Constraining the medium properties with the anisotropic flow and its correlations in Pb–Pb collisions with ALICE

Cindy Mordasini for the ALICE Collaboration
CoE in Quark Matter – University of Jyväskylä
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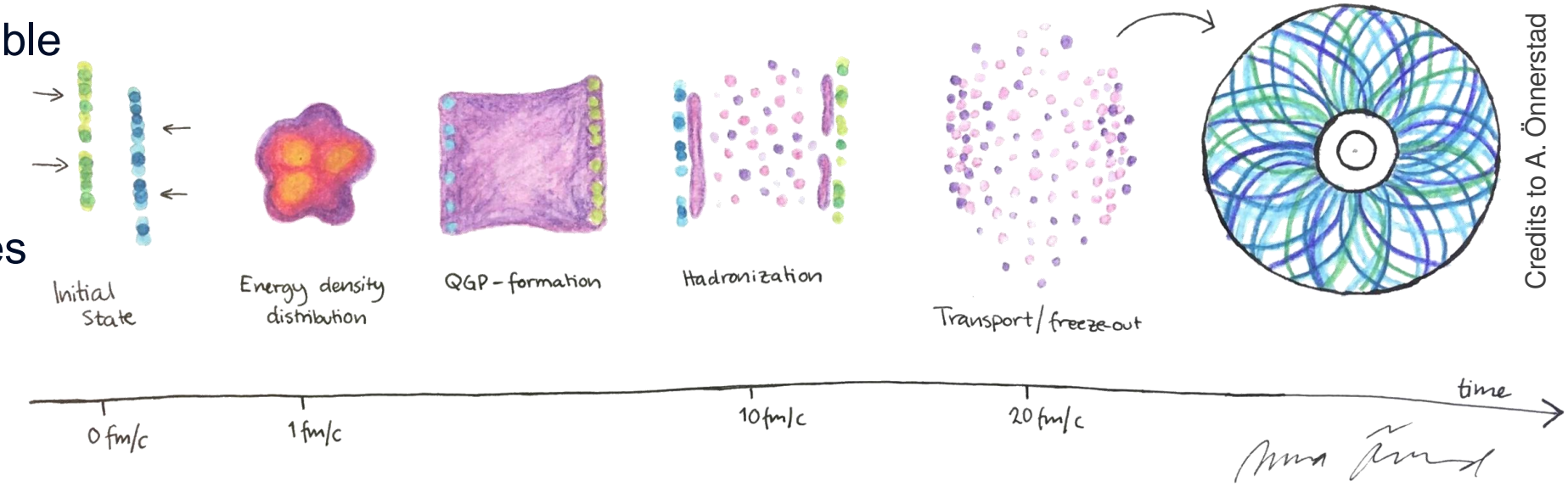
JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Constraining the medium properties

- QGP not directly accessible
- Understanding of the full collision evolution required
- Task: Identify observables sensitive to the different phases



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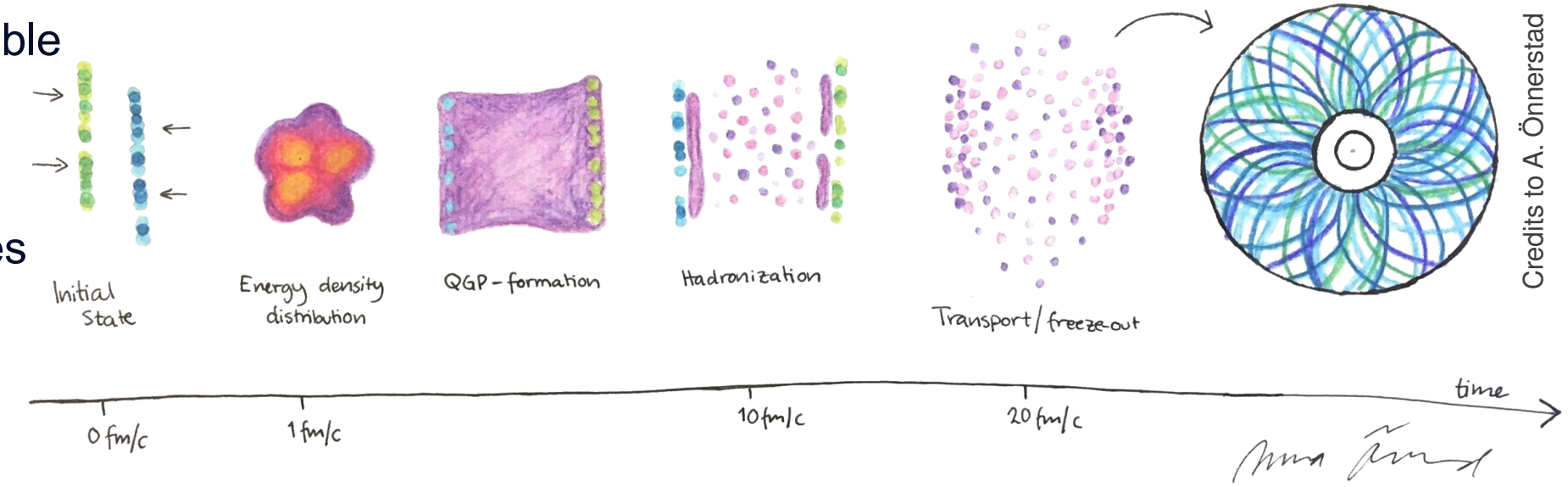
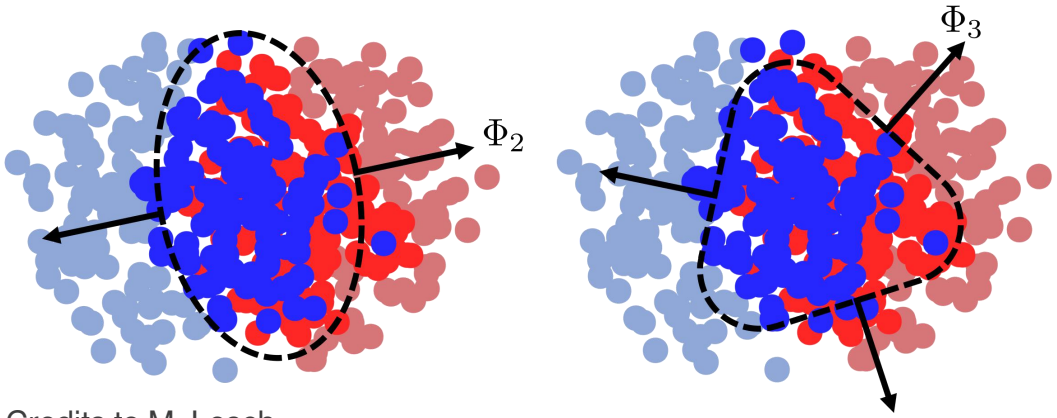


- Use anisotropic flow observables

$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\varphi - \Psi_n)]$$

S. Voloshin *et al.*, Z. Phys. C **70**, 665-672 (1996)



Credits to M. Lesch

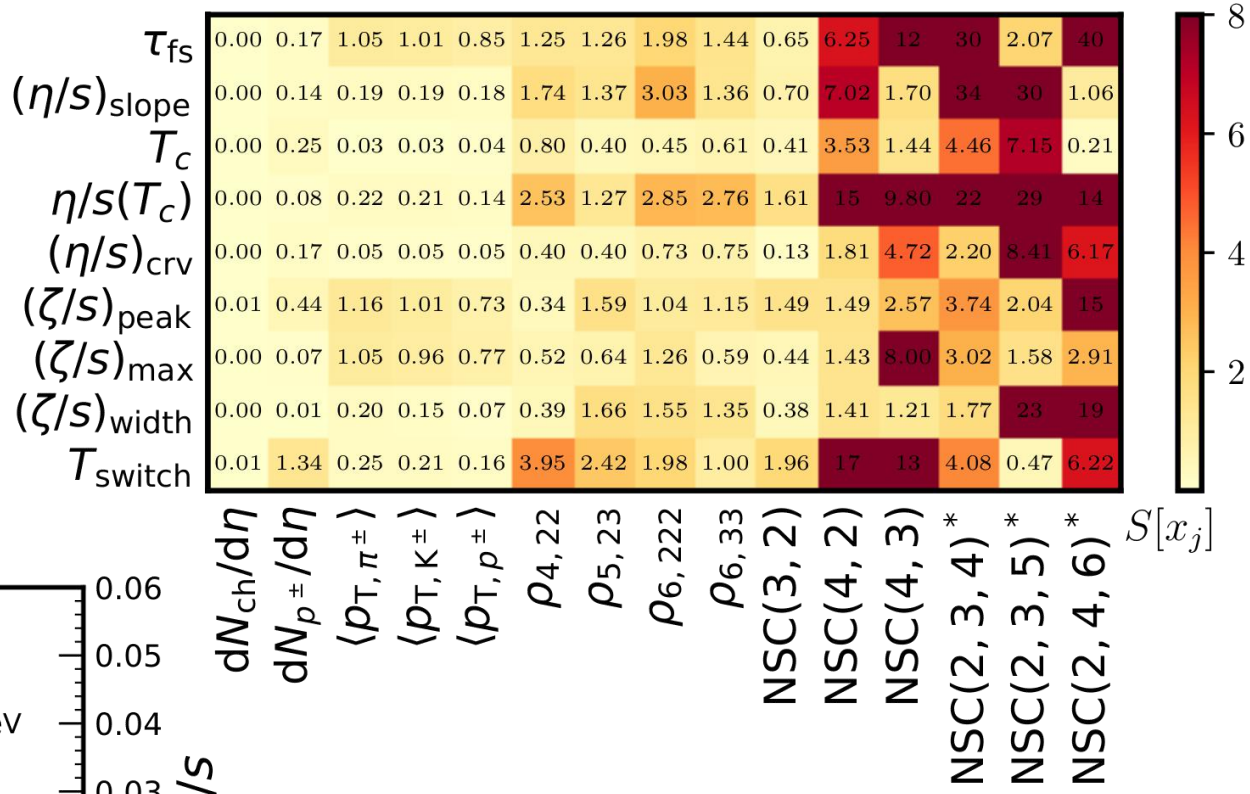
Valuable information on QGP properties from flow measurements!

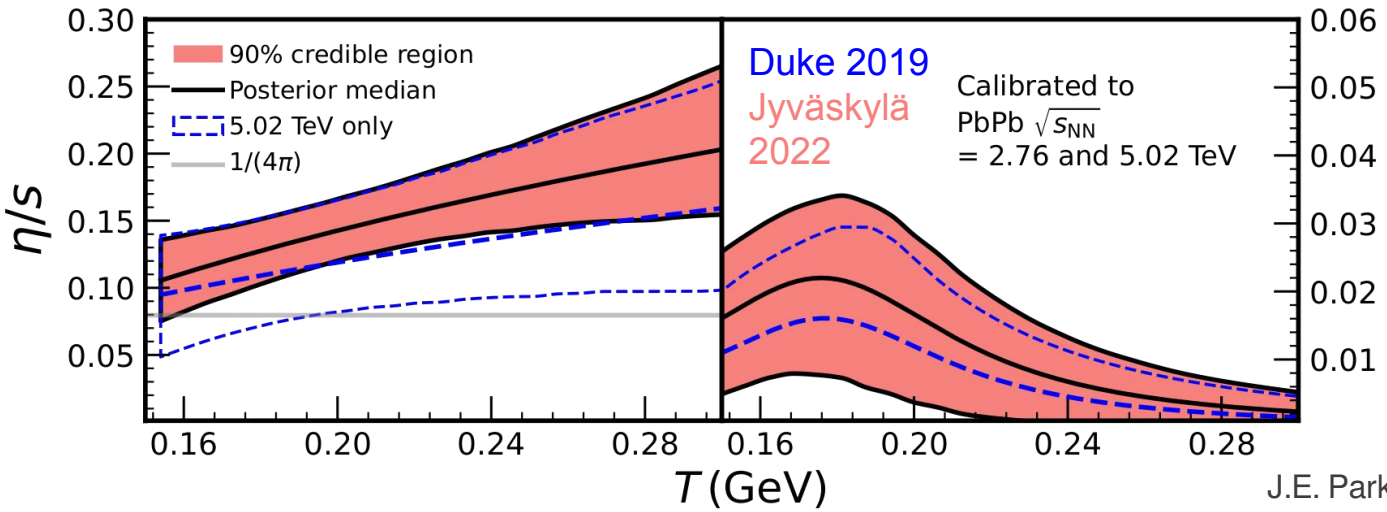
Which observables?

- The sensitivity of observables to model parameter variations depends on
  - which harmonics are used
  - the order of the largest correlator in the observable

→ Greater sensitivity of higher-order flow observables to QGP properties!

J.E. Parkkila *et al.*, Phys. Lett. B **835**, 137485 (2022)





$$\mathrm{S}[x_j] = \Delta/\delta \text{ with } \Delta = \frac{|\hat{O}(\mathbf{x}') - \hat{O}(\mathbf{x})|}{|\hat{O}(\mathbf{x})|}$$

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- A broad new set of opportunities to investigate

→ New observables: correlations between different moments of the flow amplitudes

→ New bias-free estimator of symmetry plane correlations

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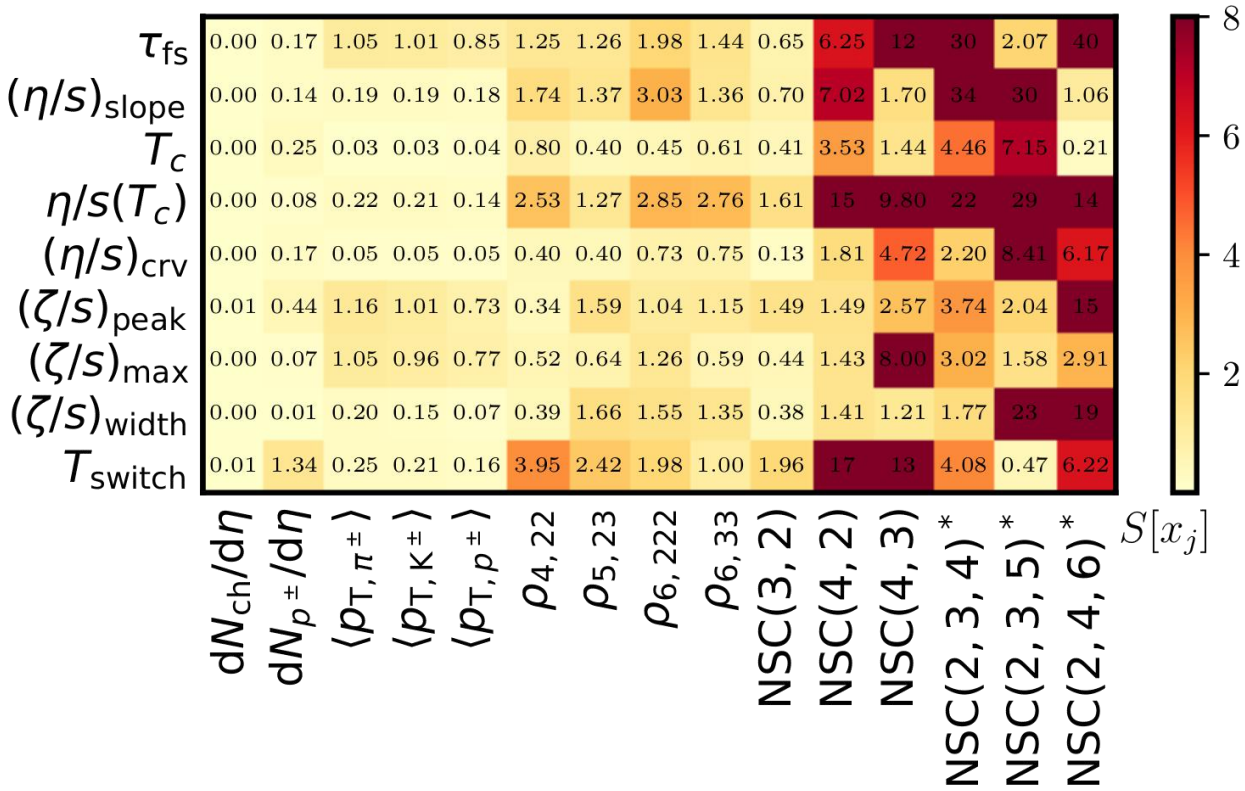
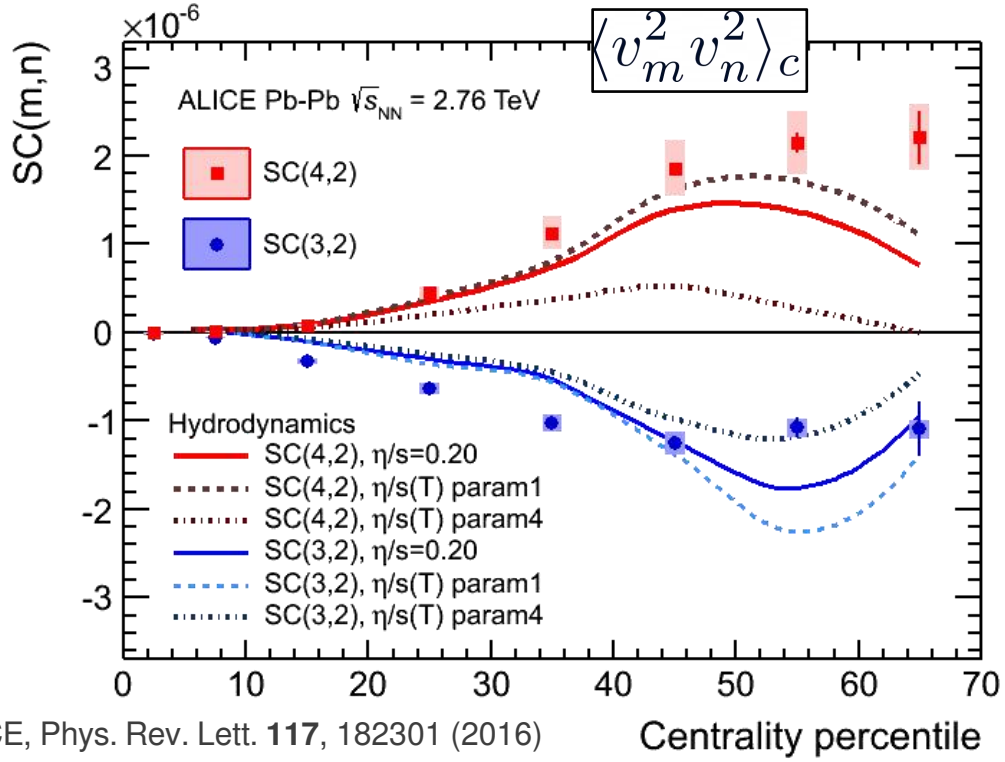


Flow amplitude correlations

- Symmetric cumulants (SC)

$$\langle v_m^2 v_n^2 \rangle_c$$

  - measure the genuine correlations between v_m^2 and v_n^2



ALICE, Phys. Rev. Lett. **117**, 182301 (2016)

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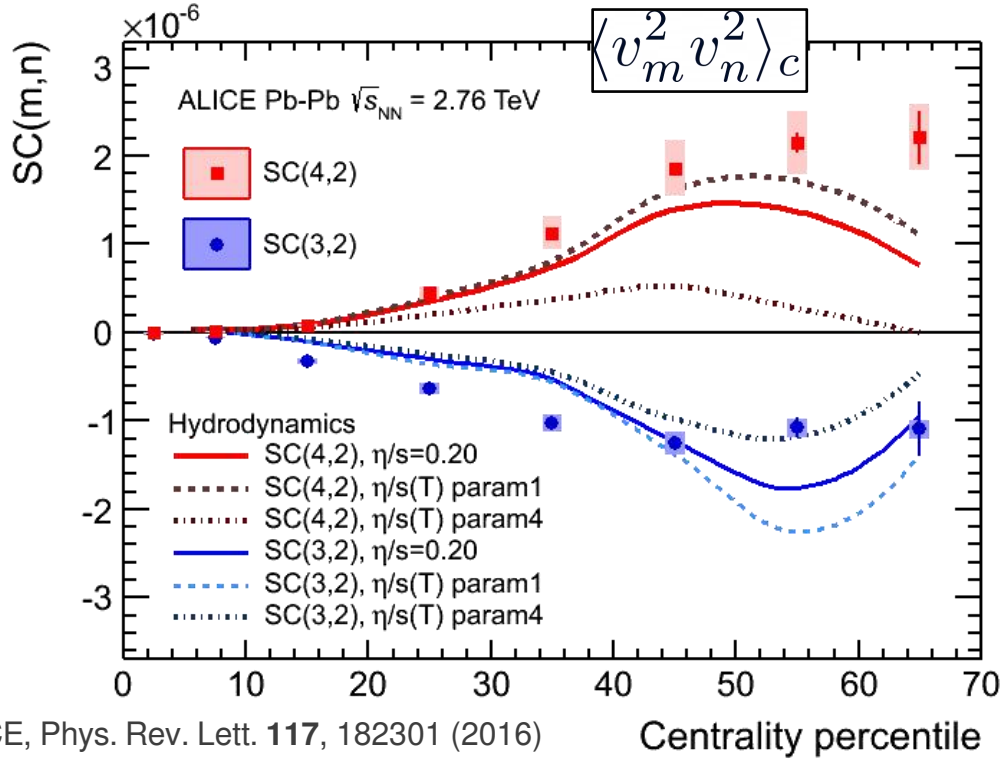
  - sensitivity to *η/s(T)* previously not accessible



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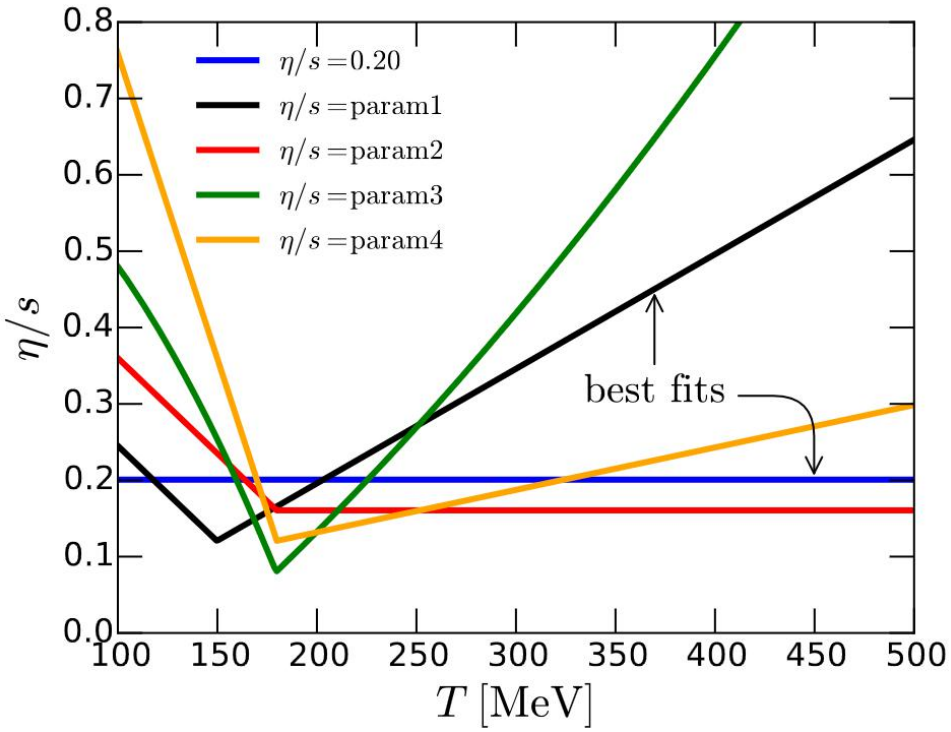
H. Niemi *et al.*, Nucl. Phys. A **956**, 312-315 (2016)



Flow amplitude correlations

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$$\langle v_m^2 v_n^2 \rangle_c$$

- Asymmetric cumulants (AC)

$$\langle v_m^4 v_n^2 \rangle_c, \langle v_m^6 v_n^2 \rangle_c, \ldots$$

- Most general form for two harmonics (*a,b*: moments)

$$\mathrm{AC}_{a,b}(m,n) \equiv \langle v_m^{2a} v_n^{2b} \rangle_c$$

$$\mathrm{NAC}_{a,b}(m,n) \equiv \frac{\mathrm{AC}_{a,b}(m,n)}{\langle v_m^2 \rangle^a \langle v_n^2 \rangle^b}$$

  - for *a,b* = 1: $\mathrm{AC}_{1,1}(m,n) \rightarrow \mathrm{SC}(m,n)$
  - easily generalized to more harmonics and moments

A. Bilandzic *et al.*, Phys. Rev. C **105**, 024912 (2022)

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- $\mathrm{AC}_{a,b}(m,n)$ and $\mathrm{AC}_{b,a}(m,n)$: sensitive to different terms of non-linear response

- 34 new measurements with *a* = 1–4 and *b* = 1 for the pairs of harmonics *(m,n)*: (2,3), (2,4) and (3,4)

ALICE, arXiv:2303.13414 (Submitted to Phys. Rev. C)

AC(2,4)

New paper

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- First measurements in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

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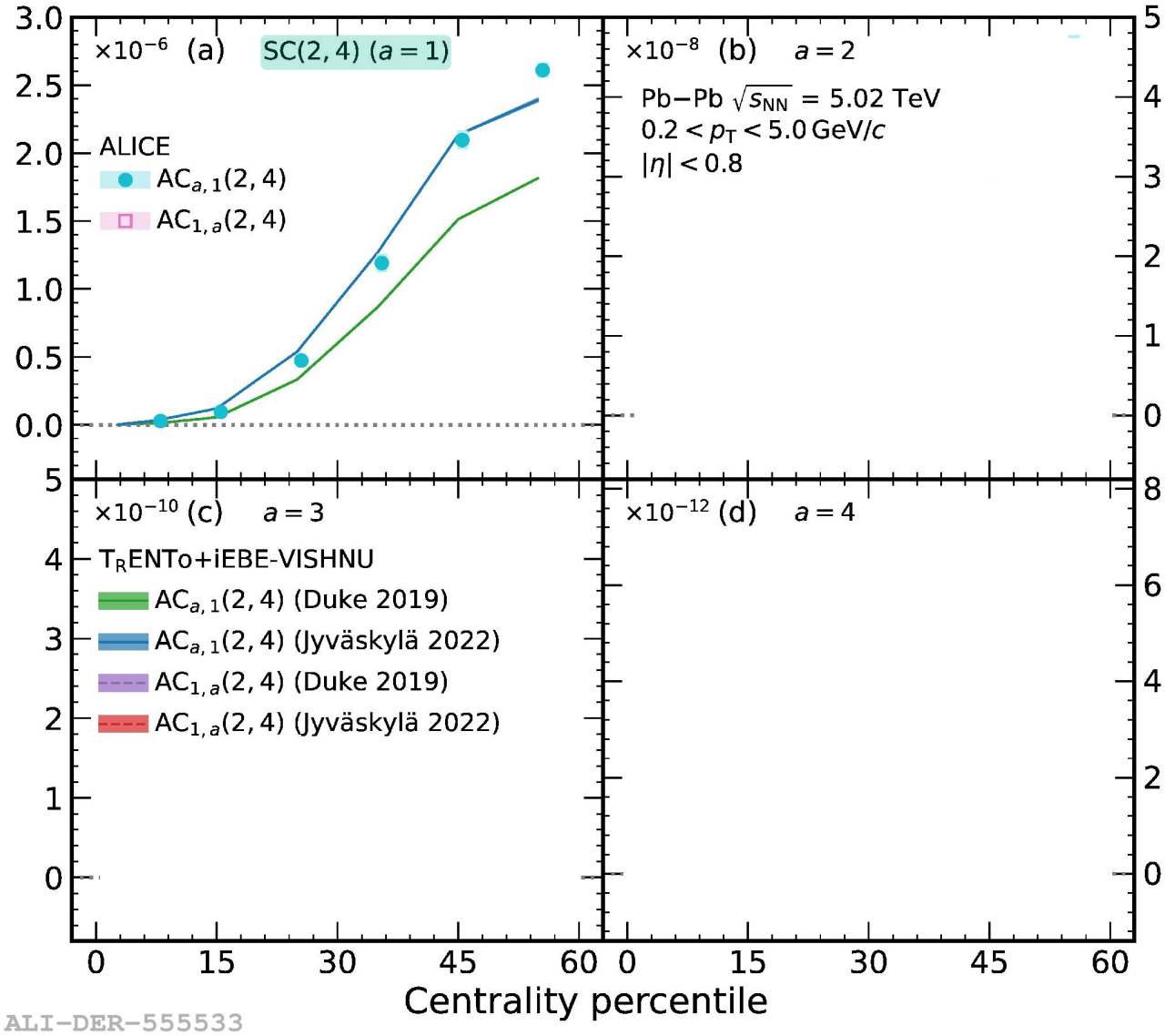
- Better description with Jyväskylä 2022[1] compared to Duke 2019[2]
  - quantitative: $\mathrm{SC}(2,4)$



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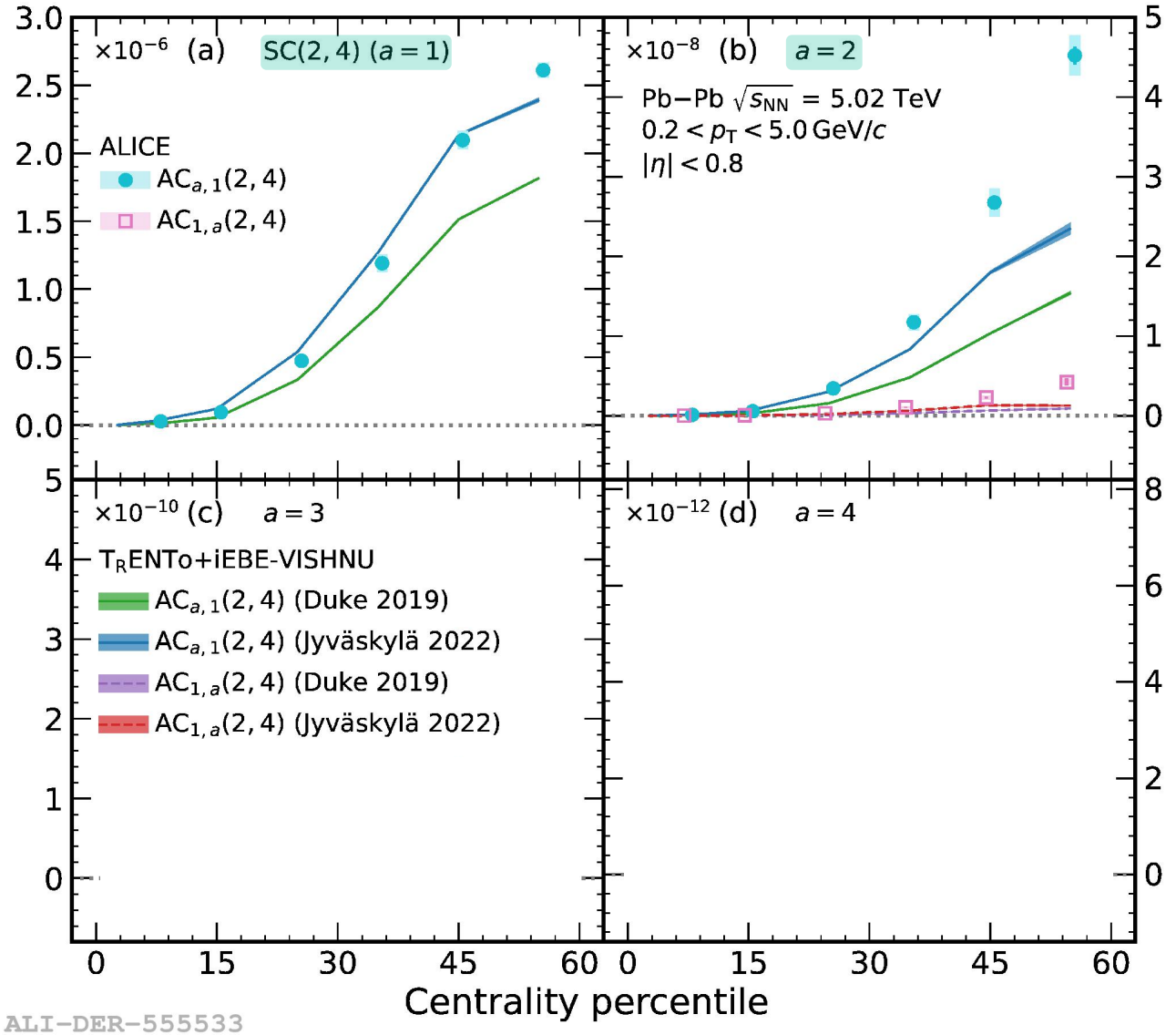
  - qualitative: $\mathrm{AC}_{a,1}(2,4)$ and $\mathrm{AC}_{1,a}(2,4)$, *a* = 2



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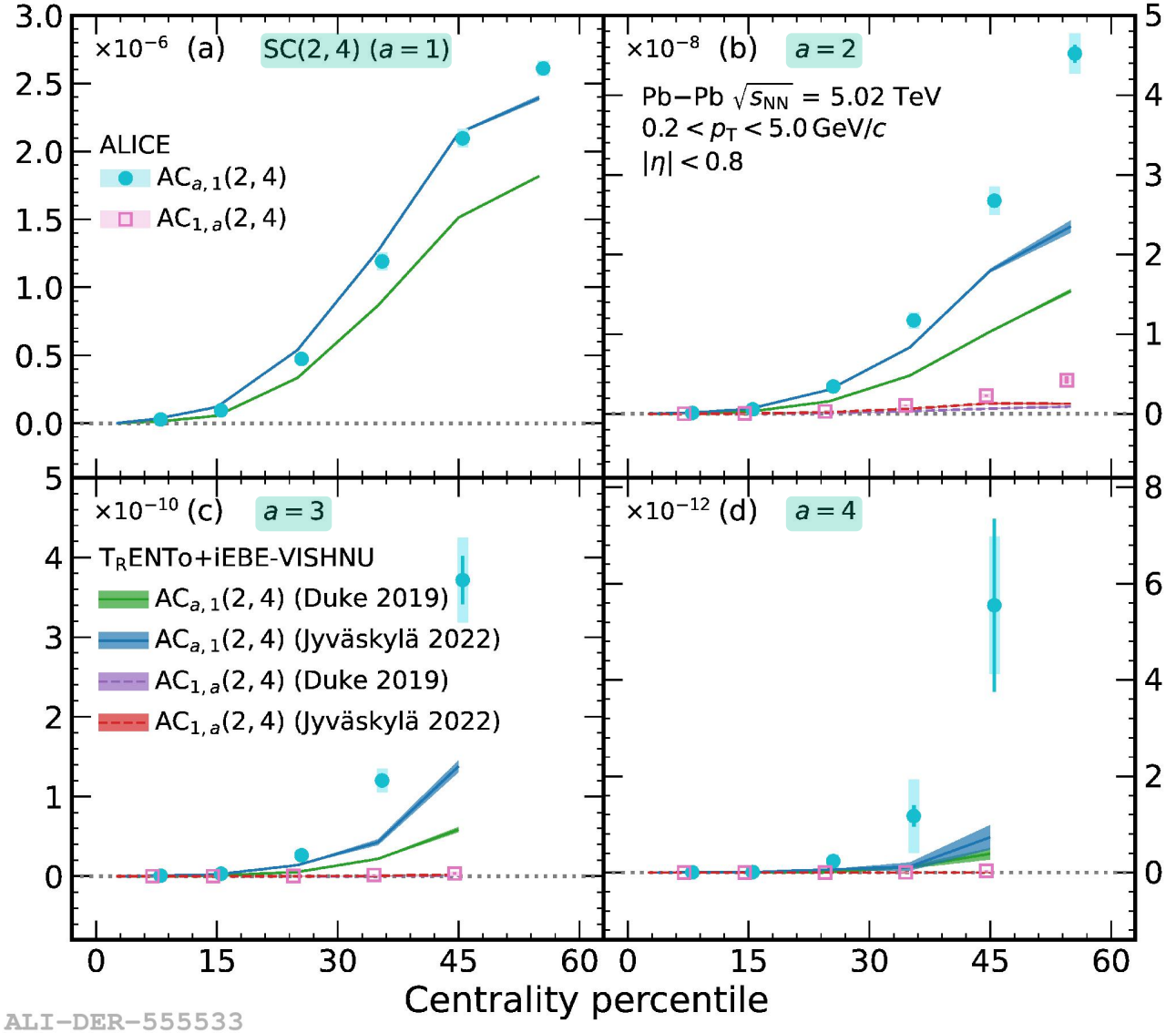
→ Discriminative power of AC(2,4) can lead to further improvements in model predictions



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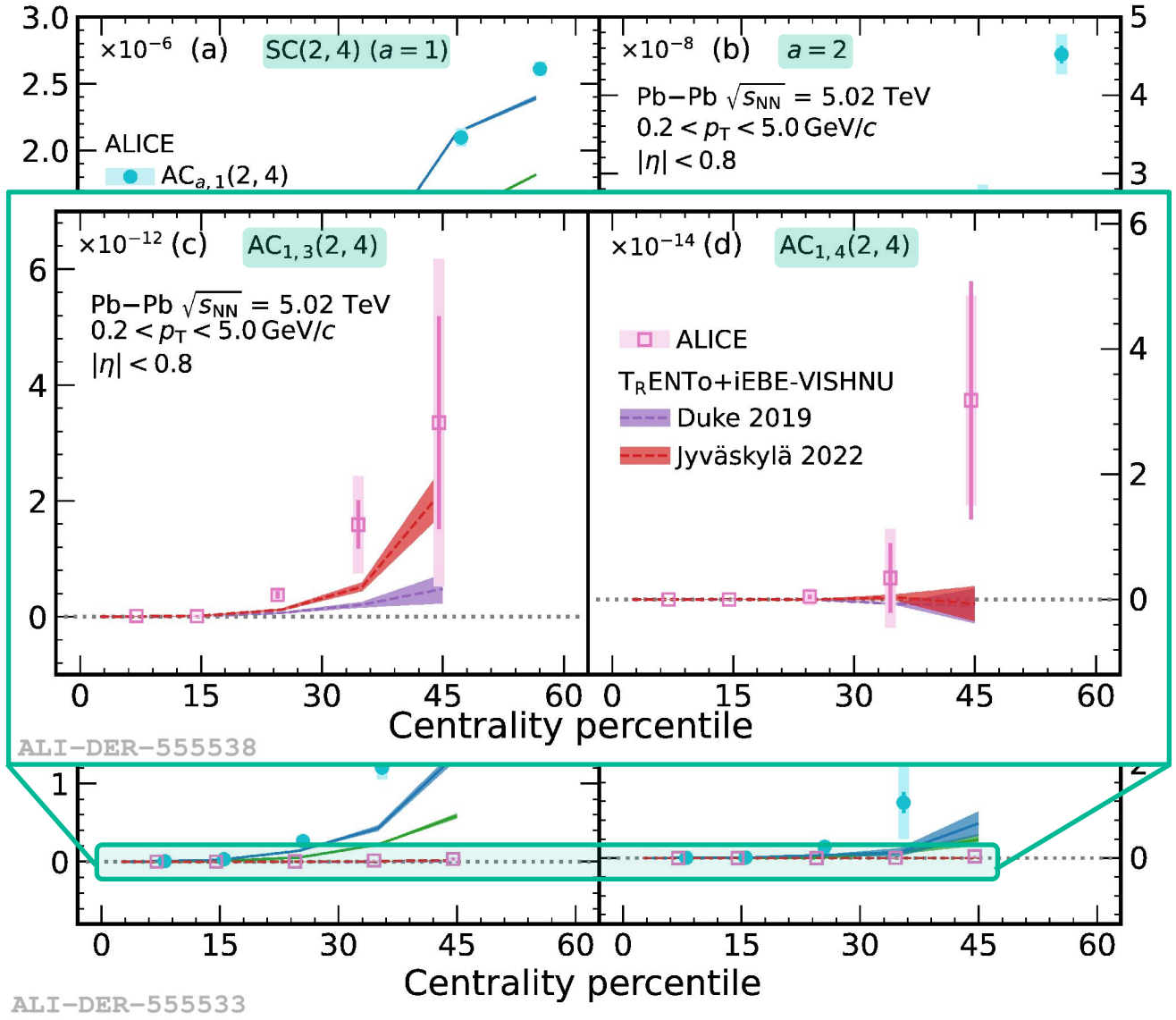
- Compatible with zero within uncertainties for $\mathrm{AC}_{1,3}(2,4)$ and $\mathrm{AC}_{1,4}(2,4)$

→ Potential constraints on non-linear response of v_4



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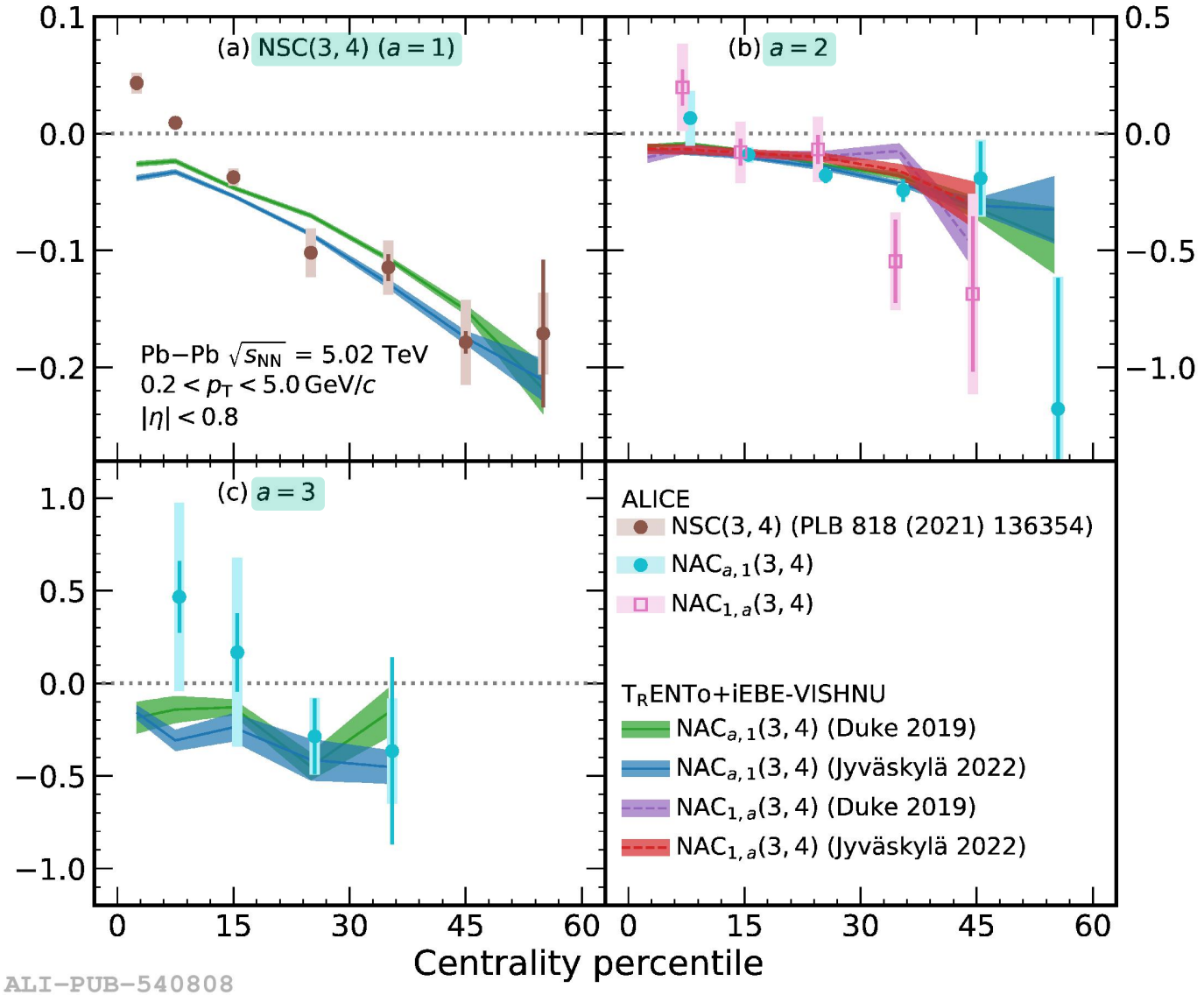

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- "Good" agreement between
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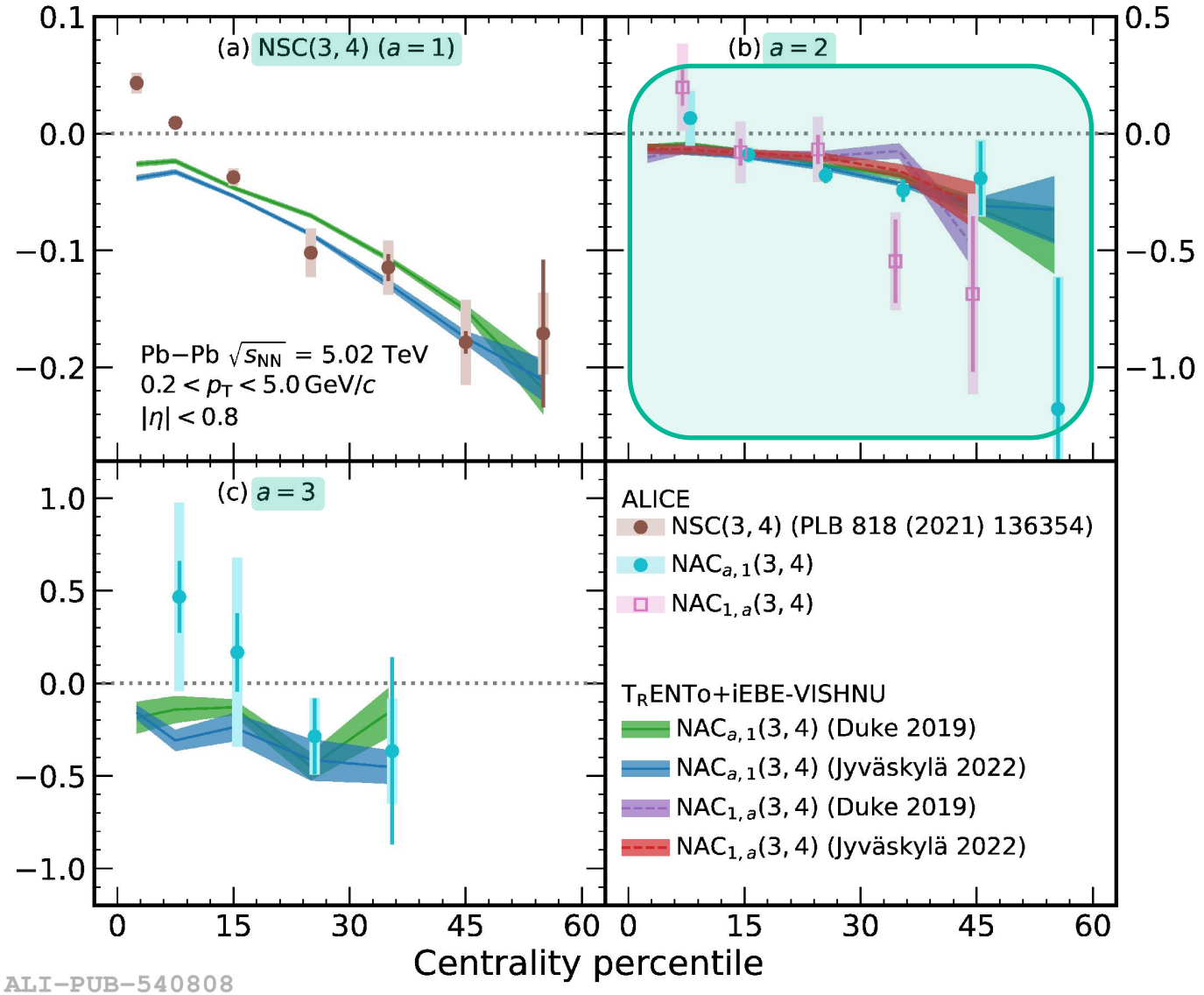
  - Duke 2019[1] and Jyväskylä 2022[2]
- Overlap between $\mathrm{NAC}_{2,1}(3,4)$ and $\mathrm{NAC}_{1,2}(3,4)$

→ May originate from interplay between the different phases of the collision

- Initial state predictions required



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Symmetry plane correlations (SPC)

- Some examples of SPC observables

$$\langle \cos[4(\Psi_4 - \Psi_2)] \rangle, \langle \cos[6(\Psi_2 - \Psi_3)] \rangle, \langle \cos[2\Psi_2 + 3\Psi_3 - 5\Psi_5] \rangle, \ldots$$

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- Previously: Scalar Product (SP) method[1,2]

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Problem: $\langle v_2^4 v_4^2\rangle \neq \langle v_2^4\rangle\langle v_4^2\rangle$
→ Biased measurements

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→ Sensitive only to contributions of symmetry planes

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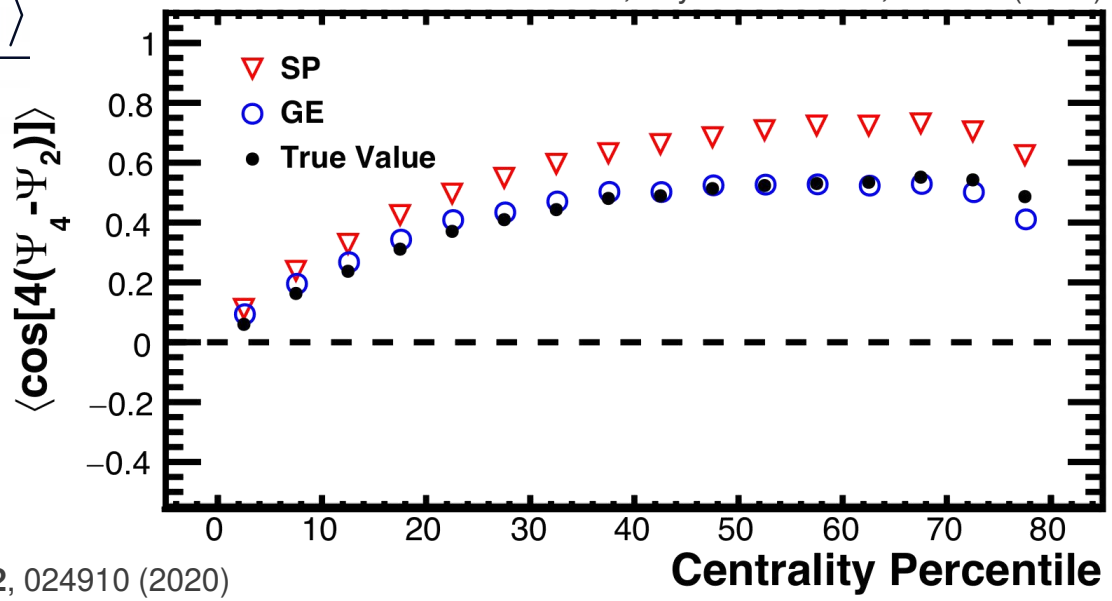
- Predictions from MC-Glauber+iEBE-VISHNU in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV

→ GE overcomes bias in SP method

A. Bilandzic *et al.*, Phys. Rev. C **102**, 024910 (2020)



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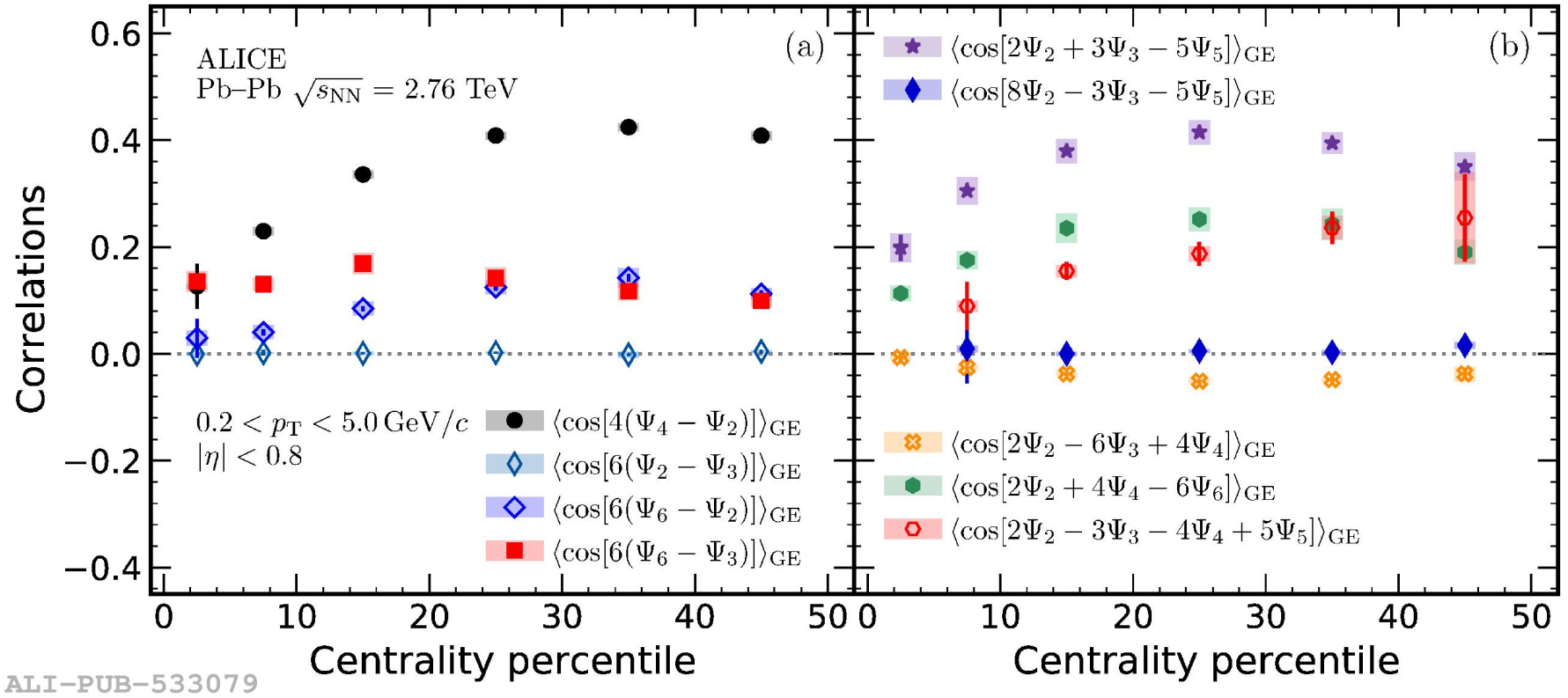
New SPC at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV

ALICE, Eur. Phys. J. C **83**, 576 (2023)

New paper



- First measurements of SPC between two and three symmetry planes with the GE in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV

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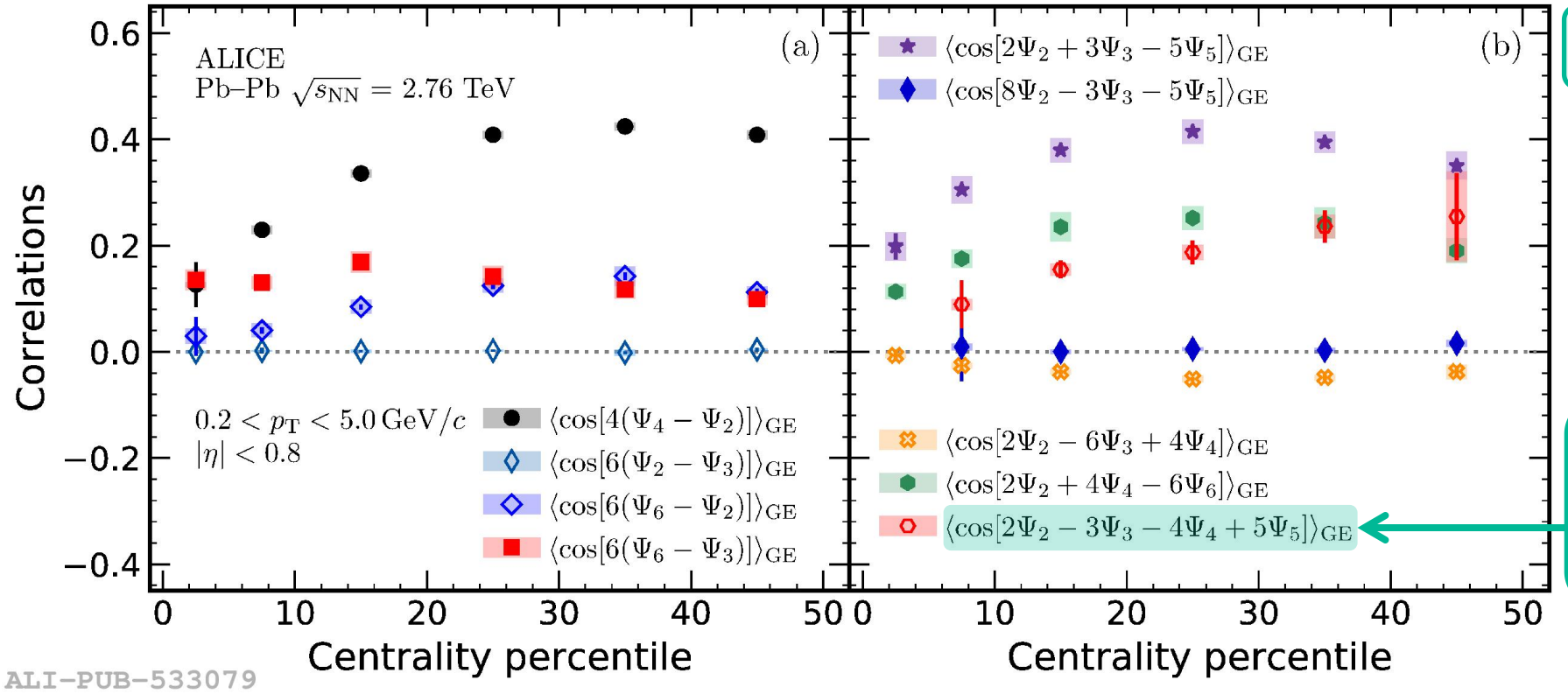

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Measured for the first time!

ALI-PUB-533079

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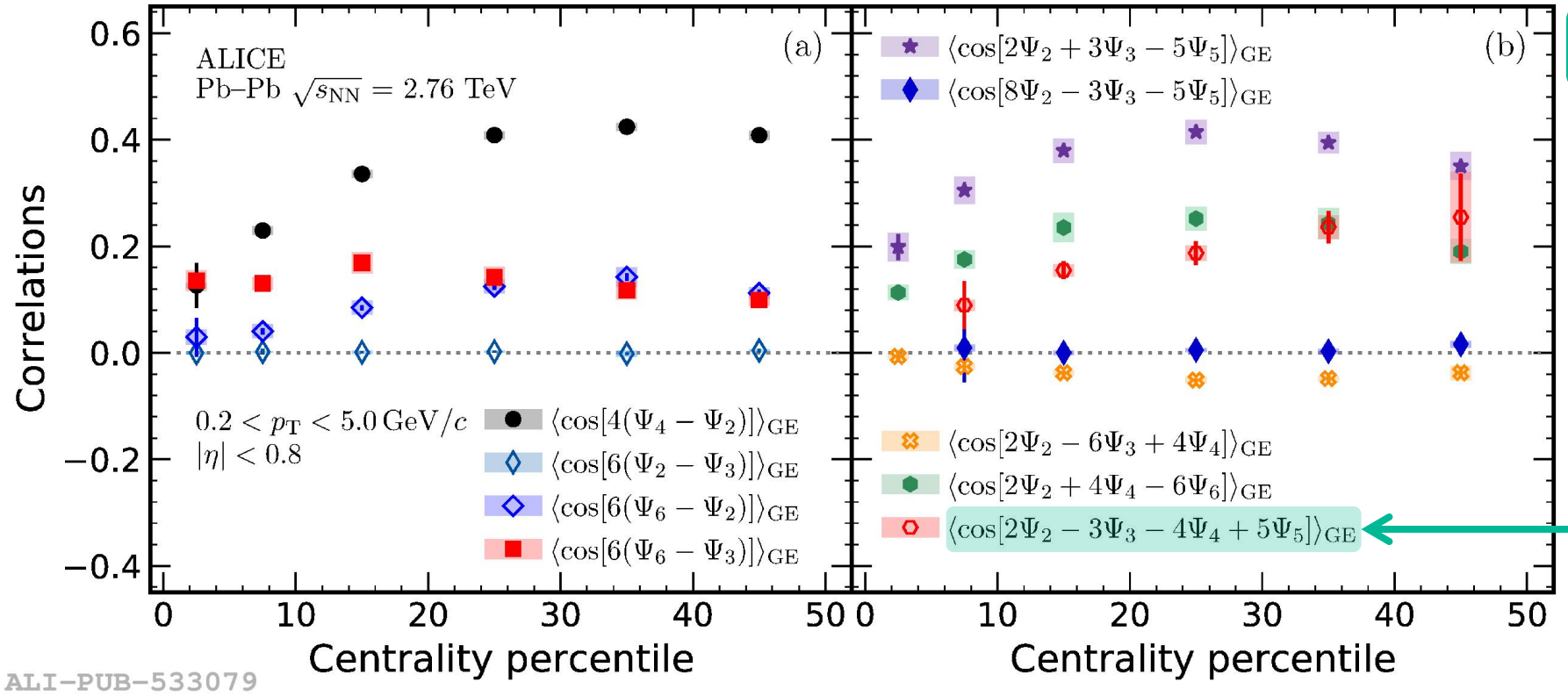

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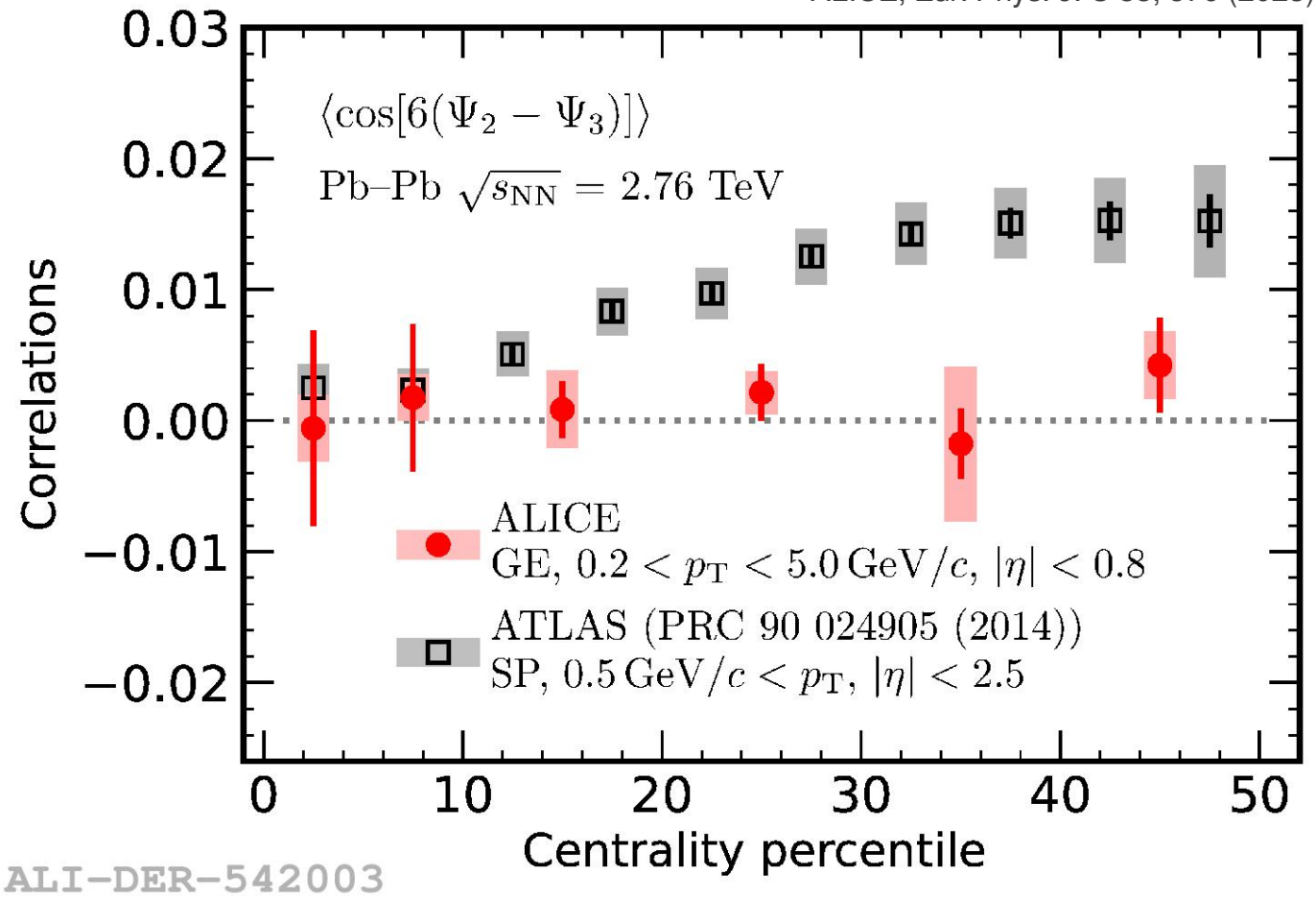
- Magnitudes of SPC depend on the order of the involved correlators

Comparison with previous measurements

- Comparison with previous measurements with SP method
  ATLAS, Phys. Rev. C **90**, 024905 (2014)
- Results with GE significantly smaller than with SP
  - SP: positive trend in semicentral collisions
  - GE: compatible with zero within uncertainties
- Bias from flow amplitude correlated fluctuations also visible in the data

→ May change the physics interpretation of the data

ALICE, Eur. Phys. J. C **83**, 576 (2023)



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Correlations between Ψ_2 and Ψ_3

- Comparison with predictions from T$_R$ENTo + VISH2+1 + UrQMD with Duke 2019[1]
- Final state slightly overestimate the data

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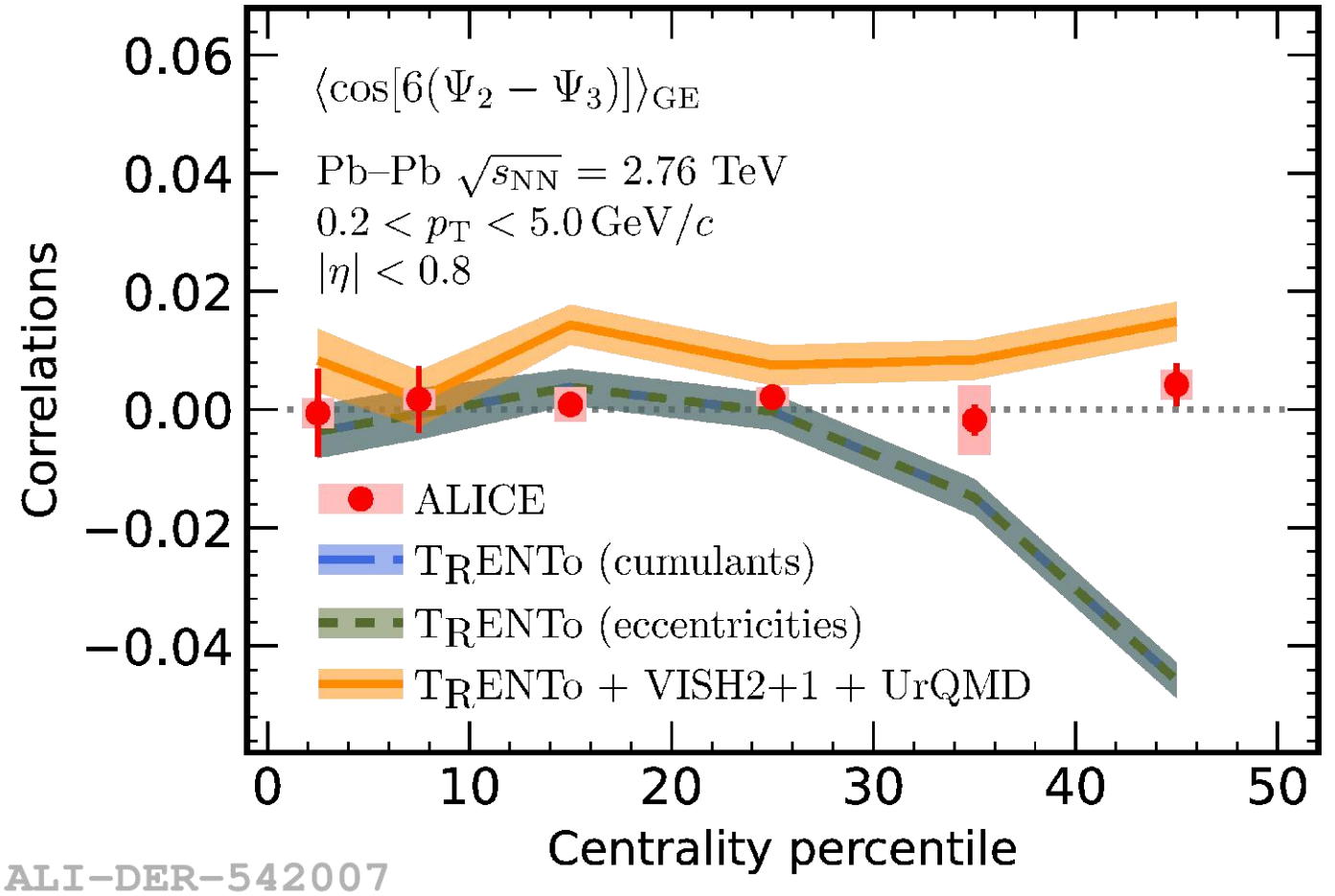

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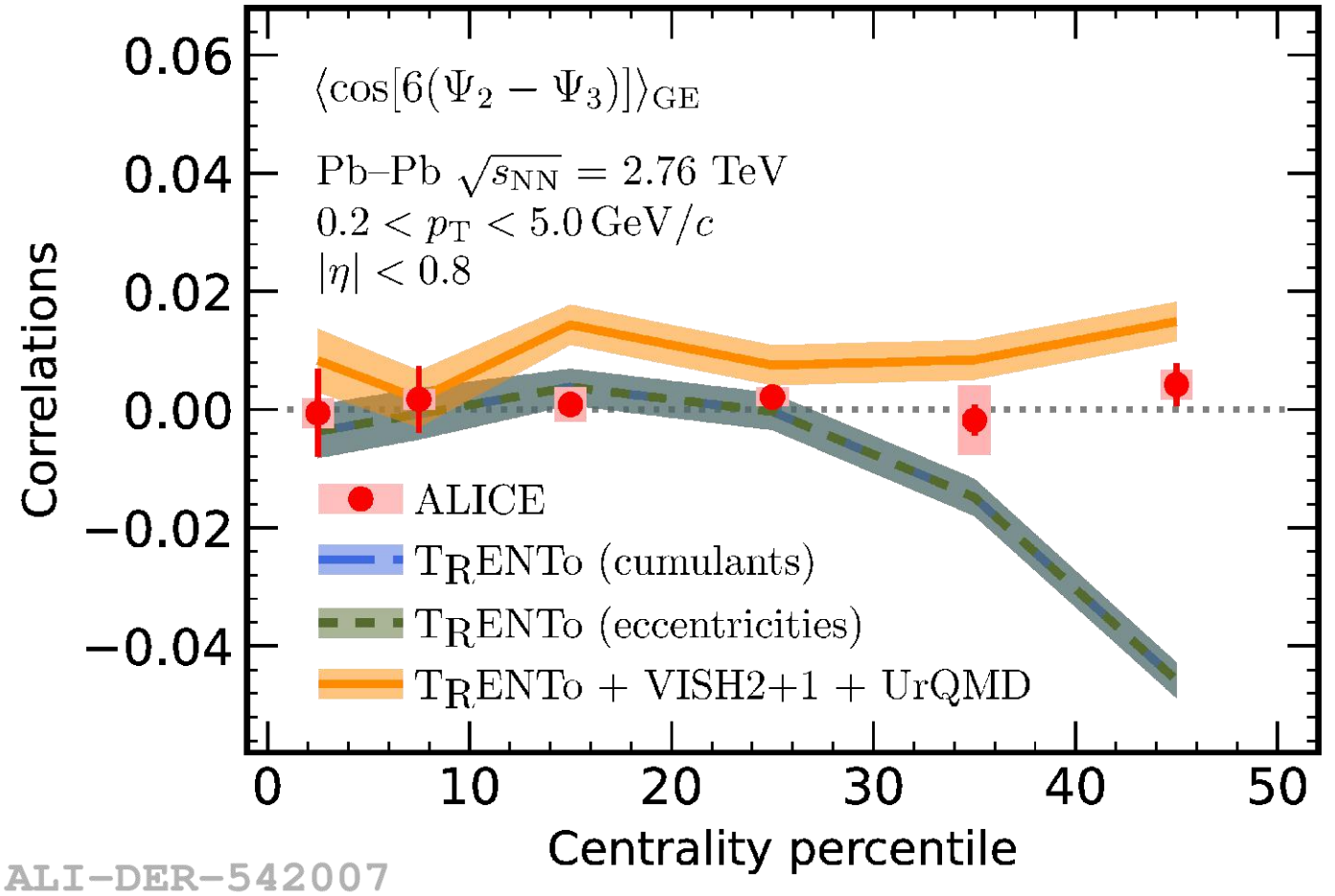
- Comparison with predictions from T$_R$ENTo + VISH2+1 + UrQMD with Duke 2019[1]
- Final state slightly overestimate the data
- Clear negative trend in the initial state
- Expected overlap of initial and final states from dominant linear response for n = 2,3

→ Vanishing correlations due to higher-order non-linear terms?

ALICE, Eur. Phys. J. C **83**, 576 (2023)



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Summary

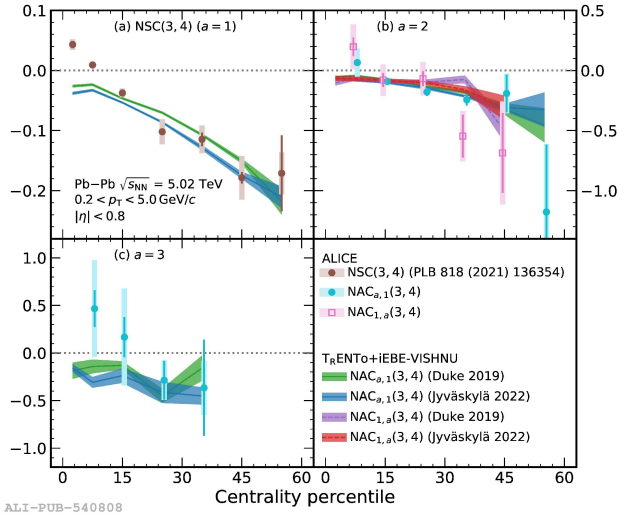
- Broad set of first measurements of new higher-order observables in Pb–Pb collisions
  - 34 two-harmonic (N)AC ALICE, arXiv:2303.13414 (Submitted to Phys. Rev. C)
  - 9 two-, three- and four-symmetry planes SPC with new GE method ALICE, Eur. Phys. J. C **83**, 576 (2023)
- New look at the interplay between the different phases of the collision

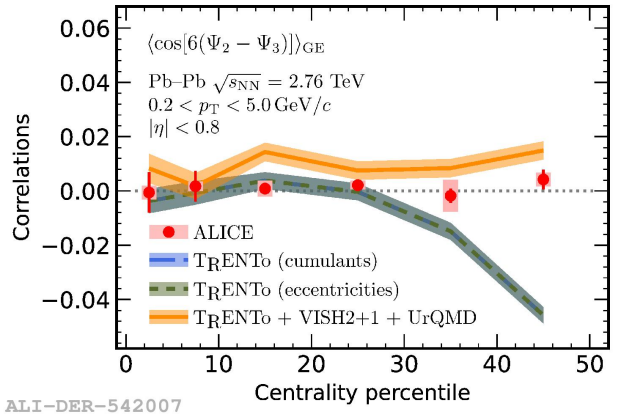
→ Impact of hydro evolution on initial state correlations

- Deviations between data and state-of-the-art model predictions

→ New constraints on the initial state and QGP properties in future Bayesian analyses

- Stay tuned: future Run 3 Pb–Pb collisions are incoming!





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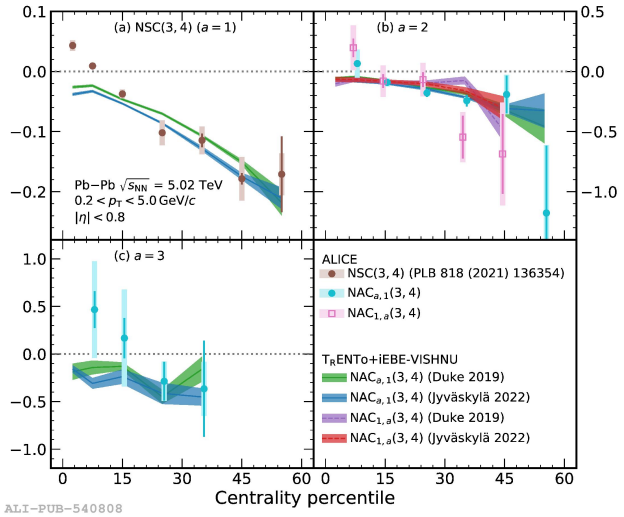
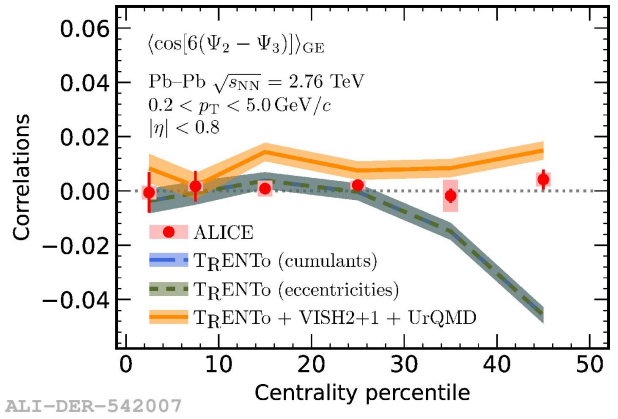




See also
Mingrui: Talk 05.09 at 15:10
Ante: Poster 246 05.09 at 17:30
Emil: Poster 455 05.09 at 17:30

Summary

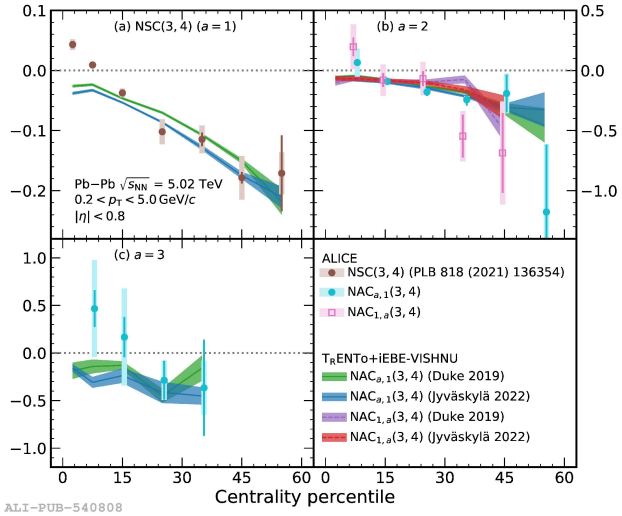
- Broad set of first measurements of new higher-order observables in Pb–Pb collisions
  - 34 two-harmonic (N)AC ALICE, arXiv:2303.13414 (Submitted to Phys. Rev. C)
  - 9 two-, three- and four-symmetry planes SPC with new GE method ALICE, Eur. Phys. J. C **83**, 576 (2023)
- New look at the interplay between the different phases of the collision

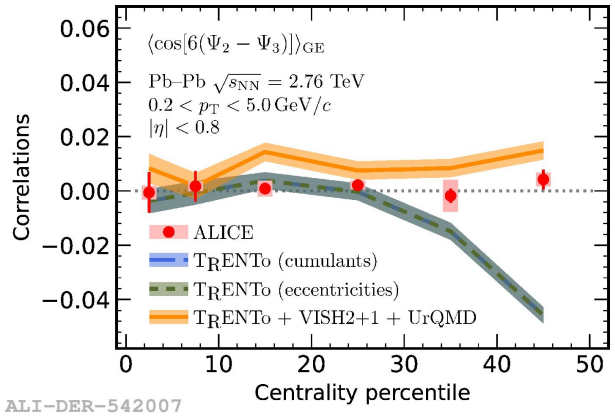
→ Impact of hydro evolution on initial state correlations

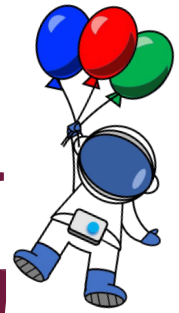
- Deviations between data and state-of-the-art model predictions

→ New constraints on the initial state and QGP properties in future Bayesian analyses

- Stay tuned: future Run 3 Pb–Pb collisions are incoming!







Thank you for your attention!

See also
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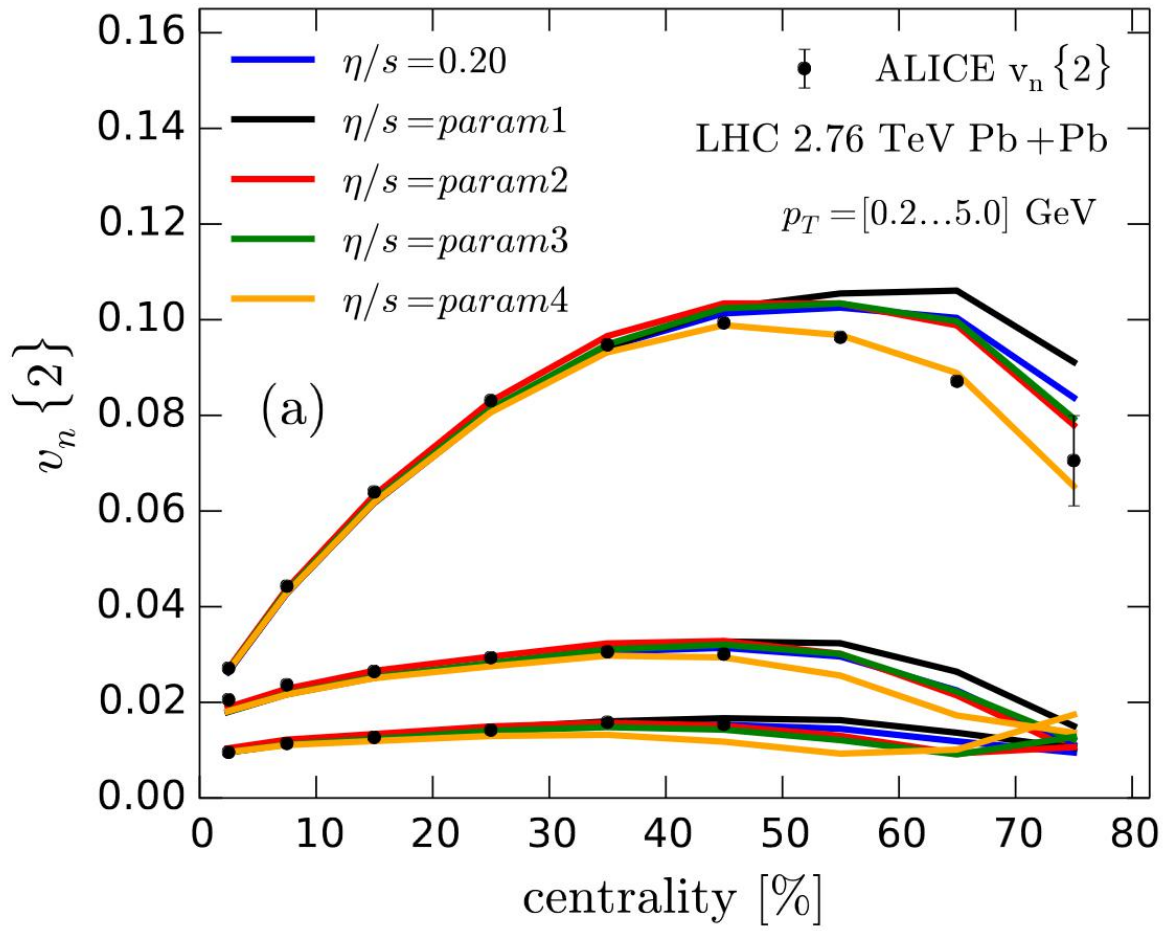
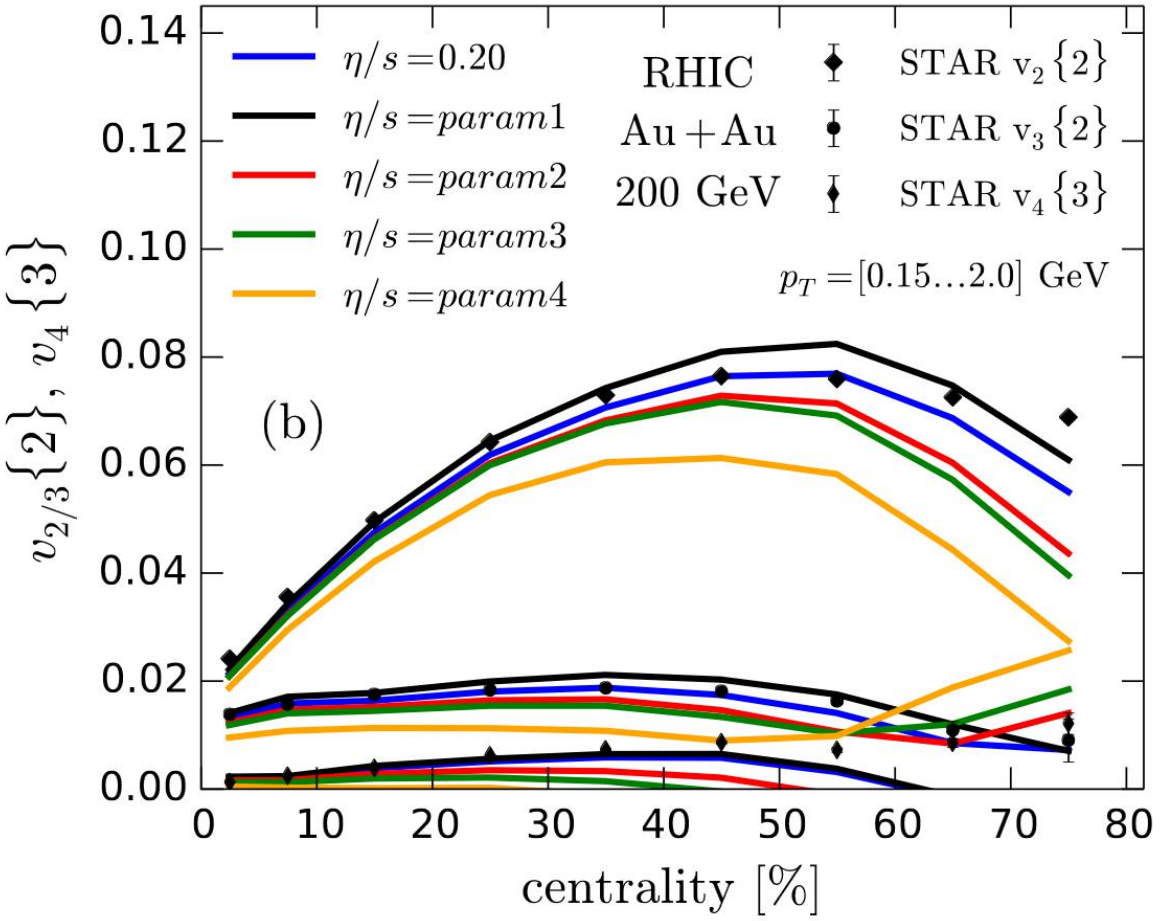
Additional slides

Flow amplitude measurements





H. Niemi *et al.*, Nucl. Phys. A **956**, 312-315 (2016)

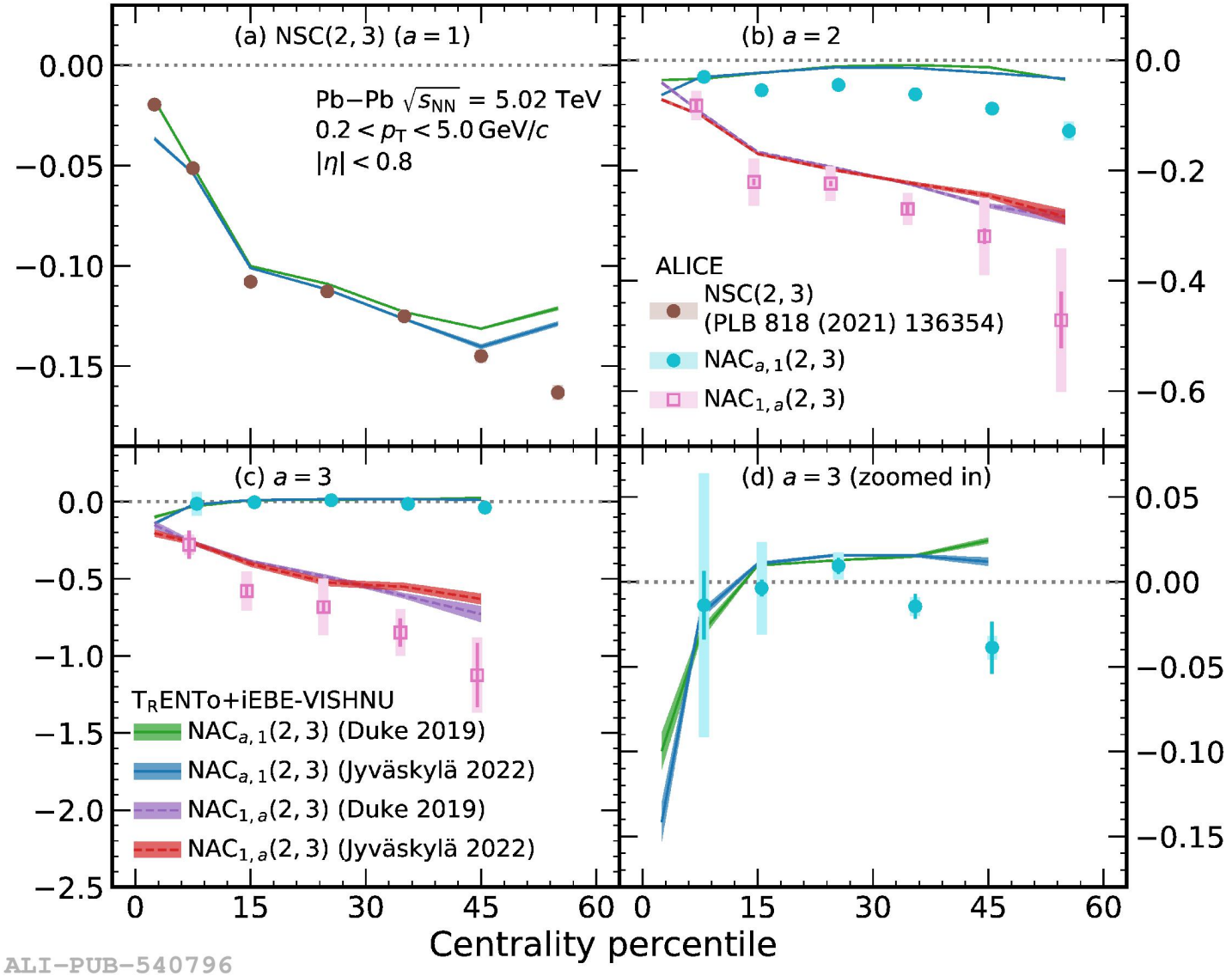
NAC(2,3)

- First measurements in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

ALICE, arXiv:2303.13414 (Submitted to Phys. Rev. C)

- Tensions between data and models for $\mathrm{NAC}_{2,1}(2,3)$ and $\mathrm{NAC}_{3,1}(2,3)$
- Similar predictions between Duke 2019[1] and Jyväskylä 2022[2] due to T$_R$ENTo?

→ $\mathrm{NAC}_{a,1}(2,3)$ can constrain initial conditions modelling



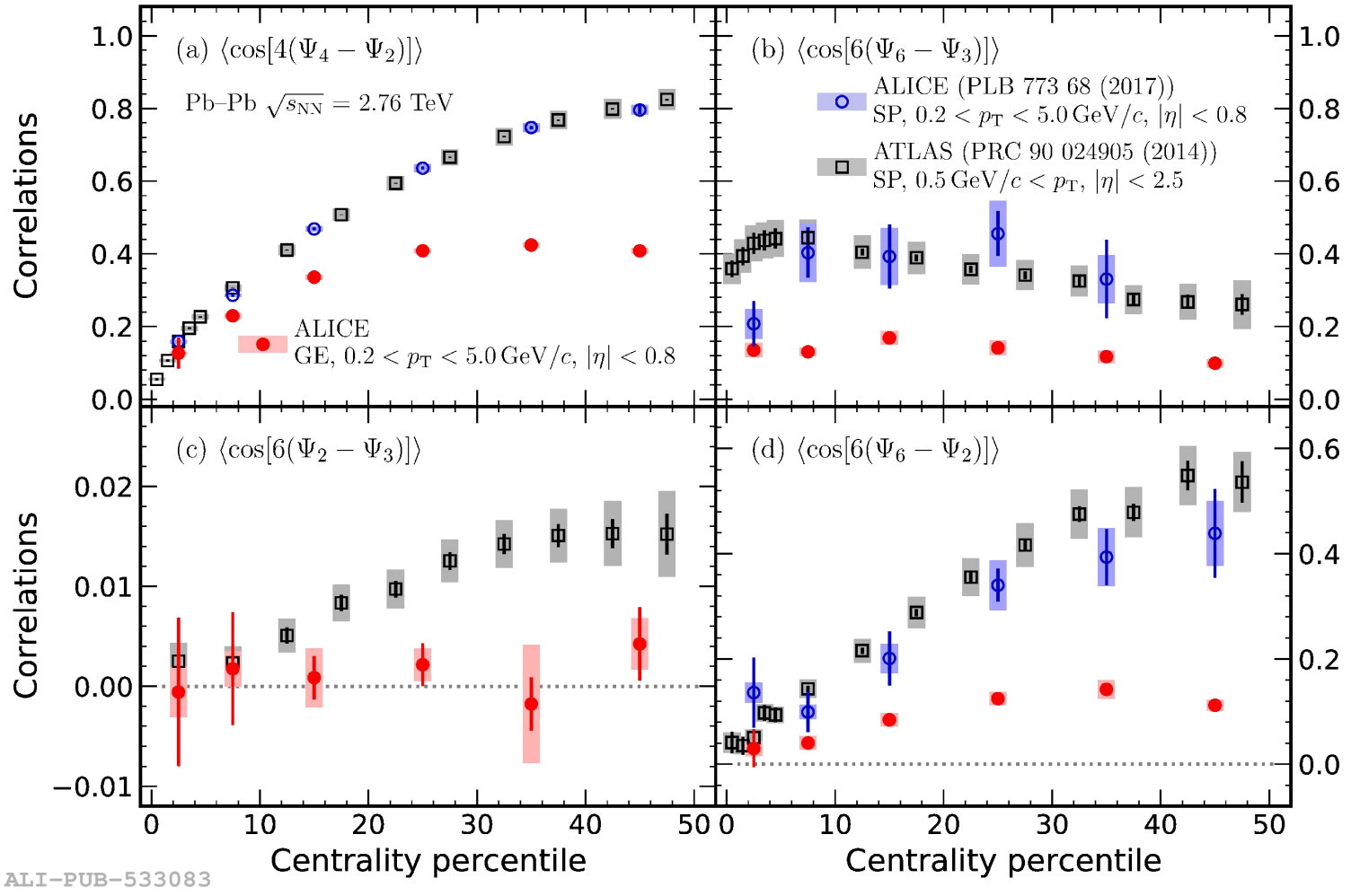
[1] J.E. Bernhard *et al.*, Nature Phys. **15**, 1113-1117 (2019)
[2] J.E. Parkkila *et al.*, Phys. Lett. B **835**, 137485 (2022)

Comparison with previous measurements

- Comparisons with the previous measurements with SP method
  - ATLAS, Phys. Rev. C **90**, 024905 (2014)
  - ALICE, Phys. Lett. B **773**, 68 (2017)
- Good agreement of SPC with SP between ALICE and ATLAS within uncertainties
- Results with GE significantly smaller than with SP

→ Bias from flow amplitude correlated fluctuations also visible in data

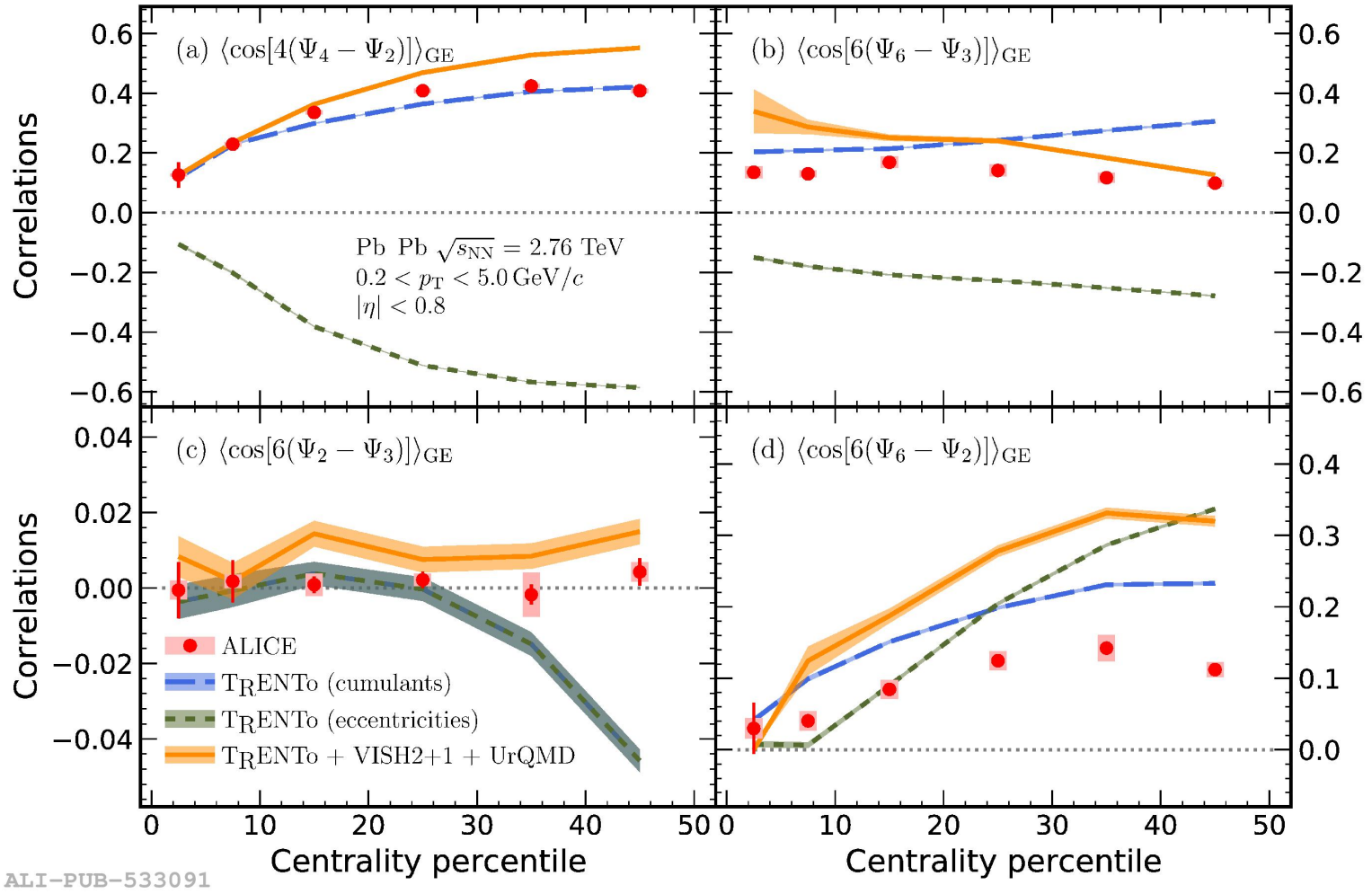
ALICE, Eur. Phys. J. C **83**, 576 (2023)



2-harmonic SPC

- Comparison with predictions from T$_R$ENTo-VISH2+1-UrQMD[1]
- Correlations between Ψ_2 and Ψ_4 well reproduced only in the linear regime
- SPC between Ψ_2 and Ψ_3 zero within uncertainties
  → Impact of higher-order terms in non-linear response?
- Large tensions between data and models for SPC with Ψ_6

ALICE, Eur. Phys. J. C **83**, 576 (2023)

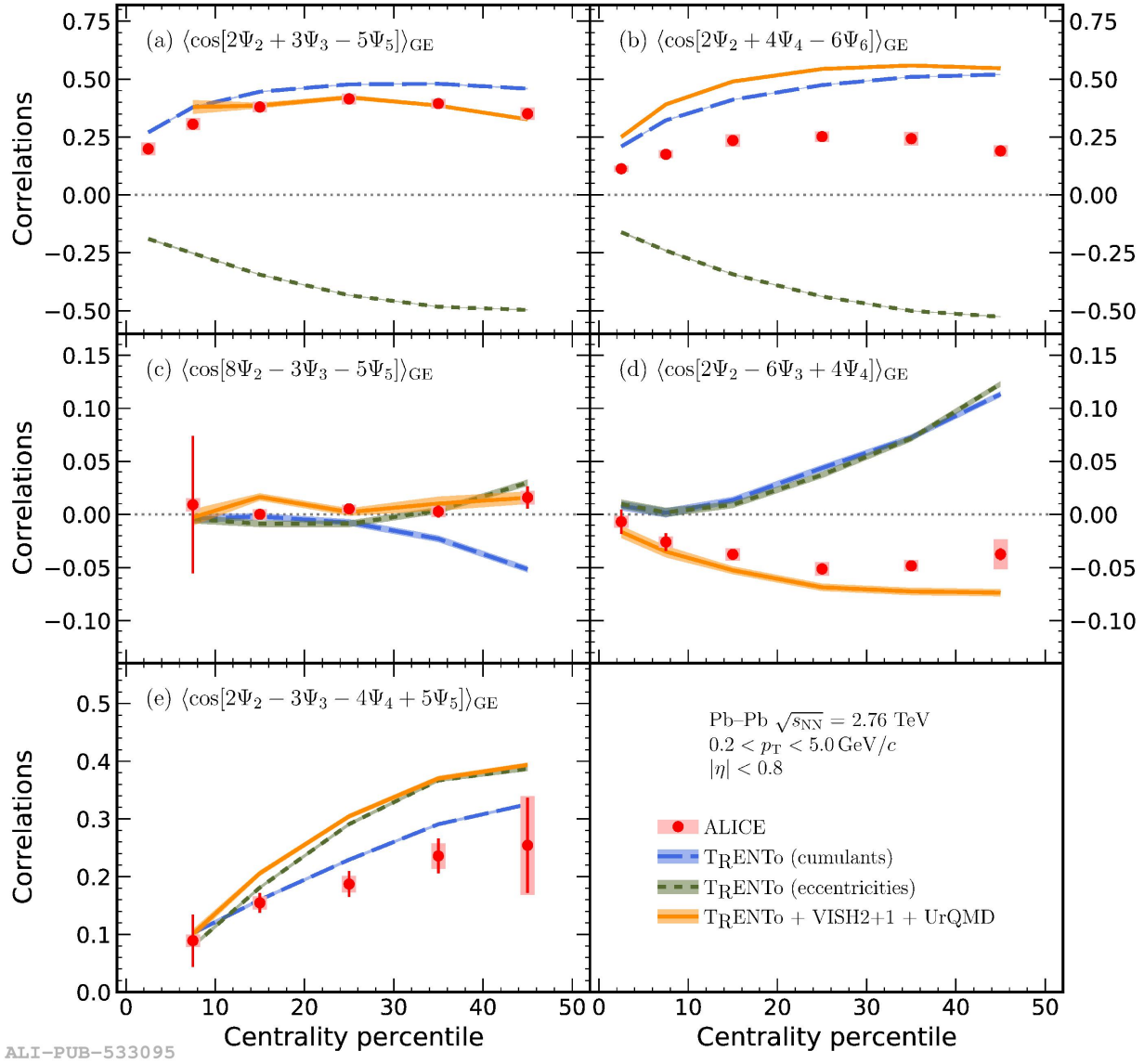


[1] J.E. Bernhard *et al.*, Nature Phys. **15**, 1113-1117 (2019)

3-harmonic SPC

- Comparison with predictions from T$_R$ENTo-VISH2+1-UrQMD[1]

ALICE, Eur. Phys. J. C **83**, 576 (2023)



[1] J.E. Bernhard *et al.*, Nature Phys. **15**, 1113-1117 (2019)