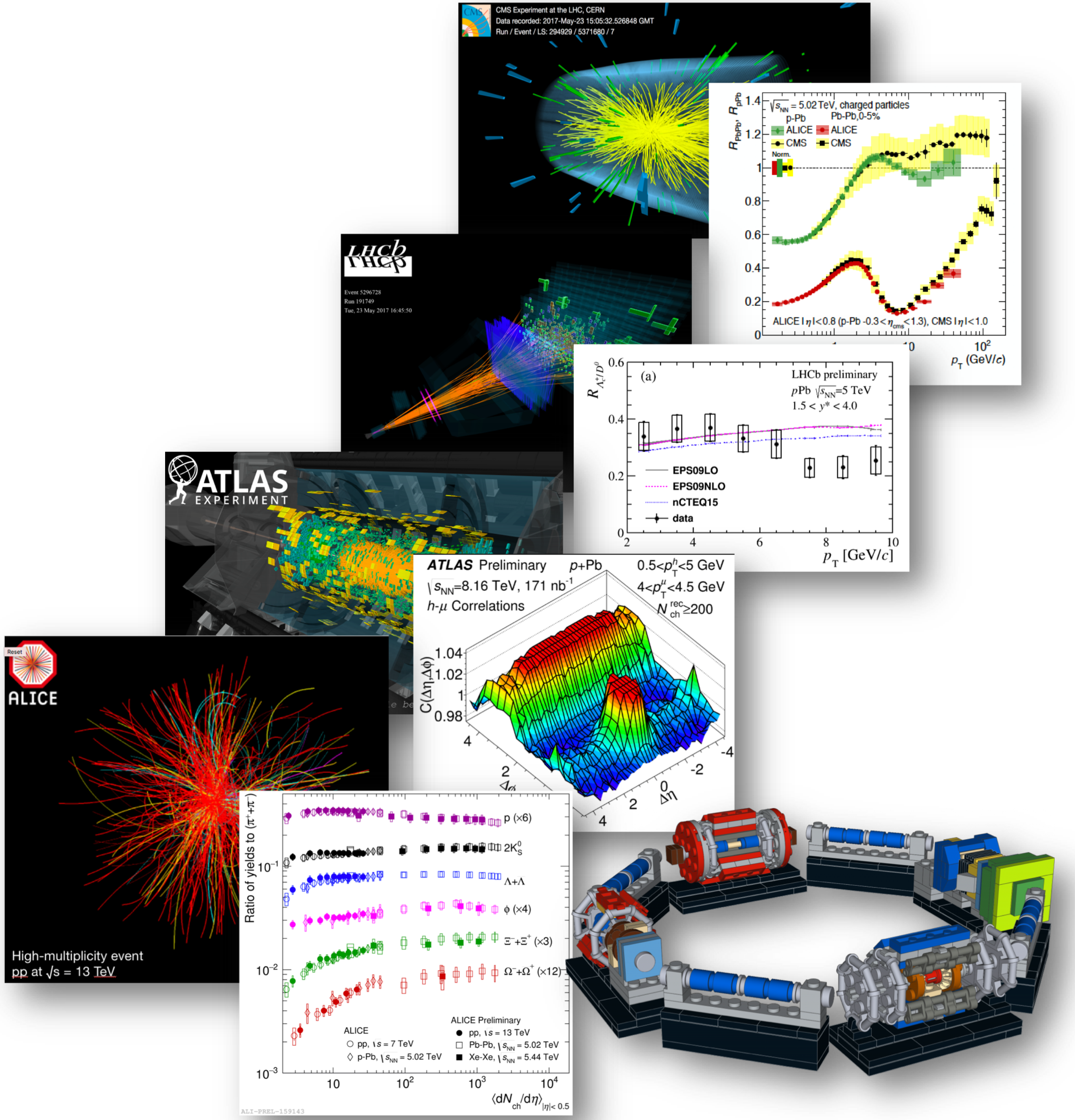


FROM SMALL TO LARGE COLLIDING SYSTEMS: LESSONS LEARNED AND FUTURE PERSPECTIVES

F. Bellini (CERN)

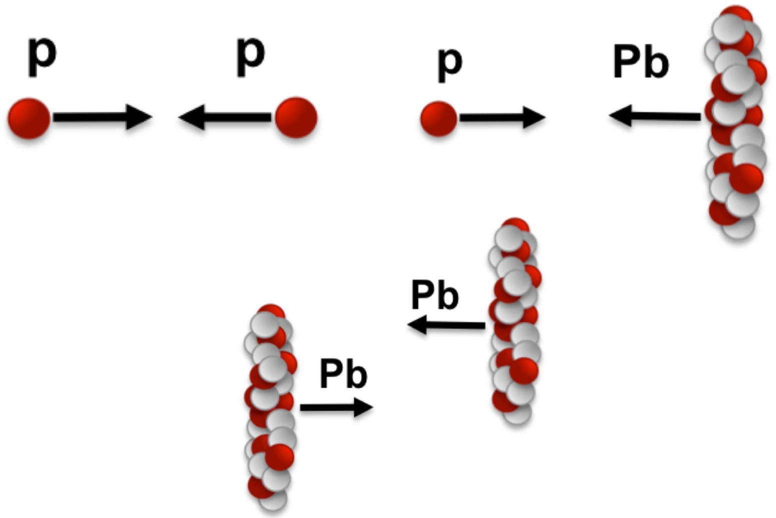
for the ALICE, ATLAS, CMS, and LHCb Collaborations

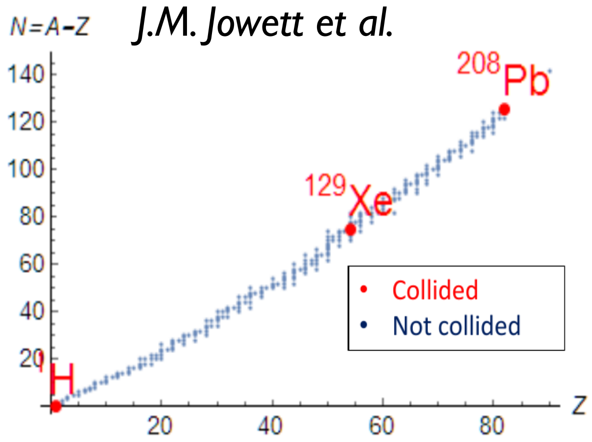
Bologna, 6th June 2018

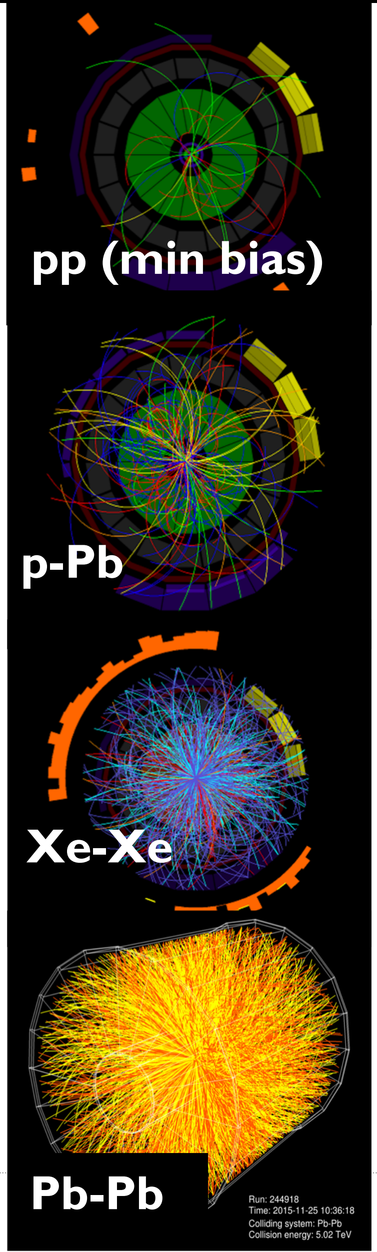
LHCP Bologna 2018

"Small" and "large" systems

Colliding system size

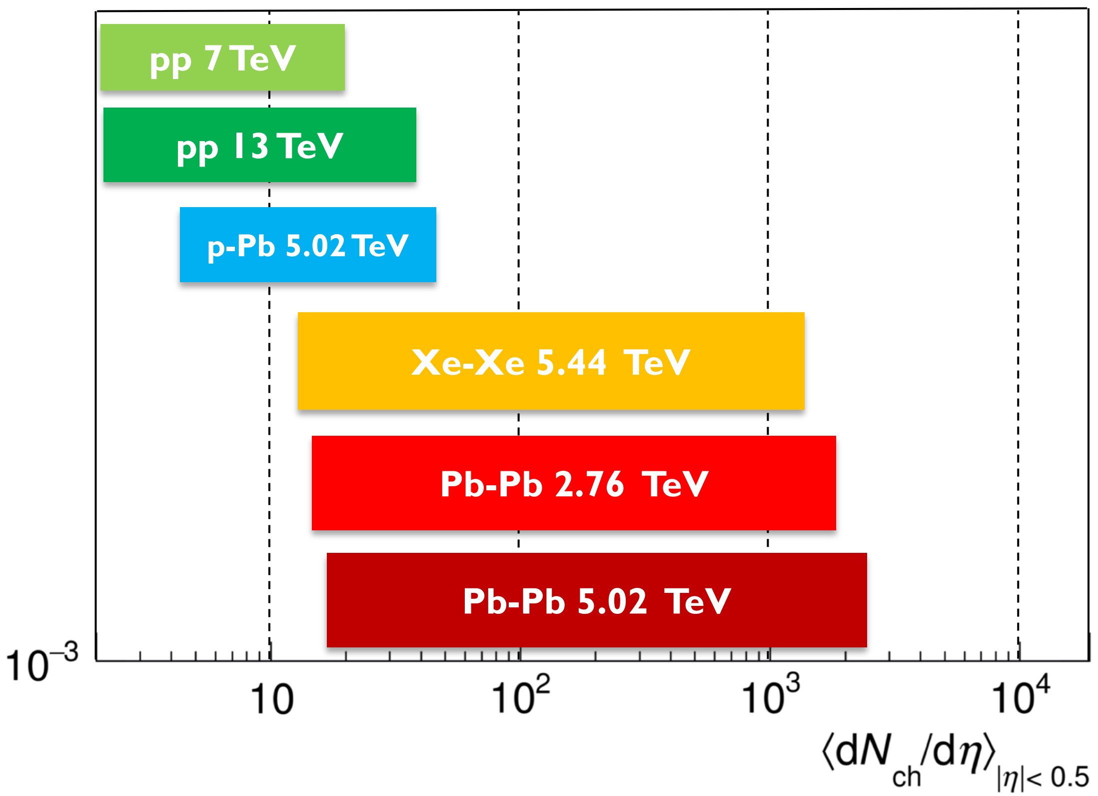






Resulting system size

→ charged particle **multiplicity**



Small systems much more than a reference

First lesson learned at the LHC:

pp, p-nucleus collisions much more than a “reference” for heavy-ion collisions

Focus of today’s talk:

1. **Smooth evolution of particle composition** across collision systems
2. Signatures of **emergent collectivity** in pp, p-Pb collisions
3. Collectivity **without energy loss**?

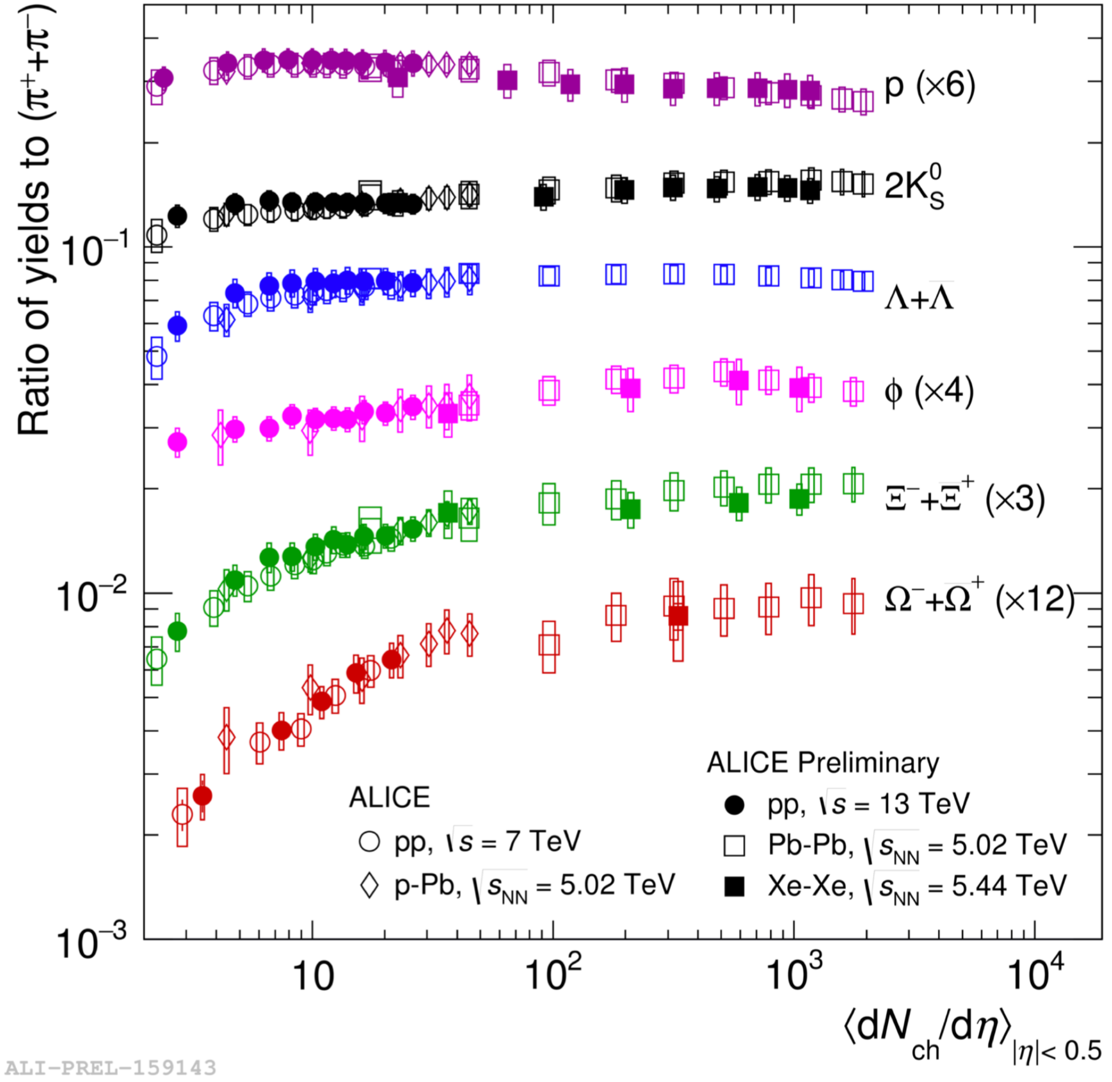
via a **selection** of (few) well known and (mostly) new **experimental** results, as well as some **open points and perspectives** (apologies if biased)!

Smooth evolution of hadro-chemistry

Particle composition evolves smoothly across collision systems, depending on charged particle multiplicity.

Common origin in all systems?

C. Oppedisano - QCD, Thu. 12:57



Strangeness production

Enhancement of strangeness from low to high multiplicity pp, p-Pb collisions, until saturation in Pb-Pb
[ALICE, *Nat. Phys. 13, 535–539 (2017)*]

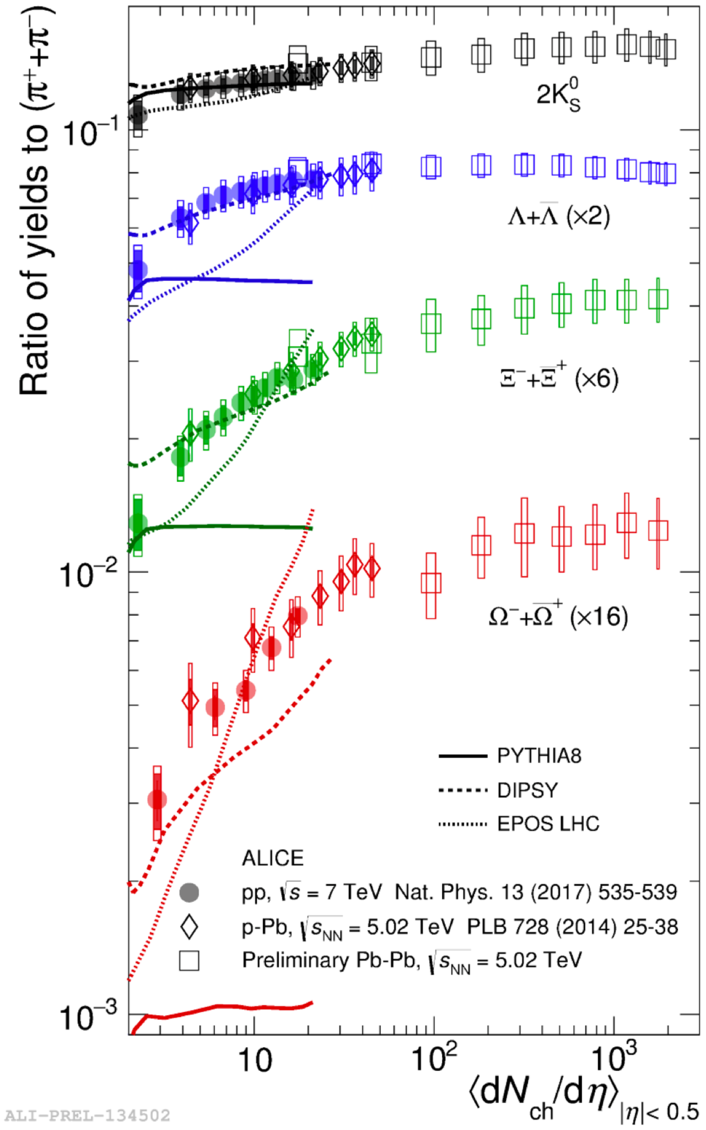
→ confirmed with new data from LHC Run II

Ongoing efforts to explain behavior with models

- Lund string, color ropes (PYTHIA, DIPSY)
- core-corona (EPOS-LHC)
- thermal-statistical (canonical suppression)
  [V.Vislavicius, A. Kalweit, aXiv:1610.03001]

- Conventional pp generators successful, with MPI + CR generating some collectivity, but now cracks.
- Need new framework for baryon production.

T. Sjostrand, Quark Matter 2018



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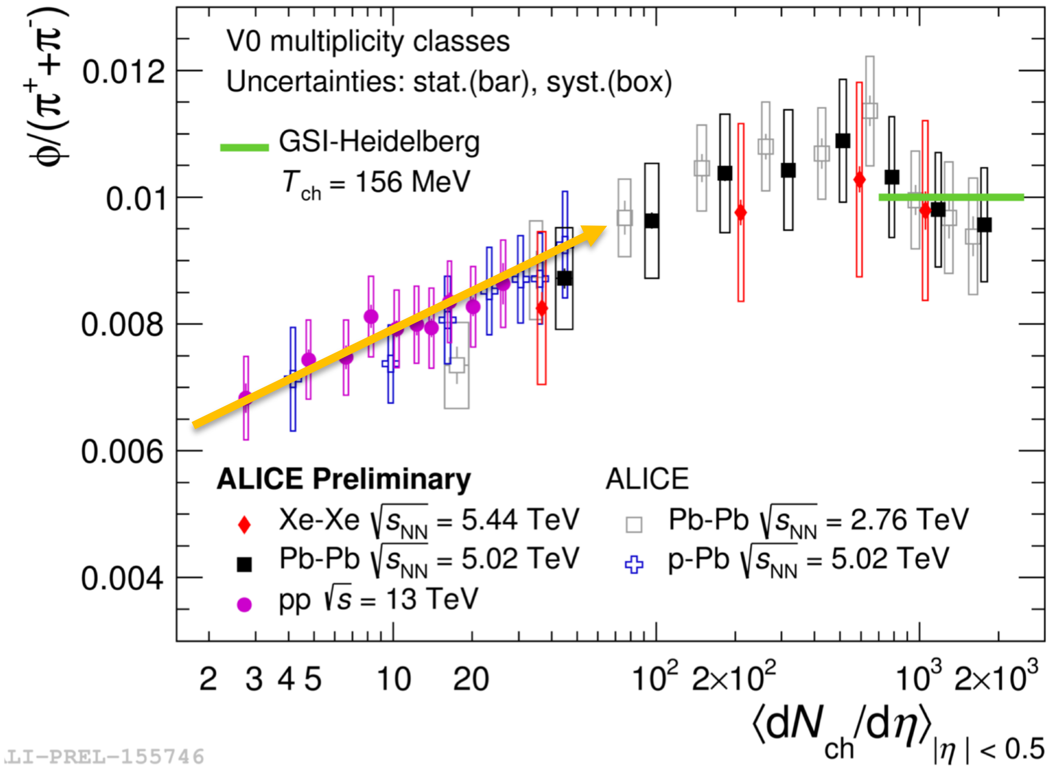
- thermal-statistical (canonical suppression)
  [V.Vislavicius, A. Kalweit, aXiv:1610.03001]

… and with more data, by measuring production of ϕ-meson (hidden strangeness) in small systems!

A. Knospe - HIN, Wed. 12:06



Collectivity (in short)

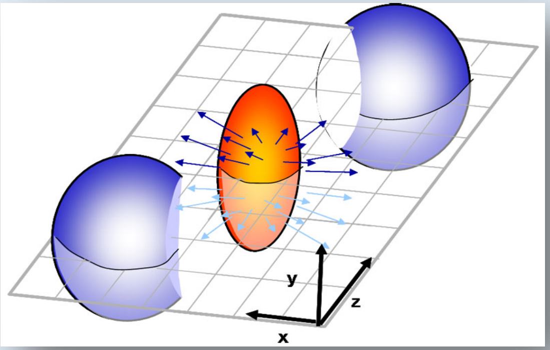
"Loose" definition: correlations of (more than 2) particles across rapidity due to a common source

Origin of collectivity:

- **Initial state** correlations → among hadrons in the final state arise from momentum correlations at partonic level
  [gluon saturation, CGC, see B. Schenke's talk]

- **Final state** correlations → anisotropies and correlations in space converted into anisotropies in momentum space, e.g. via hydrodynamic flow
  [established in Pb-Pb collisions]

Flow in heavy-ion collisions



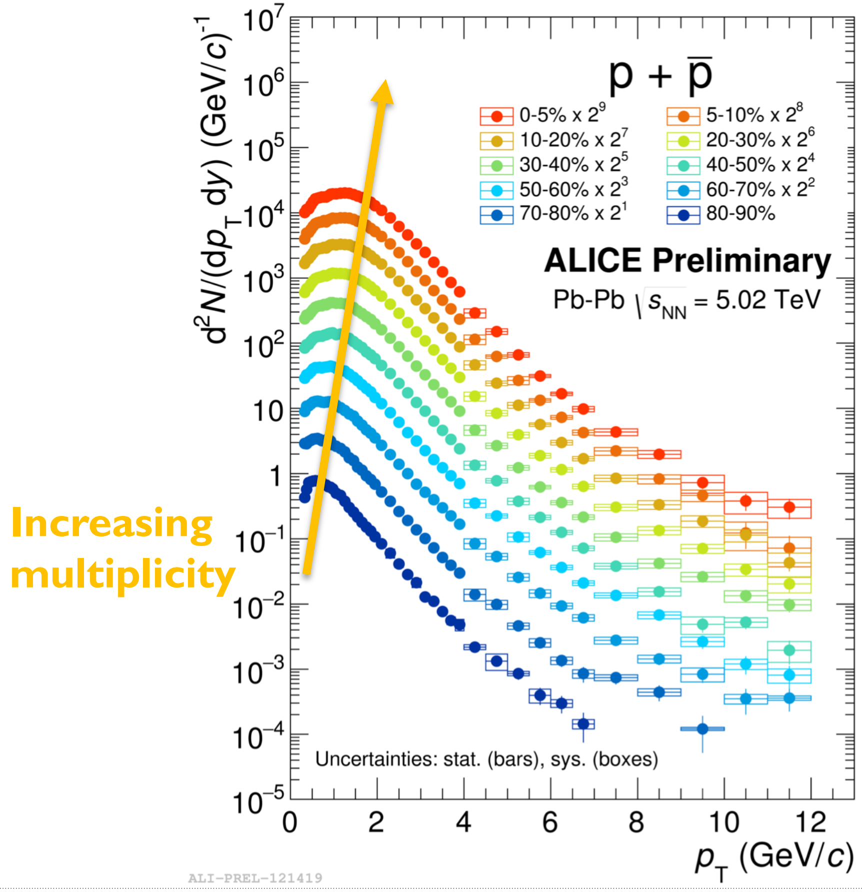
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+2\sum_{n=1}^{\infty} v_n \cos[n(\varphi-\Psi_n)]\right),$$

Characteristic features:

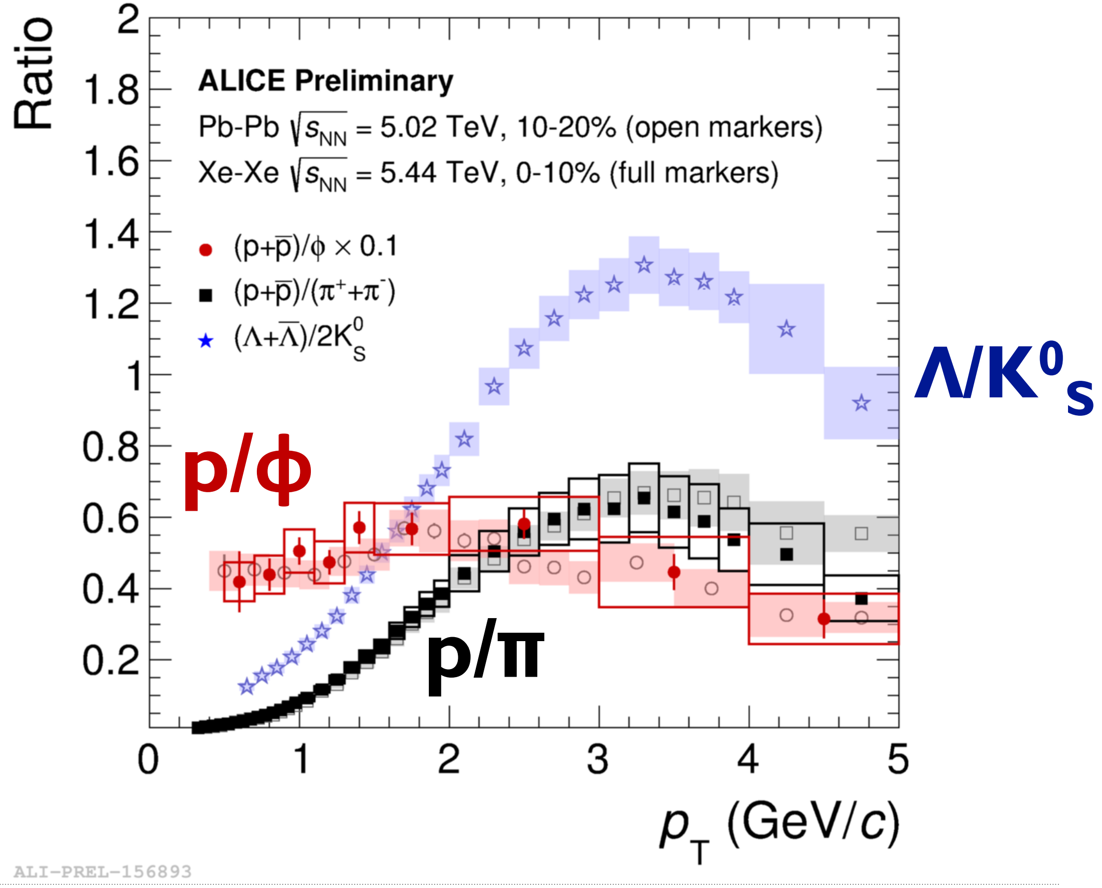
- Multiplicity dependence
- Higher harmonics azimuthal flow
- Mass scaling of v_2
- Correlations between harmonics

The hallmarks of flow in heavy-ion collisions (1)

Increase in mean p_T with increasing centrality
→ Push from radial flow affects low p_T part of spectra

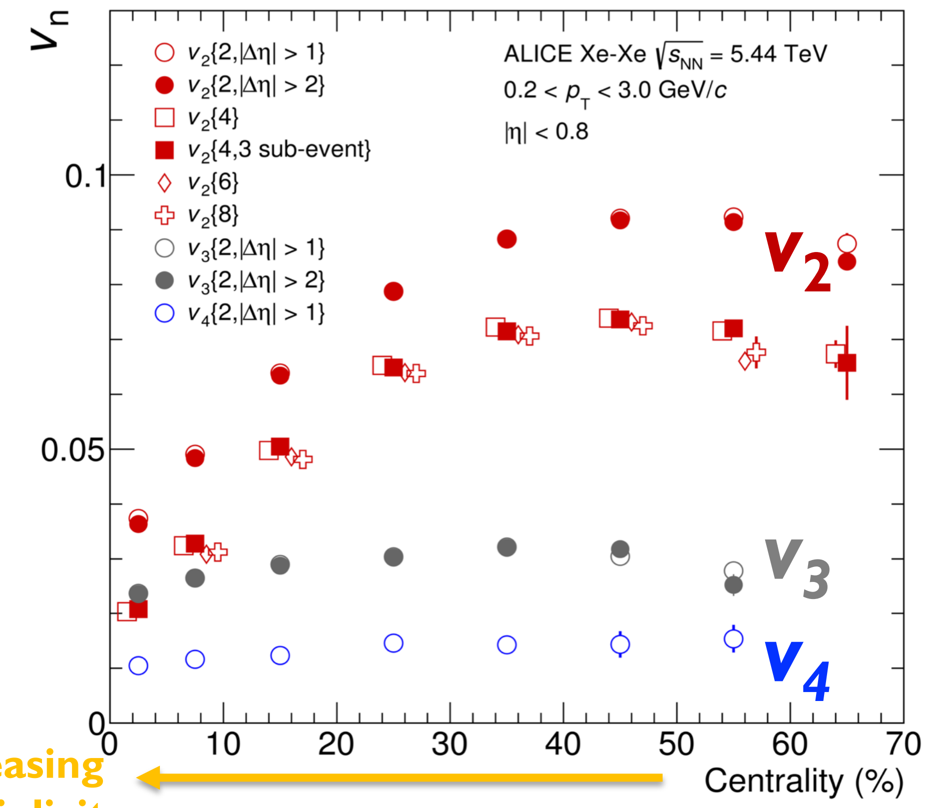


Baryon-to-meson ratios (with Δm)
→ sensitive to particle production mechanisms (radial flow at low p_T, recombination at mid-p_T)



The hallmarks of flow in heavy-ion collisions (2)

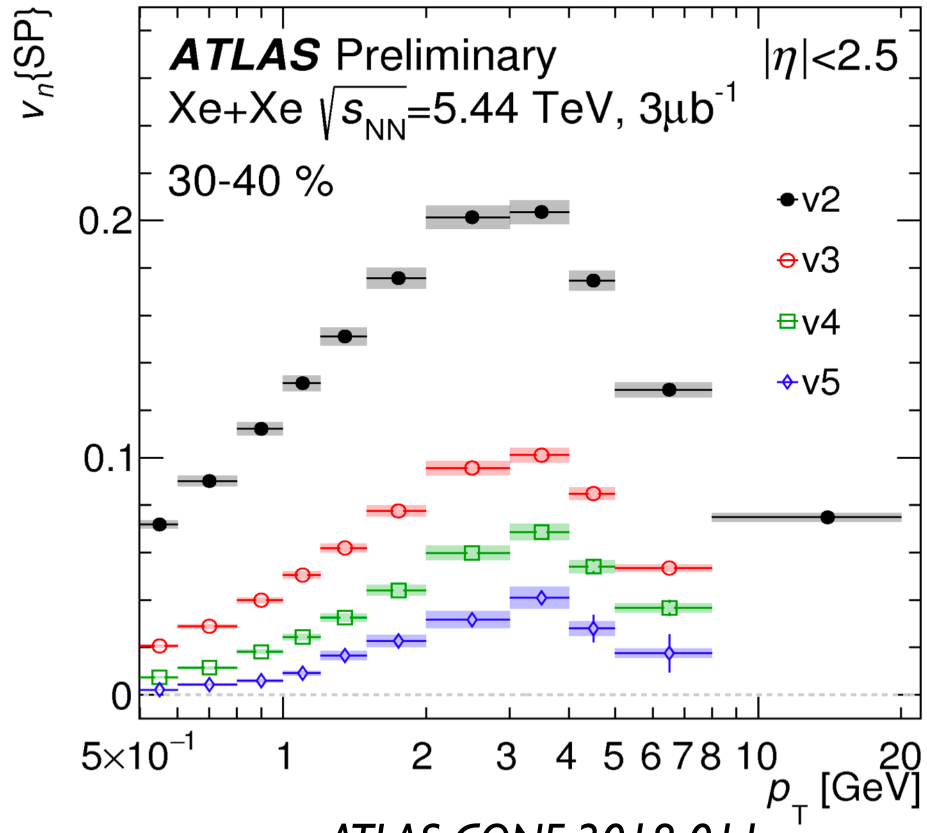
Centrality / multiplicity dependence
→ reflects the degree of "anisotropy" in the initial geometry of the collision



Increasing multiplicity

ALICE, arXiv:1805.01832

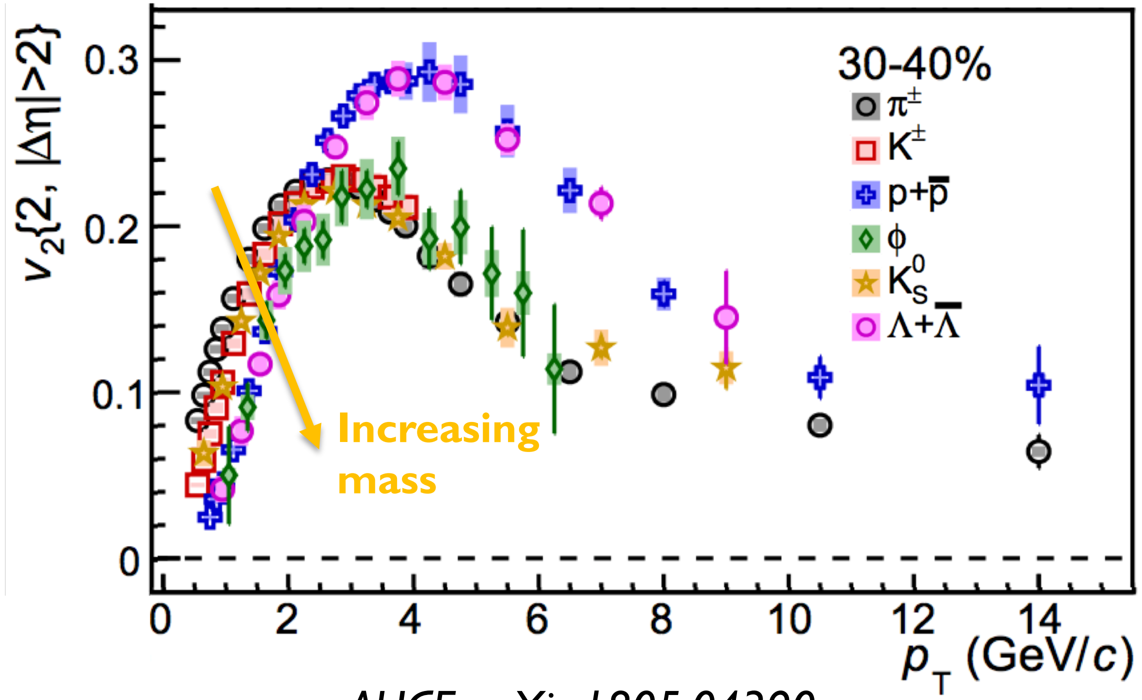
Non-zero higher-order flow coefficients ("harmonics")
→ sensitivity to fluctuations of initial geometry



ATLAS-CONF-2018-011

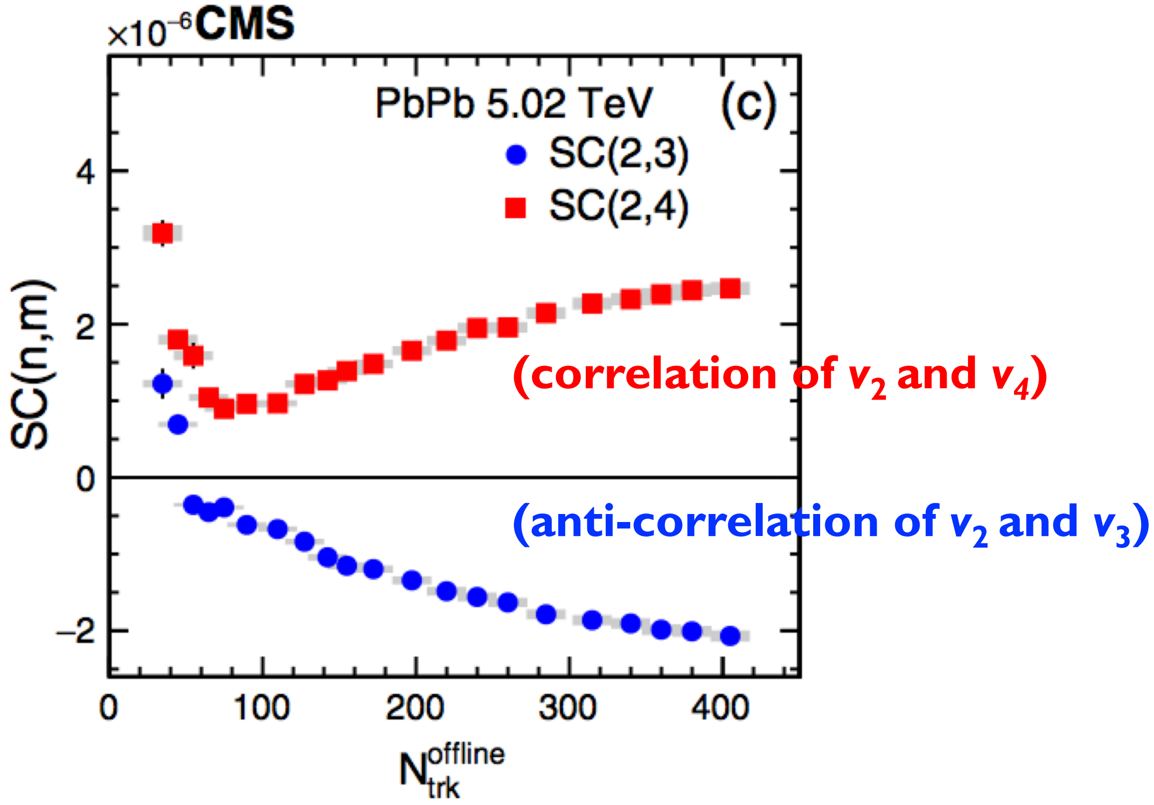
The hallmarks of flow in heavy-ion collisions (3)

Mass scaling of flow coefficients
→ Expansion under a common velocity field



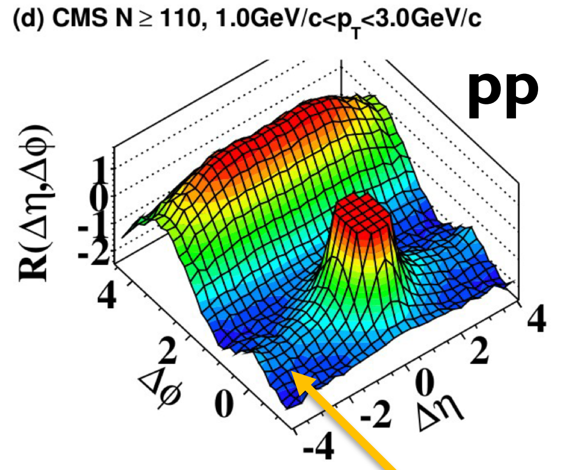
ALICE, arXiv:1805.04390

Correlations between harmonics
→ Sensitivity to fluctuations in initial geometry (v_2, v_3) and medium-transport properties (v_2, v_4)

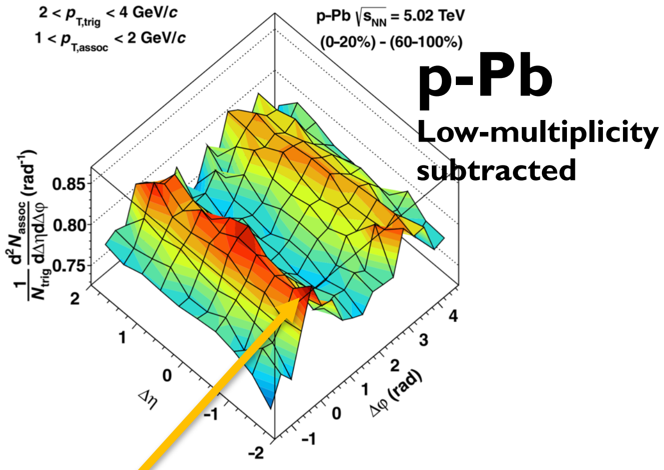


CMS, PRL 120, 092301 (2018)

Signs of collectivity in small systems

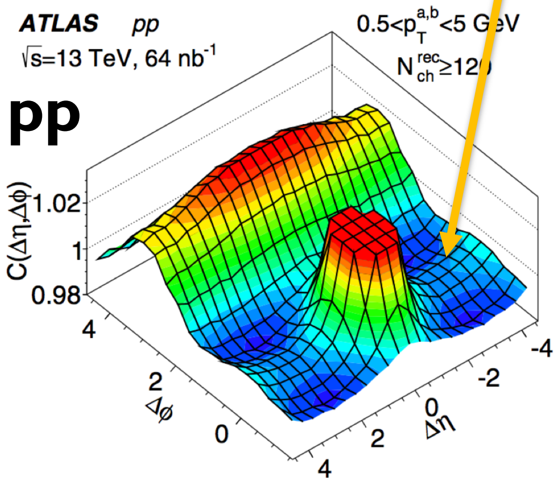


CMS, JHEP 09 (2010) 091

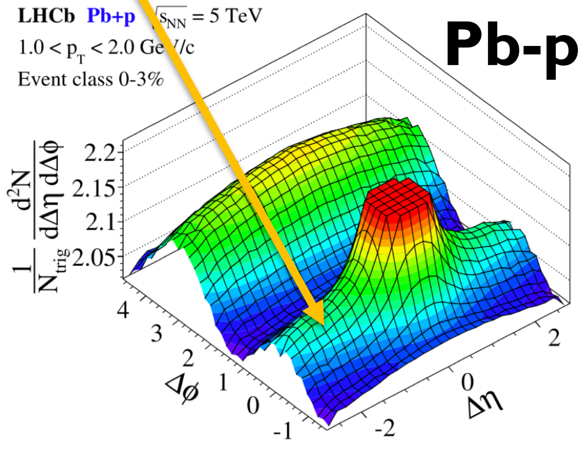


ALICE, PLB 719 (2013) 29

Near side ridge



ATLAS, PRC 96, (2017) 024908



LHCb, PLB 762 (2016) 473–483

Signs of collectivity in **small systems** “discovered” at the LHC in terms of long-range ($2 < |\Delta\eta| < 4$) near-side ($\Delta\phi = 0$) “ridge” in 2-particle correlations, visible in **high multiplicity** pp, p-Pb, Pb-p collisions

Are these long-range correlations coming from (hydrodynamic) flow?

→ Investigated with new measurements with run 2 data, new analysis techniques

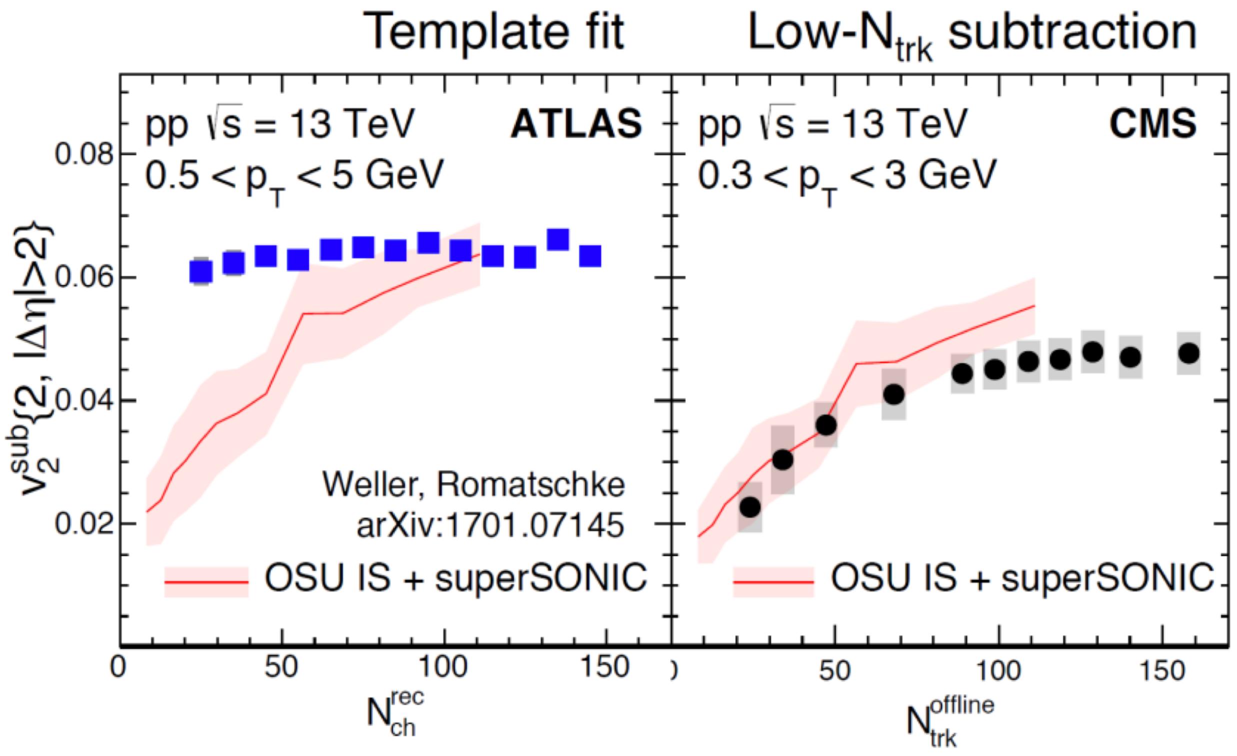
The challenge of removing "non-flow"

In **small systems** the contribution of **non-flow** cannot be neglected:

- Different contribution from jets
- Larger fluctuations in the number of particle sources

A word of **caution**:

- Sensitivity to the event class definitions used in analysis *[ATLAS, EPJ C (2017) 77-428]*
- Sensitivity to strategy for non-flow background subtraction



Non-flow subtraction / suppression is a delicate business in pp, p-Pb!
Big effort ongoing in defining "smart" observables / new techniques

If collectivity, it involves more than 2 particles

Measure elliptic flow v_2 using correlations among k particles in a single event, subtracting correlations from smaller number of particles

[A. Bilanzic et al., PRC 83 (2011) 044913]

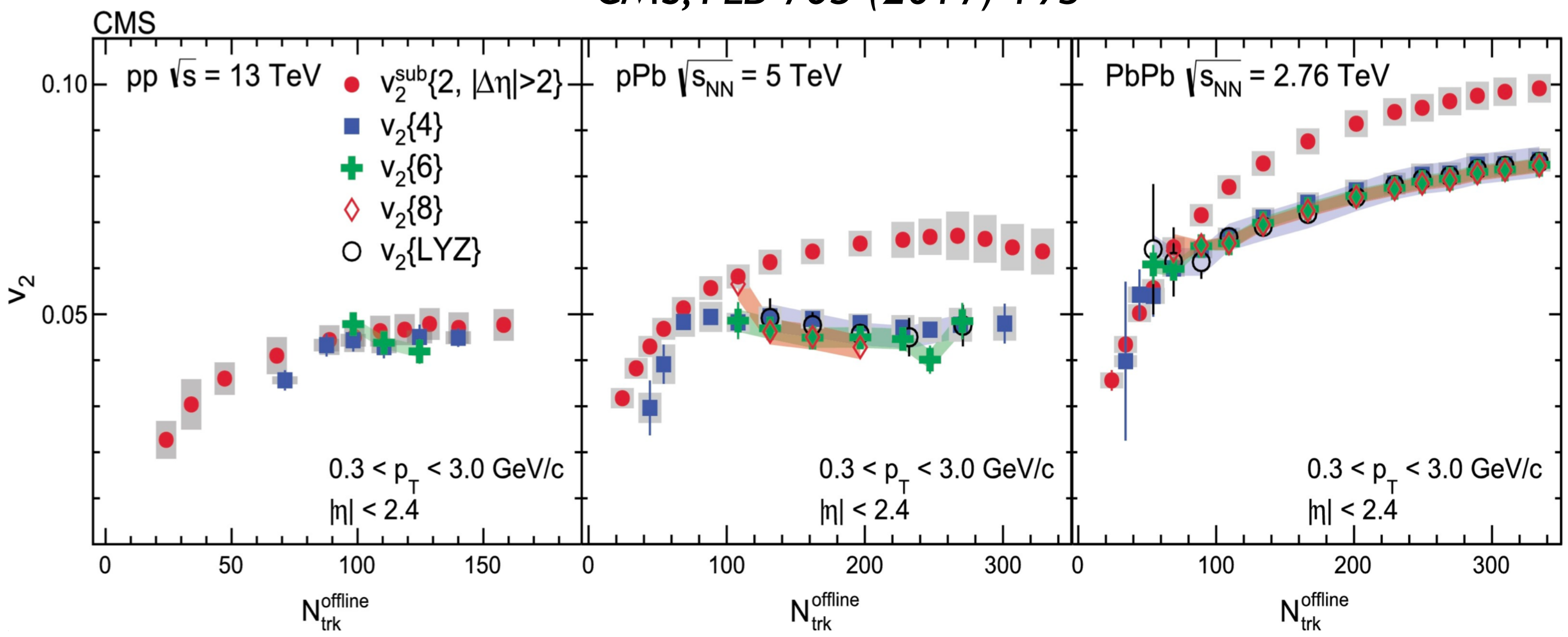
Multi-particle cumulants, $c_n\{k\}$

$$c_n\{2\} = \langle\langle 2\rangle\rangle = \langle\langle \cos n(\varphi_1 - \varphi_2)\rangle\rangle$$
$$c_n\{4\} = \langle\langle 4\rangle\rangle - 2\langle\langle 2\rangle\rangle^2$$
$$c_n\{6\} = \langle\langle 6\rangle\rangle - 9\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle + 12\langle\langle 2\rangle\rangle^3$$

Related to the flow harmonics, $v_n\{k\}$

$$v_n\{2\} = \sqrt{c_n\{2\}},\quad v_n\{4\} = \sqrt[4]{-c_n\{4\}},$$
$$v_n\{6\} = \sqrt[6]{c_n\{6\}/4}.$$

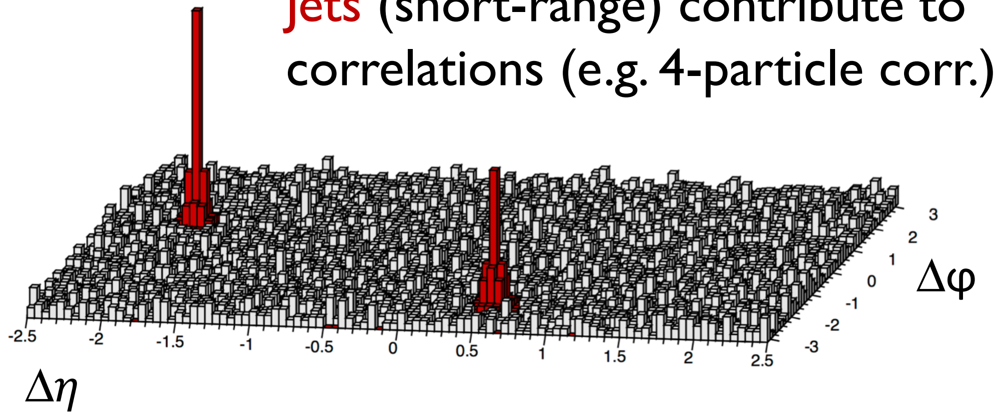
CMS, PLB 765 (2017) 193



If long-range, correlations stay across sub-events

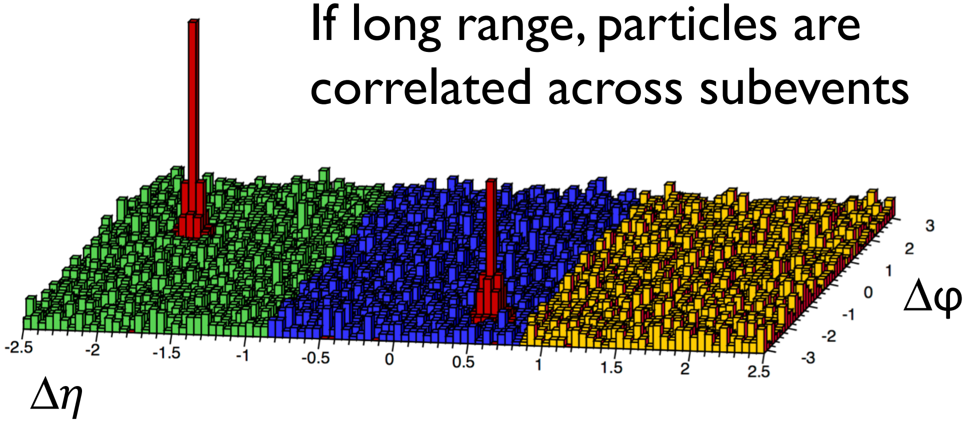
Whole event

Jets (short-range) contribute to correlations (e.g. 4-particle corr.)



≥ 2 Sub-events

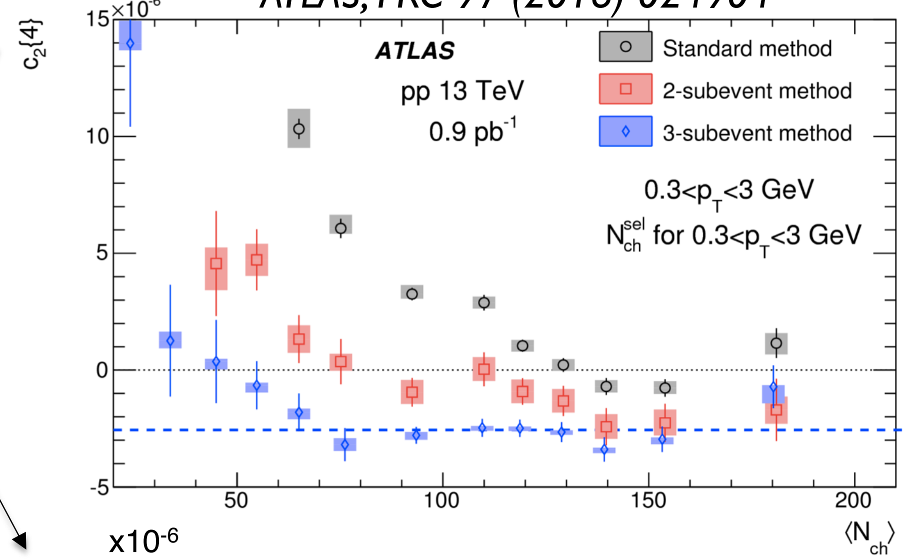
If long range, particles are correlated across subevents



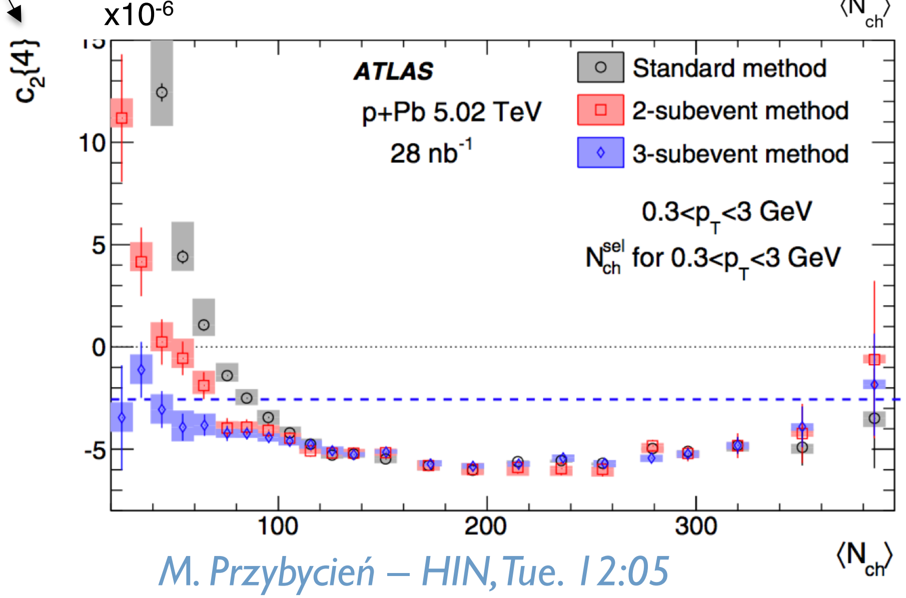
Figures from M. Zhou, QM 2017

J. Jia et al., PRC 96, 034906 (2017)

ATLAS, PRC 97 (2018) 024904



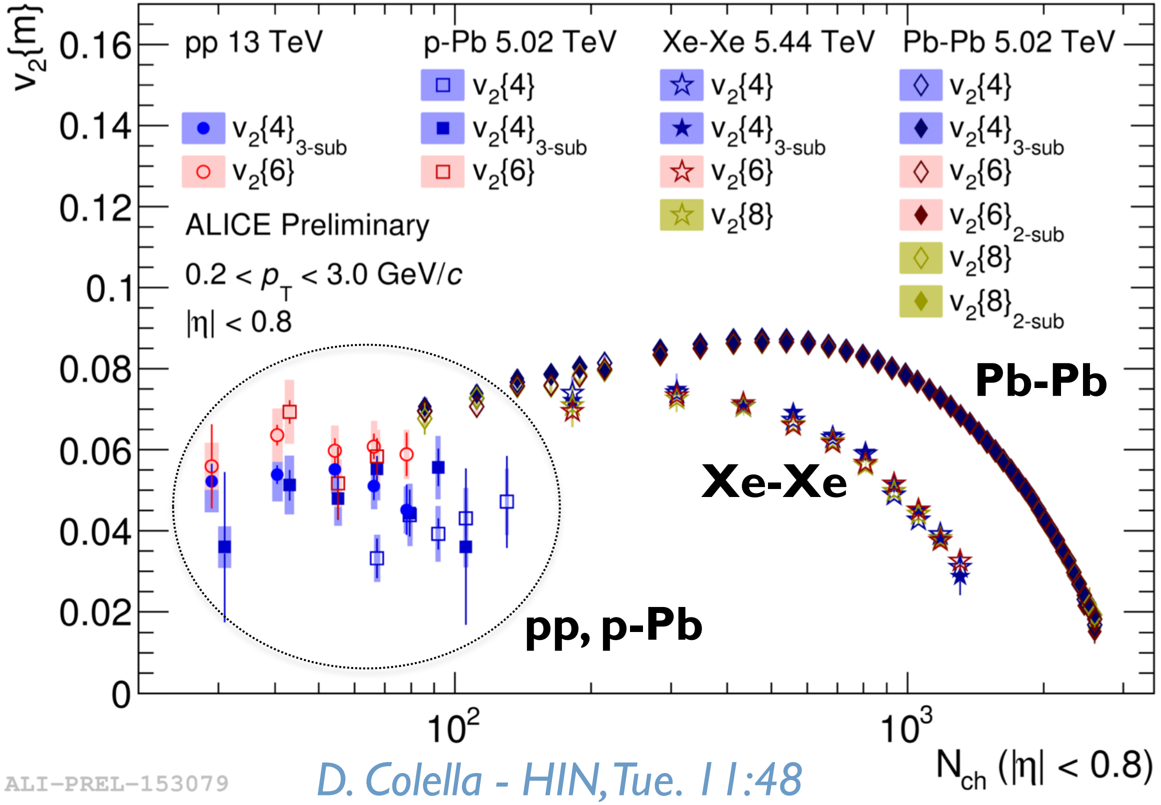
pp



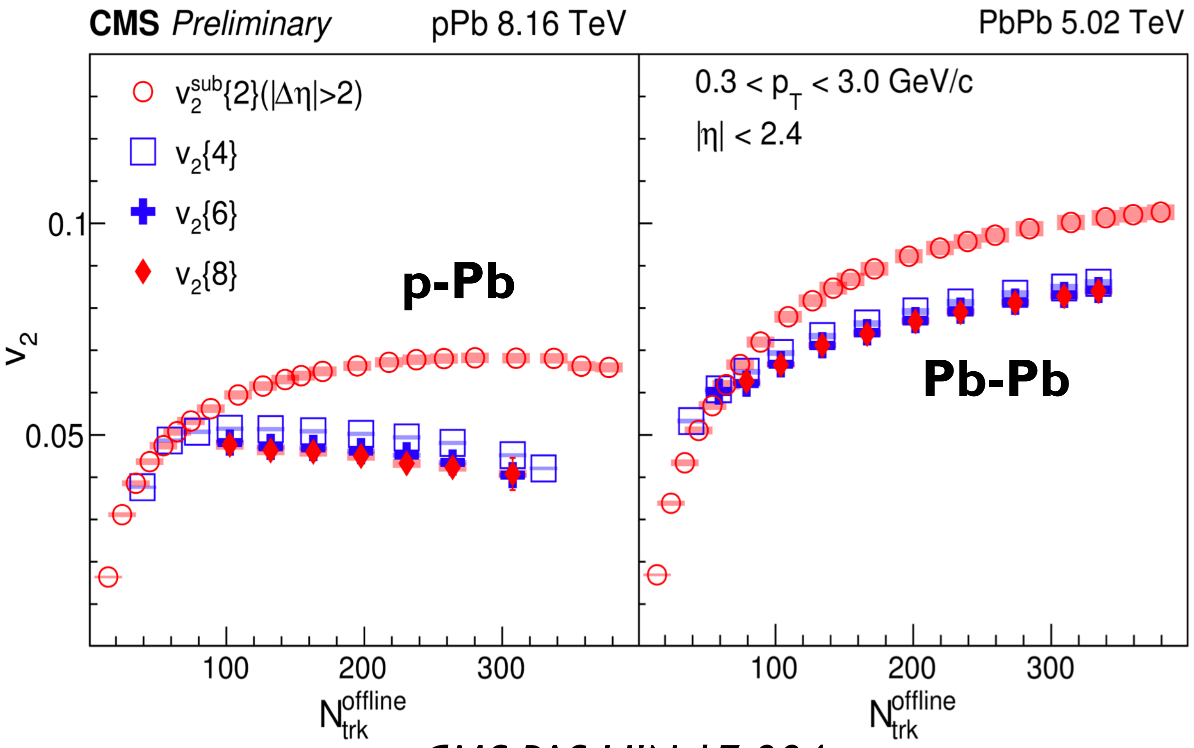
p-Pb

M. Przybycień – HIN, Tue. 12:05

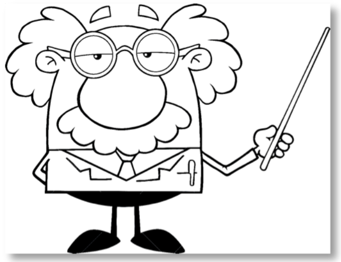
True collectivity in small systems!



D. Colella - HIN, Tue. 11:48

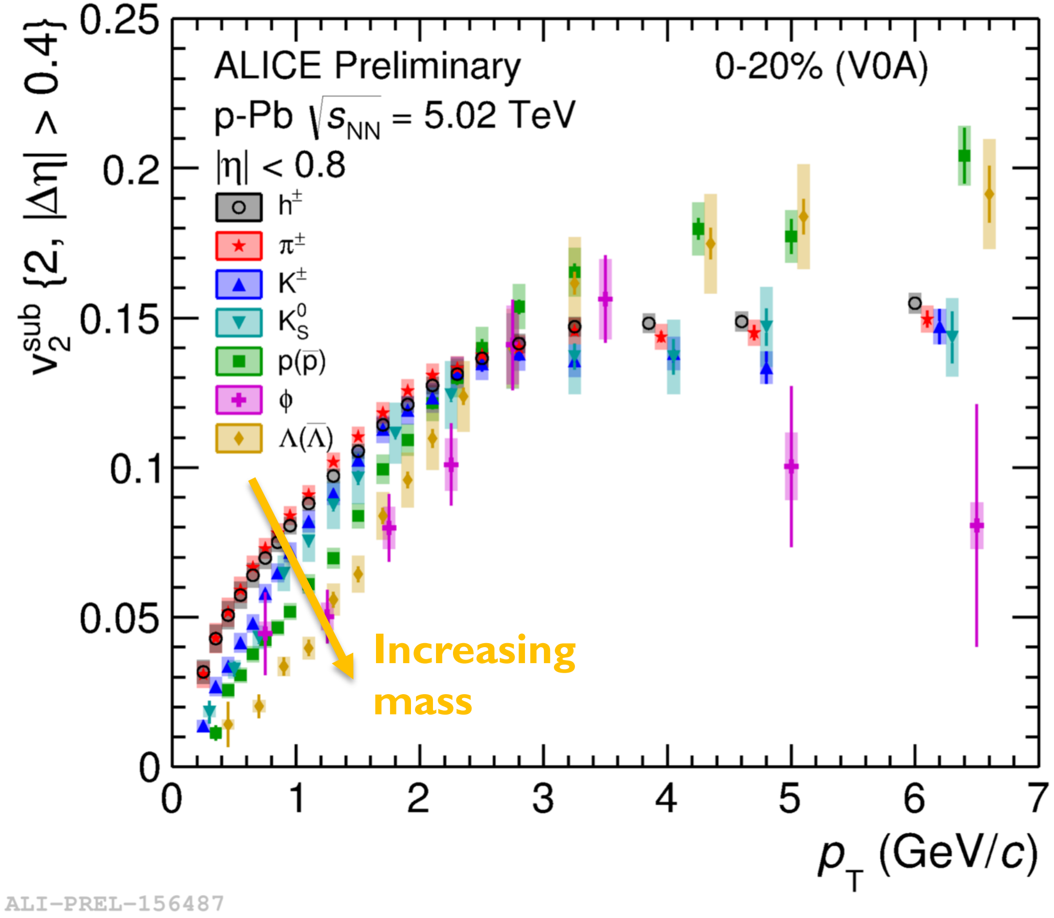


CMS-PAS-HIN-17-004



$v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$ → true collectivity (even) in smallest systems
$v_2\{2\}$ larger → residual "non-flow"

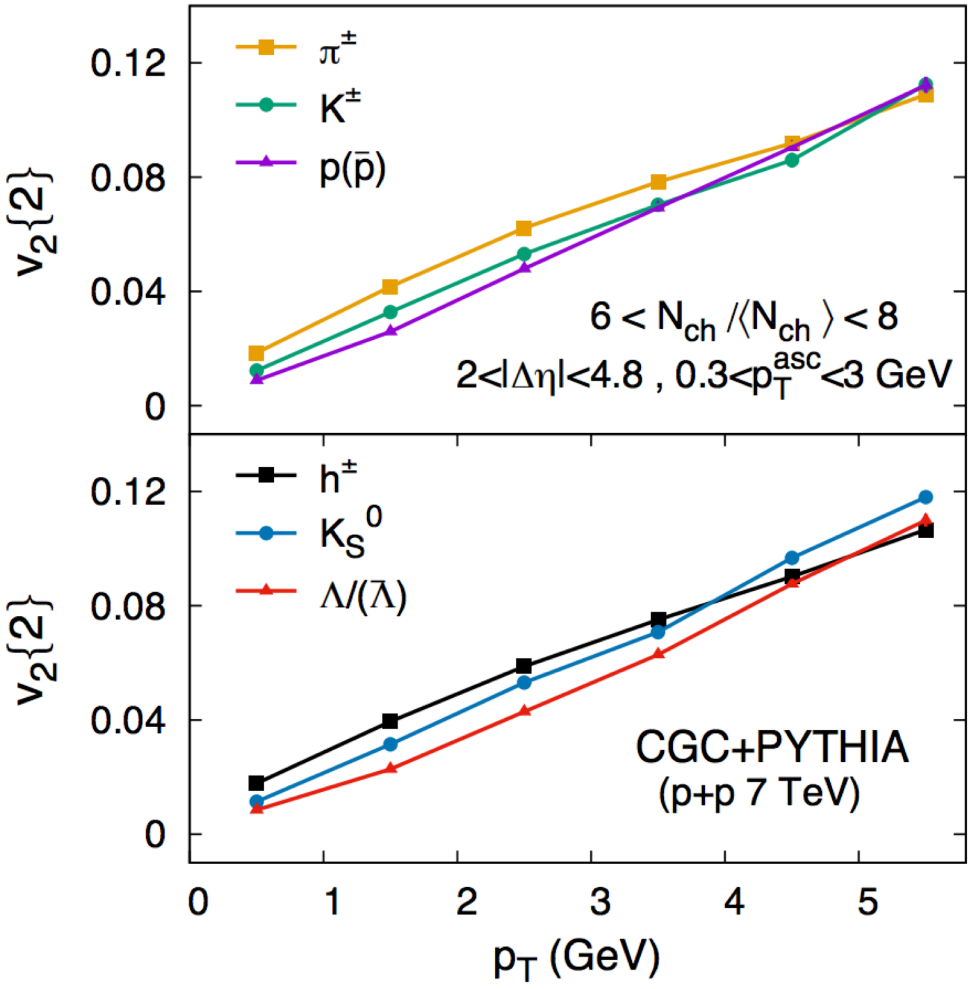
Light-flavor particle v_2



Clear **mass ordering** at **low p_T** in p-Pb from new results on v_2^{sub} for identified hadrons

→ Consistent with hydrodynamics (and AA)

Light-flavor particle v_2



P.Tribedy, Quark Matter 2018

Clear **mass ordering** at **low** $\boldsymbol{p_T}$ in p-Pb from new results on v_2^{sub} for identified hadrons

→ Consistent with hydrodynamics (and AA)

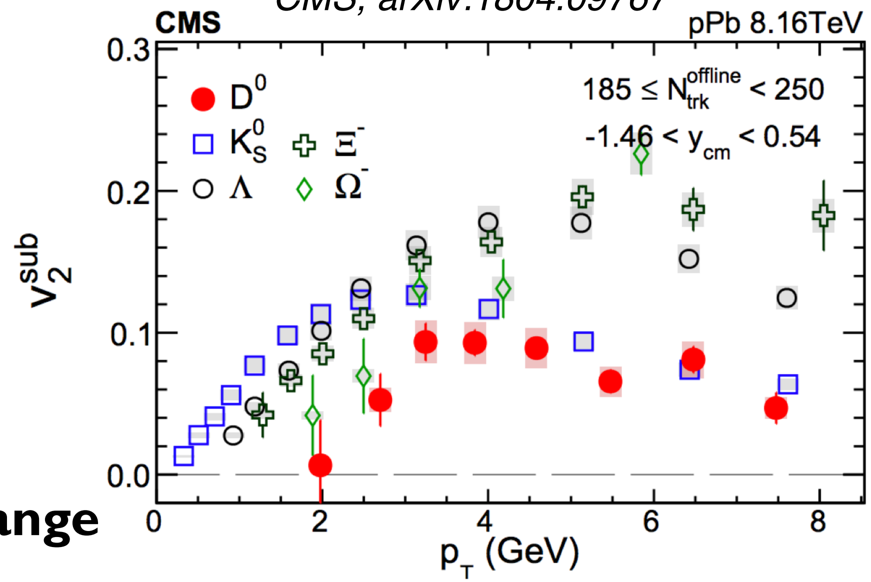
BUT it could also be due to other effects

- Initial stage effects (CGC + PYTHIA)
- Parton escape (AMPT)
- Hadronic rescattering (UrQMD)

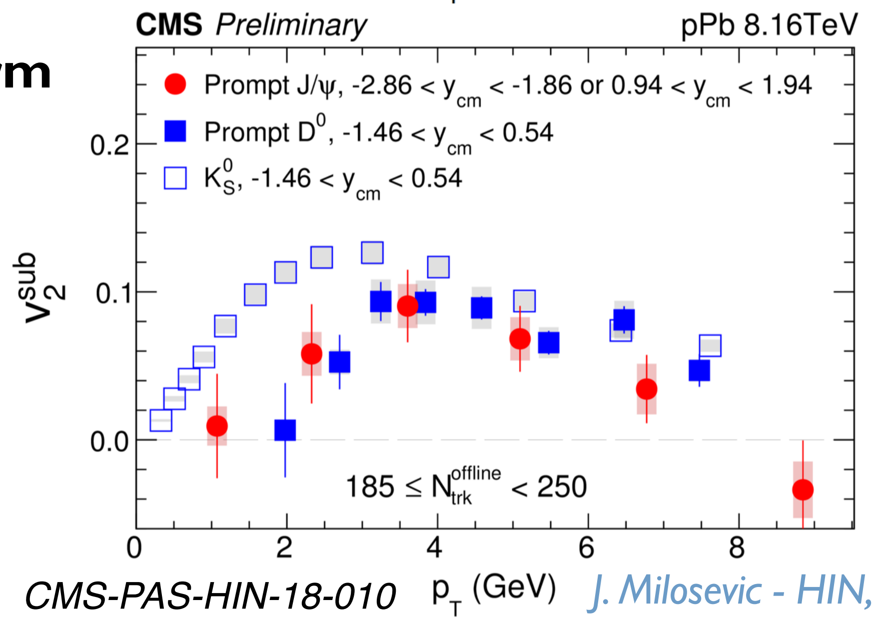
Is mass ordering no longer an exclusive product of hydrodynamic flow?

Heavy-flavor particle v_2 in p-Pb

CMS, arXiv:1804.09767

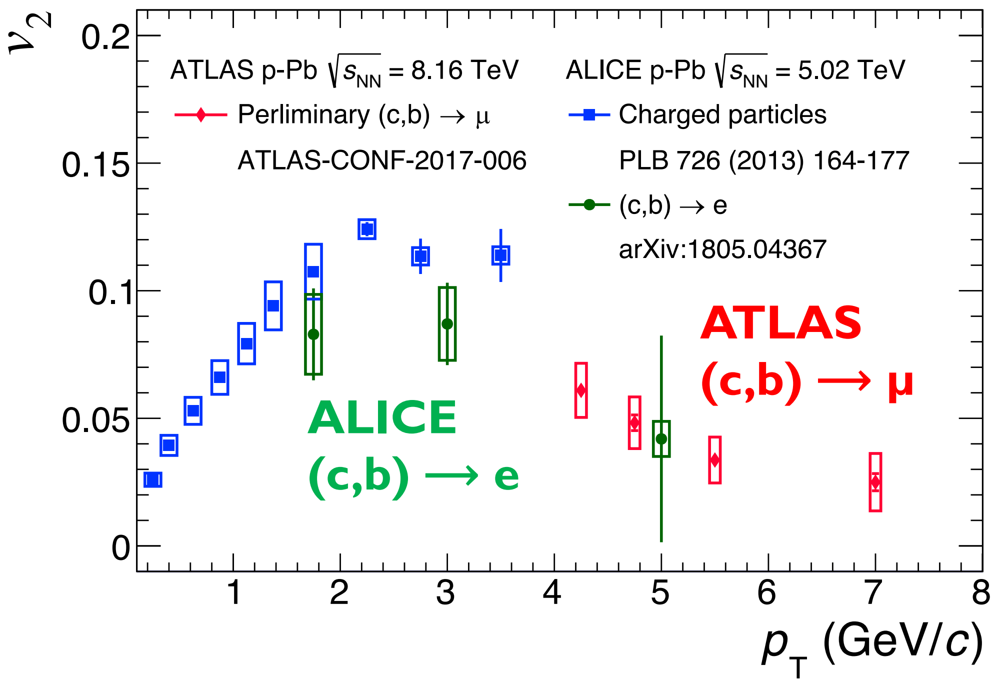


Strange and charm

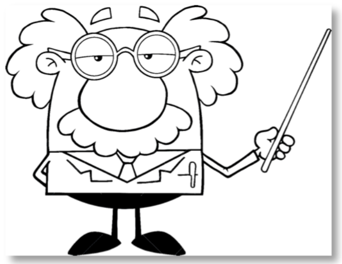


CMS-PAS-HIN-18-010

ALICE, arXiv:1805.04367, ATLAS-CONF-2017-006



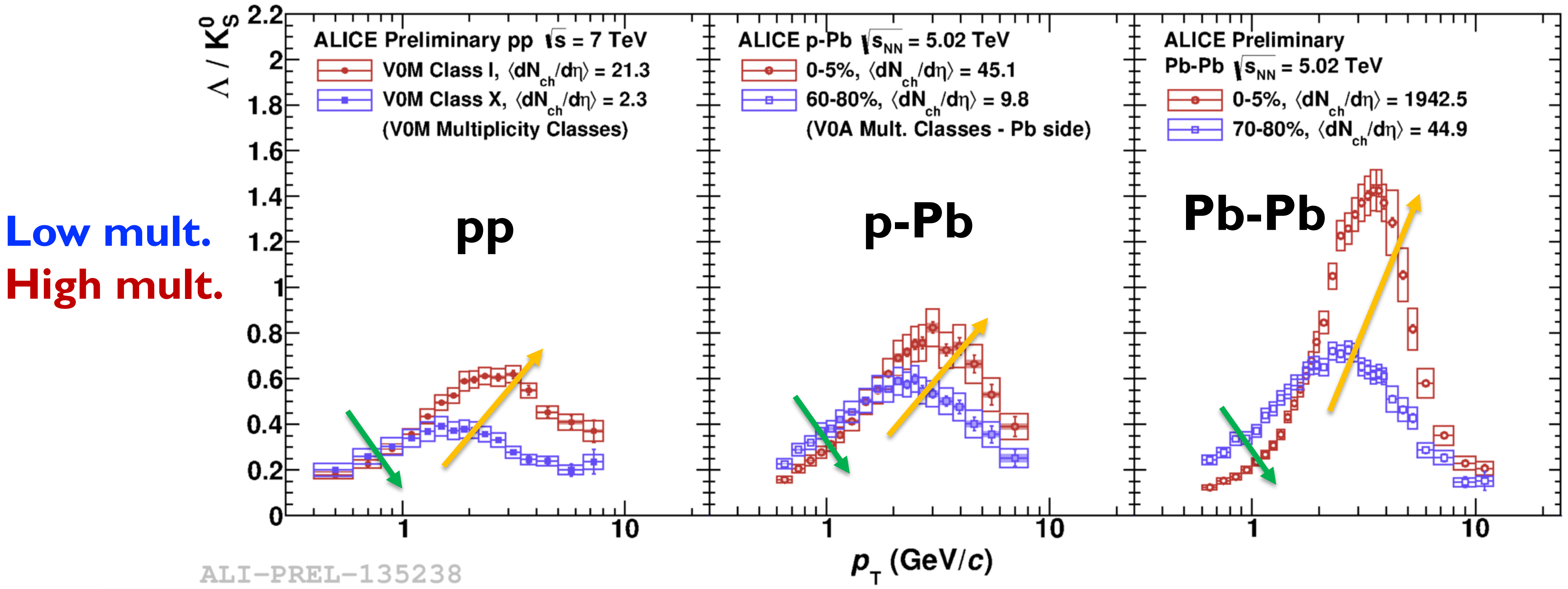
Charm, beauty to leptons

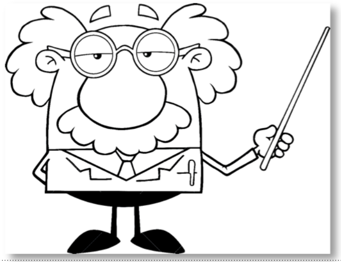


Both light- and heavy-flavour hadrons show large azimuthal anisotropy in p-Pb collisions, up to 7-8 GeV/c

J. Milosevic - HIN, Tue. 12:24

Baryon-to-meson production – light-flavor sector

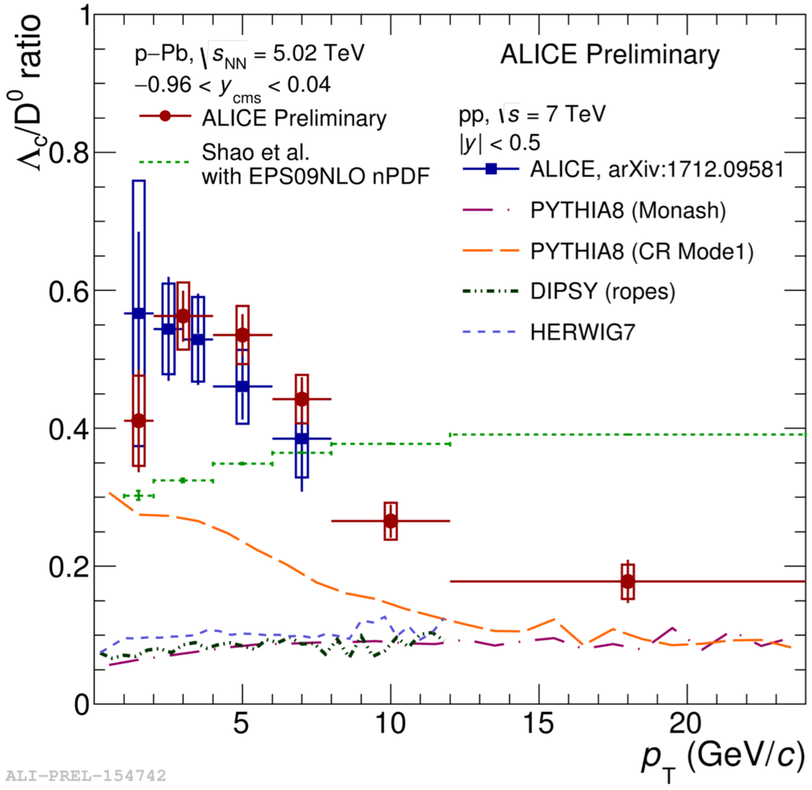




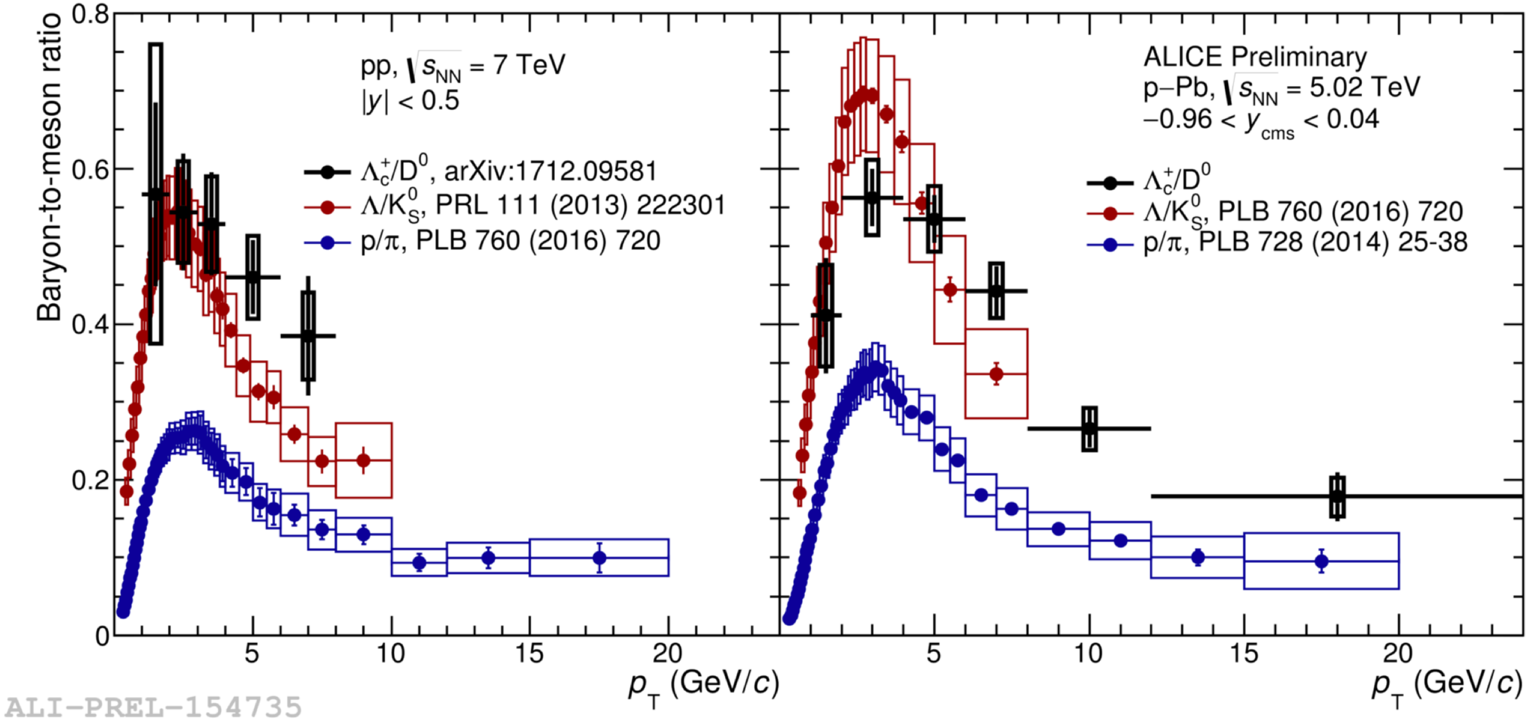
Across the three systems the baryon-to-meson ratios evolve **with multiplicity** in a qualitatively similar way

Baryon-to-meson production – heavy-flavor sector

ALICE, arXiv:1712.09581

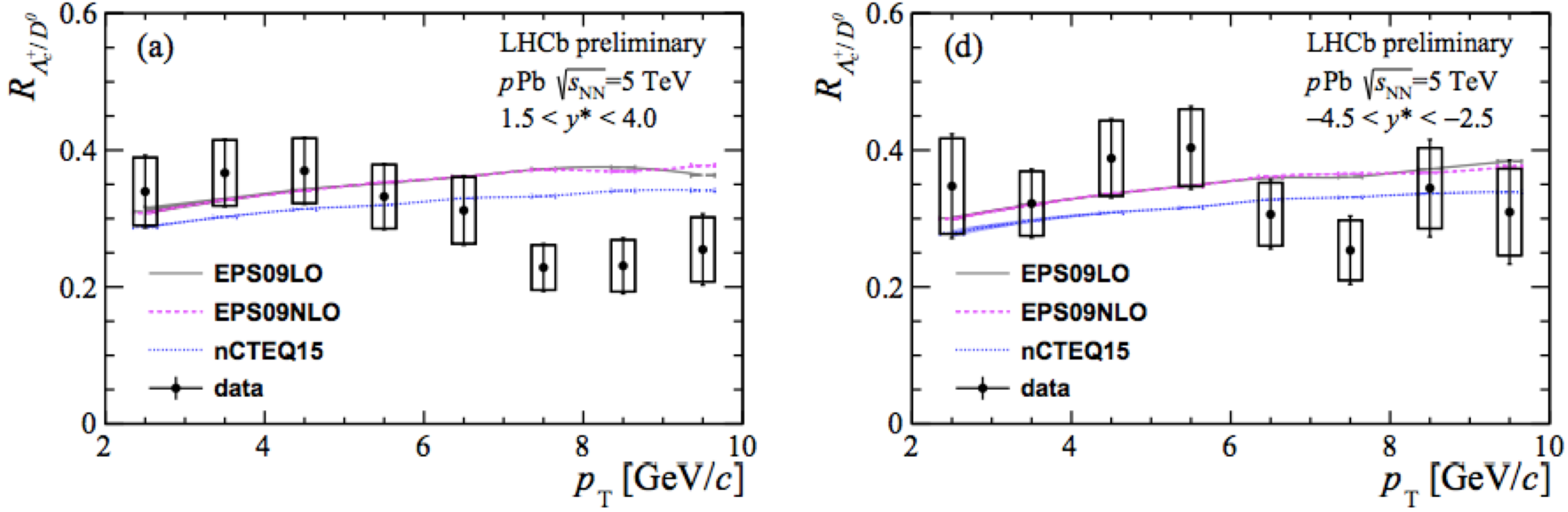


F. Prino – QCD/HF, Tue. 15:15



MC generators fail in reproducing the measured Λ_c/D^0
Heavy flavor baryon-to-meson ratio similar to light-flavors (Λ/K^0_S)

Baryon-to-meson production – heavy-flavor sector



LHCb-PAPER-2018-021

Measurements in forward rapidity region provide further input for understanding charm fragmentation

Collectivity but no jet quenching?

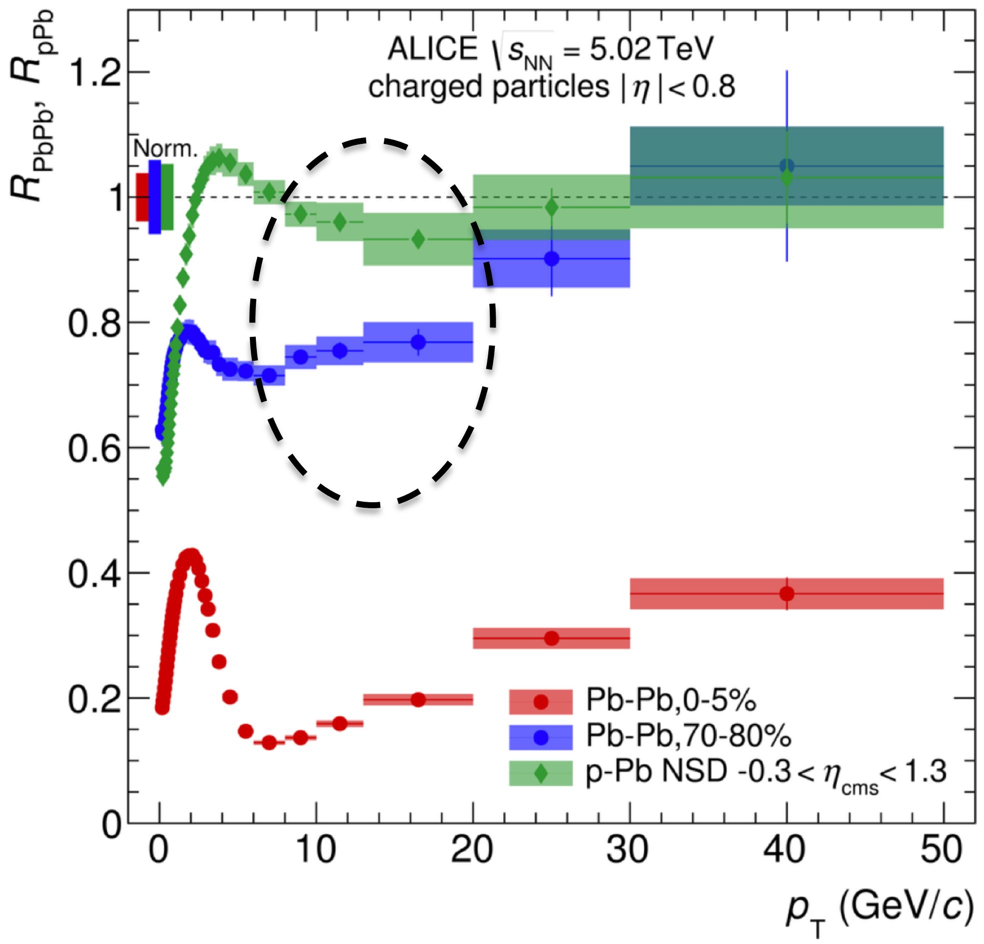
Similarities are observed for flow observables between **peripheral Pb-Pb and high multiplicity p-Pb** collisions.

New and more precise measurements from ALL experiments on nuclear modification factors.

In (minimum bias) **p-Pb**, no suppression at high-p_T is observed, contrary to **peripheral Pb-Pb.**

→ *Do we understand this?*

ALICE, arXiv:1802.09145



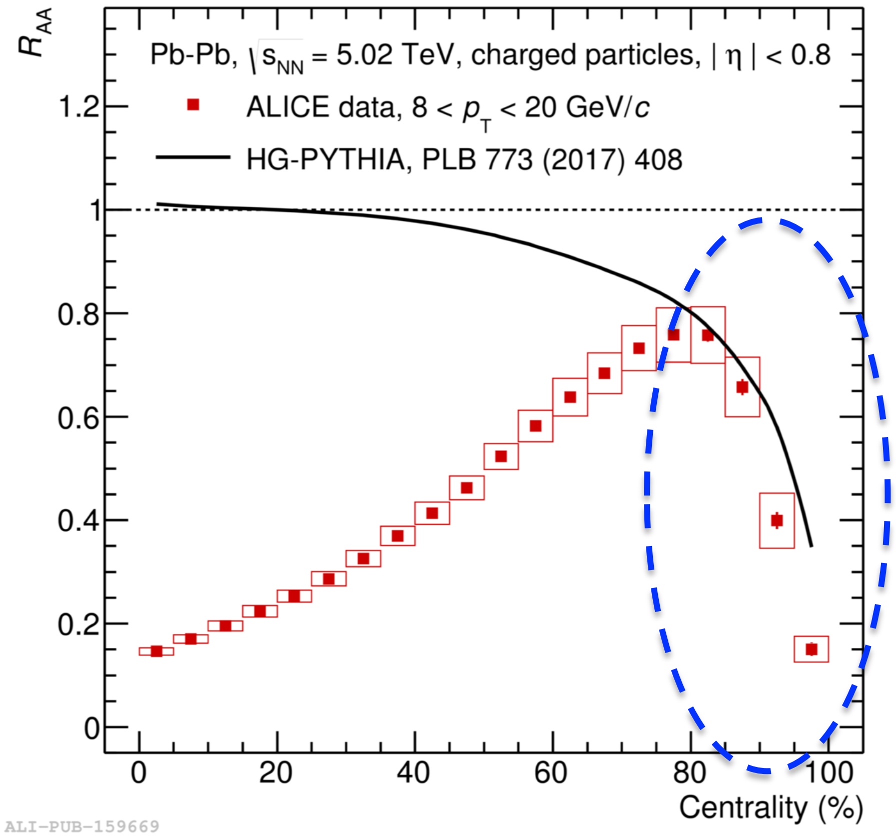
Nuclear modification in very peripheral collisions

Strong change of behaviour of R_{AA} beyond 80% centrality

→ reproduced by HG-PYTHIA with **biases** in event selection and collision geometry, and no nuclear modification.

Considering this, the jet quenching signal is smaller than typical systematics above ~80% centrality → **consistent with R_{pPb}**

ALICE, arXiv:1805.05212



C. Klein-Boesing – HIN, Fri. 15:30

Look for jet quenching in p-Pb

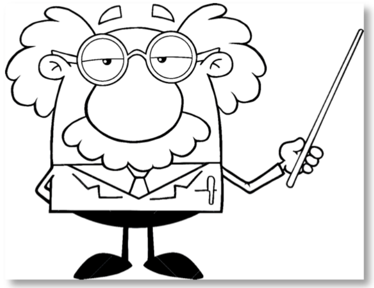
Look for **jet quenching in p-Pb** by

- comparing jet-hadron correlations in low and high multiplicity p-Pb events
  [C. Klein-Boesing – HIN, Fri. 15:30]
- checking how much energy is transferred "out-of-cone" by jet-quenching
  [ALICE, arXiv:1712.05603]
- caution with biases in centrality selections
  [ATLAS, PLB 748 (2015) 392-413, ALICE, arXiv:1712.05603]

If existing at all, jet quenching in p-Pb is a very small effect.

Beware of selection biases !

Conclusions and outlook



Continuity in chemistry and dynamics across collision systems (dependence on charged particle **multiplicity**) is observed.

Many **new** precise measurements, new techniques and efforts to provide **"bullet-proof" observables** to measure collective effects in small systems.

MC generators can generate collective-like behaviour but **fail in the details** of hadron (baryon) production as a function of multiplicity.

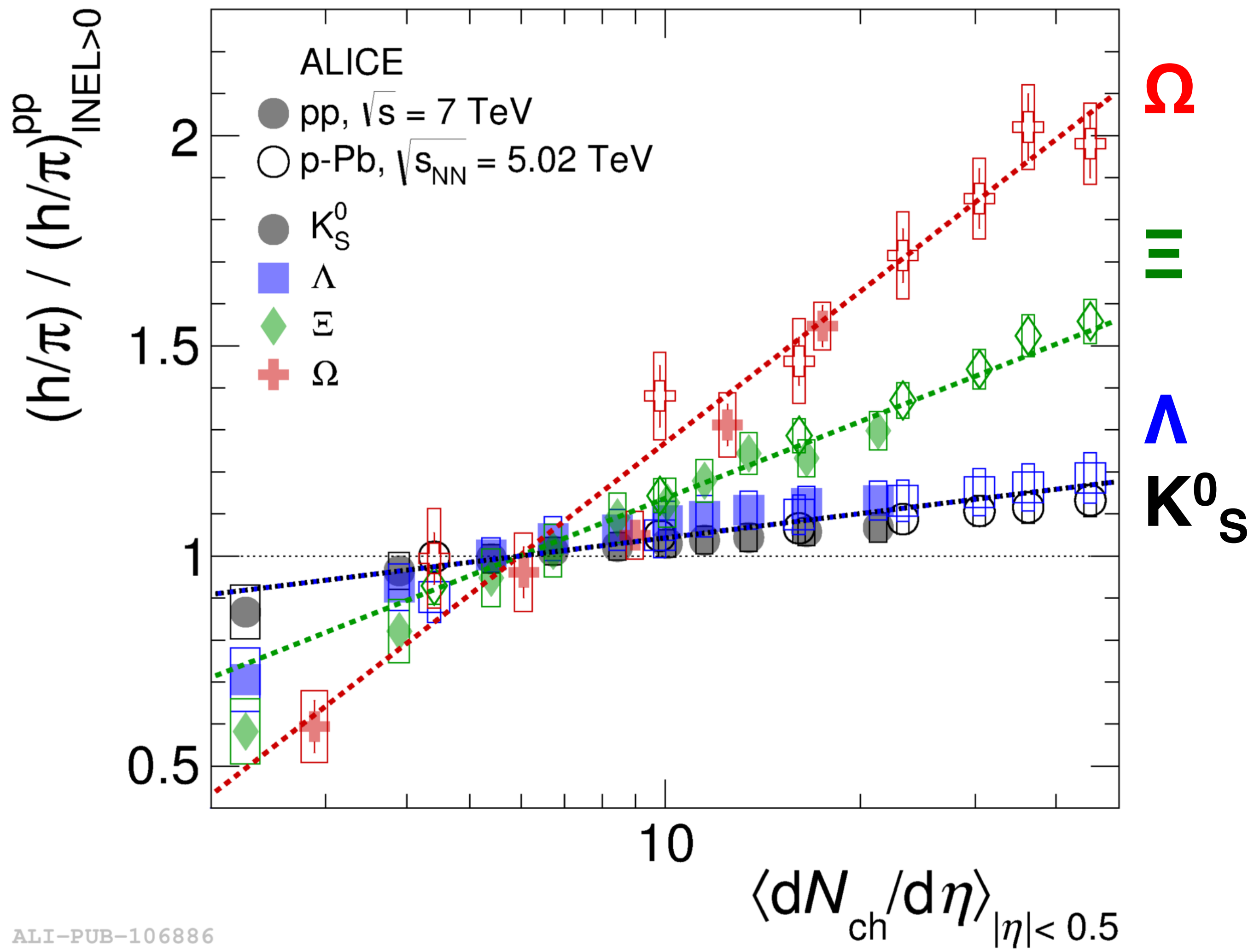
Absence of jet-quenching in small systems remains as the main **challenge to the final-state effect interpretation**.

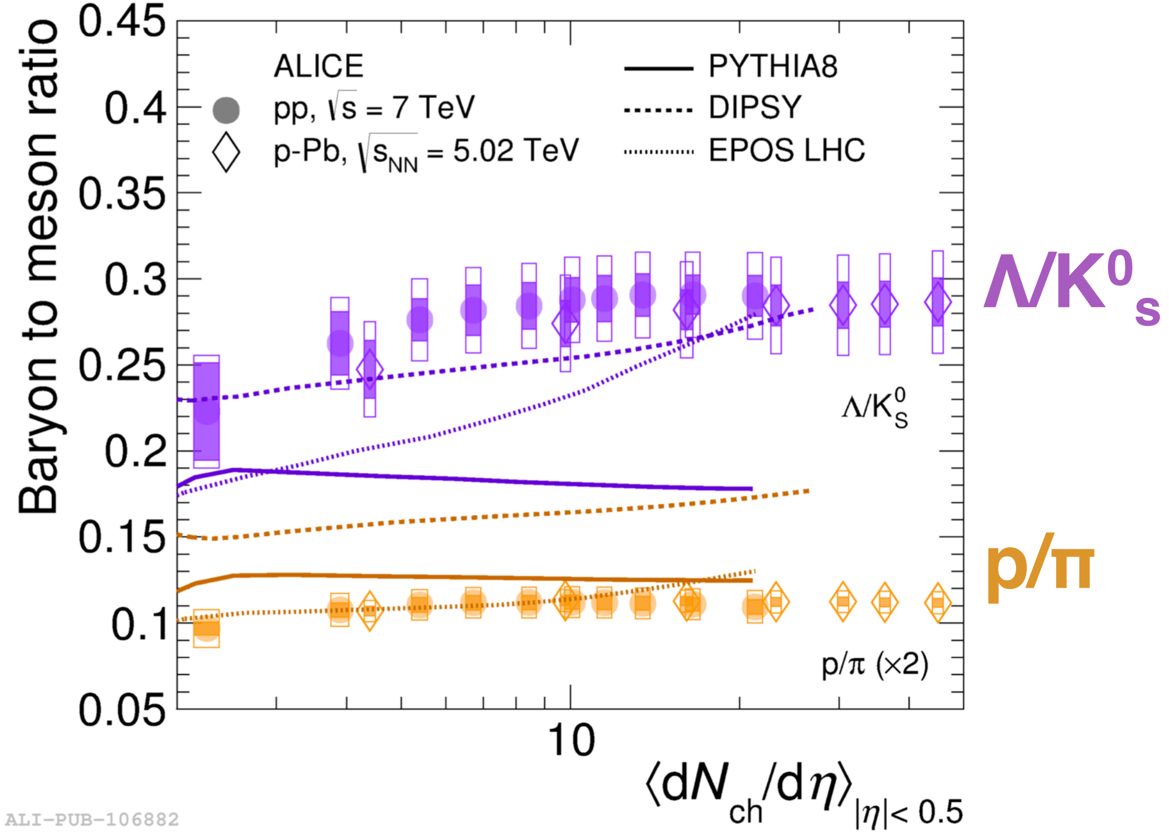
Origin of collectivity in small systems is still **to be understood**.

EXTRA

Strangeness enhancement in small systems

ALICE, *Nat. Phys. 13, 535–539 (2017)*





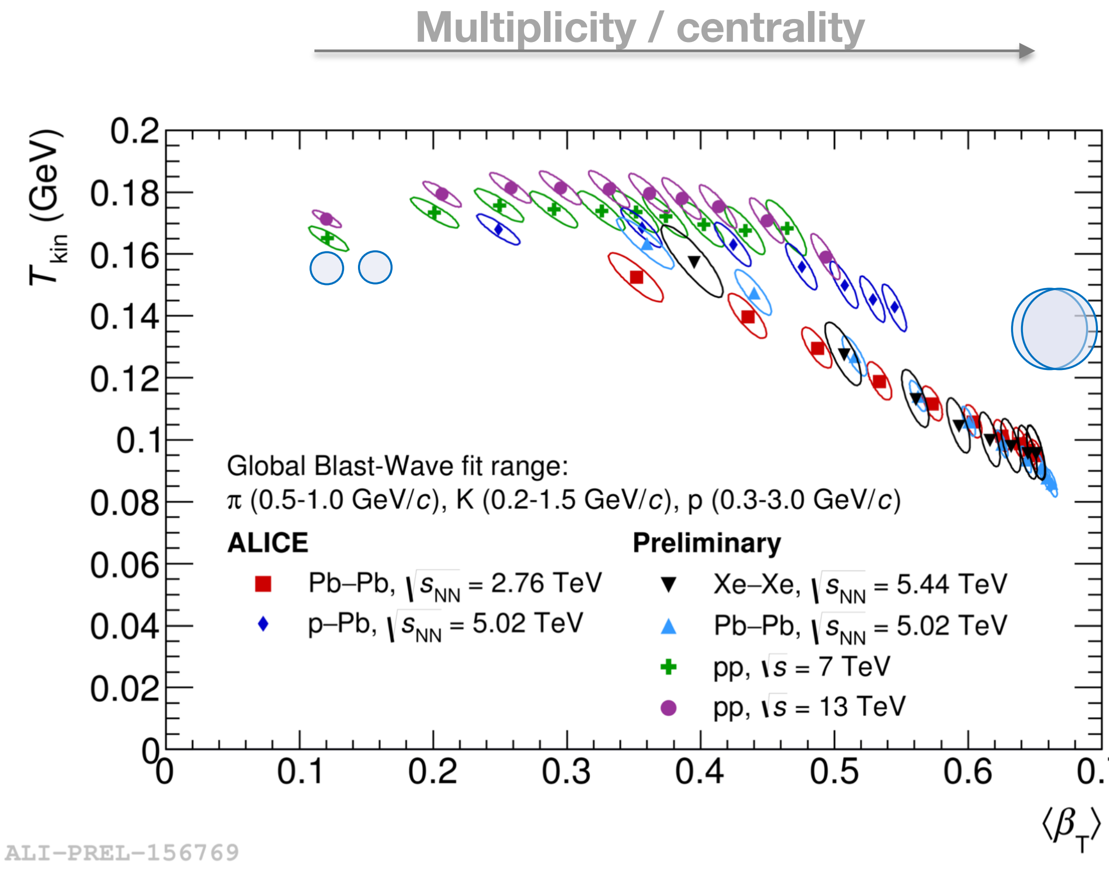
Blast-Wave model fits to particle spectra

Boltzmann-Gibbs Blast-Wave used to quantify radial flow *[E. Schnedermann et al., Phys. Rev. C48 (1993) 2462]*

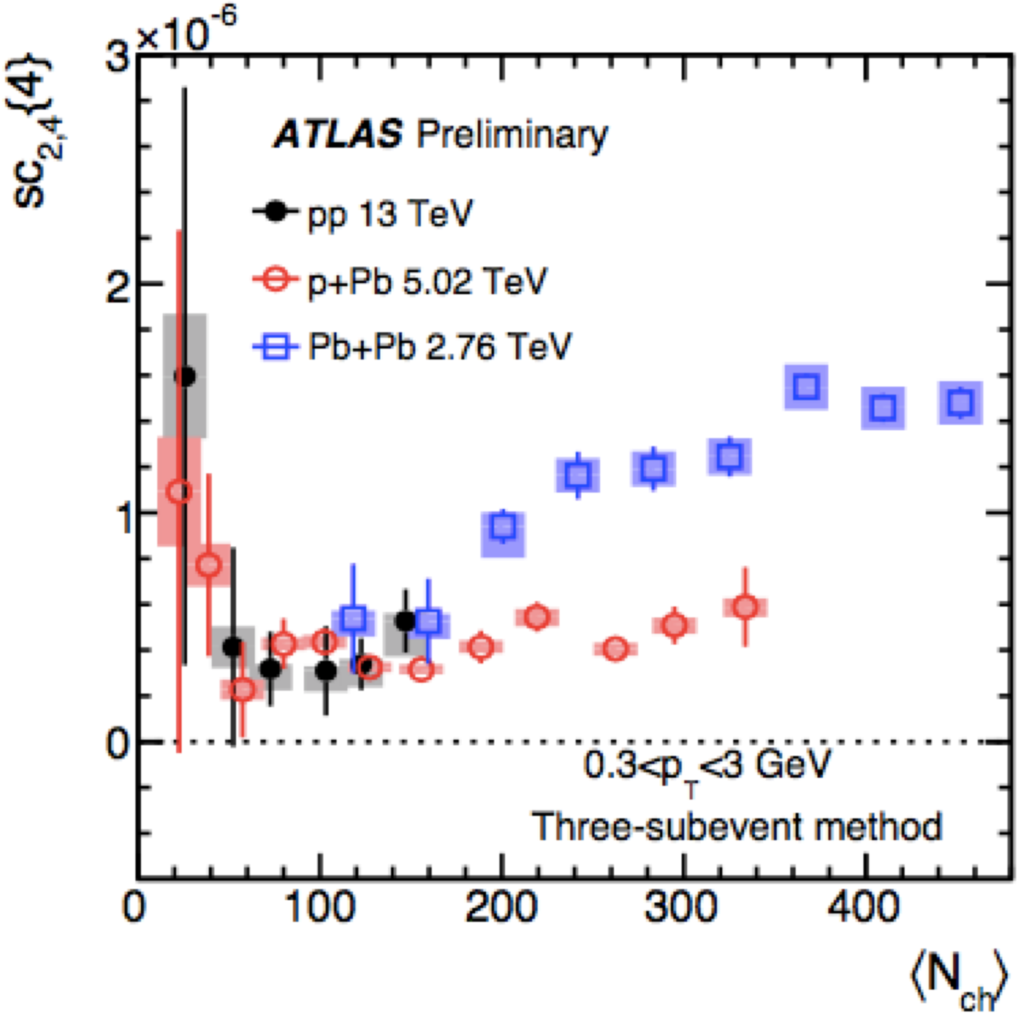
A **simplified hydrodynamic model** with 3 free fit parameters,
- T_{kin} = kinetic freeze-out temperature
- $\langle \beta_T \rangle$: transverse radial flow velocity
- n: velocity profile

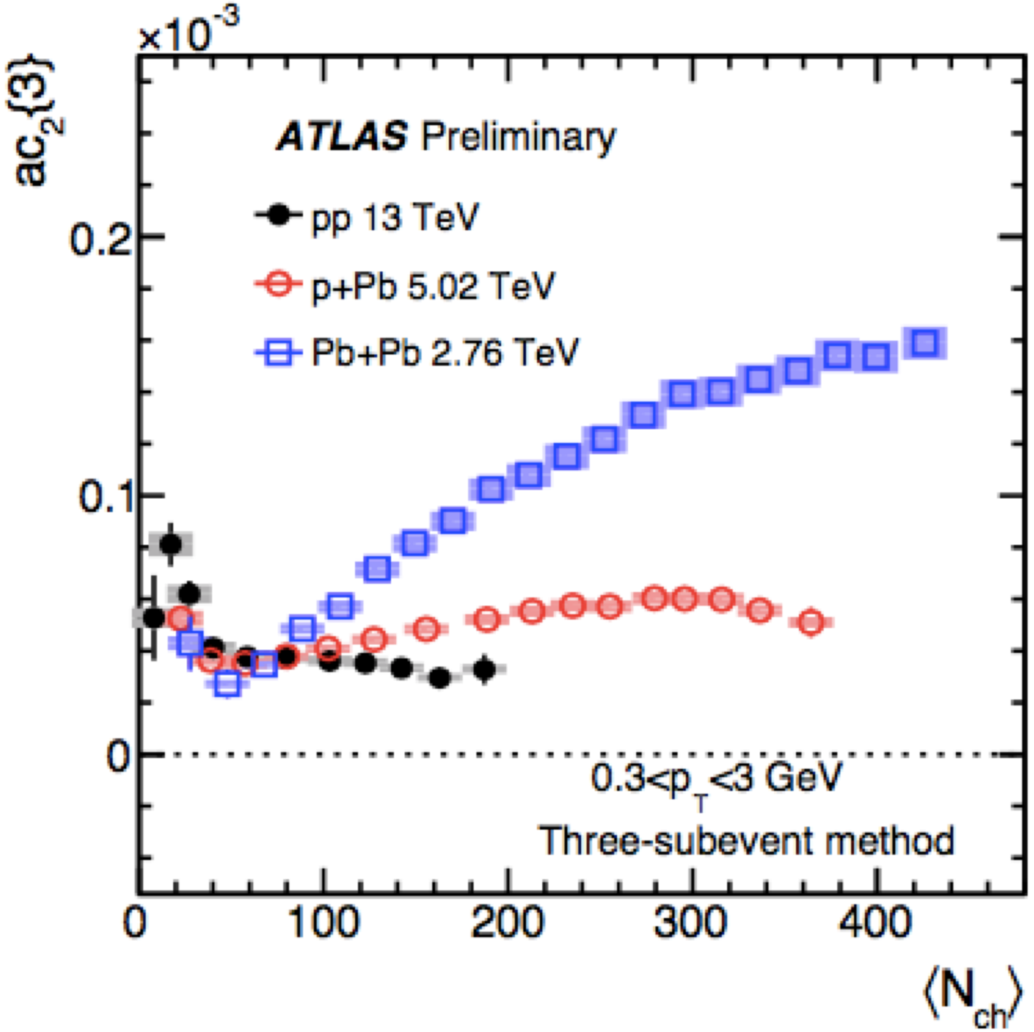
to describe particle **production from a thermalized source + radial flow boost**

Simultaneous fit to the **π, K, p spectra**
- increase of $\langle \beta_T \rangle$ with centrality **in AA**
- Xe-Xe and Pb-Pb consistent
- **in pp and p-Pb**, similar evolution of the parameters towards high multiplicity
- at similar multiplicity, $\langle \beta_T \rangle$ is larger for smaller systems



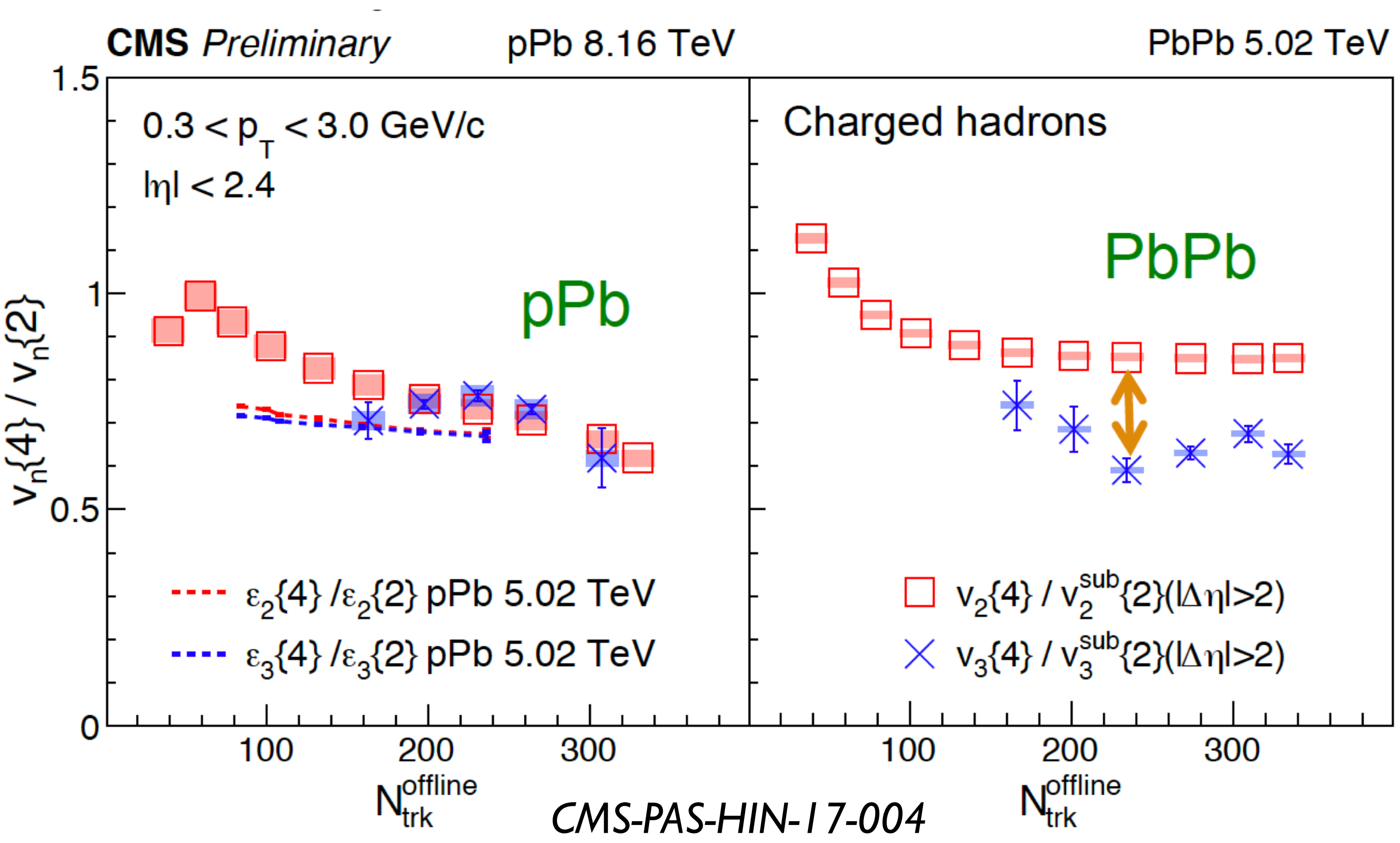
Harmonic correlations in pp





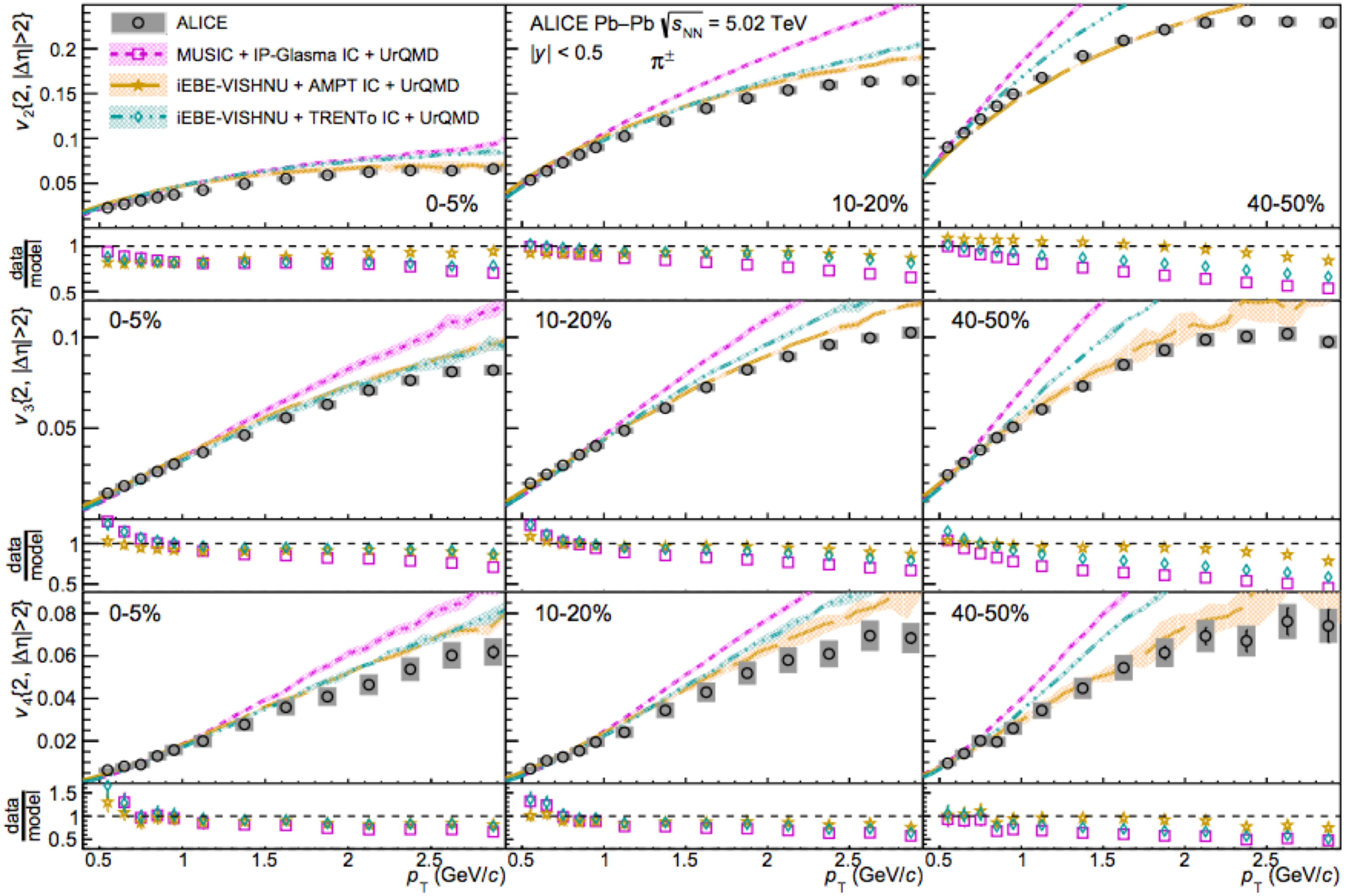
ATLAS-CONF-2018-012

First measurement of v_3 with 4-particles in p-Pb



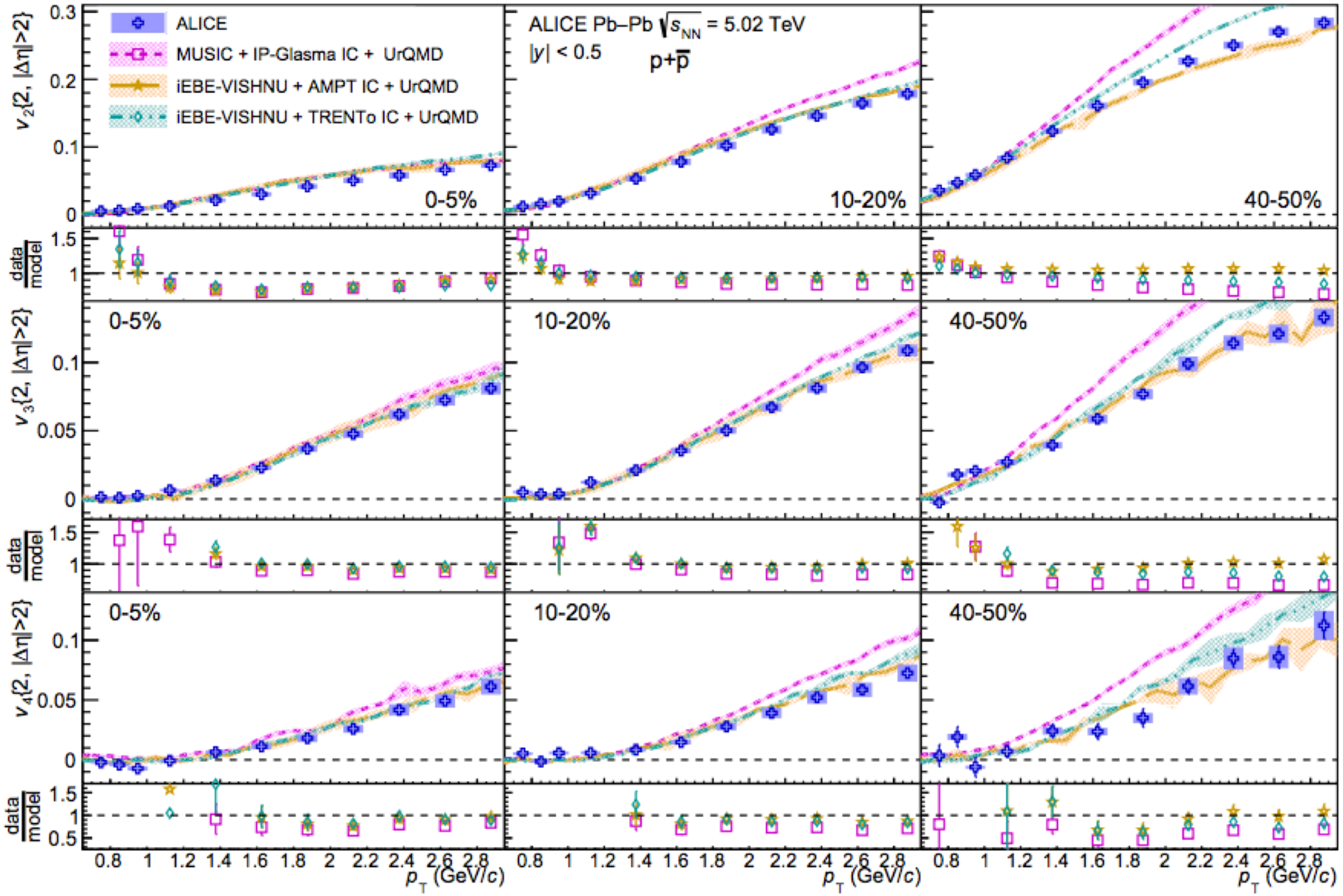
In Pb-Pb $v_n\{4\}/v_n\{2\}$ **larger for v2 than v3** → **global geometry** dominates for v_2
In p-Pb $v_n\{4\}/v_n\{2\}$ **similar for v2 than v3** → **initial state fluctuations** as important

Comparison to hydro models: π v_n



ALICE, arXiv:1805.04390

Comparison to hydro models: p v_n



ALICE, arXiv:1805.04390