Anisotropic flow measurements in Pb-Pb collisions at 5.02 TeV with ALICE

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SQM Berkeley 2016

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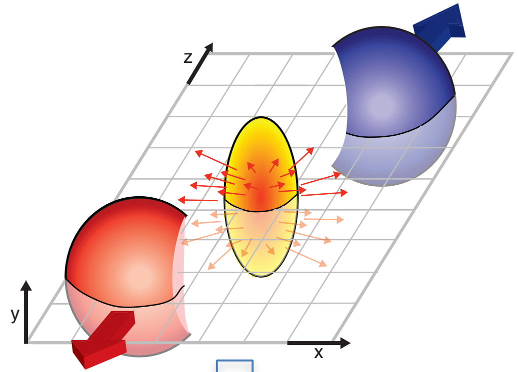
ALICE

Anisotropic Flow

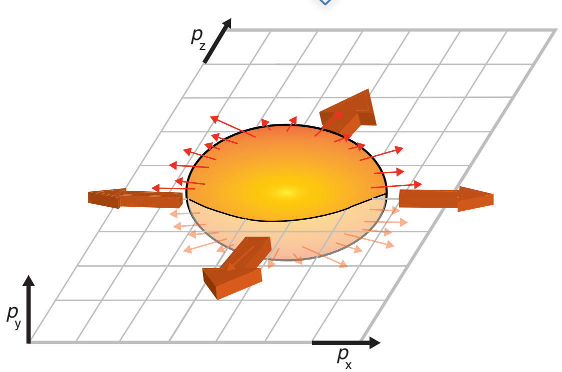
- Spatial anisotropies in the initial state converted to momentum anisotropies
  - known as ***anisotropic flow*** J.Y. Ollitrault, Phys. Rev., D46 (1992) 229
  - its magnitude sensitive to details of initial state and transport properties of QGP



$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos n\varphi\rangle^2 + \langle r^n \sin n\varphi\rangle^2}}{\langle r^n\rangle}$$

coordinate space Anisotropy

system expansion

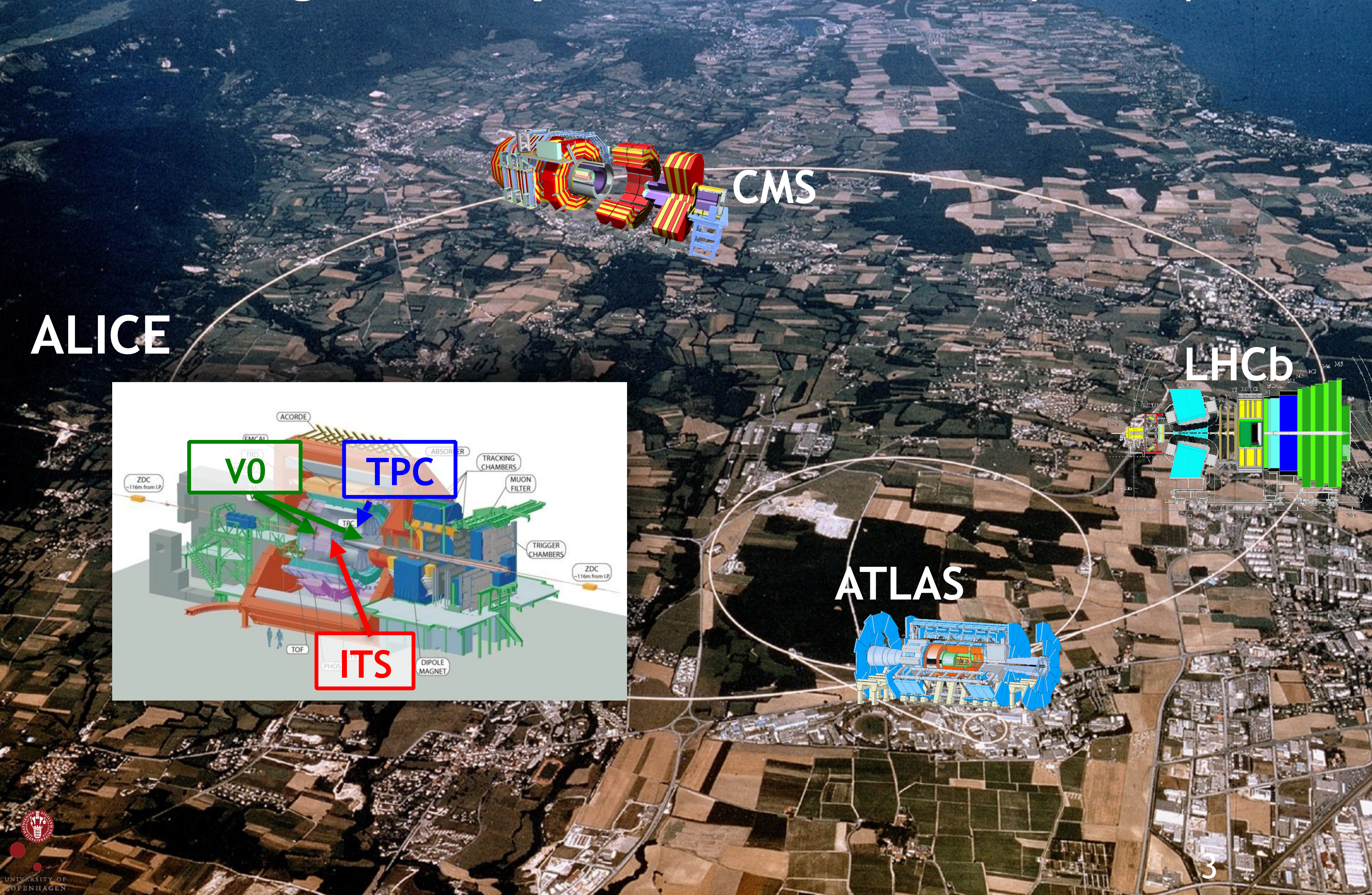


$$v_n = \langle \cos n(\varphi - \Psi_n)\rangle$$

momentum space Anisotropic Flow

Large Hadron Collider (LHC)

“Large Heavy-ion Collider” (LHC)



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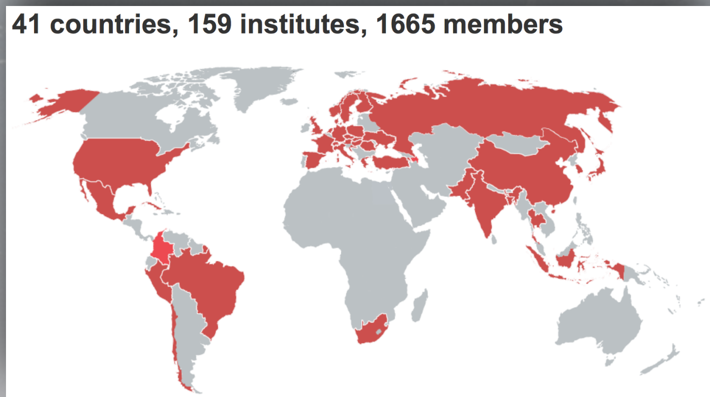
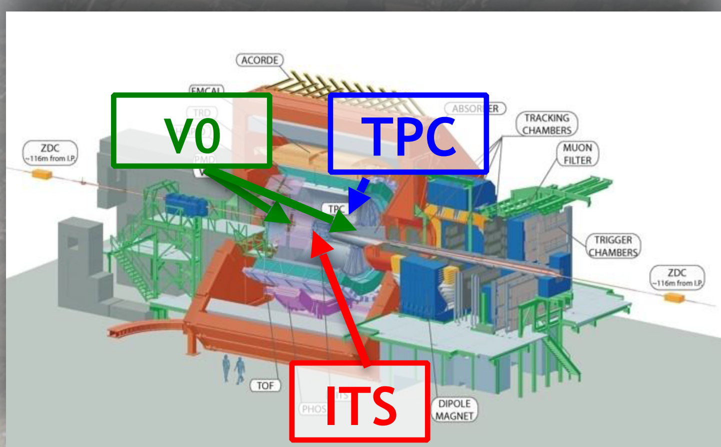




❖ Detectors used:

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

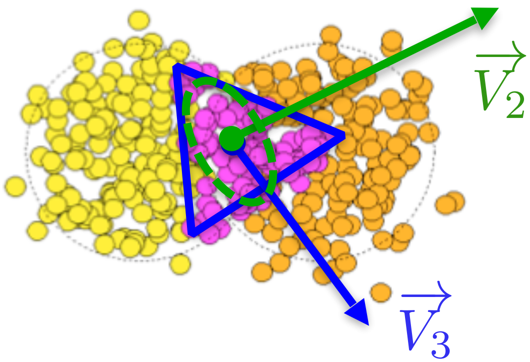
❖ Data Samples (Pb-Pb collisions):

- 2.76 TeV: 12 million M.B. events
- 5.02 TeV: 140 k M.B. events

❖ Questions:

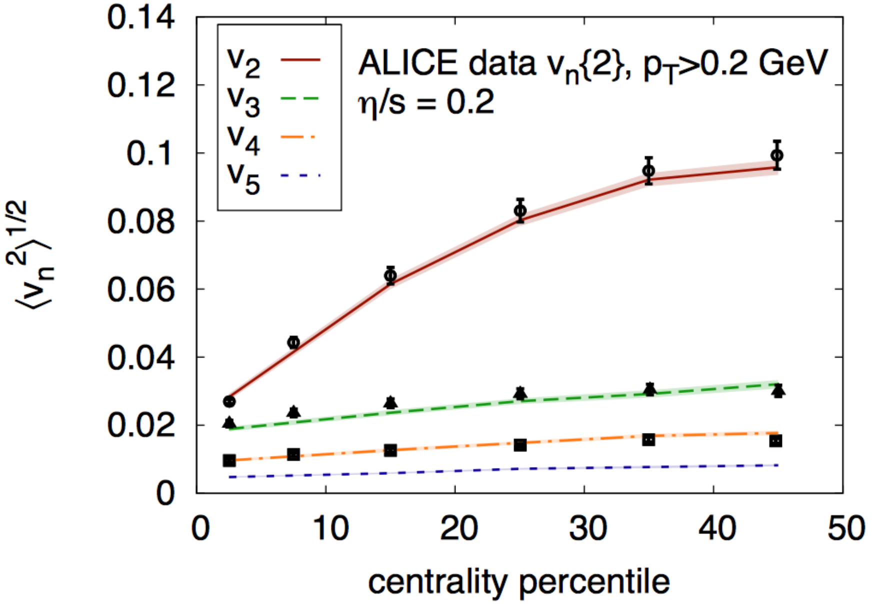
- What has been learnt in Pb-Pb collisions at 2.76 TeV (Run 1)?
- What's new in Pb-Pb collisions at 5.02 TeV (Run 2)?

Centrality dependence of v_n



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

ALICE Collaboration: PRL 107, 032301
IP-Glasma+MUSIC: PRL 110, 012302



- v_2, v_3 and v_4 are nicely described by hydrodynamic calculations with Impact Parameter (IP) Glasma initial condition & shear viscosity over entropy density ratio η/s = 0.20.
- QGP: a state of perfect liquid
  - liquid: described by hydrodynamics; perfect: η/s is close to the quantum limit $1/4\pi$
  - more precise information can be obtained from differential measurements

Transverse momentum dependence of v_n

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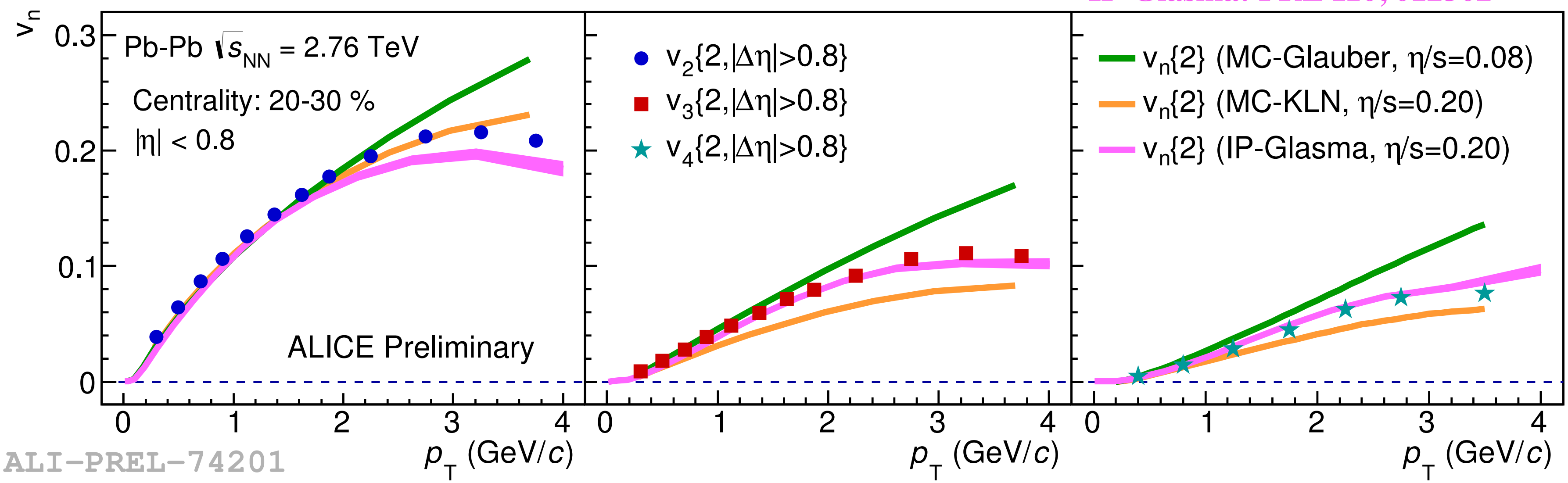
- More detailed information is carried by transverse momentum or pseudorapidity dependence of anisotropic flow v_n

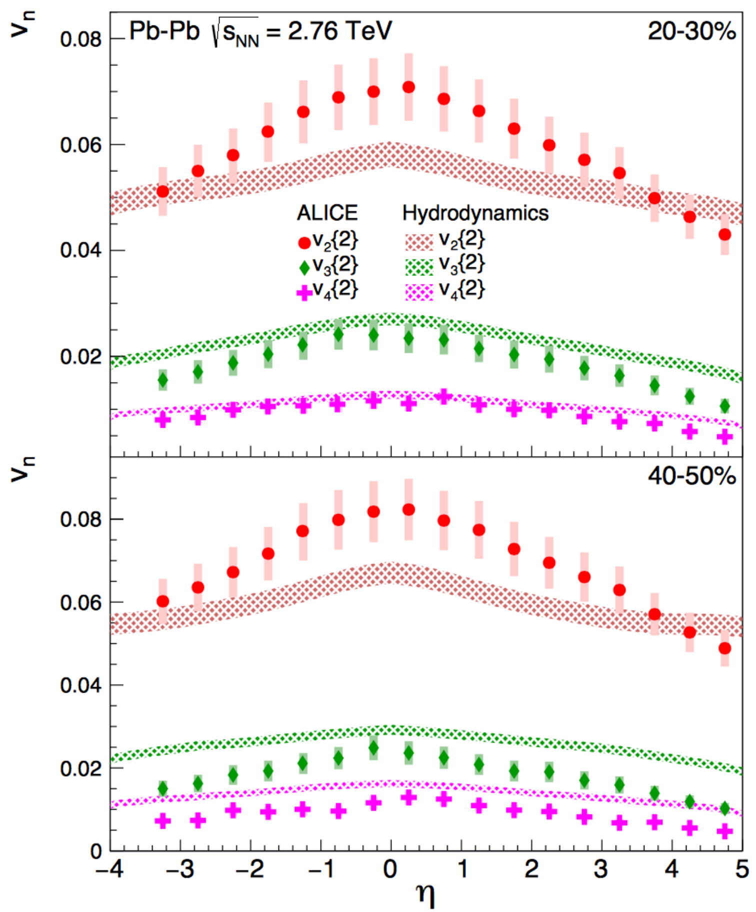
Y. Zhou (ALICE Collaboration), Quark Matter 14

IP-Glasma: PRL 110, 012302



- comparisons of data and hydrodynamic calculations show:
  - calculations with IP-Glasma initial conditions give the best description of data
  - Neither calculation with MC-Glauber not MC-KLN (CGC) initial conditions can reproduce the data.
  - strong constraints on the initial state and η/s of QGP.

Pseudorapidity dependence of v_n



ALICE Collaboration, [arXiv: 1605.02035]

Hydrodynamics: PRL 116, 212301 (2016)

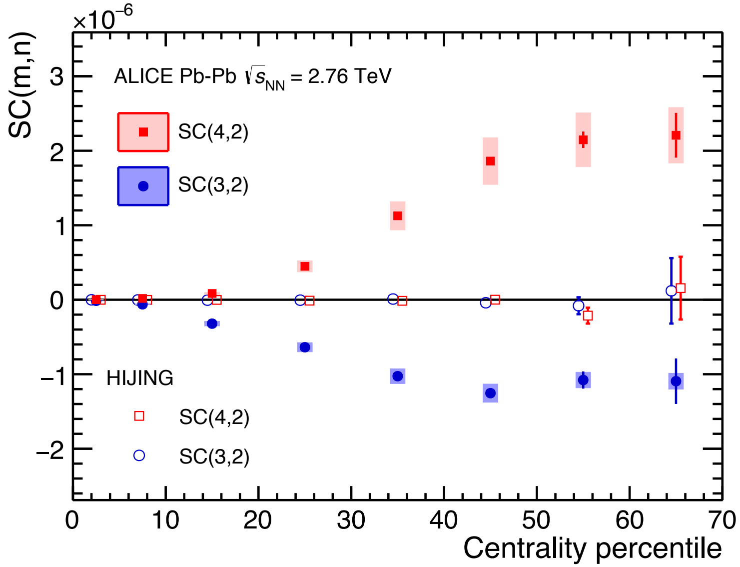
- We find that the shape of $v_n(\eta)$ is largely independent of centrality for the flow harmonics n = 2, 3 and 4,

- 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

Correlations between v_m and v_n

- New observable: ***SC(m,n)***, measures the correlations of v_m and v_n
  - $$SC(m,n) = \langle v_m^2 \, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$
  - Details see: Phys. Rev. C 89, 064904 (2014)
  - 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
    - SC measurements are nearly insensitive to non-flow effects.
  - ALICE data shows
    - positive SC(4,2) -> correlation between v_2 and v_4,
    - negative SC(3,2) -> anti-correlation between v_2 and v_3.

ALICE Collaboration, arXiv:1604.07663



Correlations between v_m and v_n

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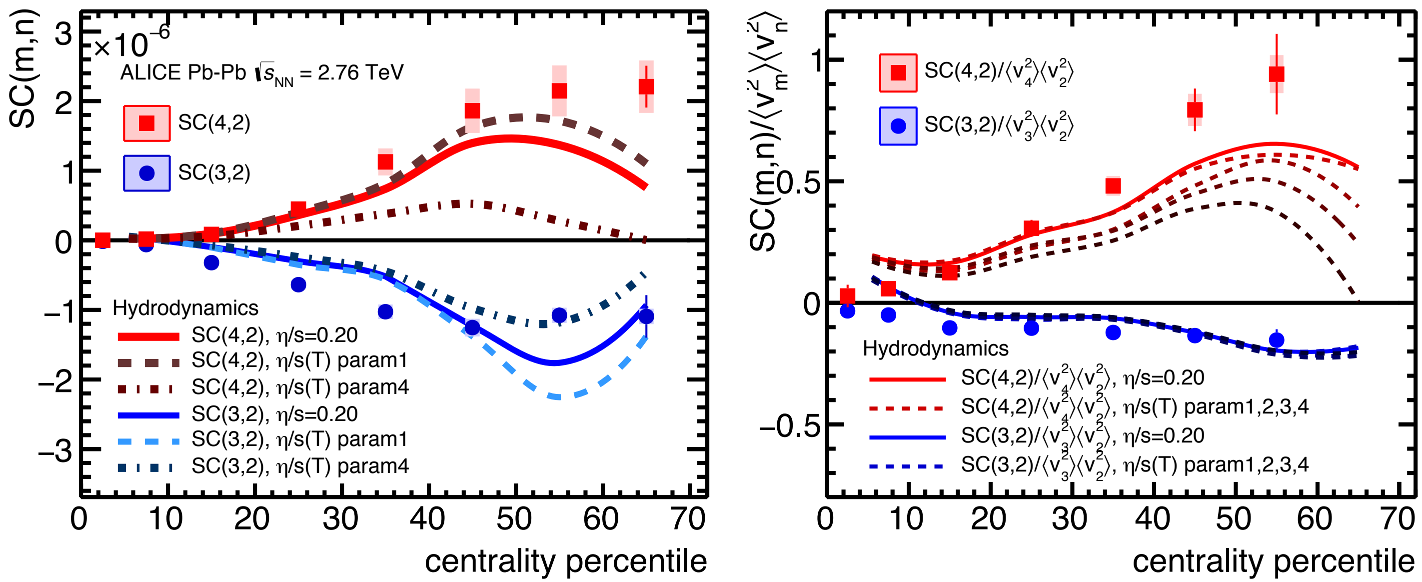


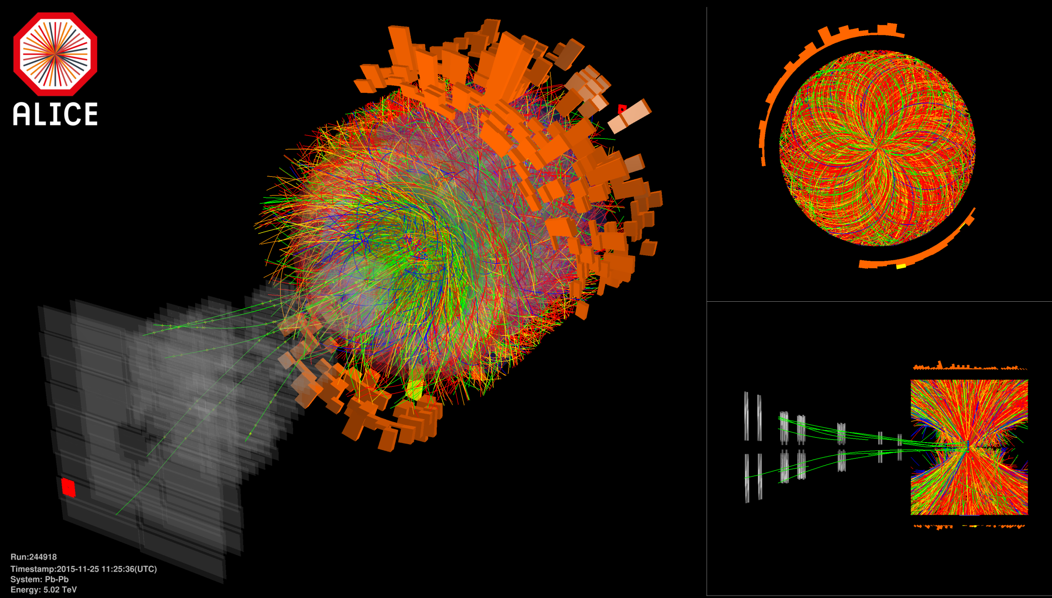
❖ Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations

- Although hydro describes the v_n fairly well, there is not a single centrality for which a given η/s parameterization describes simultaneously SC and NSC.
- NSC(3,2) is insensitive to parameterization of η/s(T)

  -> direct constraints on initial conditions.
- SC and NSC measurements provide stronger constrains on the η/s in hydro than standard v_n measurements alone.

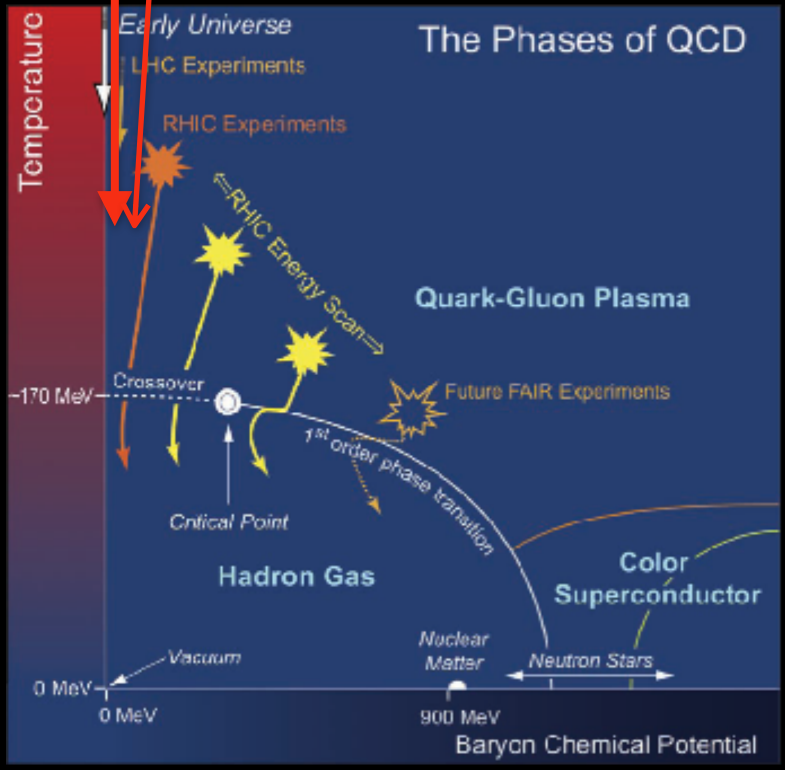
From 2.76 to 5.02 TeV

5.02 TeV Pb-Pb collisions



5.02 TeV

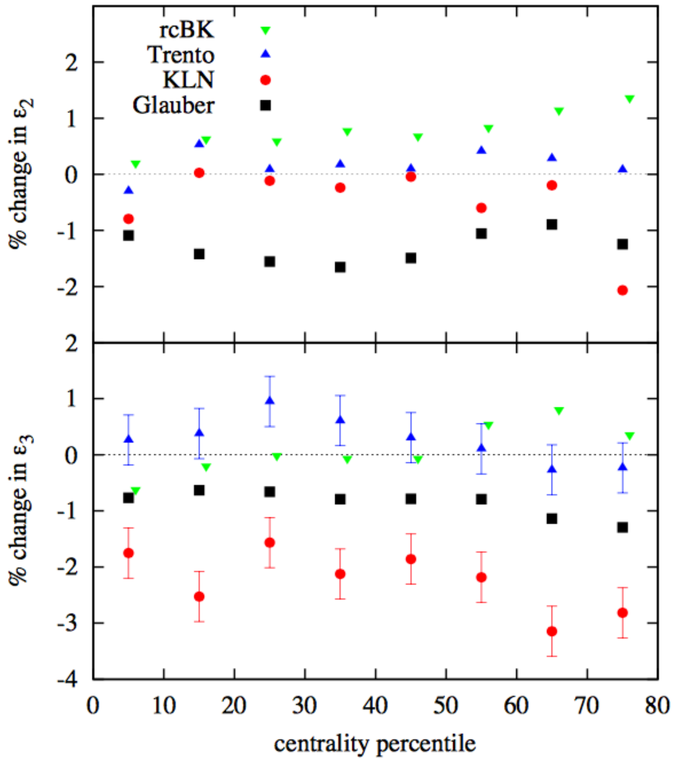
2.76 TeV

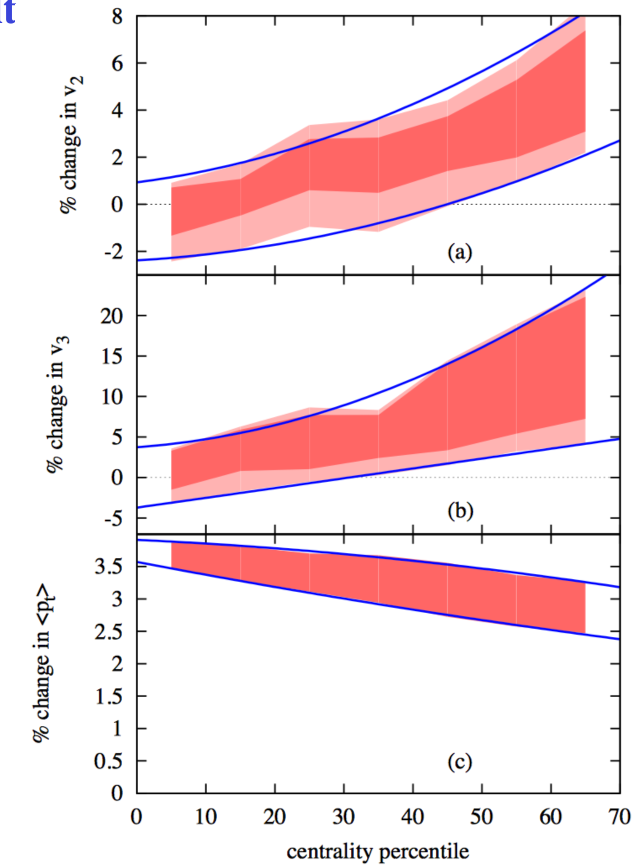


- Pb-Pb 2.76 TeV: 2010, 2011
- Pb-Pb 5.02 TeV: 2015

Theoretical predictions (I)

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

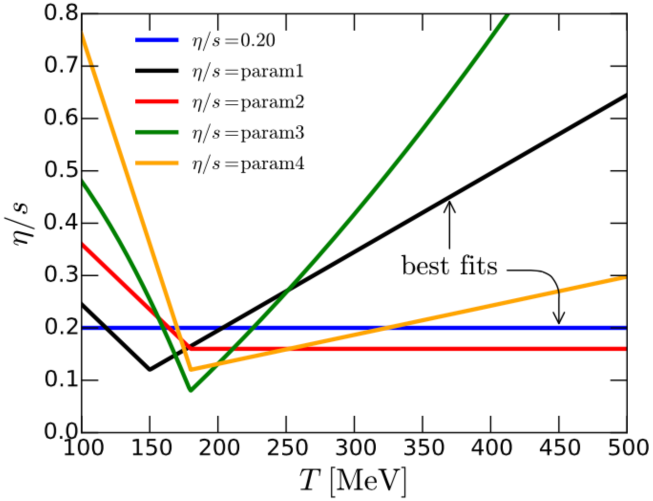


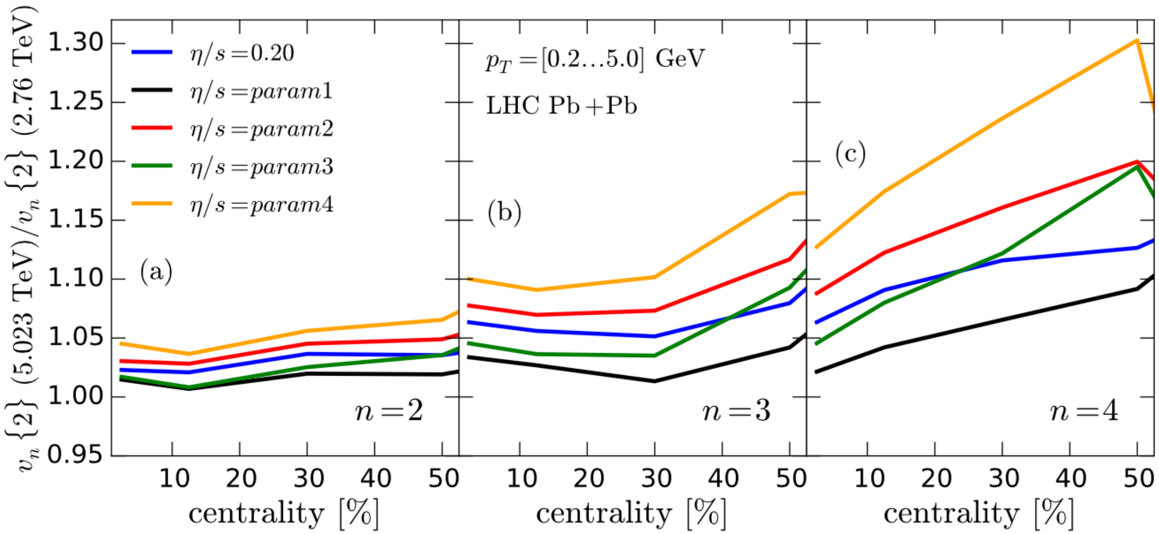


- For all centralities and every model, the change from 2.76 TeV to 5.02 TeV is between -2% and 2% for ε_2 and between -3% and 1% for ε_3.
- v_2 and v_3 should see the largest increases in peripheral collisions, while in central collisions they will show little increase

Theoretical predictions (II)

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

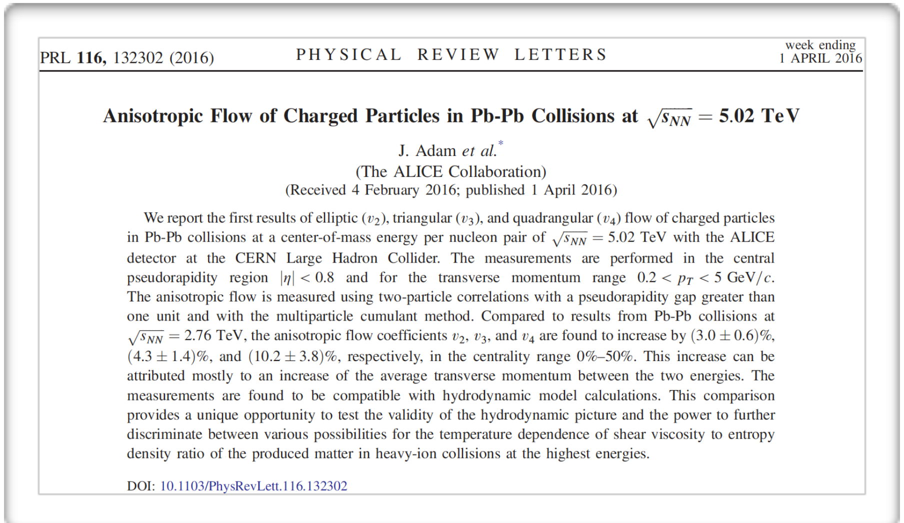




- ❖ The anisotropic flow and its increasing from 2.76 TeV to 5.02 TeV are sensitive to the detailed setting of η/s(T)
  - the increase of v_n from 2.76 TeV to 5.02 TeV could be a new constraint on the η/s(T).

Anisotropic flow at 5.02 TeV

ALICE Collaboration
PRL 116, 132302 (2016)



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

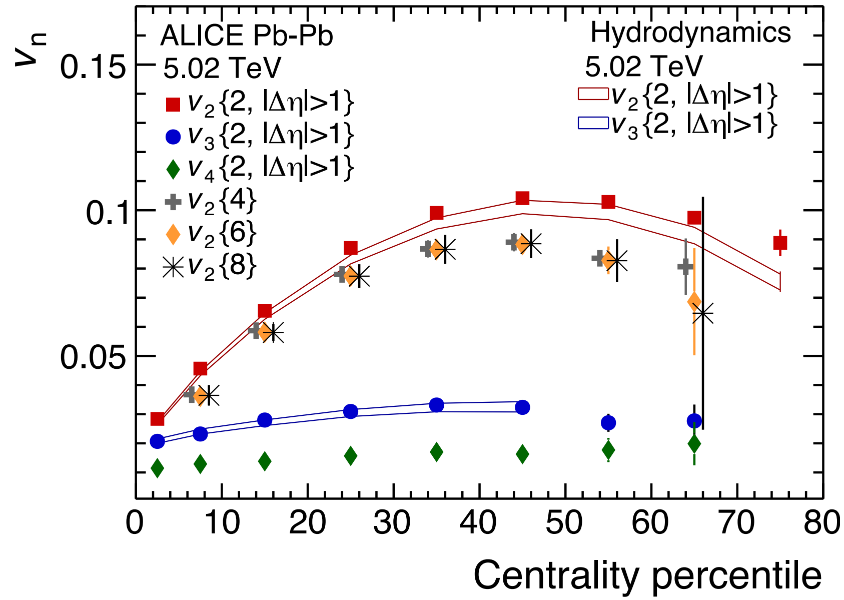
Anisotropic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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 ± 0.6)%, (4.3 ± 1.4)%, and (10.2 ± 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.

DOI: 10.1103/PhysRevLett.116.132302

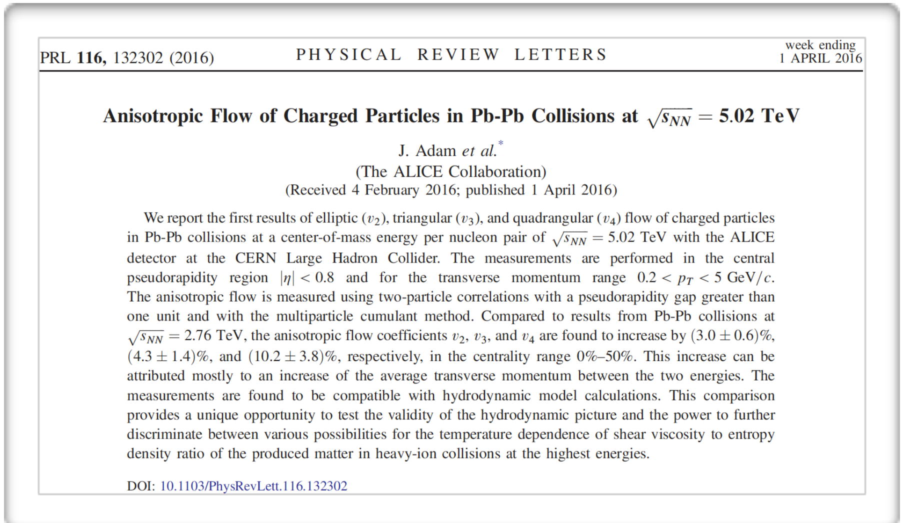
Hydro: J. Noronha-Hostler et al., PRC93 (2016) 034912



- ❖ v_2 increases from central to peripheral collisions, and maximum value in 40-50%.
- ❖ v_3 and v_4, the values are smaller and the centrality dependence is much weaker.
- ❖ agreements with hydrodynamic predictions using various possibilities of initial conditions and η/s.
  - provides a unique opportunity to test the validity of the hydrodynamic framework.

Anisotropic flow at 5.02 TeV

ALICE Collaboration
PRL 116, 132302 (2016)



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

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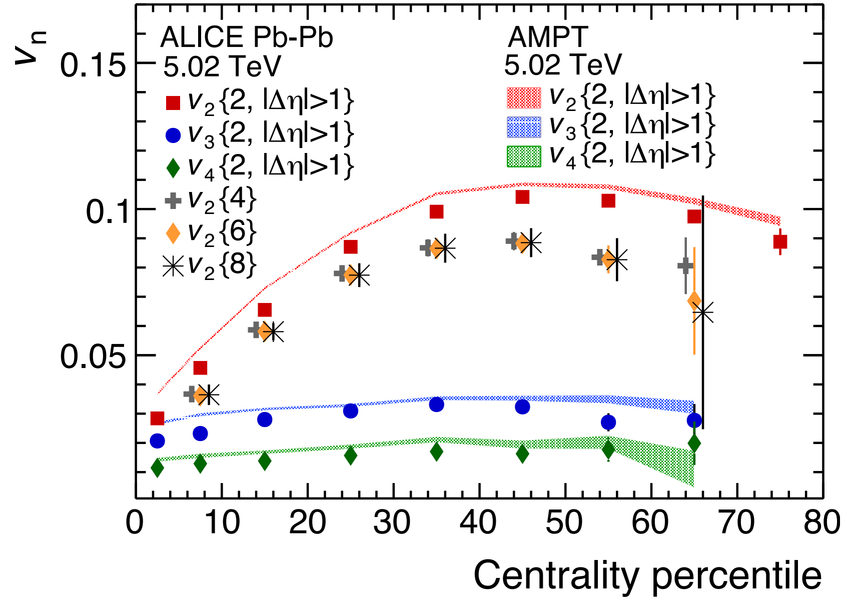
AMPT: **Z. Feng et al. (Wuhan group), arXiv:1606.02416**

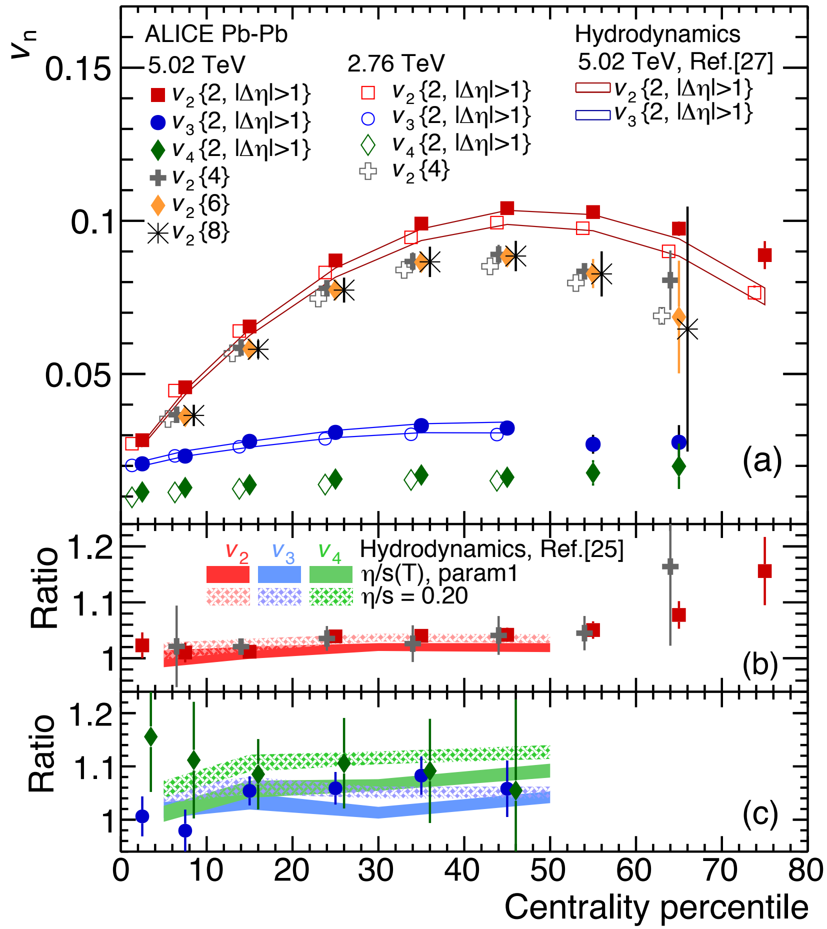


- AMPT with string melting calculations
  - parameters tuned for Pb-Pb collisions at 2.76 TeV, details see: G. Ma, Z.W. Lin, Phys. Rev. C 93 (2016), 054911
  - calculations of v_2, v_3 and v_4 are compatible with ALICE data

v_n from 2.76 to 5.02 TeV

ALICE Collaboration
PRL 116, 132302 (2016)

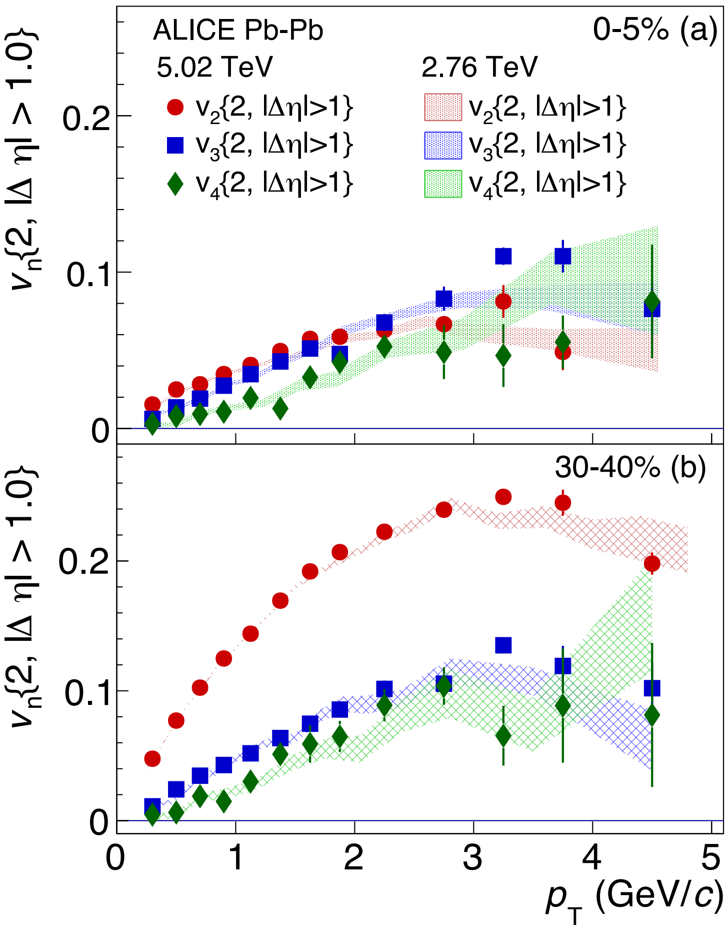
Ref [27]: J. Noronha-Hostler et al., PRC93 (2016) 034912
Ref [25]: H. Niemi et al, PRC 93, 014912 (2016)



- ❖ 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.

p_T differential flow (I)

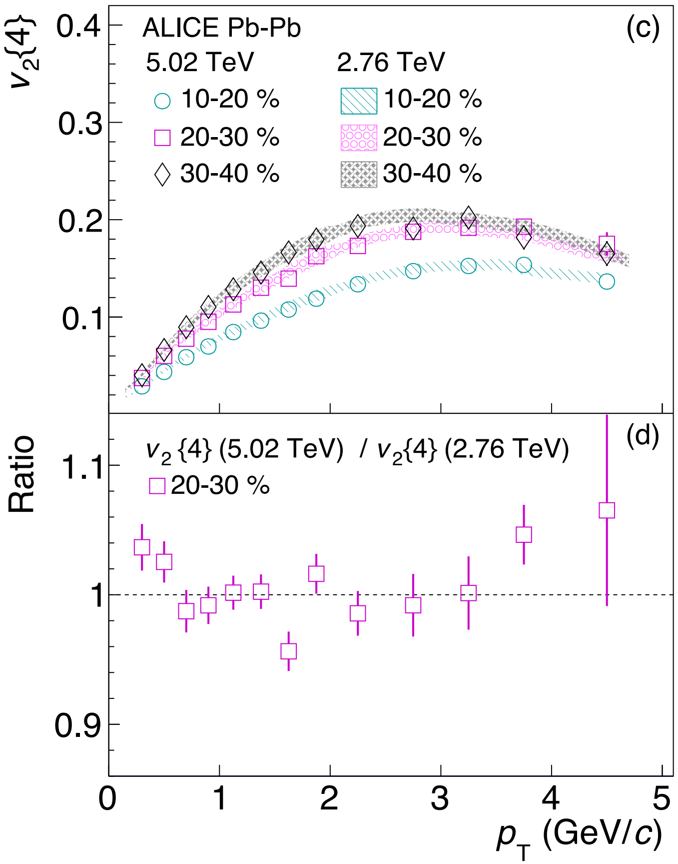
ALICE Collaboration
PRL 116, 132302 (2016)



- For the 0–5% centrality class, at p_T > 2 GeV/*c*, $v_3\{2\}$ is observed to be larger than $v_2\{2\}$, while $v_4\{2\}$ is compatible with $v_2\{2\}$
- For the 30–40% centrality class $v_2\{2\}$ is higher than $v_3\{2\}$ and $v_4\{2\}$ for the entire p_T range measured: no crossing
- Comparable results to Run 1 results, increase in integrated flow can be attributed to the increase in radial flow

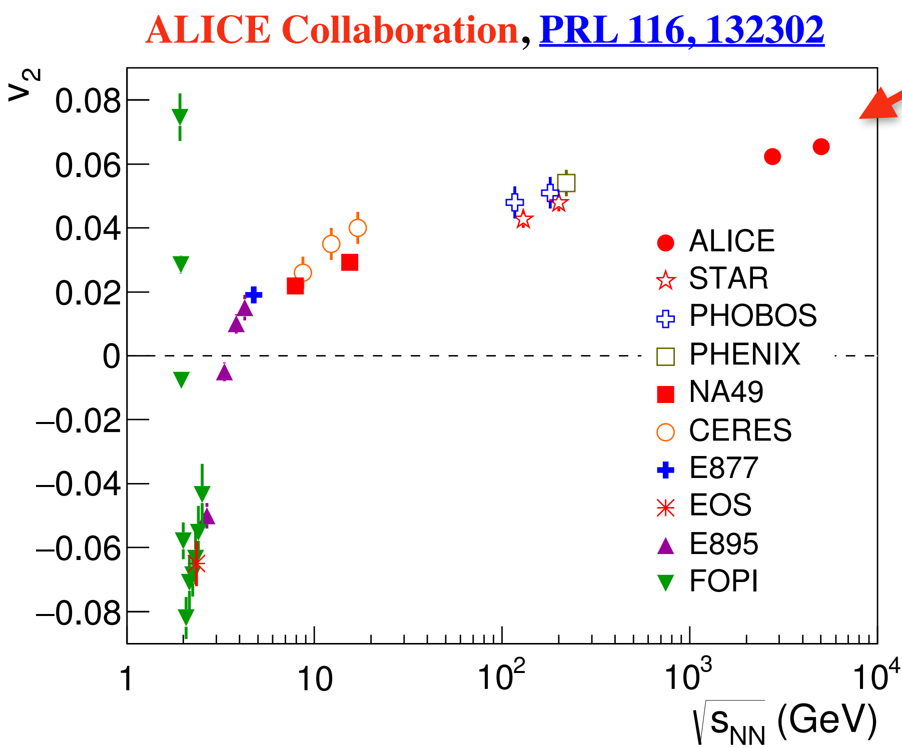
p_T differential flow (II)

ALICE Collaboration
PRL 116, 132302 (2016)

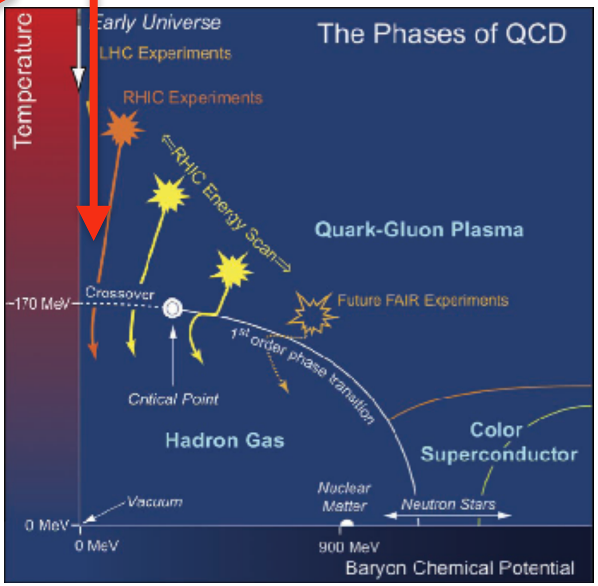


- $v_2\{4\}$ decreases from mid-central to central collisions over the entire p_T range
- ratio of $v_2\{4\}$ (5.02 TeV)/$v_2\{4\}$ (2.76 TeV) indicates there is no change in the p_T dependence between both energies

v_2 vs $\sqrt{s_{NN}}$



Pb-Pb 5.02 TeV



❖ ALICE has measured the largest hydro-like flow so far!

Summary

- The anisotropic flow of charged particles measured in Pb-Pb collisions at 5.02 TeV
  - v_n keep increasing from 2.76 to 5.02 TeV, with weak centrality dependence in 0-50%, mainly explained by the increase of radial flow.
  - results are compatible with hydrodynamic predictions, confirm the validity of current knowledge of hydrodynamic framework.
  - new challenges to the theory community to describe the differential measurements

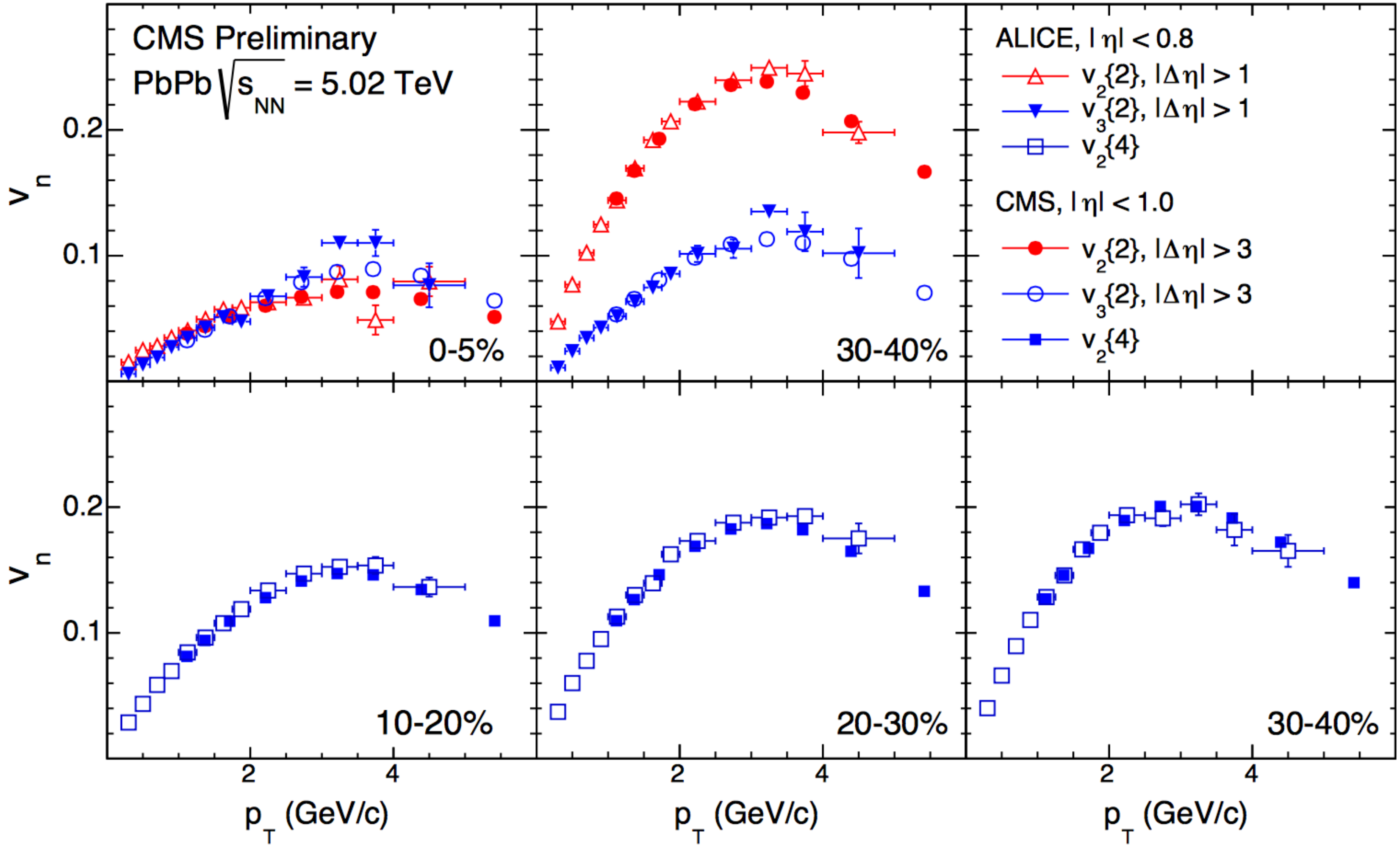
- The LHC RUN2 program provides new opportunities
  - the anisotropic flow measurements will shed new light into the properties of produced QGP

Thanks for your attention!

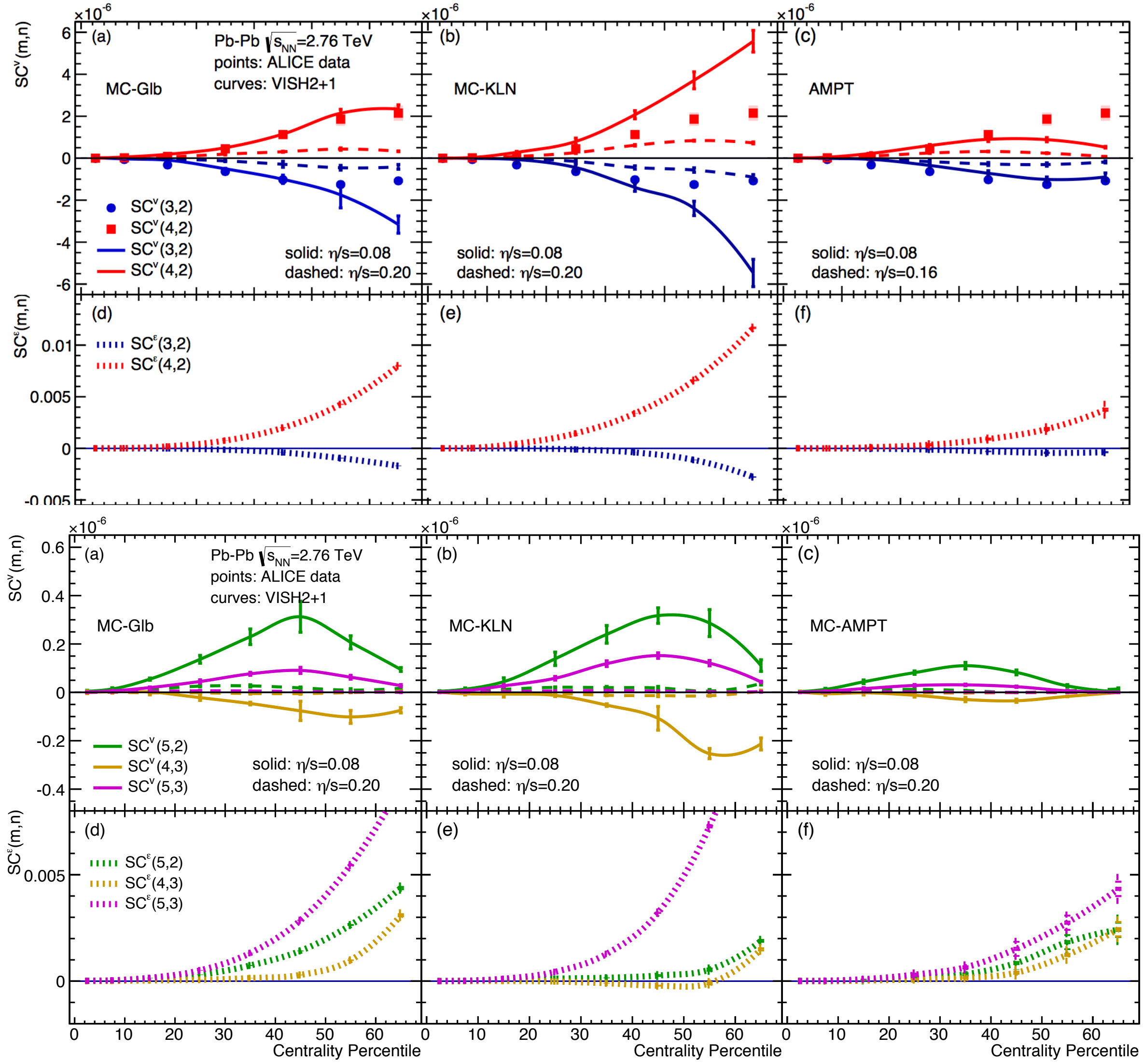
backup

v_n at 5.02 TeV: ALICE vs CMS

CMS: CMS-HIN-15-014



SC(m,n) from VISH2+1



X.-R. Zhu et. al, IS2016