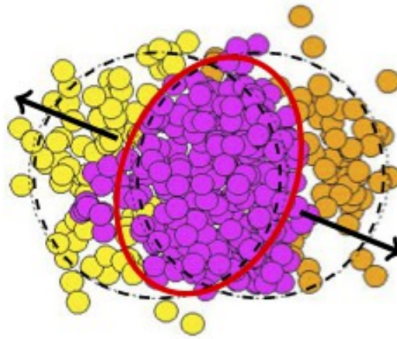
Anisotropic flow of inclusive and identified particles in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

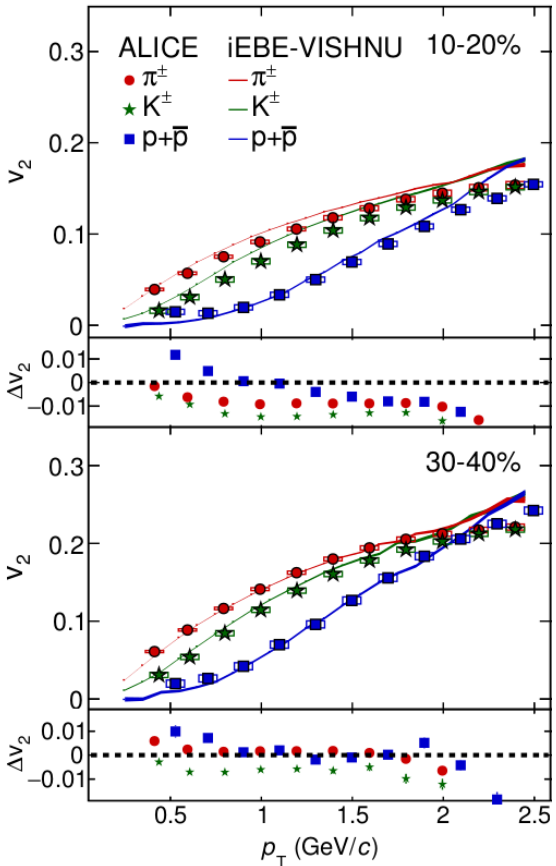
Redmer Alexander Bertens - on behalf of the ALICE collaboration

Anisotropic flow - what and why?

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

$$v_n = \langle\cos(n[\varphi-\Psi_n)]\rangle$$





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Flow - multiple interactions between medium constituents convert initial **geometric** anisotropy into a final state **momentum** anisotropy

- Interplay between effects of initial **geometry** of the overlap zone and **flucatuations** in the nucleon distributions

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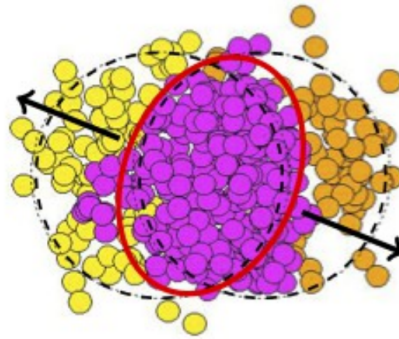

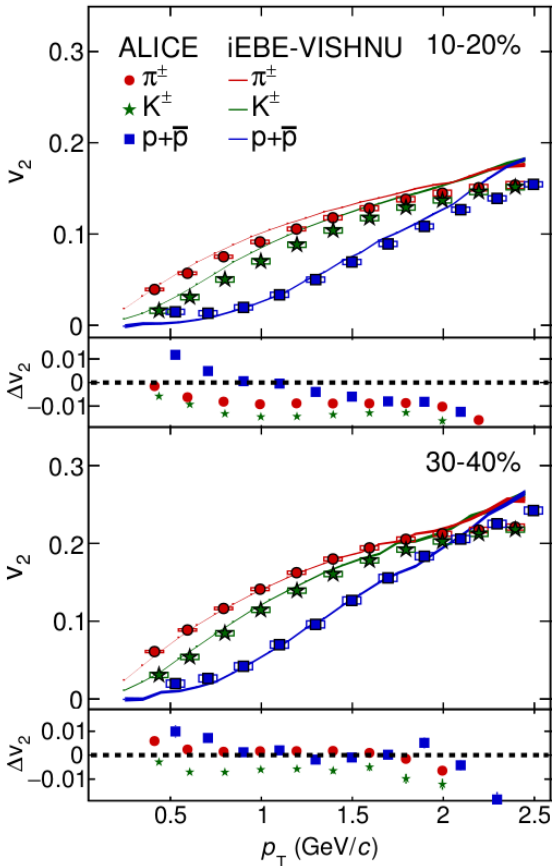

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Flow - multiple interactions between medium constituents convert initial **geometric** anisotropy into a final state **momentum** anisotropy

- Interplay between effects of initial **geometry** of the overlap zone and **flucatuations** in the nucleon distributions

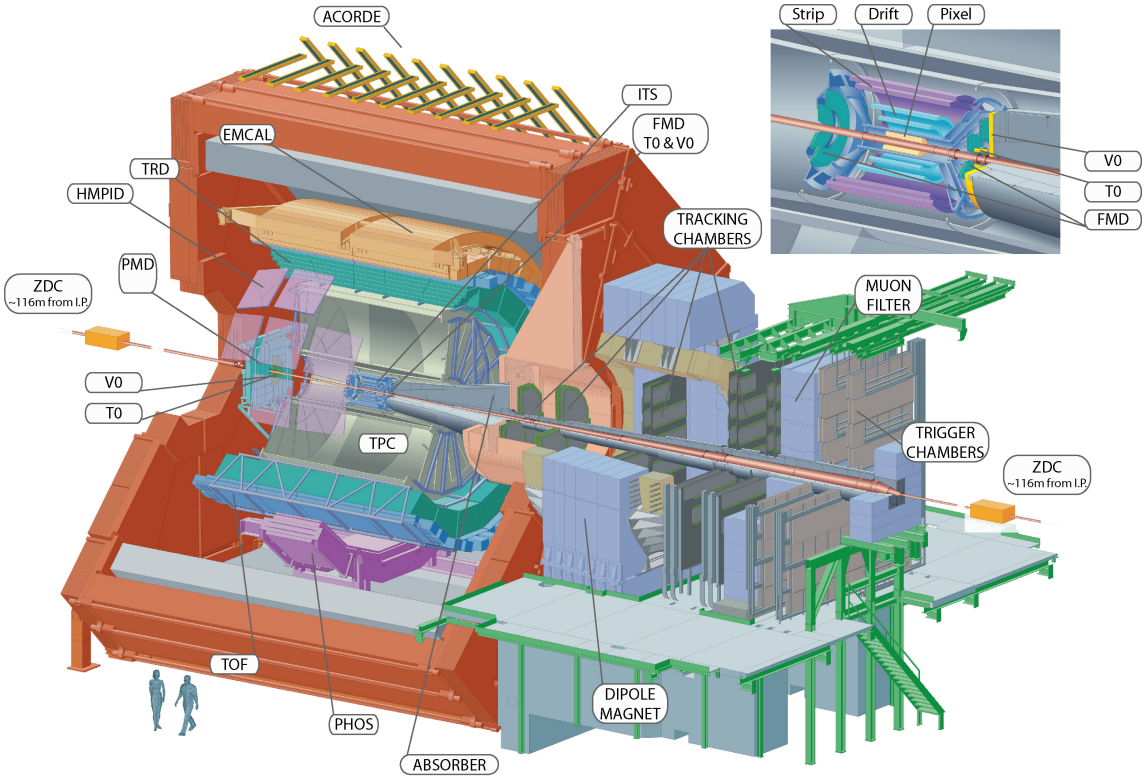
v_n are sensitive to the **full evolution** of the collision system

- Initial conditions $\rightarrow$ QGP phase $\rightarrow$ hadronization

Three kinematic regions of interest

- Low p_T ($\lesssim$ 2 GeV/c) - **hydrodynamic** expansion
- Intermediate p_T ($2 \lesssim p_\mathrm{T} \lesssim 7$ GeV/c)- quark **scaling**
- High p_T ($\gtrsim$ 7 GeV/c) - parton **energy loss**

Detectors and data sample



Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

- $\approx 60{\times}10^6$ minimum bias events

Track selection

- Identified: $|y| < 0.5$
- Unidentified: $|\eta| < 0.8$

Inner **T**racking **S**ystem

- Tracking, vertexing, triggering

Time **P**rojection **C**hamber

- Tracking, vertexing, particle identification from specific energy loss

Time-**o**f-**F**light

- Particle identification from flight time and track length

V0

- V0A ($2.8 < \eta < 5.1$) and V0C ($-3.7 < \eta < -1.7$)
- Triggering, centrality determination, Q-vector

Flow harmonics v_n of charged hadrons

v_n of charged hadrons is measured using the **scalar product** method

- Hits measured by the forward **V0C** are used as reference particles
- The η gap for reference particles and particles of interest suppresses **non-flow**

$$v_n = \frac{\langle u \cdot Q_{\mathrm{V0C}} \rangle}{\sqrt{\frac{\langle Q_{\mathrm{V0C}} \cdot Q_{\mathrm{V0A}} \rangle \langle Q_{\mathrm{V0C}} \cdot Q_{\mathrm{TPC}} \rangle}{\langle Q_{\mathrm{V0A}} \cdot Q_{\mathrm{TPC}} \rangle}}} \qquad u, Q = \sum w_i \exp(in\varphi)$$

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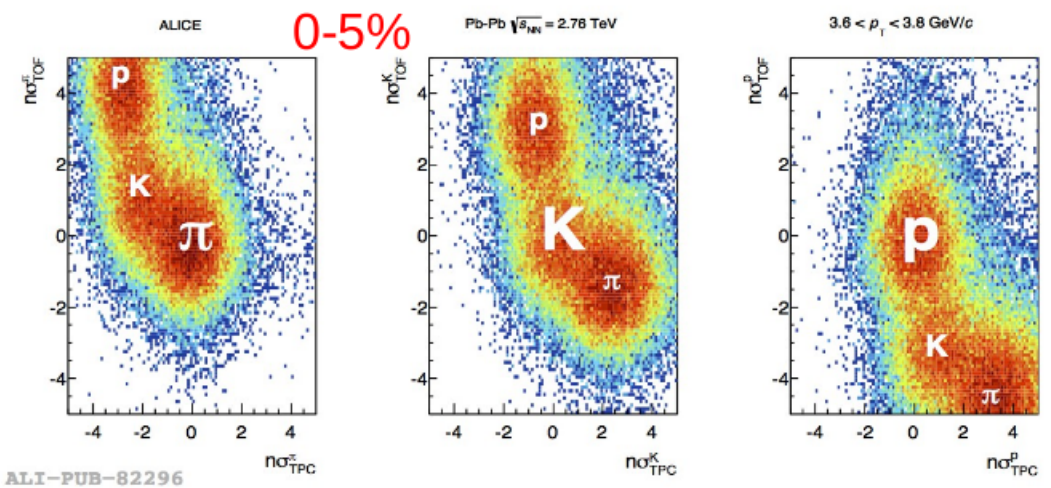
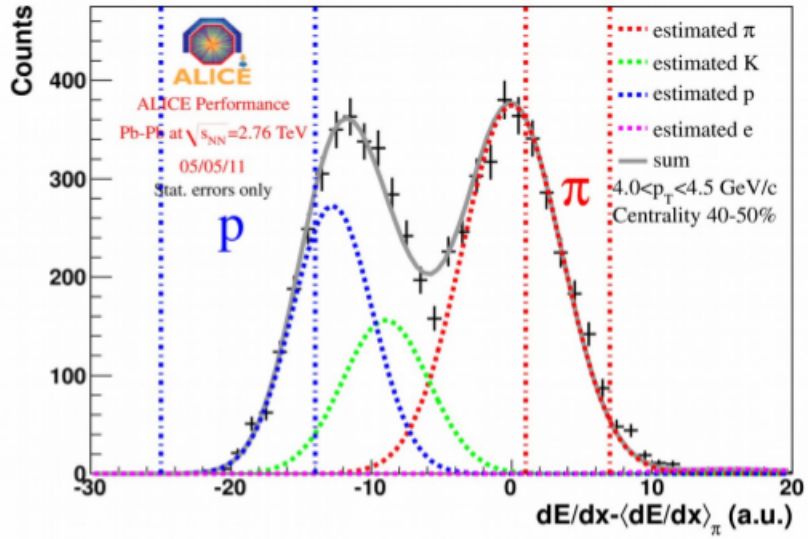
Particle identification uses the **TPC** and **TOF** systems

$$p_{\mathrm{T}} < 4 \text{ GeV}/c \longrightarrow n^2_{\sigma\mathrm{PID}} = n^2_{\sigma\mathrm{TPC}} + n^2_{\sigma\mathrm{TOF}}$$
$$p_{\mathrm{T}} > 4 \text{ GeV}/c \longrightarrow \Delta_\pi = \mathrm{d}E/\mathrm{d}x_\pi - \langle \mathrm{d}E/\mathrm{d}x \rangle_\pi$$





ϕ-meson v_2

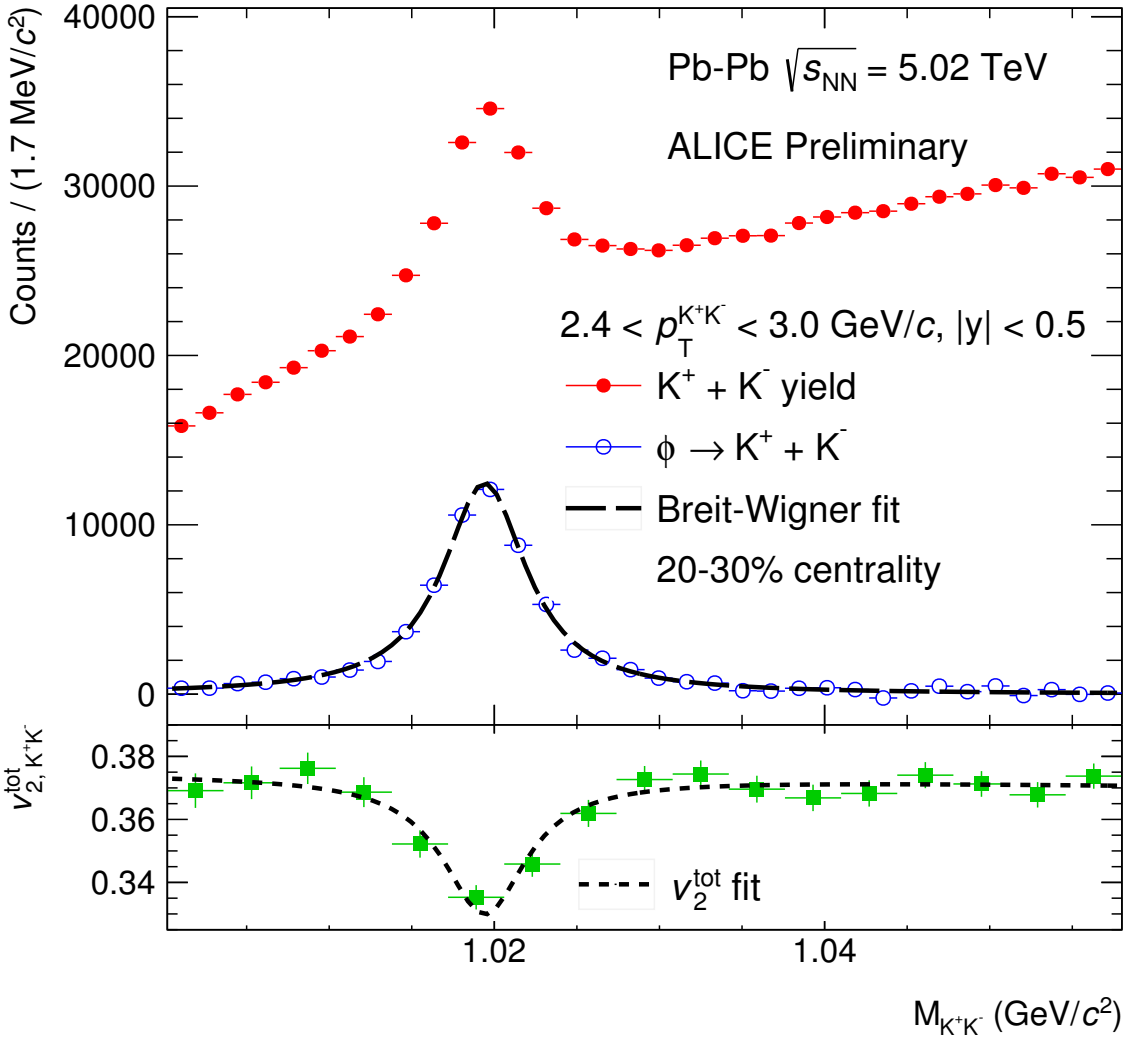
ϕ-meson flow is measured using the v_2 vs. **invariant mass** method

$$v_2^{\text{tot}}(\text{M}_{\text{K}^+\text{K}^-}) = v_2^{\text{sig}} \frac{N^{\text{sig}}}{N^{\text{sig}} + N^{\text{bg}}}(\text{M}_{\text{K}^+\text{K}^-}) + v_2^{\text{bg}}(\text{M}_{\text{K}^+\text{K}^-}) \frac{N^{\text{bg}}}{N^{\text{sig}} + N^{\text{bg}}}(\text{M}_{\text{K}^+\text{K}^-})$$

$v_2^{\text{tot}}(\text{M}_{\text{K}^+\text{K}^-})$ of kaon **pairs** is measured using the scalar product method

ϕ is reconstructed in the $\phi \longrightarrow K^+ + K^-$ channel

- Yields N^{sig} and N^{bg} are extracted from fits of the invariant mass distributions



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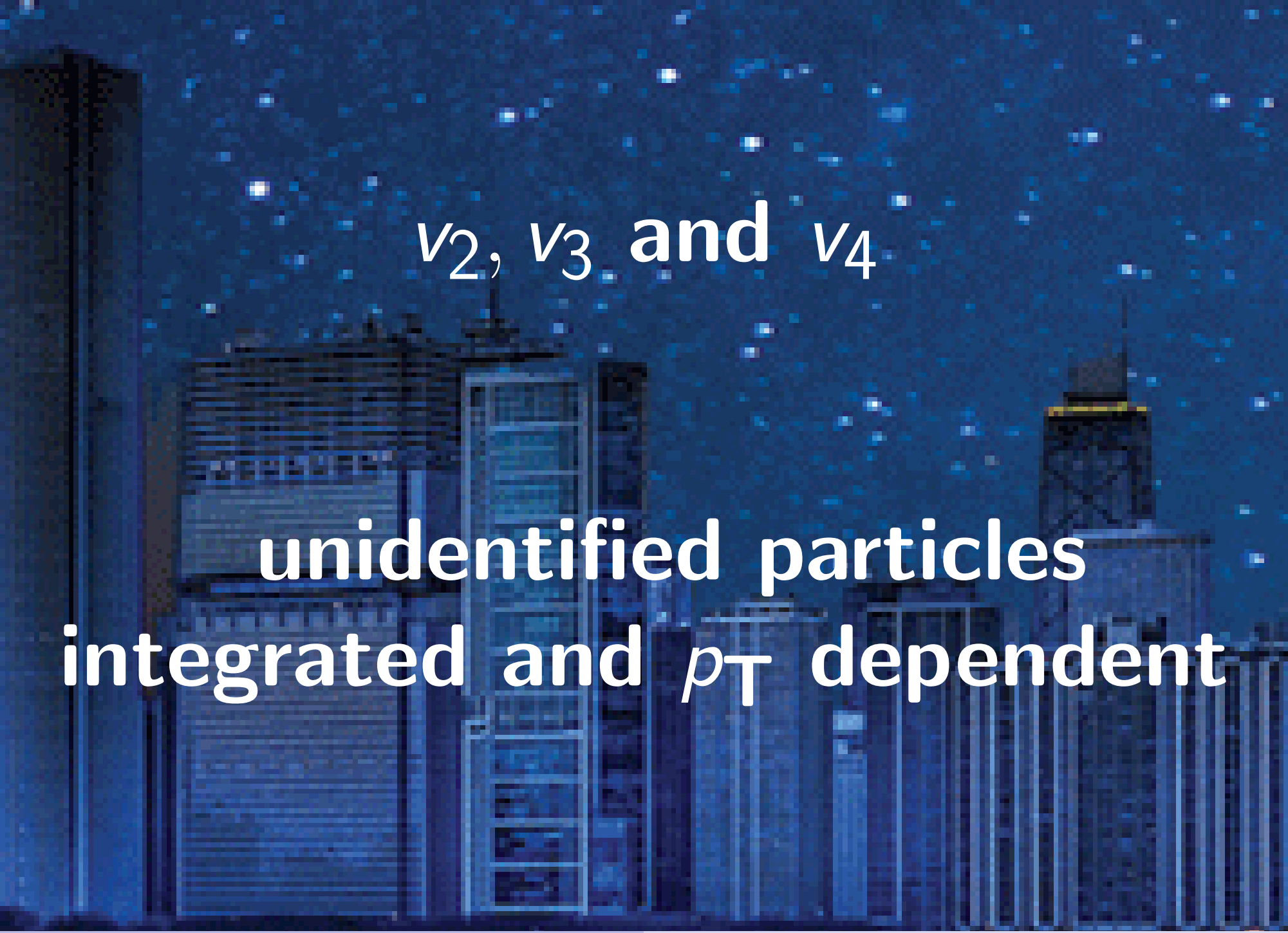
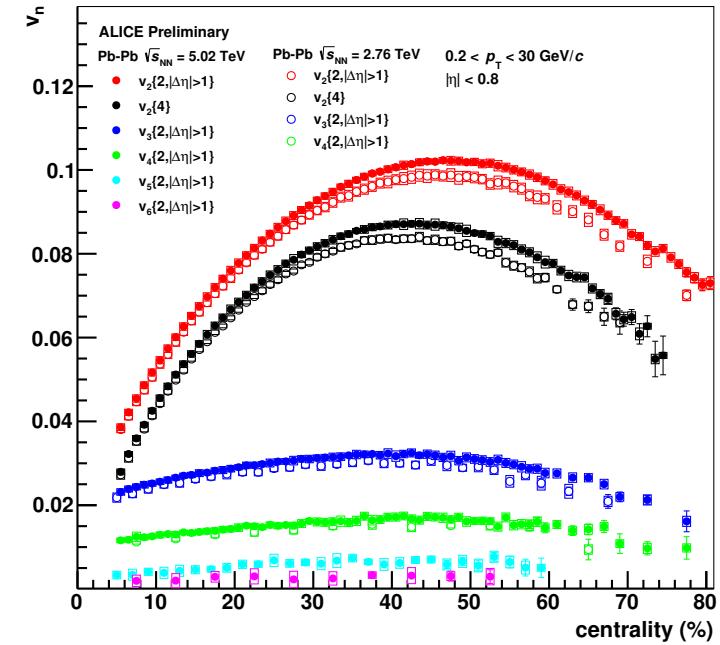
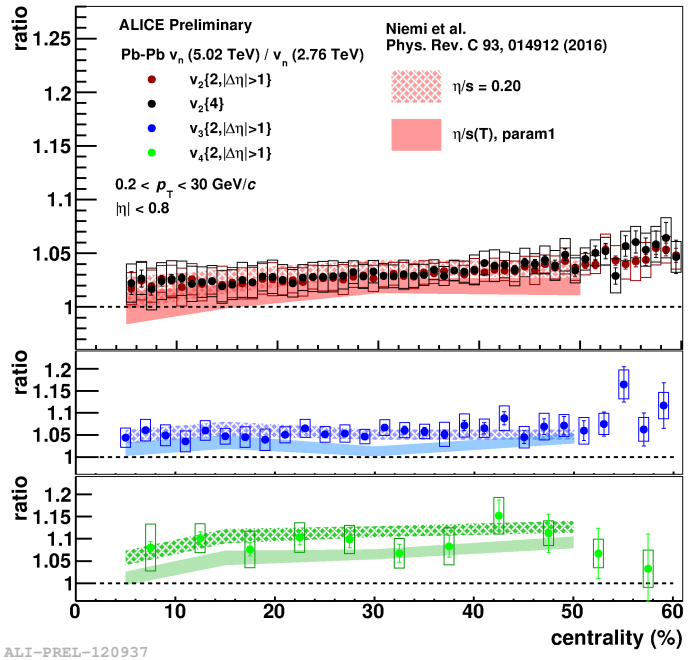
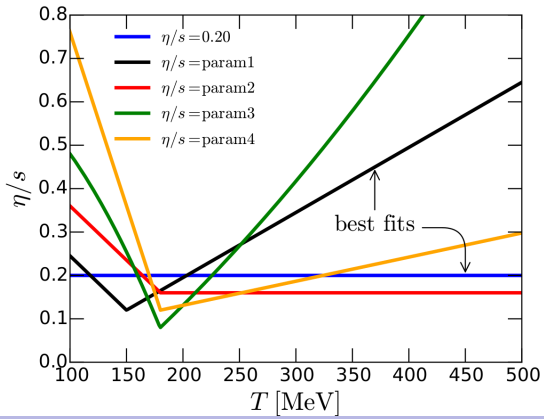

v_2, v_3 and v_4
unidentified particles
integrated and p_T dependent

Integrated v_n of unidentified particles

Integrated v_n measured **up to** v_6 between $0.2 < p_T < 30$ GeV/c for $\sqrt{s_{NN}} = 5.02$ TeV





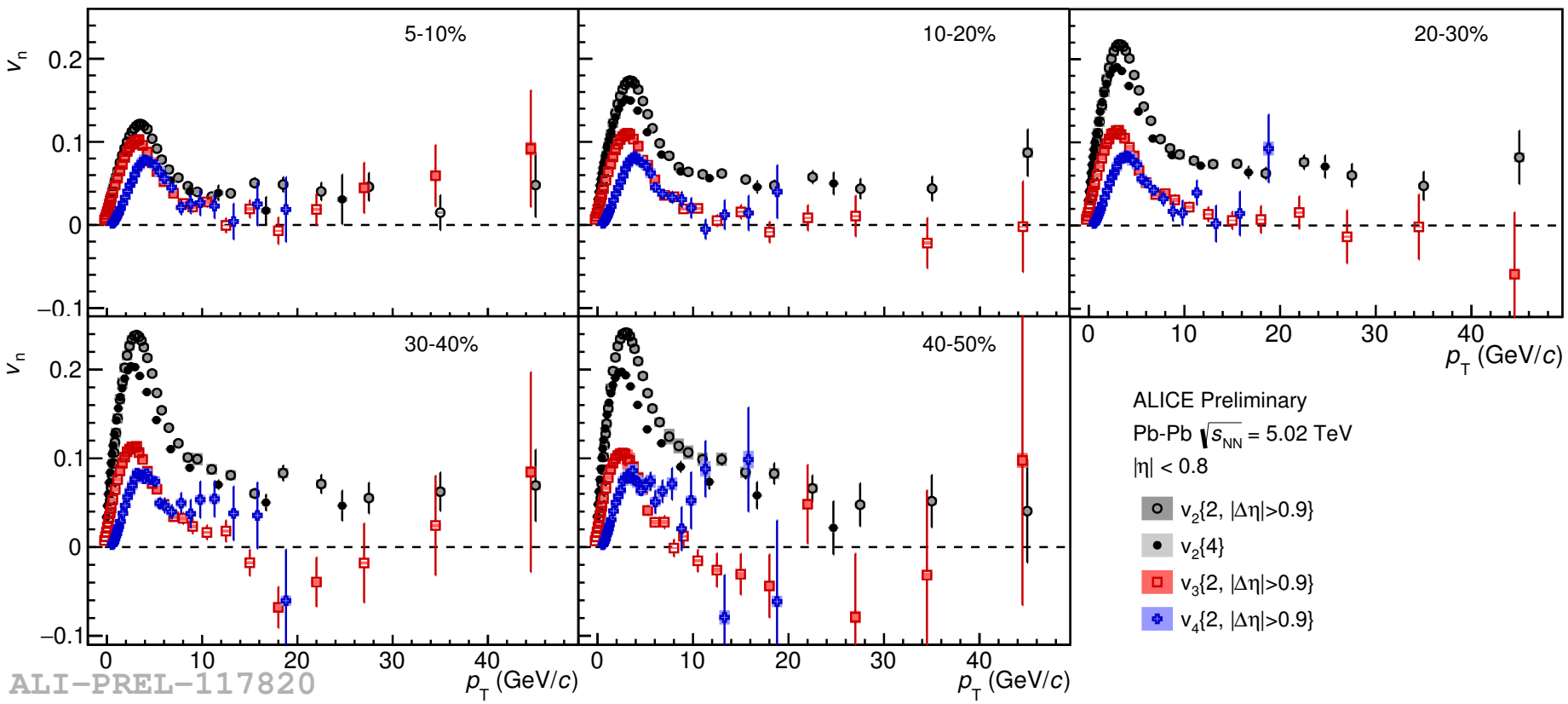


Great potential for testing e.g. temperature dependence of η/s for fixed initial conditions (EKRT)

- Theoretical uncertainties **cancel partially** in the ratio of v_n at $\sqrt{s_{NN}} = 5.02$ TeV to v_n at $\sqrt{s_{NN}} = 2.76$ TeV
- Data favor fixed η/s of 0.2

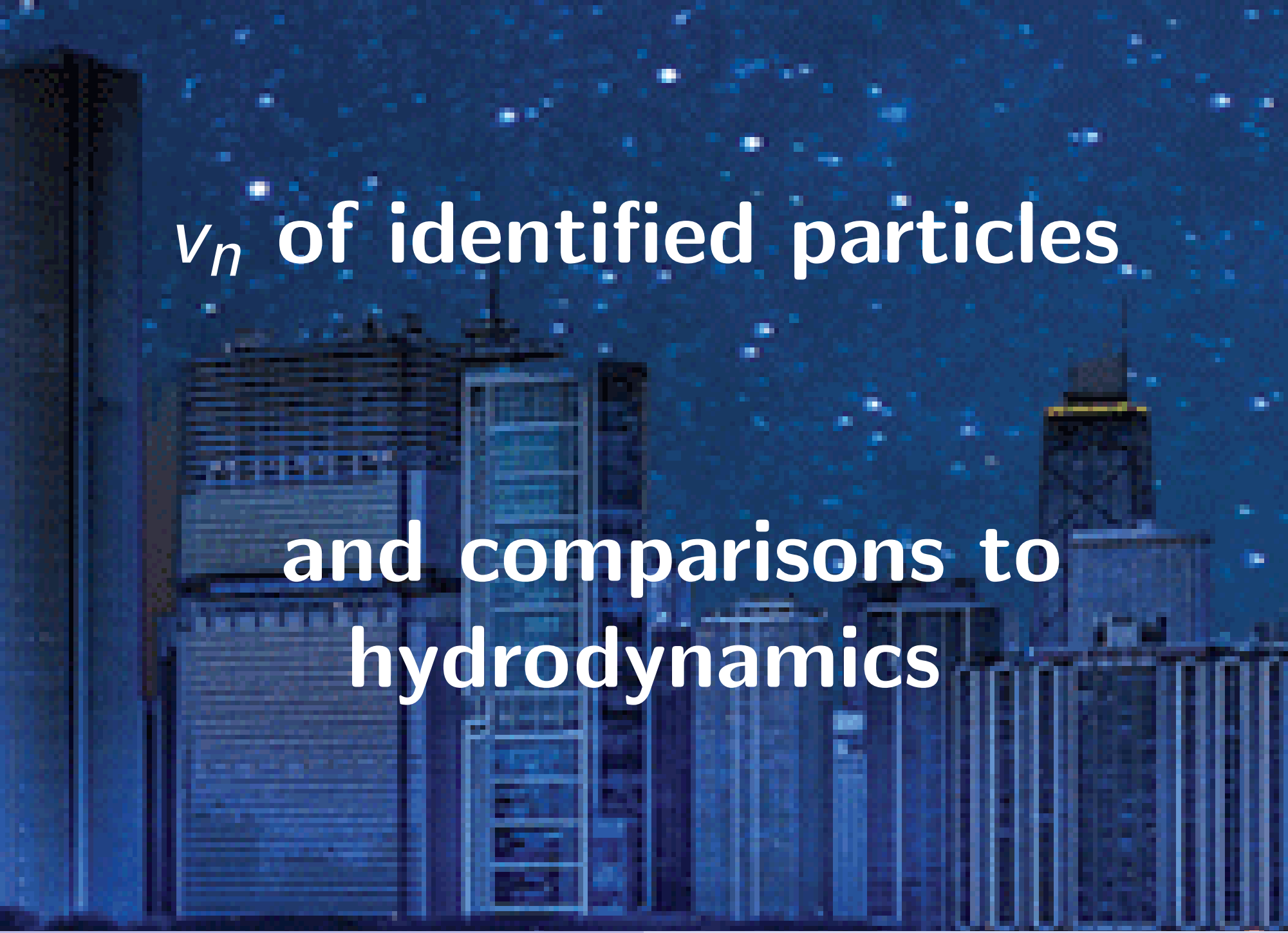
  ← Phys. Rev. C 93, 014912 (2016)

p_T dependence of charged hadron v_n



$v_2 > v_3 > v_4$ for measured centralities for $p_T < 5$ GeV/c, $v_2 > 0$ up to $p_T = 50$ GeV/c

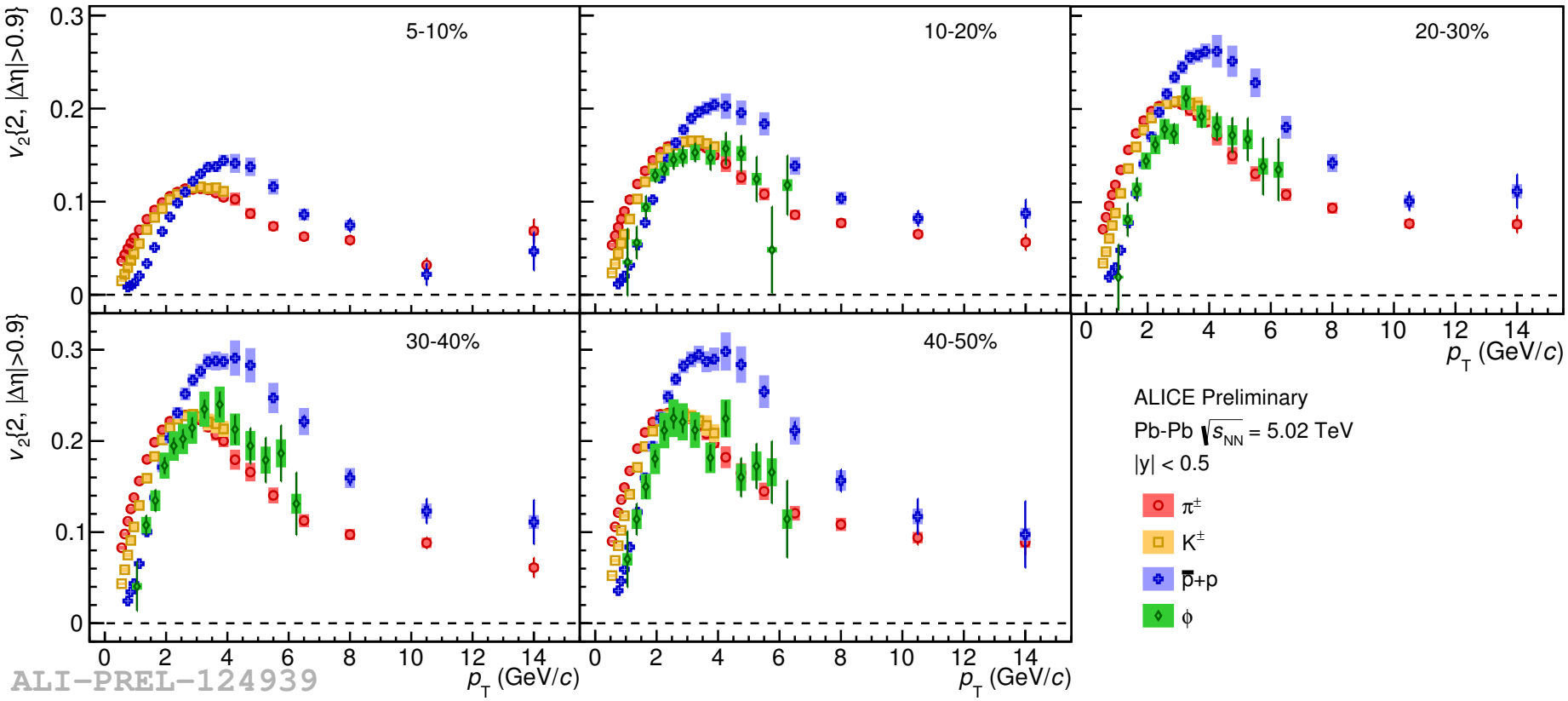
- $v_2\{4\} < v_2\{2\}$, most clearly at low ($p_T < 7$GeV/c) momentum
- $p_T \lesssim 7$ GeV/c - **hydrodynamic** expansion of the medium
- $p_T \gtrsim 7$ GeV/c - effects from parton **energy loss**



v_n of identified particles

and comparisons to hydrodynamics

v_2 of identified particles - π, K, p, ϕ

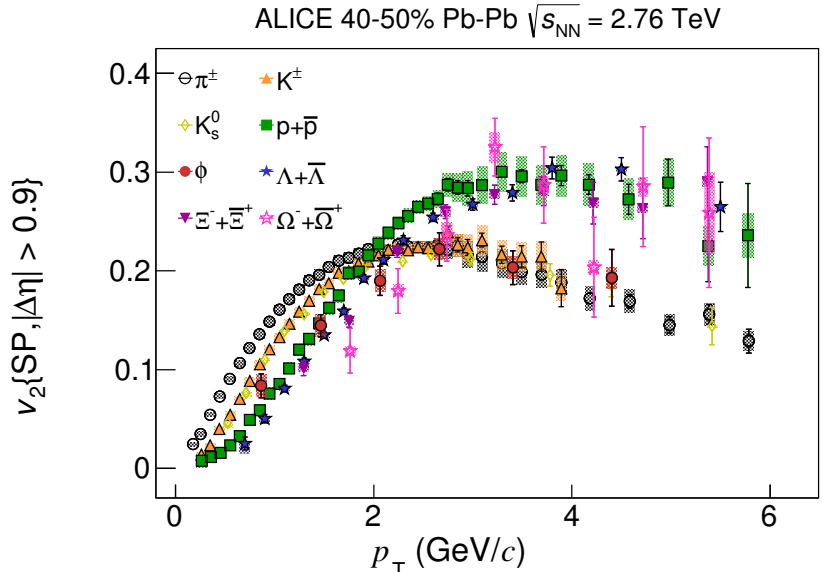


- For $p_T < 2$ GeV/c v_2 follows a mass ordering, indicative of **strong radial flow**
- For $3 < p_T < 8$ GeV/c particle **type dependence** is seen
  $\rightarrow$ The ϕ is a **meson** with a **mass** close to **proton** mass
  $\rightarrow$ ϕ-meson v_2 follows **proton** v_2 at low p_T, but **pion** v_2 at intermediate p_T
- Proton $v_2 >$ pion v_2 up to $p_T \approx 10$ GeV/c, similar to R_{AA}

v_2 - improvements over run I

Larger data sample gathered in run II compared to run I

- Kinematic range of measurements is **extended**
- **High-precision** measurements of e.g. ϕ-meson v_2 possible
- Provides more stringent **constraints** for models



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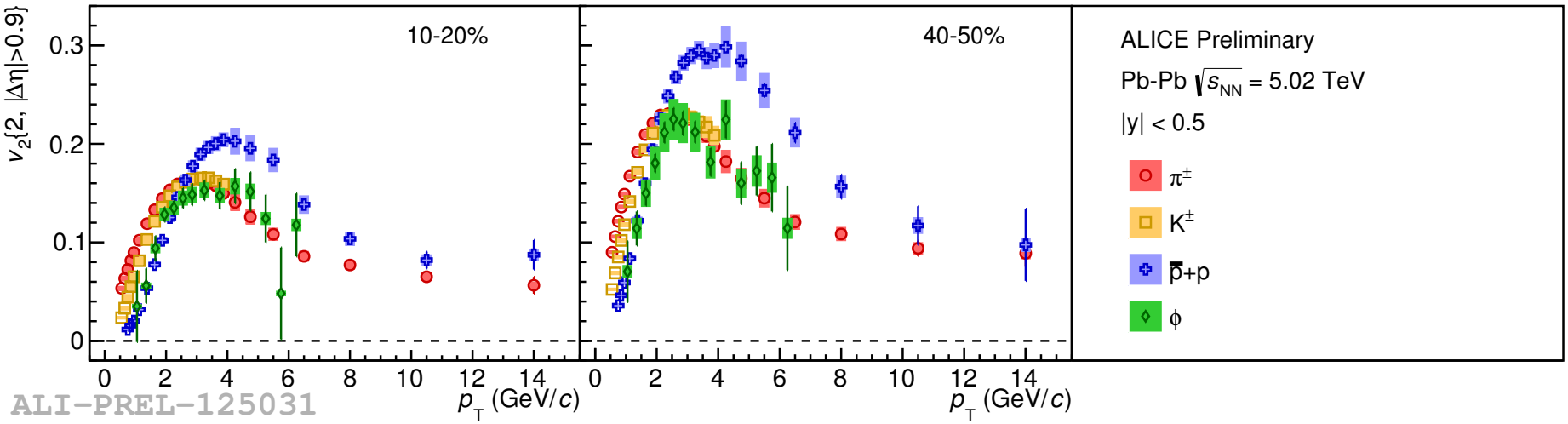

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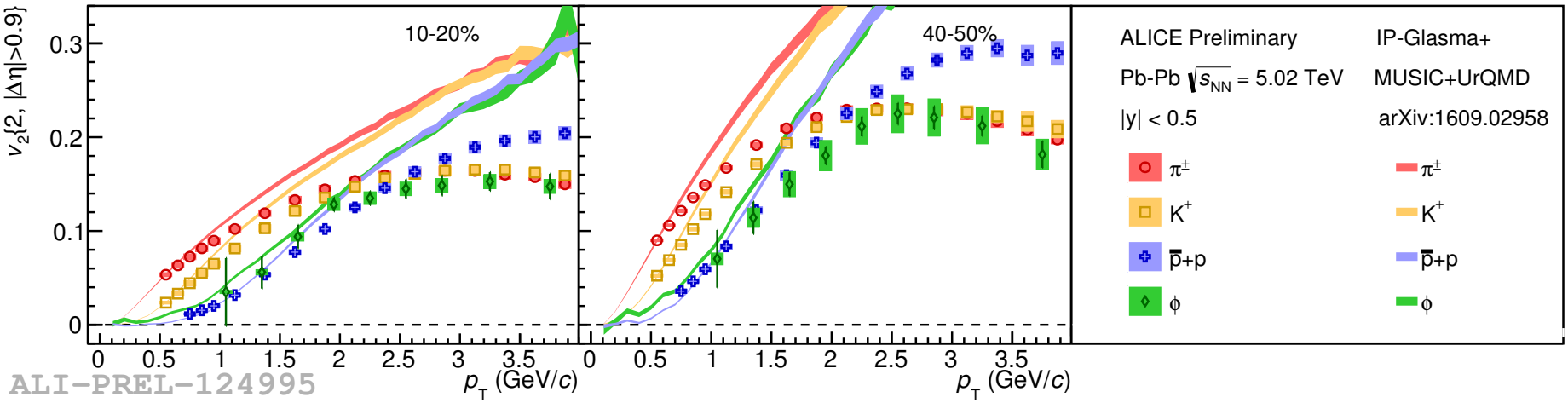
v_2 of identified particles and hydrodynamics

Low-p_T v_2 as test for **hydrodynamic expansion** and initial conditions

- IP-Glasma initial state, viscous hydrodynamic medium evolution, hadronic cascade for hadronization, $\eta/s = 0.095$, temperature dependent bulk viscosity $\zeta/s(T)$ (arXiv:1609.02958)
- Mass ordering **broken** in hydro (ϕ-meson $v_2 >$ proton v_2)



Good agreement with data at **low** p_T ($p_T < 1$ GeV/c) for central collisions

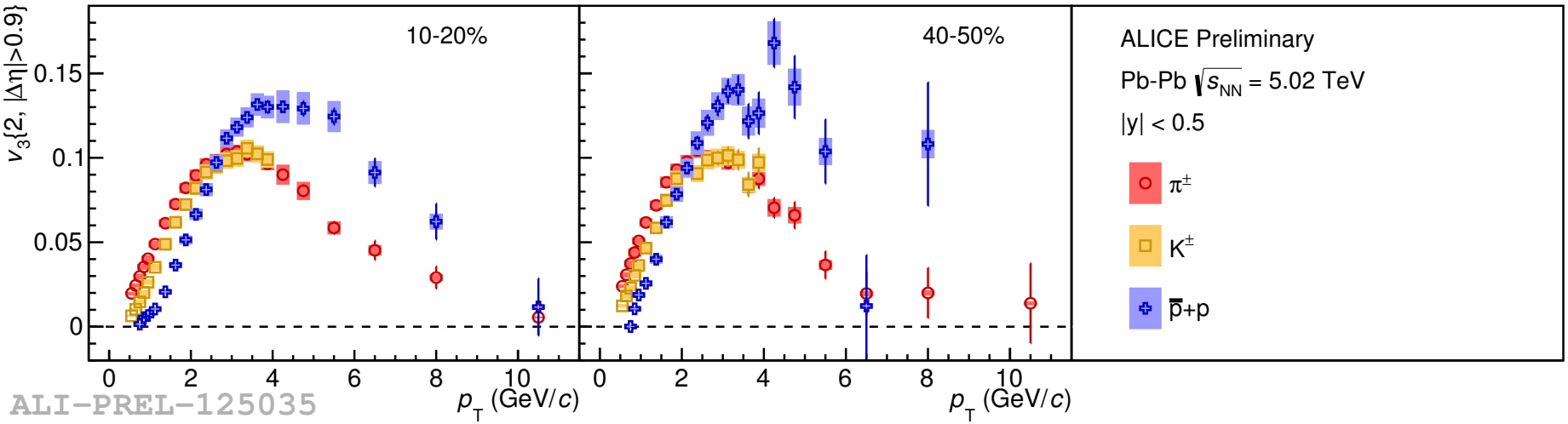
- Overestimation of v_2 for more peripheral collisions

other centralities available **in backup**

Higher harmonics: v_3 of identified particles

Higher harmonic flow coefficients are generated by **inhomogeneities** in the initial nucleon distribution

- $v_{n,n>2}$ are more **sensitive** to transport coefficients of medium than v_2



Non-zero v_3 for all particle species up to $p_T \approx 8$ GeV/c

- Clear **mass ordering** at low p_T
- Proton v_3 > pion v_3 up to $p_T = 10$ GeV/c
- Crossing of meson and baryon trends at $p_T \approx 2.5$ GeV/c, **similar** to observations for v_2

other centralities in backup

v_3 of identified particles - hydrodynamics

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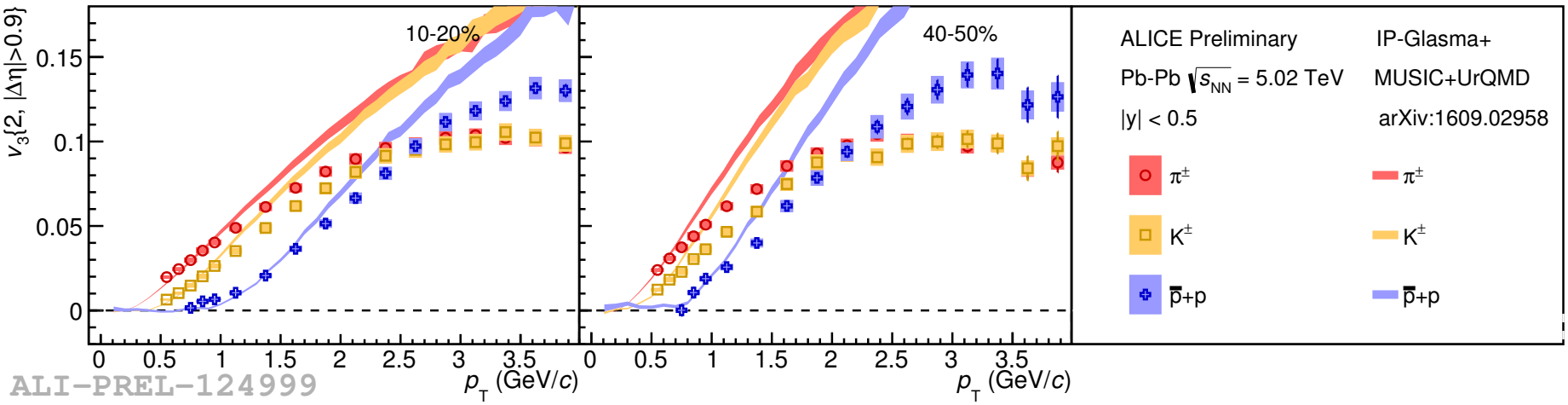


Comparison to **hydrodynamics**

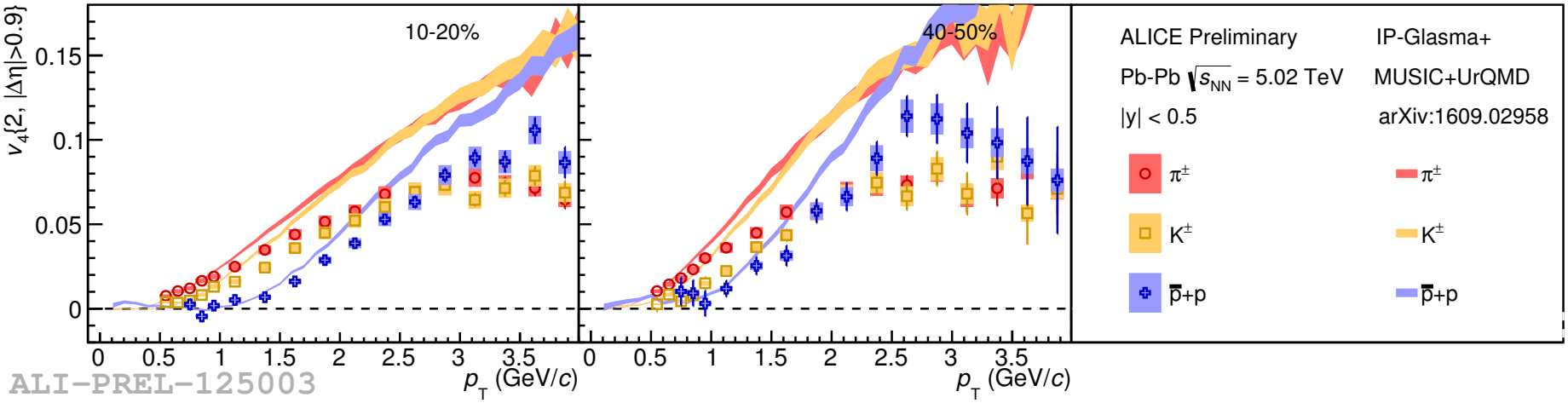
- Good agreement with data for central and peripheral collisions for low p_T (< 1 GeV/c)
- General features described in central collisions at intermediate p_T (< 2 GeV/c)

other centralities in backup

... and lastly, v_4

Higher harmonic flow coefficients are generated by **inhomogeneities** in the initial nucleon distribution

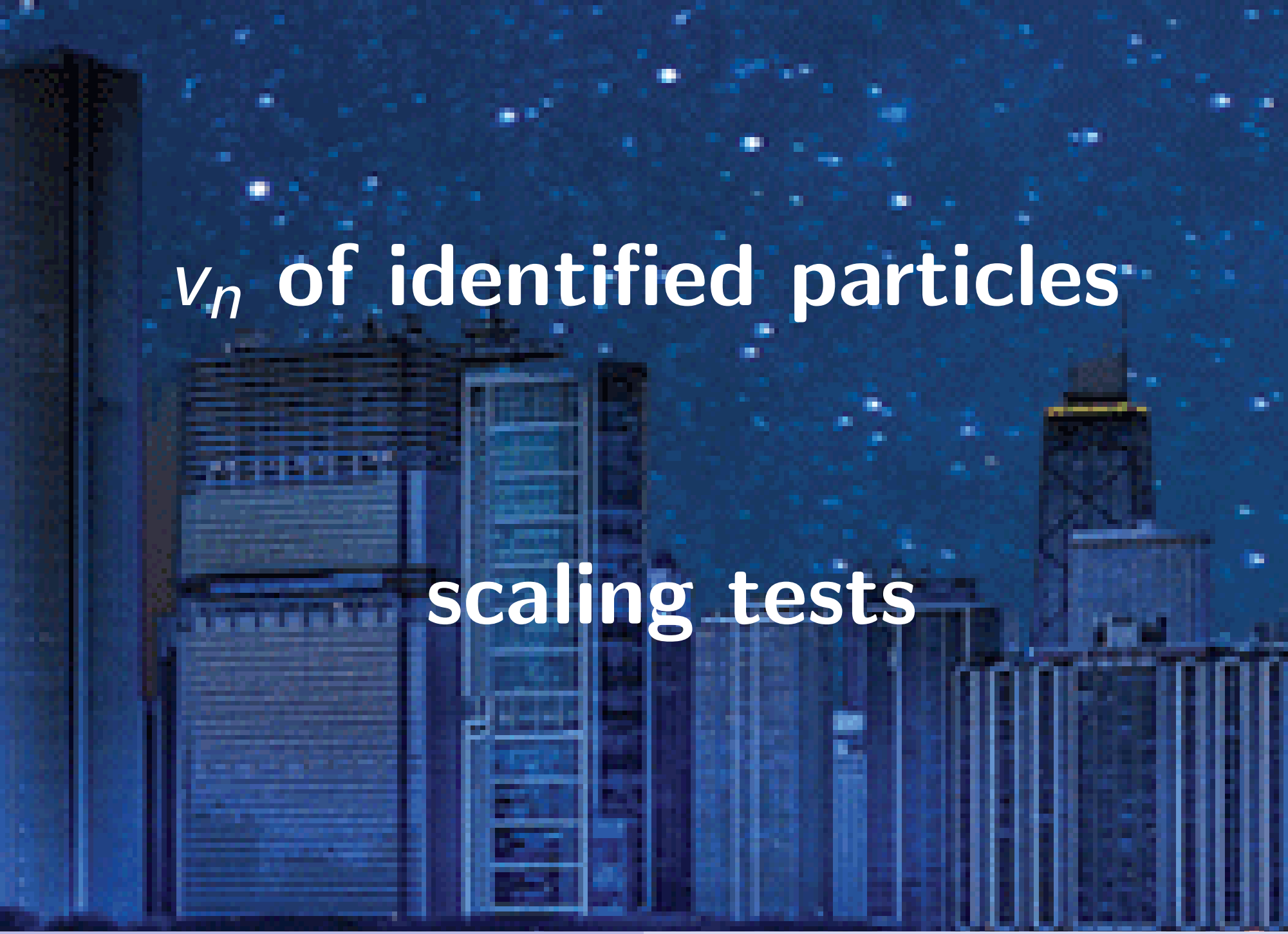
- $v_{n,n>2}$ are more **sensitive** to transport coefficients of medium than v_2



Comparison to **hydrodynamics**

- v_4 of identified particles has been measured **up to** $p_T = 4$ GeV/c
- Good agreement with data for central and peripheral collisions for low p_T (< 1 GeV/c)
- General features described for central collisions at intermediate p_T (< 2 GeV/c)

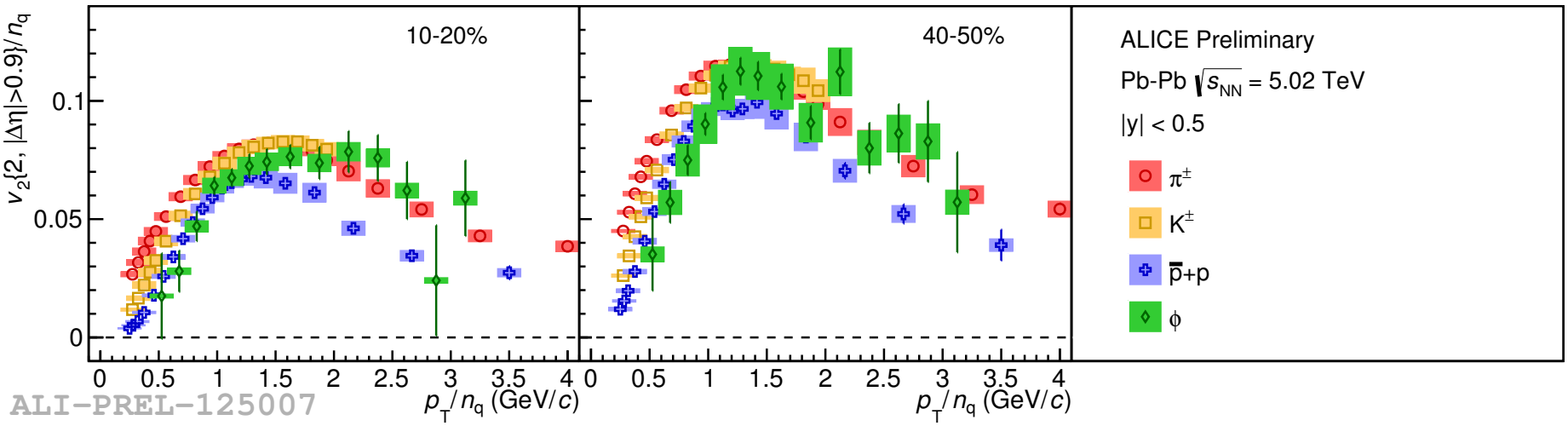
other centralities in backup


v_n of identified particles
scaling tests

n_q scaling test for identified particle v_2

Particle production via **coalescence** at $p_T > 3$ GeV/c ?

- NCQ scaling: scale axes by number of **constituent quarks** n_q

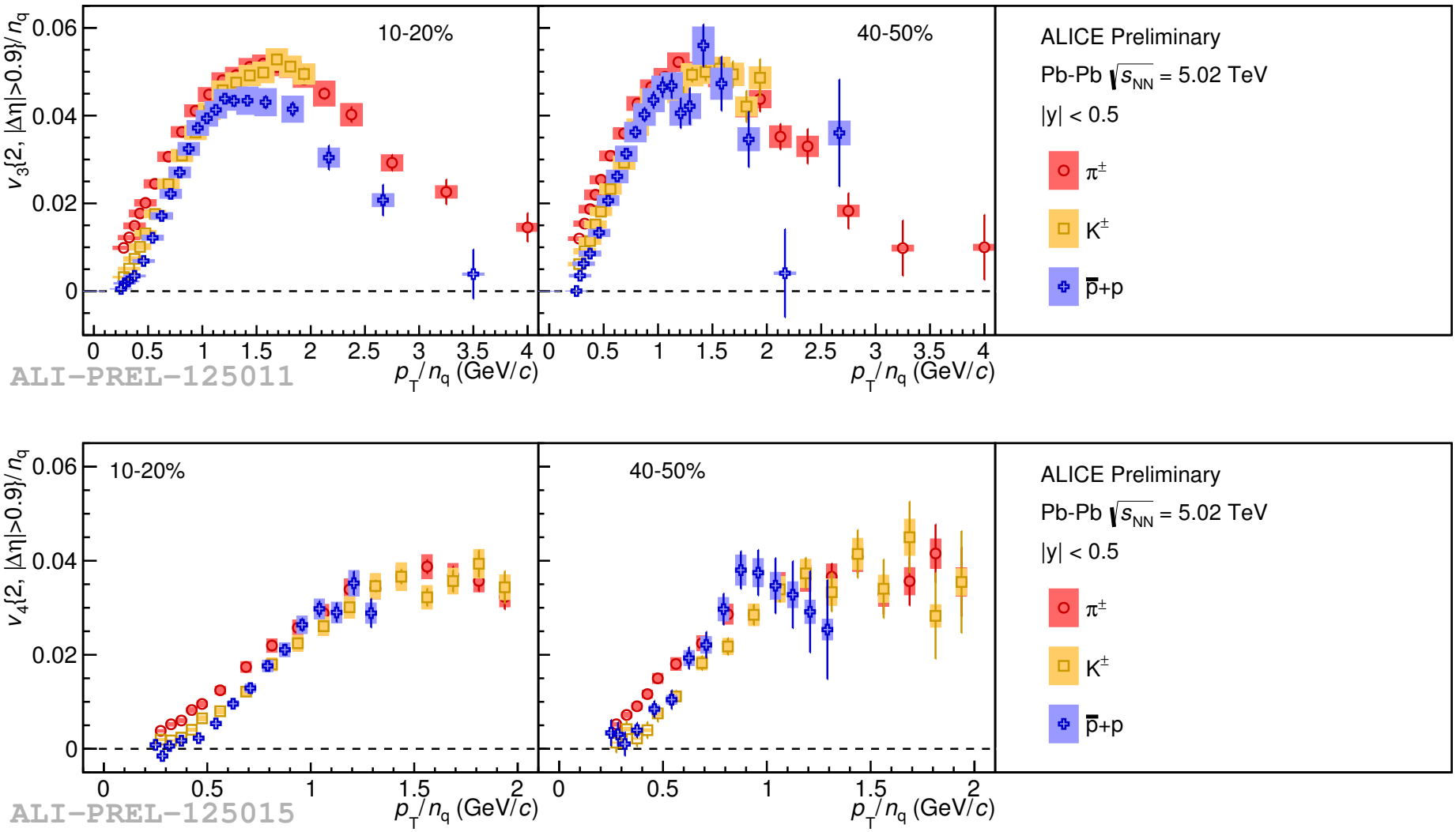


From $p_T/n_q > 1.5$ GeV/c particles group according to their type (baryon, meson)

- Transition from **mass ordering** to baryon/meson ordering happens around $p_T \approx 1$ GeV/c
- Grouping is observed for all measured species

Only **approximate** scaling observed

n_q scaling test for higher harmonics

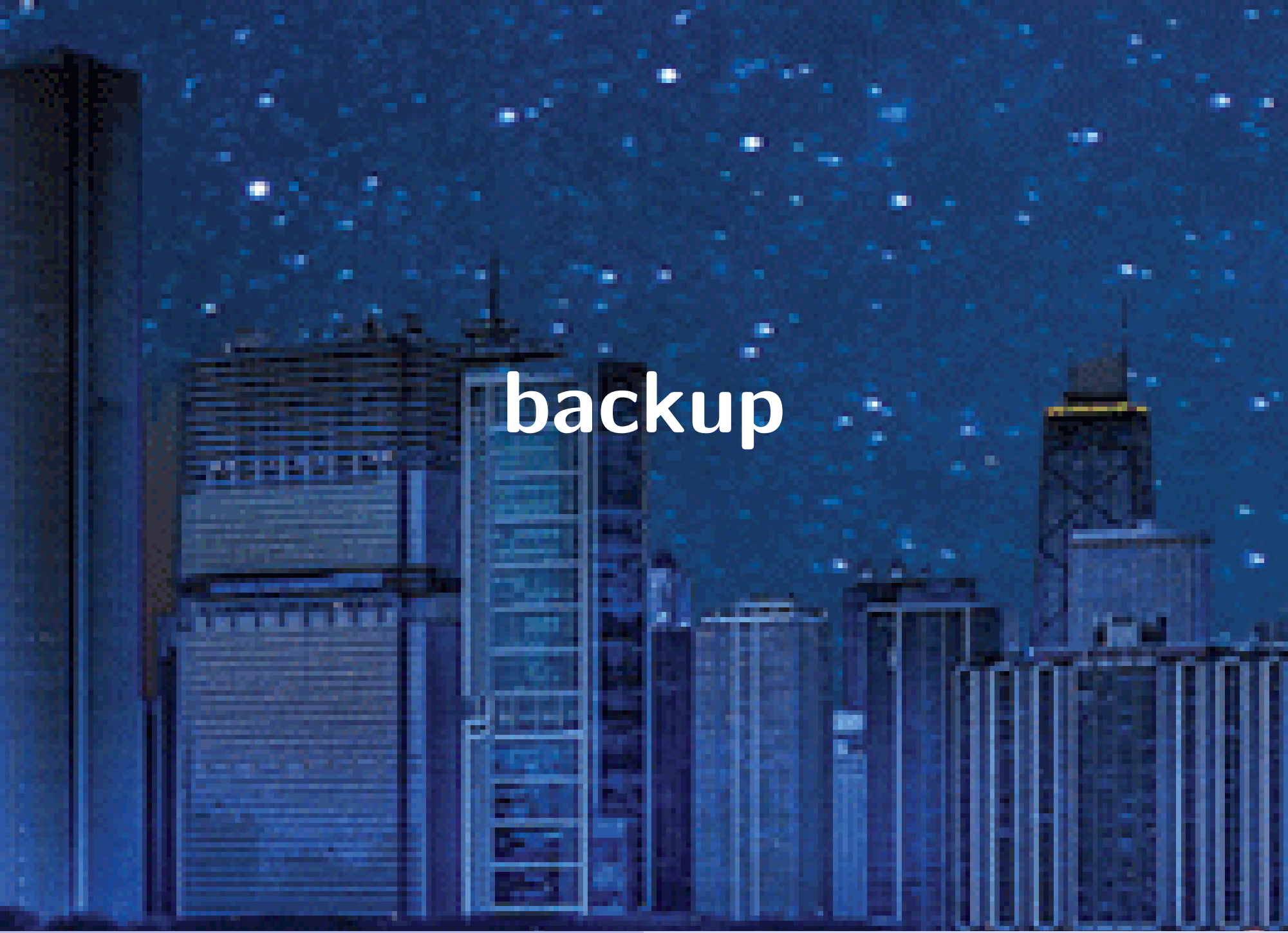


scaling above $p_T = 1$ GeV/c holds **better** for v_3 (top) and v_4 (bottom)

in conclusion

v_2, v_3 and v_4 of unidentified and identified particles have been measured at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV PbPb collisions

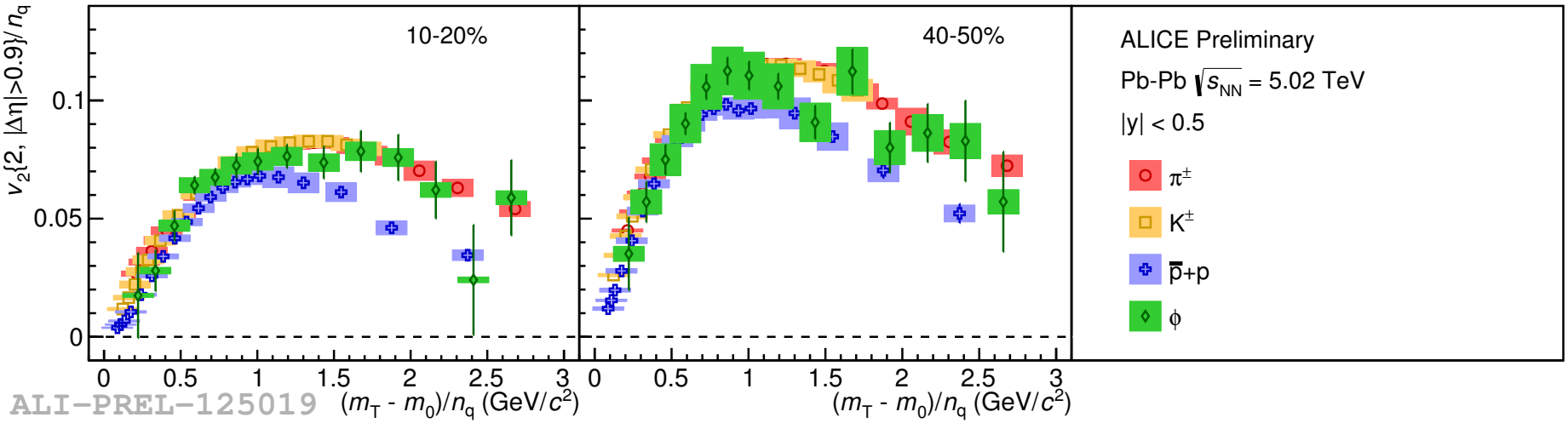
- ratios of integrated v_n at various energies provide constraints to temperature dependence of η/s
- v_2 of unidentified particles non-zero up to high p_{T}
- mass ordering is observed for $p_{\mathrm{T}} < 2$ GeV/c
- viscous hydrodynamics gives reasonable description of results at low p_{T}
- approximate particle type scaling for $p_{\mathrm{T}} > 2.5$ GeV/c
- proton $v_2 >$ pion v_2 up to $p_{\mathrm{T}} > 10$ GeV/c, similar to R_{AA}


backup

v_2 of identified particles, KE_T scaling

Proposed scaling for lower momenta

$$KE_T = m_T - m_0 = \sqrt{{p_T}^2 - m_0^2} - m_0$$



Only approximate scaling observed for v_2

- What about higher harmonics?

v_3 of identified particles, KE_T scaling

Proposed scaling for lower momenta

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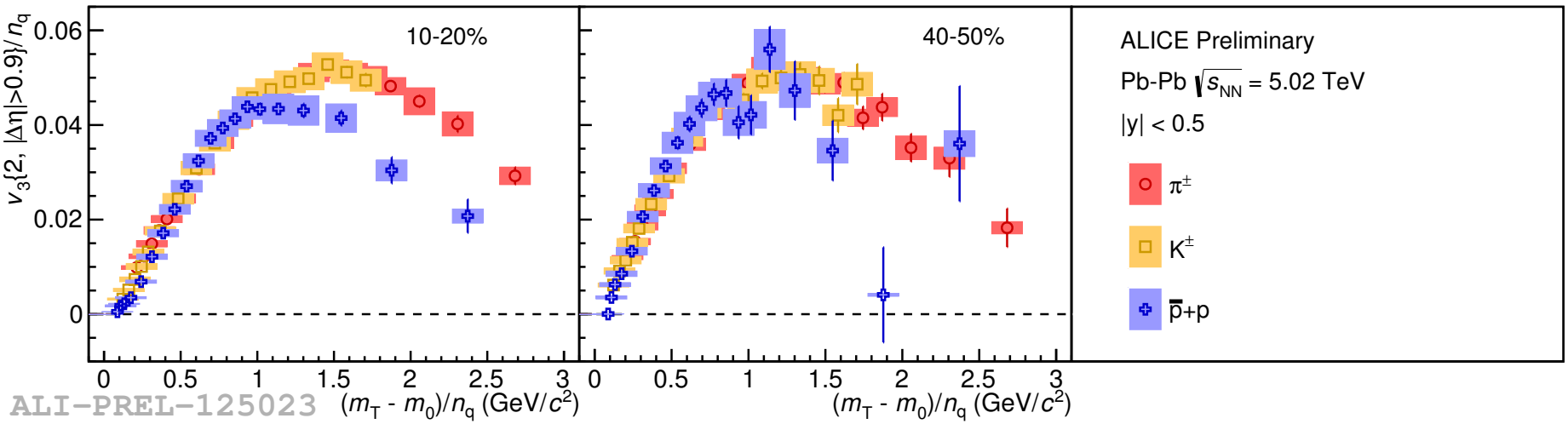
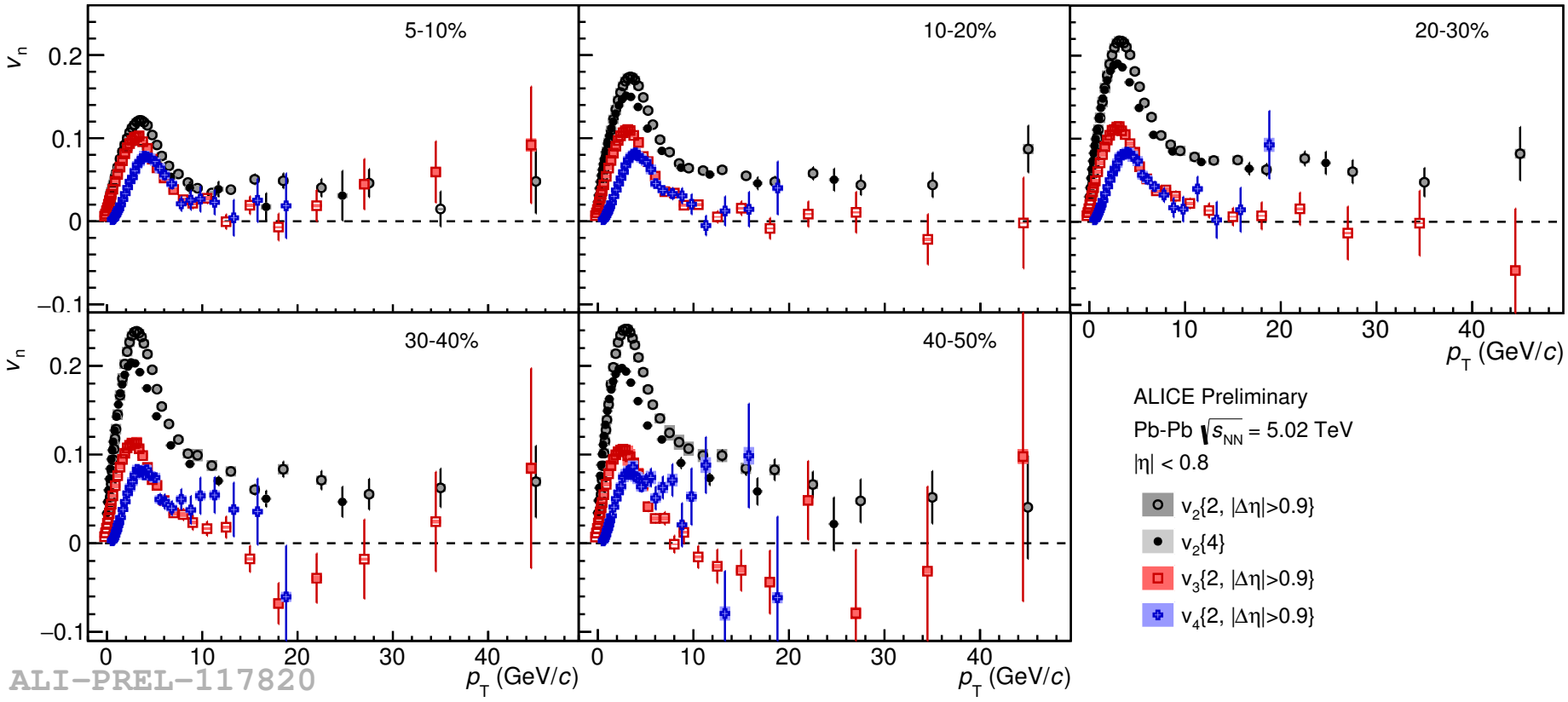
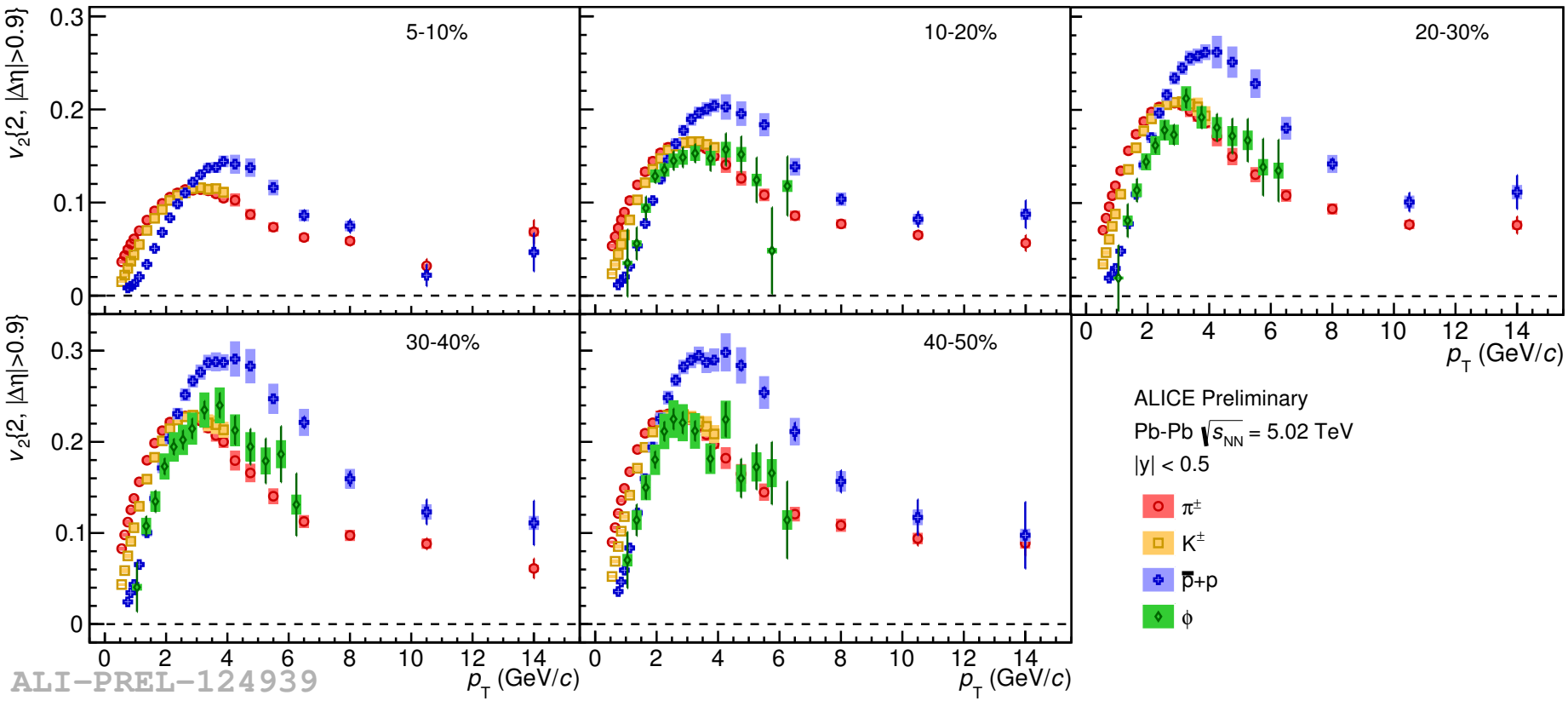


- Scaling of v_3 seems to hold better than that of v_2

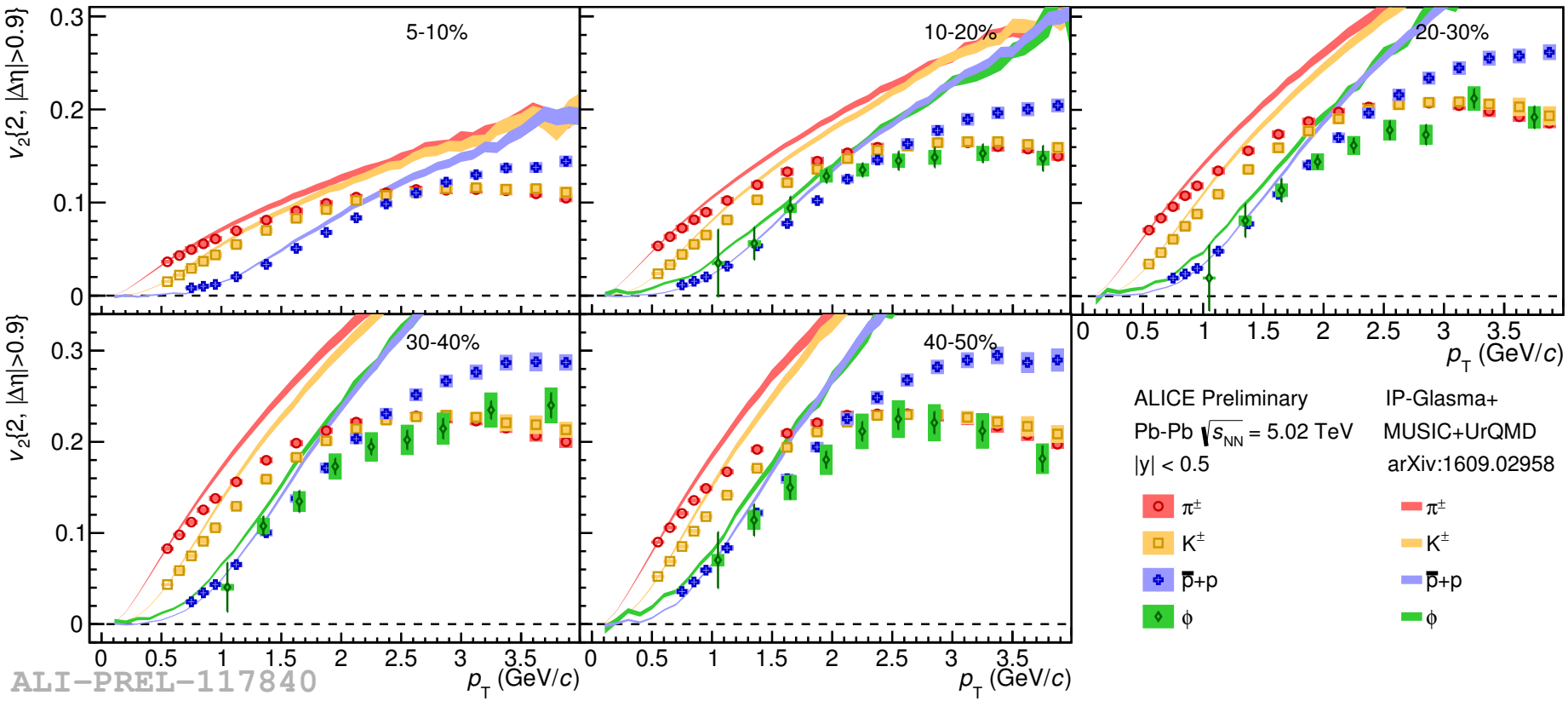
v_n of unidentified particles



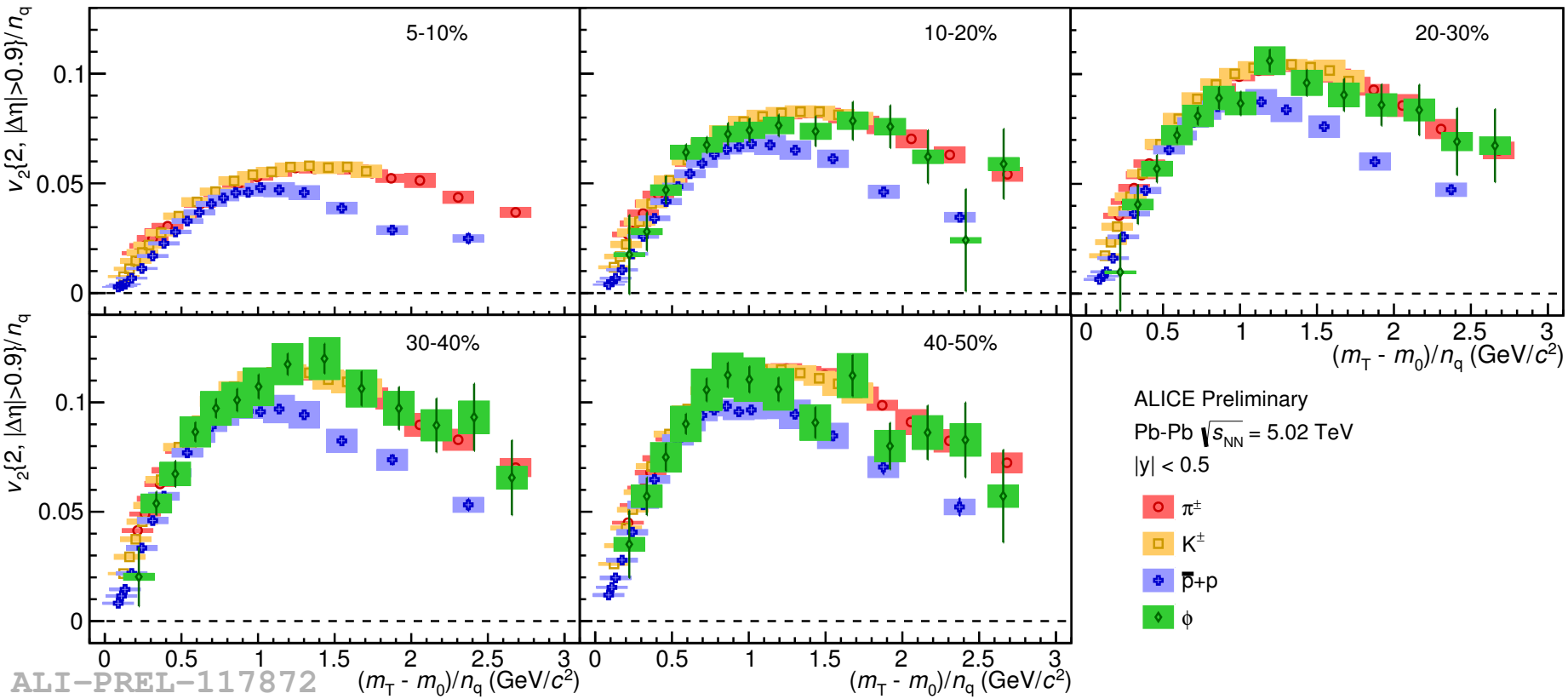
v_2 of identified particles



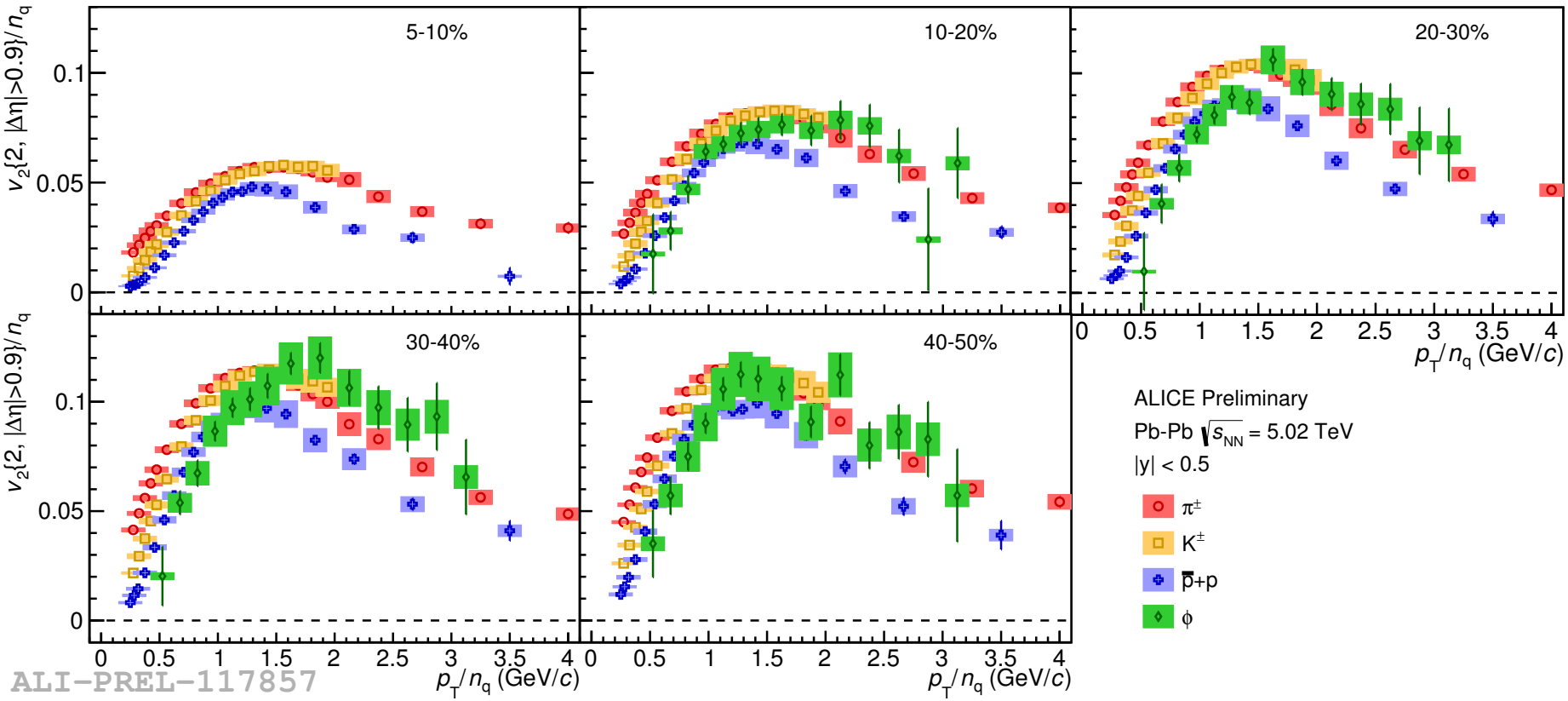
v_2 of identified particles compared to hydrodynamics



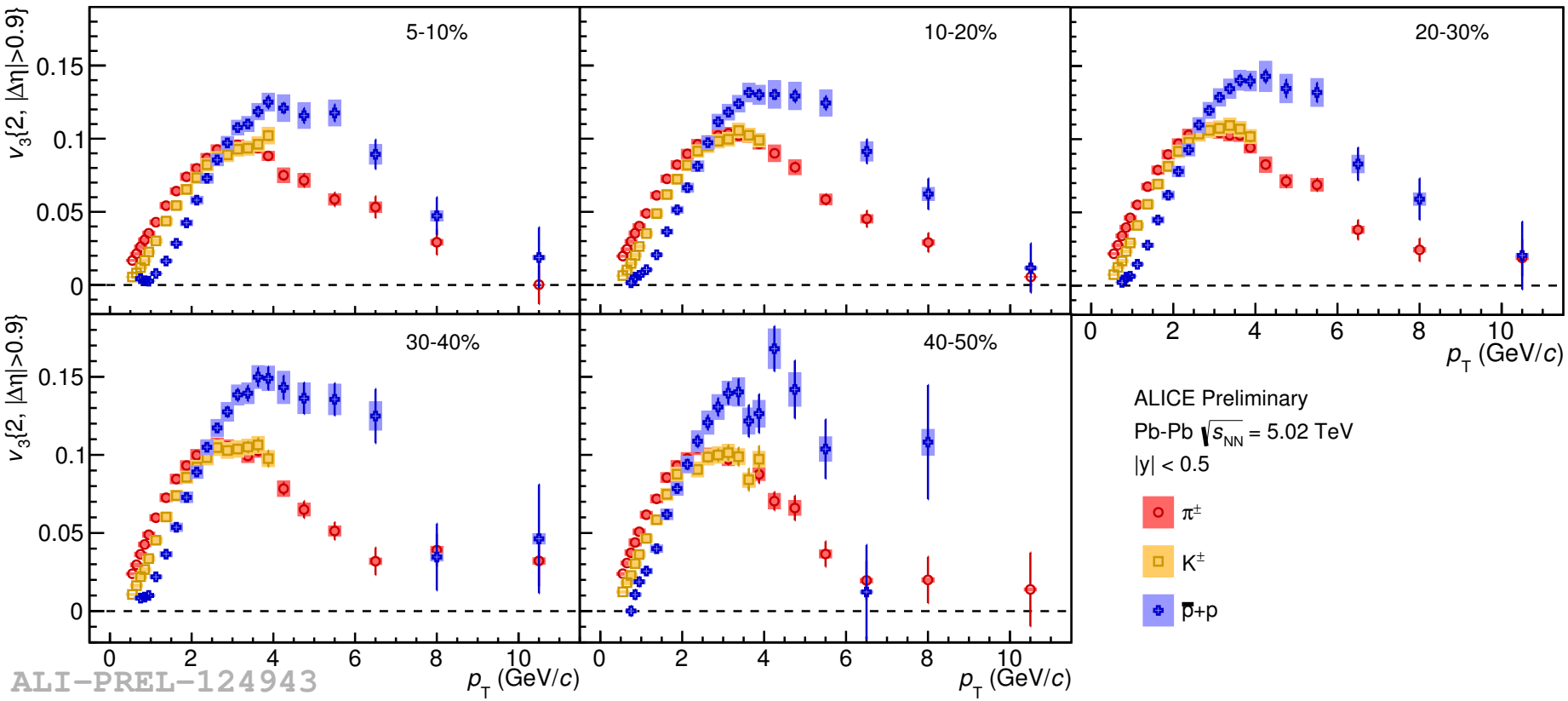
v_2 of identified particles, KE_T scaling



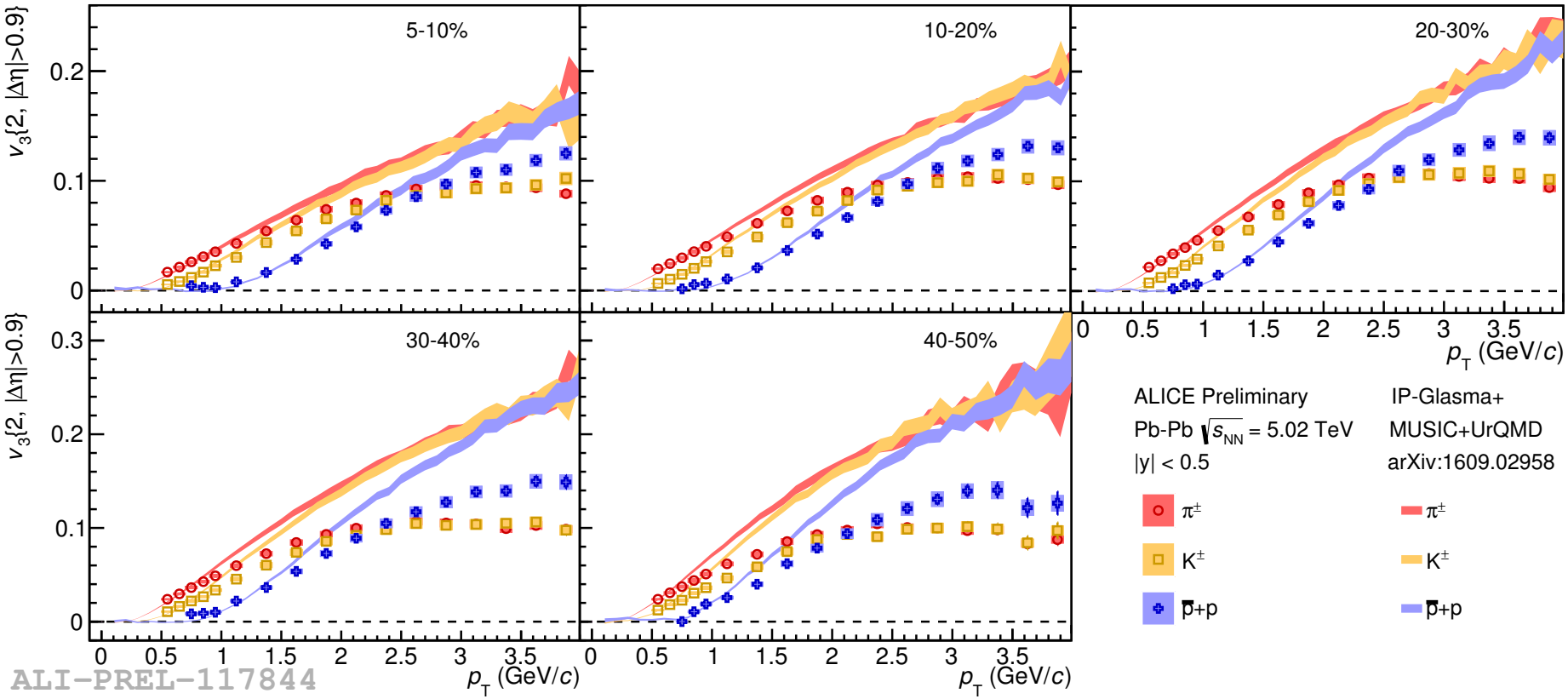
v_2 of identified particles, n_q scaling



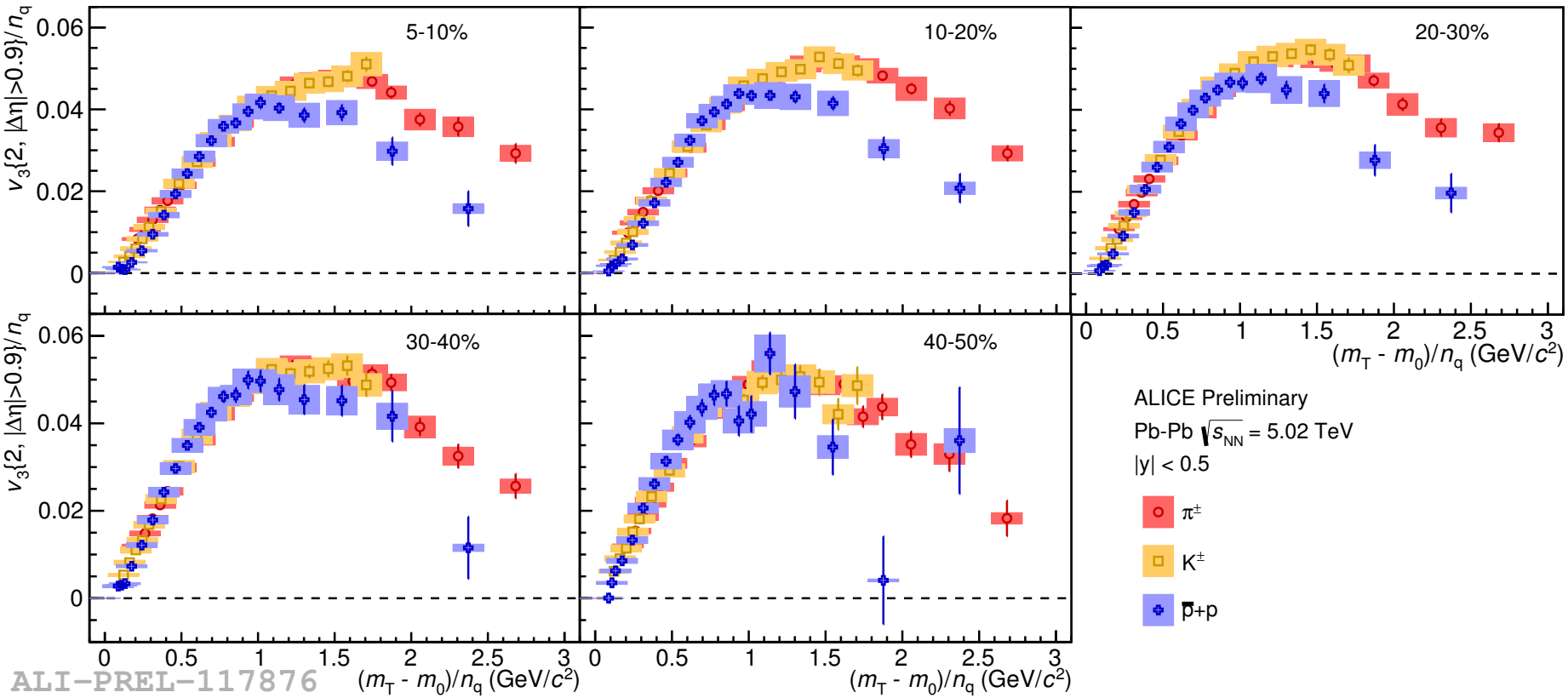
v_3 of identified particles



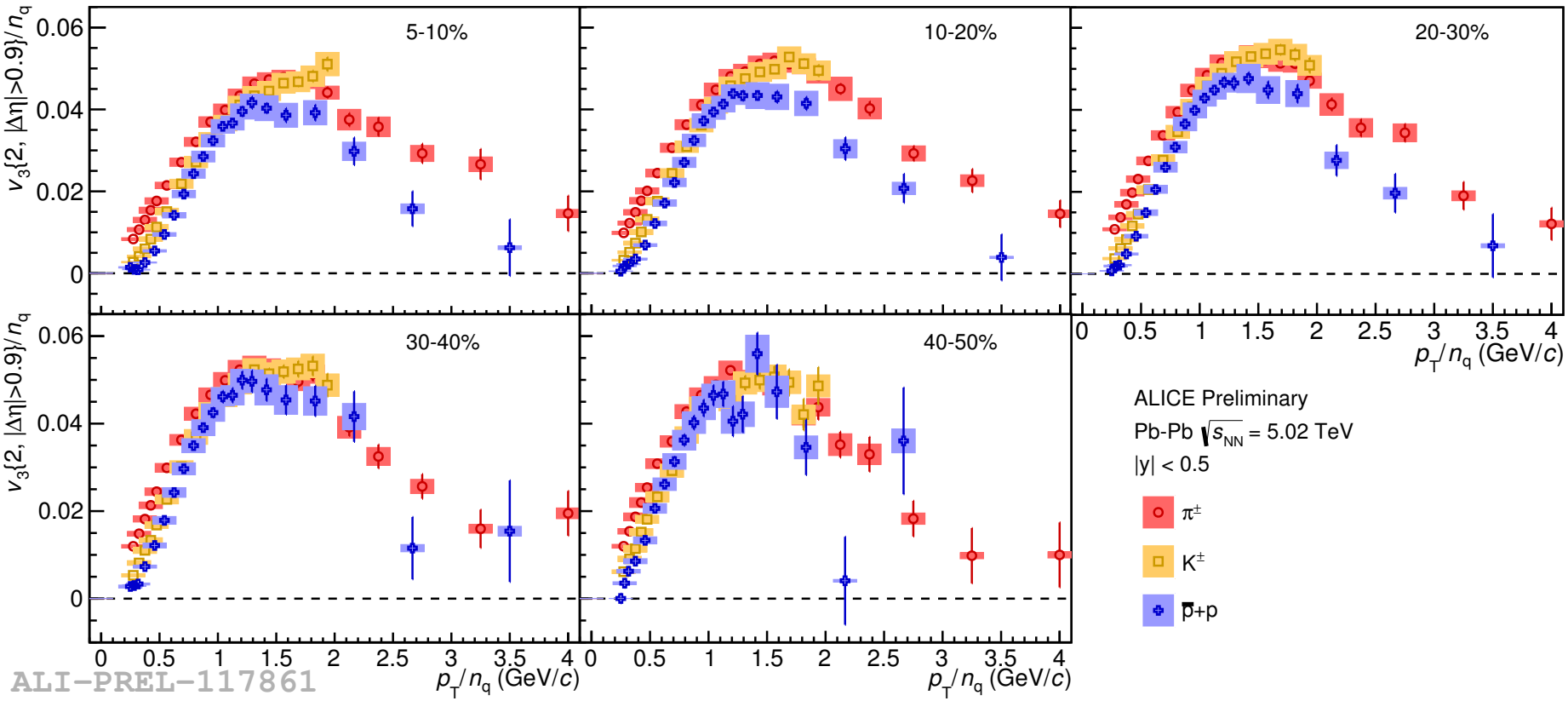
v_3 of identified particles compared to hydrodynamics



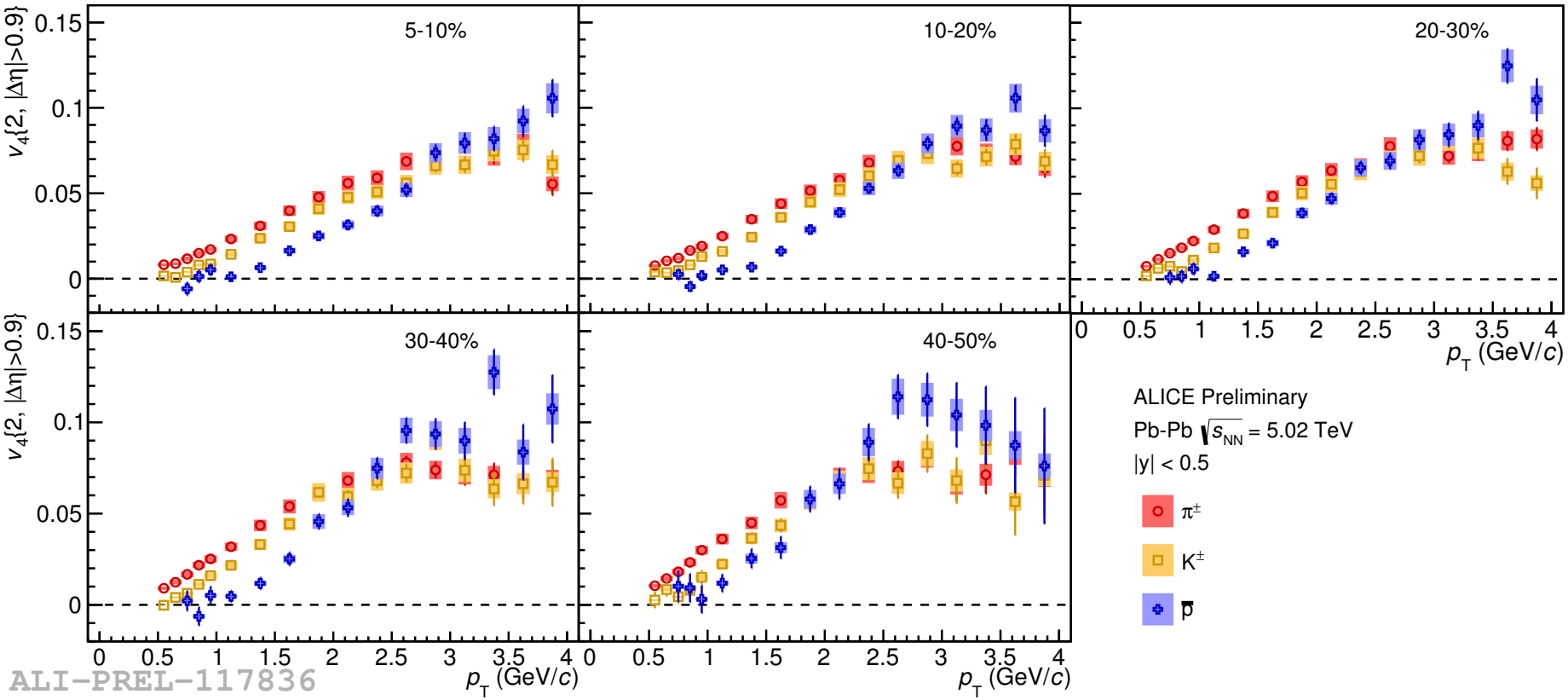
v_3 of identified particles, KE_T scaling



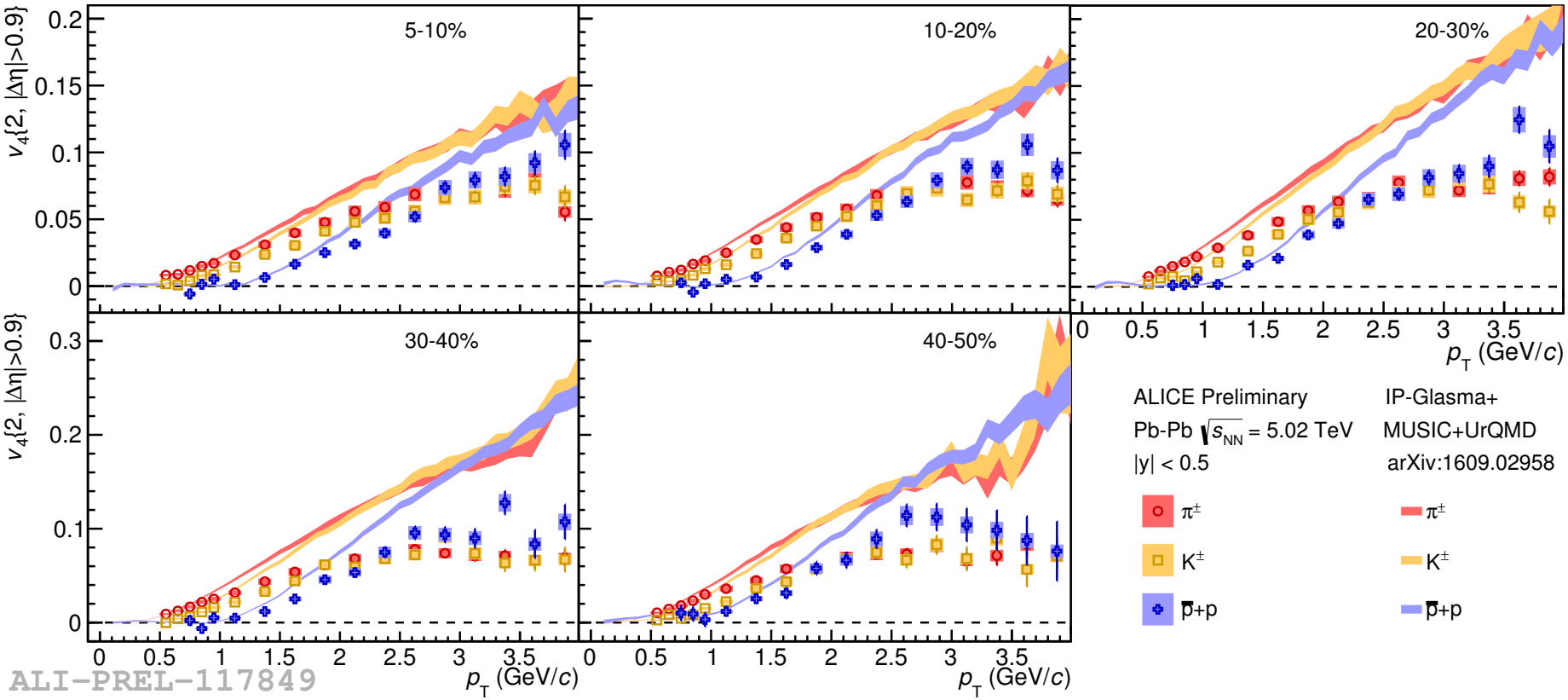
v_3 of identified particles, n_q scaling



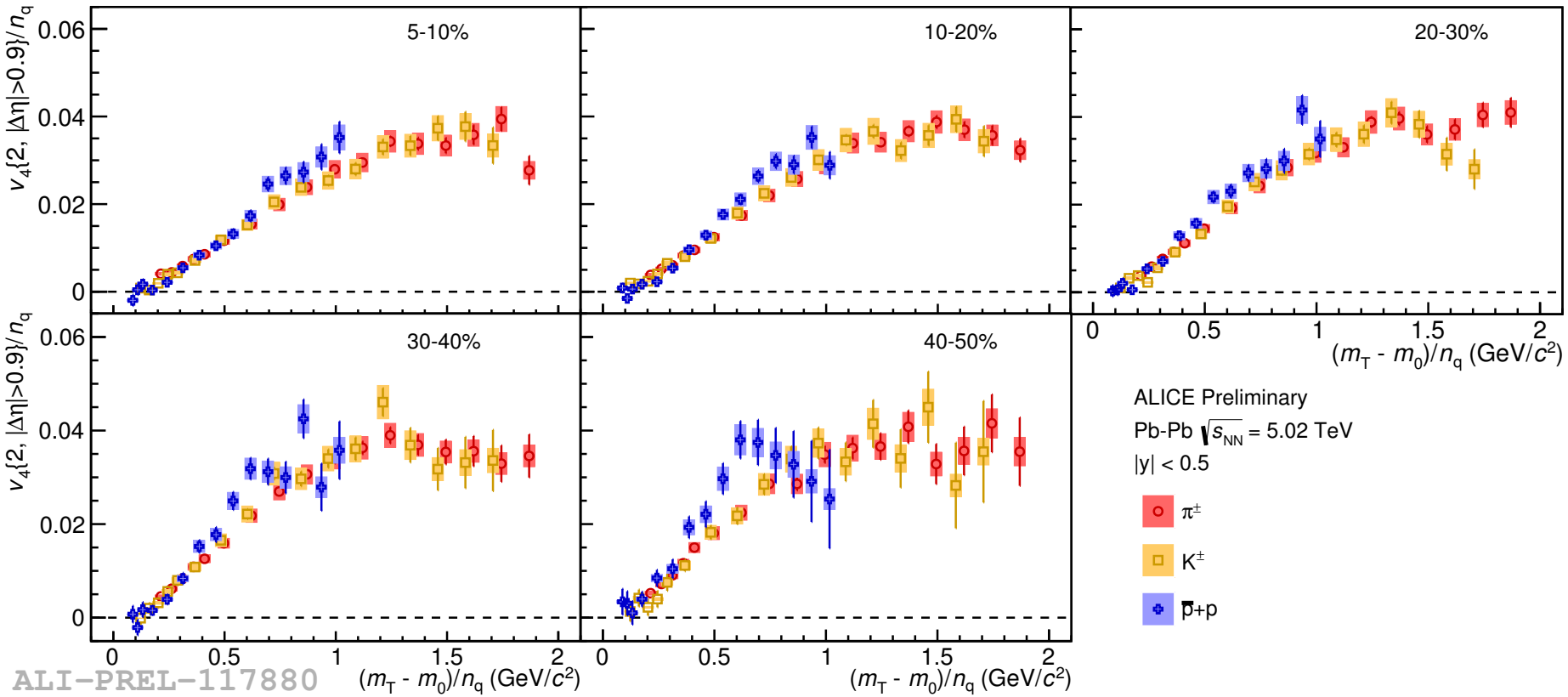
v_4 of identified particles



v_4 of identified particles compared to hydrodynamics



v_4 of identified particles, KE_T scaling



v_4 of identified particles, n_q scaling