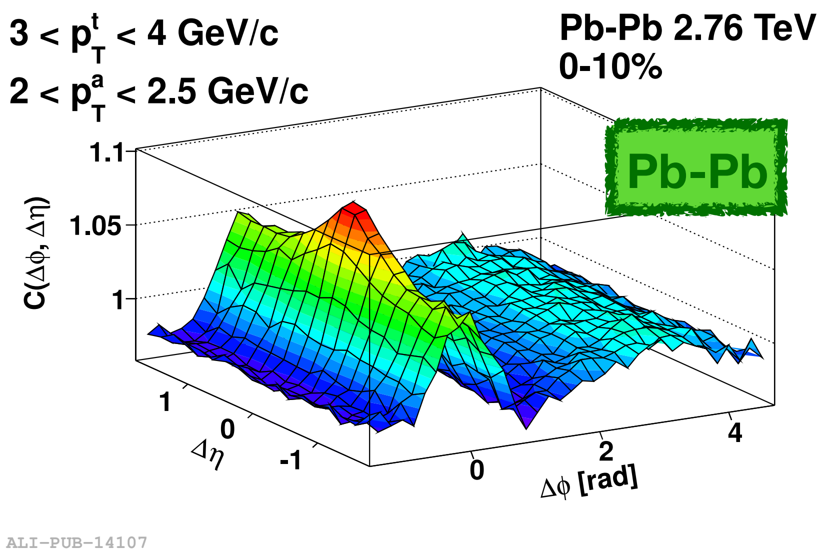
Investigation of collectivity in small collision systems with ALICE

Vojtěch Pacík
(Niels Bohr Institute, Copenhagen)

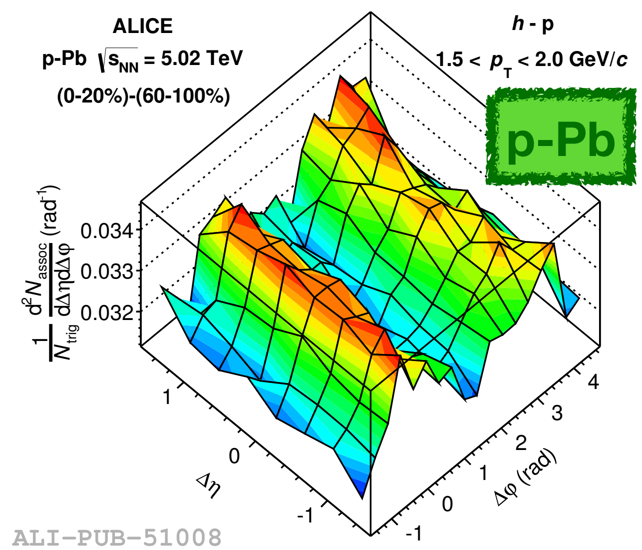
on behalf of the
ALICE Collaboration

Collectivity & anisotropic flow

Double ridge structures observed in Pb-Pb and p-Pb collisions

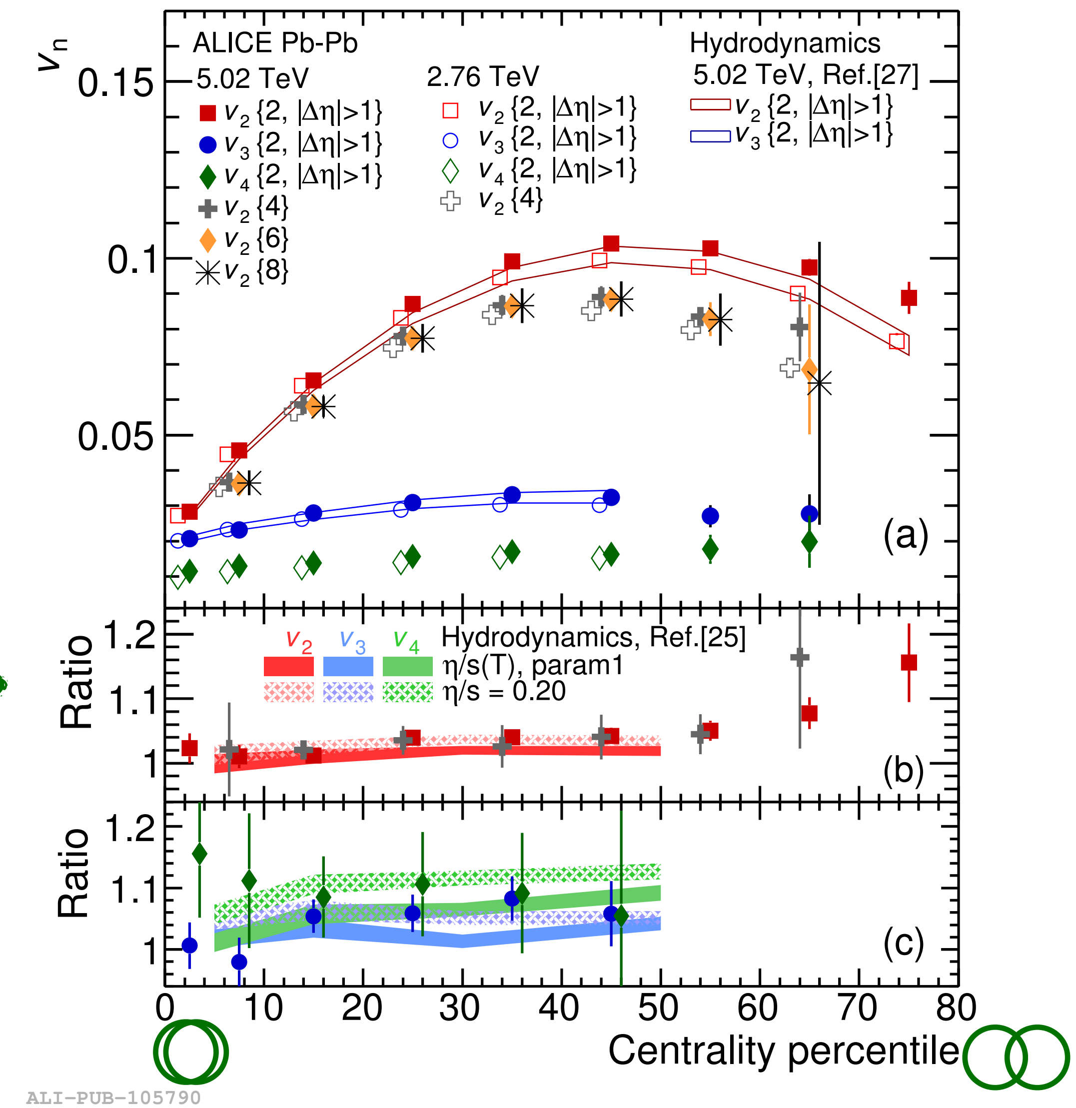


[ALICE, PLB 708 (2012) 249]

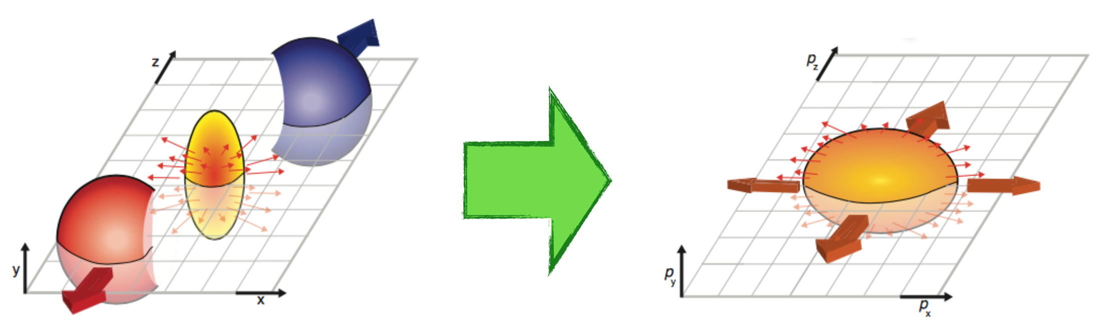


[ALICE, PLB 726 (2013) 164]

[ALICE, PRL 116 (2016) 132302]



Azimuthal anisotropy wrt. common symmetry plane

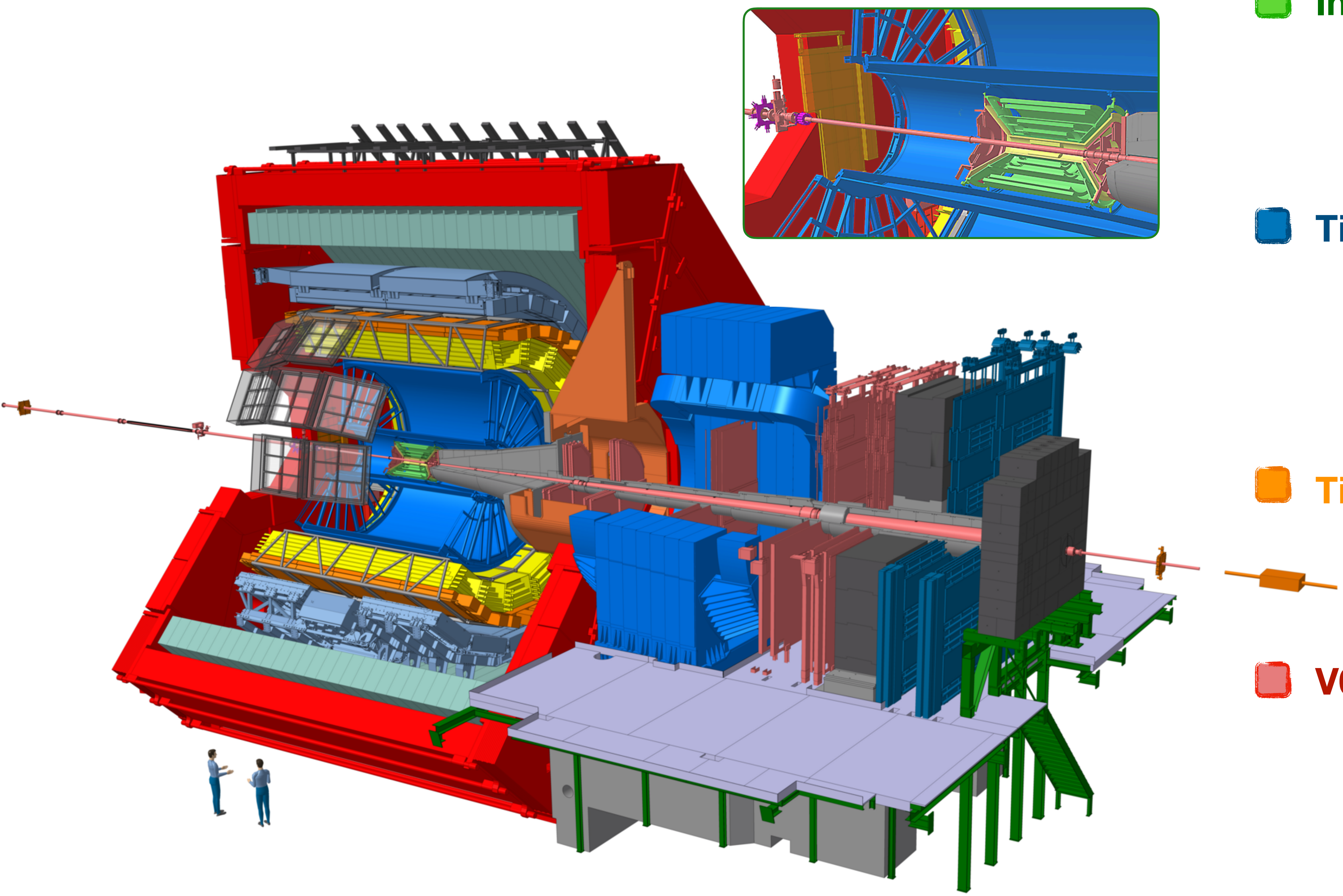


Collectivity = long-range and multi-particle correlations

- Indication of collectivity in small collision systems
- What is its origin? Initial or final state effects?

A Large Ion Collider Experiment

Unique PID and tracking capabilities 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 scintilators

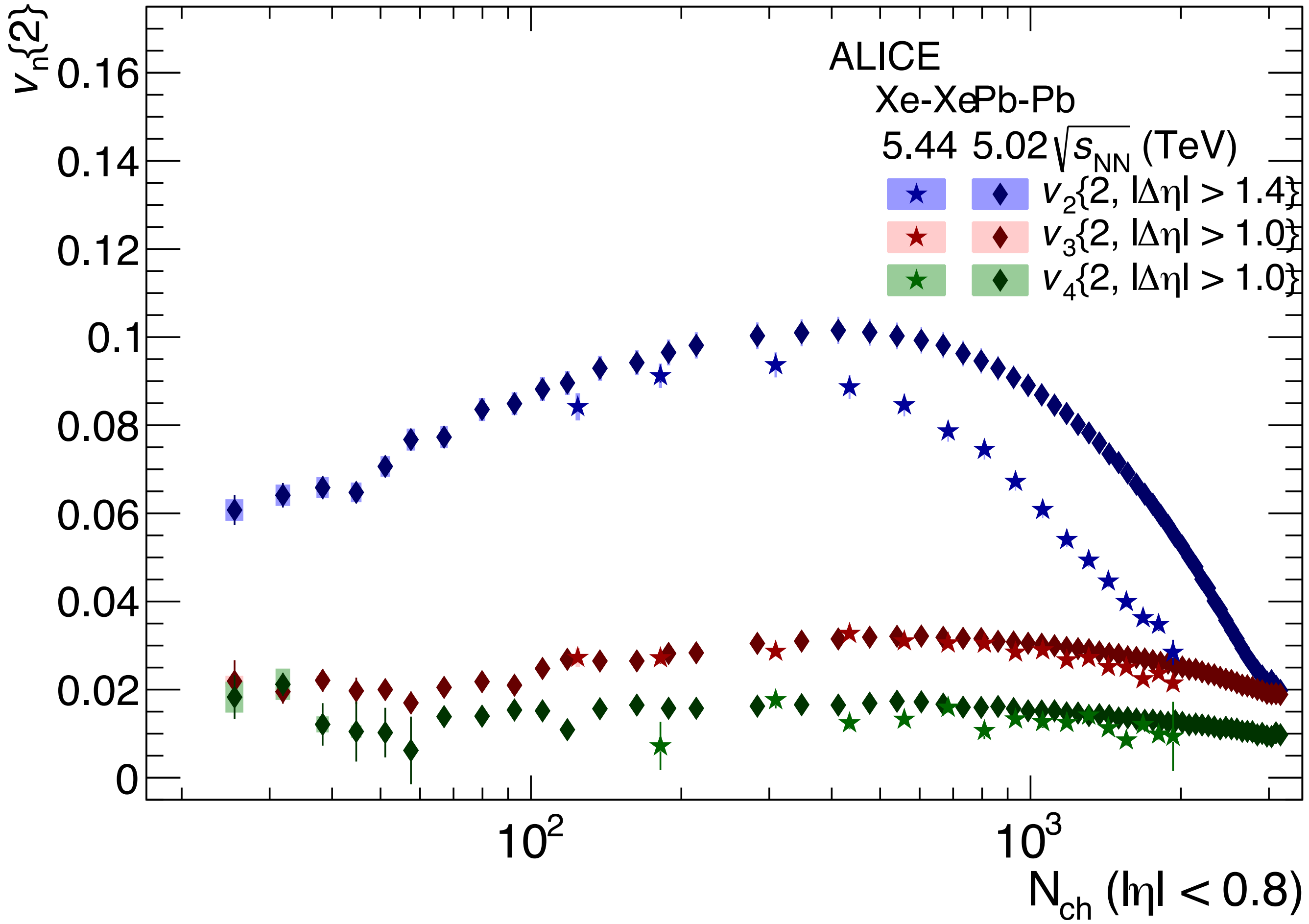
V0A : $2.8 < \eta < 5.1$
V0C : $-3.7 < \eta < -1.7$

- Triggering
- Event multiplicity determination

System size comparison of v_n's

Large systems (central Pb-Pb & Xe-Xe)

- Strong N_{ch} dependence of v_2
- Ordering $v_2 > v_3 > v_4$ (except for very high N_{ch})



[arXiv: 1903.01790]

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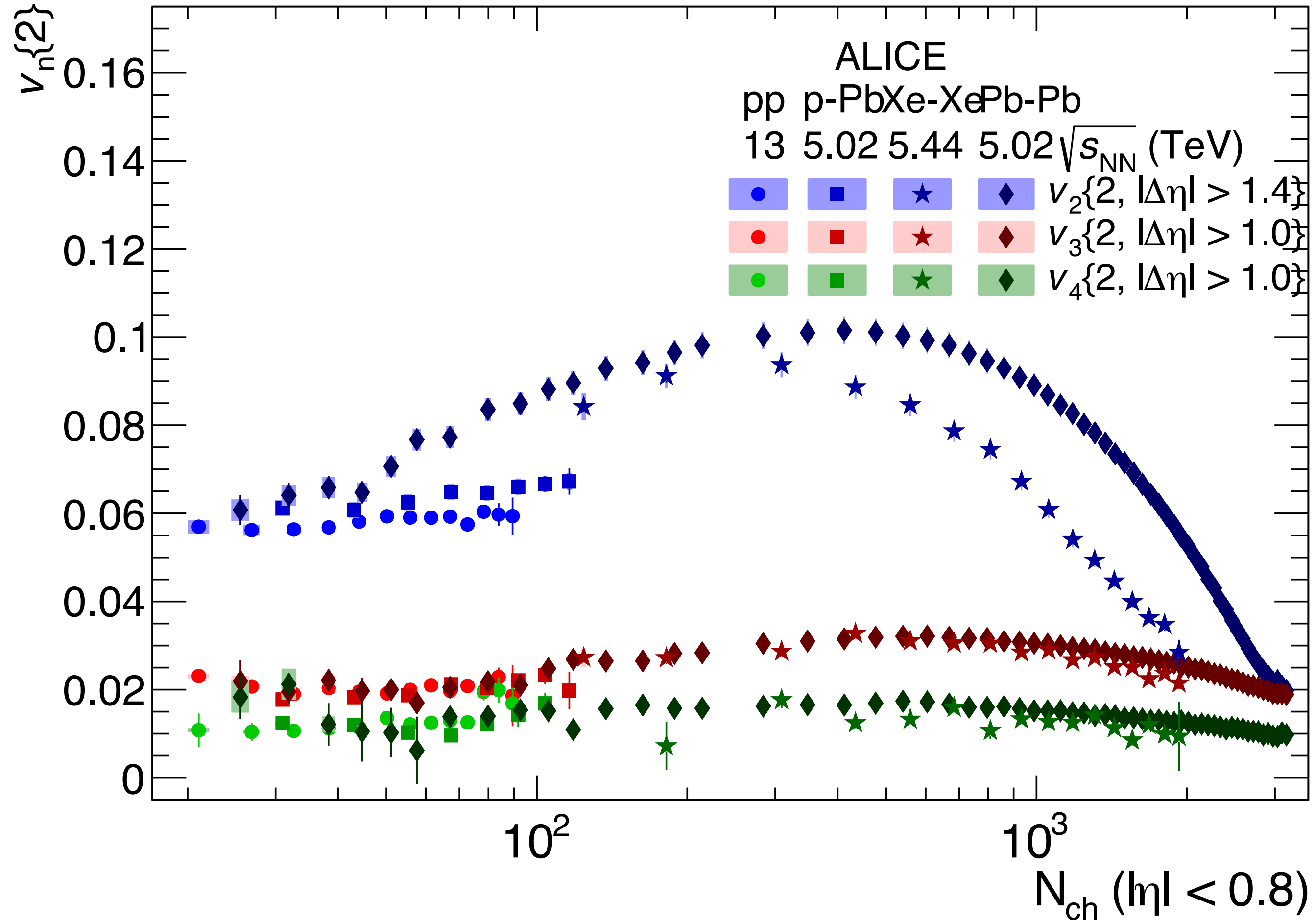

Small systems (p-Pb & pp)

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- Long-range: $v_2\{m\} \sim v_2\{m\}_{sub}$

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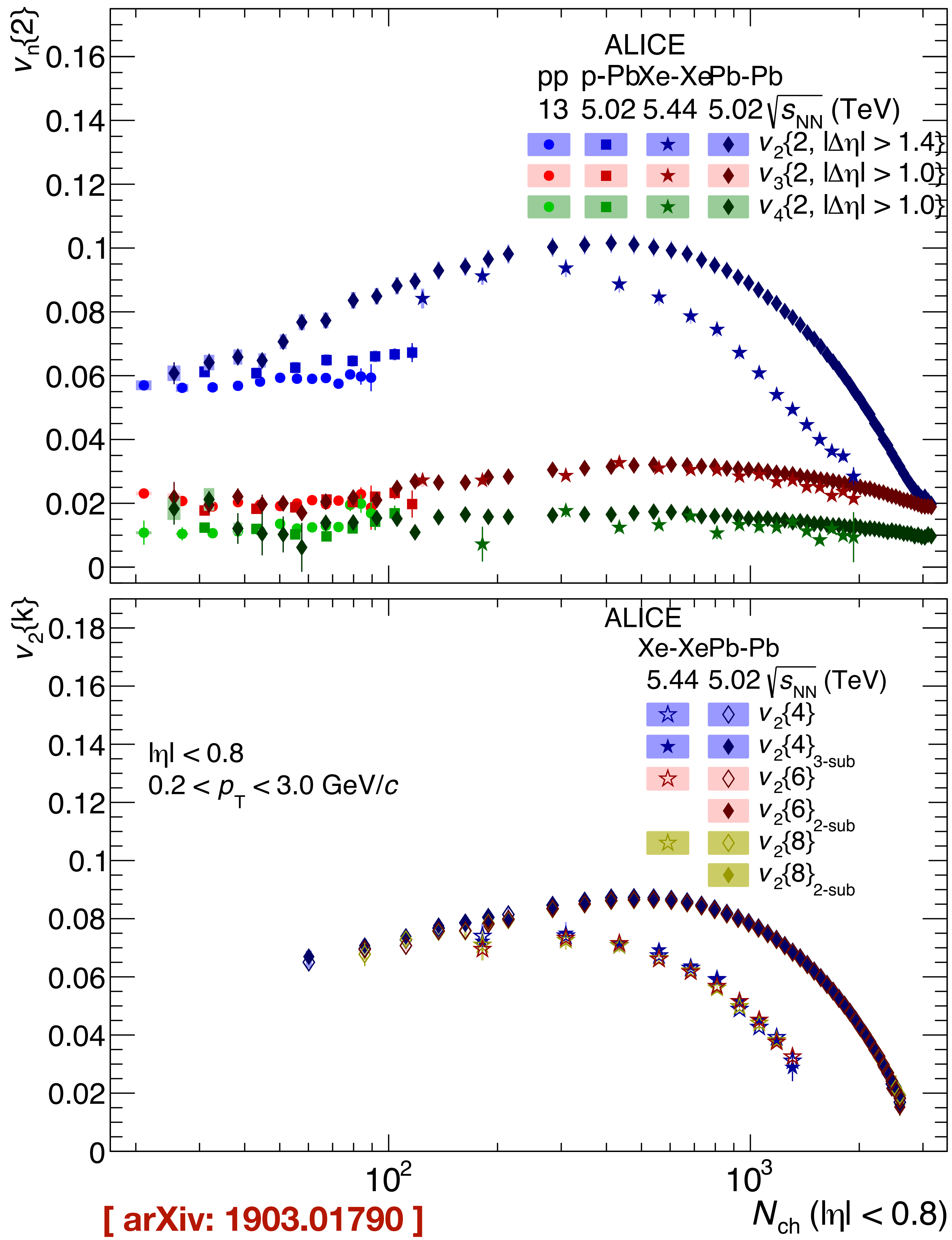

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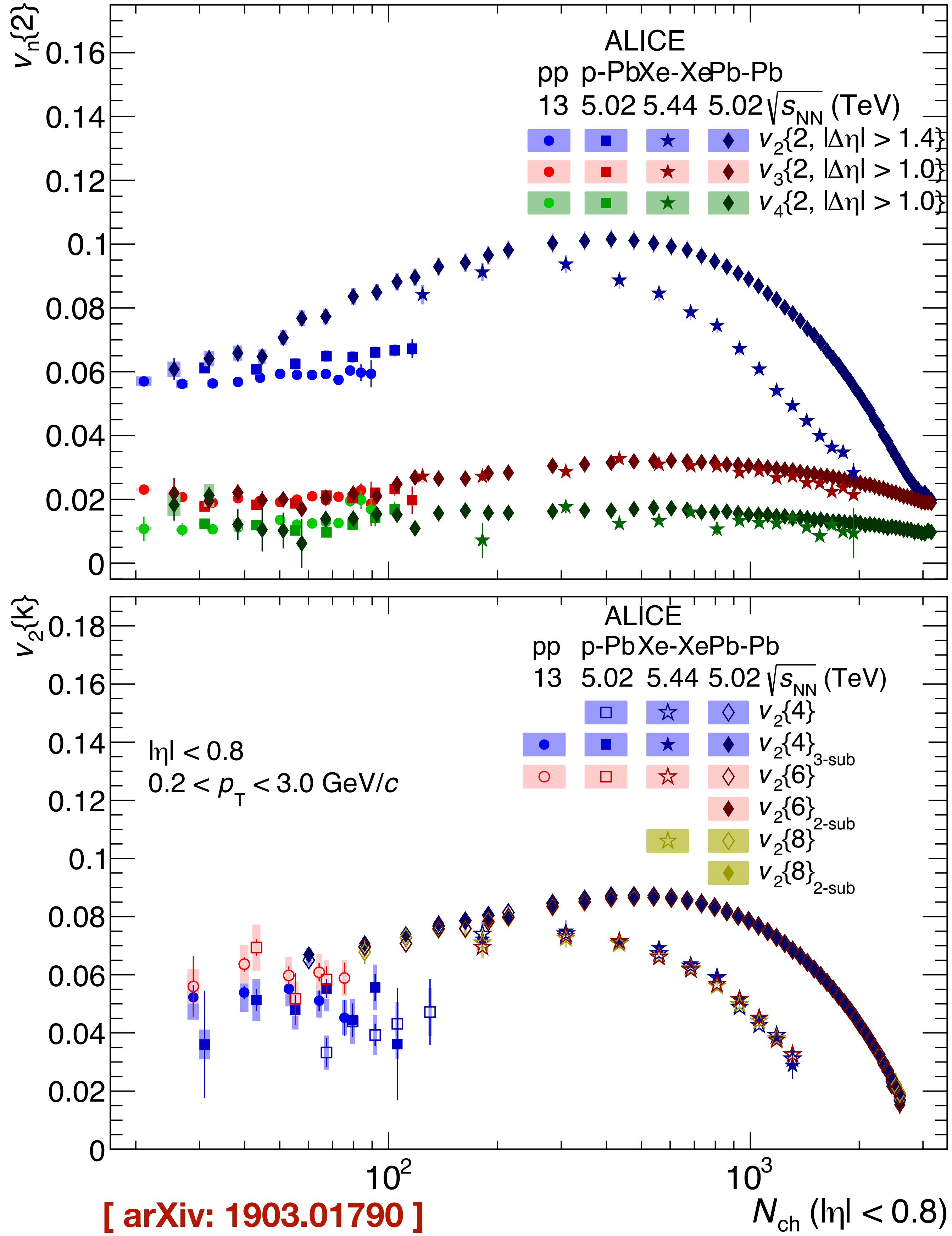

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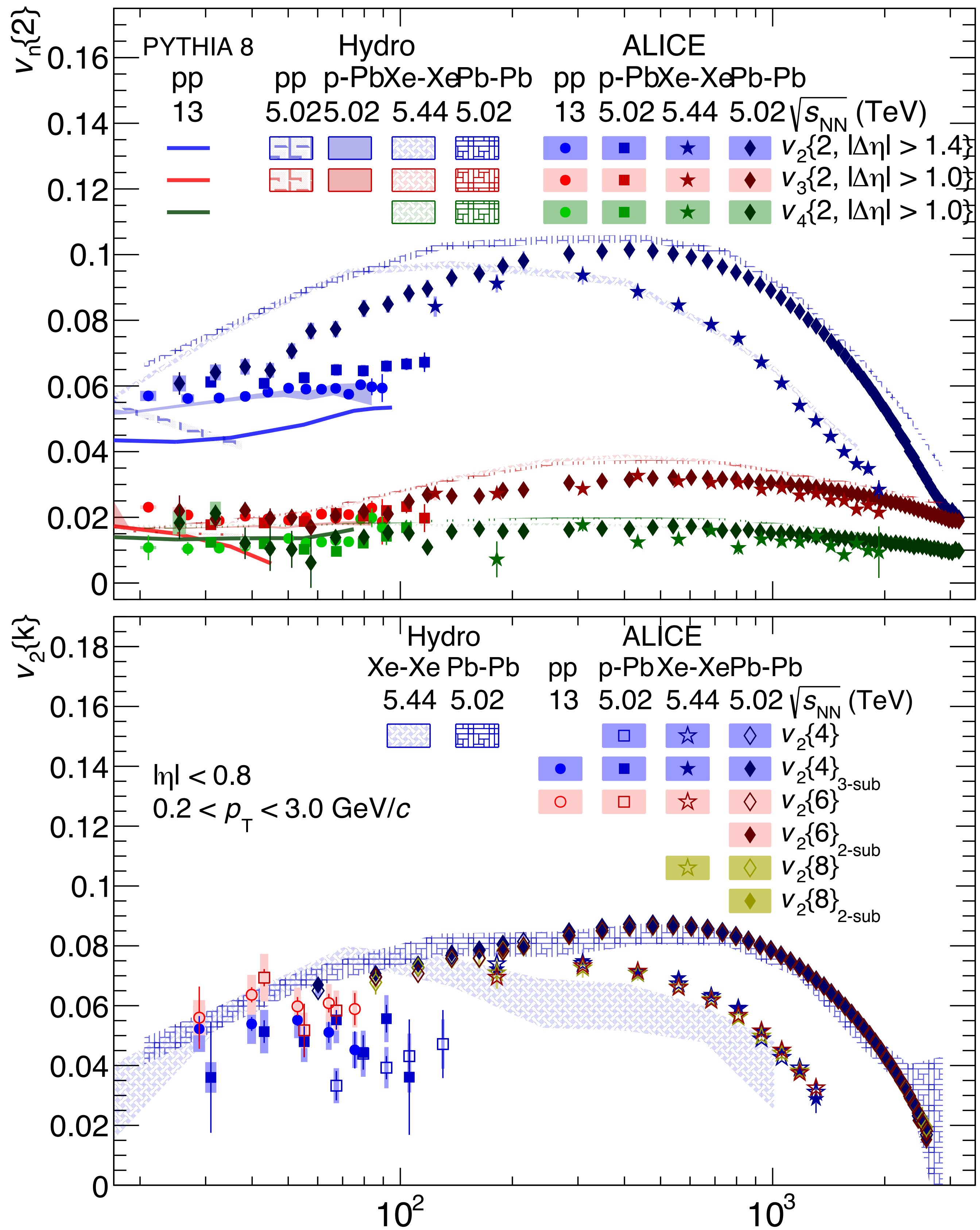

*IP-Glasma+MUSIC+UrQMD

PYTHIA 8.210 Monash 2013

[arXiv: 1903.01790]

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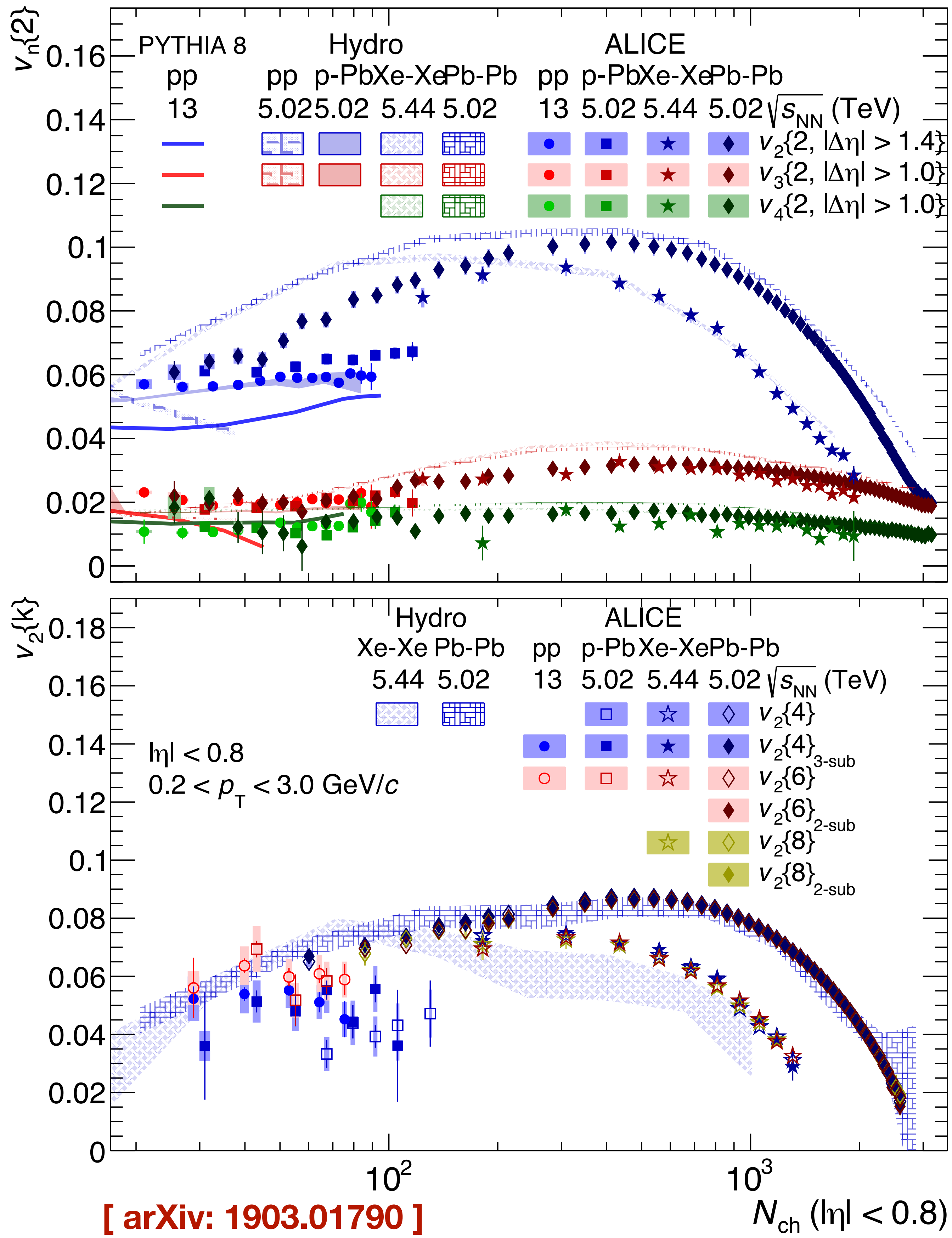
Long-range multi-particle correlations observed in small collision systems!



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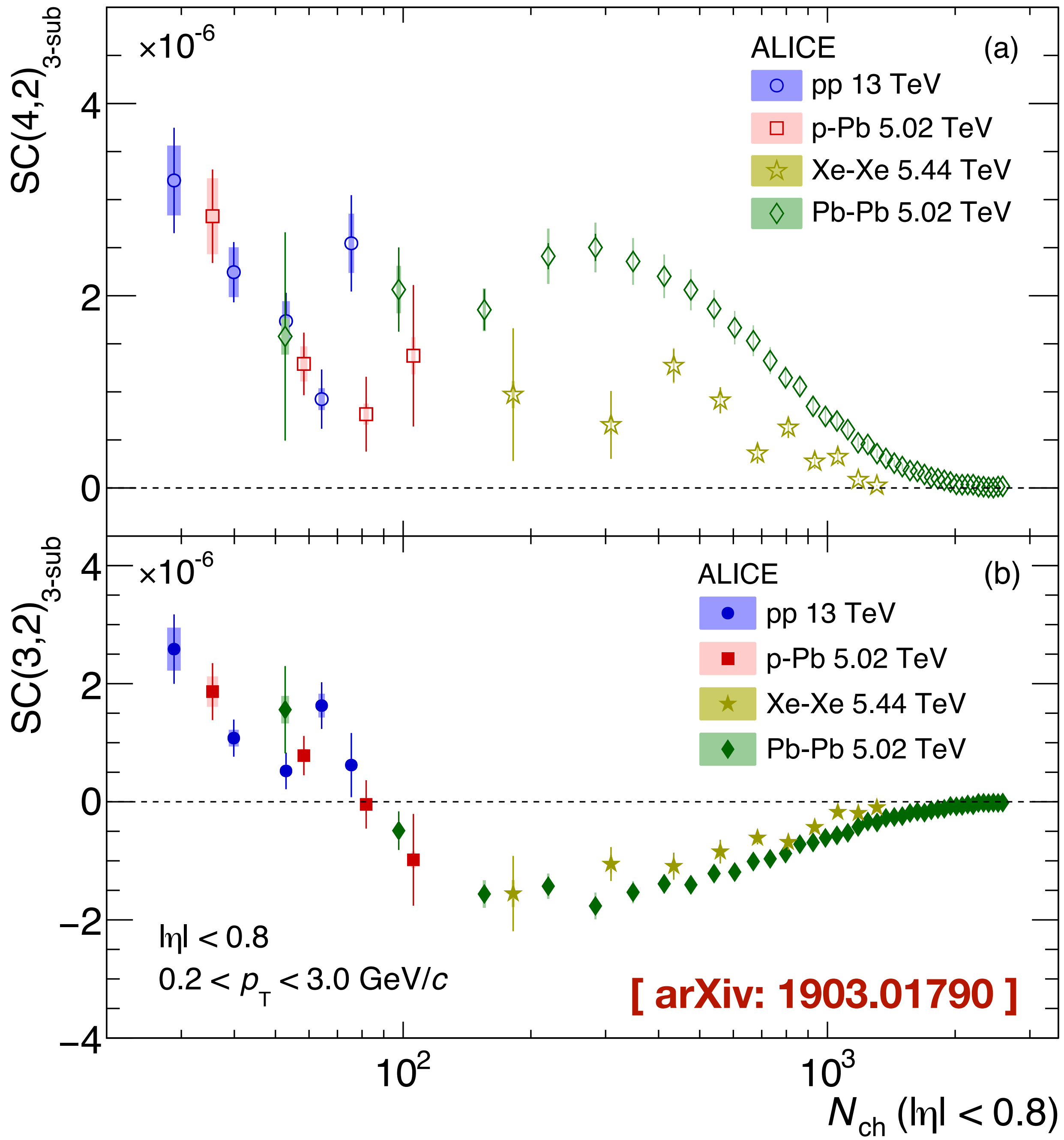
Correlations between flow coefficients

ALICE measurements

- $SC(4,2)_{\text{3-sub}}$
  - Positive in all collision systems
- $SC(3,2)_{\text{3-sub}}$
  - Negative at large multiplicities
  - Change of sign in Pb-Pb, followed by small systems

$$SC(m,n) = \langle v_n^2 \cdot v_m^2 \rangle - \langle v_n^2 \rangle \cdot \langle v_m^2 \rangle$$



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- Does not reproduce $SC(4,2)$
- Exhibits similar trend in $SC(3,2)$

IP-Glasma+MUSIC+UrQMD

- Qualitatively describes heavy-ions
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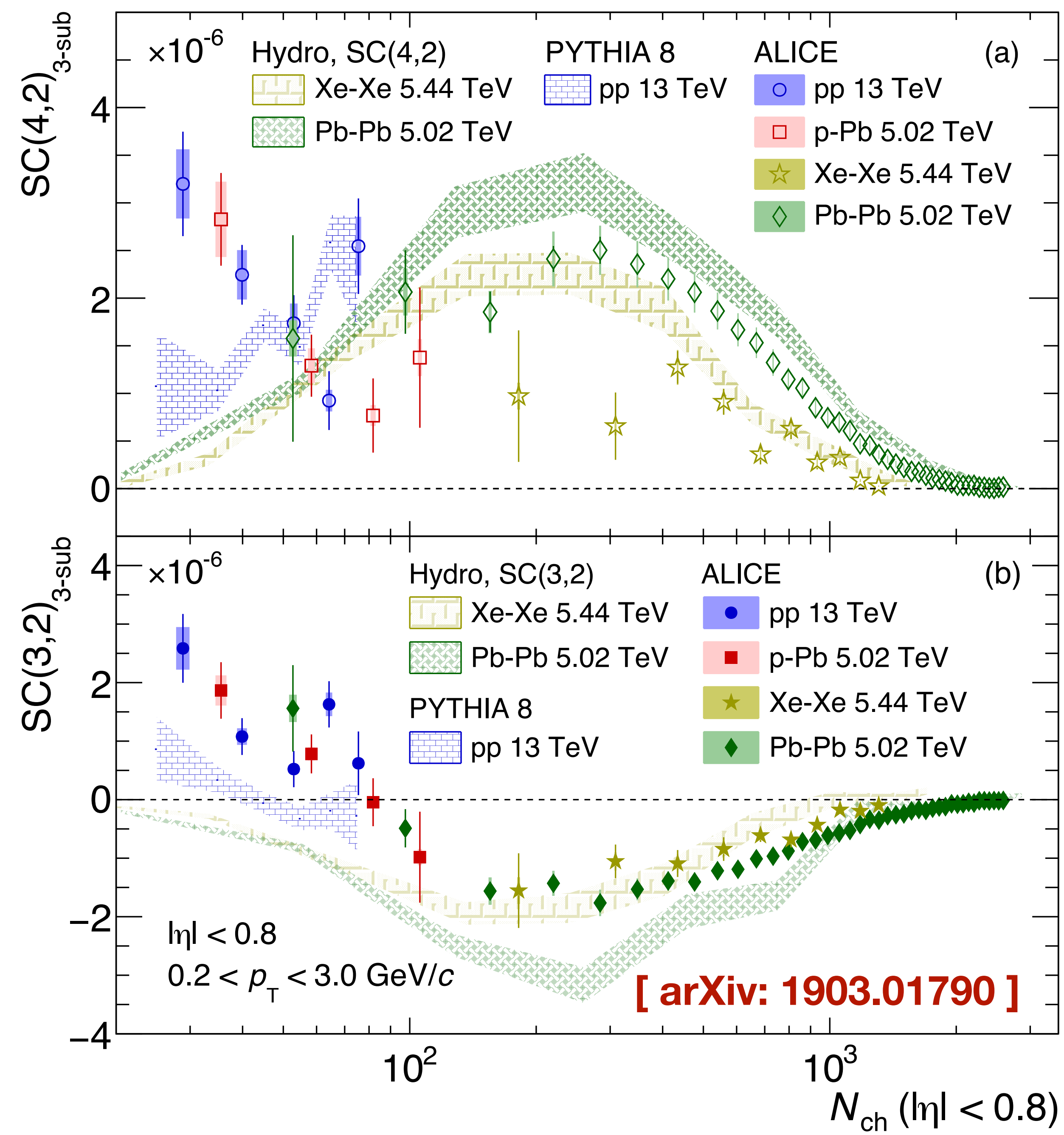

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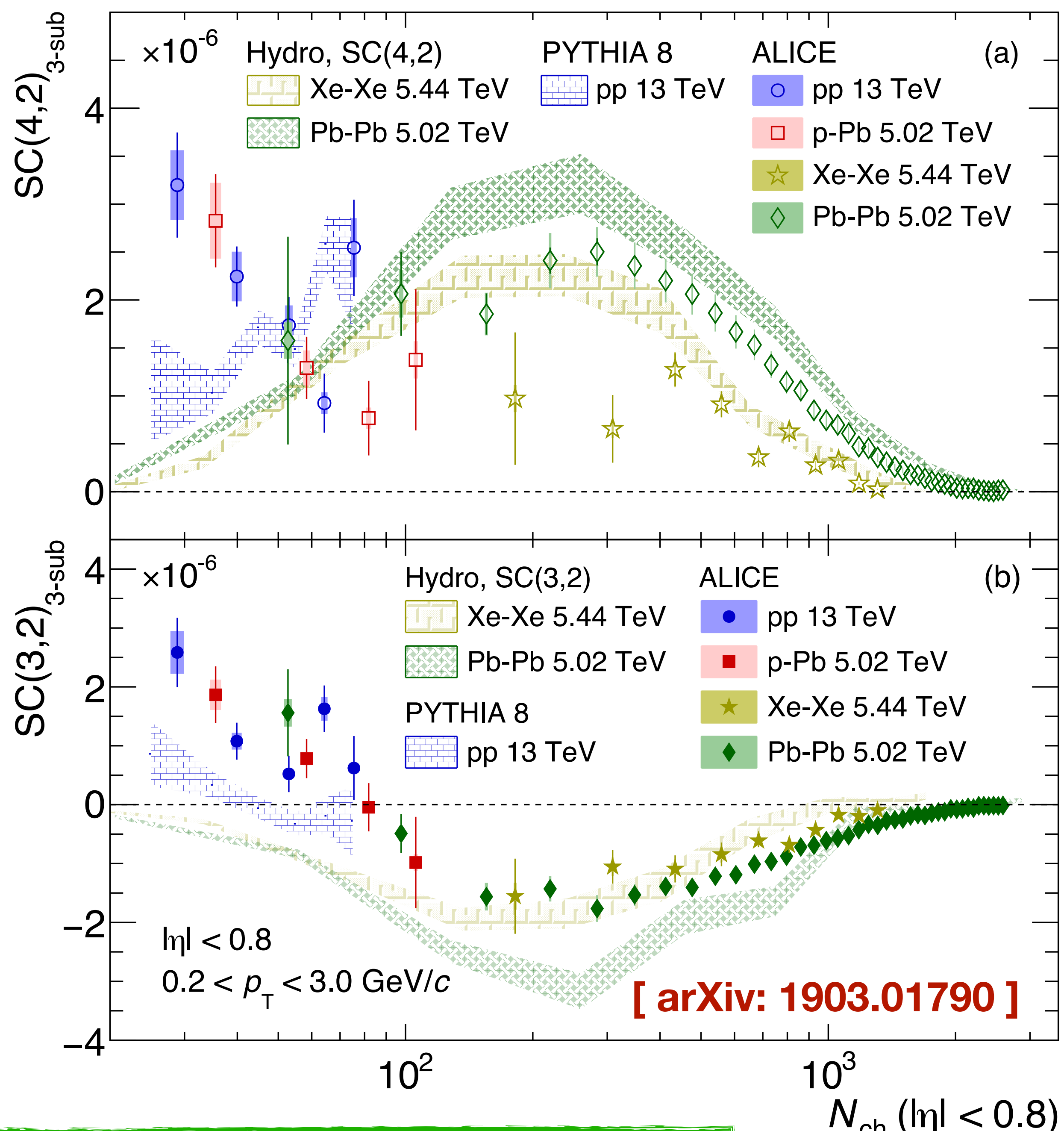


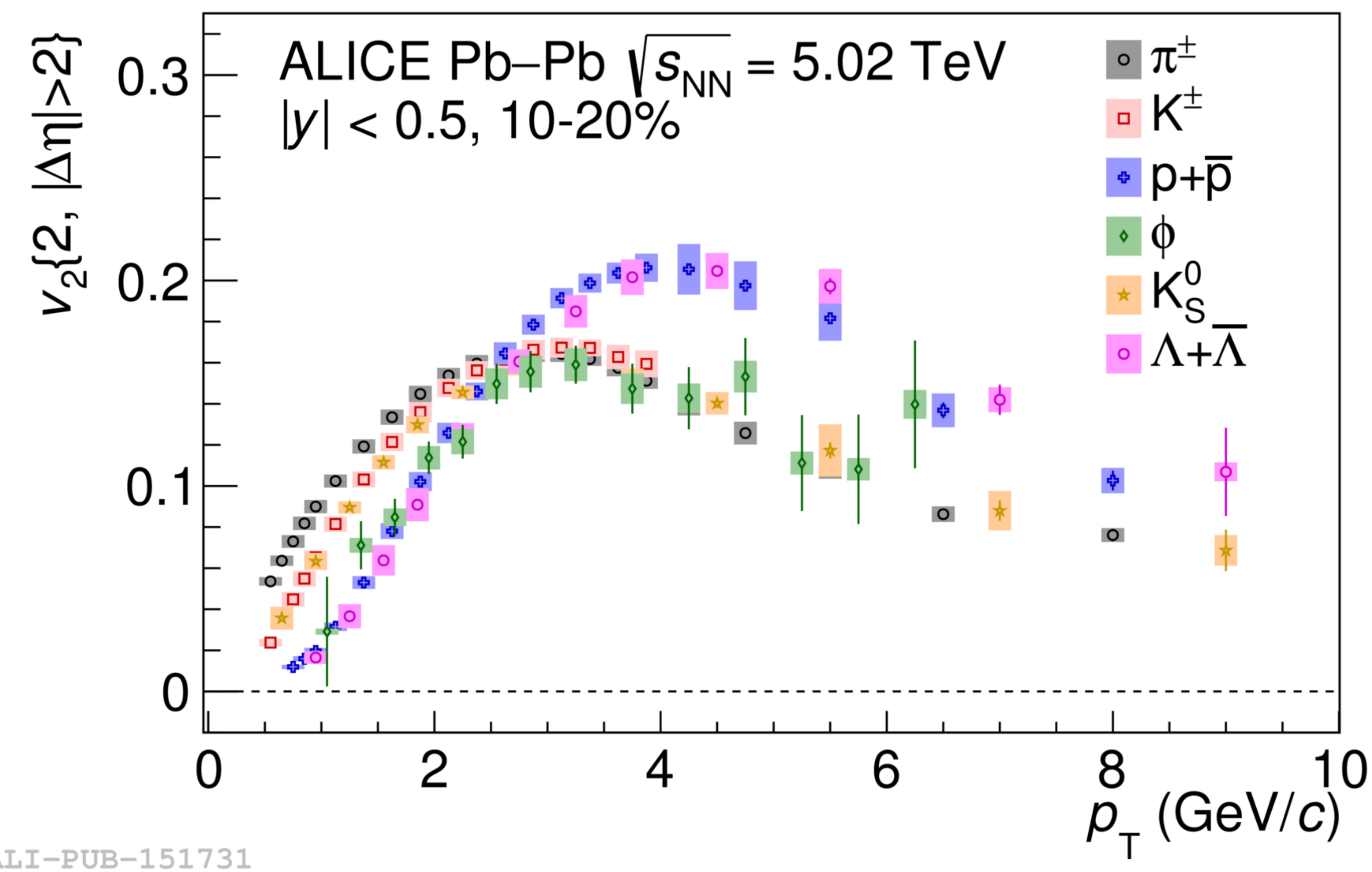
Rather smooth evolution with N_{ch} across colliding systems

Indication of a similar origin of the collectivity

v_n coefficient & identified hadrons

- Studying **particle behaviour** in different p_T regions

[JHEP 1809 (2018) 006]

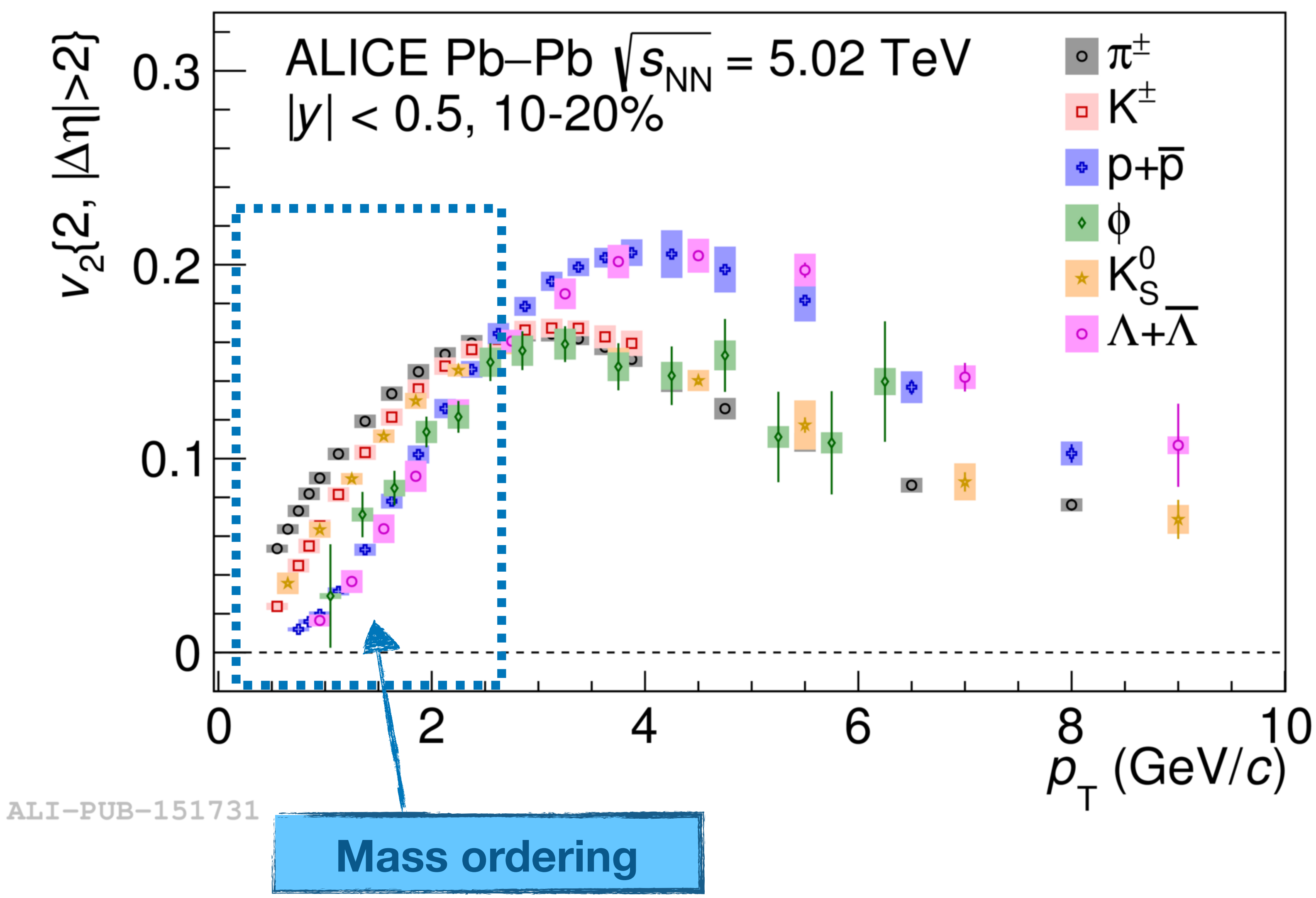


- However, 2-particle correlations sensitive to non-flow contaminations (decays, jets, …)

v_n coefficient & identified hadrons

- Studying **particle behaviour** in different p_T regions
  - **Mass ordering** (hydrodynamic flow, hadron re-scattering)

[JHEP 1809 (2018) 006]

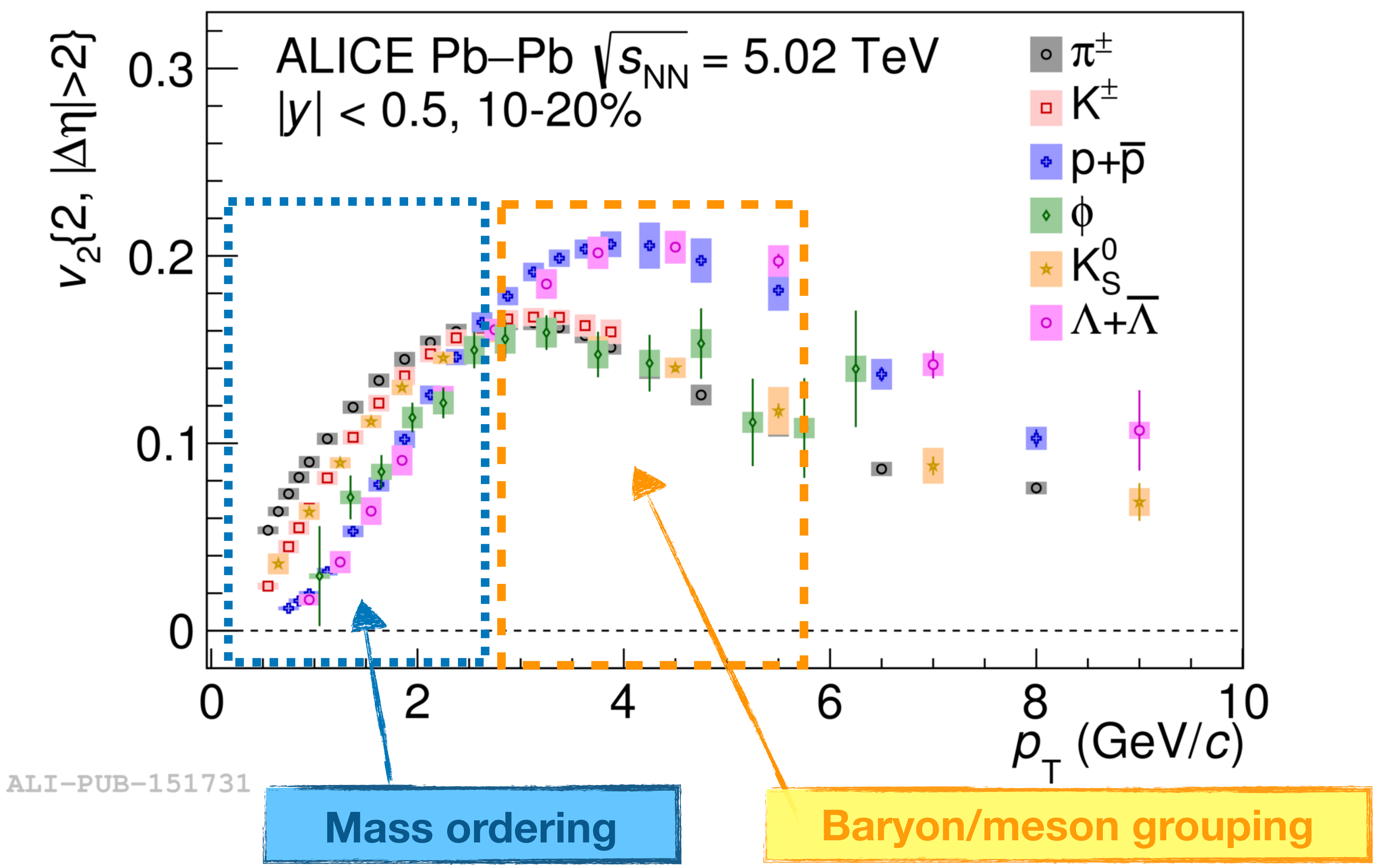


- However, 2-particle correlations sensitive to non-flow contaminations (decays, jets, …)

v_n coefficient & identified hadrons

- Studying **particle behaviour** in different p_T regions
  - **Mass ordering** (hydrodynamic flow, hadron re-scattering)
  - **Baryon/meson grouping** (recombination/coalescence?)

[JHEP 1809 (2018) 006]

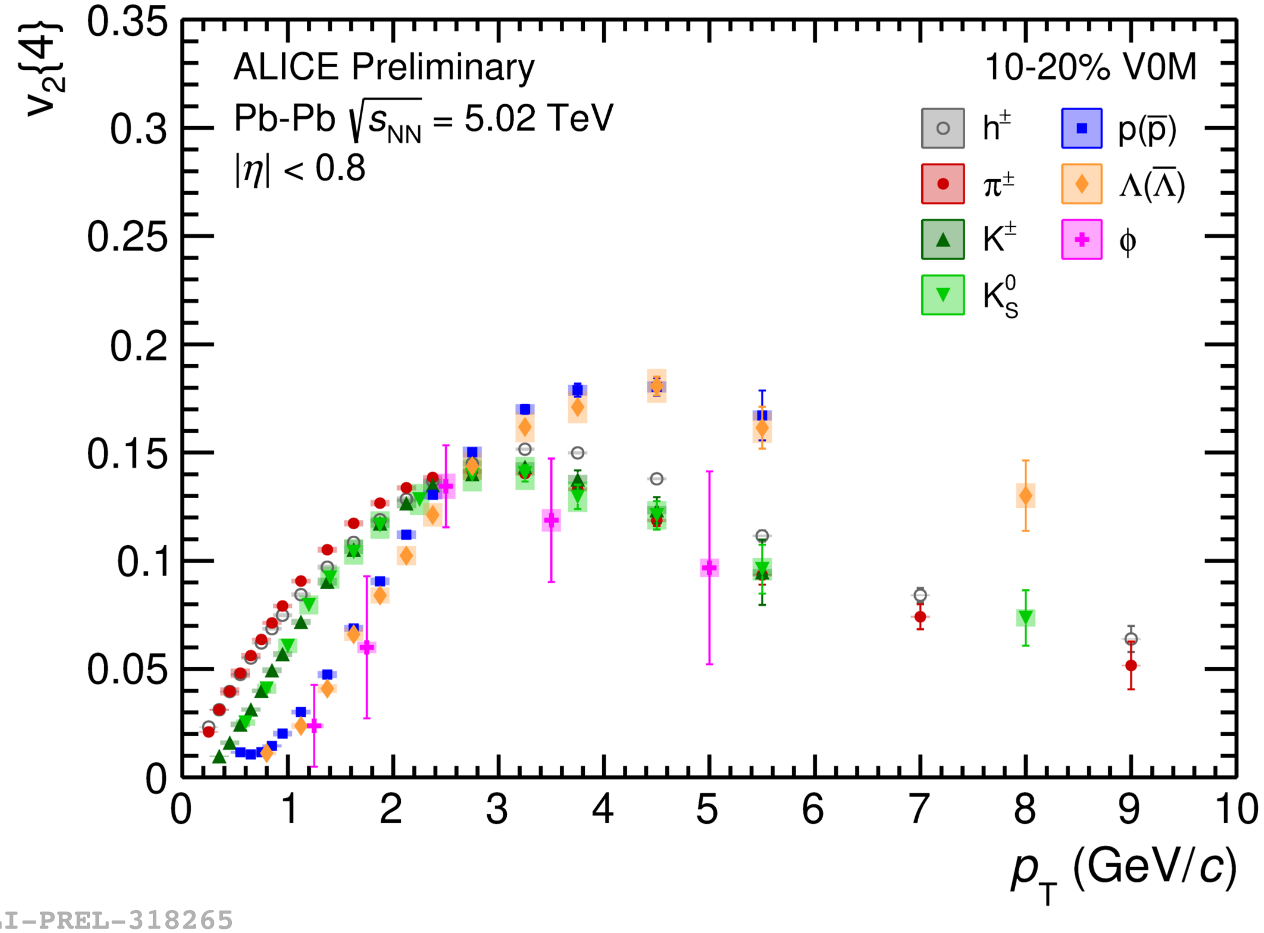


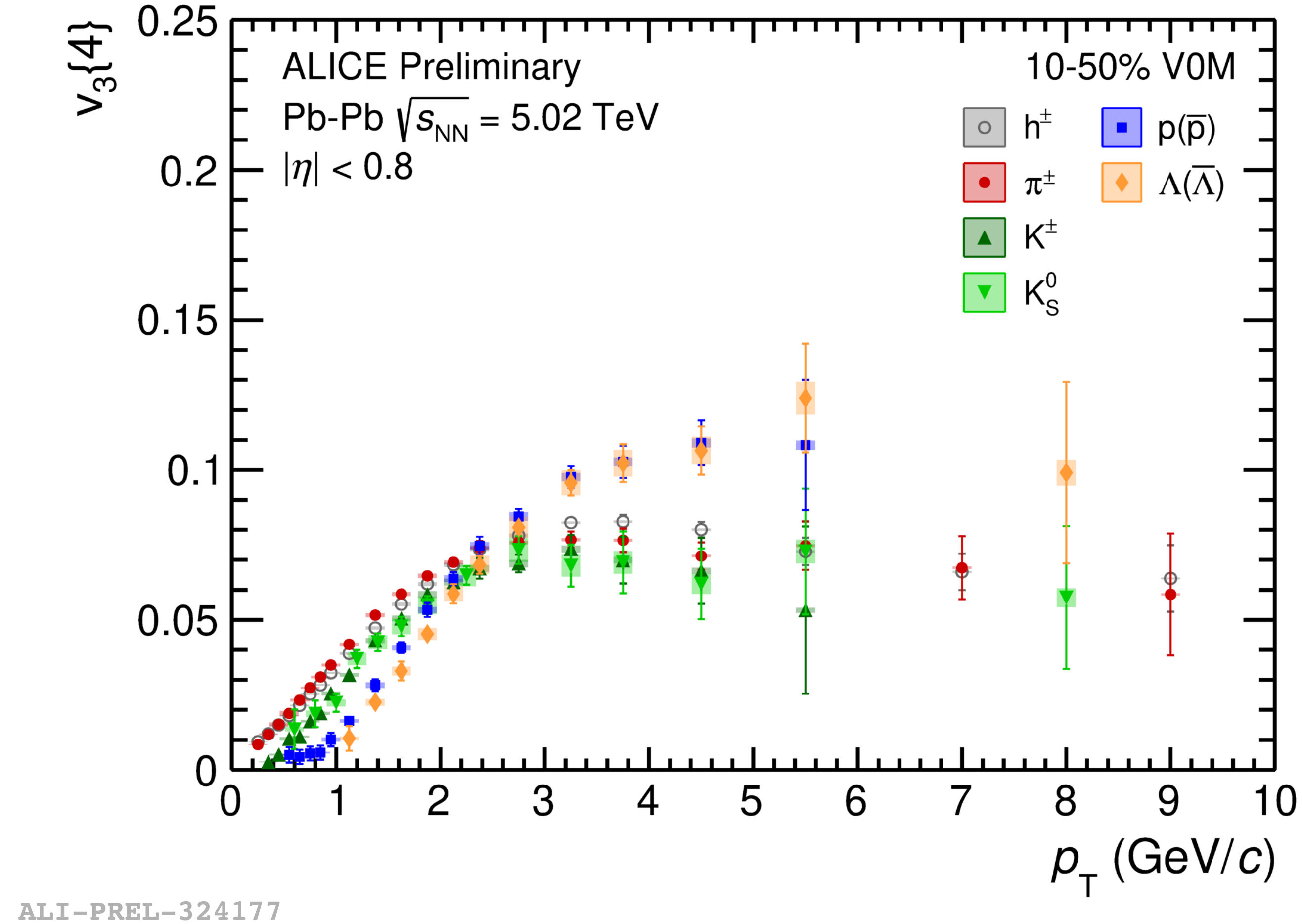
- However, 2-particle correlations sensitive to non-flow contaminations (decays, jets, …)

Results of 4-particle cumulants

- First measurement of $v_n(p_T)$ of identified hadrons using 4-particle cumulant method

  [NB: $v_2\{4\}$ in all cent. in back-up]





- Qualitatively similar behaviour as of $v_2\{2\}$ measurements
  - Mass-ordering and baryon/meson grouping effects preserved
  - Less sensitive to non-flow contamination
- Analysis of large data sample collected in 2018 ongoing to further improve the precision

Flow and flow fluctuation

NEW

- Measurements of 2- & 4-particle correlations used to study v_n fluctuations (if non-flow is negligible in 2-PC) **[Voloshin, Poskanzer, Tang, Wang, PLB 659 (2008) 537-541]**

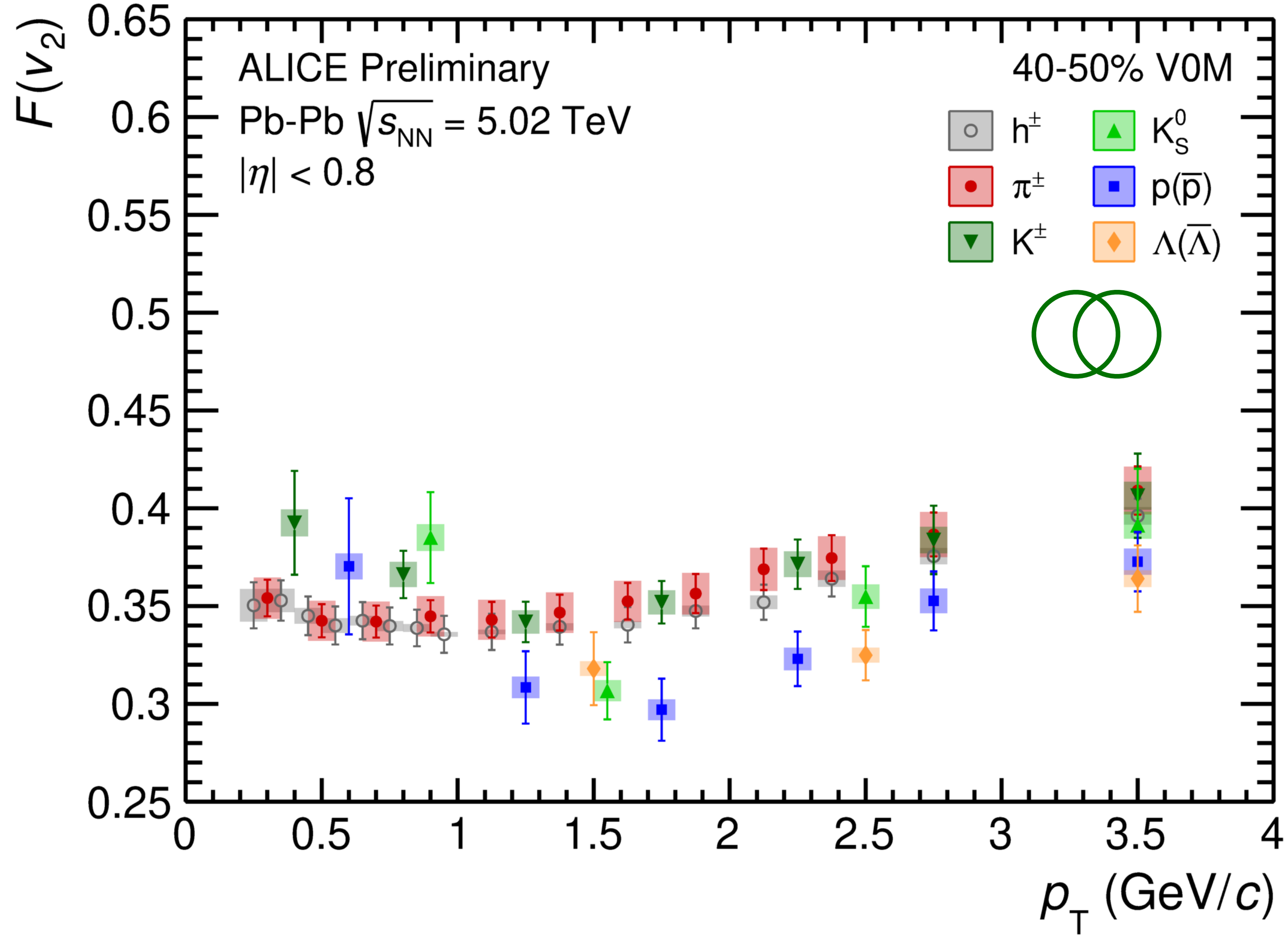
$$v_n\{2\}^2 = \langle v_n\rangle^2 + \sigma_{v_n}^2$$
$$v_n\{4\}^2 \approx \langle v_n\rangle^2 - \sigma_{v_n}^2$$

- First two moments of v_n p.d.f.

$$\langle v_n\rangle \approx \sqrt{(v_n\{2\}^2 + v_n\{4\}^2)/2}$$
$$\sigma_{v_n} \approx \sqrt{(v_n\{2\}^2 - v_n\{4\}^2)/2}$$

- Relative v_n fluctuations

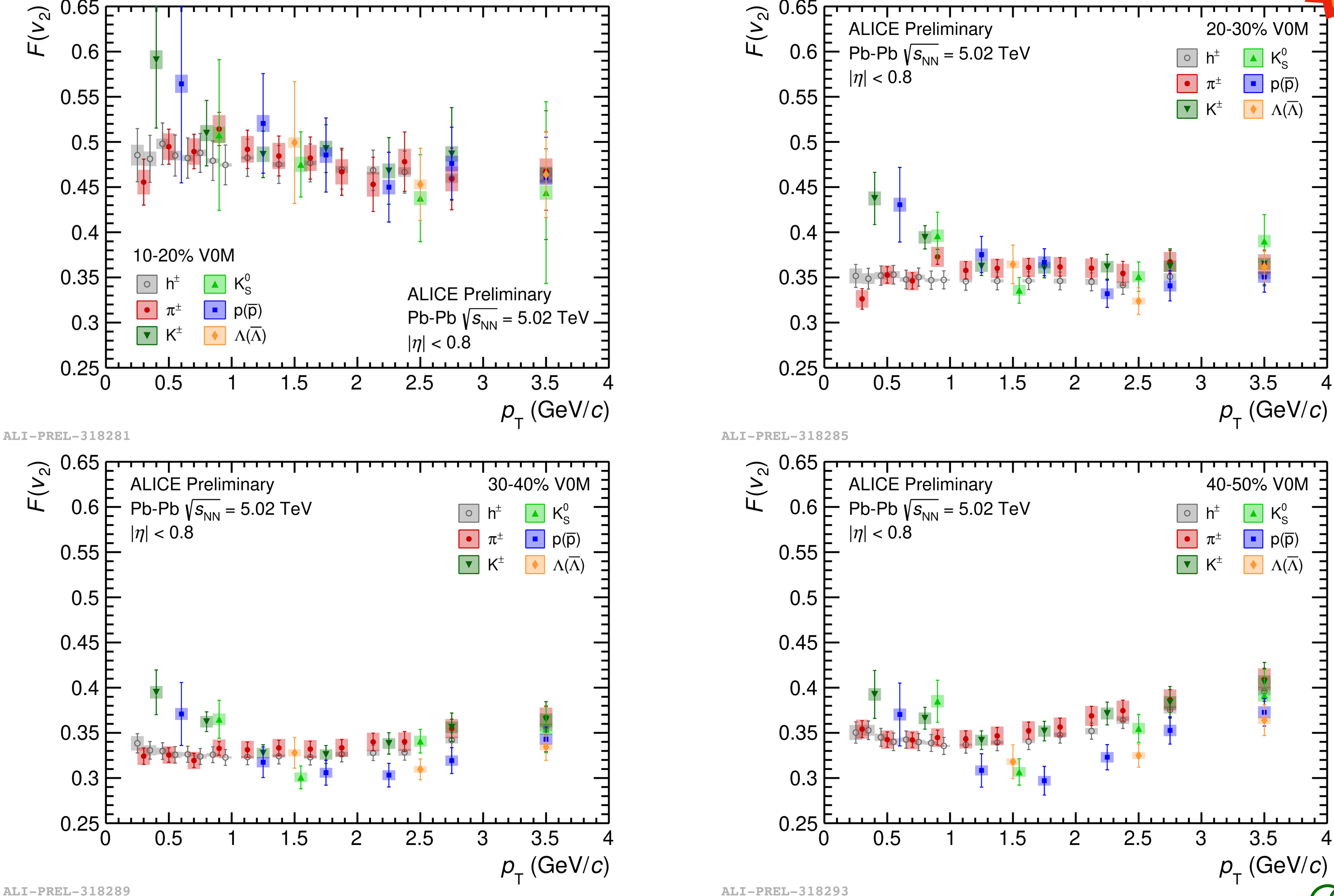
$$F(v_n) = \frac{\sigma_{v_n}}{\langle v_n\rangle}$$



ALI-PREL-318293

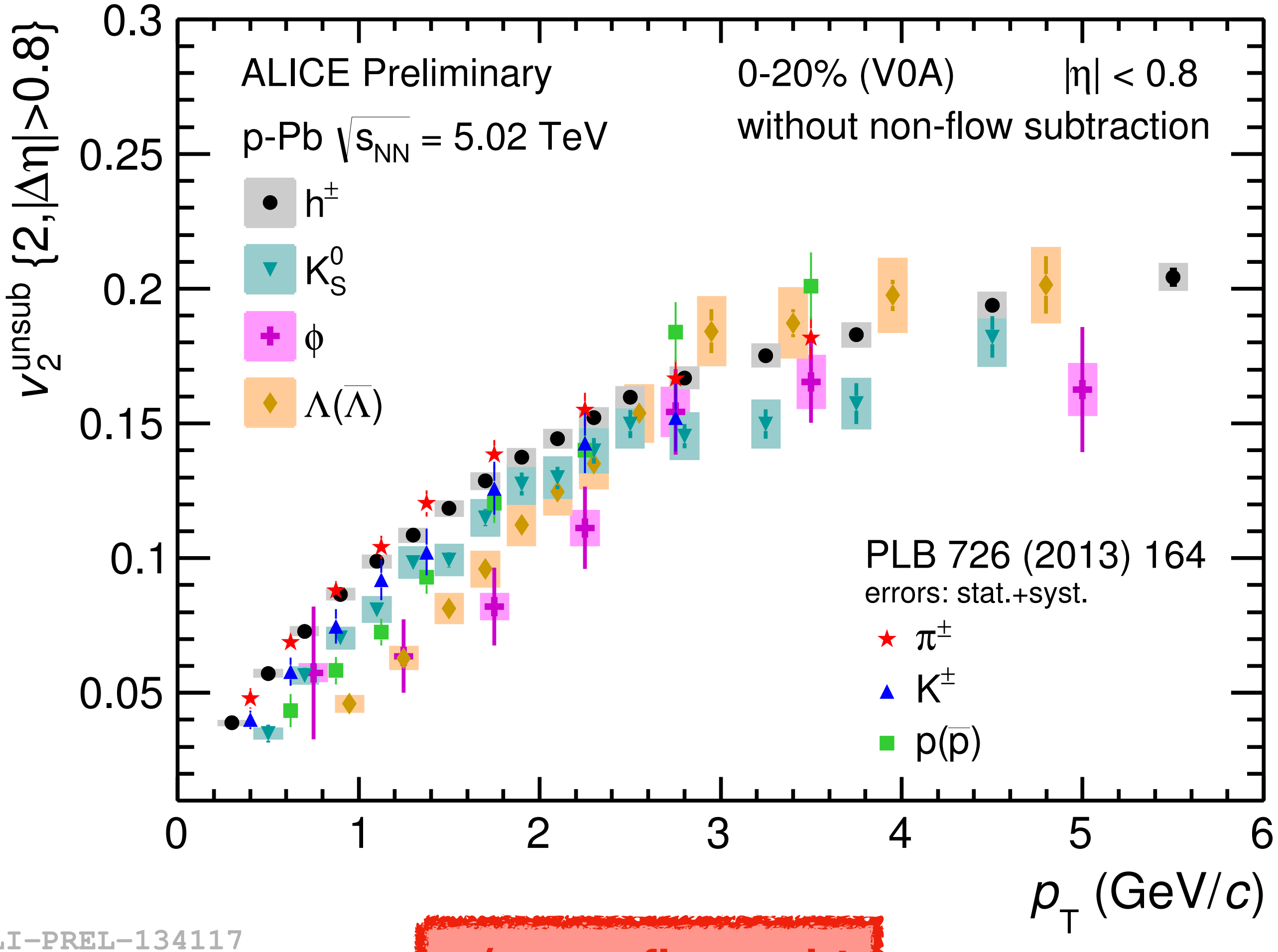
- First measurement of p_T-diff. $F(v_2)$ for identified hadrons
  - Non-trivial mass dependence observed
  - Would be interesting to see if hydro (or other models) can reproduce the trend

Centrality dependence of $F(v_2)$

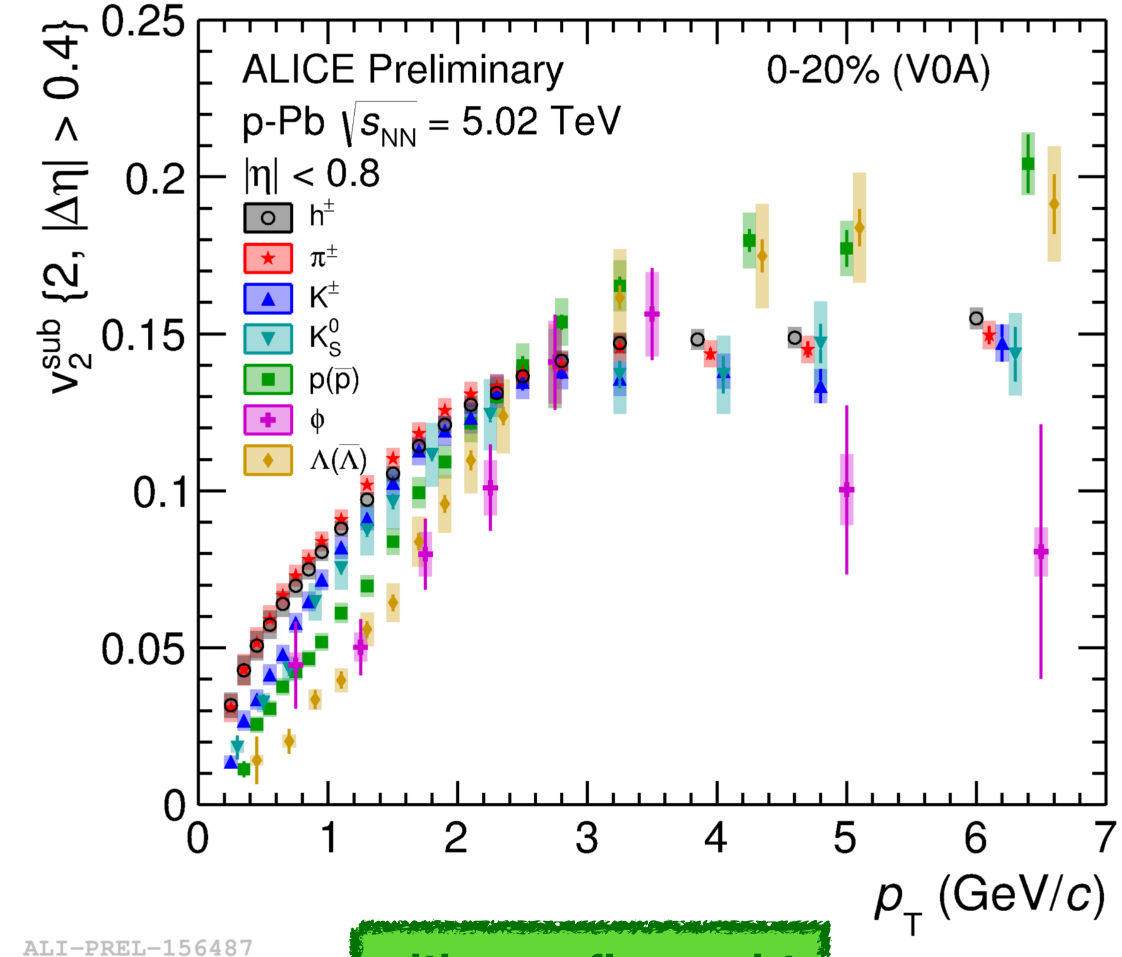


- Mass dependence less pronounced towards more central collisions

p-Pb: Looking at small systems



w/o non-flow subt.



with non-flow subt.

- Hint of mass ordering and baryon/meson grouping similar to Pb-Pb
    - Significantly clearer after non-flow subtraction by min. bias pp collisions
    - v_n saturates at high p_T: remaining non-flow contamination ?
    - Very sensitive to multiplicity fluctuations, further investigation in progress

Summary

- **Collective phenomena observed even in small collision systems**
  - Rather smooth evolution with N_{ch} across all systems
  - More differential studies provide tighter constrains on theoretical models

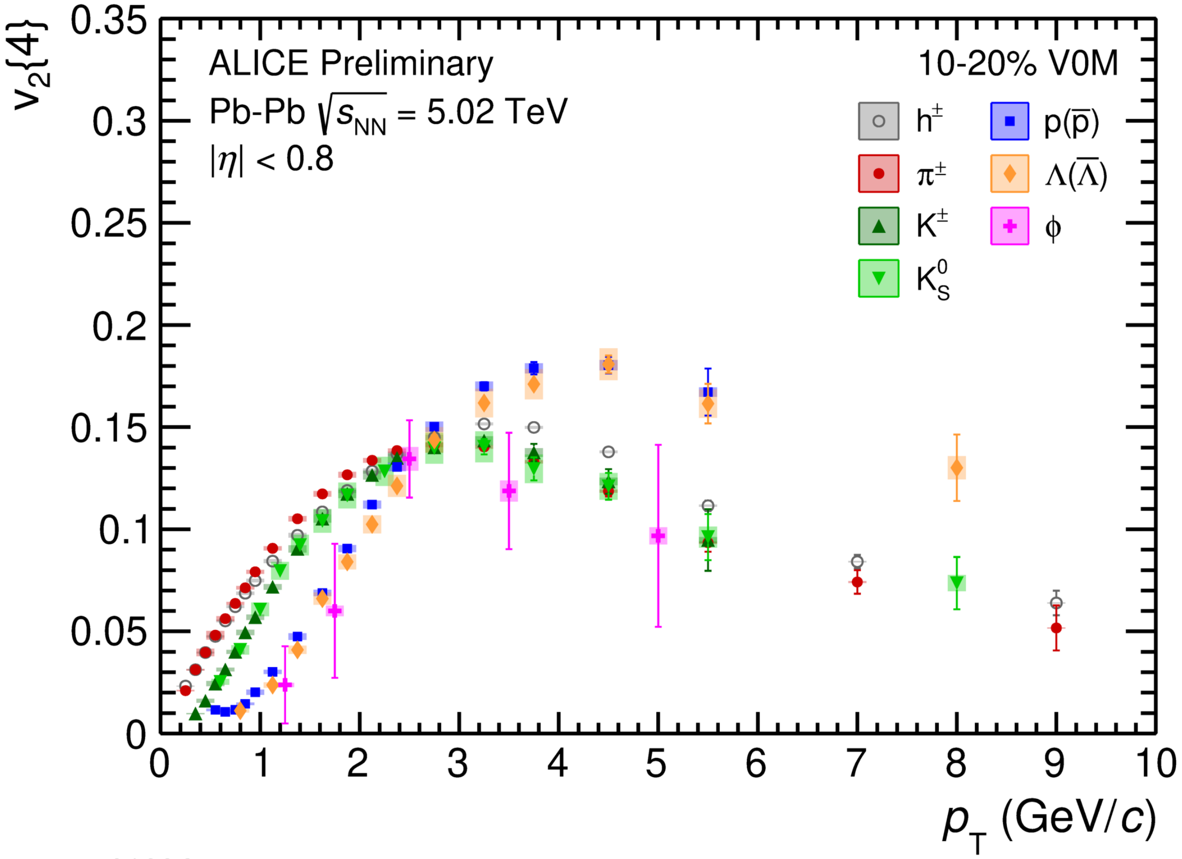
- **First measurement of $v_n(p_T)$ of identified hadrons using 4-particle cumulants in Pb-Pb**
  - Less sensitive to non-flow (crucial for small systems!)
  - Non-trivial **mass dependence of relative fluctuations** of v_n p.d.f.

- **Pursuing collectivity in small systems is a challenging task**
  - Systematic study ongoing on multiple frontiers, careful treatment essential
  - Stay tuned for new results in p-Pb (e.g. 4-particle cumulants)

— Thank you for your attention ! —

— Back-up —

Centrality dependence of $v_2\{4\}$



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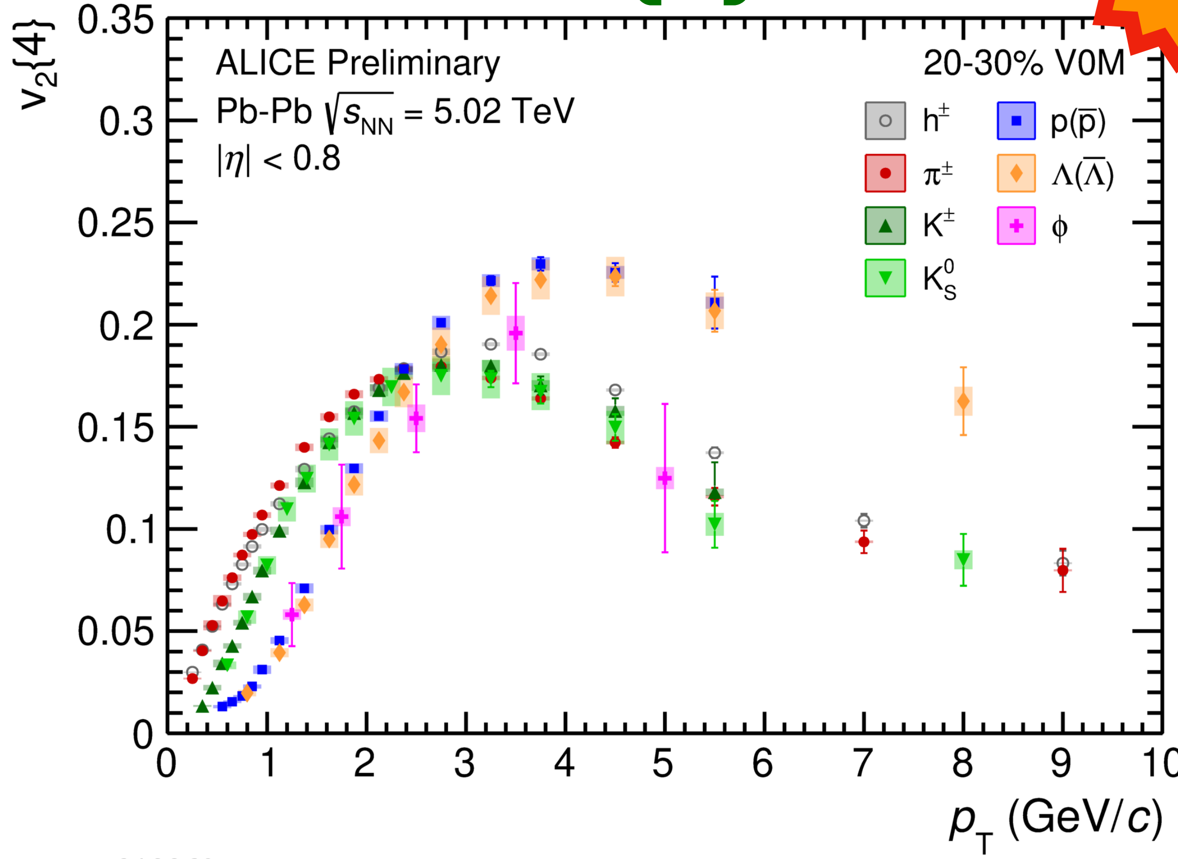

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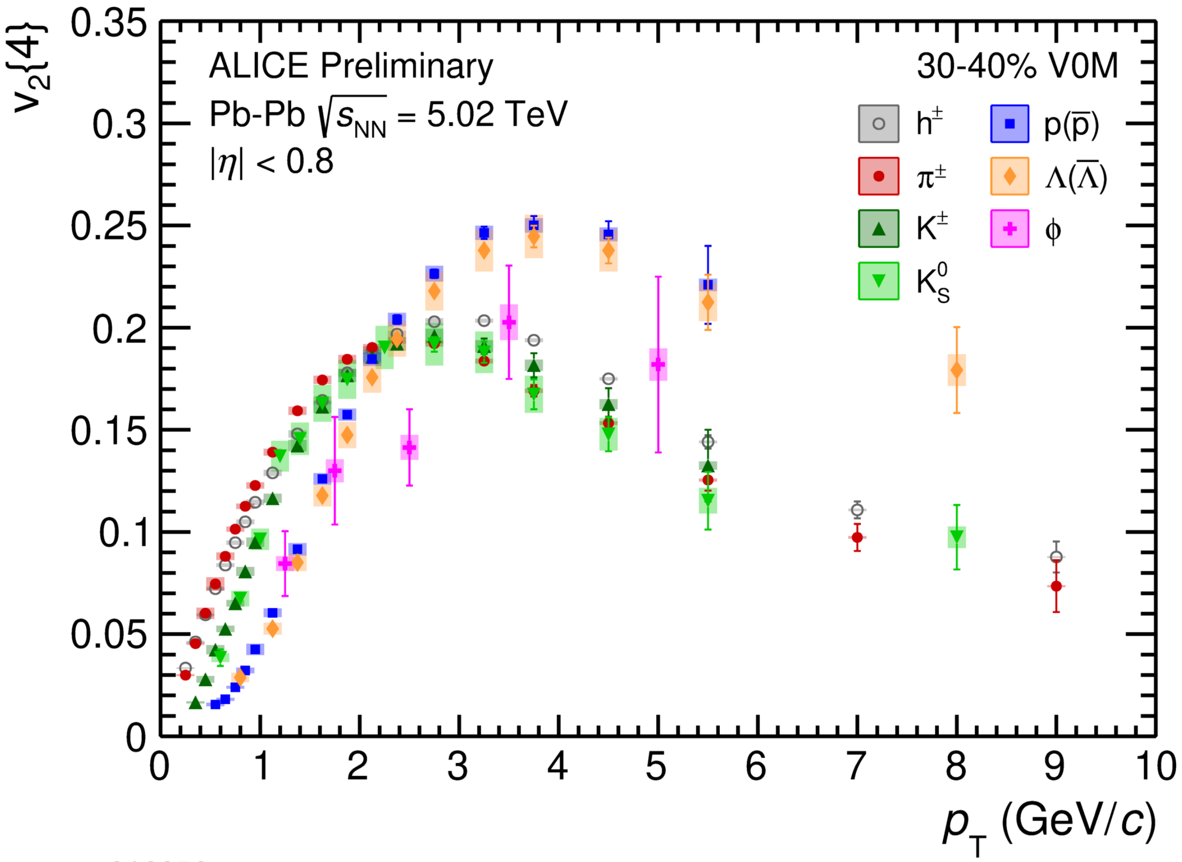

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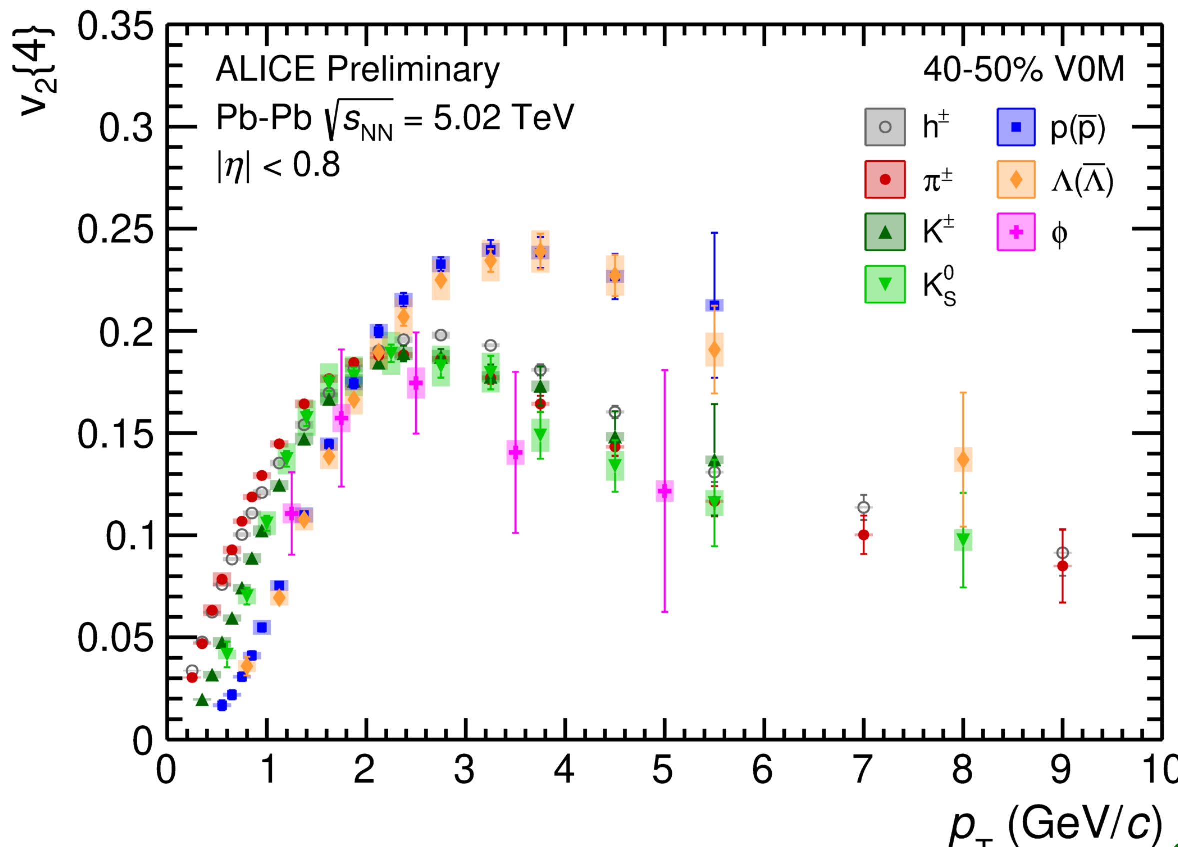

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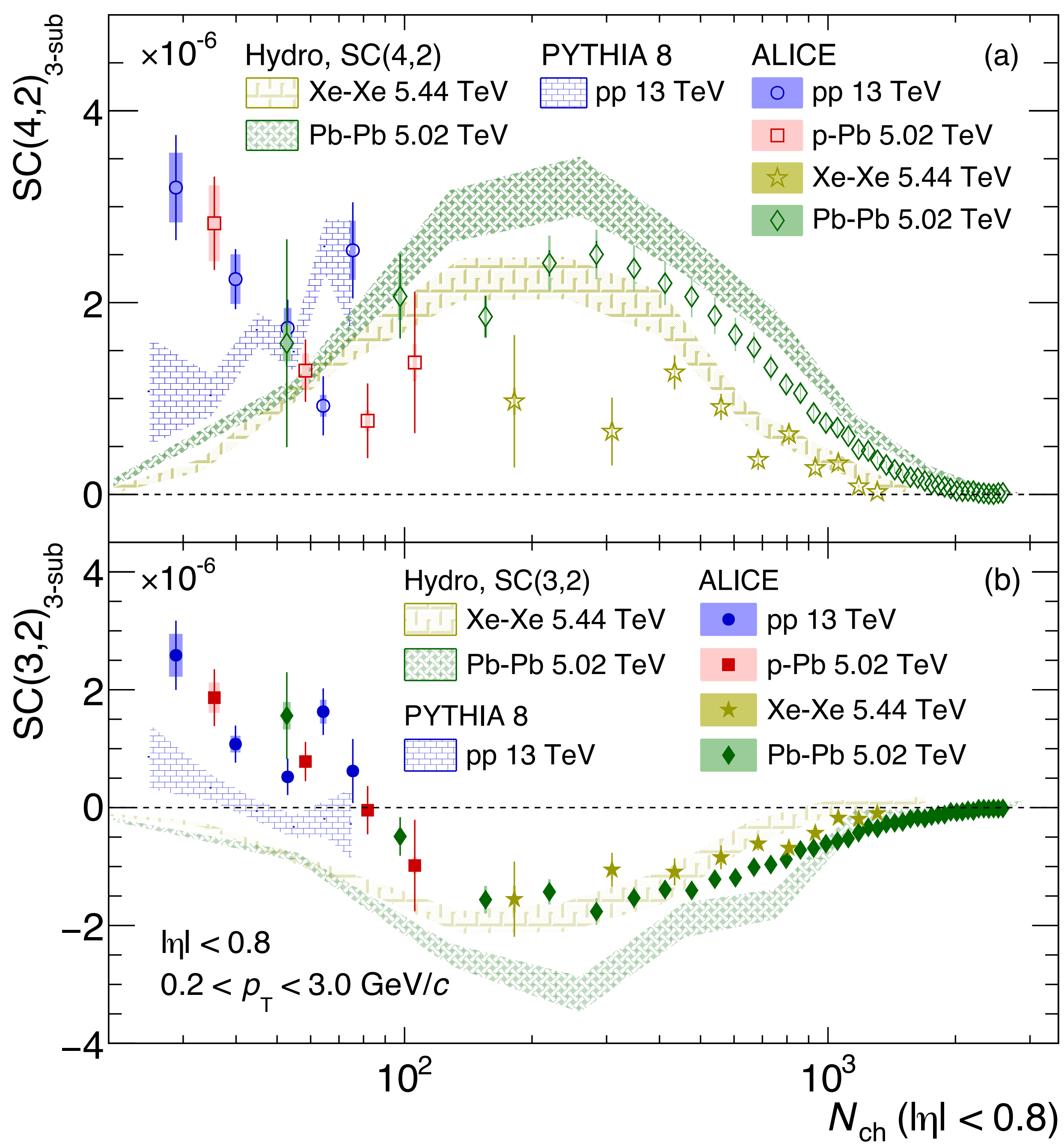
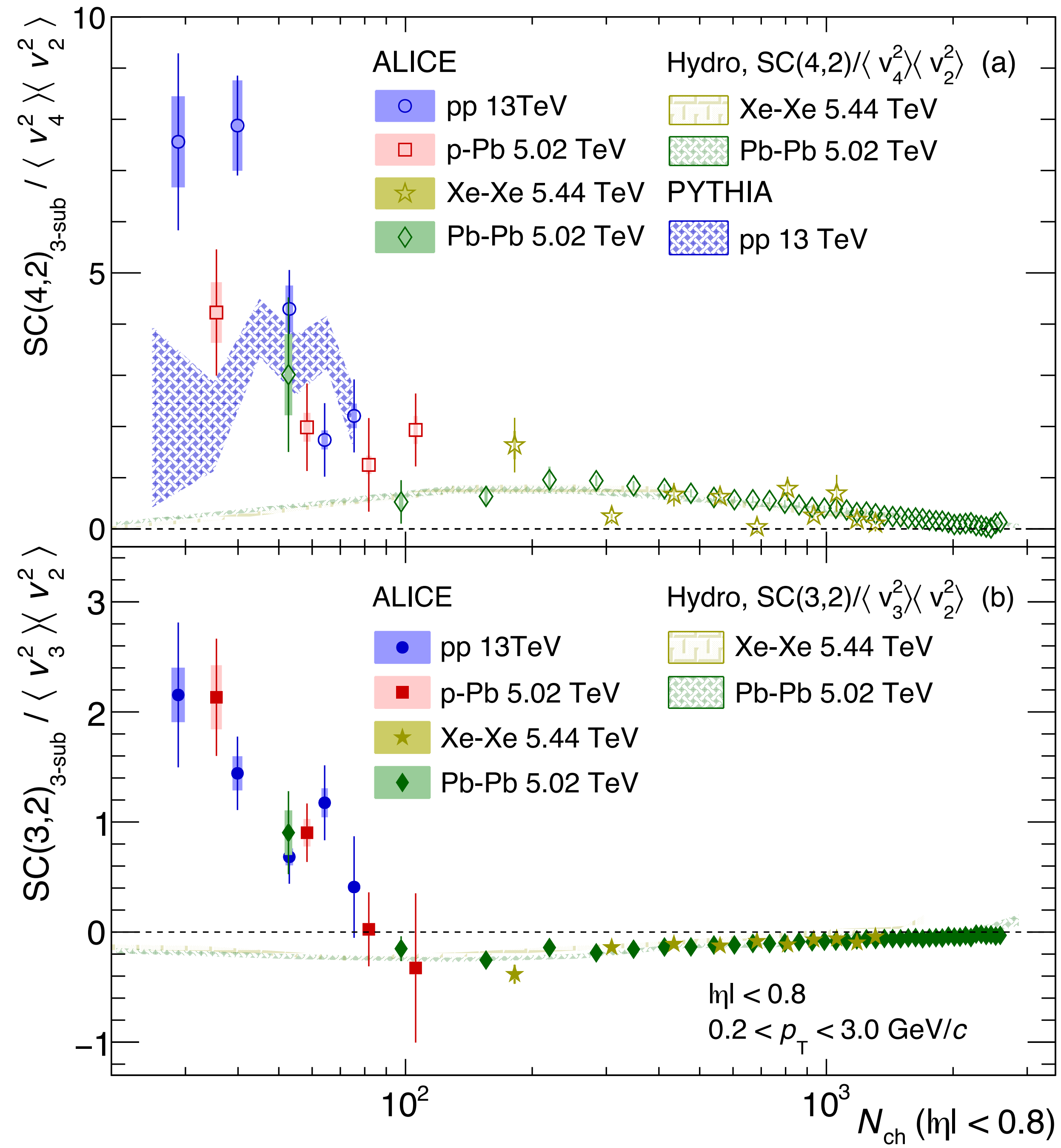
NEW

Normalised SC

$$SC(m,n) = \langle v_n^2 \cdot v_m^2 \rangle - \langle v_n^2 \rangle \cdot \langle v_m^2 \rangle$$

$$\frac{SC(m,n)_{3-\mathrm{sub}}}{\langle v_n^2 \rangle \langle v_m^2 \rangle}$$



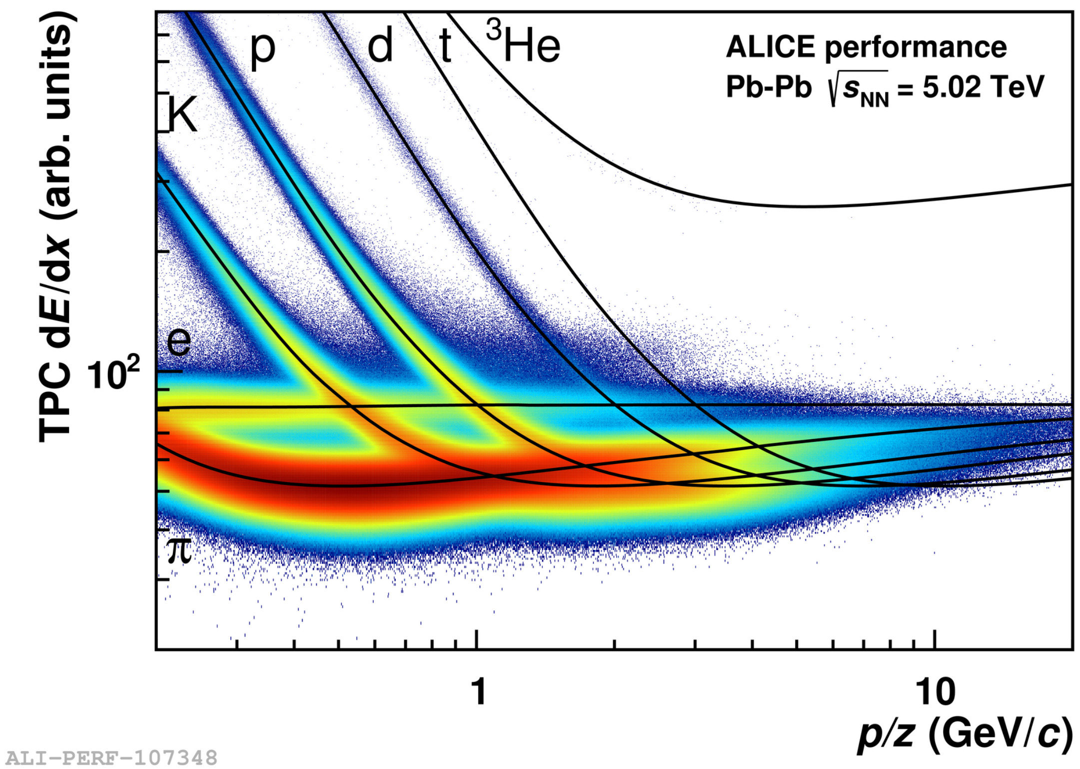


Particle identification & reconstruction

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

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

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



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

- Short-lived & no charge
  - Cannot be measured directly
- On statistical basis via decay products
  - Particle identification of products
  - Constraining decay topology

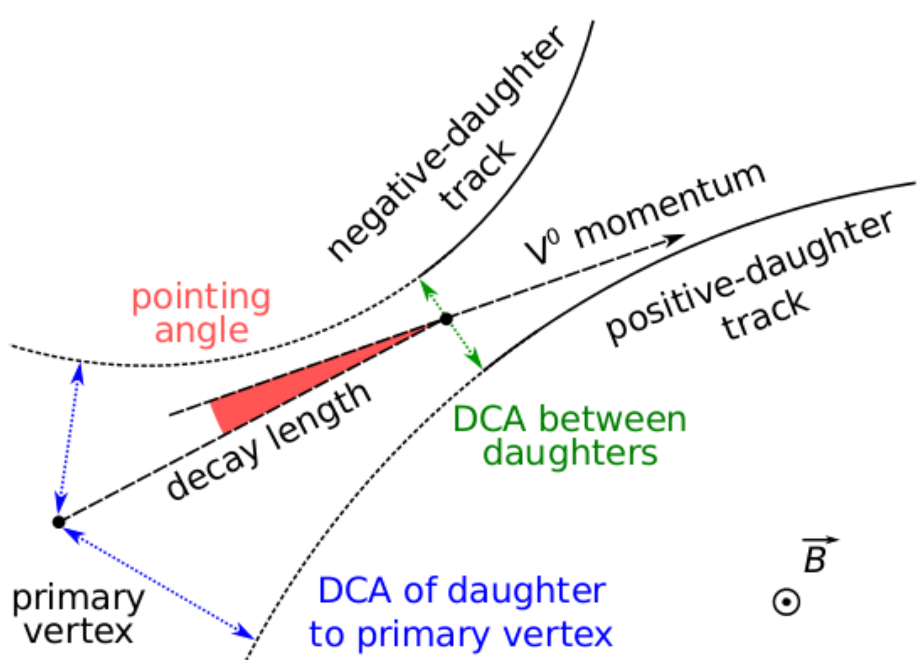
Decay channels

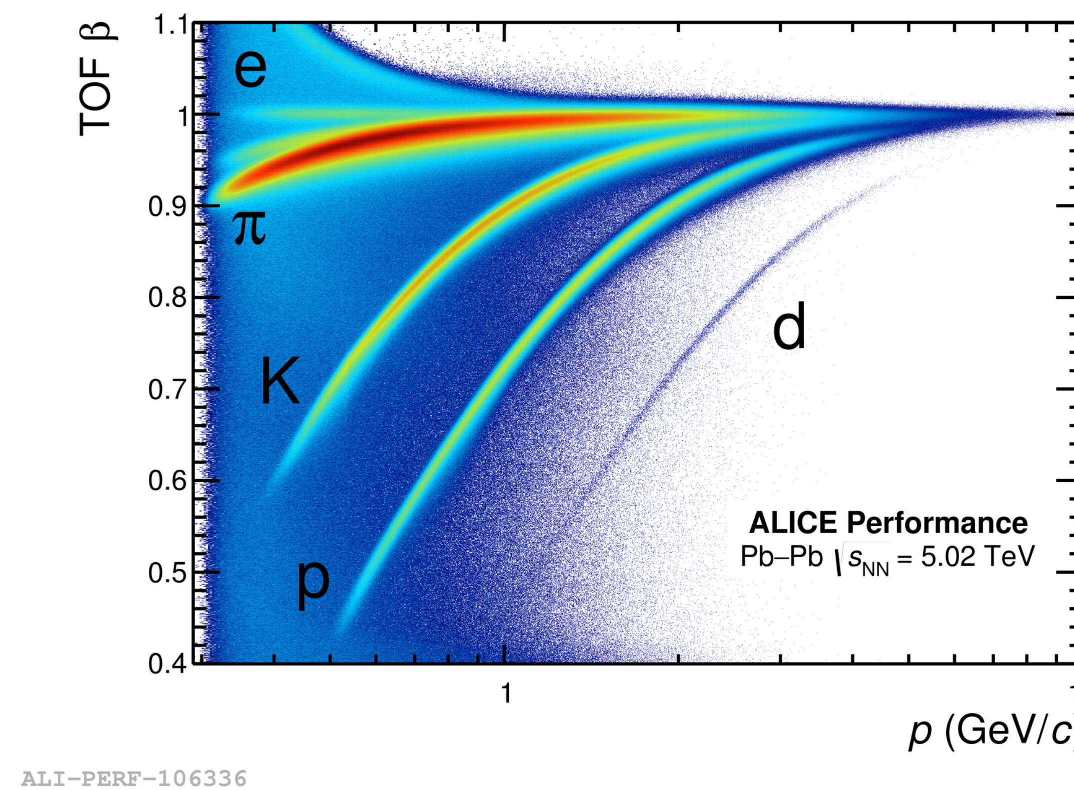
$\phi \longrightarrow \mathrm{K}^+ + \mathrm{K}^-$

$\mathrm{K^0_S} \longrightarrow \pi^+ + \pi^-$

$\Lambda \longrightarrow \mathrm{p} + \pi^-$

$\bar{\Lambda} \longrightarrow \bar{\mathrm{p}} + \pi^+$





Generic framework

- v_n extracted from 2- & 4-particle Q-cumulant using Generic Framework (GF)
  [A. Bilandzic et al., Phys.Rev. C89 (2014) 064904, Phys.Rev. C83 (2011) 044913]
  - **Reference Flow Particles (RFPs)** - inclusive particle in 0.2 < pT < 3 GeV/c
  - **Particles of Interest (POIs)** - (identified) particles in finite differential bins
- **Non-uniform acceptance** corrections using per-particle weights $\boldsymbol{w_j}$

Flow vectors

$$Q_{n,p} = \sum_{j\in\mathrm{RFPs}}^{M} w_j^p e^{in\varphi_j} \qquad p_{n,p}(p_\mathrm{T},\mathrm{species}) = \sum_{j\in\mathrm{POIs}}^{m} w_j^p e^{in\varphi_j} \qquad S_{n,p}(p_\mathrm{T},\mathrm{species}) = \sum_{j\in\mathrm{POIs}\cap\mathrm{RFPs}}^{s} w_j^p e^{in\varphi_j}$$

Correlations (single event)

$$\langle 2\rangle_n = \frac{\mathrm{N}\langle 2\rangle_{n,-n}}{\mathrm{D}\langle 2\rangle_{n,-n}} = \frac{Q_{n,1}\cdot Q_{-n,1} - Q_{0,2}}{Q_{0,1}^2 - Q_{0,2}} \qquad \langle 4\rangle_n = \frac{\mathrm{N}\langle 4\rangle_{n,n,-n,-n}}{\mathrm{D}\langle 4\rangle_{n,n,-n,-n}}$$

$$\langle 2'\rangle_n = \frac{\mathrm{N}\langle 2'\rangle_{n,-n}}{\mathrm{D}\langle 2'\rangle_{n,-n}} = \frac{p_{n,1}\cdot Q_{-n,1} - S_{0,2}}{p_{0,1}\cdot Q_{0,1} - S_{0,2}} \qquad \langle 4'\rangle_n = \frac{\mathrm{N}\langle 4'\rangle_{n,n,-n,-n}}{\mathrm{D}\langle 4'\rangle_{n,n,-n,-n}}$$

Cumulants (event-averaged)

$$c_n\{2\} = \langle\langle 2\rangle\rangle_n \qquad c_n\{4\} = \langle\langle 4\rangle\rangle_n - 2\cdot\langle\langle 2\rangle\rangle_n{}^2$$

$$d_n\{2\} = \langle\langle 2'\rangle\rangle_n \qquad d_n\{4\} = \langle\langle 4'\rangle\rangle_n - 2\cdot\langle\langle 2'\rangle\rangle_n\cdot\langle\langle 2\rangle\rangle_n$$

$v_n(p_T)$

$$v_n\{2\}(p_\mathrm{T},\mathrm{species}) = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}} \approx \frac{\langle v_n(p_\mathrm{T})\cdot v_n\rangle}{\langle v_n^2\rangle^{1/2}} \qquad v_n\{4\}(p_\mathrm{T},\mathrm{species}) = \frac{-d_n\{4\}}{(-c_n\{4\})^{3/4}} \approx \frac{\langle v_n(p_\mathrm{T})\cdot v_n^3\rangle}{\langle v_n^4\rangle^{3/4}}$$

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)

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

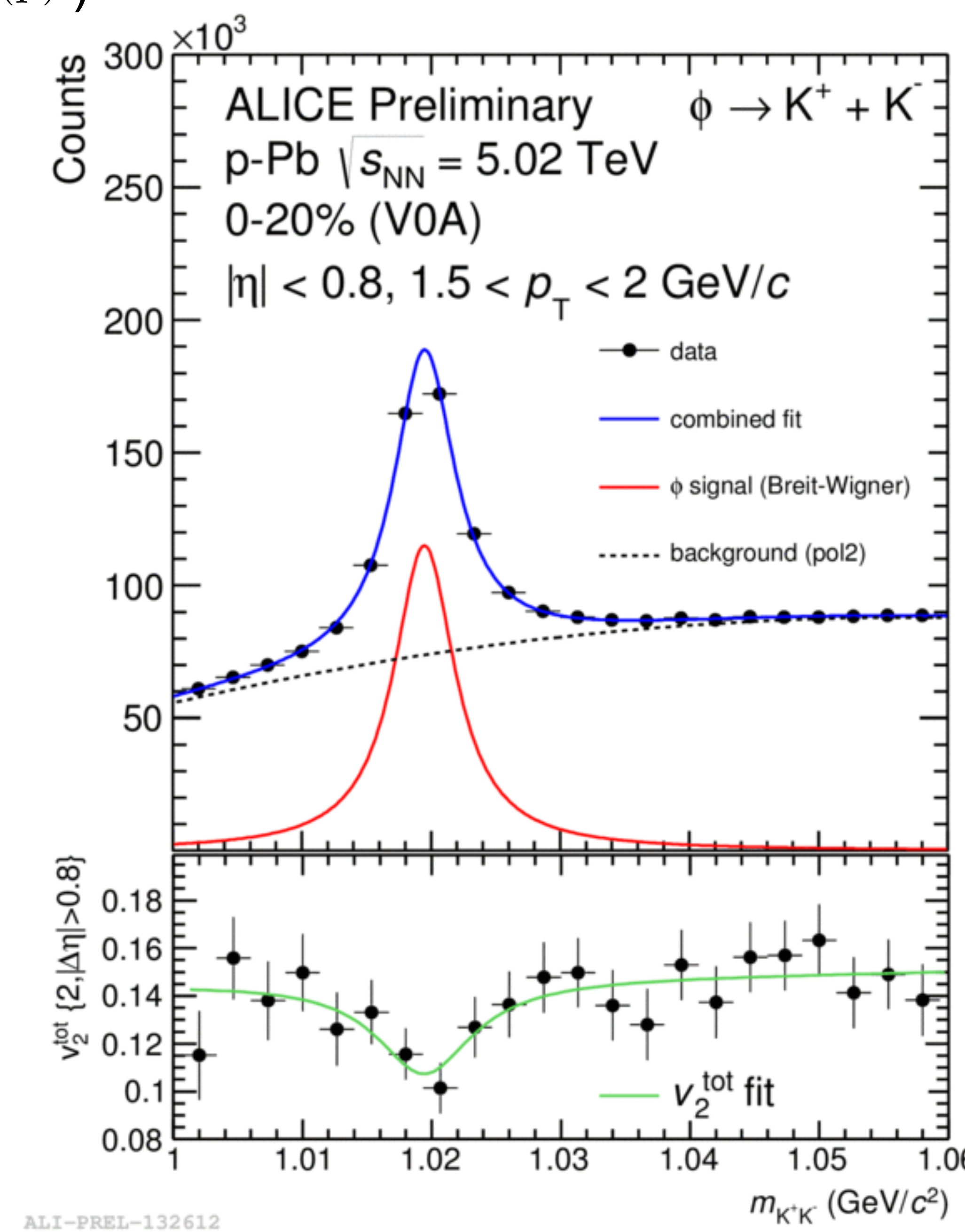
- Reconstructed candidates consisting of signal particles & combinatorial background
  - v_n coefficient of signal particles extracted using v_n vs. inv. mass method

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

  - Based on additivity of v_n coefficients weighted by their fractions

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

  - For $v_n\{4\}$, differential correlations <<2'>> & <<4'>> fitted separately

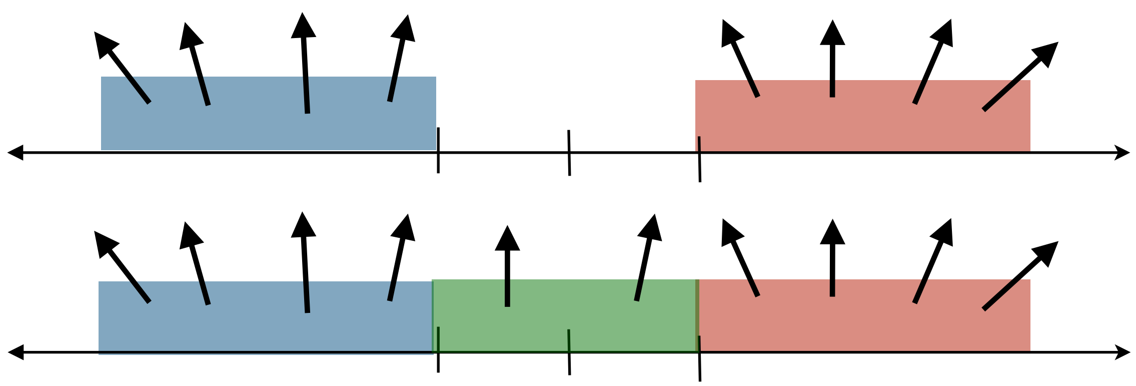


Non-flow suppression

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

$|\Delta\eta| > 0.4$

3-sub-event



- Additional non-flow subtraction using MB pp collisions performed directly on cumulants level (not correlation function)

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

- Contribution of non-flow scaled by mean event multiplicities
  - Based on assumption for non-flow

[Voloshin et al., arXiv:0809.2949]

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