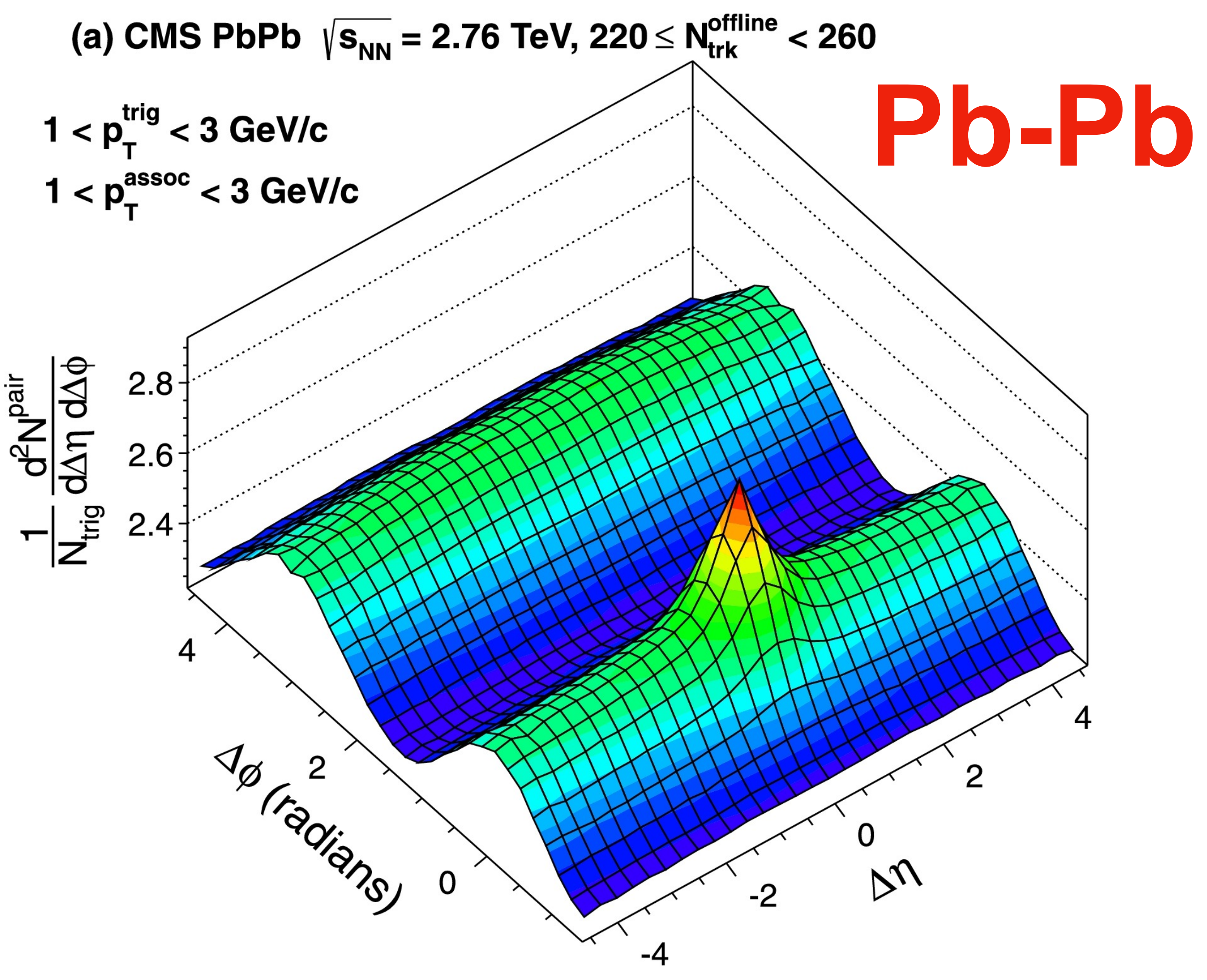
Experimental highlights on collectivity in small collision systems

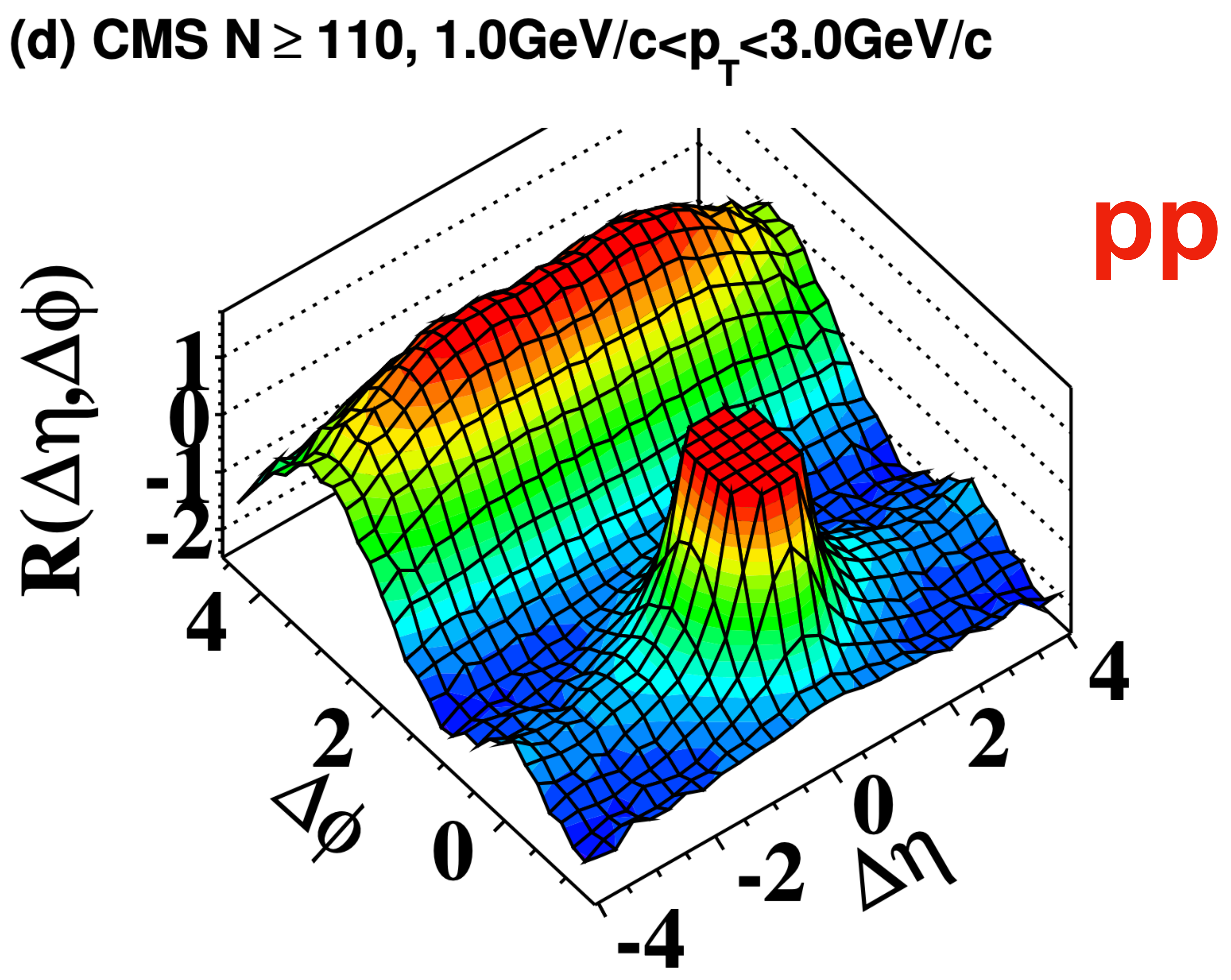
Alberto Calivà
University of Salerno and INFN

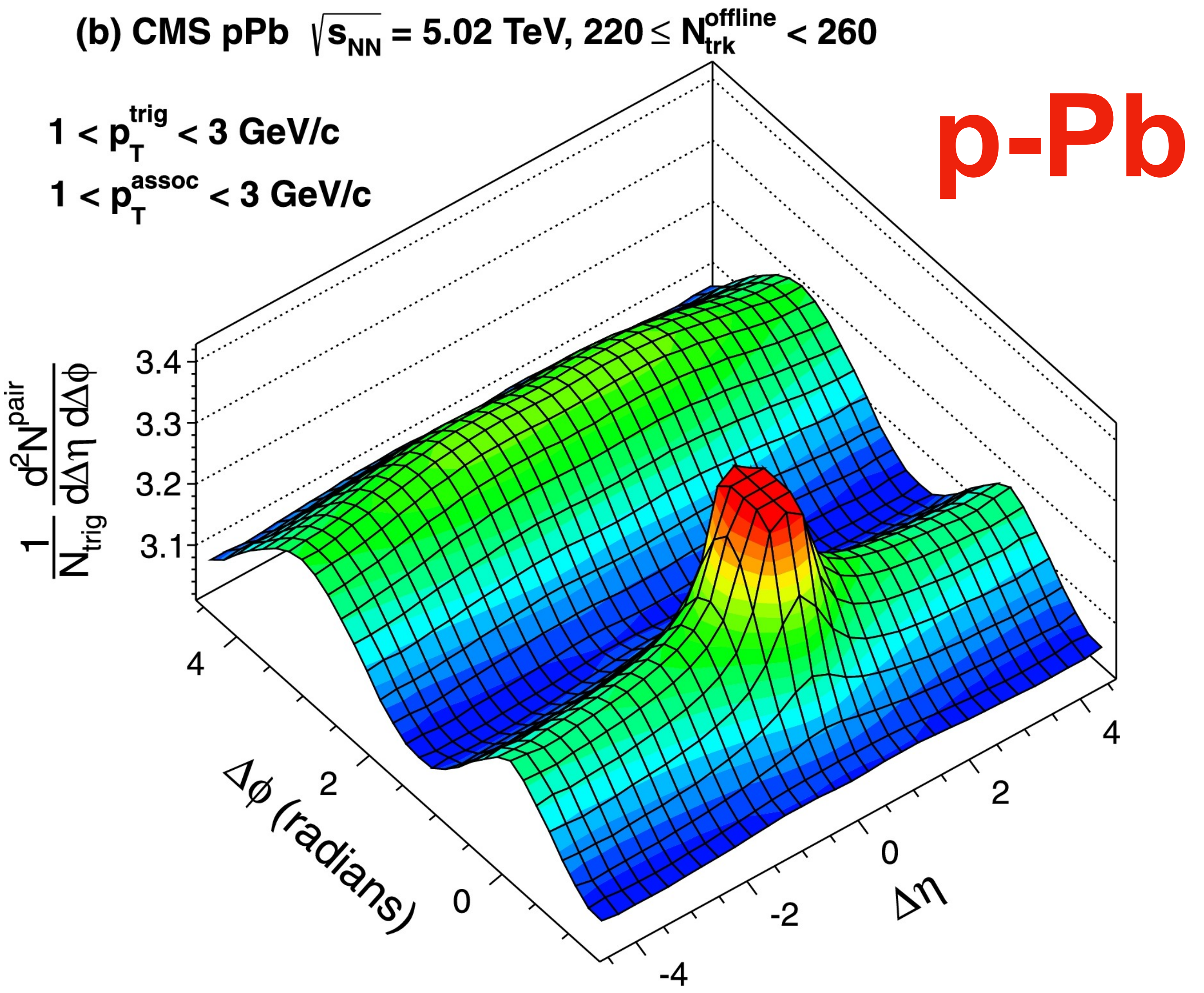
University of Salerno

INFN
Istituto Nazionale di Fisica Nucleare
SEZIONE DI NAPOLI
Gruppo Collegato di Salerno

Introduction







Long-range correlations in AA collisions typically attributed to the collective expansion of a strongly-interacting medium

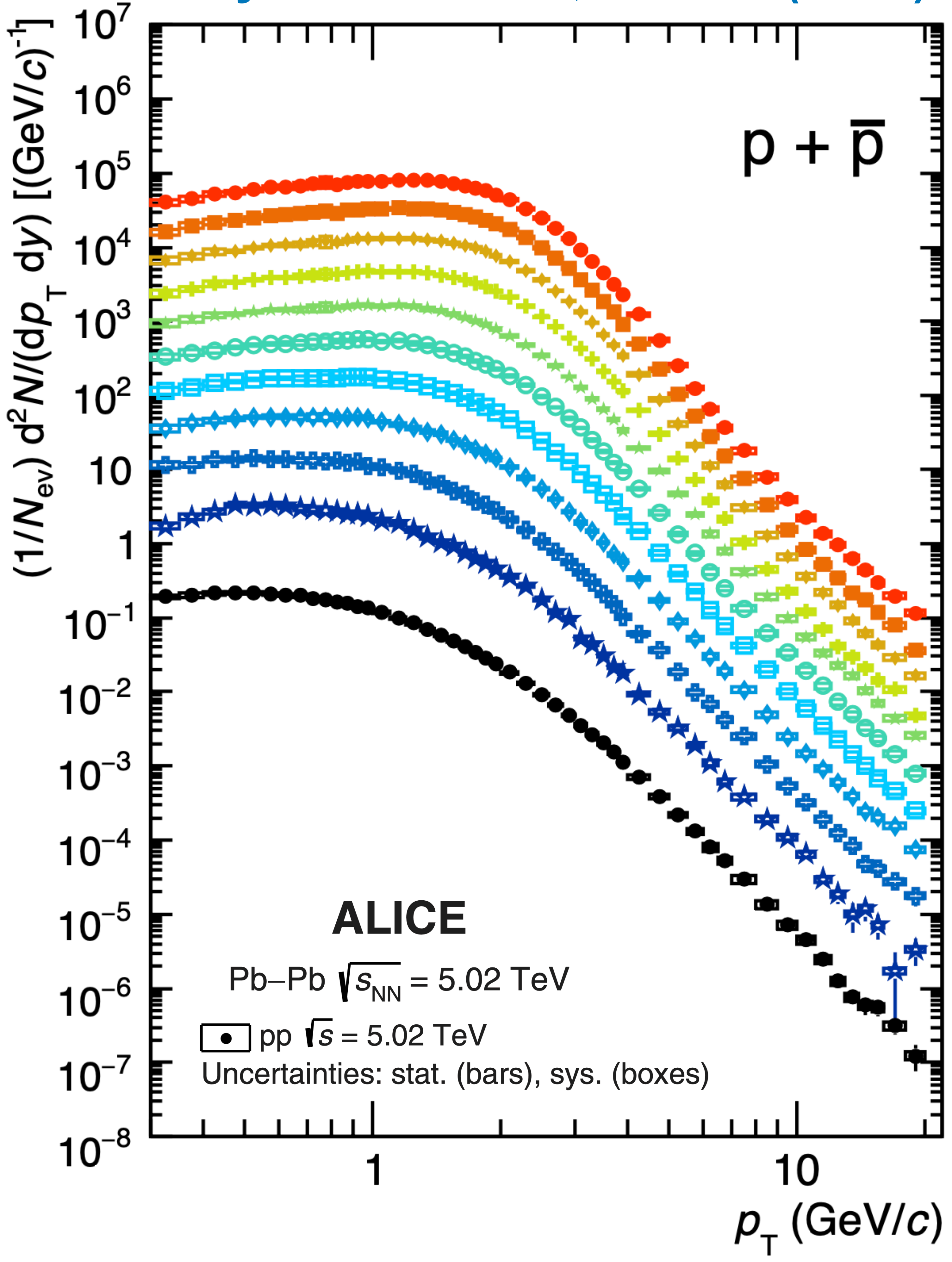
Remarkable similarities observed in high-multiplicity pp and p-Pb collisions

Phys. Lett. B 724 (2013) 213-240

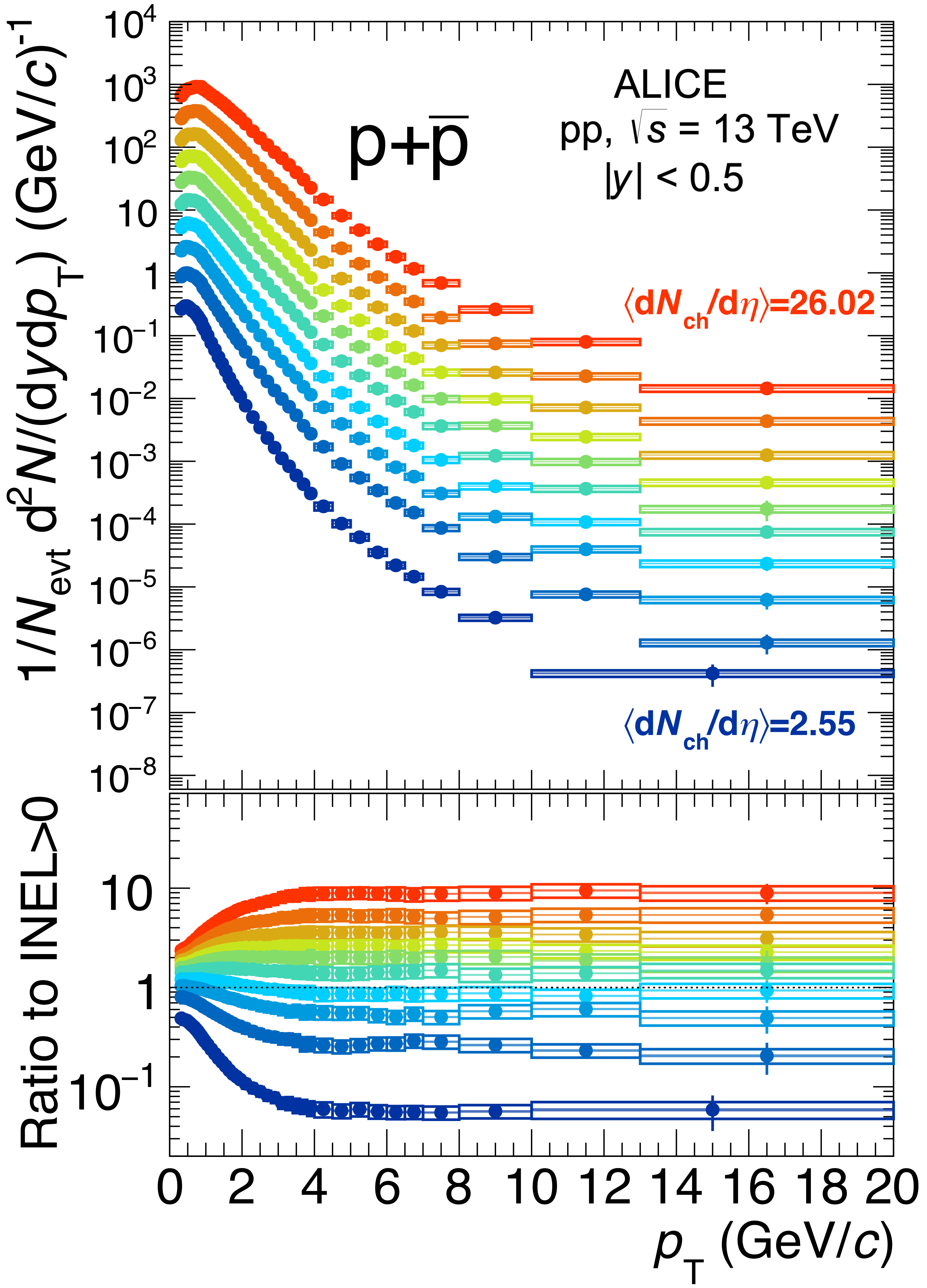
JHEP 1009 (2010) 091

Radial flow

Phys. Rev. C 101, 044907 (2020)



Eur. Phys. J. C 80 (2020) 693



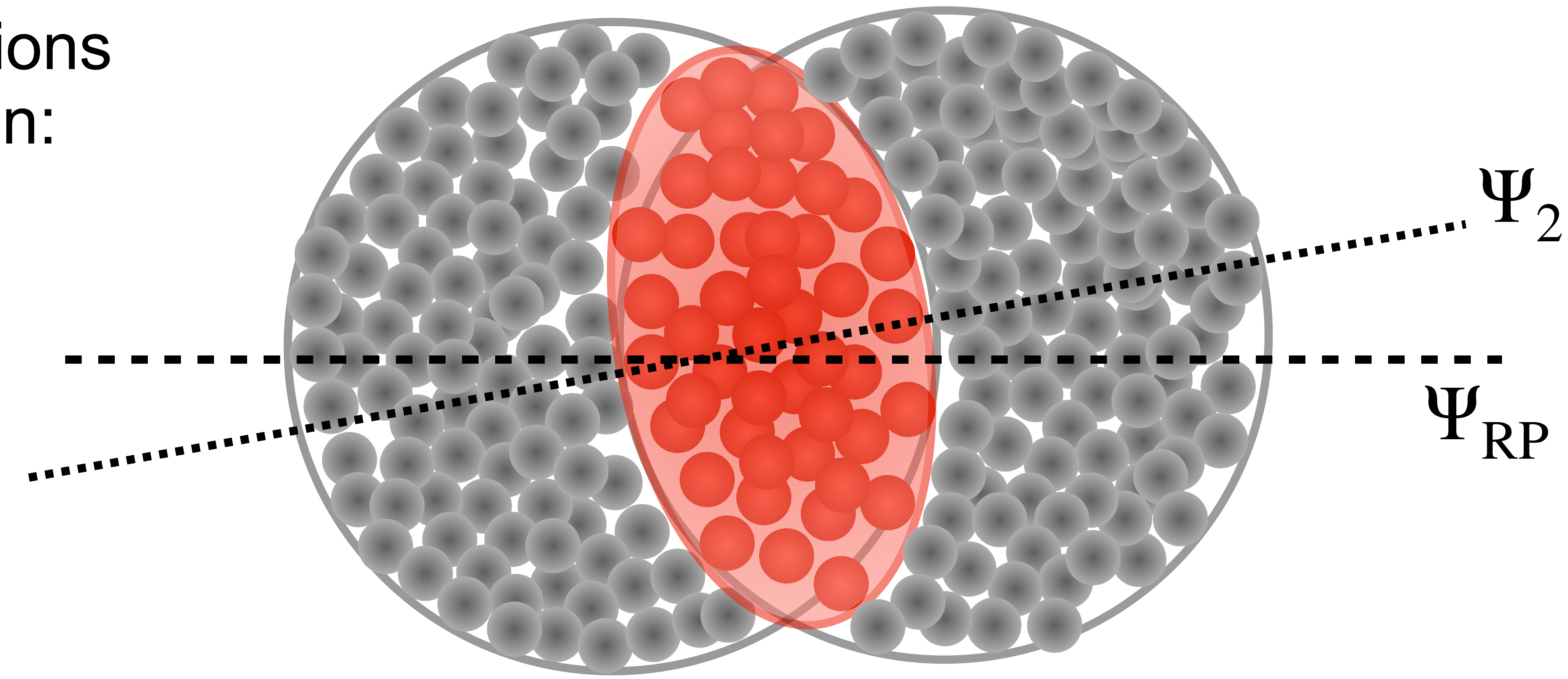
Effect of radial flow in AA collisions: hardening of p_T spectra and shift of the maximum

→ observed also in pp collisions with increasing multiplicity

Elliptic flow: hydro

Initial geometrical asymmetry of non-central collisions results in azimuthal asymmetry of particle emission:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))\right]$$



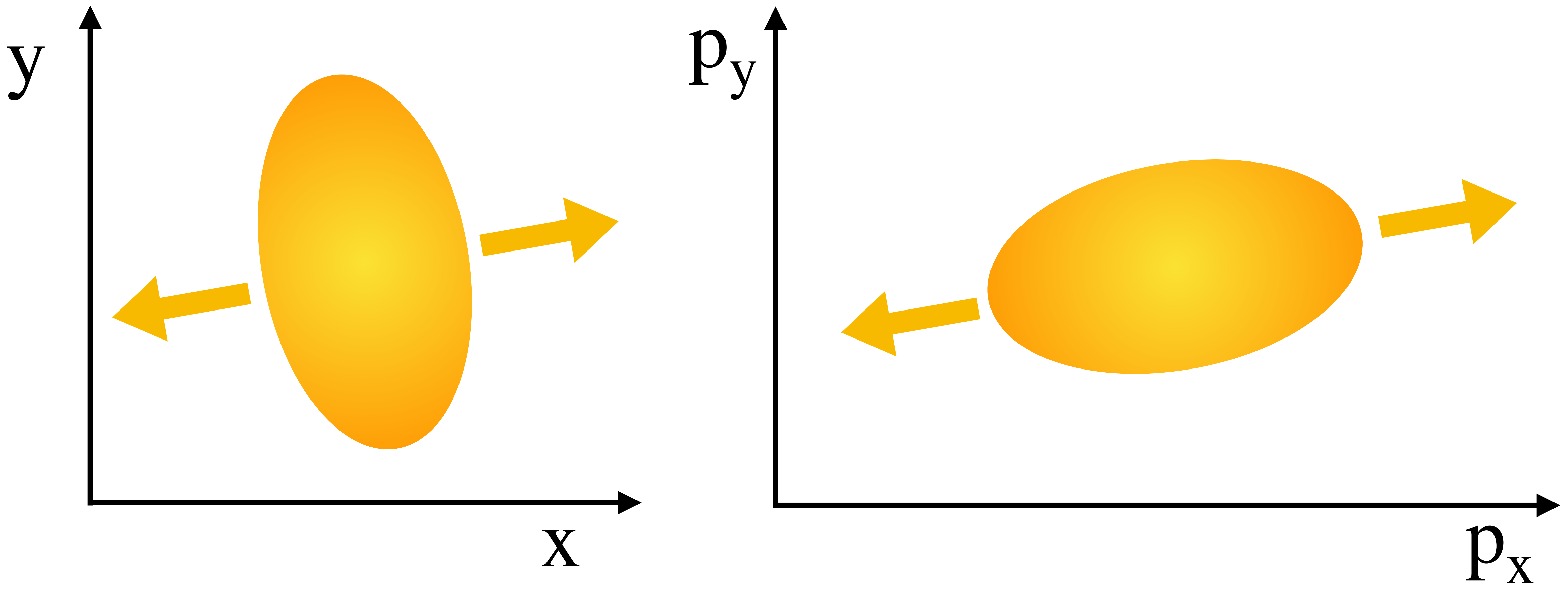
The second harmonic is the **elliptic flow**

$$v_2 = <\cos(2(\phi - \Psi_2))>$$

connected to initial state eccentricity

$$\epsilon = <\frac{x^2 - y^2}{x^2 + y^2}>$$

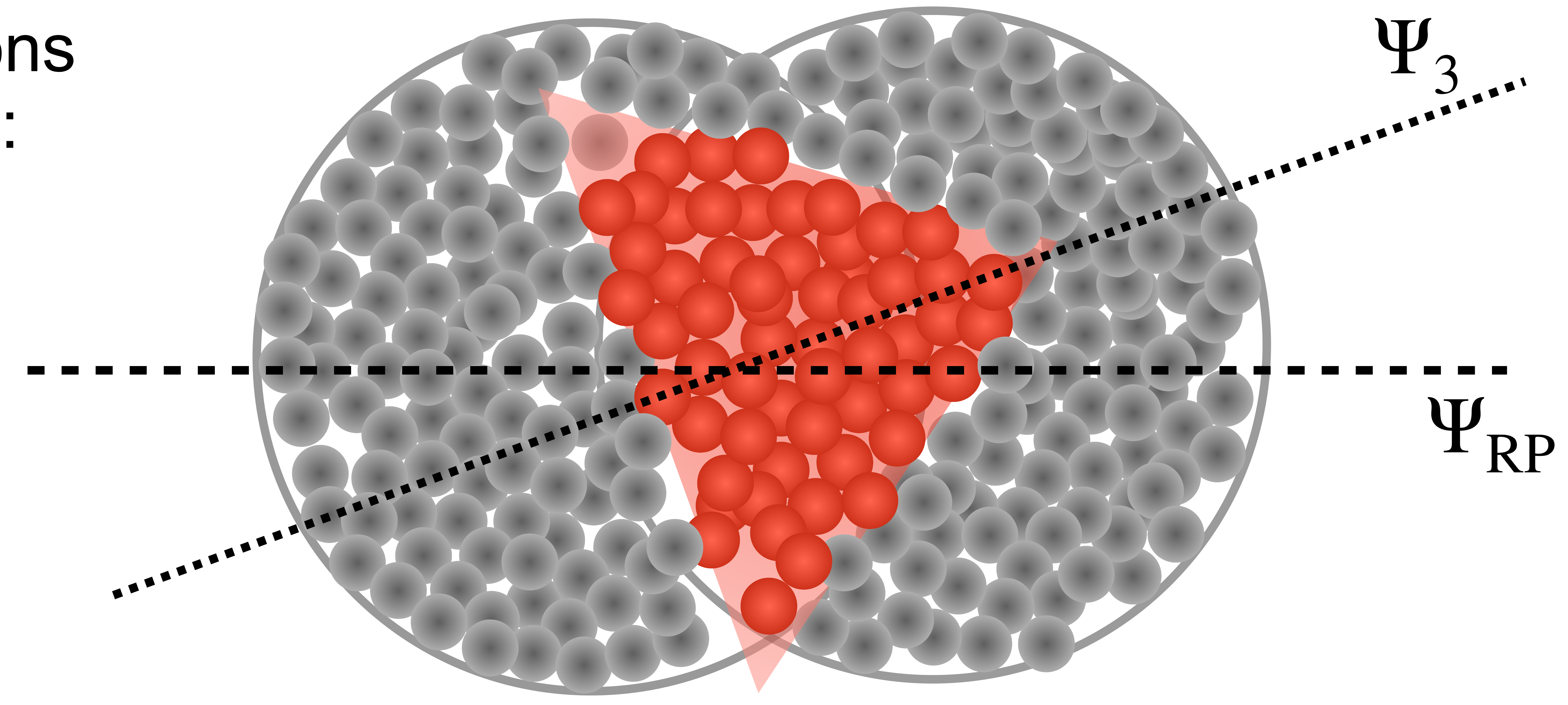
Stronger pressure gradient along symmetry plane



Triangular flow: hydro

Initial geometrical asymmetry of non-central collisions results in azimuthal asymmetry of particle emission:

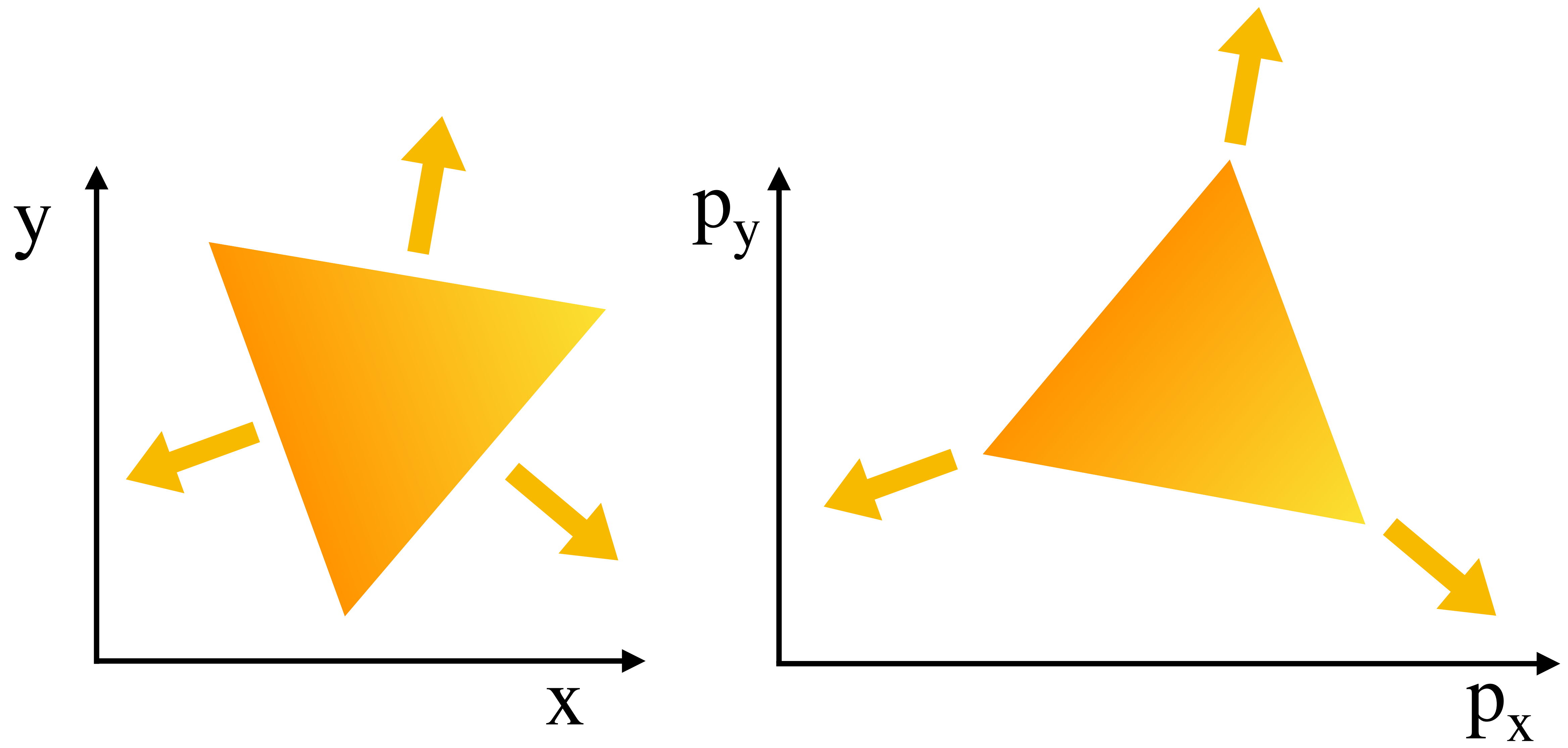
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos(n(\phi - \Psi_n))\right]$$



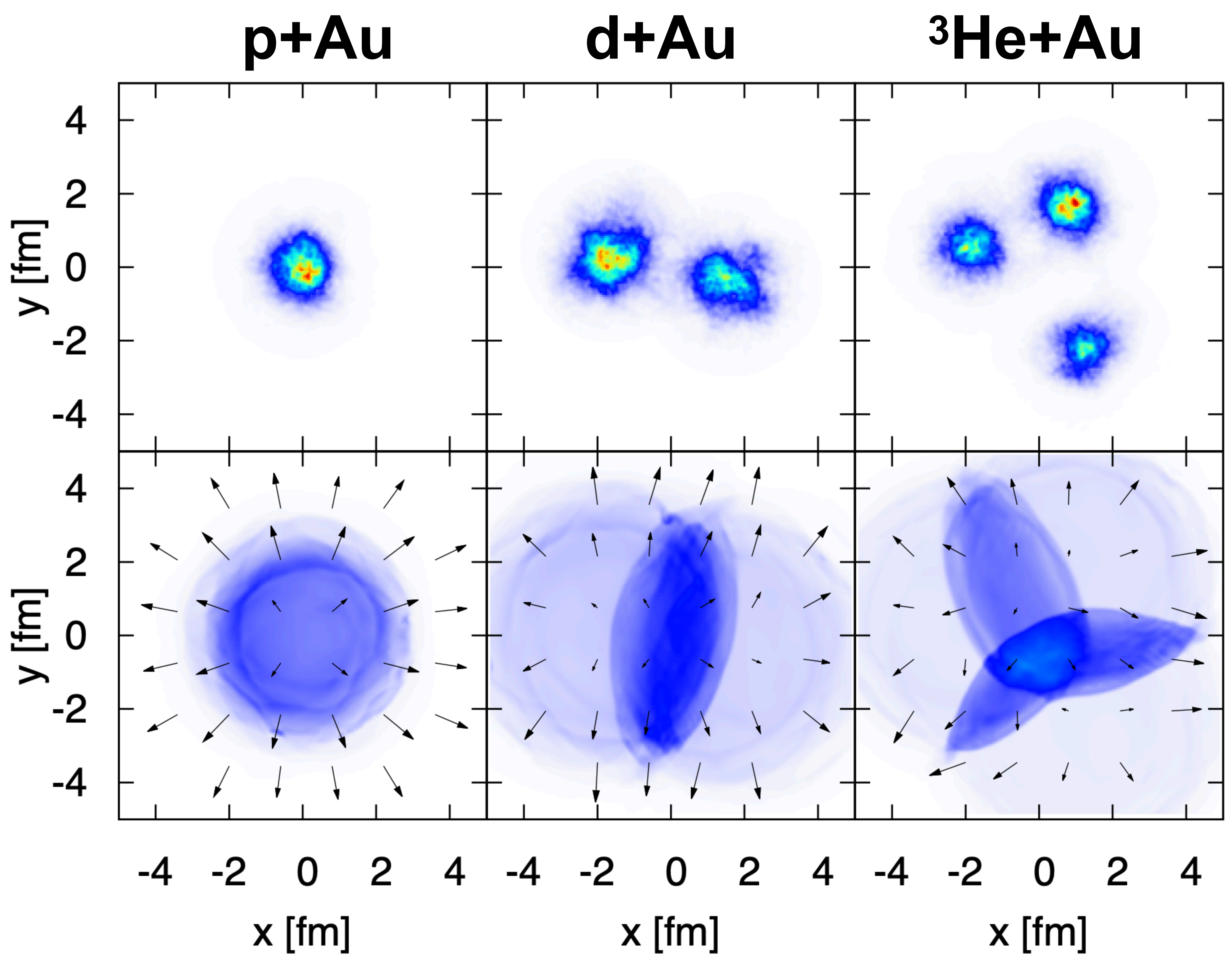
Third harmonic is the **triangular flow**

$$v_3 = < \cos(3(\phi - \Psi_3)) >$$

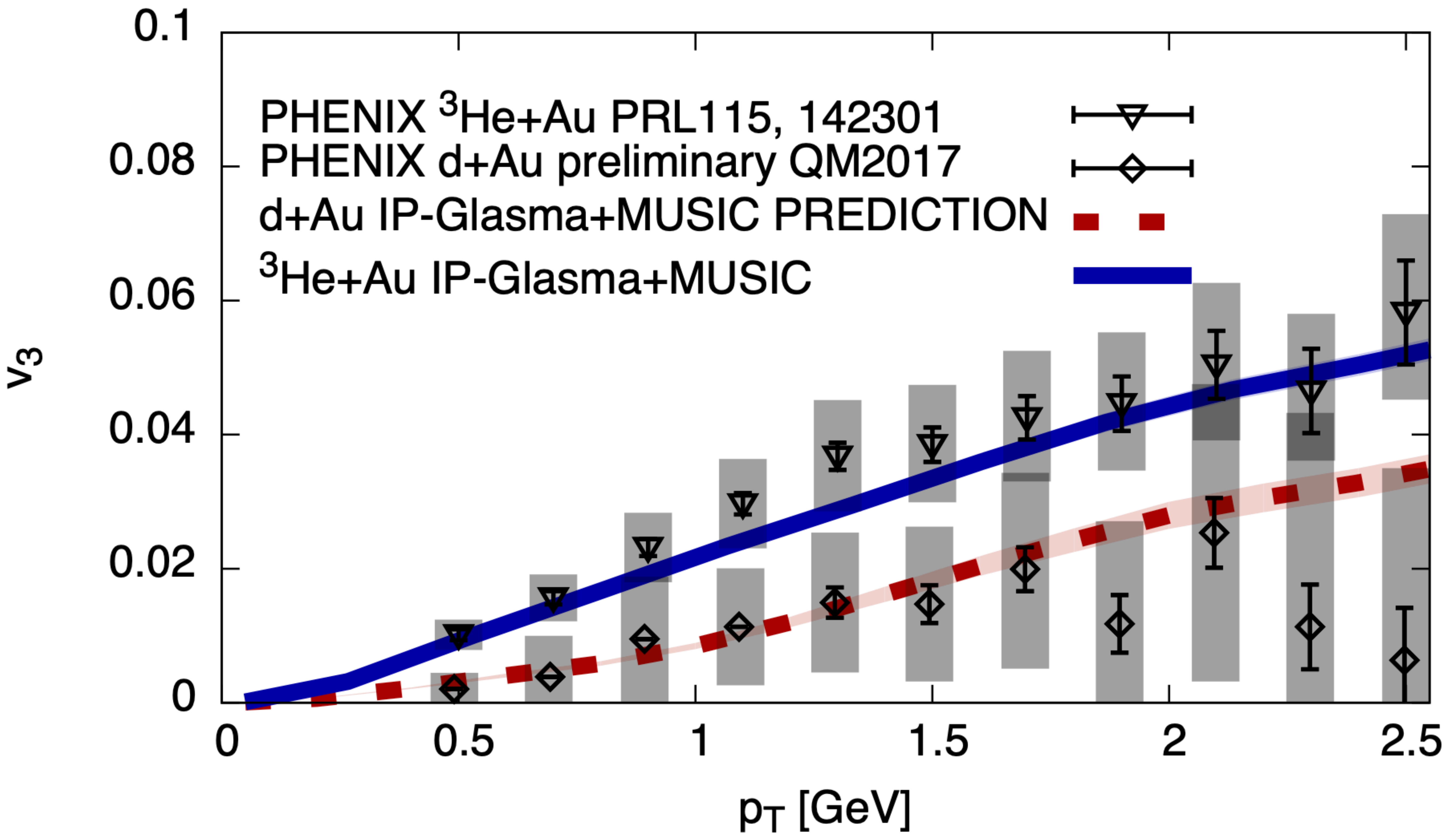
connected to fluctuations of the initial distributions of participant nucleons



Role of initial conditions



B. Schenke, Nuclear Physics A 00 (2021) 1–9

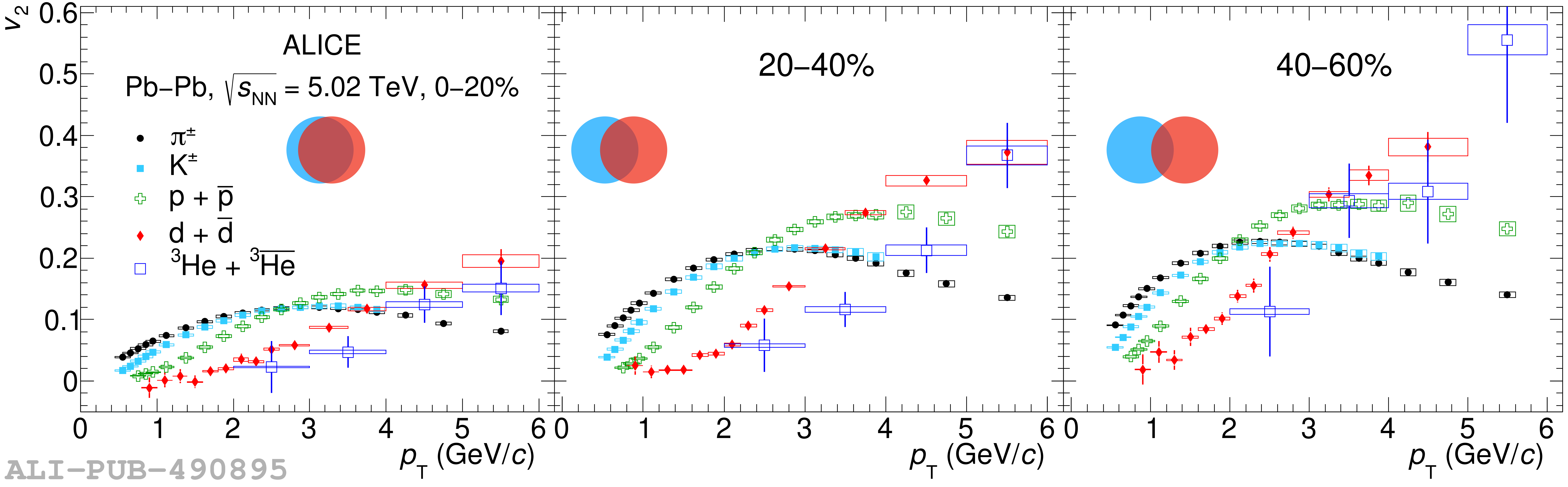


- IP-Glasma initial configurations of energy density in small systems
- flow directions (arrows) after hydrodynamic evolution of the IP-Glasma initial conditions

→Characteristic elliptic and triangular flow patterns are visible

Mass ordering of v_2

Phys. Rev. C 102 (2020) 055203



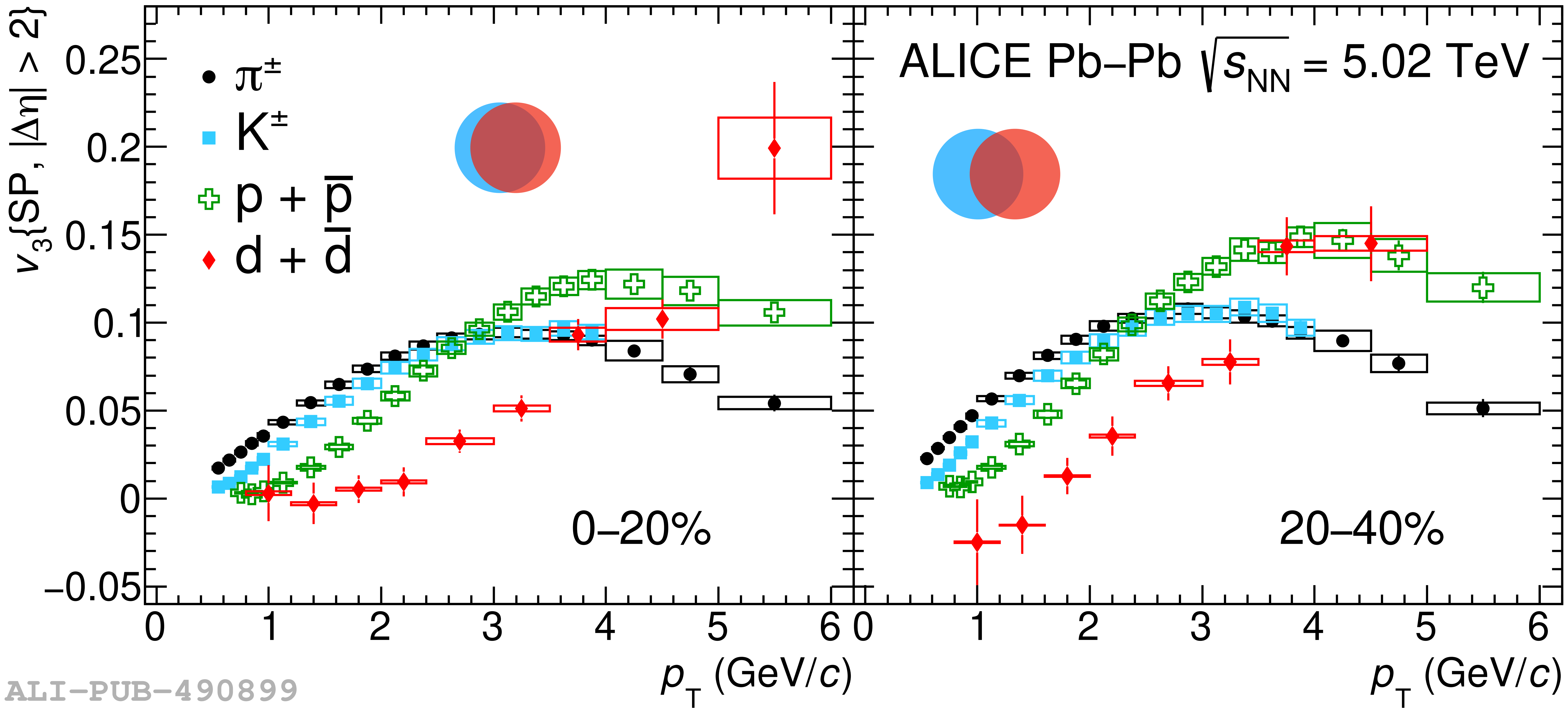
Mass ordering of v_2 for different hadron species (<u>including nuclei</u>) in Pb-Pb collisions

> qualitatively consistent with the assumption of a common flow velocity field

$$p \approx m \cdot \langle \beta \rangle$$

Mass ordering of v_3

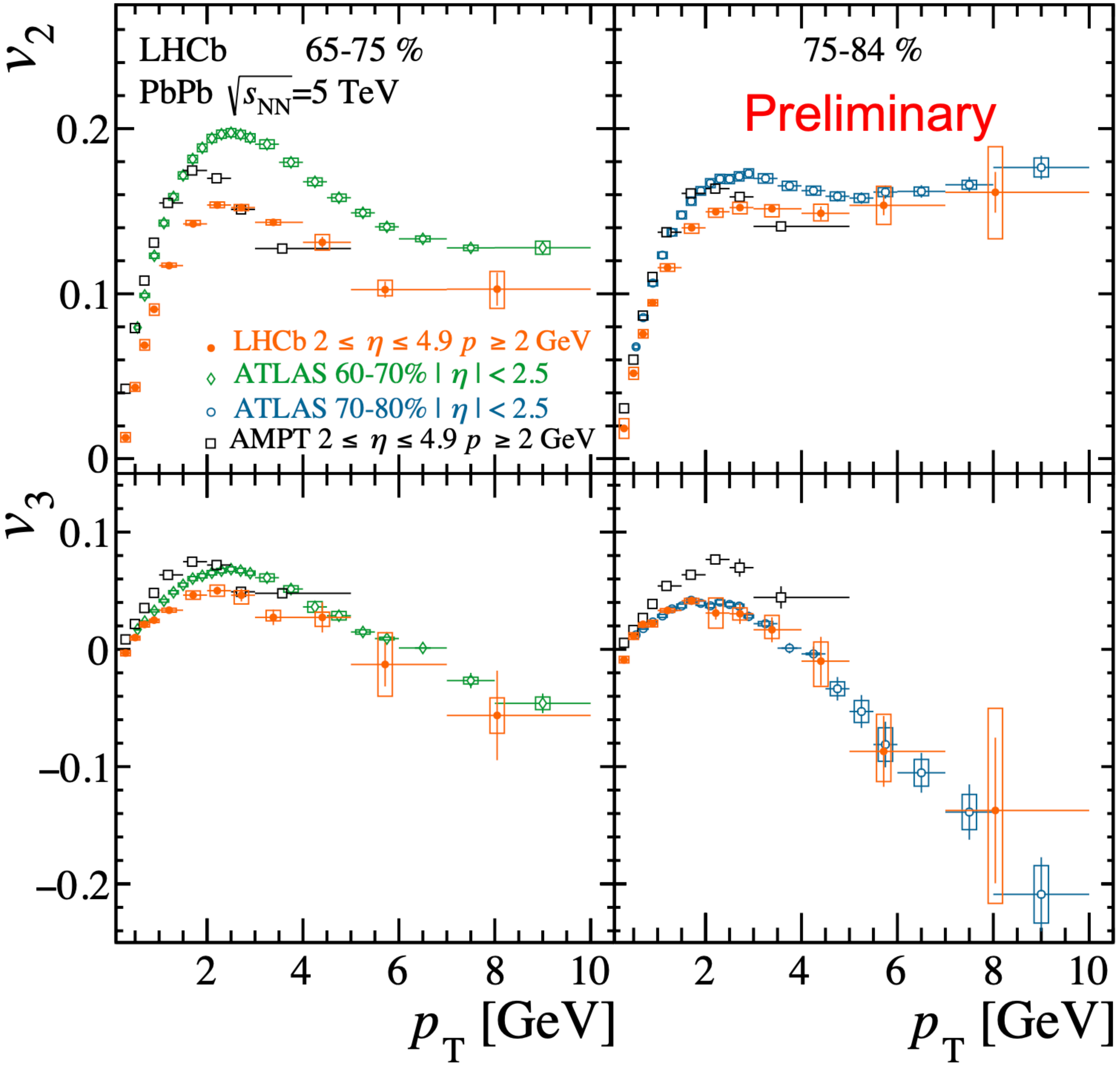
Phys. Rev. C 102 (2020) 055203



Effects of initial-state fluctuations of nucleons visible also for light nuclei

Mass ordering of v_3 as expected from relativistic hydro

Forward measurements of v_n



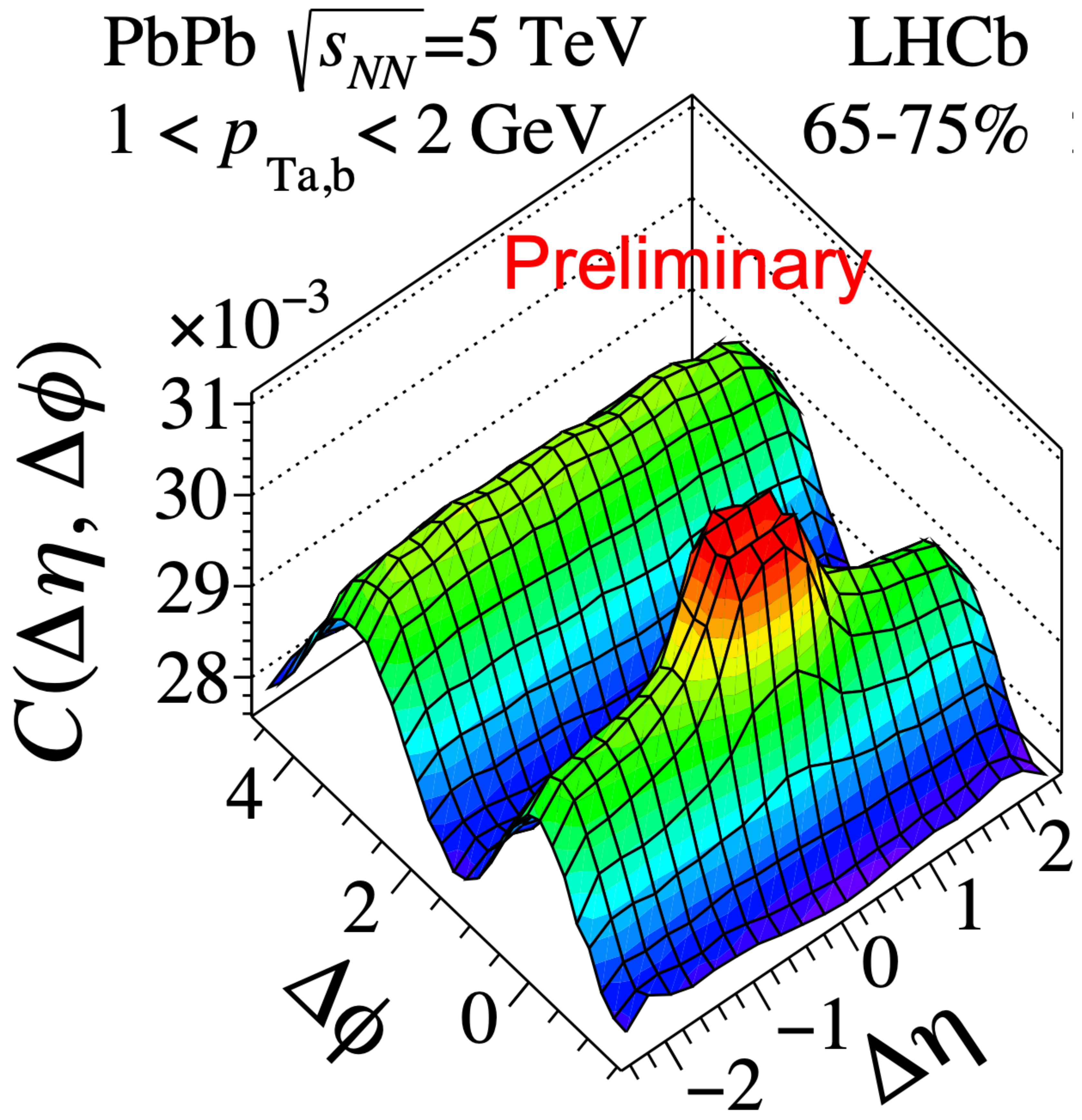
First measurements of charged-hadron v_n at forward rapidity by LHCb

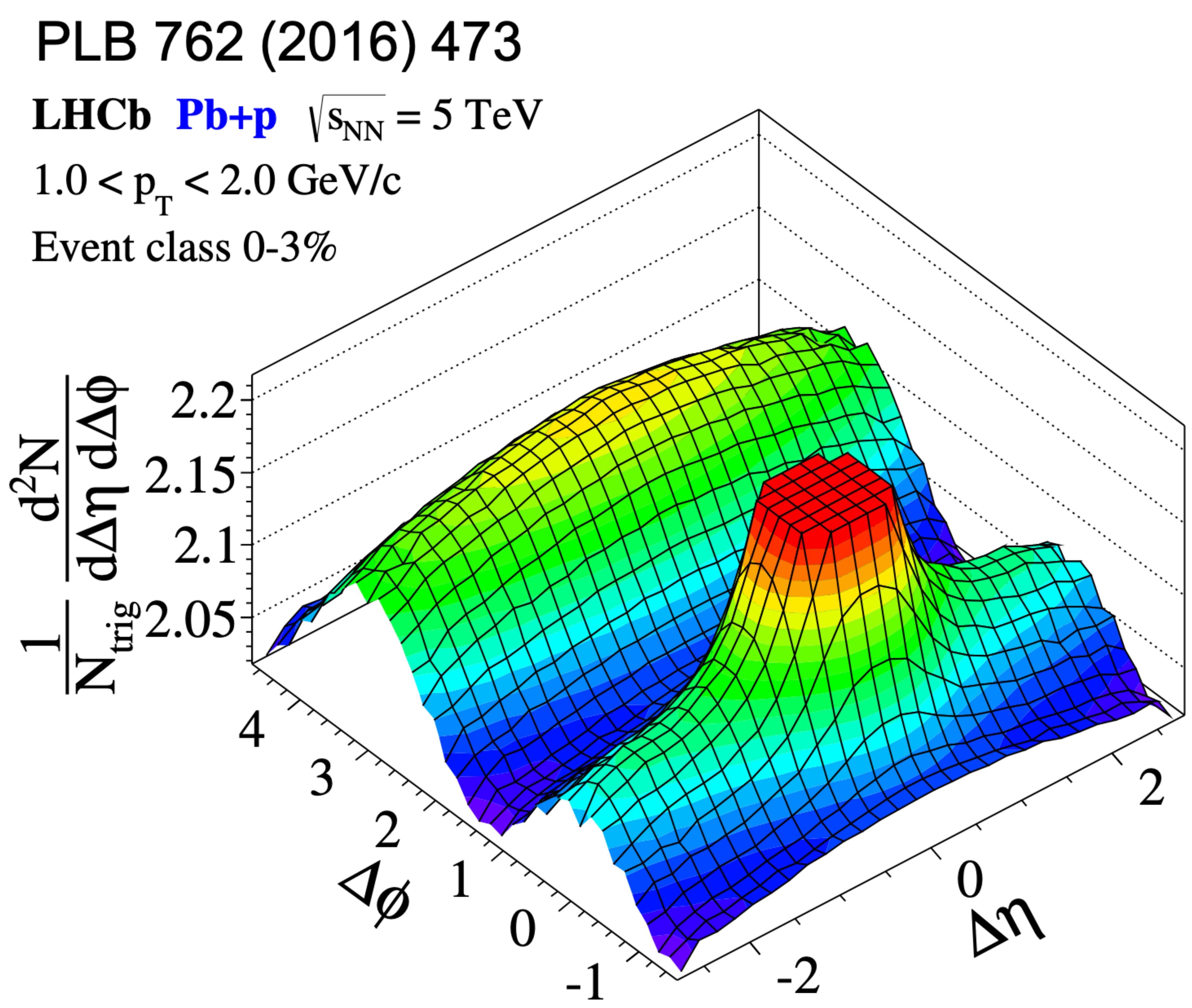
- Similar magnitude and p_T shape of v_n measured at mid-rapidity
- Rising v_2 at high p_T in 75-84% centrality may be due to non-flow contributions

v_3 becomes negative at high p_T

Forward region dominated by hadronic phase
→ weaker flow

Correlations at forward rapidity

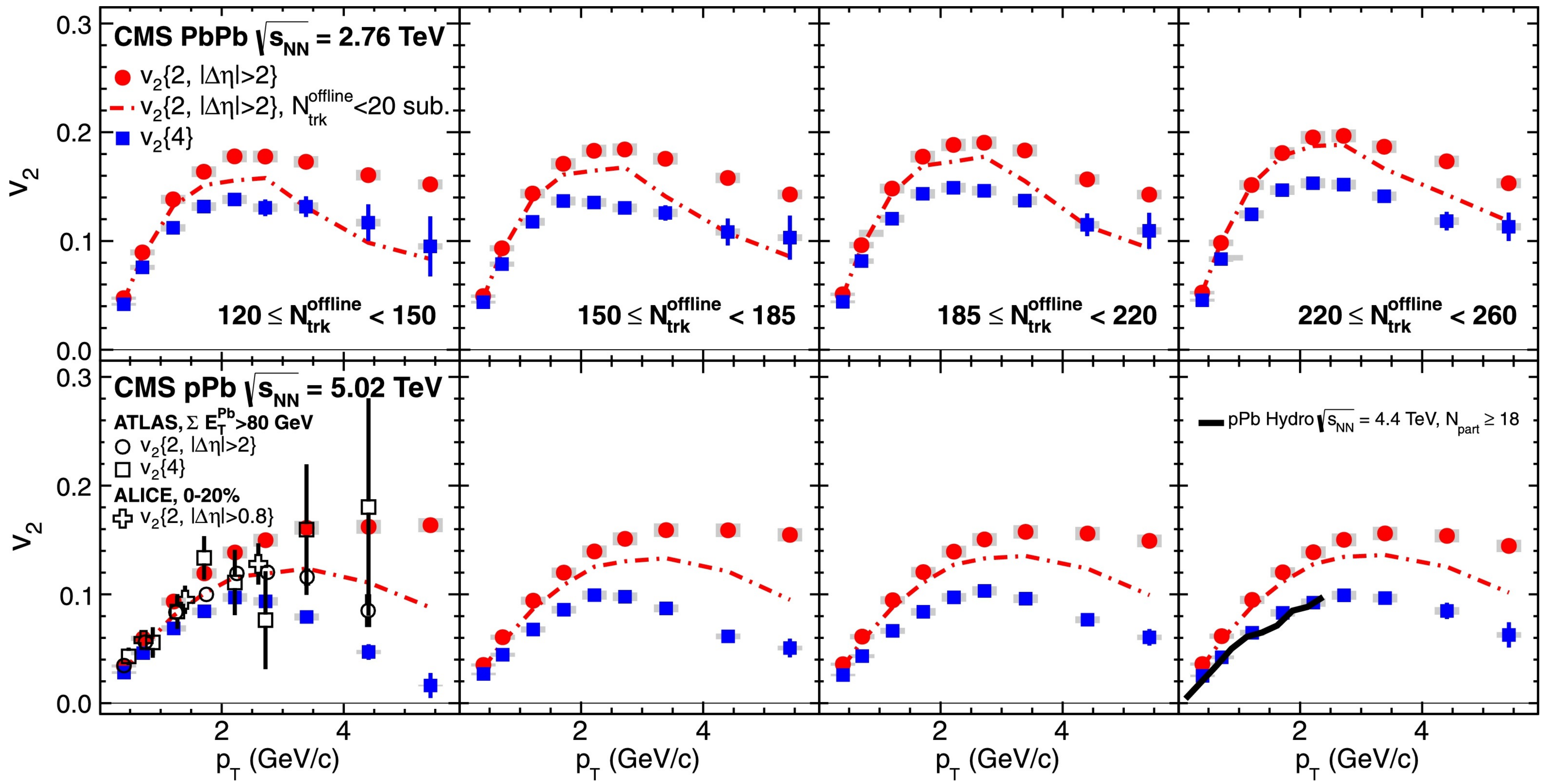




Stronger flow at forward rapidity in peripheral PbPb collisions wrt p-Pb collisions

v_2 in p-Pb and Pb-Pb collisions

CMS, Phys. Lett. B 724 (2013) 213-240

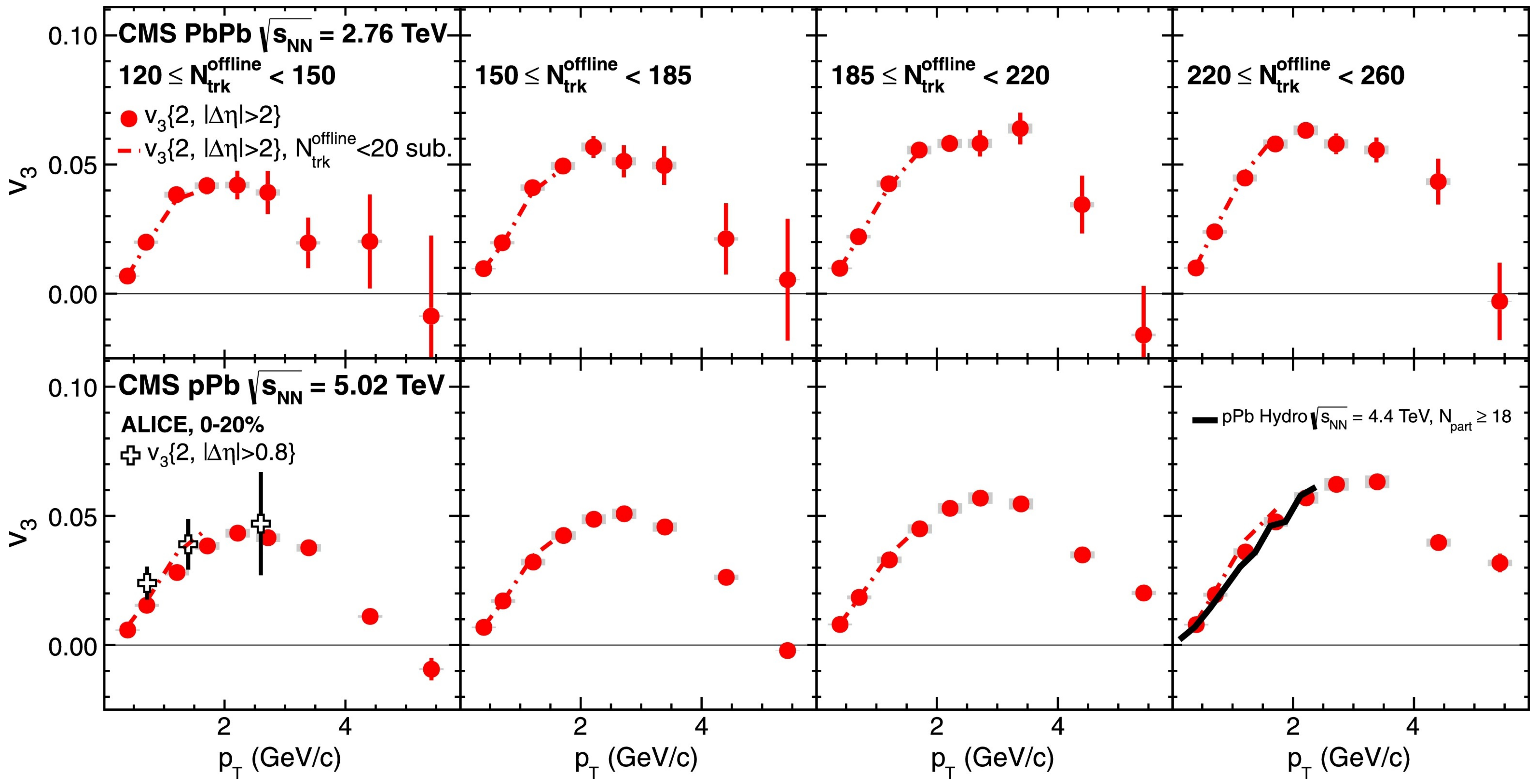


- Very similar p_T-dependence of v_2 in Pb-Pb and p-Pb in the same multiplicity intervals
- v_2 in p-Pb smaller by $\sim$ 30% wrt v_2 in Pb-Pb

Hydro (+ fluctuating initial conditions) consistent with the data at low p_T

v_3 in p-Pb and Pb-Pb collisions

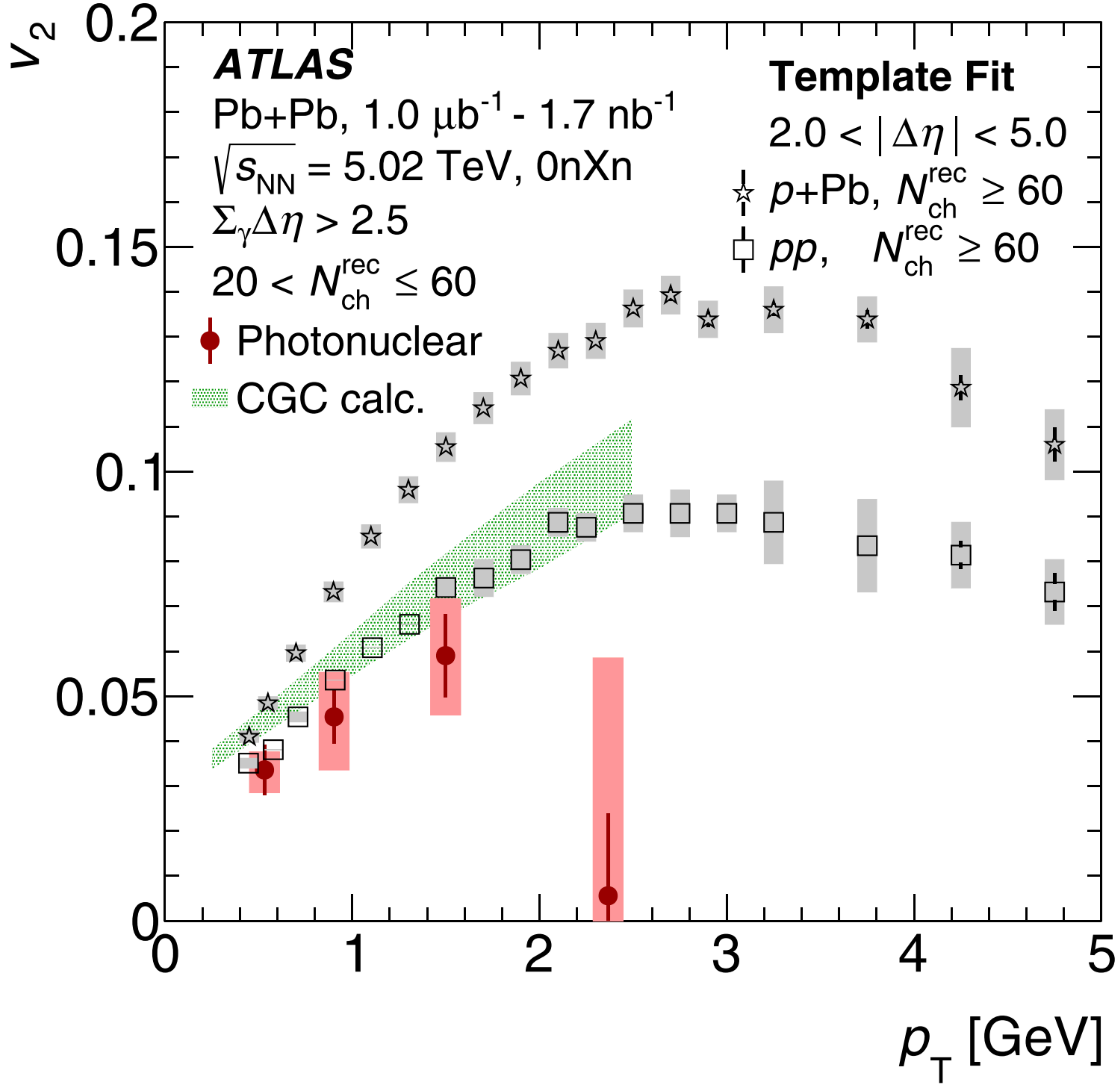
CMS, Phys. Lett. B 724 (2013) 213-240



The v_3 component reaches the same maximum value for the two systems
→ probing similar initial conditions?

v_2 in ultra-peripheral collisions

Phys. Rev. C 104, 014903 (2021)



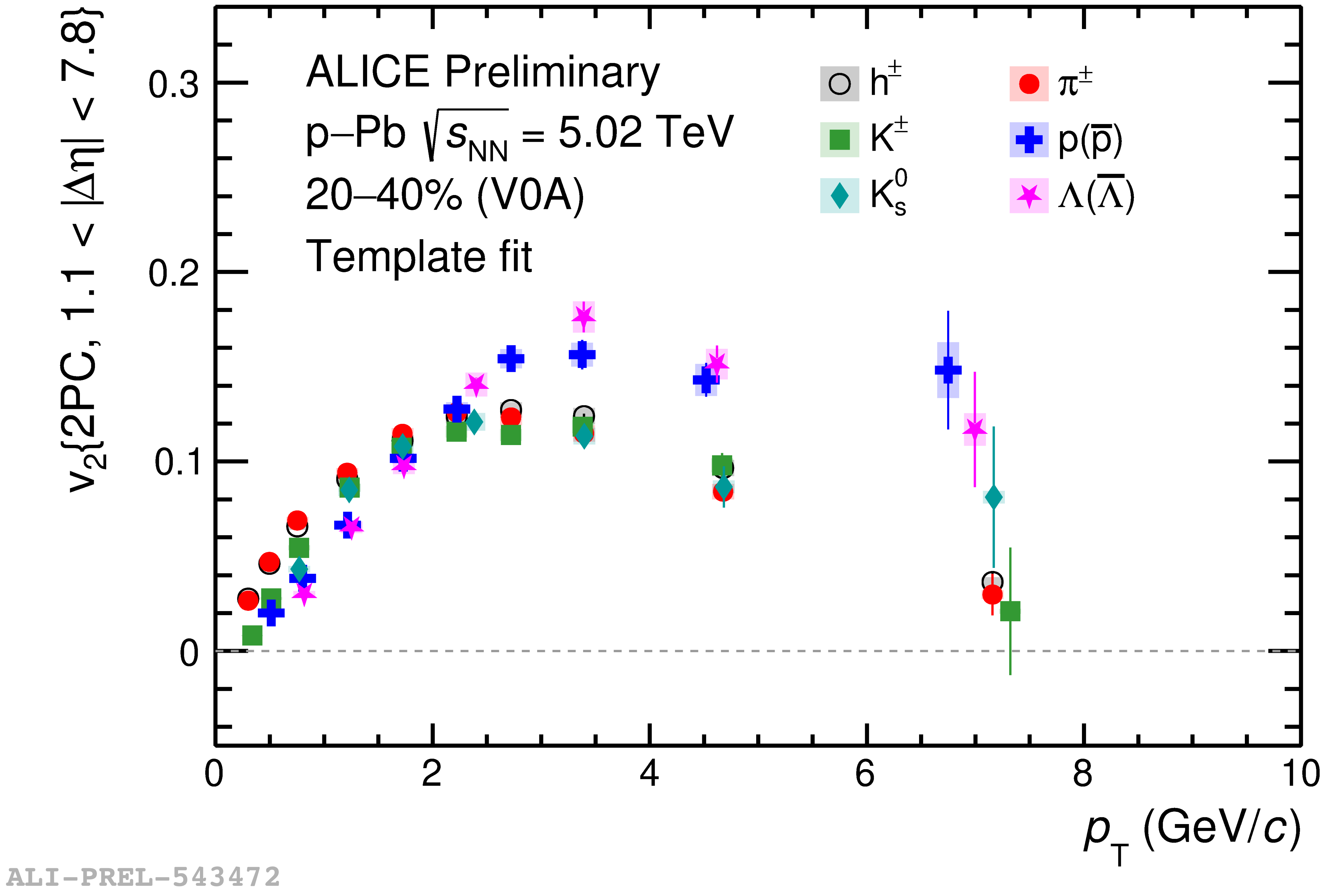
Ultra-peripheral collisions: photo-nuclear reactions

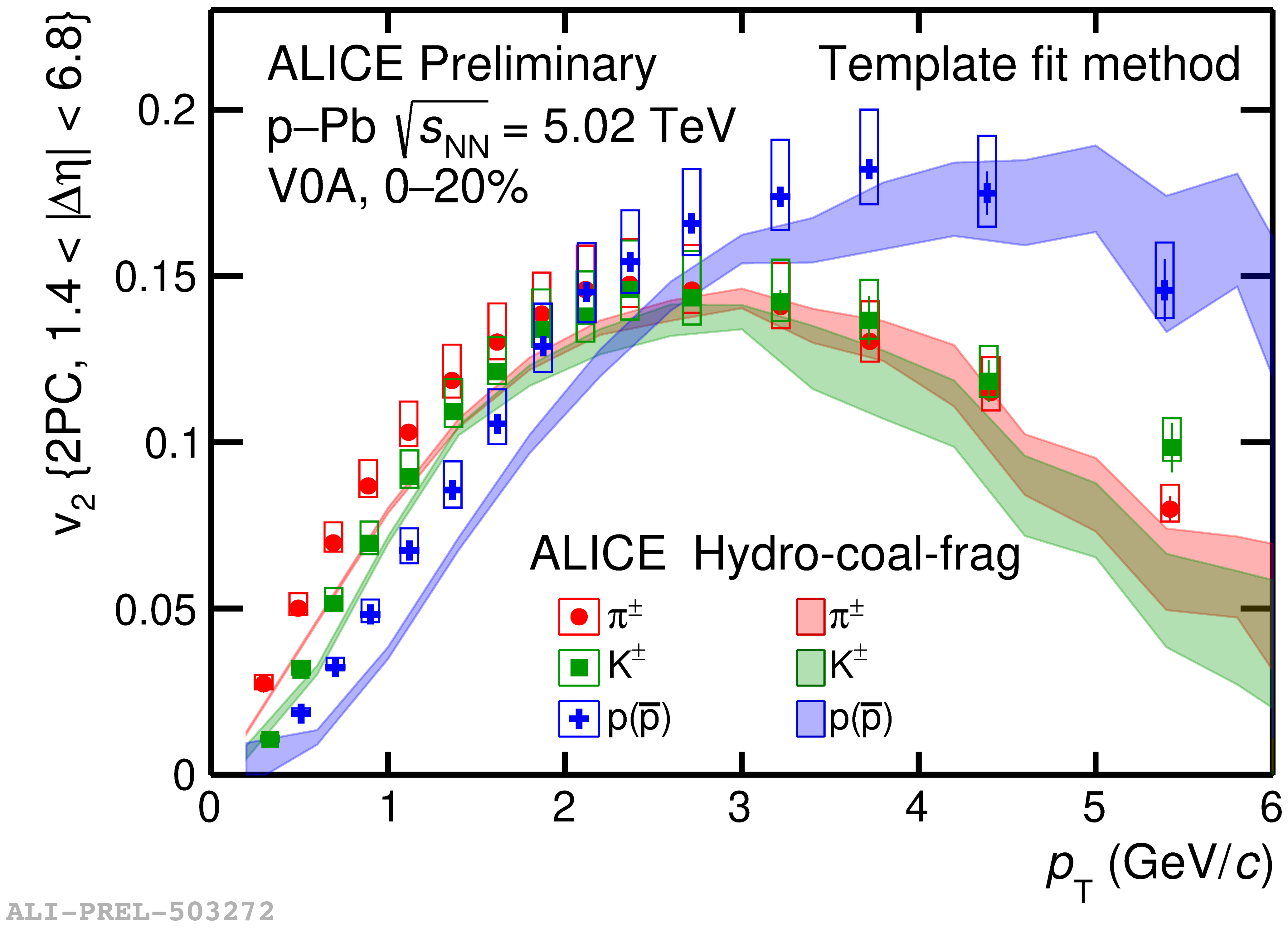
→ high-multiplicity events selected for analysis

Non-zero v_2 observed (lower than pp and p-Pb collisions)

- Can be explained using CGC predictions
- Caveat: v_2 coefficients vulnerable to (residual) non-flow

Mass ordering in small systems



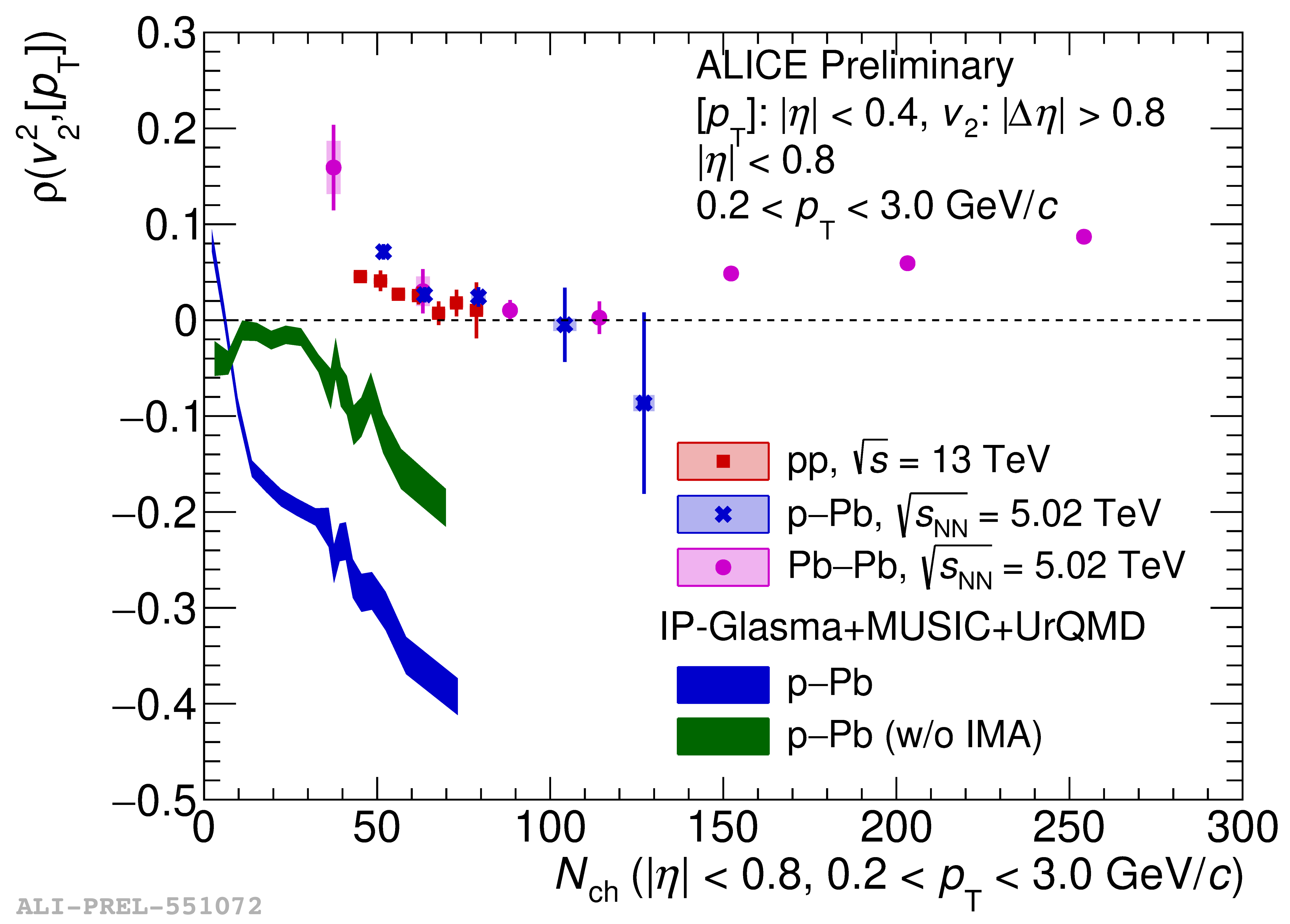


v_2 of identified hadrons in small systems

- Mass ordering at low p_T
- Baryon/meson grouping at intermediate p_T

Consistent with hydrodynamical calculations

Correlation between v_2 and $\langle p_T \rangle$



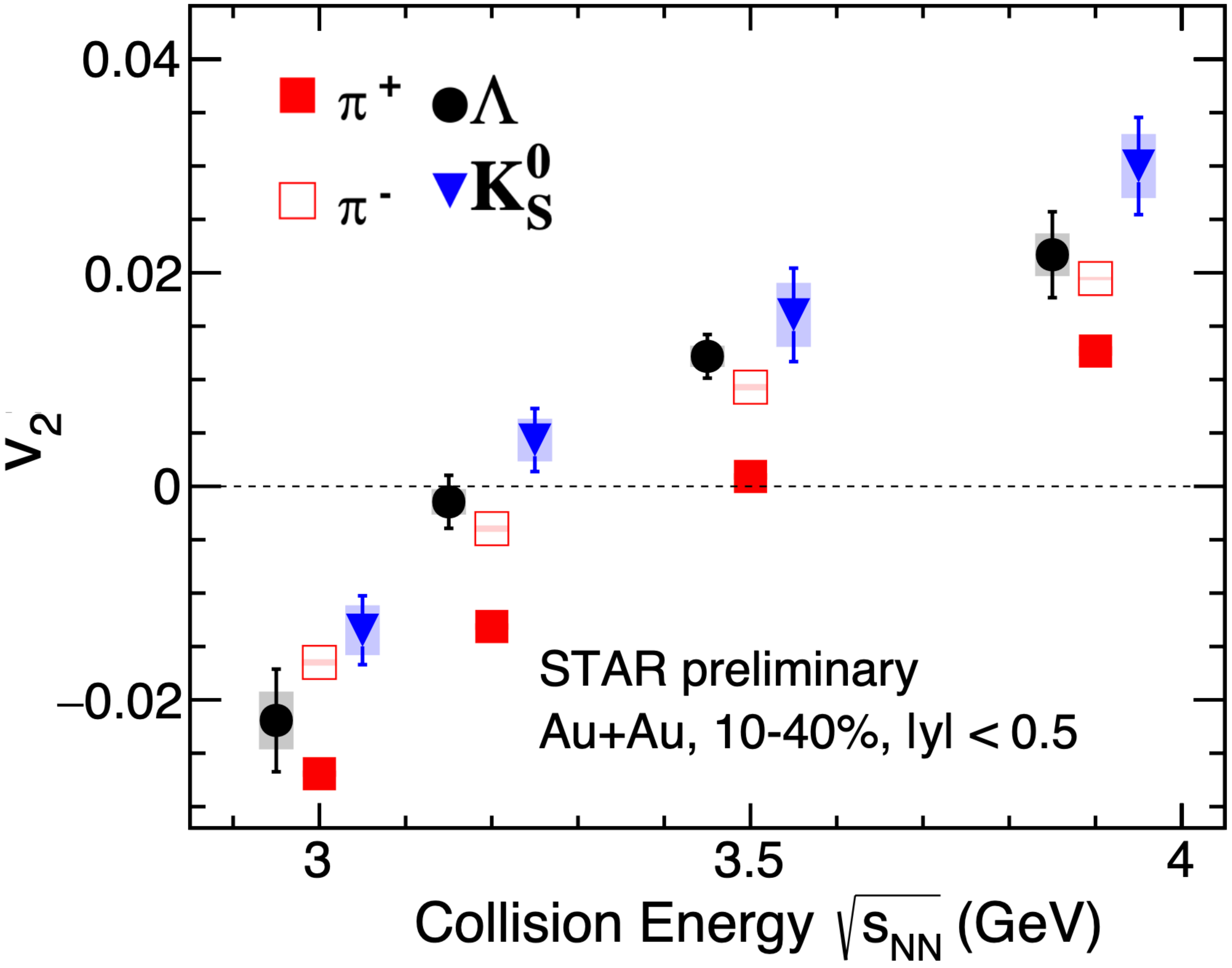
Correlation between v_2 and $\langle p_T \rangle$ to disentangle role of initial geometrical anisotropy and radial flow

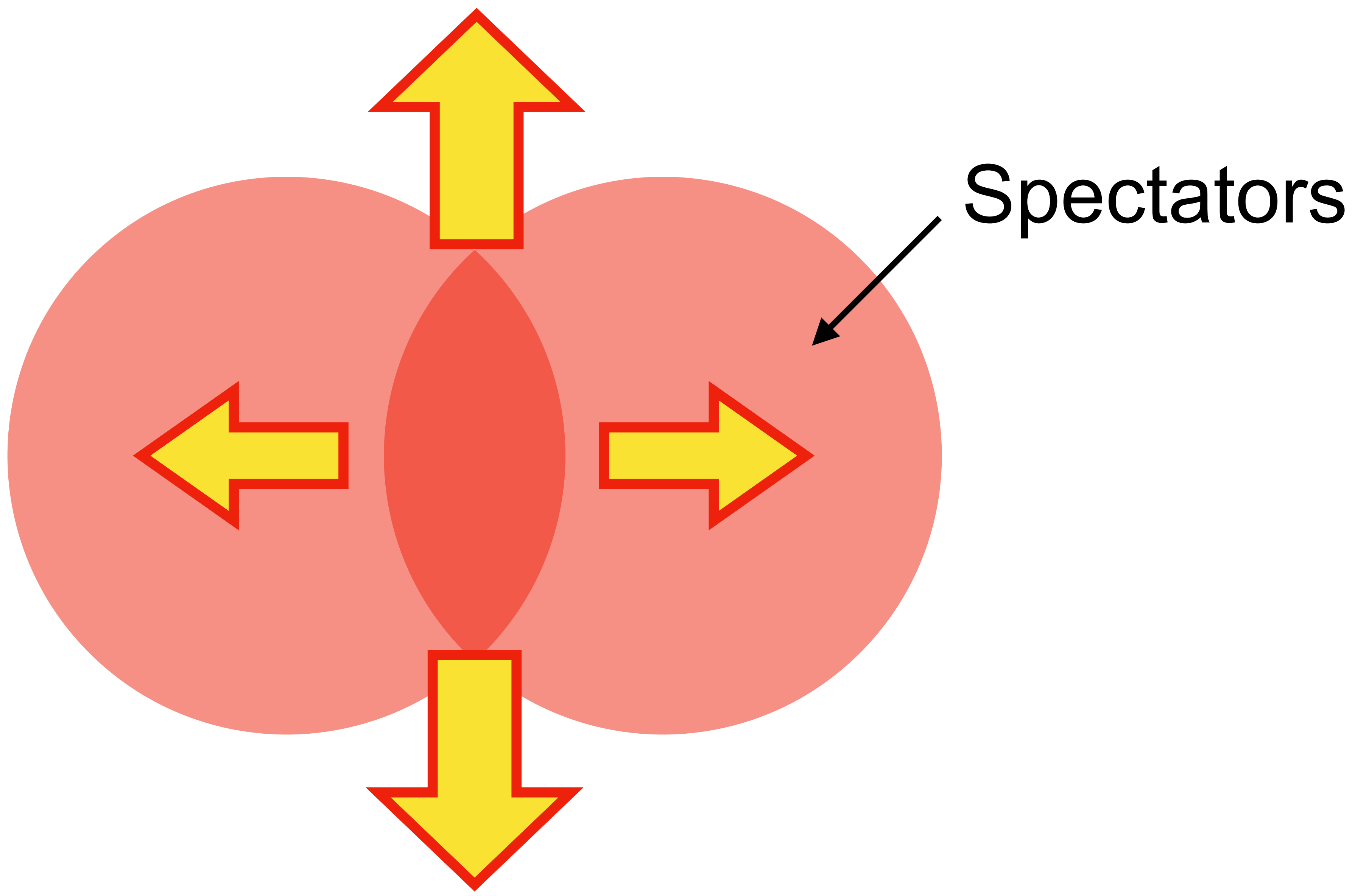
$\langle p_T \rangle$ rises when going from peripheral to central collisions while v_2 decreases
→ anti-correlated in a geometrical model

Tested against state-of-the-art hydro model with and without initial momentum anisotropy

Predictions far from measurements at low multiplicity
→ breakdown of hydro picture in small systems?

Role of spectators



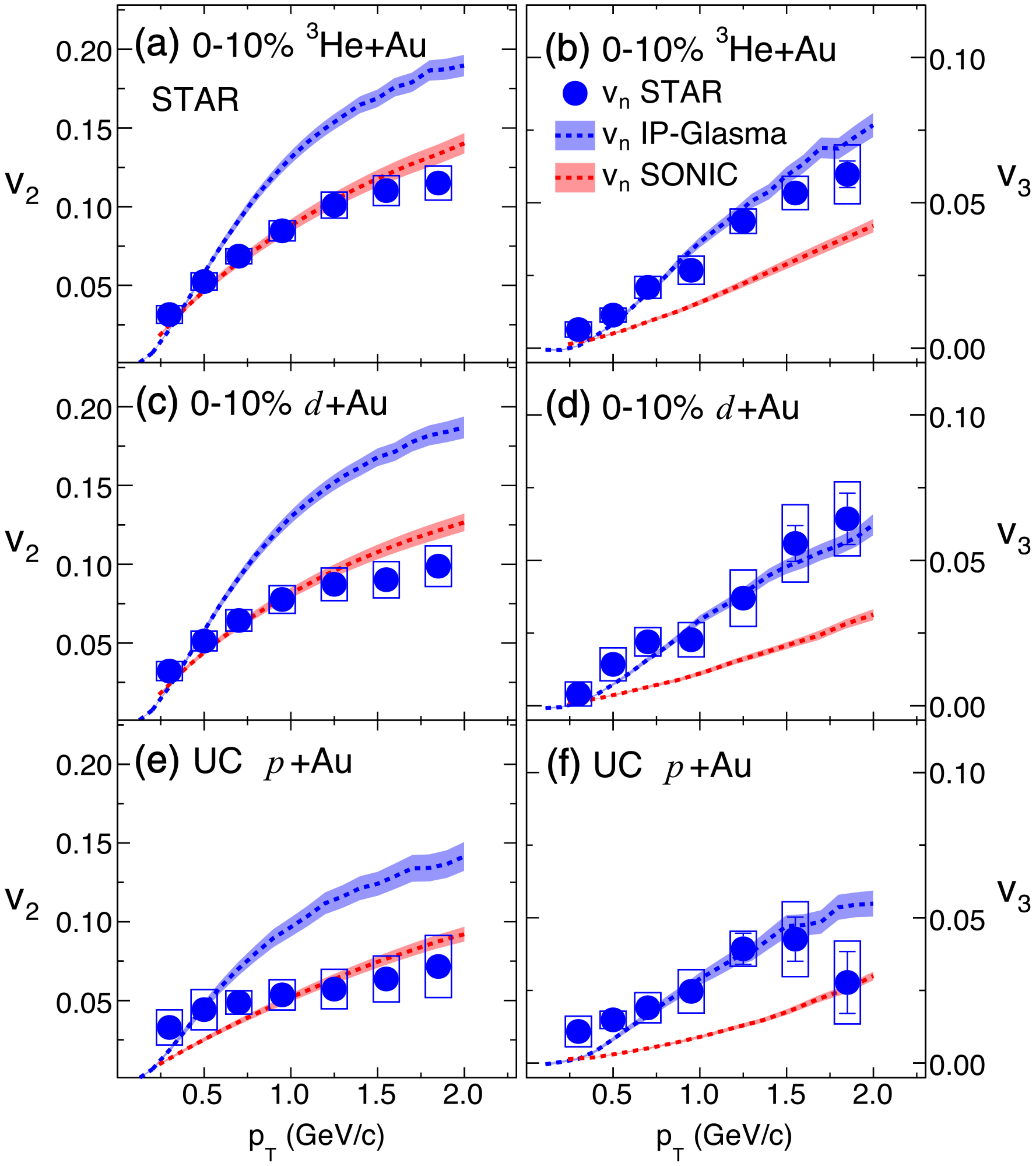


v_2 measured by STAR vs. $\sqrt{s_{NN}}$ during the BES:

switchover between out-of-plane and in-plane flow observed at around 3.2 GeV

- Spectators affect particle emission at low energy
- Regime of progressively more intense in-plane flow from collective expansion at high energy

v_n in small systems at RHIC



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

$v_{2,3}$ measured in small systems at RHIC at 200 GeV

SONIC model:

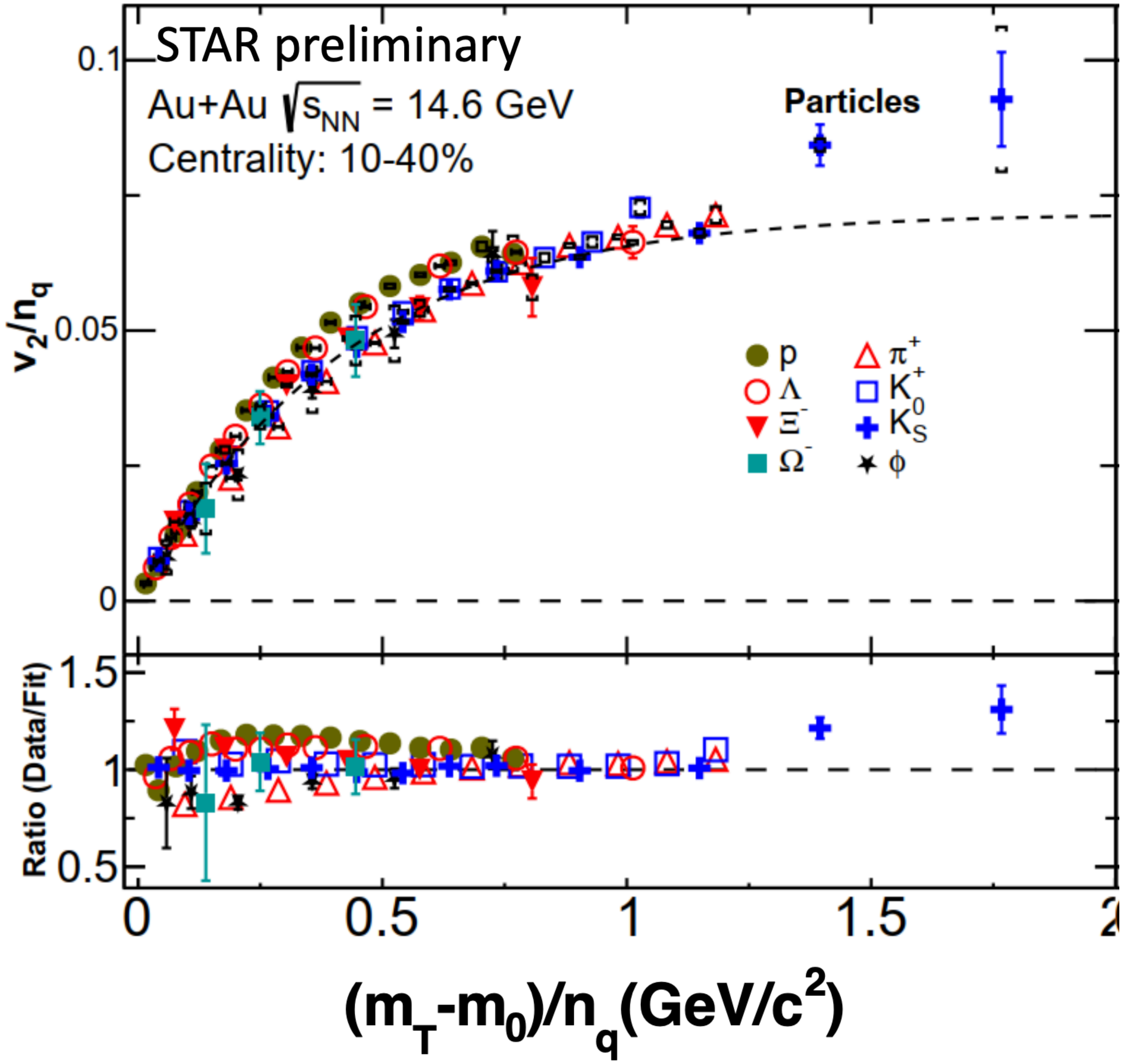
- initial eccentricity from Glauber
- no sub-nucleonic fluctuations

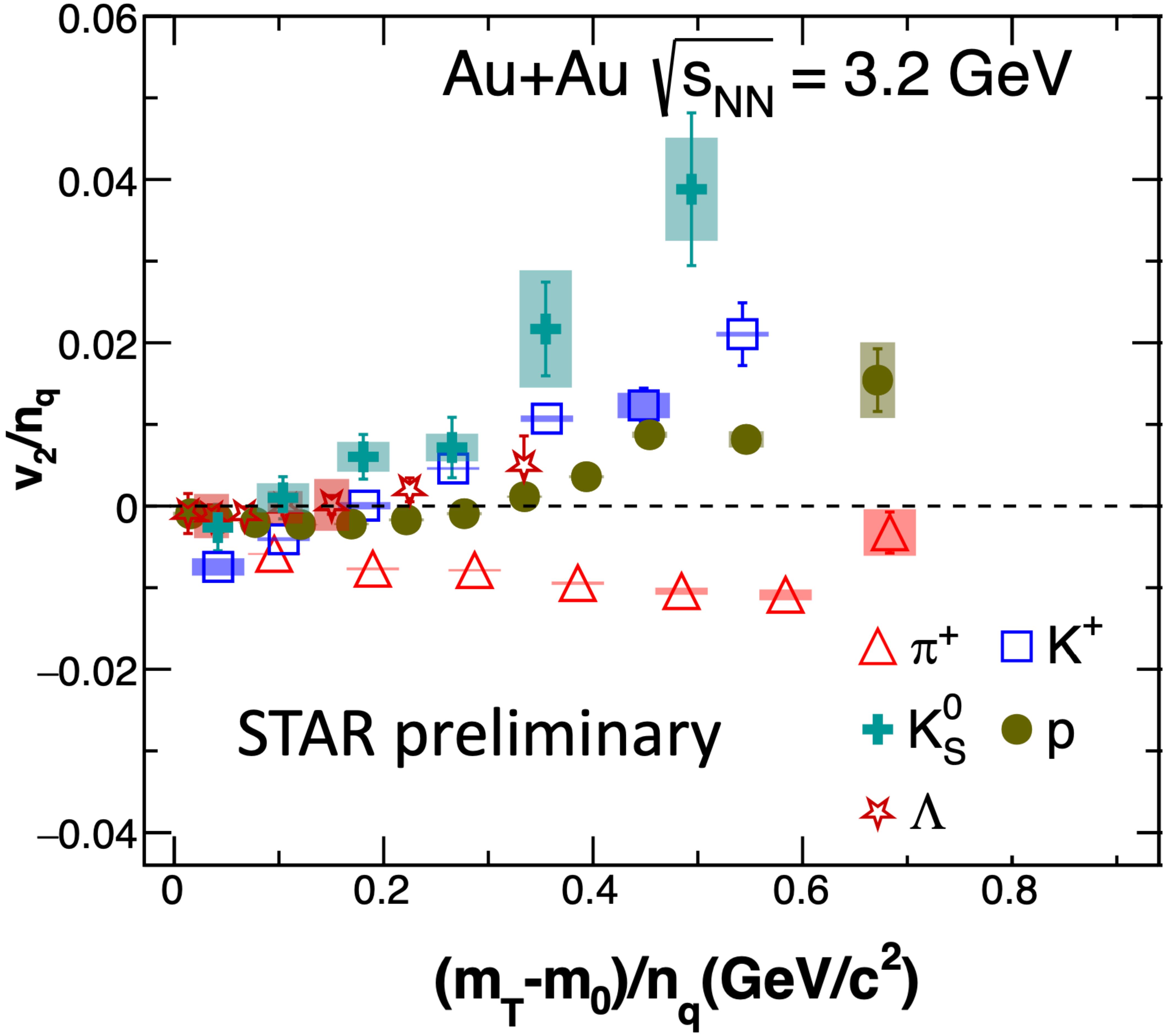
IP-Glasma + MUSIC + UrQMD model

- includes sub-nucleonic fluctuations
- initial momentum correlations
- viscous hydrodynamic evolution in the final state
- UrQMD model for evolution in the hadronic phase

Hydro models do not provide a simultaneous description of v_2 and v_3

NQ Scaling



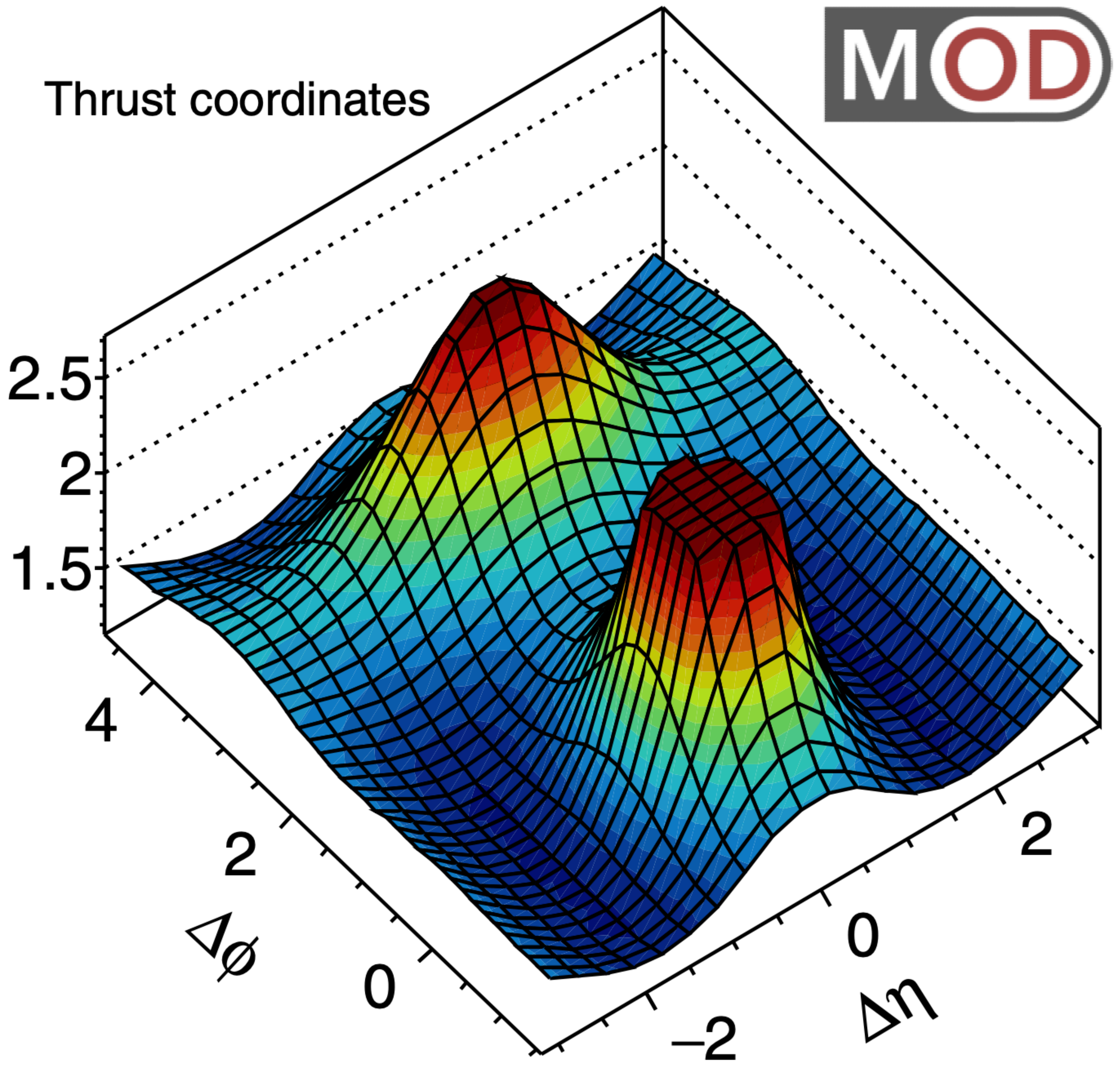


n_q scaling of v_2 in the BES

- followed in Au-Au collisions at 14.6 GeV
- breaks down at 3.2 GeV: hadronic vs. partonic regime and role of spectators

Ridge structure in e^+e^- ?

Phys. Rev. Lett. 123, 212002 (2019)



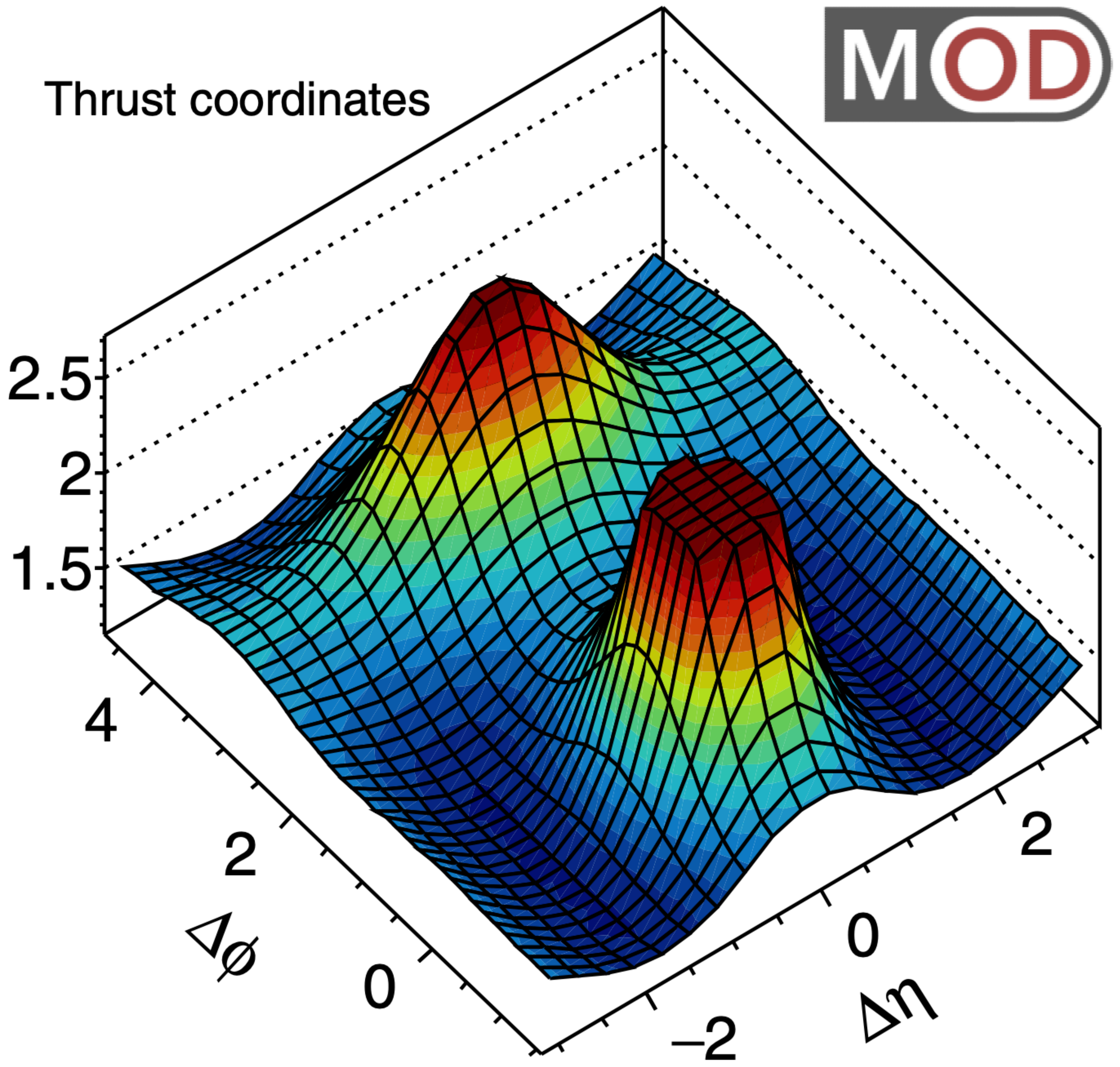
Elementary collisions:

- No multi-parton interactions
- absence of initial state correlations

→ No ridge structure observed in min. bias e^+e^- collisions

Ridge structure in e^+e^- ?

Phys. Rev. Lett. 123, 212002 (2019)

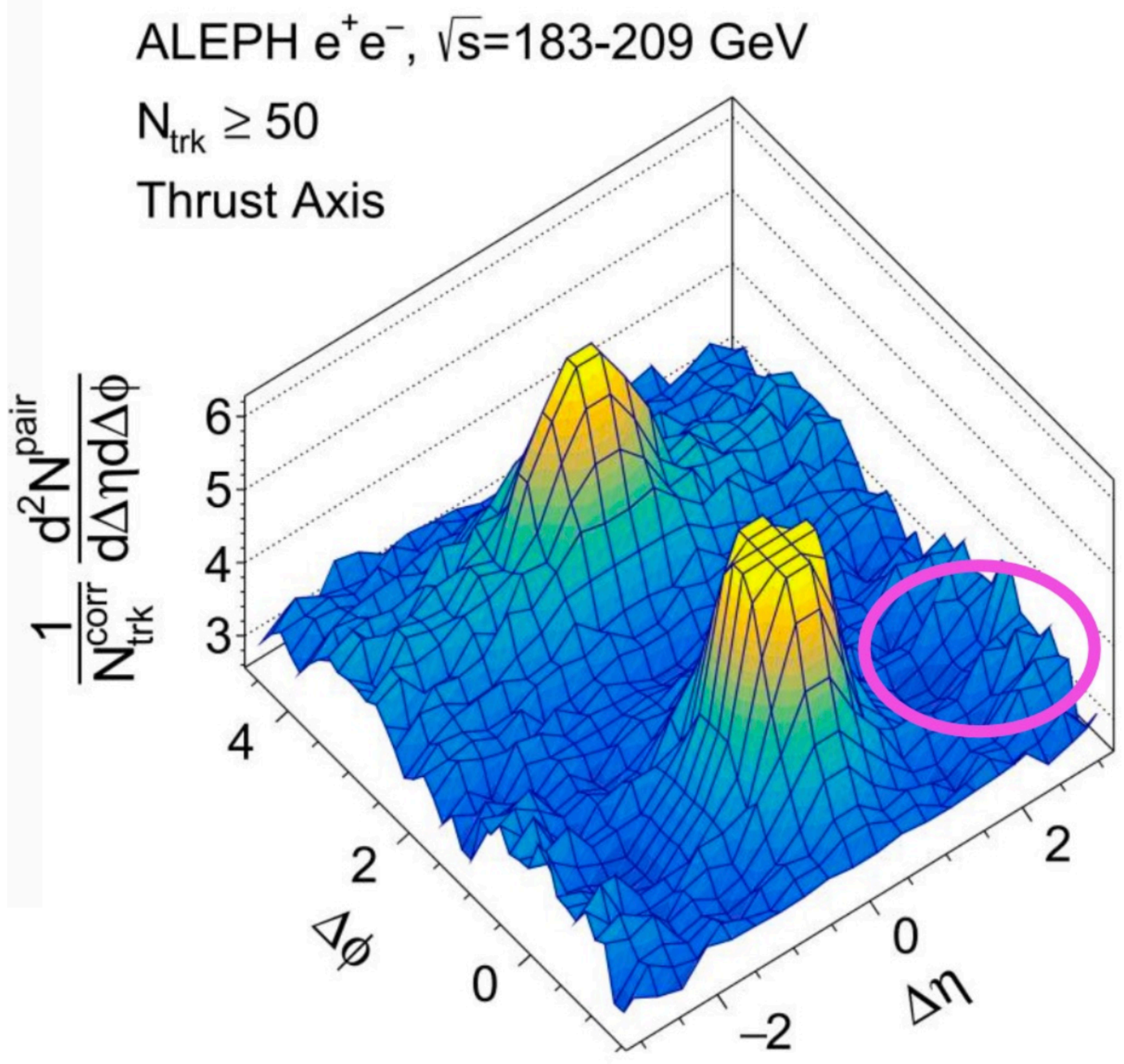


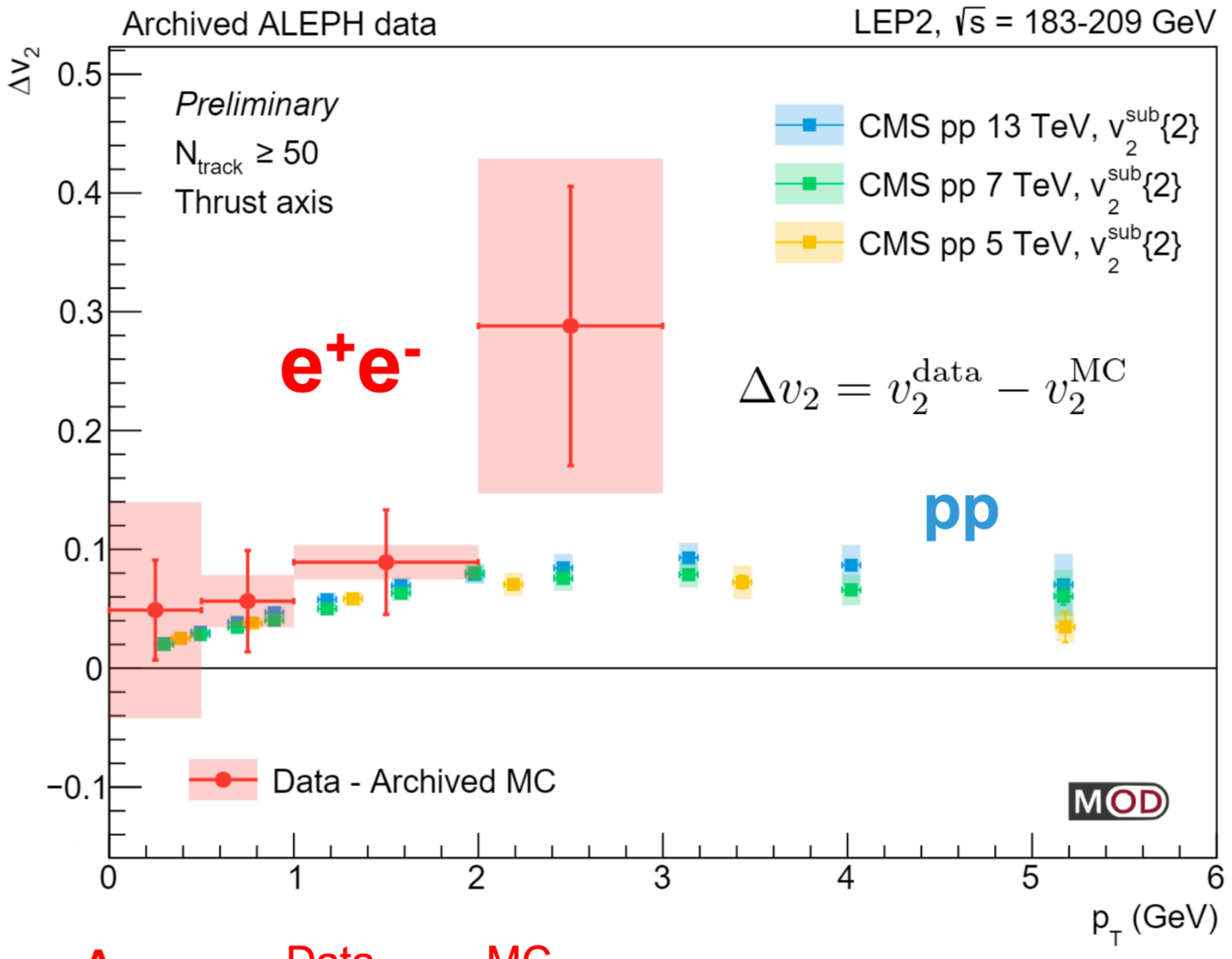
Elementary collisions:

- No multi-parton interactions
- absence of initial state correlations

→ No ridge structure observed in min. bias e^+e^- collisions

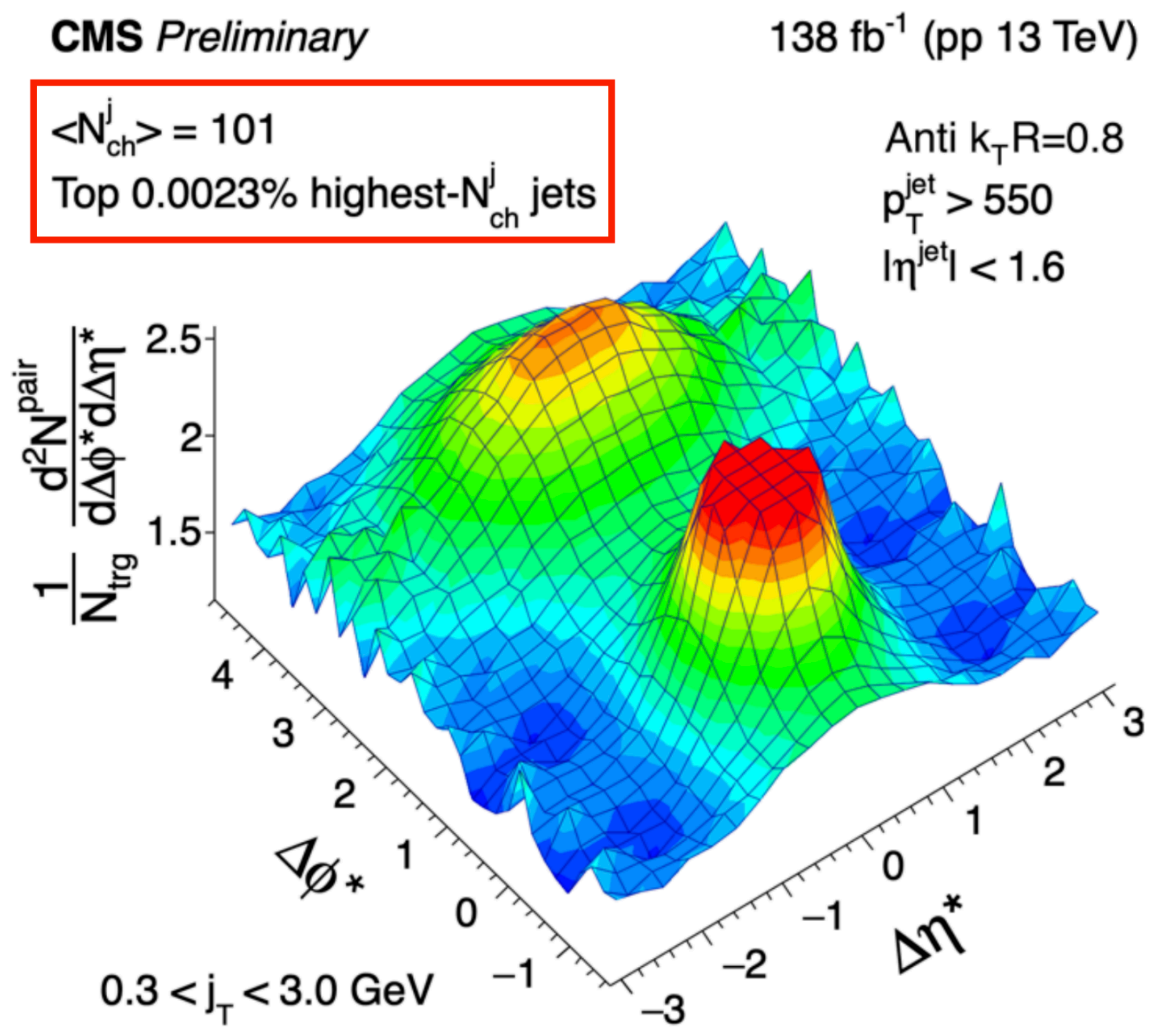
No conclusive statement on HM e^+e^- collisions

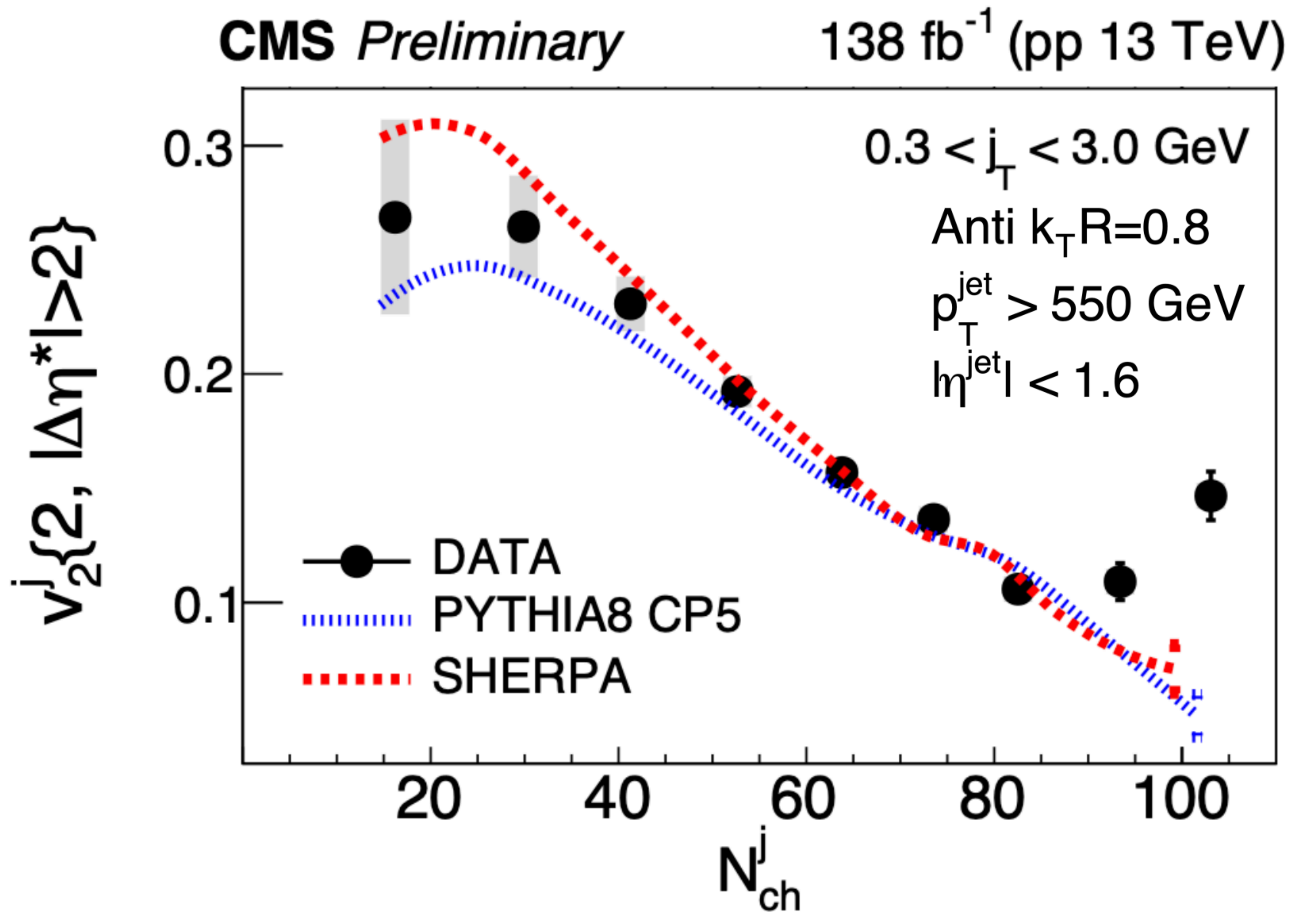




- $\Delta v_2 = v_2^{Data} - v_2^{MC}$

Collectivity inside jets?





v_2 inside jets in HM pp collisions:

- Good agreement with models up to N_{ch} ~ 80
- Interesting deviation for N_{ch} > 80

Summary

v_n and $\Delta\eta\Delta\phi$ correlation measurements show remarkable similarities in small and large systems

- v_2 shows a hierarchy with system size
- v_3 rather independent

Competing theoretical approaches: hydrodynamical (collective) expansion vs. initial momentum correlations in small systems

Summary

v_n and $\Delta\eta\Delta\phi$ correlation measurements show remarkable similarities in small and large systems

- v_2 shows a hierarchy with system size
- v_3 rather independent

Competing theoretical approaches: hydrodynamical (collective) expansion vs. initial momentum correlations in small systems

More (high-precision) measurements are on their way

Thank you for your attention