UNIVERSITY OF
COPENHAGEN

centre for particle physics
Discovery

Measurements of Correlations of Anisotropic Flow Harmonics in Pb–Pb Collisions with ALICE

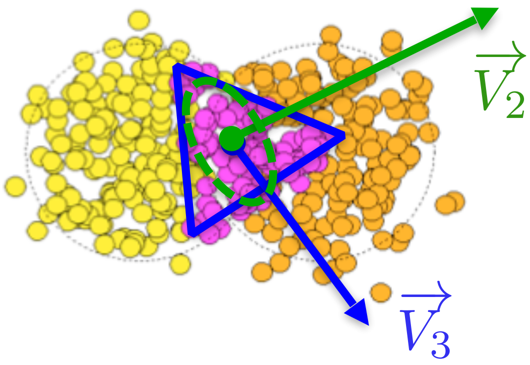
You Zhou (周铀)

Niels Bohr Institute

(on behalf of the ALICE Collaboration)

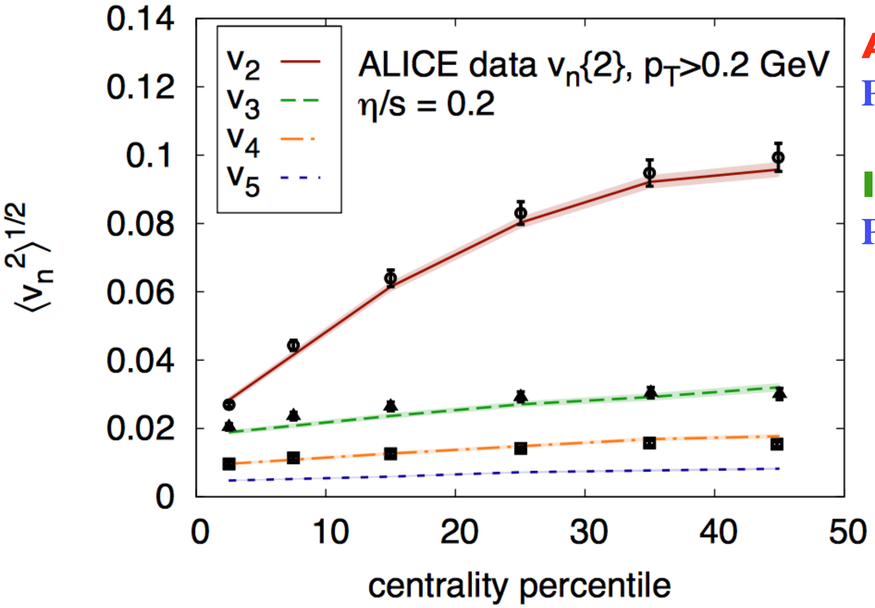
ALICE

Flow-vector $\overrightarrow{V_m}$ and $\overrightarrow{V_n}$



$$\overrightarrow{V_m} = v_m e^{-im\Psi_m}$$
$$\overrightarrow{V_n} = v_n\, e^{-in\Psi_n}$$

v_n measurements

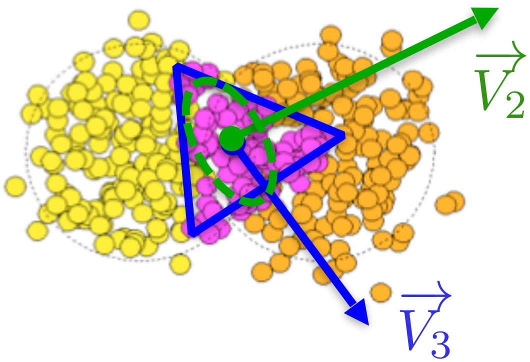


ALICE: PRL107, 032301

IP-Glasma: PRL110, 012302

- The magnitudes of the Flow-vector, anisotropic flow harmonics v_n, have been measured in great details (centrality, p_T, η, PID)
  - constraints on the initial conditions, η/s, EoS, freeze-out conditions et al.

Flow-vector $\overrightarrow{V_m}$ and $\overrightarrow{V_n}$



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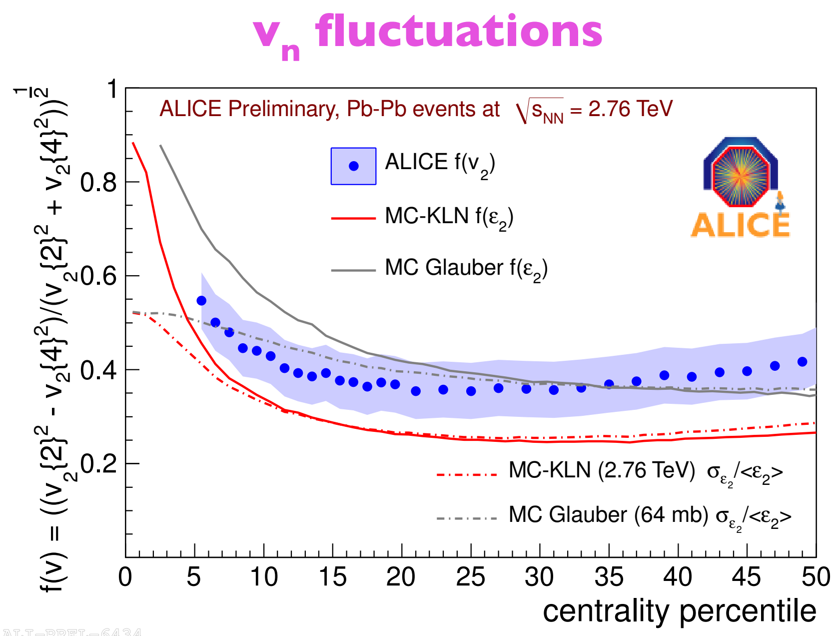
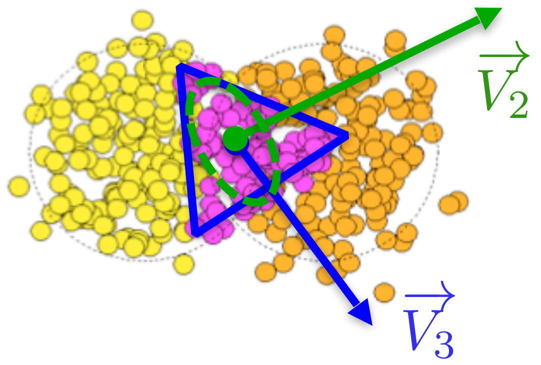


- The fluctuations of each individual flow harmonic have been investigated.
  - further understanding of underlying p.d.f. of v_n distributions

Correlations between $\overrightarrow{V_m}$ and $\overrightarrow{V_n}$



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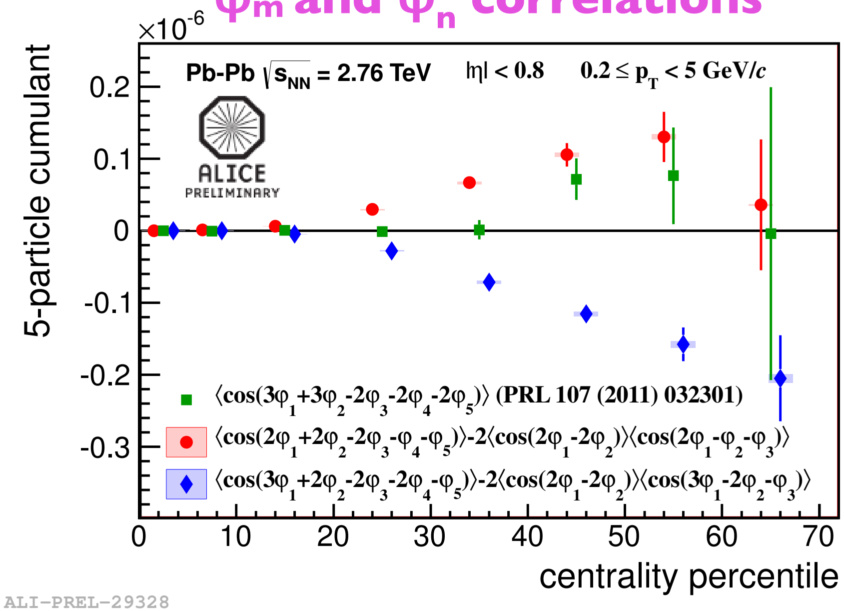


- Correlations between m-*th* and n-*th* Flow-vectors:
  - Flow angle correlations: Ψ_m and Ψ_n correlations (have been studied)
  - Flow magnitude correlations: v_m and v_n correlations
    - Does v_m and v_n correlated? anti-correlated? or not correlated?
    - How can we investigate the relationship of v_m and v_n without contribution from Ψ_m and Ψ_n ?

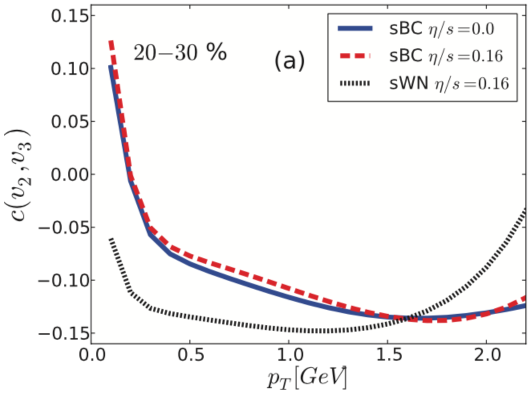
Correlations of v_m and v_n

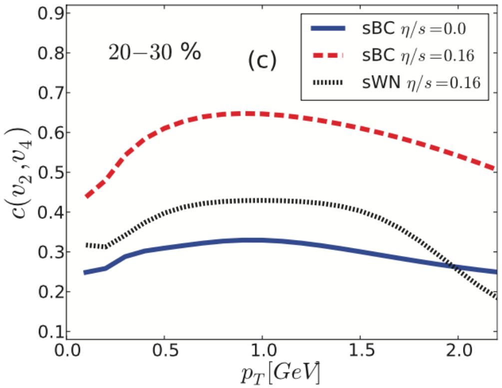
❖ A linear correlation coefficient $c(v_m, v_n)$ was proposed to study the correlations between v_m and v_n:

H. Niemi et al., PRC 87, 054901 (2013)

$$c(v_m, v_n) = \left\langle \frac{(v_m - \langle v_m \rangle_{ev})(v_n - \langle v_n \rangle_{ev})}{\sigma_{v_n}\sigma_{v_m}} \right\rangle_{ev}$$

- This correlation function is 1 (−1) if a and b are linearly (anti-linearly) correlated and zero in the absence of linear correlation.





- negative correlations of $c(v_2, v_3)$ and positive correlations of $c(v_2, v_4)$
- $c(v_2, v_3)$ is sensitive to initial conditions and insensitive to η/s, $c(v_2, v_4)$ is sensitive to both ⇨ $c(v_m, v_n)$ is a new observable to constrain initial conditions and η/s.
- However, this observable cannot be accessible easily in flow measurements which relying on two- and multi-particle correlations.

SC(m,n)

❖ New observable:

A. Bilandzic etc,
PRC 89, 064904 (2014)

Symmetric 2-harmonic 4-particle **C**umulants, ***SC(m,n)***, measures the correlations of v_m and v_n

$$\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle_c$$
$$=\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle-\langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\,\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle$$
$$=\langle v_m^2 v_n^2\rangle-\langle v_m^2\rangle\langle v_n^2\rangle\,.$$

❖ By construction not sensitive to:

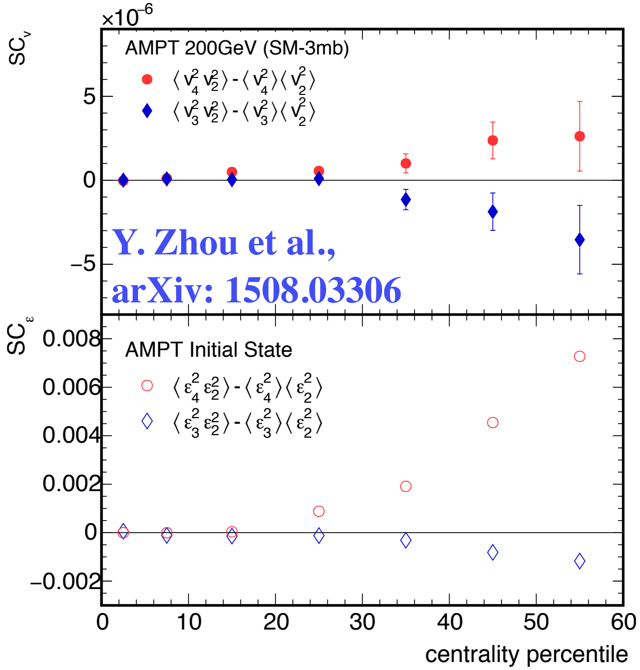
- non-flow effects, due to usage of 4-particle cumulant
- inter-correlations of various symmetry planes (Ψ_m and Ψ_n correlations)

❖ It is non-zero if the event-by-event amplitude fluctuations of v_m and v_n are (anti-)correlated.

- more details, see Section IV in:

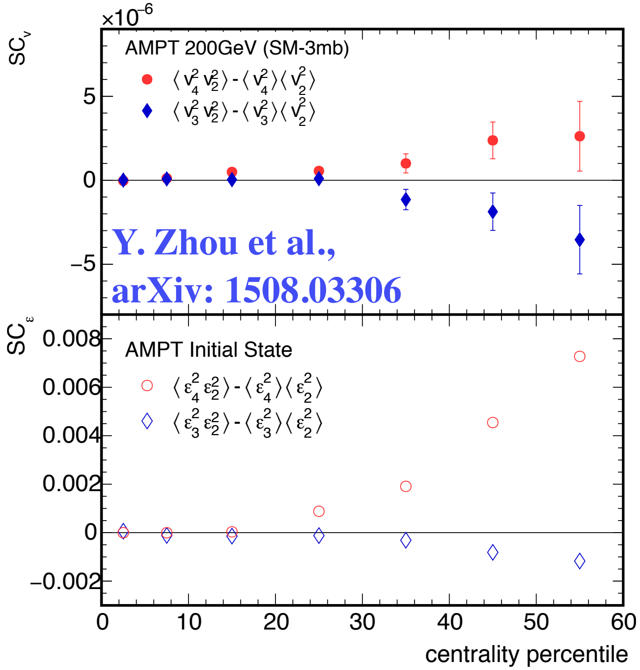
http://journals.aps.org/prc/abstract/10.1103/PhysRevC.89.064904

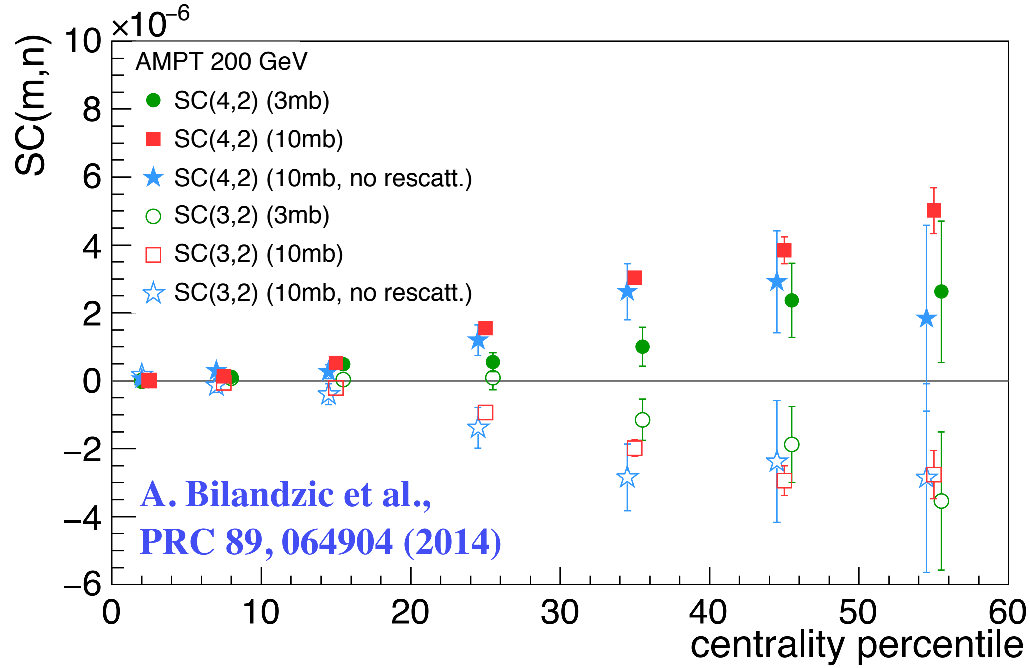
SC(m,n) calculation in models



- In previous AMPT study, it predicted a positive SC(4,2) and negative SC(3,2), the signs of SC(m,n) in the final state seem to be determined by $SC(m,n)_{\varepsilon}$ in the initial state.

SC(m,n) calculation in models





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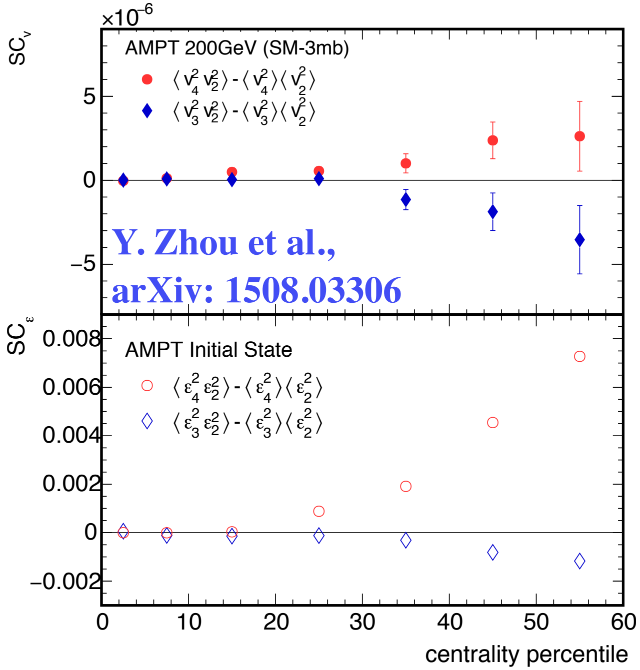
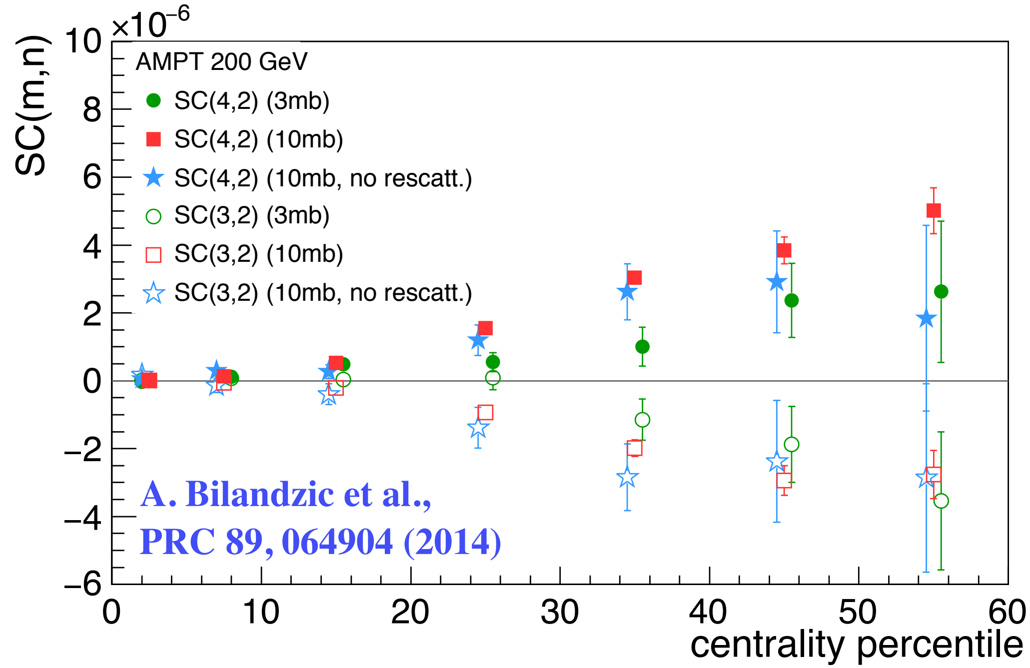
- Both the partonic and hadronic interactions contribute to the magnitudes of SC(m,n).

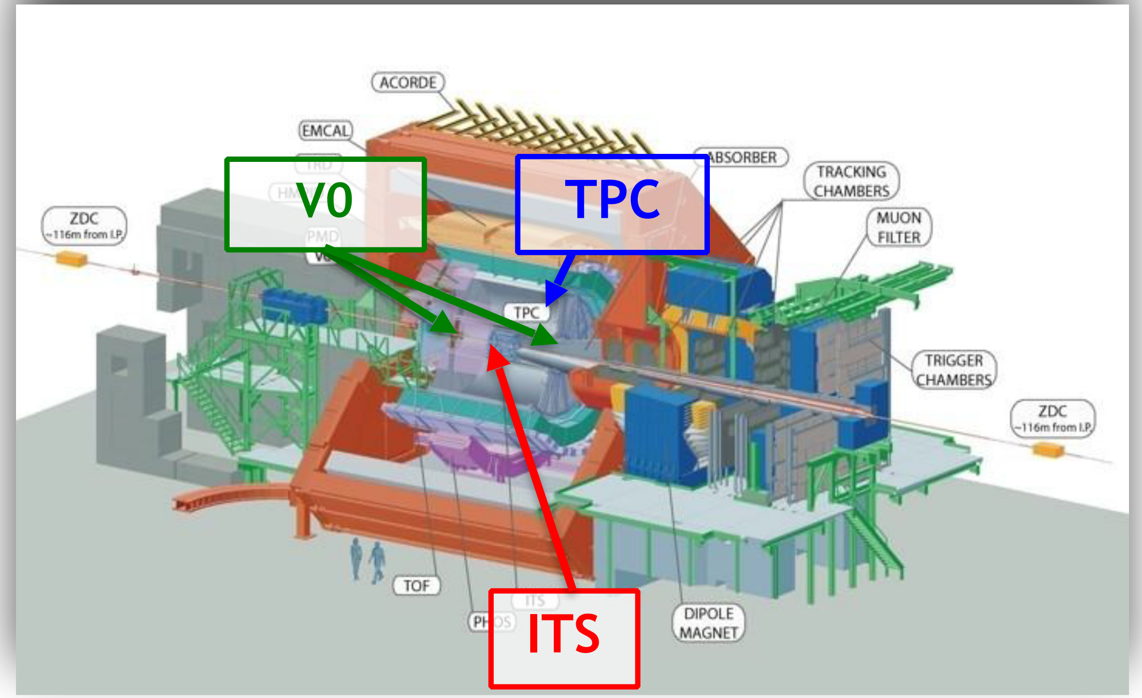
SC(m,n) calculation in models





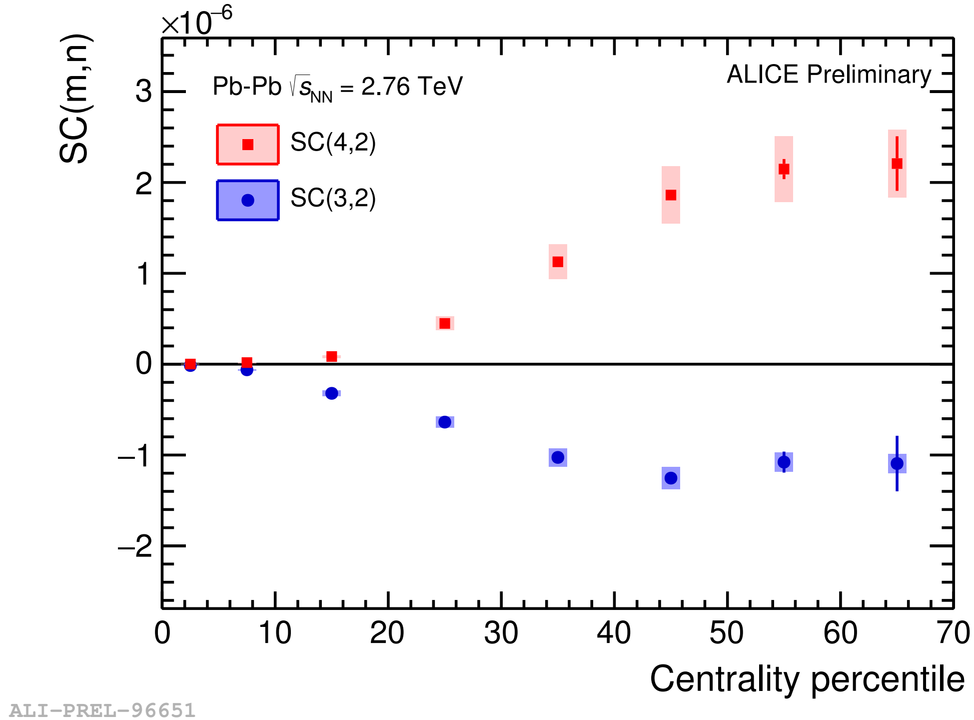
- ❖ In previous AMPT study, it predicted a positive SC(4,2) and negative SC(3,2), the signs of SC(m,n) in the final state seem to be determined by SC(m,n)$_\varepsilon$ in the initial state.
- ❖ Both the partonic and hadronic interactions contribute to the magnitudes of SC(m,n).
- ❖ SC(m,n), a new observable to constrain initial conditions and the properties of the system.

Analysis Details



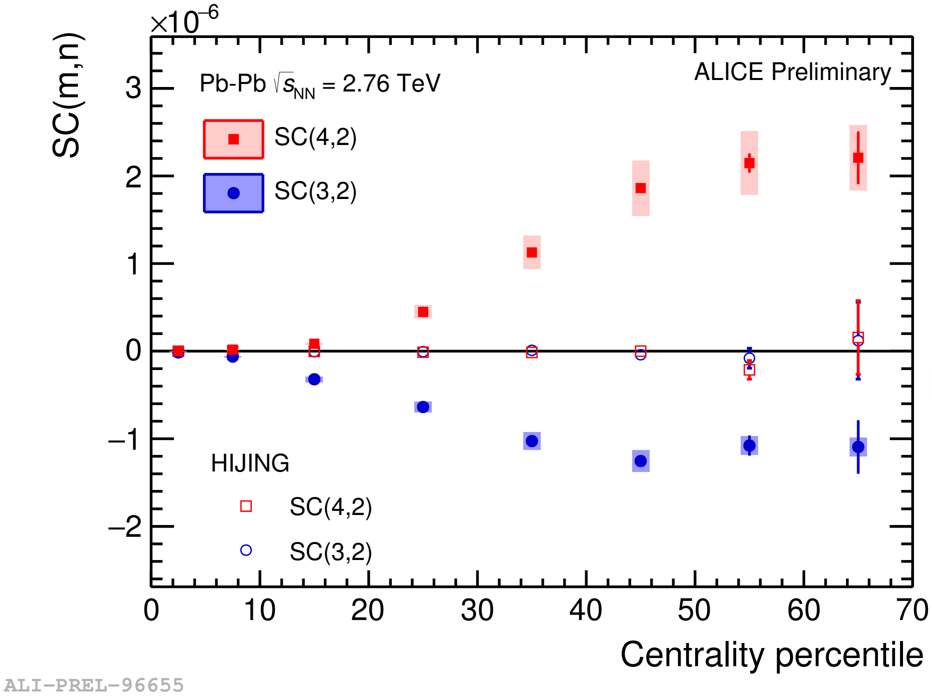
- Detectors used:
  - Inner Tracking System (trigger, tracking and vertexing)
  - Time Projection Chamber (tracking, centrality determination)
  - V0 detectors (trigger, centrality determination)
- Data sample:
  - Pb-Pb at $\sqrt{s_{NN}}$ = 2.76 TeV
    - ~ 12 M events analyzed
  - Tracks used:
    - $-0.8 < \eta < 0.8$
    - $0.2 < p_T < 5.0$ GeV/c

Centrality dependence of SC(m,n)



- The positive values of SC(4,2) and negative SC(3,2) are observed for all centralities.
  - suggests a correlation between v_2 and v_4, and an anti-correlations between v_2 and v_3.
  - indicates finding $v_2 > \langle v_2 \rangle$ in an event enhances the probability of finding $v_4 > \langle v_4 \rangle$ and finding $v_3 < \langle v_3 \rangle$ in that event.

Non-flow contributions?



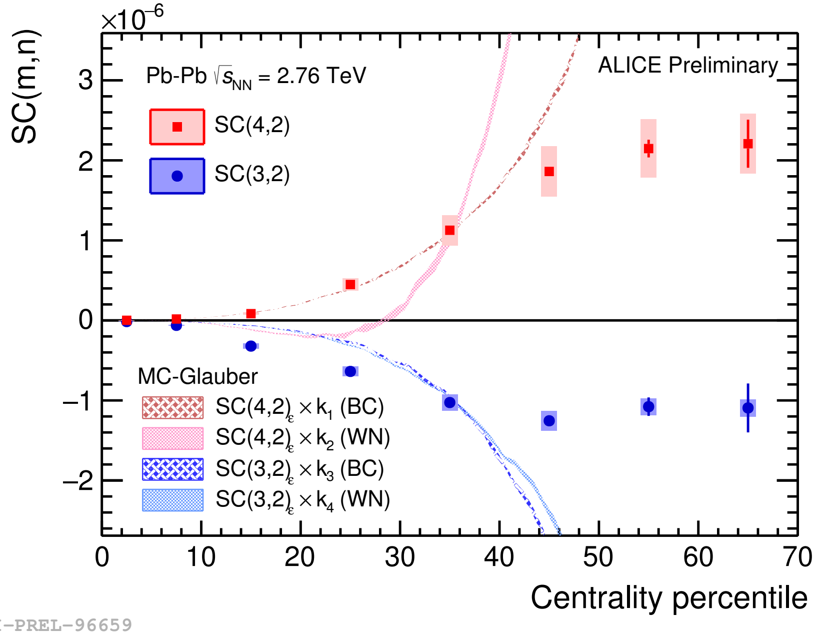
$$SC(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

- SC(m,n) calculations from HIJING
- It is found that $\langle v_m^2 v_n^2 \rangle > 0$ and $\langle v_m^2 \rangle \langle v_n^2 \rangle > 0$ in HIJING, but SC(m,n) are compatible with zero

  -> suggests SC measurements are nearly insensitive to non-flow effects.

- non-zero values of SC measurements cannot be explained by non-flow effects, thus confirms the existence of (anti-)correlations between v_m and v_n harmonics.

Contributions from the initial state ?



❖ Comparisons to MC-Glauber model calculations

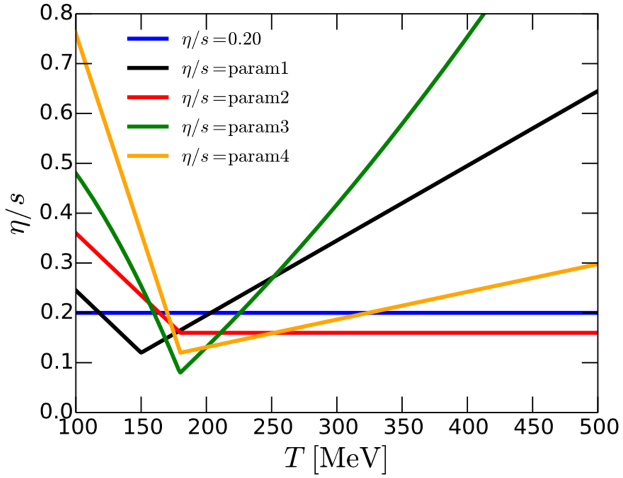
- $SC(m,n)_\varepsilon$ from MC-Glauber model using weights of wounded nucleon (WN) and binary collisions (BC) weights are scaled and compared to data.
- Increasing trend from central to peripheral collisions with different signature has been observed for $SC(4,2)_\varepsilon$ and $SC(3,2)_\varepsilon$, the centrality dependence of corresponding measurements cannot be captured well.
- correlations in the initial conditions are not the only contribution to SC measurements.

v_n harmonics and hydrodynamics

H. Niemi, arXiv: 1505.02677

TABLE I. The constant-slope parametrizations of $\eta/s(T)$, constructed so that they reproduce the LHC v_n data.

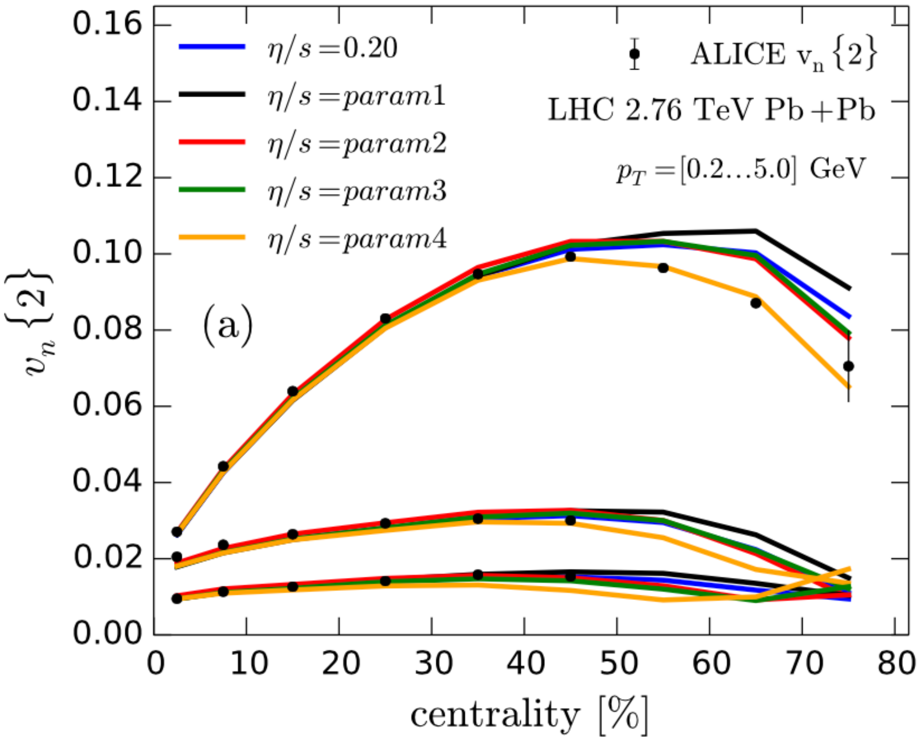
	T_{min}/MeV	$(\eta/s)_{min}$	$\eta/s(100\,\text{MeV})$	$\eta/s(500\,\text{MeV})$
param1	150	0.12	0.24	0.65
param2	180	0.16	0.36	0.16
param4	180	0.12	0.76	0.30



IC: perturbative QCD + saturation model (also known as EKRT)

$v_n\{2\}$

ALICE: PRL107, 032301



- ❖ Various settings of η/s in hydro calculations have been investigated
  - standard flow measurements are not very sensitive to η/s(T) at least for central- and mid-central collisions.

Comparisons to hydrodynamics

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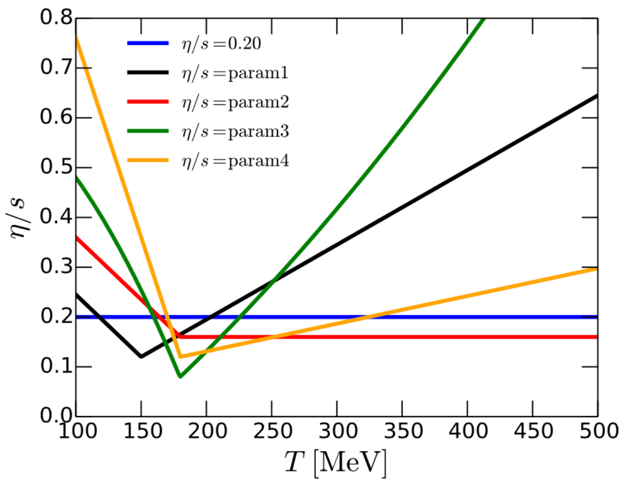
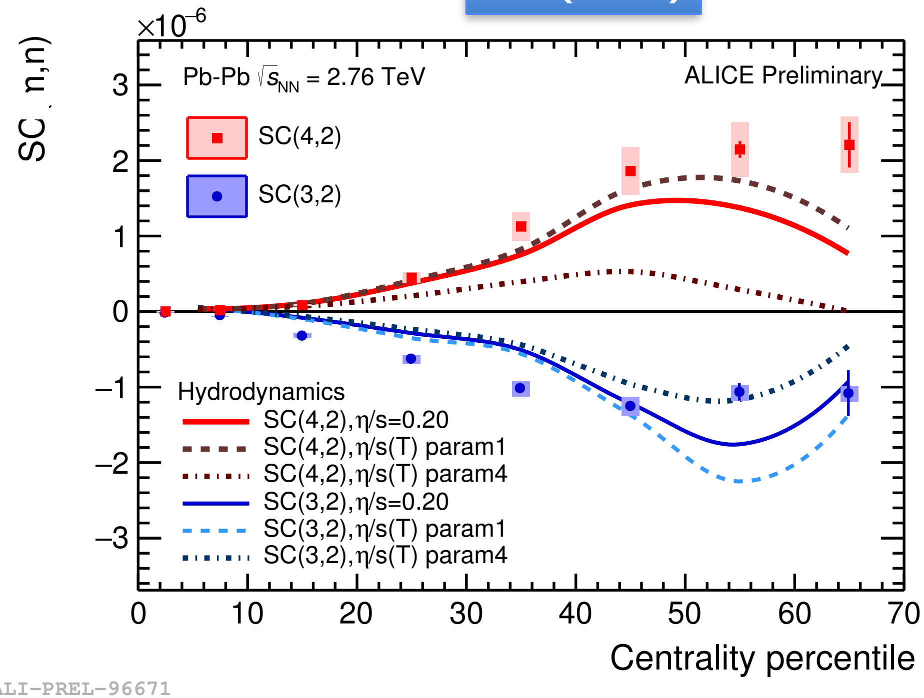


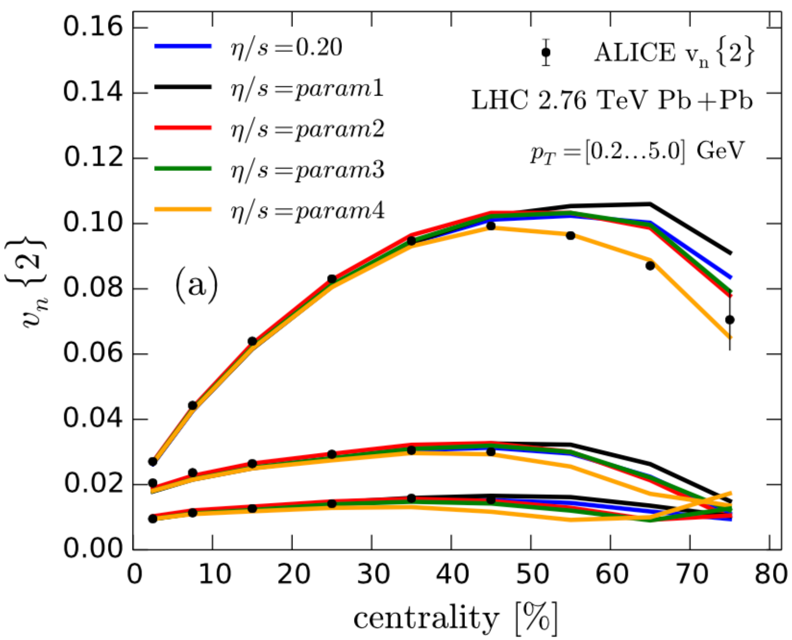
SC(m,n)



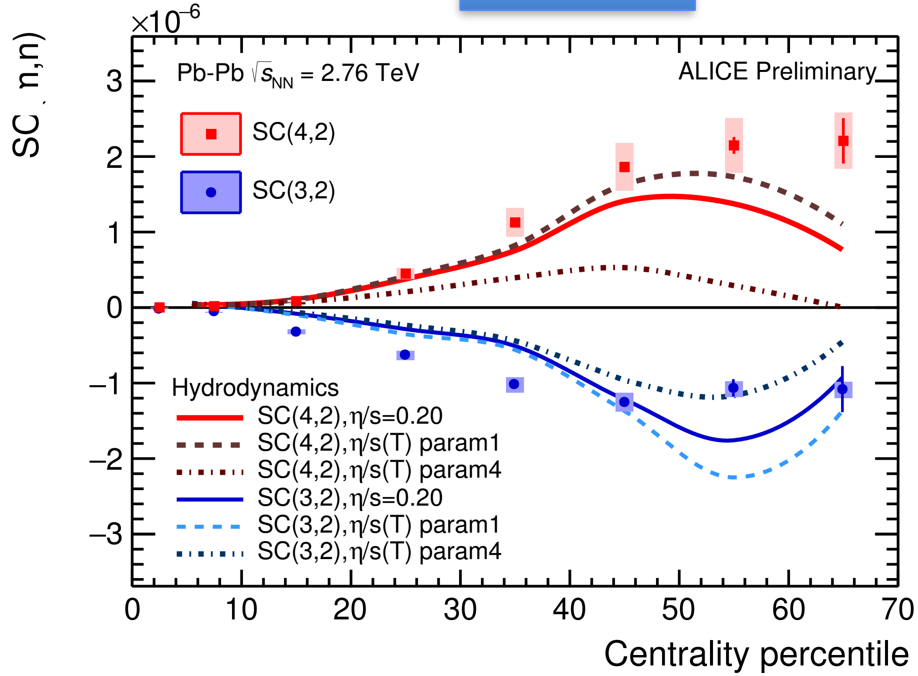
- Comparison of SC measurements to hydrodynamic calculations
  - Although hydro describes the v_n fairly well, there is no a single centrality for which a given η/s parameterization describes simultaneously SC(4,2) and SC(3,2).
  - SC measurements provide stronger constrains on the η/s in hydro than standard v_n measurements alone.

Better sensitivity to η/s

$v_n\{2\}$



SC(m,n)



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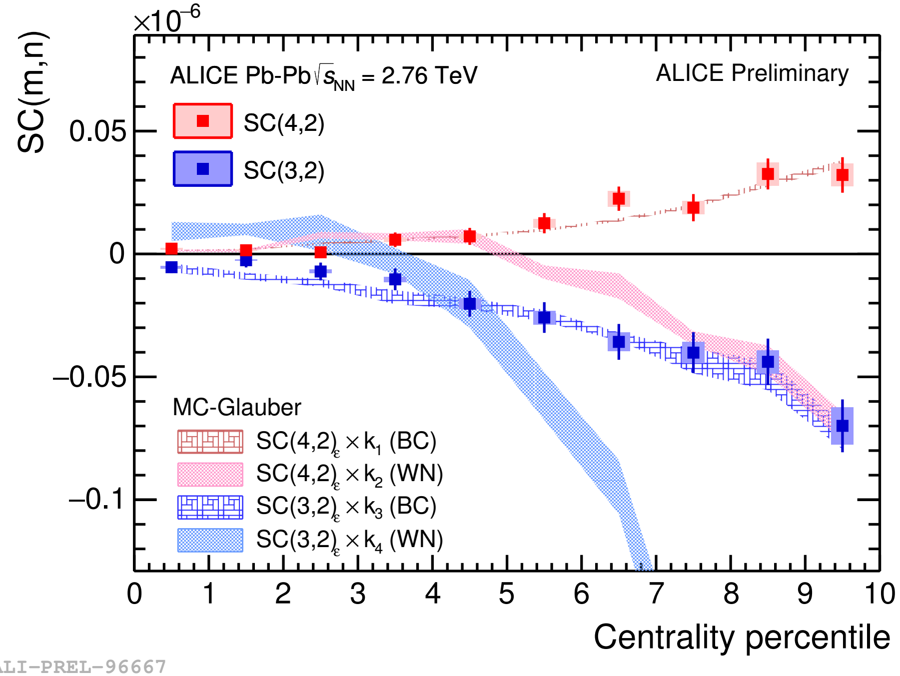
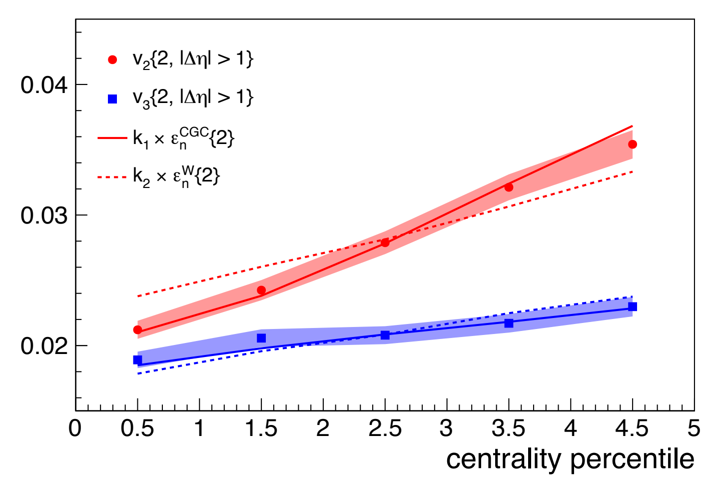
Probe the initial conditions



ALICE: PRL107, 032301



$v_n \propto \varepsilon_n$ for most central collisions
discriminate the initial conditions

- Assuming $v_n \propto \varepsilon_n$ in the central collisions, the $SC(m,n)_{\varepsilon}$ after scaling might be able to describe SC(m,n) measurements.
- Comparison to MC-Glauber calculations (initial conditions)
  - the one with Binary Collisions weight (BC) quantitatively describes SC for 0-10%, while Wounded Nucleon (WN) fails completely.

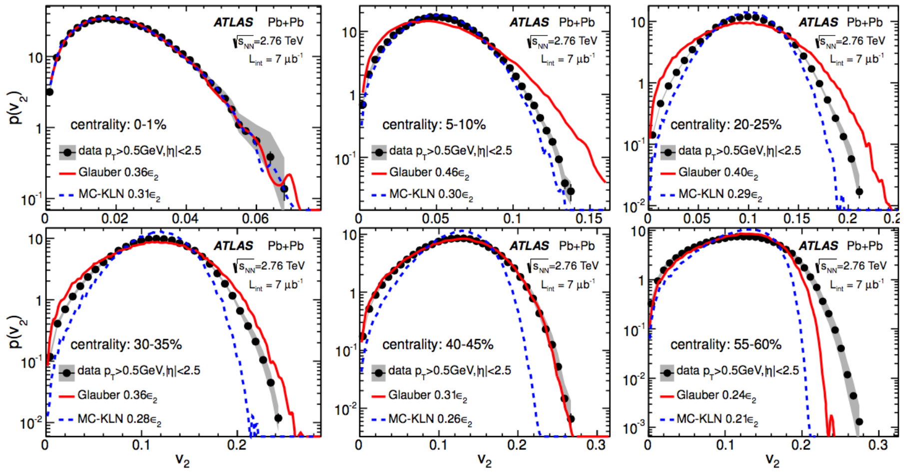
Conclusion

- We have measured for the first time the new multi-particle observables SC(m,n) which quantify the relationship between event-by-event fluctuations of two different flow harmonics.
  - v_2 and v_4 are correlated, v_2 and v_3 are anti-correlated in all centralities, the centrality dependence can't be described quantitively by existed calculations.
  - SC(m,n) measurements are more sensitive to input values of η/s than the individual flow harmonics, discriminate the inputs to hydro model with different parameterizations of η/s.
  - In fluctuation-dominated regime the MC-Glauber initial conditions with binary collisions weights are favored over wounded nucleon weights by data.

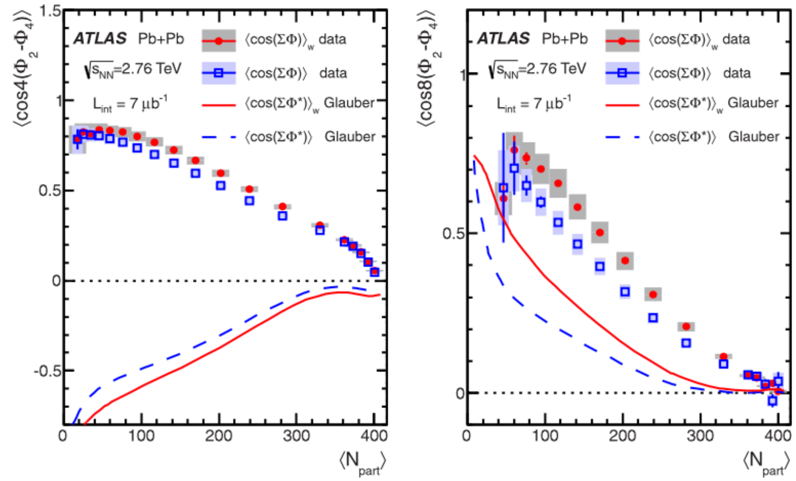
→ **SC(m,n), better sensitivity to initial conditions and η/s, provide new parameters to improve the theoretical calculations.**

Backup

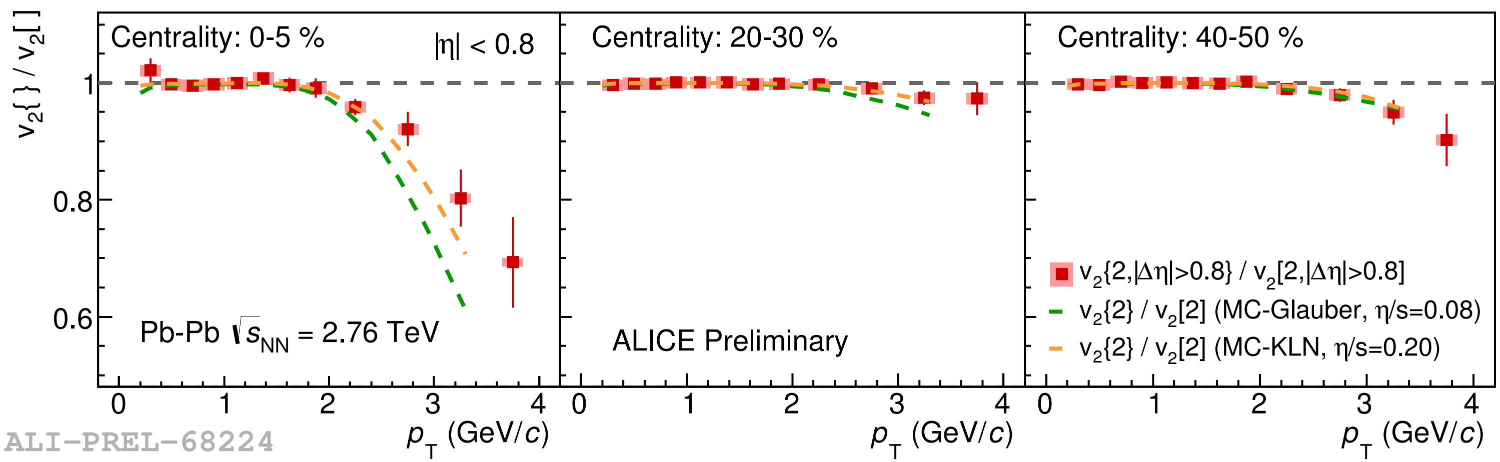
JHEP 11 (2013) 183



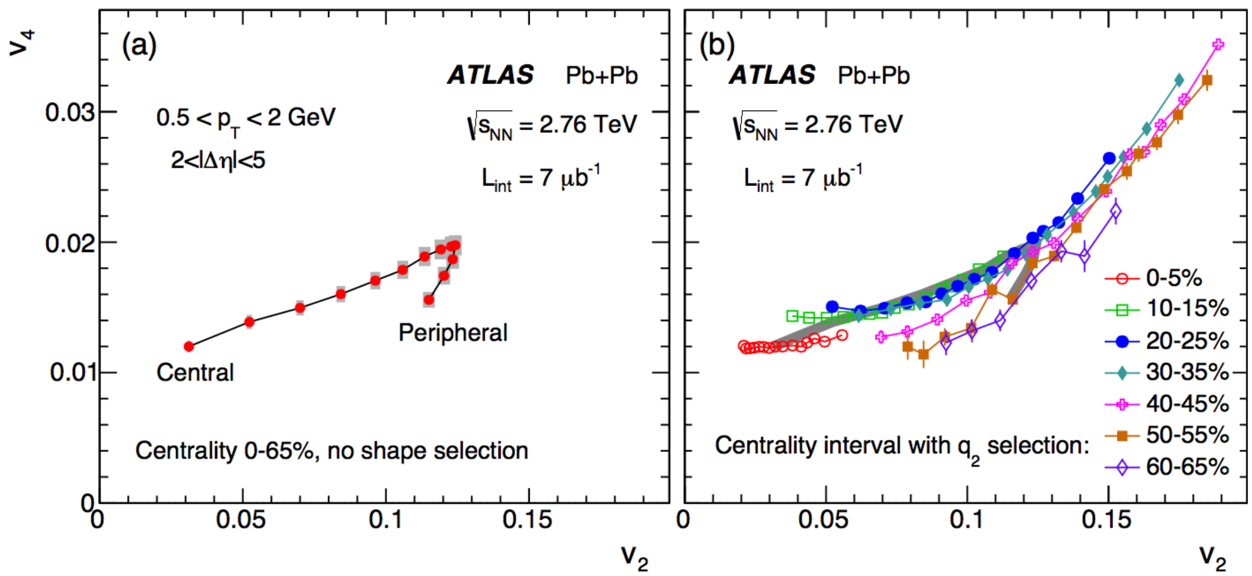
ATLAS, PRC 90, 024905 (2014)



Y. Zhou, NPA 931 (2014) 949-953



v_n, v_m correlations via ESE



- SC observables are not influenced by non-flow, as shown in slide 8, not the case for the study using 2-particle correlations.
- SC measurements provide a compact quantitative measure of these correlations, without needing knowledge of the functional relation between v_m and v_n
- Finally, our SC observables can easily be obtained from hydrodynamical calculations.

Systematic uncertainty

SC(3,2)	systematic uncertainty
non-uniform acceptance	$< 1\%$
reconstruction inefficiency	7 %
vertex z range	< 1 %
high multiplicity outliers	< 1 %
track types	5 %
minNClustersTPC	< 1 %
pseudorapidity range	< 1 %
charge combinations	5 %
DCA xy	3 %
DCA z	3 %
minChi2PerClusterTPC	< 1 %
maxChi2PerClusterTPC	< 1 %
Total	**10.8 %**