# Characterization of the initial state and medium properties of heavy-ion collisions at the LHC

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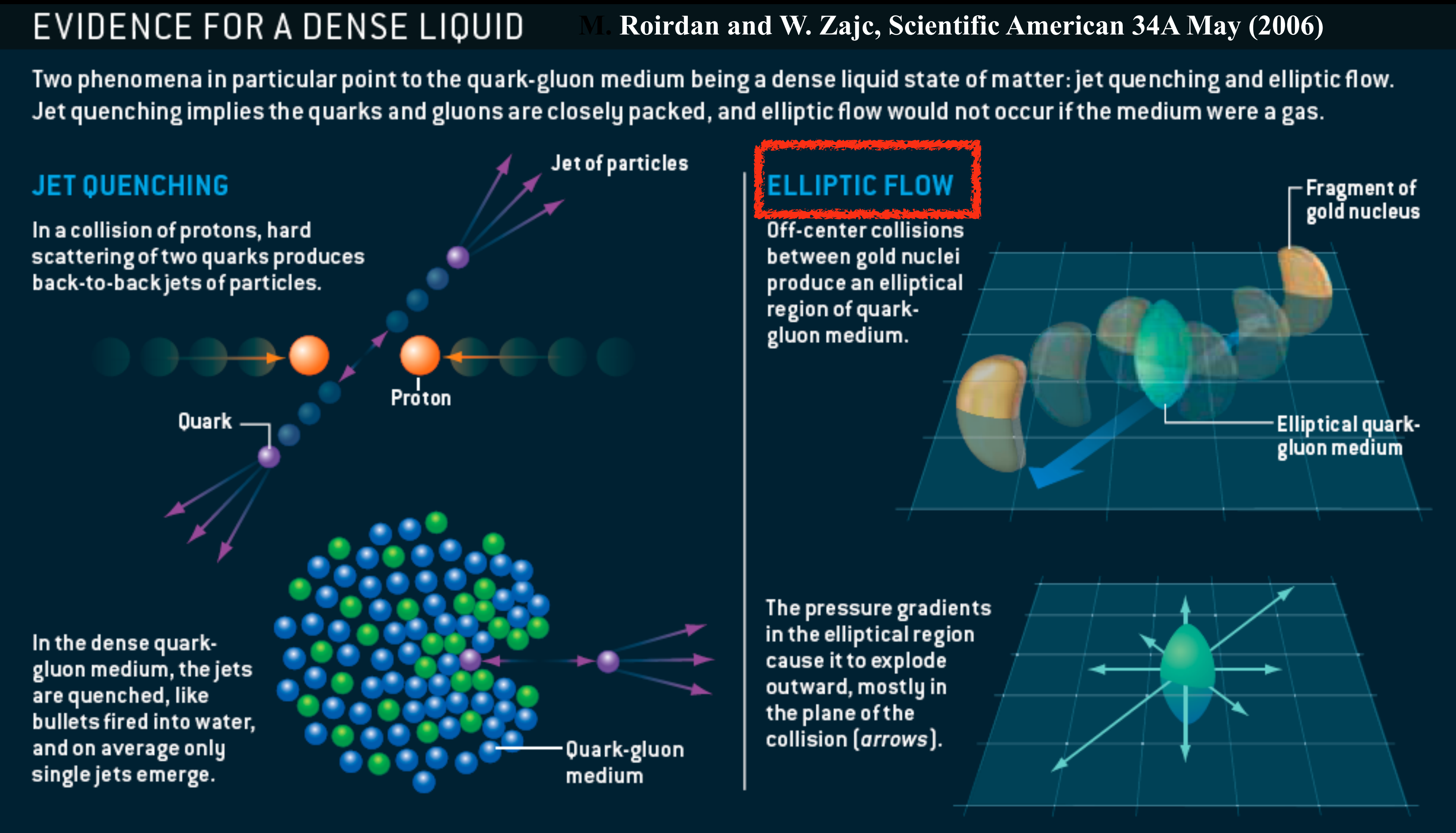
# Cooking QGP soup with Large Heavy-ion Collider (LHC)


## Pb-Pb collisions:

- 2.76 TeV (2010, 2011)
- 5.02 TeV (2015)

# Probes of QGP

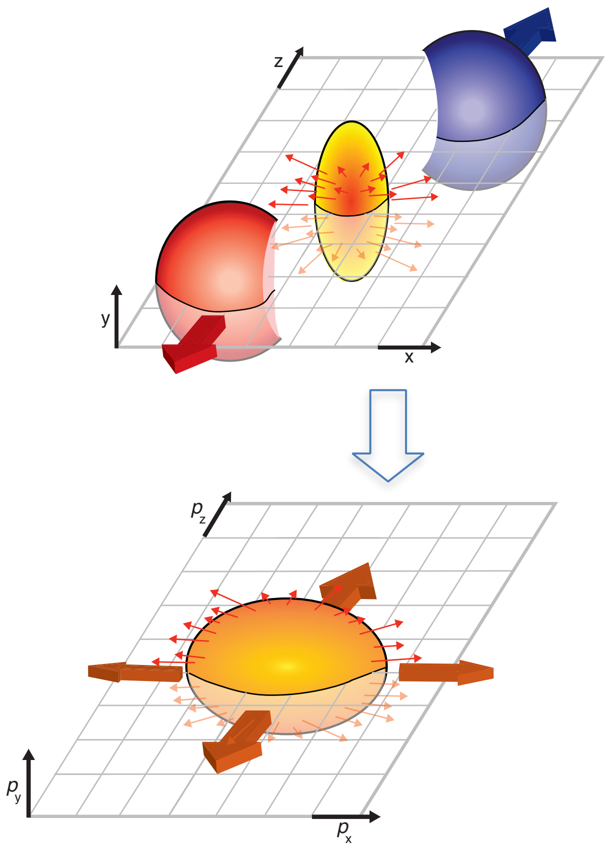
M. Roirdan and W. Zajc, Scientific American 34A May (2006)



# Elliptic Flow

- "Elliptic flow, described by the Fourier coefficients of the azimuthal particle distributions *w.r.t.* the reaction plane, could be used to probe the Quark-Gluon Plasma."

**J.Y. Olltriault, PRD 46, 229 (1992)**




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

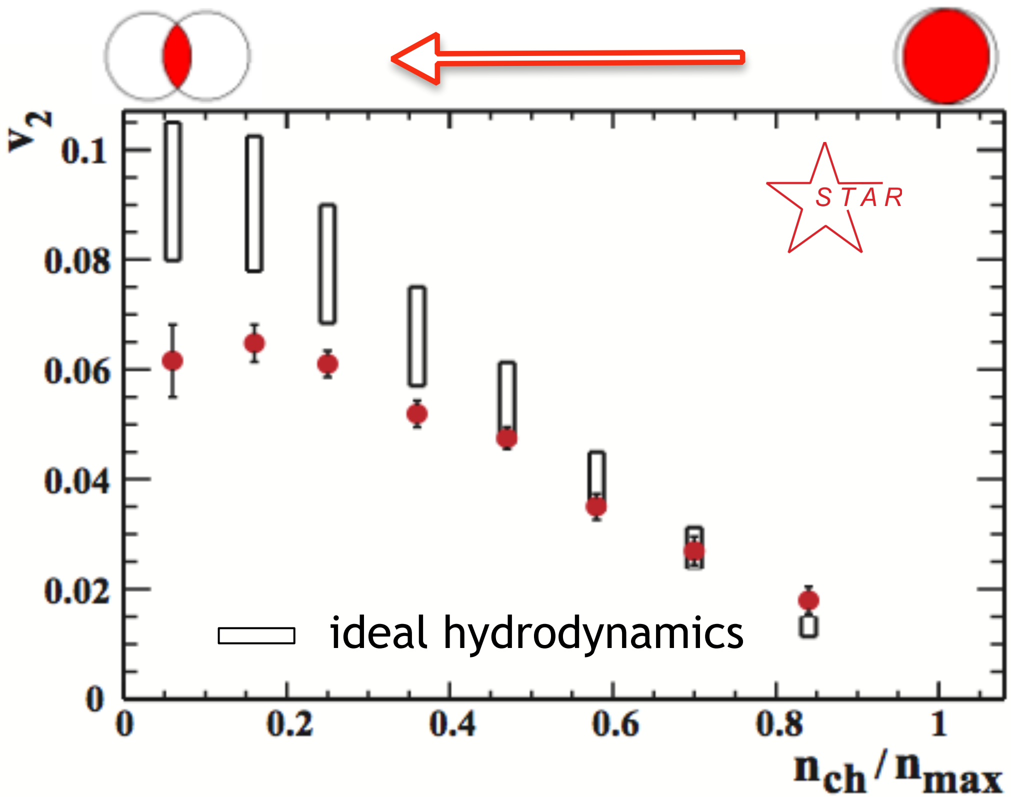
coordinate space Eccentricity

⇩

$$v_2 = \langle \cos 2\left(\varphi - \Psi_{\mathrm{RP}}\right) \rangle$$

momentum space Elliptic Flow

# First flow measurements at RHIC

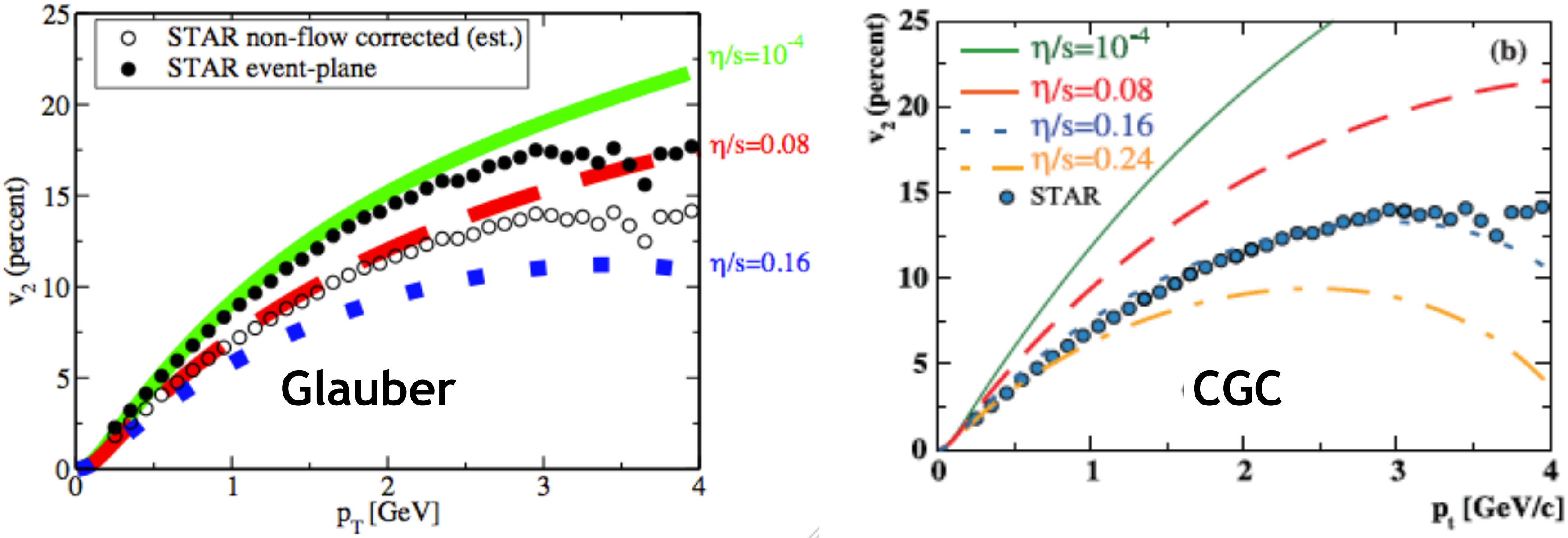



STAR Collaboration, PRL 86, 402 (2001)

❖ The measured elliptic flow agrees with an *ideal liquid* (negligible specific shear viscosity η/s~0)

# η/s, initial conditions

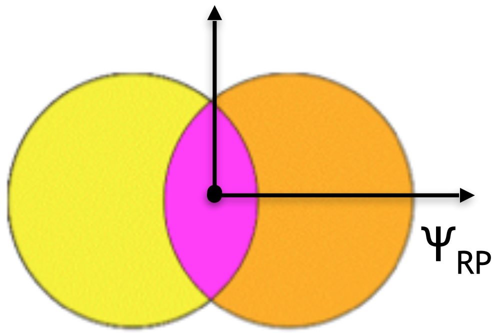
P. Romatschke & M. Luzum (2008)




- ❖ Extracted η/s strongly depends on initial conditions
  - η/s = 0.08 with Glauber-IS and 0.16 with CGC-IS —>100% uncertainty!

# Anisotropic Flow and symmetry planes

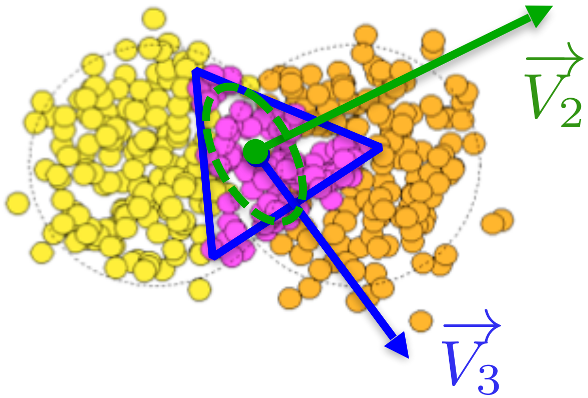
**1992**




$$v_2\{\Psi_{RP}\} = \langle \cos 2(\phi - \Psi_{RP}) \rangle$$

$\Psi_{RP}$: Reaction Plane

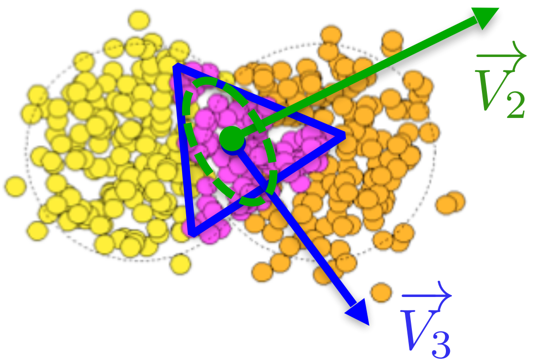
**2010**

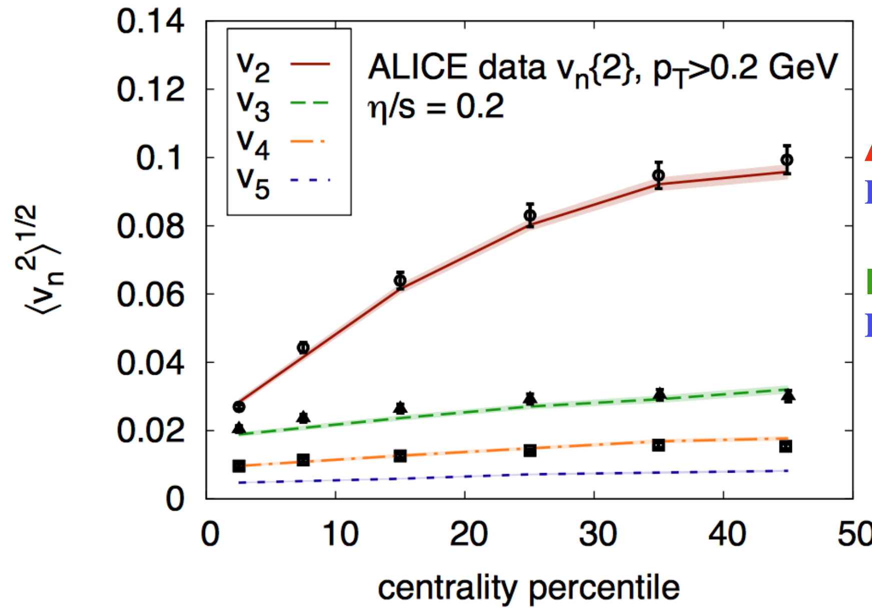



$$\overrightarrow{V_m} = v_m e^{-im\Psi_m}$$
$$\overrightarrow{V_n} = v_n e^{-in\Psi_n}$$

$v_2$: Elliptic flow
$v_3$: Triangular flow
$v_4$: Quadrangular flow
$v_5$: Pentagonal flow

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

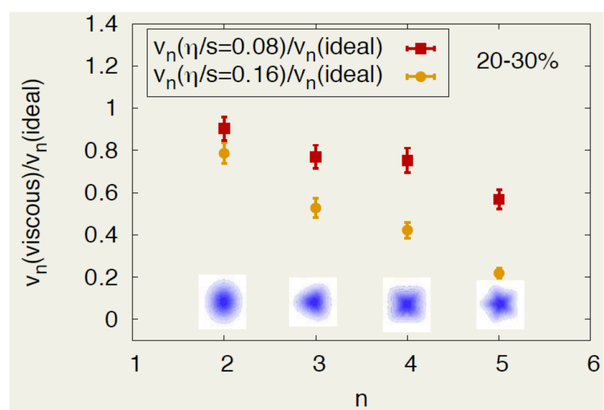



**ALICE:** PRL107, 032301 (2011)

**IP-Glasma:** PRL110, 012302 (2013)

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

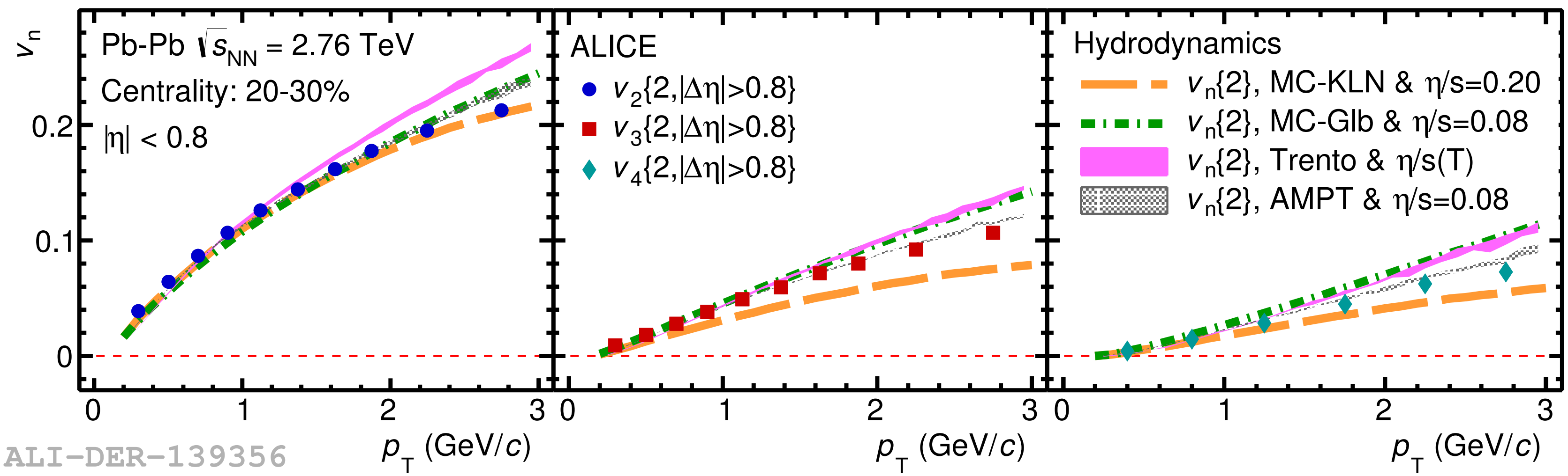



- ❖ The anisotropic flow coefficients $v_n$ measured in great detail
  —> constraints on the initial conditions, $\eta/s$, EoS, freeze-out conditions …

# Transverse momentum dependence of $v_n$

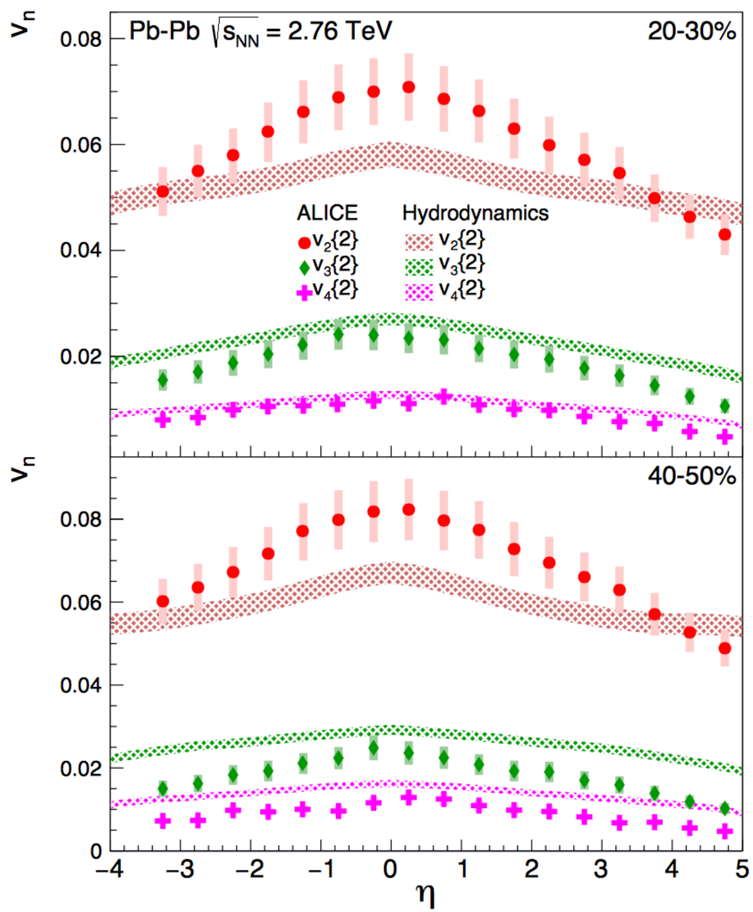
- More detailed information is carried by transverse momentum or pseudorapidity dependence of anisotropic flow $v_n$

ALICE, JHEP 09 (2017) 032




- comparisons of data and hydrodynamic calculations show:
  - calculations with IP-Glasma initial conditions and $\eta/s$ =0.20 give the best description of data
  - calculation with MC-Glauber initial conditions using the same eta/s gives poorer description.
  - strong constraints on the initial state and $\eta/s$ of QGP.

# Pseudorapidity dependence of $v_n$

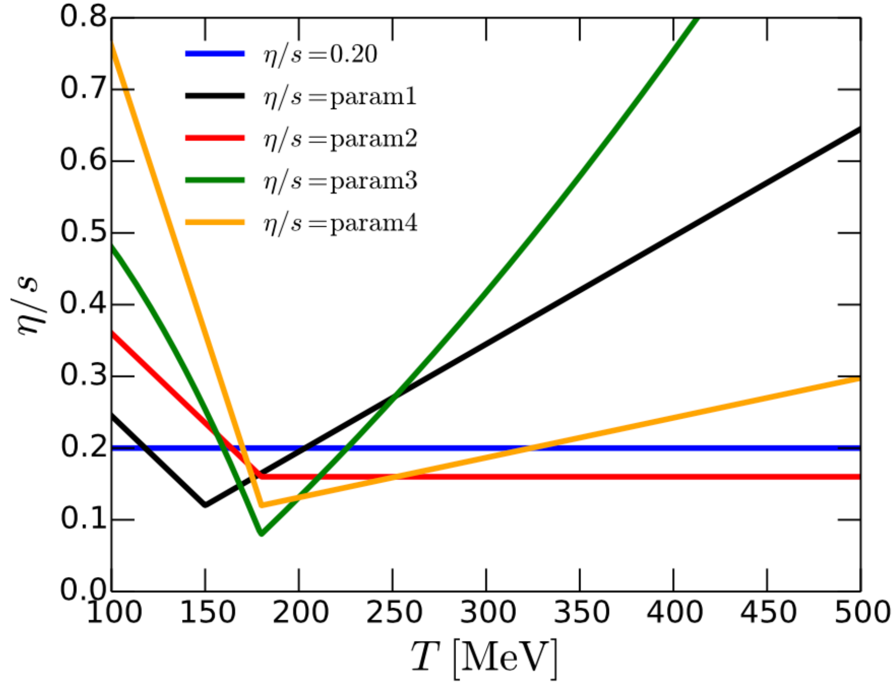



ALICE Collaboration, **PLB 762 (2016) 376**
Hydrodynamics: **PRL 116, 212301 (2016)**

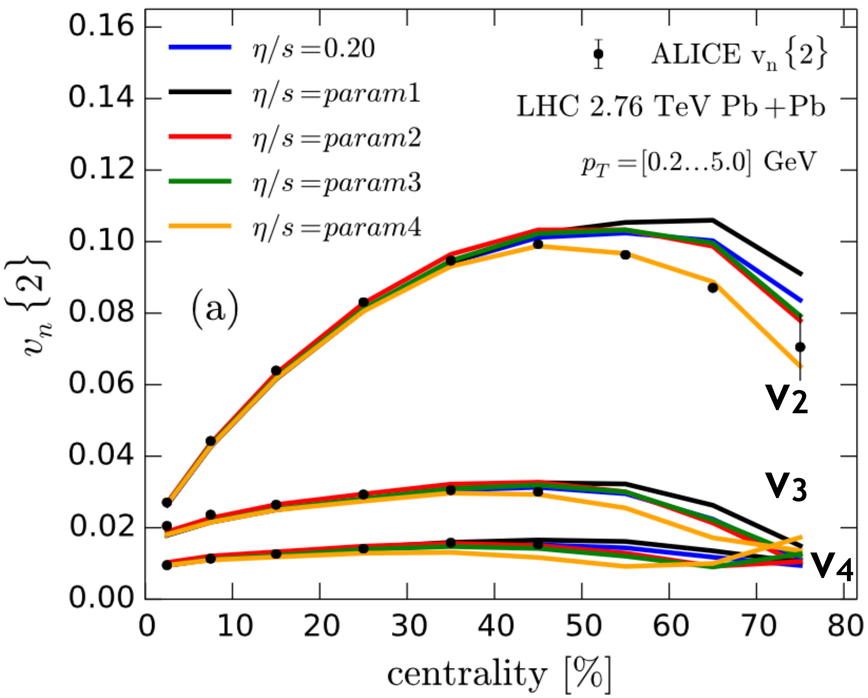
- We find that the shape of $v_n(\eta)$ is largely independent of centrality for the flow harmonics n = 2, 3 and 4,
- hydrodynamic calculations:
  - tuned $\eta/s(T)$ to fit $v_n(\eta)$ at RHIC
  - do not reproduce the data well, new challenge to the theory community

# Constraint from higher harmonic flow

EKRT: H. Niemi et. al, PRC 93, 024907 (2016)



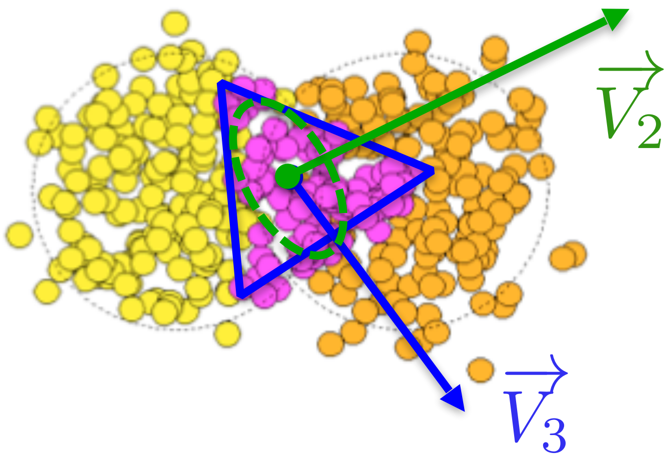

ALICE Collaboration, PRL 107, 032301 (2011)




- $v_n$ measurements are also quantitatively described by hydrodynamic calculations using EKRT, AMPT, Trento initial conditions (not MC-Glauber, nor MC-KLN) with different η/s(T)
  - weak sensitivity to η/s(T)
  - not easy to discriminate which set is the best

# $V_n$ and $V_m$

2010




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

❖ General questions:

- what are the correlations between $v_n$ and $v_m$ ?
- what are the correlations between $\psi_n$ and $\psi_m$ ?
- will these correlations provide new information ?

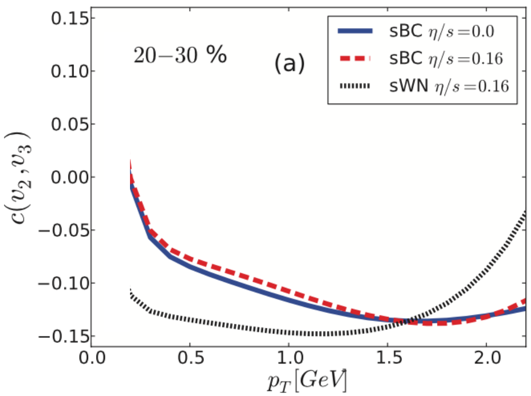
# Correlations of $v_m$ and $v_n$

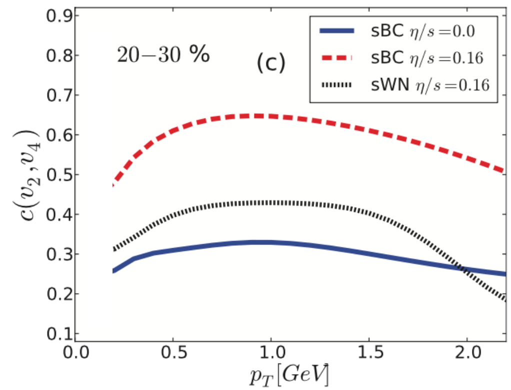
- A linear correlation coefficient $c(v_m, v_n)$ was proposed to study the correlations between $v_m$ and $v_n$:

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

# SC(m,n)

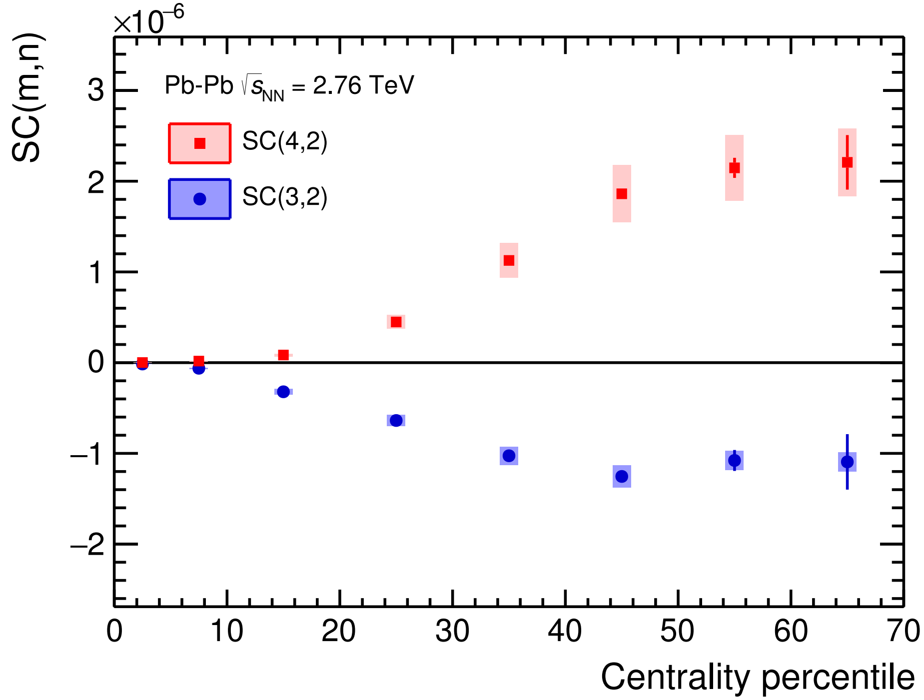
- **S**ymmetric **C**umulants, ***SC(m,n)***, measures the correlations of $v_n$ and $v_m$

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

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

- By construction not sensitive to:
  - non-flow effects, due to usage of 4-particle cumulant
  - inter-correlations of various symmetry planes ($\Psi_n$ and $\Psi_m$ correlations)
- It is non-zero if the event-by-event amplitude fluctuations of $v_n$ and $v_m$ are (anti-)correlated

# Centrality dependence of SC(m,n)



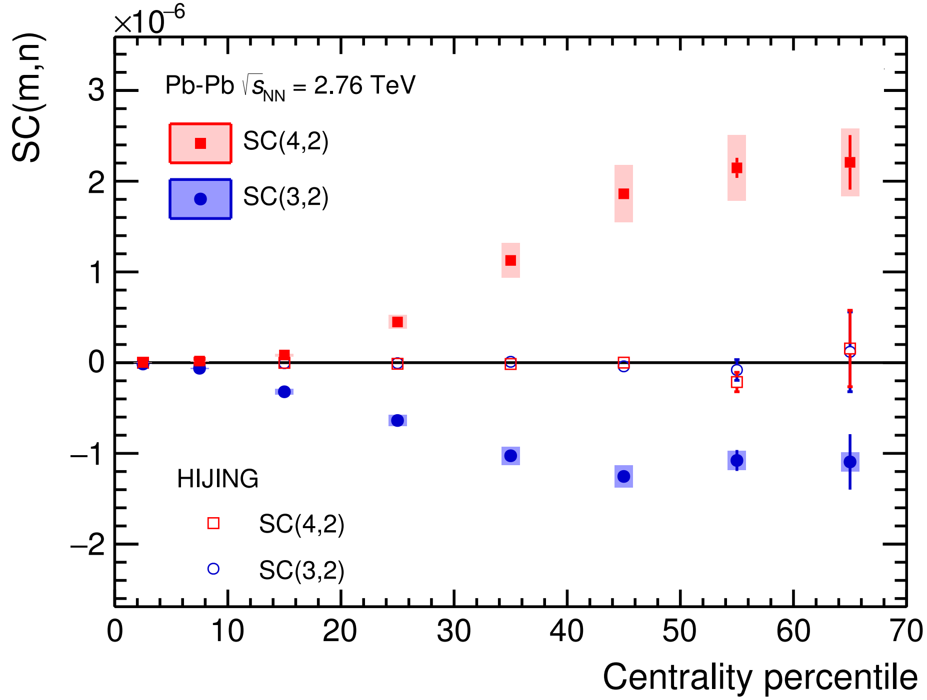

**ALICE**:
**PRL 117, 182301 (2016)**

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

❖ 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?




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

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

- 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

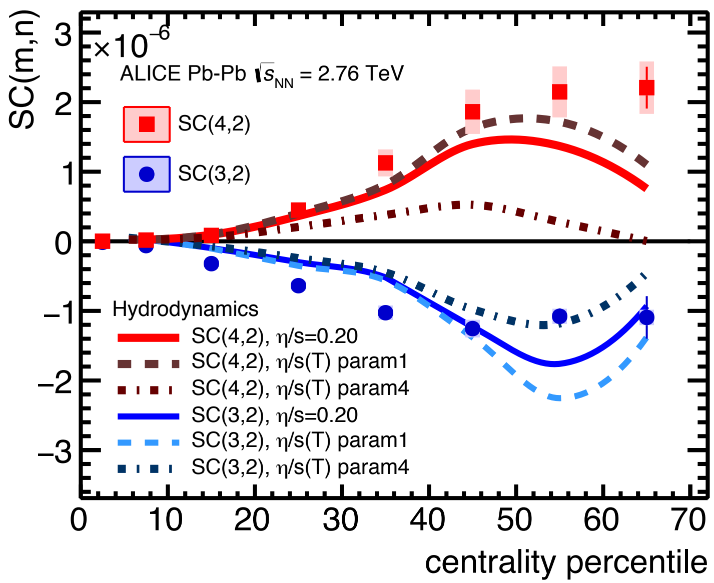
  -> suggests SC measurements are nearly insensitive to non-flow effects.

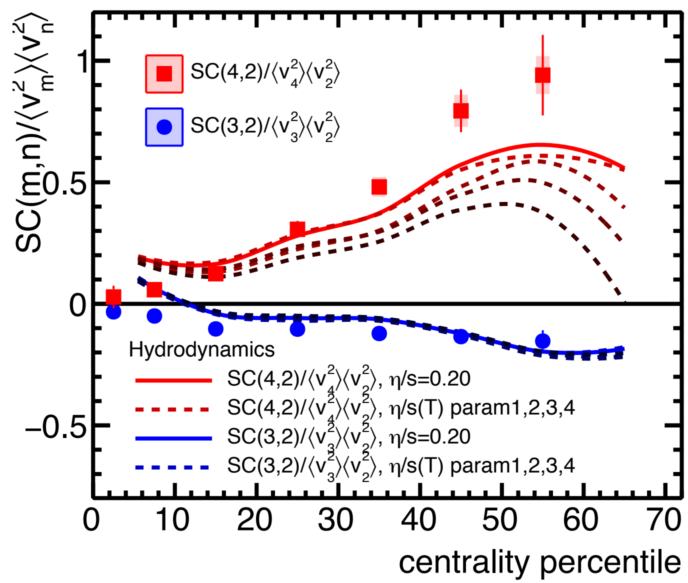
  - non-zero values of SC measurements cannot be explained by non-flow effects, thus confirms the existence of (anti-)correlations between $v_n$ and $v_m$ harmonics.

# Correlations between $v_m$ and $v_n$

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

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




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

❖ Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations

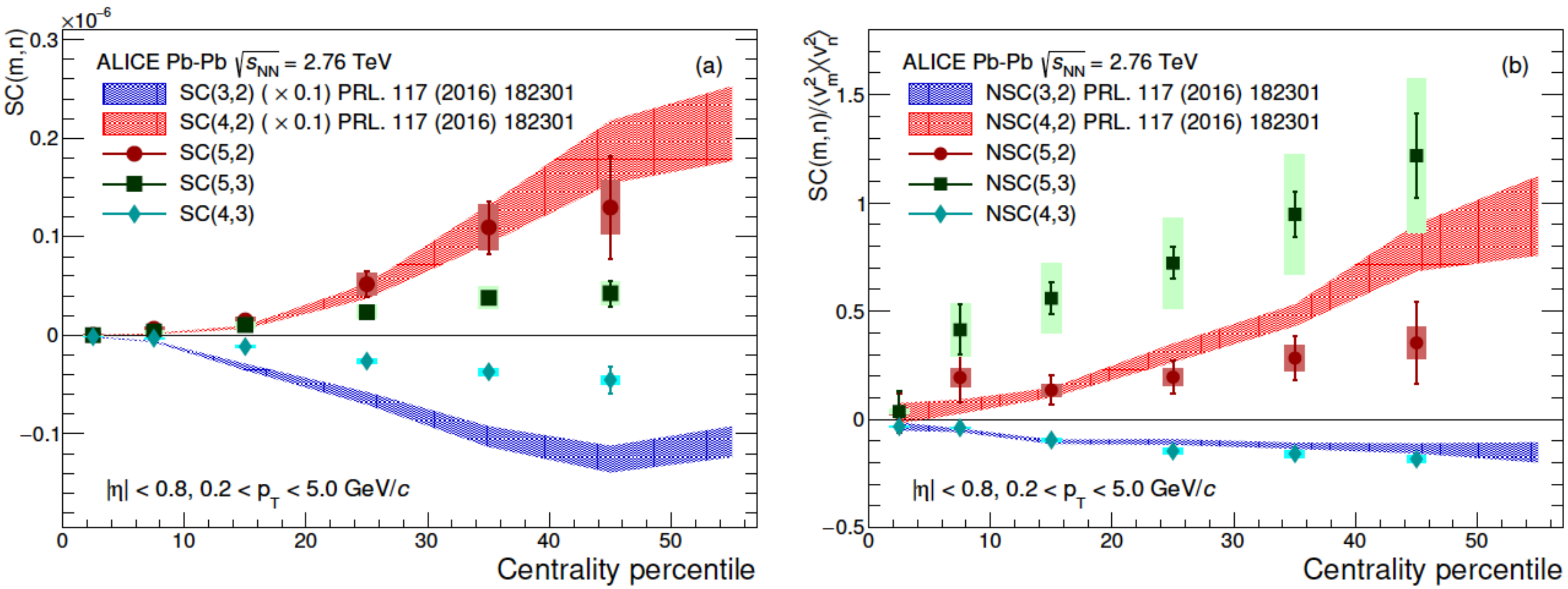
- Although hydro describes the $v_n$ fairly well, hydro with whatever η/s parameterizations give poor descriptions of SC and NSC.
- SC and NSC measurements provide stronger constrains on the η/s in hydro than standard $v_n$ measurements alone
- NSC(3,2) is insensitive to parameterization of η/s(T)

  -> direct constraints on initial conditions.

# SC and NSC with other harmonics

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

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

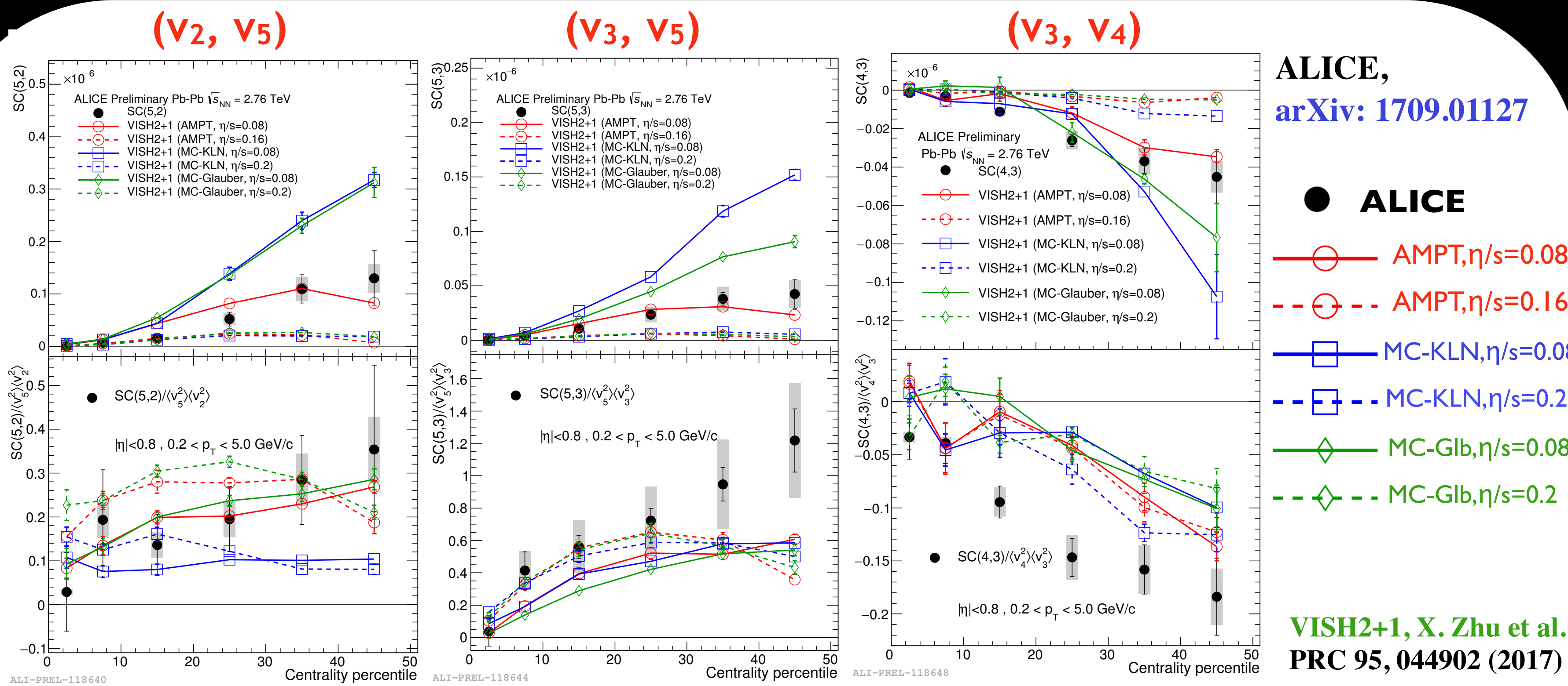



- ❖ SC(m,n) and NSC(m,n) with other harmonics:
  - correlations between ($v_2$, $v_5$) and ($v_3$,$v_5$) observed
  - anti-correlations between ($v_3$, $v_4$) observed
  - |NSC(5,3)| > |NSC(5,2)| > |NSC(4,3)| as predicted by hydrodynamic calculations

VISH2+1, X. Zhu et al., PRC 95, 044902 (2017)

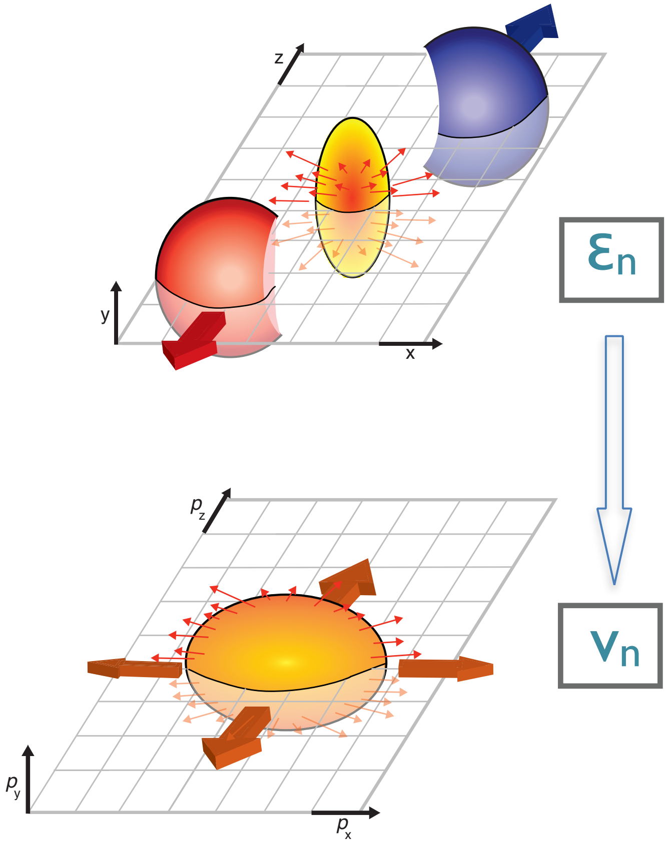
ALICE, arXiv: 1709.01127

# SC and NSC with other harmonics




- Comparison to VISH2+1 hydrodynamic calculations
  - hydrodynamic calculation ***can not*** describe all data with one combination of initial condition and η/s
  - ***tight constraints on initial conditions and η/s of QGP,*** in addition to SC(3,2) and SC(4,2)
  - Recent topic review, see: Y. Zhou, AHEP 9365637 (2016)

# initial anisotropy and final state flow




✓ $v_2 \propto \varepsilon_2$

✓ $v_3 \propto \varepsilon_3$

→ ***Linear response***

✖ ~~$v_4 \propto \varepsilon_4$~~

✖ ~~$v_5 \propto \varepsilon_5$~~

✖ ~~$v_6 \propto \varepsilon_6$~~

→ ***Linear & Non-linear response***

# linear and non-linear response in $V_n$

❖ Higher harmonic flow is modeled as the sum of linear and nonlinear response terms to the initial anisotropy coefficients $\varepsilon_n$

$$V_n = V_n^{NL} + V_n^{L}$$

non–linear response | linear response

- Non-linear response $V_n^{NL}$

  - corresponds to lower order initial anisotropy coefficient $\varepsilon_{2,3}$

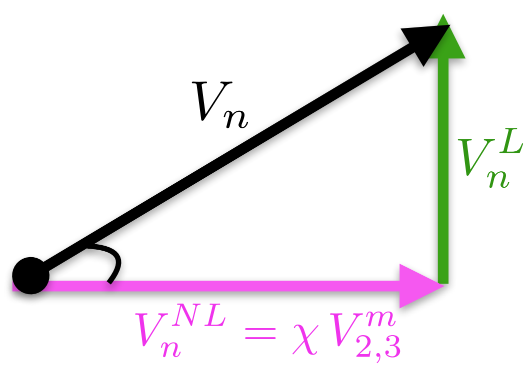
  - $V_n$ projection on $V_2$ or $V_3$

  - $v_{n,m}$ : magnitude of non-linear response in $V_n$

- Linear response $V_n^{L}$

  - expected to correspond to the cumulant-defined same order initial anisotropy coefficient $\varepsilon_n$'

  - $v_n^L$: magnitude of linear response in $V_n$



# Non-linear mode-coupling

- $\rho$: ratio of $v_{n,m}$ and $v_n$:

$$\rho_{422} = \frac{v_{4,22}}{v_4\{2\}} \approx \langle \cos(4\Psi_4 - 4\Psi_2) \rangle$$

$$\rho_{532} = \frac{v_{5,32}}{v_5\{2\}} \approx \langle \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2) \rangle$$

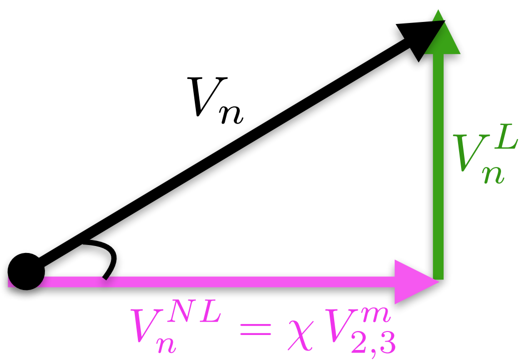
$$\rho_{6222} = \frac{v_{6,222}}{v_6\{2\}} \approx \langle \cos(6\Psi_6 - 6\Psi_2) \rangle$$

$$\rho_{633} = \frac{v_{6,33}}{v_6\{2\}} \approx \langle \cos(6\Psi_6 - 6\Psi_3) \rangle$$

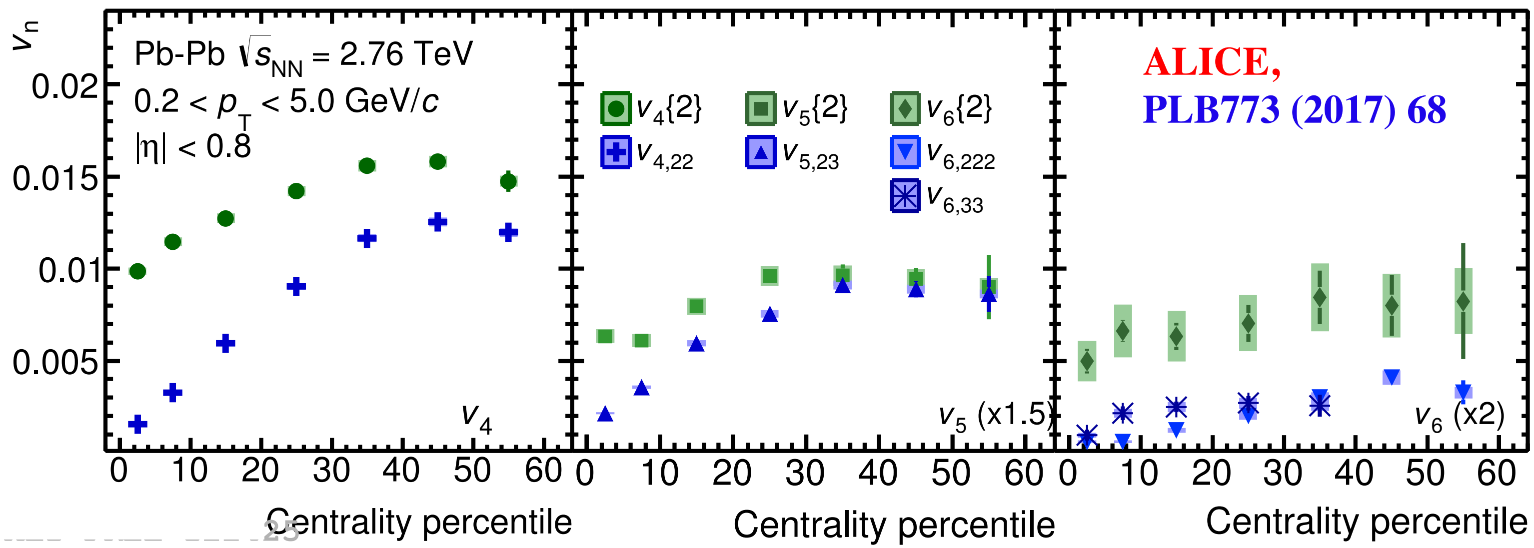
L. Yan et al,
PLB744 (2015) 82

J. Qian et al,
PRC 93, 064901 (2016)

- probes the correlations between different order flow symmetry planes
- Similar with previous "event-plane correlations"



# $v_n$ : linear and non-linear terms




- non-linear component $v_{n,m}$
  - increase with increasing centrality
  - becomes dominant in peripheral collisions

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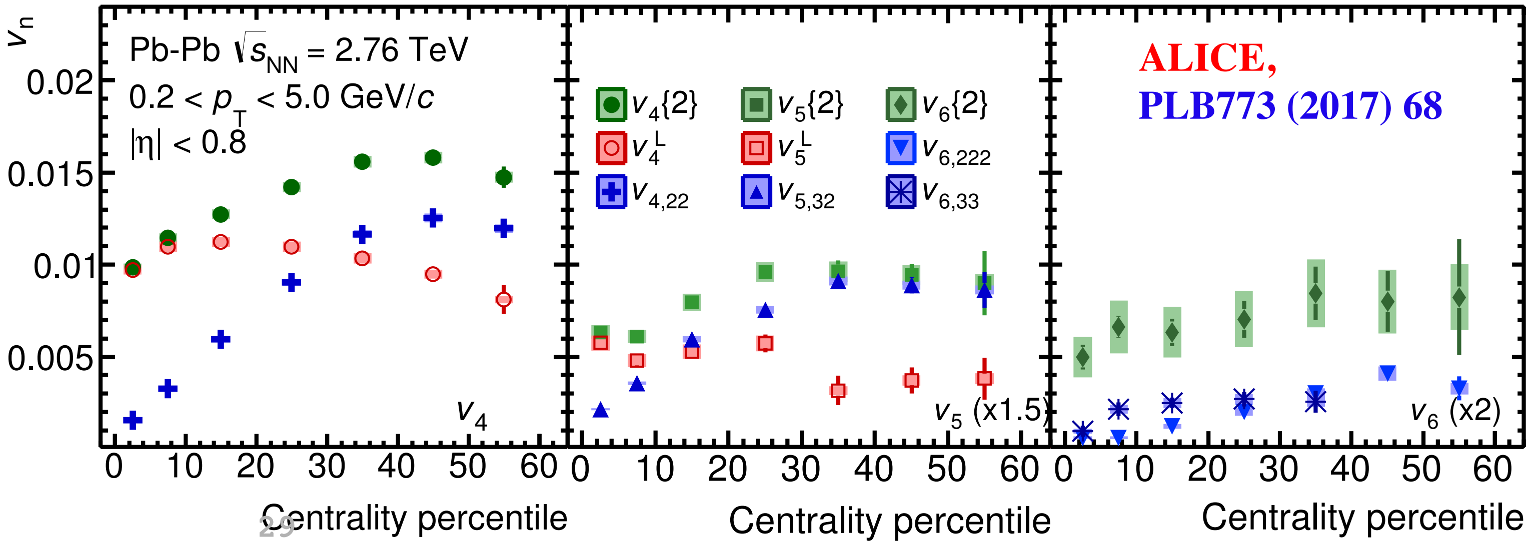


- non-linear component $v_{n,m}$
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- linear component $v_n^L$
  - plays dominant role in $v_n$ in central collisions
  - weak centrality dependence

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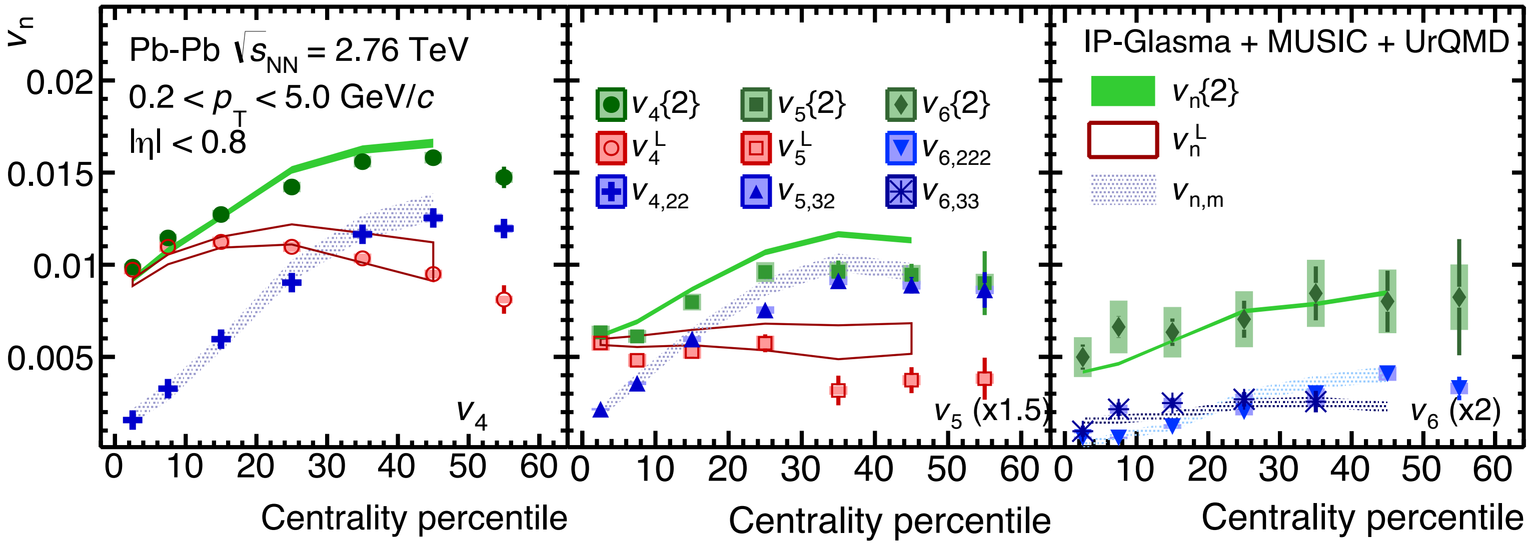


- non-linear component $v_{n,m}$
  - increase with increasing centrality
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- linear component $v_n^L$
  - plays dominant role in $v_n$ in central collisions
  - weak centrality dependence
- results are quantitatively described by hydro with IP-Glasma & η/s = 0.095
  - suggest a small η/s

ALICE,
PLB773 (2017) 68

IP-Glasma:
S. McDonald et al.,
arXiv: 1609.02958

# Symmetry plane correlations

**IP-Glasma, PRC 95, 064913 (2017)**

**ALICE, PLB773 (2017) 68**

$$\rho_{4,22} = \langle \cos(4\Psi_4 - 4\Psi_2) \rangle,$$

$$\rho_{5,32} = \langle \cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2) \rangle,$$

$$\rho_{6,222} = \langle \cos(6\Psi_6 - 6\Psi_2) \rangle,$$

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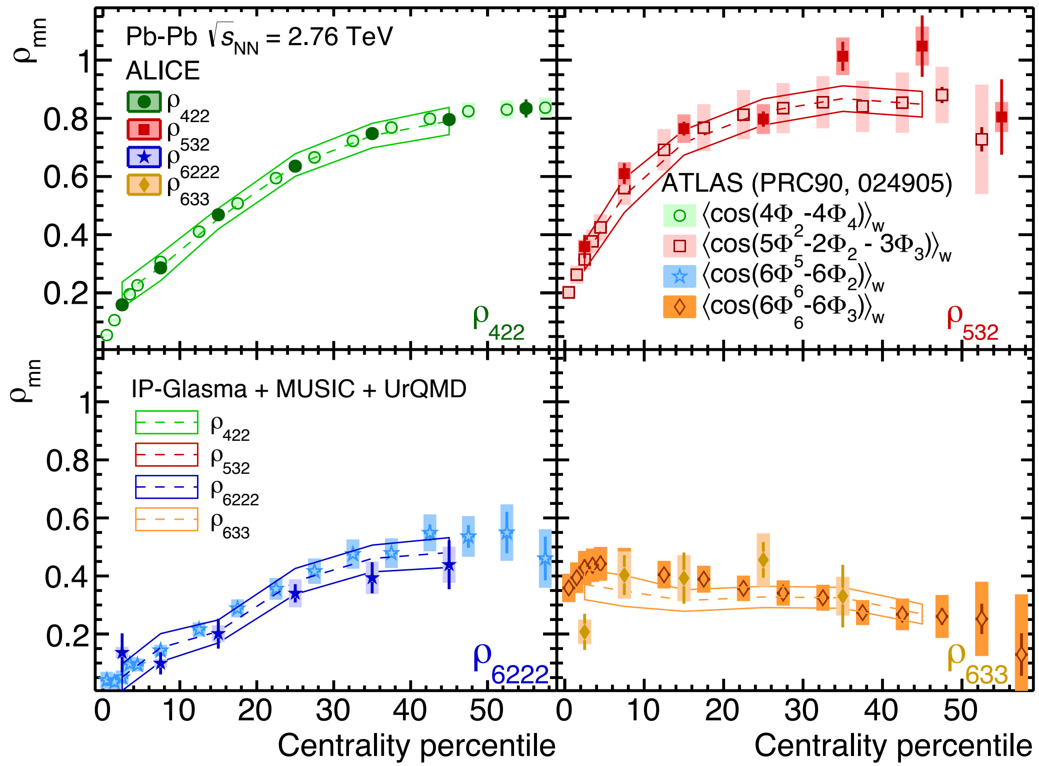


- $\rho_{mn}$
  - Agreement between ALICE and ATLAS (different eta coverage)
  - ***Results are compatible with hydrodynamic calculations using IP-Glasma &*** $\eta/s$***=0.095***,
  - calculations using MC-Glauber, MC-KLN initial conditions have difficulties to quantitatively describe the data.

# Symmetry plane correlations

**IP-Glasma, PRC 95, 064913 (2017)**

**ALICE, PLB773 (2017) 68**

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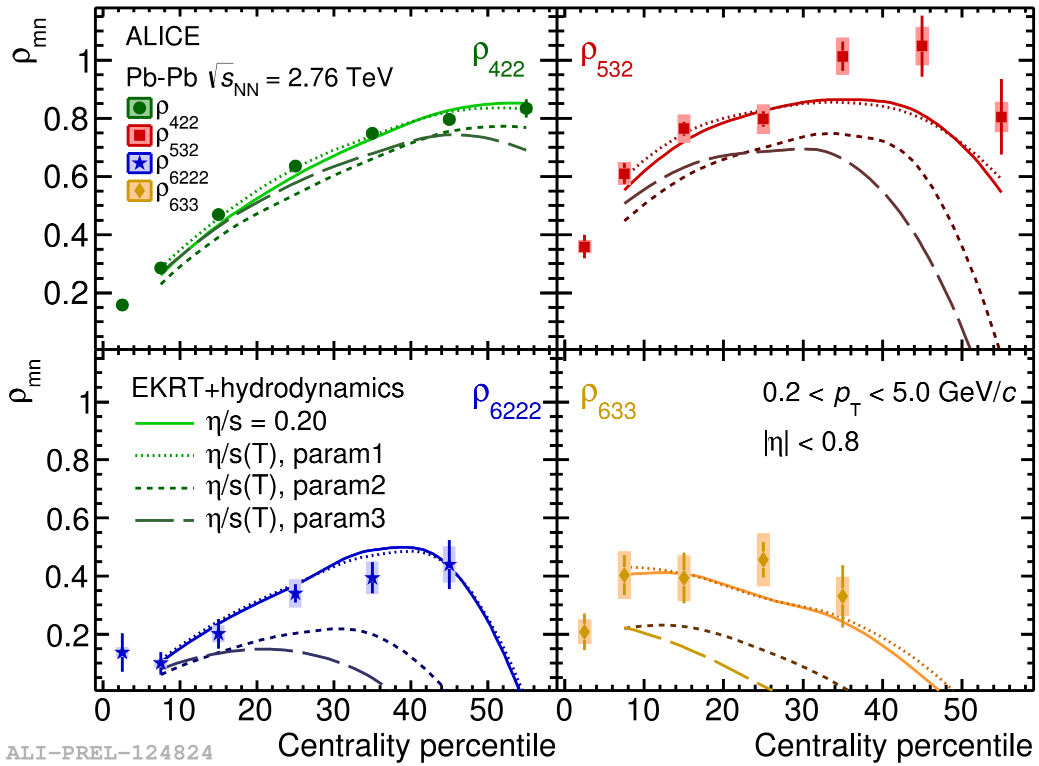


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  - ***Results are compatible with hydrodynamic calculations using IP-Glasma & η/s=0.095***,
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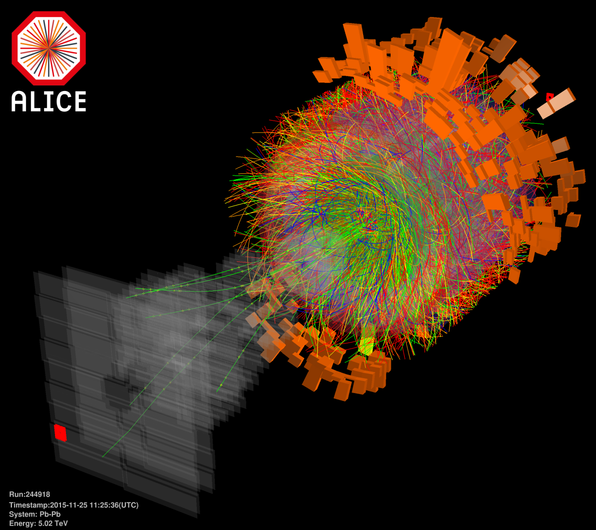
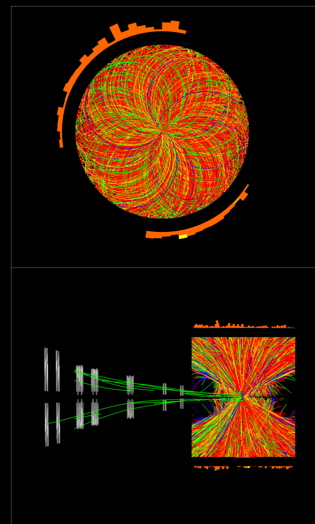
5.02 TeV Pb-Pb collisions

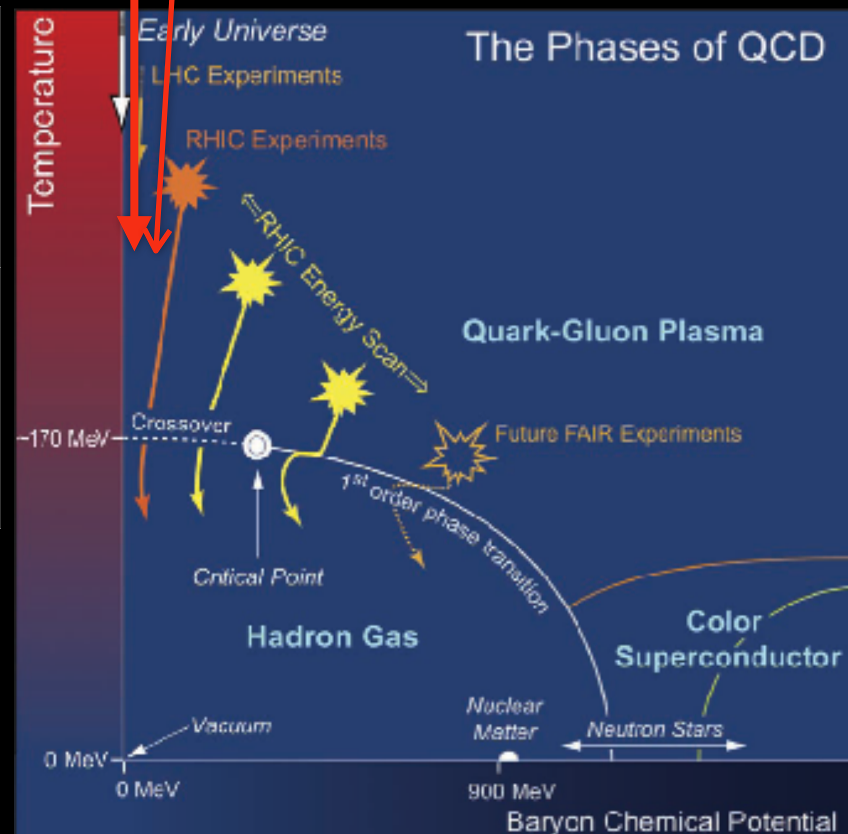
ALICE



5.02 TeV

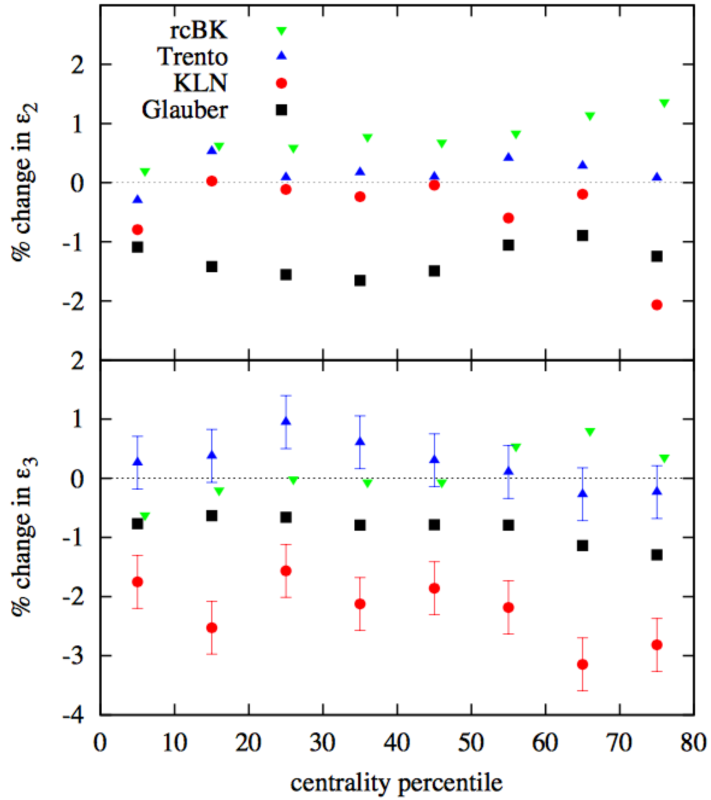
2.76 TeV

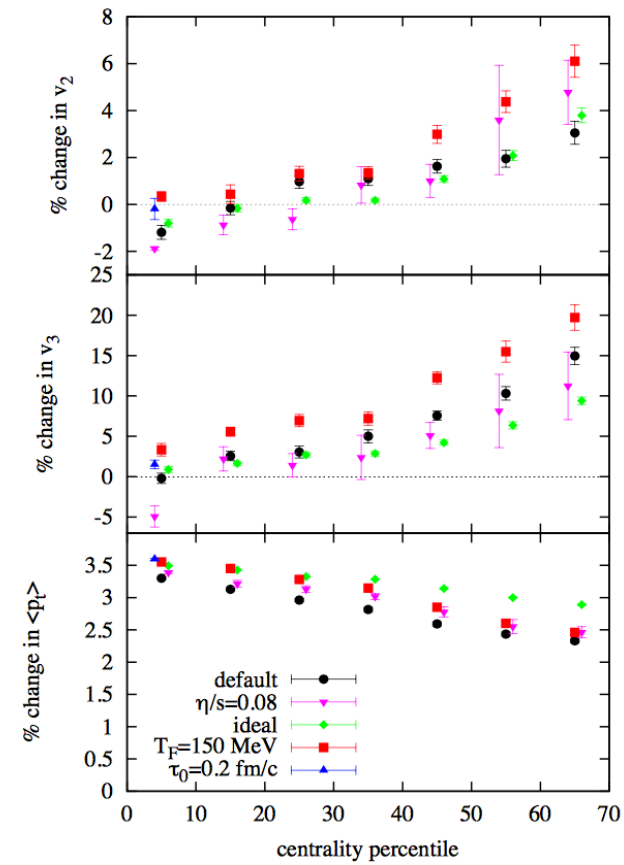



- **Pb-Pb 2.76 TeV: 2010, 2011**
- **Pb-Pb 5.02 TeV: 2015**

# Theoretical predictions (I)

J. Noronha-Hostler, M. Luzum, and J.Y. Ollitrault
PRC93 (2016) 034912



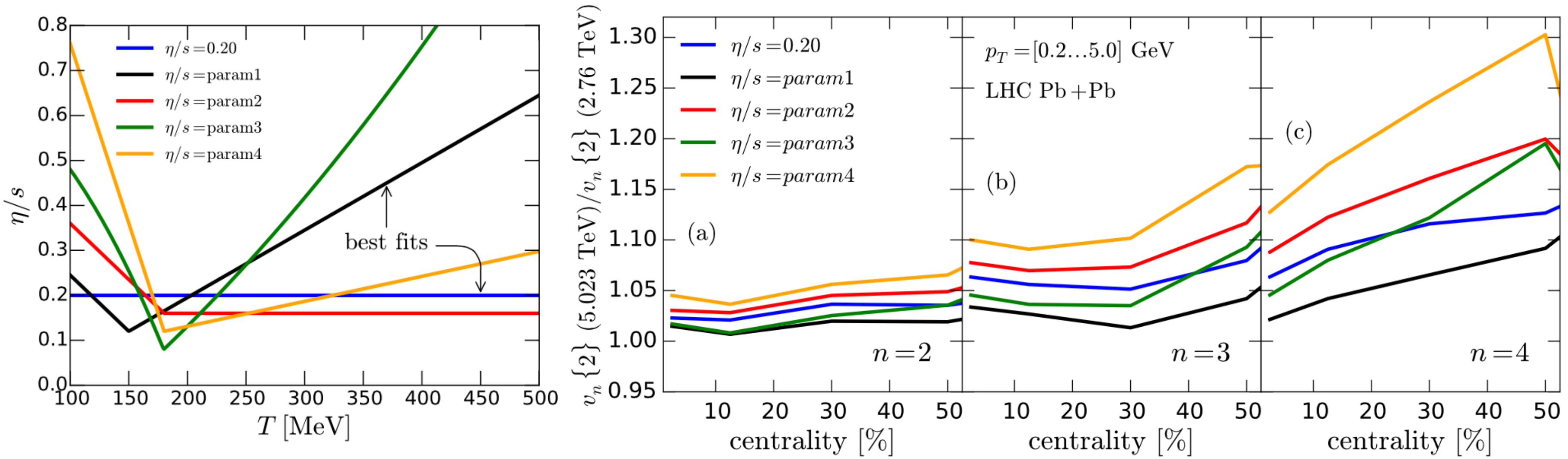




- Over all centralities and every model, the change from 2.76 TeV to 5.02 TeV is between -2% and 2% for $\varepsilon_2$ and between-3% and 1% for $\varepsilon_3$ .

- The predicted changes are at the several percent level.

# Theoretical predictions (II)

**EKRT: H. Niemi et. al, PRC 93, 014912 (2016)**




❖ The anisotropic flow and the increasing from 2.76 TeV to 5.02 TeV are sensitive to the detailed setting of eta/s(T).

# Anisotropic flow in Run 2

PRL 116, 132302 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

**Anisotropic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV**

J. Adam *et al.*[*]
(The ALICE Collaboration)
(Received 4 February 2016; published 1 April 2016)

We report the first results of elliptic ($v_2$), triangular ($v_3$), and quadrangular ($v_4$) flow of charged particles in Pb-Pb collisions at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector at the CERN Large Hadron Collider. The measurements are performed in the central pseudorapidity region $|\eta| < 0.8$ and for the transverse momentum range $0.2 < p_T < 5$ GeV/$c$. The anisotropic flow is measured using two-particle correlations with a pseudorapidity gap greater than one unit and with the multiparticle cumulant method. Compared to results from Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, the anisotropic flow coefficients $v_2$, $v_3$, and $v_4$ are found to increase by $(3.0 \pm 0.6)\%$, $(4.3 \pm 1.4)\%$, and $(10.2 \pm 3.8)\%$, respectively, in the centrality range 0%–50%. This increase can be attributed mostly to an increase of the average transverse momentum between the two energies. The measurements are found to be compatible with hydrodynamic model calculations. This comparison provides a unique opportunity to test the validity of the hydrodynamic picture and the power to further discriminate between various possibilities for the temperature dependence of shear viscosity to entropy density ratio of the produced matter in heavy-ion collisions at the highest energies.

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## How the early universe behaved like a LIQUID: Cern's atom smasher recreates the 'primordial soup' that began the universe

- **Feat was achieved by colliding lead atoms at an extremely high energy**
- **The test took place in the 16.7 mile (27km) long Large Hadron Collider**
- **Allowed scientists to carry out measurements on a drop of 'early universe', that only has a radius of about one millionth of a billionth of a meter**

By ELLIE ZOLFAGHARIFARD FOR DAILYMAIL.COM

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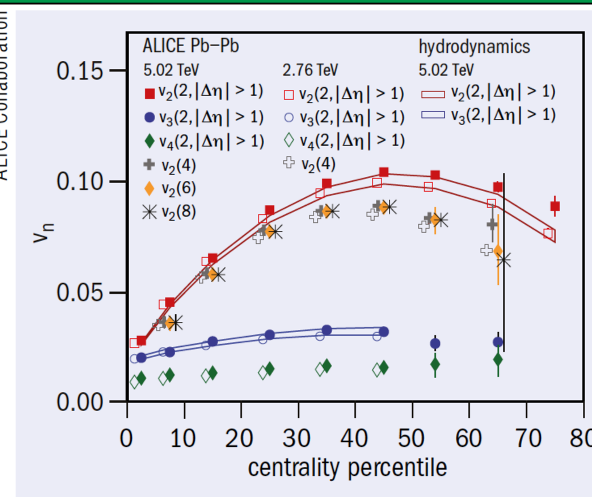
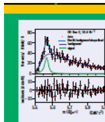
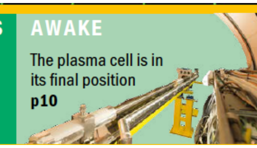
ALICE



**TETRAQUARKS**
DZero collaboration discovers a new particle
p13



**AWAKE**
The plasma cell is in its final position
p10

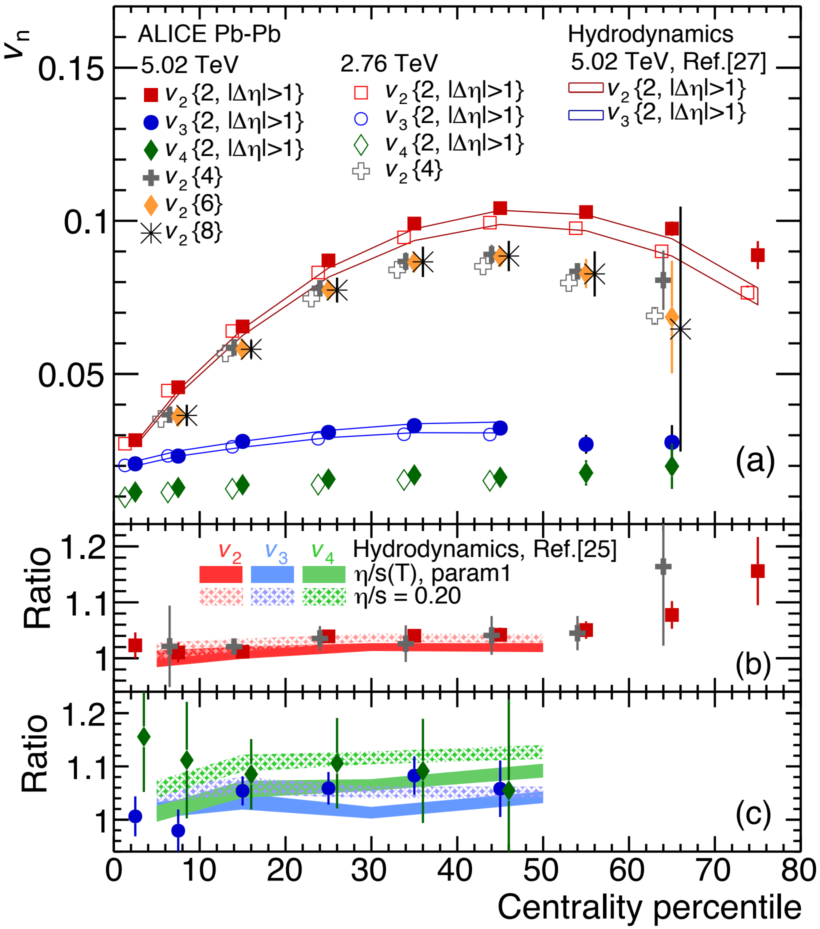
**ACCELERATOR MILESTONE**
Japan's SuperKEKB achieves "first turns" p11

**ALICE: PRL 116, 132302 (2016)**
**hydro: J. Noronha-Hostler et al, PRC93 (2016) 034912**

# $v_n$ from 2.76 to 5.02 TeV

ALICE Collaboration
[PRL 116, 132302 (2016)]

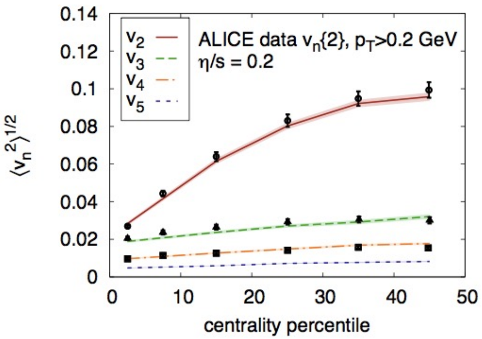
Ref [27]: J. Noronha-Hostler et al., PRC93 (2016) 034912
Ref [25]: H. Niemi et al, PRC 93, 014912 (2016)

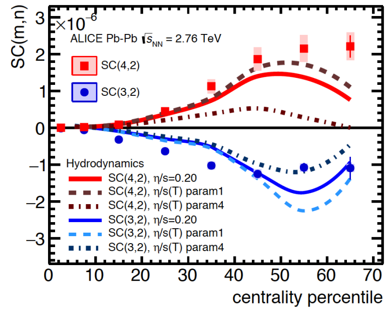


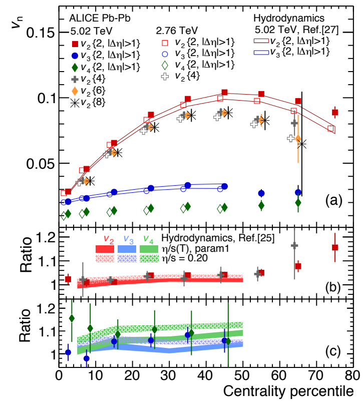

- The anisotropic flow coefficients $v_2$, $v_3$ and $v_4$ are found to increase by (3.0±0.6)%, (4.3±1.4)% and (10.2±3.8)%, respectively, in the centrality range 0-50%.
- None of the ratios 5.02 TeV/2.76 TeV of flow harmonics exhibit a significant centrality dependence in the centrality range 0–50%,
- Changes of anisotropic flow are compatible with theoretical predictions.

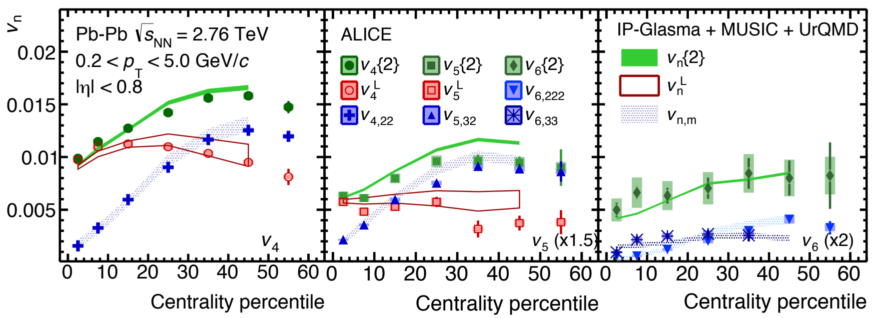
# Constrain the theory

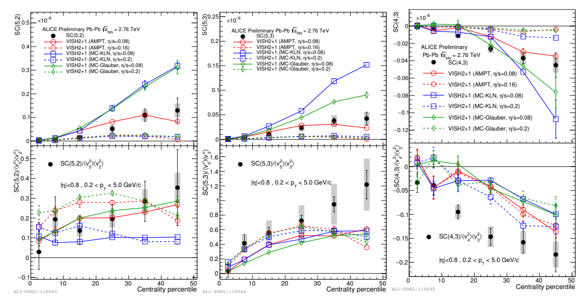
- Many flow measurements are discussed, the results are compared to theoretical calculations



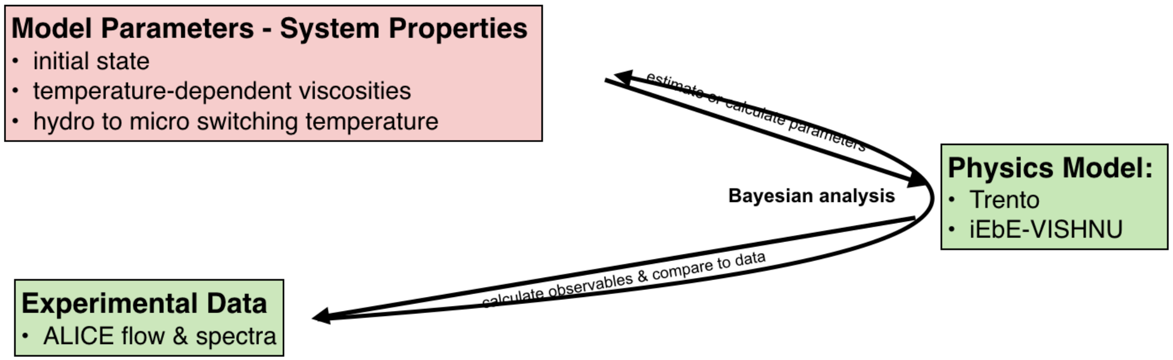



=> constrain the initial conditions and η/s(T)

- Question: can we do better?
  - YES, WE CAN!

# Global Bayesian Analysis

Each computational model relies on a set of physics parameters to describe the dynamics and properties of the system. These physics parameters act as a representation of the information we wish to extract from RHIC & LHC.




## Bayesian analysis

- allows to simultaneously calibrate all model parameters via a model-to-data comparison
- determine parameter values such that the model best describes experimental observables
- extract the probability distributions of all parameters

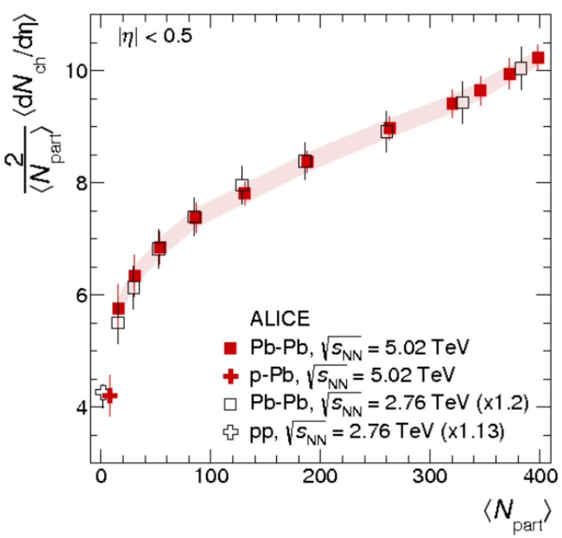
S. Bass, QM2017: https://indico.cern.ch/event/433345/contributions/2321600/

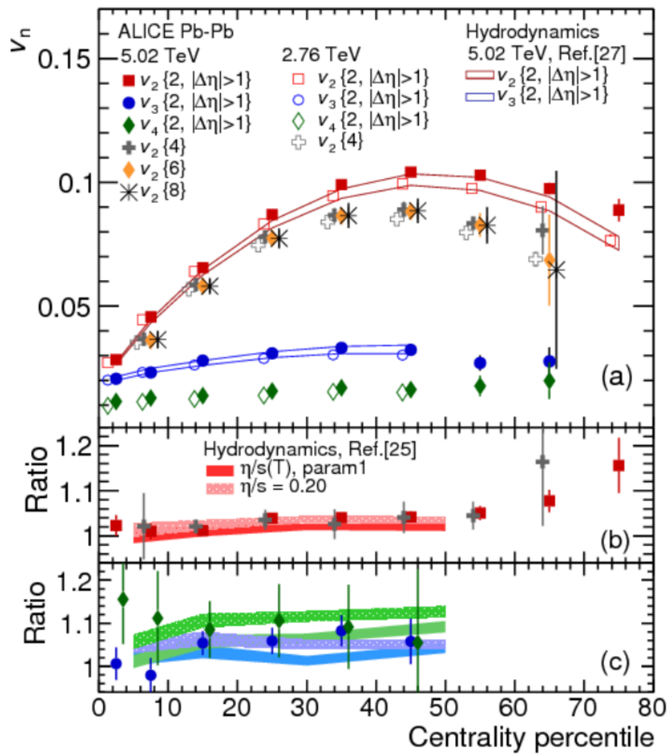
# Training Data

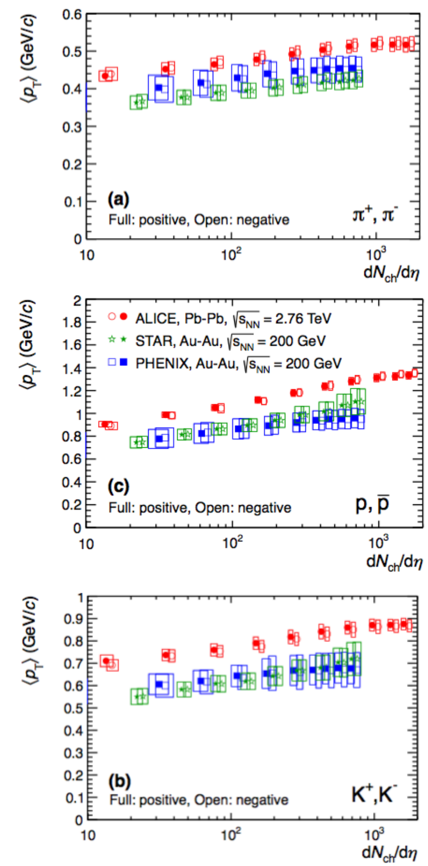
**Data:**

- ALICE $v_2$, $v_3$ & $v_4$ flow cumulants
- identified & charged particle yields
- identified particle mean $p_T$
- 2 beam energies: 2.76 & 5.02 TeV

**the entire success of the analysis depends on the quality of the exp. data!**

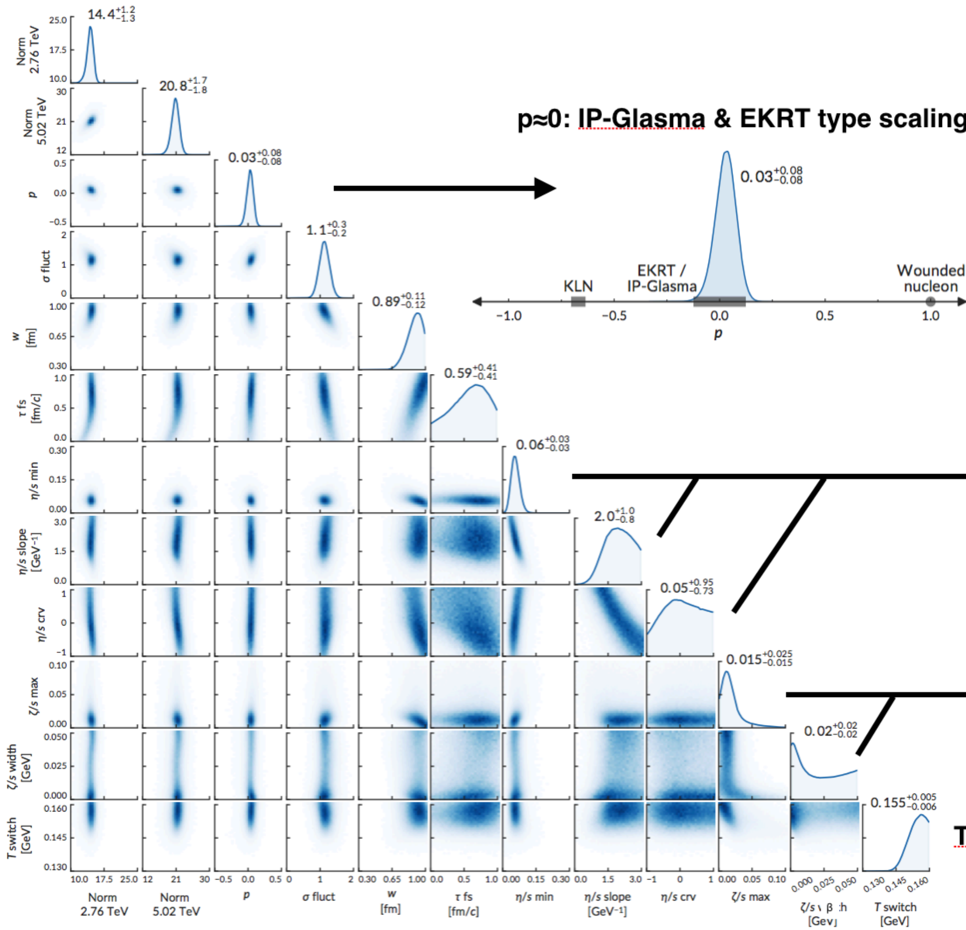



S. Bass, QM2017: https://indico.cern.ch/event/433345/contributions/2321600/

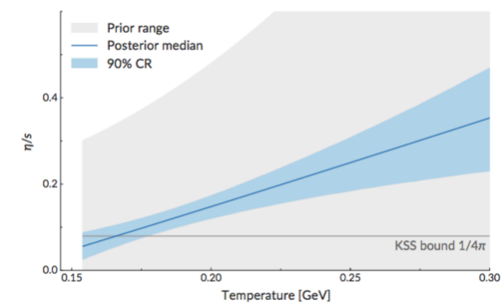
# Constrain the initial conditions and η/s(T)

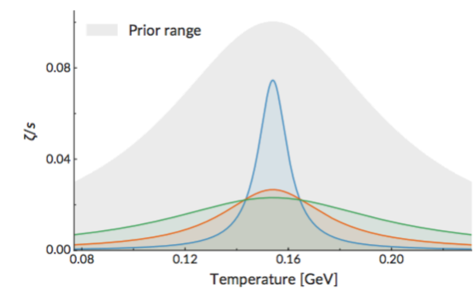



$T_{sw} \lesssim T_c$

- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

**temperature-dependent viscosities:**




S. Bass, QM2017: https://indico.cern.ch/event/433345/contributions/2321600/

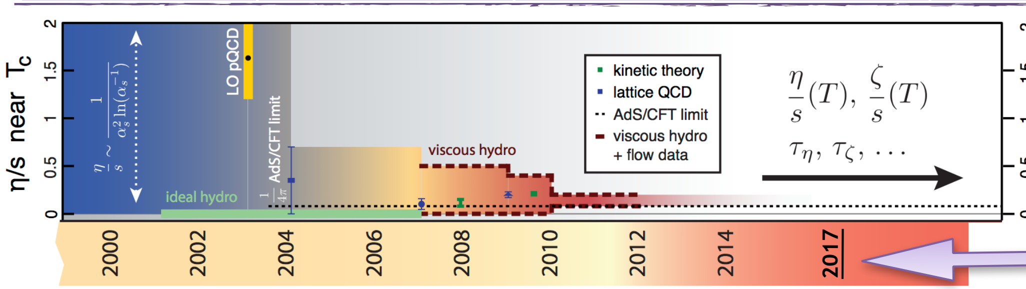
# Summary

- We present correlations between different order anisotropic flow in Pb-Pb collisions.
- These measurements provide novel constraints on the initial conditions and the η/s(T) which were not very well constrained by previous flow data.

| Observable \ IC | *MC-Glauber* | *MC-KLN* | *AMPT* | *IP-Glasma* | *EKRT* |
|---|---|---|---|---|---|
| $v_2$ | ✓ | ✓ | ✓ | ✓ | ✓ |
| $v_n$ | ✗ | ✗ | ✓ | ✓ | ✓ |
| $(v_n, v_m)$ | ✗ | ✗ | ✗ | *N/A* | ✗ |
| $(\Psi_n, \Psi_m)$ | ✗ | ✗ | *N/A* | ✓ | ✓ |

✗/✓ : not this talk
✗/✓ : this talk
**N/A:** not available

this talk




a small η/s

this talk

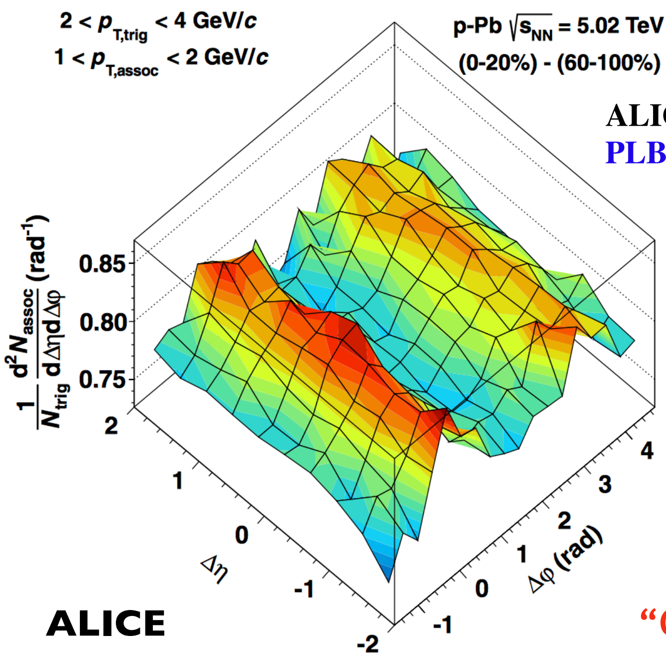
Bonus slides

(for discussions)

# Two-particle correlations (ridge)

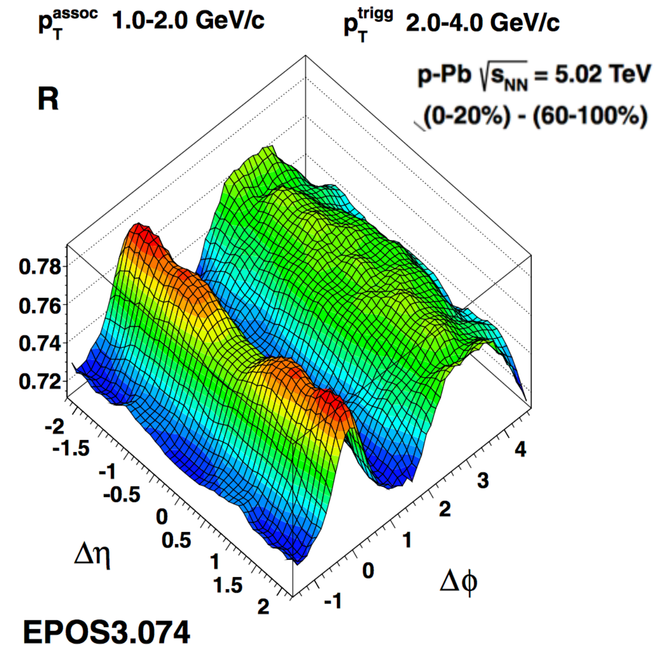
❖ Long-range correlations observed in small systems
- similar correlation structure could be reproduced by hydrodynamic calculations
- collectivity?

K. Werner, et al., PRL. 112, 232301 (2014)

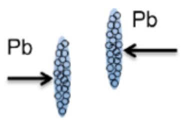


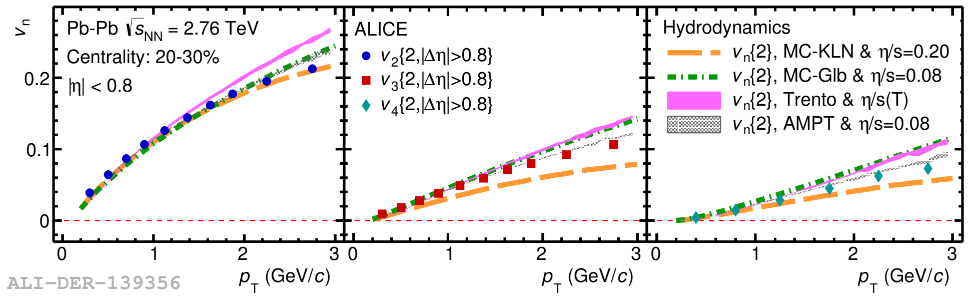

ALICE, PLB 719, 29 (2013).

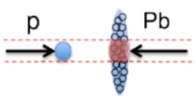
"Central-Peripheral"



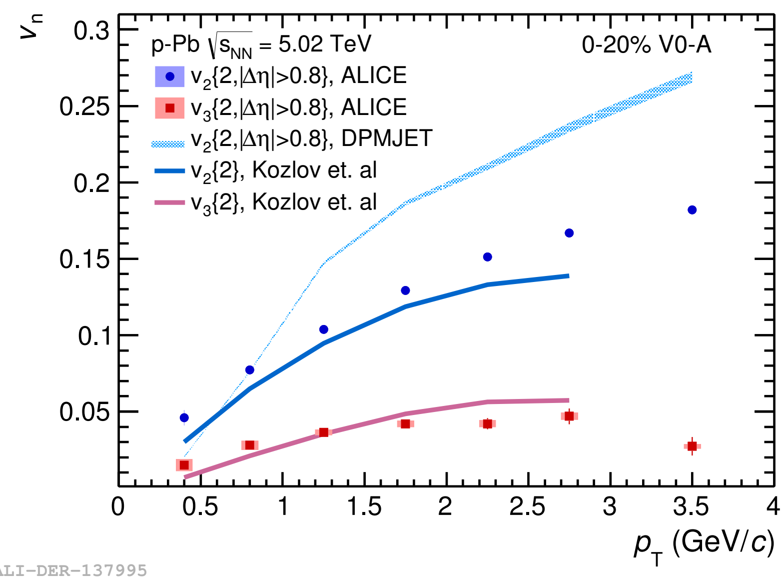
# $v_n(p_T)$ of charged particles



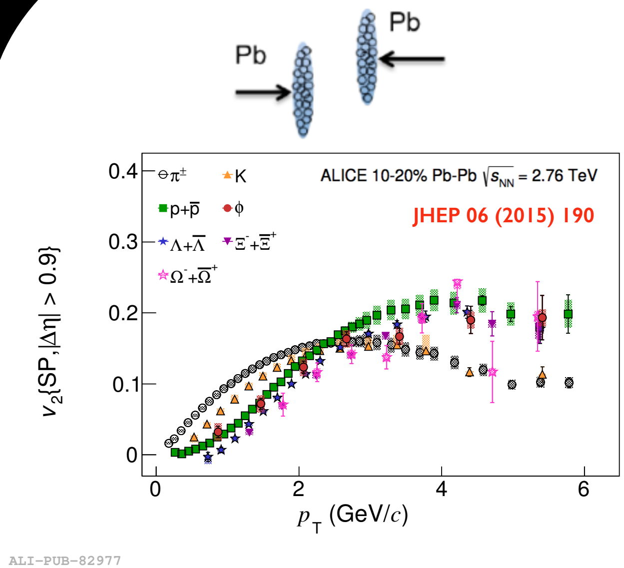



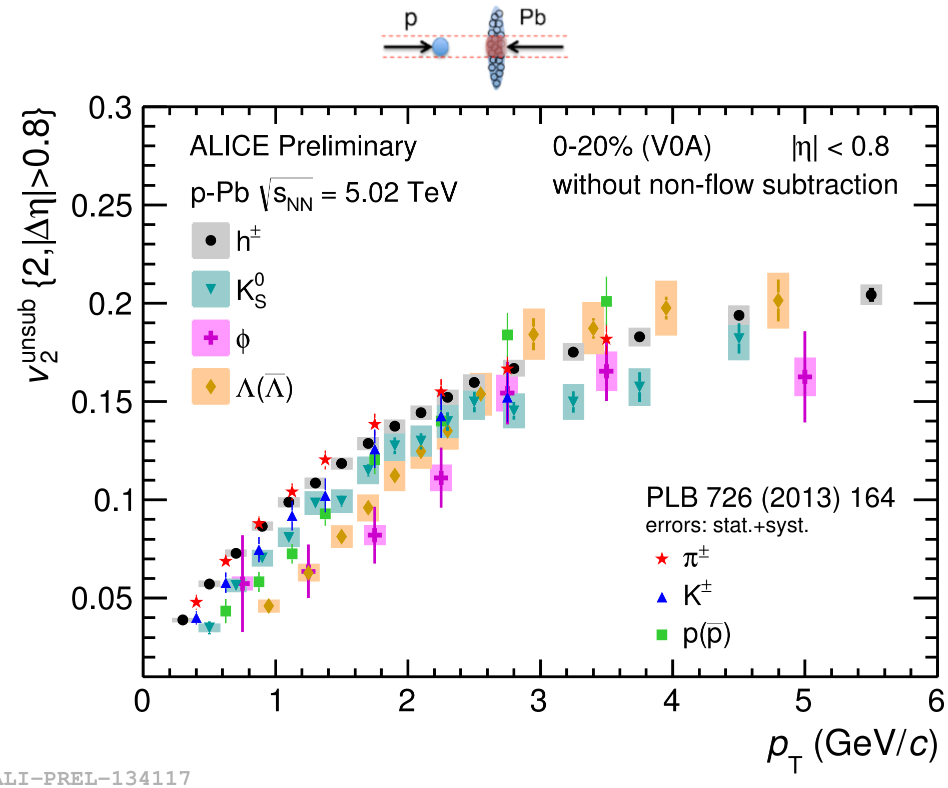

ALICE, JHEP 09 (2017) 032




- $v_n(p_T)$ in high multiplicity p-Pb collisions looks similar to Pb-Pb
  - measurements are reproduced by hydrodynamic calculations
  - DPMJET (no anisotropic flow generation) overestimates $v_2$ and predicts negative $v_3^2$

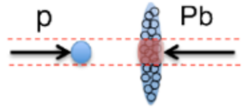
# Identified particle $v_2$ in p-Pb

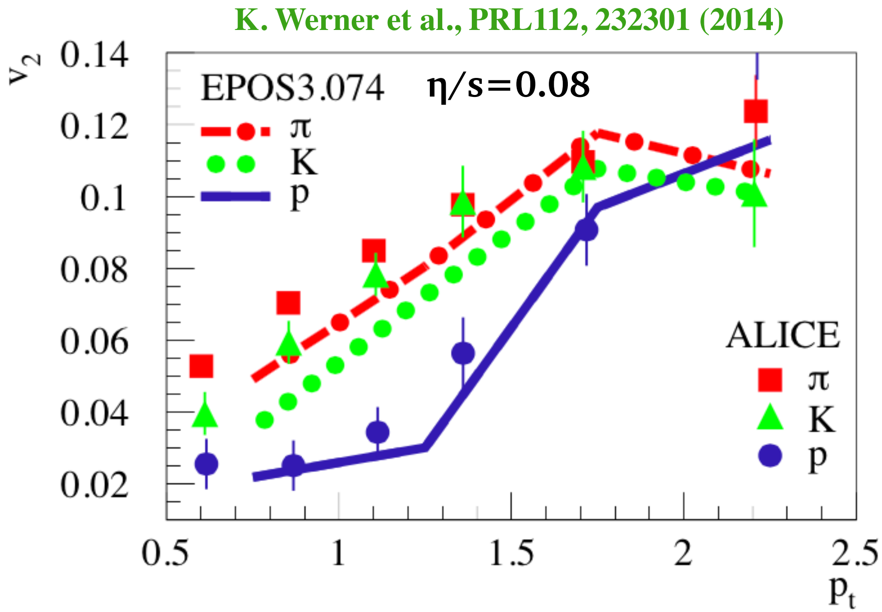


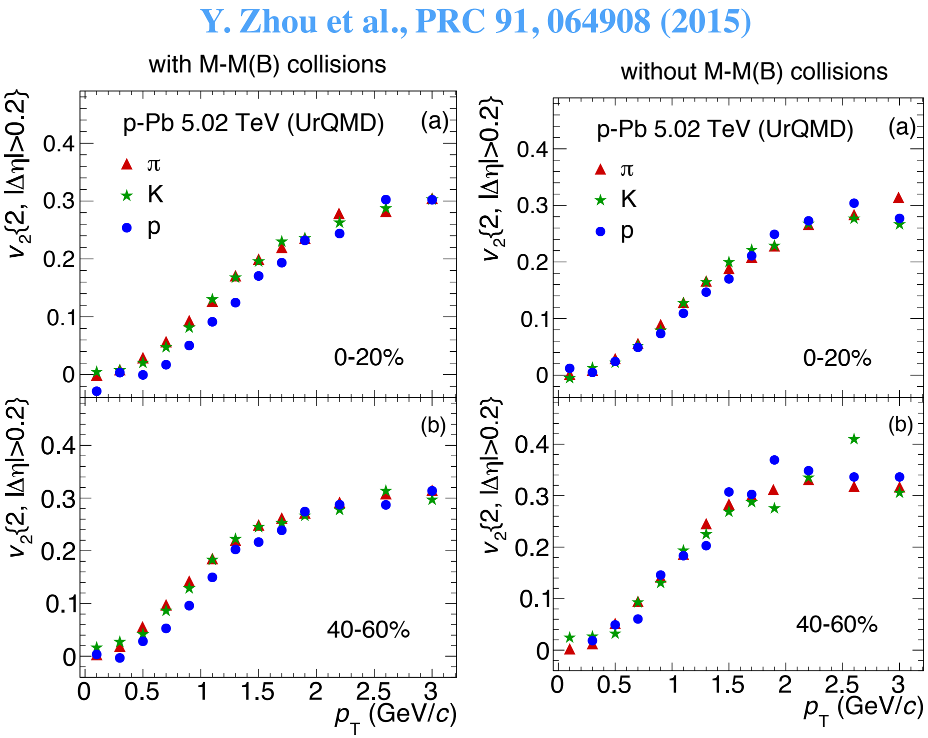




- What we know already: $v_2$ of identified particles in Pb-Pb
  - at low $p_T$: mass ordering, described by hydrodynamic calculations (VISHNU)
  - at intermediate $p_T$: approximate baryon/meson grouping
- What's new: $v_2$ of identified particles in p-Pb
  - at low $p_T$: most particle species follow mass ordering
  - at intermediate $p_T$: baryon $v_2$ > meson $v_2$, still inconclusive w/o non-flow subtraction

# Hydrodynamics? Rescattering?



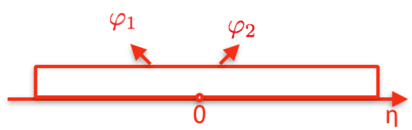



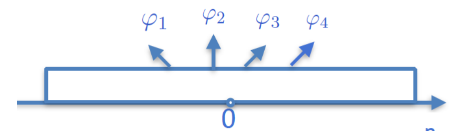



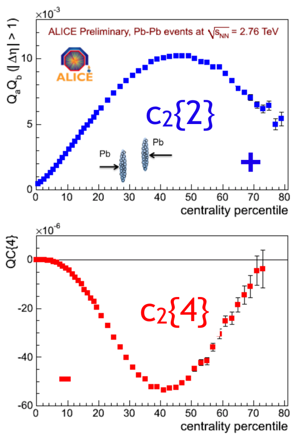

❖ Mass ordering of identified particles in high multiplicity p-Pb collisions

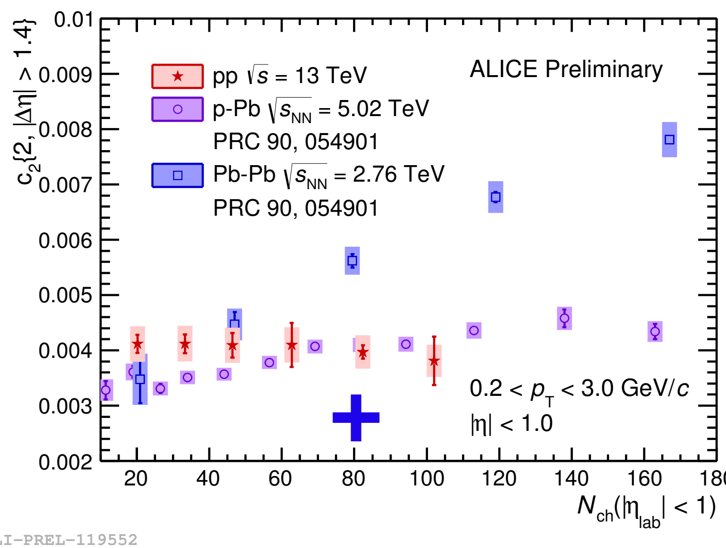
- similar feature observed in (hybrid-)hydrodynamic calculations (e.g. EPOS)
  - indication of hydrodynamic flow (?)
- mass splitting can be reproduced qualitatively in pure hadronic systems w/o generation of flow (pure non-flow effects) e.g. UrQMD.

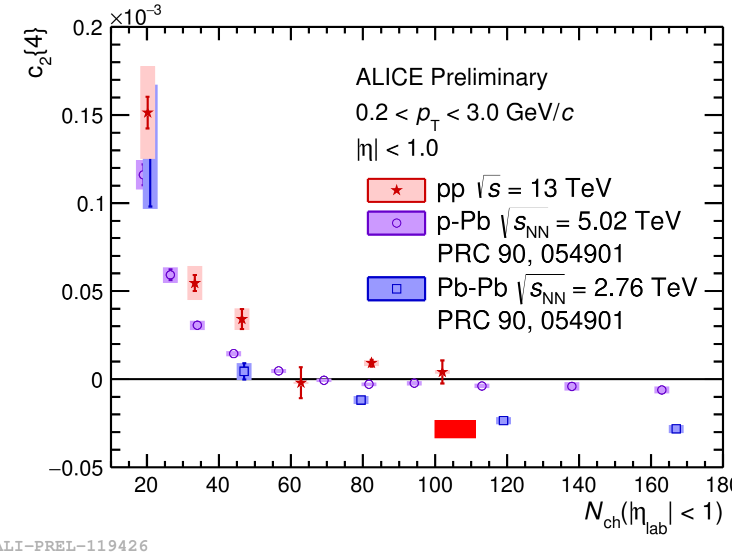
# 2- and multi-particle cumulants



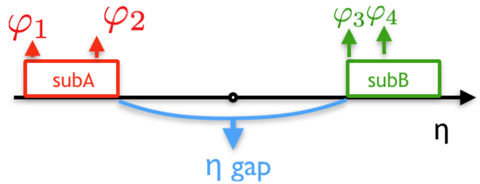



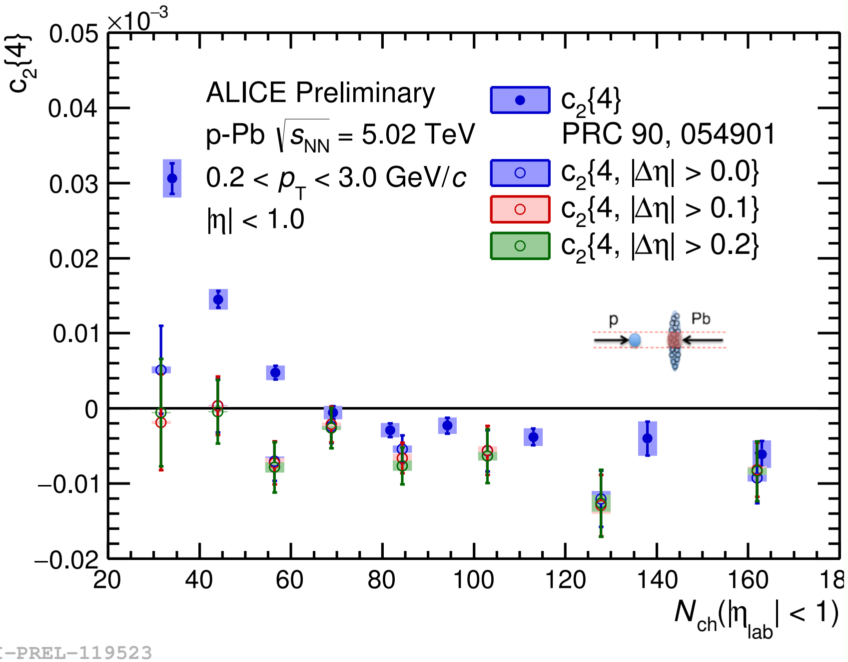

$c_n\{2\} = v_n^2$

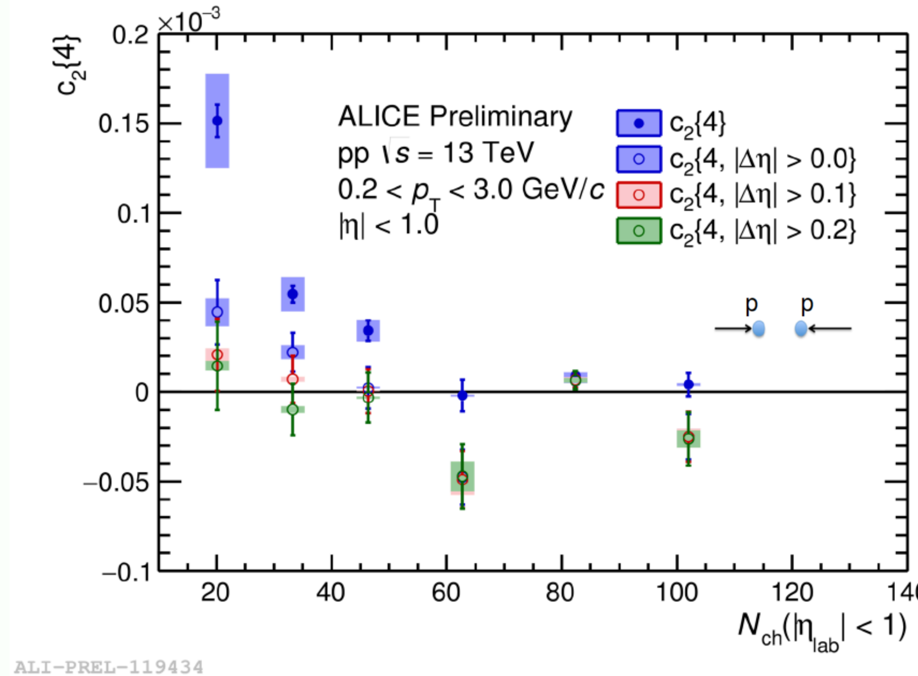
$c_n\{4\} = -v_n^4$

- ❖ 2- and multi-particle cumulants show +, - signs in Pb-Pb collisions
  - typical feature of collective behavior
- ❖ Similar results observed in high multiplicity p-Pb collisions
  - positive $c_2\{2\}$ and negative $c_2\{4\}$

# multi-particle cumulants with η gap



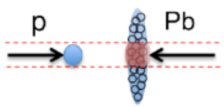

❖ $c_2\{4, |\Delta\eta|\}$ decreases compared to $c_2\{4\}$, especially in low multiplicity region.

- further suppression of non-flow in 4-particle cumulants
- still no definitive flow signal in pp collisions with data collected in 2015
- analysis of 2016 and 2017 pp data ongoing

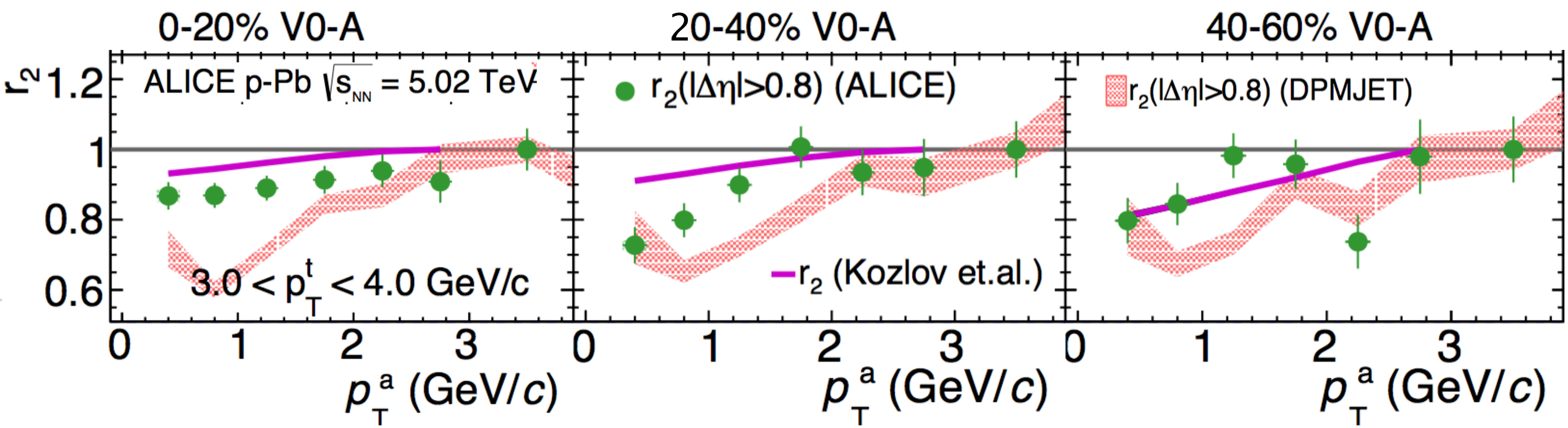
# Factorization broken in p-Pb

$$r_n = \frac{V_{n\Delta}(p_T^a, p_T^b)}{\sqrt{V_{n\Delta}(p_T^a, p_T^a) \cdot V_{n\Delta}(p_T^b, p_T^b)}}$$

- $r_n$ probes < a, b > ➡ < a, a > & < b, b >
- $r_n$ < 1, Factorization broken




ALICE, JHEP 09 (2017) 032



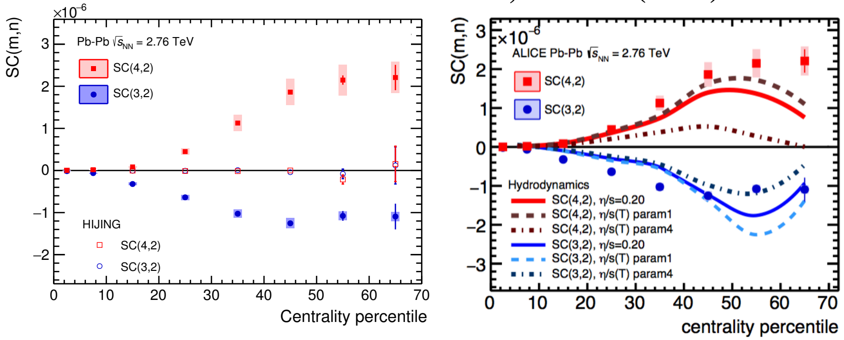

❖ Factorization broken also in p-Pb, similar to Pb-Pb collisions

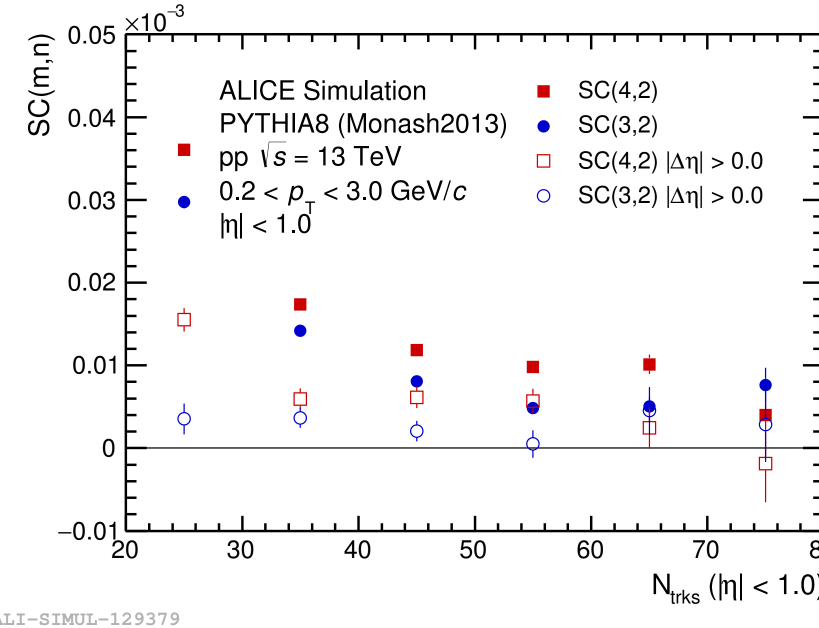
- $r_2$ measured with 2-particle correlations (not completely free of non-flow)
- can be qualitatively described by hydrodynamic calculations (modified MC-Glauber initial conditions and $\eta/s$=0.08 -> similar mechanism with Pb-Pb?
- DPMJET (no anisotropic flow production) also reproduces similar trend

# Symmetric Cumulants in small systems

- **S**ymmetric **C**umulants SC(m,n) measure the correlations of $v_n$ and $v_m$

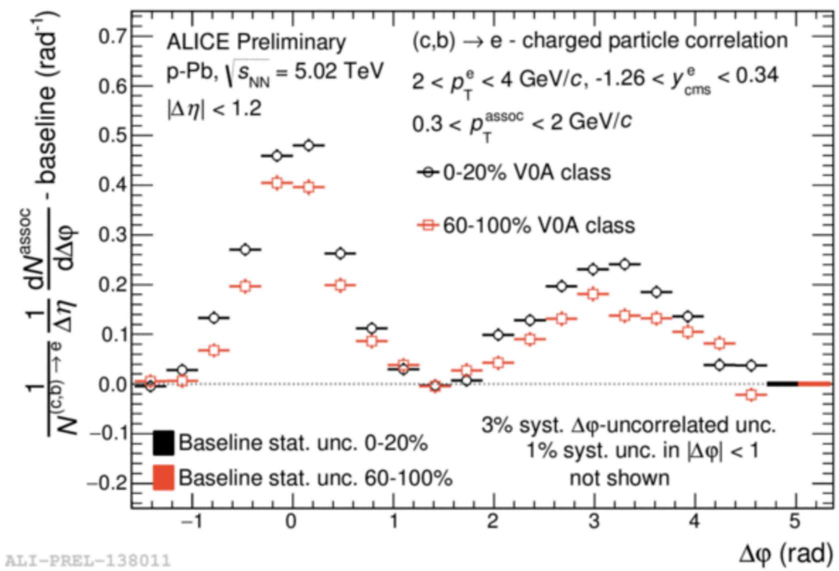
ALICE: PRL 117, 182301 (2016)

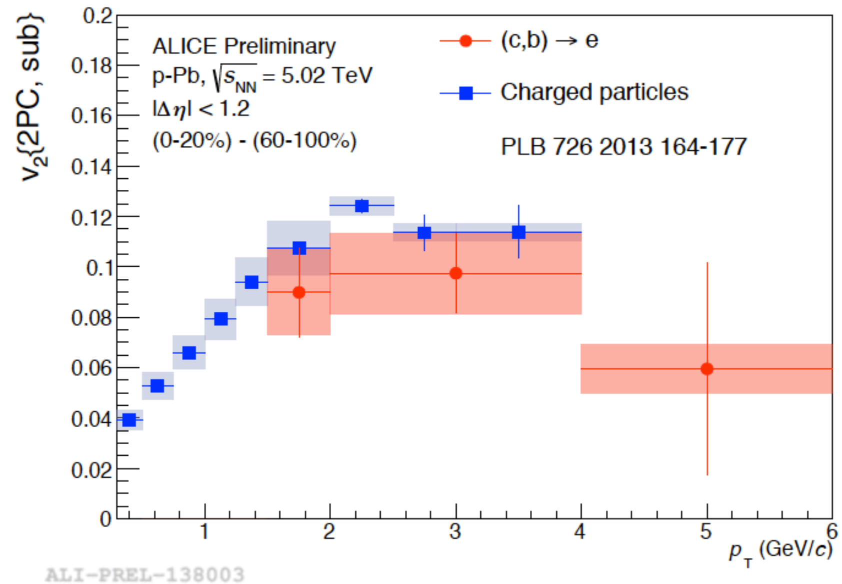



- In Pb-Pb collisions
  - SC is insensitive to non-flow, provides stronger constraints on the η/s than $v_n$ alone
  - Normalized SC(3,2) is insensitive to η/s(T), direct constraints on initial conditions
- In pp collisions
  - SC might NOT be free of non-flow effects
    - PYTHIA8 (no flow generation) shows non-zero values of SC(4,2) and SC(3,2)
    - 2- and 3-subevent method (see backup) should be applied to suppress non-flow
  - Strong constraints on initial conditions require full understanding of non-flow

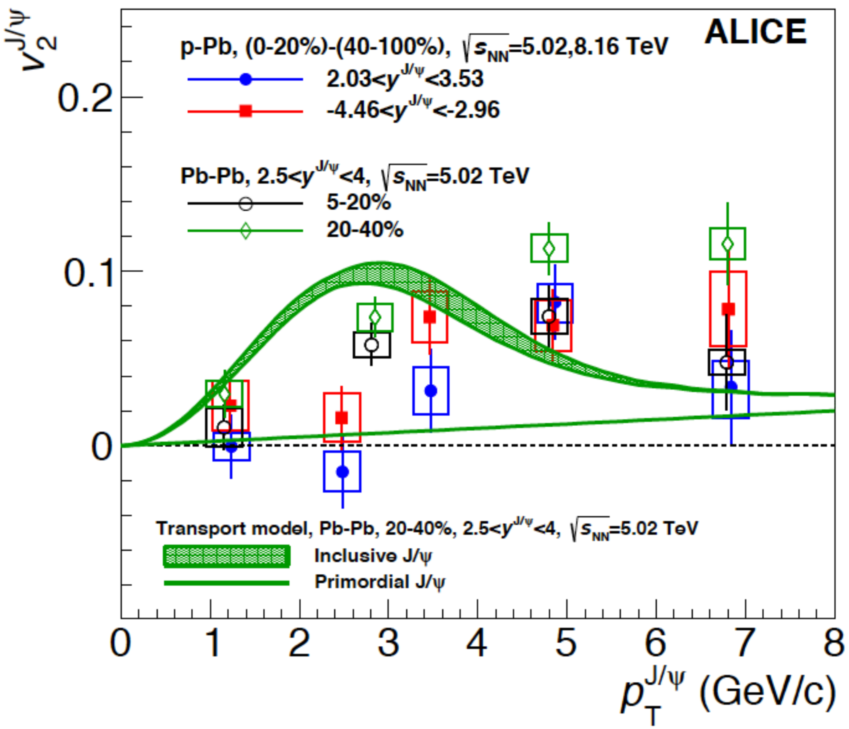
# HF-decay electron & hadron




- ❖ 2-particle correlation of HF-decay electron and charged hadron similar to Pb-Pb collisions
- ❖ $v_2$\{2PC,sub\} of HF-decay electron is non-zero
  - results are compatible with $v_2$\{2PC,sub\} of charged hadron
  - non-flow remains or signal of anisotropic collectivity?

# $J/\Psi$ $v_2$ in p-Pb




ALICE, arXiv: 1709.06807

- Significant $v_2$ in central and semi-central Pb-Pb collisions
- In p-Pb collisions (combined 5.02 and 8.16 TeV data),
  - For $3<p_T<6$ GeV/$c$, $v_2^{J/\Psi}\{2,sub\}$ are found to be non-zero with a significance about $5\sigma$
  - Results are comparable with those measured in Pb–Pb collisions
    - indication of the same underlying mechanism?

backup

# List of observables

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

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

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

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

$$\rho_{422} = \frac{v_{4,22}}{v_4\{2\}}$$

$$\rho_{532} = \frac{v_{5,32}}{v_5\{2\}}$$

$$\rho_{6222} = \frac{v_{6,222}}{v_6\{2\}}$$

$$\rho_{633} = \frac{v_{6,33}}{v_6\{2\}}$$

$$\chi_{422} = \frac{v_{4,22}}{\sqrt{\langle v_2^4\rangle}}$$

$$\chi_{523} = \frac{v_{5,32}}{\sqrt{\langle v_2^2\, v_3^2\rangle}}$$

$$\chi_{6222} = \frac{v_{6,222}}{\sqrt{\langle v_2^6\rangle}}$$

$$\chi_{633} = \frac{v_{6,33}}{\sqrt{\langle v_3^4\rangle}}$$

❖ Observables based on 2- and multi-particle correlations

- can be directly obtained using ***Generic framework*** of multi-particle correlations

  (details see back up slides)

**A.Bilandzic, C.H. Christensen, K. Gulbrandsen, A. Hansen, and Y. Zhou, PRC 89, 064904 (2014)**

# linear and non-linear response in $V_n$

❖ Higher harmonic flow are modeled as the sum of linear and nonlinear response terms to the initial anisotropy coefficients $\varepsilon_n$

- $V_n = V_n^{NL} + V_n^{L}$ non–linear response linear response
- the magnitudes of $V_n^{NL}$ ($V_n$ projection on $V_2$ or $V_3$):

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

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

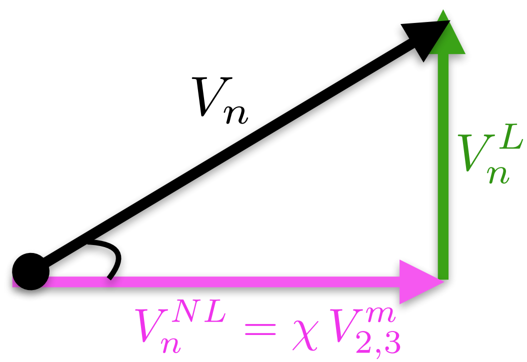
$$v_{6,222} = \frac{\langle v_6\, v_2^3\, \cos(6\Psi_6 - 6\Psi_2)\rangle}{\sqrt{\langle v_2^6\rangle}} \approx \langle v_6\, \cos(6\Psi_6 - 6\Psi_2)\rangle$$

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

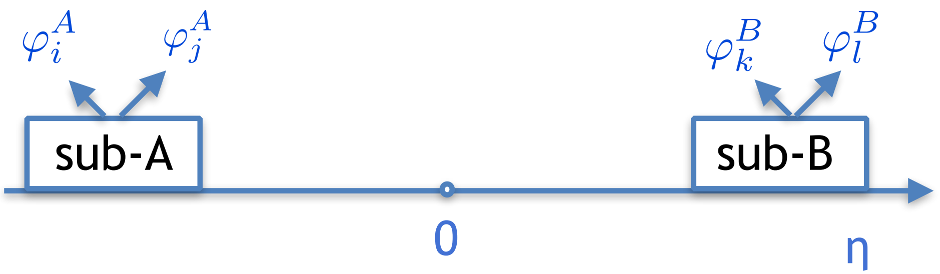
- the magnitudes of $V_n^{L}$:

$$v_4{}^L = \sqrt{v_4^2\{2\} - v_{4,22}^2}$$

$$v_5{}^L = \sqrt{v_5^2\{2\} - v_{5,32}^2}$$



# multi-particle correlations with an eta gap




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

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

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

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

$$v_{4,22}^A = \frac{\langle\langle \cos(4\varphi_1^A - 2\varphi_2^B - 2\varphi_3^B)\rangle\rangle}{\sqrt{\langle\langle \cos(2\varphi_1^A + 2\varphi_2^A - 2\varphi_3^B - 2\varphi_4^B)\rangle\rangle}}$$

$$v_{5,32}^A = \frac{\langle\langle \cos(5\varphi_1^A - 3\varphi_2^B - 2\varphi_3^B)\rangle\rangle}{\sqrt{\langle\langle \cos(3\varphi_1^A + 2\varphi_2^A - 3\varphi_3^B - 2\varphi_4^B)\rangle\rangle}}$$

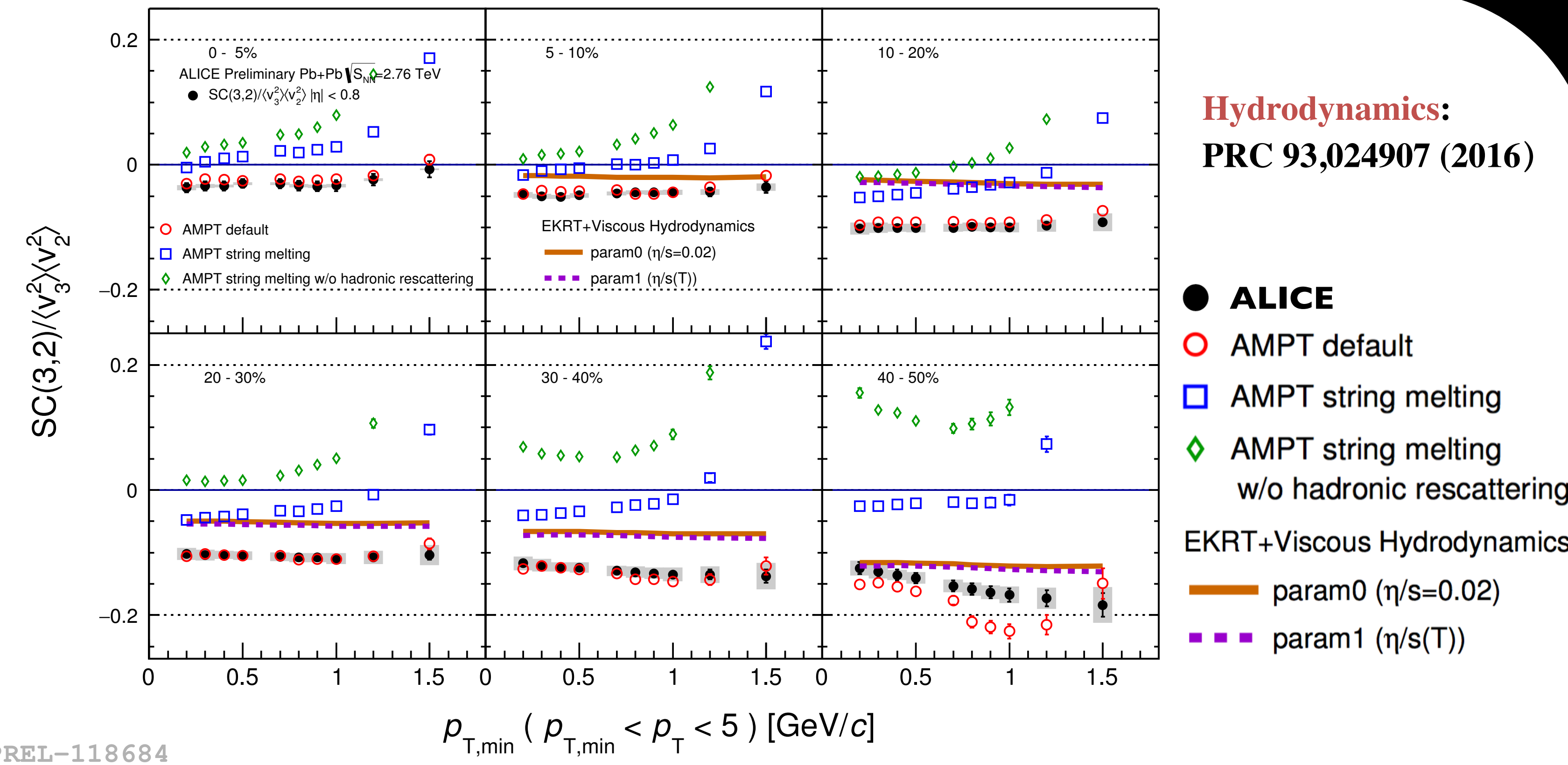
$$v_{6,222}^A = \frac{\langle\langle \cos(6\varphi_1^A - 2\varphi_2^B - 2\varphi_3^B - 2\varphi_4^B)\rangle\rangle}{\sqrt{\langle\langle \cos(2\varphi_1^A + 2\varphi_2^A + 2\varphi_3^A - 2\varphi_4^B - 2\varphi_5^B - 2\varphi_6^B)\rangle\rangle}}$$

$$v_{6,33}^A = \frac{\langle\langle \cos(6\varphi_1^A - 3\varphi_2^B - 3\varphi_3^B)\rangle\rangle}{\sqrt{\langle\langle \cos(3\varphi_1^A + 3\varphi_2^A - 3\varphi_3^B - 3\varphi_4^B)\rangle\rangle}}$$

❖ Here 3-, 4- and 6-particle correlations can be calculated via modified Generic framework (remove self-correlations, with NUA/NUE corrections)

A.Bilandzic, C.H. Christensen, K. Gulbrandsen, A. Hansen, and Y. Zhou, PRC 89, 064904 (2014)

# NSC(3,2) vs $p_T$

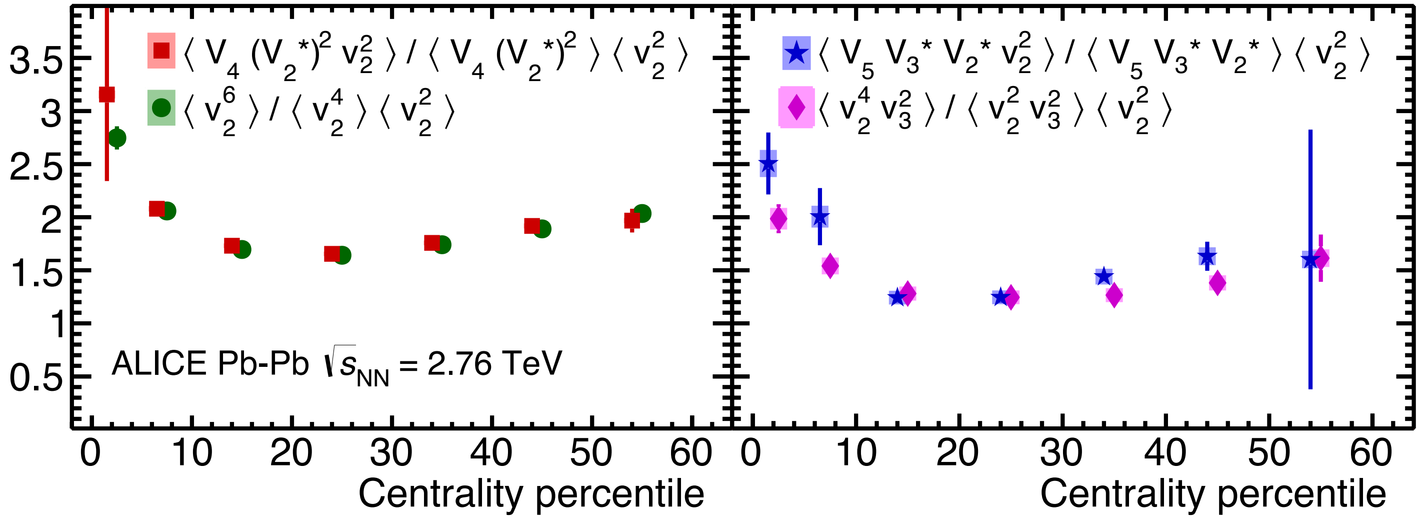



❖ ALICE NSC(3,2) measurements

- ***independent of $p_{T,\,min}$ cut*** in the centrality range <30%,
- for centrality above 30%, a moderate decreasing trend with increasing $p_{T,\,min}$ range.
- calculation from AMPT-default (can not describe $v_n$) agrees with data for 0-40% centrality
- other models overestimate NSC(3,2) $\xrightarrow{?}$ further improvement of initial state models

# Uncorrelated Linear and Non-linear response

**ALICE, arXiv: 1705.04377**



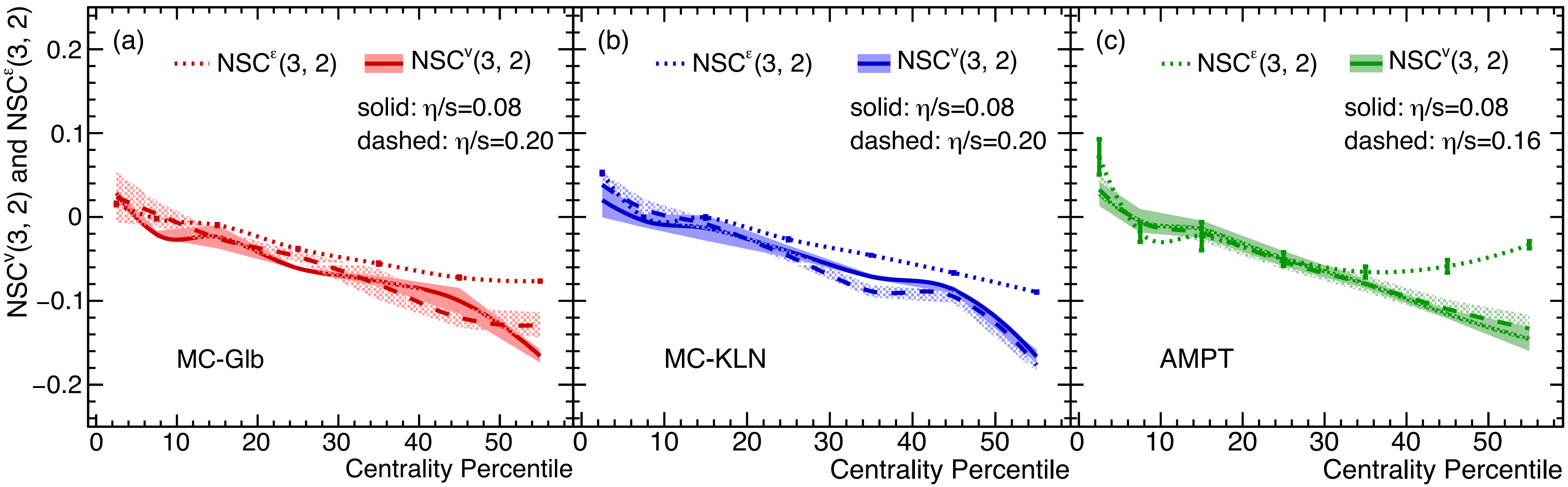

L. Yan et al,
PLB744 (2015) 82

$$\frac{\langle V_4 (V_2^*)^2 v_2^2 \rangle}{\langle V_4 (V_2^*)^2 \rangle \langle v_2^2 \rangle} = \frac{\langle v_2^6 \rangle}{\langle v_2^4 \rangle \langle v_2^2 \rangle} \qquad \frac{\langle V_5 V_2^* V_3^* v_2^2 \rangle}{\langle V_5 V_2^* V_3^* \rangle \langle v_2^2 \rangle} = \frac{\langle v_2^4 v_3^2 \rangle}{\langle v_2^2 v_3^2 \rangle \langle v_2^2 \rangle}$$

- If the above equations are valid
  - ***indicate Linear and Non-linear terms are uncorrelated***
  - valid in hydrodynamic and AMPT calculations
- Agreement observed in data
  - suggests uncorrelated (or very weakly correlated) linear and non-linear responses

# NSC$^v$(3,2) and NSC$^\varepsilon$(3,2)

VISH2+1, X. Zhu et al., PRC 95, 044902 (2017)



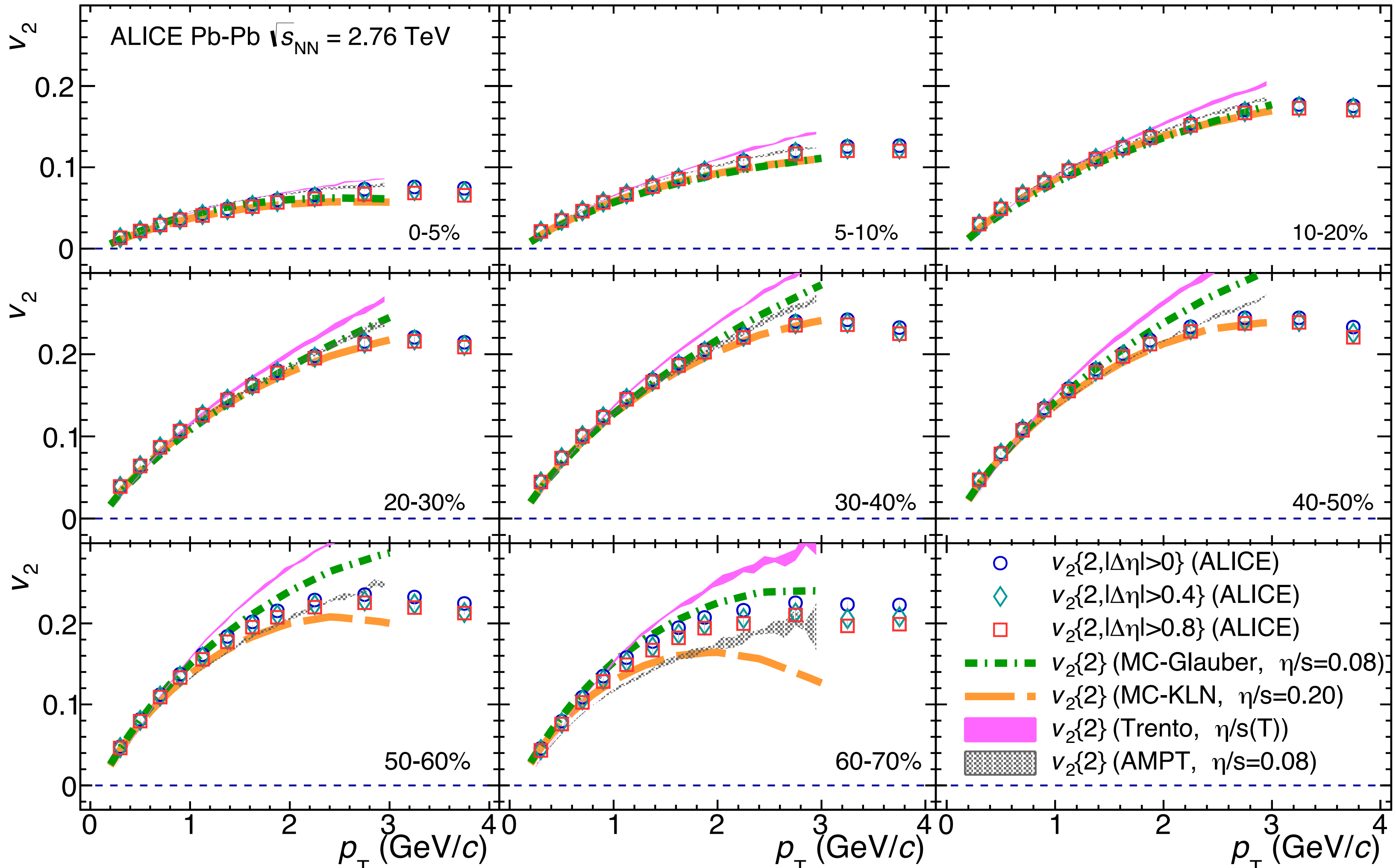

$$v_2 \propto \varepsilon_2$$
$$v_3 \propto \varepsilon_3$$

$$\frac{\langle v_3^2\, v_2^2 \rangle}{\langle v_3^2 \rangle \langle v_2^2 \rangle} \approx \frac{\langle \varepsilon_3^2\, \varepsilon_2^2 \rangle}{\langle \varepsilon_3^2 \rangle \langle \varepsilon_2^2 \rangle}$$

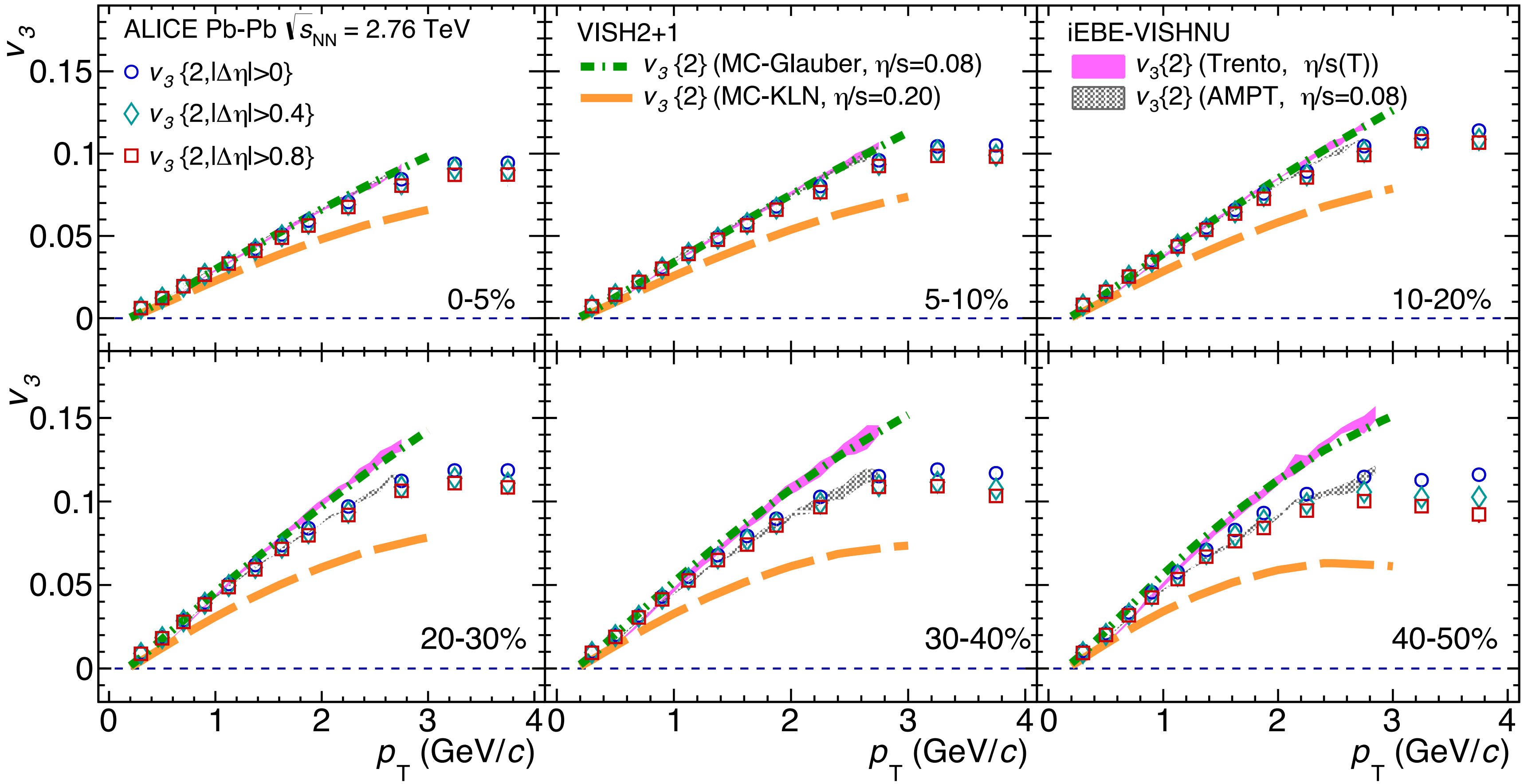
NSC$^v$(3,2) NSC$^\varepsilon$(3,2)

- NSC(3,2) in hydrodynamic calculations
  - mainly driven by initial NSC$^\varepsilon$(3,2) for central- and middle-central collisions
  - ***New approach to tune initial state models***
  - independent of kinematic cuts

ALICE, JHEP 09 (2017) 032



ALICE, JHEP 09 (2017) 032

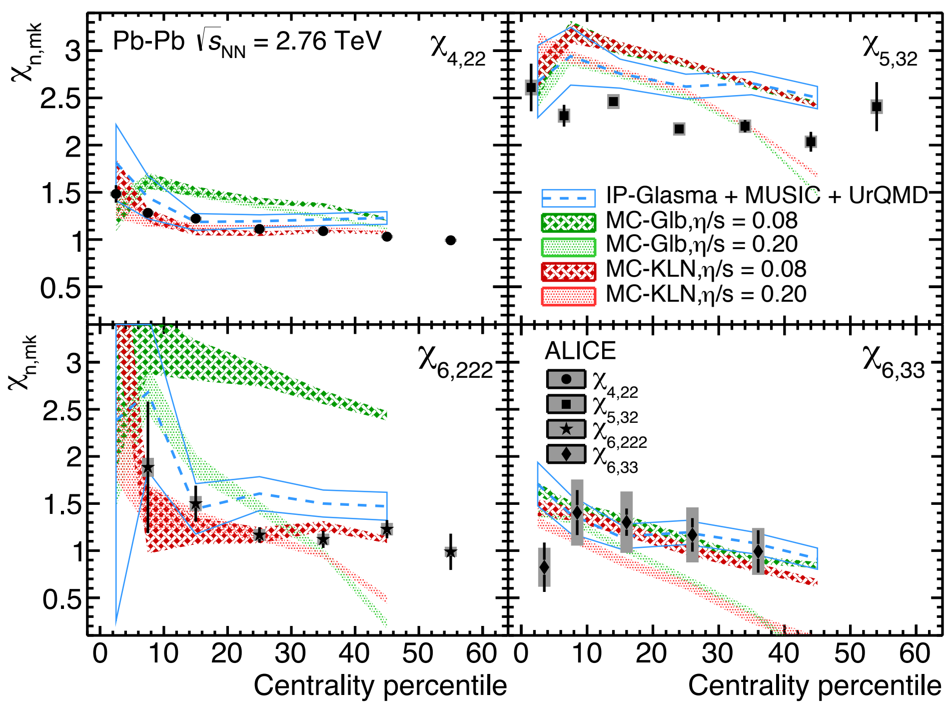


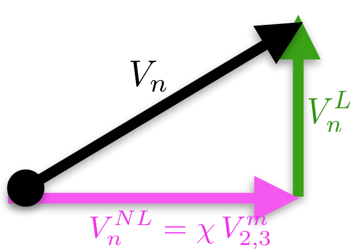
# Nonlinear response coefficients

**ALICE, PLB773 (2017) 68**

**IP-Glasma: S. McDonald et al., arXiv:1609.02958**

**MC-Glb&MC-KLN: J. Qian et al., PR93, 064901 (2016)**




- $X_{422}$ is insensitive to η/s but sensitive to initial conditions
  - ***unique observable to tune the initial conditions w/o influences from η/s***
  - in favor of MC-KLN and IP-Glasma initial conditions than MC-Glb
- $X_{532}$ and $X_{633}$: very weak sensitivity to initial conditions, vary significantly with different η/s values.
  - ***Sensitive to η/s at freeze-out*** (poorly understood so far), not sensitive to **η**/s during the system evolution
  - None of the hydrodynamic calculation quantitatively describes $X_{532}$
- weak centrality dependence, ***suggests a small η/s***.