Measurement of higher harmonic flow coefficients of identified hadrons in Pb-Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV

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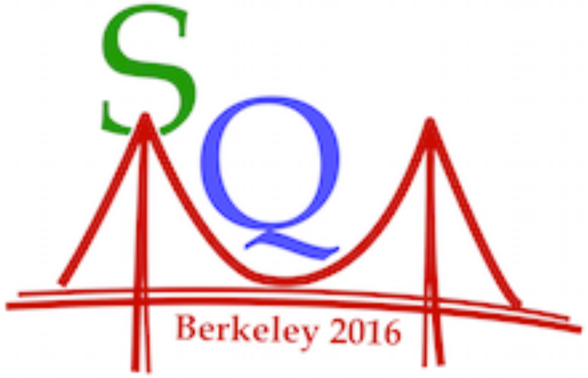
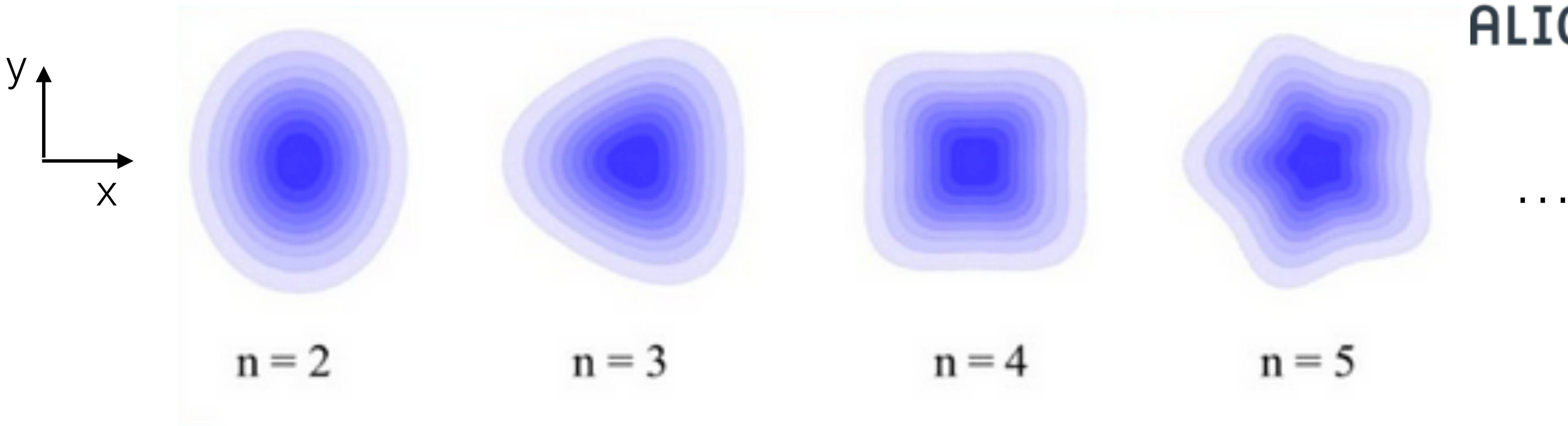
for the ALICE Collaboration
results in arXiv: 1606.06057



Flow harmonics



Flow harmonics are sensitive to:

- Initial conditions
- Transport properties (η/s)

For different particle species, probe in addition:

- Effects of hadronisation mechanism, e.g. quark coalescence
- Effects of hadronic rescattering

Flow measurement

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

azimuthal angle (φ) symmetry plane angle (Ψ_n)

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

Flow measurement

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azimuthal angle (φ) symmetry plane angle (Ψ_n)

Scalar product method:

$$v_n^a(p_T) = \frac{\left\langle\left\langle \vec{u}_n^k(p_T)\cdot\frac{\vec{Q}_n^{b*}}{M^b}\right\rangle_{k\in a}\right\rangle}{\sqrt{\left\langle\frac{\vec{Q}_n^a}{M^a}\cdot\frac{\vec{Q}_n^{b*}}{M^b}\right\rangle}}$$

M: Multiplicity

$$\vec{Q}_n = \sum_{k\in RP}^{M} e^{in\varphi_k}$$

total flow vector

u: unit flow vector

Flow measurement

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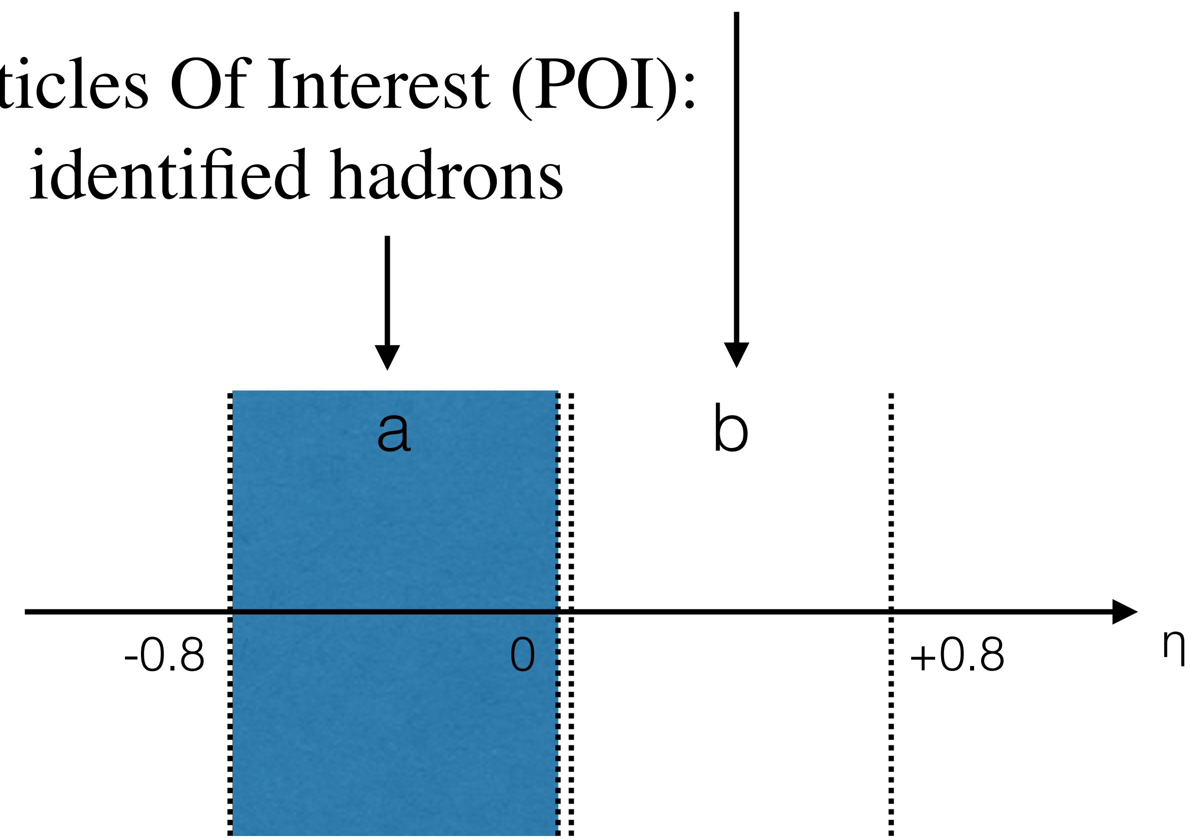
Reference Particles (RP):
charged particles

Particles Of Interest (POI):
identified hadrons



No η gap non-overlapping subevents

TPC acceptance

Flow measurement

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Scalar product method:

$$v_n^b(p_T) = \frac{\left\langle \left\langle \vec{u}_n^k(p_T)\cdot\frac{\vec{Q}_n^{a*}}{M^b}\right\rangle_{k\in b}\right\rangle}{\sqrt{\left\langle \frac{\vec{Q}_n^a}{M^a}\cdot\frac{\vec{Q}_n^{b*}}{M^b}\right\rangle}}$$

Particles Of Interest (POI): identified hadrons

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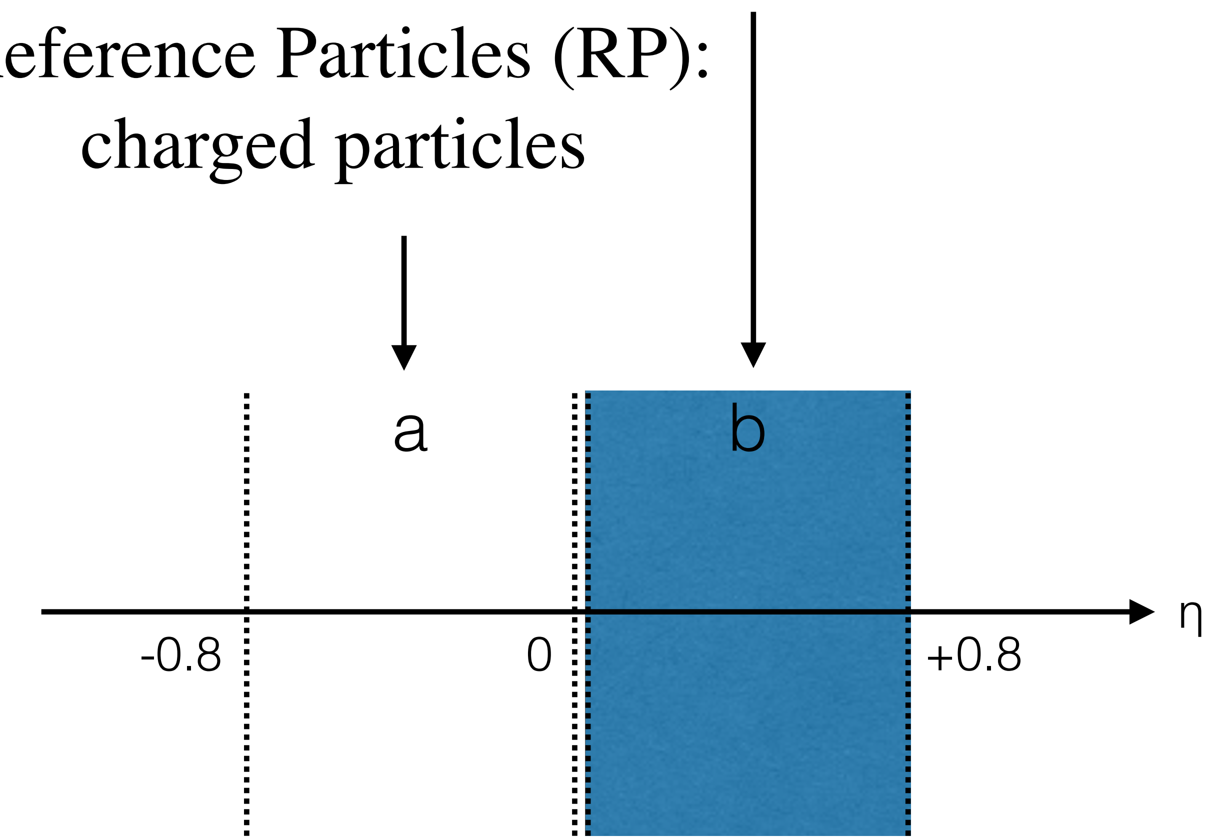


TPC acceptance

v_n= Average of v_n^a and v_n^b

Non flow treatment

2-particle azimuthal correlation $\begin{cases} \text{Anisotropic flow} \\ \text{Resonance decays, jets a.k.a. non-flow} \end{cases}$

Subtract non-flow estimate:

- $v_n^{\text{sub}}(p_{\text{T}}) = v_n^{\text{AA}}(p_{\text{T}}) - \delta_n^{\text{AA,pp}}(p_{\text{T}})$
- v_n^{AA}: flow coefficients measured in Pb-Pb collisions
- $\delta_n^{AA,pp}$: estimate of non-flow → from pp + Pb-Pb events
  - Assumption: scales with 1/M

$$\delta_n^{(\text{a})\text{AA,pp}}(p_{\text{T}}) = \frac{\langle M \rangle^{\text{pp}} \left\langle \left\langle \vec{u}_n^k(p_{\text{T}}) \cdot \frac{\vec{Q}_n^{b*}}{M^b} \right\rangle_{k \in a} \right\rangle^{\text{pp}}}{\langle M \rangle^{\text{AA}} \sqrt{\left\langle \frac{\vec{Q}_n^a}{M^a} \cdot \frac{\vec{Q}_n^{b*}}{M^b} \right\rangle^{\text{AA}}}}$$

Analysis Details

Data sample:
- Pb-Pb at $\sqrt{s_{NN}}$=2.76 TeV

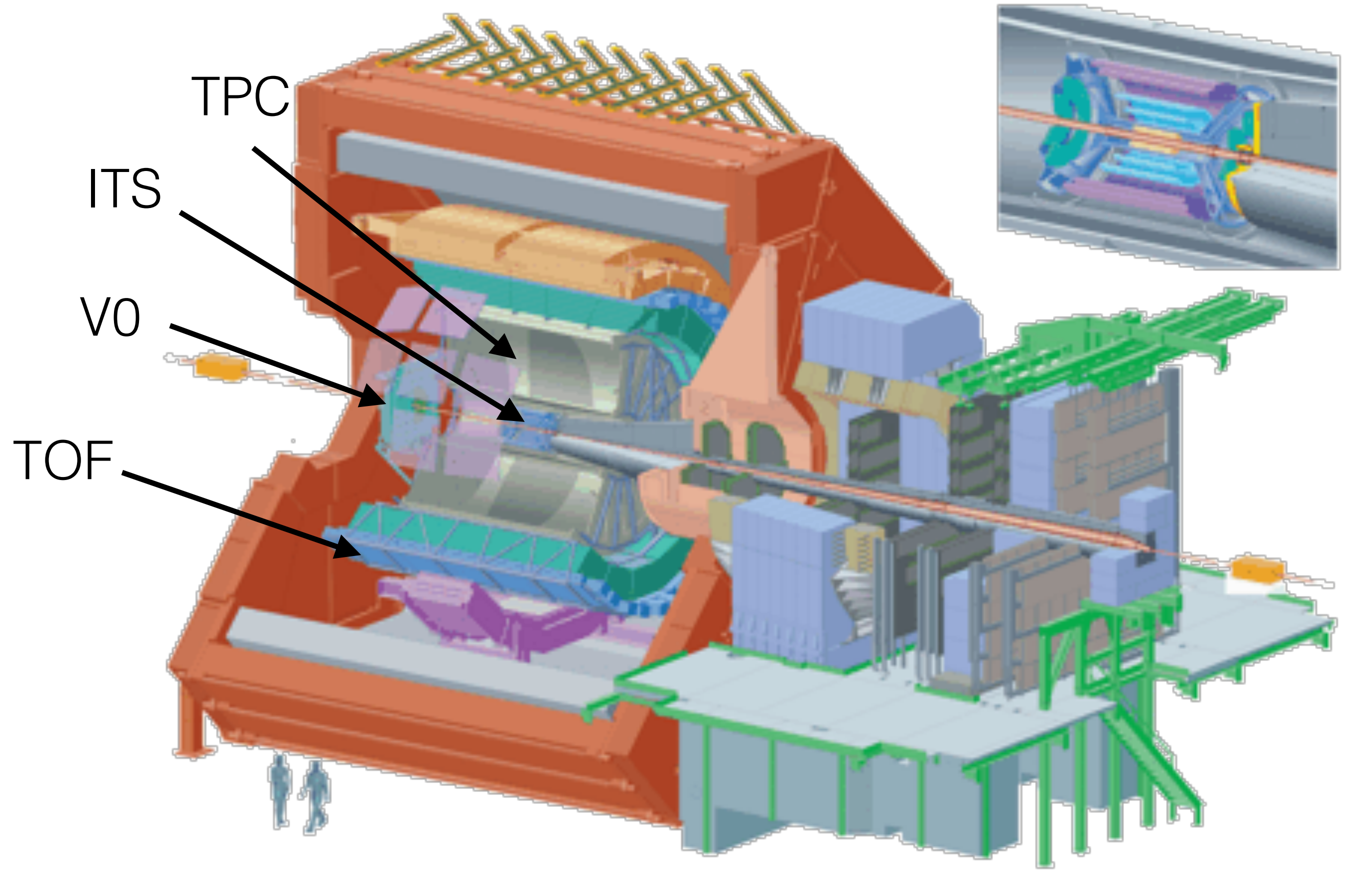
Trigger:
- 0-10% (central),
- 10-50% (SemiCentral)

Statistics:
- 25M events analysed

Data sample:
- pp at $\sqrt{s_{NN}}$=2.76 TeV

Trigger:
- Minimum bias

Statistics:
- 20M events analysed



Tracks used: $-0.8<\eta<0.8$

Particles of interest (POI):
- $\pi^{\pm}$, $K^{\pm}$, $p(\bar{p})$

Reference Particles (RP):
- All charged particles

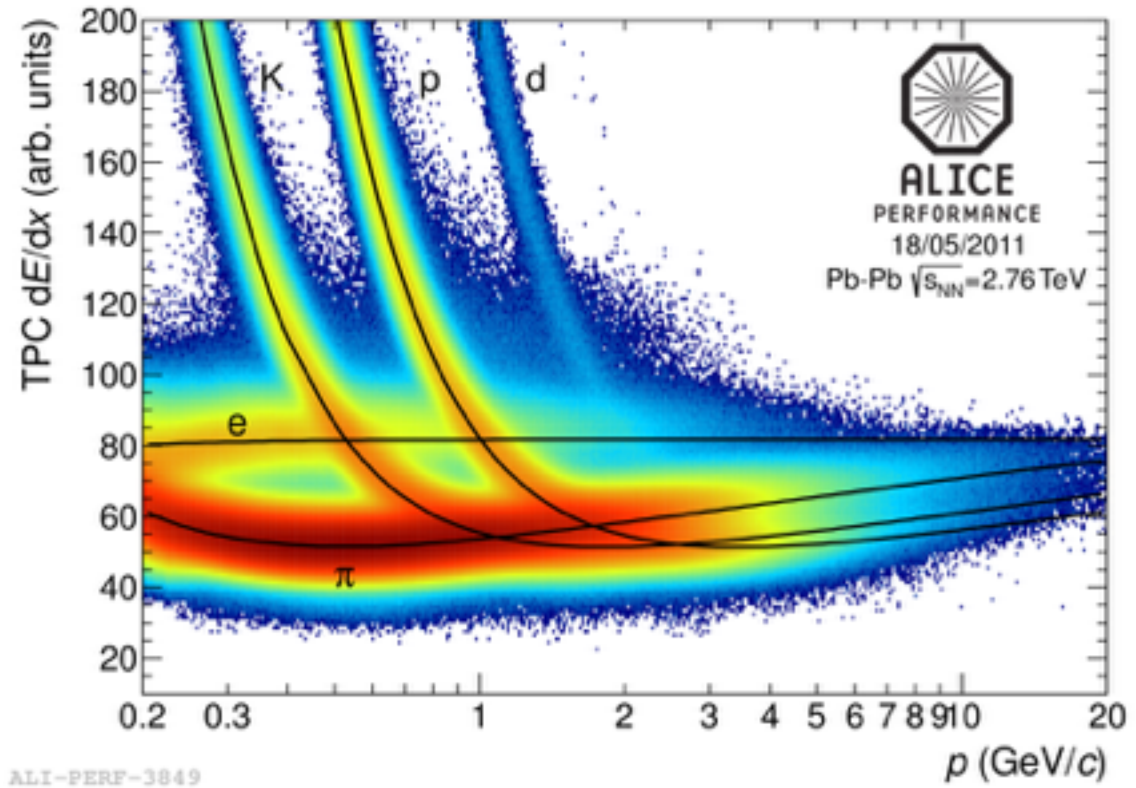
POI p_T range:
- $\pi^{\pm}$: $0.3<p_T<6$ GeV/c
- $K^{\pm}$: $0.3<p_T<4$ GeV/c
- $p(\bar{p})$: $0.4<p_T<6$ GeV/c

RP p_T range:
- $0.2<p_T<5$ GeV/c

Particle Identification

Time Projection Chamber (TPC)

dE/dx : the specific energy loss
Resolution: $\sigma_{dE/dx} \approx 5\%$



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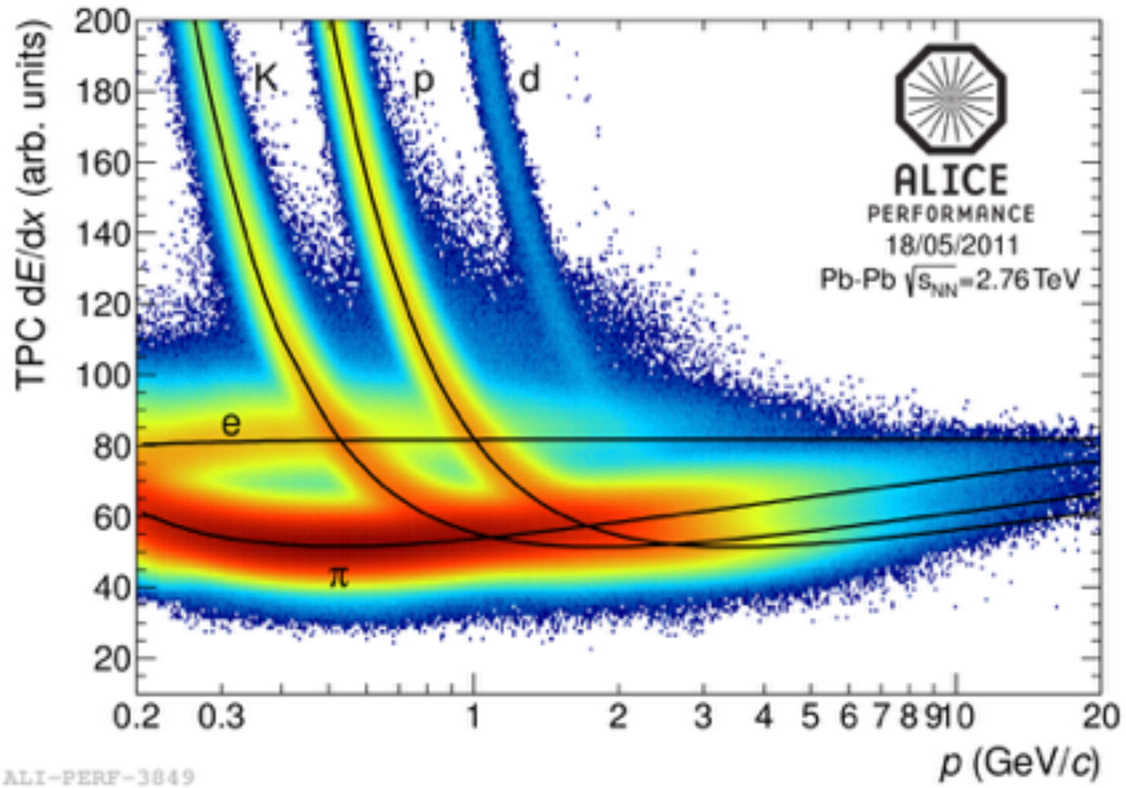
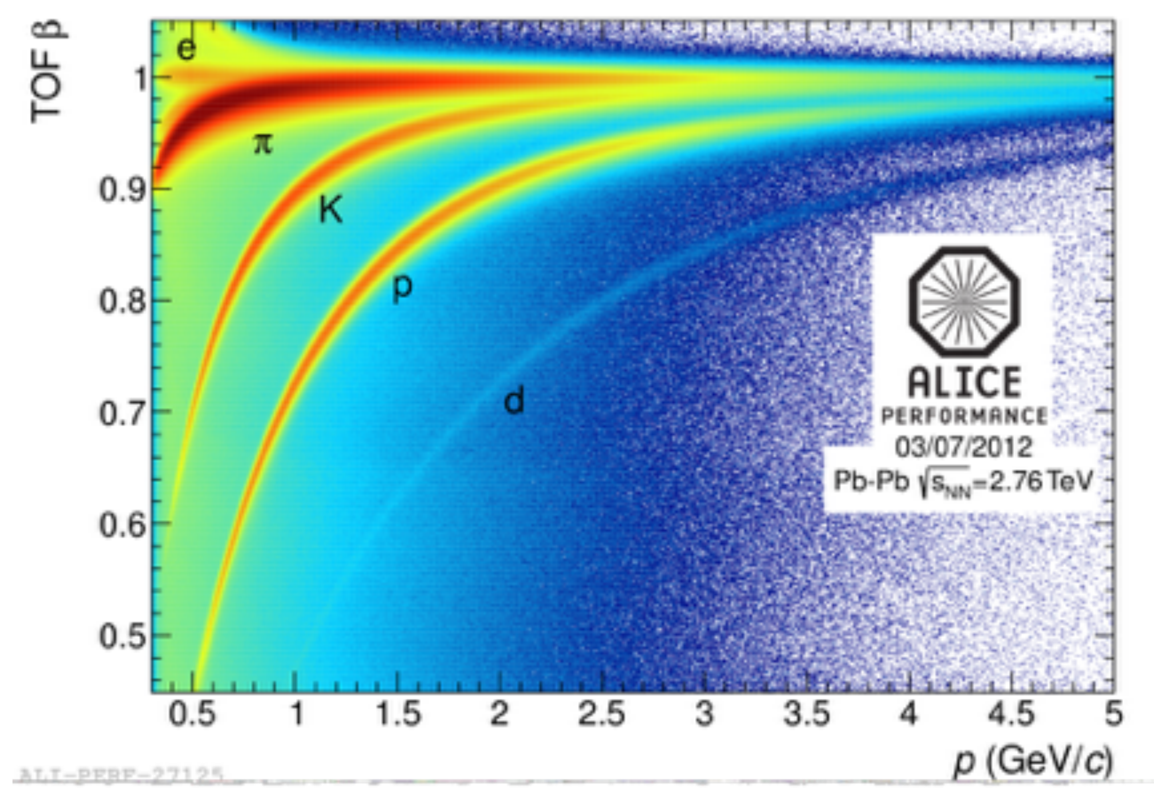


Time of Flight (TOF)

β=Track length/arrival time
Resolution: $\sigma_{TOF} \simeq$ 86 ps for Pb-Pb collisions



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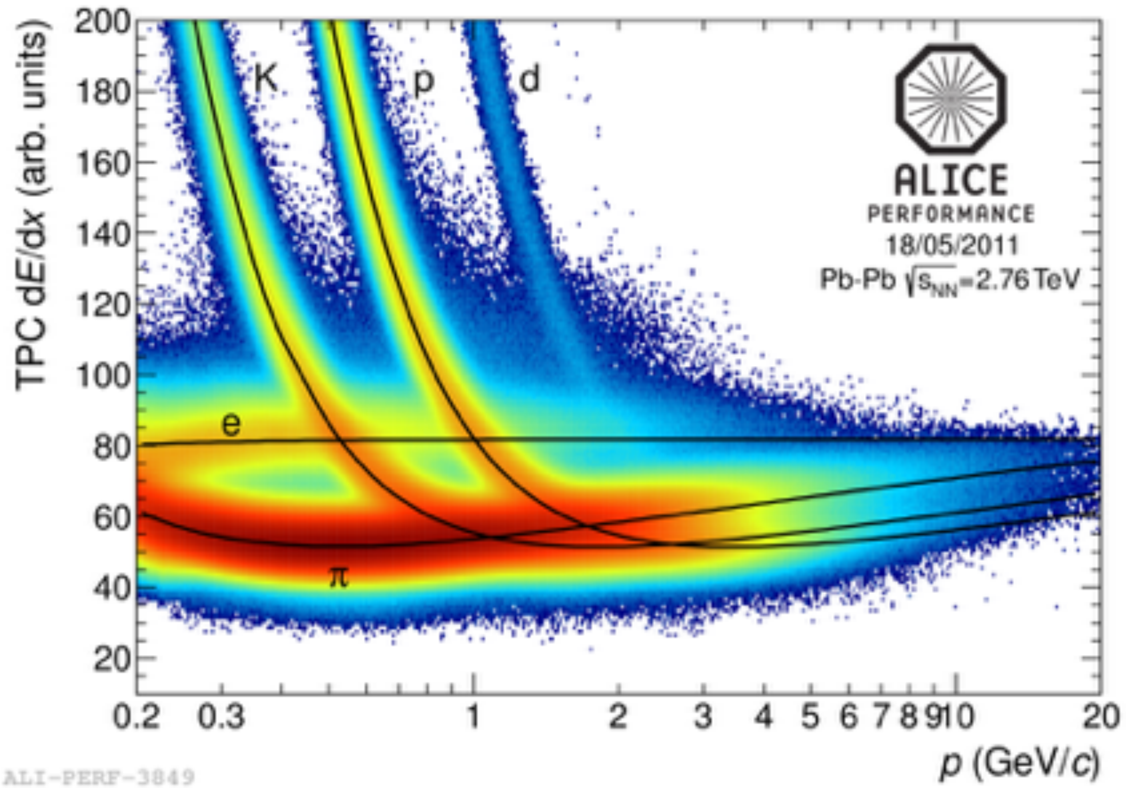

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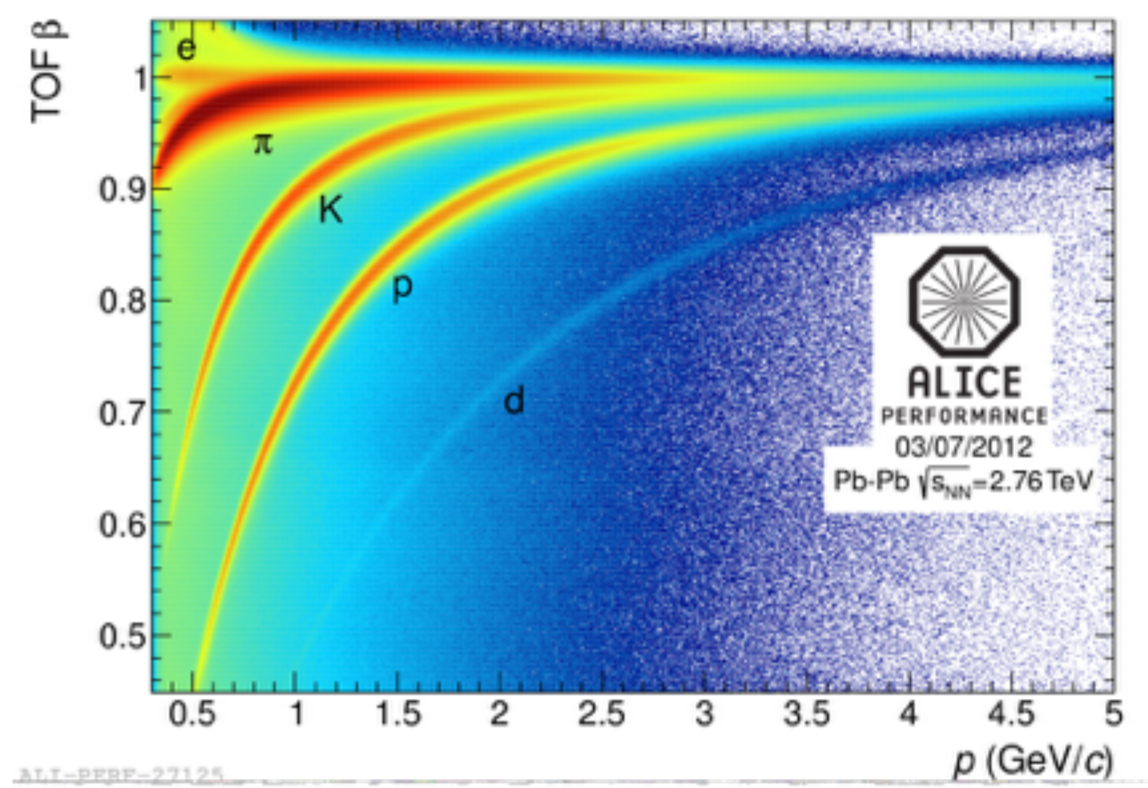


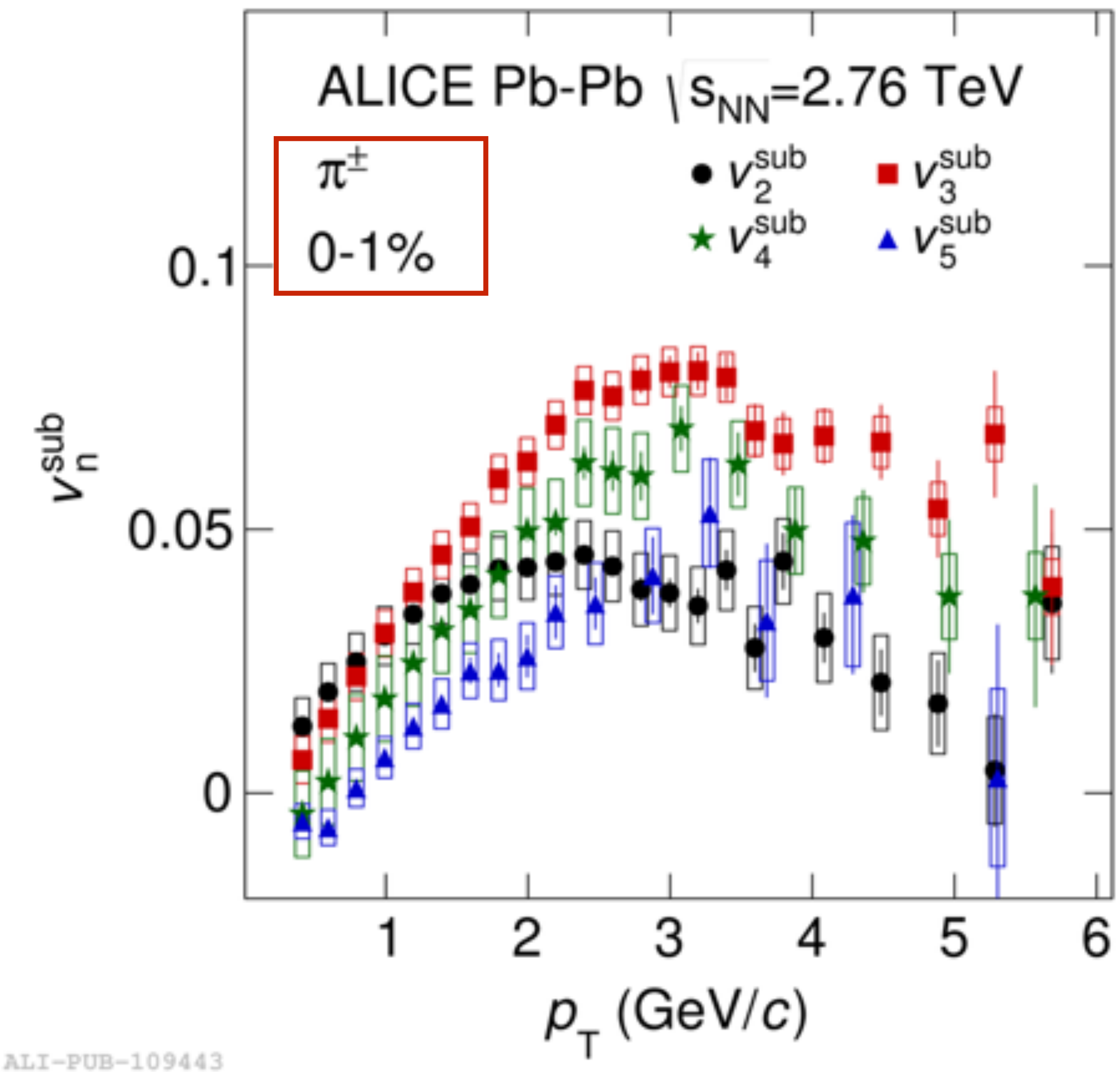
Bayesian PID (arXiv:1602.01392):

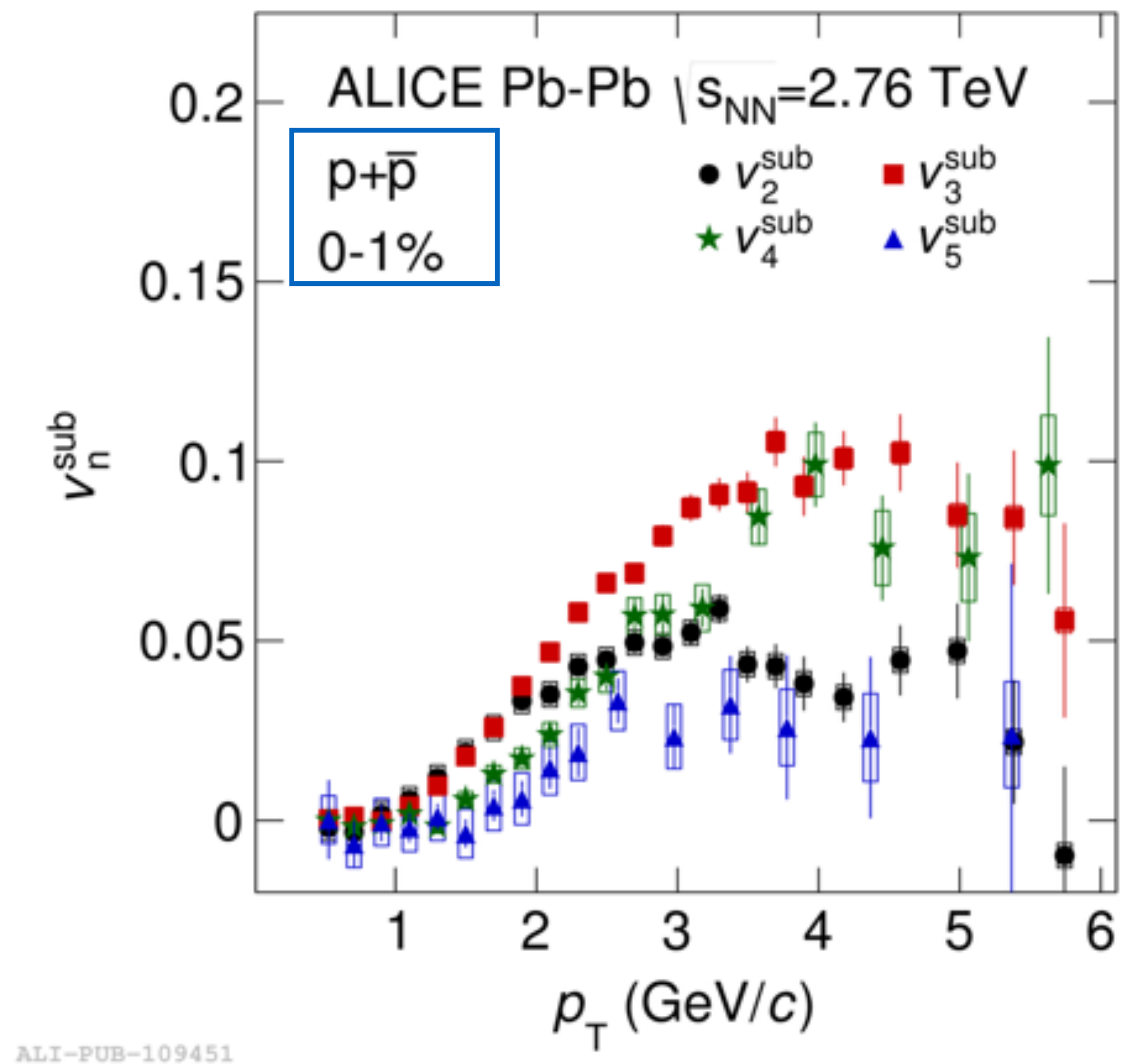
- Input quantities: <dE/dx>, β
- Identification Probability > 90%

Results

p_T evolution of flow harmonics: 0-1%

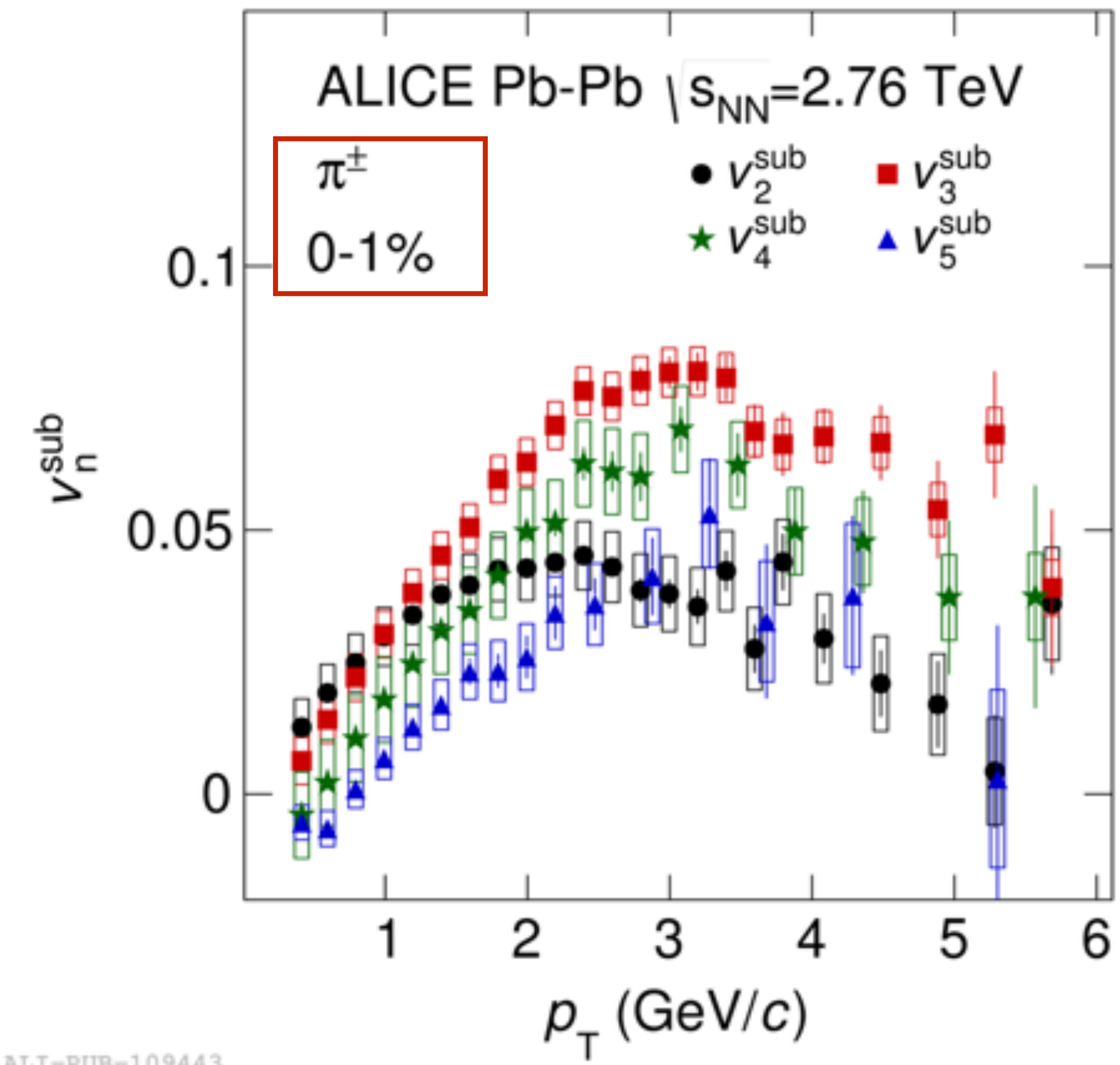
- Depending on p_T for most central (0-1%): $v_3 > v_4 > v_5 \sim v_2$
- Crossing between v_2 and other harmonics shows a mass dependence
  - interplay of different flow harmonics with radial flow

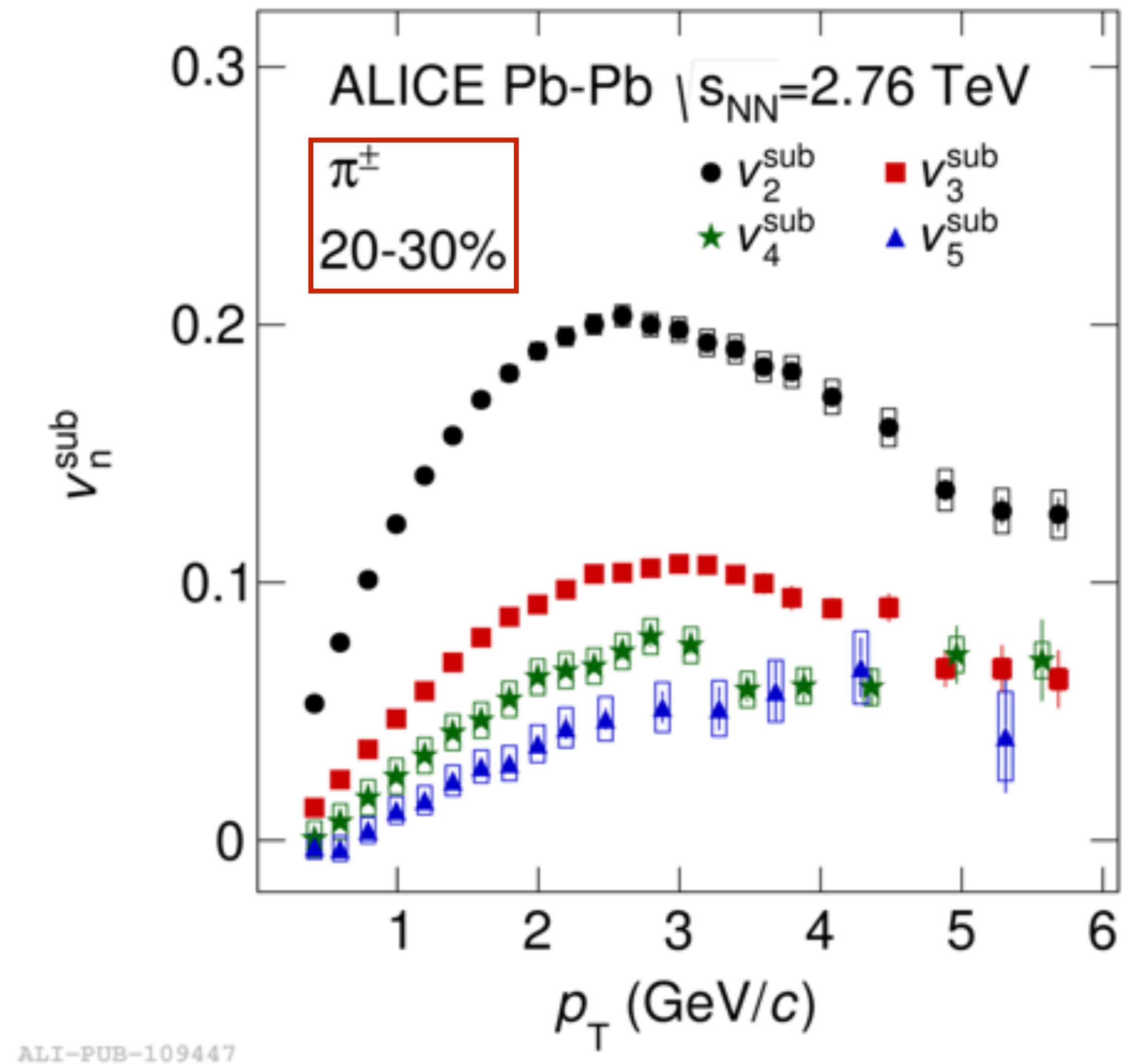




p_T evolution of flow harmonics: 0-1% vs. 20-30%

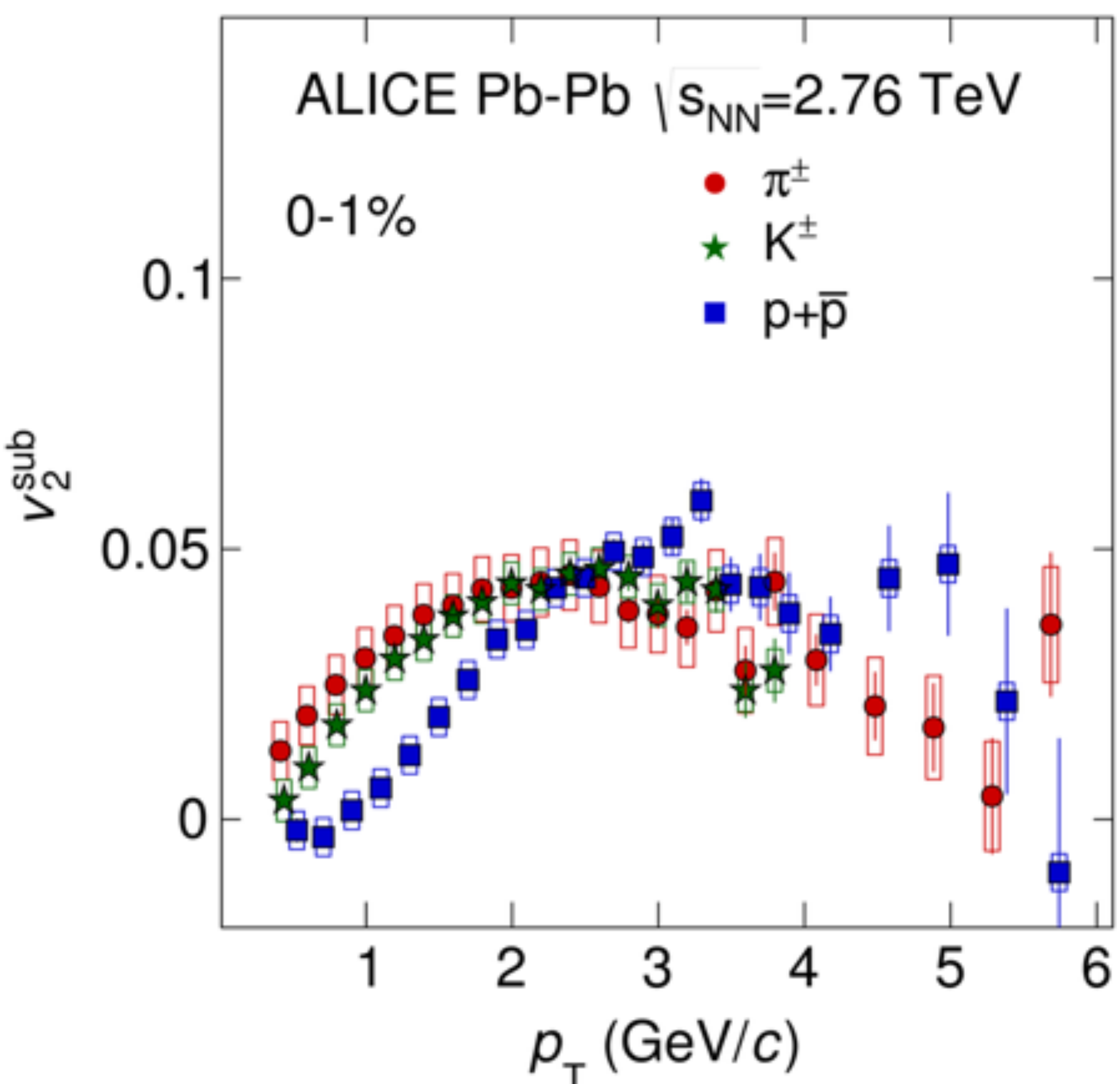
- For mid central (20-30%): $v_2 > v_3 > v_4 > v_5$

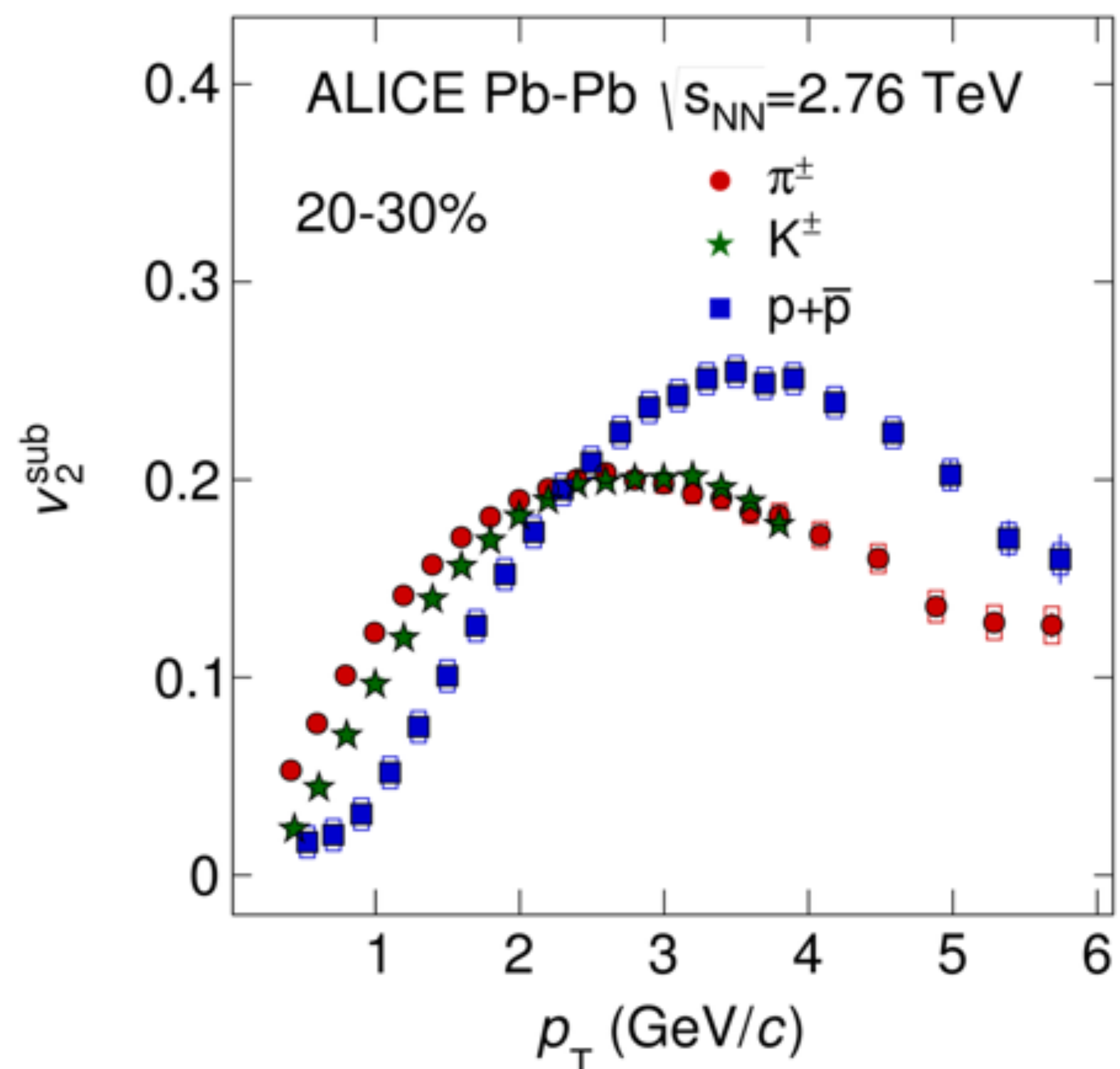




v_2^{sub} vs. particle species

- p_T<2.5 GeV/c: mass ordering indicative of radial flow
- p_T~2.5-3 GeV/c: crossing between v_2^{sub} of $\pi^\pm$, $K^\pm$ and $p+\bar{p}$
- p_T>3 GeV/c: baryon-meson grouping, approximate NCQ scaling (within ~20%)





v_3^{sub} vs. particle species

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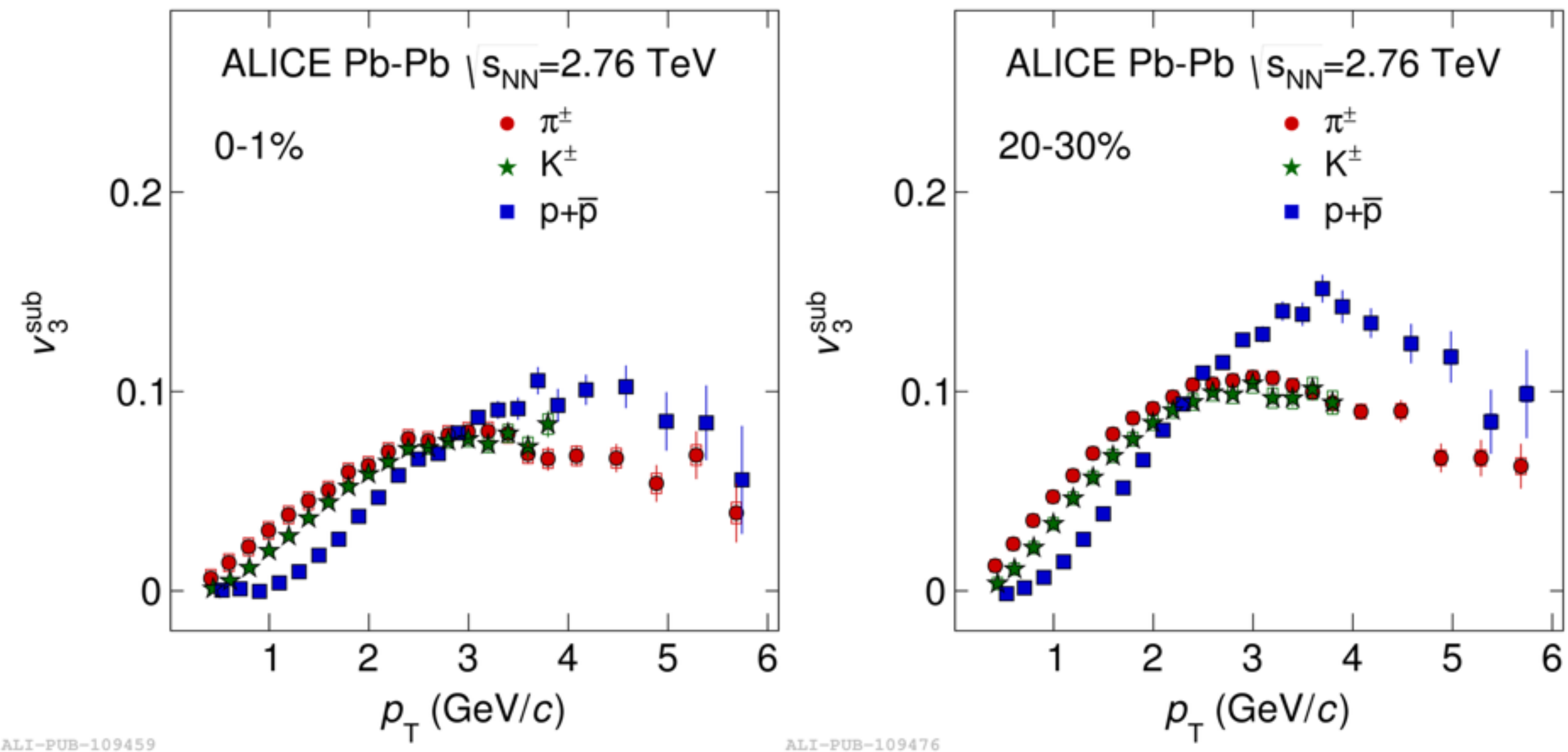
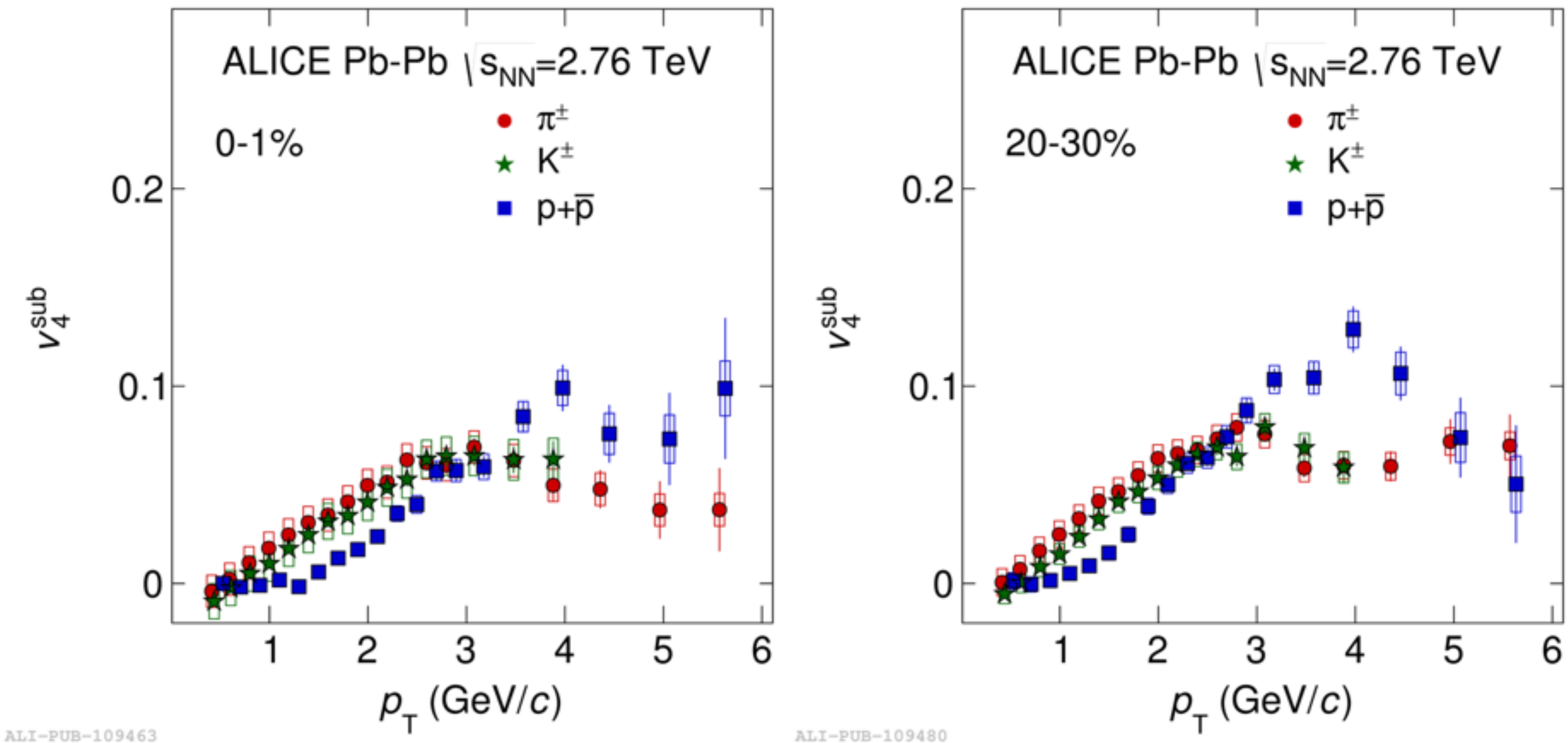


v_4^{sub} vs. particle species

- p_T<2.5 GeV/c: mass ordering indicative of radial flow
- p_T~2.5-3 GeV/c: crossing between v_4^{sub} of $\pi^{\pm}$, $K^{\pm}$ and p+$\bar{p}$
- p_T>3 GeV/c: baryon-meson grouping, approximate NCQ scaling (within ~20%)



v_5^{sub} vs. particle species

- p_T<2.5 GeV/c: mass ordering indicative of radial flow within statistical and systematic uncertainties
- p_T~2.5-3 GeV/c: crossing between v_5^{sub} of $\pi^\pm$, $K^\pm$ and $p+\bar{p}$
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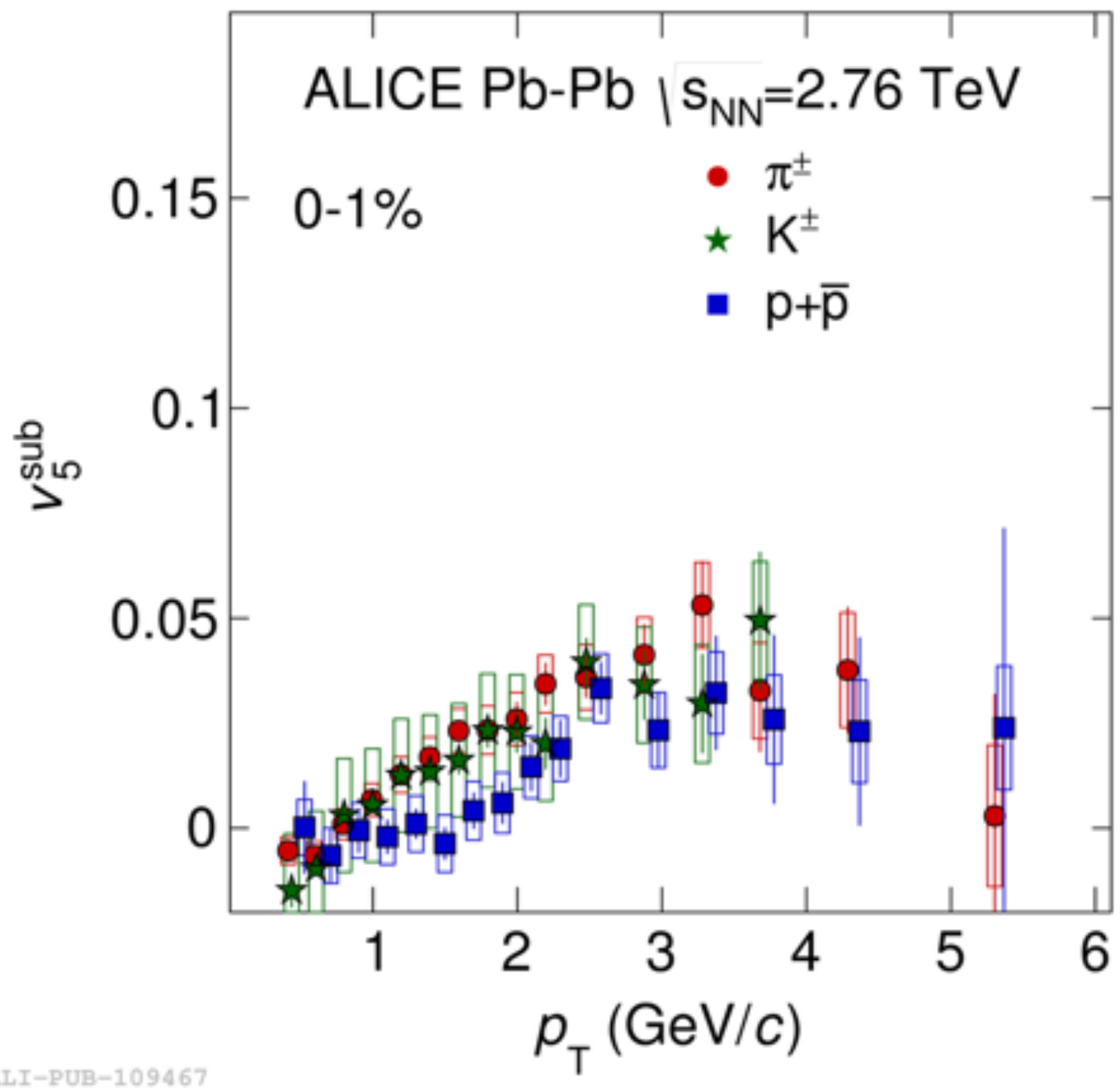
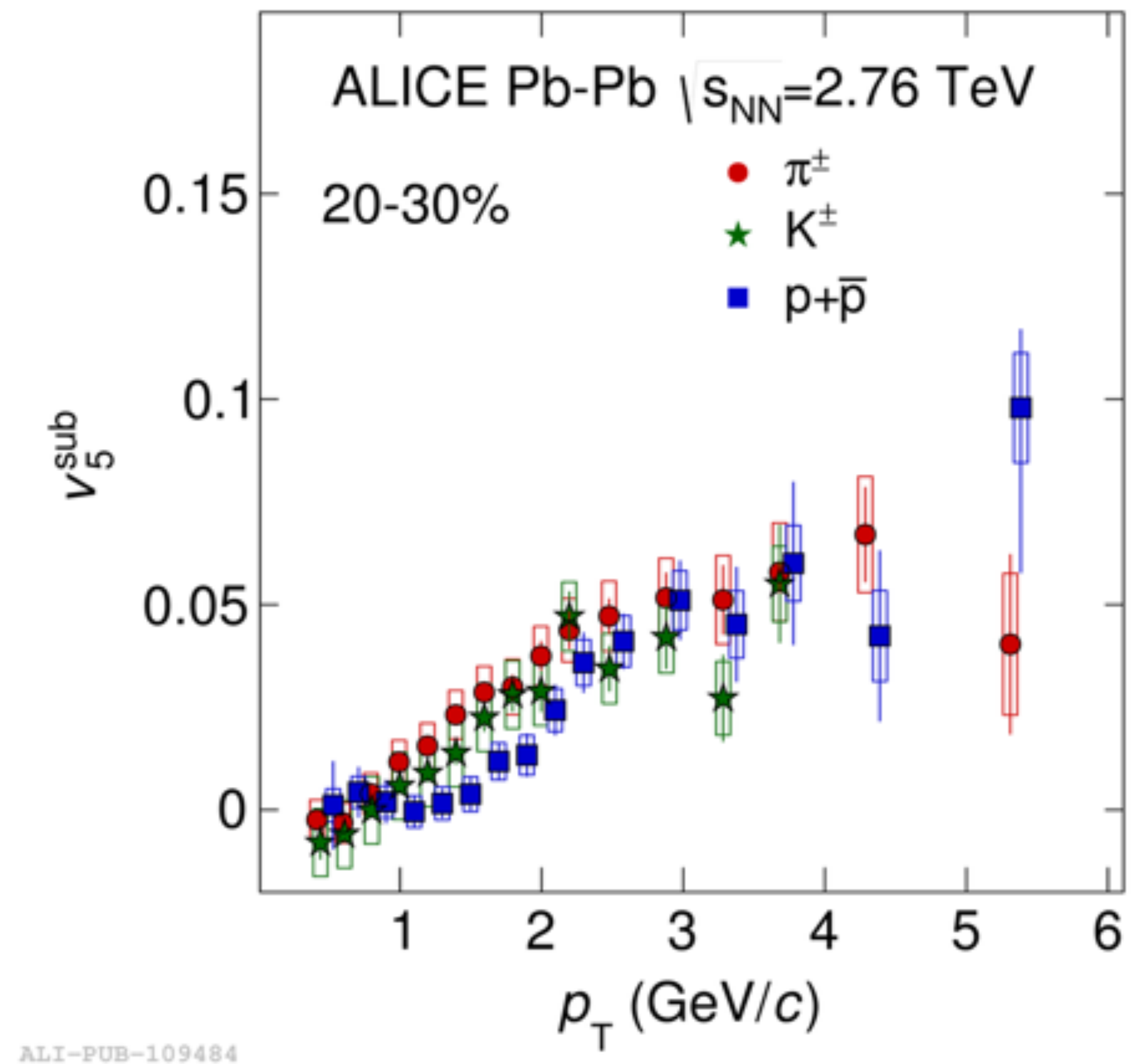




Model comparison

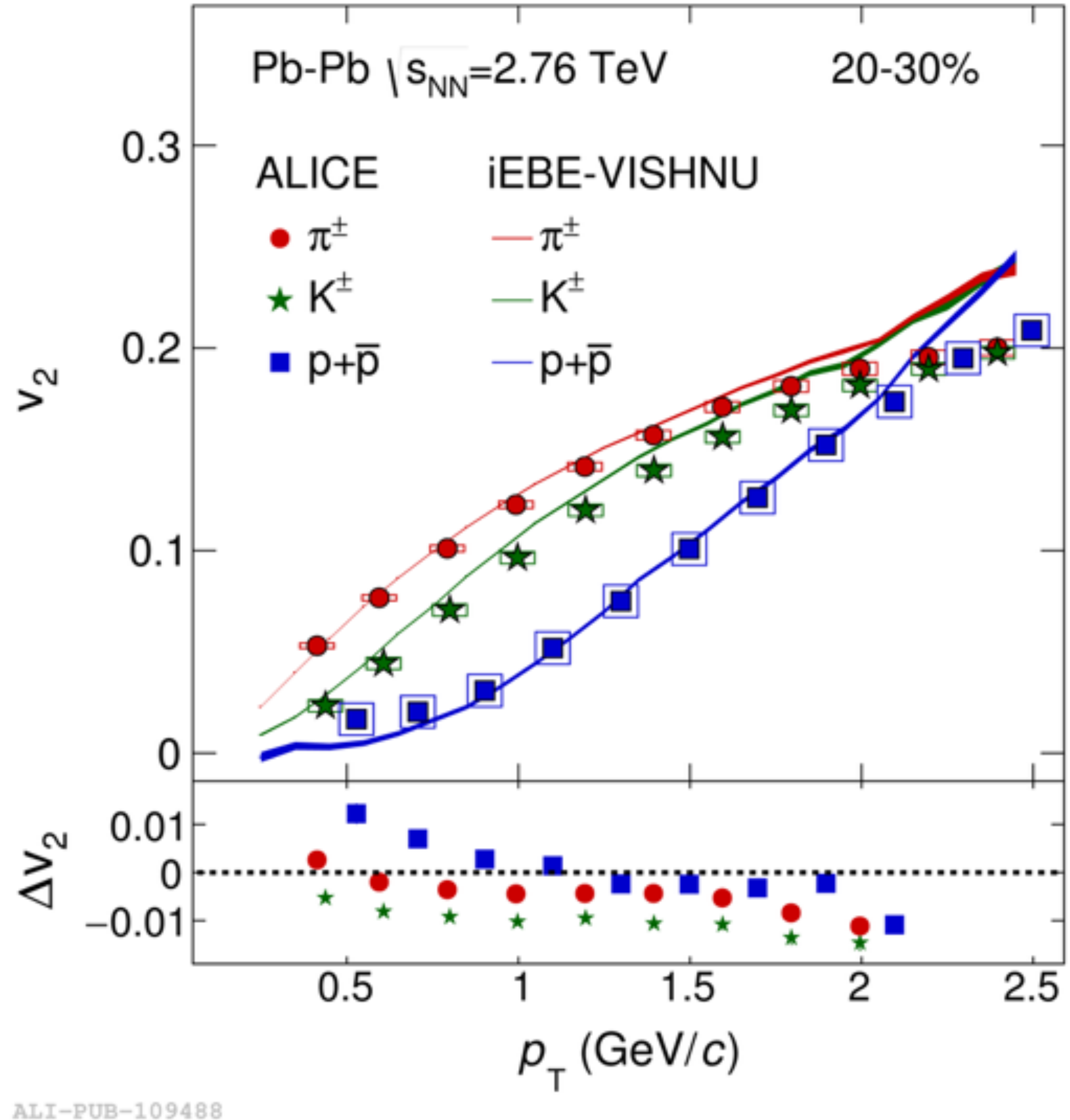
Comparison with hydro calculations

arXiv:1602.02029

- iEBE-VISHNU:
  - 2+1 dimensional viscous hydrodynamics (VISH2+1) coupled to hadron cascade model (UrQMD)
  - $\eta/s = 0.08$

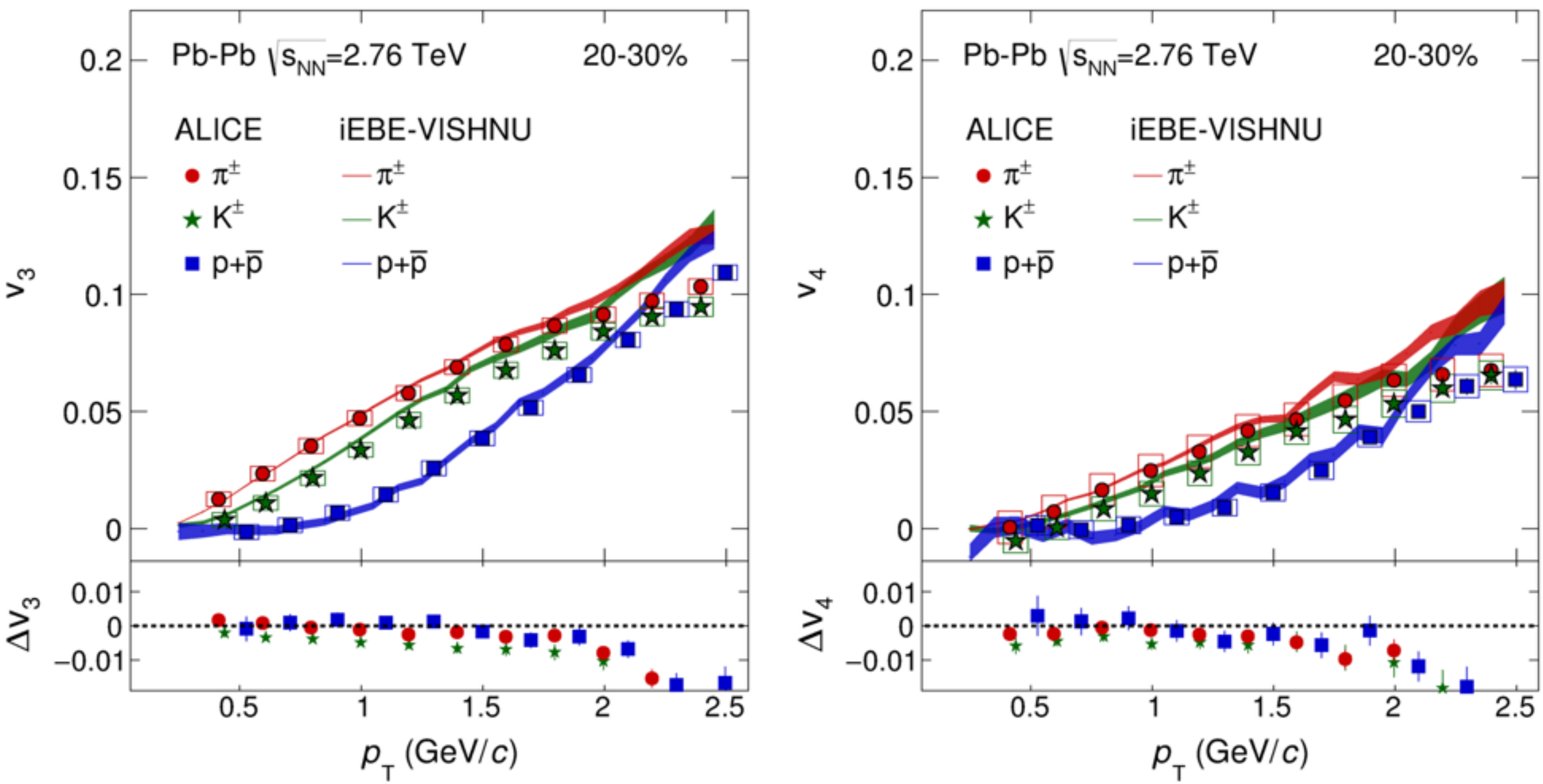
Comparison with hydro calculations

- iEBE-VISHNU:
  - 2+1 dimensional viscous hydrodynamics (VISH2+1) coupled to hadron cascade model (UrQMD)
  - $\eta/s = 0.08$
  - reproduces the observed mass ordering of v_2 for p_T <2 GeV/c
  - describes the measurements for v_2 within 15%



Comparison with hydro calculations

- iEBE-VISHNU:
- reproduces the observed mass ordering of v_3 and v_4 for p_T <2 GeV/c
- describes the measurements for v_3 and v_4 within 5%



A MULTI-PHASE TRANSPORT MODEL (AMPT)

- AMPT versions:
  - String melting (+quark coalescence) with hadronic rescattering
  - String melting (+quark coalescence) without hadronic rescattering
  - default (No string melting)

- This comparison allows one to study:
  - Effects of hadronic rescattering
  - Effects of quark coalescence

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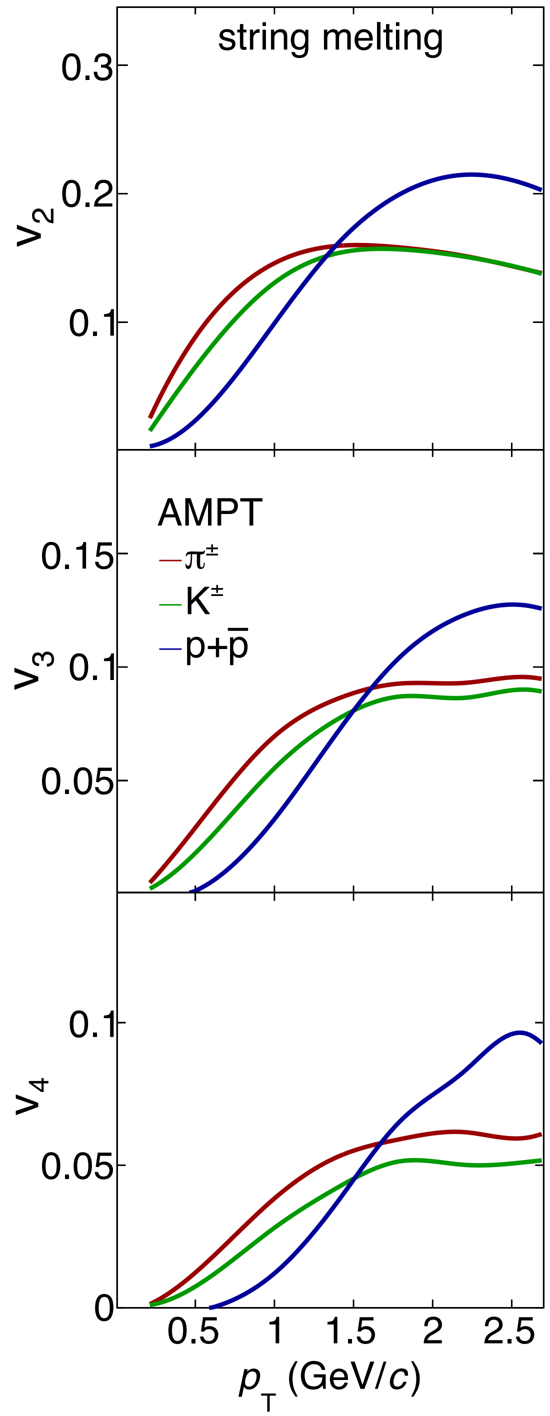

- Distinct mass ordering in low p_T region
- baryon-meson grouping in intermediate p_T region

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- AMPT versions:
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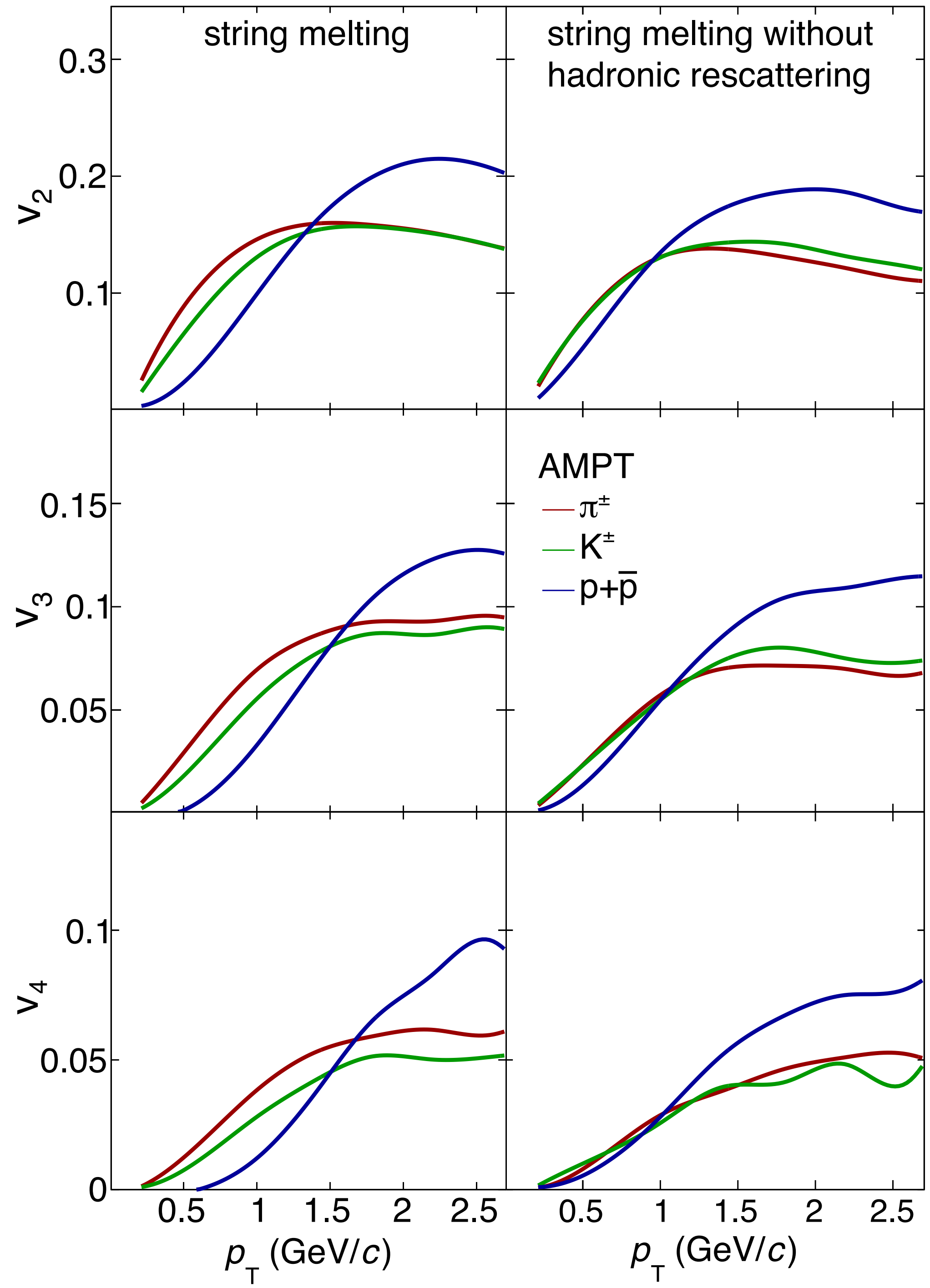
- Distinct mass ordering in low p_T region:
  - Effect of hadronic rescattering in development of radial flow



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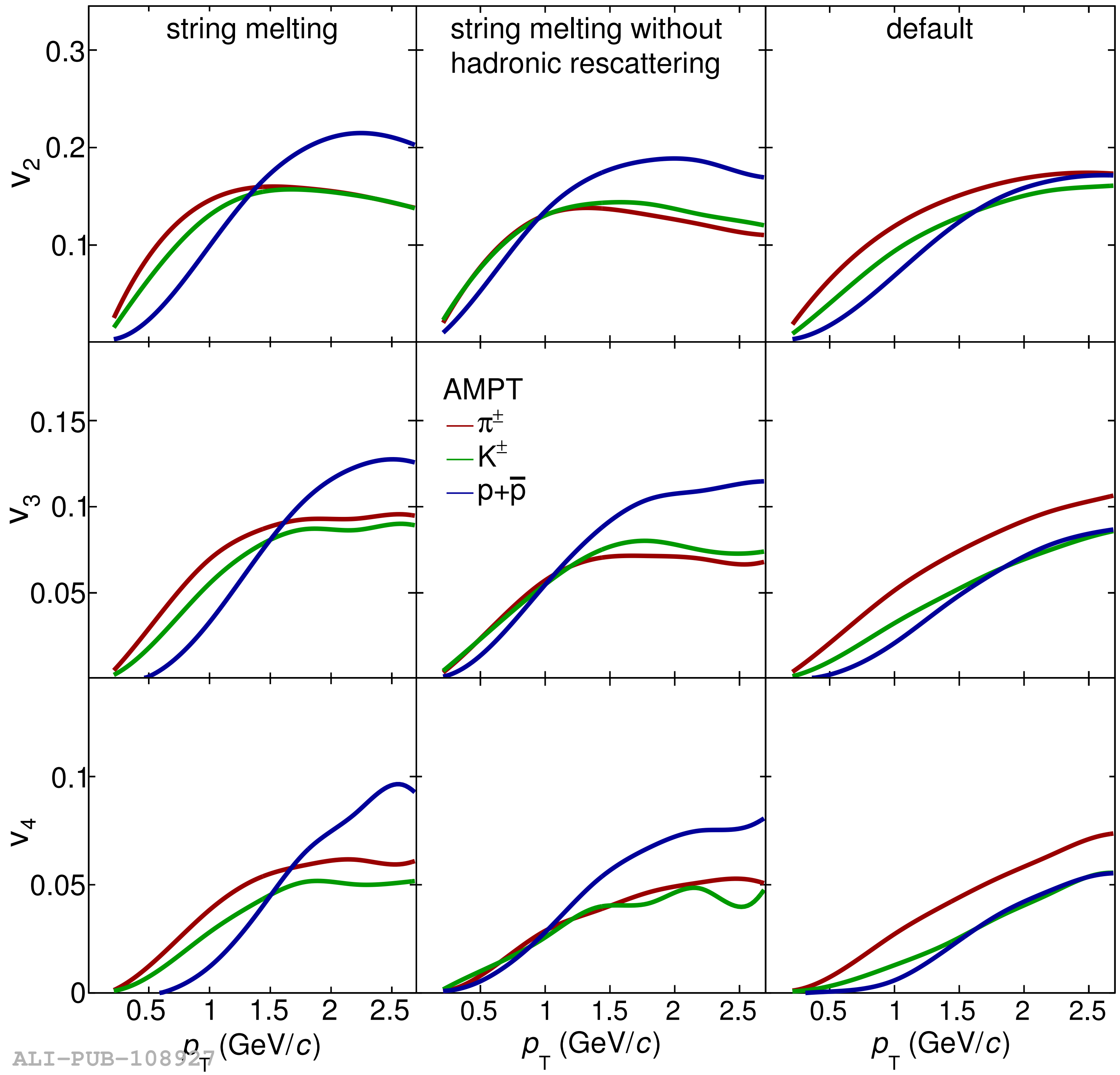
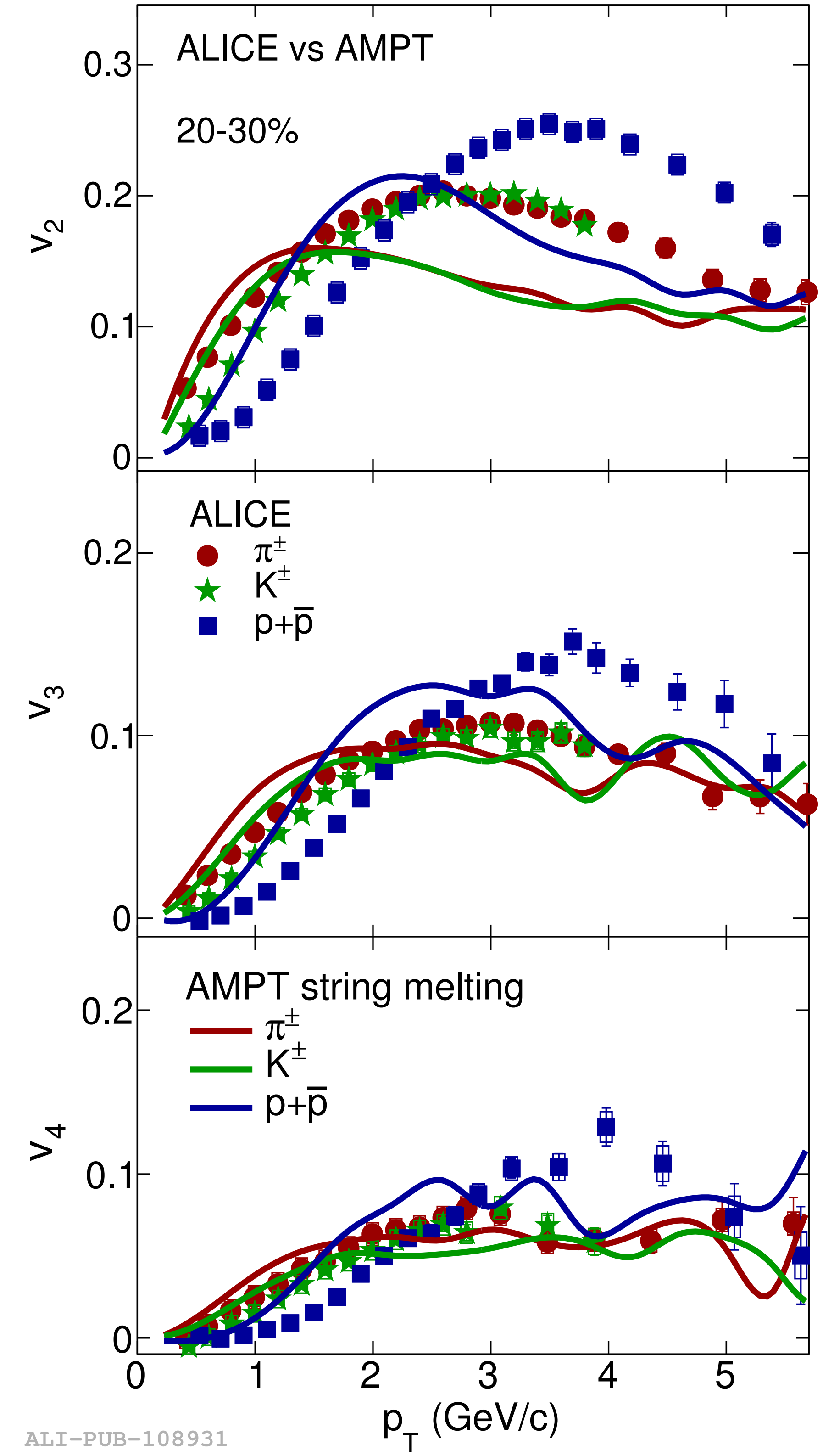
- Distinct mass ordering in low p_T region:
  - Effect of hadronic rescattering in development of radial flow
- Baryon-meson grouping:
  - Effect of quark coalescence



Comparison with AMPT

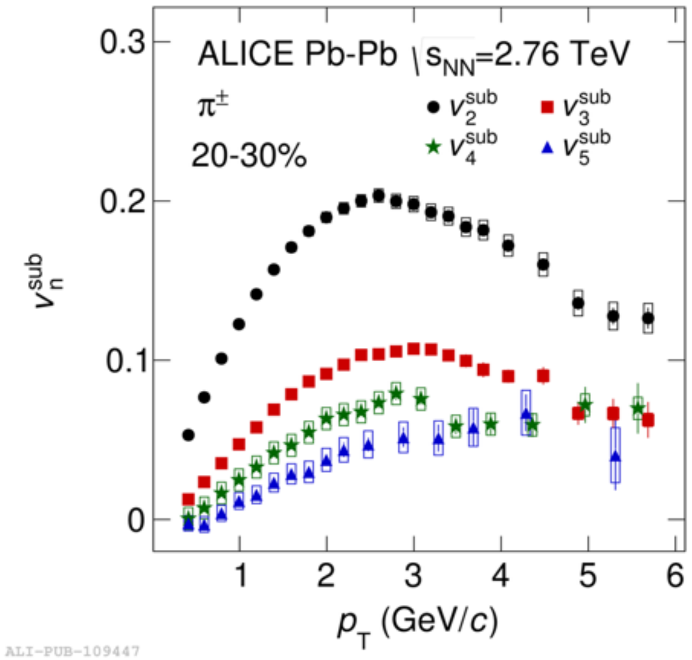
- AMPT string melting version:
    - Reproduces both the mass ordering and the baryon-meson grouping at low and intermediate p_T for all harmonics
    - Fails to quantitatively reproduce the measurements

- This discrepancy could rise from:
    - Radial flow in AMPT 25% lower than the measured value at the LHC



Summary

- ultra-central: $v_3 > v_4 > v_5 \sim v_2$
- mid-central: $v_2 > v_3 > v_4 > v_5$



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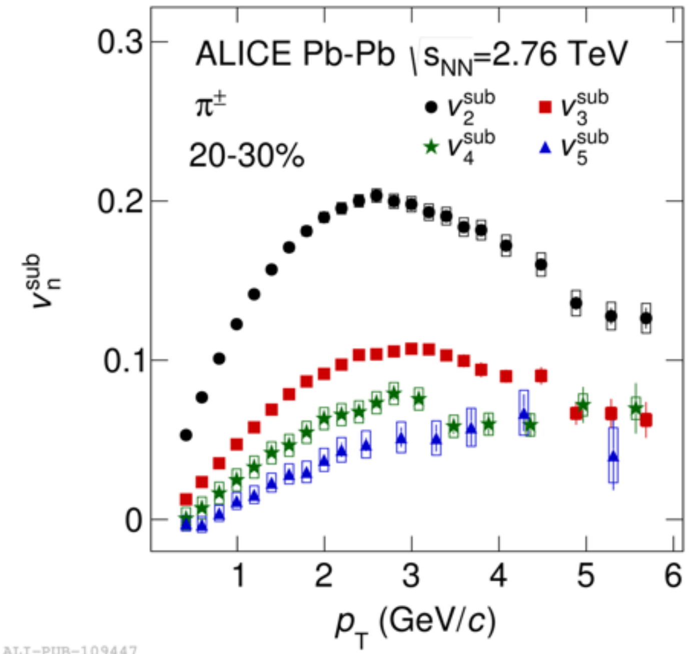
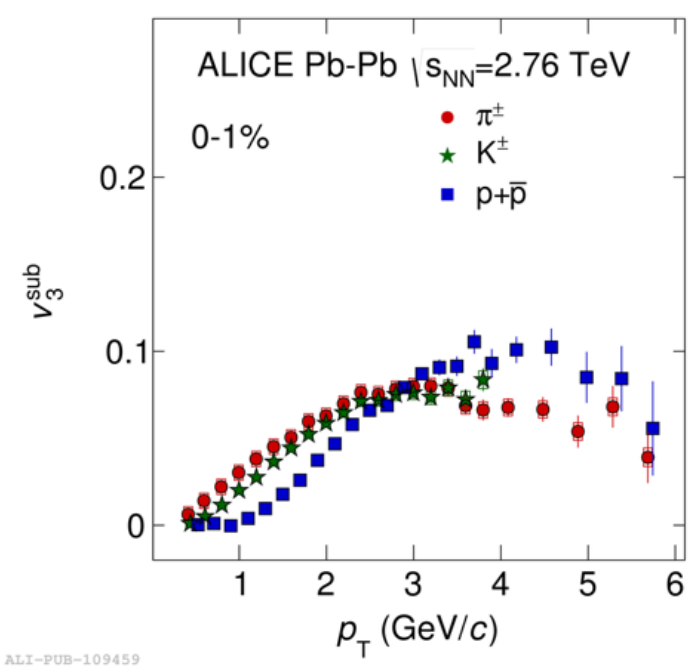


- For all flow harmonics:
  - mass ordering
  - baryon-meson grouping



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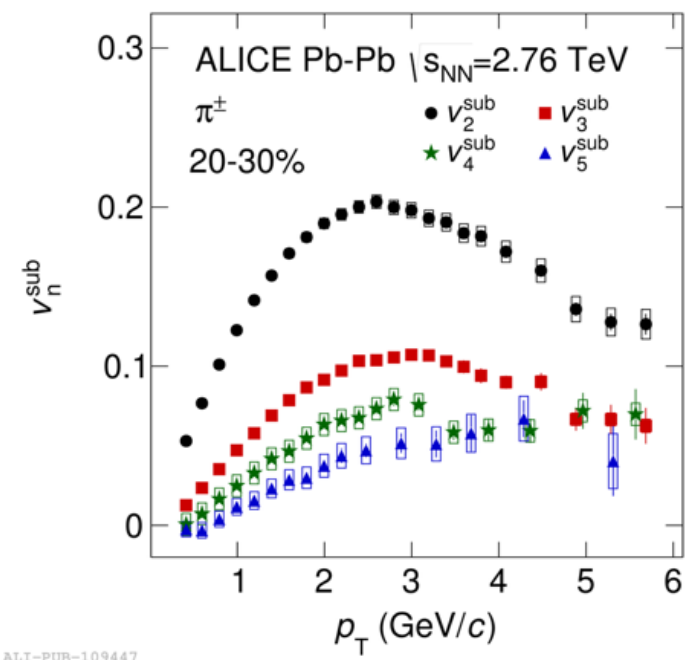

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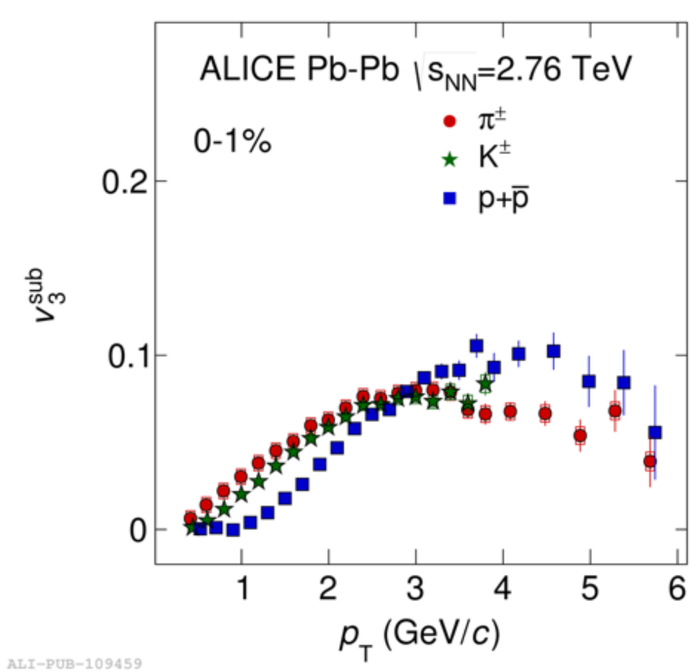
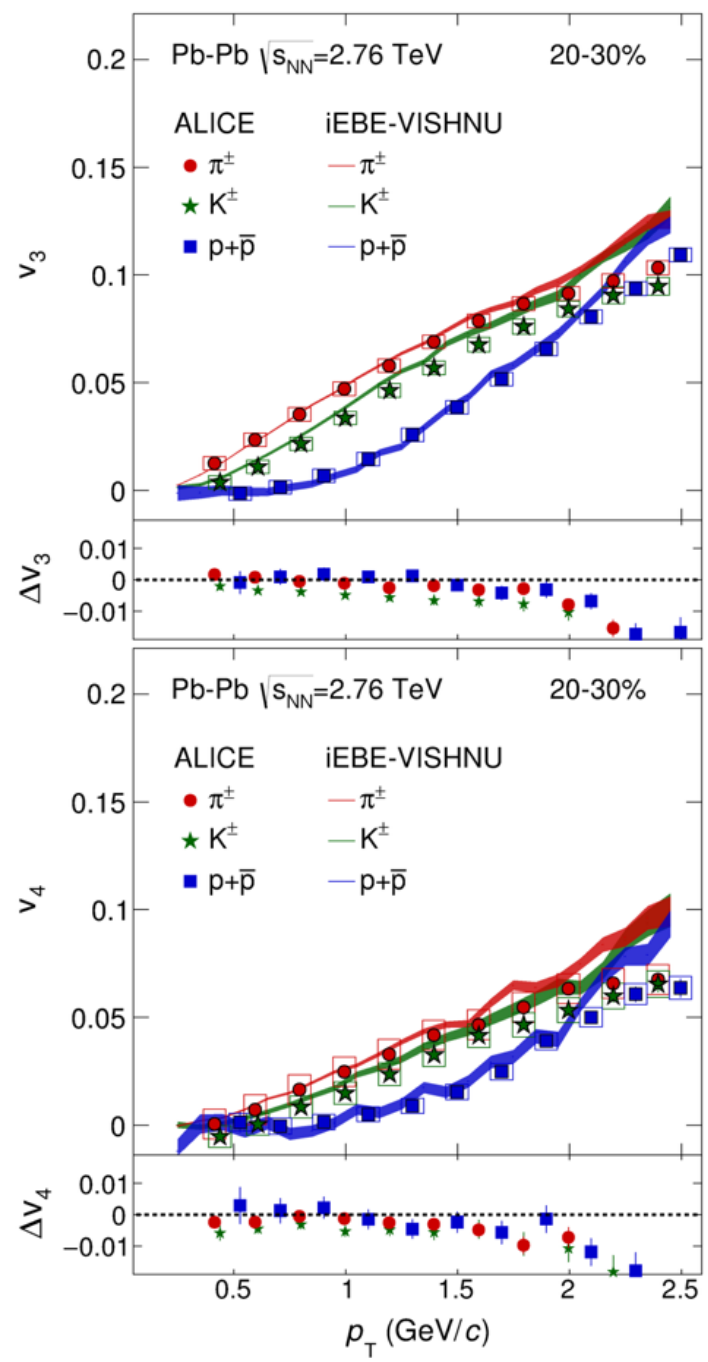


- iEBE-VISHNU:
  - reproduces the observed mass ordering for v_2, v_3 and v_4
  - describes data ~5-15%



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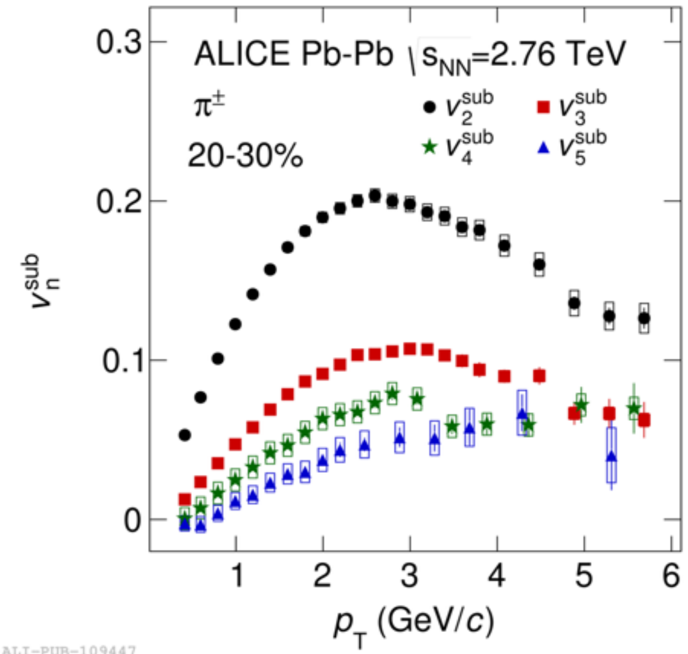

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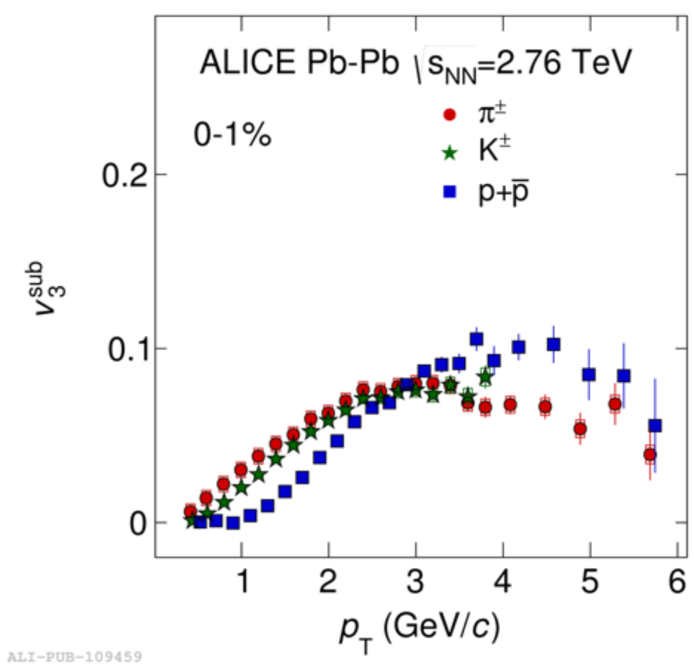

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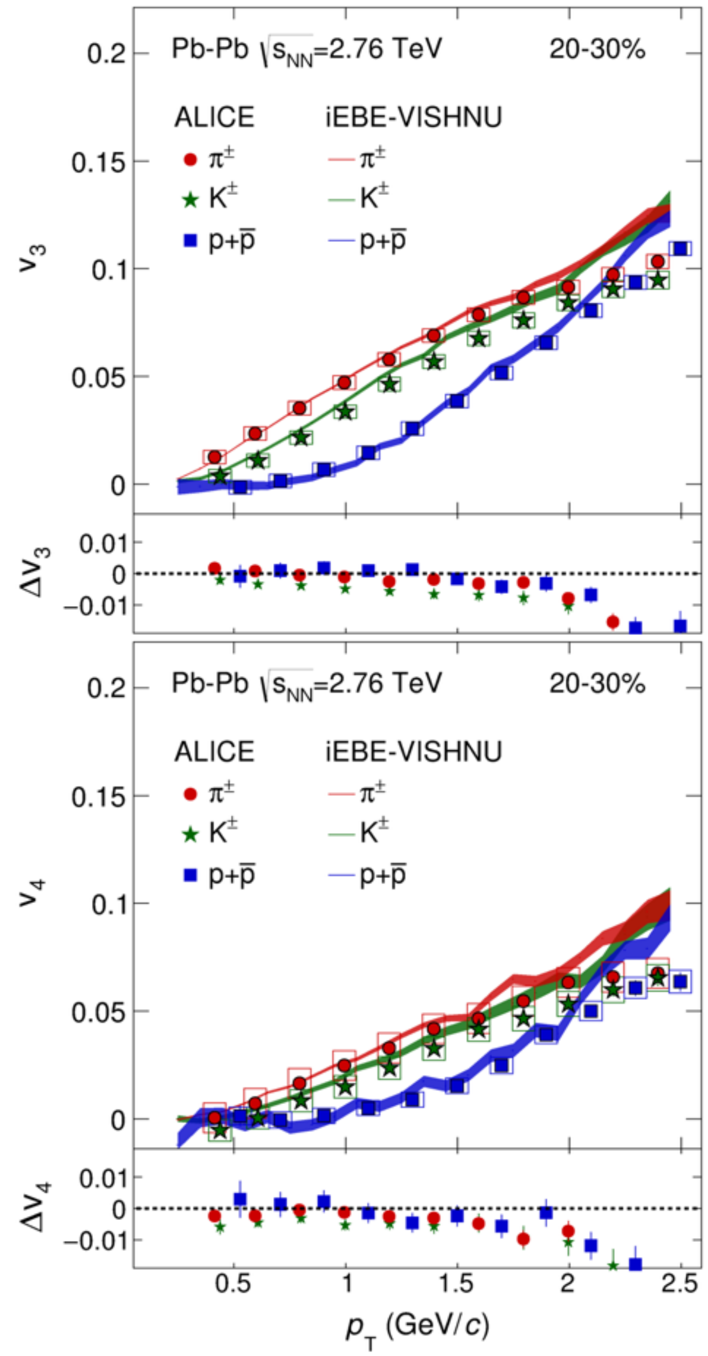

- AMPT:
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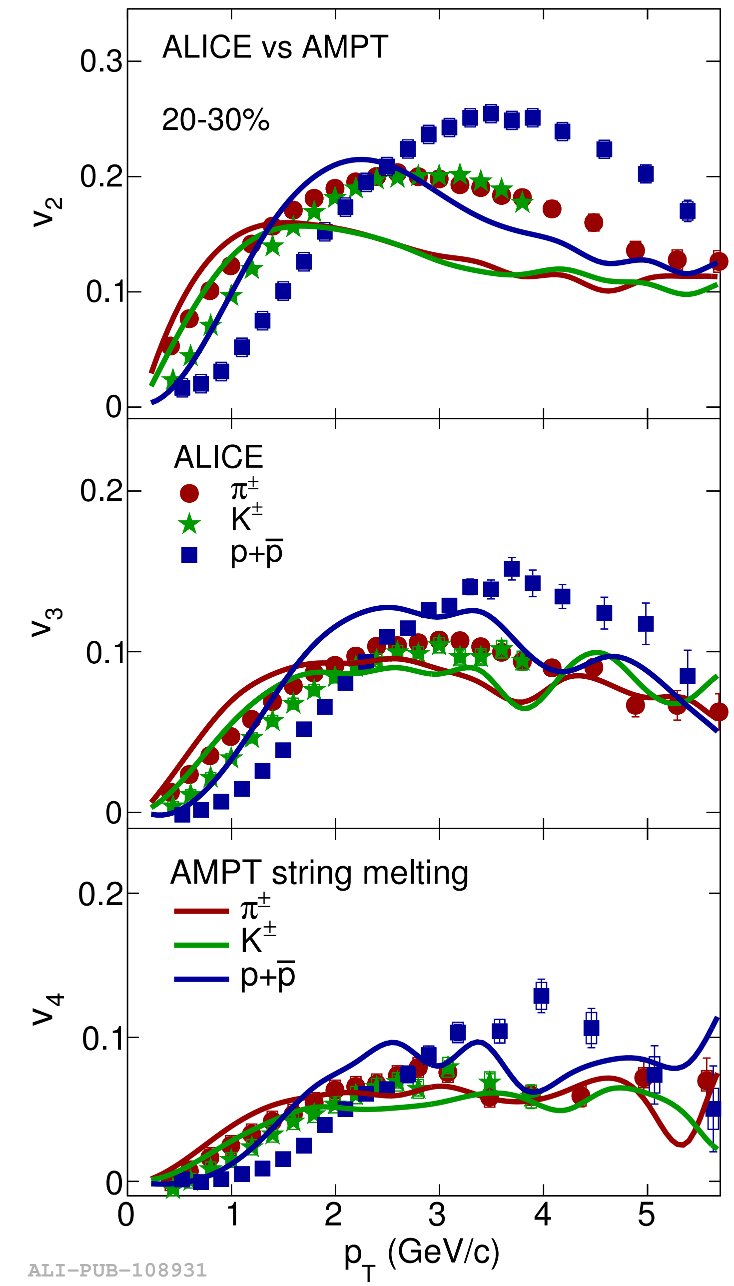
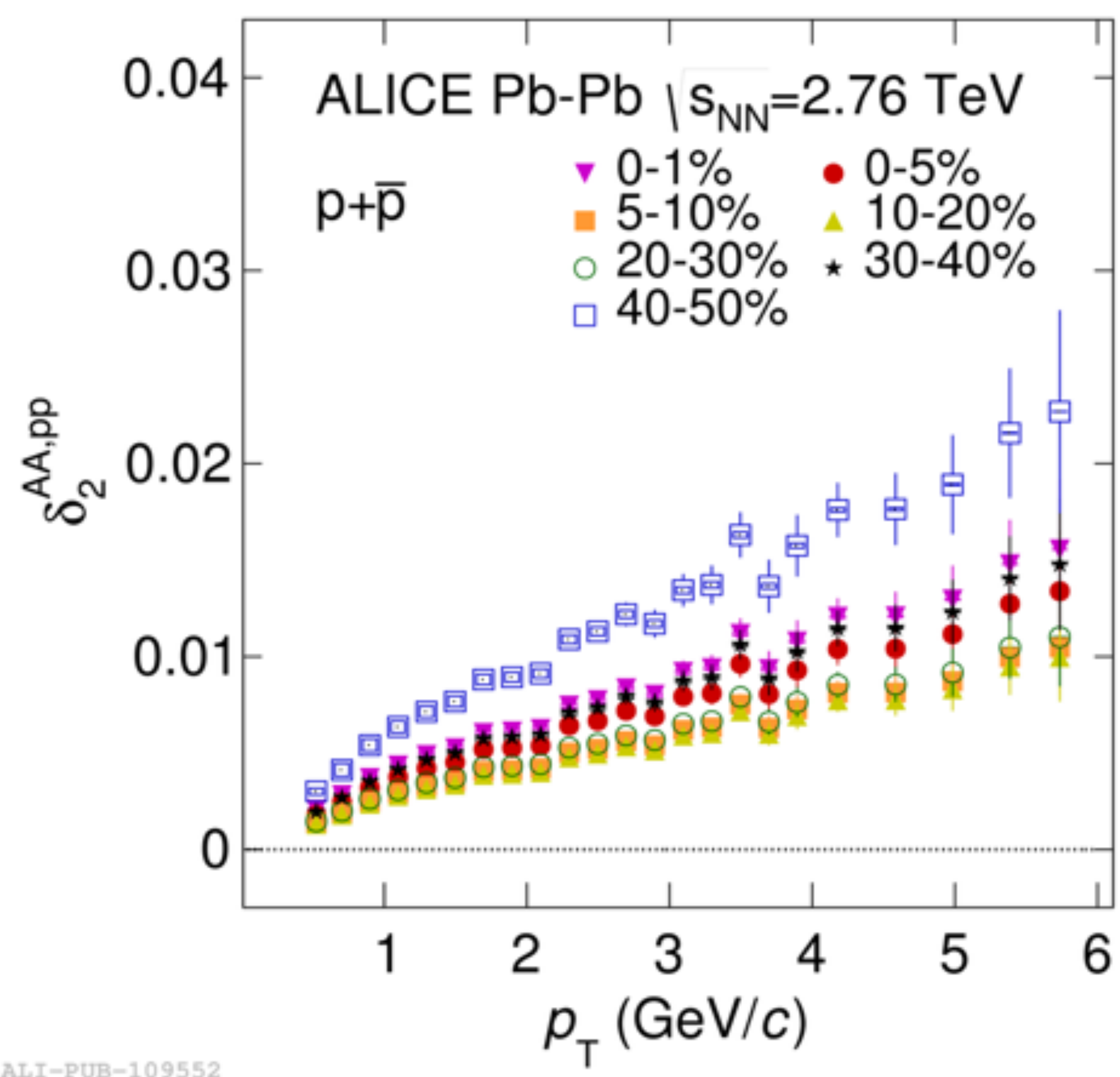
  - quark coalescence

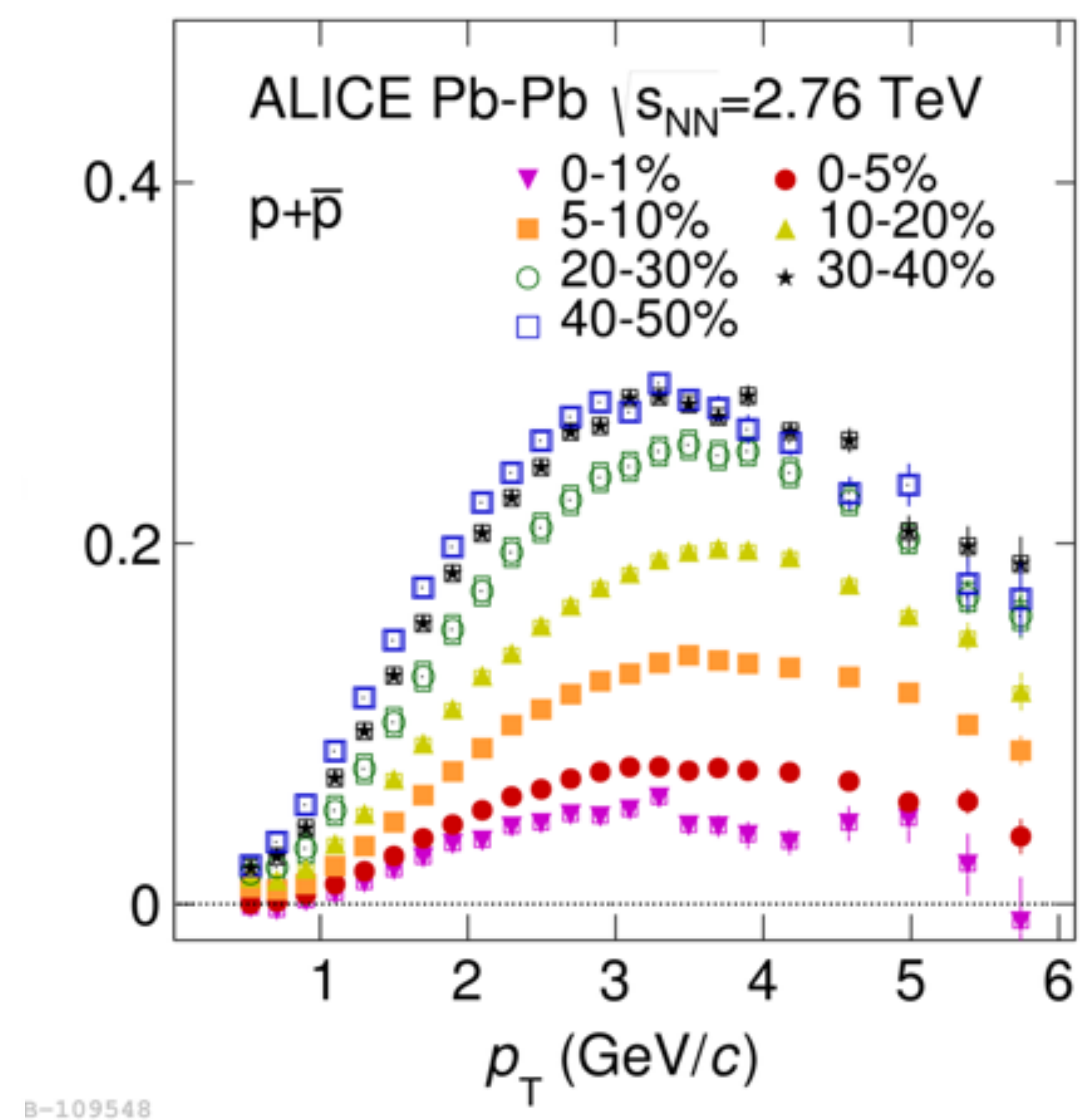


Back up

Non flow subtracted terms: $\delta_n^{AA,pp}$

- Value of $\delta_n^{AA,pp}$ depends on centrality
  - interplay of decreasing multiplicity and increasing reference flow
- $\delta_n^{AA,pp}$ dependence on p_T is different from v_n
- Value of $\delta_n^{AA,pp}$ depends on centrality
- For 0-1%: $\delta_2^{AA,pp} \sim 20\%$ of v_2^{AA}
- For 40-50%: $\delta_2^{AA,pp} \sim 7\%$ of v_2^{AA}

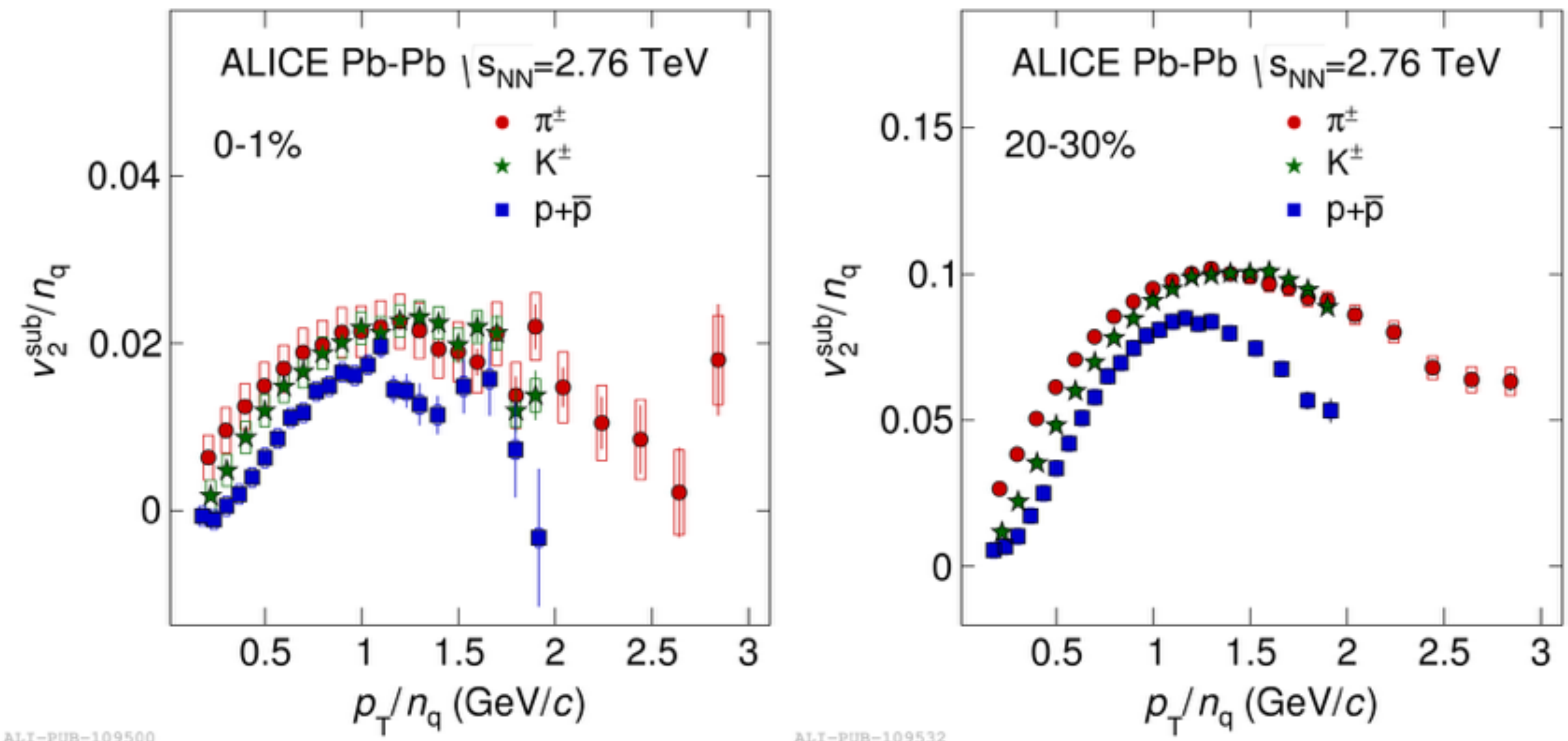




NCQ scaling: v_2^{sub}

Intermediate p_T (p_T>3 GeV/c): v_n of baryons > v_n of mesons

- Particle production mechanism: Quark coalescence?
- NCQ scaling: p_T/n_q → Proposed at RHIC



- Scaling for v_2: ±20%

NCQ scaling: v_3^{sub}

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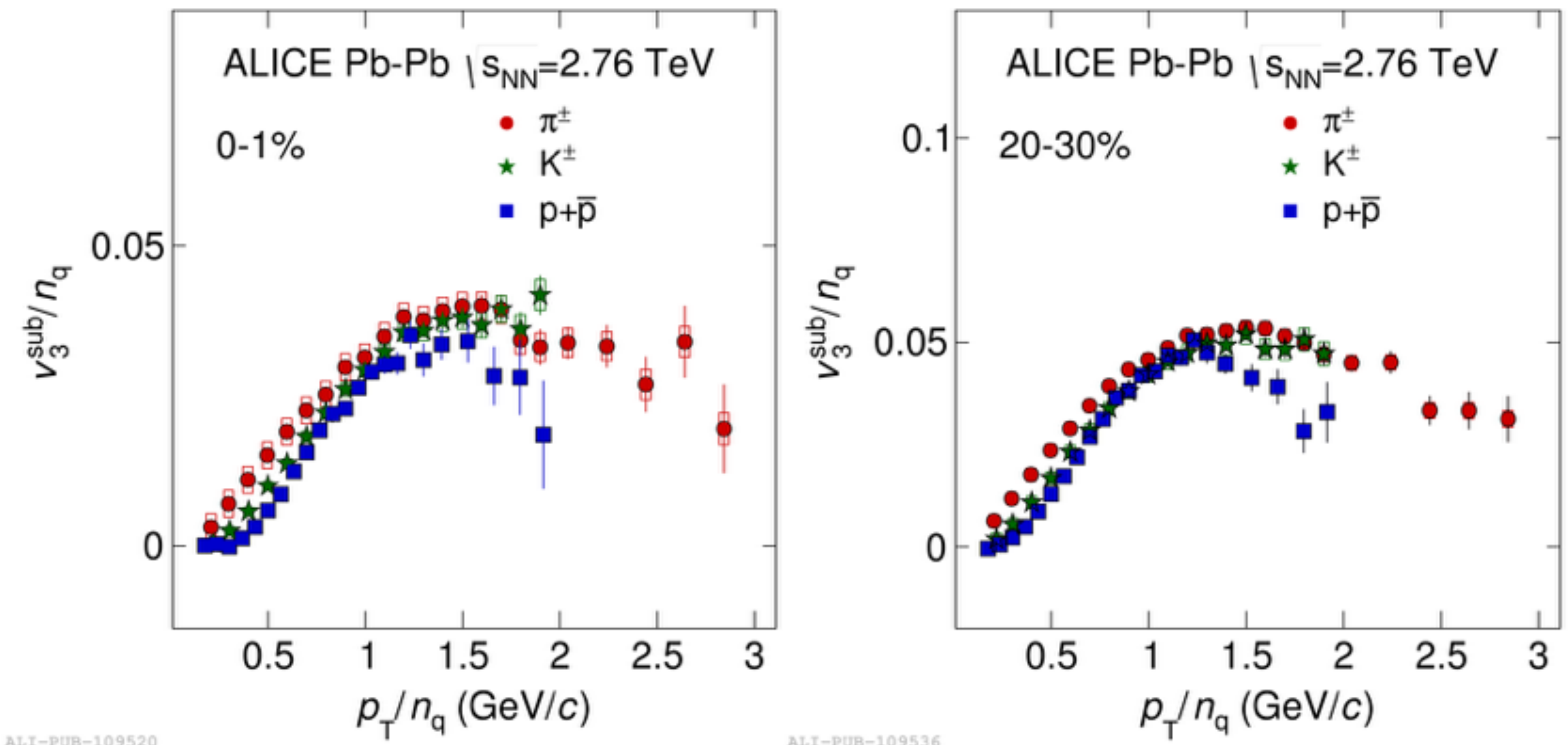

- Scaling for v_3: ±20% within the statistical and systematical uncertainties

NCQ scaling: v_4^{sub}

Intermediate p_T (p_T>3 GeV/c): v_n of baryons > v_n of mesons

- Particle production mechanism: Quark coalescence?
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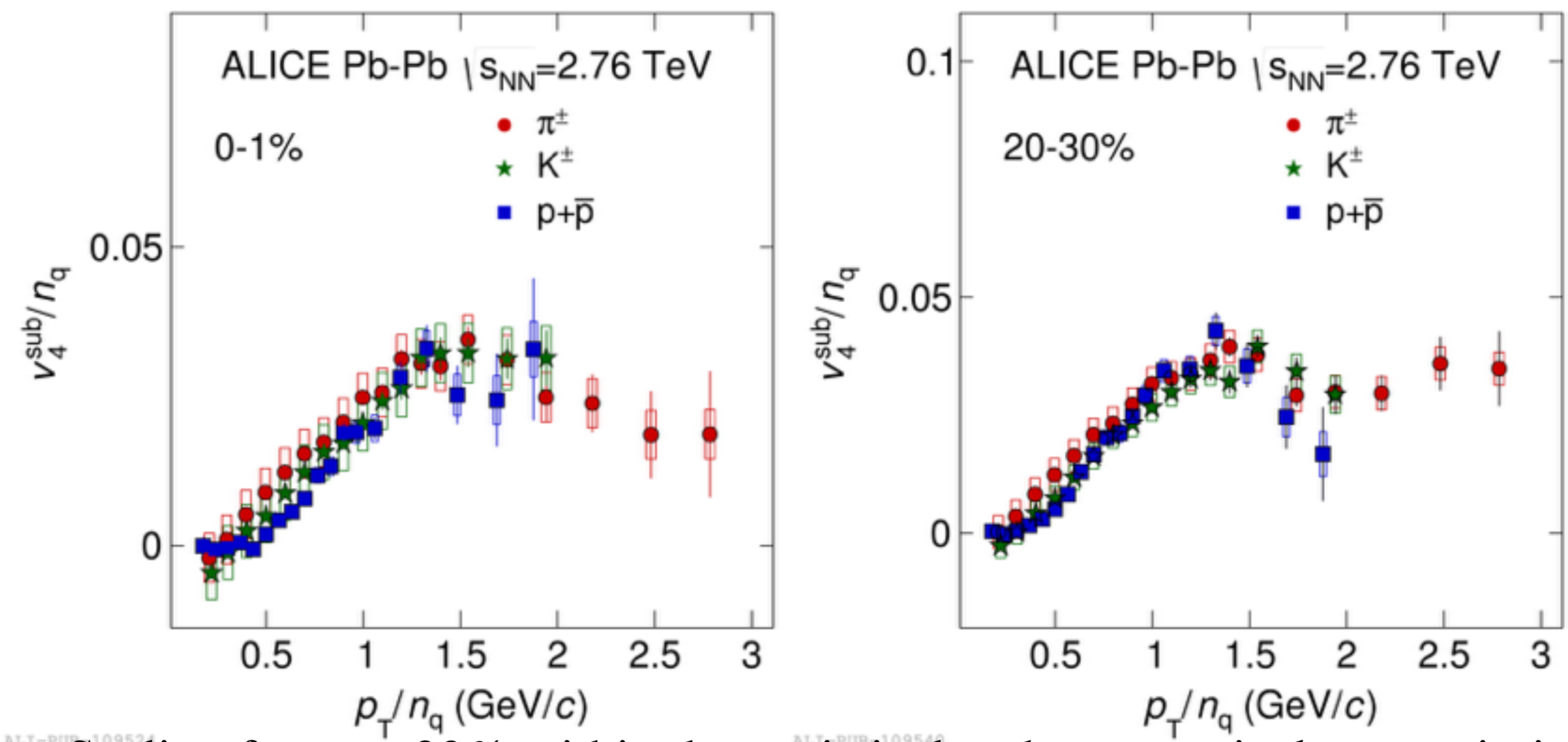
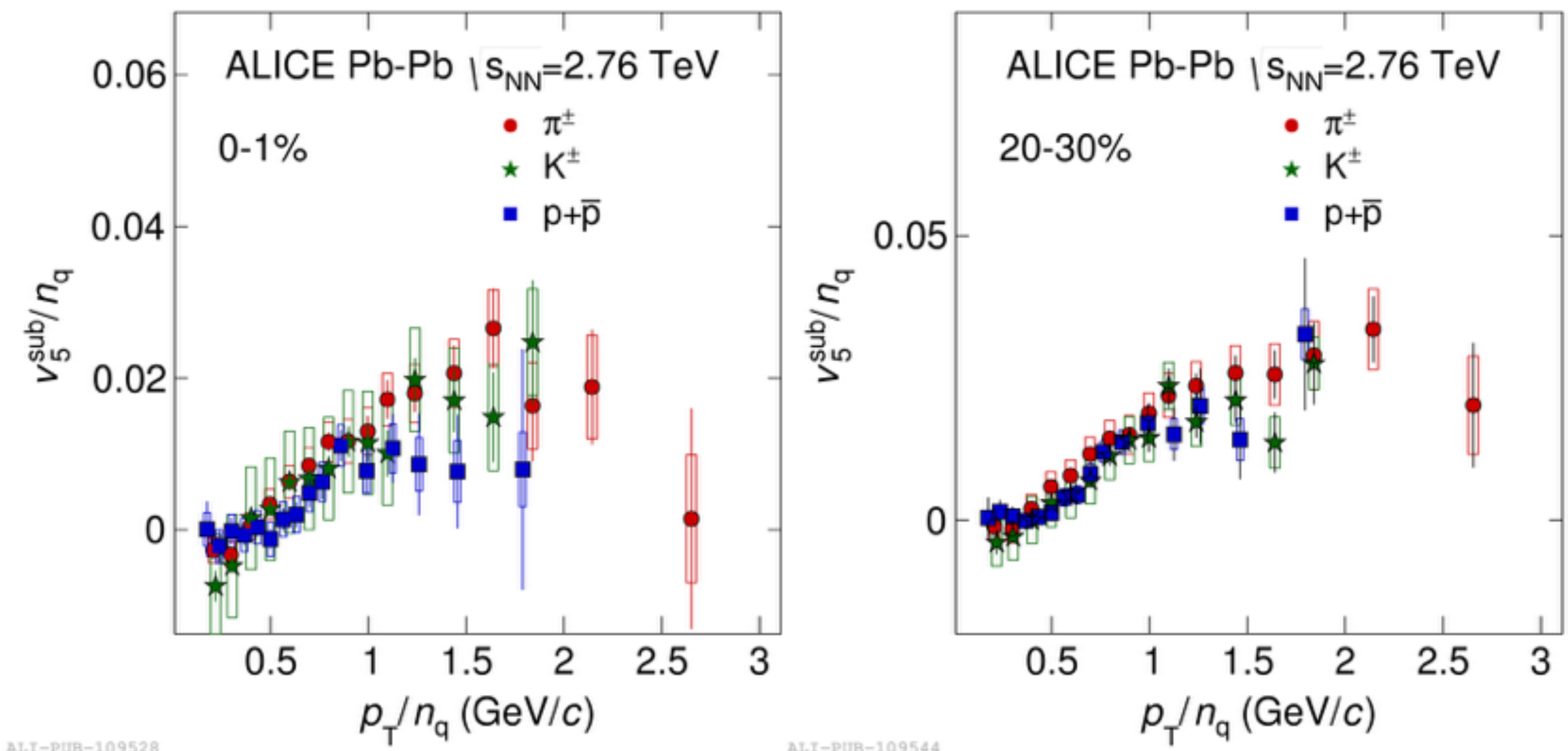


- Scaling for v_4: ±20% within the statistical and systematical uncertainties

NCQ scaling: v_5^{sub}

Intermediate p_T (p_T>3 GeV/c): v_n of baryons > v_n of mesons

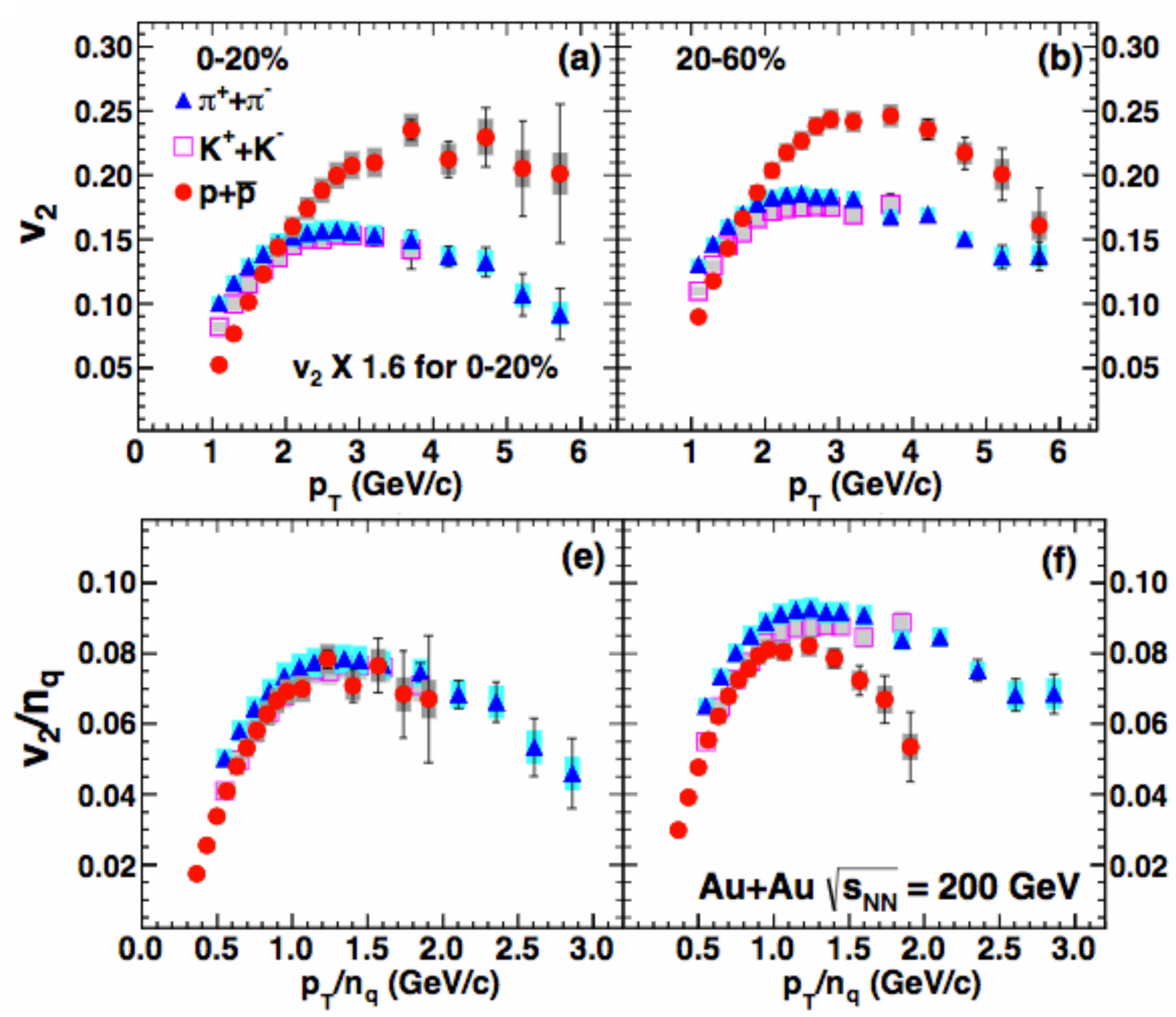
- Particle production mechanism: Quark coalescence?
- NCQ scaling: p_T/n_q → Proposed at RHIC



- Scaling for v_5: ±20% within the statistical and systematical uncertainties

NCQ scaling: PHENIX

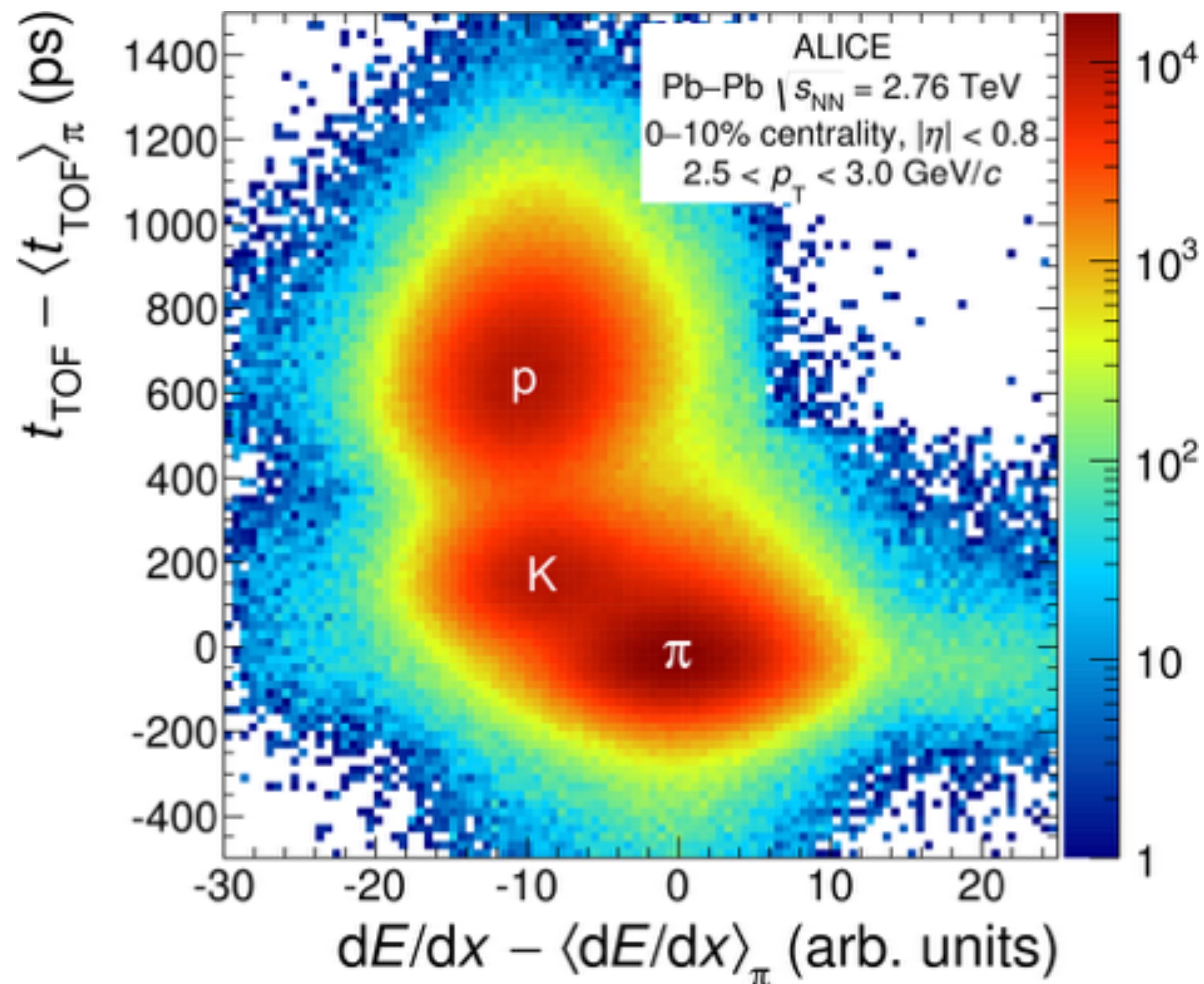
arXiv:1203.2644v1



Bayesian PID

arXiv:1602.01392v2

- Different particle species are identified by requiring a minimum probability of 90%.
- for pions and protons: efficiency > 95% up to $p_{\mathrm{T}} \approx 2.5$ GeV/c, contamination < 5%
- for kaons: efficiency = 60% at 2.5 GeV/c with a minimum of 25% at 4 GeV/c, contamination < 10%



$$\begin{pmatrix} \pi_{\mathrm{meas}} \\ \mathrm{K}_{\mathrm{meas}} \\ \mathrm{p}_{\mathrm{meas}} \end{pmatrix} = \begin{pmatrix} \varepsilon_{\pi\pi} & \varepsilon_{\pi\mathrm{K}} & \varepsilon_{\pi\mathrm{p}} \\ \varepsilon_{\mathrm{K}\pi} & \varepsilon_{\mathrm{KK}} & \varepsilon_{\mathrm{Kp}} \\ \varepsilon_{\mathrm{p}\pi} & \varepsilon_{\mathrm{pK}} & \varepsilon_{\mathrm{pp}} \end{pmatrix}^{\mathrm{T}} \cdot \begin{pmatrix} \pi_{\mathrm{true}} \\ \mathrm{K}_{\mathrm{true}} \\ \mathrm{p}_{\mathrm{true}} \end{pmatrix}$$

$$\varepsilon_{ii} = \frac{N_{i \text{ identified as } i}}{A^{i}_{\mathrm{true}}} \qquad \vec{A}_{\mathrm{true}} = (\varepsilon^{\mathrm{T}}_{\mathrm{PID}})^{-1} \times \vec{A}_{\mathrm{meas}}$$

contamination: $$c_{ji} = \frac{N_{i \text{ identified as } j}}{A^{j}_{\mathrm{meas}}}, i \neq j \qquad c_{ji} = \frac{\varepsilon_{ij} A^{i}_{\mathrm{true}}}{\varepsilon_{jj} A^{j}_{\mathrm{true}} + \sum_{j \neq k} \varepsilon_{jk} A^{k}_{\mathrm{true}}}$$