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TUM ALICE

First measurements of genuine three-harmonic correlations in Pb–Pb collisions with ALICE

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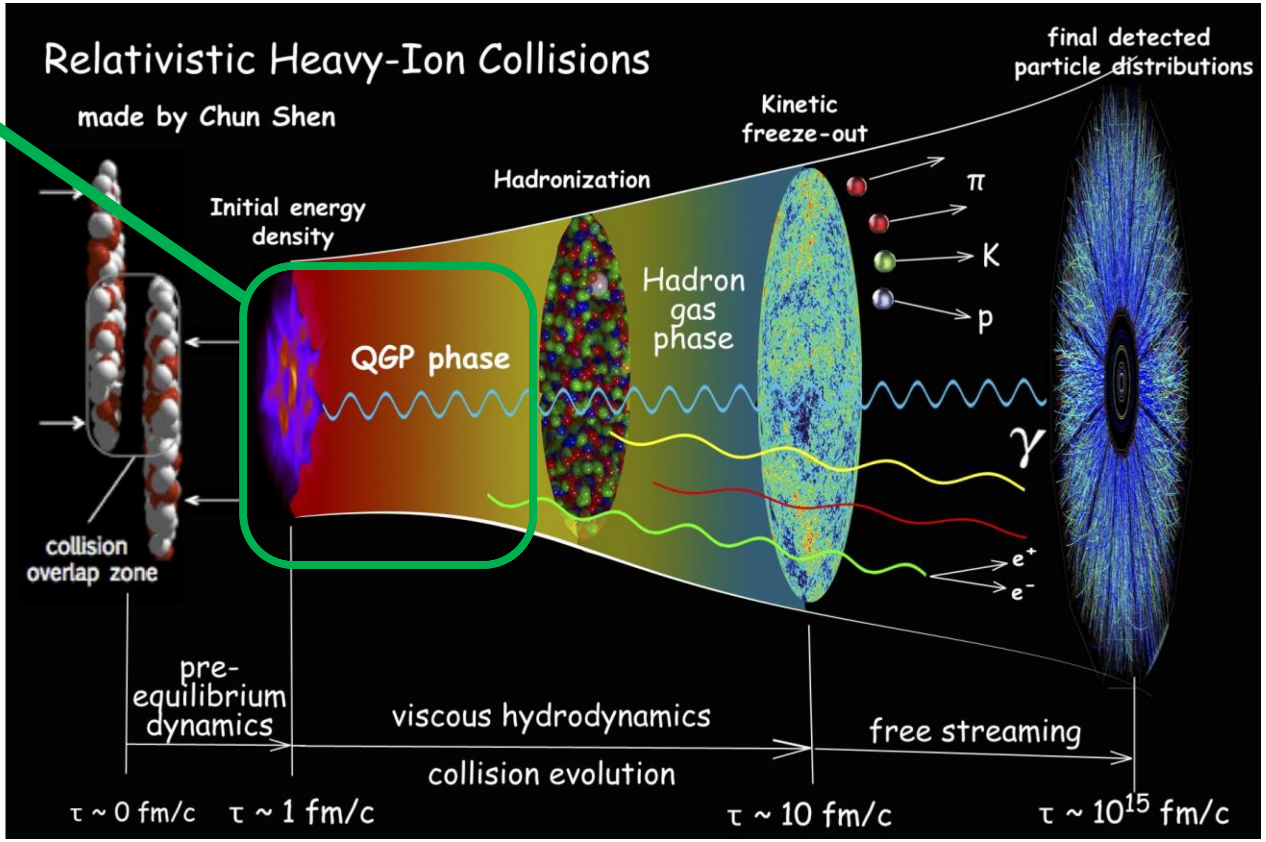
10-15.01.2021

How do we study QGP?

- **What we want**
- Characterised by
  - initial state, initial geometry
  - collective dynamics, transport properties



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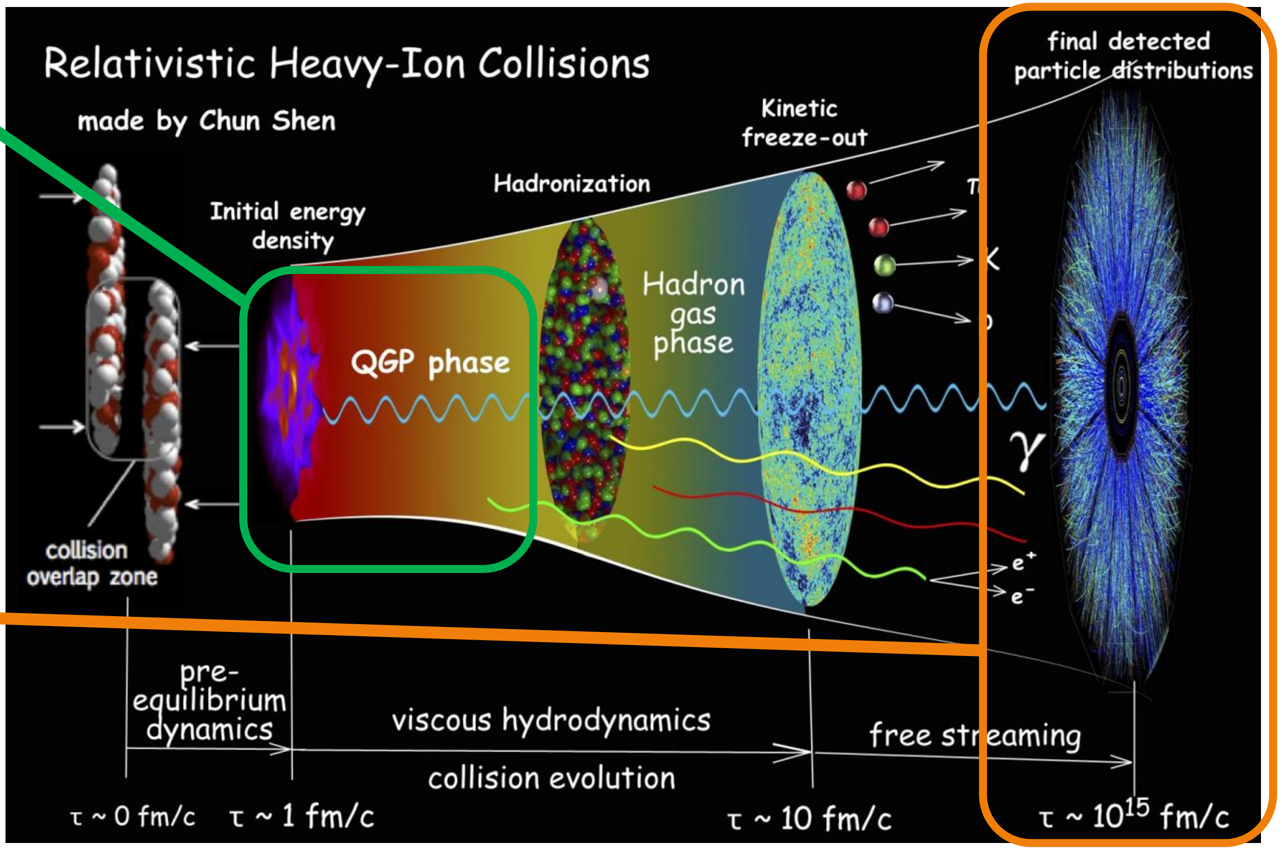
- **What we measure**
- Final state distributions
  - $p_T, \eta, \varphi, \ldots$
  - identified particles



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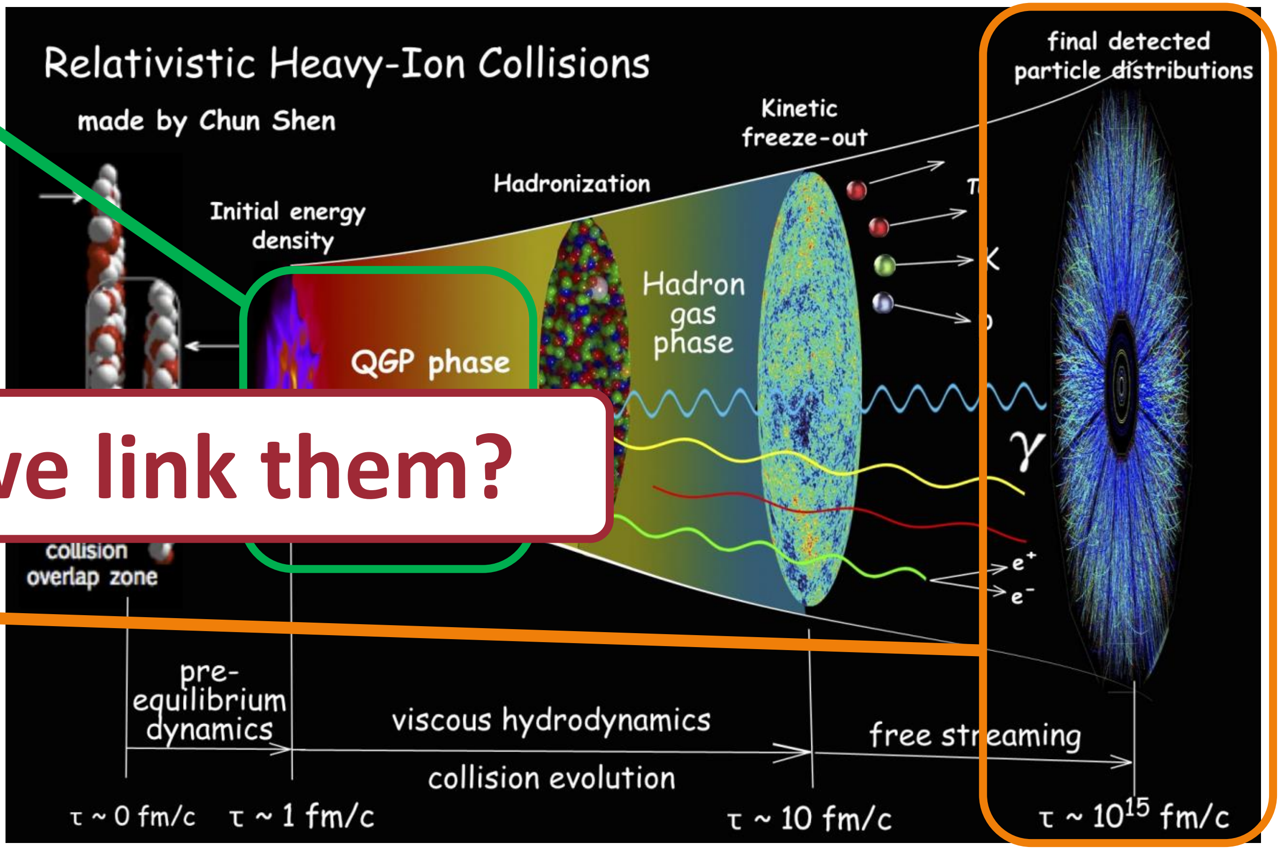
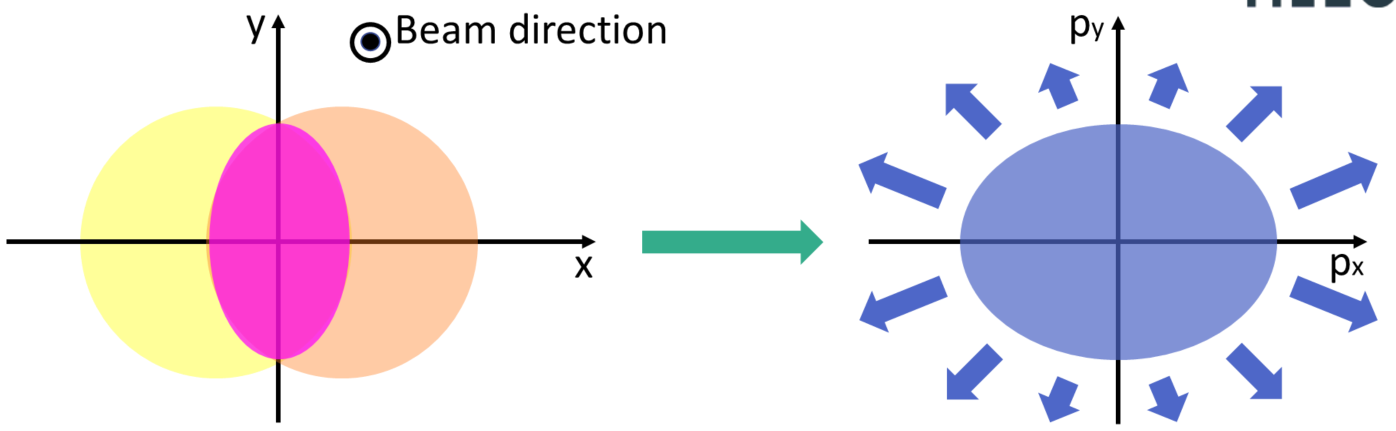


Anisotropic flow phenomenon

Anisotropic flow: transfer of the initial anisotropy into anisotropy in momentum space via the thermalized medium



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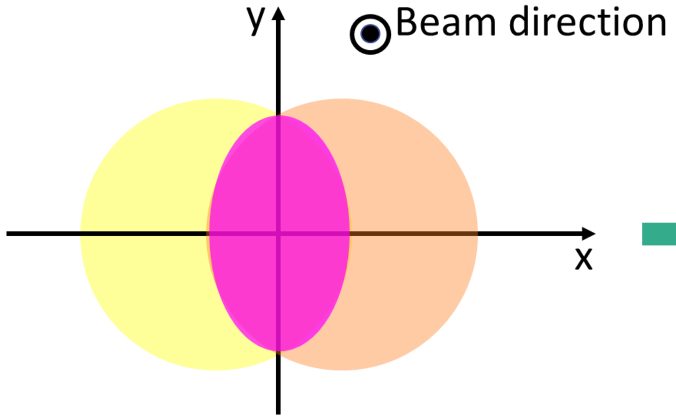
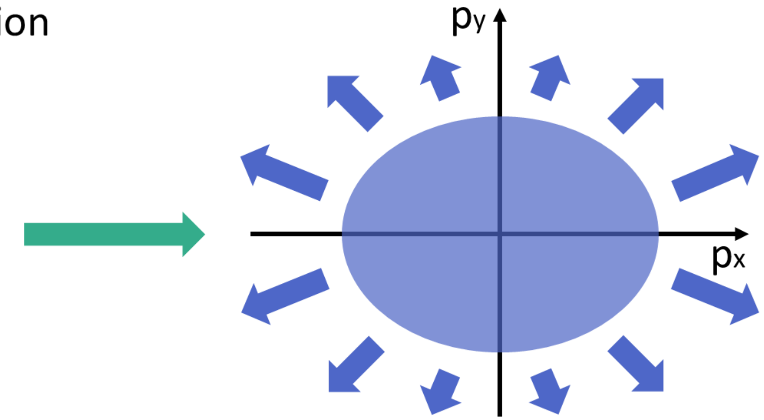


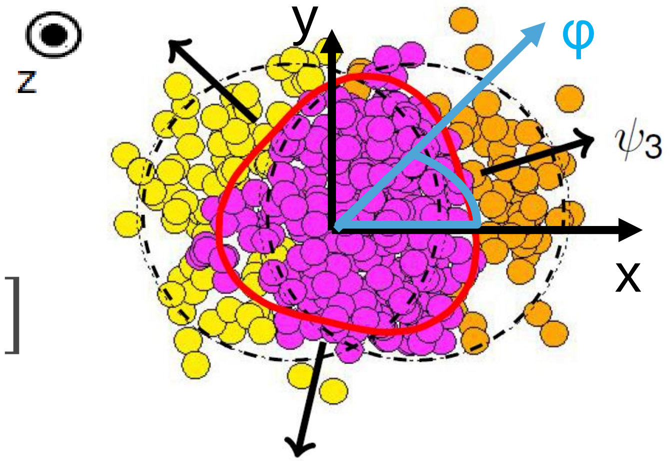


- Distribution described by Fourier series[1]:

$$f(\varphi) = \frac{1}{2\pi}\left[1 + 2\sum_{n=1}^{\infty}\left[v_n \cos\left(n(\varphi - \Psi_n)\right)\right]\right]$$

- Analytic relation between v_n , Ψ_n and φ[2]:

$$\langle\cos[n_1\varphi_1 + \cdots + n_k\varphi_k]\rangle = v_{n_1} \ldots v_{n_k} \cos[n_1\Psi_{n_1} + \cdots + n_k\Psi_{n_k}]$$



[1] S. Voloshin and Y. Zhang, Z. Phys. C **70**, 665 (1996)
[2] R.S. Bhalerao, M. Luzum and J.-Y. Ollitrault, PRC **84**, 034910 (2011)

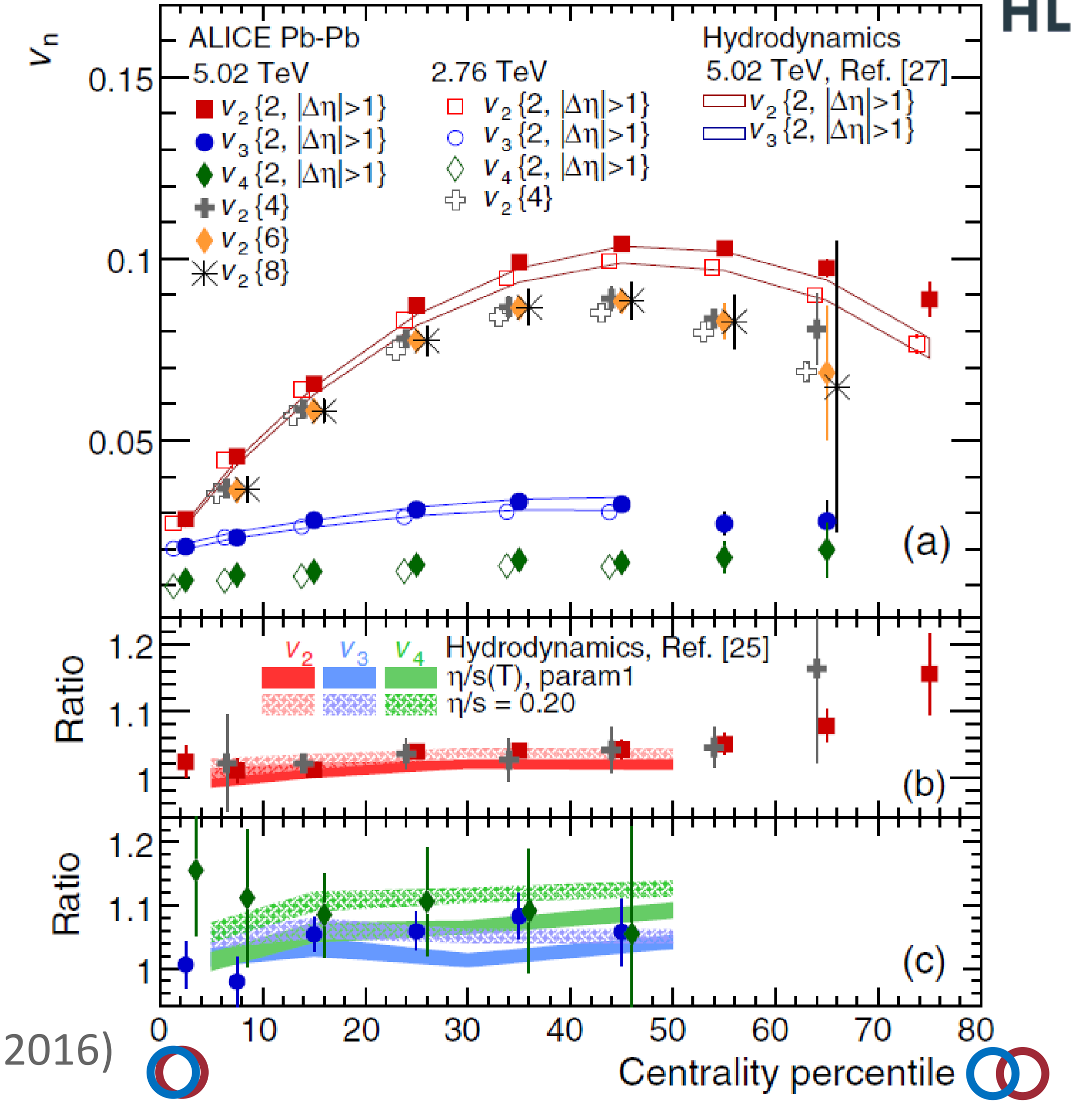
M. Luzum, J. Phys. G **38**, 124026 (2011)

What can we measure?

- v_n with k-particle cumulants of φ:

$$
\begin{aligned}
v_n\{2\}^2 &= \langle v_n^2 \rangle \\
-v_n\{4\}^4 &= \langle v_n^4 \rangle - 2\langle v_n^2 \rangle^2
\end{aligned}
$$

→ Dominated by $\langle \eta/s \rangle$



ALICE Collaboration, PRL **116**, 132302 (2016)

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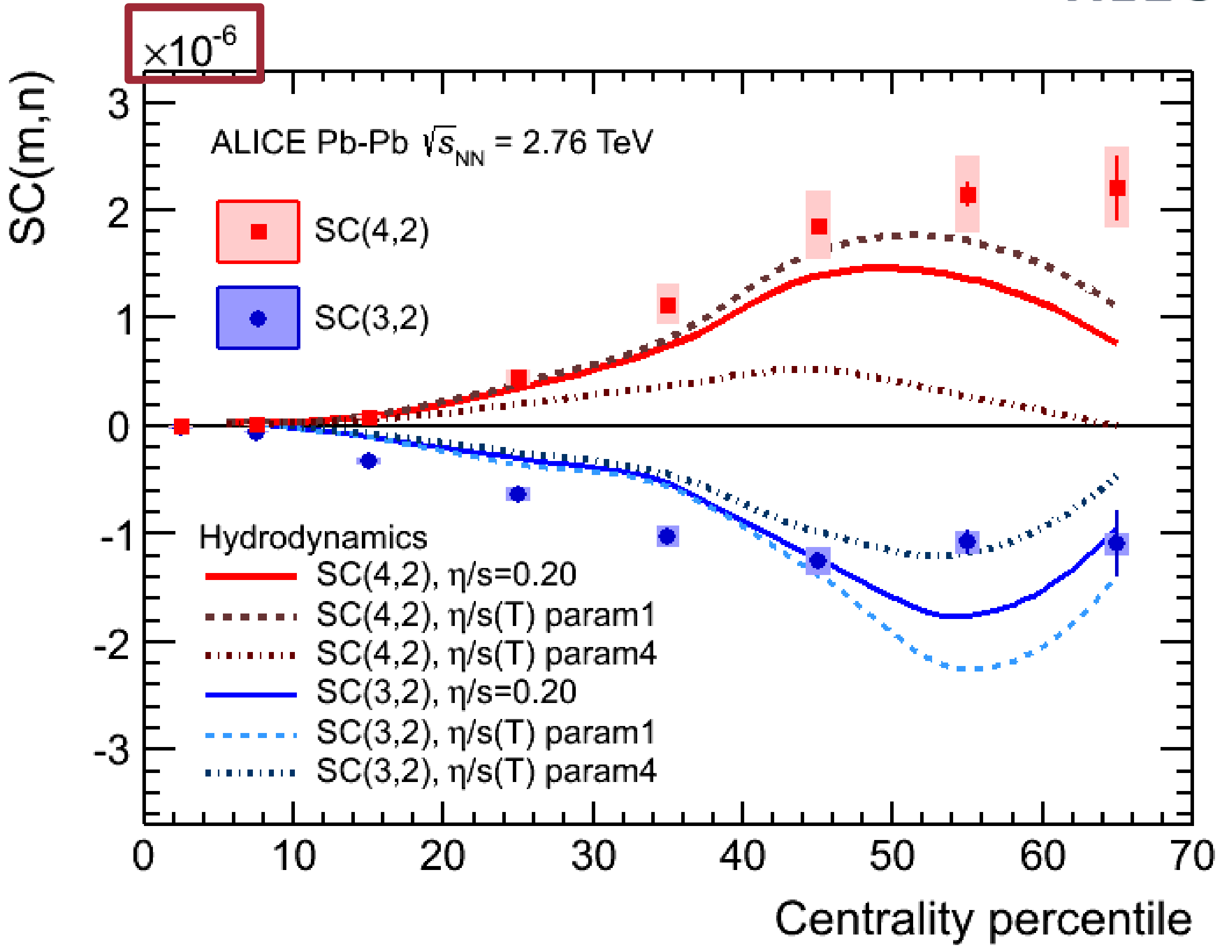
- Symmetric Cumulants: generalisation to two different harmonics m and n:

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

→ Sensitive to $\eta/s(T)$



ALICE Collaboration, PRL **117**, 182301 (2016)

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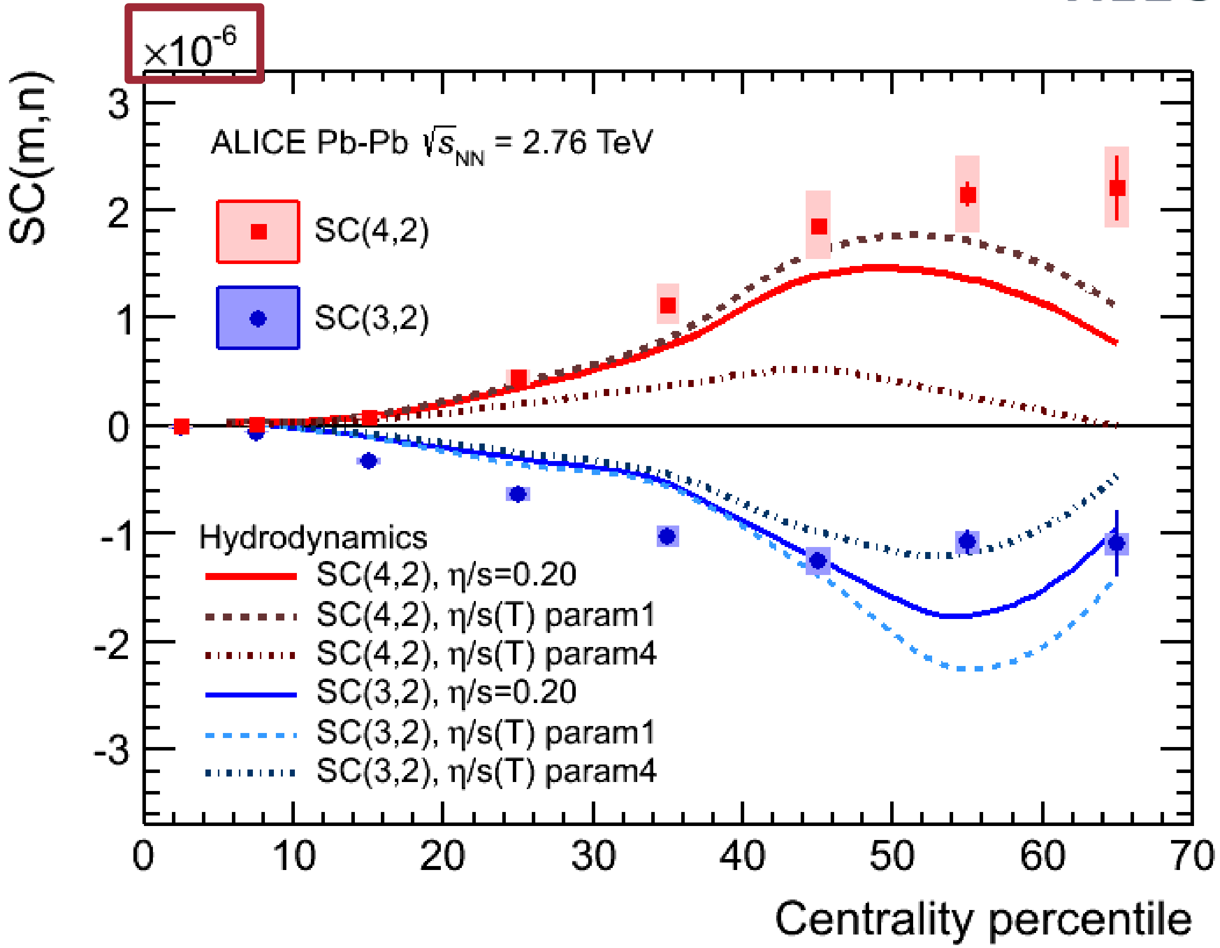
→ Sensitive to $\eta/s(T)$

→ New set of constraints on the system!



ALICE Collaboration, PRL **117**, 182301 (2016)

Can we go further?

- Why do we need to go further?
  - new information on the initial and final state correlations
  - new and independent constraints on the models

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  - new information on the initial and final state correlations
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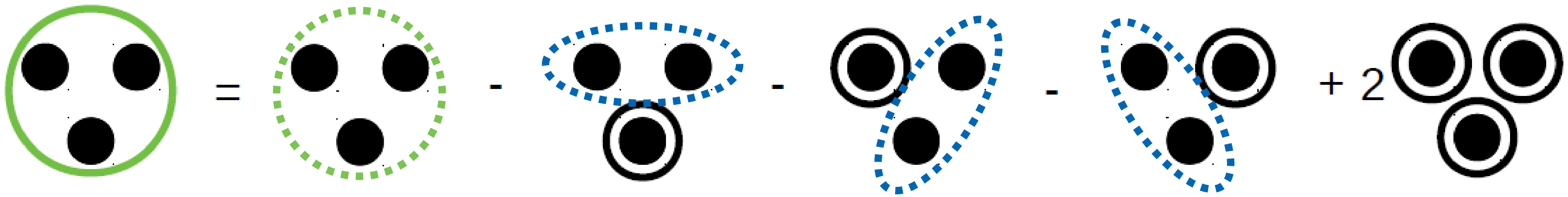
➔ Measure the genuine correlations between three and more flow amplitudes

- How can we achieve this?
  - use the mathematical formalism of higher order cumulants
  - ensure the new observables are cumulants of the flow amplitudes

Higher order Symmetric Cumulants

- New theoretical framework[1] developed for any number of flow amplitudes
- **Focus of this analysis:** 3-harmonic Symmetric Cumulants

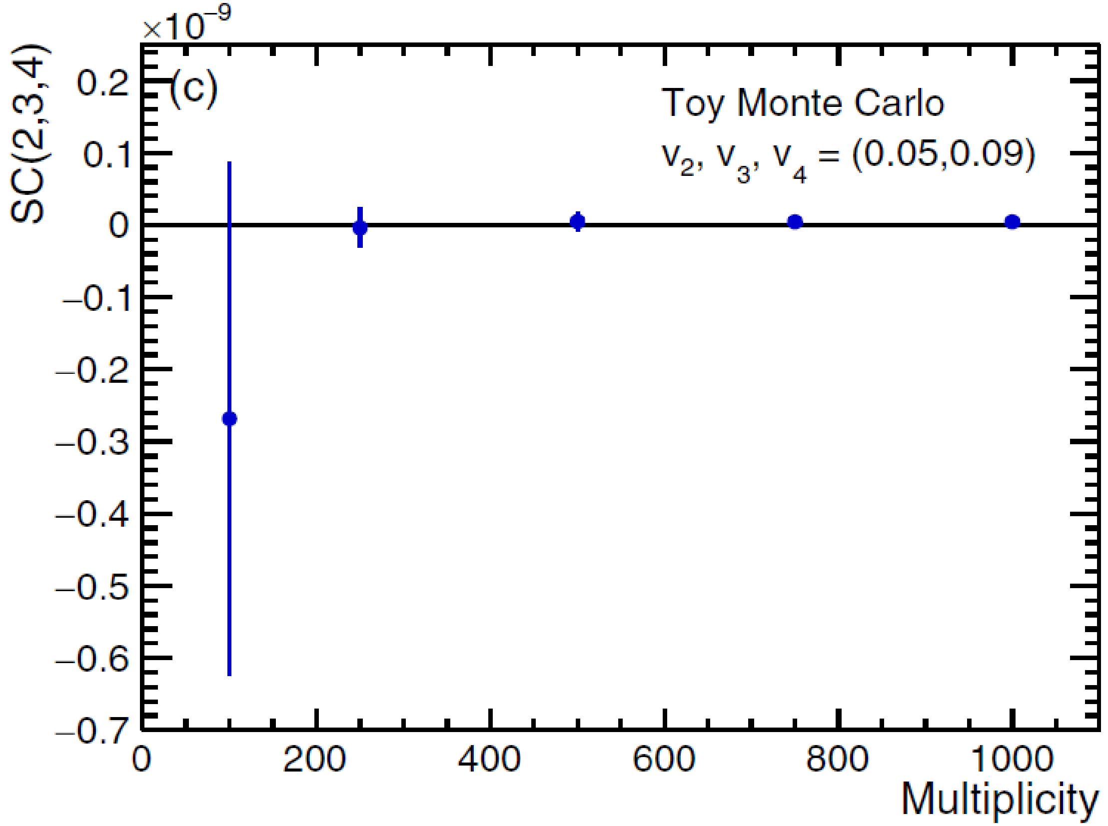
$$\mathrm{SC}(k,l,m) = \langle v_k^2 v_l^2 v_m^2\rangle - \langle v_k^2 v_l^2\rangle\langle v_m^2\rangle - \langle v_k^2 v_m^2\rangle\langle v_l^2\rangle - \langle v_l^2 v_m^2\rangle\langle v_k^2\rangle + 2\,\langle v_k^2\rangle\langle v_l^2\rangle\langle v_m^2\rangle$$

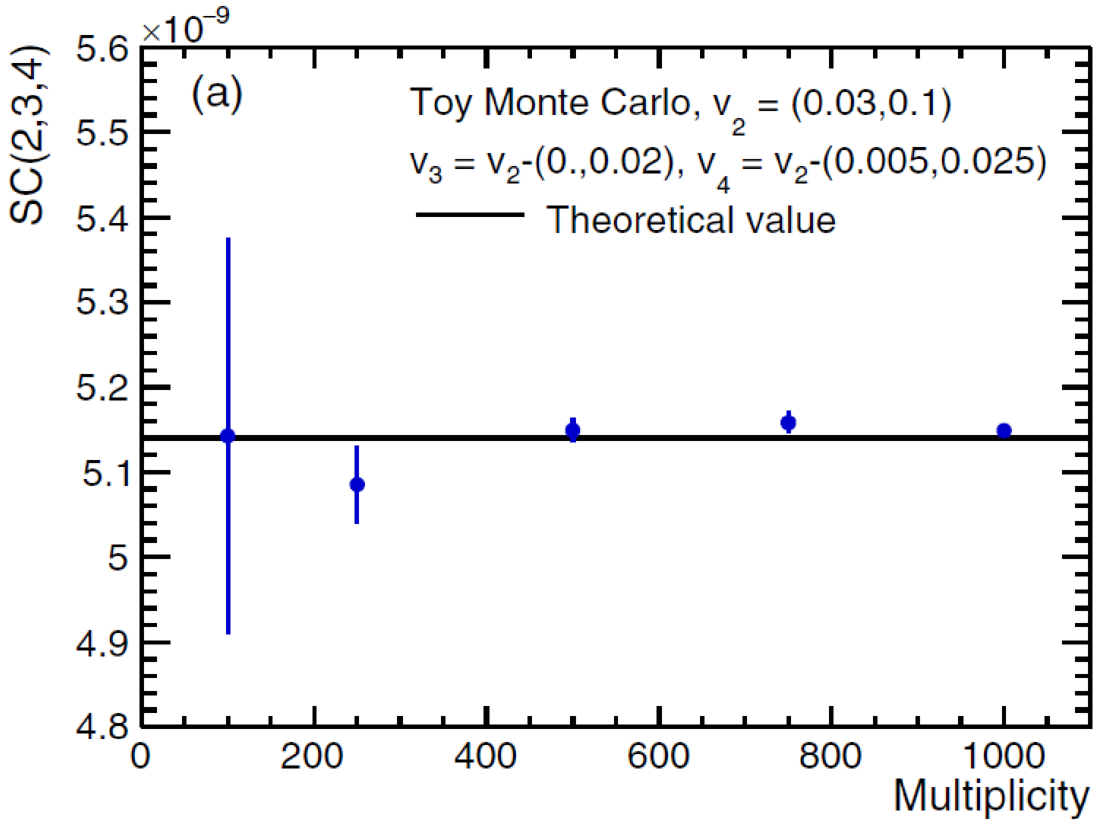


$$\mathrm{NSC}(k,l,m) = \frac{\mathrm{SC}(k,l,m)}{\langle v_k^2\rangle\langle v_l^2\rangle\langle v_m^2\rangle}$$

[1] CM, A. Bilandzic, D. Karakoç, S.F. Taghavi, PRC **102**, 024907 (2020)

Validation with toy Monte Carlo



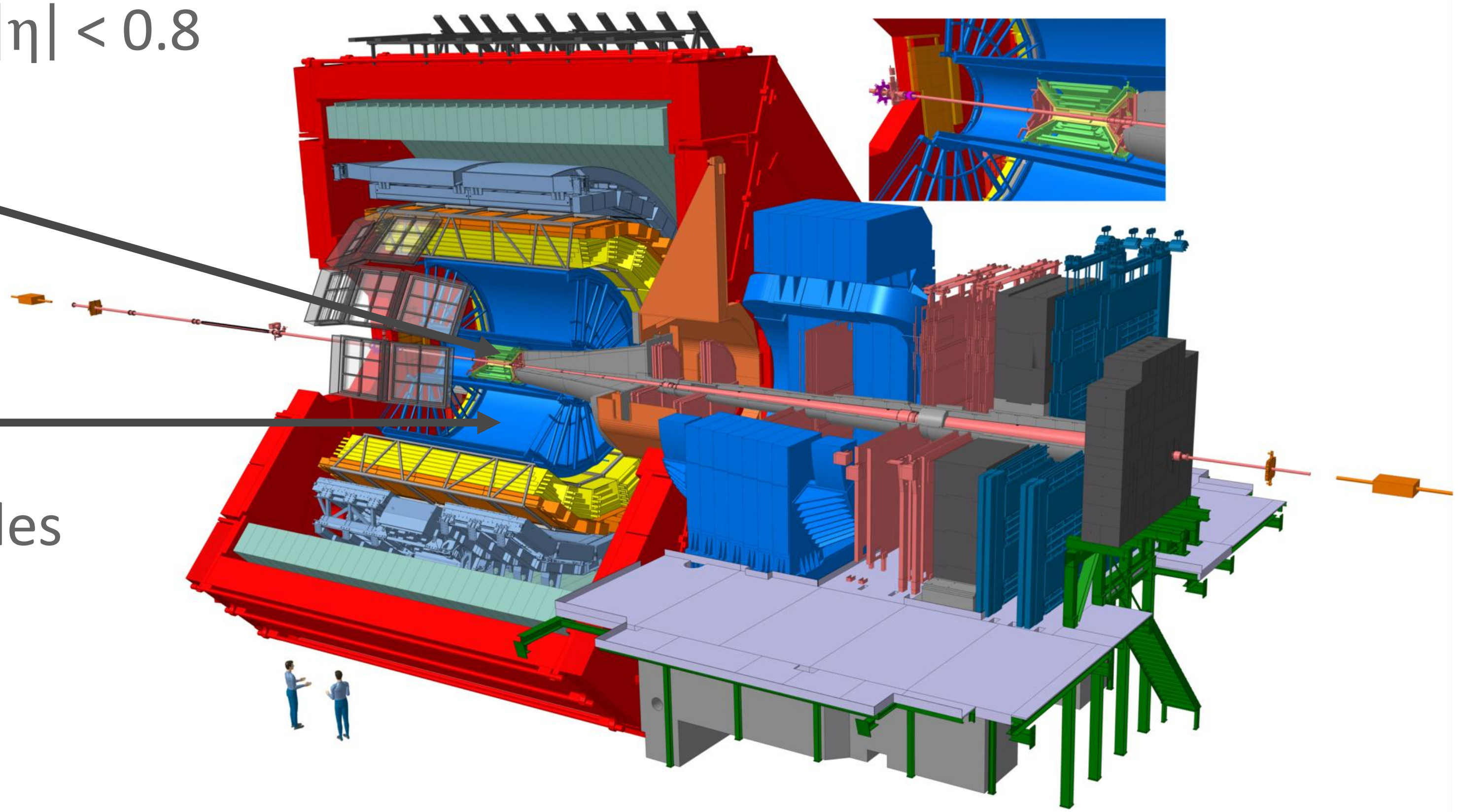


- No correlation between amplitudes → $SC(k,l,m) = 0$
- Genuine correlations between all amplitudes → $SC(k,l,m) \neq 0$

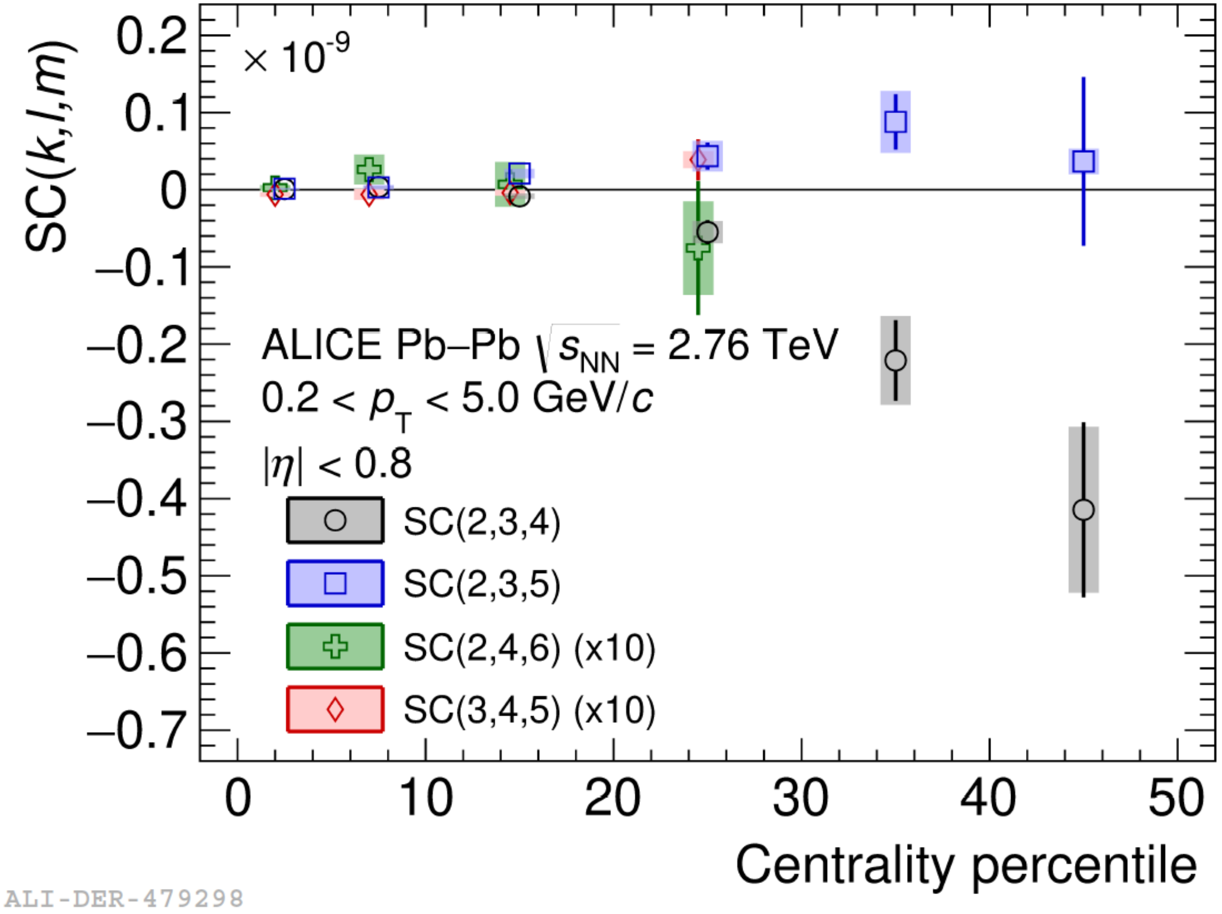
CM, A. Bilandzic, D. Karakoç, S.F. Taghavi, PRC **102**, 024907 (2020)

Analysis of ALICE data

- Run 1 (2010) Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 TeV
  - 8.2·10^{6} events for the 0–50% centrality range
  - tracks in 0.2 < p_{T} < 5 GeV/c and |η| < 0.8
- **Inner Tracking System**
  - centrality estimations
  - vertex determination
- **Time Projection Chamber**
  - reconstruction of charged particles
  - particle identification



$SC(k,l,m)$ in ALICE



- First experimental observations of genuine correlations between three flow amplitudes
- Dependency of the magnitude on the order of the amplitudes

New

ALICE Collaboration, arXiv:2101.02579 (2021)

Signature of $\mathrm{SC}(k, l, m)$

$$\mathrm{SC}(k,l,m) = \langle \left(v_k^2 - \langle v_k^2 \rangle\right) \left(v_l^2 - \langle v_l^2 \rangle\right) \left(v_m^2 - \langle v_m^2 \rangle\right) \rangle$$

- If $\mathrm{SC}(k, l, m) > 0$ → (+,+,+) and (+,-,-)
- If $\mathrm{SC}(k, l, m) < 0$ → (+,+,-) and (-,-,-)

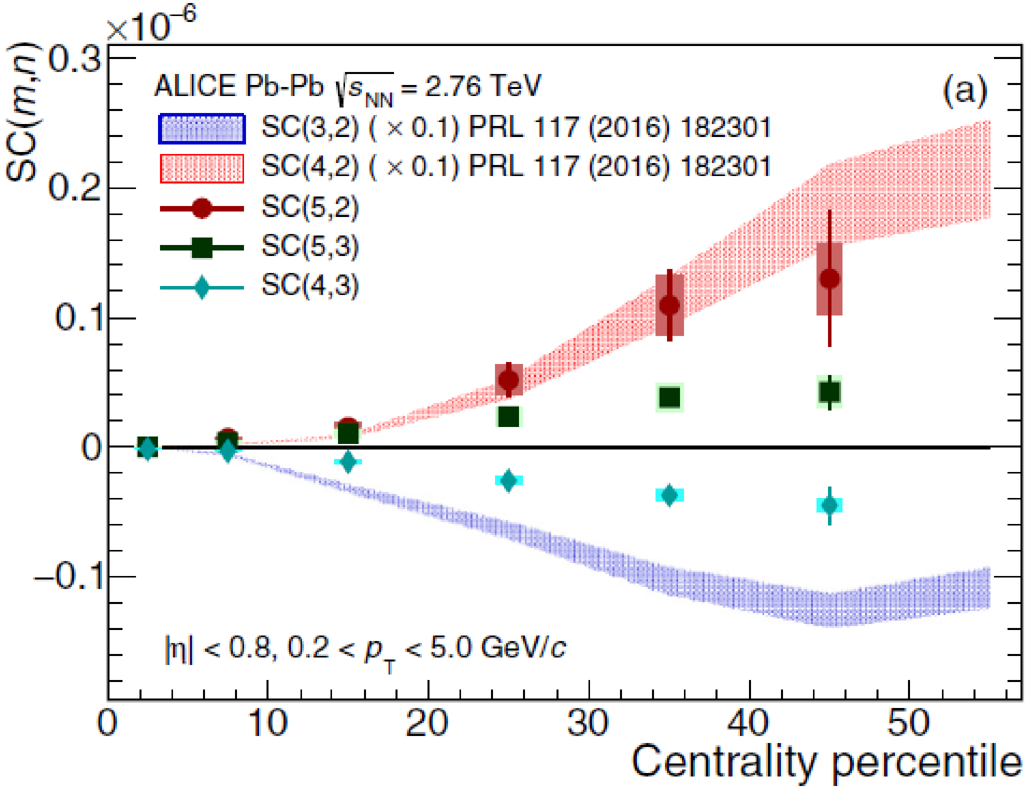
Signature of $SC(k,l,m)$

$$SC(k,l,m) = \langle \left(v_k^2 - \langle v_k^2 \rangle\right) \left(v_l^2 - \langle v_l^2 \rangle\right) \left(v_m^2 - \langle v_m^2 \rangle\right) \rangle$$

- If $SC(k,l,m) > 0$ → (+,+,+) and (+,-,-)
- If $SC(k,l,m) < 0$ → (+,+,-) and (-,-,-)
- Example:
  - $SC(3,2) < 0$ → (+,-)
  - $SC(4,2) > 0$ → (+,+)
  - $SC(4,3) < 0$ → (+,-)

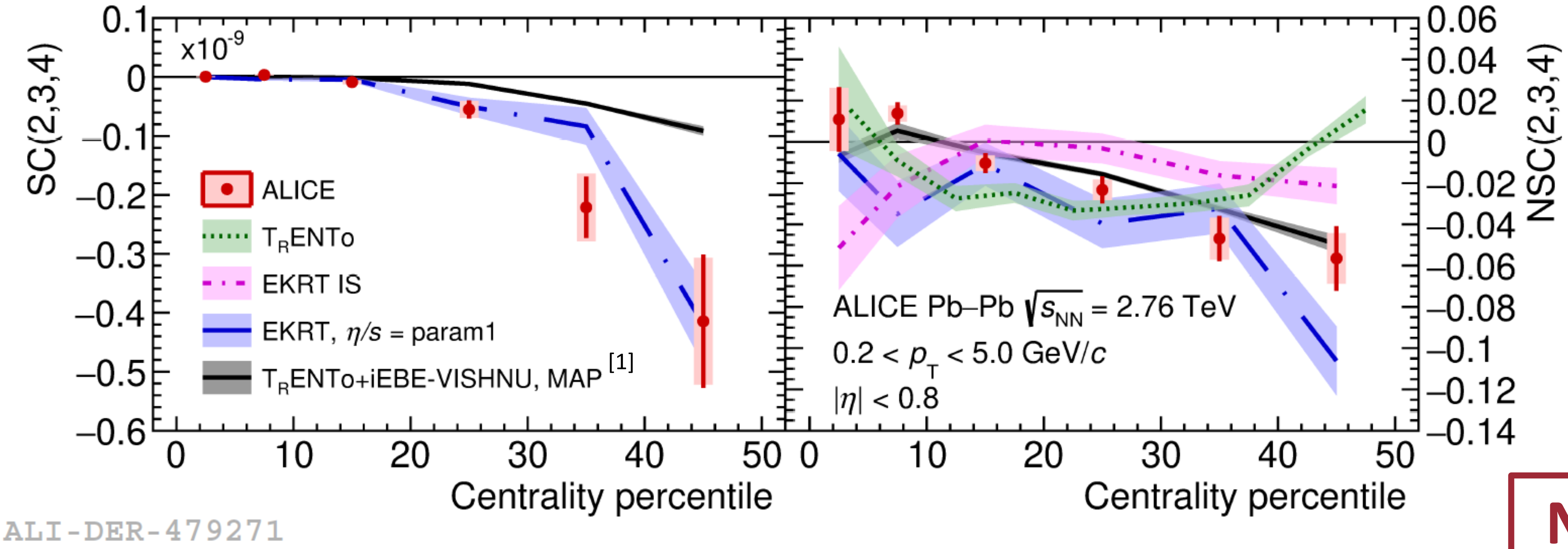
  } (+,-,-) or (+,+,-)? → $SC(2,3,4) > 0$ or $SC(2,3,4) < 0$?
  - $SC(2,3,4) < 0$ observed in data

→ $SC(k,l,m)$ can extract new information



ALICE Collaboration, PRC **97**, 024906 (2018)

SC(2,3,4) and NSC(2,3,4)

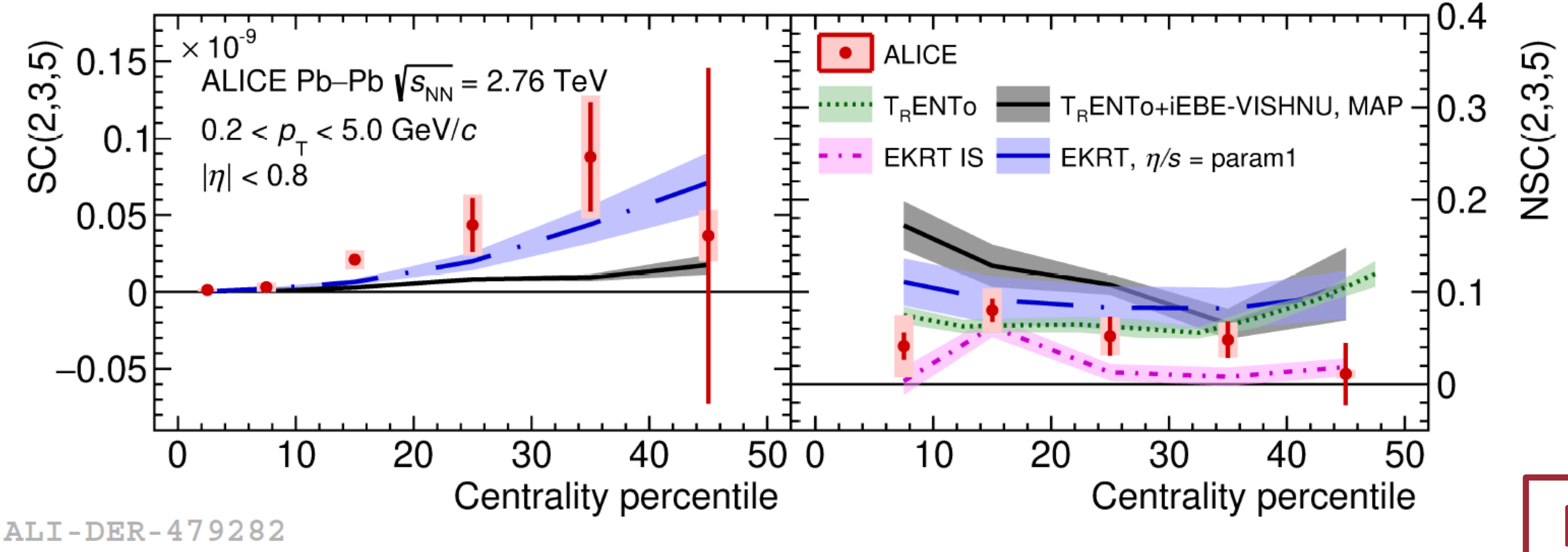


New

- Sensitivity of SC(2,3,4) to the model used for prediction
- Development of genuine correlations during hydrodynamical evolution

[1] J. E. Bernhard, J. S. Moreland and S. A. Bass, Nature Phys. 15, 11 (2019)
ALICE Collaboration, arXiv:2101.02579 (2021)

SC(2,3,5) and NSC(2,3,5)

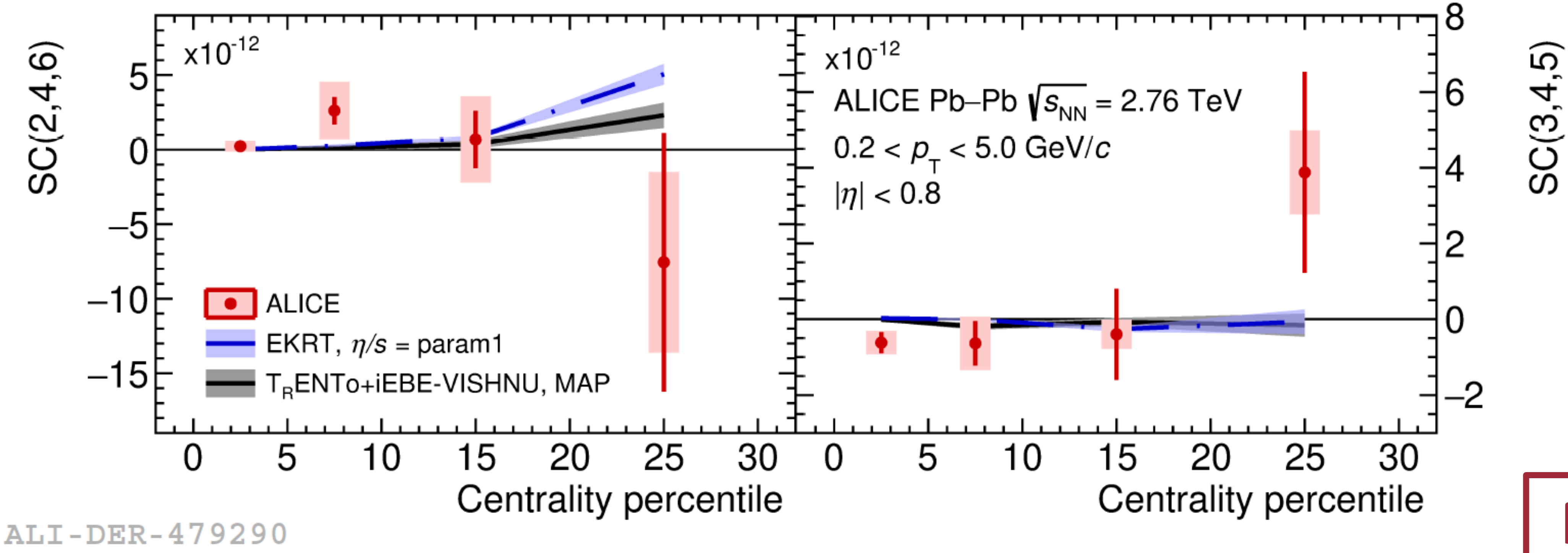


New

- Hint at the development of correlations during hydrodynamical evolution
- Non-linear response to v_5 from v_2 and v_3

ALICE Collaboration, arXiv:2101.02579 (2021)

SC(2,4,6) and SC(3,4,5)



New

- Good agreement between the models
- SC(2,4,6) and SC(3,4,5) ~ 0 → No correlations in the final state

ALICE Collaboration, arXiv:2101.02579 (2021)

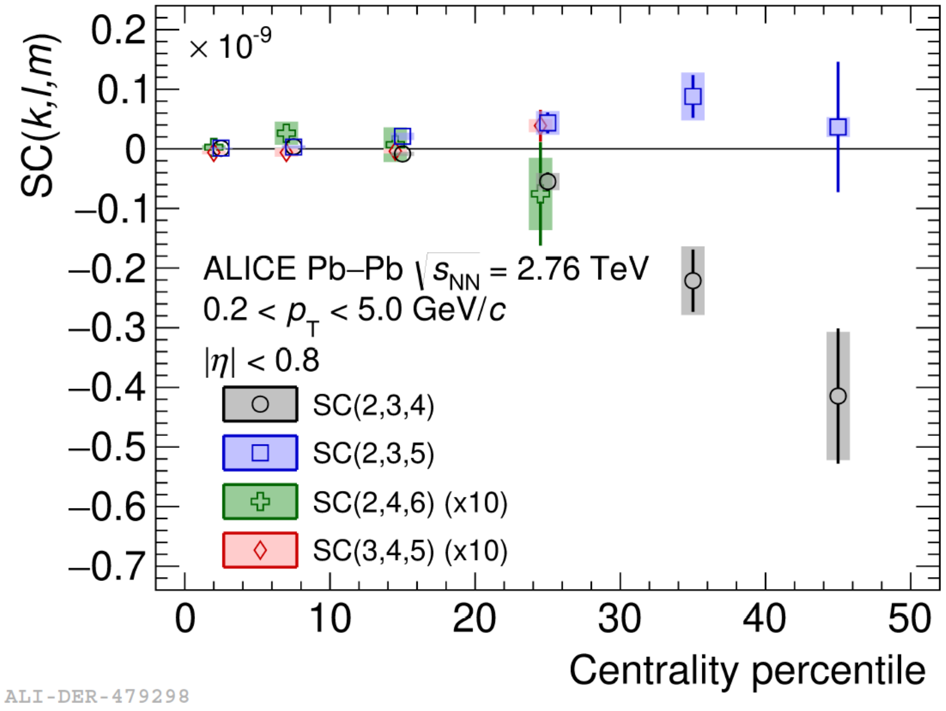
In a nutshell

- First measurements of genuine three-harmonic correlations in Pb—Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

→ Development of genuine correlations during the hydrodynamical evolution

→ Whole new set of constraints on the

- initial conditions and transport properties of QGP
- parameterizations of the hydro models



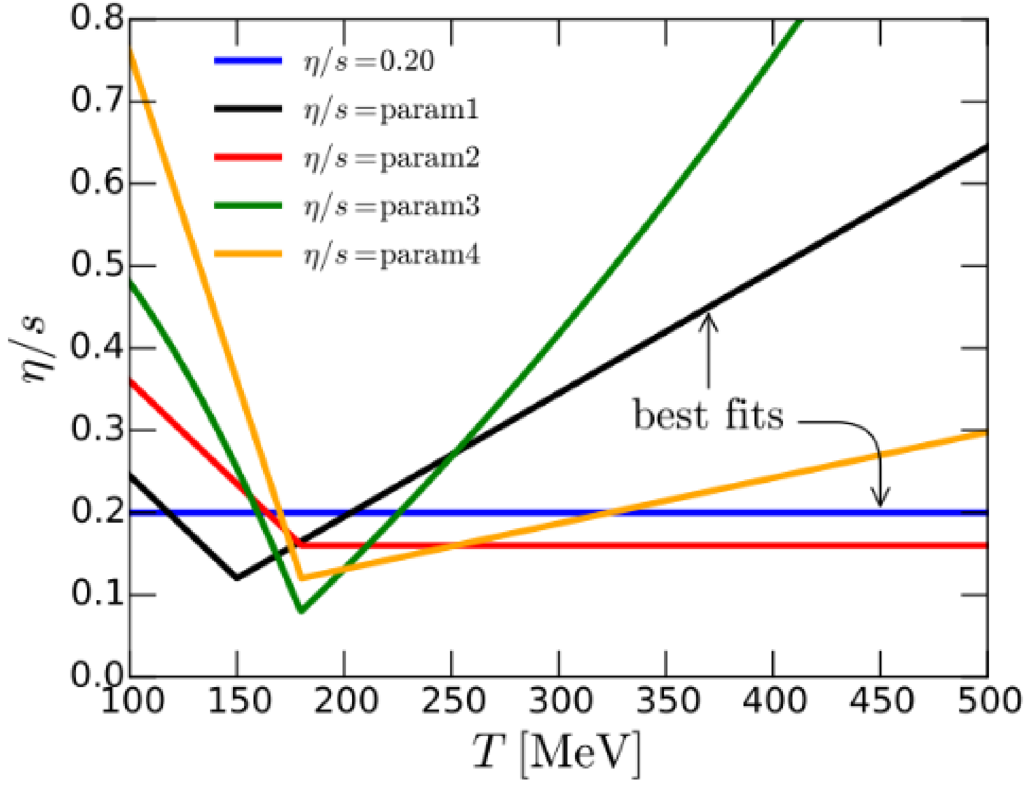
Thank you for your attention

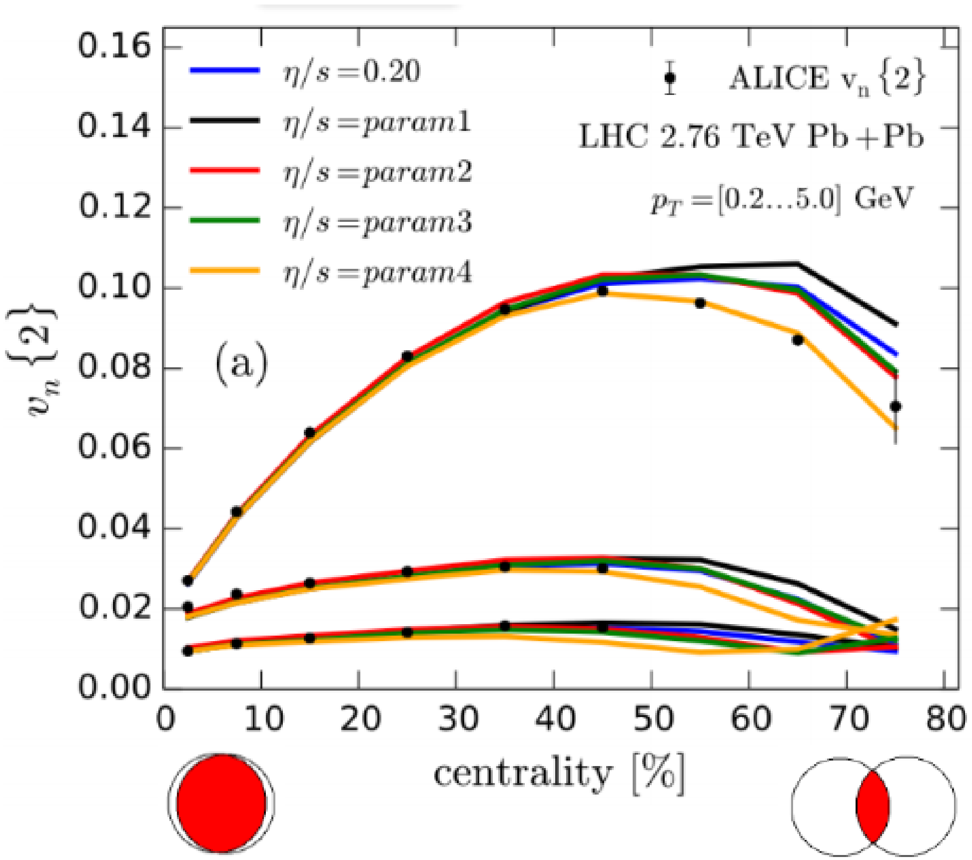
Backup Slides

Experimental Expression for $\mathrm{SC}(k,l,m)$

$$
\begin{aligned}
\mathrm{SC}(k,l,m) \quad = \quad & \langle\langle \cos[k\varphi_1 + l\varphi_2 + m\varphi_3 - k\varphi_4 - l\varphi_5 - m\varphi_6] \rangle\rangle \\
- \quad & \langle\langle \cos[k\varphi_1 + l\varphi_2 - k\varphi_3 - l\varphi_4] \rangle\rangle \, \langle\langle \cos[m(\varphi_5 - \varphi_6)] \rangle\rangle \\
- \quad & \langle\langle \cos[k\varphi_1 + m\varphi_2 - k\varphi_5 - m\varphi_6] \rangle\rangle \, \langle\langle \cos[l(\varphi_3 - \varphi_4)] \rangle\rangle \\
- \quad & \langle\langle \cos[l\varphi_3 + m\varphi_4 - l\varphi_5 - m\varphi_6] \rangle\rangle \, \langle\langle \cos[k(\varphi_1 - \varphi_2)] \rangle\rangle \\
+ \quad & 2 \, \langle\langle \cos[k(\varphi_1 - \varphi_2)] \rangle\rangle \, \langle\langle \cos[l(\varphi_3 - \varphi_4)] \rangle\rangle \, \langle\langle \cos[m(\varphi_5 - \varphi_6)] \rangle\rangle
\end{aligned}
$$

Parametrisations for η/s





H. Niemi, K. J. Eskola, R. Paatelainen, Phys. Rev. C 93, 024907 (2016)

Individual Flow Harmonics

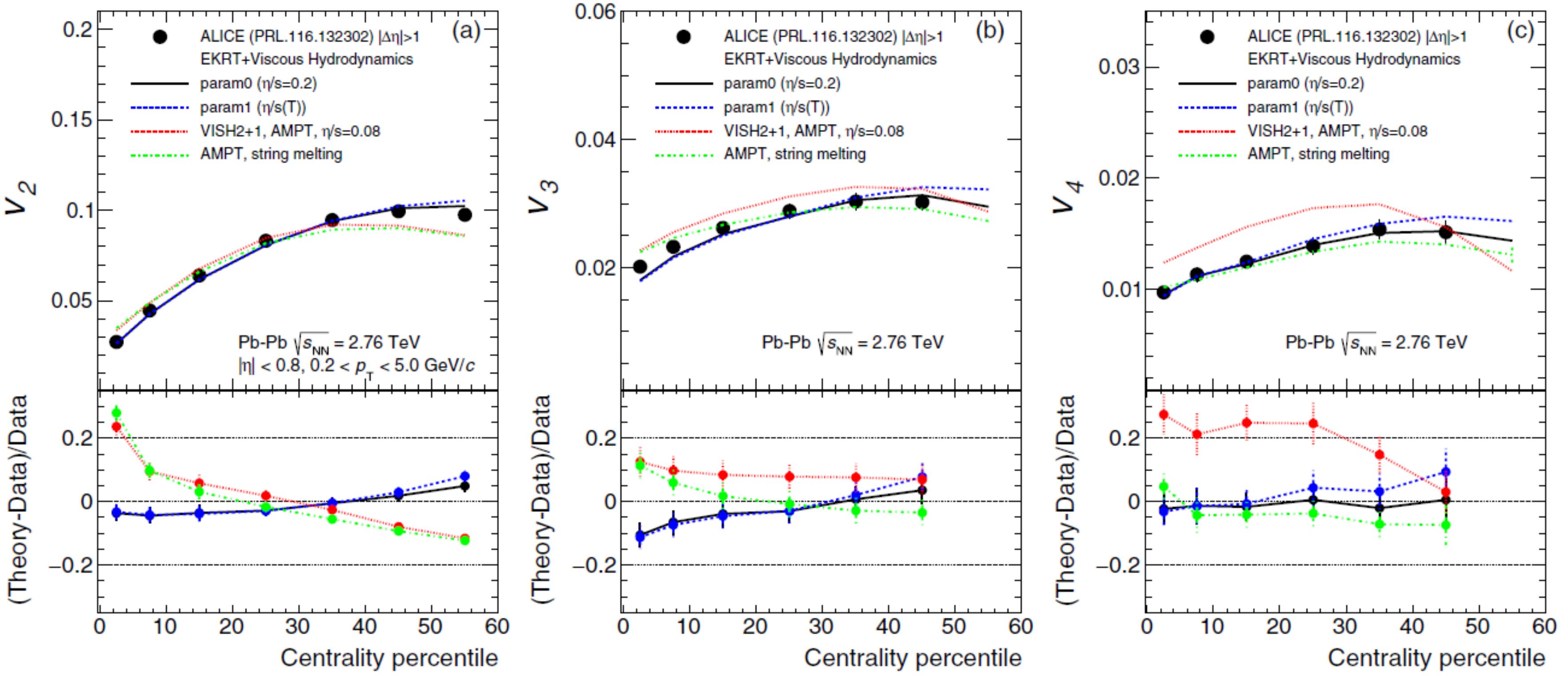


FIG. 13. The individual flow harmonics v_n for $n = 2–4$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [11]. Results are compared with selected calculations from three different types of models which are best in describing v_n coefficients.

ALICE Collabo

Toy Monte Carlo

$$\begin{aligned}\langle v_1^2 v_2^2 v_3^2 \rangle_{c,\mathrm{OLD}} &= \langle v_1^2 v_2^2 v_3^2 \rangle - \langle v_1^2 v_2^2 \rangle \langle v_3^2 \rangle - \langle v_1^2 v_3^2 \rangle \langle v_2^2 \rangle - \langle v_2^2 v_3^2 \rangle \langle v_1^2 \rangle \\ &- \langle v_1 v_2 v_3 \cos(3\Psi_3 - 2\Psi_2 - \Psi_1) \rangle^2 - \langle v_1 v_2 v_3 \sin(3\Psi_3 - 2\Psi_2 - \Psi_1) \rangle^2 \\ &+ 2 \langle v_1^2 \rangle \langle v_2^2 \rangle \langle v_3^2 \rangle \,,\end{aligned}$$

$$\begin{aligned}\langle v_1^2 v_2^2 v_3^2 \rangle_{c,\mathrm{NEW}} &= \langle v_1^2 v_2^2 v_3^2 \rangle - \langle v_1^2 v_2^2 \rangle \langle v_3^2 \rangle - \langle v_1^2 v_3^2 \rangle \langle v_2^2 \rangle - \langle v_2^2 v_3^2 \rangle \langle v_1^2 \rangle \\ &+ 2 \langle v_1^2 \rangle \langle v_2^2 \rangle \langle v_3^2 \rangle \,.\end{aligned}$$

- Old: method using azimuthal angles, New: approach used for this analysis
- Toy Monte Carlo setup as follows:
  - v_1, v_2, v_3 sampled randomly for each event in (0.03, 0.1), (0.04, 0.1), (0.05, 0.1) respectively
  - Ψ_1, Ψ_2 independently sampled for each event in (0, 2π) and $\Psi_3 = \frac{1}{3}(\frac{\pi}{4} + 2\Psi_2 + \Psi_1)$

Toy Monte Carlo