10th Asian Triangle Heavy-Ion Conference

Gopalpur, 13 - 17 January

ATHIC 2025

# Collectivity in large and small collision systems

Sushanta Tripathy

CERN, Geneva, Switzerland

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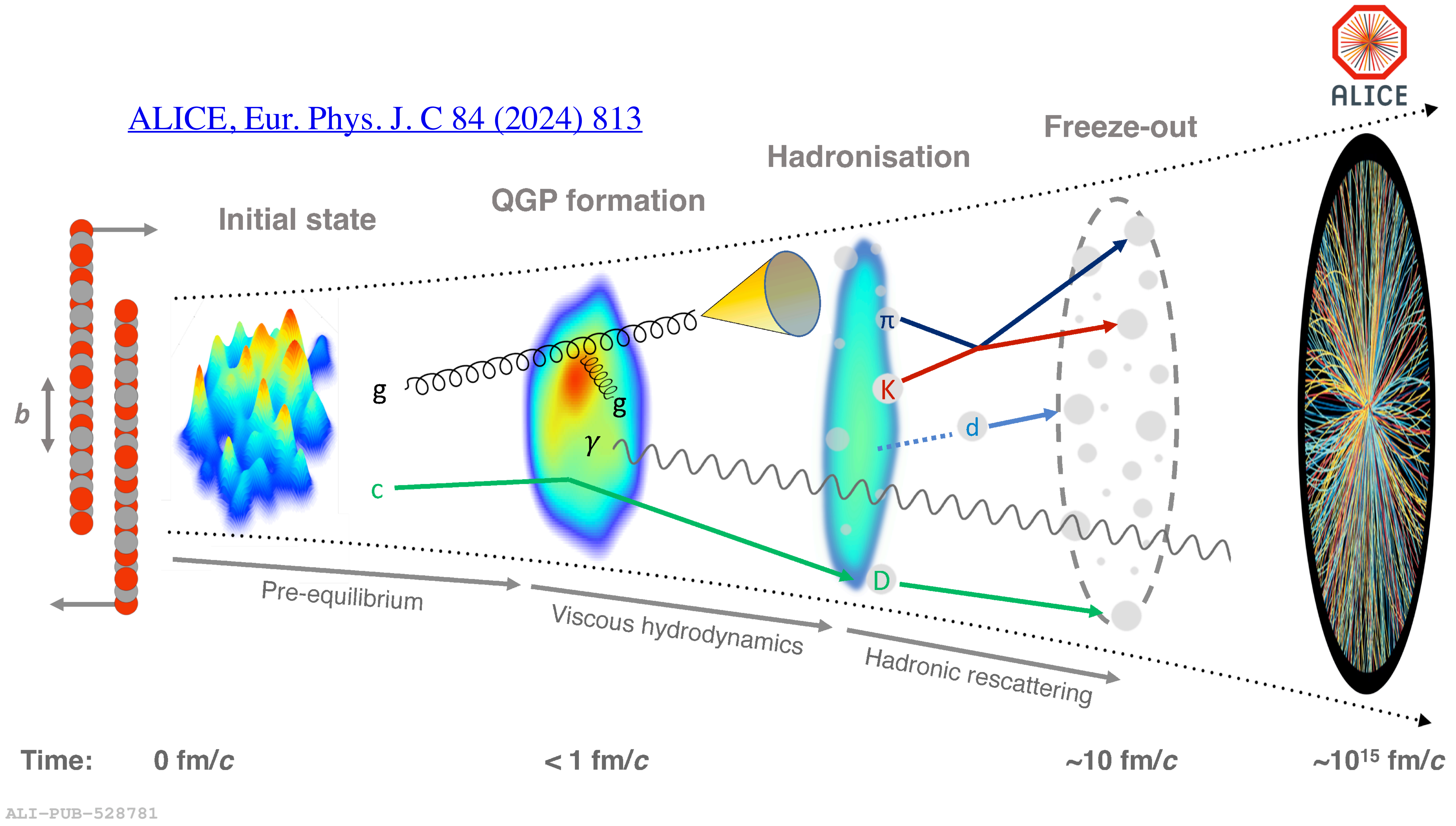
None of the contents about small systems were predicted when LHC started.

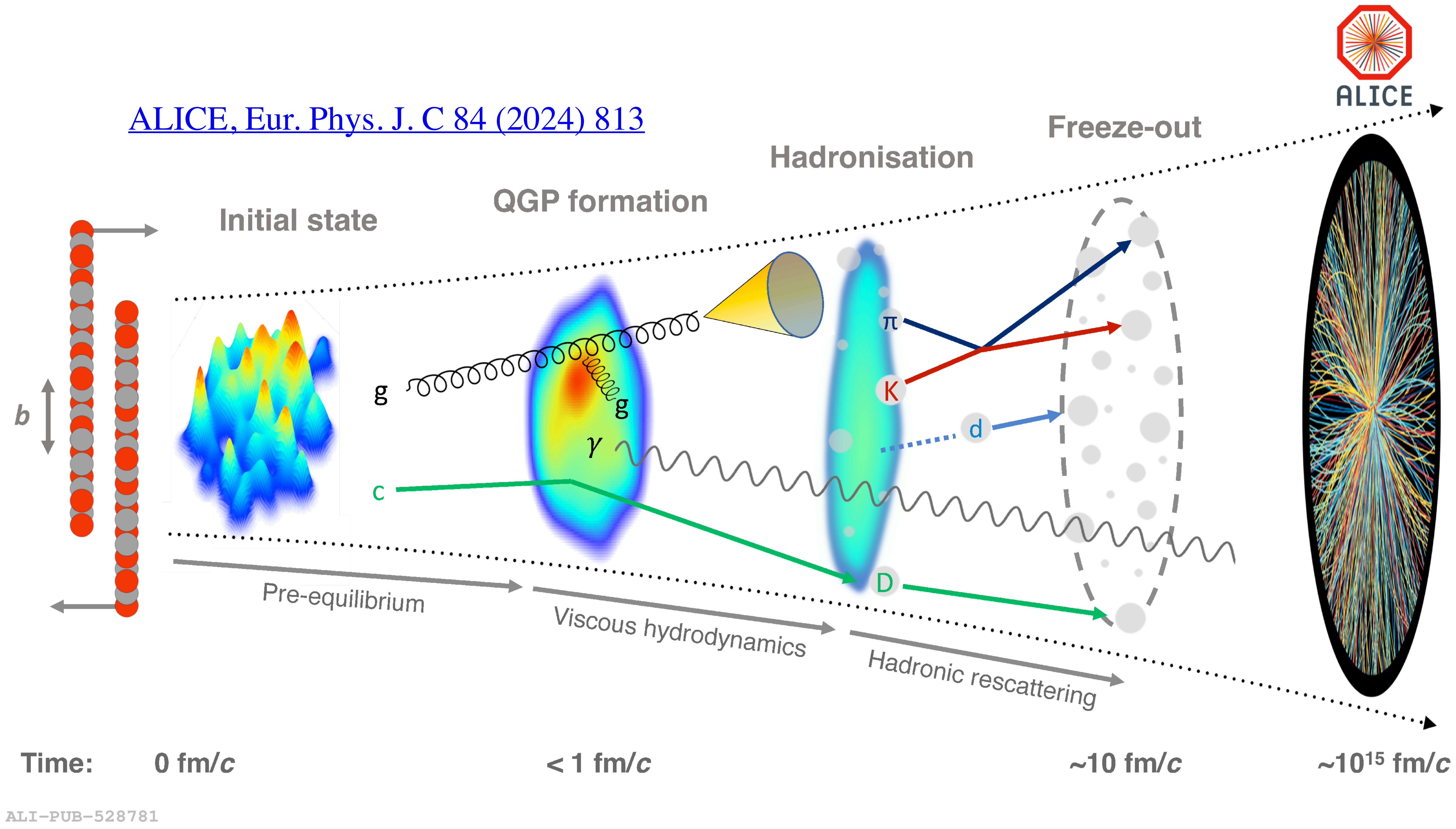
# Heavy-ion collisions, QGP and Collectivity

ALICE, Eur. Phys. J. C 84 (2024) 813

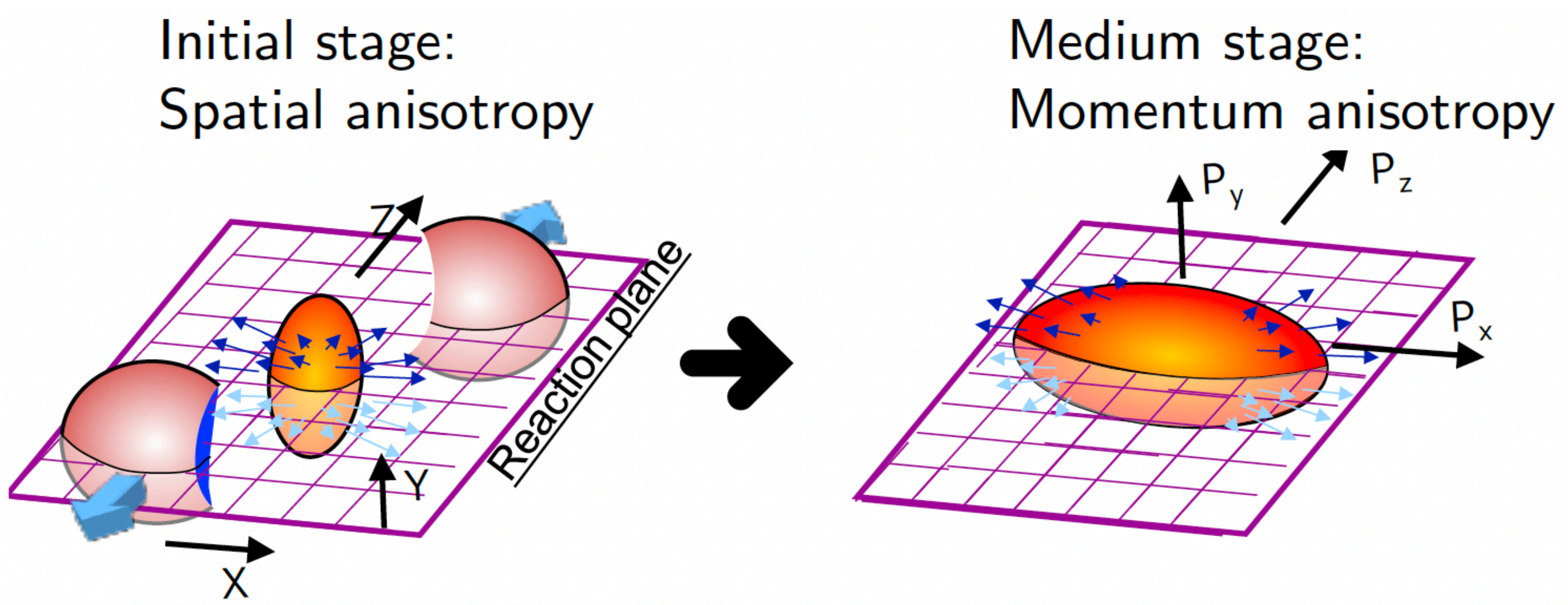



- A primordial state of matter existed in the early Universe, known as QGP, where quarks and gluons were in a deconfined state
- Several signatures confirm its formation in relativistic heavy-ion collisions

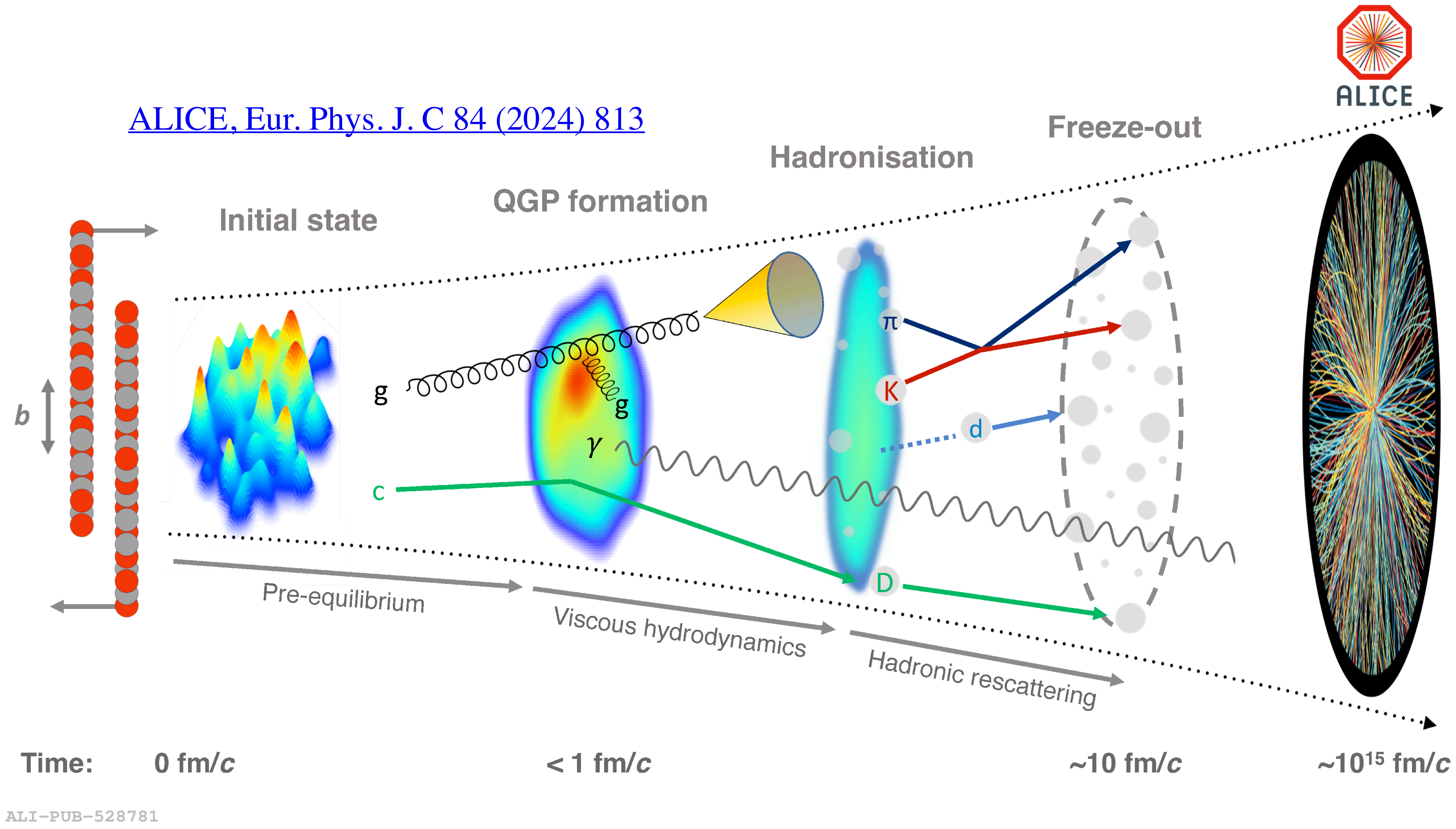
# Heavy-ion collisions, QGP and Collectivity




- Medium is **fluid-like**, implied by the anisotropic momentum pattern of the hadronic products
- Anisotropic expansion is a result of **collective** behaviour: very prominent in heavy-ion systems



# Heavy-ion collisions, QGP and Collectivity

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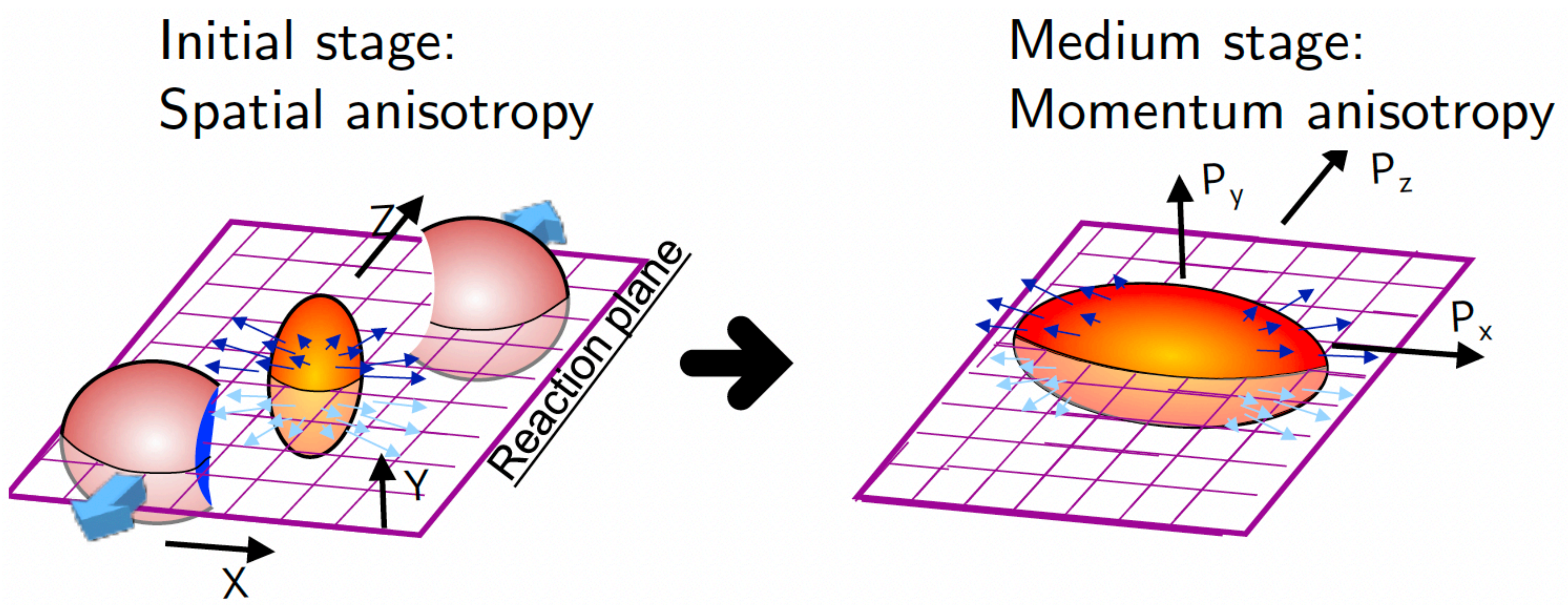
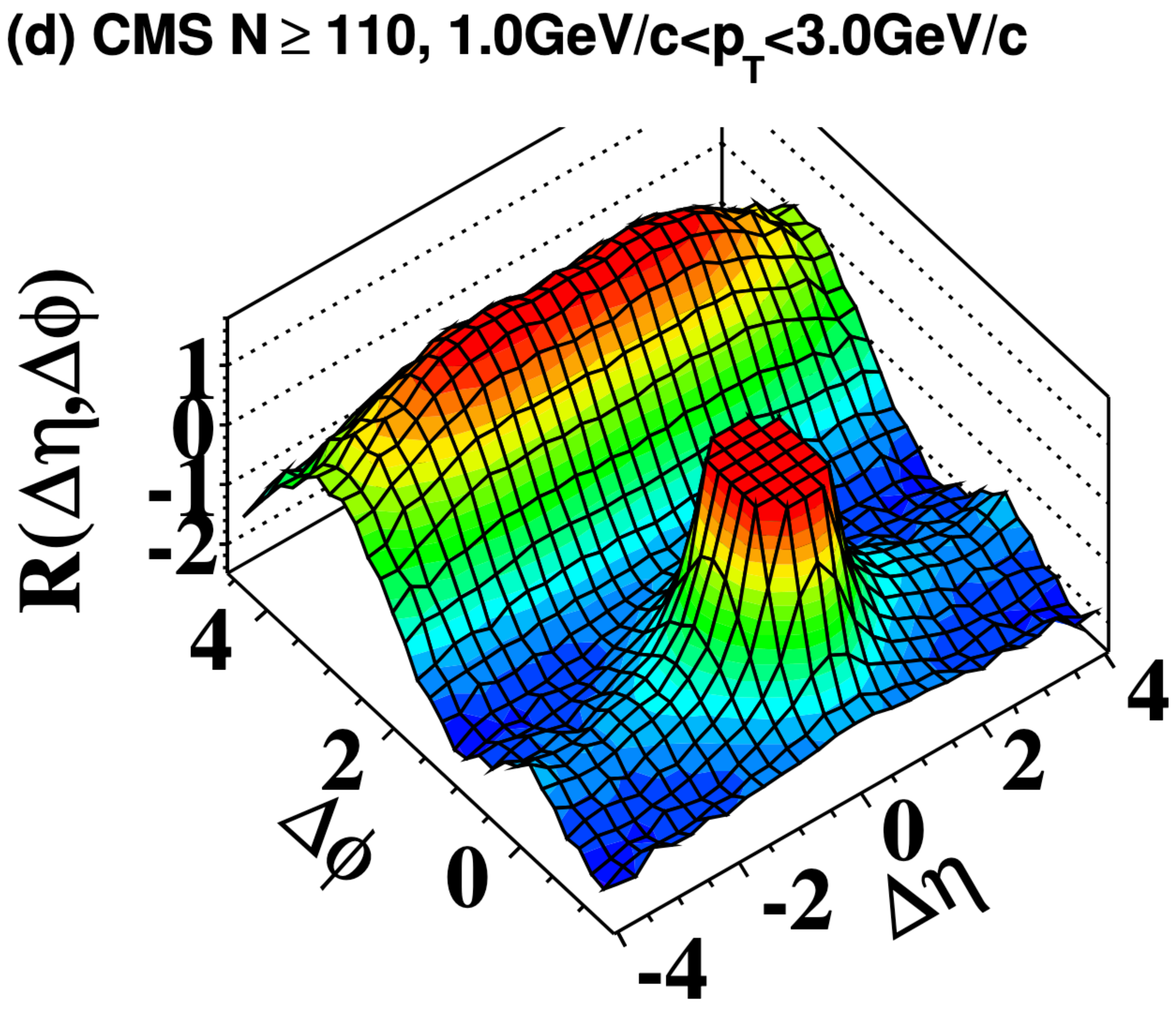



- Unexpected measurements of **collective-like behaviors in small systems** have shaken the basic paradigm of heavy-ion physics

# Ridges and Anisotropic Flow



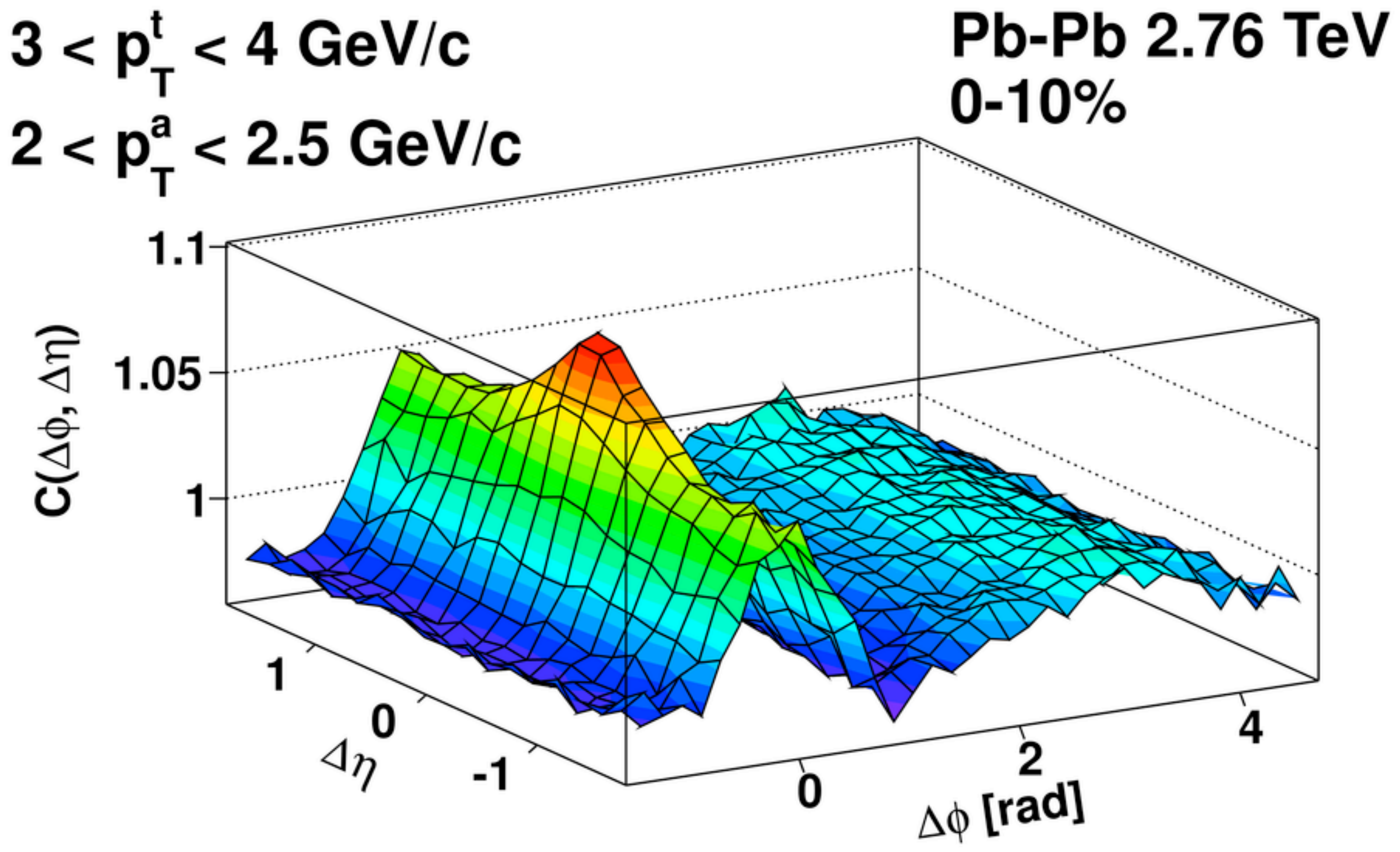

Recollections by Jürgen Schukraft, 18/10/24

"A feeble, but distinct, very long-range correlation between particles, never before seen in any elementary collisions, was announced in 2010 to a packed auditorium by the CMS Spokesperson with an apology (we present this signal to the scrutiny of the scientific community because we didn't succeed in killing it)"

"… the first, and arguably still the most unexpected, LHC discovery."

# Quantification of collectivity with particle correlations

- **Two-particle correlations**:
  - Probability density to find the second particle with the measurement of azimuthal angle and pseudorapidity between all pairs of charged particles produced in the collisions
  - Experimental quantification of medium expansion




ALICE, Phys.Lett. B 708 (2012) 249

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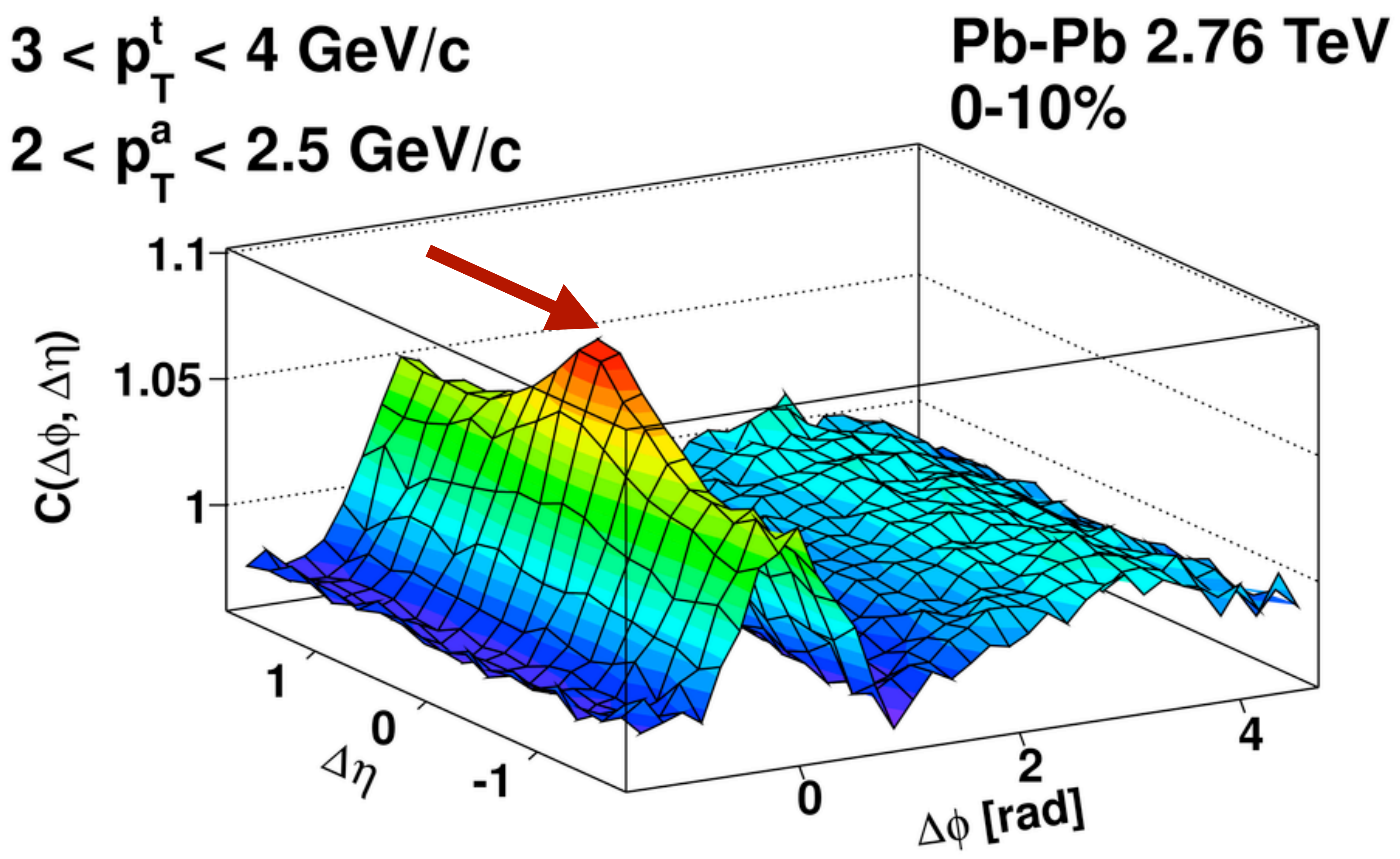


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ALICE, Phys.Lett. B 708 (2012) 249

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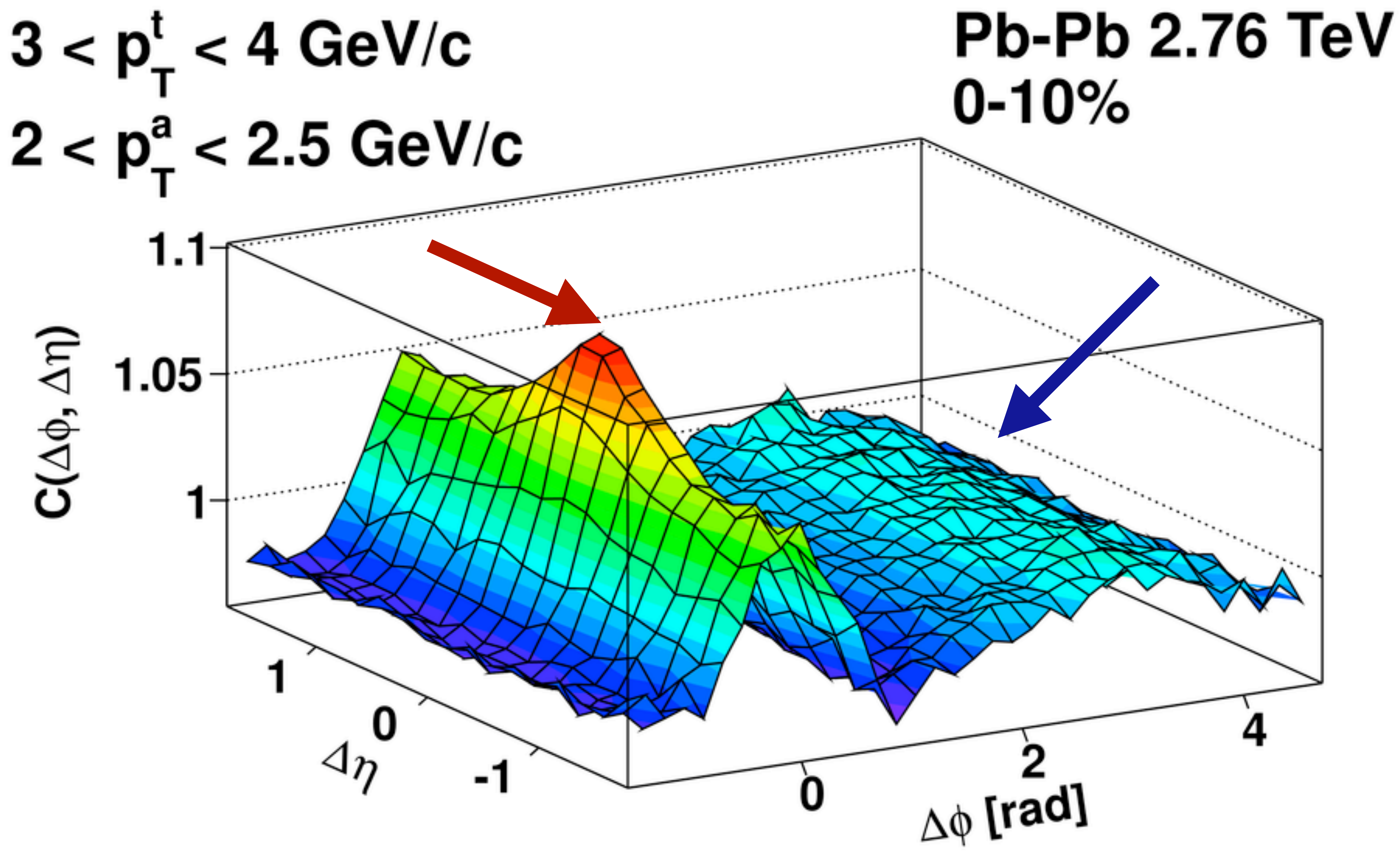


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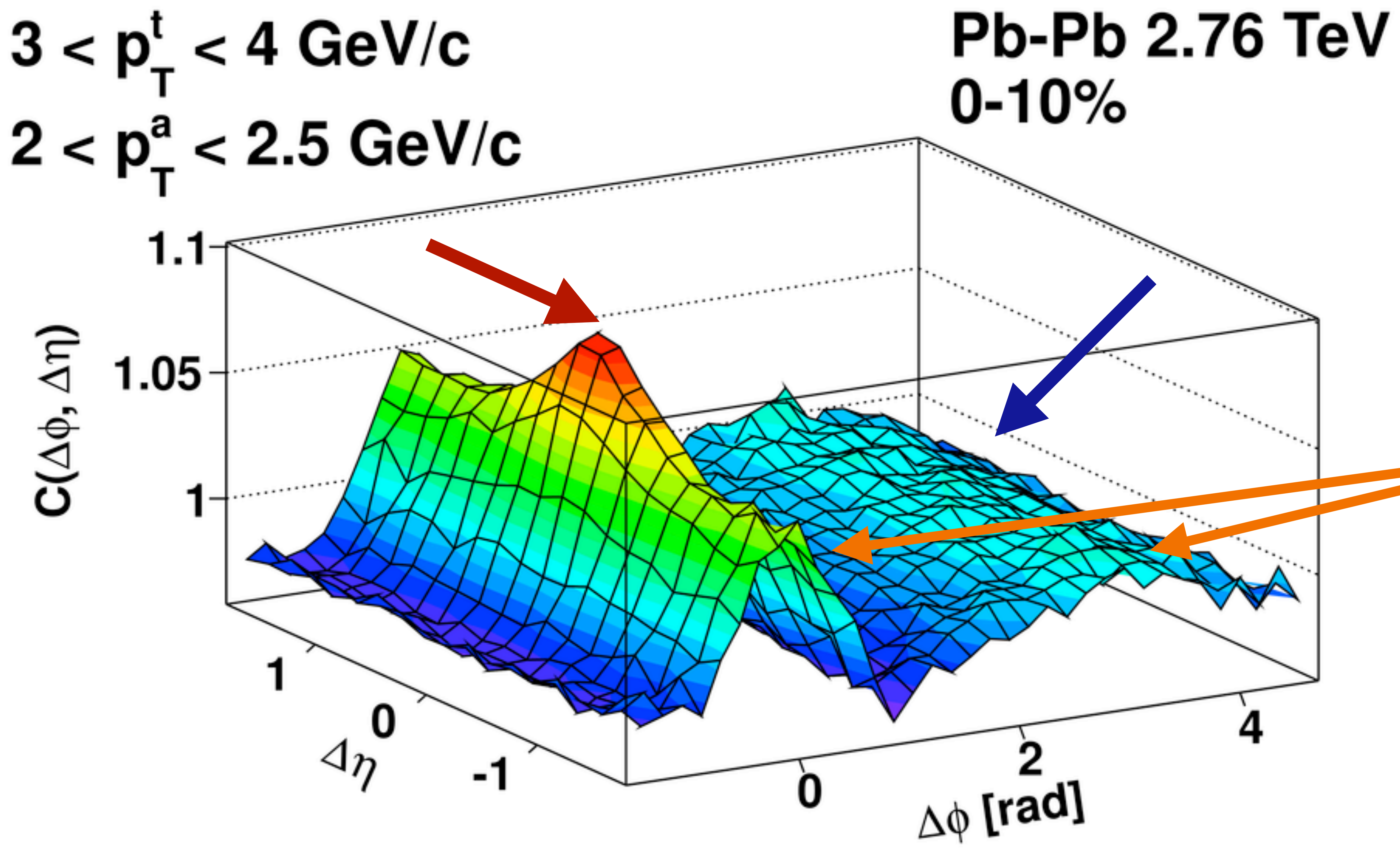


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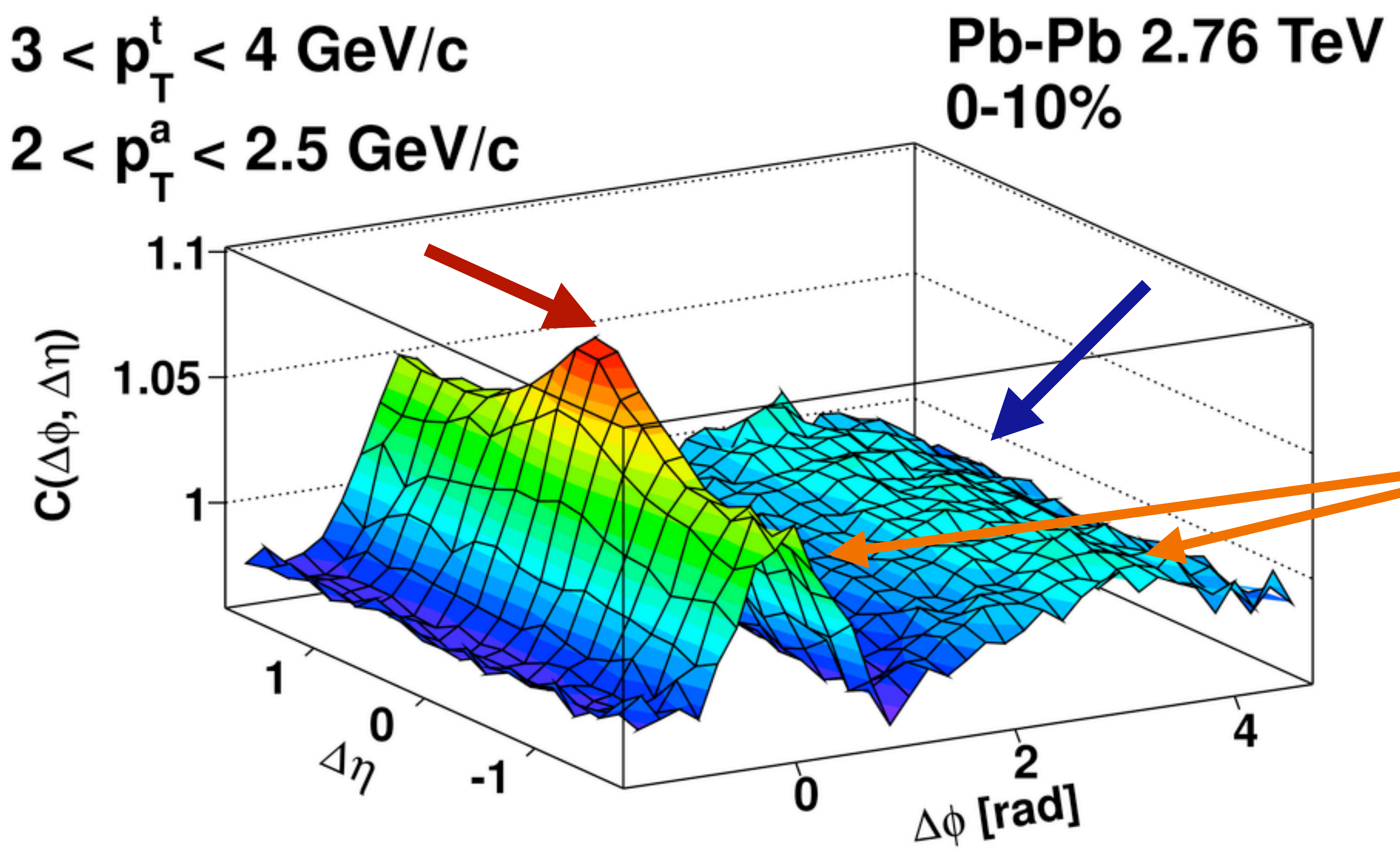


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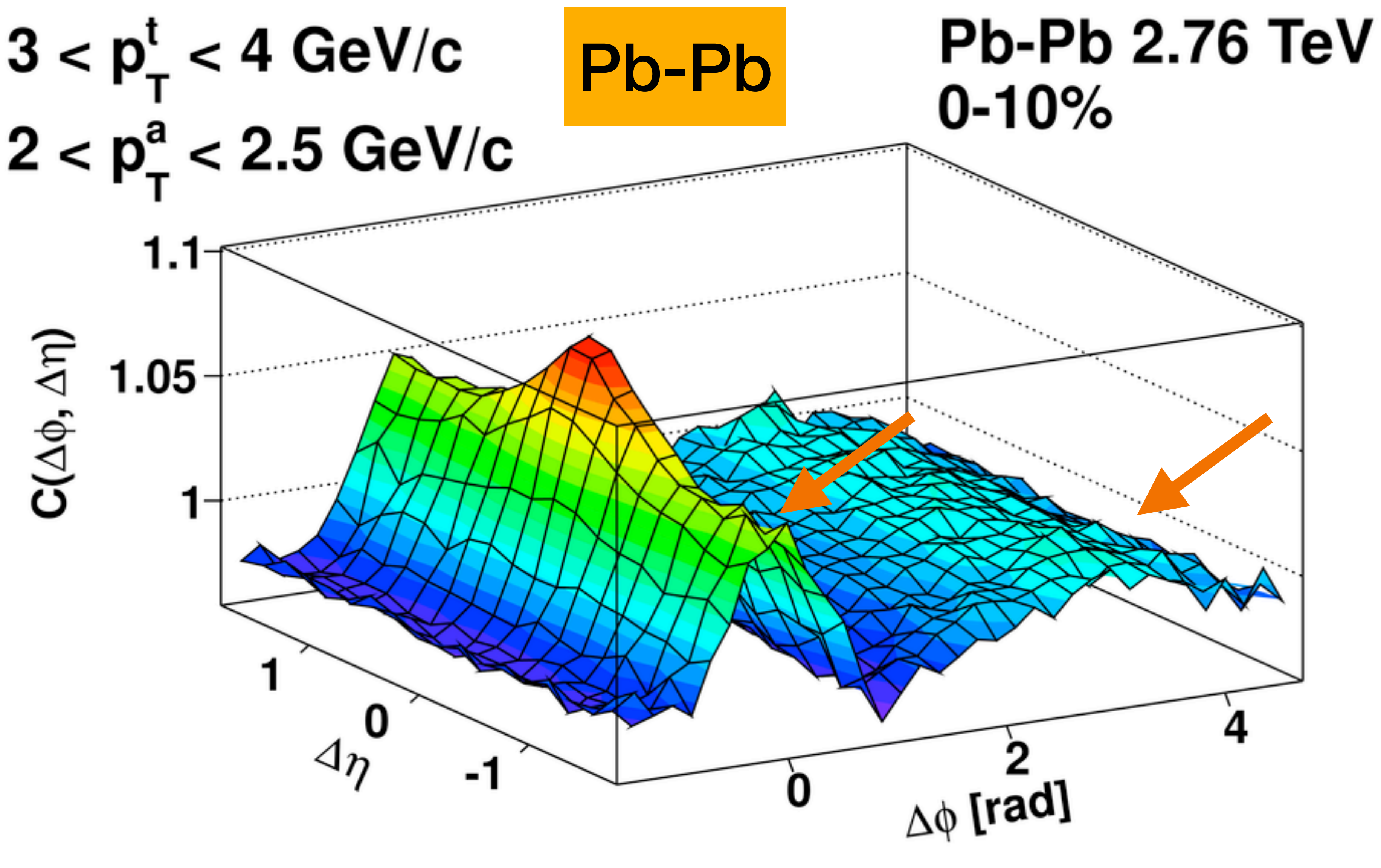
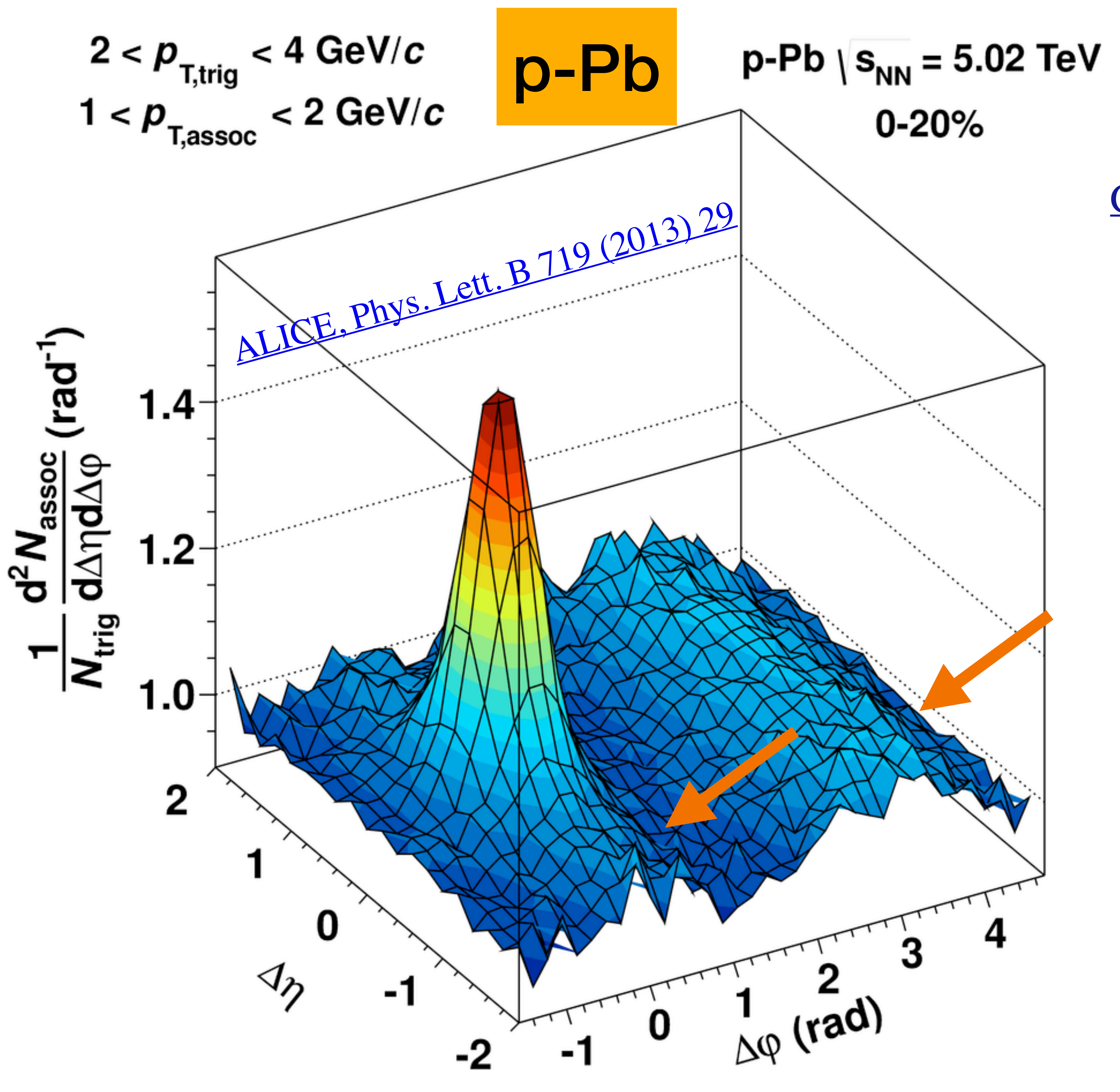
- **The 2nd Fourier harmonic component of the ridge → $v_2$**
- **Yield from ridges → $Y_{ridge}$**

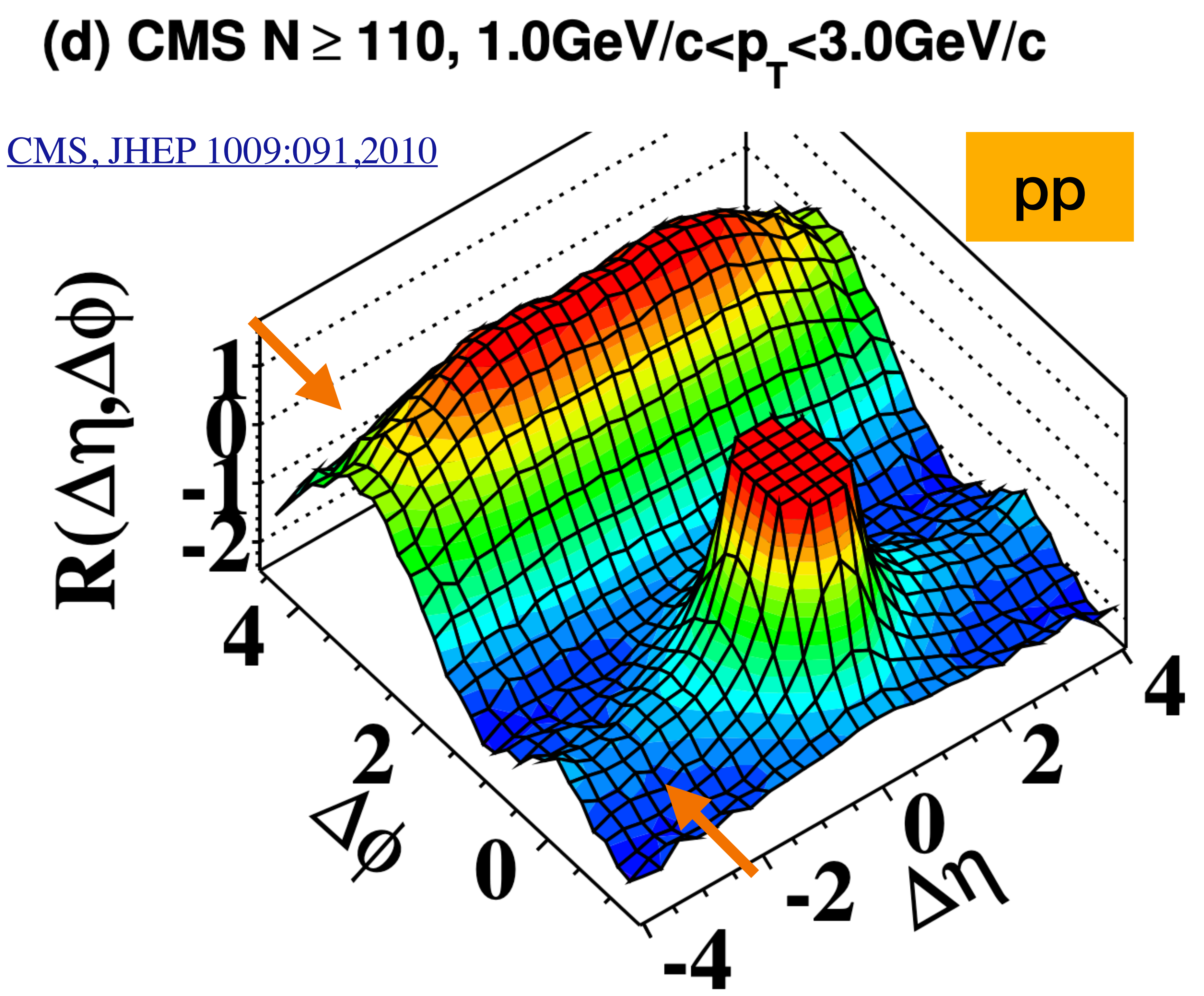
ALICE, Phys.Lett. B 708 (2012) 249

# Long-range correlations across collision systems




[ALICE, Phys.Lett. B 708 (2012) 249](#)




- **Double-ridge structure** in the long-range correlations appears in all collision systems at the LHC
- Collective effect due to medium response to the initial conditions in heavy-ion collisions
- The origin in pp collisions is unclear (QGP or MPI ?)

# Anisotropic flow across collision systems

- Provides information on **transport proprieties** of QGP and the **initial geometry**
- Fourier decomposition of **azimuthal distribution** of final-state particles: $\frac{\mathrm{d}N}{\mathrm{d}\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos n(\varphi - \Psi_n)$
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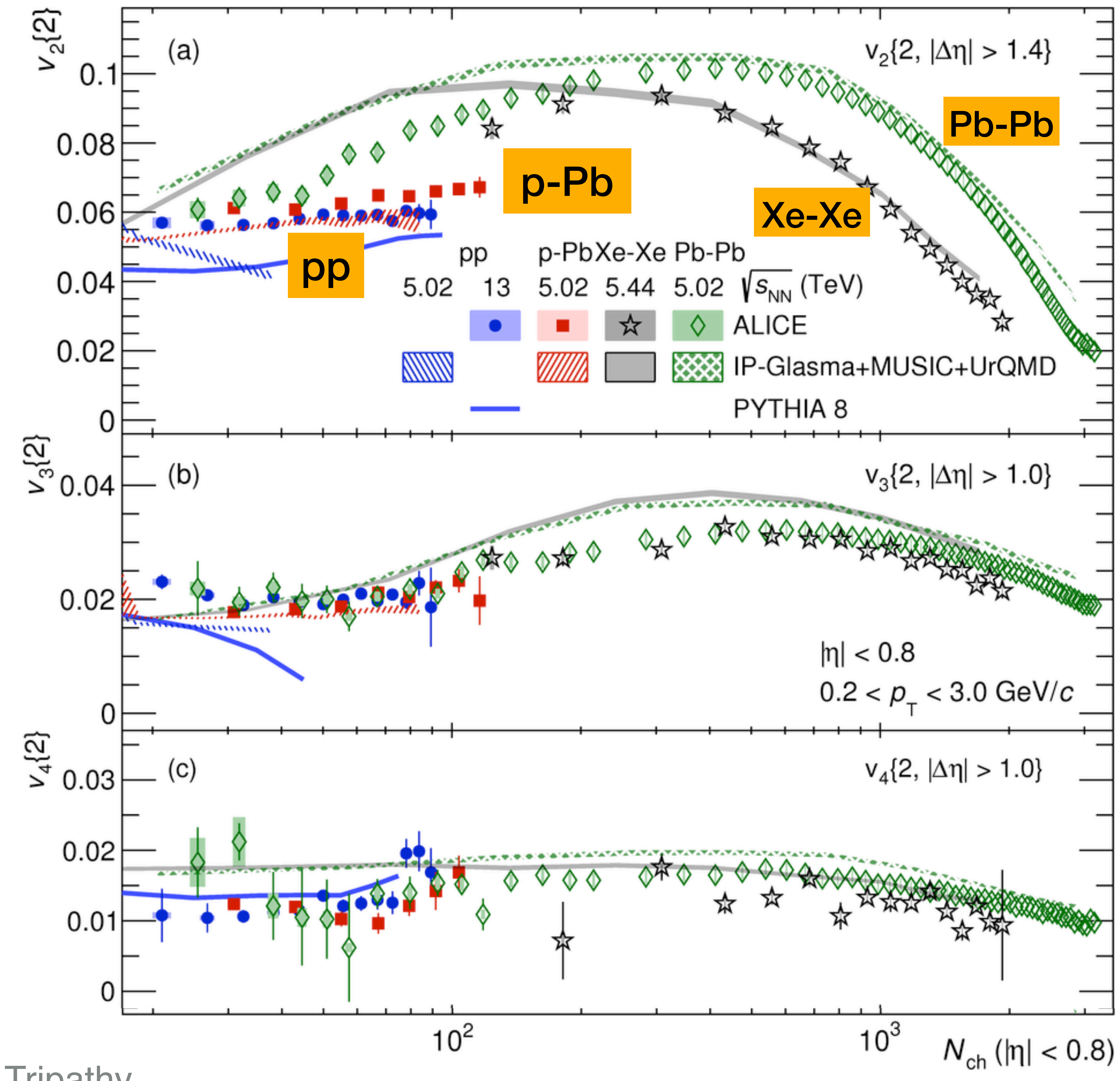
- Origin in **large systems** due to initial state geometrical anisotropy
- What is the **origin of anisotropic flow in small systems**? Why is the magnitude the same when comparing systems of different size?

ALICE, Phys. Rev. Lett. 123, 142301 (2019)



# Anisotropic flow across collision systems

CMS, Phys.Lett. B 765 (2017) 193


- Non-flow effects are expected to be suppressed due to the high number of particle correlations
- Even low-multiplicity pp and p-Pb collisions show finite $v_2$

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CMS, Phys.Lett. B 765 (2017) 193


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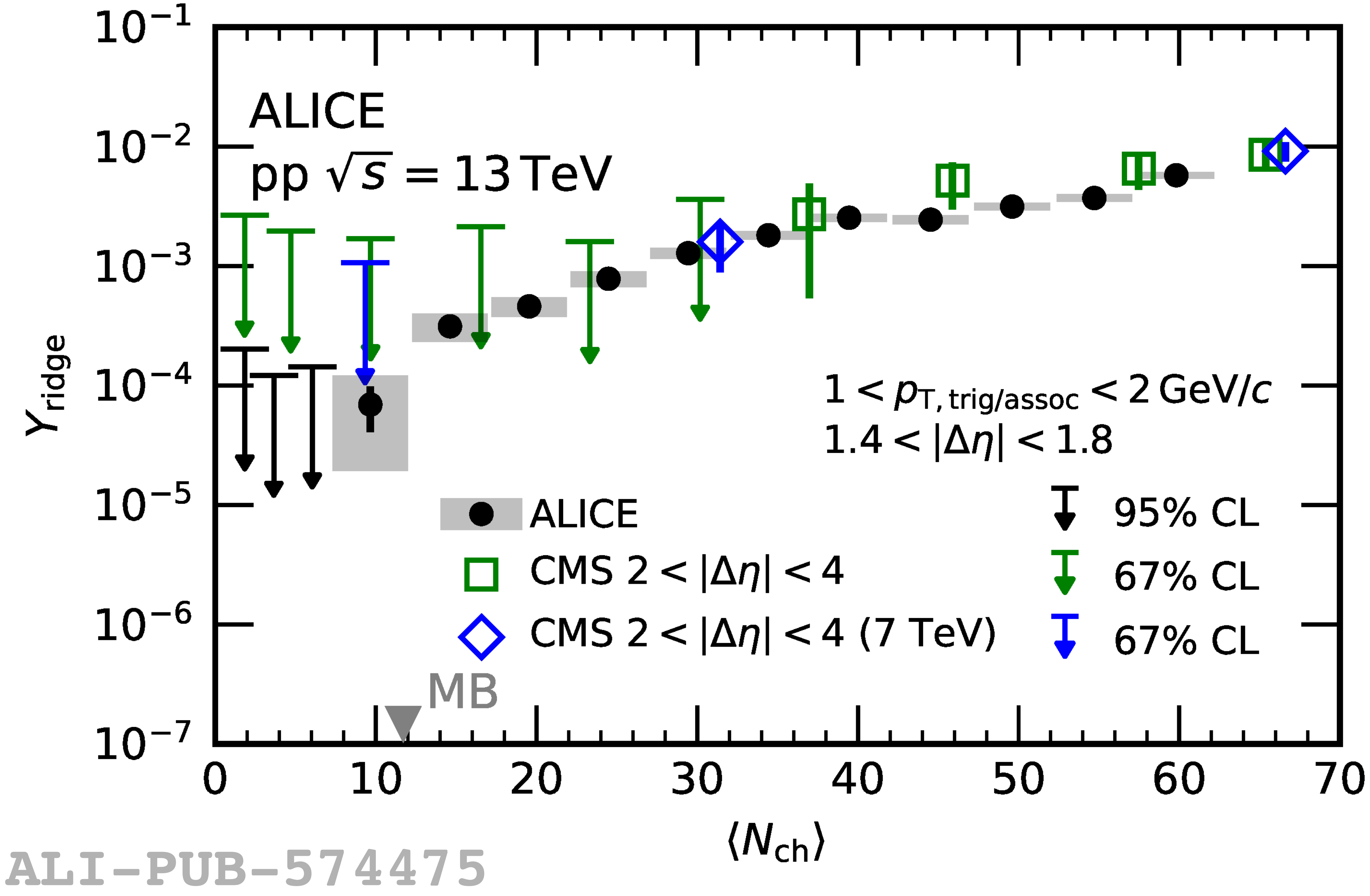
# Ridge yield in low multiplicity pp collisions

[ALICE, Phys. Rev. Lett. 132 (2024) 172302]




- Non-zero yield even in **minimum bias and low multiplicity collisions**

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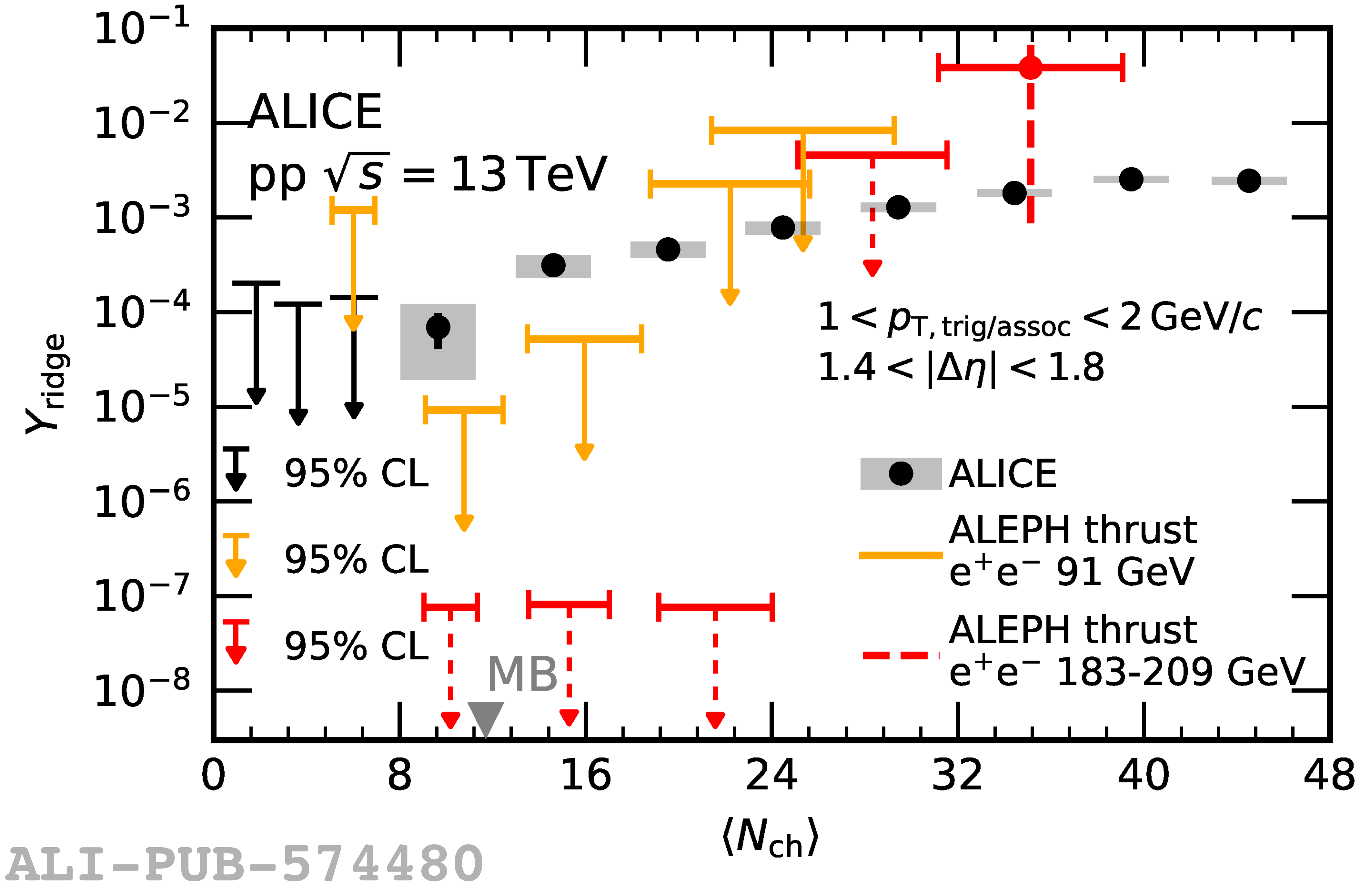
ALICE, Phys. Rev. Lett. 132 (2024) 172302



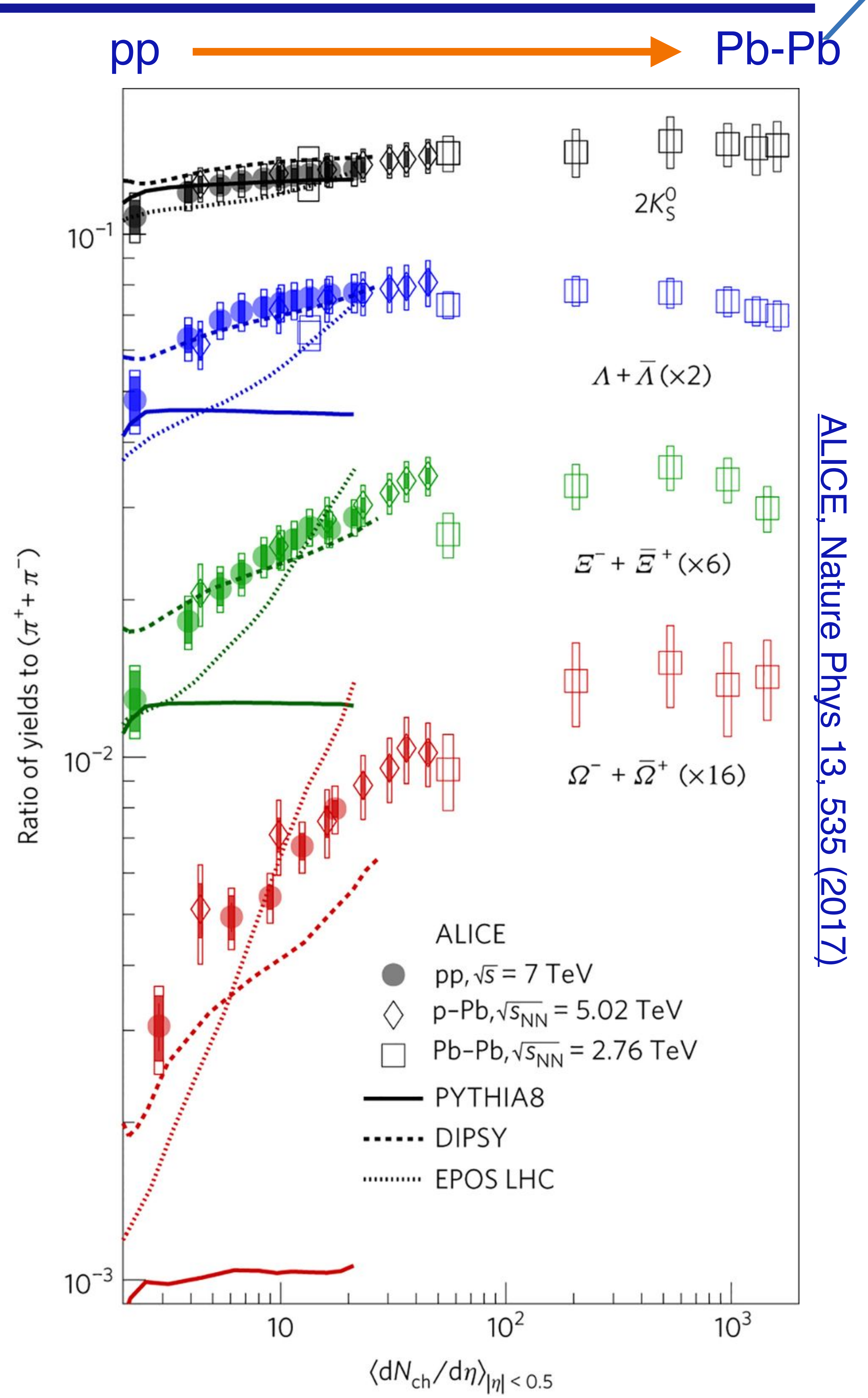

- Non-zero yield even in **minimum bias and low multiplicity collisions**
- ALICE made a **quantitative comparison** between the near-side ridge in **$e^+e^-$ and pp** collisions

**pp collisions feature additional physics compared to $e^+e^-$ collisions at the same multiplicity**

# Strangeness Enhancement

# Strangeness production across collision systems

- Smooth evolution of hadron to pion ratios across multiplicity:
  Independent of collision energy and system




ALICE, Nature Phys 13, 535 (2017)

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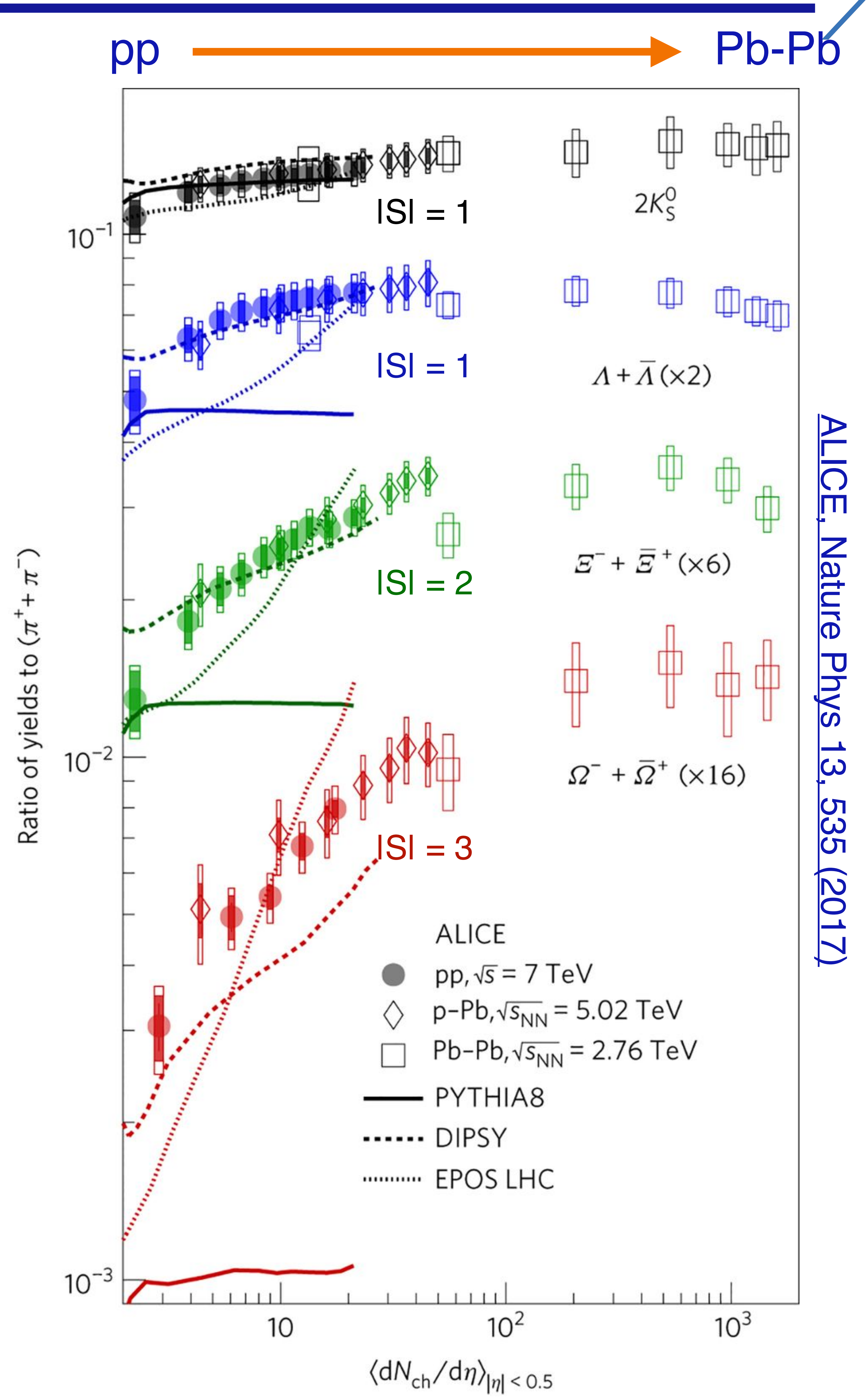


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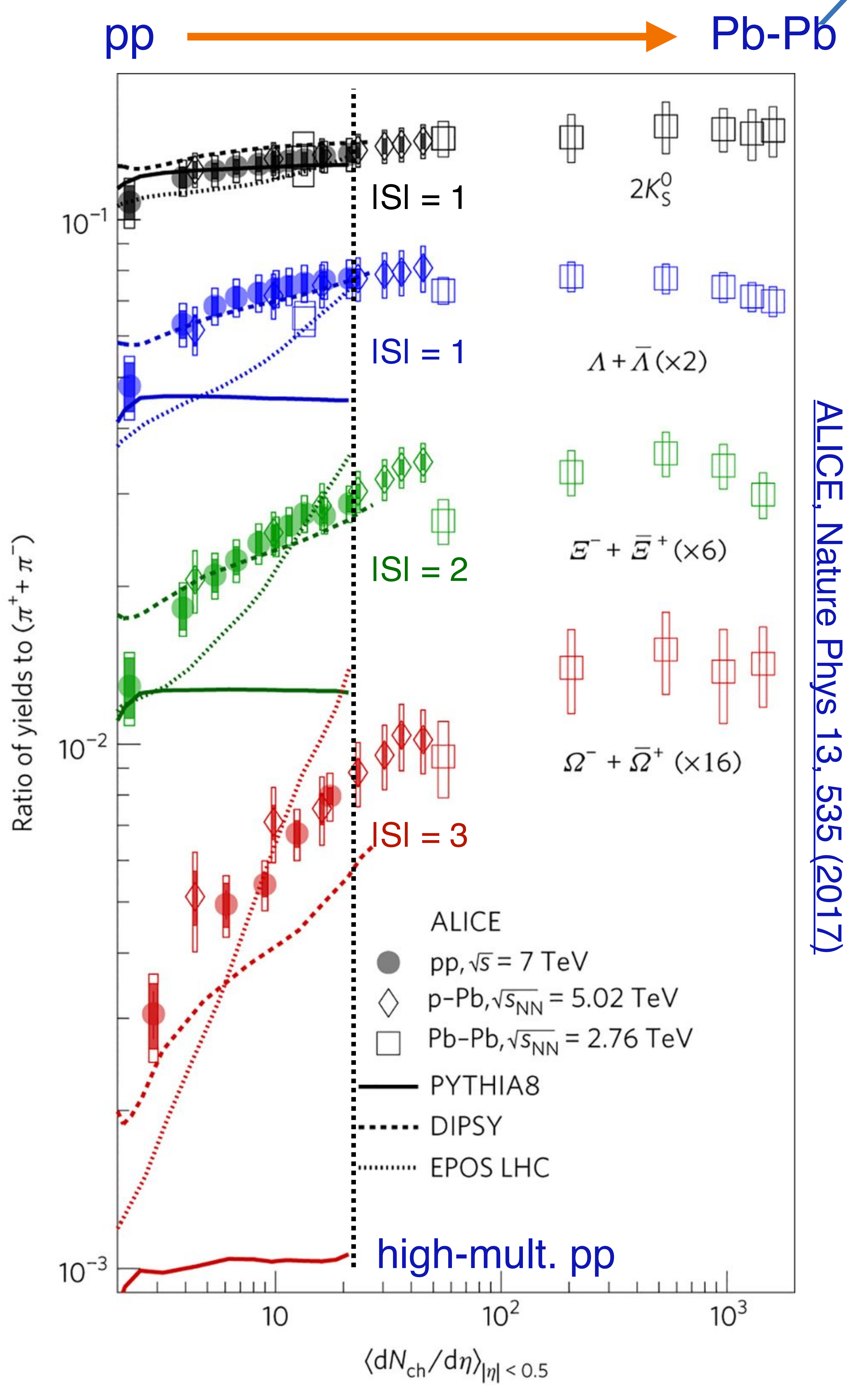

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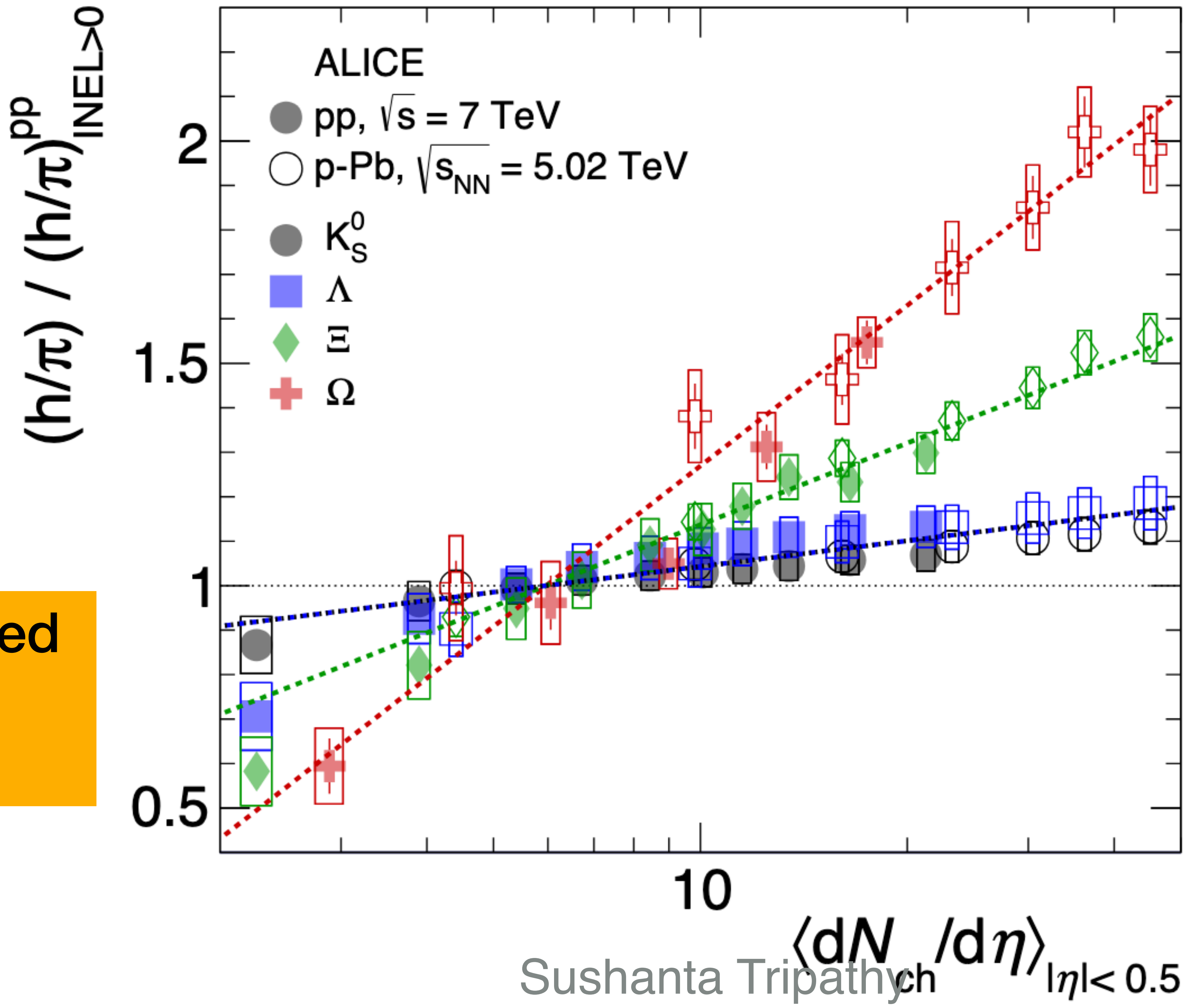
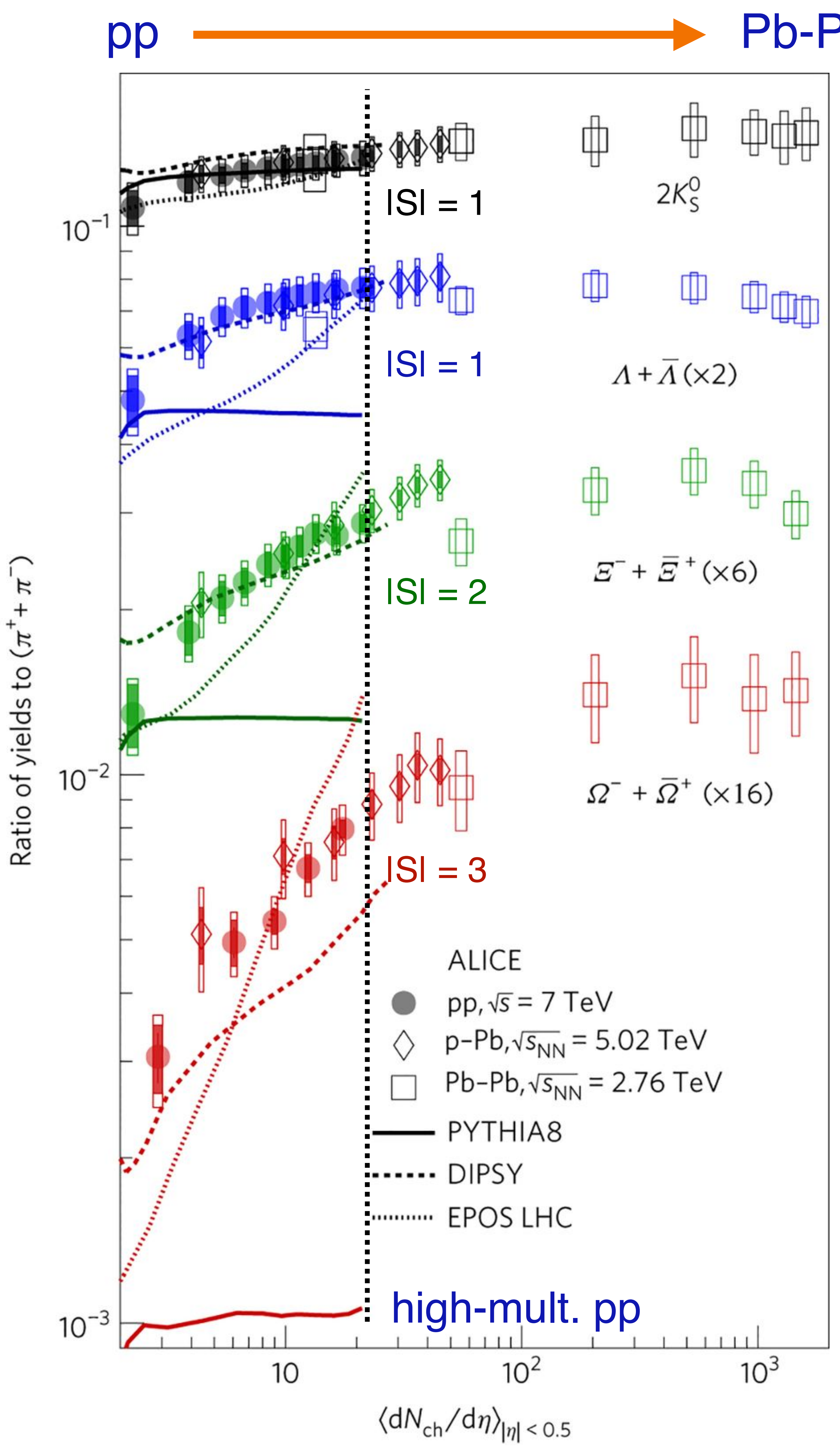
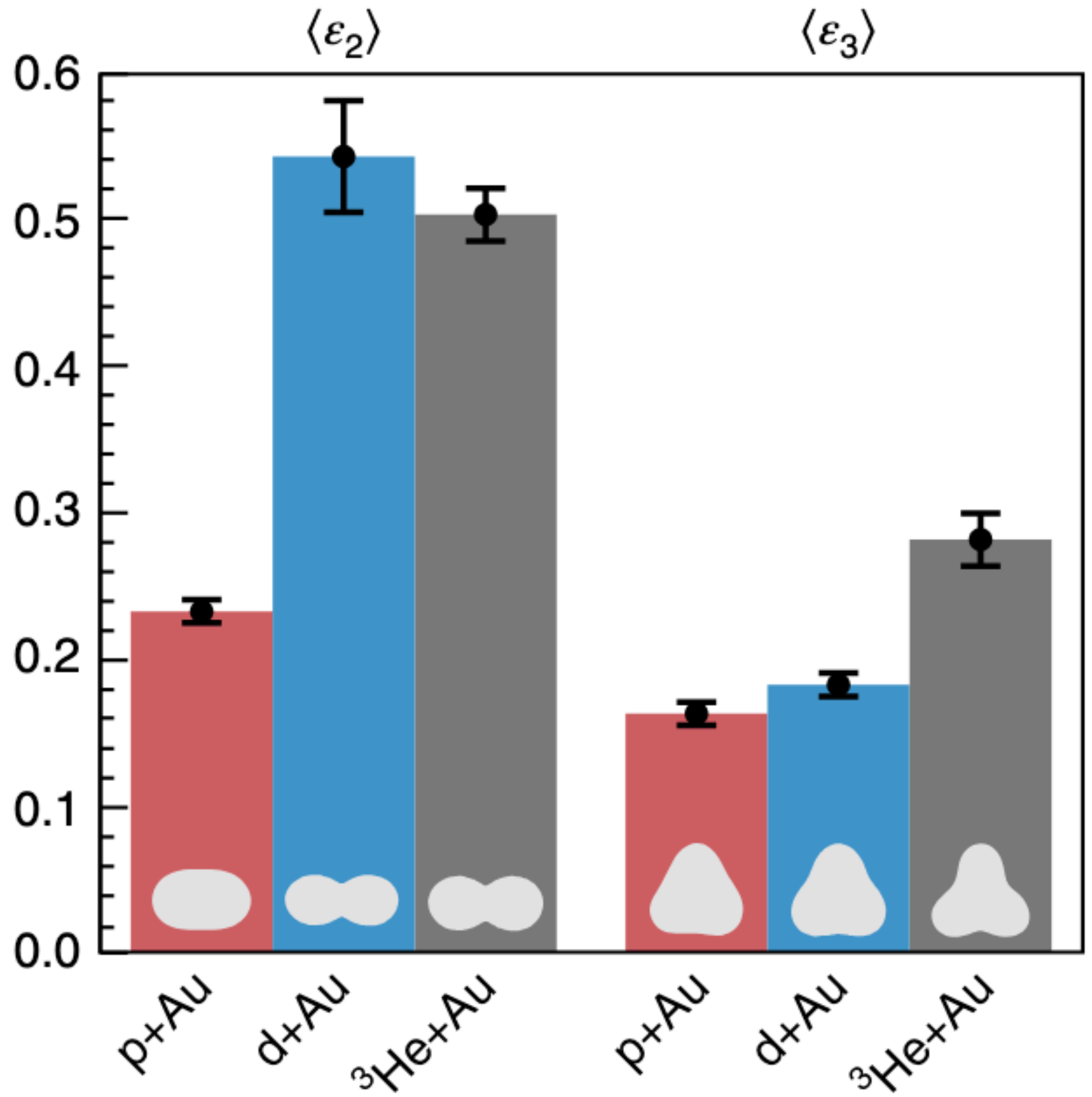



**Strangeness is significantly enhanced in high-mult. pp with respect to minimum bias collisions**

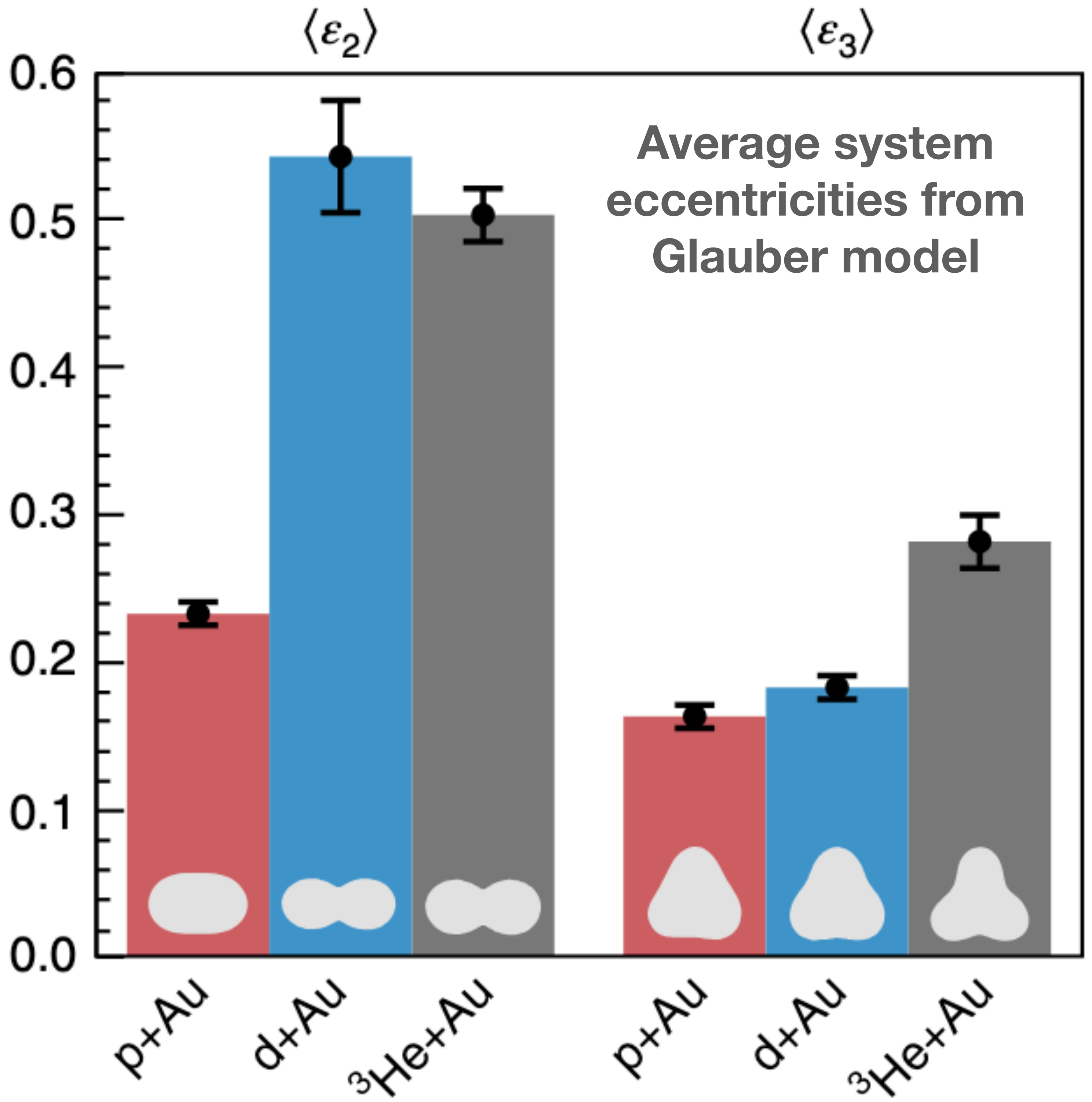



ALICE, Nature Phys 13, 535 (2017)

# Other species: p+Au, d+Au, $^3$He+Au



# Three distinct geometries: p+Au, d+Au, $^3$He+Au




PHENIX, Nature Phys. 15 (2019) 3, 214-220

If the origin is purely from hydrodynamics:

$$v_2^{\mathrm{p+Au}} < v_2^{\mathrm{d+Au}} \simeq v_2^{^3\mathrm{He+Au}}$$

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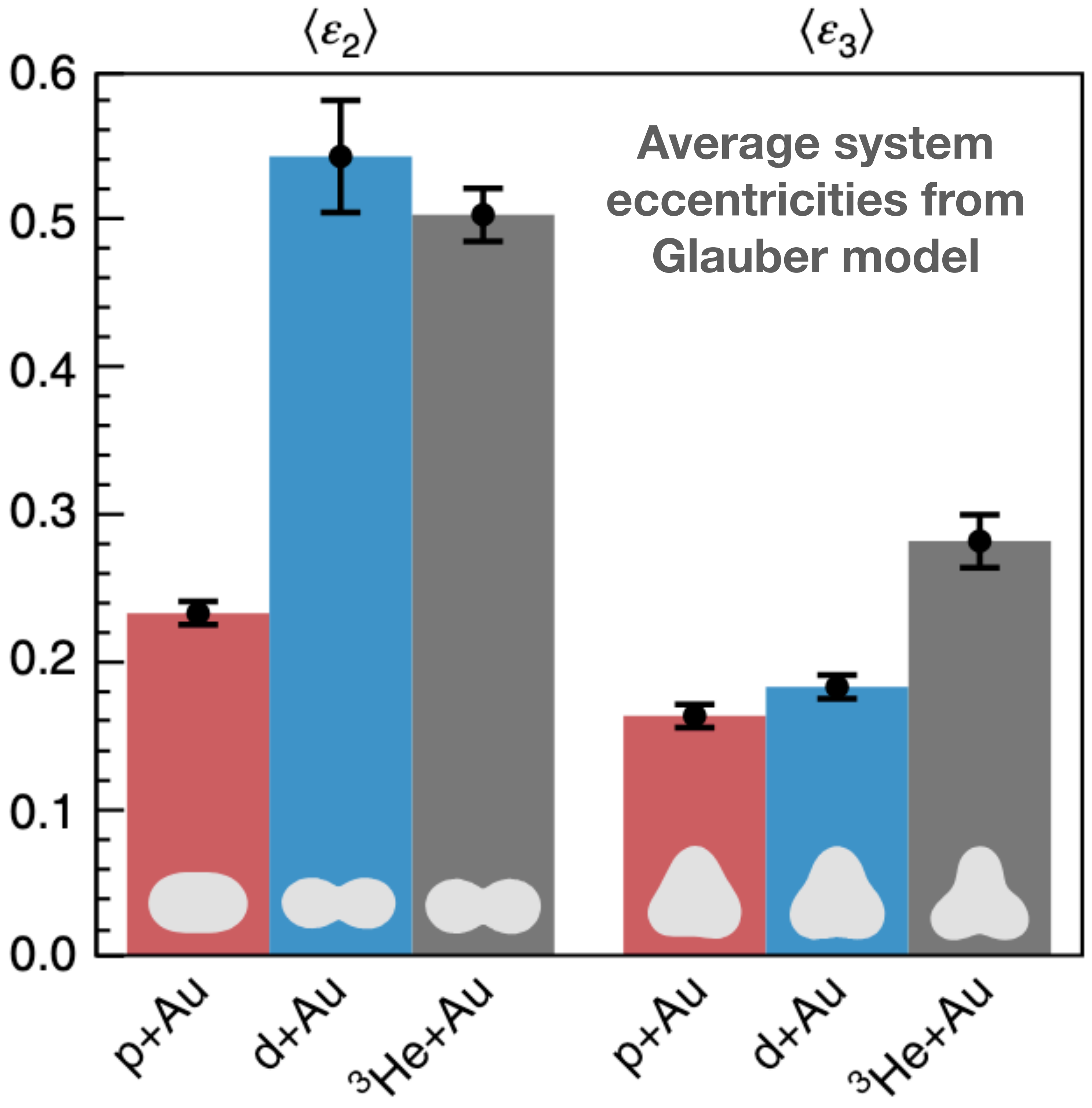


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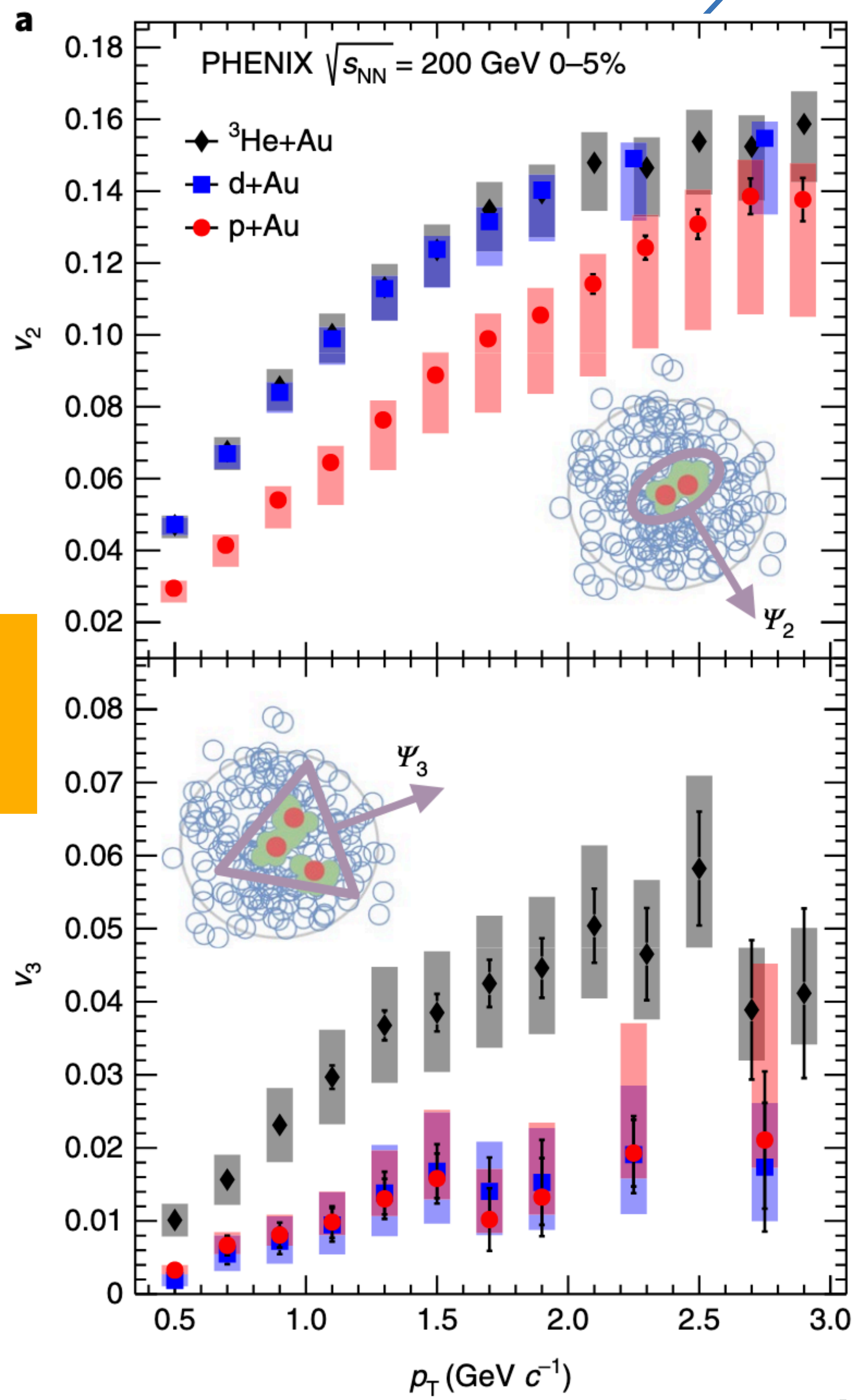
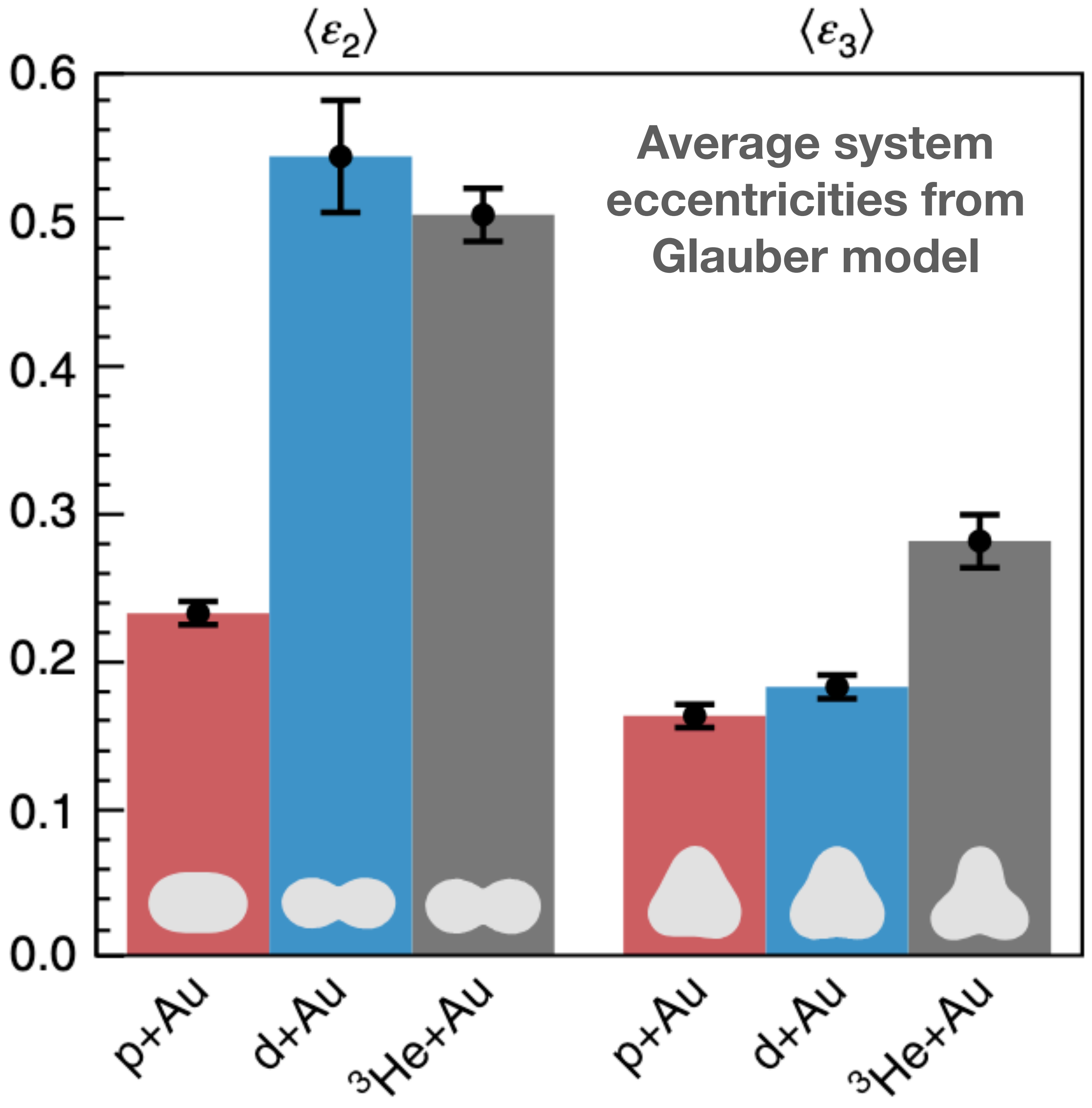
**PHENIX measures a similar behavior indicating small systems collectivity is purely driven by hydrodynamics**




*Quotes from the paper:*

- **Flow coefficients are correlated with the initial geometry**, removing ambiguities related to event multiplicity and initial event geometry
- **Hydrodynamical models**, which include the formation of a short-lived QGP droplet, provide the **best simultaneous description**.

# Three distinct geometries: p+Au, d+Au, ³He+Au

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[STAR, Phys. Rev. Lett.,130(24), 242301, 2023]

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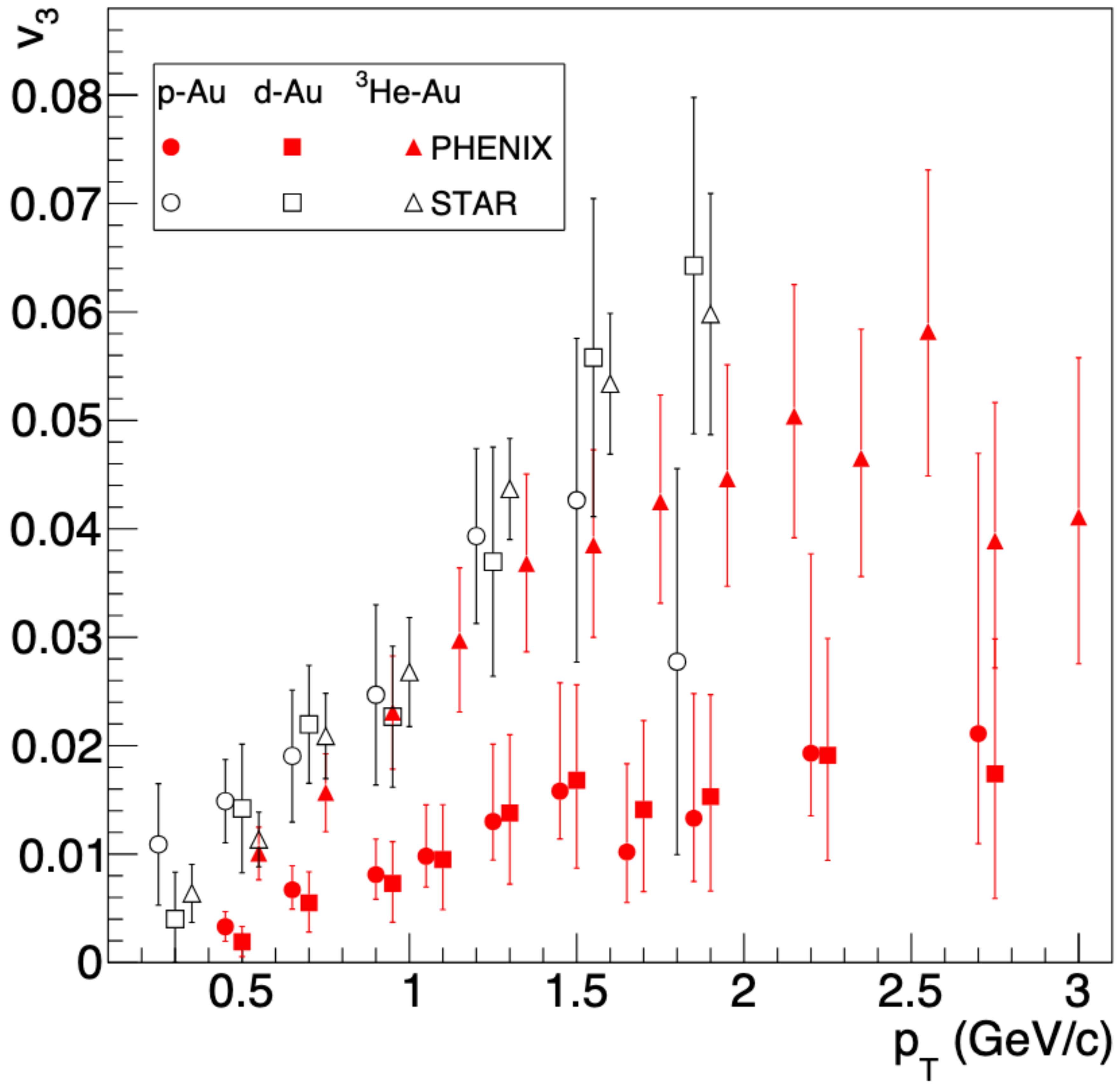
[J. F. Grosse-Oetringhaus and U. A. Wiedemann, arXiv:2407.07484 [hep-ex]]

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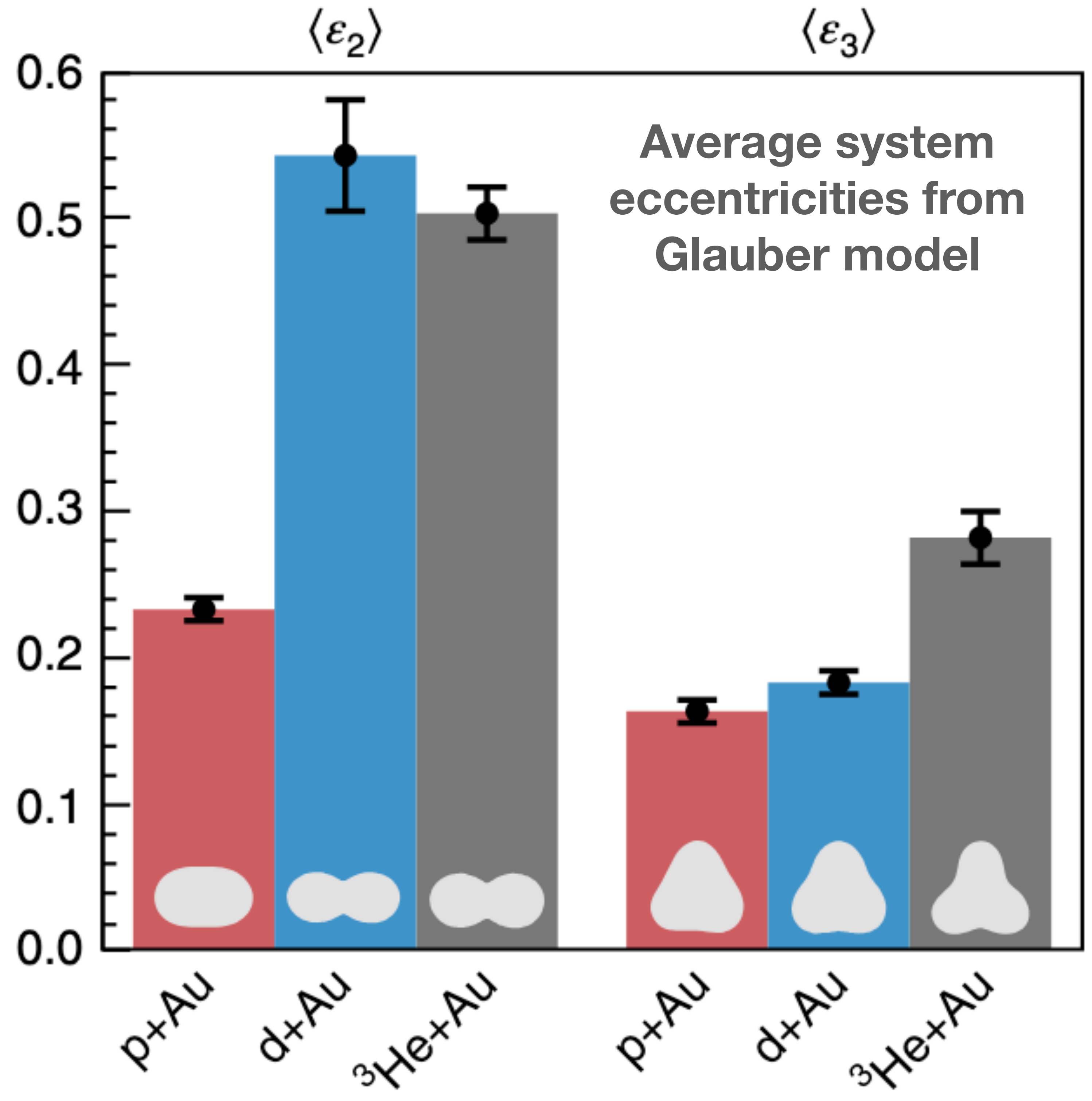
# Three distinct geometries: p+Au, d+Au, $^3$He+Au

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**It is important to resolve this experimental discrepancy***

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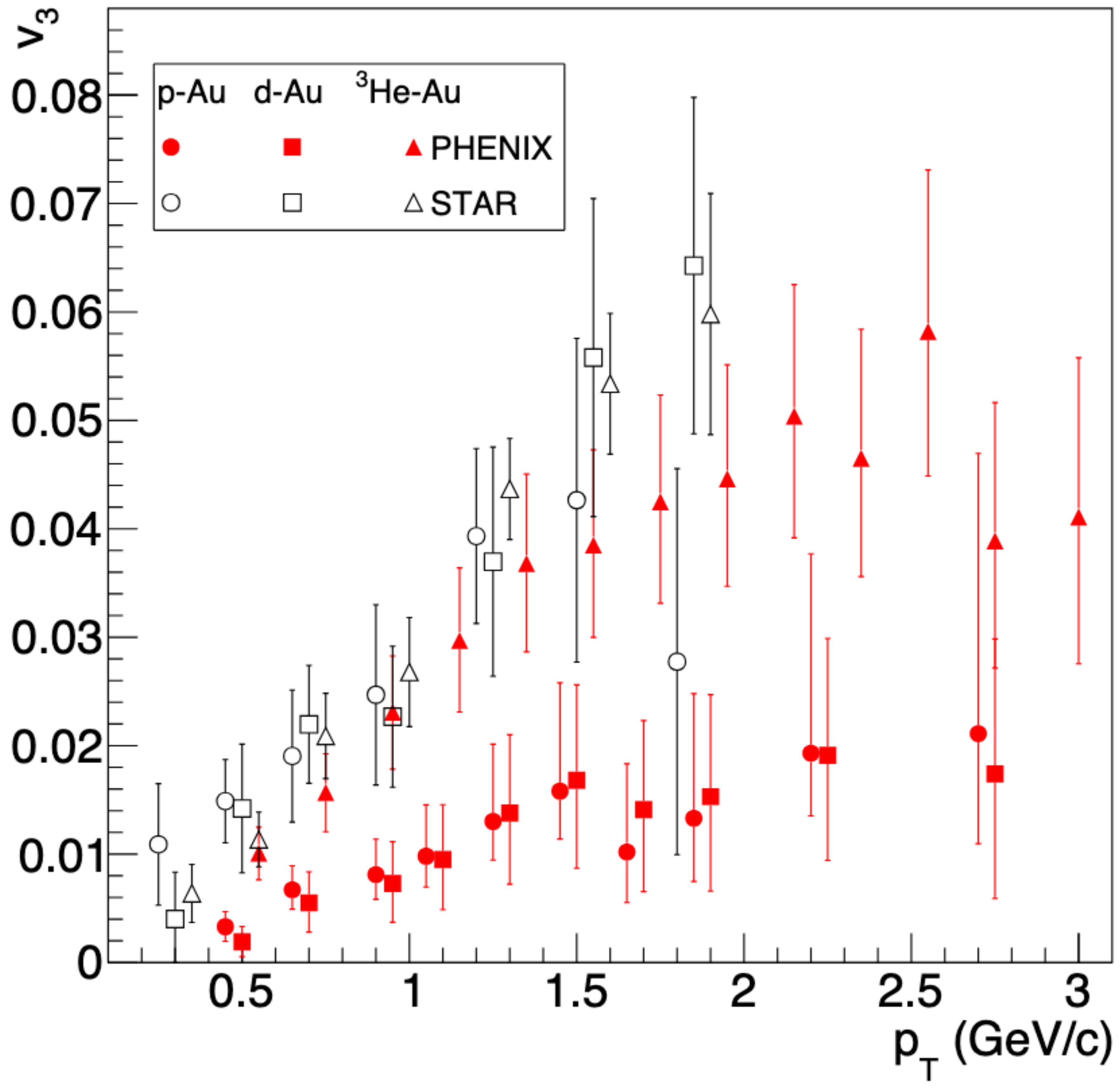
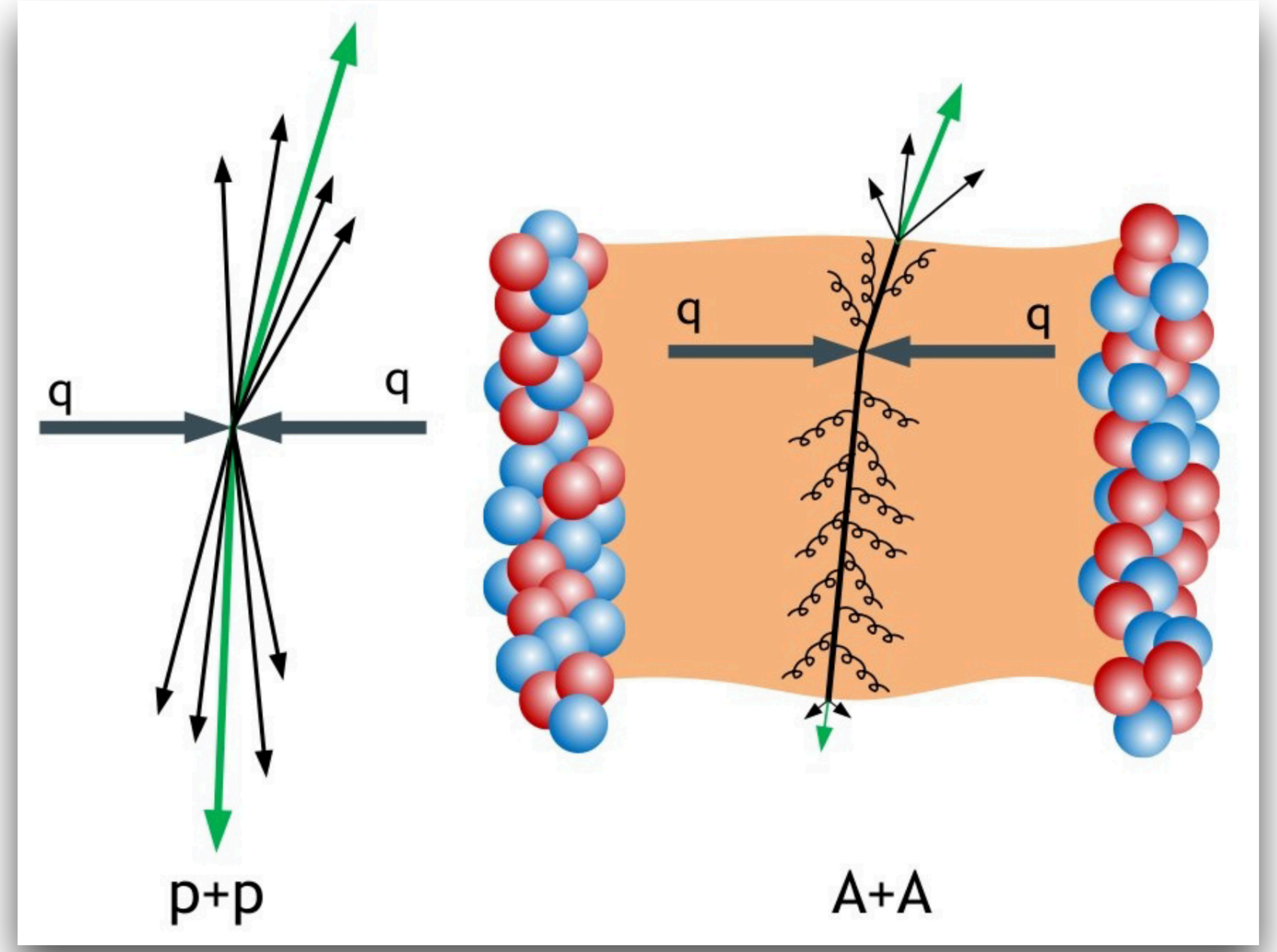
*Only part of the differences can be attributed to the measurement method

[J. F. Grosse-Oetringhaus and U. A. Wiedemann, arXiv:2407.07484 [hep-ex]](#)

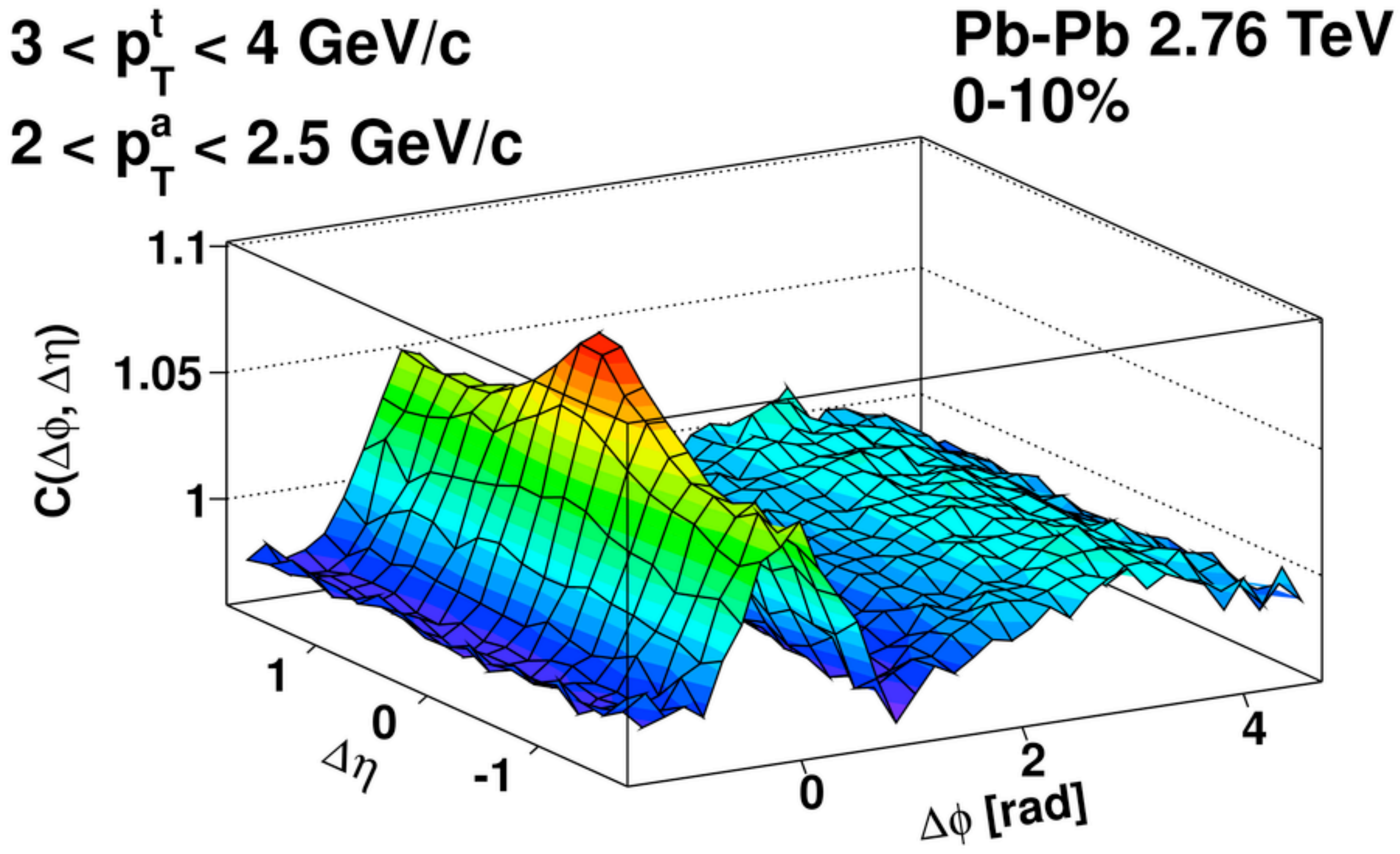


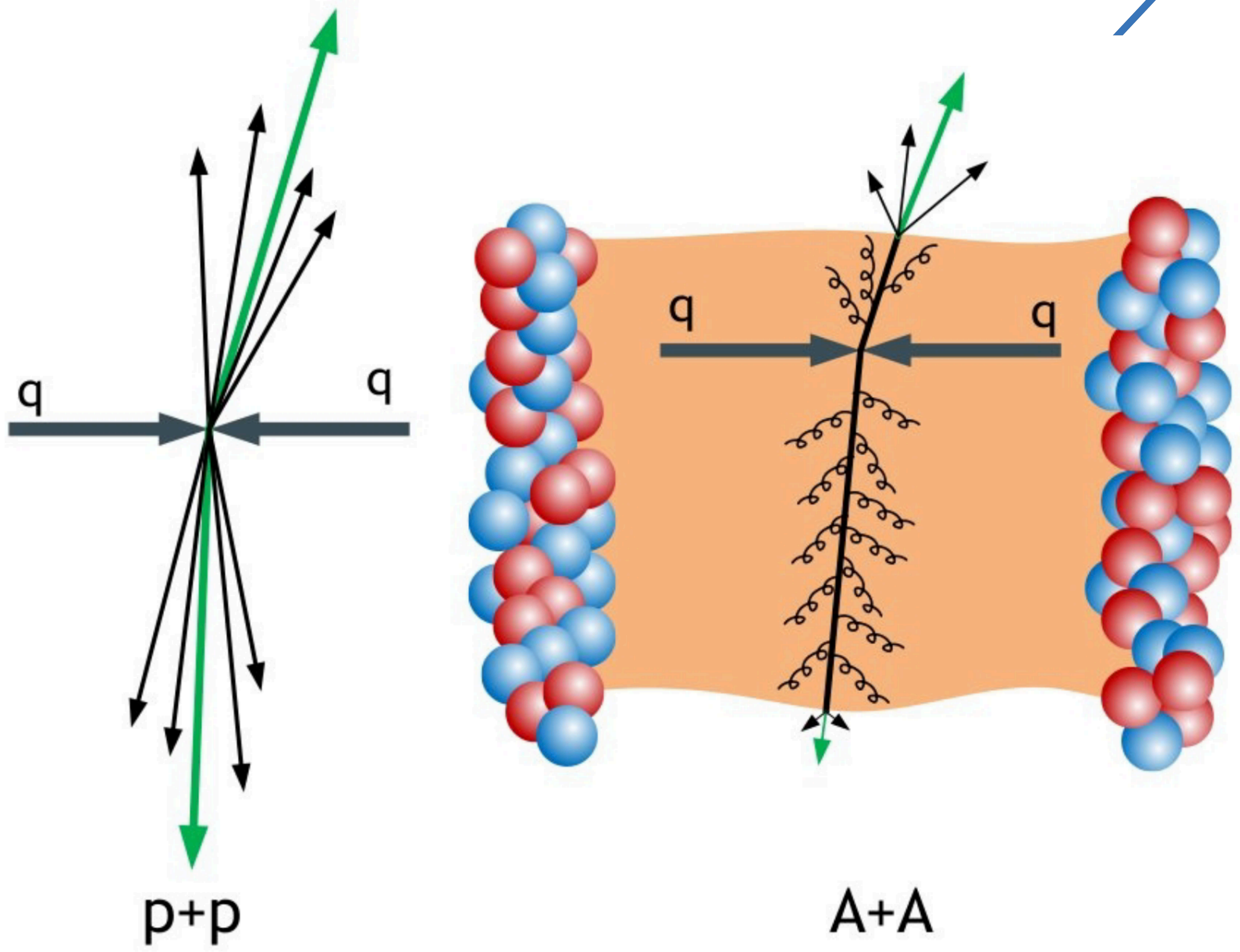
# Jet-like region modifications



# Jet-like region modifications

- With the help of correlation studies in high-$p_T$, one can characterise the medium by comparing quenched and unquenched collisions
- One can look for jet modifications in the di-jet structure by dihadron two-particle azimuthal correlations




ALICE, Phys.Lett. B 708 (2012) 249

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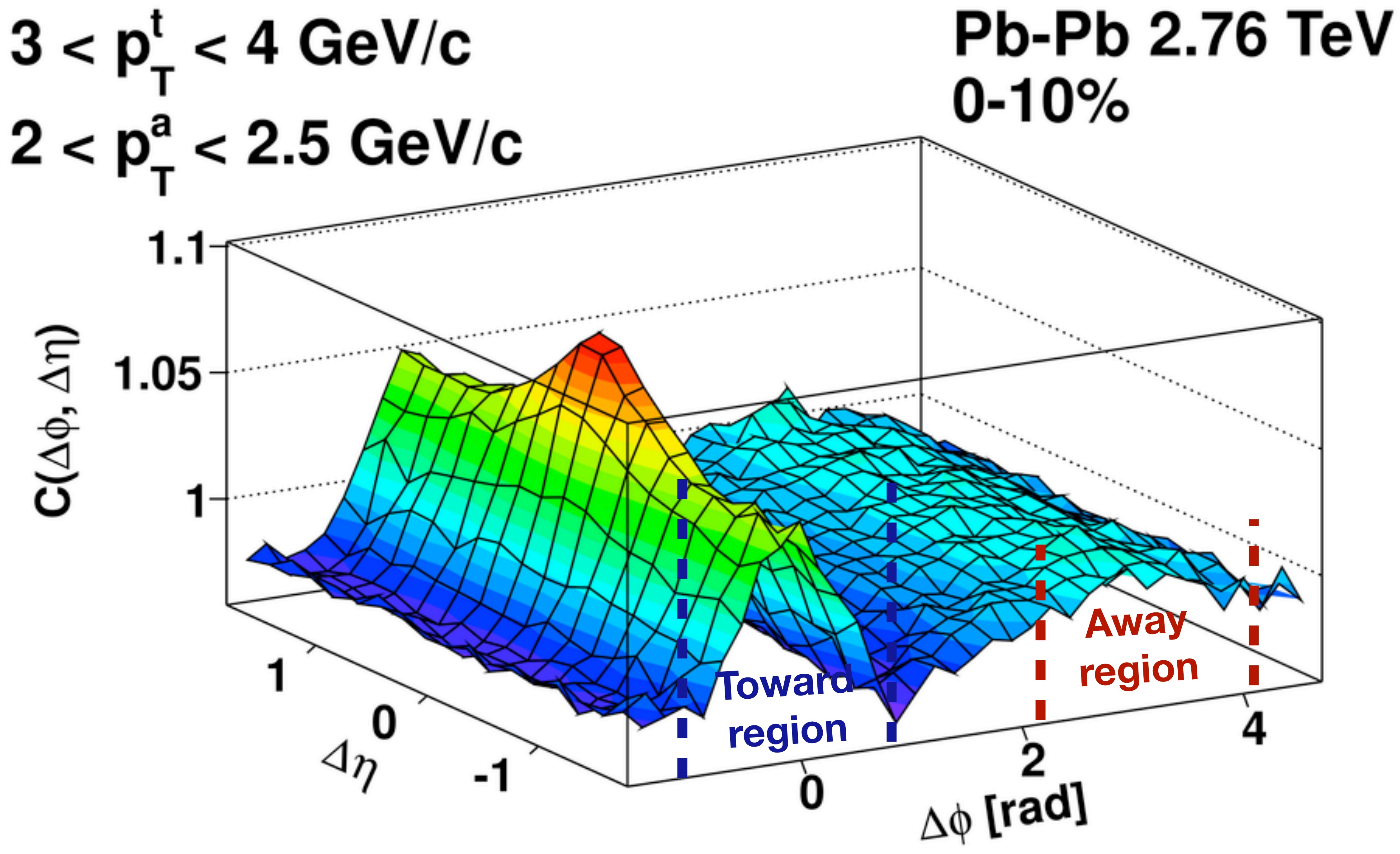


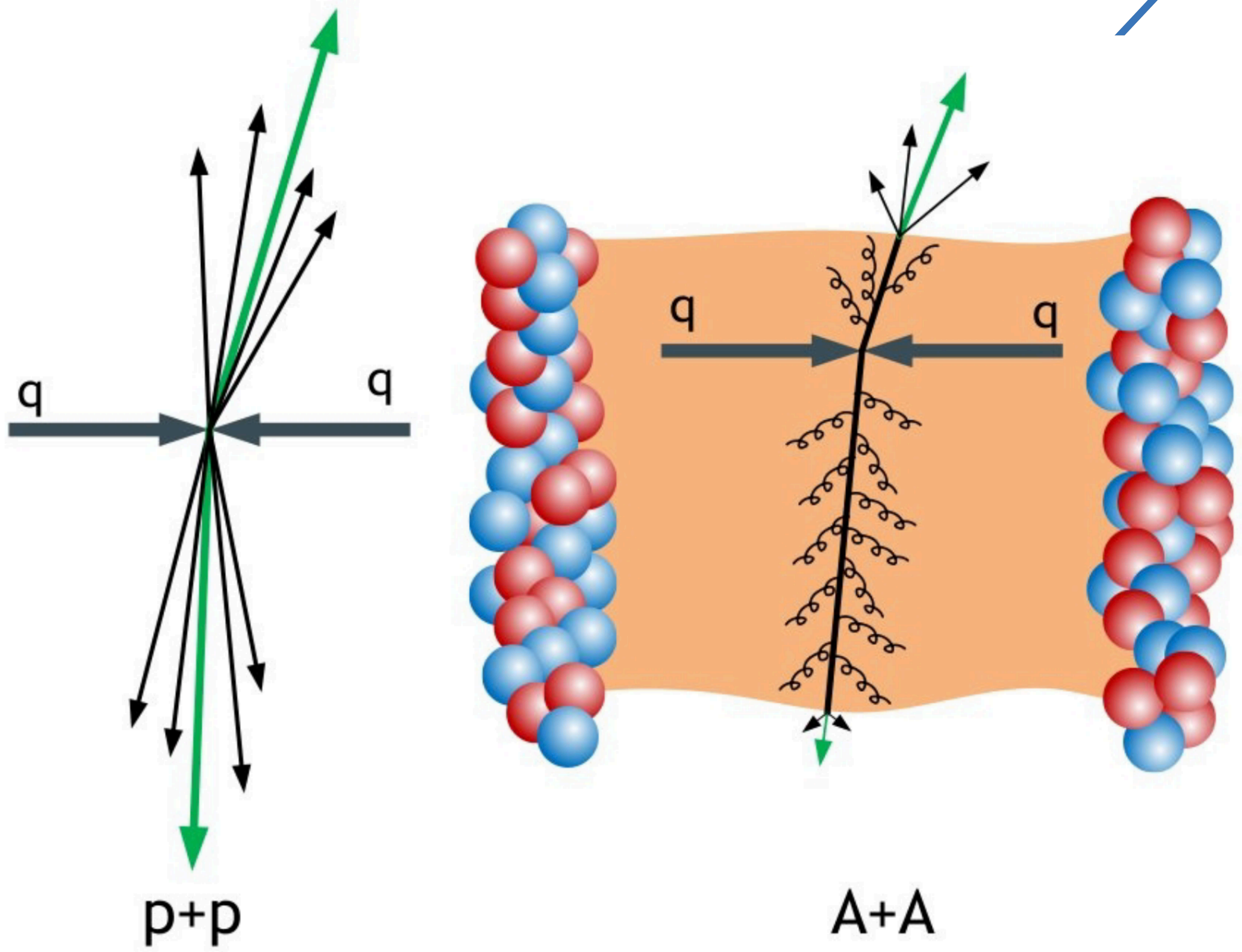


**Toward region:** around $\Delta\varphi \simeq 0$

**Away region:** around $\Delta\varphi \simeq \pi$

ALICE, Phys.Lett. B 708 (2012) 249

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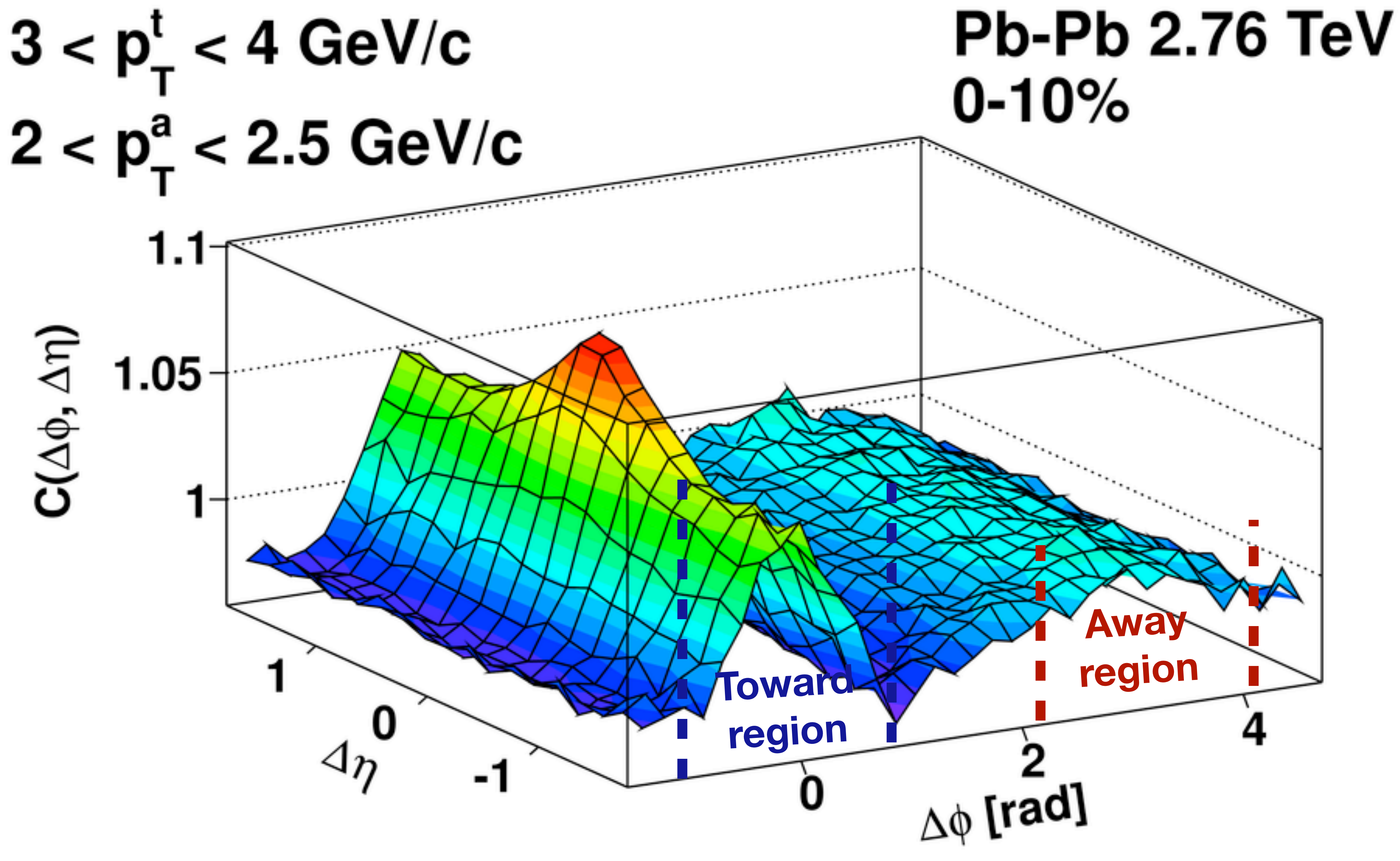


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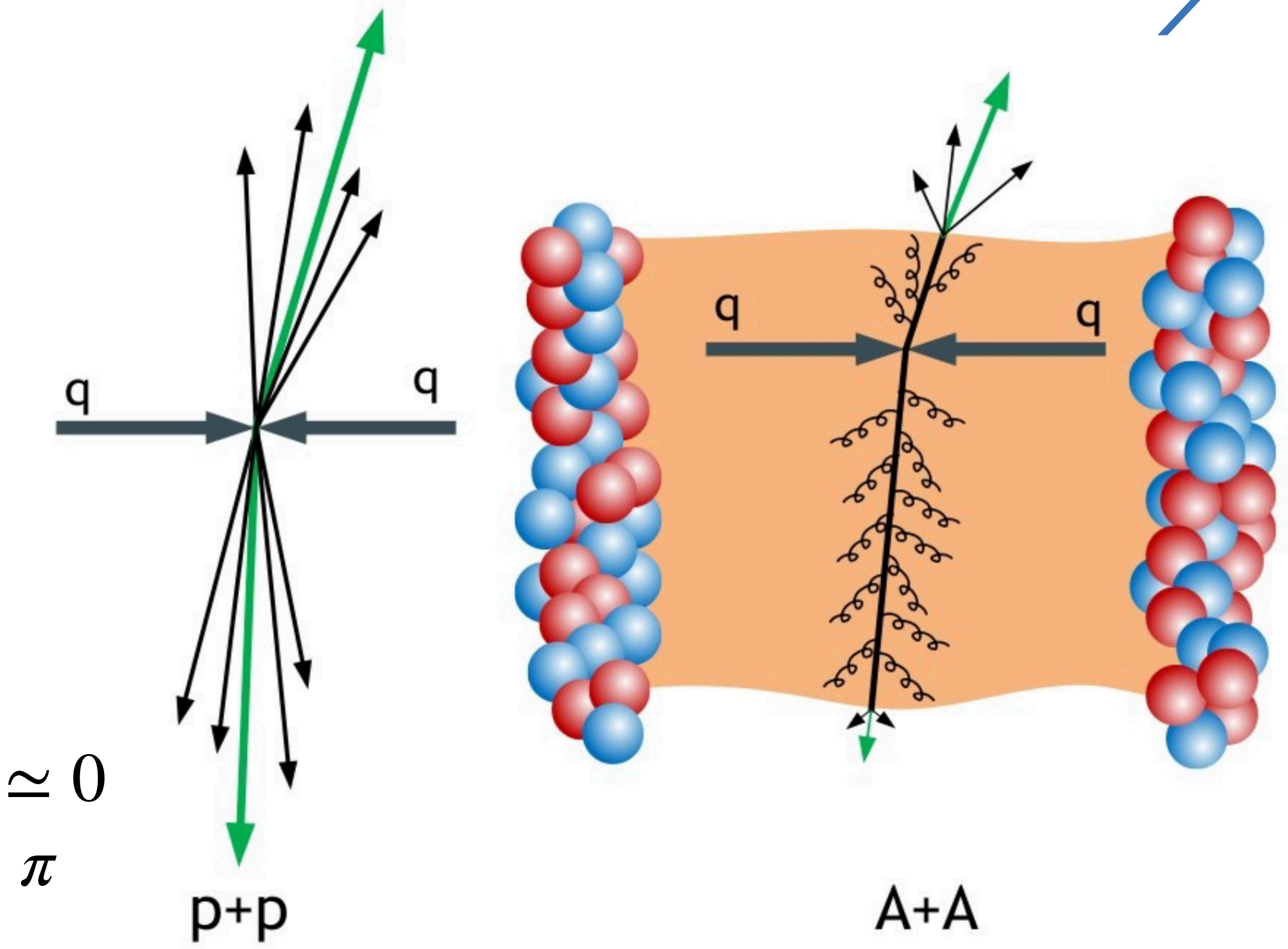



**Toward region:** around $\Delta\varphi \simeq 0$

**Away region:** around $\Delta\varphi \simeq \pi$

$I_{CP} = Y^{central}/Y^{peripheral}$

$I_{AA} = Y^{AA}/Y^{pp,MB}$

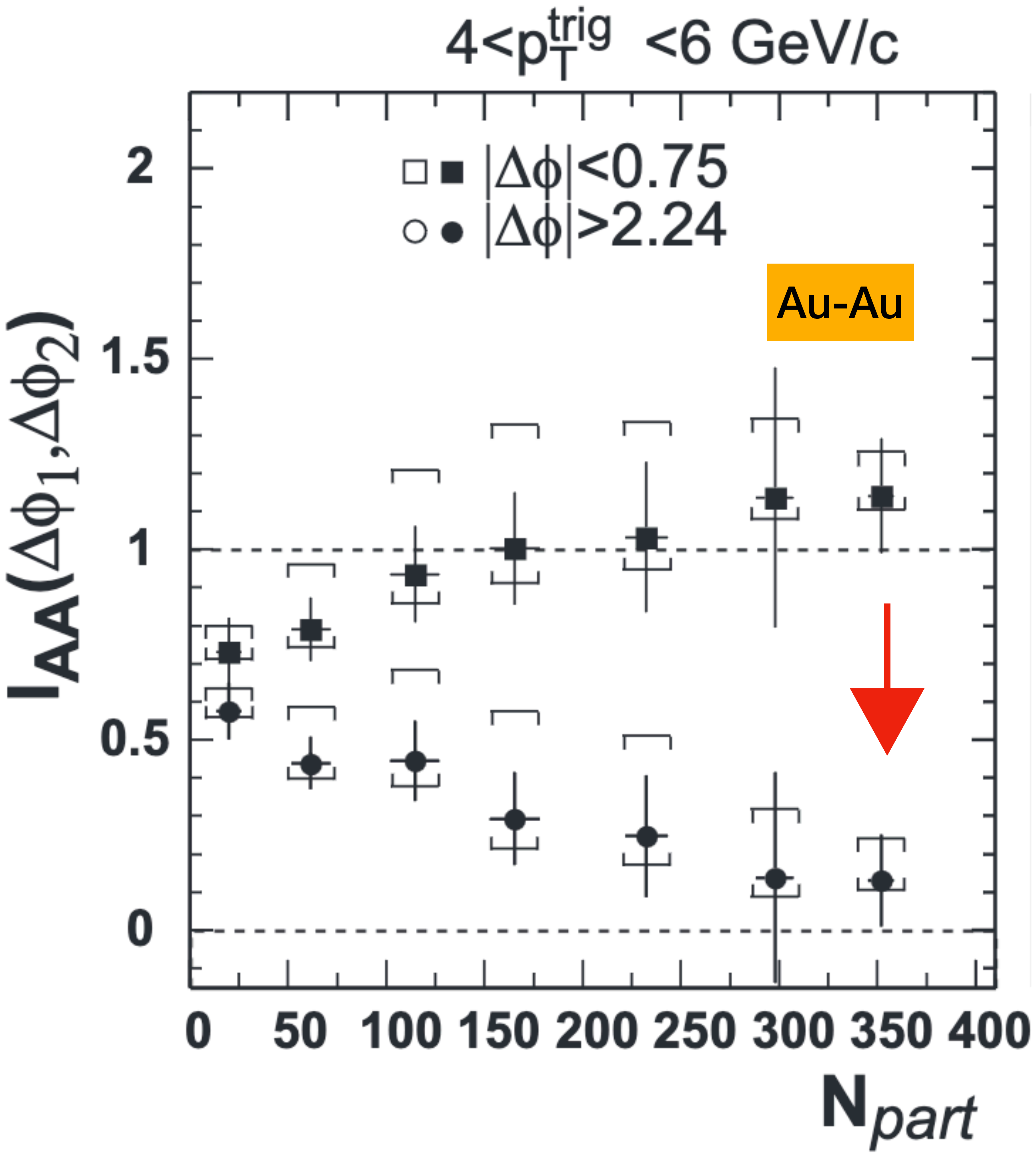
measured in toward and away regions

*Y* : yield

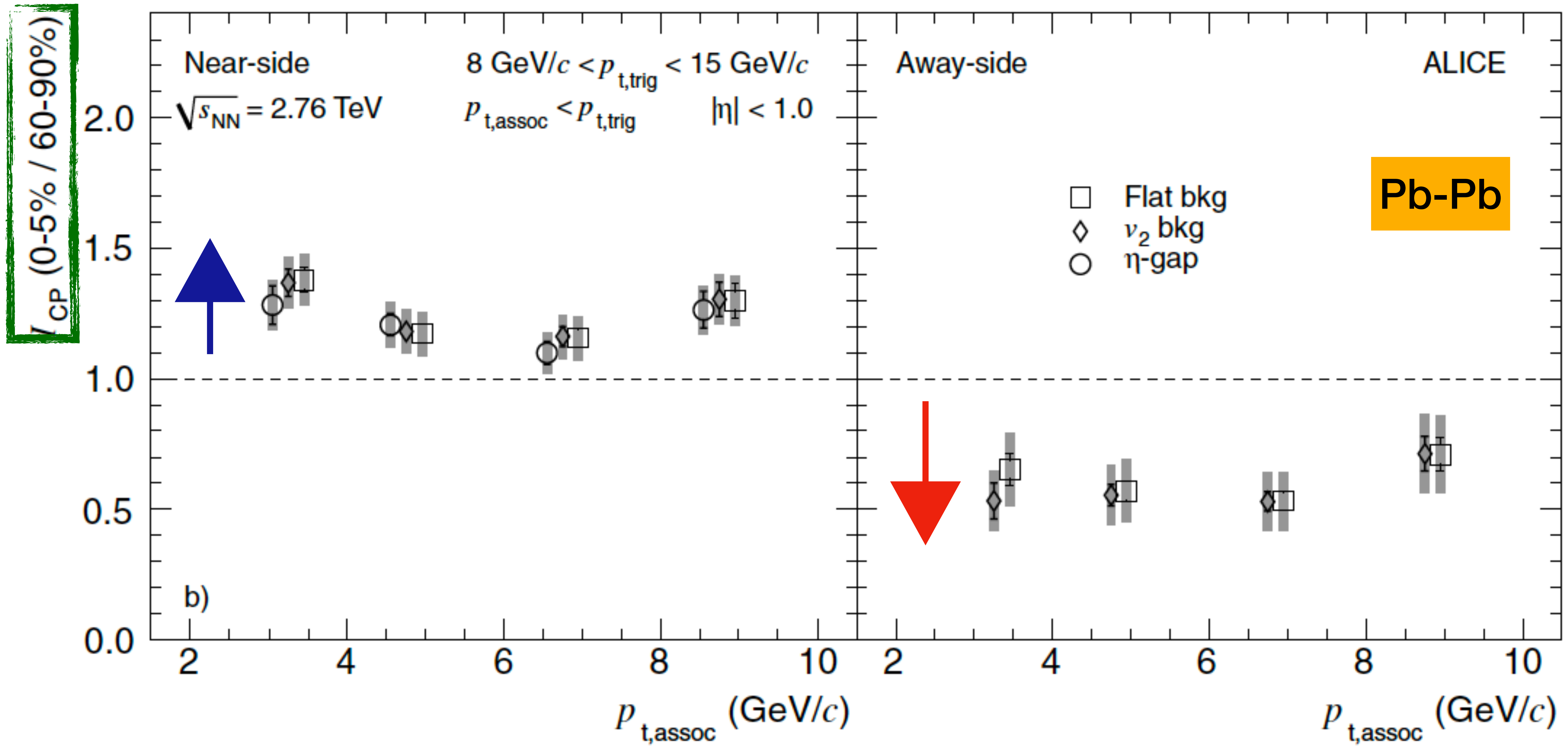
- $I_{AA}$ and $I_{CP}$ give insight into in-medium energy loss and jet-quenching effects
- < 1 in away region: presence of in-medium energy loss
- >1 in toward region: recovery of quenched energy

# Jet-like region modifications

STAR, Phys. Rev. Lett. 90, 082302 (2003)




ALICE, Phys. Rev. Lett. 108 (2012) 092301




**Significant away-side suppression is seen in central heavy-ion collisions in both RHIC and LHC energies**

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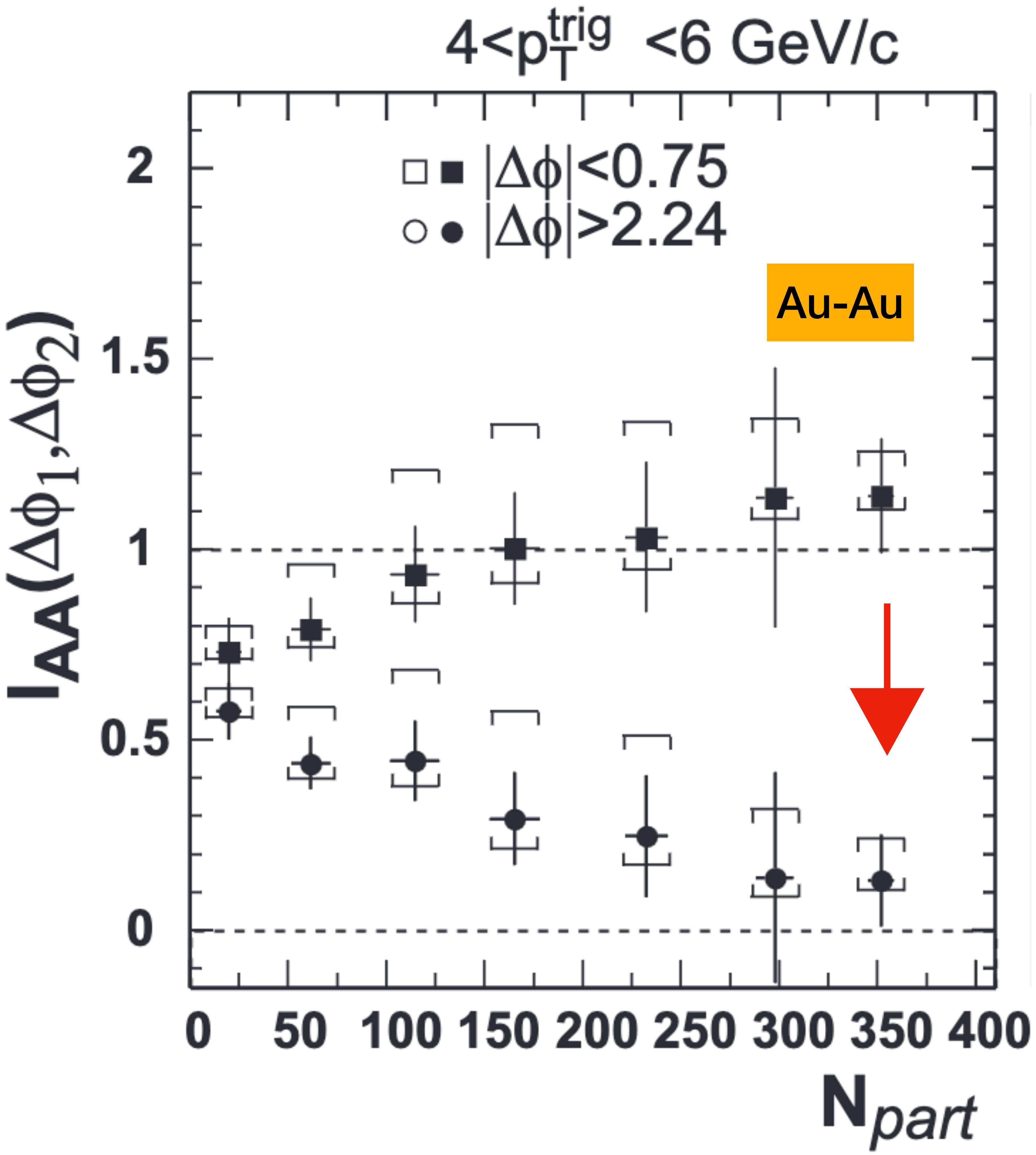
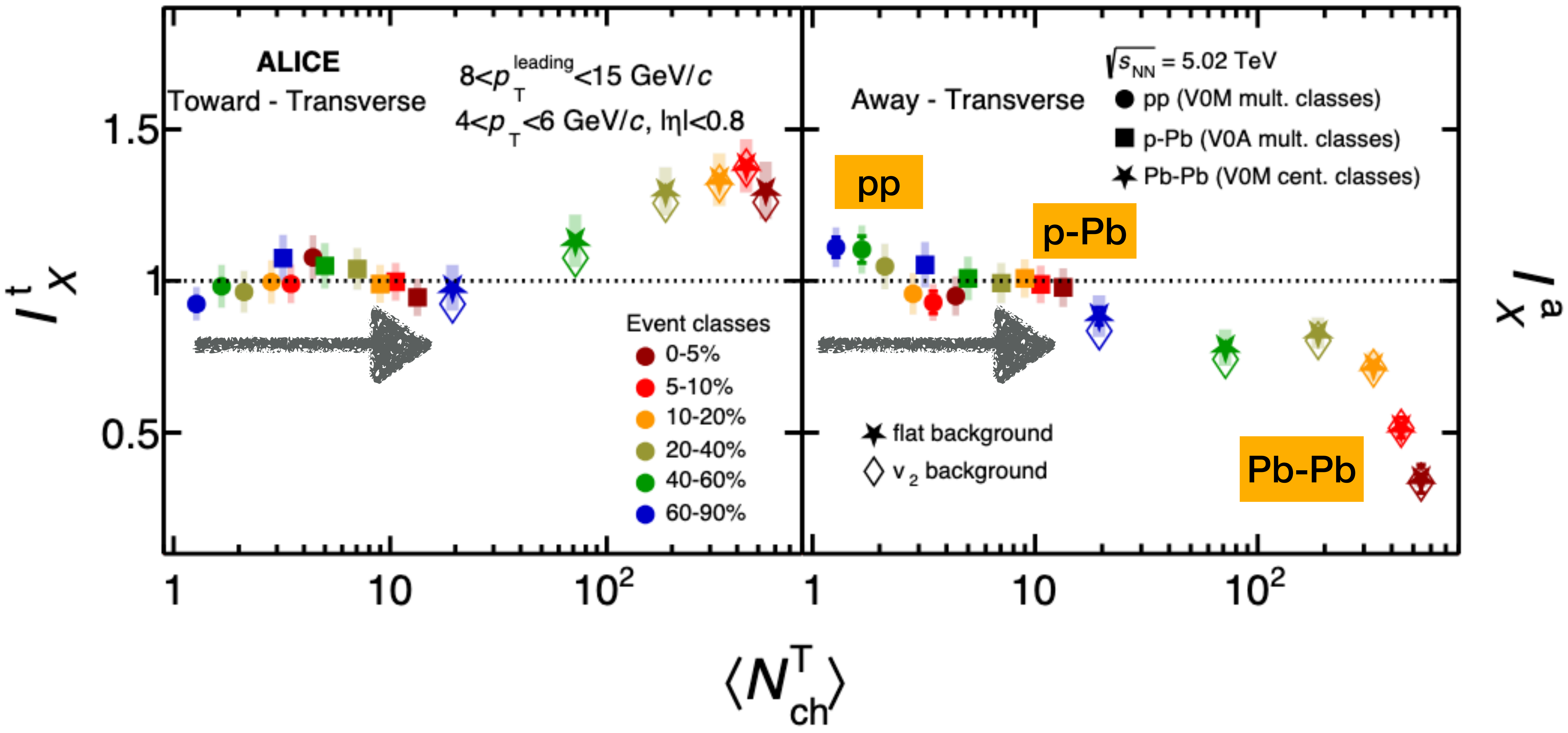
STAR, Phys. Rev. Lett. 90, 082302 (2003)




ALICE, Phys. Lett. B 843 (2022) 137649




**No jet-like region modification in small systems is seen in experiments**

# Jet-like region modifications

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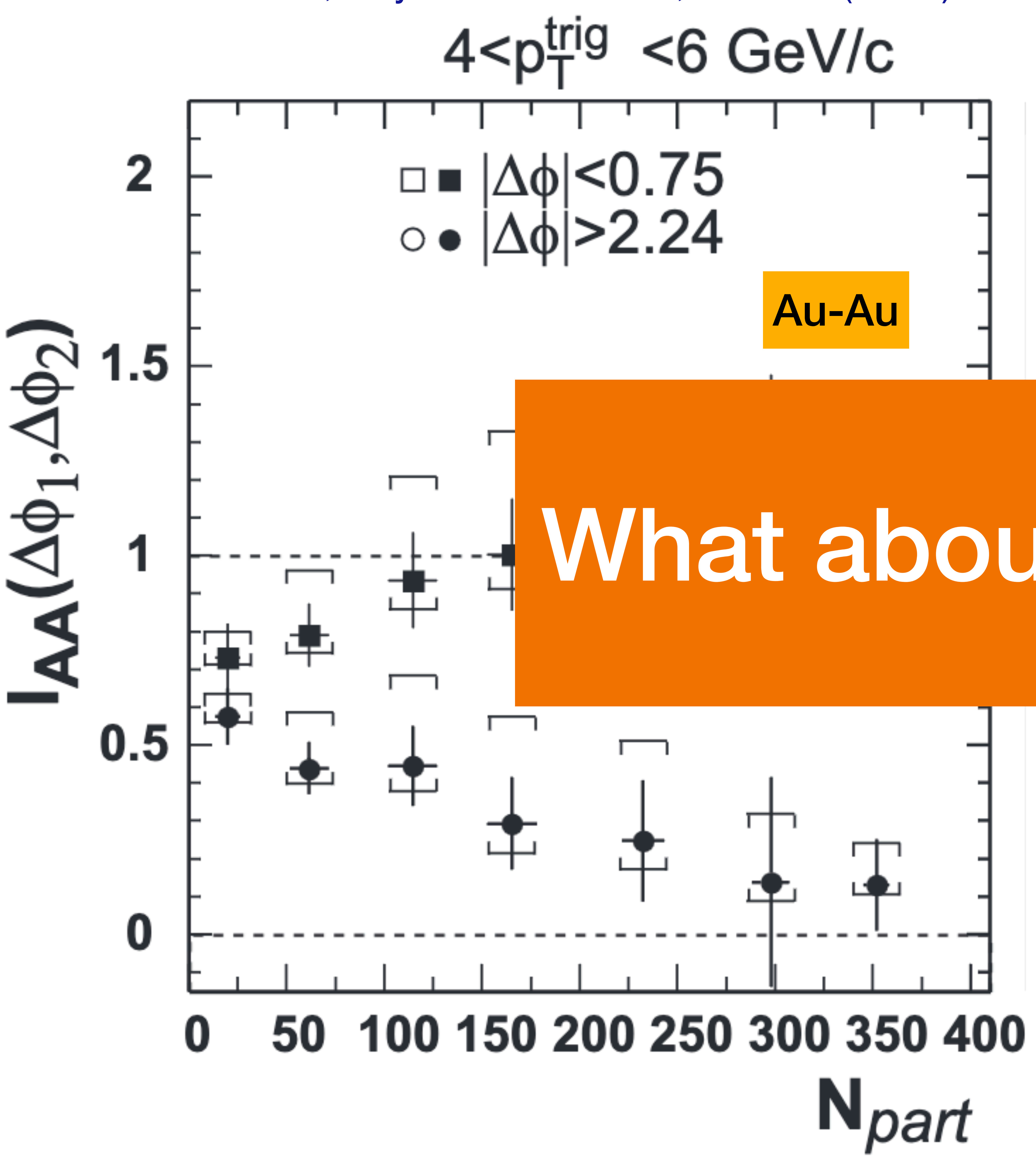


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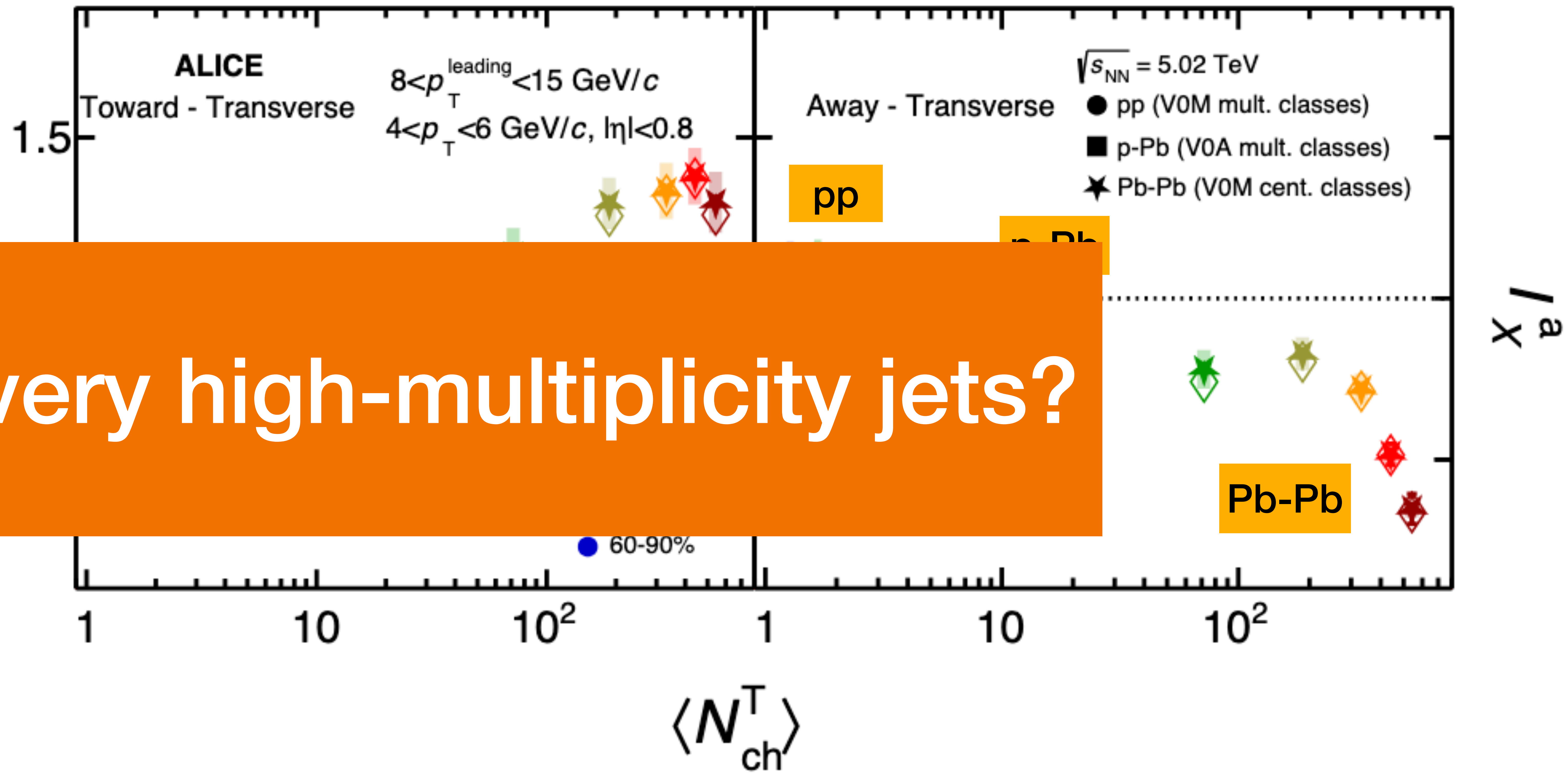
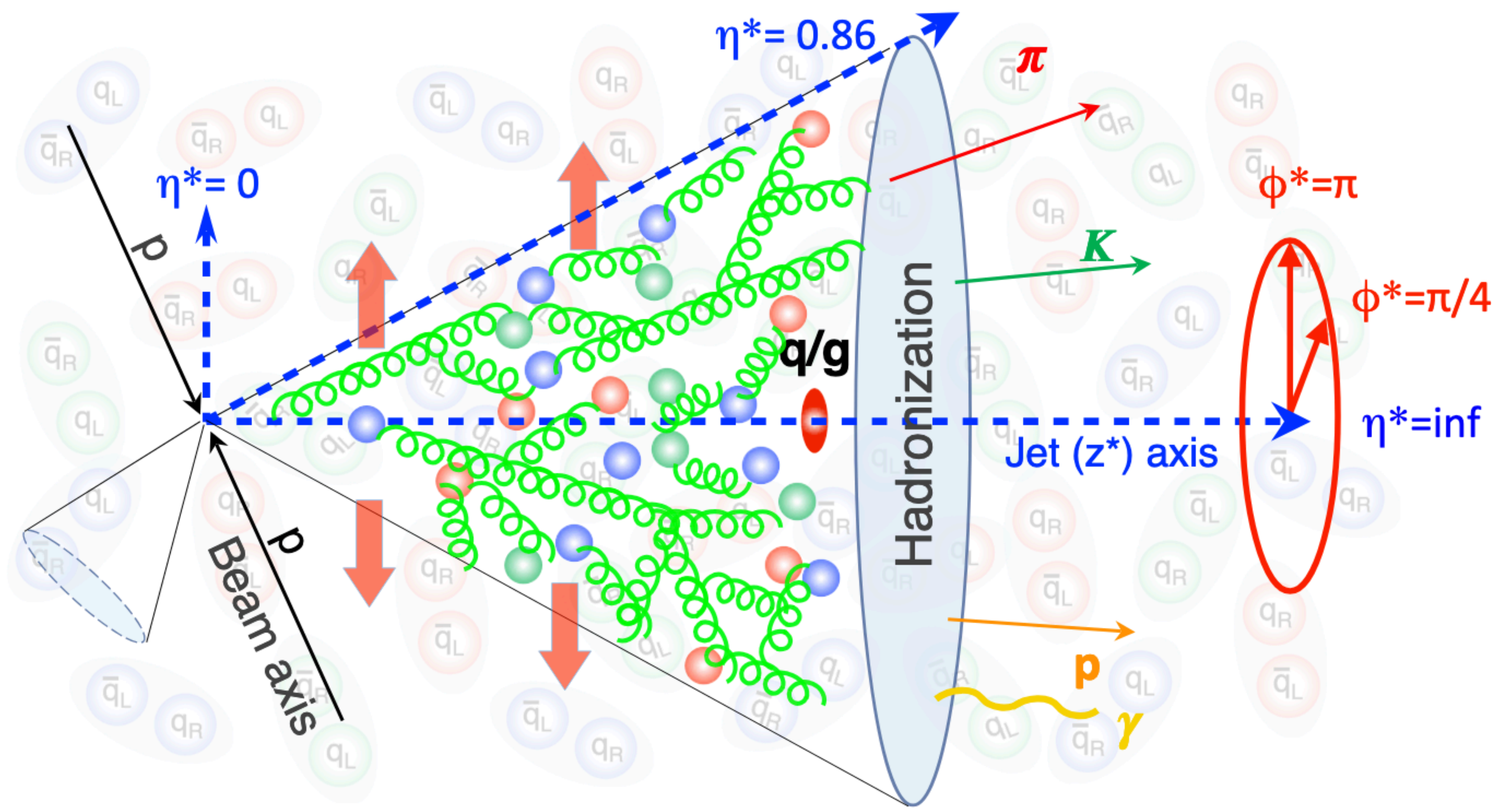



**What about very high-multiplicity jets?**

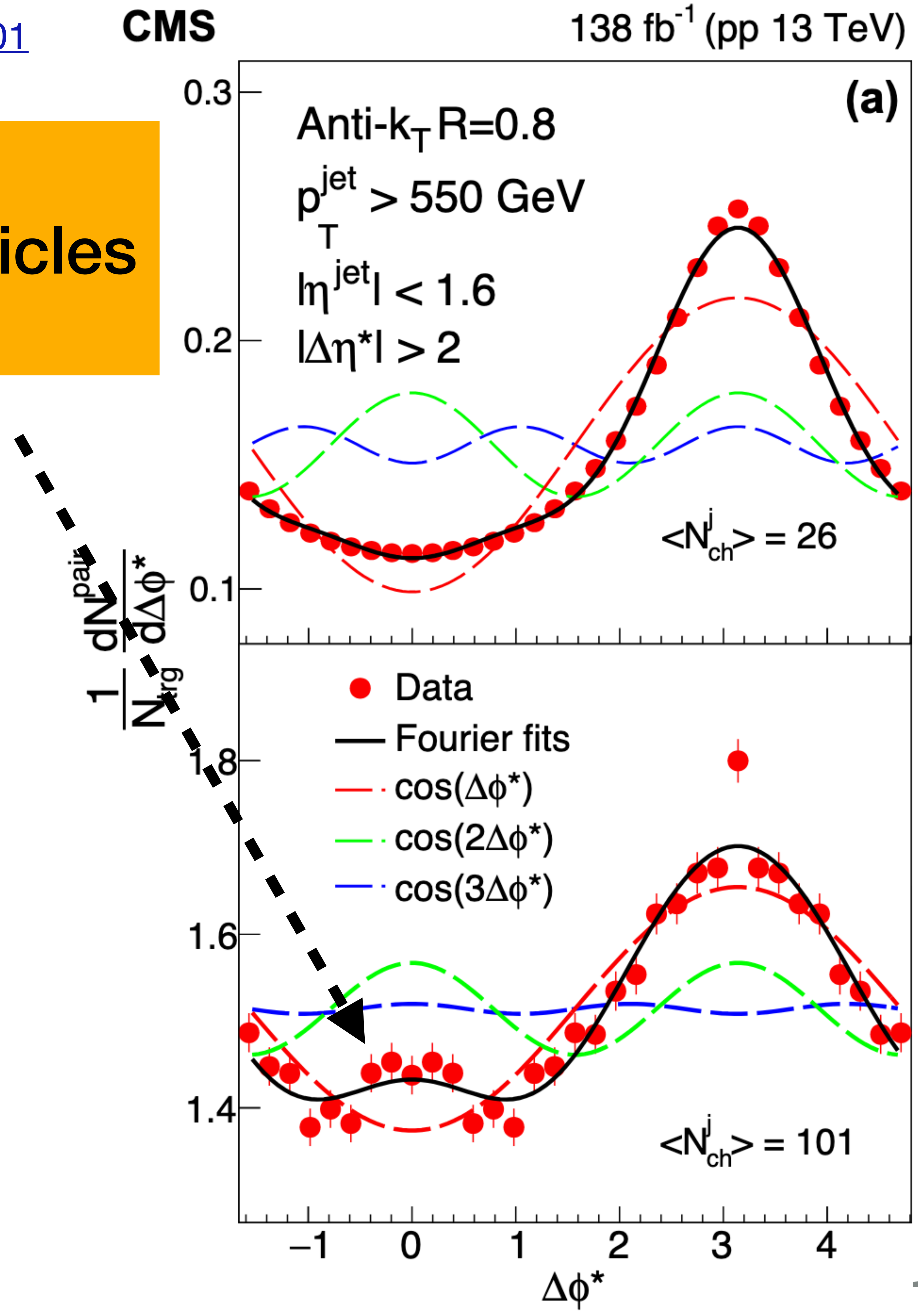
No jet-like region modification in small systems is seen in experiments

# Ridge yield in high multiplicity jets in pp collisions




[CMS, Phys. Rev. Lett. 133 (2024) 142301](#)

**Ridge-like yield contribution from particles in very dense jets**



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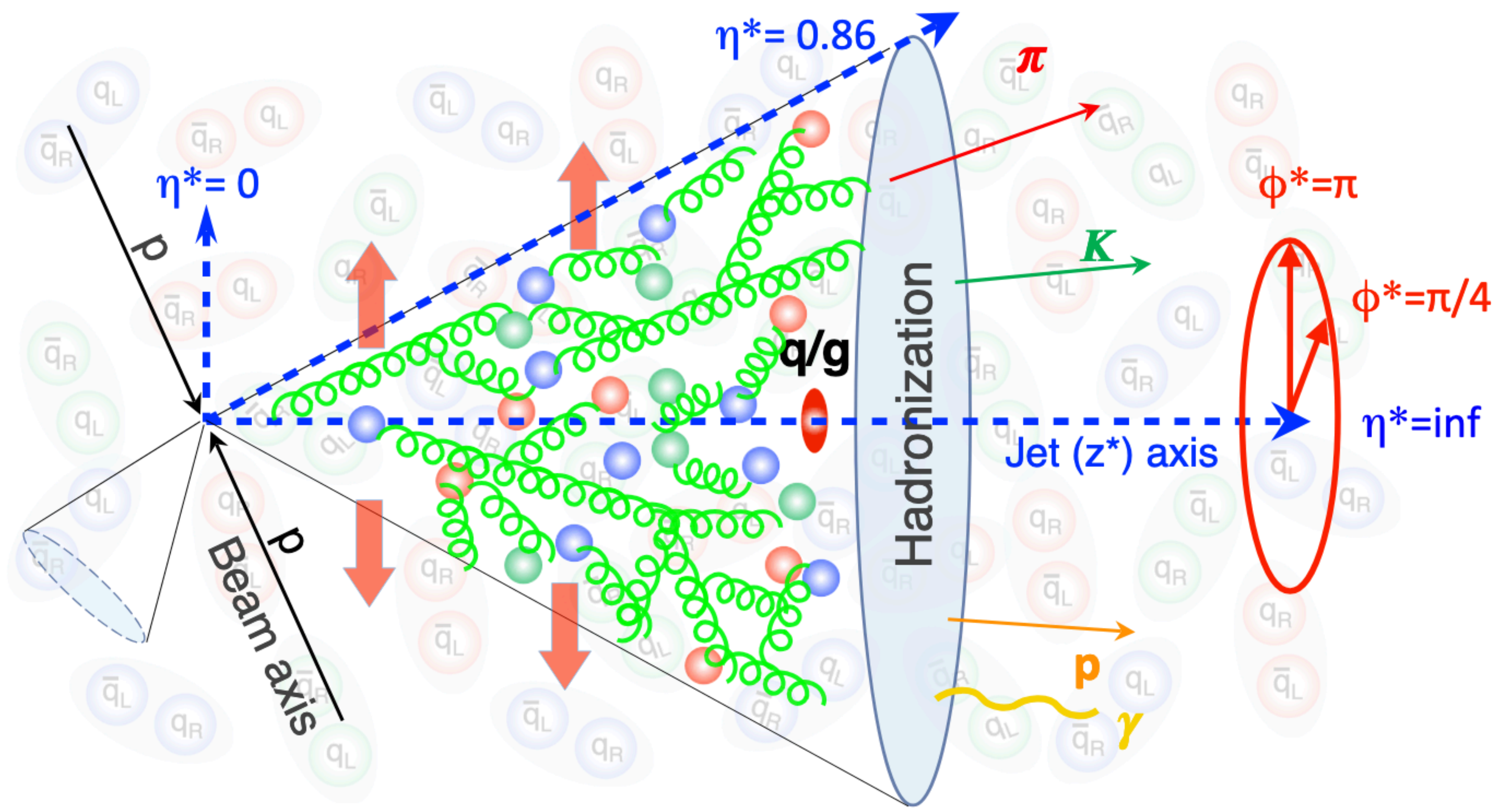
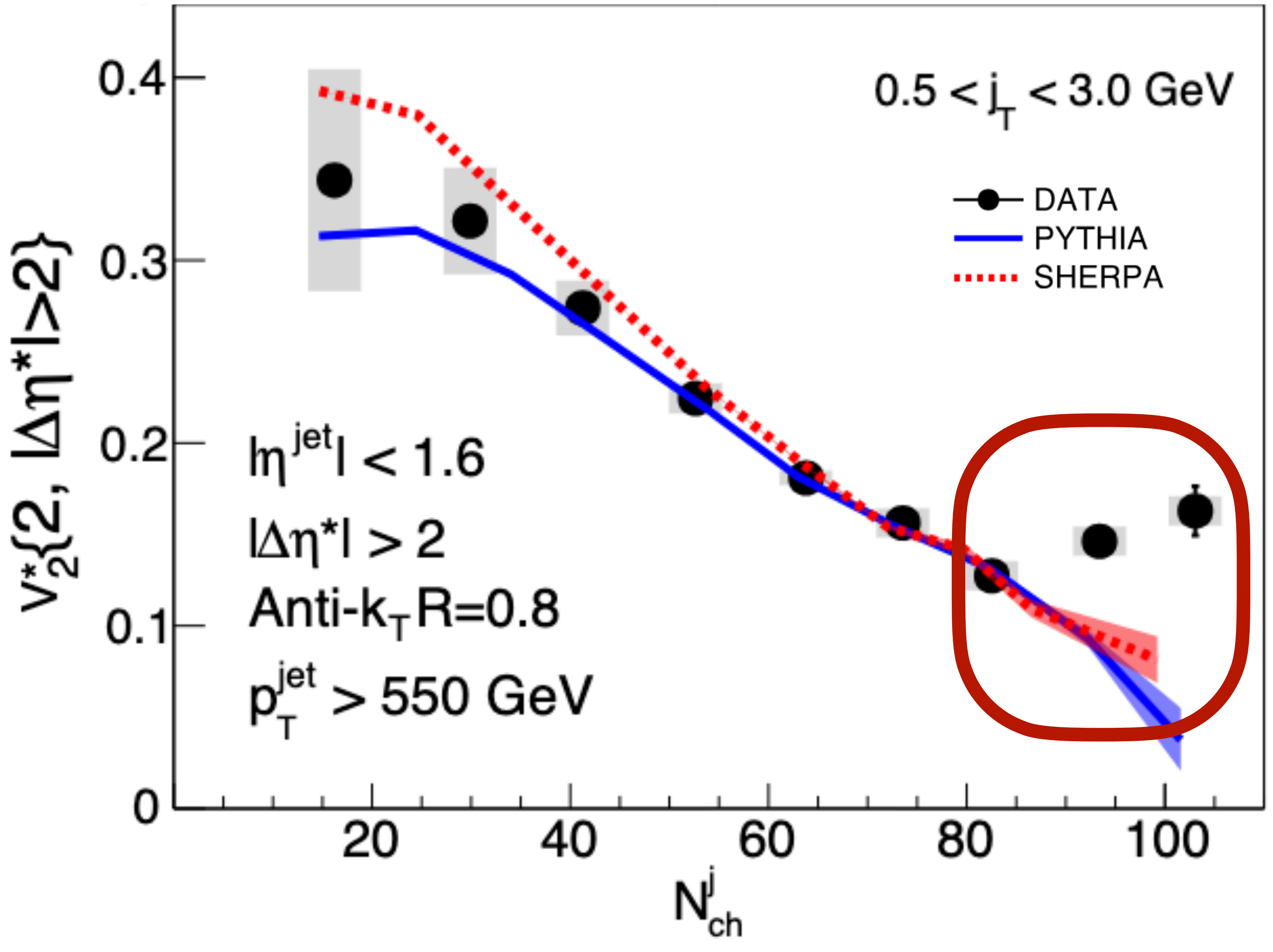
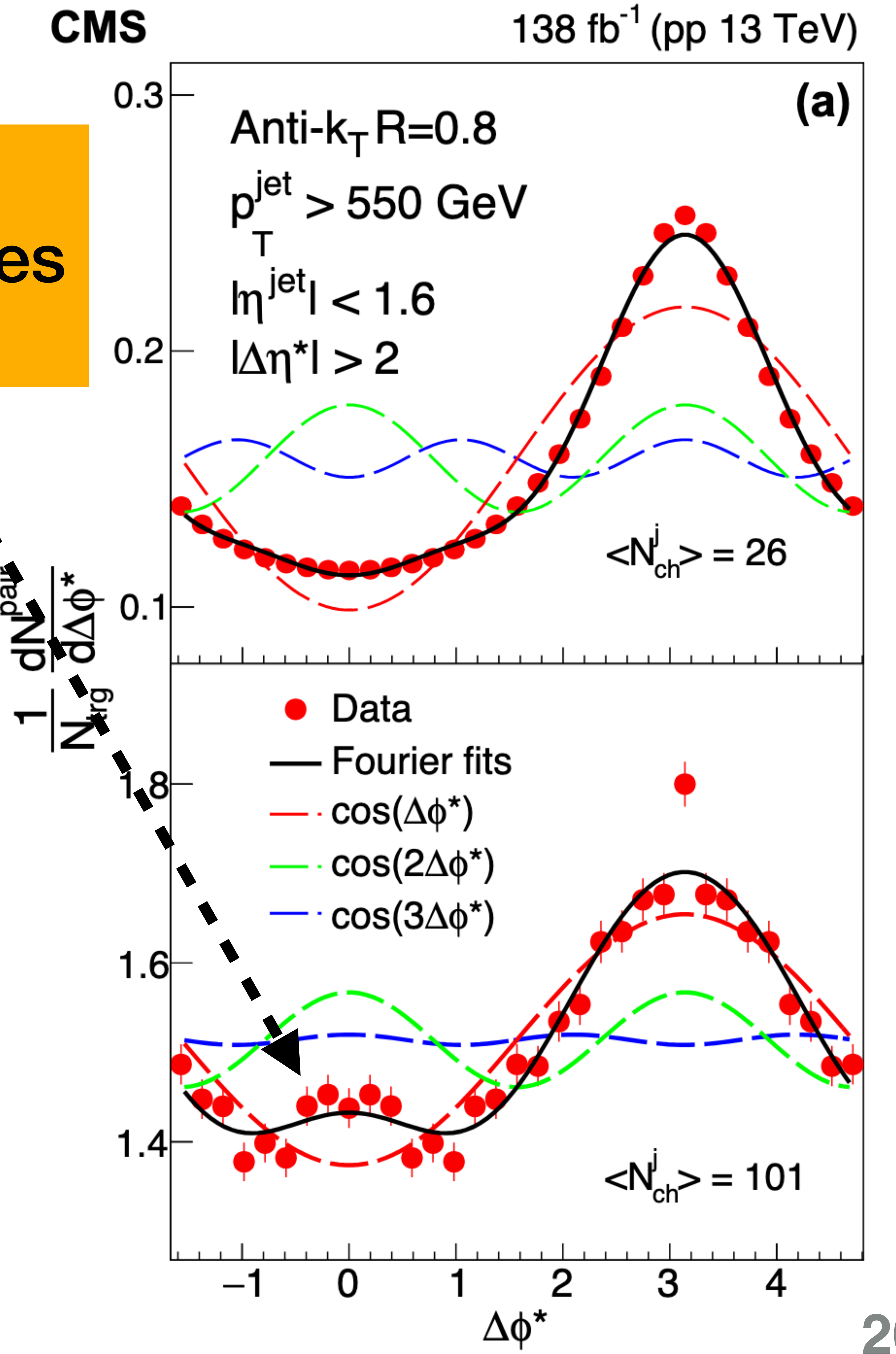



CMS, Phys. Rev. Lett. 133 (2024) 142301

**Ridge-like yield contribution from particles in very dense jets**

**long-range elliptic flow shows a distinct increase in data, indicating the onset of collective behavior**

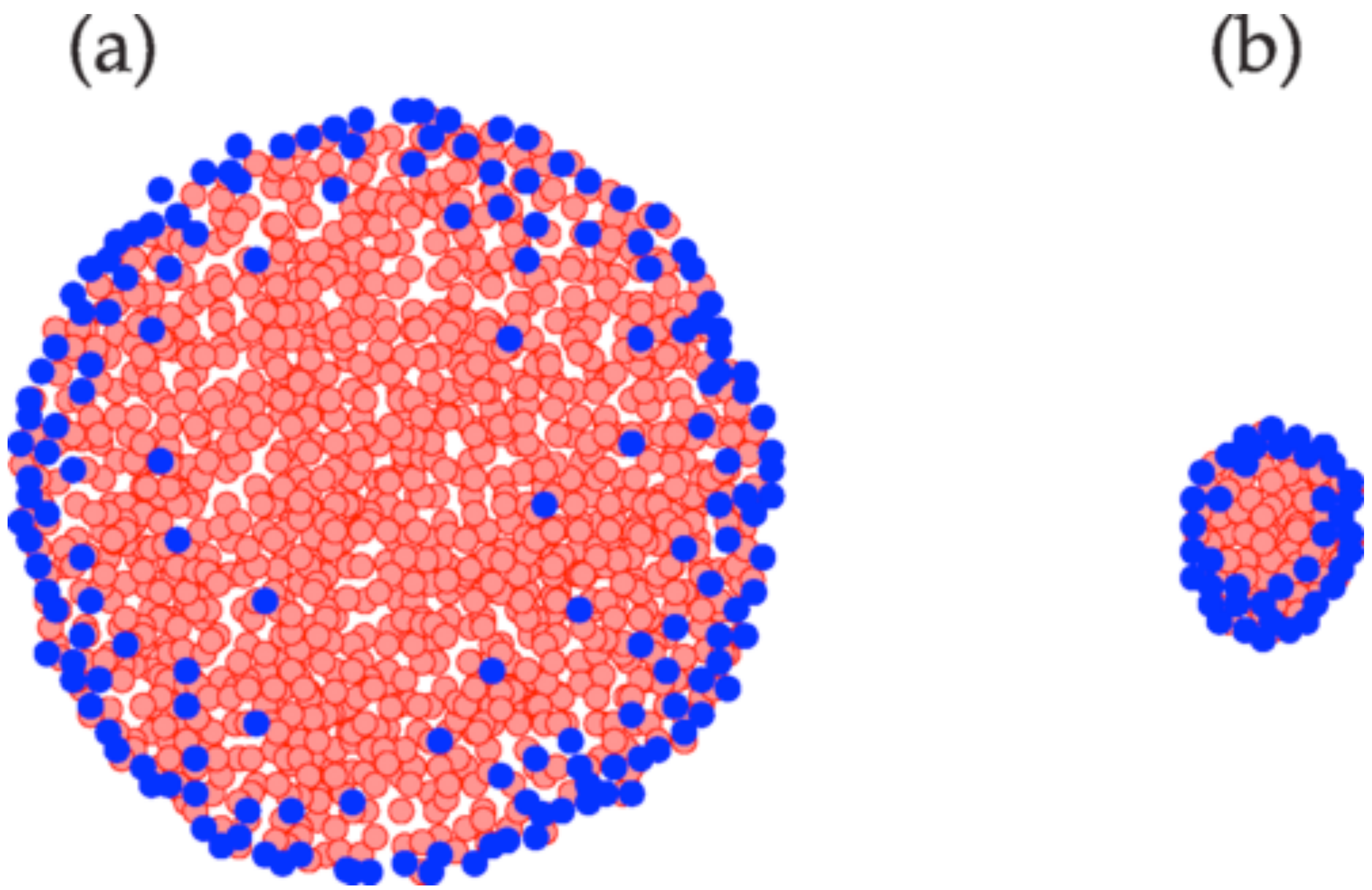


# Phenomenological interpretations

# Phenomenological models

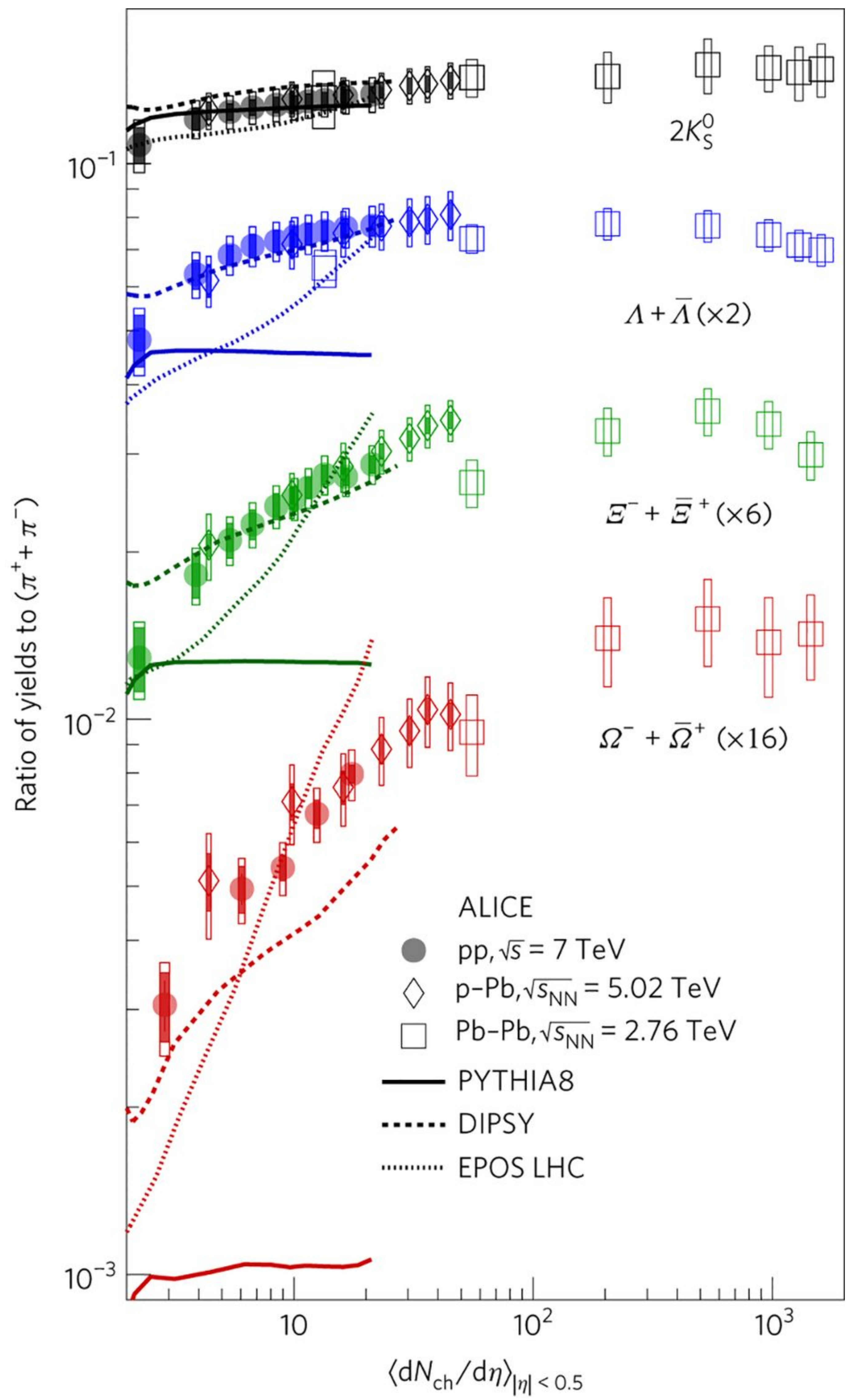
- Combining vacuum and collectivity in core-corona models: **EPOS** picture




Sketch of the core-corona separation for "big" and "small" systems.

The dots are prehadrons in the transverse plane; red refers to core, blue to corona.

K. Werner, Phys. Rev. C 108, 064903 (2023)

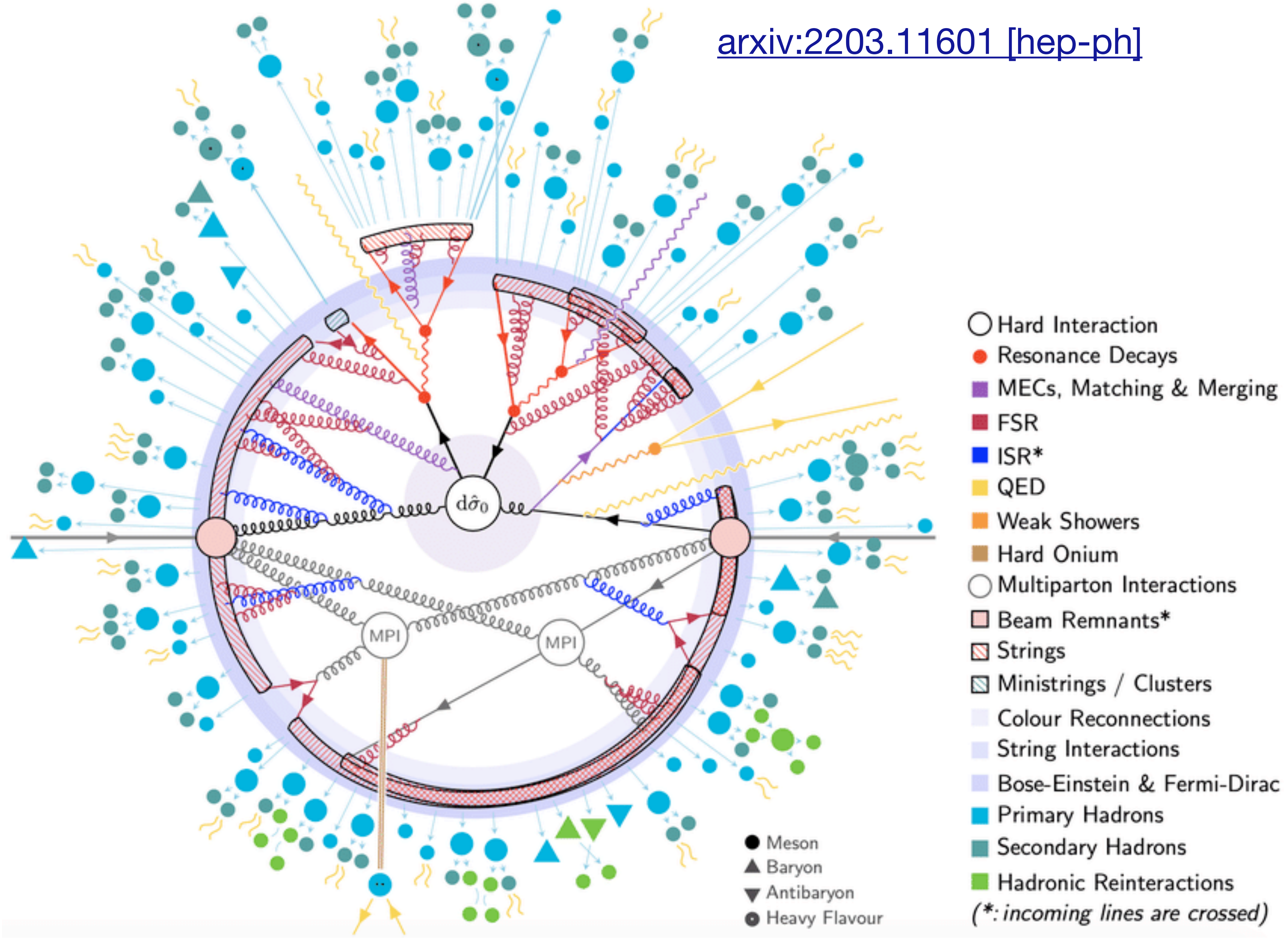


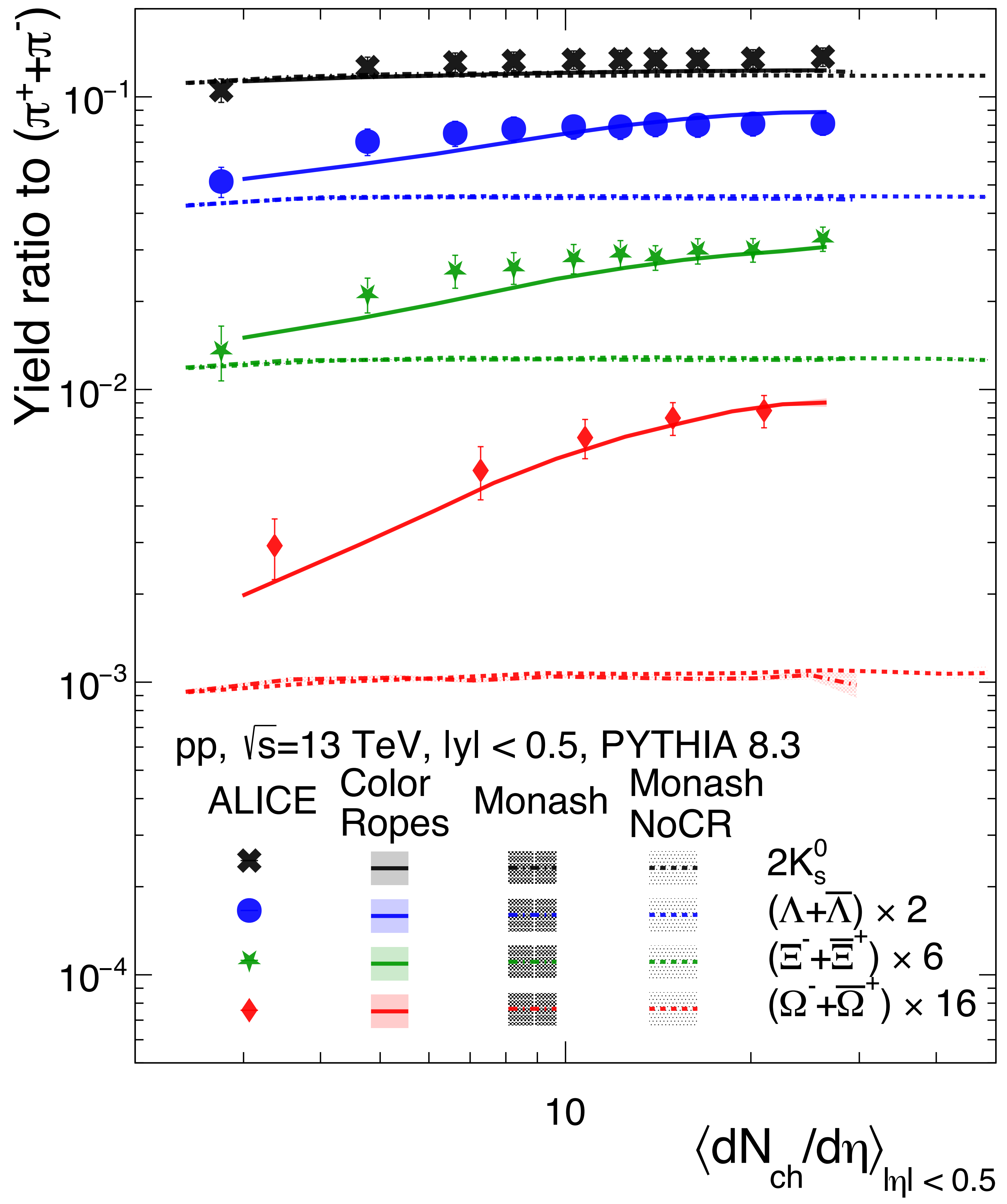

ALICE, Nature Phys 13, 535 (2017)

# Phenomenological models

- Combining vacuum and collectivity in core-corona models: **EPOS** picture
- Multiparton interactions, collective-like phenomena and enhanced strangeness production (color reconnection and ropes): **PYTHIA 8**

arxiv:2203.11601 [hep-ph]



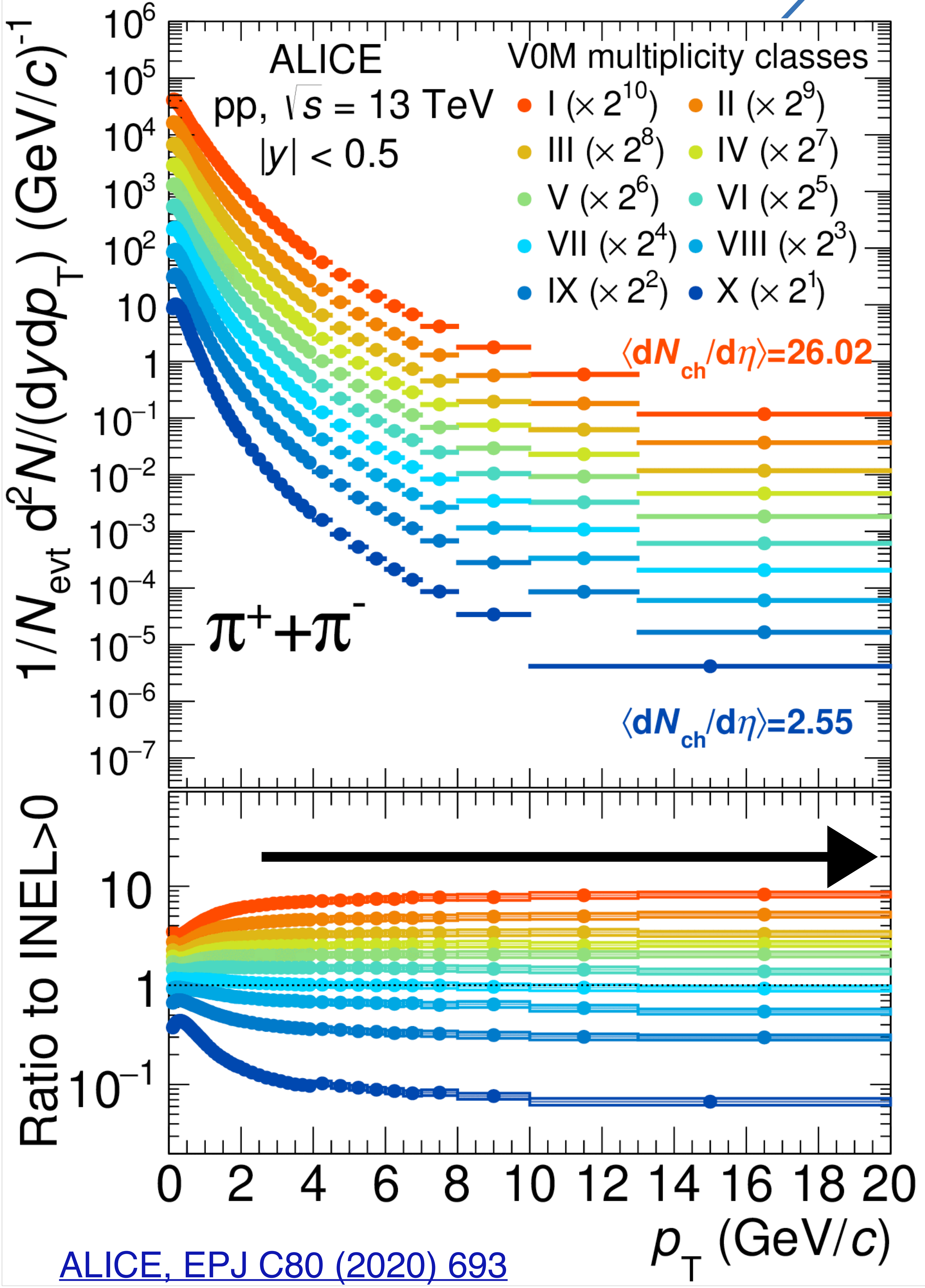




S. Prasad, B. Sahoo, **S. Tripathy**, N. Mallick and R. Sahoo, arxiv:2409.05454 [hep-ph] + paper in preparation

# A word on event classifiers

- Event classifiers based on multiplicity are sensitive to autocorrelation bias and biases on high-$p_T$ yield

**Adrian Fereydon Nassirpour, 15 Jan, 9:20**

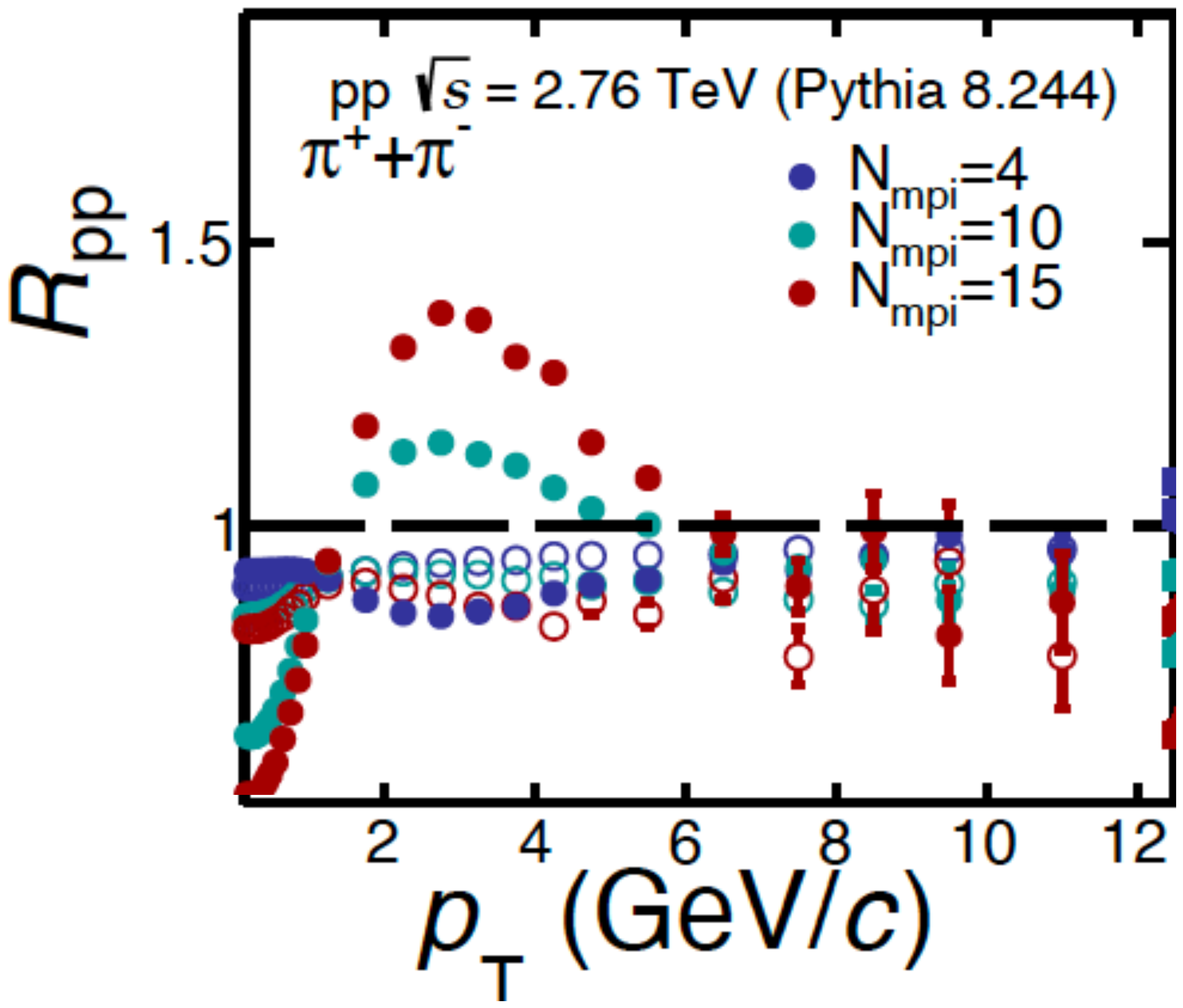



ALICE, EPJ C80 (2020) 693

# A word on event classifiers

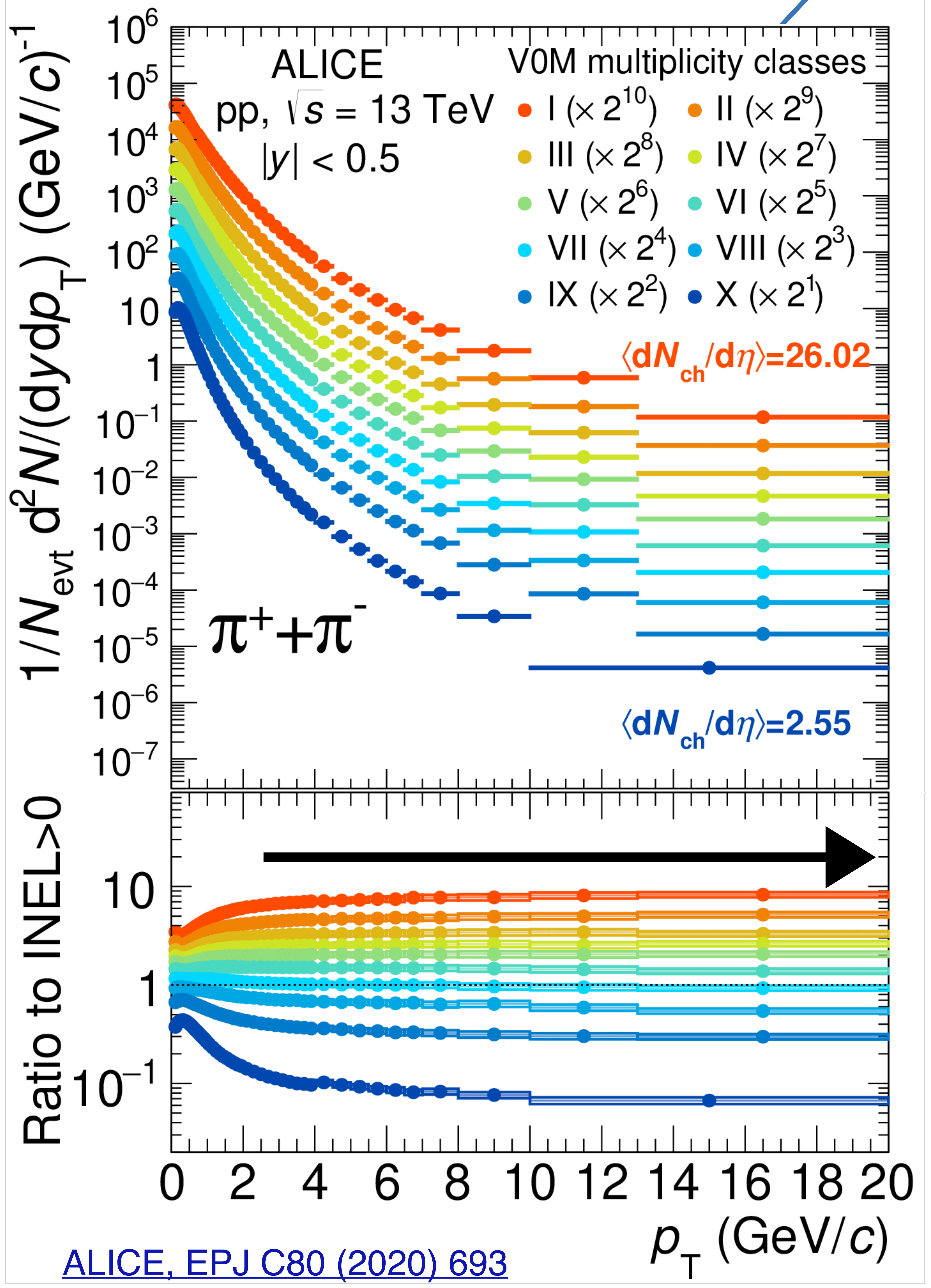
- Event classifiers based on multiplicity are sensitive to autocorrelation bias and biases on high-$p_T$ yield
- Number of multiparton interaction (MPI) selections does not bias the high-$p_T$ yield

A. Ortiz, A. Paz, J. D. Romo, **S. Tripathy**, et. al., Phys. Rev. D 102, 076014 (2020)




Ratio of yield in MPI-enhanced pp collisions to yield for minimum bias (MB) pp collisions:

$$R_{\mathrm{pp}} = \frac{\mathrm{d}^2 N_{\pi}^{\mathrm{mpi}} / (\langle \mathrm{N}_{\mathrm{mpi}} \rangle \mathrm{d}y \mathrm{d}p_{\mathrm{T}})}{\mathrm{d}^2 N_{\pi}^{\mathrm{MB}} / (\langle \mathrm{N}_{\mathrm{mpi,\,MB}} \rangle \mathrm{d}y \mathrm{d}p_{\mathrm{T}})}$$

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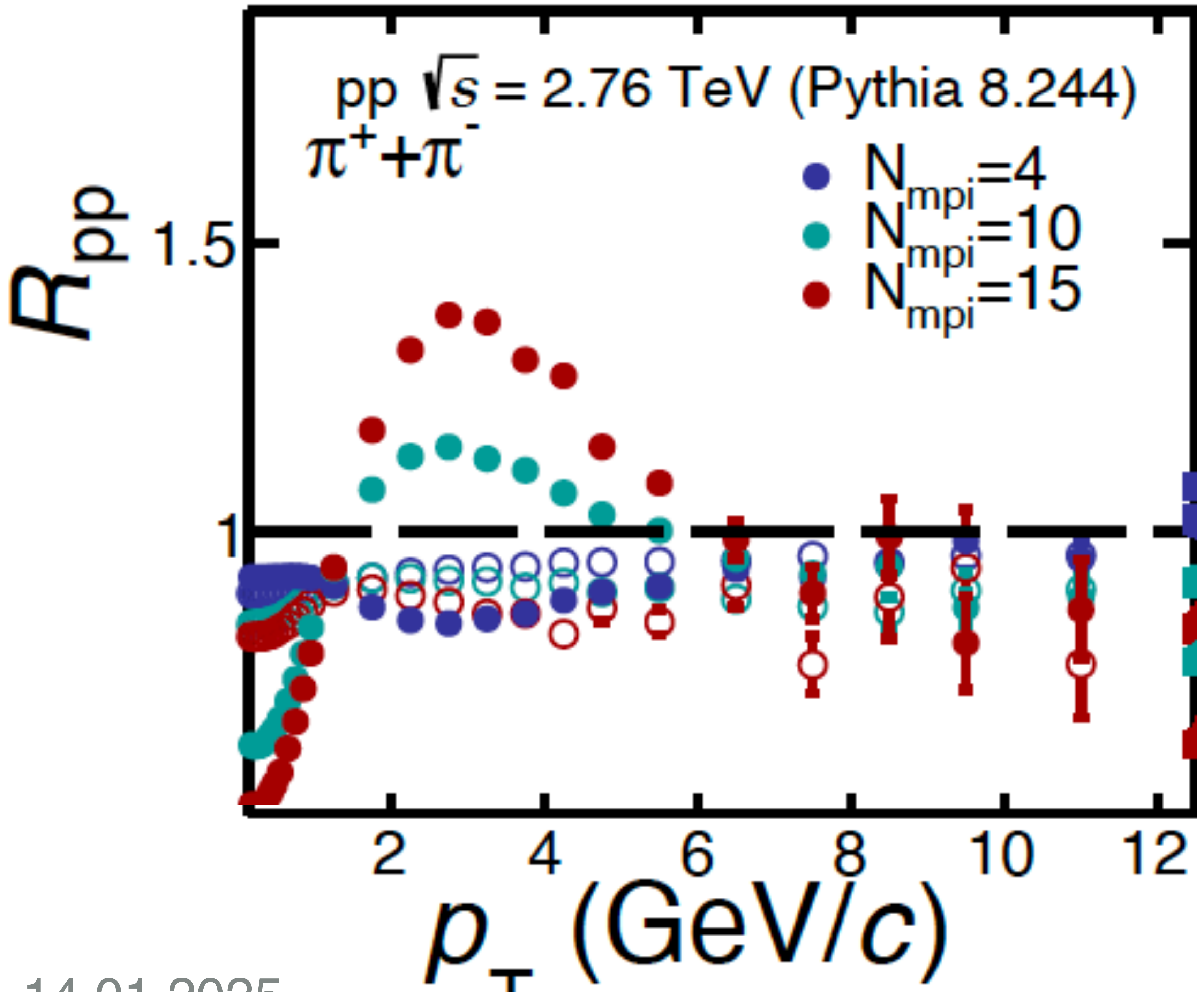


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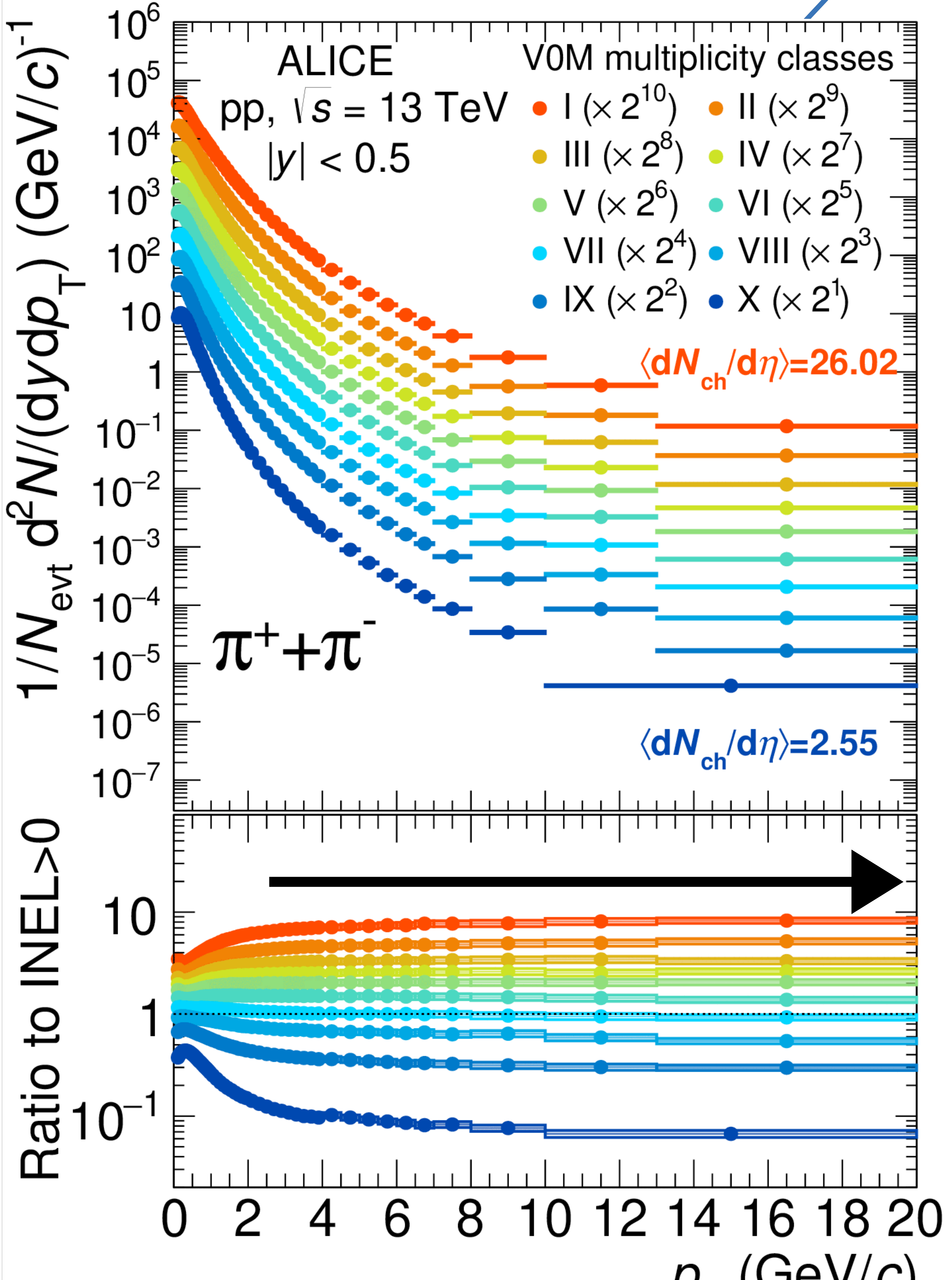
**One should explore event classifiers with sensitivity to MPI with reduced selection bias**




[ALICE, EPJ C80 (2020) 693]

# Event shape observables


- Event shape observables such as Spherocity, $R_T$ and Flattenicity are found to be highly sensitive to MPI with reduced selection bias
- They also have the advantage of separating isotropic and jet-like events

S. Prasad, B. Sahoo, **S. Tripathy**, N. Mallick and R. Sahoo, arxiv:2409.05454 [hep-ph] + paper in preparation

# Summary

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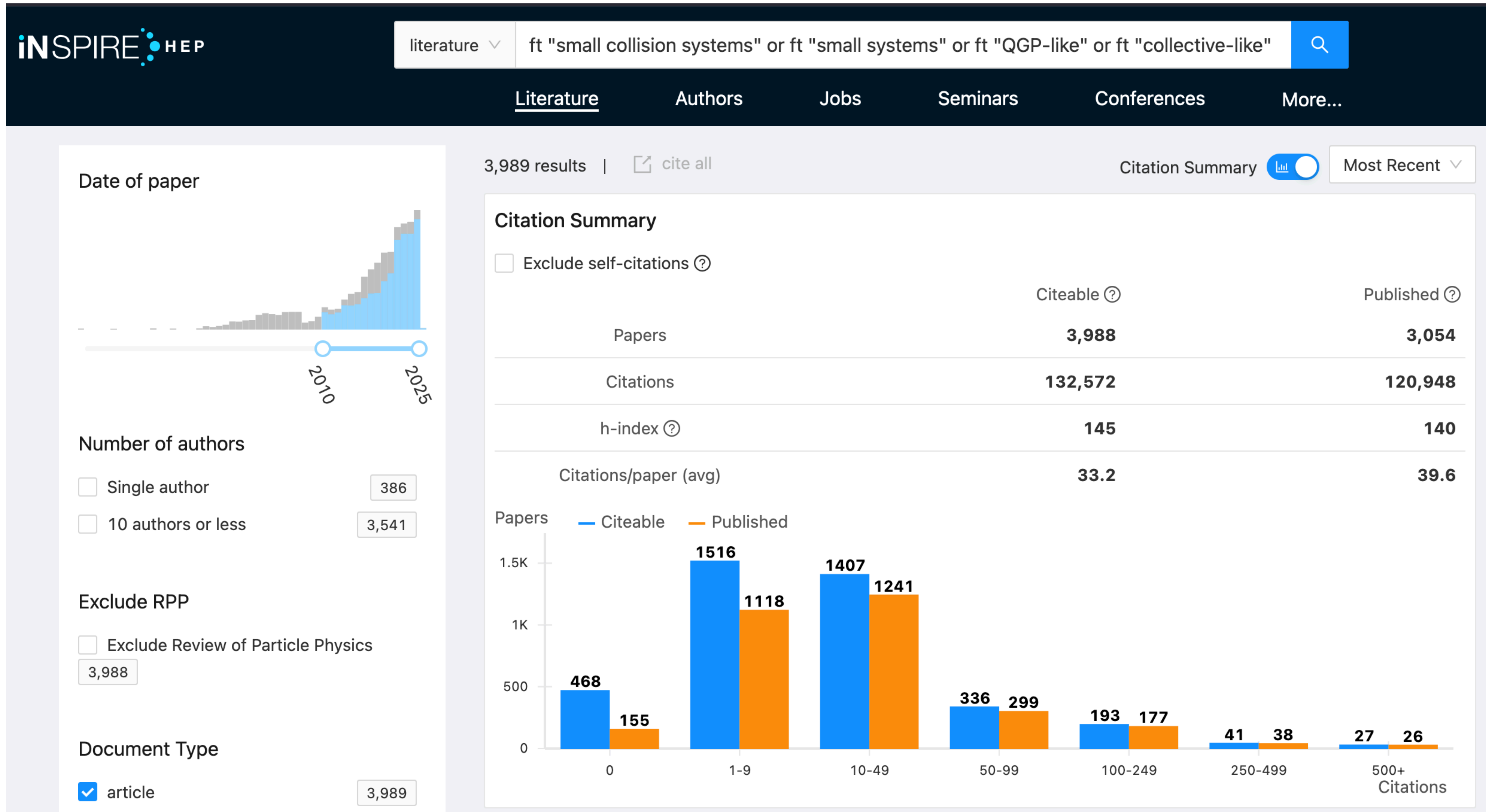

# Summary

- Run 1 + 2 of LHC and RHIC measurements have established heavy-ion collectivity.

- Small system discoveries at the LHC have opened up a new physics programme led to nearly 4000 publications in the last 15 years!

- Although pp collisions and dense heavy-ion collisions seem quite distinct, the similarities between these systems are quite striking, however, one must be cautious when applying concepts from one to the other

# Outlook

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Neelkamal Mallick, Parallel D, 15 Jan, 9:40

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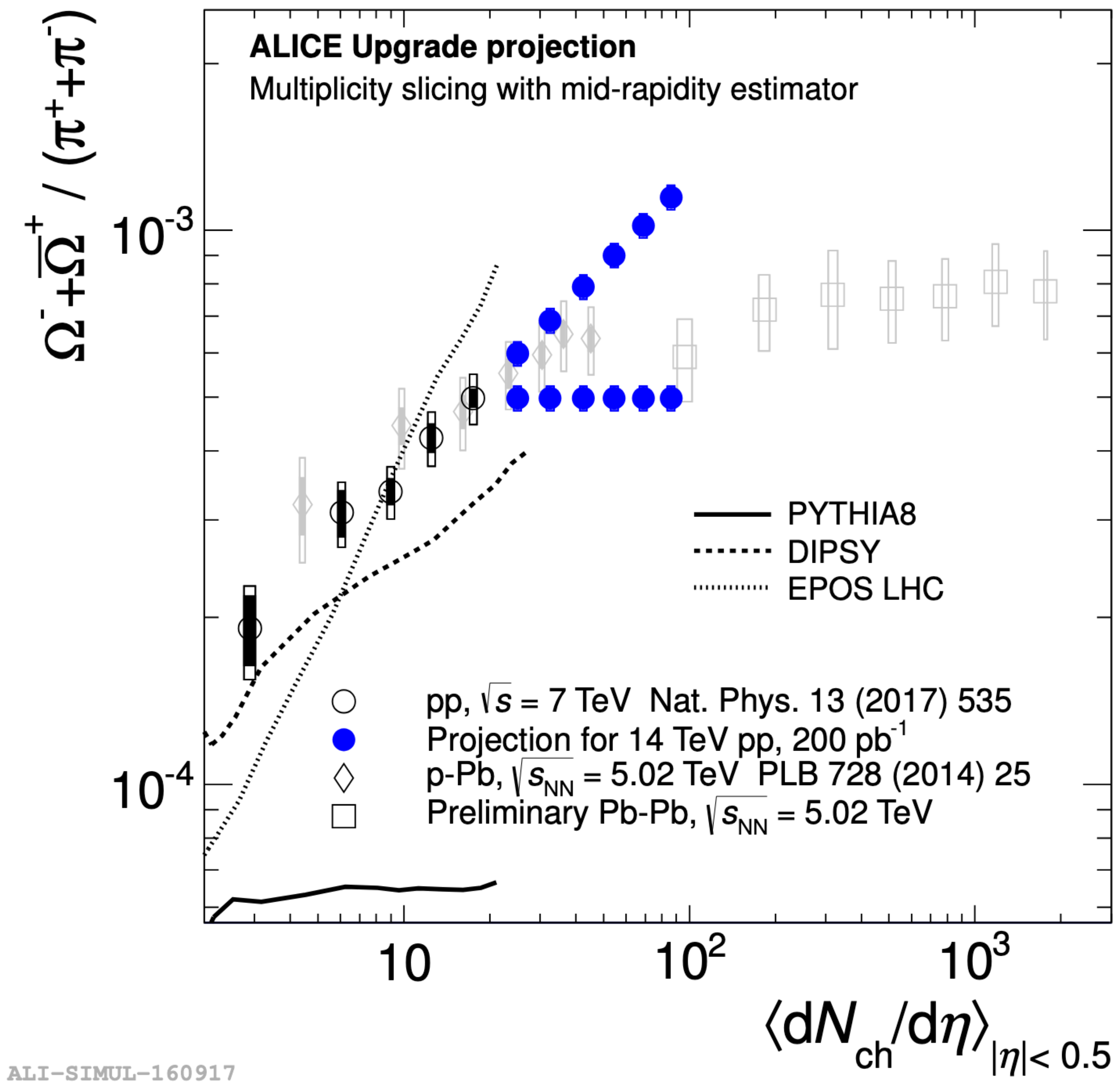


CERN Yellow Rep.Monogr. 7 (2019) 1159

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**Studying small systems has never been more exciting than it is now!!!**

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**Studying small systems has never been more exciting than it is now!!!**

Happy reading!

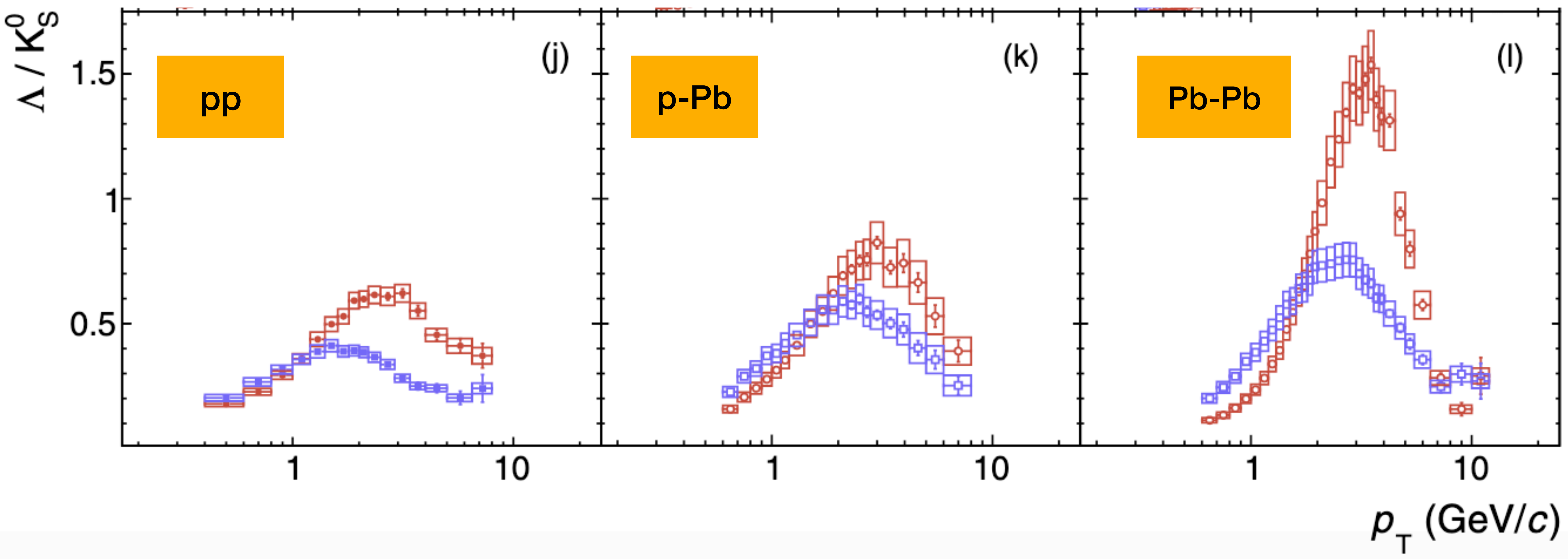

- *A Decade of Collectivity in Small Systems,* J. F. Grosse-Oetringhaus, U. A. Wiedemann, arXiv:2407.07484 [hep-ex]
- *Soft QCD Physics at the LHC: highlights and opportunities,* P. Christiansen, P. V. Mechelen, arXiv:2412.02672 [hep-ex]
- *Probing strangeness with event topology classifiers in pp collisions at the LHC,* S. Prasad, B. Sahoo, S. Tripathy, N. Mallick, R. Sahoo, arxiv:2409.05454 [hep-ph]
- *A review on event topology studies at the Large Hadron Collider,* S. Prasad, S. Tripathy, B. Sahoo, N. Mallick, R. Sahoo (in preparation)


**Thanks for your attention**

Email: sushanta.tripathy@cern.ch

# Backup

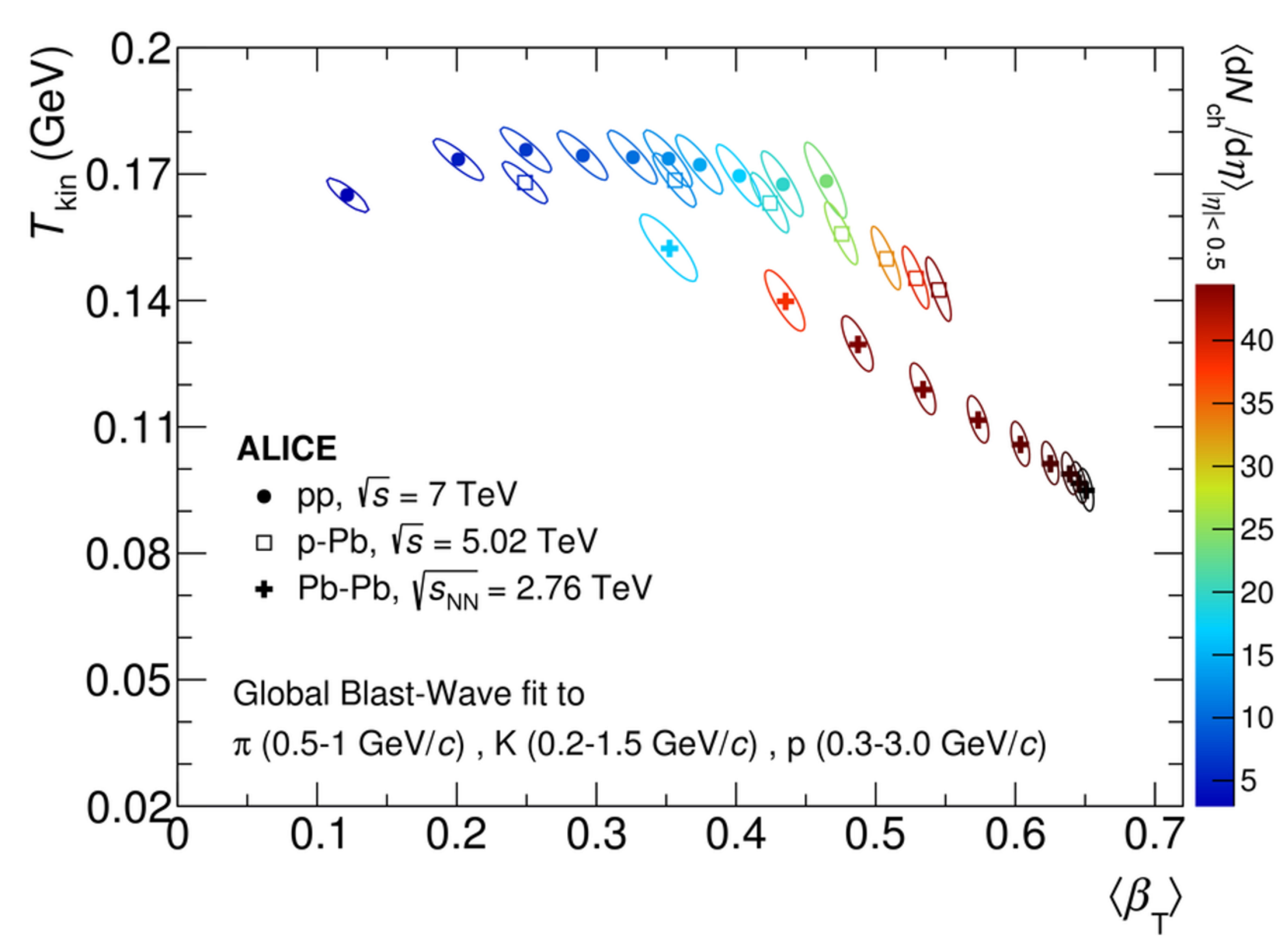
# Spectral shapes and particle ratios



# Spectral shapes vs multiplicity across collision systems

- Spectral shapes can be quantified based on the blast-wave model (simplified hydro model)
- describes π/K/p data in pp, p-Pb and Pb-Pb collisions: consistent with a common radial expansion of all particles

**At similar multiplicities, smaller collision systems' spectra seem harder (larger average expansion velocity).**



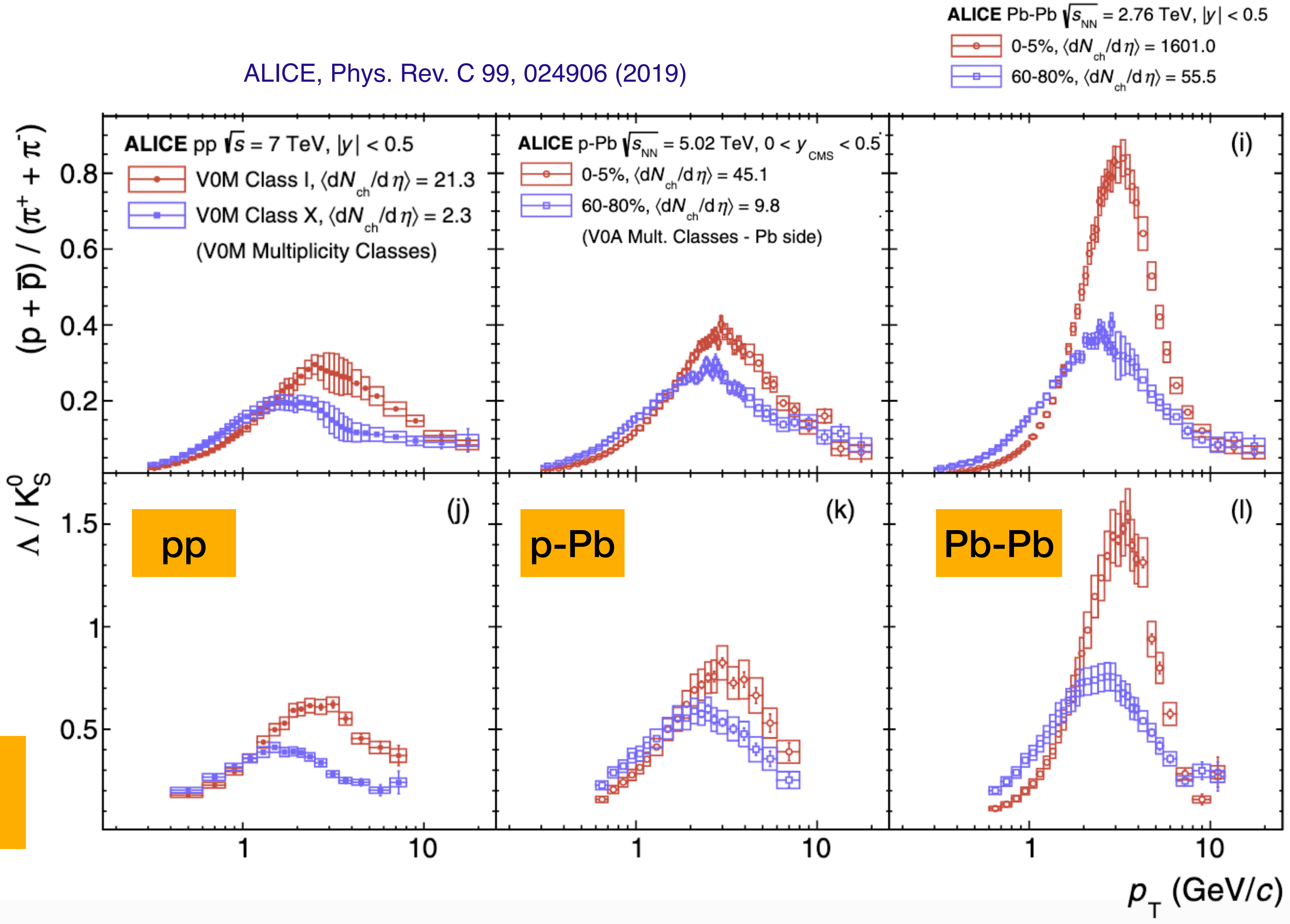
# Baryon to meson ratios across collision systems

- A characteristic depletion of baryon to meson ratios at $p_T \sim 0.7$ GeV/c and an enhancement at intermediate $p_T$ is observed

- Qualitatively similar behaviour is observed across collision systems

**Similar features of baryon to meson ratios in pp, p-Pb and Pb-Pb collisions**

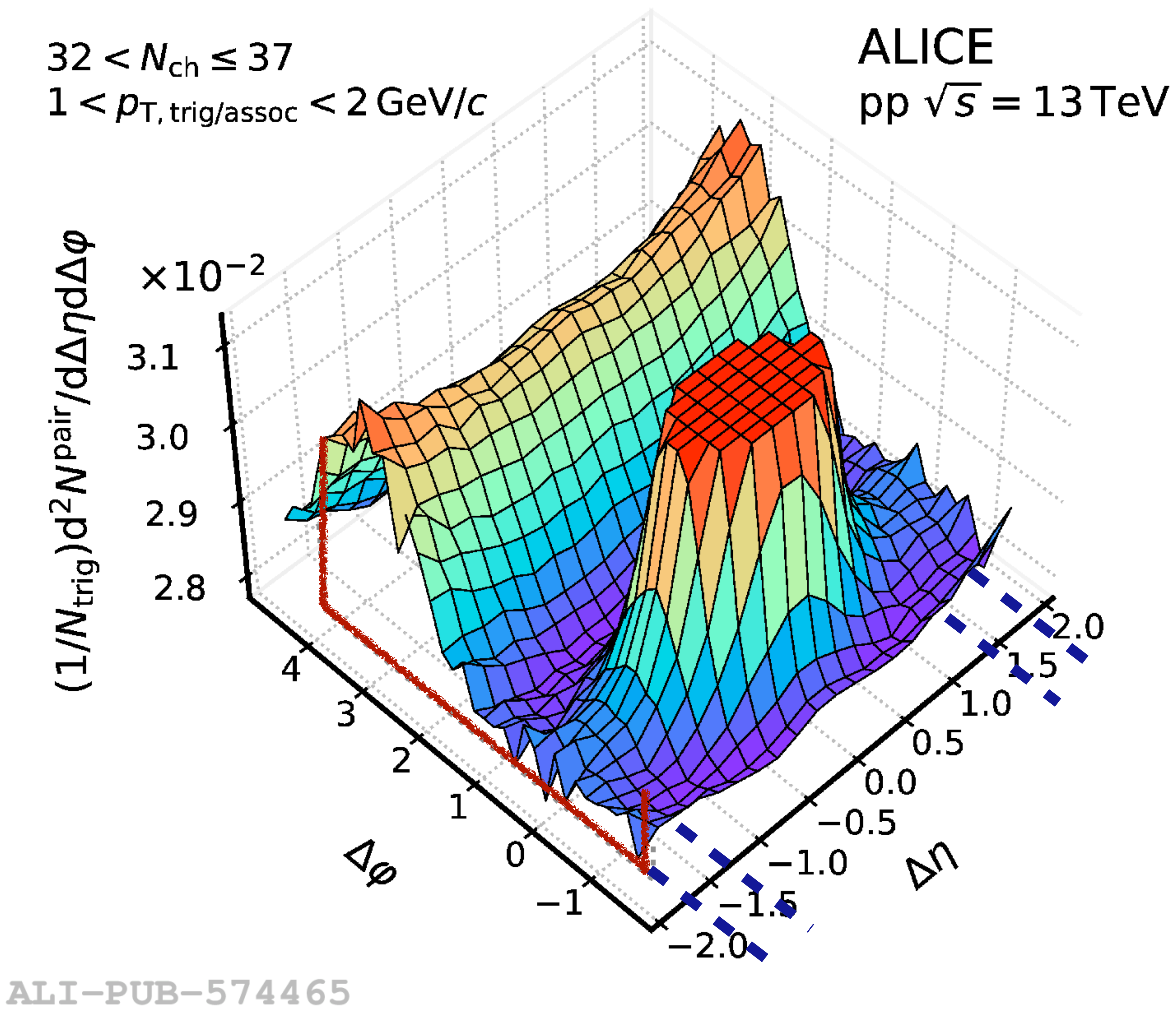
ALICE, Phys. Rev. C 99, 024906 (2019)



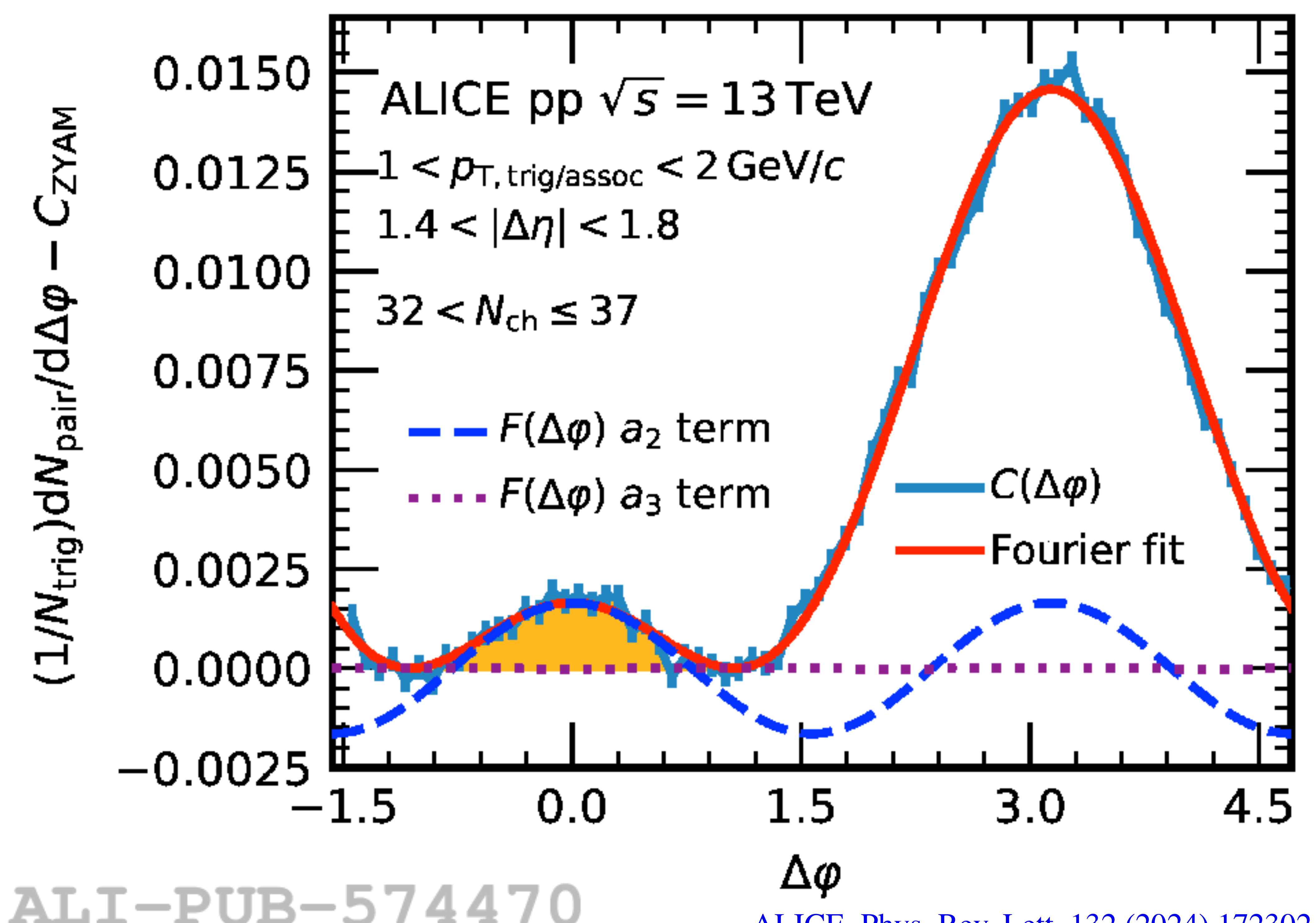
# Phenomenological models

- Combining vacuum and collectivity in core-corona models: **EPOS** picture
- Microscopic string interactions and hadronisation beyond leading color (color reconnection): **PYTHIA 8**
- Collective-like phenomena and enhanced strangeness production (color ropes): **PYTHIA 8.3**
- Kinetic theory and transport models: **AMPT**
- **Coalescence**: partons in similar phase space coalesce to form hadrons
- **Statistical hadronisation models**: ideal gas of hadrons in thermal and chemical equilibrium

# Long-range correlations in low multiplicity



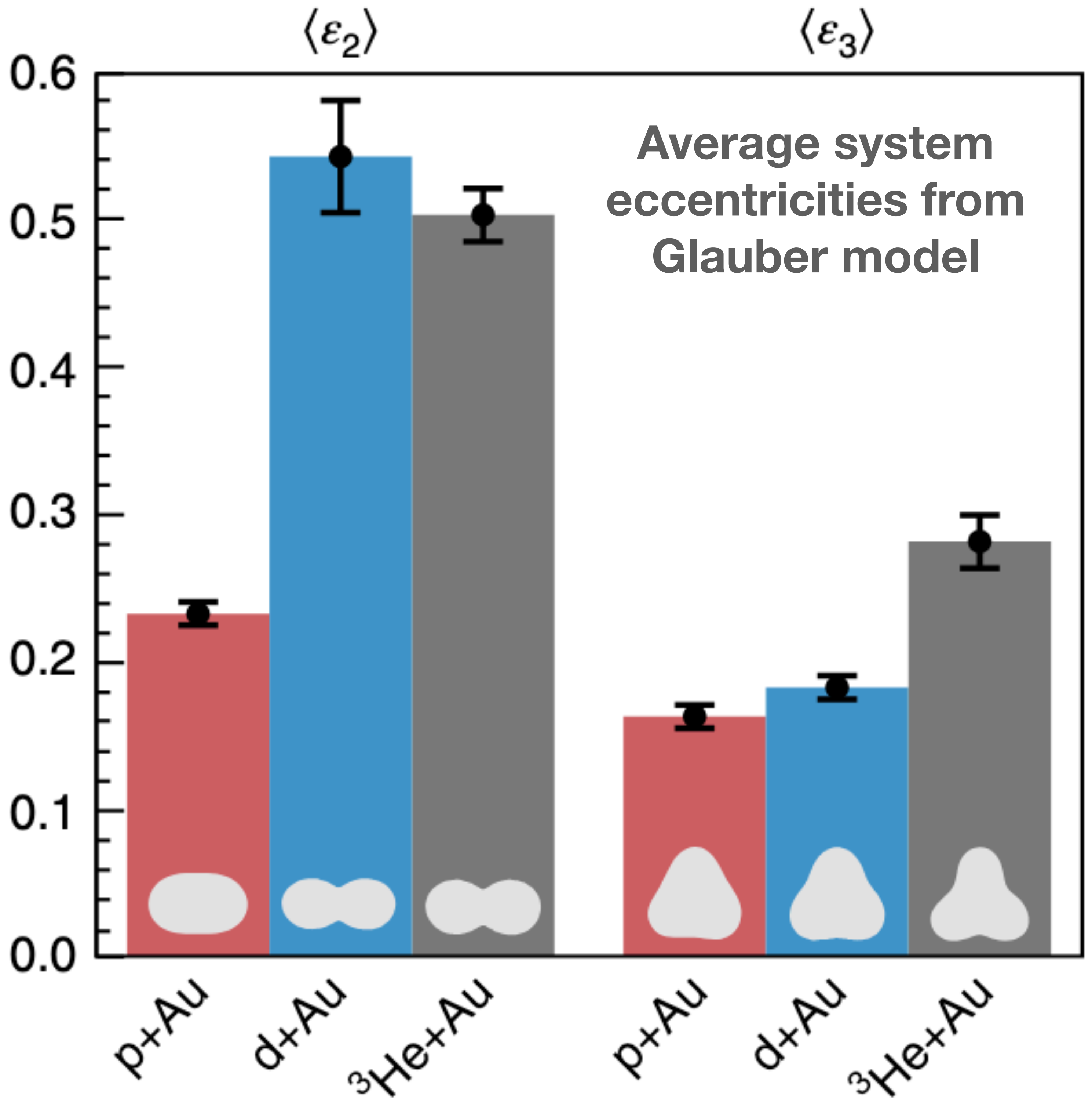

Projection in $\Delta\varphi$




ALICE, Phys. Rev. Lett. 132 (2024) 172302

- Near-side ridge clearly visible in high-multiplicity events - 1D projection of $\Delta\varphi$ is taken in the range of $1.4 < |\Delta\eta| < 1.8$ to suppress short-range nonflow correlations.
- 1D distribution is fitted with $F(\Delta\varphi) = A(1 + 2\Sigma_{n=1}^{3} v_n^2 \cos(n\Delta\varphi)) + C_{ZYAM}$ and the near-side ridge yield is obtained.

# Three distinct geometries: p+Au, d+Au, ³He+Au



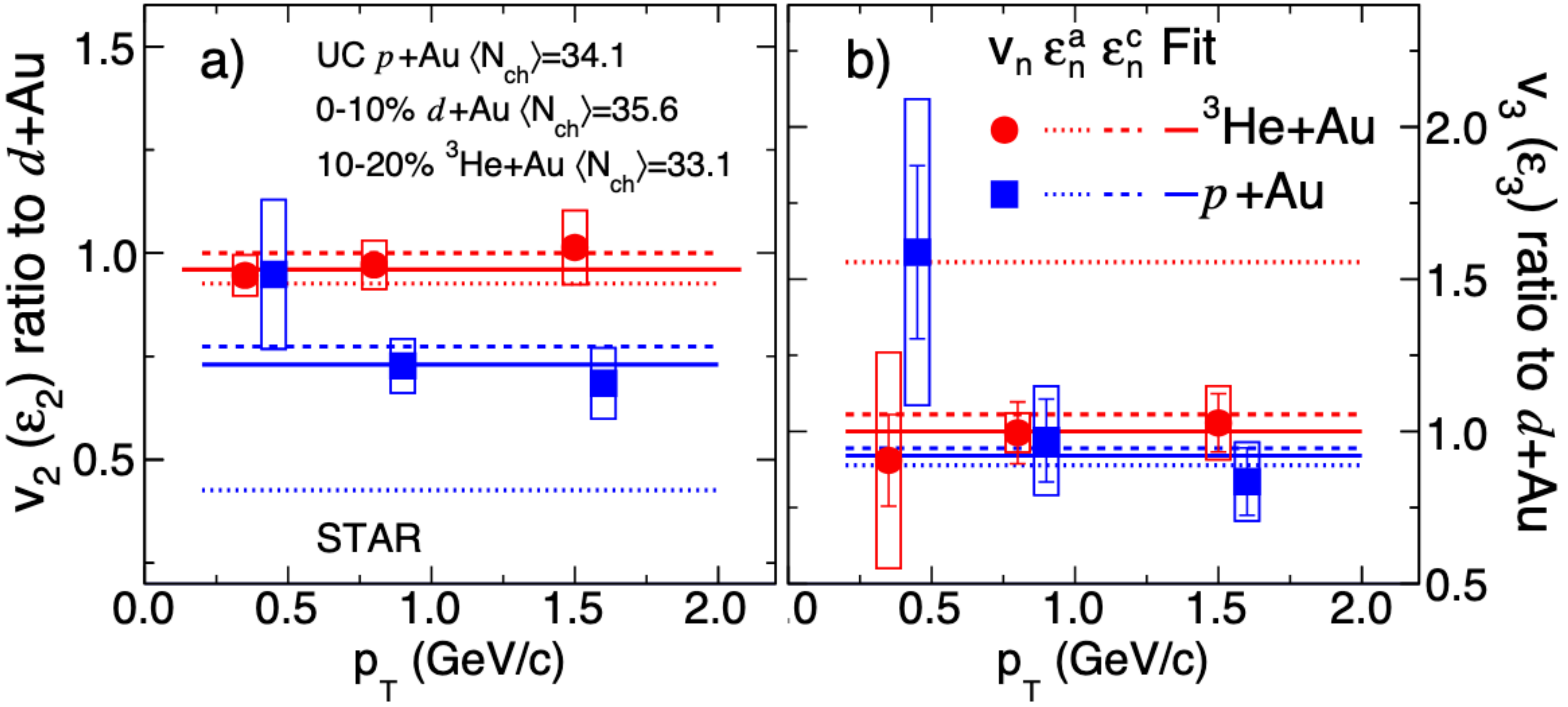

PHENIX, Nature Phys. 15 (2019) 3, 214-220
STAR, Phys. Rev. Lett.,130(24), 242301, 2023

If the origin is purely from hydrodynamics:

$$v_2^{\text{p+Au}} < v_2^{\text{d+Au}} \simeq v_2^{^3\text{He+Au}}$$
$$v_3^{\text{p+Au}} \simeq v_3^{\text{d+Au}} < v_3^{^3\text{He+Au}}$$

**STAR** measures something different:

$$v_2^{\text{p+Au}} < v_2^{\text{d+Au}} \simeq v_2^{^3\text{He+Au}}$$
$$v_3^{\text{p+Au}} \simeq v_3^{\text{d+Au}} \simeq v_3^{^3\text{He+Au}}$$



# Measurement in Pb-Pb collisions

Same event

$$\frac{1}{N_{\rm trig}}\frac{d^2N_{\rm assoc}}{d\Delta\eta d\Delta\varphi} = \frac{S(\Delta\eta,\Delta\varphi)}{B(\Delta\eta,\Delta\varphi)}$$

Signal

$S(\Delta\eta,\Delta\varphi) \rightarrow$ associated yield per trigger particle for particle pairs from the same event

$$S(\Delta\eta,\Delta\varphi) = \frac{1}{N_{\rm trig}}\frac{d^2N_{\rm same}}{d\Delta\eta d\Delta\varphi}$$

Mixed event

$B(\Delta\eta,\Delta\varphi) \rightarrow$ background distribution accounts for the acceptance and efficiency of pair reconstruction

$$B(\Delta\eta,\Delta\varphi) = \alpha \times \frac{1}{N_{\rm trig}}\frac{d^2N_{\rm mixed}}{d\Delta\eta d\Delta\varphi}$$

- 5 events are mixed
- scaled by a factor ($\alpha$) which is chosen such that B(0,0) is unity for pairs where both particles travel in approximately the same direction, and thus the efficiency and acceptance for the two particles are identical by construction