|\Delta\eta| > 5.0$)

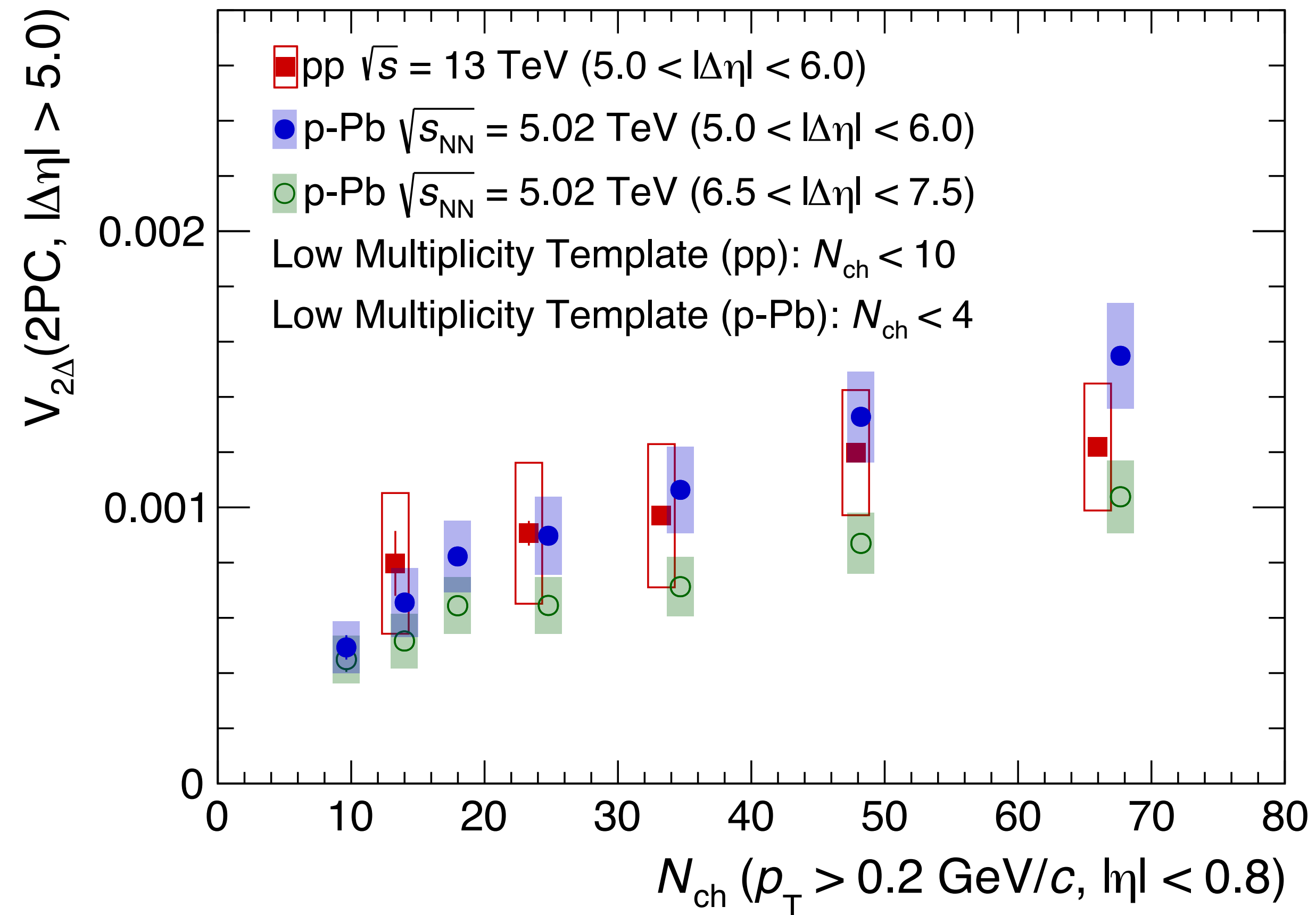
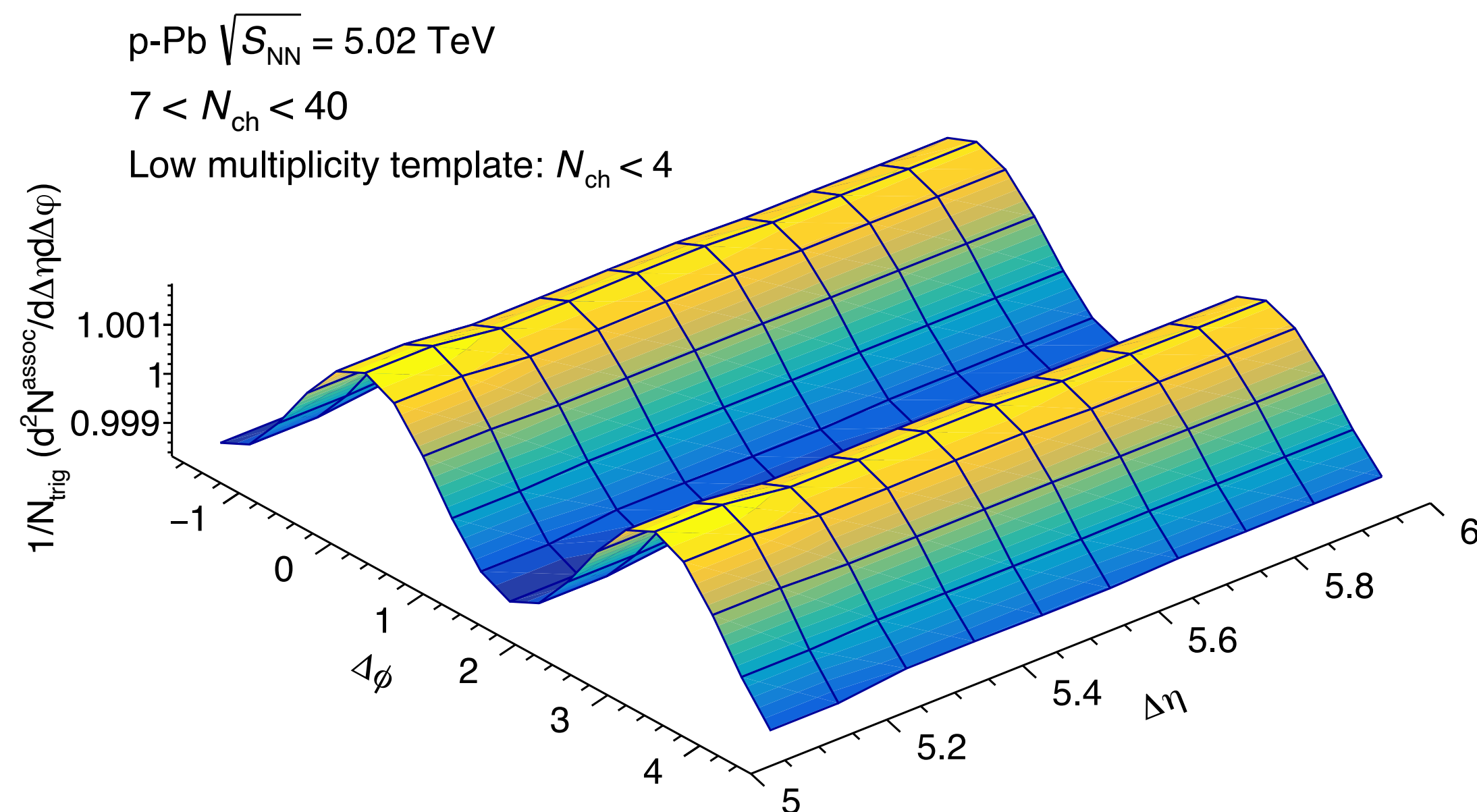


ALICE, JHEP 01 (2024) 199

Goal: Explore the longest-range correlation down to minimum bias multiplicity



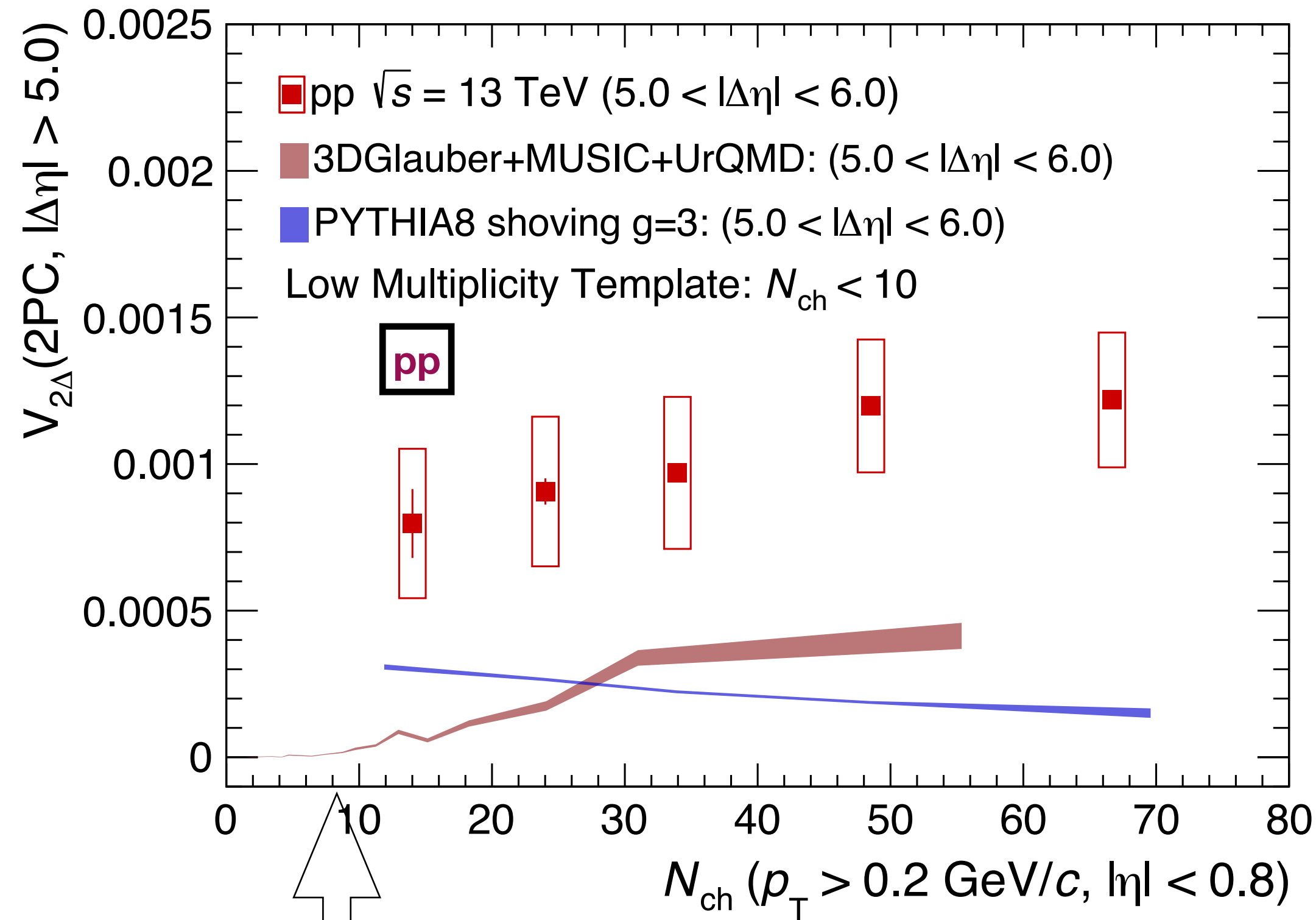
Flow coefficients: Ultra long-range correlation in ALICE



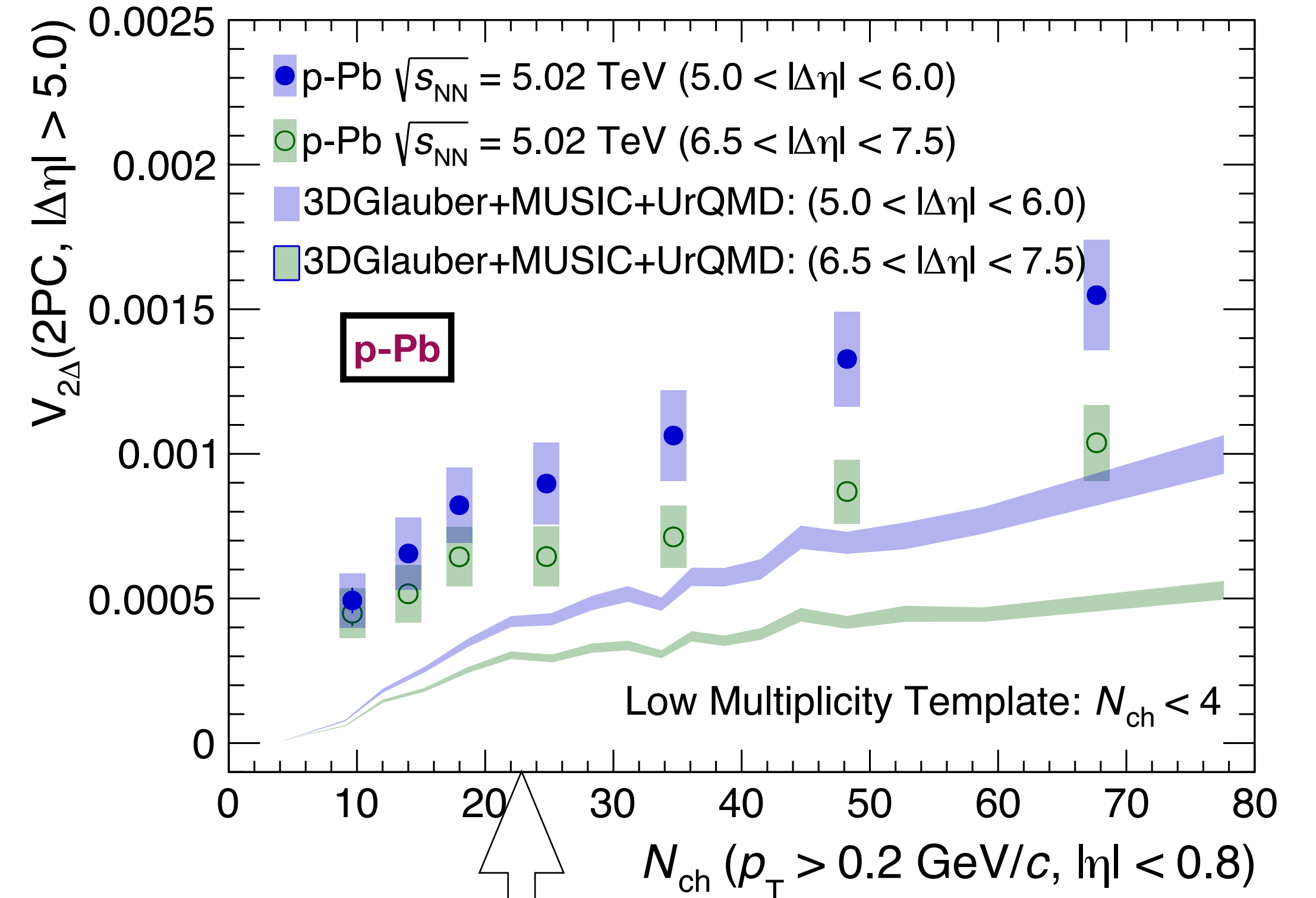
- Longest-range correlation ever measured down to or lower than minimum bias multiplicity in pp and p–Pb collisions.



Flow coefficients: Ultra long-range correlation in ALICE



3dGlauber+MUSIC+UrQMD: W Zhao, S Ryu, C Shen, and B Schenke;
Phys. Rev. C 107, 014904 (2023)

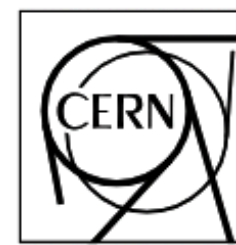


- SM of heavy-ions: Hydro (3DGlauber+MUSIC+UrQMD) doesn't explain the results.
- SM of pp physics (PYTHIA) fails. Alternative approach such as PYTHIA with shoving fails too!
- Critical challenge to both paradigms (HI and small systems) at once.



Flow coefficients: Ultra long-range correlation in ALICE

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH



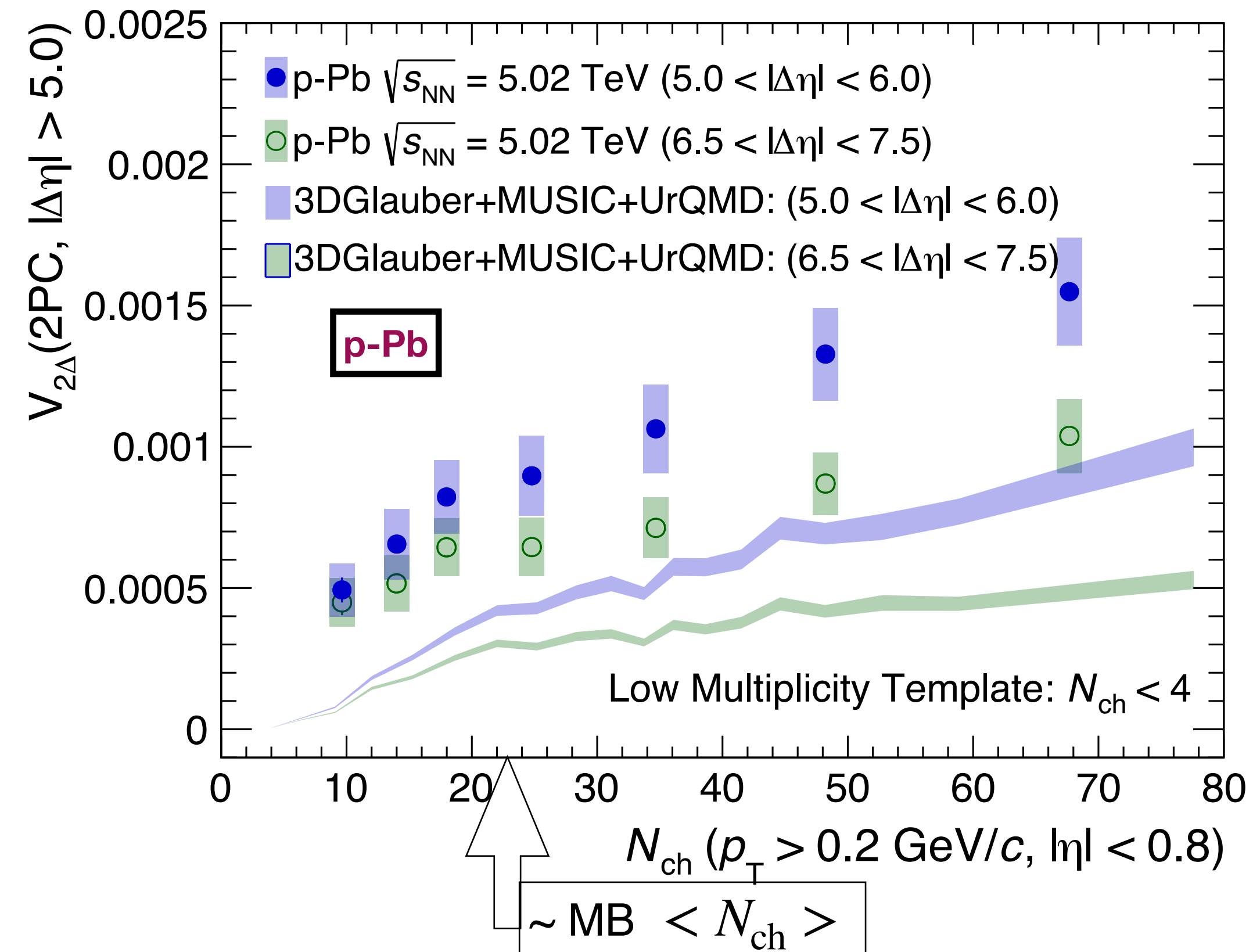
CERN-EP-XXXX-XXX
Day Month XXXX

First observation of Ultra-Long Range Azimuthal Correlations in Low Multiplicity pp and p-Pb Collisions at the LHC

ALICE Collaboration*

Abstract

This study presents the first observation of two-particle correlations with pseudorapidity separation of $|\Delta\eta| > 5.0$ and $|\Delta\eta| > 6.5$ (ultra-long range) in proton-proton (pp) and proton-lead (p-Pb) collisions at the LHC, down to or below the minimum-bias multiplicity. The two-particle correlation coefficients ($V_{2\Delta}$) are measured after removing non-flow contributions using the template-fit method across various multiplicity classes, providing novel insights into the origin of long-range correlations in small systems. Initial-state momentum anisotropy, as modeled in 3D Glasma models generate only short-range correlations and do not contribute to ultra-long correlations measured in this paper. Comparisons with the 3D Glauber + MUSIC + UrQMD hydrodynamic model reveal significant discrepancies at low multiplicities, indicating possible dynamics beyond typical hydrodynamic behavior and highlighting the current lack of understanding of the initial conditions in small systems. PYTHIA simulations with string shoving mechanism, fail to capture these ultra-long range correlations, emphasizing the limitations of current models. These results challenge existing paradigms, suggesting that neither initial-state models, hydrodynamics, nor PYTHIA variants can fully account for the underlying mechanisms in low-multiplicity pp and p-Pb collisions. The findings impose significant constraints on models describing collective phenomena in small collision systems and advance the understanding of origin of long-range correlations at LHC energies.

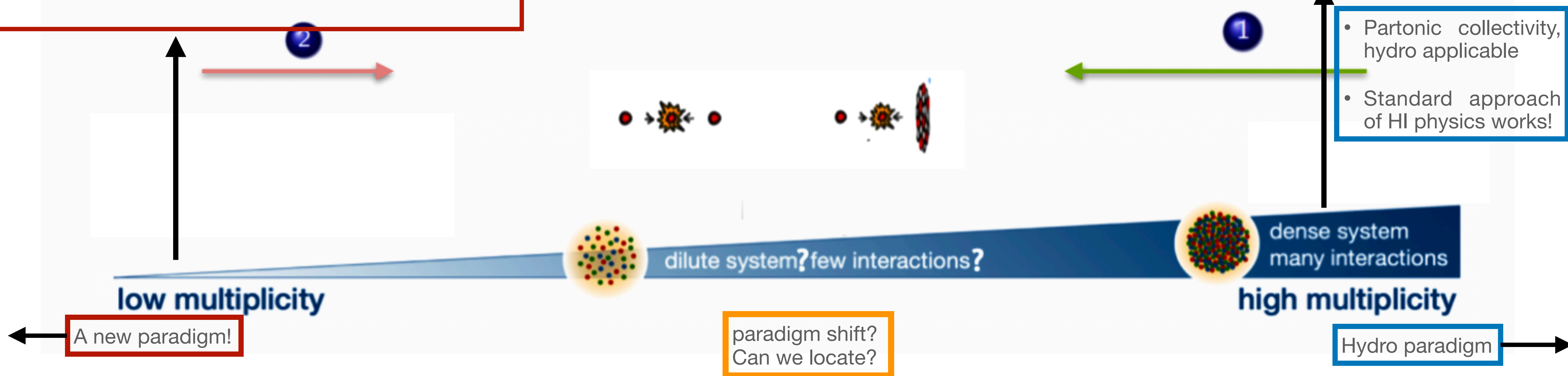
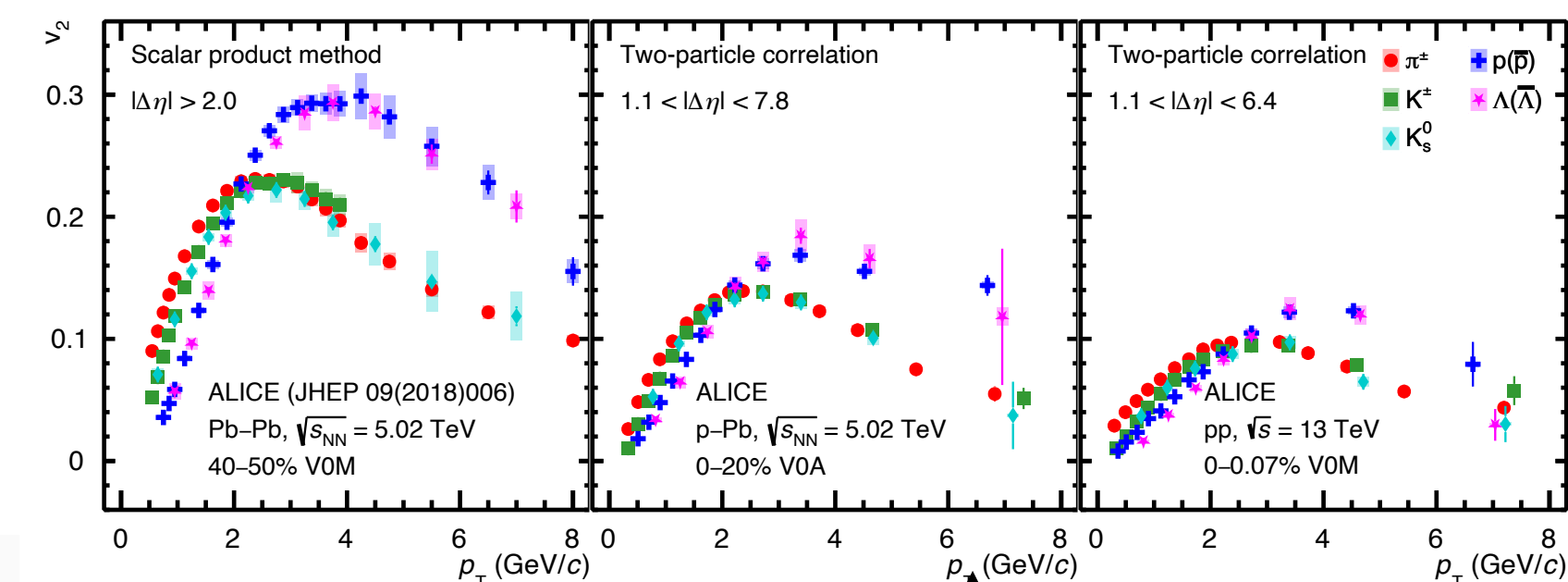


- SM of heavy-ions: Hydro (3D Glauber+MUSIC+UrQMD) doesn't explain the results.
- SM of pp physics (PYTHIA) fails. Alternative approach such as PYTHIA with shoving fails too!
- **Critical challenge to both paradigms (HI and small systems) at once.**



Collectivity in low multiplicity pp and p-Pb: A new paradigm!

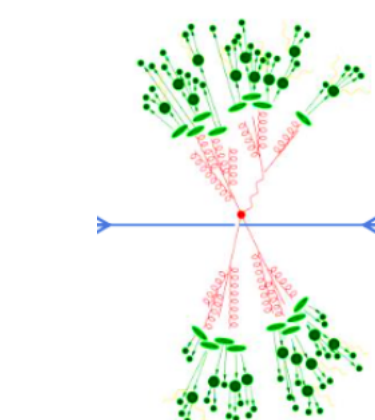
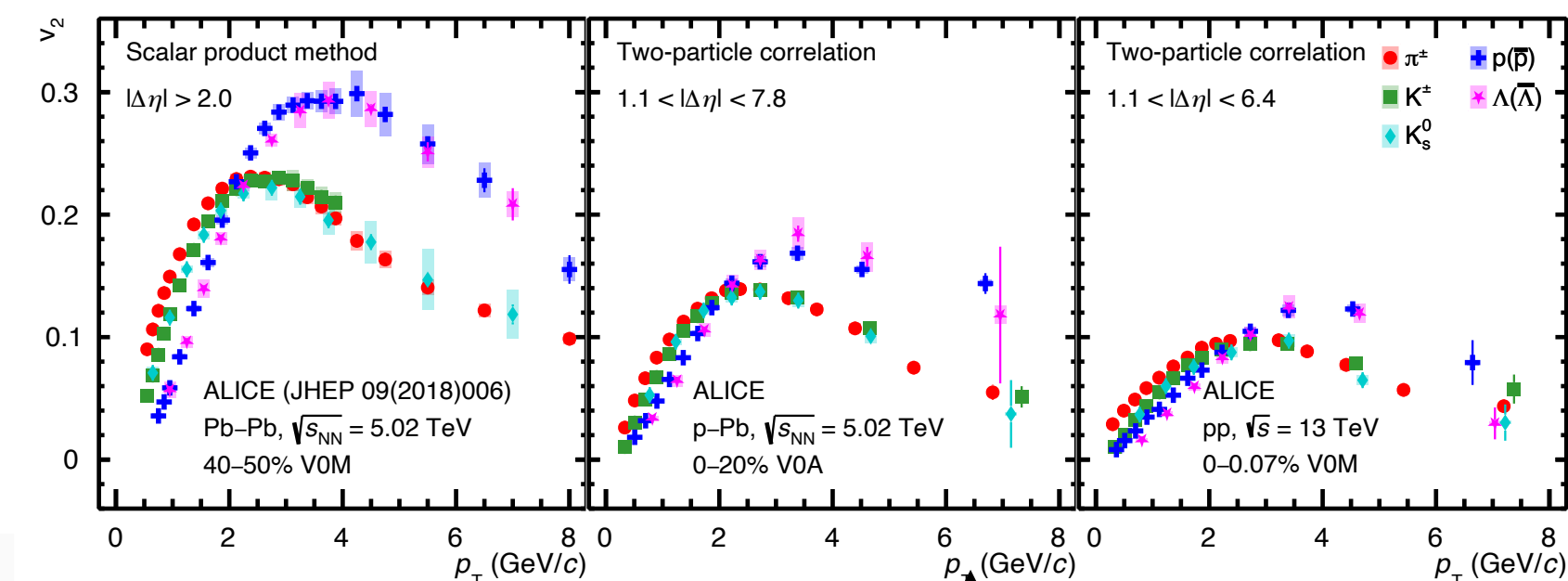
- Ultra Long range correlation exist after non-flow removal even below min bias multiplicity (First observation).
- **Hydro paradigm** fails.
- **PYTHIA paradigm** (including shoving) fails.
- **CGC** doesn't contribute.
- **Transport model (AMPT)** fails (see the back up).





Collectivity in low multiplicity pp and p-Pb: A new paradigm!

- Ultra Long range correlation exist after non-flow removal even below min bias multiplicity (First observation).
- **Hydro paradigm** fails.
- **PYTHIA paradigm** (including shoving) fails.
- **CGC** doesn't contribute.
- **Transport model (AMPT)** fails (see the back up).



e⁺e⁻: new baseline?

low multiplicity

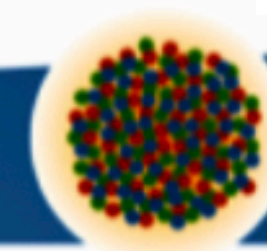
A new paradigm!

Only Initial state effects (not CGC)?
Initial state effects (not CGC)? + final state effects ?
Hydro still applicable?
new physics?
What are the possibilities?



dilute system? few interactions?

paradigm shift?
Can we locate?



dense system
many interactions

high multiplicity

Hydro paradigm

- Partonic collectivity, hydro applicable
- Standard approach of HI physics works!



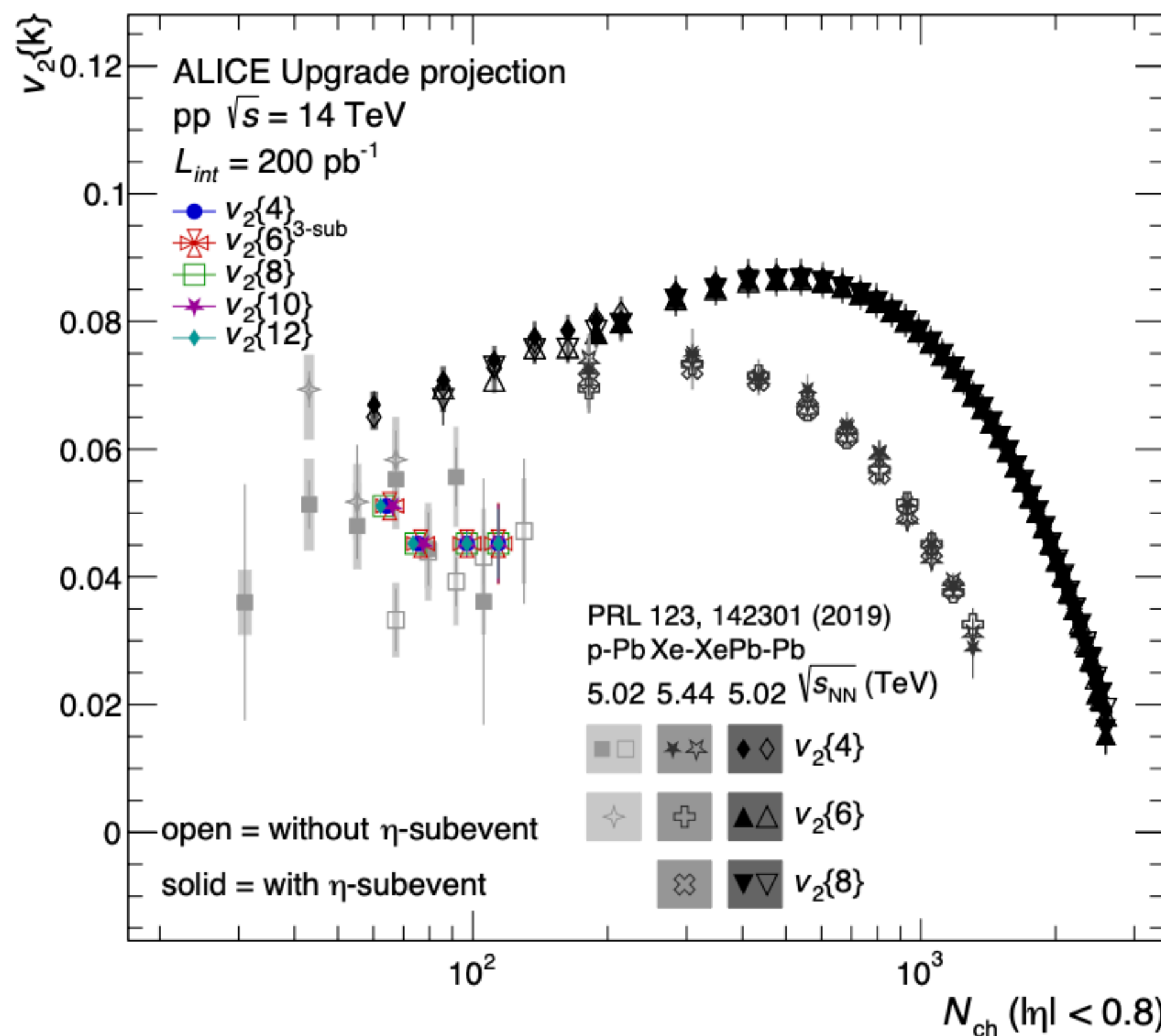
Summary and Outlook

- Small systems: partonic collectivity in high multiplicity classes of small systems!
- A new open question: Collective effects at low multiplicity pp and p–Pb collisions (down to MB multiplicity). Origin: initial and/or final state effects? Run 3 pp and O-O data will be useful.
- Ultra long-range correlation ($|\Delta\eta| > 5.0$) down to the minimum bias multiplicity measured in pp and p–Pb collisions for the first time.
- Inclusive e+e- collisions at 91 GeV and 183-209 GeV show no ridge. New baseline?
- High multiplicity e+e- collisions (183-209 GeV) show ridge. Where is the onset of collective phenomena?
- New paradigm of collectivity search in small systems. Baseline: Min Bias e+e-; Target system: low mult pp, p-Pb and OO, UPC, DIS etc. LHC Run3 will provide more insights.

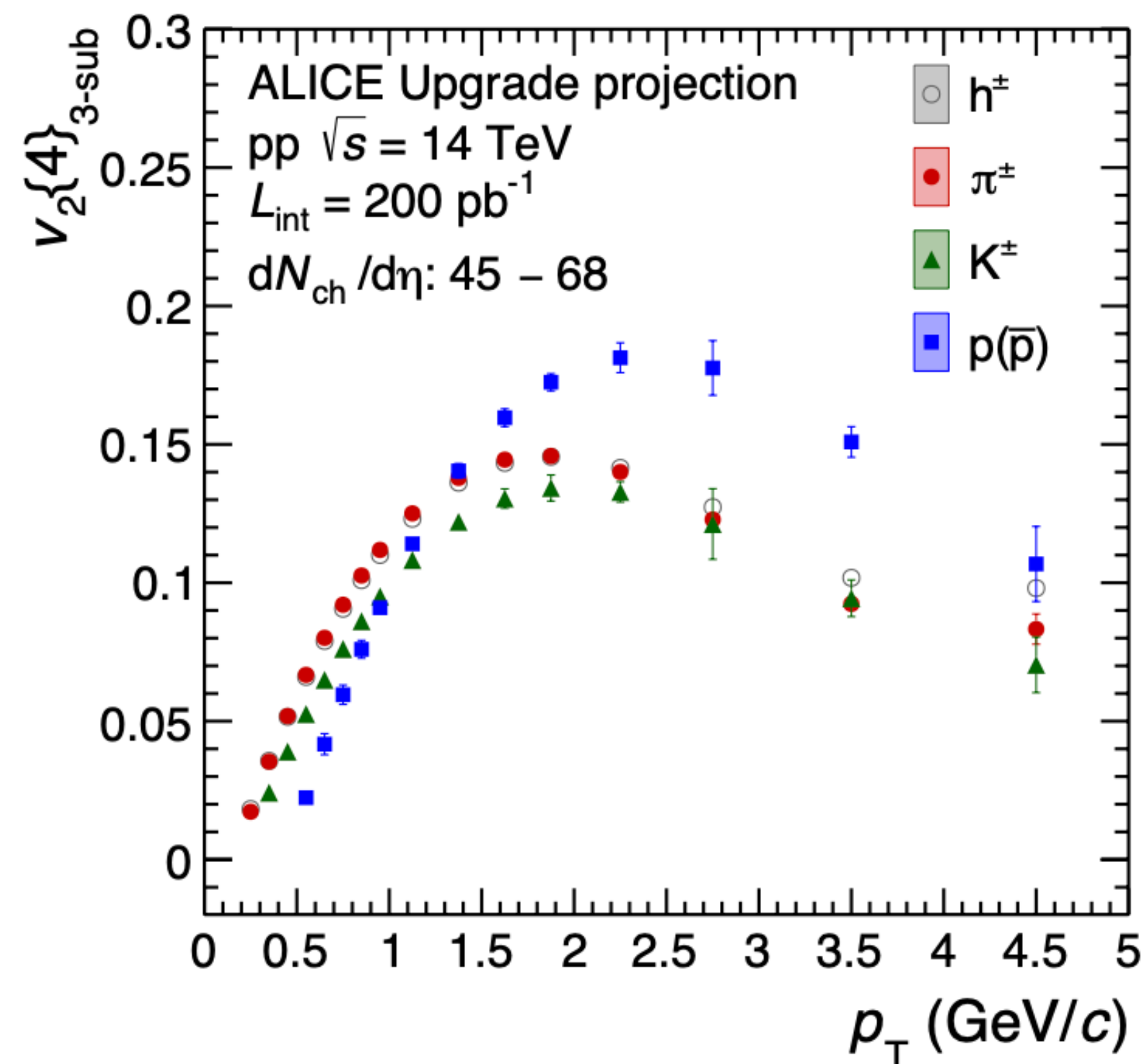
Thank You



Boundaries to be pushed with the Run 3 data



pp



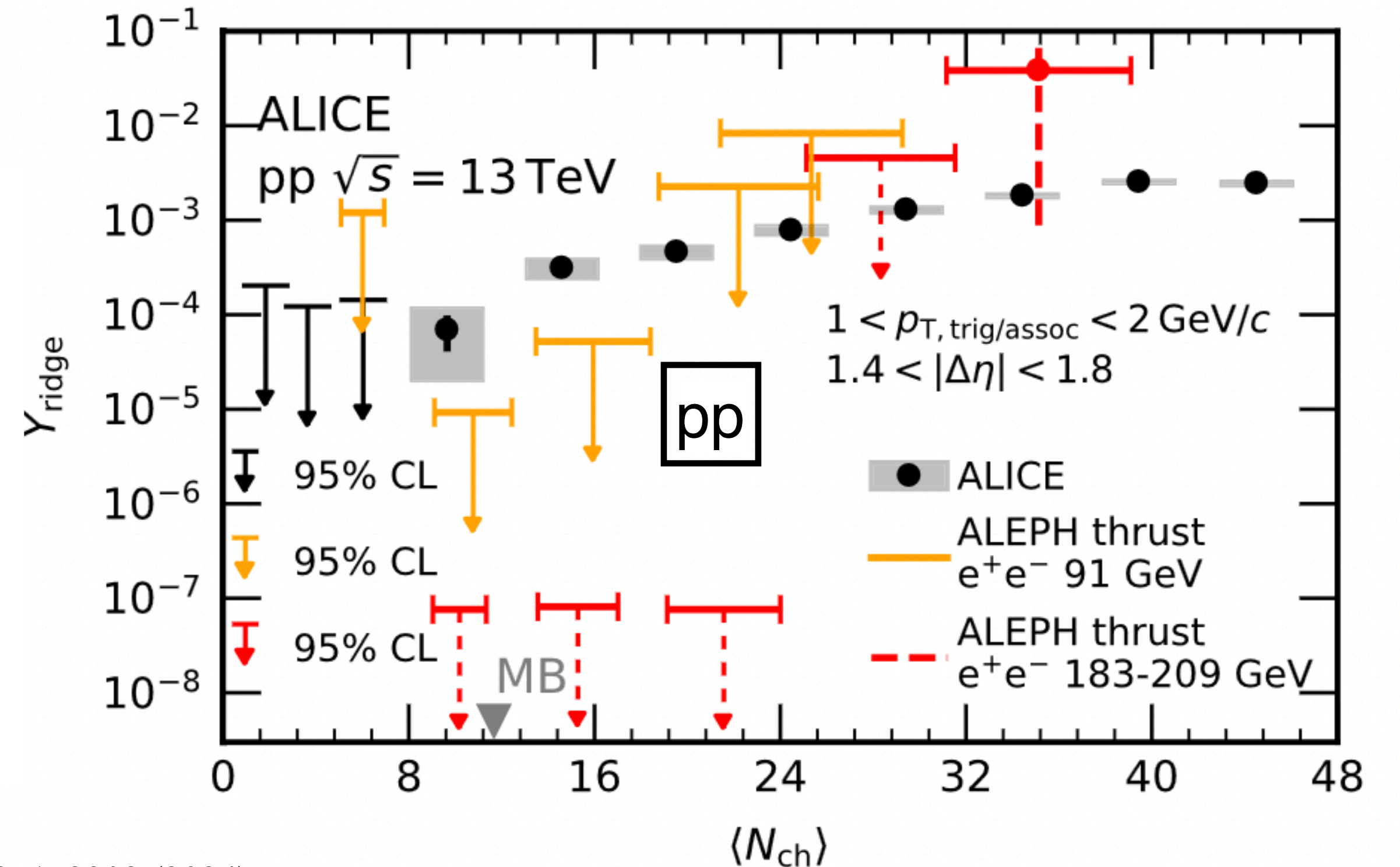
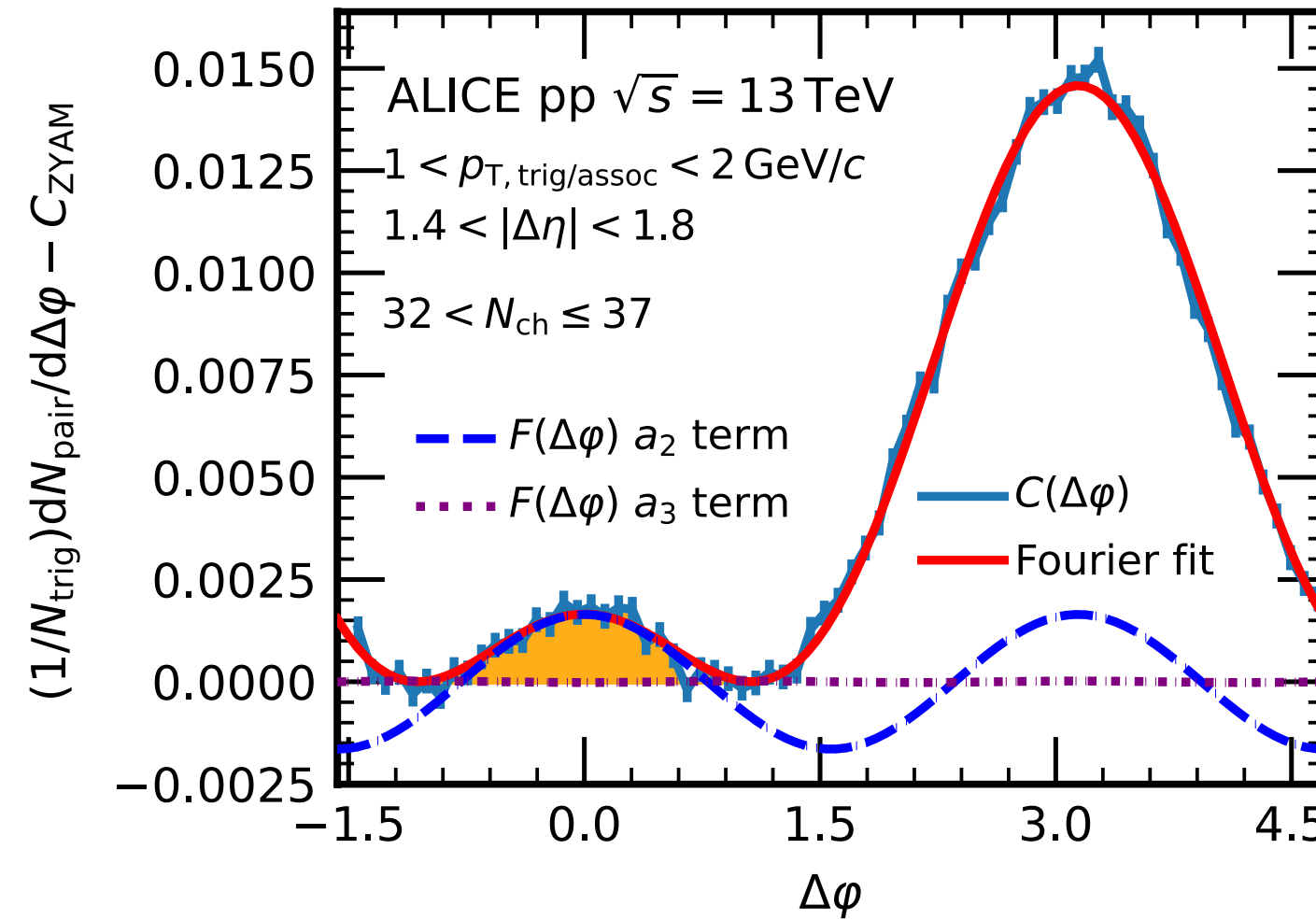
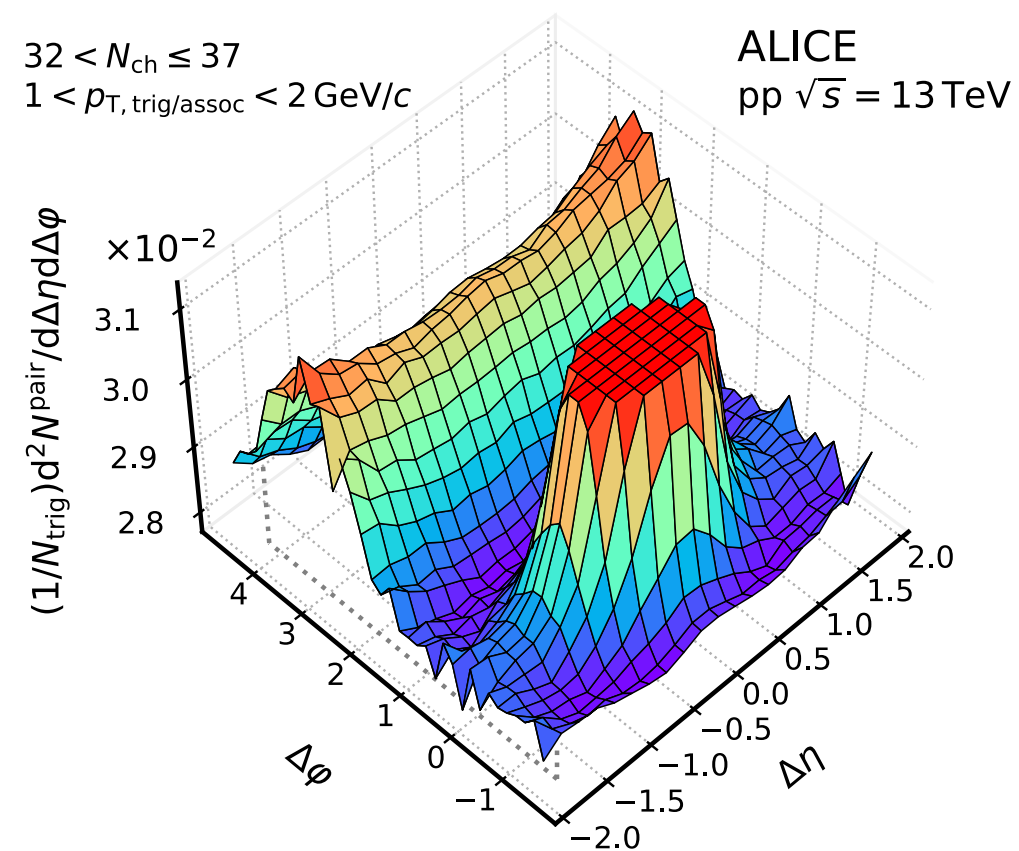
ALICE-PUBLIC-2020-005

- Multiplicity dependent precision measurements for PID flow, long range correlations— search for the onset of collectivity
- Multiplicity dependent flow vector fluctuations study using mid and forward rapidity detectors — constrain the 3D initial state effects.



What is the low multiplicity limit for collectivity?

Ridge yield: No non-flow subtraction



ALICE, PRL 132, 172302 (2024)

- Ridge Yield: $Y^{pp} > Y^{e^+e^-} 5\sigma$ (best) at 91 GeV; 6.3σ (best) at 183–209 GeV
- Correlation at mid-rapidity: relatively short range ($|\Delta\eta| < 1.8$), non-flow removal might depend on the kinematics.

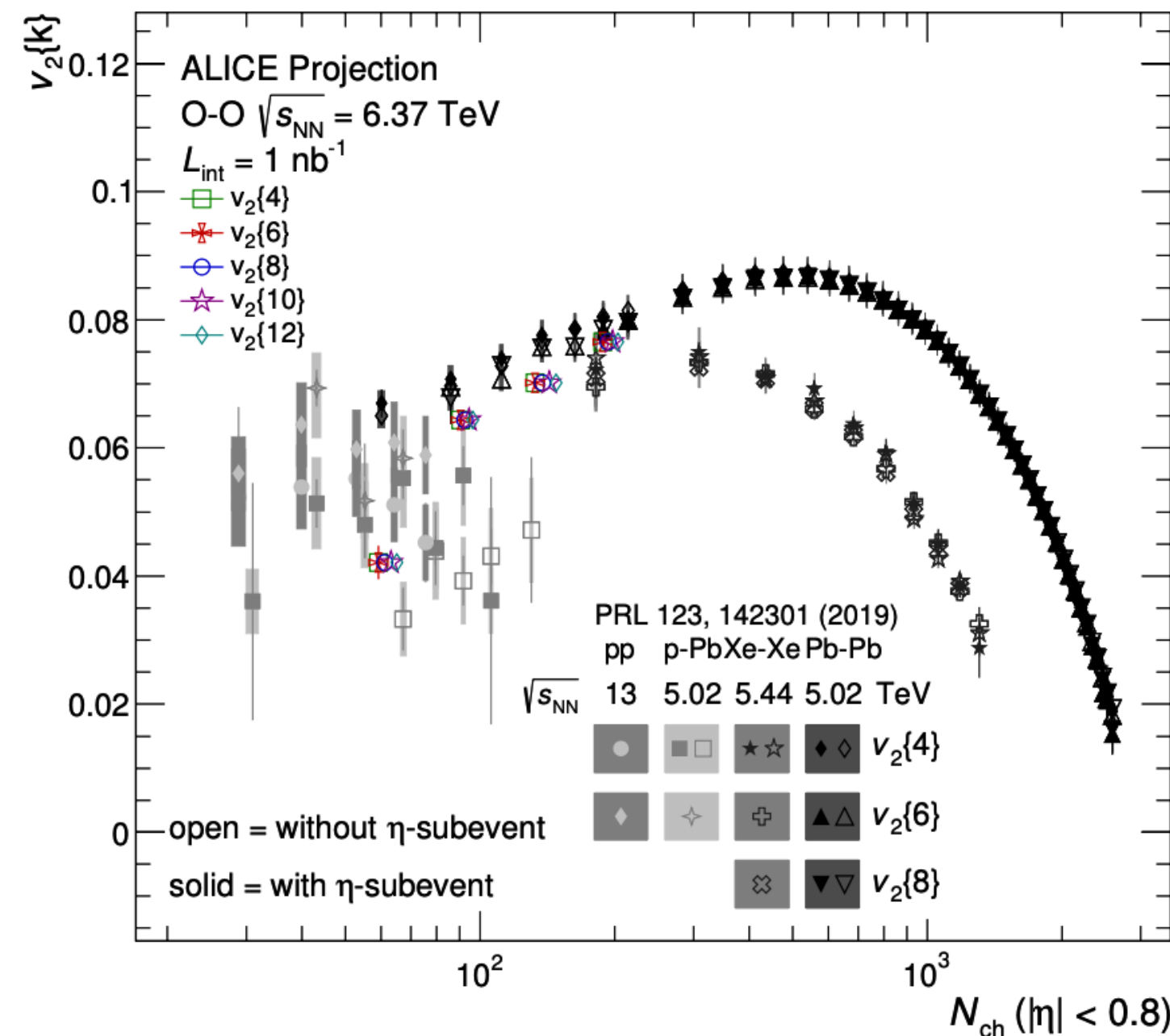
What is the origin of flow-like behavior at low multiplicity?

Initial and/or Final effects?

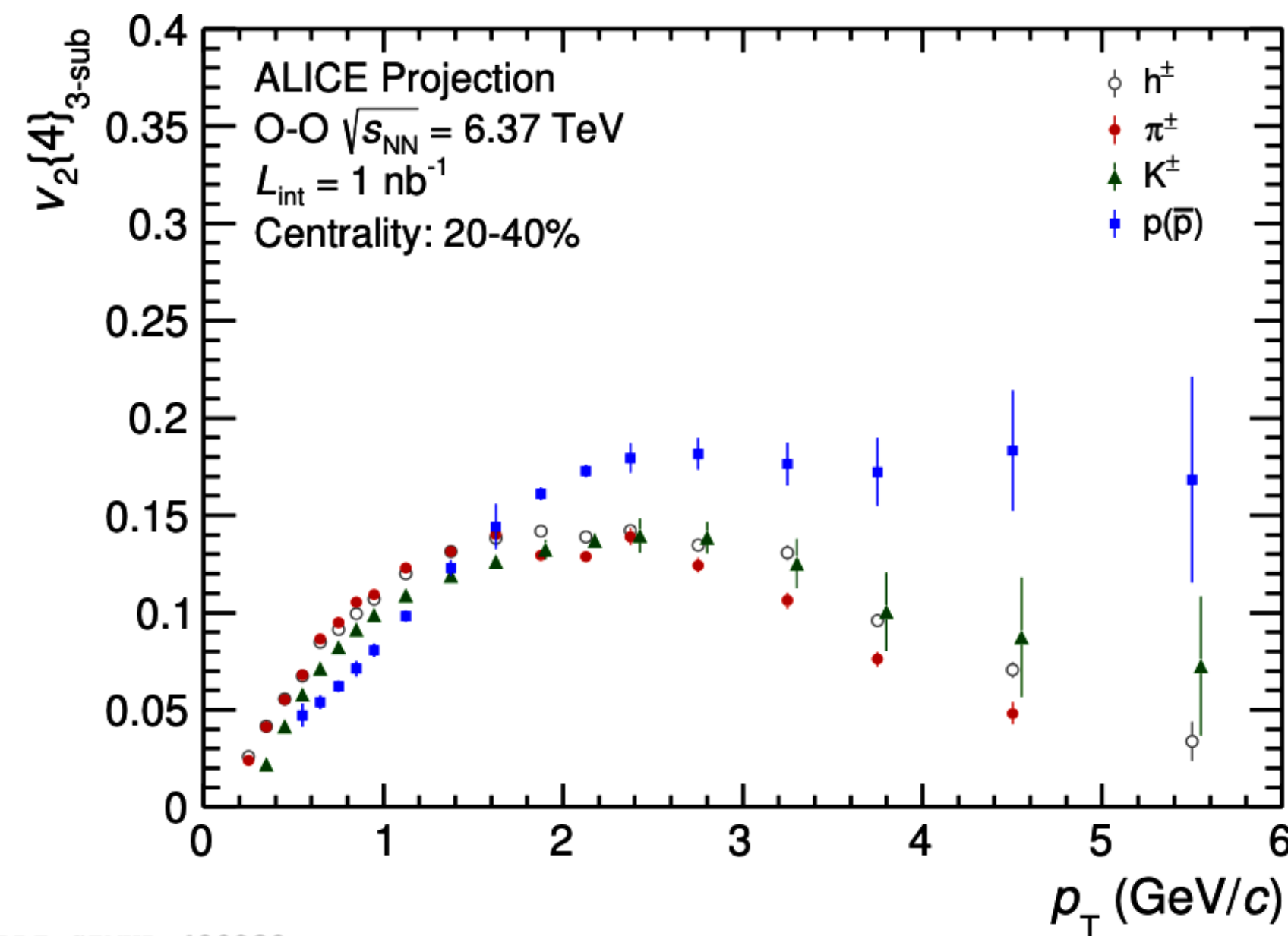


Boundaries to be pushed with the Run 3 data

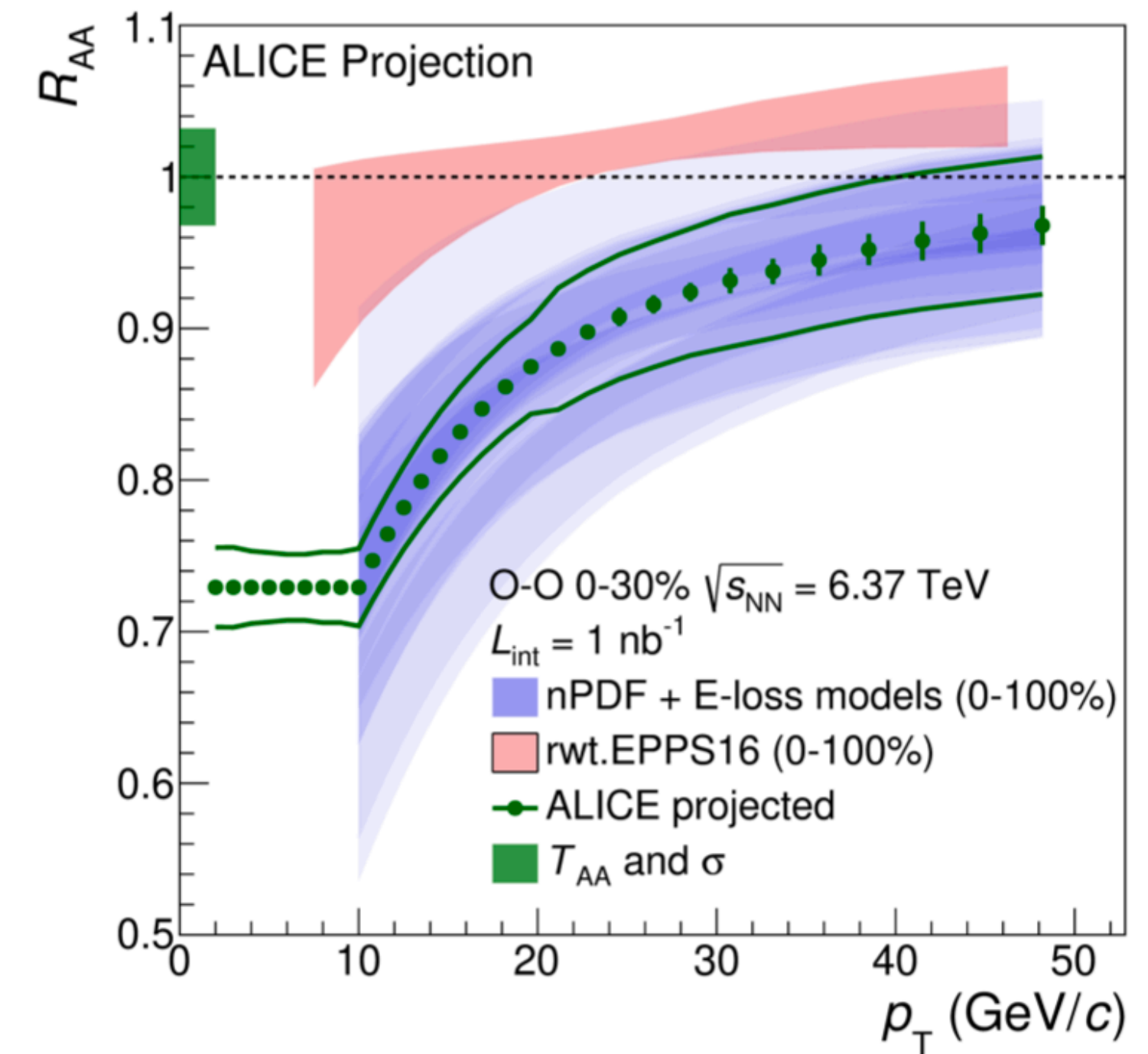
O-O



ALI-SIMUL-480242



ALI-SIMUL-480238



ALI-SIMUL-480657

See talk by C. Cheshkov : [Link](#)

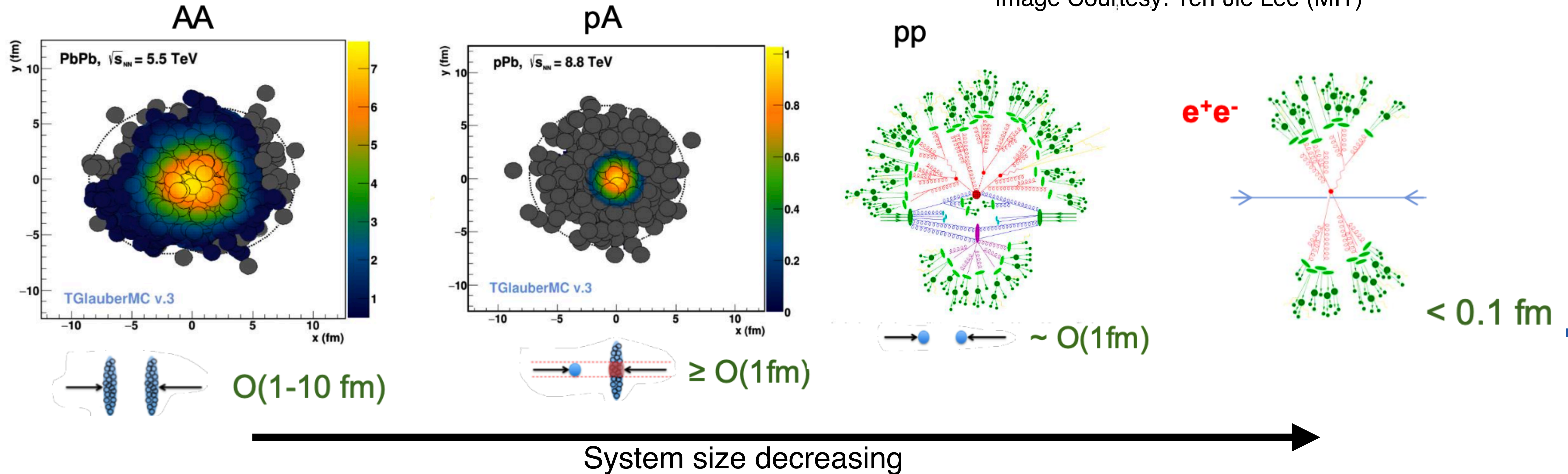
ALICE-PUBLIC-2021-004

- Multiplicity overlap with pp, p-Pb and Pb-Pb: scanning from fluctuation-dominant region to geometry-dominant region.
- Multiplicity dependence of ultralong range correlation, PID flow, flow vector fluctuations can probe the initial conditions (role of α -clustering).
- Measurements will provide constraints on initial state effects in both small systems and heavy-ion collisions.



The Endgame: A consistent description with an onset possible?

Image Courtesy: Yen-Jie Lee (MIT)



- e^+e^- : Well-defined initial conditions. No uncertainties on initial geometry or PDF description.
- No multi-parton interaction.
- No gluonic initial state radiation.



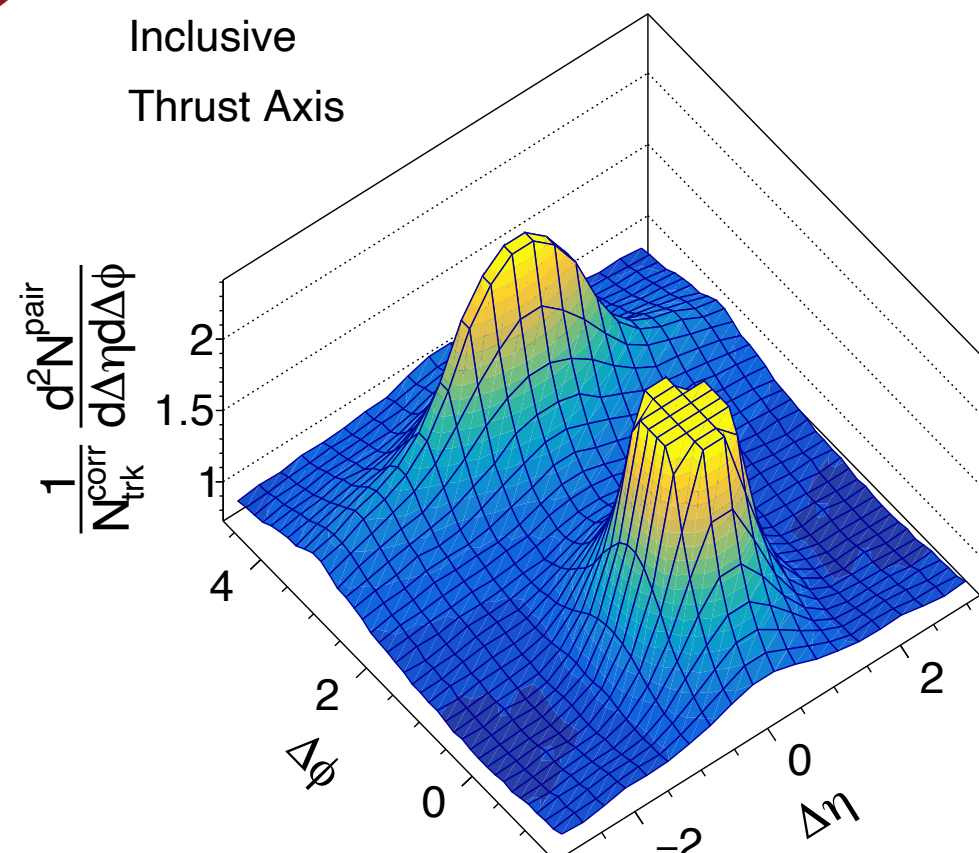
low multiplicity or smaller system: where is the limit?

Inclusive

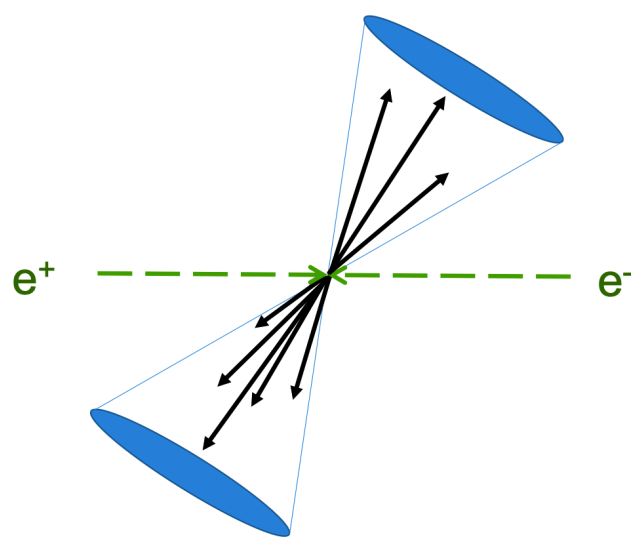
High multiplicity event

ALEPH e^+e^- , $\sqrt{s}=183\text{-}209$ GeV

Inclusive
Thrust Axis

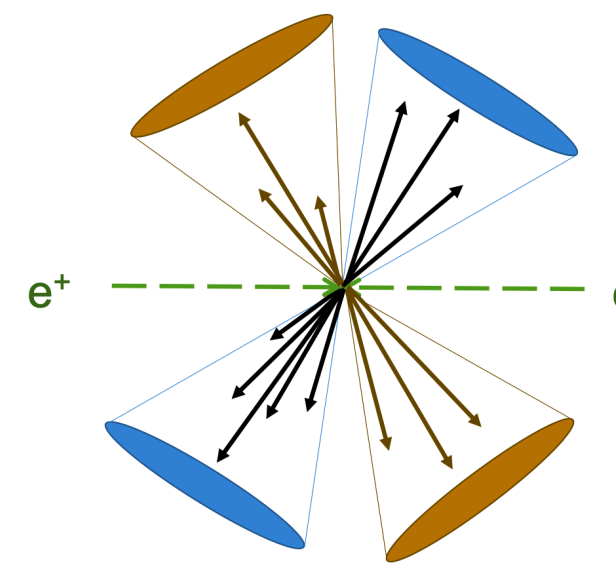


$e^+e^- \rightarrow q\bar{q}$



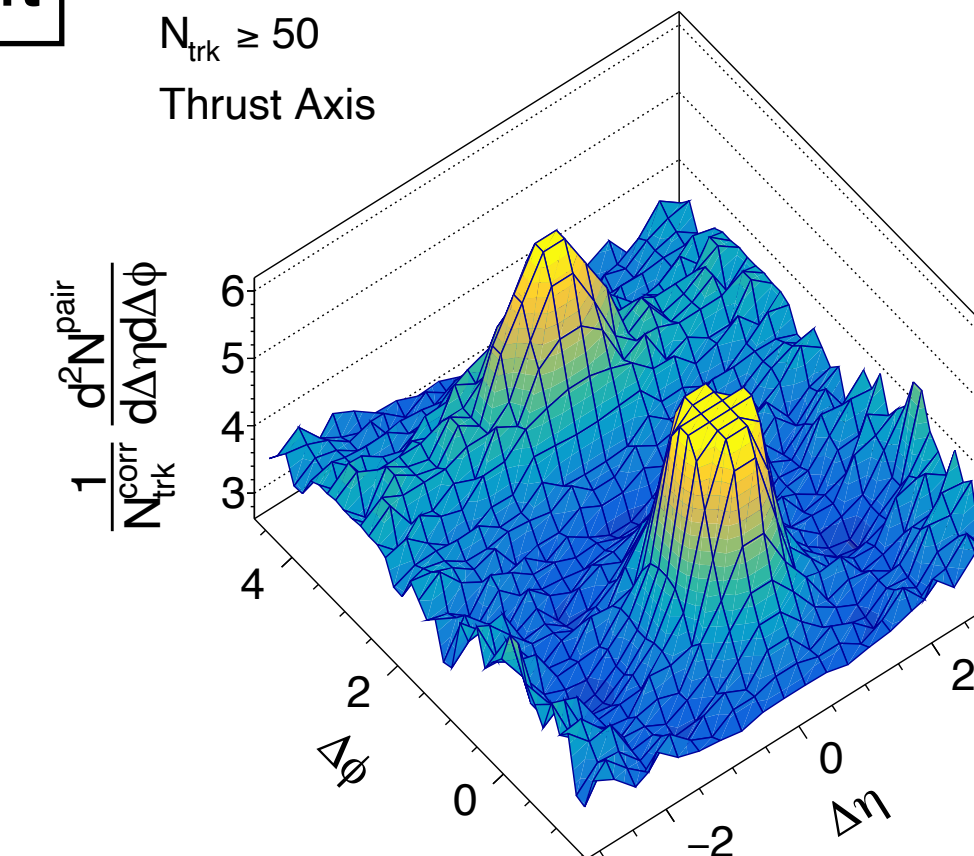
ALEPH, arXiv:2312.05084

$e^+e^- \rightarrow W^+W^- \rightarrow q\bar{q}q\bar{q}$

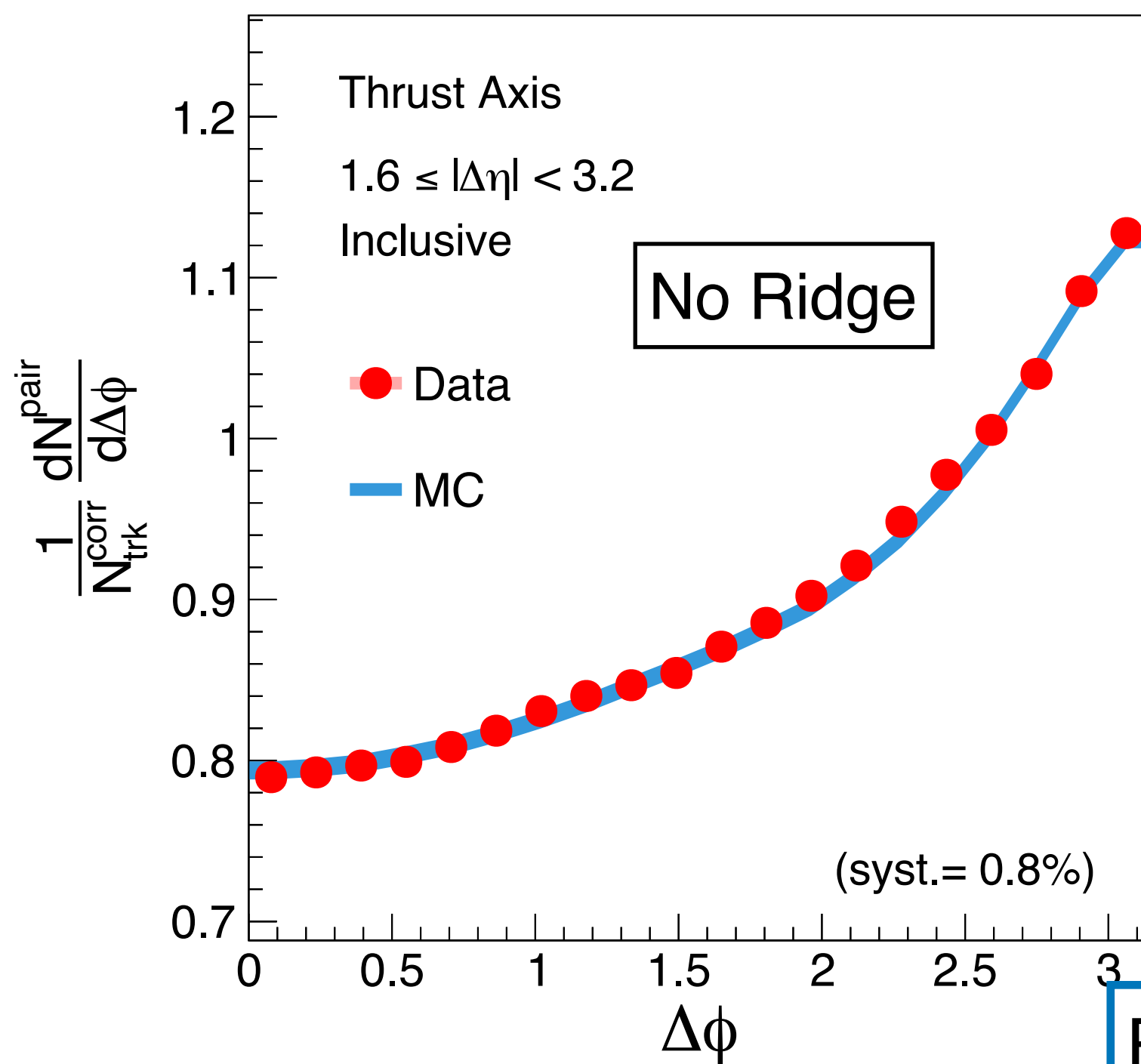


ALEPH e^+e^- , $\sqrt{s}=183\text{-}209$ GeV

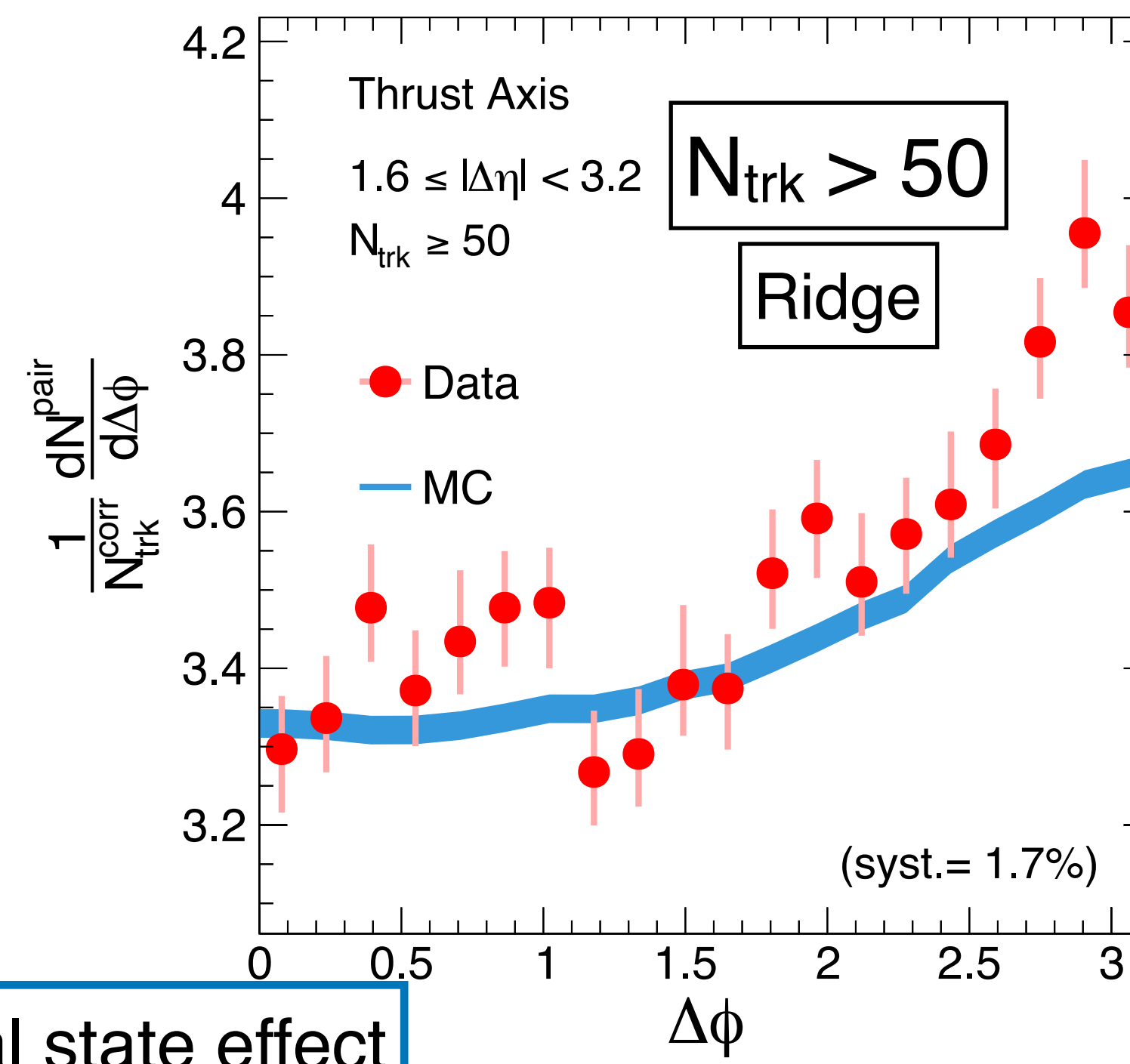
$N_{\text{trk}} \geq 50$
Thrust Axis



ALEPH e^+e^- , $\sqrt{s}=183\text{-}209$ GeV



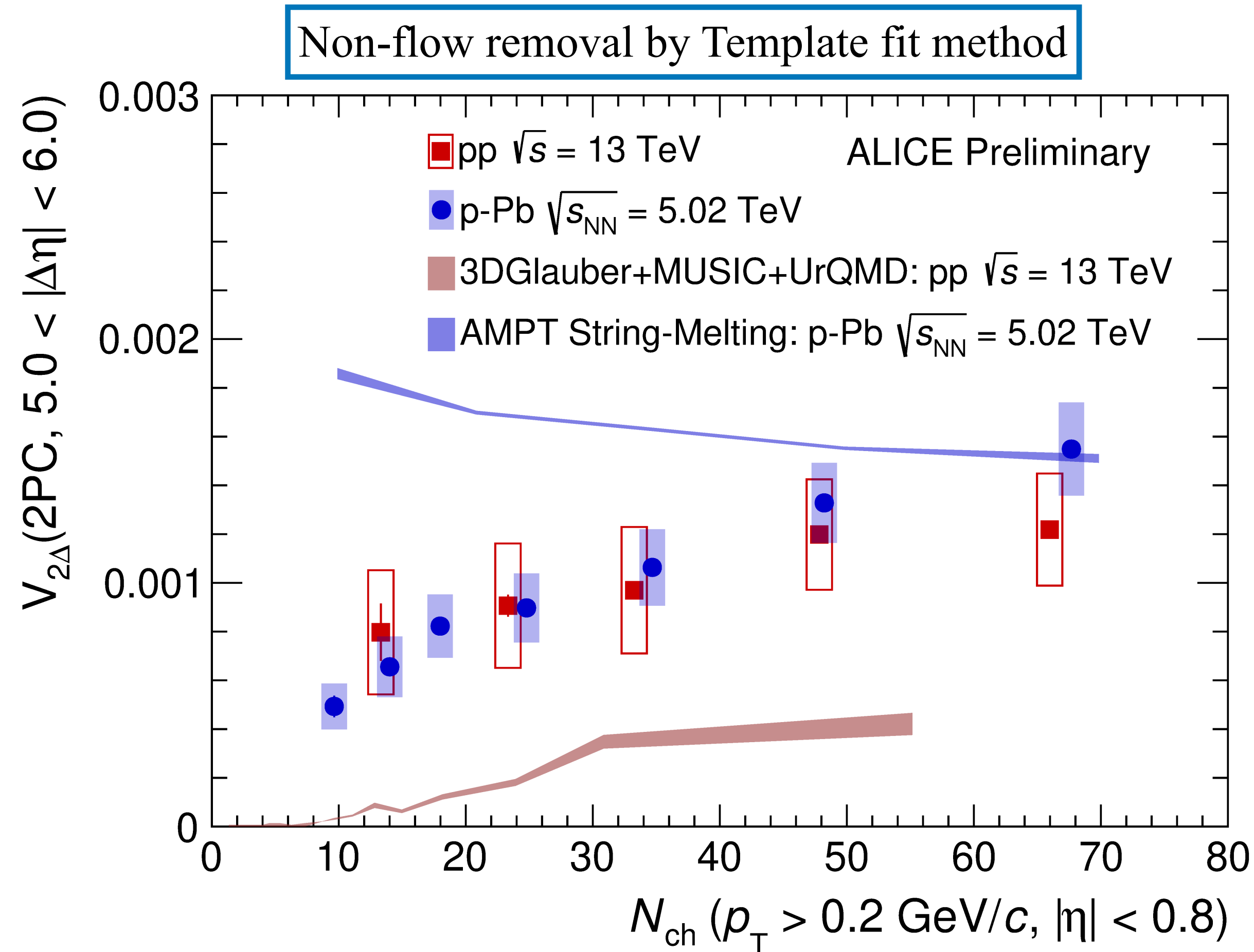
ALEPH e^+e^- , $\sqrt{s}=183\text{-}209$ GeV



Ridge in high multiplicity e^+e^- event — final state effect



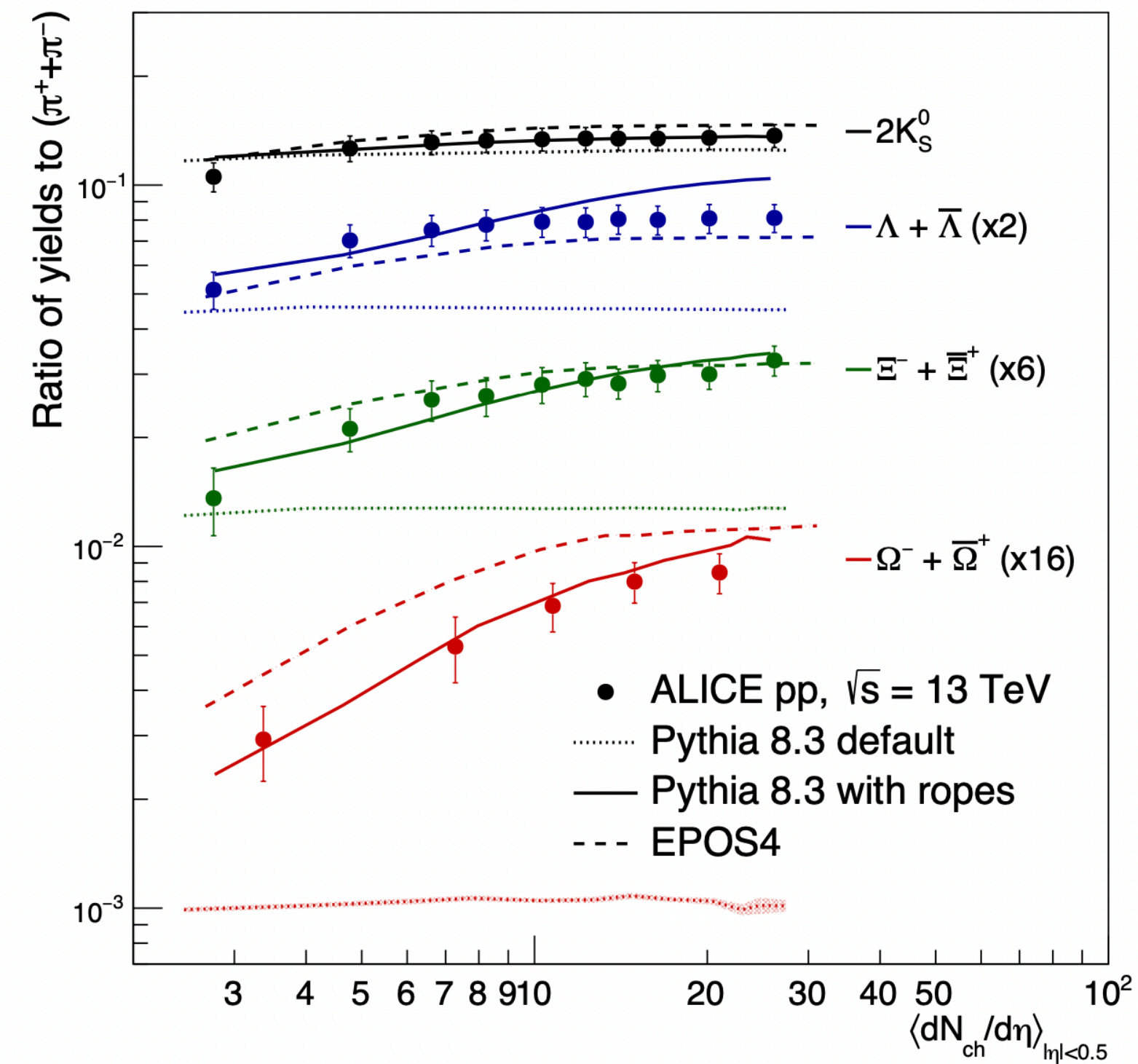
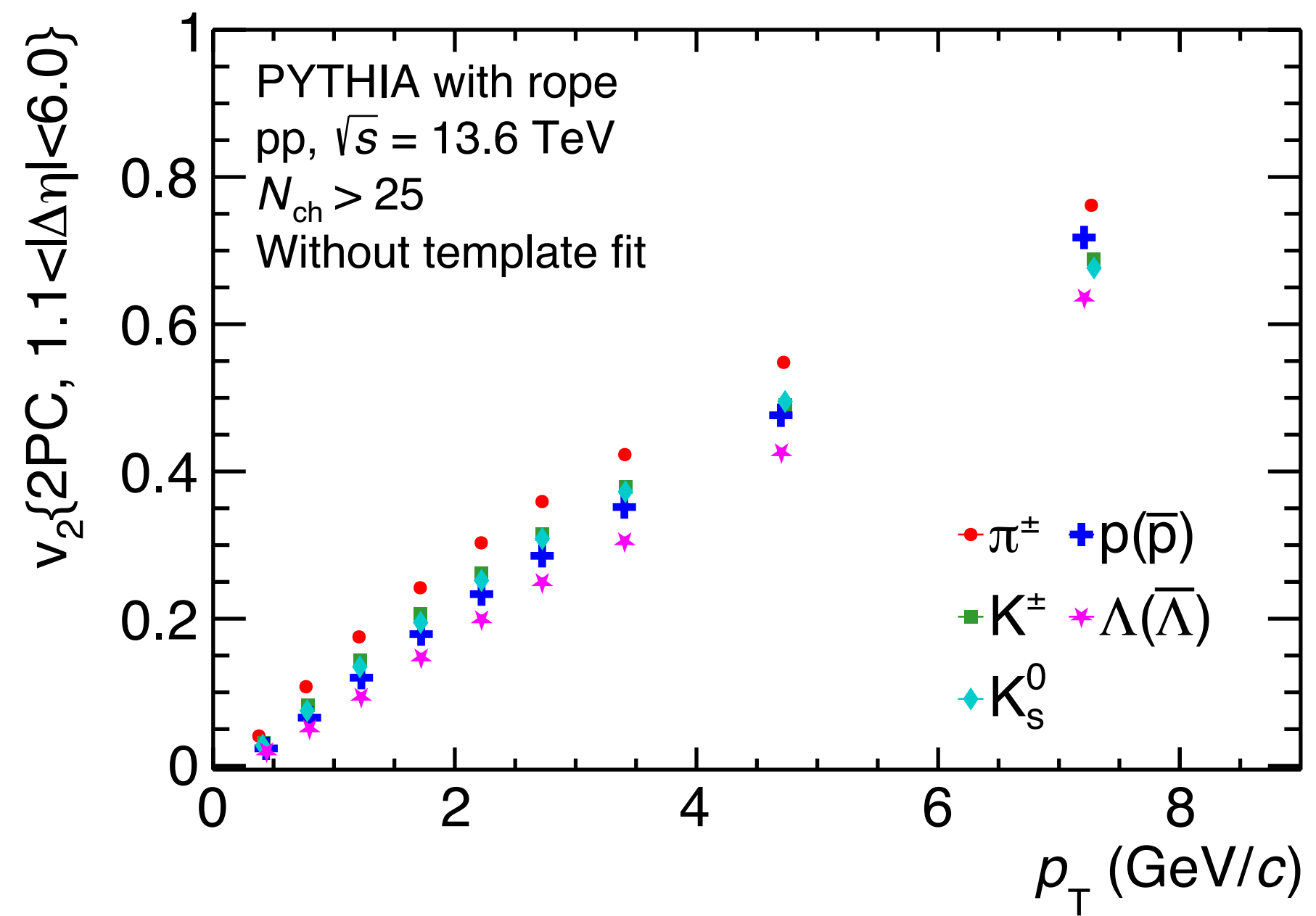
Collective features at low multiplicity: Need more model input



ALI-PREL-573662

- Hydrodynamics (3DGlauber + Music + UrQMD) underestimates the data. AMPT overestimates.
- Proper understanding of the initial state is missing.

Unprecedented constraint for hydrodynamic and alternative models. Need more theory/model input.



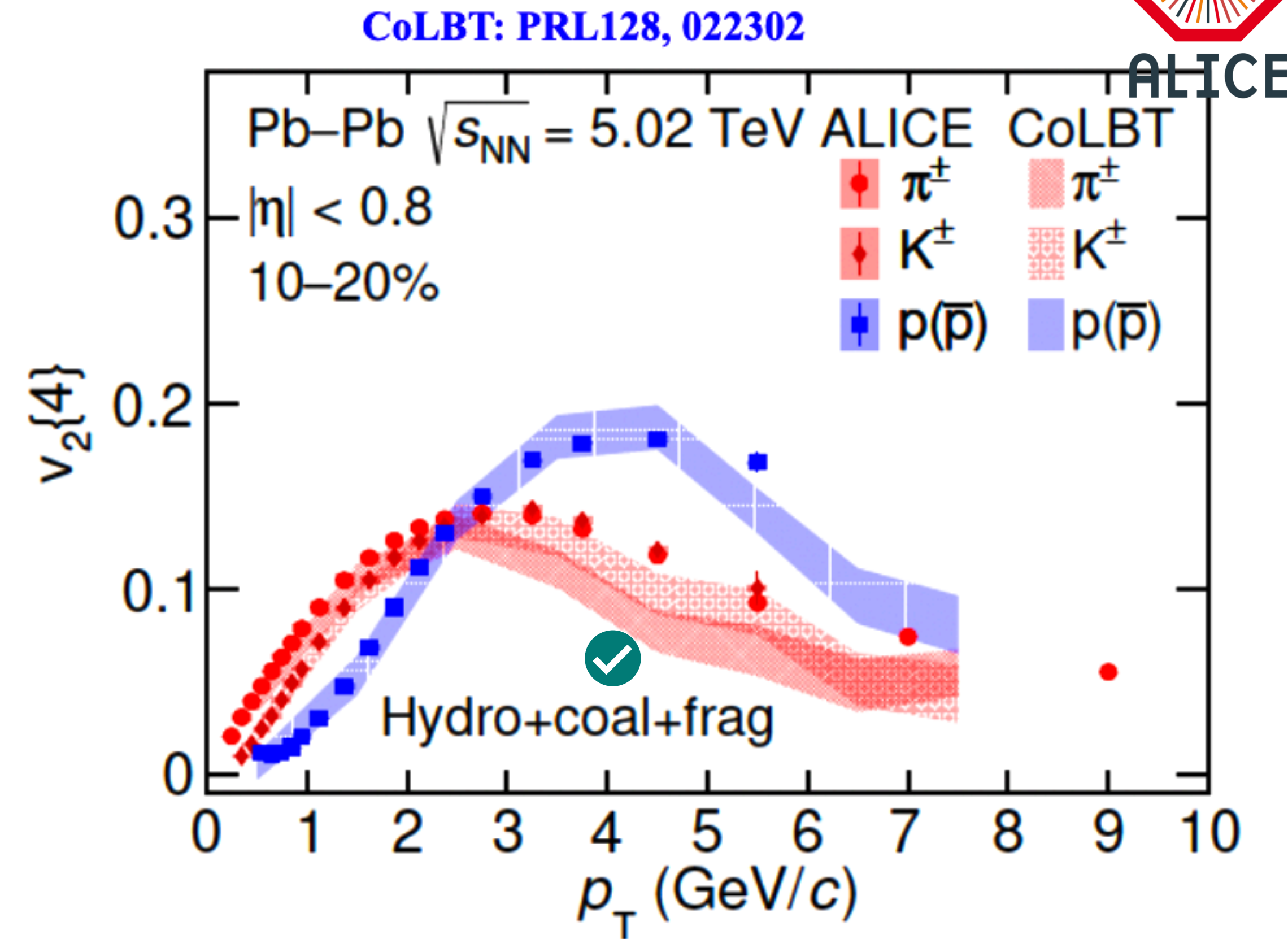
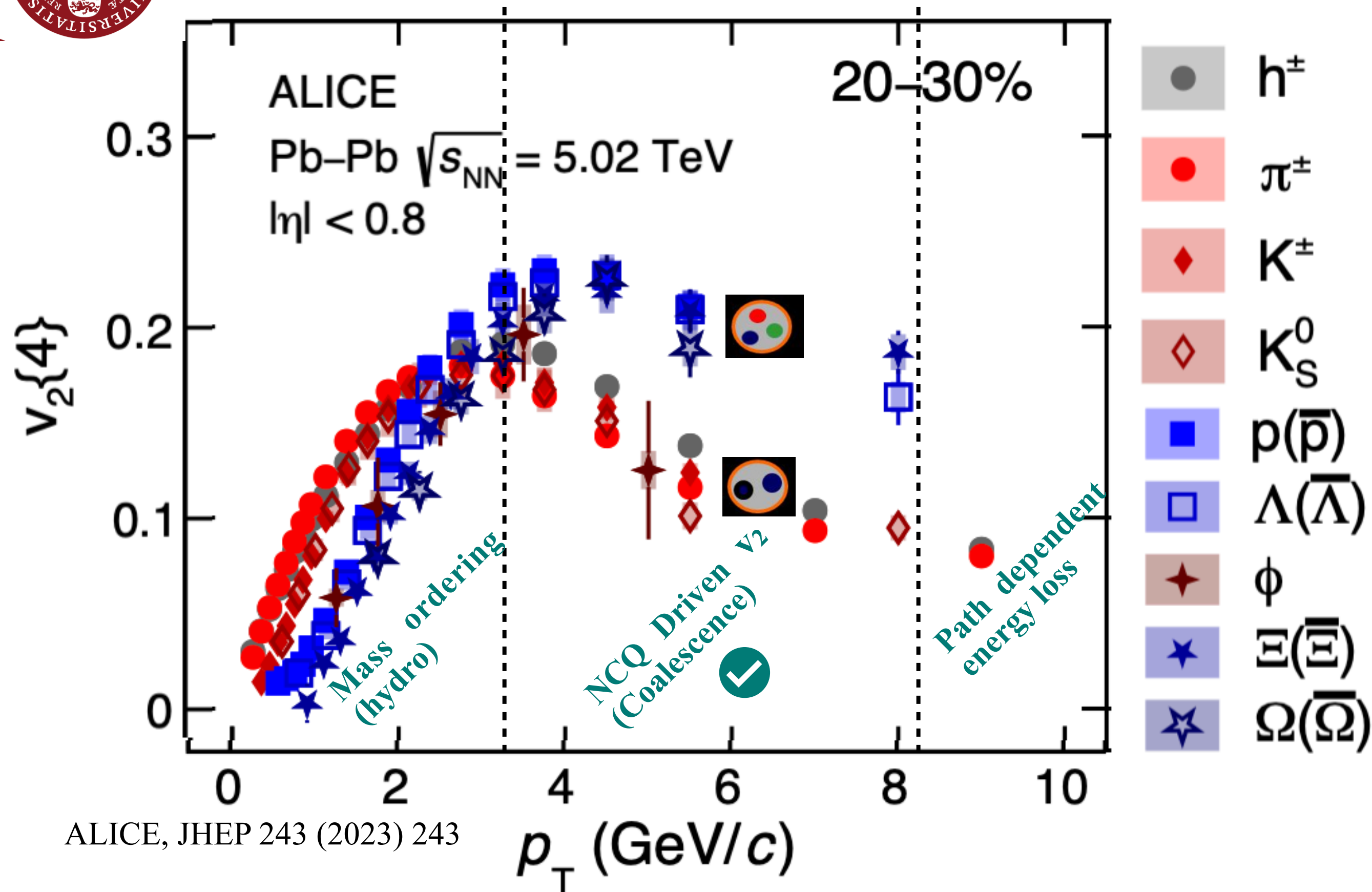
ALICE Collaboration, S.Acharya *et al.*, *Eur.Phys.J.C* 80 (2020) 8, 693



Baseline: Collective features in heavy-ion collisions



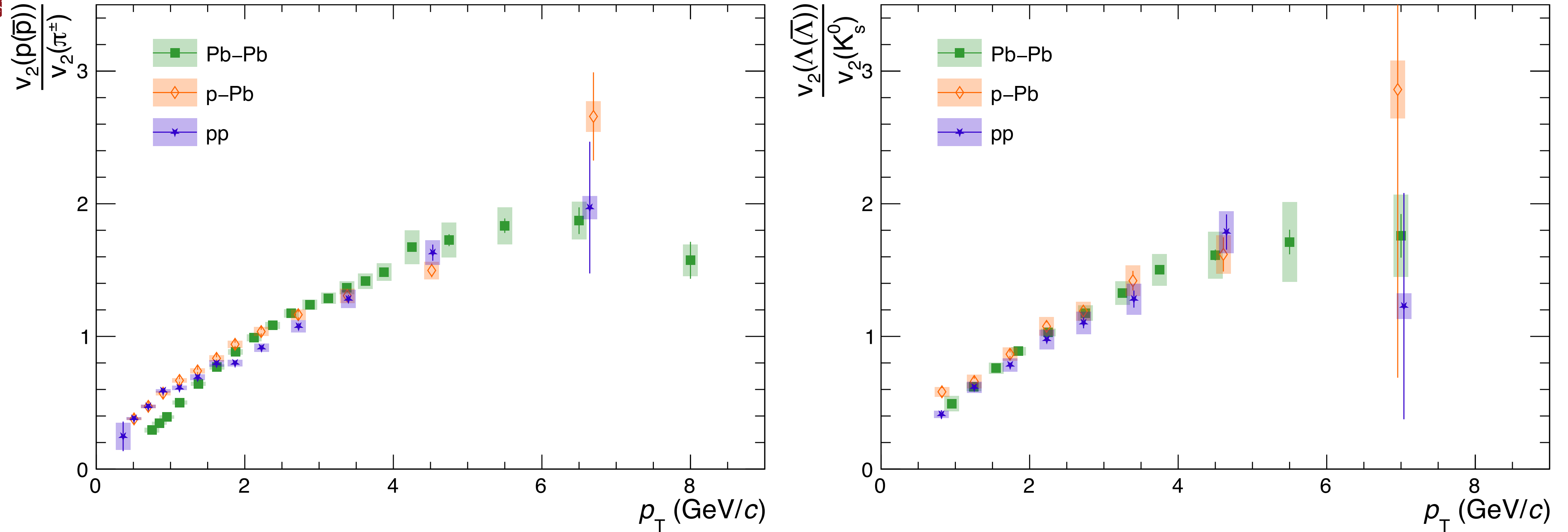
ALICE



- low p_T ($p_T \lesssim 3$ GeV/c) — Mass ordering — Interplay between radial and elliptic flow (hydrodynamics).
- **Intermediate p_T ($3 < p_T \lesssim 8$ GeV/c)** — NCQ driven Baryon-meson splitting and grouping — quark coalescence, sign of partonic collectivity (✓).
- **Well described by the model with hydro and quark-coalescence(✓).**



Everything flows, everywhere...



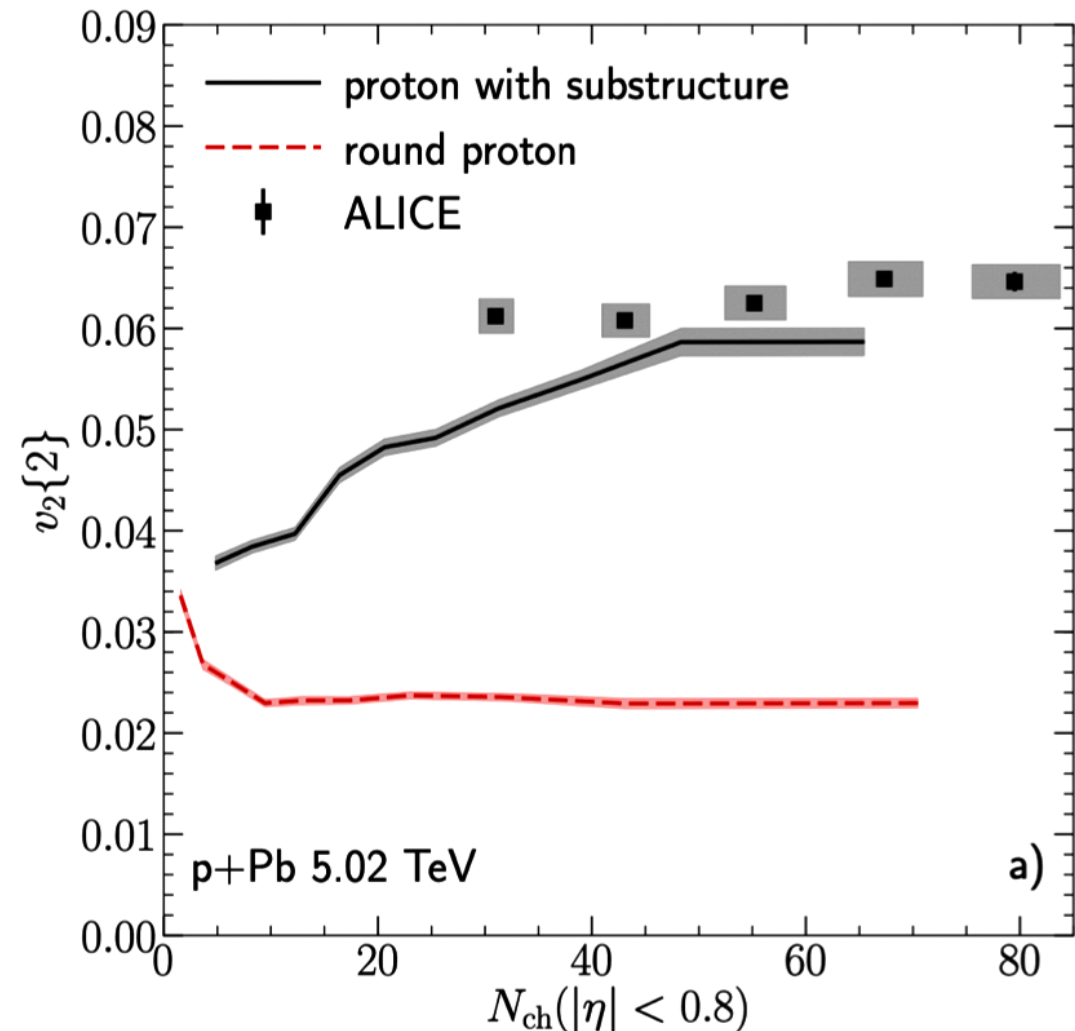
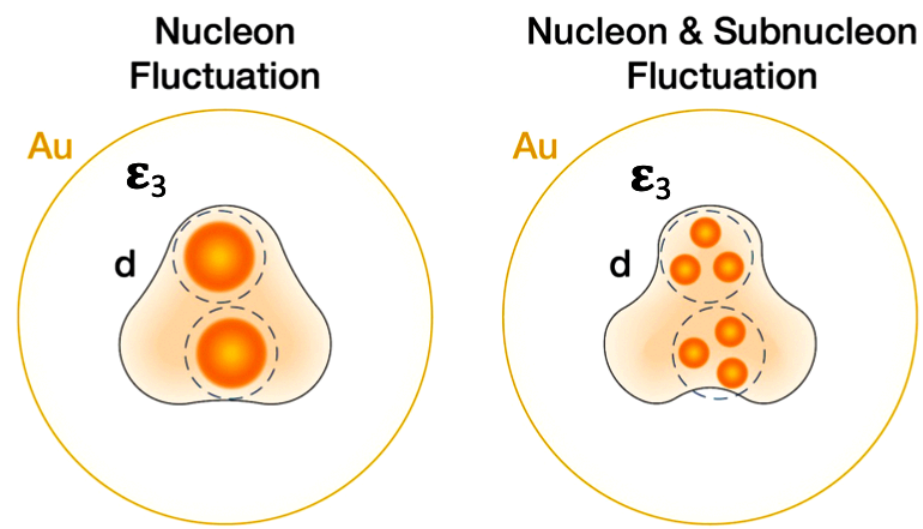
High multiplicity events in small systems: Qualitatively similar to the heavy-ion results!

- Intermediate p_T ($3 \lesssim p_T \lesssim 5$ GeV/c) — Baryon-meson grouping ($\sim 1\sigma$ confidence) + splitting ($> 5\sigma$ confidence) of v_2 — quark coalescence, evidence of partonic collectivity (✓).



Possible Initial State effects + Hydro

B. Schenke, Rept. Prog. Phys. 84, 082301 (2021)



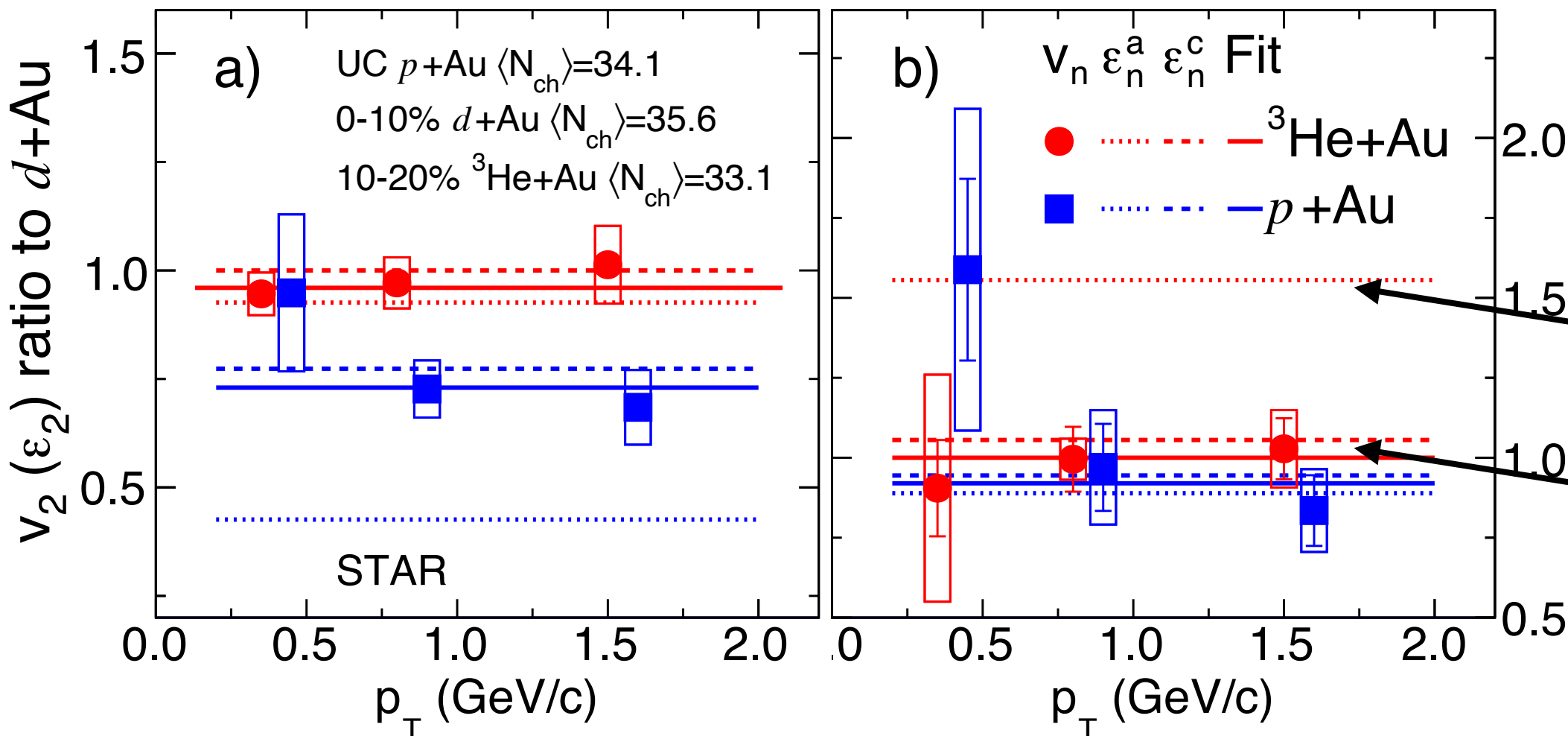
$$v_2^{p+Au} < v_2^{d+Au} \approx v_2^{^3He+Au} \quad (\text{Expected hydro ordering})$$

$$v_3^{p+Au} \approx v_3^{d+Au} \approx v_3^{^3He+Au}$$

See talk by S. Huang: [Link](#)

- SONIC (nucleonic Glauber). Describes v_2 — underestimates v_3
SONIC: P. Romatschke Eur. Phys.J.C 75, 305 (2015)
- superSONIC: Nucleon fluctuation + Pre-Flow.
Pre-Flow effect smears the v_3 hierarchy!

STAR, arXiv:2312.07464v4 [nucl-ex] 6 Nov 2024



- Nucleon + Subnucleon fluctuations smears the v_3 hierarchy!

Eccentricity with nucleon fluctuation

Eccentricity with nucleon+sub-nucleon fluctuations

	Nucleon Glauber $\epsilon_2(\epsilon_3)$	Sub-Nucleon Glauber $\epsilon_2(\epsilon_3)$
0-5% pAu	0.23(0.16)	0.38(0.30)
0-5% dAu	0.54(0.18)	0.51(0.31)
0-5% $^3\text{He}+\text{Au}$	0.50(0.28)	0.52(0.35)

Nucleon Glauber: J. L. Nagle, PRL 113, 112301 331 (2014).

Sub-Nucleon: K. Welsh, J. Singer, and U. Heinz, PRC 94, 334 024919 (2016).

STAR, Phys. Rev. Lett. 130, 242301 (2023)

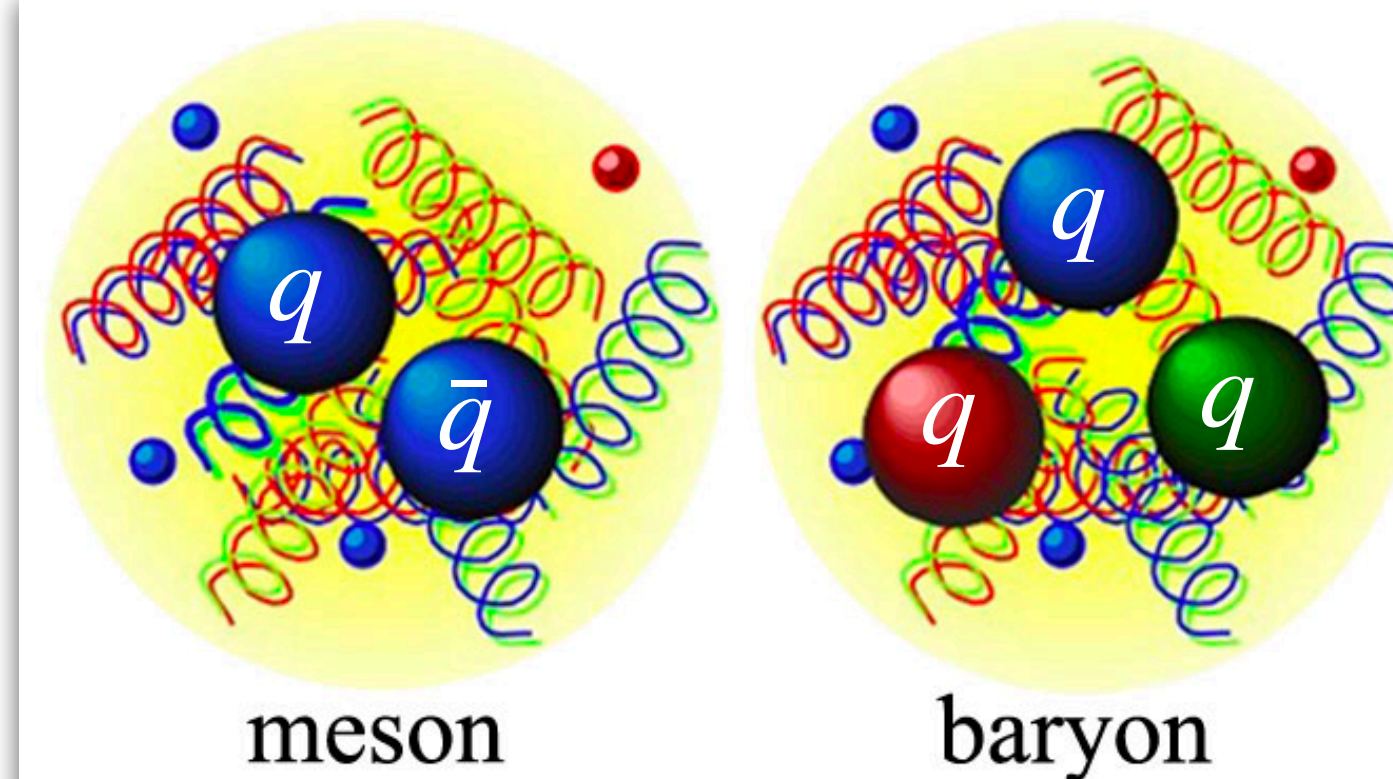


Basics

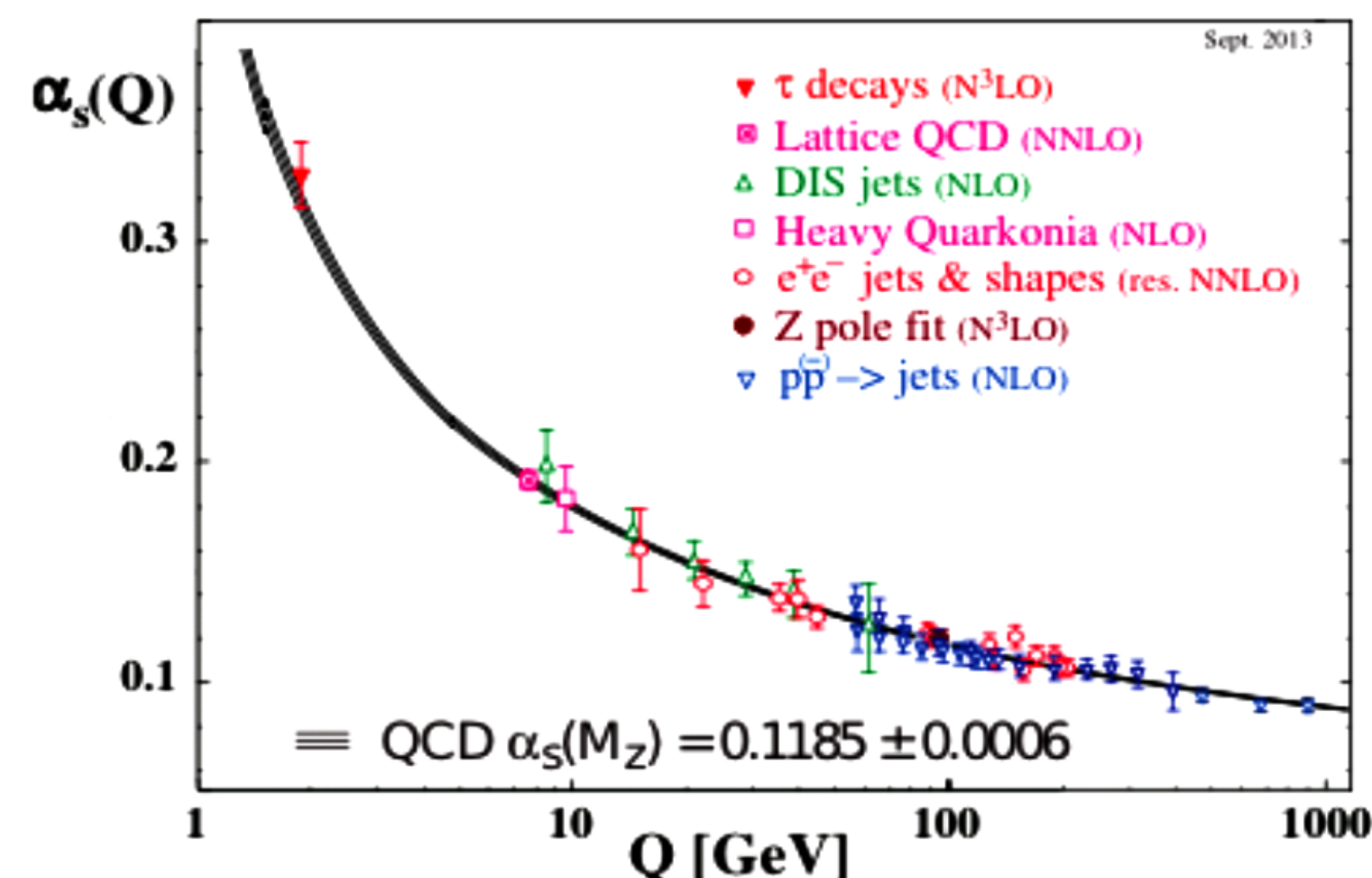
- Strong interaction with force carriers gluons. (Quarks and gluons = partons)
- Quarks have never been observed free (confinement). Quarks behave as asymptotically free at short distances (asymptotic freedom).

	I.	II.	III.
mass	2.4 MeV	1.27 GeV	171.2 GeV
charge	2/3	2/3	2/3
spin	1/2	1/2	1/2
name	u up	c charm	t top
Quarks	4.8 MeV	104 MeV	4.2 GeV
	-1/3	-1/3	-1/3
	1/2	1/2	1/2
	d down	s strange	b bottom

Hadrons



- At extreme temperatures and/or pressure, the hadronic medium undergoes a transition into quark-gluon plasma
- Extreme temperature — early Universe
- Extreme pressure — cores of neutron stars
- $T_c (\mu_b = 0) \approx 156 \text{ MeV}$

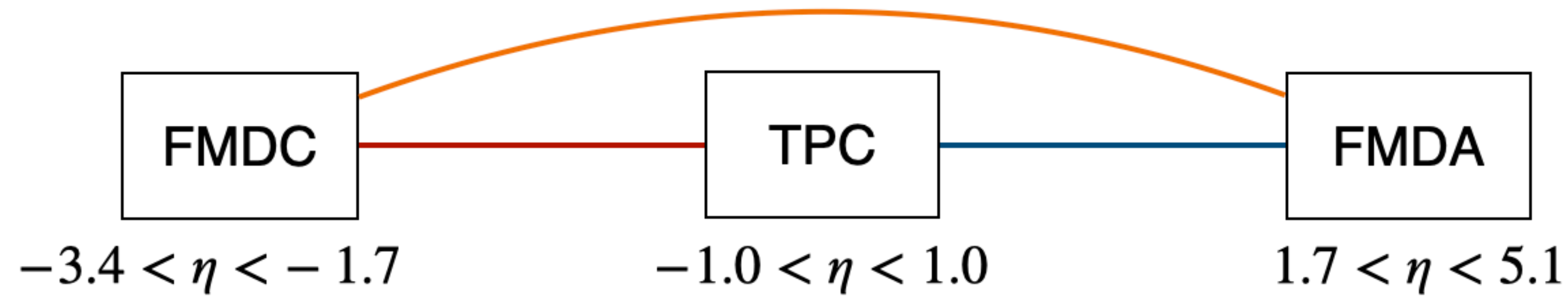


K. Olive et al. (Particle Data Group).
Review of Particle Physics.
Chin.Phys., C38:090001, 2014.

G. S. Bali and K. Schilling.
Physical Review D, 46: 2636-2646, 1992.



$V_{2\Delta}$ and v_2 measurement from long-range correlation in ALICE



- Long-range correlations: TPC—FMDA/C and FMDA—FMDC correlations.

$$v_n\{2\} = \sqrt{\frac{V_{n\Delta}^{\text{TPC-FMDA}} V_{n\Delta}^{\text{TPC-FMDC}}}{V_{n\Delta}^{\text{FMDA-FMDC}}}}$$

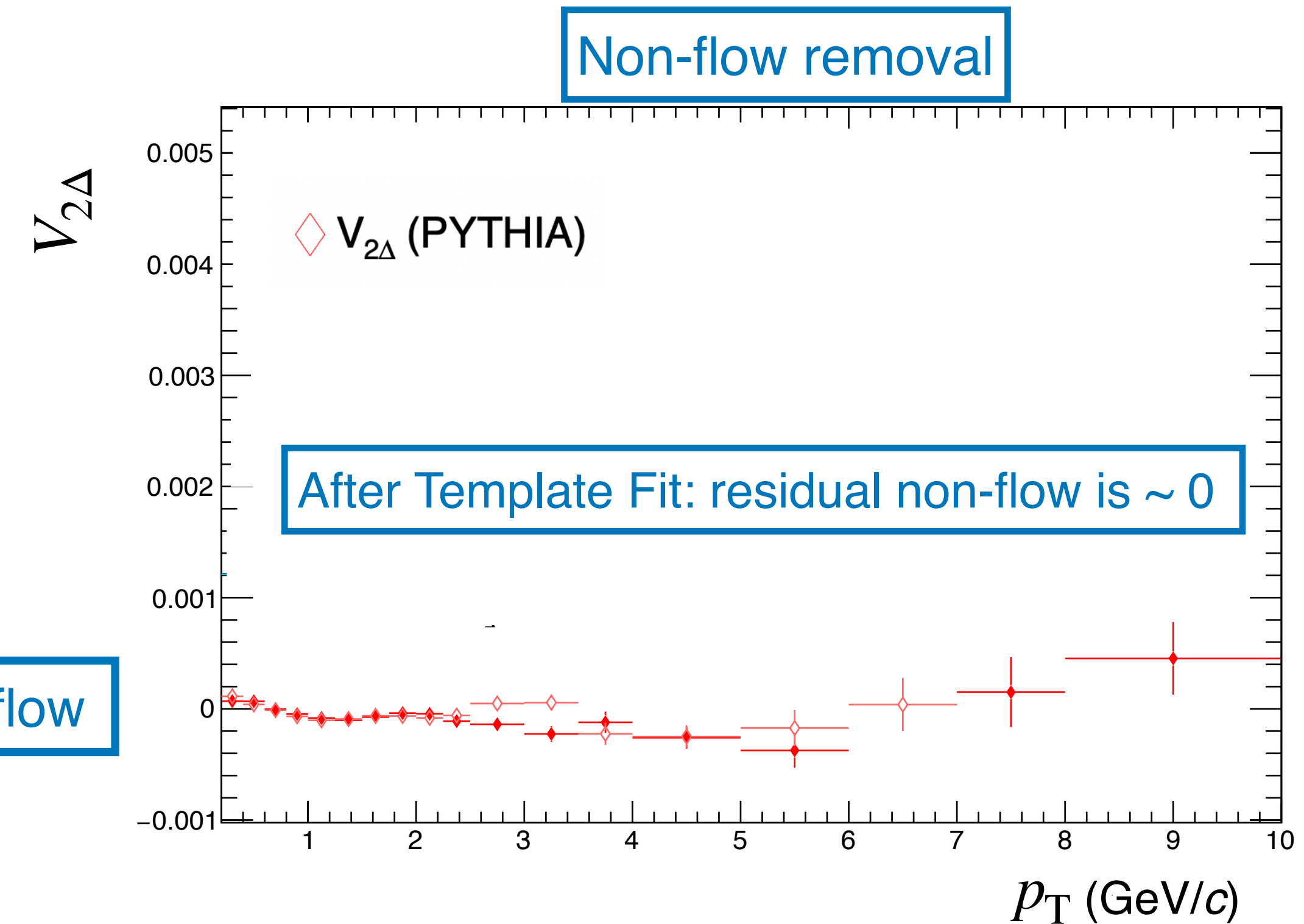
$$V_{2\Delta}^{\text{TPC-FMD}} \approx v_2^{\text{TPC}} v_2^{\text{FMD}}$$

- $V_{2\Delta}$ estimated from Template Fit method:

Higher multiplicity event = Scaled baseline event (non-flow) + Additional flow

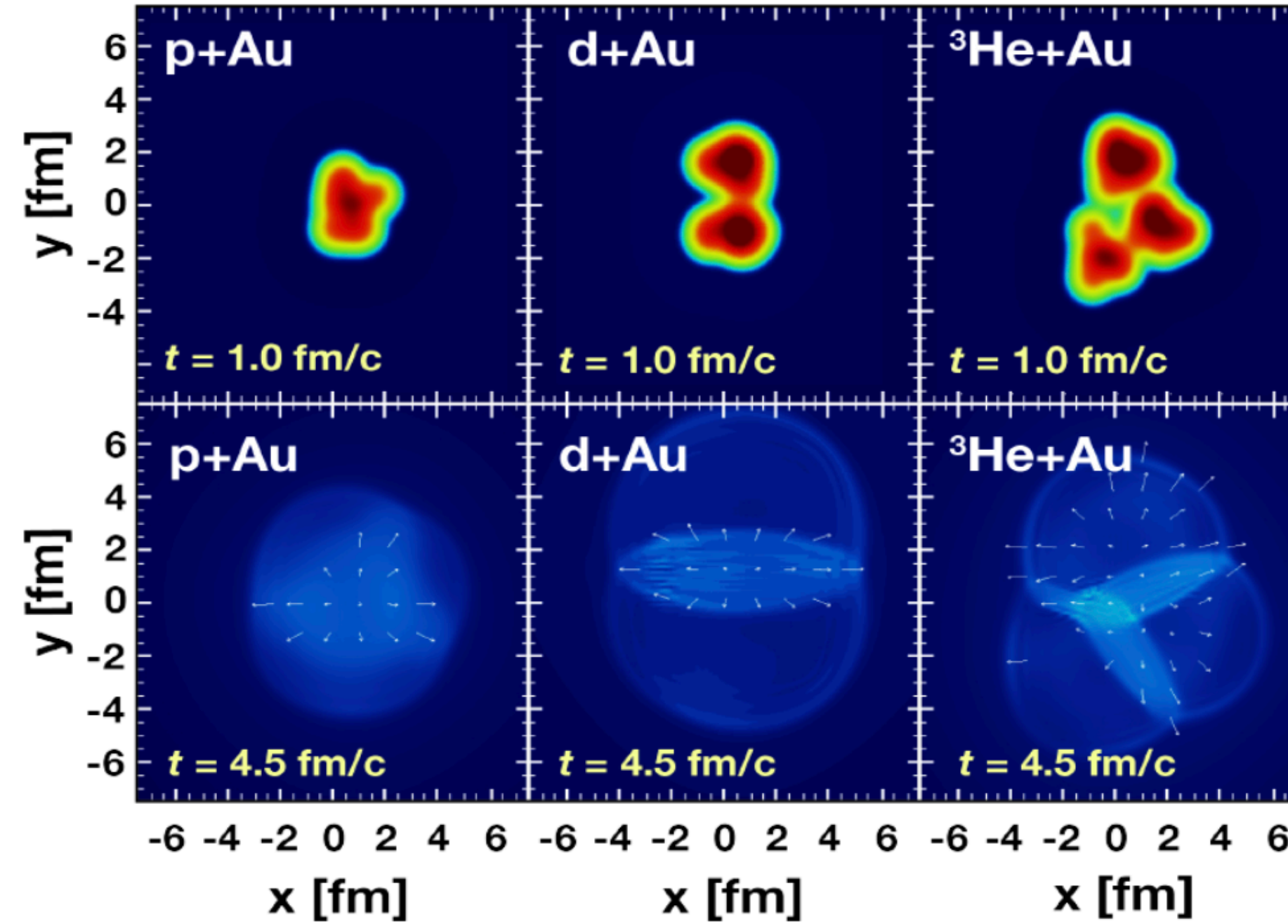
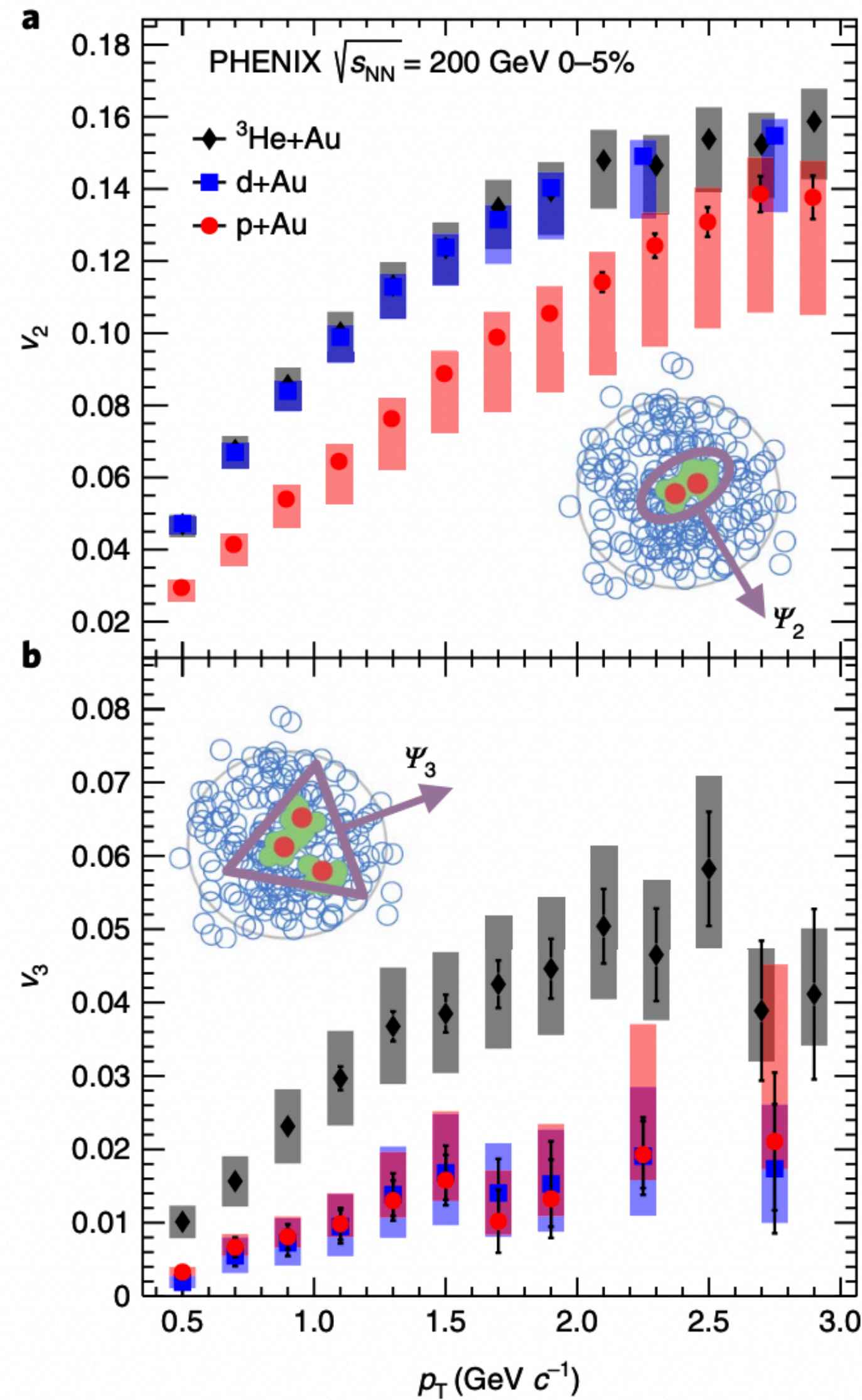
$$Y(\Delta\varphi) = \underset{\substack{\uparrow \\ \text{Probed}}}{FY(\Delta\varphi)^{\text{peri}}} + G \left[1 + \sum_{n=2}^{\infty} 2V_{n\Delta} \cos(n\Delta\varphi) \right]$$

$\nwarrow$ Baseline
 $\searrow$ Flow expansion





Initial geometry driven...



PHENIX, Nature Physics 15, 214-219 (2019)
Consistent with latest results: PHENIX: PRC 107 (2023) 024907

- Hydro prediction ($v_n \propto \epsilon_n$)
- Geometry scan results: consistent with hydro prediction:

$$v_2^{\text{p}+\text{Au}} < v_2^{\text{d}+\text{Au}} \approx v_2^{\text{He}+\text{Au}}$$

$$v_3^{\text{p}+\text{Au}} \approx v_3^{\text{d}+\text{Au}} < v_3^{\text{He}+\text{Au}}$$

Geometry driven. Hydrodynamics applicable (**initial conditions?**)