Measurements of mixed harmonic cumulants in Pb-Pb collisions at 5.02 TeV with ALICE

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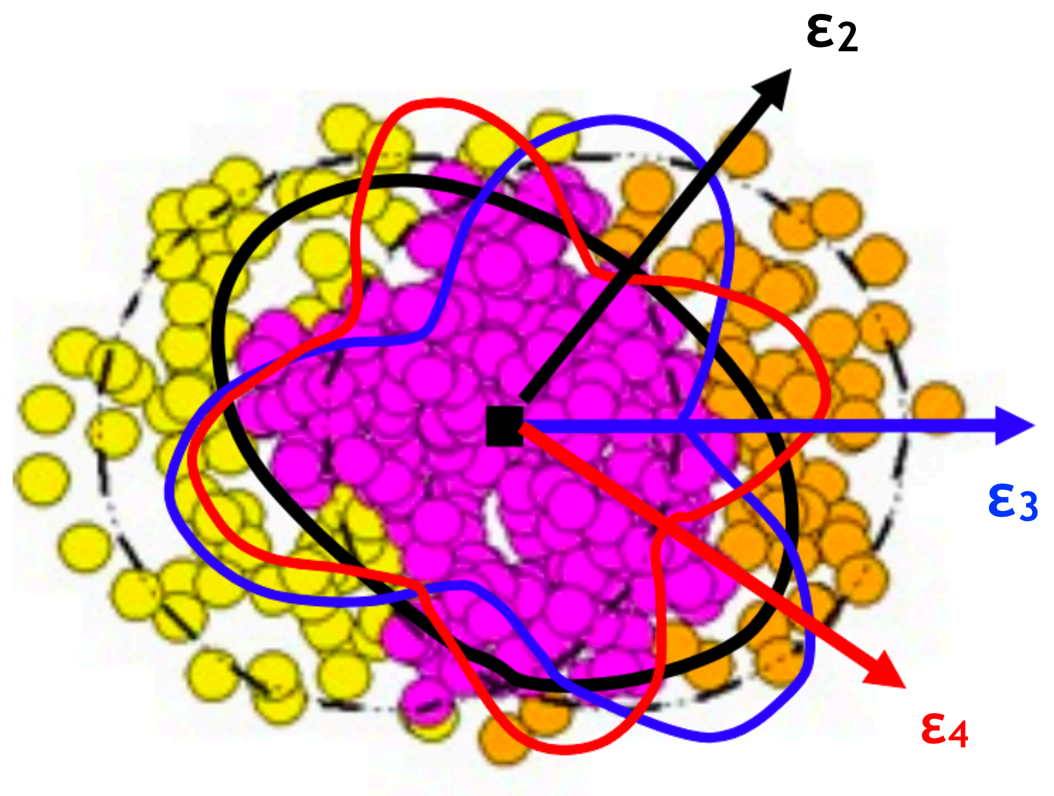
(for the ALICE Collaboration)

ALICE UNIVERSITY OF COPENHAGEN THE VELUX FOUNDATIONS VILLUM FONDEN VELUX FONDEN

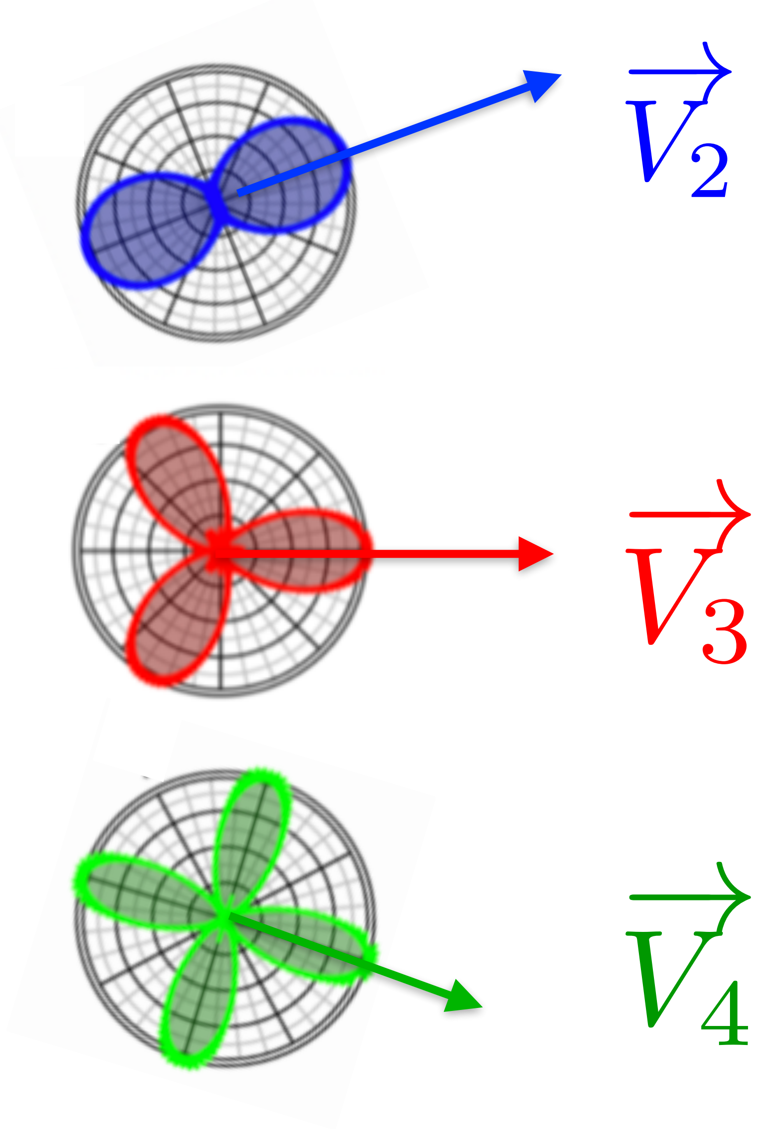
Studying QGP with anisotropic flow

Initial state



system expansion

Final state



$$\vec{V}_n = v_n \, e^{-in\Psi_n}$$

- v_n :Anisotropic flow
- Ψ_n : Flow symmetry plane

❖ General questions:

- how does v_n fluctuate
- how does Ψ_n fluctuate
- correlations between Ψ_m and Ψ_n
- **correlations between v_m and v_n**
- new information on initial conditions and/or η/s(T)?

ALICE, JHEP 07 (2018) 103
ALICE, JHEP 09 (2017) 032
ALICE, JHEP05 (2020) 085
JHEP06 (2020) 147
ALICE, PRL117, (2016) 182301
PRC97, (2018) 024906
PLB818 (2021) 136354

General correlations between flow coefficients

PHYSICAL REVIEW C **103**, 024913 (2021)

Generic algorithm for multiparticle cumulants of azimuthal correlations in high energy nucleus collisions

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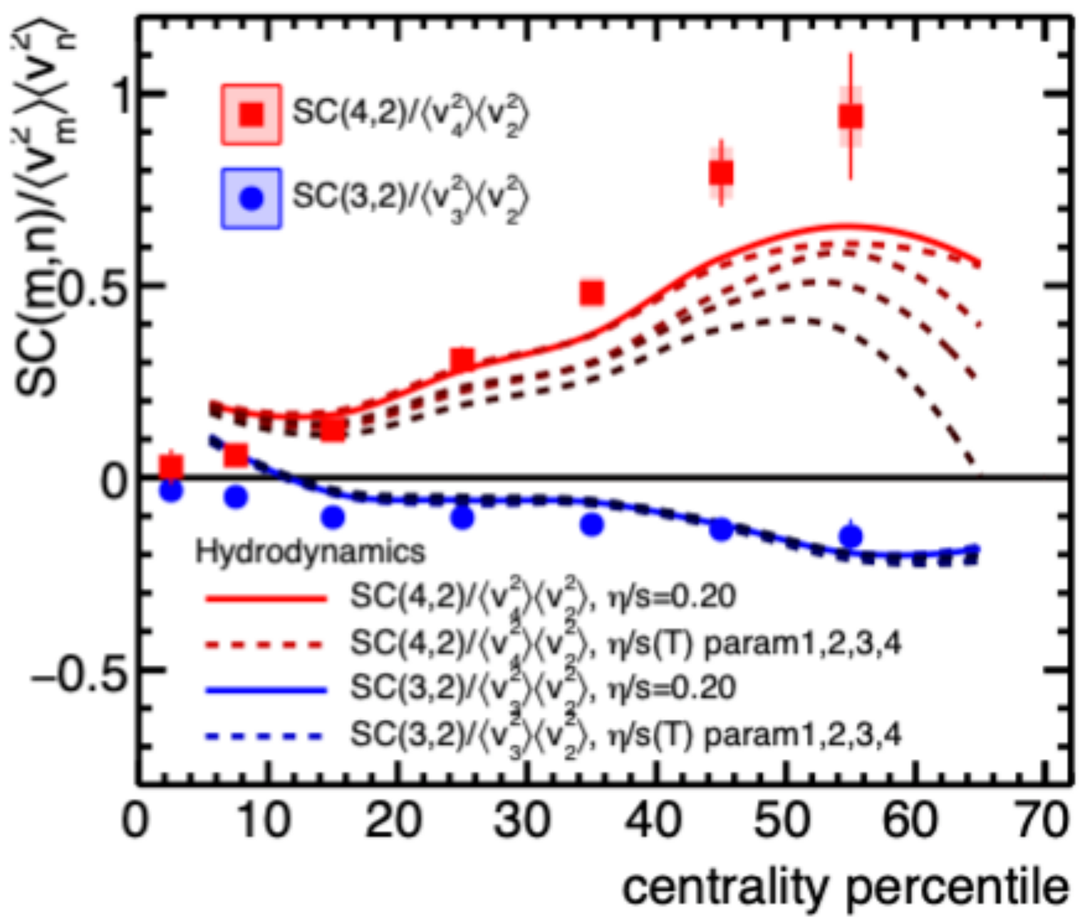
Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark

❖ Multiparticle mixed harmonic cumulants
- correlation between v_m^2, v_n^2 and v_p^2
- correlation between v_m^k and v_n^l

Mixed harmonic cumulants with 4-particles

$$\mathrm{MHC}(v_m^2, v_n^2) = \mathrm{SC}(m,n) = \langle v_m^2\, v_n^2\rangle - \langle v_m^2\rangle\,\langle v_n^2\rangle$$

$$\mathrm{NSC}(m,n) = \frac{\mathrm{SC}(m,n)}{\langle v_m^2\rangle\,\langle v_n^2\rangle}$$



Symmetric Cumulant, **PRC89, 064904 (2014)**

ALICE, **PRL117, 182301 (2016)**

- NSC(4,2) is sensitive to both initial conditions and η/s(T)
- NSC(3,2) probes initial conditions

Mixed harmonic cumulants with 6-particles

$$\begin{aligned}\mathrm{MHC}(v_2^4, v_3^2) &= \langle\langle e^{i(2\varphi_1+2\varphi_2+3\varphi_3-2\varphi_4-2\varphi_5-3\varphi_6)}\rangle\rangle_c \\ &= \langle v_2^4\, v_3^2\rangle - 4\langle v_2^2\, v_3^2\rangle\langle v_2^2\rangle - \langle v_2^4\rangle\langle v_3^2\rangle \\ &\quad + 4\langle v_2^2\rangle^2\langle v_3^2\rangle.\end{aligned}$$

$$\begin{aligned}\mathrm{MHC}(v_2^2, v_3^4) &= \langle\langle e^{i(2\varphi_1+3\varphi_2+3\varphi_3-2\varphi_4-3\varphi_5-3\varphi_6)}\rangle\rangle_c \\ &= \langle v_2^2\, v_3^4\rangle - 4\langle v_2^2\, v_3^2\rangle\langle v_3^2\rangle - \langle v_2^2\rangle\langle v_3^4\rangle \\ &\quad + 4\langle v_2^2\rangle\langle v_3^2\rangle^2.\end{aligned}$$

$$\begin{aligned}\mathrm{MHC}(v_2^2, v_3^2, v_4^2) &= \langle\langle e^{i(2\varphi_1+3\varphi_2+4\varphi_3-2\varphi_4-3\varphi_5-4\varphi_6)}\rangle\rangle_c \\ &= \langle v_2^2\, v_3^2\, v_4^2\rangle - \langle v_2^2\, v_3^2\rangle\langle v_4^2\rangle - \langle v_2^2\, v_4^2\rangle\langle v_3^2\rangle \\ &\quad - \langle v_3^2\, v_4^2\rangle\langle v_2^2\rangle + 2\langle v_2^2\rangle\langle v_3^2\rangle\langle v_4^2\rangle.\end{aligned}$$

Mixed harmonic cumulants with 8-particles

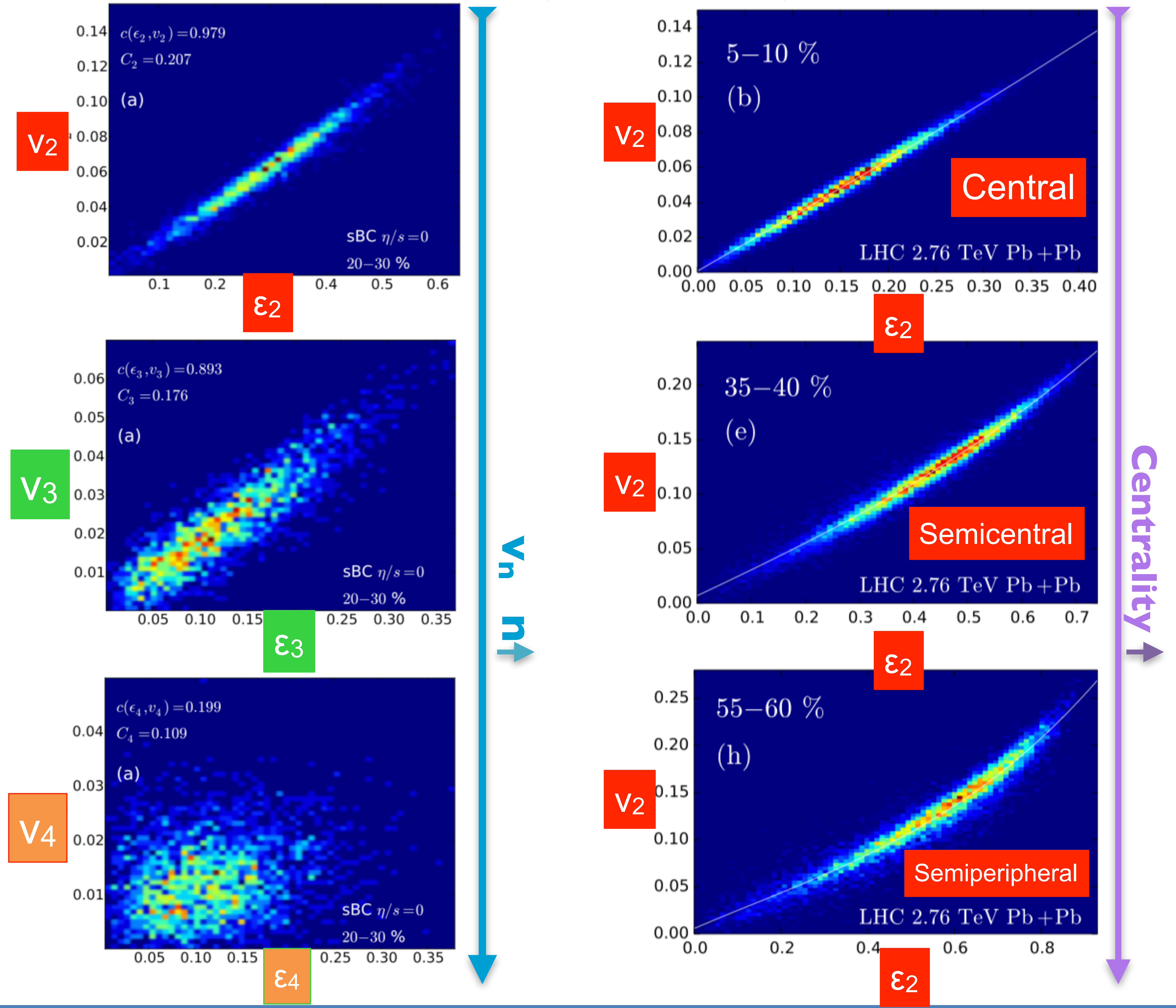
$$\begin{aligned}\mathrm{MHC}(v_2^6, v_3^2) &= \langle\langle e^{i(2\varphi_1+2\varphi_2+2\varphi_3+3\varphi_4-2\varphi_5-2\varphi_6-2\varphi_7-3\varphi_8)}\rangle\rangle_c \\ &= \langle v_2^6\, v_3^2\rangle - 9\langle v_2^4\, v_3^2\rangle\langle v_2^2\rangle - \langle v_2^6\rangle\langle v_3^2\rangle \\ &\quad - 9\langle v_2^4\rangle\langle v_2^2\, v_3^2\rangle - 36\langle v_2^2\rangle^3\langle v_3^2\rangle \\ &\quad + 18\langle v_2^2\rangle\langle v_3^2\rangle\langle v_2^4\rangle + 36\langle v_2^2\rangle^2\langle v_2^2\, v_3^2\rangle.\end{aligned}$$

$$\begin{aligned}\mathrm{MHC}(v_2^4, v_3^4) &= \langle\langle e^{i(2\varphi_1+2\varphi_2+3\varphi_3+3\varphi_4-2\varphi_5-2\varphi_6-3\varphi_7-3\varphi_8)}\rangle\rangle_c \\ &= \langle v_2^4\, v_3^4\rangle - 4\langle v_2^4\, v_3^2\rangle\langle v_3^2\rangle \\ &\quad - 4\langle v_2^2\, v_3^4\rangle\langle v_2^2\rangle - \langle v_2^4\rangle\langle v_3^4\rangle \\ &\quad - 8\langle v_2^2\, v_3^2\rangle^2 - 24\langle v_2^2\rangle^2\langle v_3^2\rangle^2 \\ &\quad + 4\langle v_2^2\rangle^2\langle v_3^4\rangle + 4\langle v_2^4\rangle\langle v_3^2\rangle^2 \\ &\quad + 32\langle v_2^2\rangle\langle v_3^2\rangle\langle v_2^2\, v_3^2\rangle.\end{aligned}$$

$$\begin{aligned}\mathrm{MHC}(v_2^2, v_3^6) &= \langle\langle e^{i(2\varphi_1+3\varphi_2+3\varphi_3+3\varphi_4-2\varphi_5-3\varphi_6-3\varphi_7-3\varphi_8)}\rangle\rangle_c \\ &= \langle v_2^2\, v_3^6\rangle - 9\langle v_2^2\, v_3^4\rangle\langle v_3^2\rangle - \langle v_3^6\rangle\langle v_2^2\rangle \\ &\quad - 9\langle v_3^4\rangle\langle v_2^2\, v_3^2\rangle - 36\langle v_2^2\rangle\langle v_3^2\rangle^3 \\ &\quad + 18\langle v_2^2\rangle\langle v_3^2\rangle\langle v_3^4\rangle + 36\langle v_3^2\rangle^2\langle v_2^2\, v_3^2\rangle.\end{aligned}$$

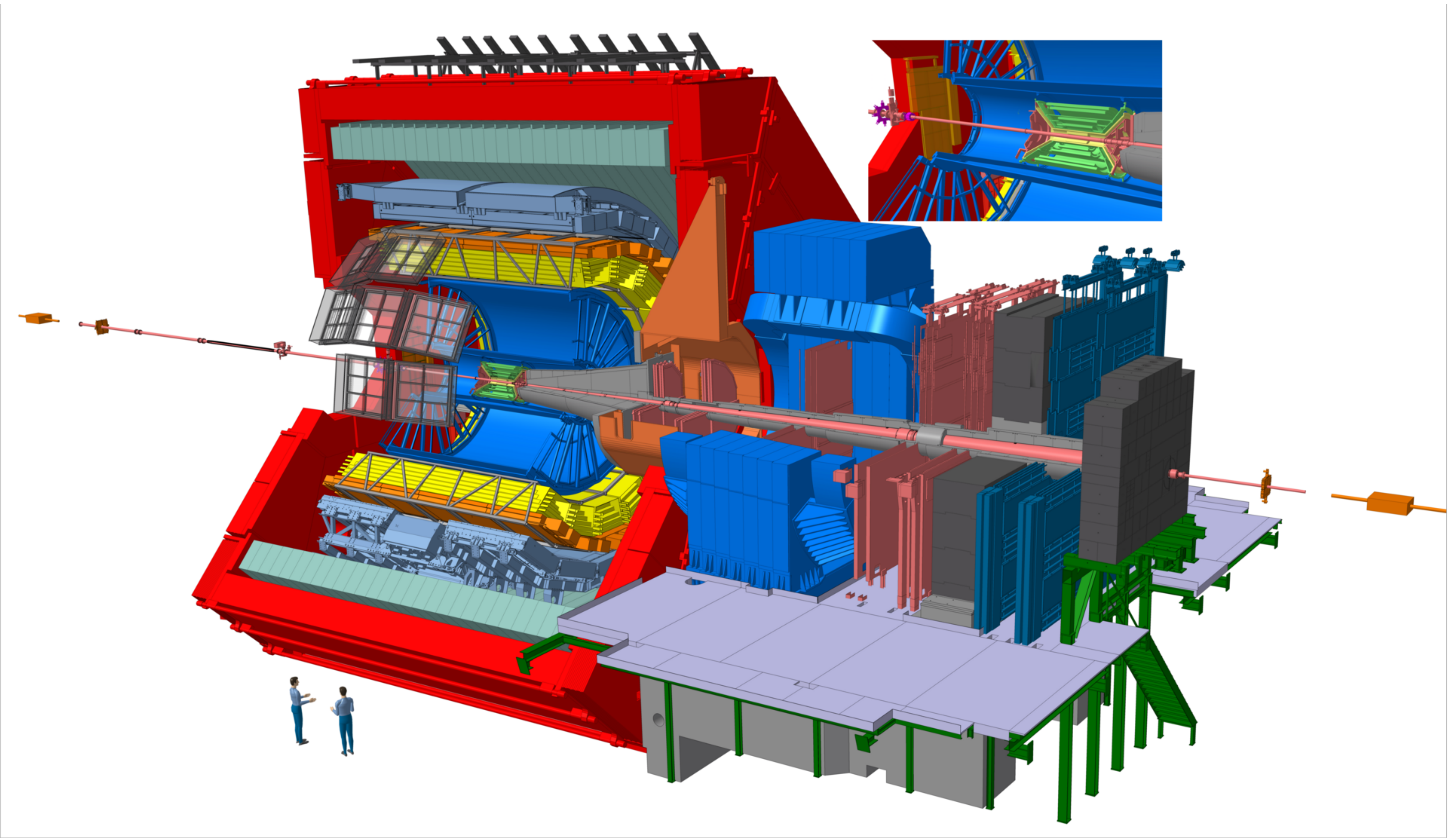
Linear and nonlinear hydrodynamic response

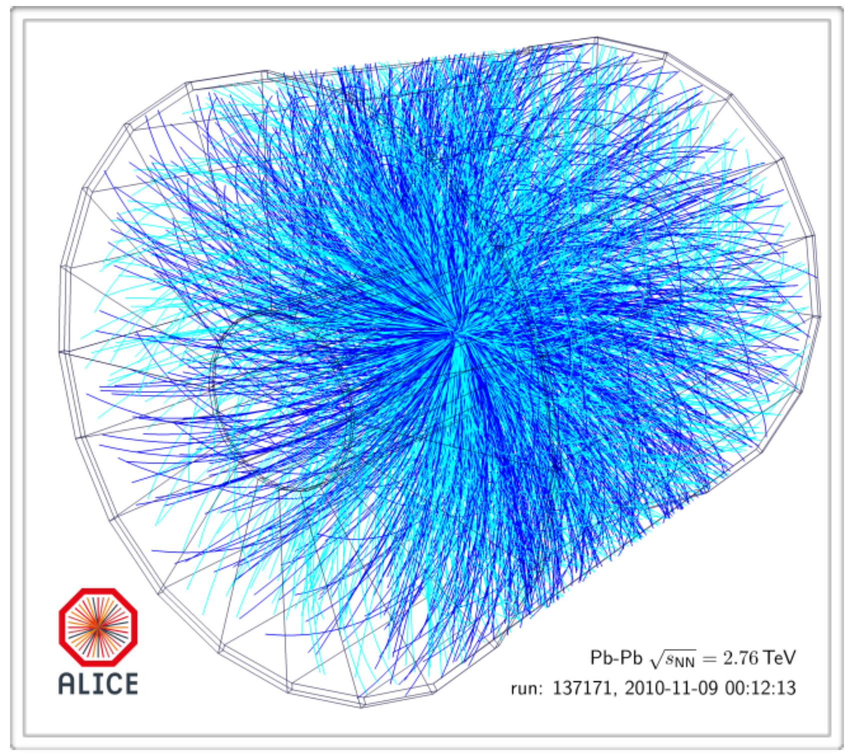
H. Niemi etc, PRC 87 (2013) 5, 054901



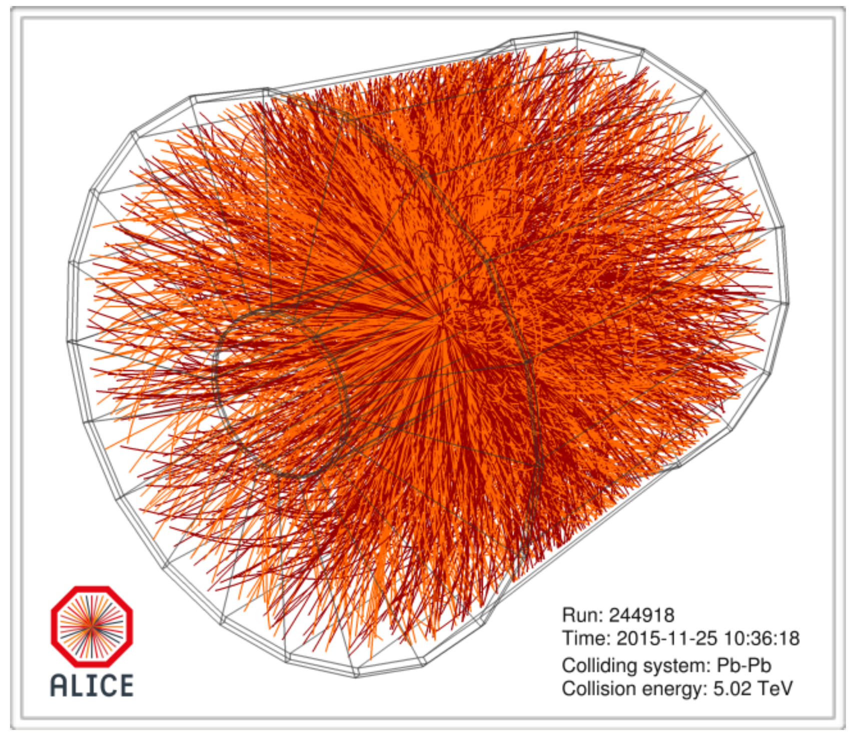
- v_n has both linear and nonlinear hydrodynamic response to initial anisotropy
  - Stronger linear response in v_2 than v_3 and v_4
  - Stronger linear correlations between v_n and ε_n in central than peripheral collision
- Study linear and nonlinear hydrodynamic response with nMHC
  - $v_n = \kappa_n \cdot \varepsilon_n$ (linear response)
    - -> nMHC(v_m^k, v_n^l) = nMHC(ε_m^k, ε_n^l)
    - -> use nMHC(v_m^k, v_n^l) to constrain the initial conditions
  - $v_n \neq \kappa_n \cdot \varepsilon_n$ (nonlinear response)
    - -> nMHC(v_m^k, v_n^l) $\neq$ nMHC(ε_m^k, ε_n^l)
    - -> use nMHC(v_m^k, v_n^l) to probe properties of QGP
- Expectations: better agreements in central collisions and for lower harmonics

This analysis





Pb-Pb 2.76 TeV



Pb-Pb 5.02 TeV

❖**Detectors used:**

- Inner Tracking System
  (trigger, tracking and vertexing)
- Time Projection Chamber
  (tracking)
- V0 detectors
  (trigger, centrality determination)

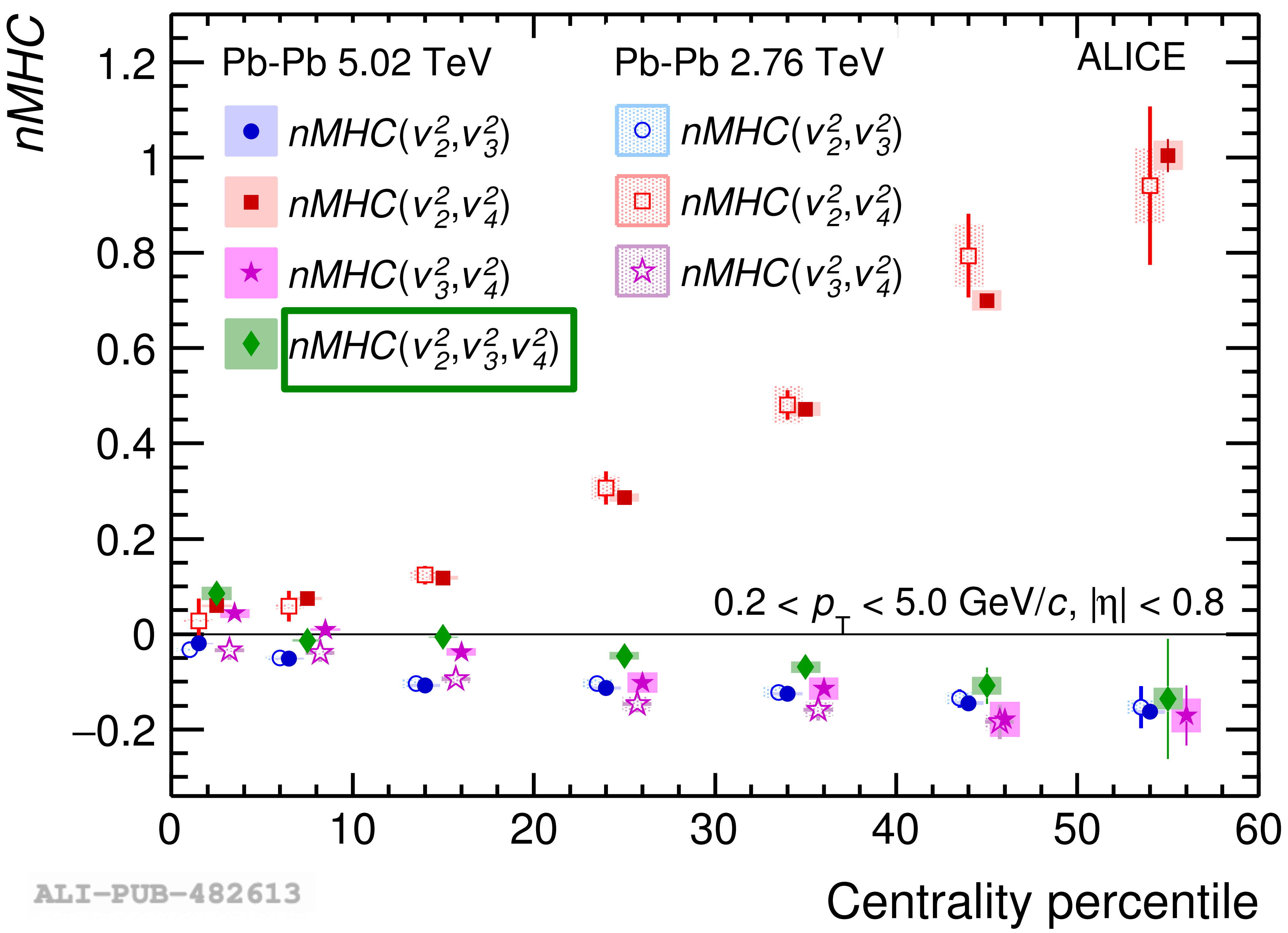
❖**Data samples:**

- Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
- Pb-Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
- Tracks used:
  - $-0.8 < \eta < 0.8$
  - $0.2 < p_T < 5.0$ GeV/c

Correlation between v_m^2, v_n^2 and v_p^2

NEW

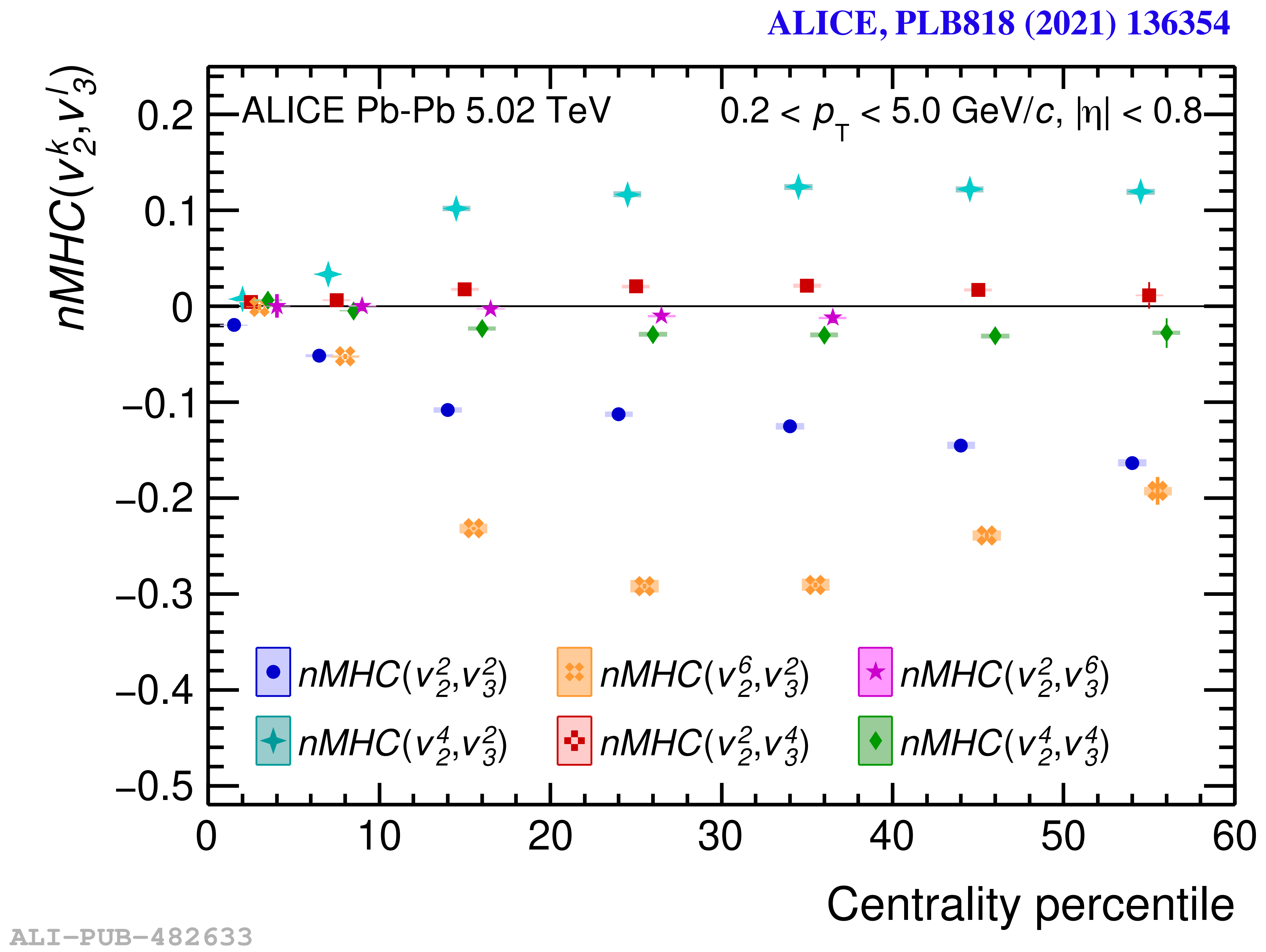
ALICE, PLB818 (2021) 136354

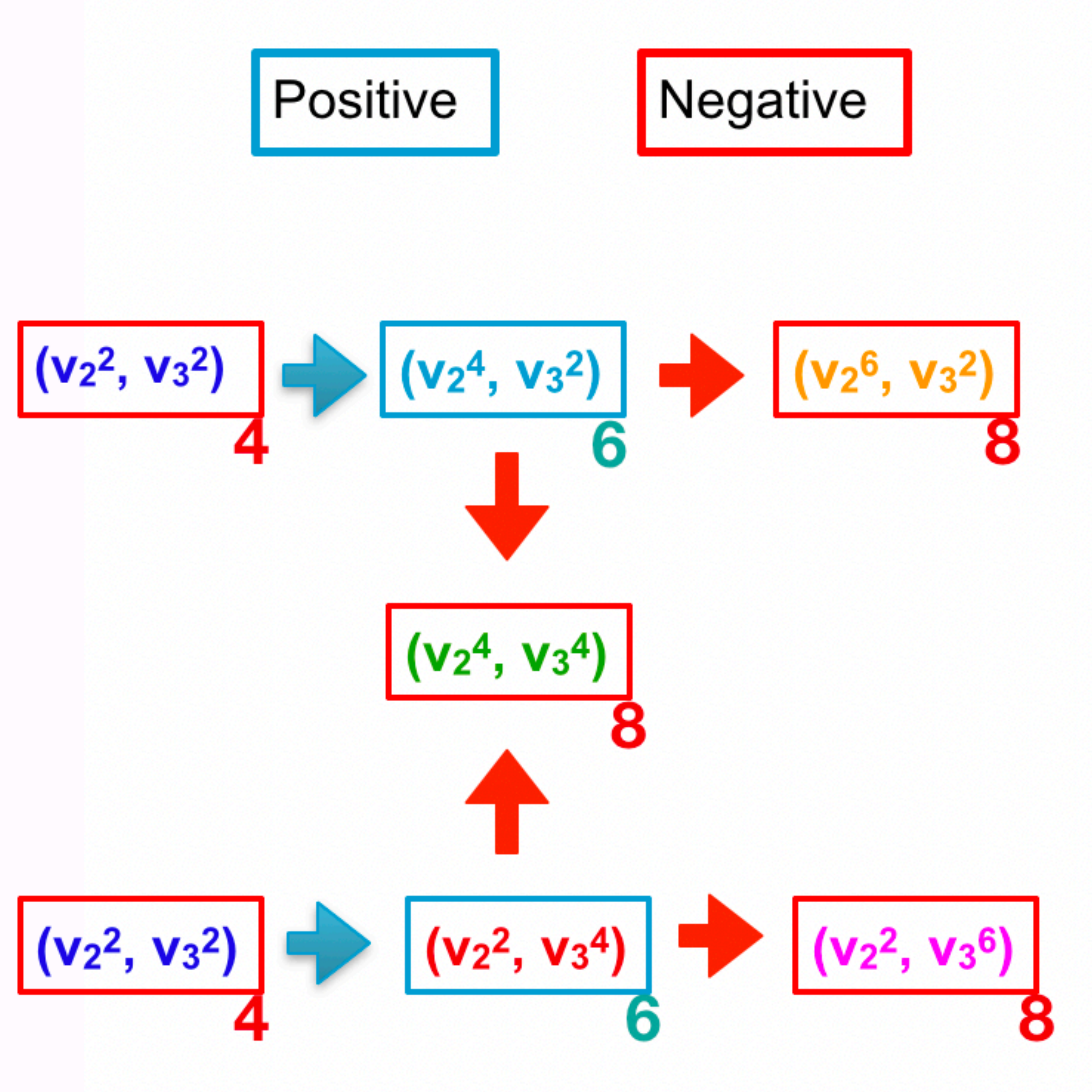


- ❖ Non-zero value of $nMHC(v_2^2, v_3^2, v_4^2)$ in Pb-Pb collisions
  - Highly non-trivial correlations among three flow coefficients
  - The result is positive and closer to $nMHC(v_2^2, v_4^2)$ and $nMHC(v_3^2, v_4^2)$ in central collisions
  - It is negative and follows $nMHC(v_2^2, v_3^2)$ and $nMHC(v_3^2, v_4^2)$ in non-central collisions

First measurement of v_m^k and v_n^l correlations

NEW



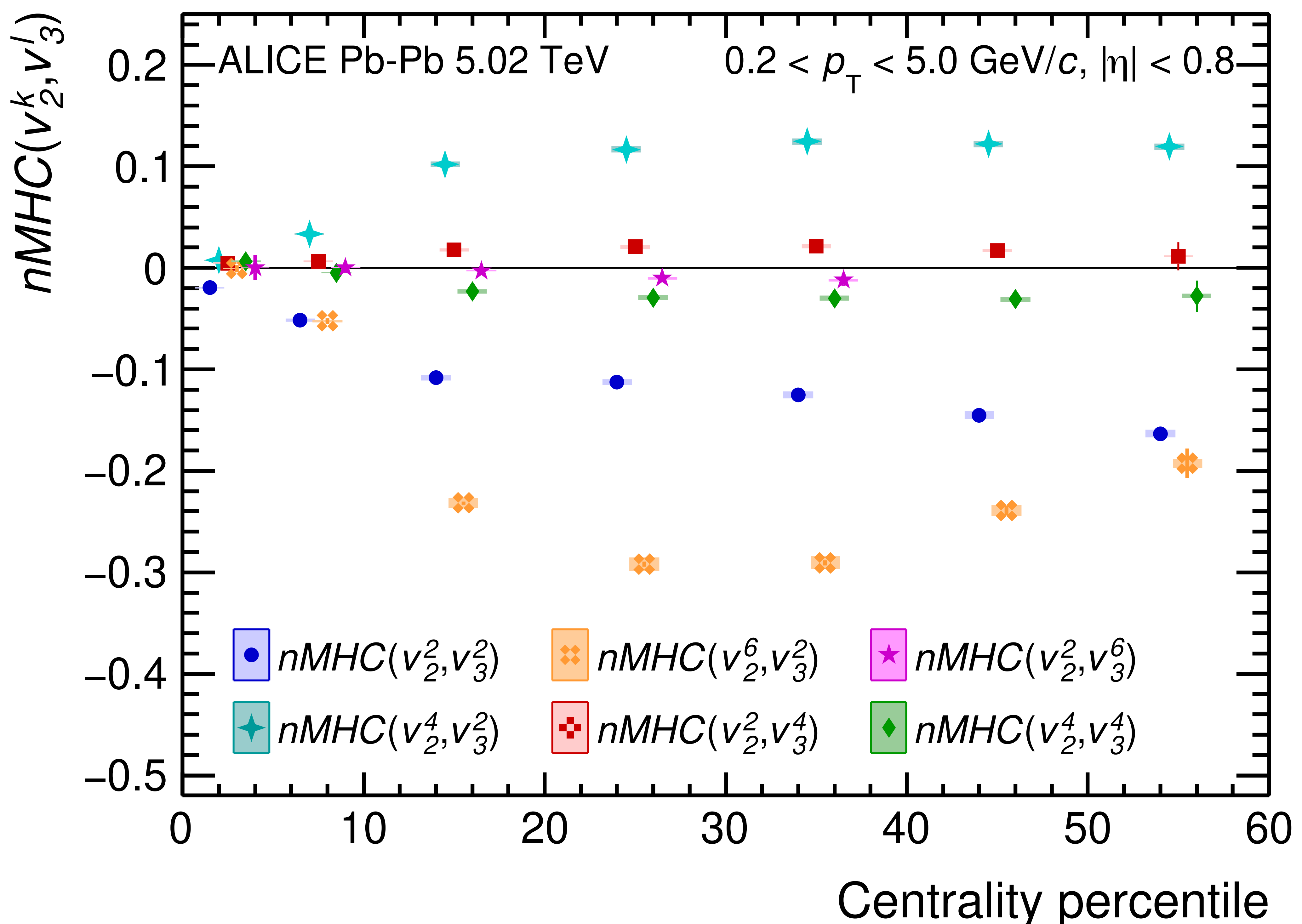


- First measurement of correlations between higher order moments of v_2 and v_3
  - characteristic -, +, - signs observed for 4-, 6- and 8-particle cumulants of *mixed harmonics*

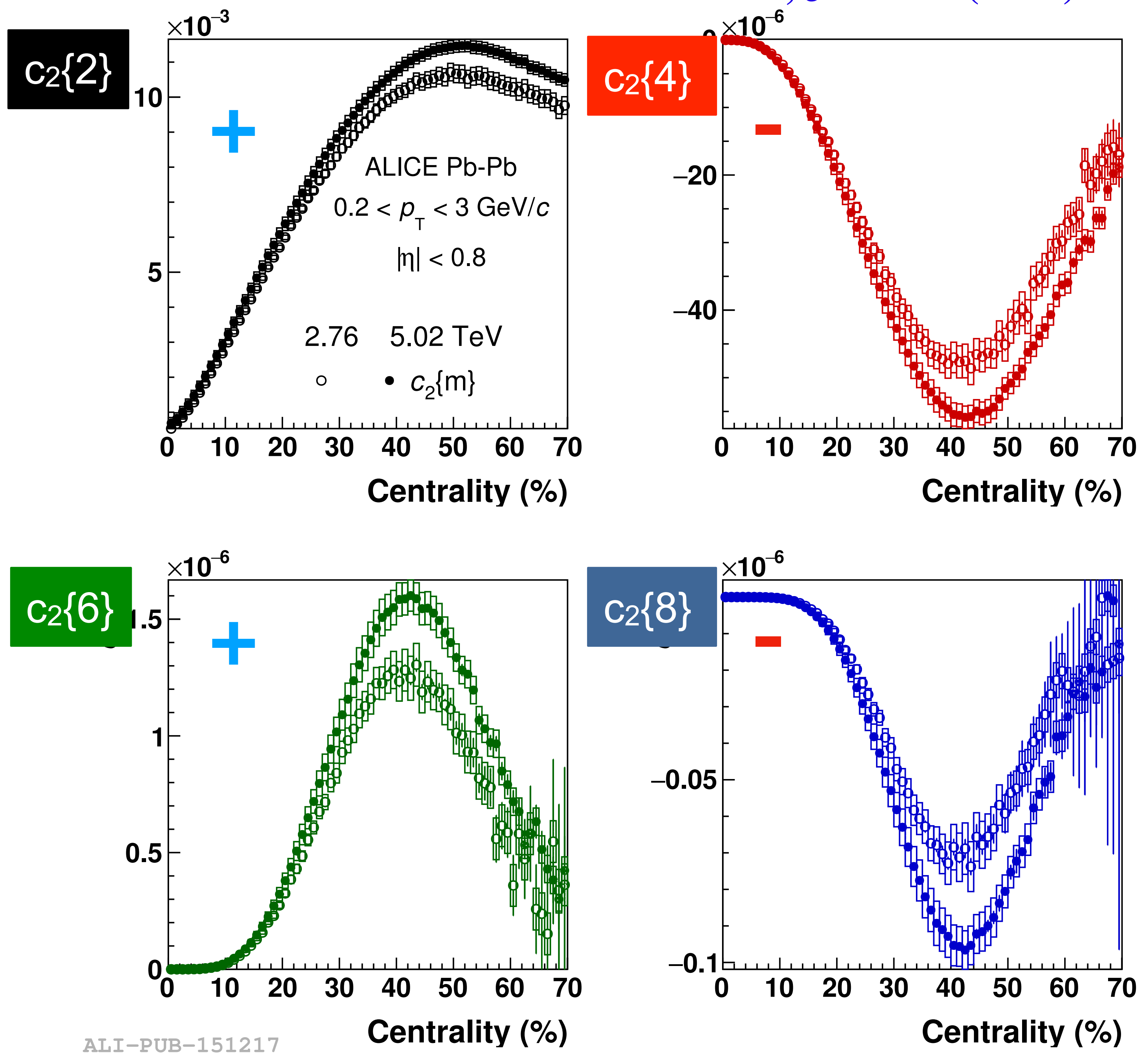
First measurement of v_m^k and v_n^l correlations

NEW

ALICE, PLB818 (2021) 136354



ALICE, JHEP07 (2018) 103

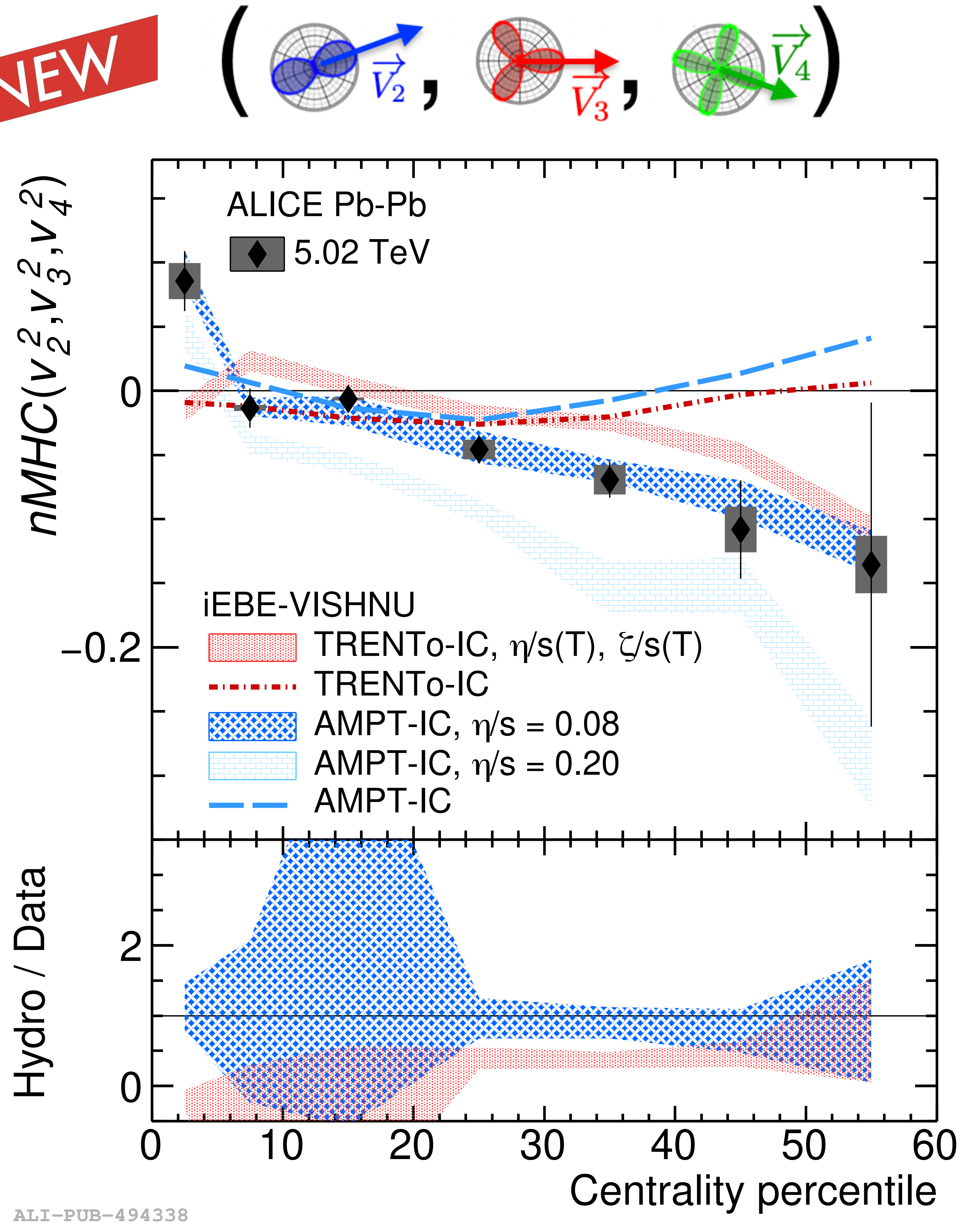


❖ First measurement of correlations between higher order moments of v_2 and v_3

- characteristic -, +, - signs observed for 4-, 6- and 8-particle cumulants of *mixed harmonic*
- Similar to +, -, +, - signs seen in 2-, 4-, 6- and 8-particle cumulants of *single harmonic*
- *A potential probe of collectivity in small systems*

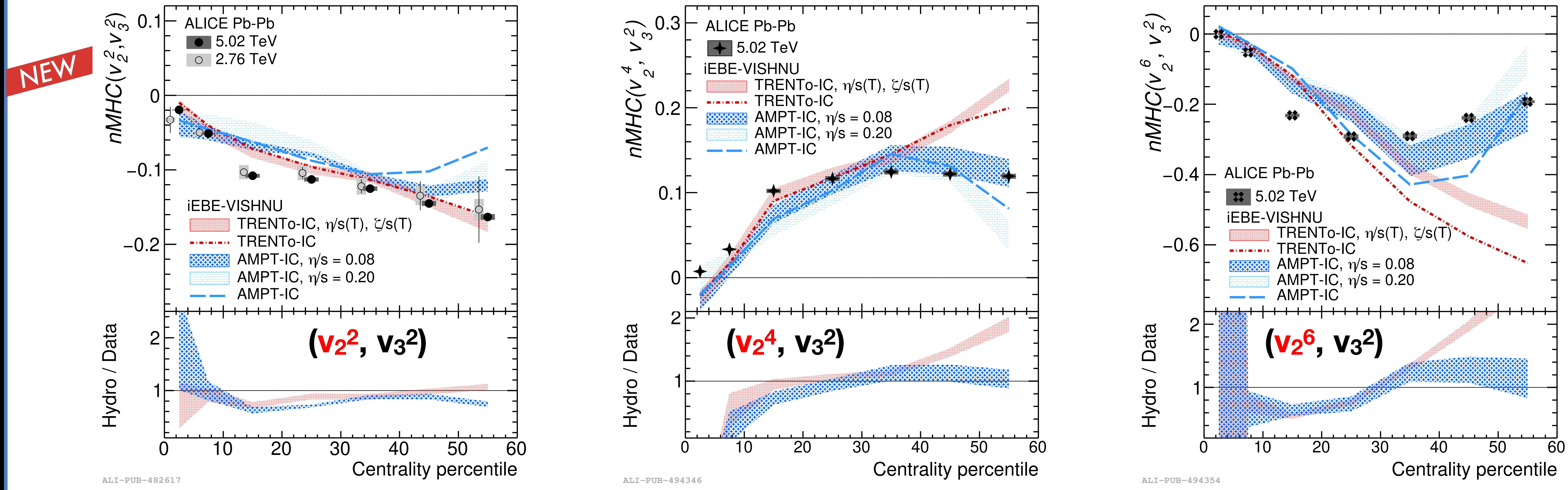
Data vs hydro: v_m^2, v_n^2 and v_p^2 correlations

NEW



- ❖ *nMHC*$(v_2^2, v_3^2, v_4^2) \neq$ *nMHC*$(\varepsilon_2^2, \varepsilon_3^2, \varepsilon_4^2)$
  - Non-linear response
  - *nMHC*(v_2^2, v_3^2, v_4^2) is sensitive to η/s of QGP
- ❖ AMPT+iEBE-VISHNU calculations quantitatively agree with the ALICE data
- ❖ TRENTo+iEBE-VISHNU calculations underestimate the data by 50%
- ❖ A new challenge for the current understanding of initial conditions and QGP properties from Bayesian analysis (TRENTo+iEBE-VISHNU) with the presented *nMHC*(v_m^2, v_n^2, v_p^2) data

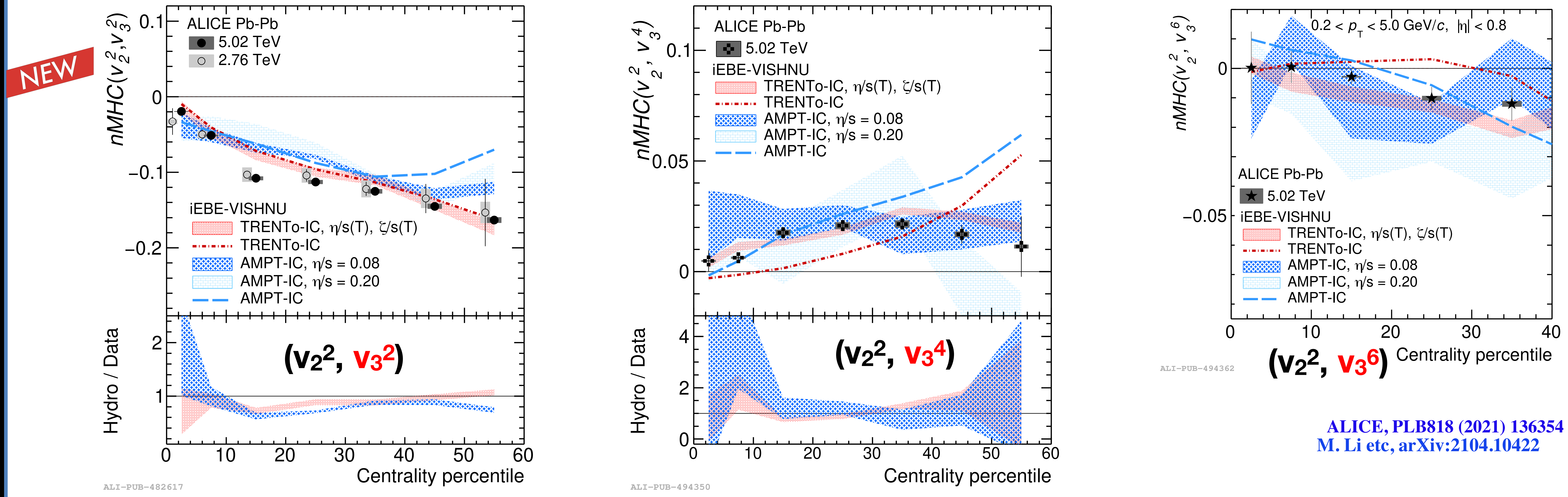
v_2^k and v_3^2 correlations



ALICE, PLB818 (2021) 136354
M. Li etc, arXiv:2104.10422

- ❖ Good agreement between initial eccentricity estimations and final *nMHC*(v_2^k, v_3^2) in central collisions
- ❖ Deviations are getting larger in more peripheral collisions and/or for higher order moments of v_2
  - ‣ Non-linear response of v_2 in non-central Pb-Pb collisions
- ❖ AMPT+iEBE-VISHNU calculations work better in peripheral collisions

v_2^2 and v_3^ℓ correlations



ALICE, PLB818 (2021) 136354
M. Li etc, arXiv:2104.10422

❖ Deviations between initial eccentricity estimations and final nMHC(v_2^2, v_3^ℓ) already in central collisions

- Stronger nonlinear response of v_3 than v_2 in Pb-Pb collisions

  -> more sensitive to η/s(T) of QGP

❖ Both hydro calculations are compatible with data within large uncertainties

Summary

- ❖ General correlations between flow coefficients are studied using mixed harmonic cumulants
  - Non-zero *nMHC*(v_2^2, v_3^2, v_4^2) is observed, results are sensitive to the initial conditions and shear and bulk viscosities of the QGP
  - ***Negative, positive and negative*** signs of 4-, 6- and 8-particle cumulants with mixed harmonics have been observed
  - The results involving higher-order moments could significantly enhance the contributions that arise from nonlinearities of v_2 and v_3 to ε_2 and ε_3
- ❖ Further information on the initial conditions and tighter constraints on the evolution of the QGP

Thanks for your attention!

Backup

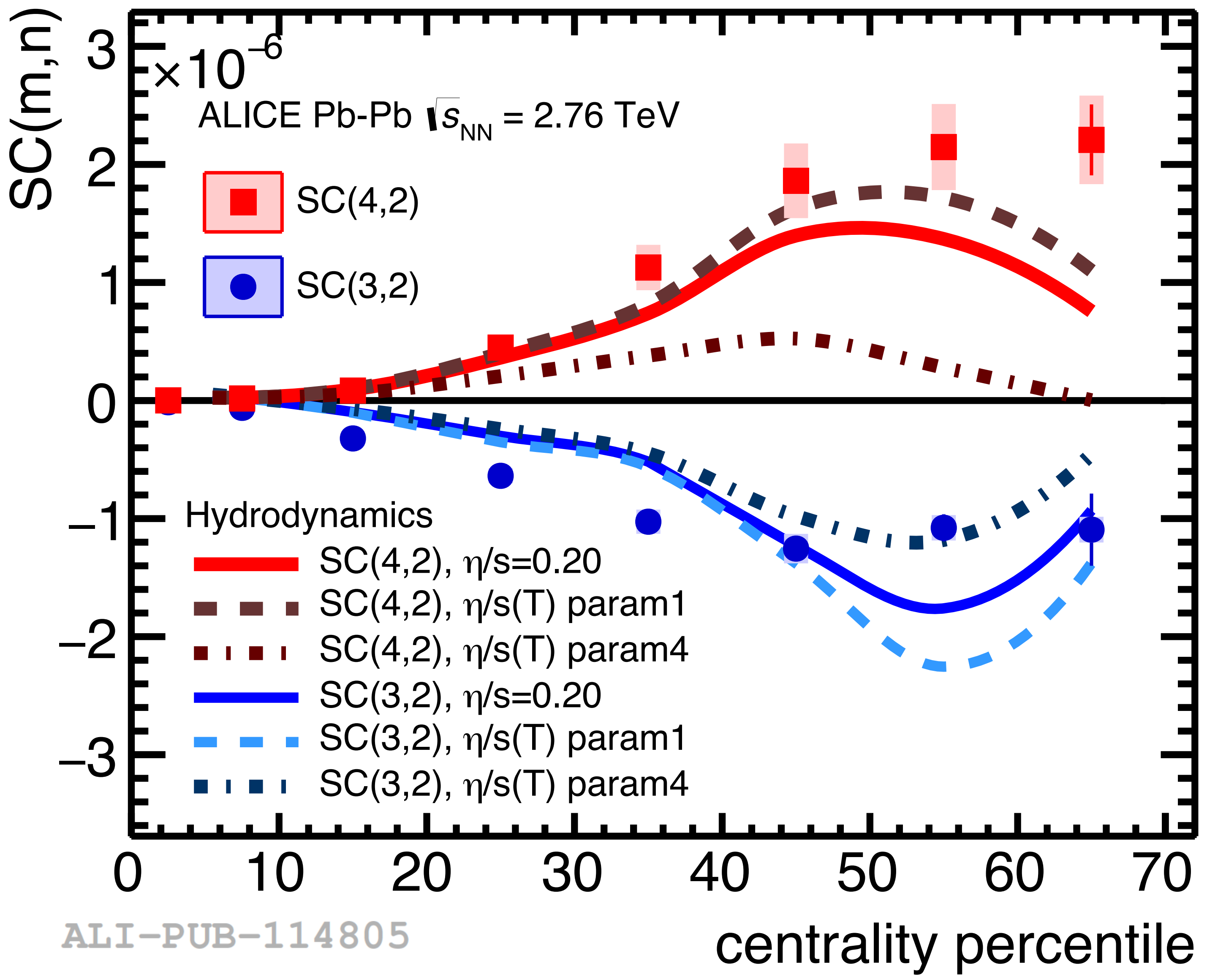
Correlations between v_m and v_n

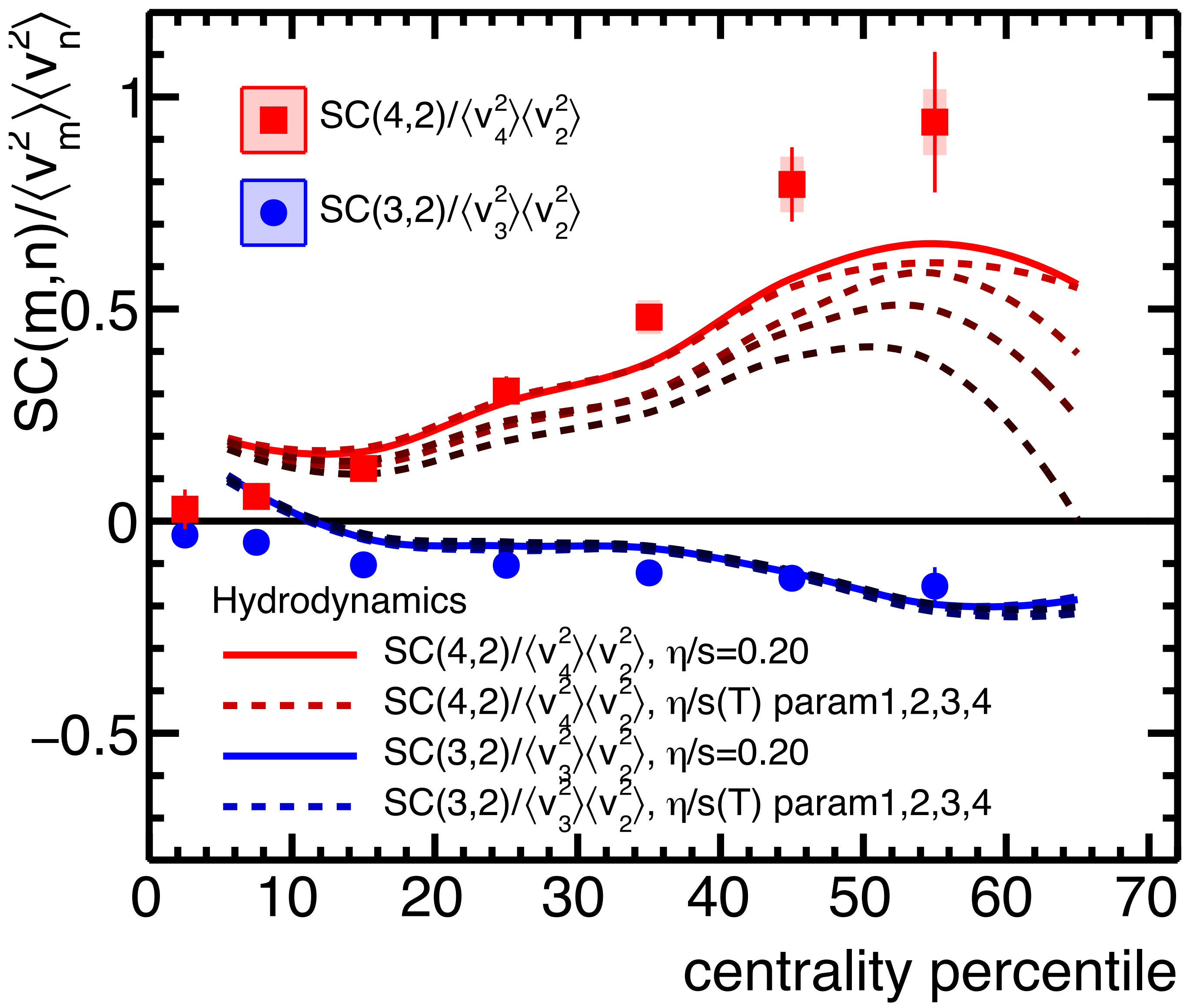
Symmetric cumulants:

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

Normalized Symmetric cumulants:

$$NSC(m,n) = \frac{SC(m,n)}{\langle v_m^2 \rangle \langle v_n^2 \rangle}$$



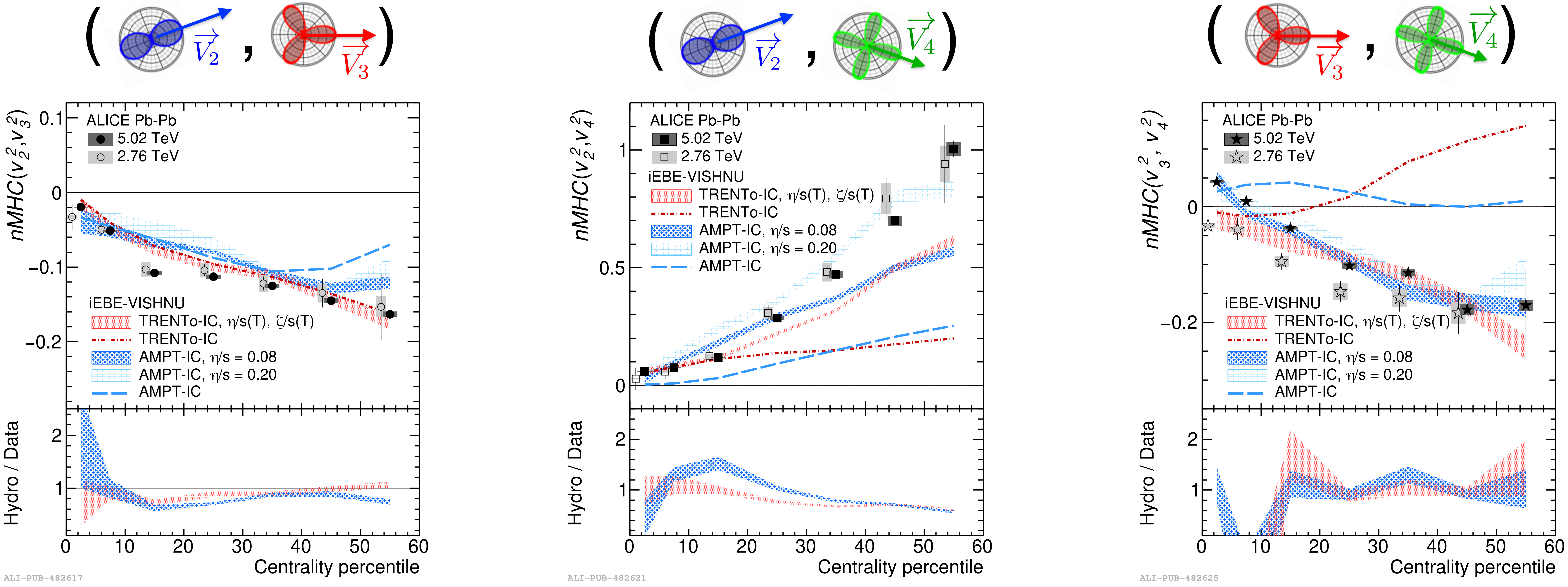


Symmetric Cumulant, PRC89, 064904 (2014)

ALICE, PRL117, 182301 (2016)

- Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations
  - Although hydrodynamic calculations describes v_n fairly well, do not describe SC and NSC
    -> tighter constraints!
  - NSC(3,2) measurements provide direct access into the initial conditions
  - NSC(4,2) is sensitive to both initial conditions and η/s(T)

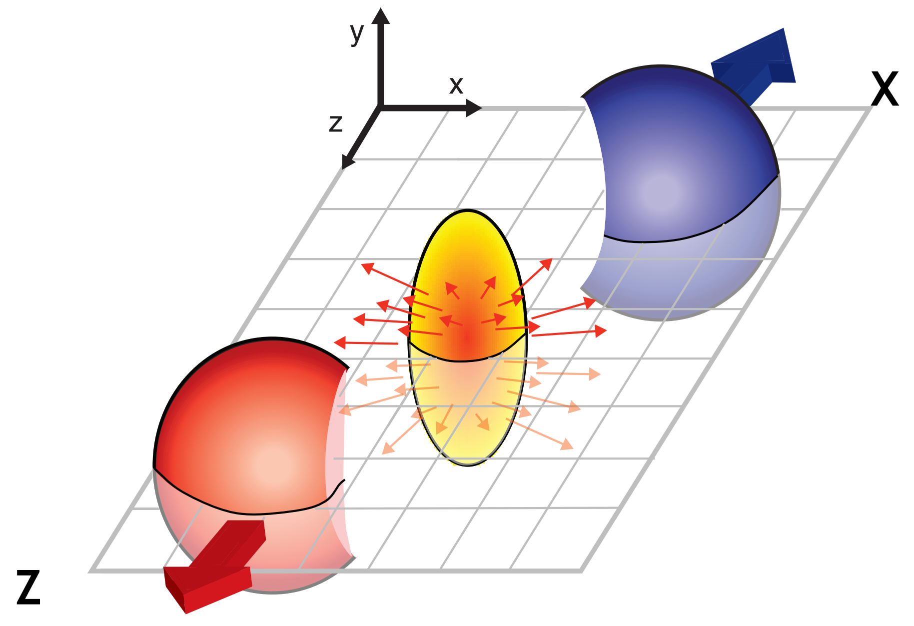
Data vs hydro: v_m^k and v_n^l correlations



ALICE, PLB818 (2021) 136354

- ❖ *nMHC(v_2^2, v_3^2)* is insensitive to η/s, reflects information from the initial conditions
- ❖ *nMHC(v_2^2, v_4^2)* and *nMHC(v_3^2, v_4^2)* are very different from nMHC(ε_m^k, ε_n^l)
  - ‣ *Significant contributions from nonlinear hydrodynamic response*
- ❖ Deviation of *nMHC(v_3^2, v_4^2)* from two energies -> larger centrality fluctuations at 5.02 TeV

Studying QGP with flow

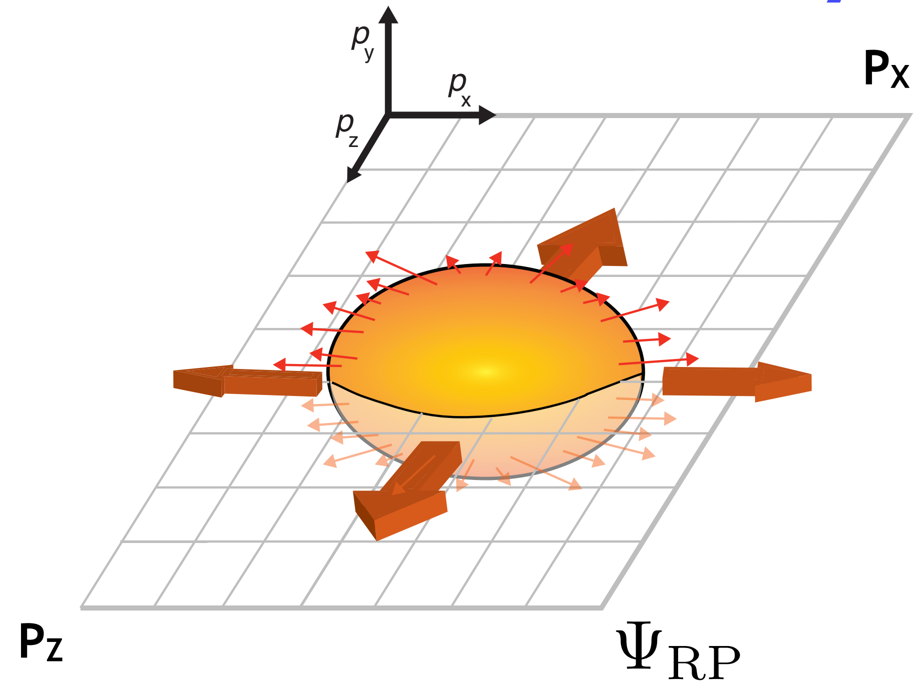


Initial state

$$\varepsilon_2 = \left\langle \frac{y^2 - x^2}{y^2 + x^2} \right\rangle$$

Initial spatial Eccentricity

system expansion



$\Psi_{\rm RP}$

Final state

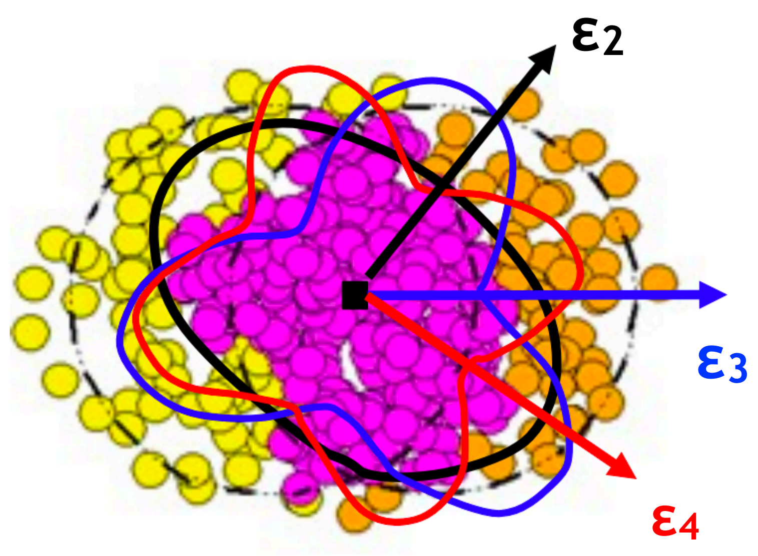
$$v_2 = \langle \cos 2\,(\varphi - \Psi_{\rm RP}) \rangle$$

momentum space Elliptic Flow

❖ Spatial eccentricity in the initial state converted to momentum anisotropic particle distributions

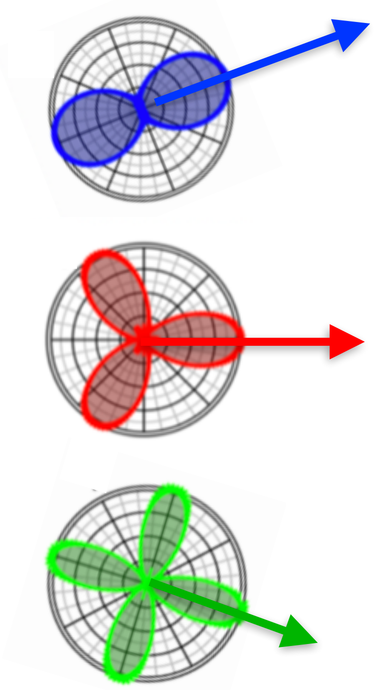
- known as ***elliptic flow***
- reflect initial **eccentricity** and **transport properties** of QGP

Initial state



system expansion

Final state



$\vec{V}_2$

$\vec{V}_3$

$\vec{V}_4$

$$\vec{V}_n = v_n\, e^{-in\Psi_n}$$

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❖ General questions:

- how does v_n fluctuate
- how does Ψ_n fluctuate
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- **correlations between v_m and v_n**
- new information on initial conditions and/or $\eta/s(T)$?

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