Non-linear flow modes with identified charged particles

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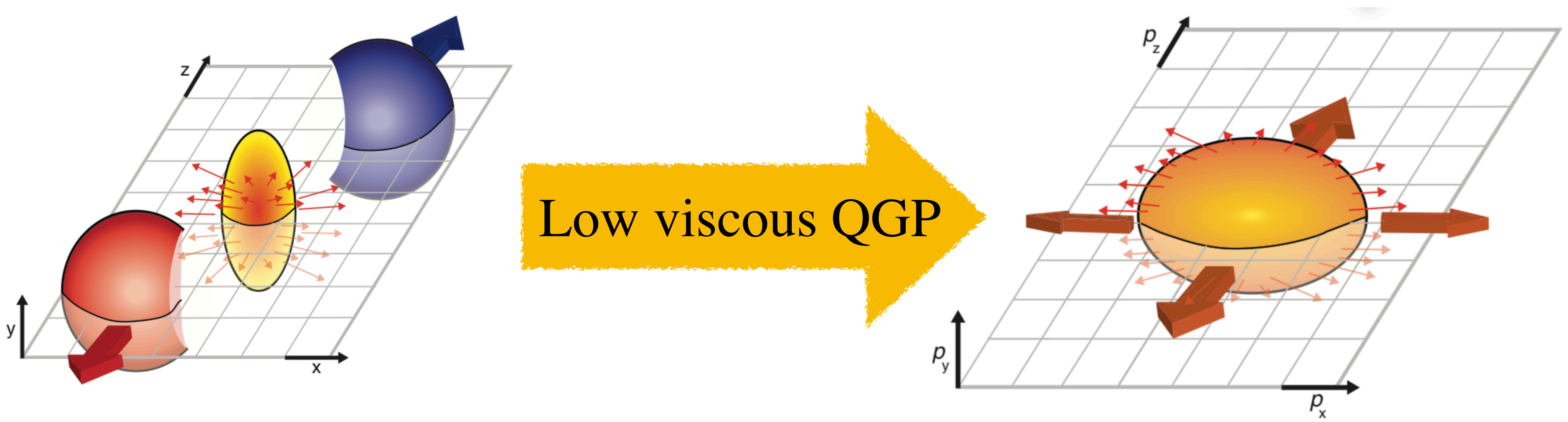
3/12/2018

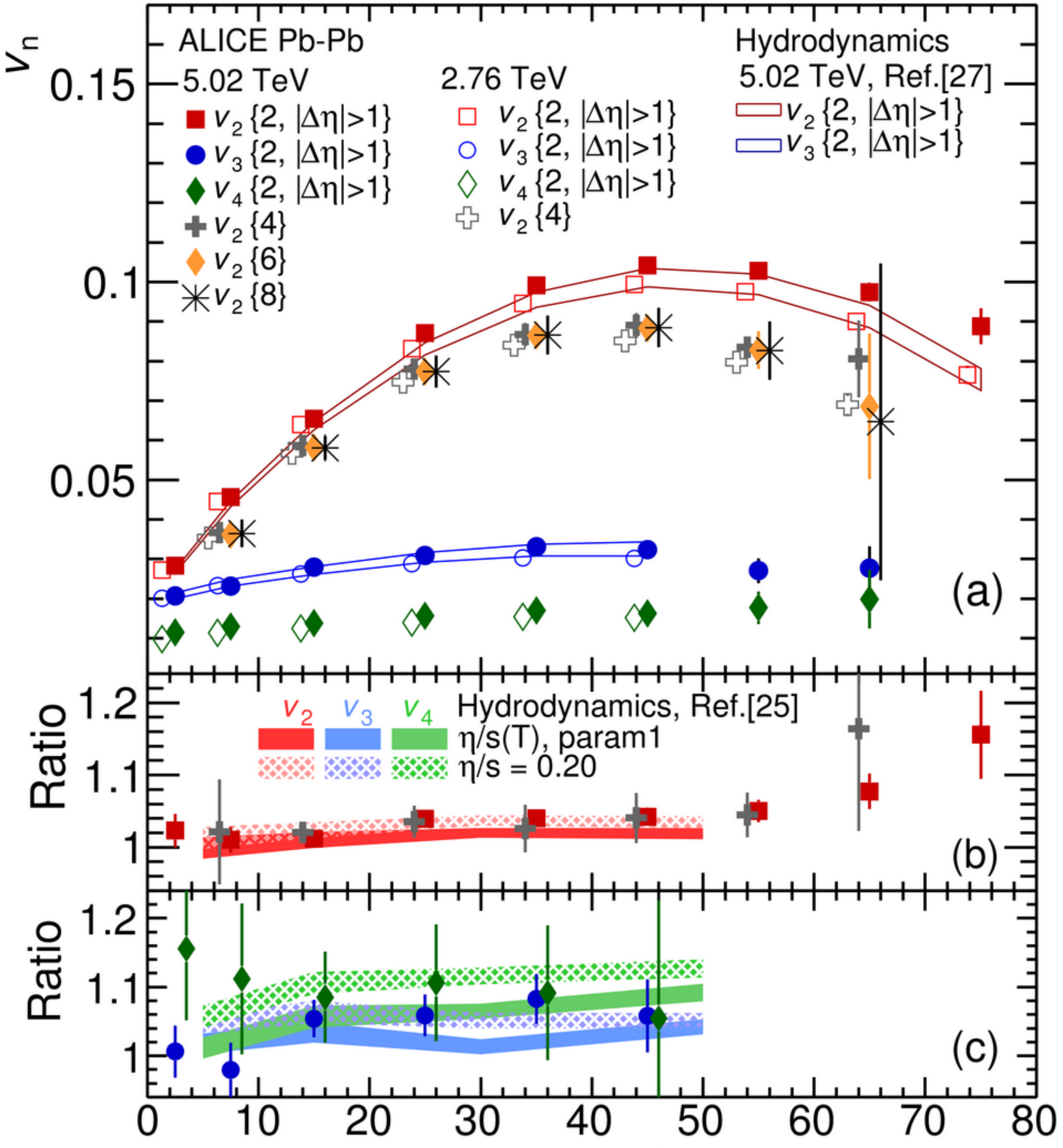
Constraining QGP properties



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

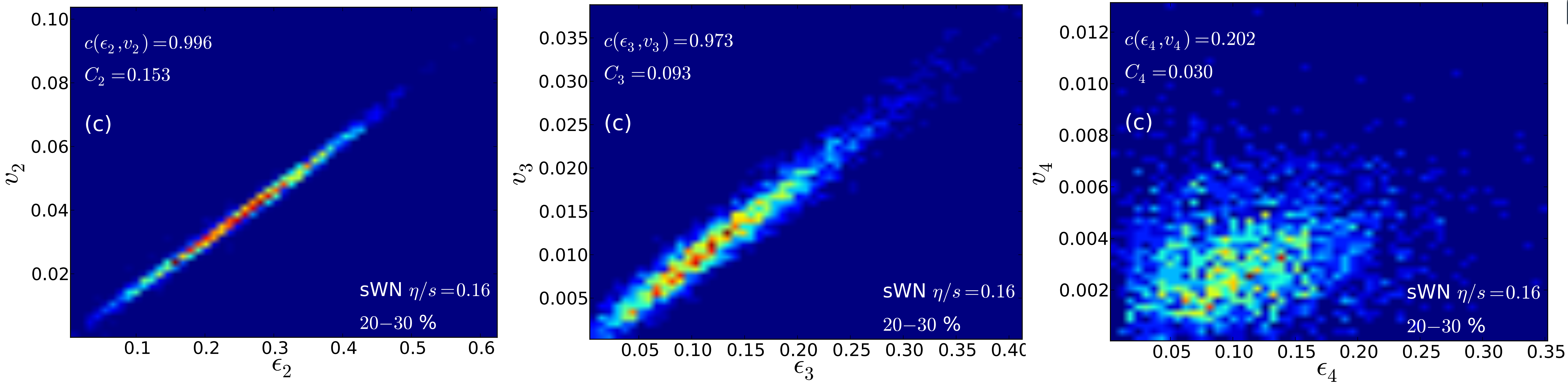
$$v_n = \langle\cos[n(\varphi-\Psi_n)]\rangle$$

- Flow harmonics constrain initial conditions and transport properties: η/s, ζ/s, EoS, freeze-out conditions
- Higher harmonics probe smaller spatial scales
  - More sensitive to
    - transport properties: e.g. η/s
    - initial density profile
- Testing details of hydrodynamical response of QGP



Phys. Rev. Lett. 116 (2016) 132302

Linear and non-linear response in higher flow harmonics



Phys. Rev. C 87, 054901 H. Niemi *et al*.

Standard (Moment-based) spatial anisotropy:

$$\varepsilon_n e^{in\Phi_n} = -\frac{\langle r^n e^{in\phi}\rangle}{\langle r^n\rangle} \qquad \text{for n>1}$$

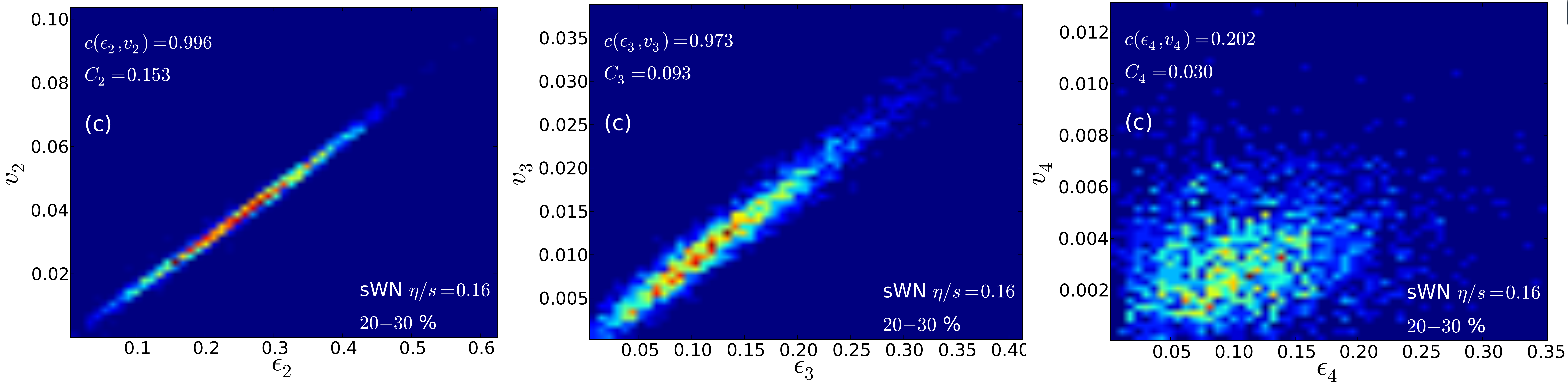
Cumulant-based spatial anisotropy:

- ✤ n=2,3 : same as the standard definition
- ✤ n>3 : contributions from lower order spatial anisotropies →

$$\varepsilon'_4 e^{i4\Phi'_4} \equiv \varepsilon_4 e^{i4\Phi_4} + \frac{3\langle r^2\rangle^2}{\langle r^4\rangle}\varepsilon_2^2 e^{i4\Phi_2}$$

Phys. Rev. C 90, 024902
D. Teaney and L. Yan

Linear and non-linear response in higher flow harmonics



Phys. Rev. C 87, 054901 H. Niemi *et al*.

$$V_n = V_n^{\mathrm{L}} + V_n^{\mathrm{NL}} \quad (n > 3)$$

Linear response　　Non-linear response

- V_n^L corresponds to the same order anisotropy
- V_n^{NL} corresponds to the lower order anisotropies, e.g. ε_2 and/or ε_3
- V_n^{NL} and V_n^L are uncorrelated

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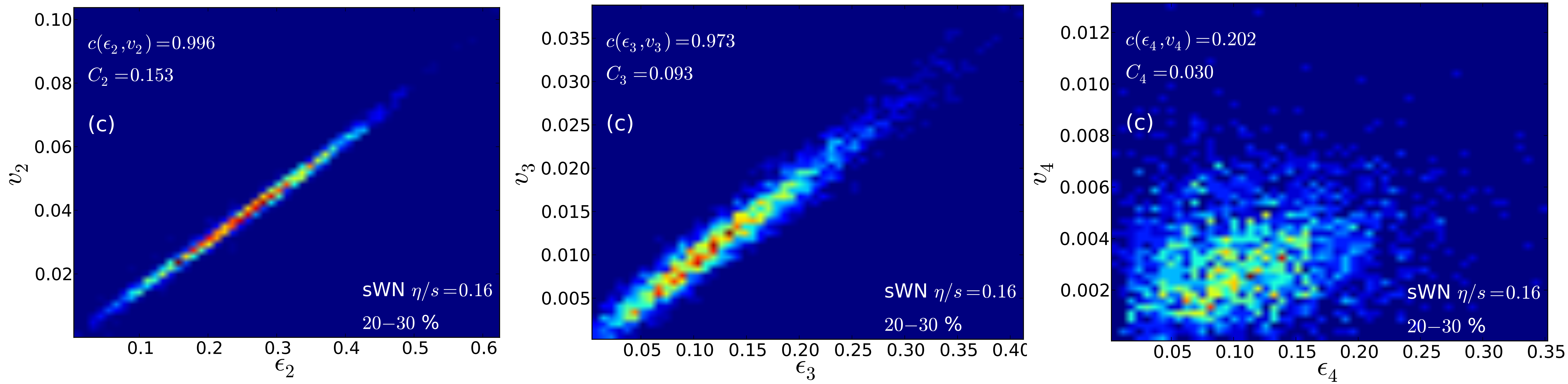
Linear and non-linear response in higher flow harmonics



Phys. Rev. C 87, 054901 H. Niemi *et al*.

$$V_n = V_n^{\mathrm{L}} + V_n^{\mathrm{NL}} \quad (n > 3)$$

Linear response ↓ Non-linear response ↓

$$V_4 = V_4^{\mathrm{NL}} + V_4^{\mathrm{L}} = \chi_{4,22}(V_2)^2 + V_4^{\mathrm{L}}$$

$$V_5 = V_5^{\mathrm{NL}} + V_5^{\mathrm{L}} = \chi_{5,32}V_3V_2 + V_5^{\mathrm{L}}$$

$$V_6 = V_6^{\mathrm{NL}} + V_6^{\mathrm{L}} = \chi_{6,222}(V_2)^3 + \chi_{6,33}(V_3)^2 + \chi_{6,24}V_2V_4^{\mathrm{L}} + V_6^{\mathrm{L}}$$

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✤ Magnitude of these non-linear responses in V_n: $v_{n,mk}$

$$v_{4,22} = \frac{\langle v_4 v_2^2\ cos(4\Psi_4 - 4\Psi_2)\rangle}{\sqrt{\langle v_2^4\rangle}}$$

$$v_{5,32} = \frac{\langle v_5 v_3 v_2\ cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2)\rangle}{\sqrt{\langle v_3^2 v_2^2\rangle}}$$

$$v_{6,33} = \frac{\langle v_6 v_3^2\ cos(6\Psi_6 - 6\Psi_3)\rangle}{\sqrt{\langle v_3^4\rangle}}$$

$$v_{6,222} = \frac{\langle v_6 v_2^3 \cos(6\Psi_6 - 6\Psi_2)\rangle}{\sqrt{\langle v_2^6\rangle}}$$

Analysis method for p_T-differential non-linear flow modes

Using 2 sub-event method:

$$v^A_{4,22}(p_T) = \frac{\langle\langle cos(4\varphi^A_1(p_\mathrm{T}) - 2\varphi^B_2 - 2\varphi^B_3)\rangle\rangle}{\sqrt{\langle\langle cos(2\varphi^A_1 + 2\varphi^A_2 - 2\varphi^B_3 - 2\varphi^B_4)\rangle\rangle}}$$

$$v^A_{523}(p_T) = \frac{\langle\langle cos(5\phi^A_1(p_\mathrm{T}) - 2\varphi^B_2 - 3\varphi^B_3)\rangle\rangle}{\sqrt{\langle\langle cos(2\varphi^A_1 + 3\varphi^A_2 - 2\varphi^B_3 - 3\varphi^B_4)\rangle\rangle}}$$

$$v^A_{633}(p_T) = \frac{\langle\langle cos(6\varphi^A_1(p_\mathrm{T}) - 3\varphi^B_2 - 3\varphi^B_3)\rangle\rangle}{\sqrt{\langle\langle cos(3\varphi^A_1 + 3\varphi^A_2 - 3\varphi^B_3 - 3\varphi^B_4)\rangle\rangle}}$$

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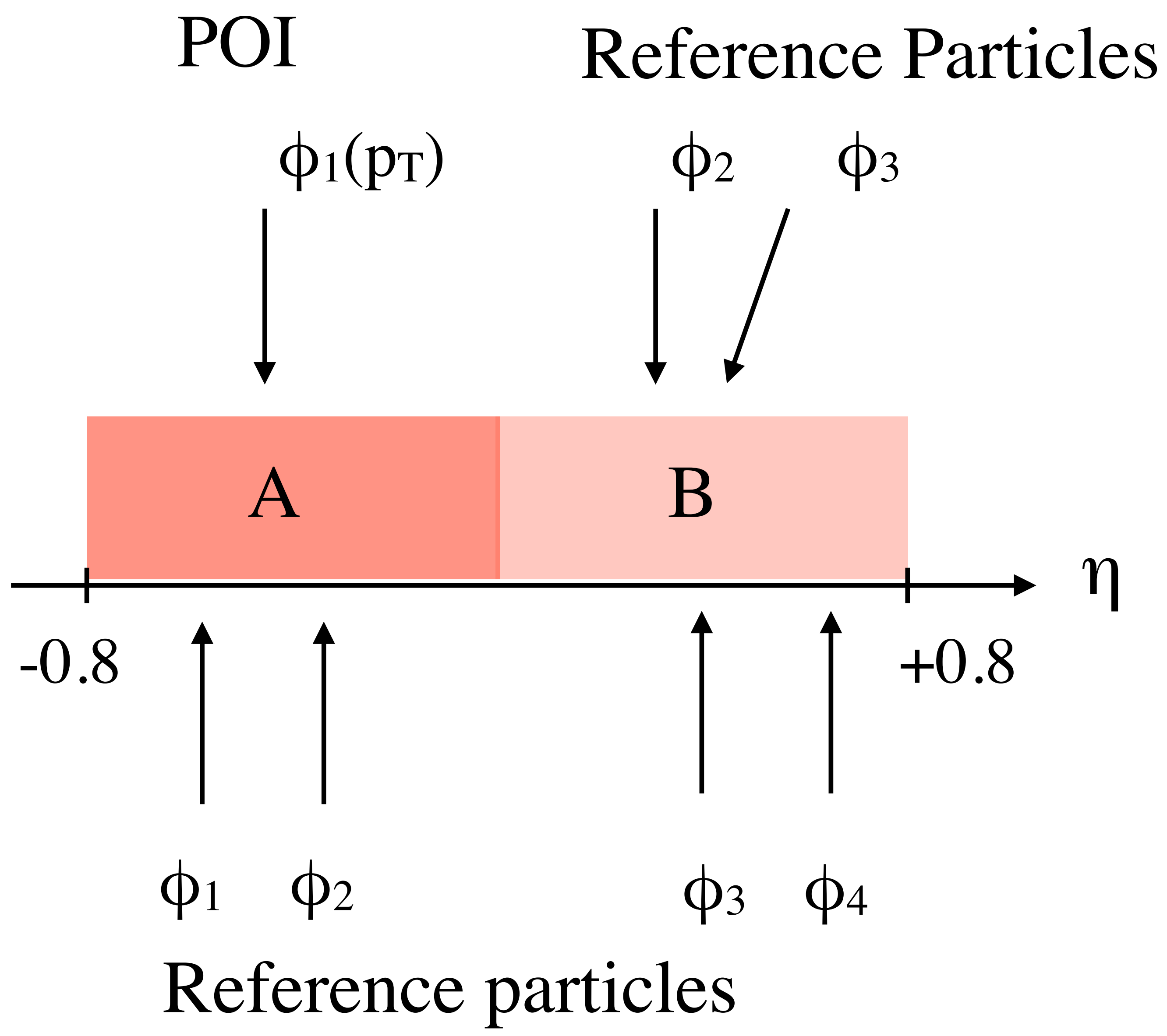


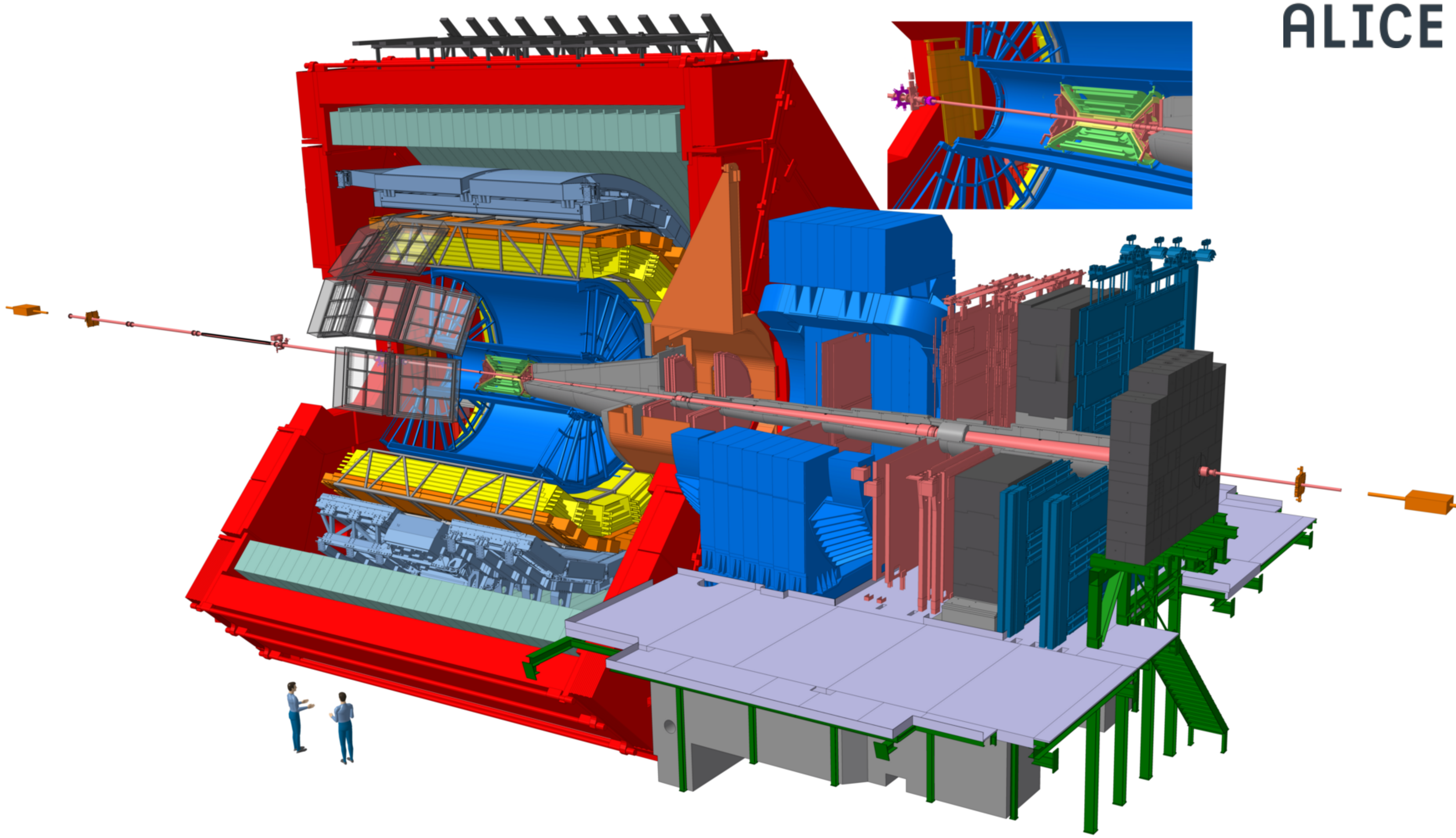
- $v_{n,mk}$ combination of $v_{n,mk}^A$ and $v_{n,mk}^B$
- Non-flow effects:
  - Suppressed largely by using multi-particle correlations in the numerator and denominator
  - Residual non-flow can be suppressed with various gaps between the sub-events or 3 sub-event method

Analysis details

- p_T-integrated v_n, $v_{n,mk}$, v_n^L :
  - Minimum Bias Pb-Pb data at 2.76 TeV
- p_T-differential $v_{n,mk}$:
  - Minimum Bias Pb-Pb data at 5.02 TeV
  - 0-1% - 10-20% and 40-50% centrality intervals

- Tracks used from TPC acceptance: $|\eta|<0.8$
- 2 sub-events with pseudo-rapidity gap:
  - $|\Delta\eta|>0.0$ for p_T-differential $v_{n,mk}$
  - $|\Delta\eta|>0.8$ for p_T-integrated v_n, $v_{n,mk}$, v_n^L

- RFPs (Reference particles): charged particles
  - p_T range: $0.2 < p_T < 5.0$ (GeV/c)
- POIs (Particles of Interest) for p_T-differential $v_{n,mk}$:
  - charged π, K and (anti-)$\bar{p}$
  - Particle Identification:
    - $p < 0.5$ GeV/c TPC (dE/dx signal) (TPCn$\sigma < 3$)
    - $p > 0.5$ GeV/c TPC+TOF combined signals (p_T dependent)

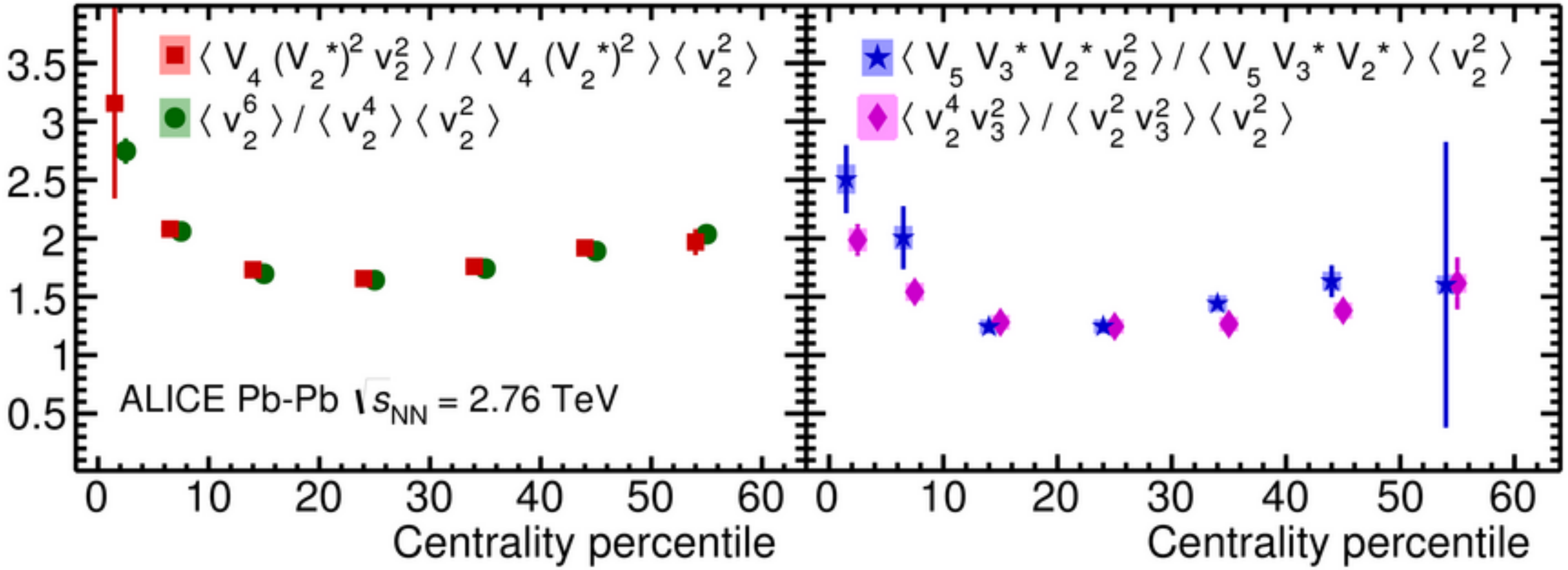


POI	p_T range (GeV/c)	Purity
$\pi^\pm$	$0.4 < p_T < 6.0$	90%
$K^\pm$	$0.4 < p_T < 4.0$	80%
$p+\bar{p}$	$0.4 < p_T < 6.0$	80%

Are V_n^{NL} and V_n^{L} orthogonal (uncorrelated)?

v_4^L and v_4^{NL} uncorrelated → $$\frac{\langle V_4 (V_2^*)^2 v_2^2 \rangle}{\langle V_4 (V_2^*)^2 \rangle \langle v_2^2 \rangle} = \frac{\langle v_2^6 \rangle}{\langle v_2^4 \rangle \langle v_2^2 \rangle}$$ eq. 1

v_5^L and v_5^{NL} uncorrelated → $$\frac{\langle V_5 V_3^* V_2^* v_2^2 \rangle}{\langle V_5 V_3^* V_2^* \rangle \langle v_2^2 \rangle} = \frac{\langle v_2^4 v_3^2 \rangle}{\langle v_2^2 v_3^2 \rangle \langle v_2^2 \rangle}$$ eq. 2



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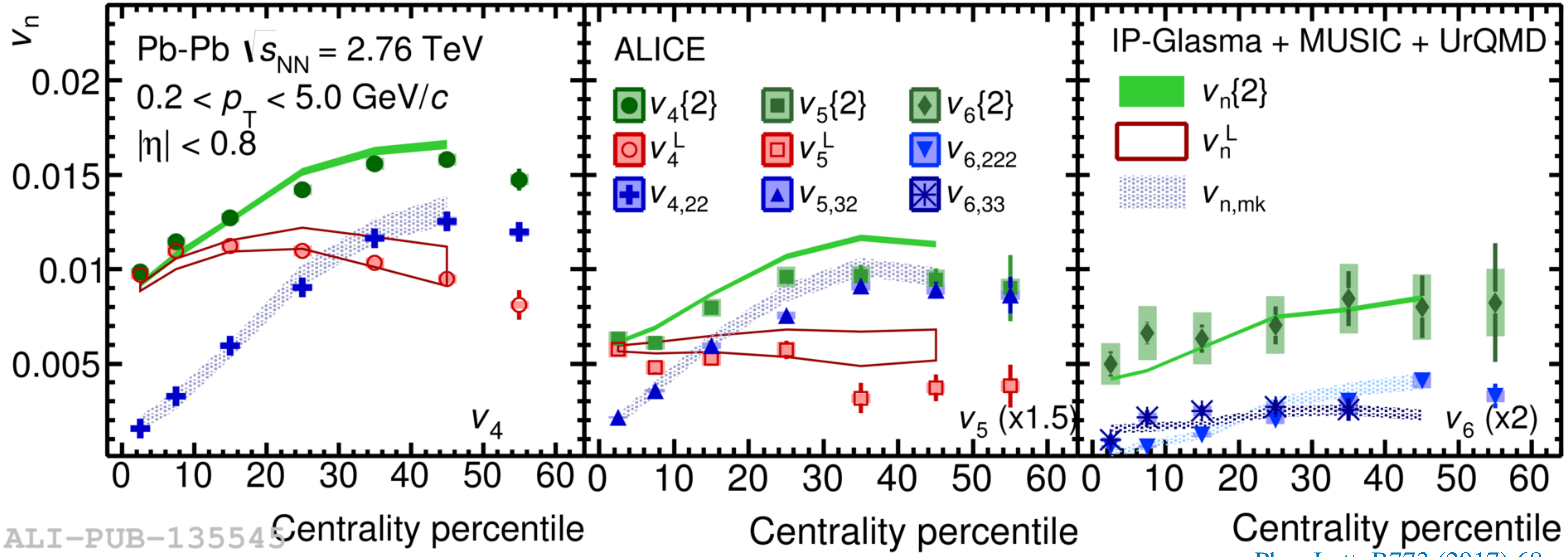
Linear and non-linear response in higher flow harmonics

- Measurements at 2.76 TeV:
  - p_T-integrated non-linear flow modes
    - Clear centrality dependence for $v_{4,22}$, $v_{5,32}$, $v_{6,222}$ (Less for $v_{6,33}$)
  - The linear and non-linear response are uncorrelated:
    - p_T-integrated linear flow terms for v_4 and v_5

$$v_4^L = \sqrt{v_4^2 - v_{4,22}^2} \qquad v_5^L = \sqrt{v_5^2 - v_{5,32}^2}$$

- Model Comparison:
  - IP-Glasma + Music + UrQMD: Initial conditions + viscous hydro + hadronic phase

Phys. Rev. C 95, 064913 (2017)



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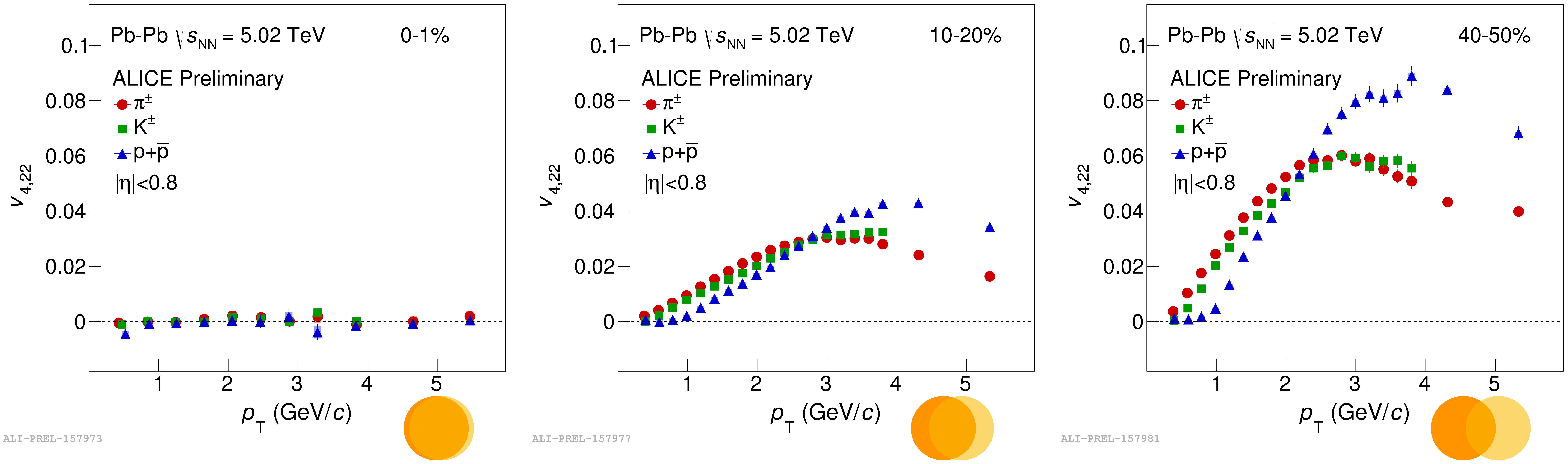
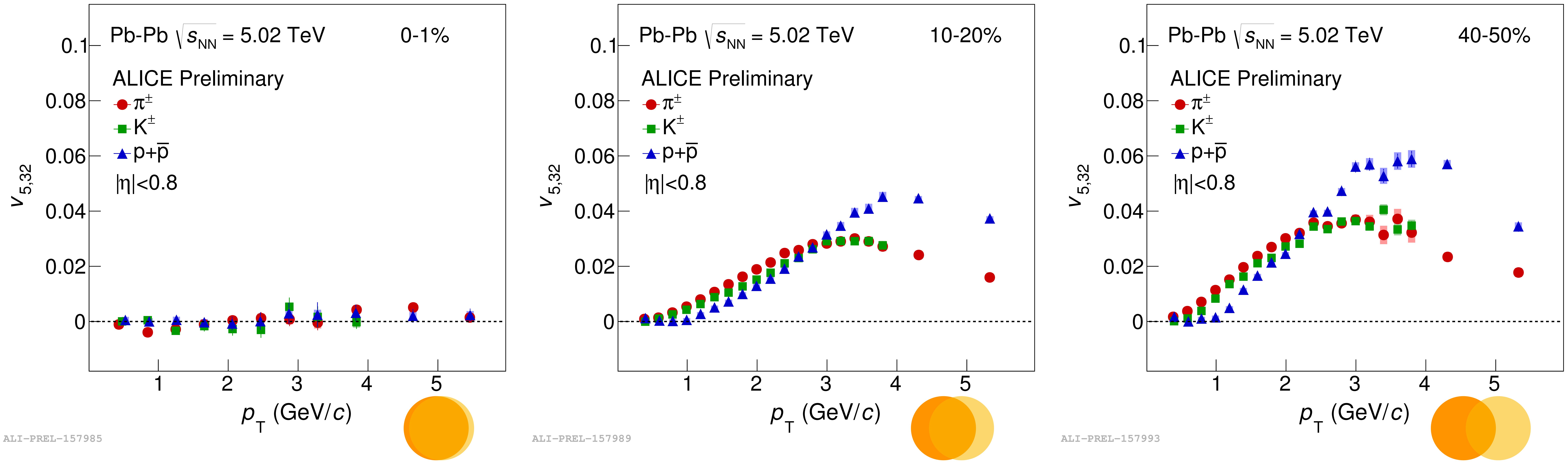
Measurement of $v_{4,22}(p_T)$ for identified particles

- Ultra-central collisions:
  - $v_{4,22}$ consistent with 0 for all particle species
  - v_4 comes mainly from the linear component (v_4^L)
- Non-central collisions:
  - Mass ordering in the low p_T region (p_T <2.5 GeV/c)
  - Particle type grouping in the intermediate p_T region (p_T >2.5 GeV/c)



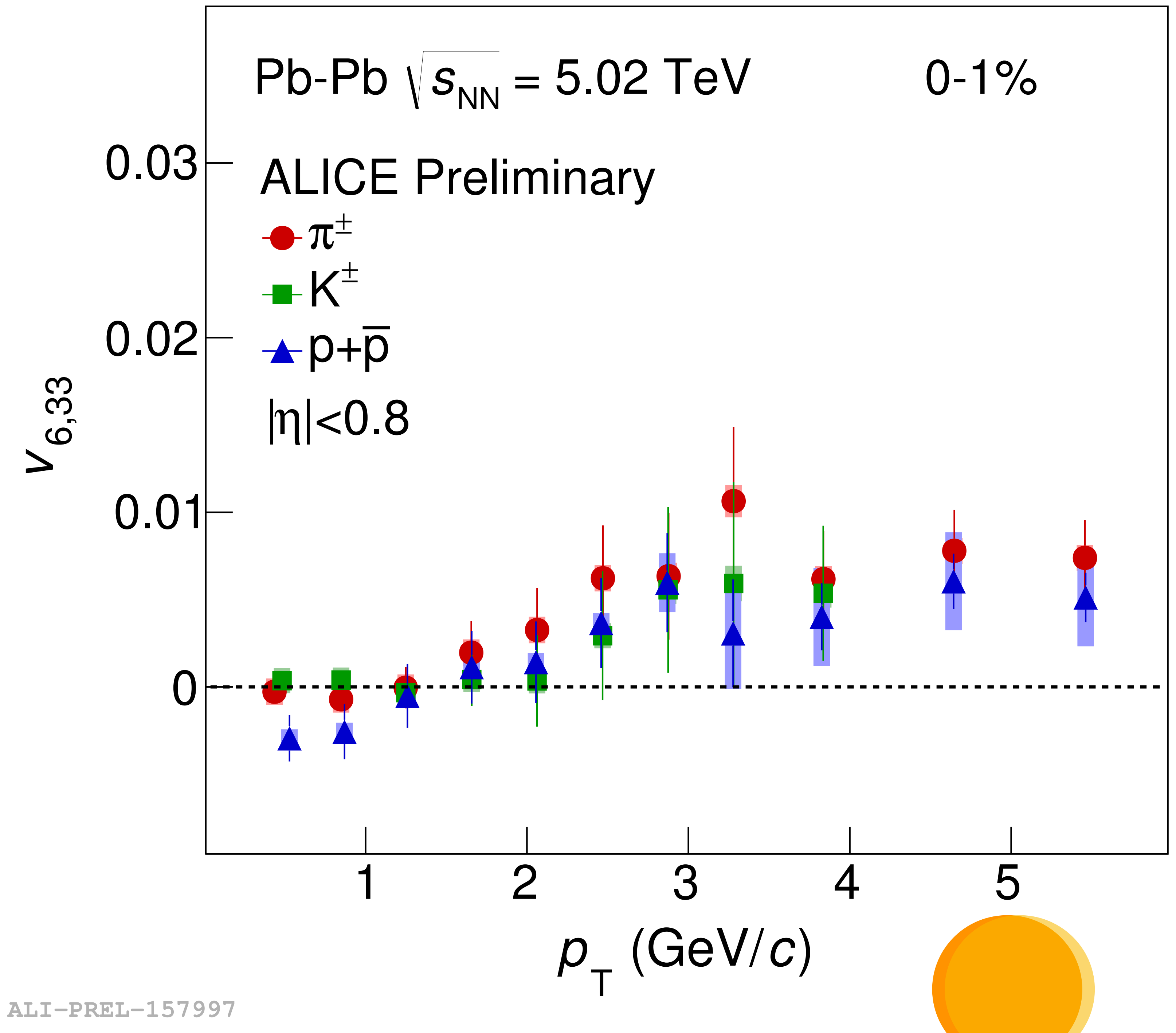
Measurement of $v_{5,32}(p_T)$ for identified particles

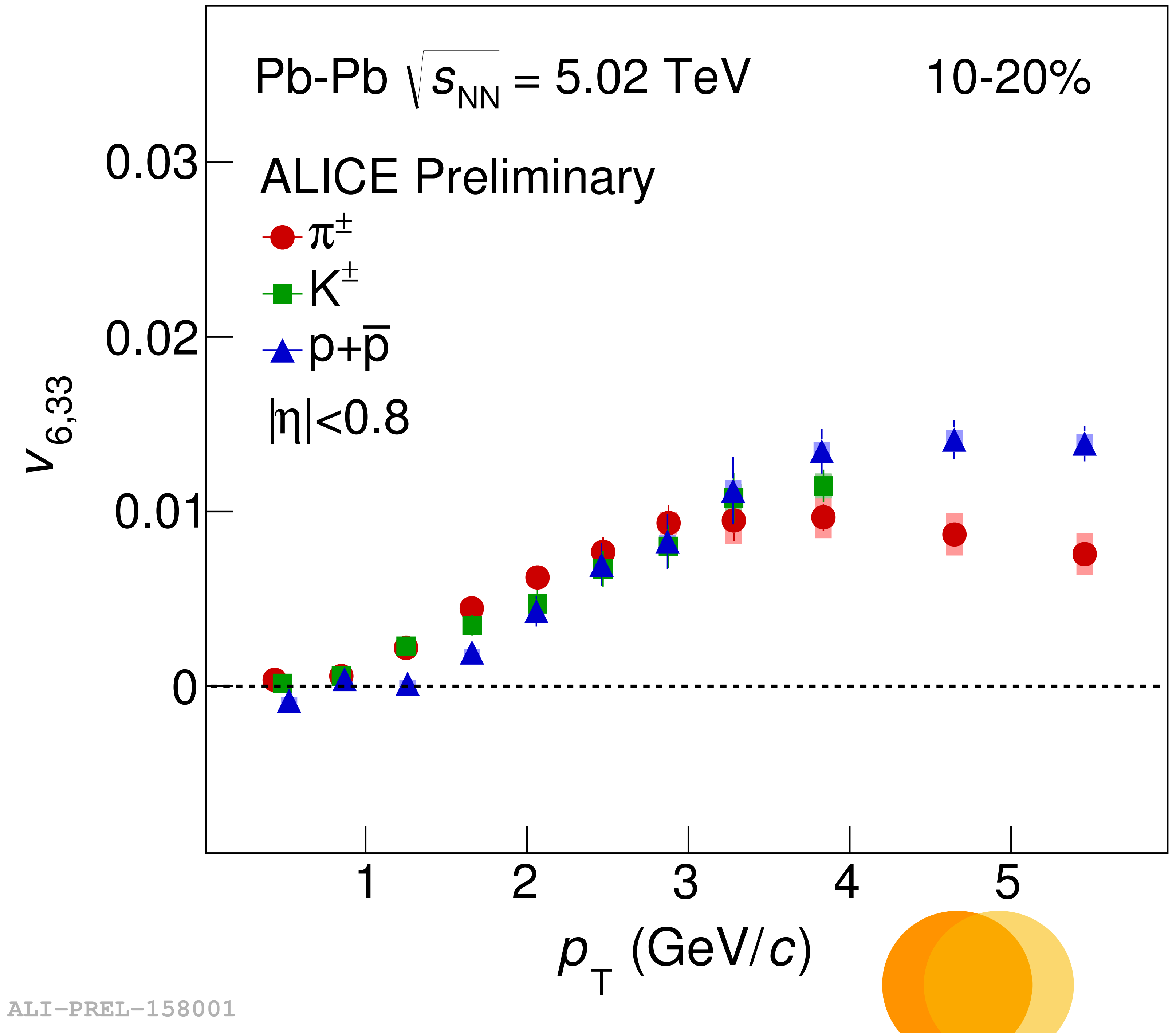
- Ultra-central collisions:
  - $v_{5,32}$ almost consistent with 0 for all particle species
  - v_5 comes mainly from the linear component (v_5^L)
- Non-central collisions:
  - Mass ordering in the low p_T region (p_T<2.5 GeV/c)
  - Particle type grouping in the intermediate p_T region (p_T>2.5 GeV/c)

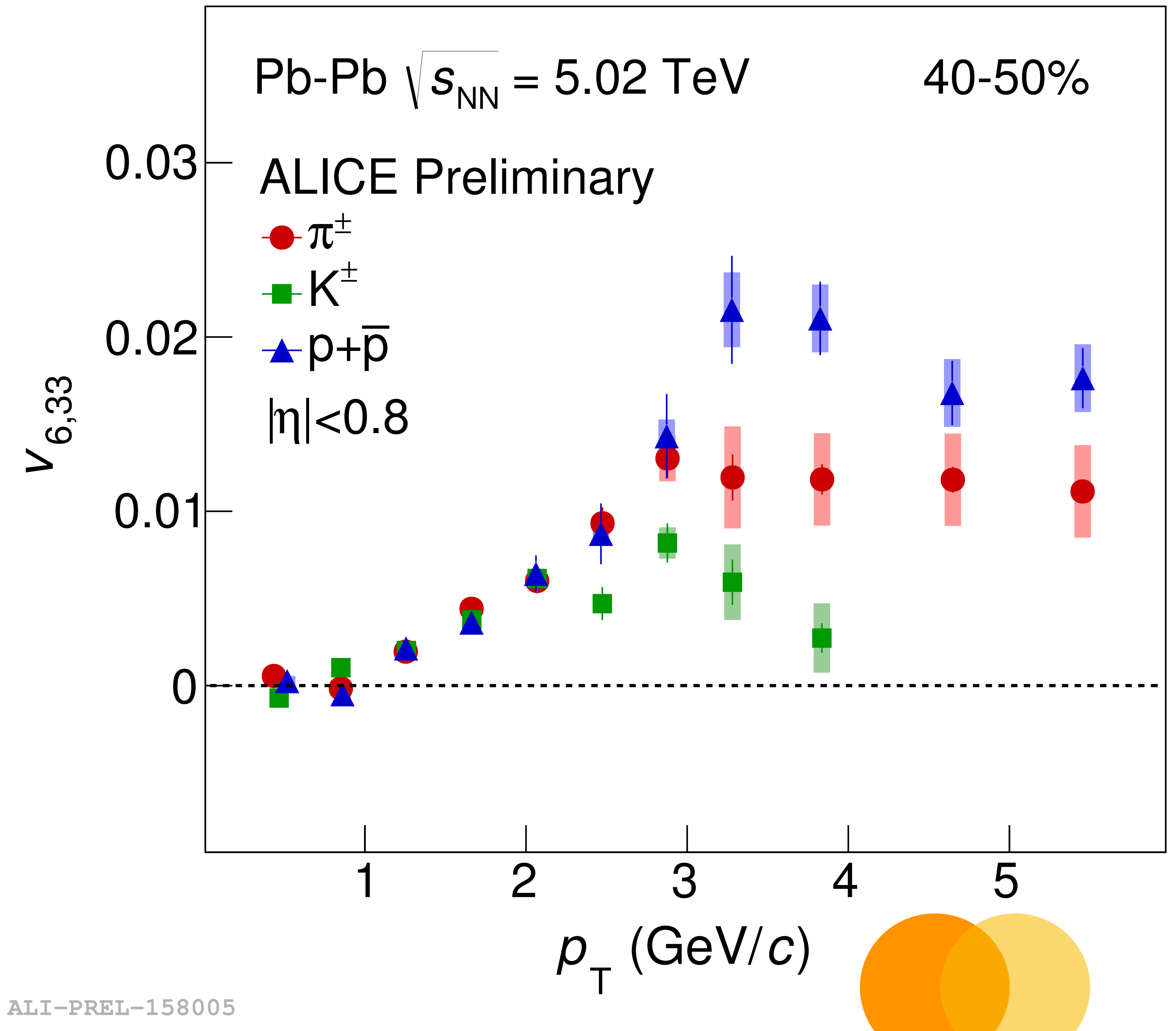


Measurement of $v_{6,33}(p_T)$ for identified particles

- The magnitude of v_{633} does not exhibit a strong centrality dependence
  - As expected since v_{633} originates from the third symmetry plane (less geometry dependence)
- Ultra-central collisions:
  - Non-zero $v_{6,33}$
- Non-central collisions:
  - Indication that some features (i.e. mass ordering and particle type grouping) persist also in $v_{6,33}$







Hydrodynamic predictions:

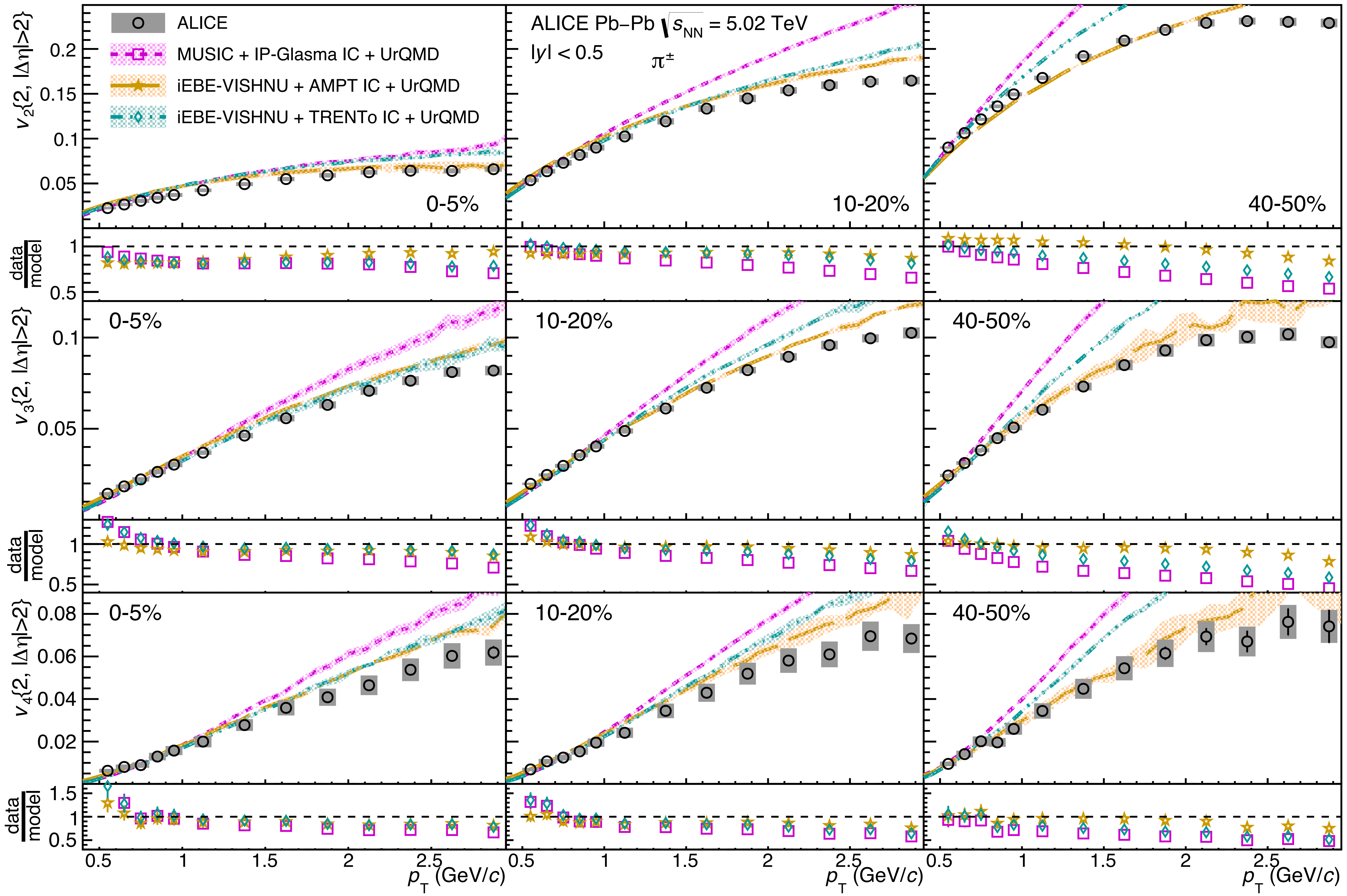
arXiv:1805.04390v1

Eur.Phys.J. C77 (2017) no.9, 645
Zhao, Wenbin *et al.*

iEBE-VISHNU hybrid model:

- VISH2+1 coupled to UrQMD
- Two initial conditions: AMPT, TRENTO
- T_{switch} = 148 MeV, τ_0 = 0.6 fm/*c*
- AMPT: η/s=0.08 and ζ/s=0
- TRENTo: η/s(T) and ζ/s(T)

Phys. Rev. C 94, 024907 (2016)
JE Bernhard *et al.*



- AMPT: Good agreement with v_n measurements of π and K for p_T < 2 GeV/*c* and v_n of protons described fairly well up to p_T =3 GeV/*c*
- TRENTo: Agreement up to slightly lower transverse momenta depending on the centrality interval: v_n of π and K only for p_T < 1-2 GeV/*c* and to p_T < 3 GeV/*c* for p

Measurements of the non-linear modes for identified particles vs. predictions

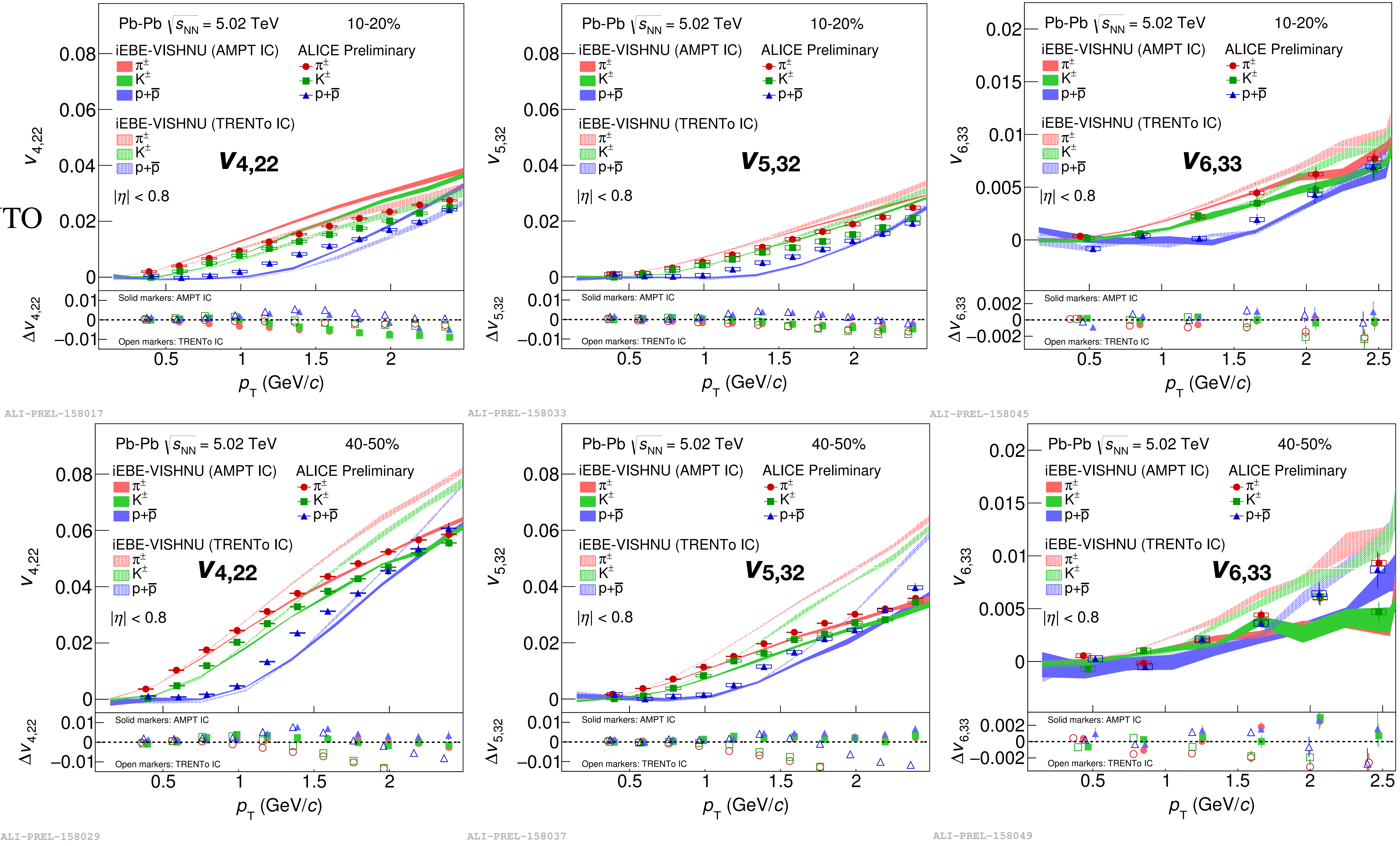
Eur.Phys.J. C77 (2017) no.9, 645
Zhao, Wenbin *et al.*

iEBE-VISHNU hybrid model:

- ✤ VISH2+1 coupled to UrQMD
- ✤ Two initial conditions: AMPT, TRENTO
- ✤ T_{switch} = 148 MeV, τ_0 = 0.6 fm/c
- ✤ AMPT: η/s=0.08 and ζ/s=0
- ✤ TRENTo: $\eta/s(T)$ and $\zeta/s(T)$

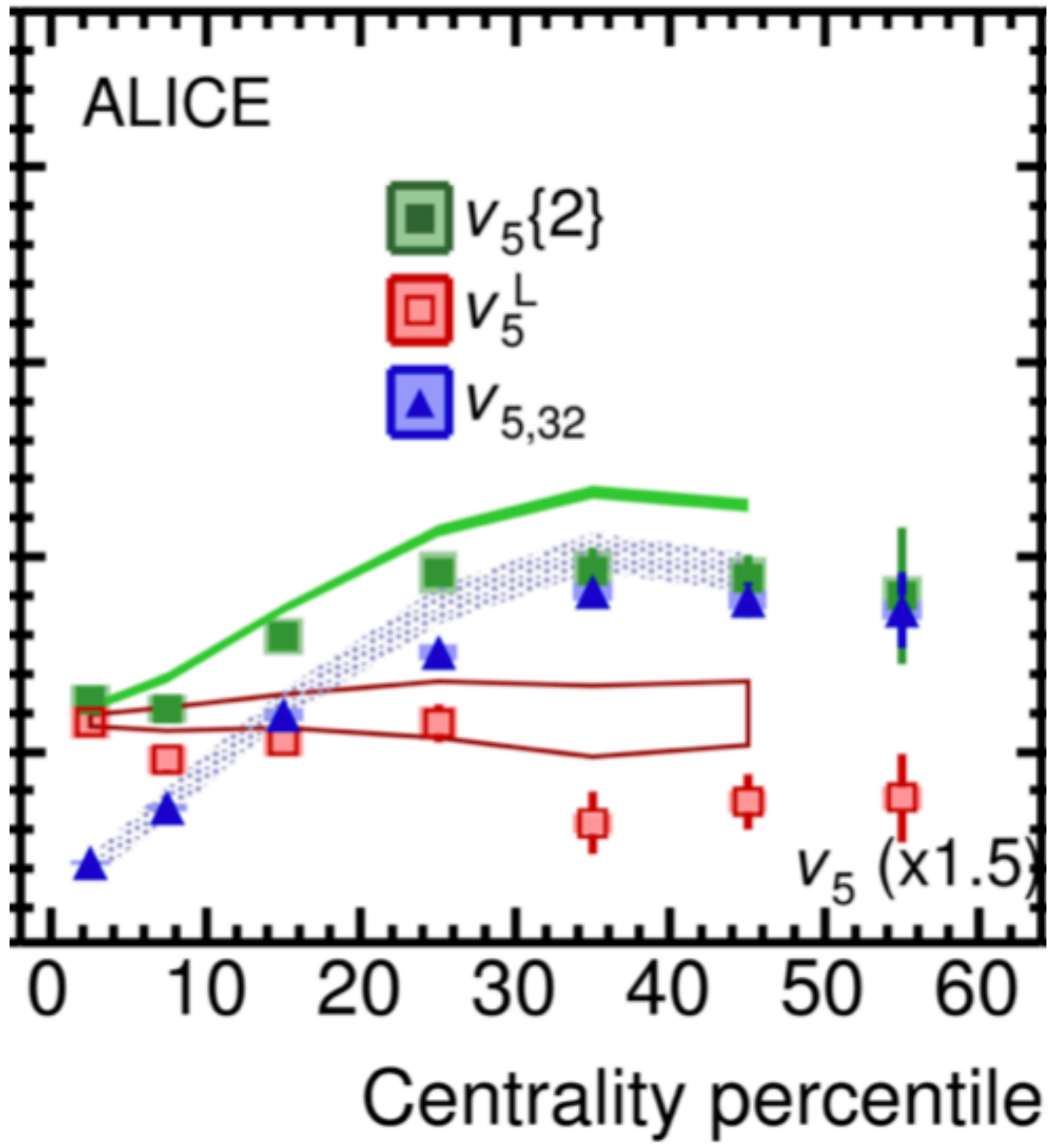
Phys. Rev. C 94, 024907 (2016)
JE Bernhard *et al.*

- ✤ AMPT better describes data in different centrality intervals
- ✤ Models require a bit more work to describe the details that data reveal

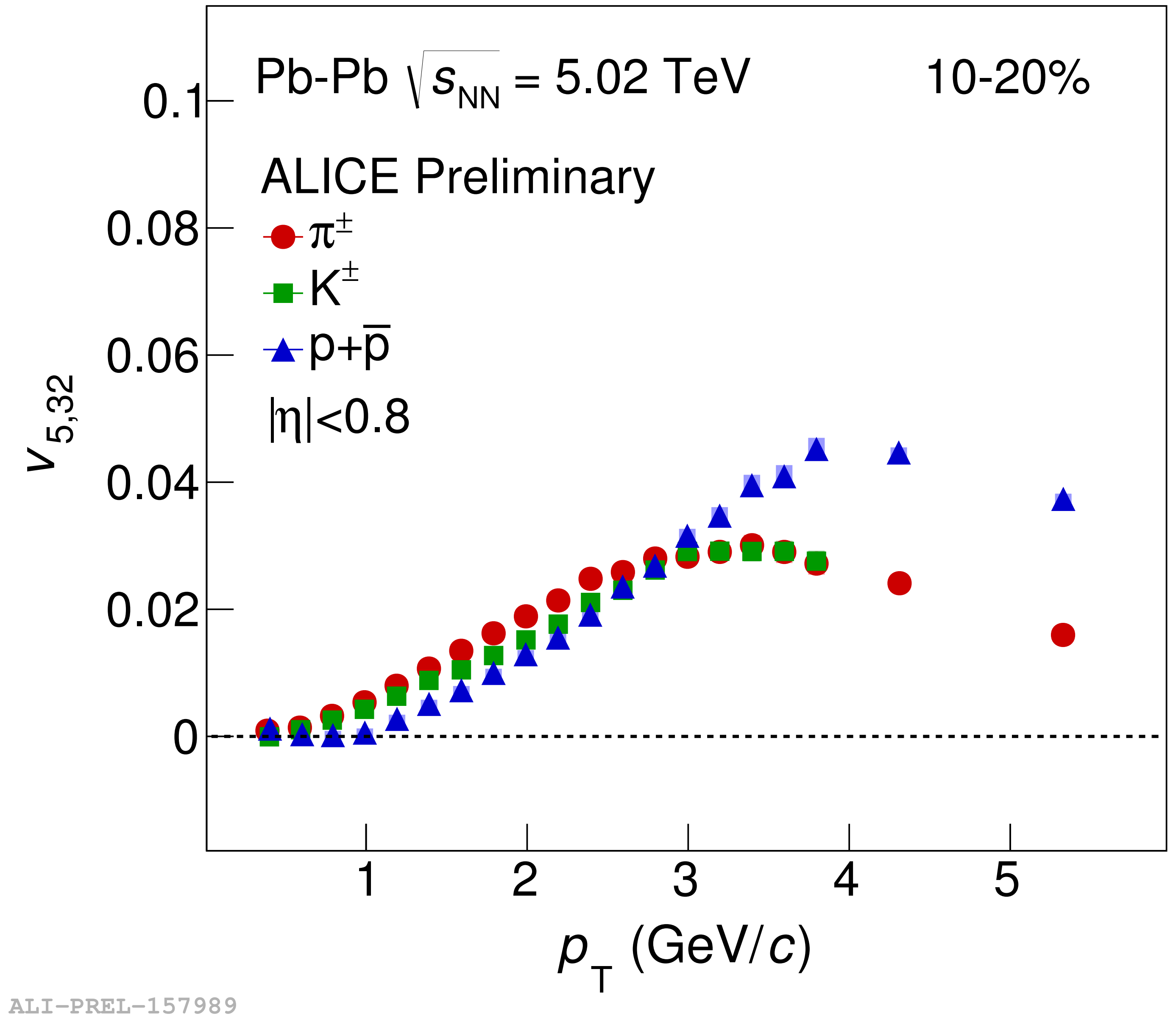


Summary

- Non-linear modes measured up to 6th harmonic and in both LHC energies
  - Clear centrality dependence for $v_{4,22}$, $v_{5,32}$, $v_{6,222}$ (Less for $v_{6,33}$)

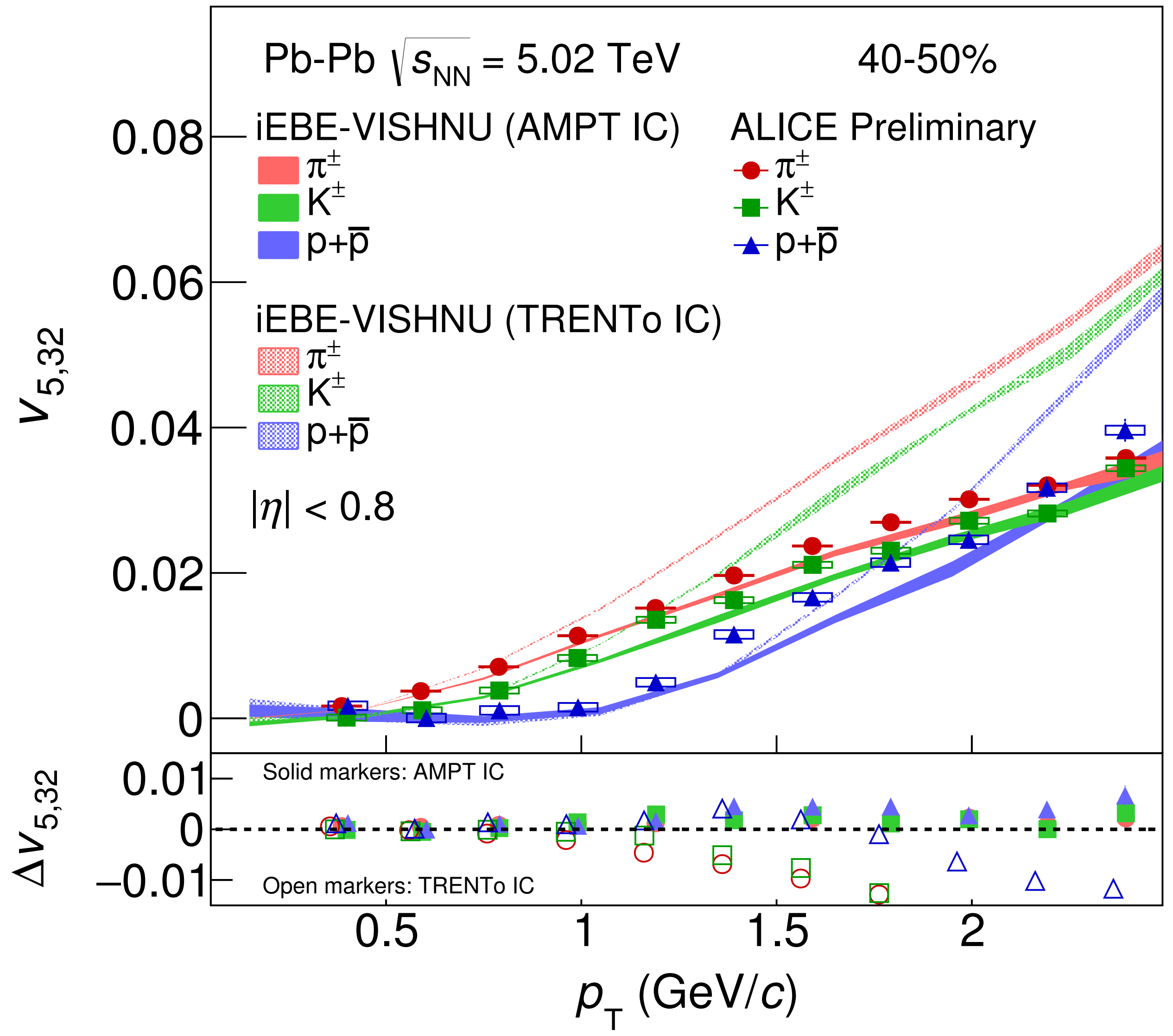


- First results on non-linear flow modes of identified particles: $v_{4,22}$, $v_{5,32}$, $v_{6,33}$
  - Mass ordering in low p_T ($p_T < 2.5$ GeV/c)
  - Particle type grouping in the intermediate p_T (p_T> 2.5 GeV/c)



ALI-PREL-157989

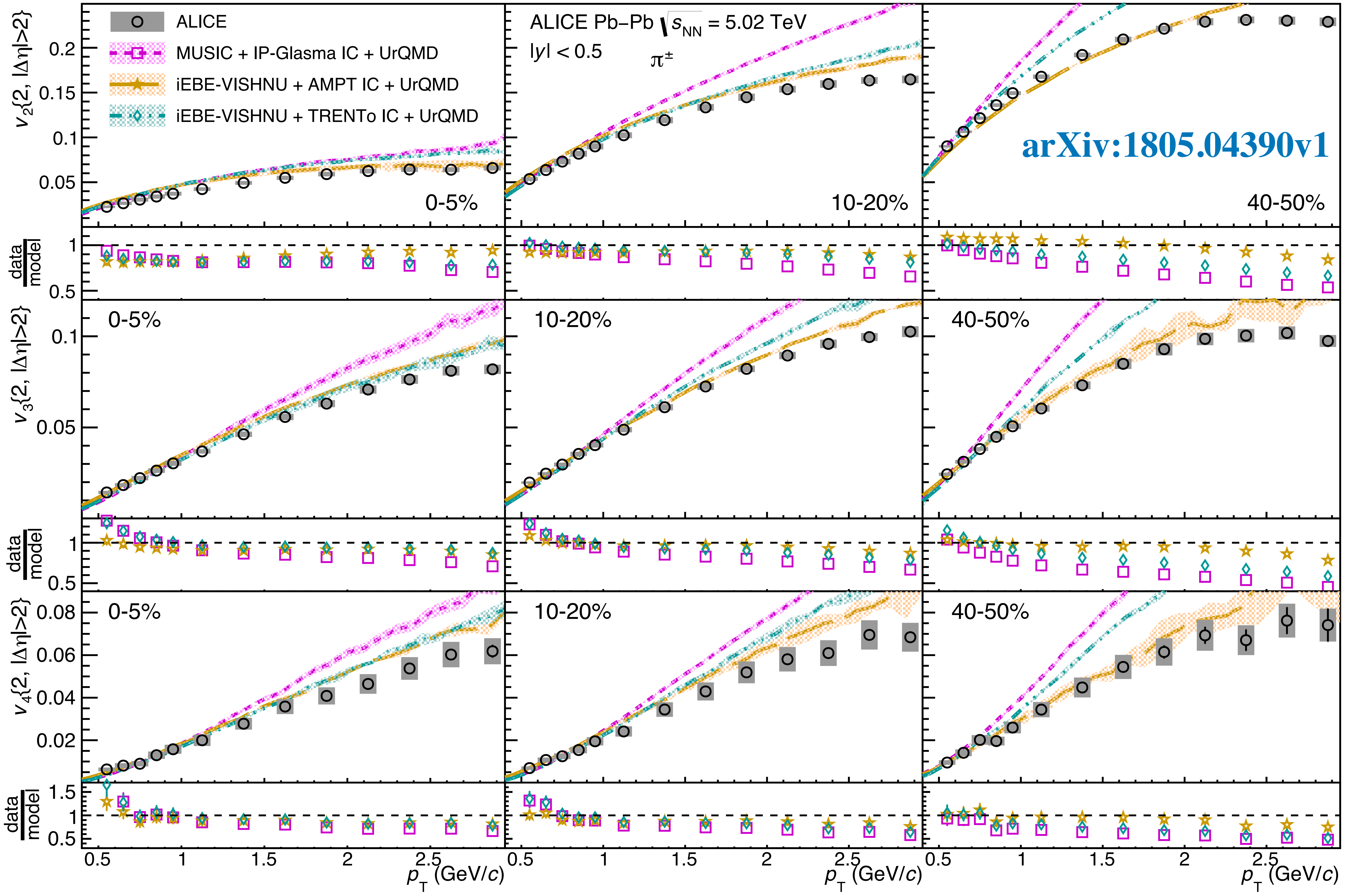
- iEBE-VISHNU: AMPT and TRENTo initial conditions with different sets of parameters
  - AMPT (η/s=0.08 and ζ/s=0) reproduces v_n and $v_{n,mk}$ measurements better than TRENTo (η/s(T) and ζ/s(T))
  - Models require a bit more work to describe the details that data reveal



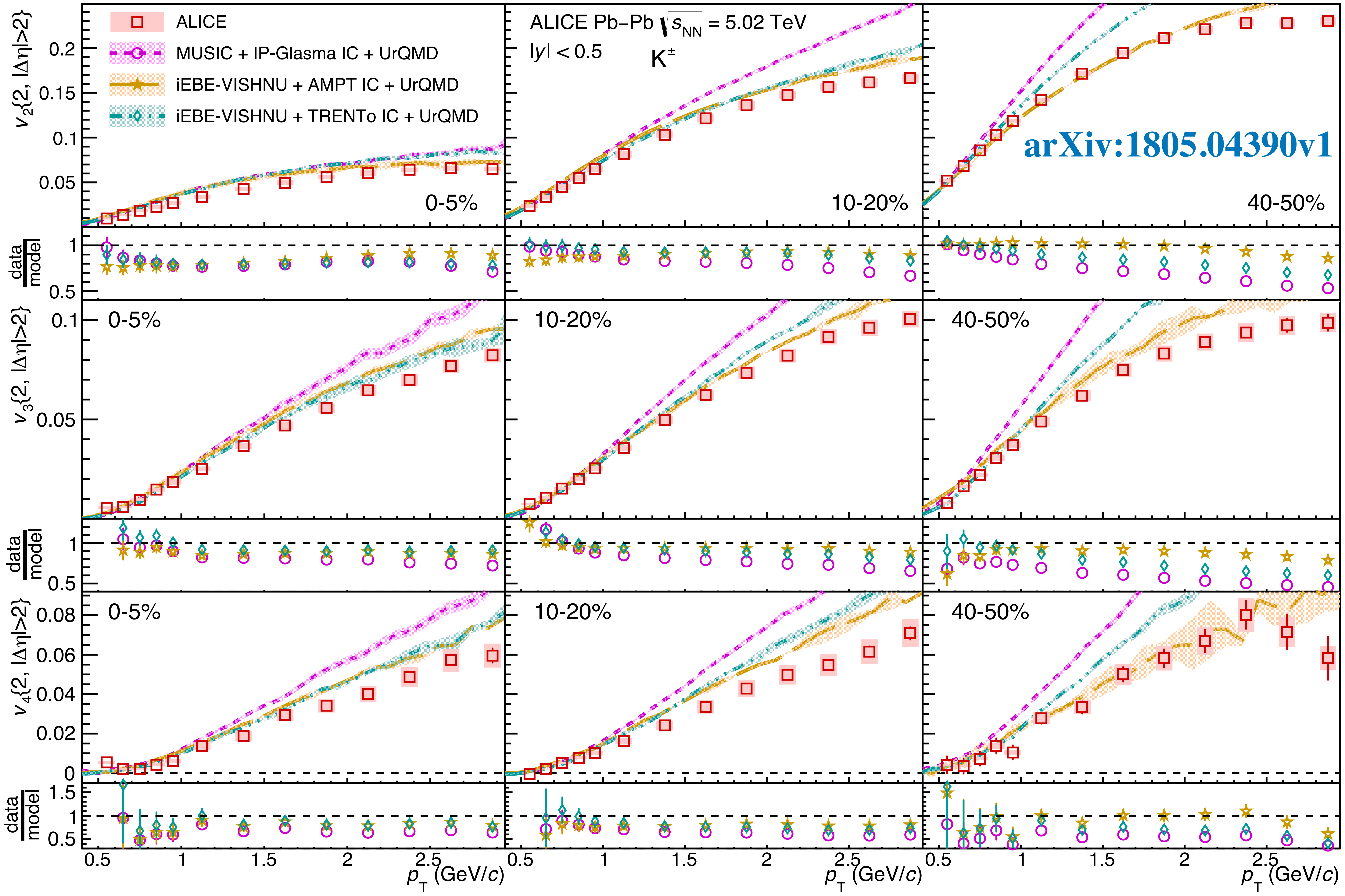
ALI-PREL-158037

Backup

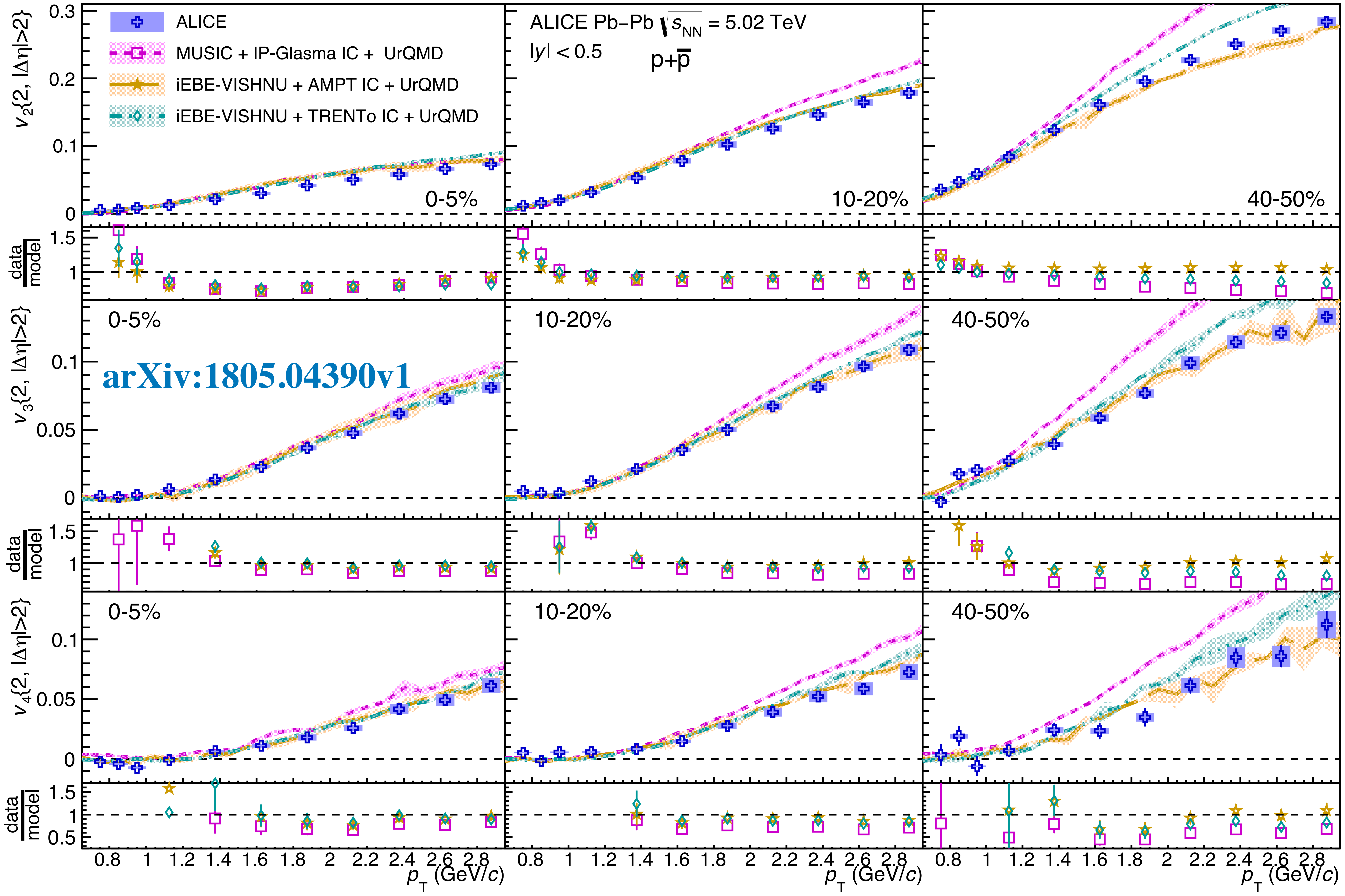
Hydrodynamic predictions: v_n of pions



Hydrodynamic predictions: v_n of kaons



Hydrodynamic predictions: v_n of protons



arXiv:1805.04390v1