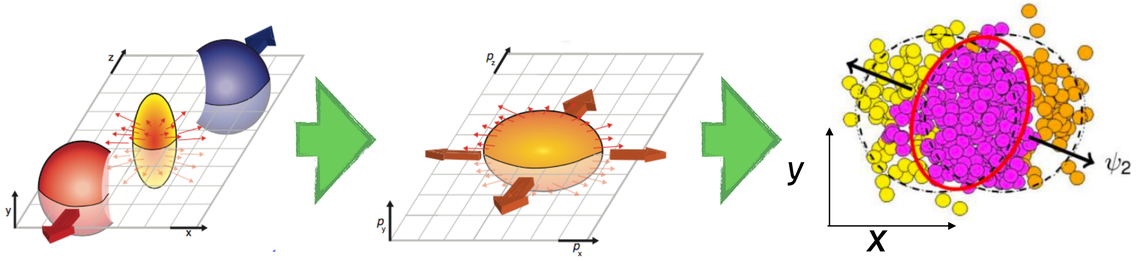
Elliptic flow coefficients of identified hadrons in p-Pb and pp collisions

Vojtěch Pacík
(Niels Bohr Institute, Copenhagen)

on behalf of the
ALICE Collaboration

Flow v_n coefficients & identified hadrons

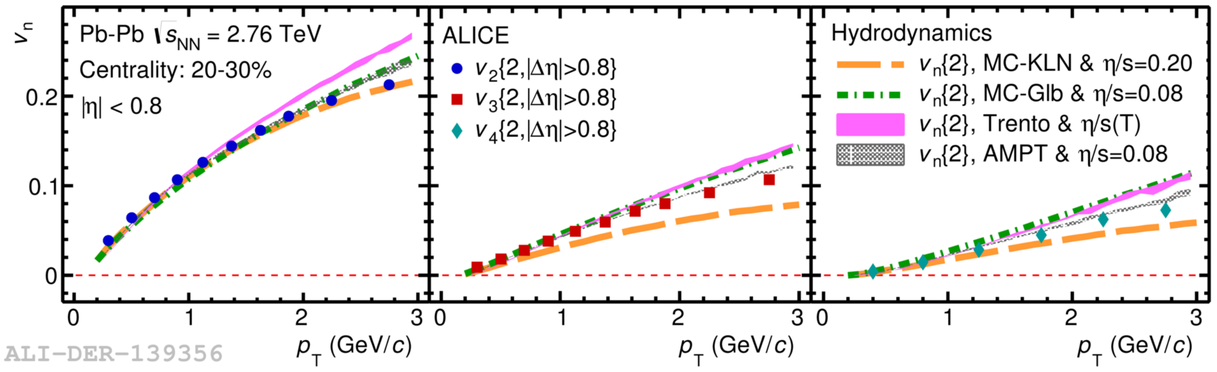


Initial geometry & event-by-event fluctuations cause azimuthal anisotropy wrt. common symmetry plane

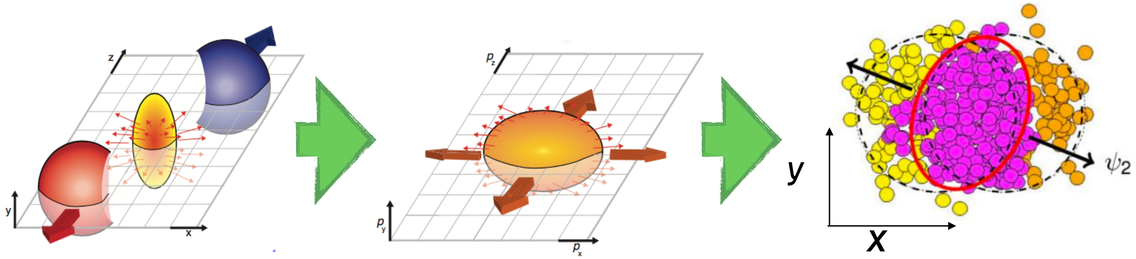
$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y}\left[1 + 2\sum_{n=1}^{\infty} v_n \cos\left[n(\varphi - \Psi_n)\right]\right]$$

- Constraining medium properties & testing initial conditions

[ALICE, JHEP 09 (2017) 032]



Flow v_n coefficients & identified hadrons

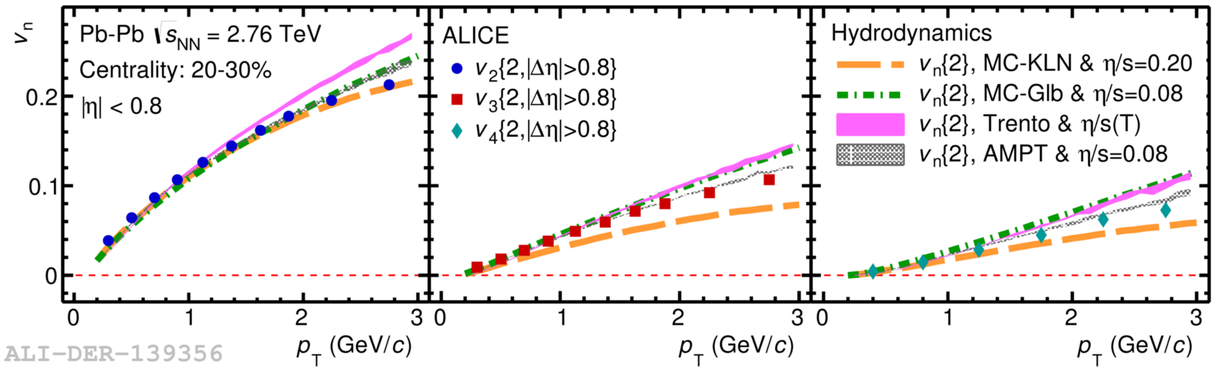


Initial geometry & event-by-event fluctuations cause azimuthal anisotropy wrt. common symmetry plane

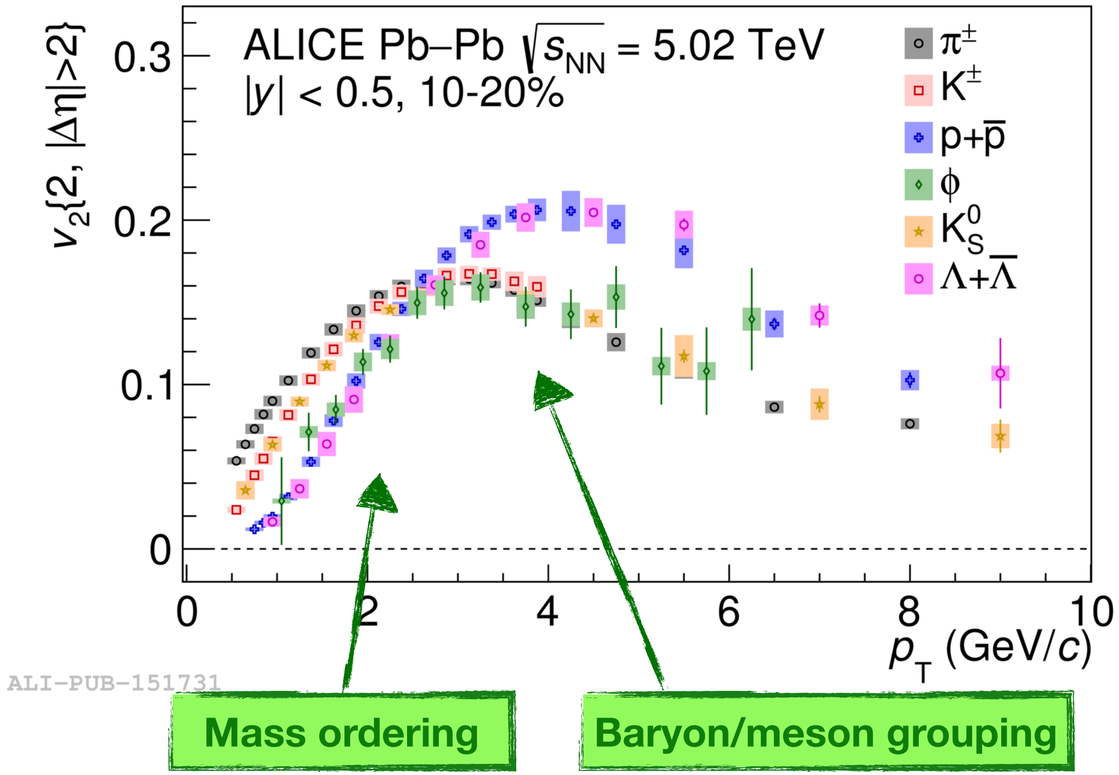
$$E\frac{\mathrm{d}^3N}{\mathrm{d}^3p} = \frac{1}{2\pi}\frac{\mathrm{d}^2N}{p_\mathrm{T}\mathrm{d}p_\mathrm{T}\mathrm{d}y}\left[1+2\sum_{n=1}^{\infty} v_n \cos\left[n(\varphi-\Psi_n)\right]\right]$$

- Constraining medium properties & testing initial conditions
- Studying the **particle production** in different p_T regions
  - **Mass ordering** (hydrodynamic flow, hadron re-scattering)
  - **Baryon/meson grouping** (recombination/coalescence)

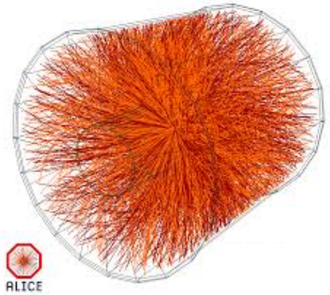
[ALICE, JHEP 09 (2017) 032]



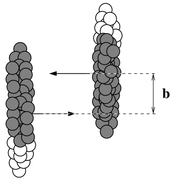
[arXiv:1805.04390]

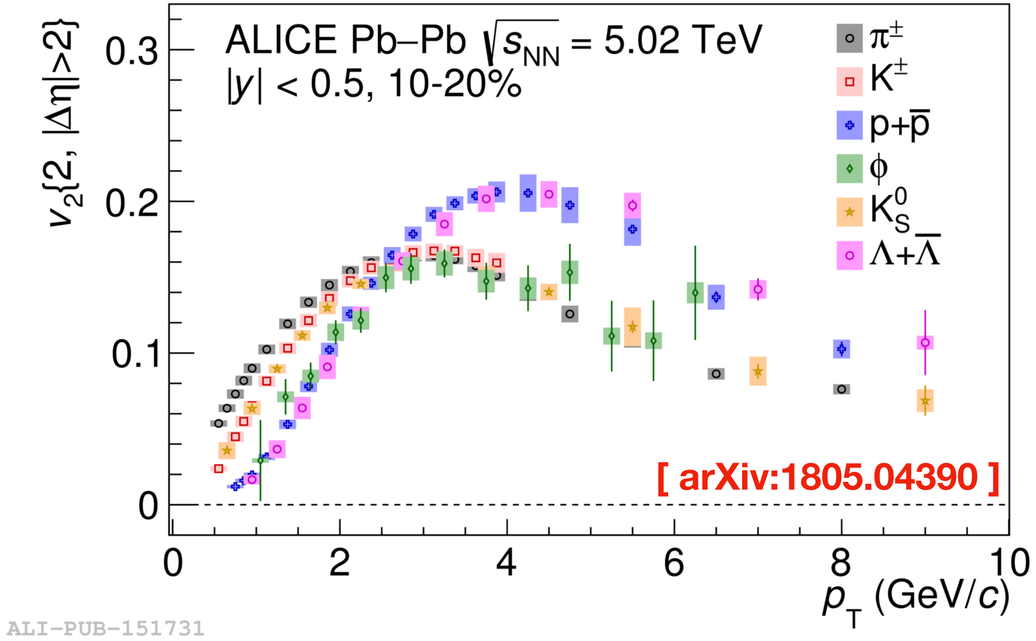


What about small systems?



Pb-Pb collisions





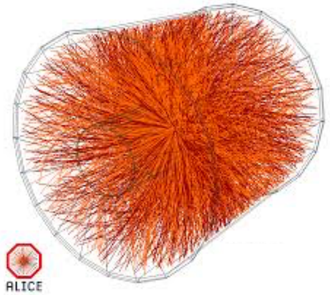
v_2, v_3, v_4 signal

Mass ordering & baryon/meson grouping

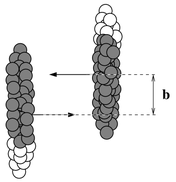
Medium induced collectivity

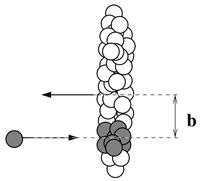
Initial geometry, hydro evolution, EbE fluctuations

What about small systems?

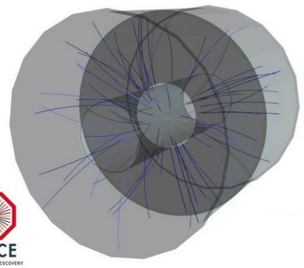


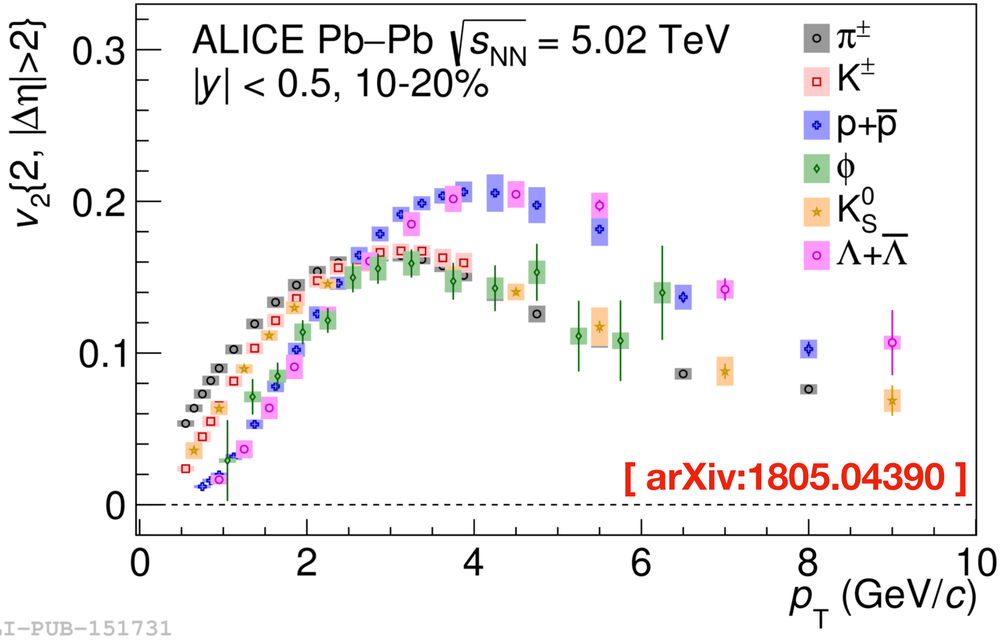
Pb-Pb collisions

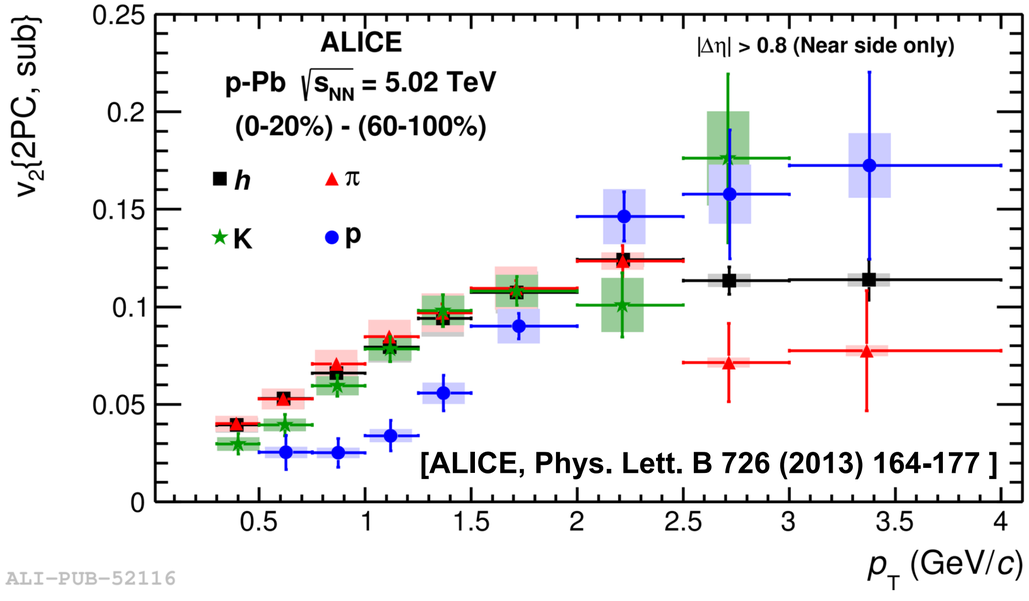




p-Pb collision







v_2, v_3, v_4 signal

Mass ordering & baryon/meson grouping

Flow-like signatures

Mass ordering? (What about grouping?)

Medium induced collectivity

Initial geometry, hydro evolution, EbE fluctuations

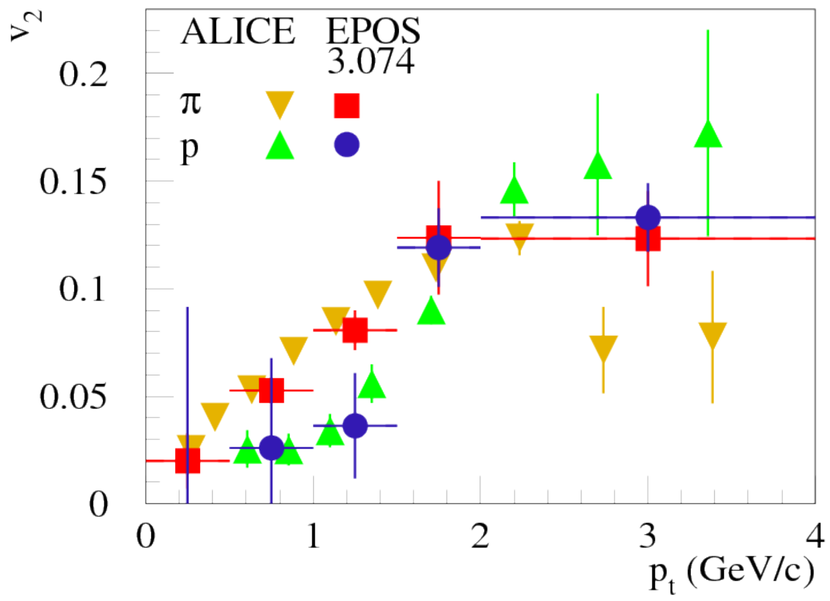
Small droplet(s) of QCD medium?

No clear picture

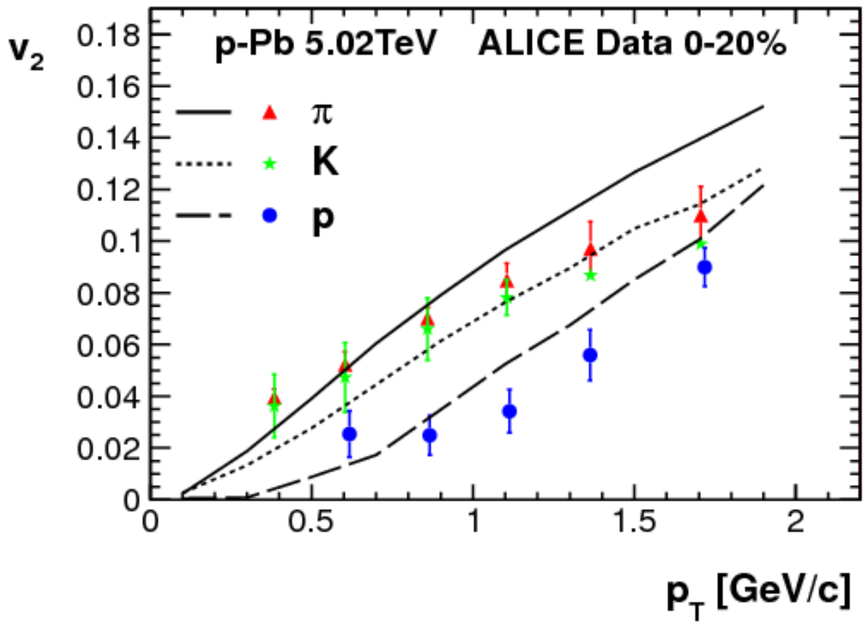
Mass ordering

- Mass ordering described by 3+1D viscous hydrodynamics with different initial conditions
  - Parton based Gribov-Regge multiple scattering (flux tubes)
  - MC Glauber initial conditions

[Werner et al., PRL 112 (2014) no. 23]



[Bozek et al., PRL 111 (2013) 172303]



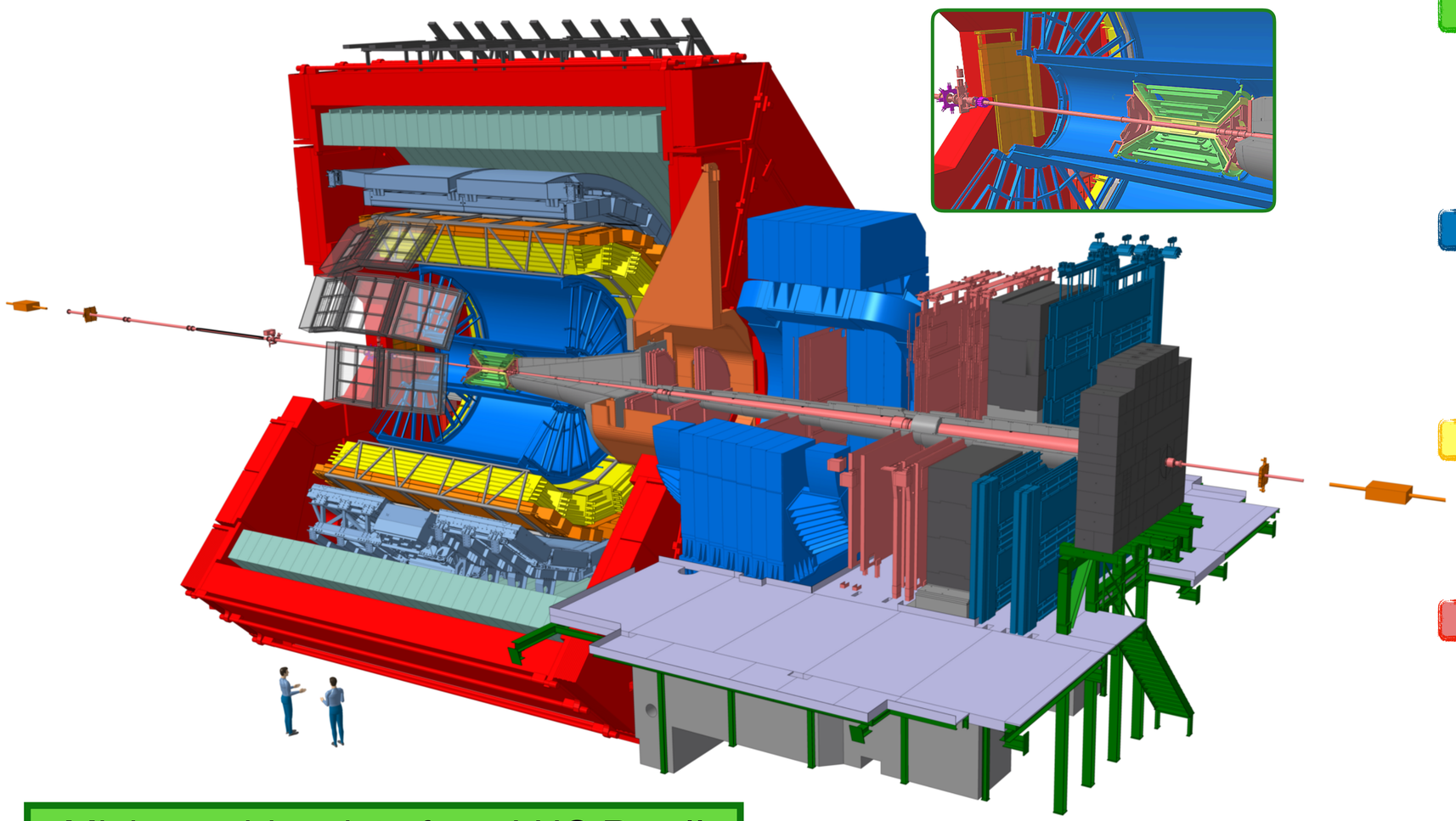
Higher precision results needed to validate and distinguish theoretical models

Collectivity in small systems

What is the origin? Initial or final state effects?

A Large Ion Collider Experiment

Multi-purpose detector at the LHC with unique particle identification capabilities and tracking down to very low momenta



Inner Tracking System (ITS)

- Tracking
- Triggering

Time-Projection Chamber (TPC)

- Tracking
- Particle identification

Time-of-flight detector (TOF)

- Particle identification

V0 detector

$2.8 < \eta < 5.1$ (**V0A : Pb-going**)

$-3.7 < \eta < -1.7$ (V0C : p-going)

- Triggering
- Event multiplicity determination

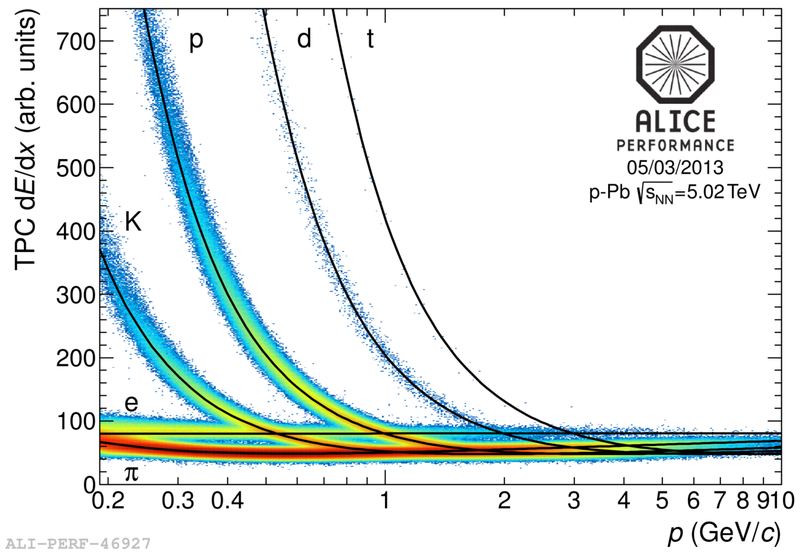
Minimum-bias data from LHC Run II
- 5.02 TeV p-Pb & 13 TeV pp

Particle identification & reconstruction

A. Identification of $\pi^{\pm}$, $K^{\pm}$, and $p(\bar{p})$

- Utilising combined TPC & TOF detector response
- Track-by-track basis with purity > 80%

[ALICE, Eur.Phys.J.Plus 131 (2016) no.5, 168]

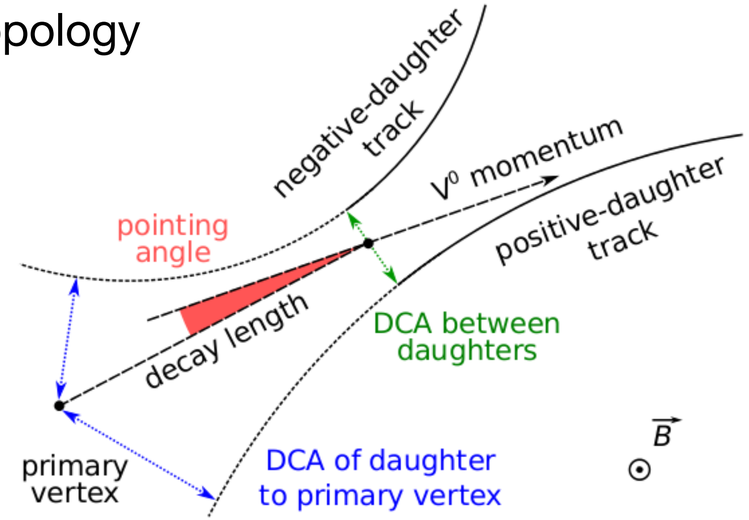


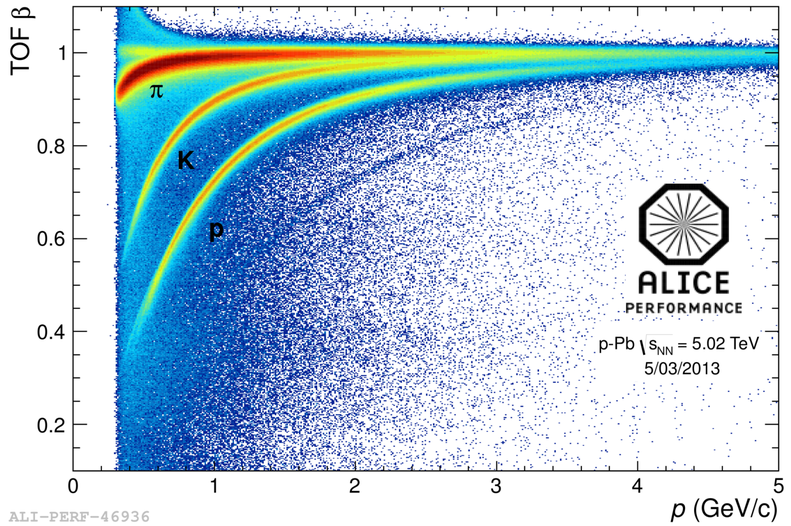
B. Reconstruction of ϕ, K^0_S, and $\Lambda(\bar{\Lambda})$

- Short-lived & no charge - cannot be measured directly
- Reconstruction via decay products on statistical basis
  - Particle identification of products
  - Constraining decay topology

Hadronic decays

$$\phi \longrightarrow K^+ + K^-$$
$$K^0_S \longrightarrow \pi^+ + \pi^-$$
$$\Lambda \longrightarrow p + \pi^-$$
$$\bar{\Lambda} \longrightarrow \bar{p} + \pi^+$$





v_n vs. invariant mass method

- v_n extracted from 2-particle Q-cumulants using Generic Framework (GF) implementation

  [A. Bilandzic et al., Phys.Rev. C89 (2014) 064904, Phys.Rev. C83 (2011) 044913]

  - Particles selected in $|\eta| < 0.8$ (& RFP in 0.3 < p_T < 3 GeV/c)

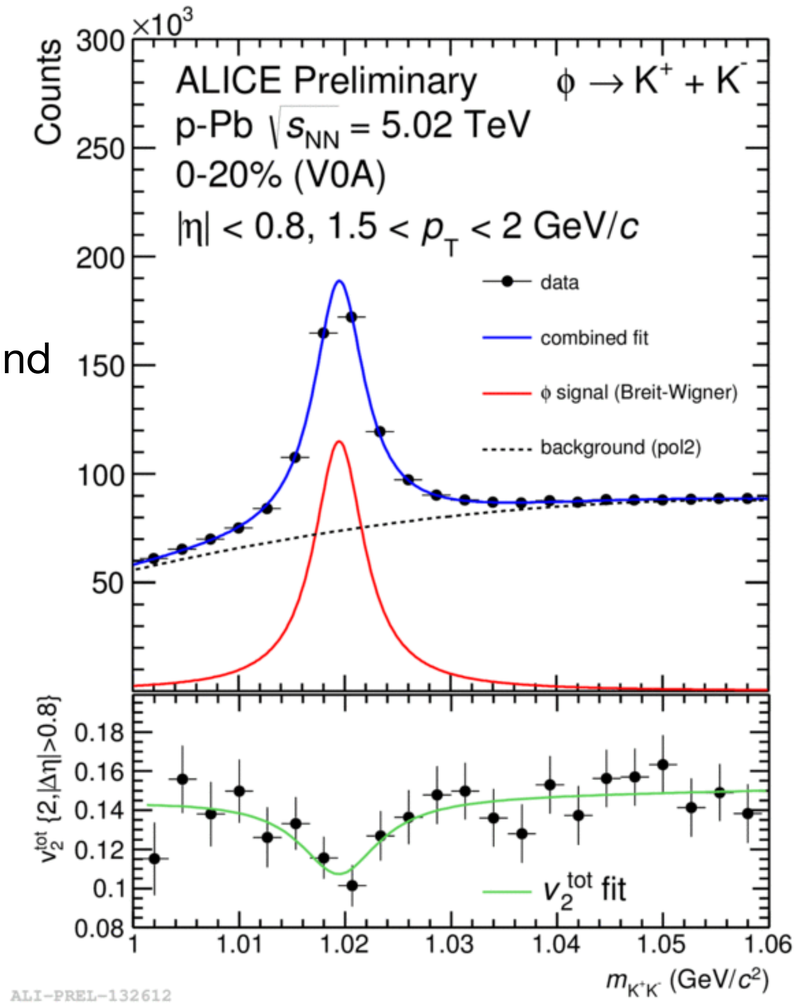
$$v_n\{2\}(p_{\mathrm{T}}) = \frac{d_n\{2\}(p_{\mathrm{T}})}{\sqrt{c_n\{2\}}} = \frac{\langle v_n(p_{\mathrm{T}}) \cdot v_n \rangle}{\sqrt{\langle v_n \cdot v_n \rangle}} \qquad (\mathrm{h}^{\pm},\ \pi^{\pm}, \mathrm{K}^{\pm},\ \mathrm{p}(\bar{\mathrm{p}}))$$

- Reconstructed candidates consisting of signal particles & combinatorial background

$$v_n^{\mathrm{tot}}\{2\}(p_{\mathrm{T}}, m_{\mathrm{inv}}) = \frac{d_n\{2\}(p_{\mathrm{T}}, m_{\mathrm{inv}})}{\sqrt{c_n\{2\}}} \qquad (\mathrm{K}^0_{\mathrm{S}}\ , \Lambda(\bar{\Lambda})\ , \phi)$$

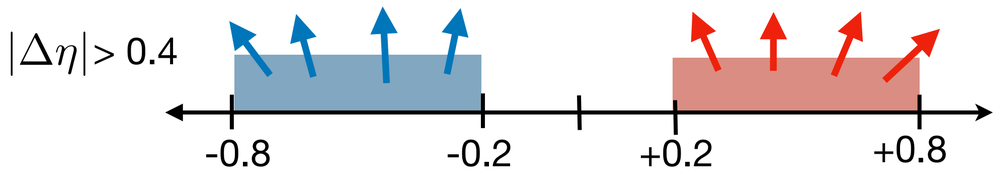
- v_n coefficient of signal particles extracted using v_n vs. inv. mass method
  - Based on additivity of v_n coefficients weighted by their fractions

$$v_n^{\mathrm{tot}}(m_{\mathrm{inv}}) = \frac{N^{\mathrm{sig}}(m_{\mathrm{inv}})}{N^{\mathrm{tot}}(m_{\mathrm{inv}})} \cdot v_n^{\mathrm{sig}} + \frac{N^{\mathrm{bg}}(m_{\mathrm{inv}})}{N^{\mathrm{tot}}(m_{\mathrm{inv}})} \cdot v_n^{\mathrm{bg}}(m_{\mathrm{inv}})$$



Non-flow suppression

- Non-flow consisting of correlation not related to common symmetry plane
  - Resonance decays, jets, …
- Pseudorapidity separation partially suppresses short-range correlations

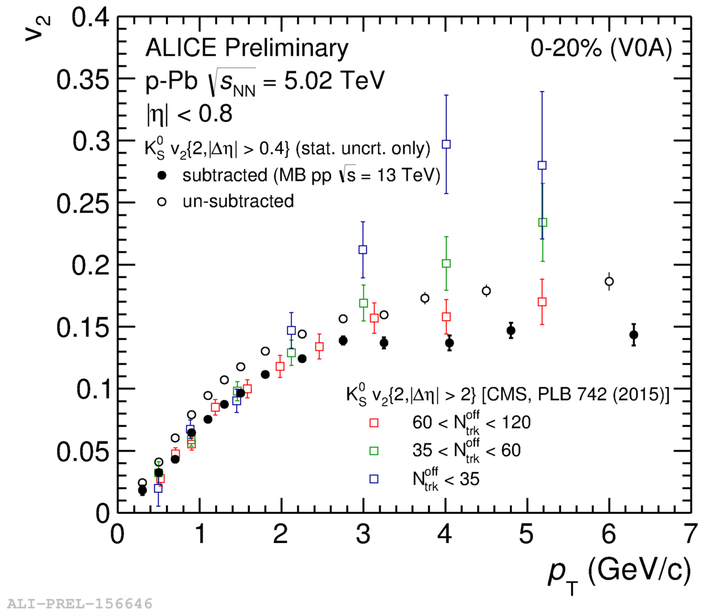


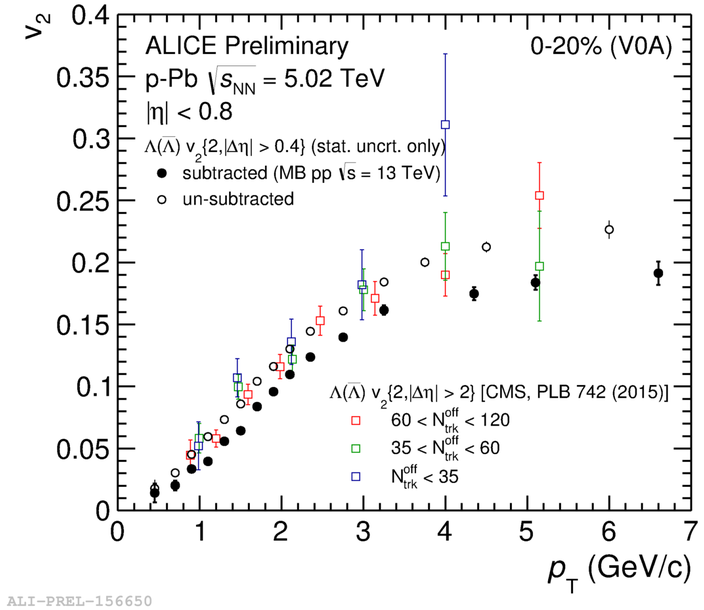
- Additional non-flow subtraction performed on cumulants using MB pp collisions

$$v_2^{\mathrm{pPb,sub}}(p_T) = \frac{d_2^{\mathrm{pPb}}\{2\} - k \cdot d_2^{\mathrm{pp}}\{2\}}{\sqrt{c_2^{\mathrm{pPb}}\{2\} - k \cdot c_2^{\mathrm{pp}}\{2\}}}$$

- Contribution of non-flow scaled by mean event multiplicities
  - Based on assumption for non-flow **[Voloshin et al., arXiv:0809.2949]**

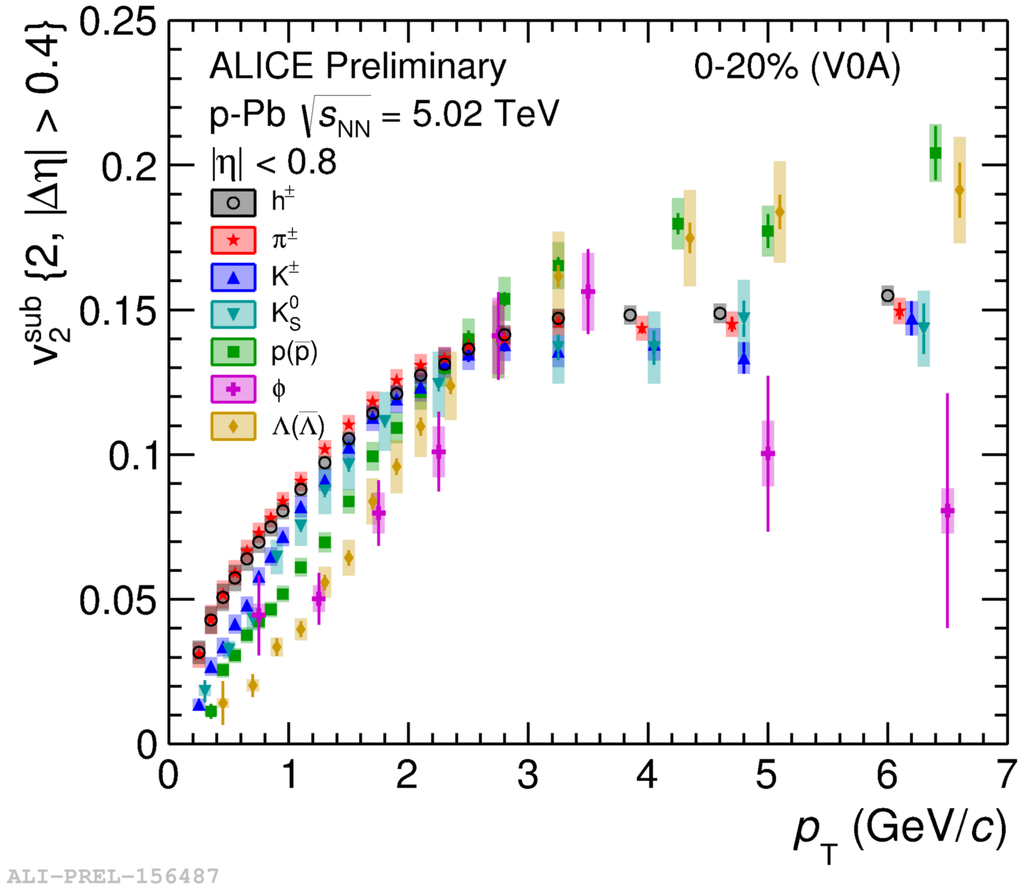
$$\delta_n \propto \frac{1}{M} \quad \Rightarrow \quad k = \frac{\langle M \rangle^{\mathrm{pp}}}{\langle M \rangle^{\mathrm{pPb}}}$$





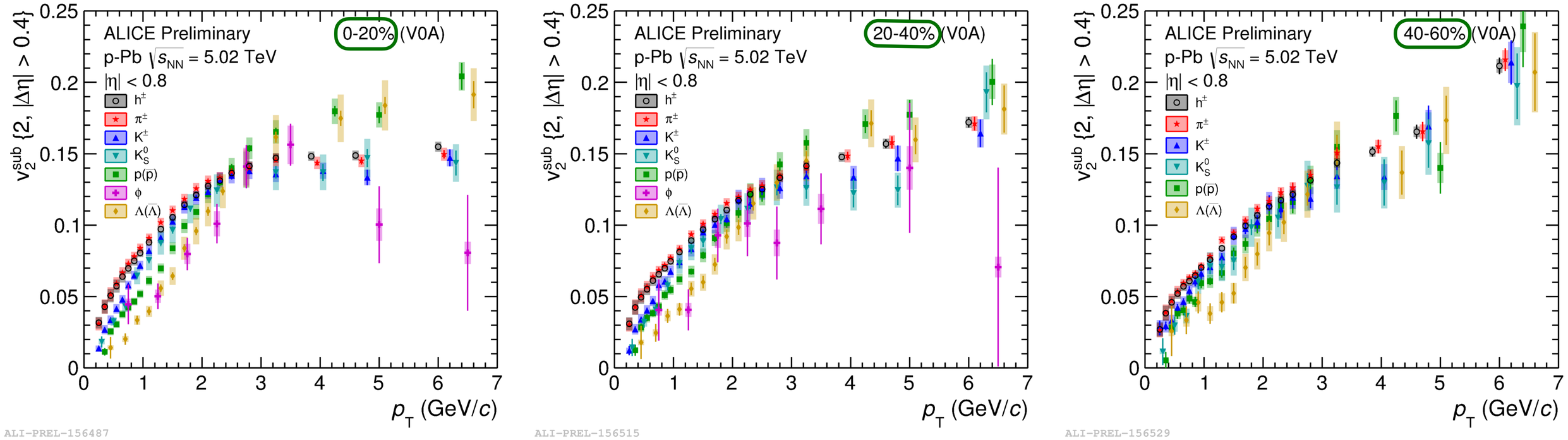
$v_2(p_T)$ coefficients of identified hadrons in 5.02 TeV p-Pb collisions

Non-flow subtracted $v_2(p_T)$ of identified hadrons



- $v_2(p_T)$ of identified hadrons in 5.02 TeV p-Pb using Run II data
  - Non-flow subtracted results using MB 13 TeV pp collisions
  - First ALICE measurement of K^0_S, $\Lambda(\bar{\Lambda})$ and ϕ v_2 in small systems
- Similar features as Pb-Pb measurements
  - Clear mass ordering (low p_T region)
    - Qualitatively predicted by hydrodynamic models
  - Indication of baryon/meson grouping (intermediate p_T)

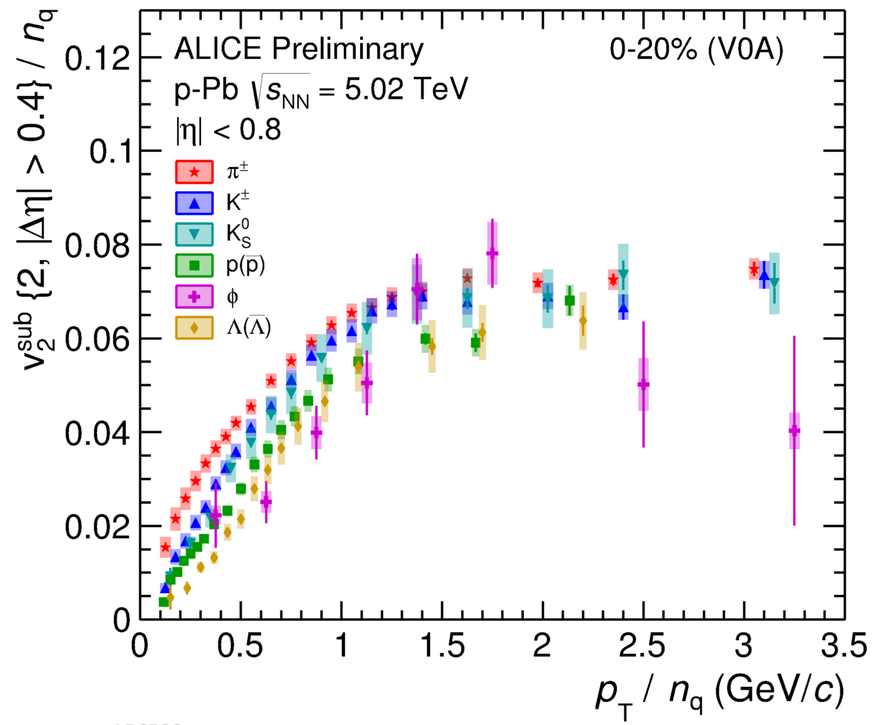
Multiplicity class evolution

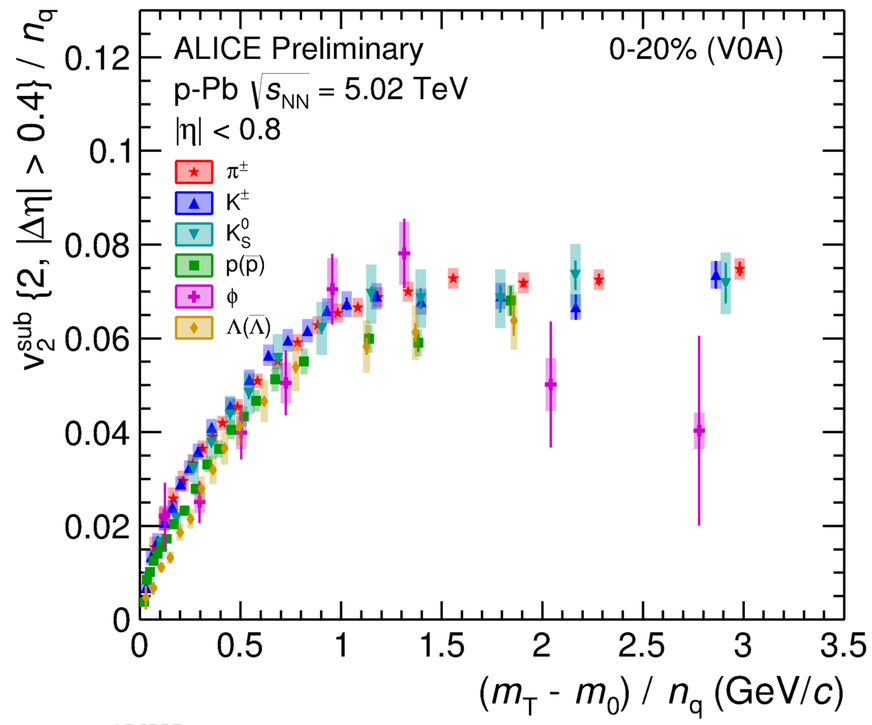


Mass ordering and baryon/meson grouping persists but slowly vanishes towards low multiplicity events

Examination of NCQ scaling

- Test of number of constituent quarks (NCQ) scaling properties originally investigated by RHIC experiments

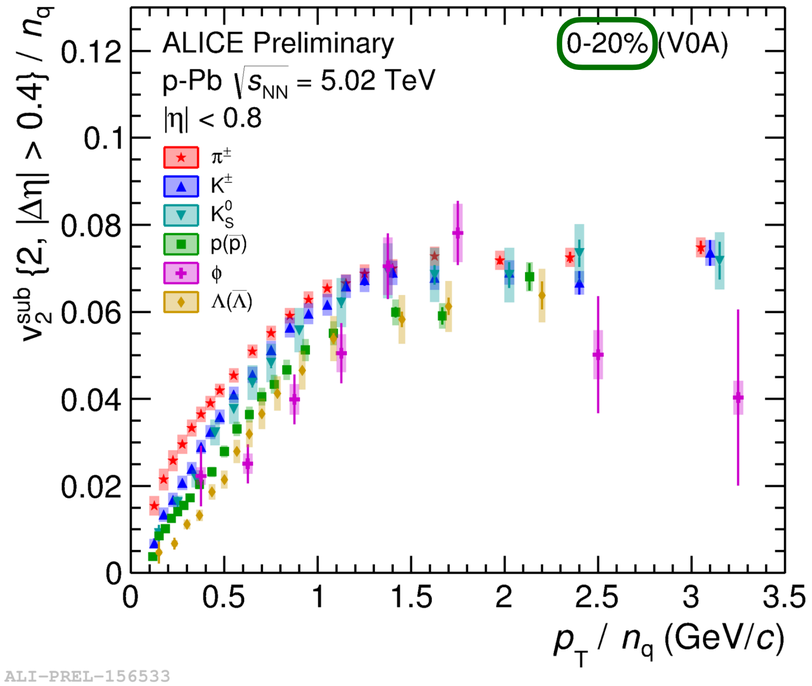


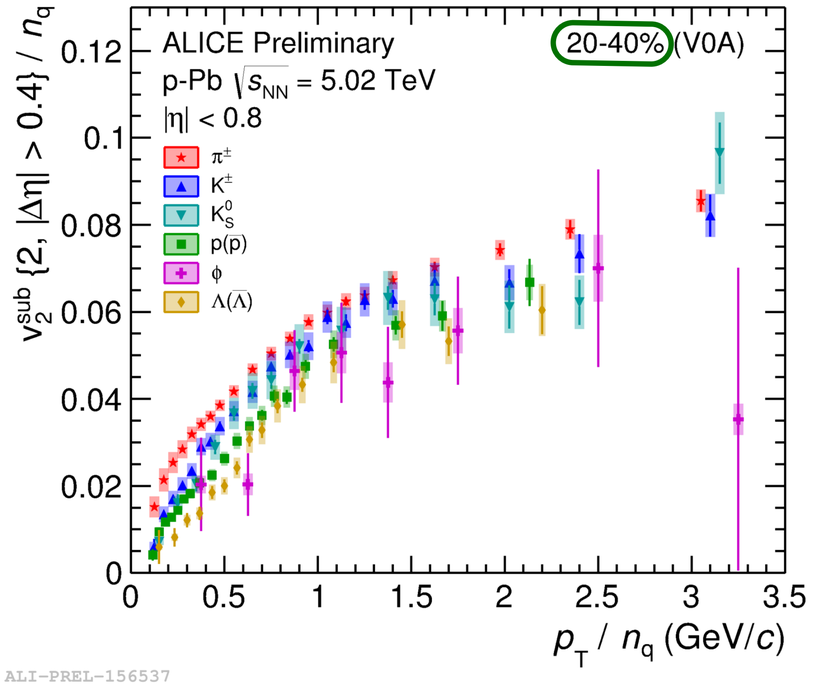


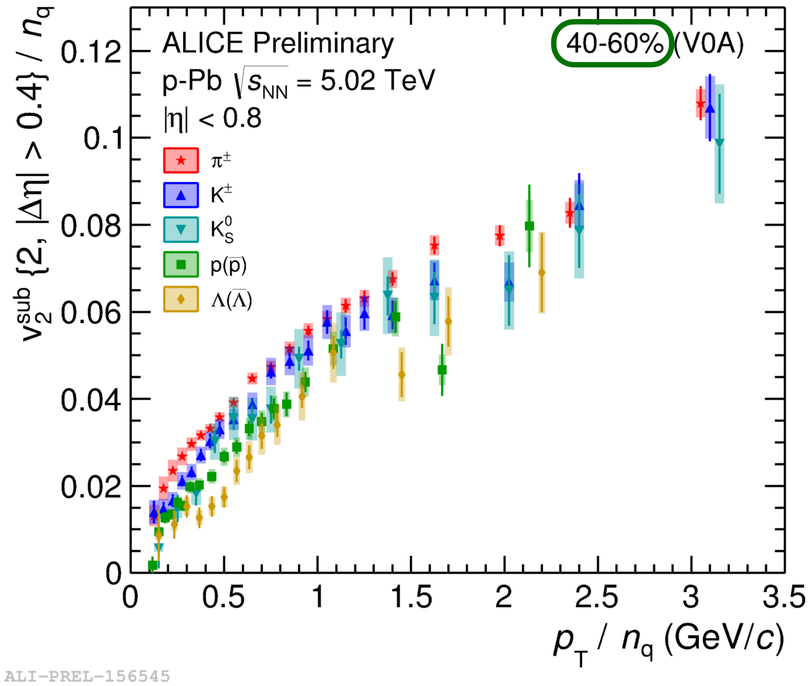
Only approximate NCQ (and KE_T) scaling similar to previously reported results in Pb-Pb collisions

$$\mathrm{KE_T} = m_\mathrm{T} - m_0 = \sqrt{p_\mathrm{T}^2 - m_0^2} - m_0$$

Multiplicity evolution of NCQ scaling







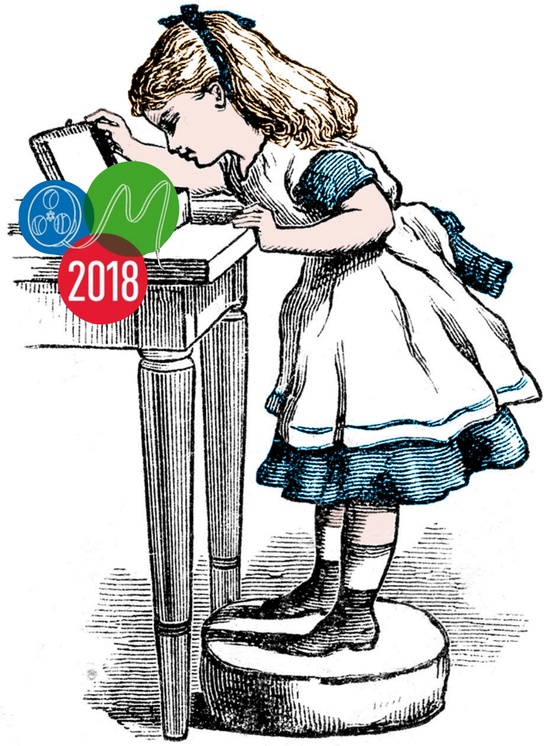
Approximate NCQ-scaling holds across all multiplicity classes

Conclusion

- Results of p_T-differential $v_2\{2\}$ of identified hadrons in 5.02 TeV p-Pb collisions in LHC Run II
  - First ALICE measurement of K^0_S, $\Lambda(\bar{\Lambda})$ and ϕ meson $v_2(p_T)$ in small systems
  - Precision measurement of $\pi^{\pm}$, $\mathrm{K}^{\pm}$ and $\mathrm{p}(\bar{\mathrm{p}})$ v_2 in p-Pb collisions
  - Non-flow subtraction using minimum-bias 13 TeV pp collision

- Features observed in p-Pb collisions similar to previously reported Pb-Pb measurements
  - Low p_T region, clear mass ordering - predicted by hydrodynamic models
  - Intermediate p_T, indication of baryon/meson grouping
  - Approximate NCQ & KE_T scaling holds

- Collective phenomena present in small systems. Initial and final state effects?
  - Current results present tighter constrain for future comparisons of theoretical models
    - Will help to disentangle the origin of the observed collectivity



— Thank you for your attention ! —

— Back-up —

Two-particle Q-cumulants

- Flow coefficients v_n extracted from {2}-particle Q-cumulants using Generic Framework (GF) implementation

[A. Bilandzic et al., Phys.Rev. C89 (2014) 064904, Phys.Rev. C83 (2011) 044913]

- Construction of (single event) flow vectors from selected particles in $|\eta| < 0.8$

A. Reference particles (RFP)

- Un-identified charged hadrons in $0.3 < p_T < 5$ GeV/c

$$Q_n = \sum_{i \in \mathrm{RFP}}^{M} w_i \exp(\mathrm{i}n\varphi_i), \qquad W_i = \sum_{i \in \mathrm{RFP}}^{M} w_i$$

B. Particles of interest (POI)

- Differential measurement (wrt. pt range, species, …)

$$p_n = \sum_{j \in \mathrm{POI}}^{m} w_j \exp(\mathrm{i}n\psi_j), \qquad W_j = \sum_{j \in \mathrm{POI}}^{m} w_j$$

- Per-particle weights $w_k = w_k(\eta, \varphi)$ for correction

---

2-particle correlations → **2-particle cumulants** → **vn coefficients**

A

$$\langle 2 \rangle_n = \langle \cos n(\varphi_i - \varphi_j) \rangle = \frac{Q_n Q_n^*}{W_i^2}$$

$$c_n\{2\} = \langle\langle 2 \rangle\rangle_n = \langle v_n^2 \rangle$$

$$v_n\{2\}(p_T) = \frac{d_n\{2\}(p_T)}{\sqrt{c_n\{2\}}}$$

B

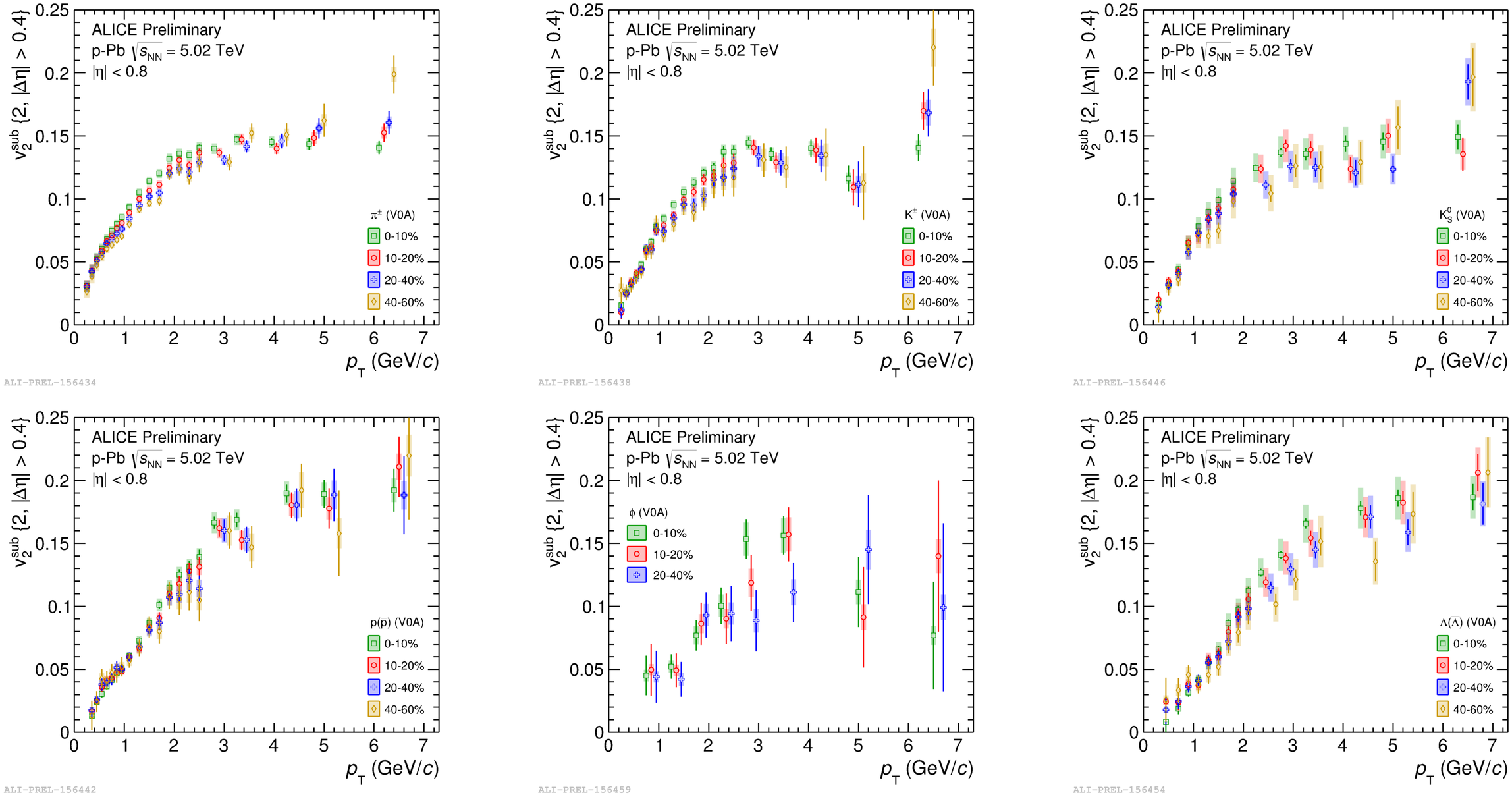
$$\langle 2' \rangle_n = \langle \cos n(\psi_j - \varphi_i) \rangle = \frac{p_n Q^*}{W_j W_i}$$

$$d_n\{2\}(p_T) = \langle\langle 2' \rangle\rangle_n = \langle v_n(p_T) \cdot v_n \rangle$$

$\langle \ldots \rangle$ … averaged over all particles in single event

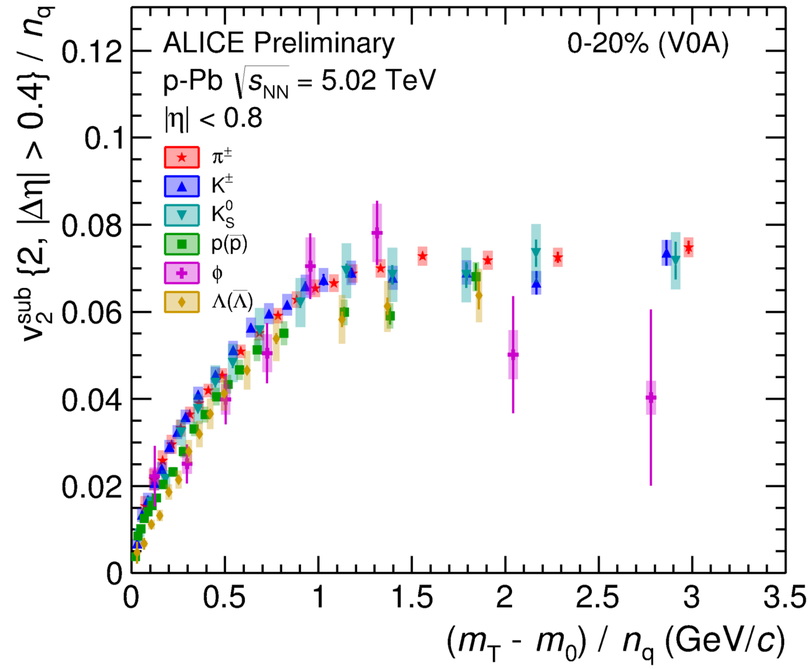
$\langle\langle \ldots \rangle\rangle$ … averaged over all particles AND all events

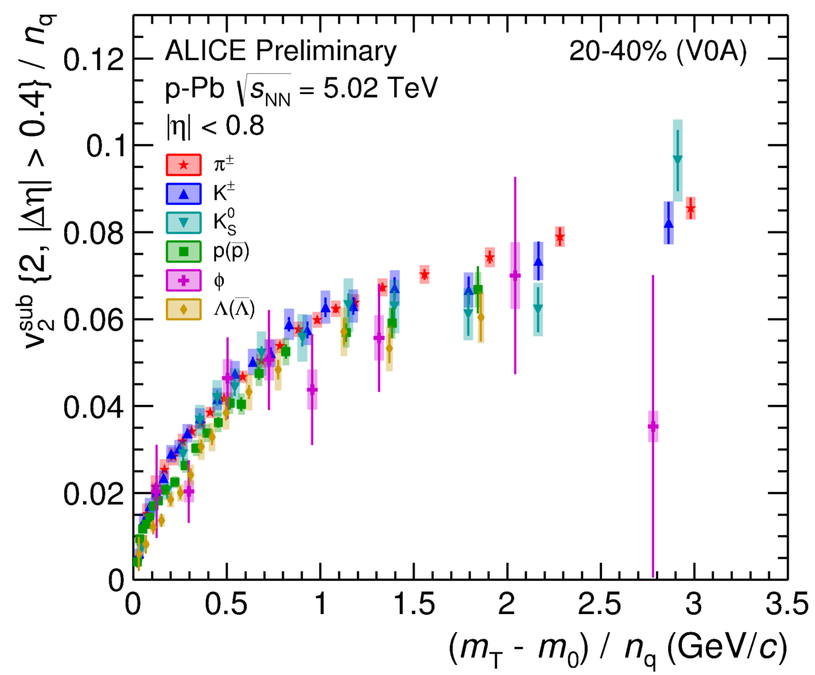
Multiplicity class dependence

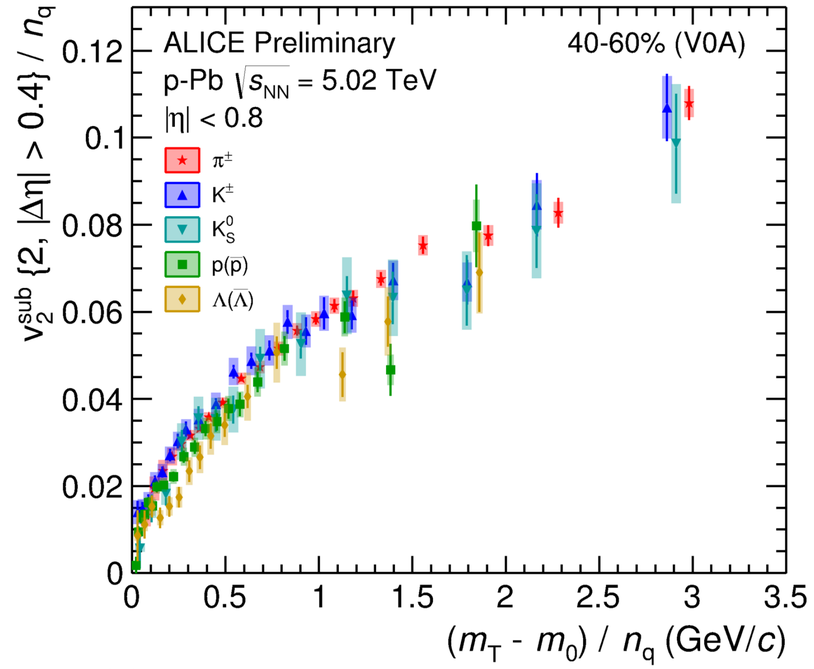


Examination of KE_T scaling

$$\mathrm{KE_T} = m_\mathrm{T} - m_0 = \sqrt{p_\mathrm{T}^2 - m_0^2} - m_0$$



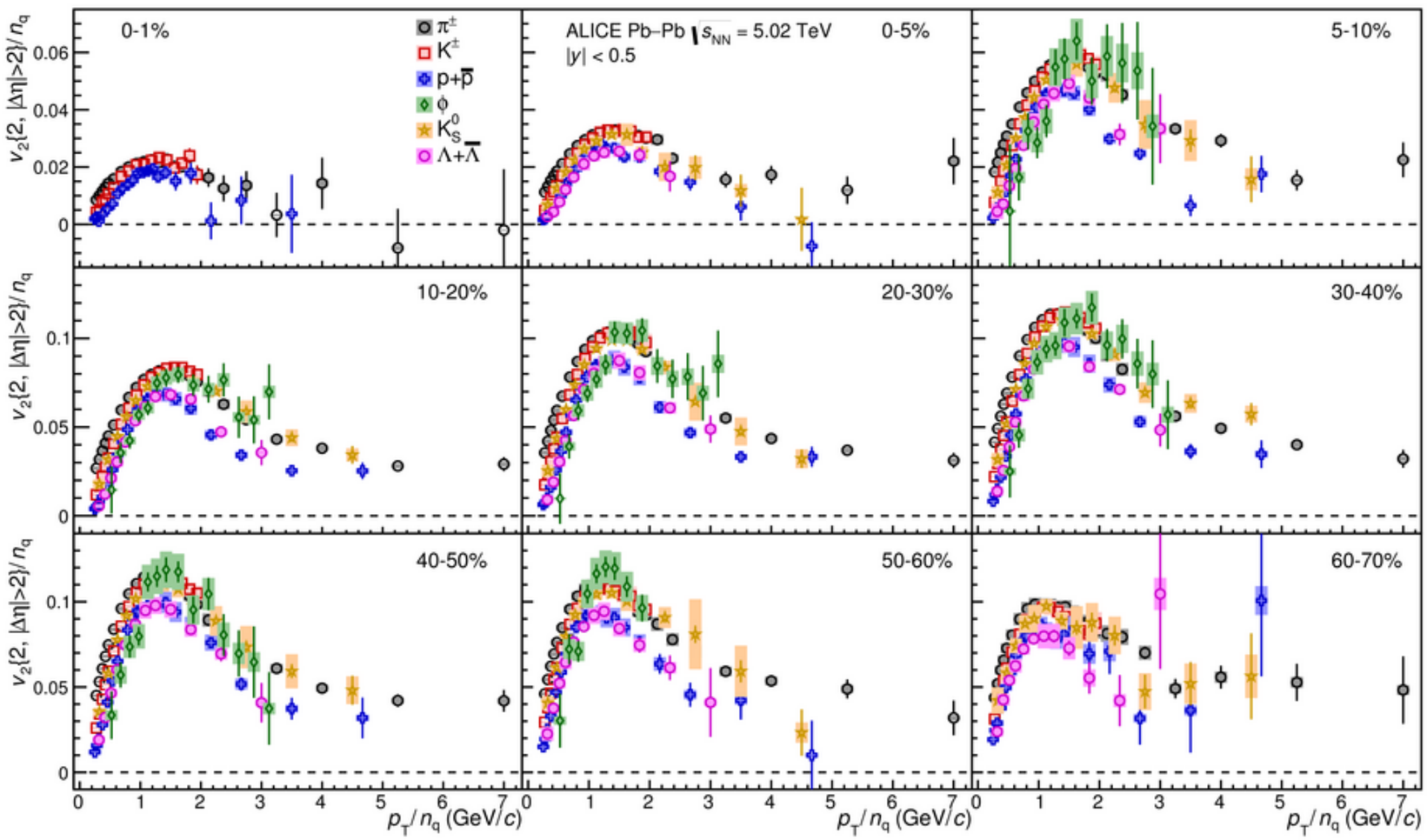




As for NCQ, KE_T scaling holds in central collisions and slowly vanishes in low multiplicity events

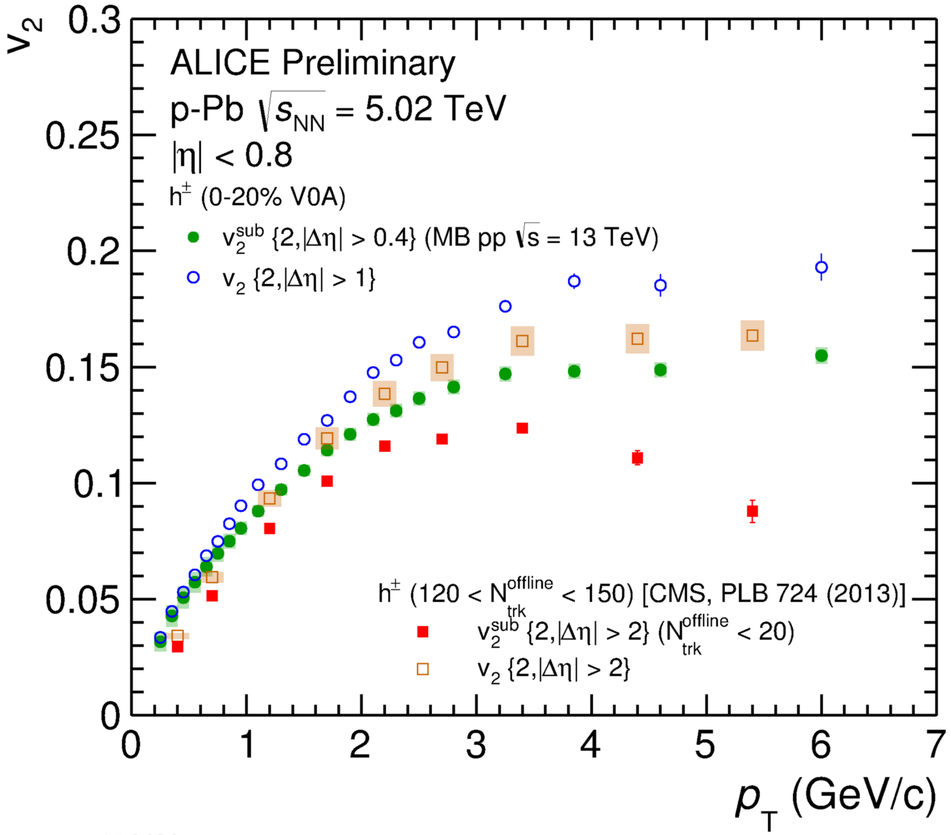
NCQ scaling in Pb-Pb at 5.02 TeV

[arXiv:1805.04390]



Comparison to published results

Comparison to CMS results form [PLB 724 (2013) 213-240]



- Differences in methodology
  - v_2 extraction (2PC vs Q-Cumulants)
  - Event classification (selection)
  - Pseudo-rapidity regions
- Similar non-flow subtraction prescription …

$$V_{n\Delta}^{sub} = V_{n\Delta} - V_{n\Delta}(N_{trk}^{offline} < 20) \times \frac{N_{assoc}(N_{trk}^{offline} < 20)}{N_{assoc}} \times \frac{Y_{jet}}{Y_{jet}(N_{trk}^{offline} < 20)}, \quad (9)$$

- … but additional scaling factor (enhancement of near-side jet)

Only qualitative comparison - differences expected