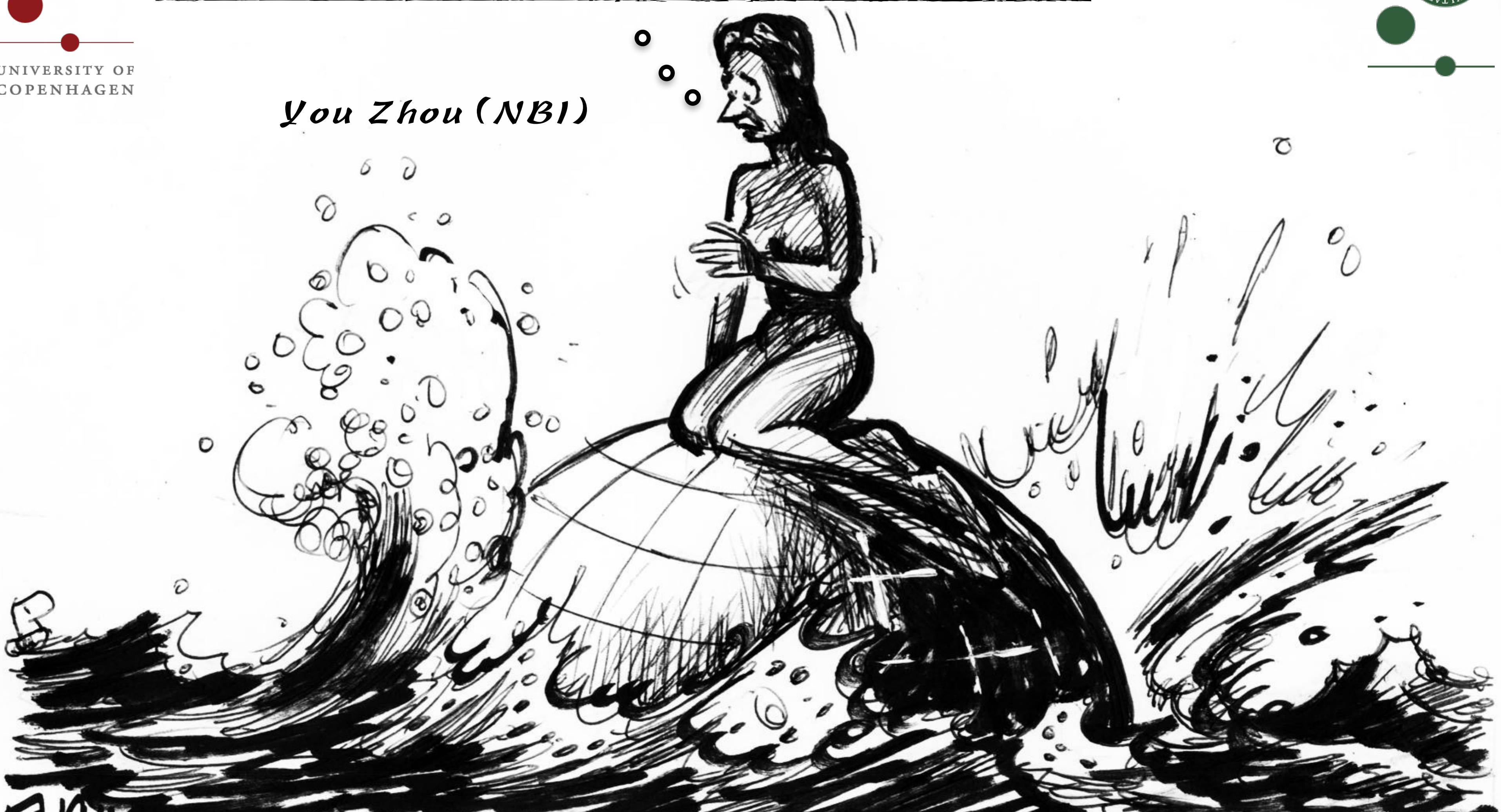
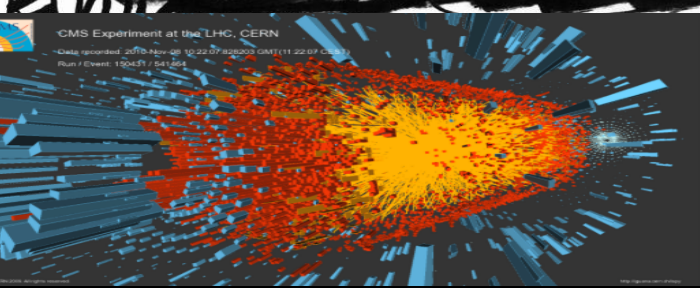
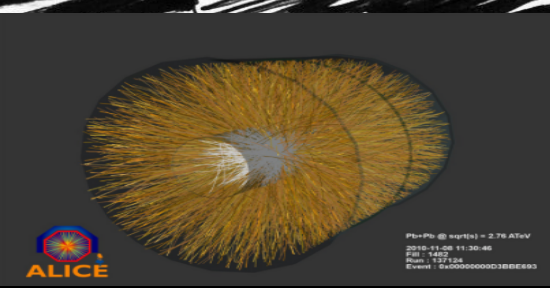
UNIVERSITY OF COPENHAGEN

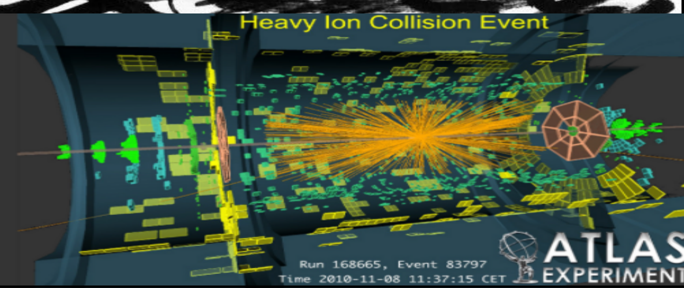
Experimental overview of Flow at the LHC

You Zhou (NBI)

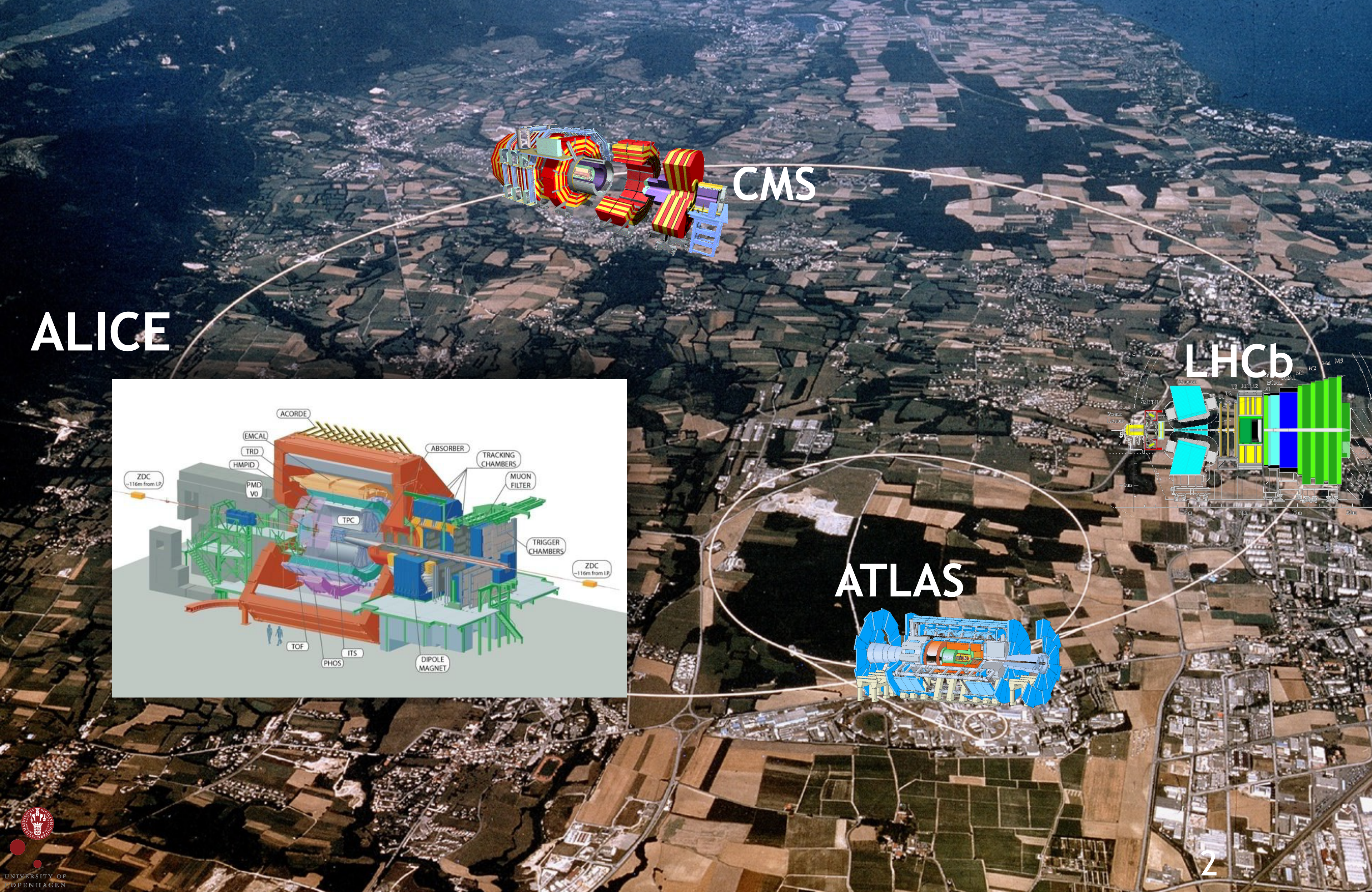






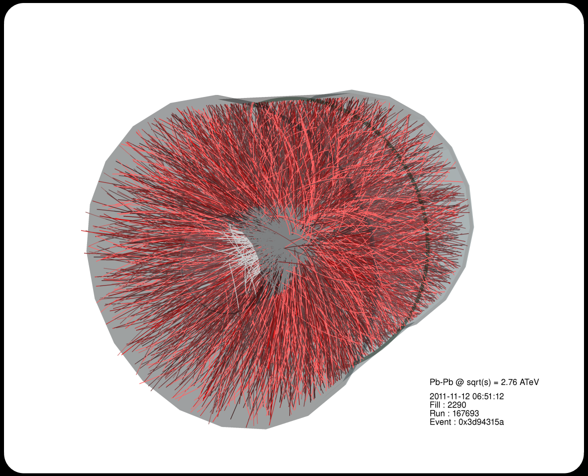


“Large Heavy-ion Collider” (LHC)



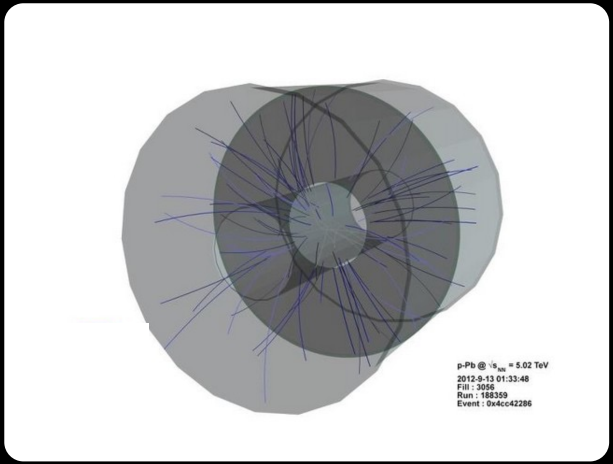
Pb-Pb, p-Pb and pp

Pb-Pb collisions



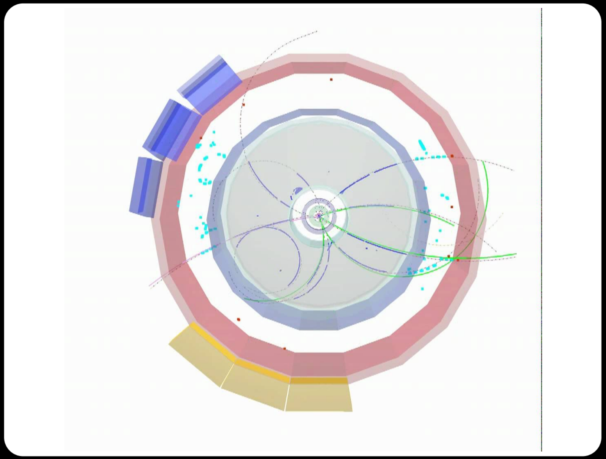
- 2.76 TeV
- 5.02 TeV

p-Pb collisions



- 5.02 TeV
- 5.02 TeV (2016)
- 8 TeV (2016)

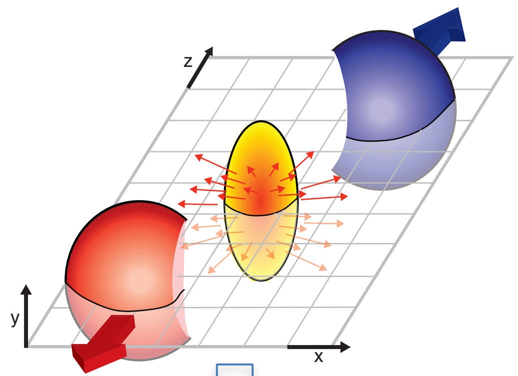
pp collisions



- 900 GeV
- 2.76 TeV
- 5.02 TeV
- 7 TeV
- 8 TeV
- 13 TeV

Anisotropic Flow

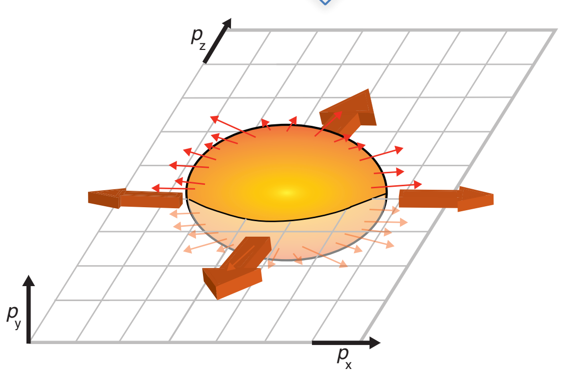
- Spatial anisotropies in the initial state converted to momentum anisotropies
  - known as ***anisotropic flow*** J. Y. Ollitrault, Phys. Rev., D46 (1992) 229
  - its magnitude sensitive to details of initial state and transport properties of QGP



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

coordinate space Anisotropy

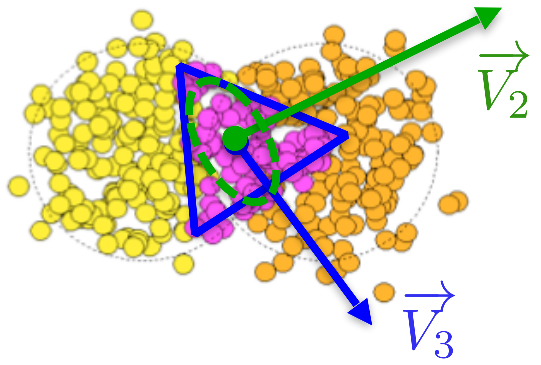
system expansion



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

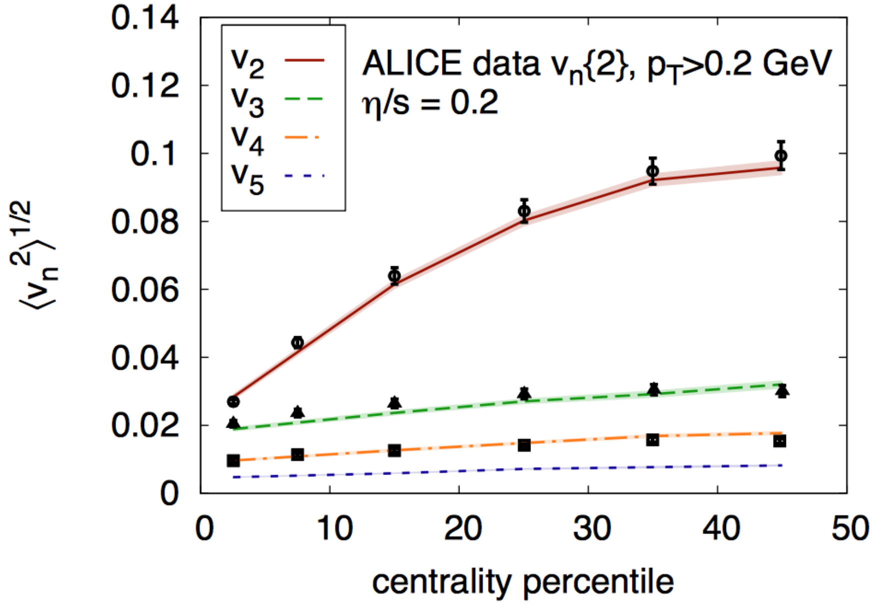
momentum space Anisotropic Flow

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

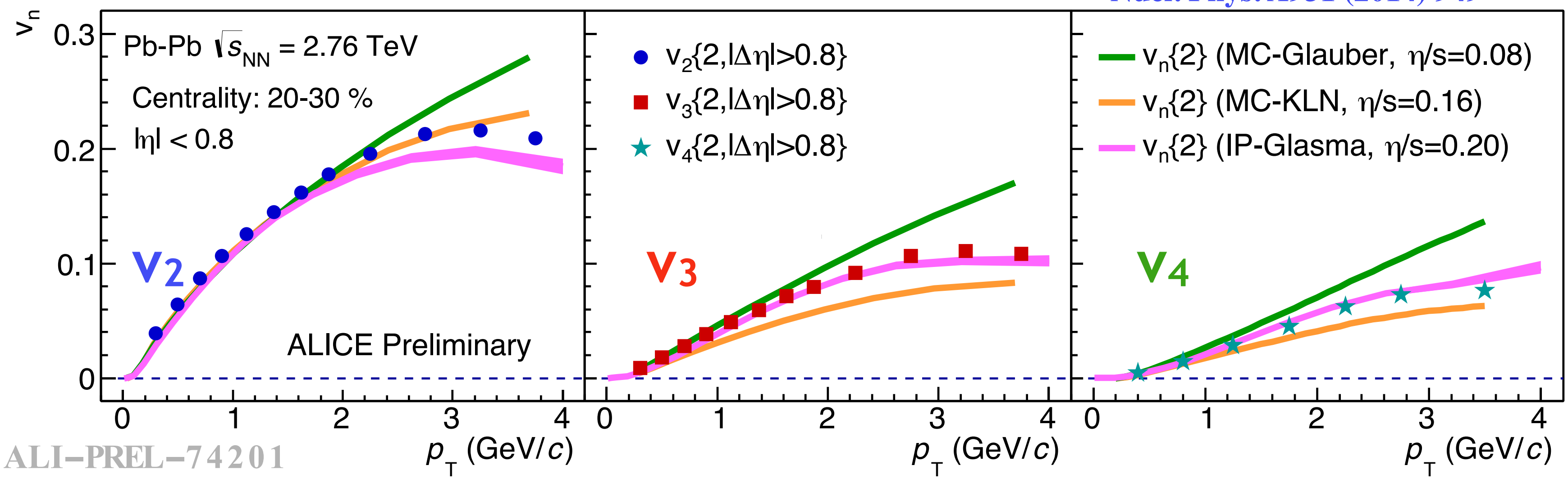


- v_2, v_3 and v_4 are nicely described by hydrodynamic calculations with IP-Glasma initial condition & shear viscosity over entropy density ratio η/s = 0.20.
- QGP: a state of perfect liquid
  - liquid: described by hydrodynamics; perfect: η/s is close to the quantum limit 1/4π
  - more precise information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

Transverse momentum dependence of v_n

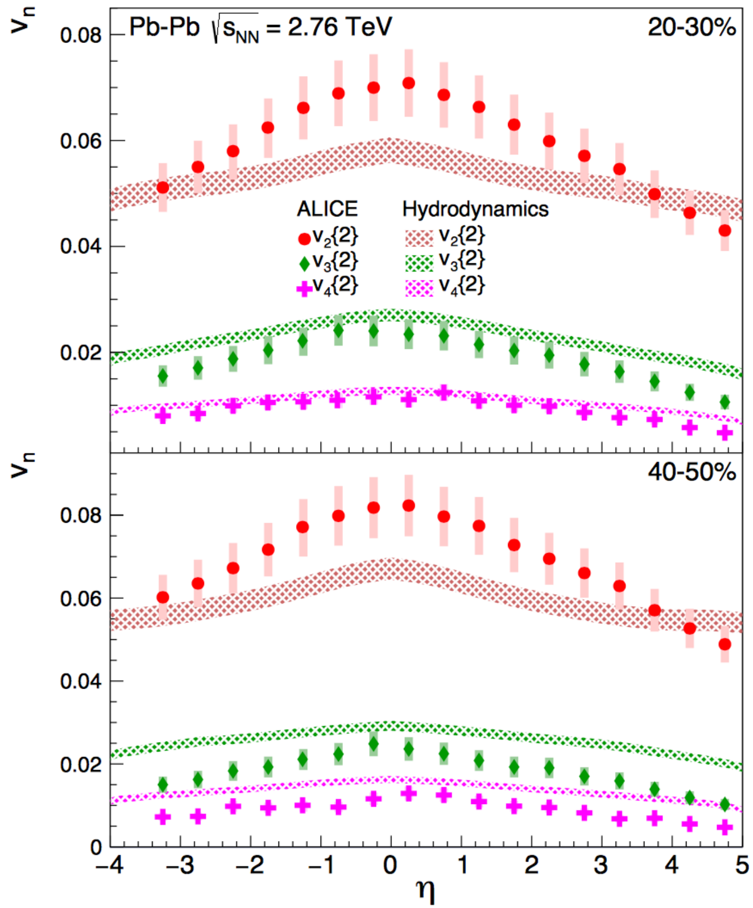
- More detailed information are carried by transverse momentum or pseudorapidity dependence of anisotropic flow v_n

Y. Zhou for ALICE Collaboration, Nucl. Phys. A931 (2014) 949



- 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

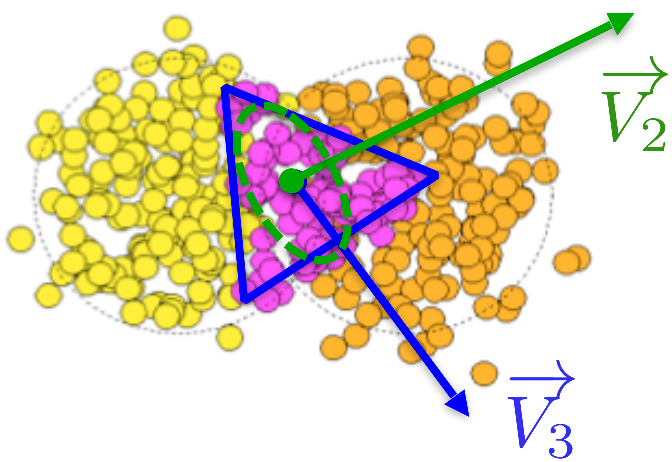


ALICE Collaboration, arXiv: 1605.02035
submitted to PLB

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,
  - v_3 and v_4 have weaker dependence on eta than v_2
- 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

de-correlations of flow-vector V_n



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

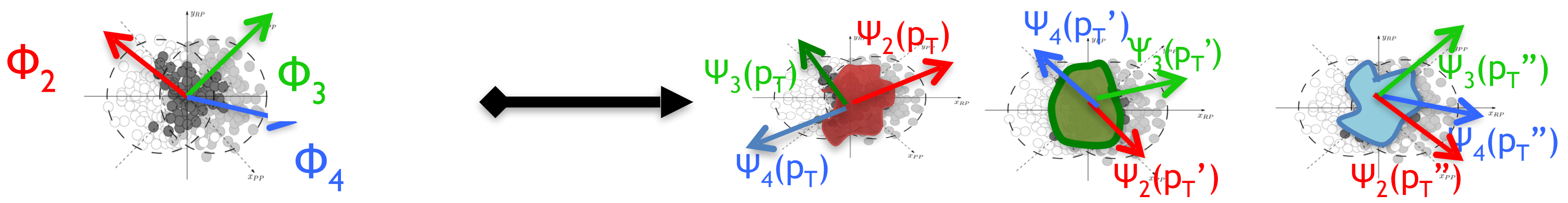
New hydrodynamic picture, better constrain the initial conditions and **η***/s*

p_T and/or η dependent flow-vector

- Traditionally *Flow* analyses look for correlations w.r.t common symmetry planes over a large range in p_T or η.
- However, hydrodynamic simulations show p_T dependent flow angle and magnitude fluctuations
  - Further constraints on the initial state and η/s.

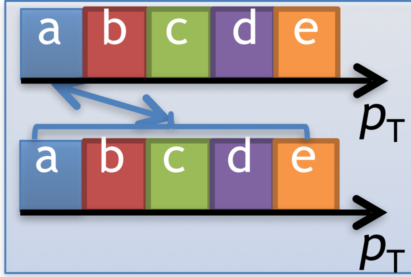
Initial symmetry planes

Final symmetry planes ??

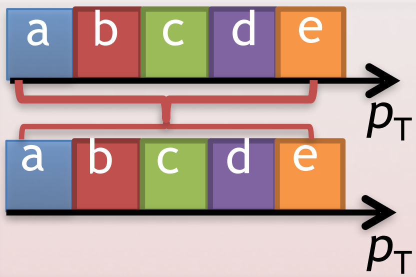


- 2 particle correlations probe these predicted effects in experiments.

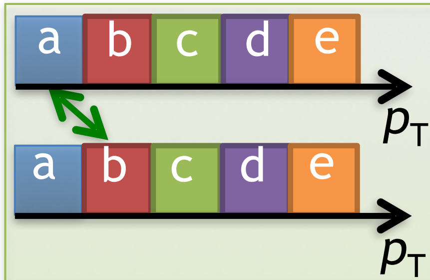
2 Particle Correlations



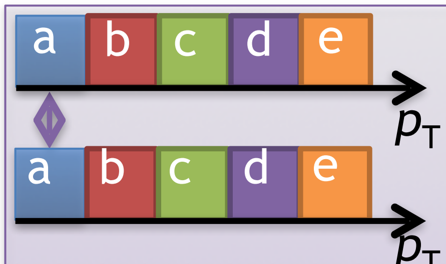
- **Type $< a, All >$**
  One particle from p_T^a, the other from entire p_T
  - $d_n\{2\}$



- **Type $< All, All >$**
  Two particles from entire p_T
  - $c_n\{2\}$



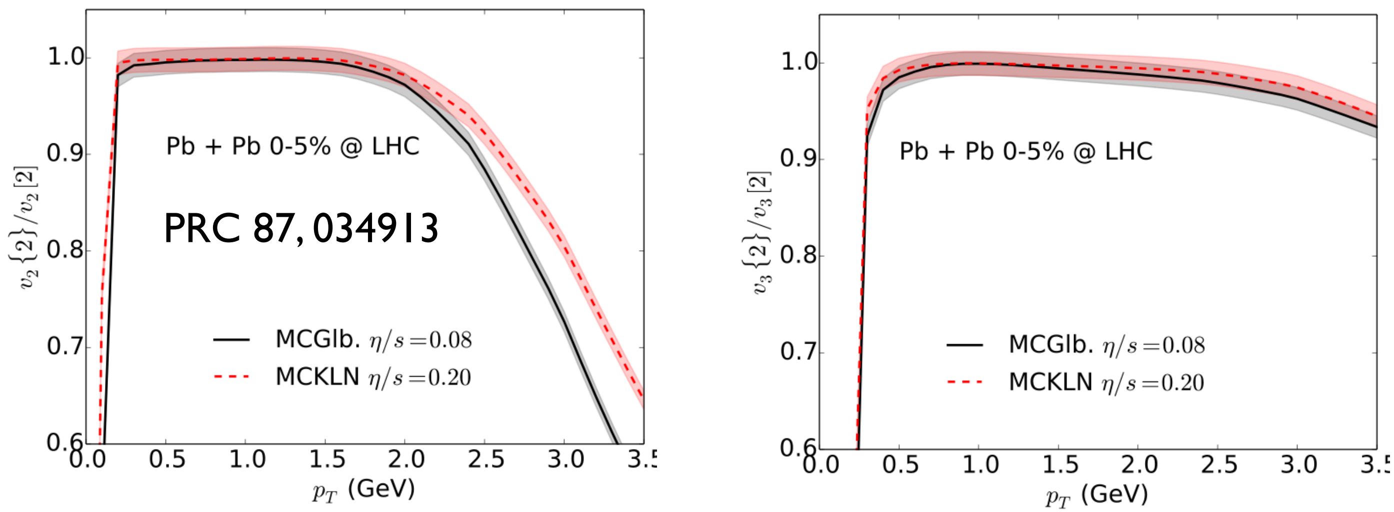
- **Type $< a, b >$**
  One particle from p_T^a, the other from p_T^b
  - $V_{n\Delta}(p_T^a, p_T^b)$



- **Type $< a, a >$**
  Two particles from p_T^a
  - $v_n[2]$
  - $V_{n\Delta}(p_T^a, p_T^a) = v_n[2]^2$

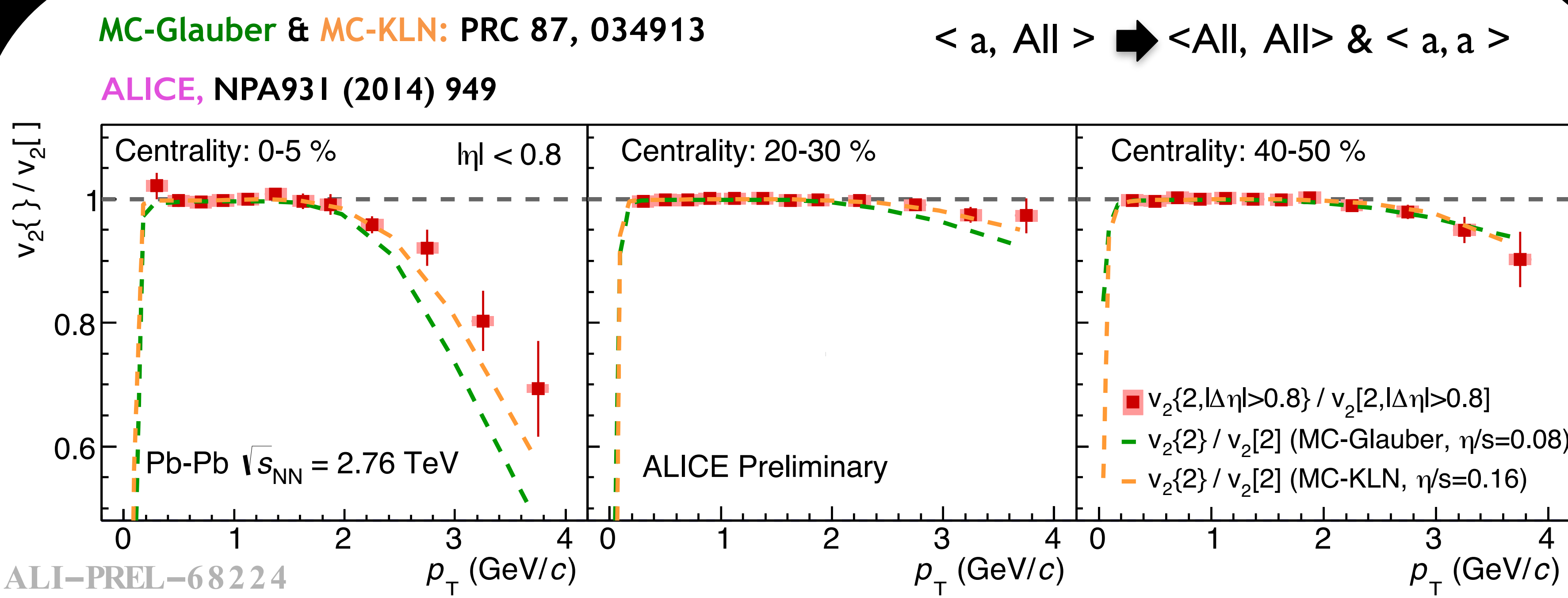
$v_n\{2\}$ and $v_n[2]$

- $v_n\{2\} = d_n\{2\}/c_n\{2\}^{1/2}$
  - < a, All > for $d_n\{2\}$ and < All, All > for $c_n\{2\}$
  - Contributions from possible p_T dependent flow angle and magnitude fluctuations, in addition from non-flow
- $v_n[2]$:
  - < a, a >
  - Contributions from non-flow
- Ratio of $v_n\{2\}/v_n[2]$: < a, All > ➡ <All, All> & < a, a >



  - Hydrodynamic calculations: $v_n\{2\}/v_2[2] < 1$ => p_T dependent flow angle and magnitude fluctuations.

$v_2\{\ \} / v_2[\ ]$



- $v_2\{2\} / v_2[2]$
  - Significant deviation for p_T >2 GeV/c in most central collisions.
- Hydrodynamic calculations (no non-flow) already overestimate the deviation of $v_2\{2\}/v_2[2]$ in most central collisions
  - Calculations with MC-KLN describe the data better than MC-Glauber.

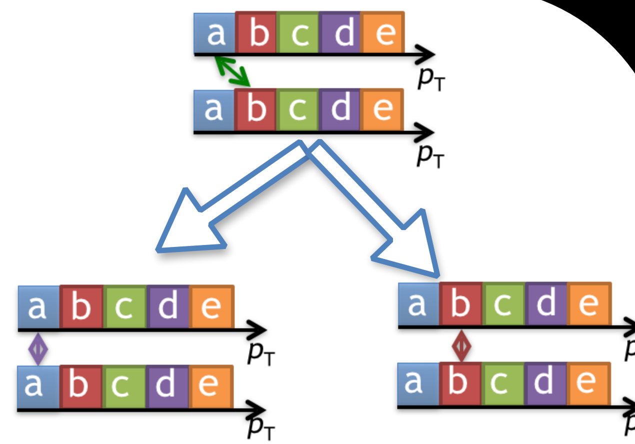
Factorization ratio r_n

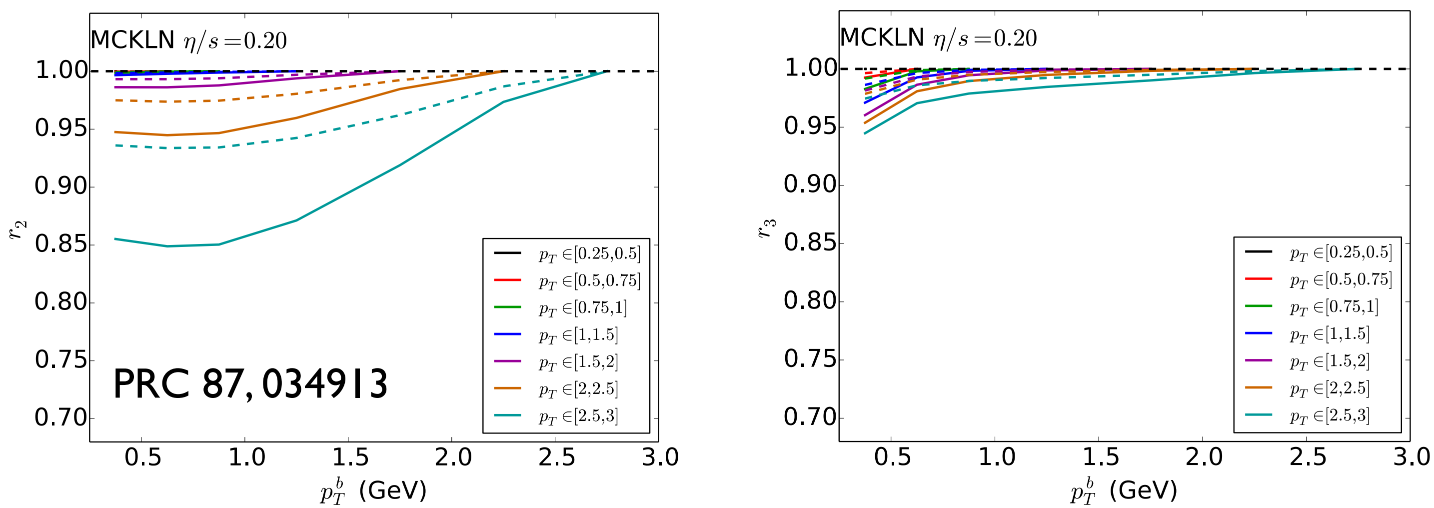
- r_n :

PRC 87, 031901(R)

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

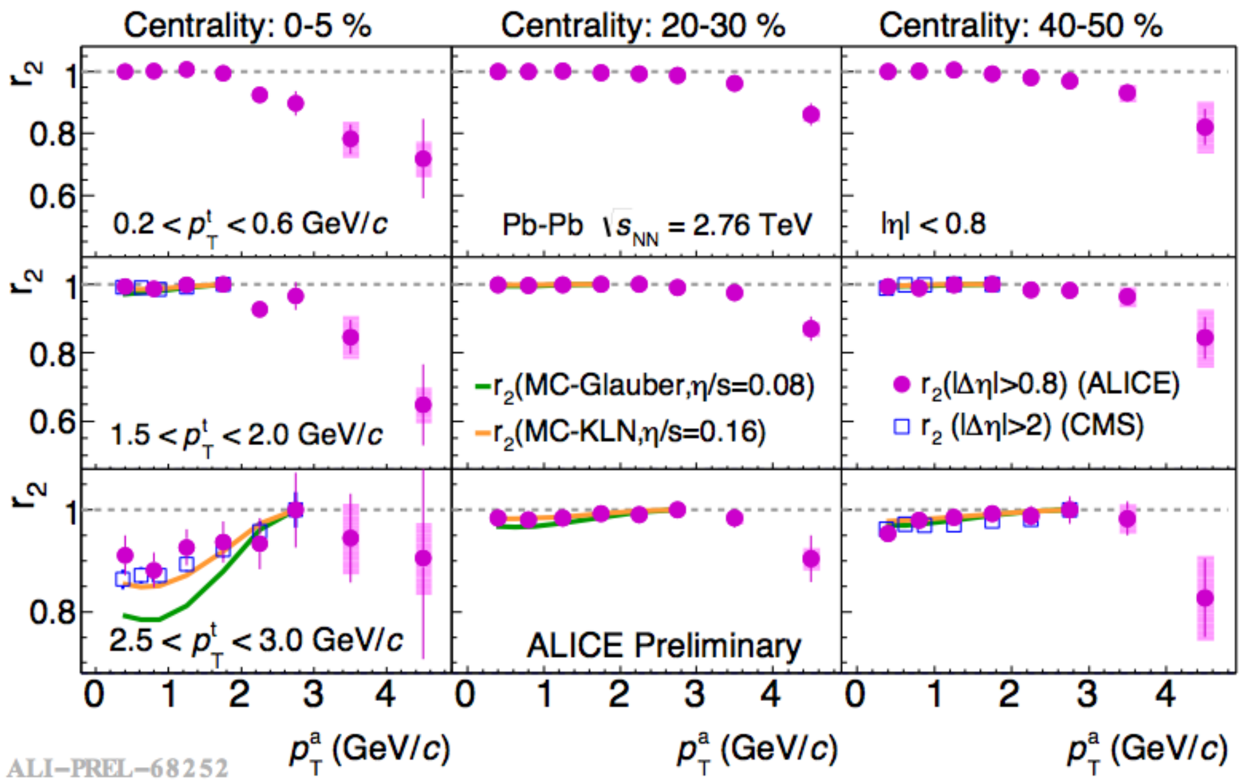
- r_n probes < a, b > ➡ < a, a > & < b, b >
- r_n < 1, Factorization broken





- r_n < 1 observed in hydrodynamic calculations
  - indication of p_T dependent fluctuations of flow angle and magnitude.

Centrality dependence of r_2



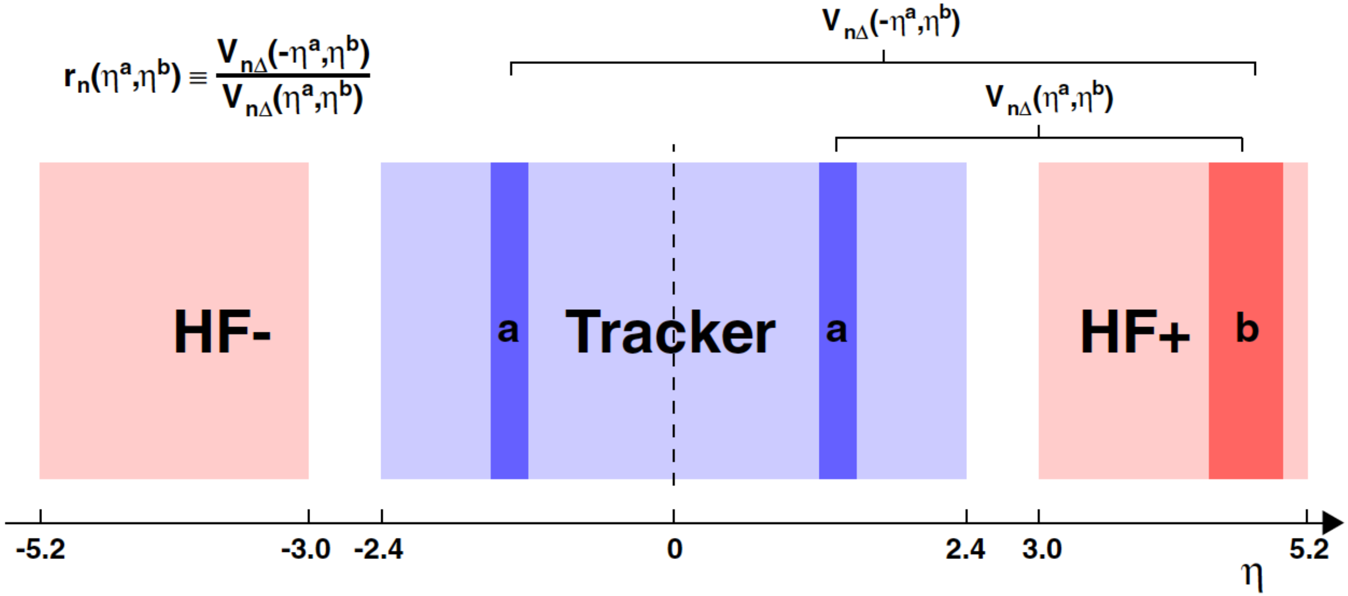
ALICE
NPA931 (2014) 949

MC-Glauber & MC-KLN:
PRC 87, 034913

CMS,
JHEP 02, 088

- Breakdown of factorization more pronounced in central collisions.
- Hydrodynamic calculations also show that the factorization is broken.
- CMS r_2 quantitatively agrees with our measurements

Factorization ratio r_n vs η

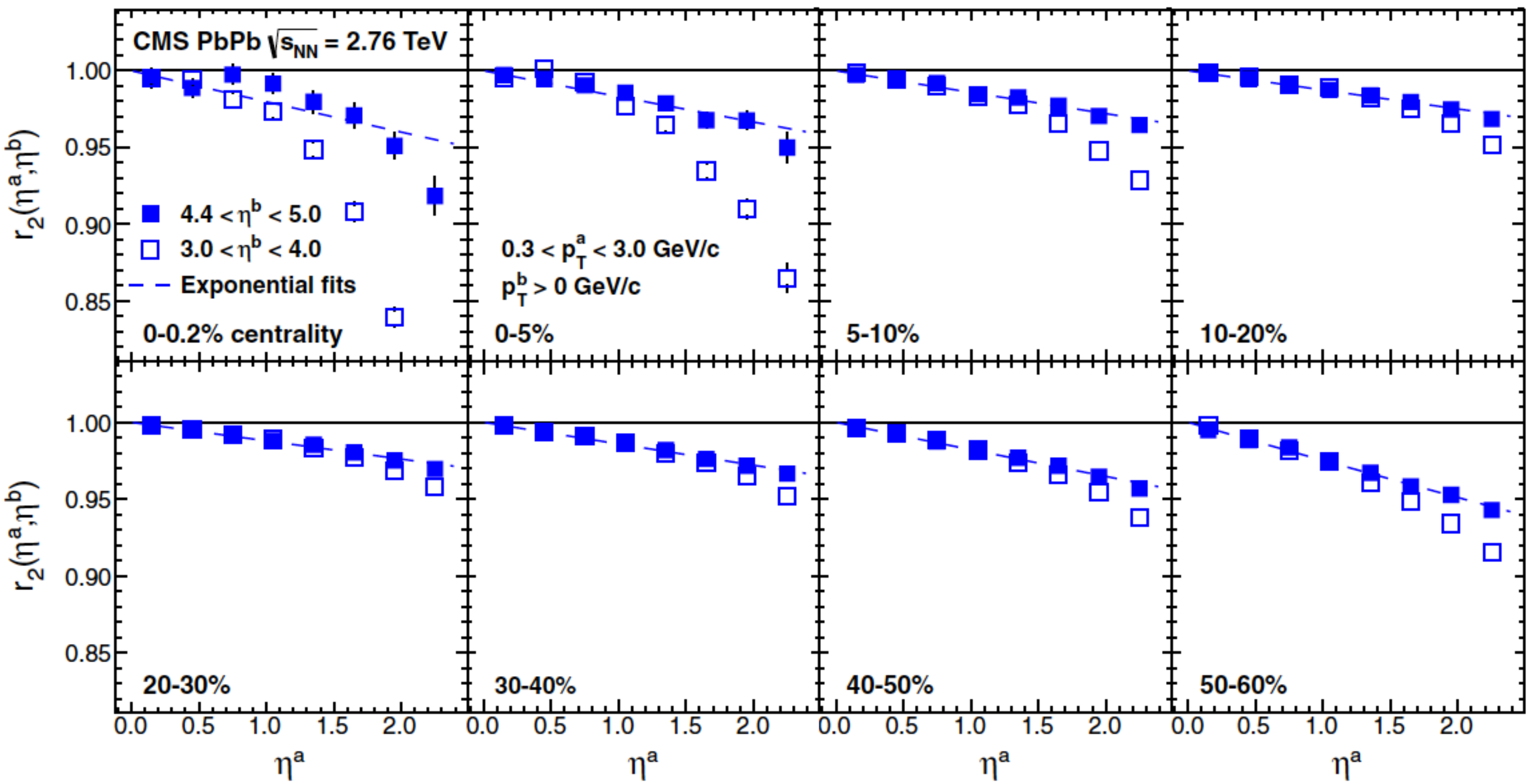


$$r_n(\eta^a,\eta^b) \equiv \frac{V_{n\Delta}(-\eta^a,\eta^b)}{V_{n\Delta}(\eta^a,\eta^b)} = \frac{\langle v_n(-\eta^a)v_n(\eta^b)\cos\{n[\Psi_n(-\eta^a)-\Psi_n(\eta^b)]\}\rangle}{\langle v_n(\eta^a)v_n(\eta^b)\cos\{n[\Psi_n(\eta^a)-\Psi_n(\eta^b)]\}\rangle}$$

- $r_n < 1$, indication of η dependent flow-vector fluctuations
  - $\frac{\langle v_n(-\eta^a)\, v_n(\eta^b)\rangle}{\langle v_n(\eta^a)\, v_n(\eta^b)\rangle} < 1$ — η dependent flow magnitude fluctuations
  - $\frac{\langle \cos[n(\Psi_n(-\eta^a)-\Psi_n(\eta^b))]\rangle}{\langle \cos[n(\Psi_n(\eta^a)-\Psi_n(\eta^b))]\rangle} < 1$ — η dependent flow angle fluctuations

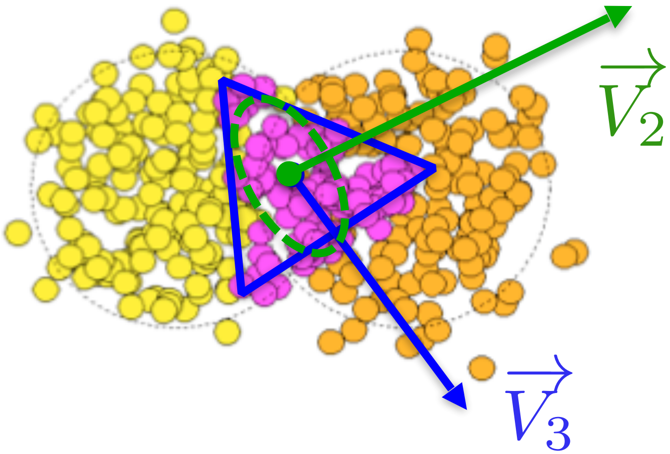
Factorization broken in η

CMS, PRC 92 (2015) 034911



- Deviation of r_2 from unity, increase as Δη increasing
  - further non-flow suppression in 2-particle correlations with large Δη gap?
  - indications of η dependent flow-vector fluctuations (angle and magnitude)

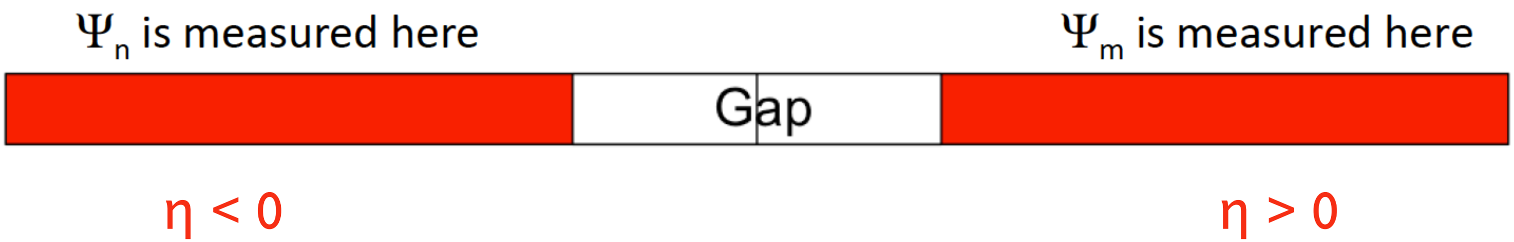
Correlations of flow-vector V_n and V_m

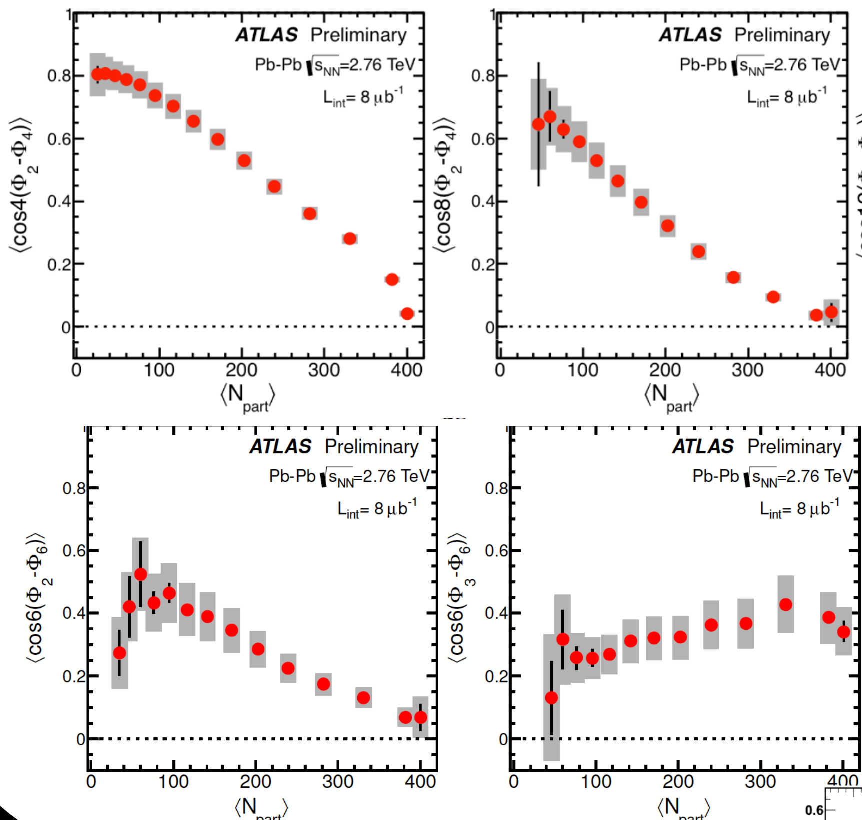


$$\overrightarrow{V_m} = v_m e^{-im\Psi_m}$$
$$\overrightarrow{V_n} = v_n\, e^{-in\Psi_n}$$

- Correlations between $\overrightarrow{V_n}$ and $\overrightarrow{V_m}$
  - Correlations between ψ_n and ψ_m
  - Correlations between v_n and v_m

Symmetry plane correlations



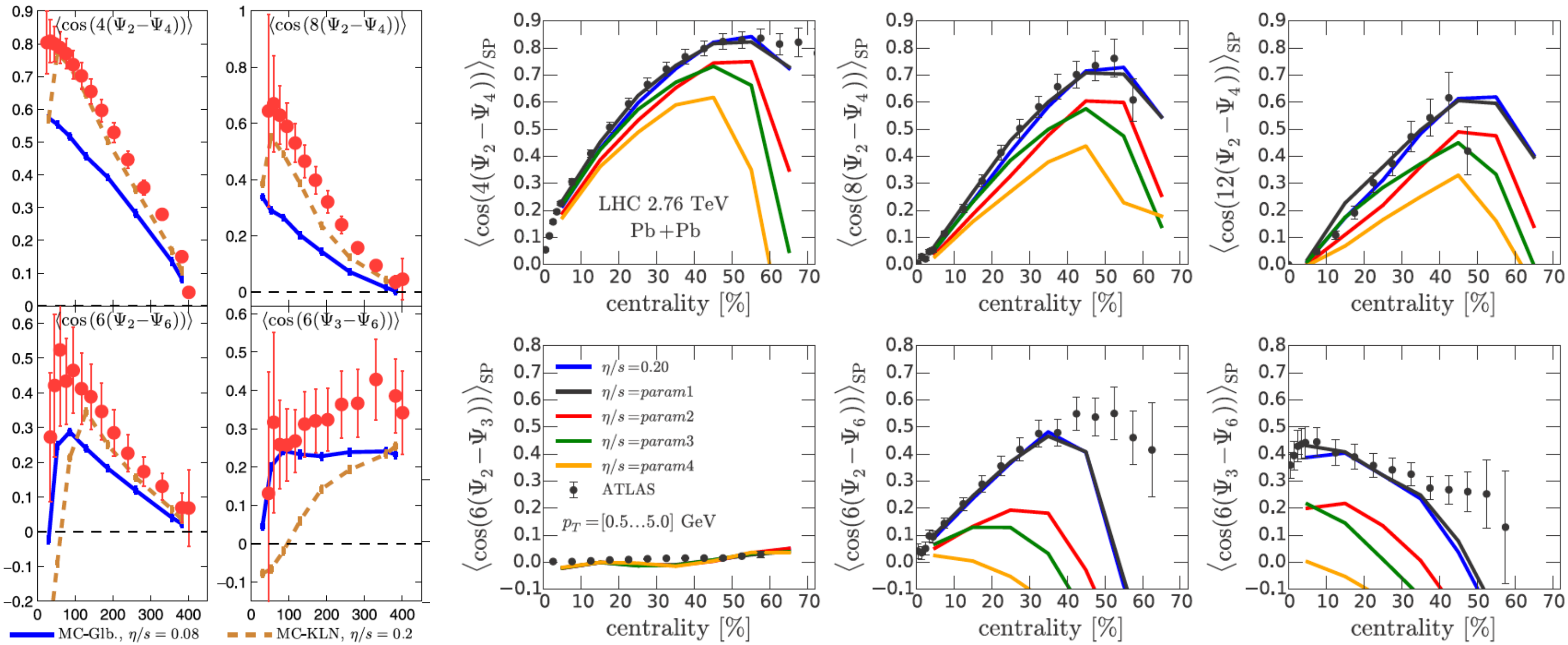


ATLAS
PRC 90, 024905 (2014)

- nonlinear hydrodynamic response in higher flow order flow

ψ_n and ψ_m

VISH2+1, PLB 717 (2012) 261 ATLAS: PRC 90, 024905 (2014) EKRT: PRC93, 024907 (2016)

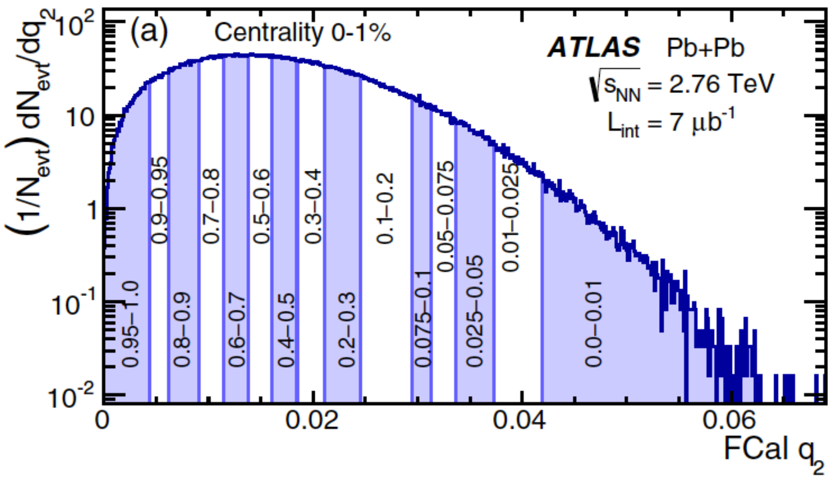


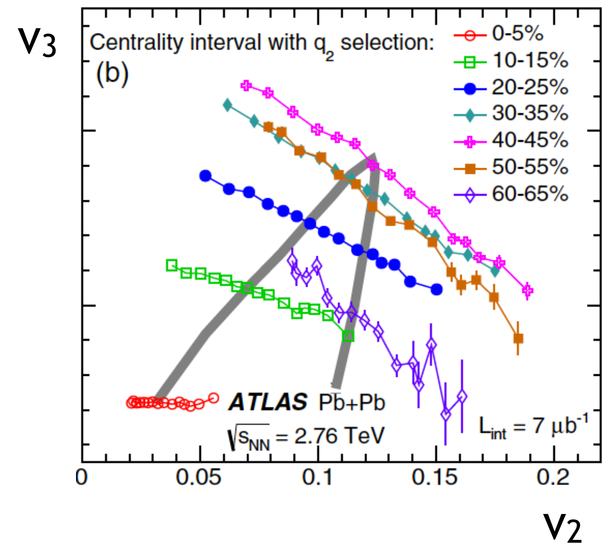
❖ symmetry plane correlations are sensitive to initial conditions and detailed setting of η/s(T)

- using multi-particle correlations instead of event-plane methods

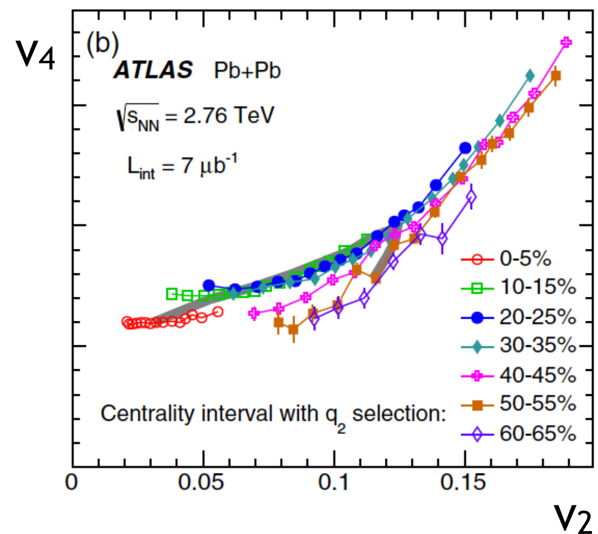
v_m and v_n correlations via ESE

ATLAS, PRC 92, 034903 (2015)





$$\boldsymbol{q}_m = q_m e^{im\Psi_m^{\text{obs}}} = \frac{\Sigma w_j e^{-im\phi_j}}{\Sigma w_j} - \langle \boldsymbol{q}_m \rangle_{\text{evts}}, \quad m = 2 \text{ or } 3,$$

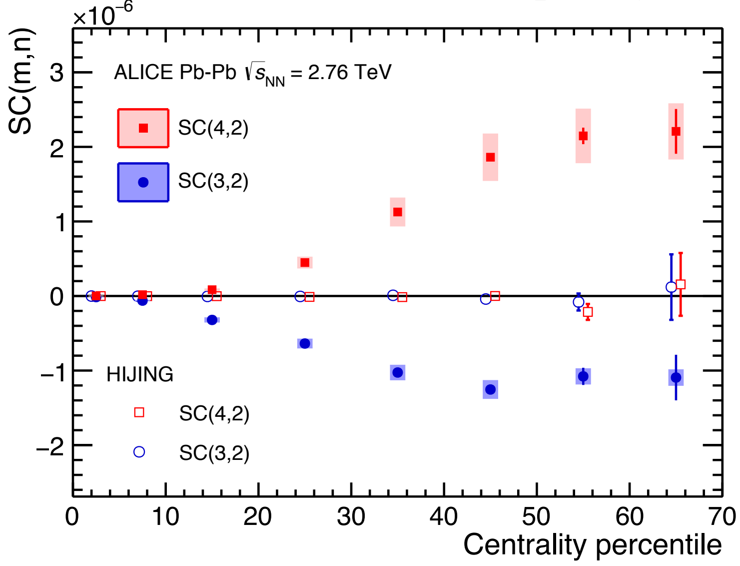


- Using Event-Shape selection with q_2, v_2 increases
  - -> v_3 decreases (anti-correlations)
  - -> v_4 increases (correlations)
  - -> qualitatively study the correlations of v_n and v_m

v_m and v_n via SC

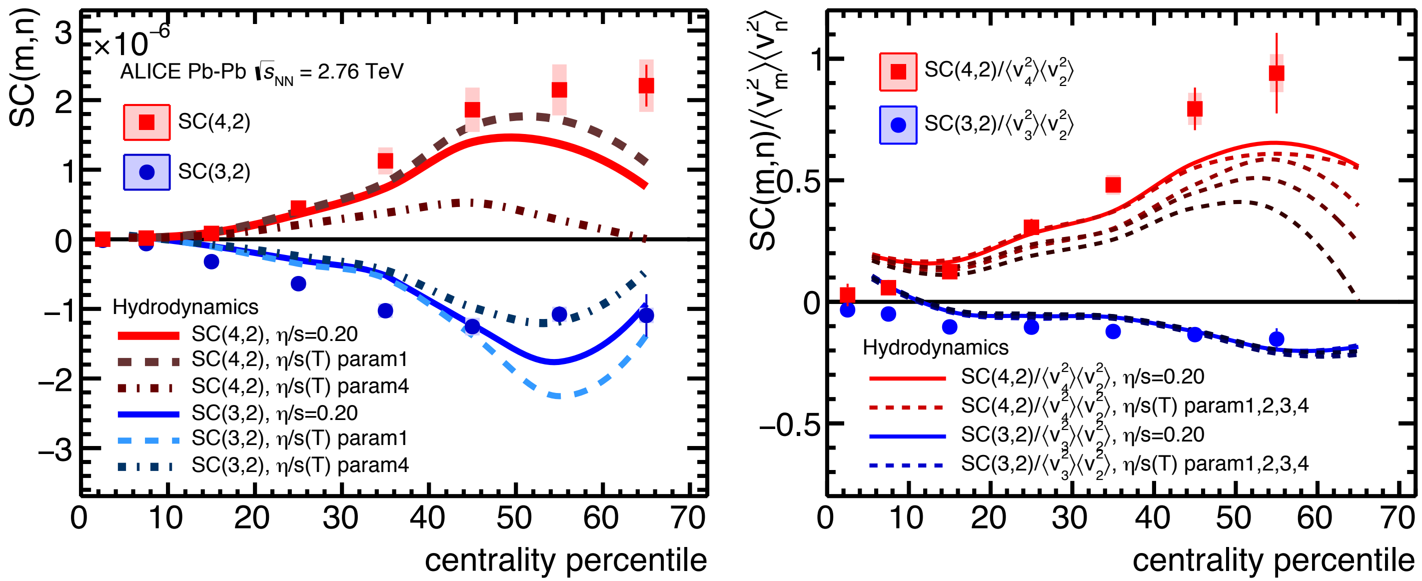
- New observable: ***SC(m,n)***, measures the correlations of v_m and v_n
  - $SC(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$
  - Details see: [Phys. Rev. C 89, 064904 (2014)]()
  - It is found that $\langle v_m^2 v_n^2 \rangle > 0$ and $\langle v_m^2 \rangle \langle v_n^2 \rangle > 0$ 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,
[arXiv:1604.07663](), accepted by PRL



Correlations between v_m and v_n

ALICE, arXiv:1604.07663, accepted by PRL   EKRT: PRC93, 024907 (2016)



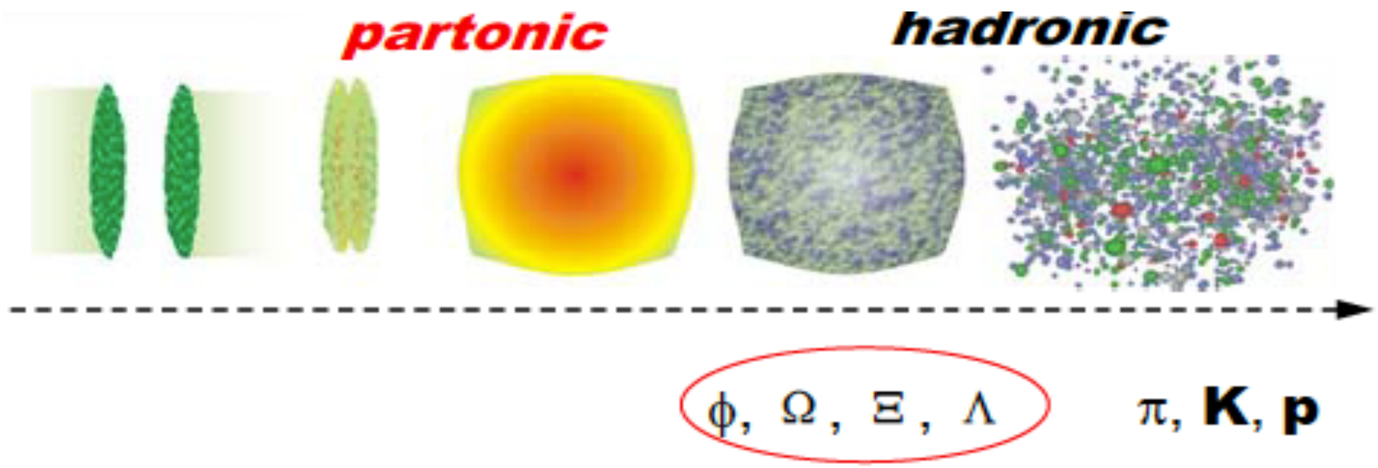
❖ Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations

- 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.

Identified particle flow

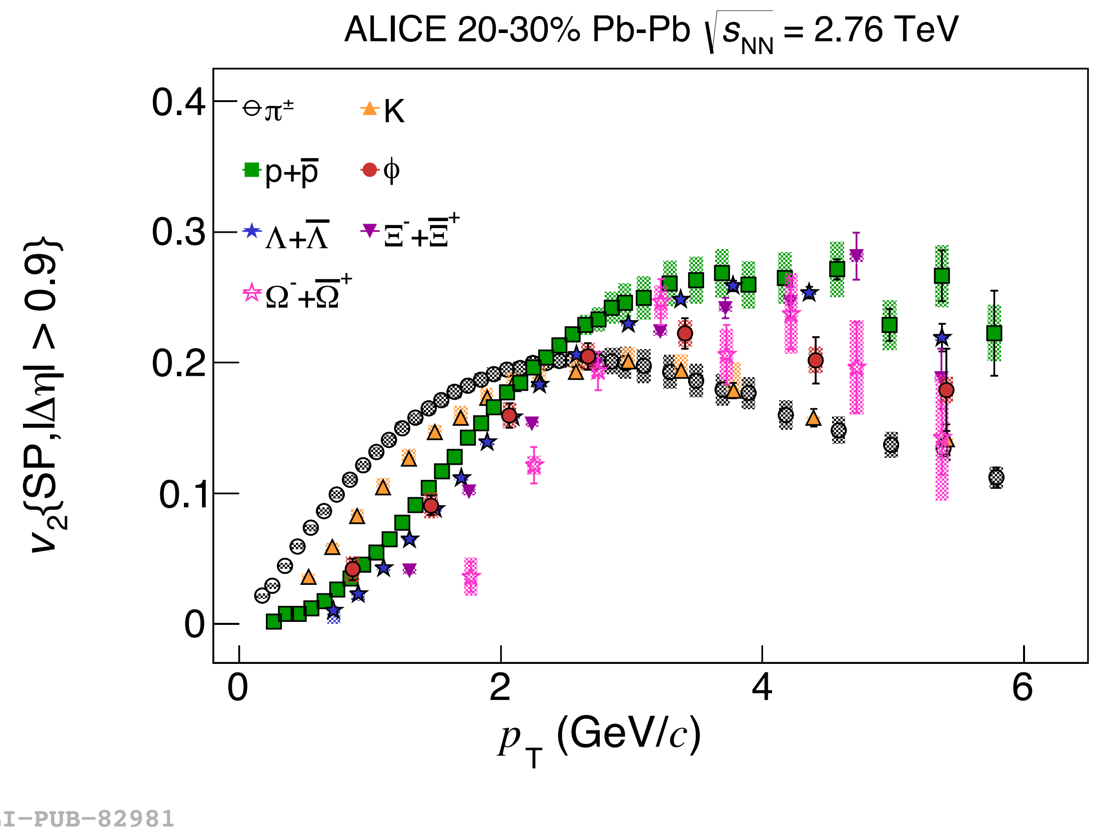
- Identified particle flow
  - further constraints of the initial state and collision dynamics
    - Anisotropy ε_n, EoS, η/s
  - (multi-)strange particles: small hadronic sections
    - insensitive to final hadronic interactions
    - additional information from early stage
  - indication of partonic collectivity
    - Number of Constituent Quark (NCQ) scaling



identified particle v_2 in Pb-Pb

ALICE Collaboration: JHEP 06 (2015) 190

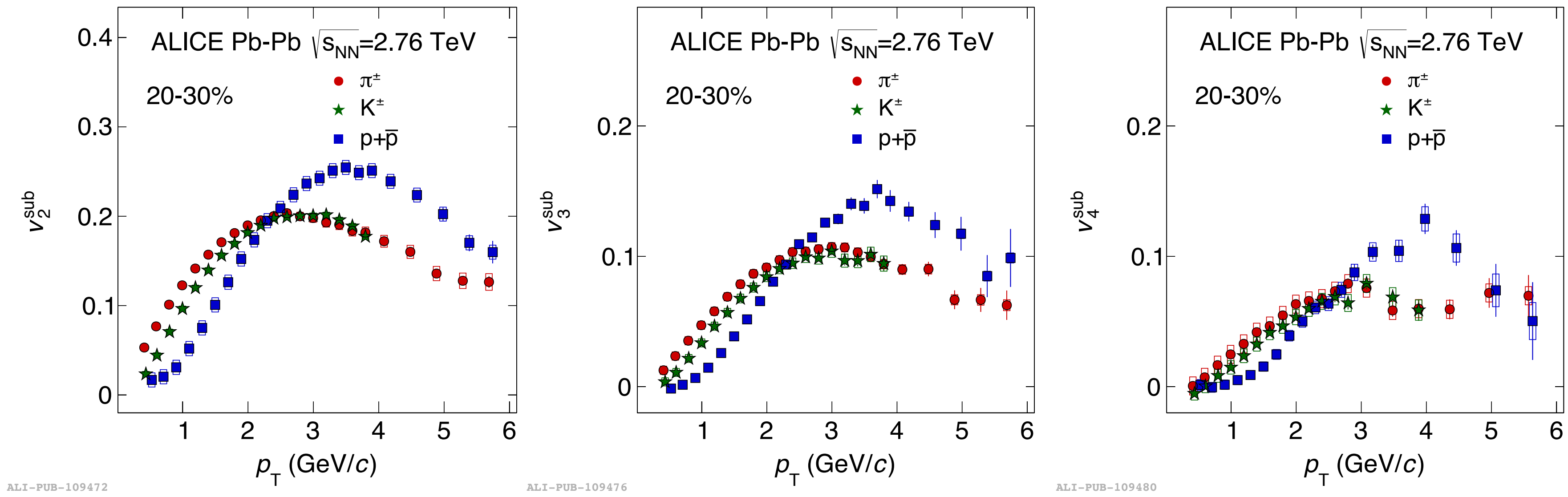
VISHNU: Phys. Rev. C 89, 034919 (2014)



- p_T < 2.5 GeV/c: mass ordering
- p_T >3 GeV/c: baryon-meson grouping

identified particle v_n in Pb-Pb

ALICE Collaboration, [arXiv:1606.06057]
submitted to JHEP

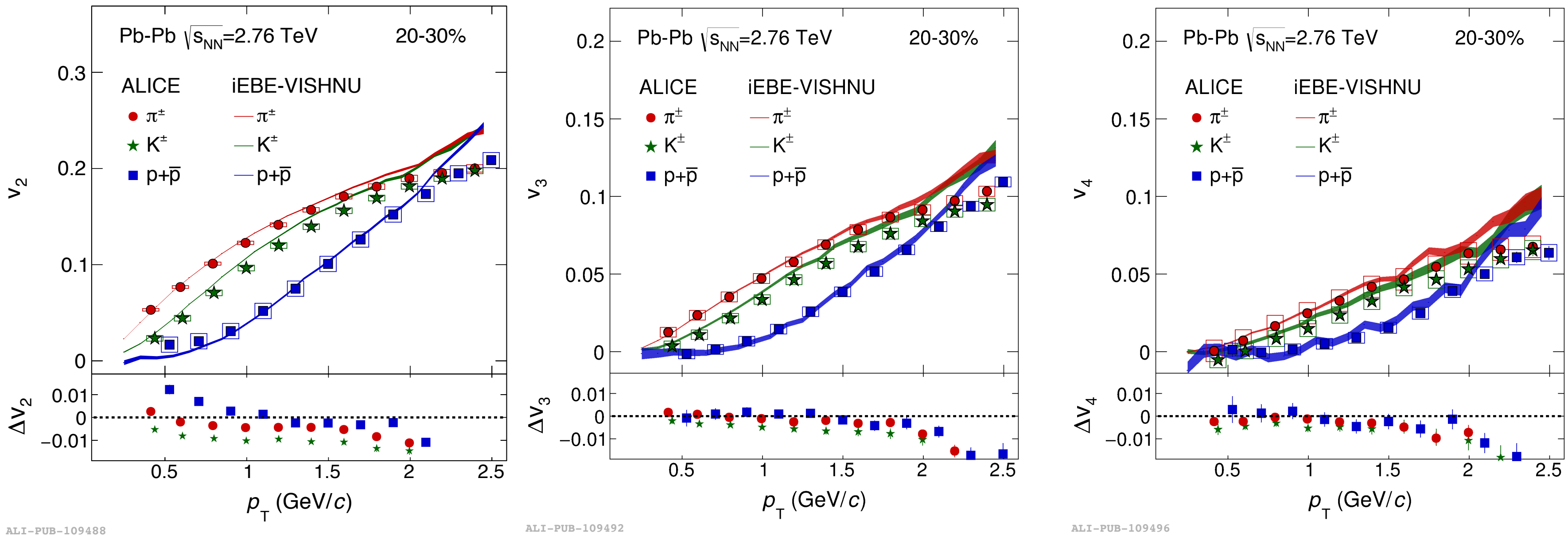


- Similar results observed for higher harmonic flow v_3 and v_4
  - mass ordering for p_T < 2.5 GeV/*c*
  - baryon-meson grouping for p_T >3 GeV/*c*

low p_T: v_n mass ordering

ALICE Collaboration, arXiv:1606.06057

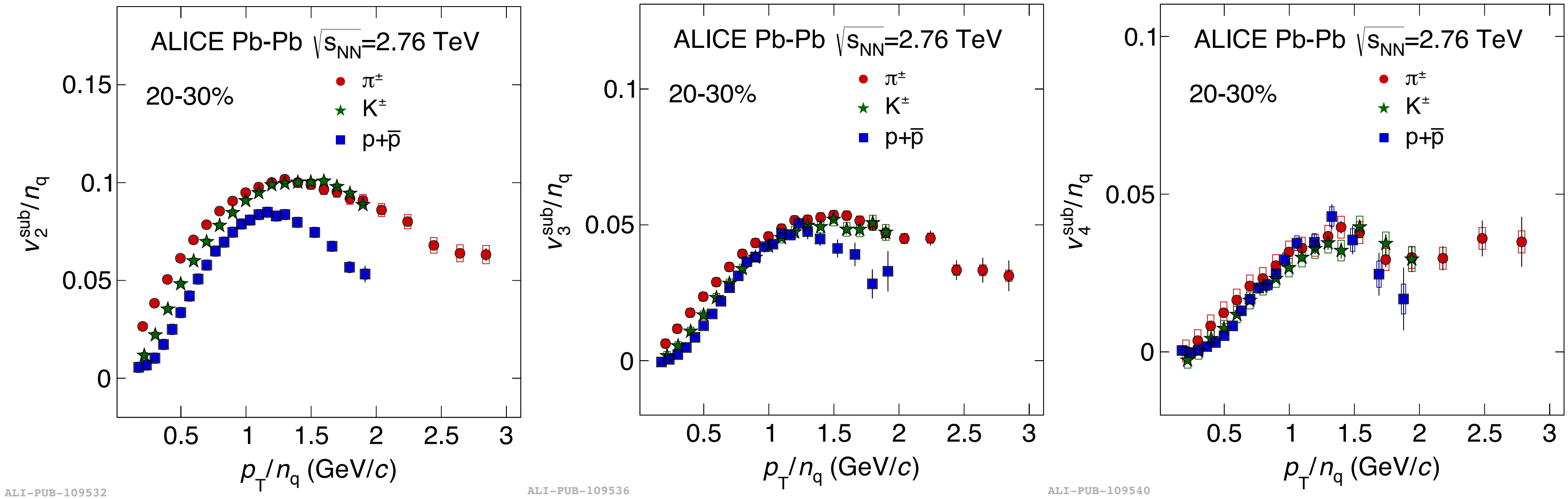
submitted to JHEP



- Hydrodynamic model (iEBE-VISHNU: AMPT-IC & η/s = 0.08)
  - reproduces the observed mass ordering of v_n for p_T <2 GeV/c
  - describes the measurements for v_n within 5%

intermediate p_T: v_n NCQ scaling

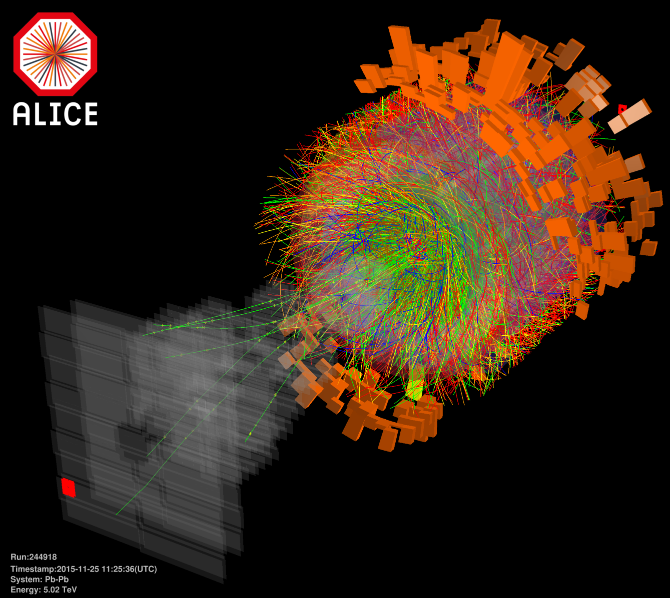
ALICE Collaboration, arXiv:1606.06057
submitted to JHEP

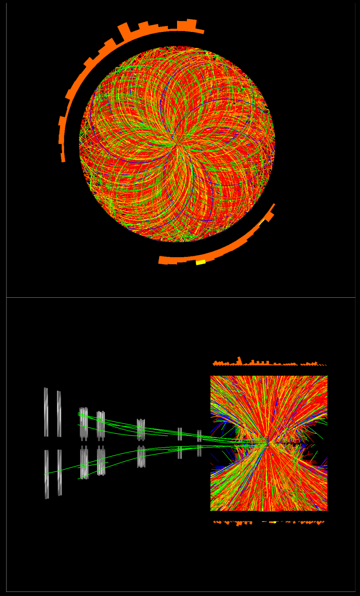


- universal number of constituent quark (NCQ) scaling observed at RHIC
- only approximate within ~20% at the LHC, works better for higher harmonics than v_2

From 2.76 to 5.02 TeV

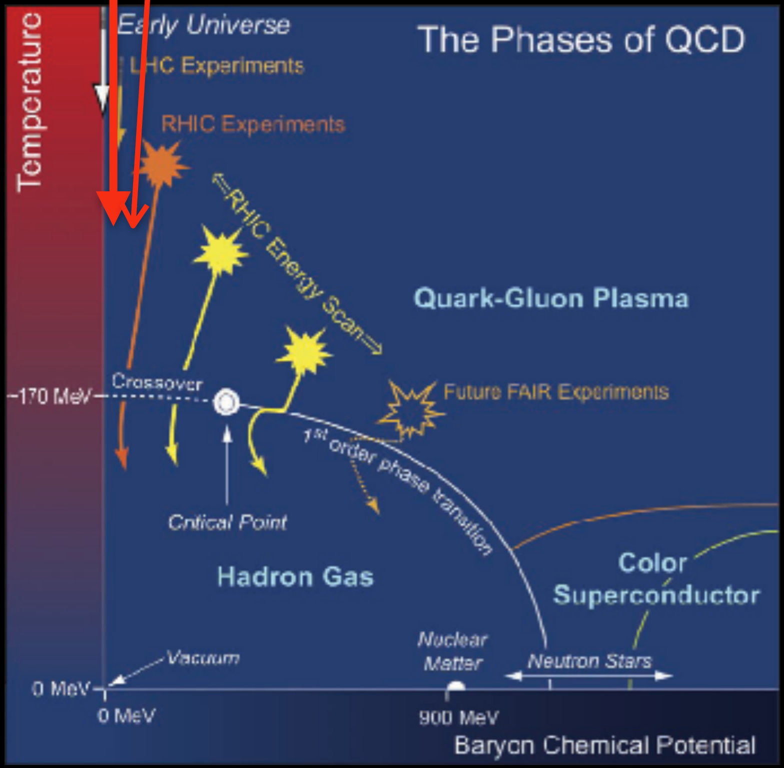
5.02 TeV Pb-Pb collisions





5.02 TeV

2.76 TeV

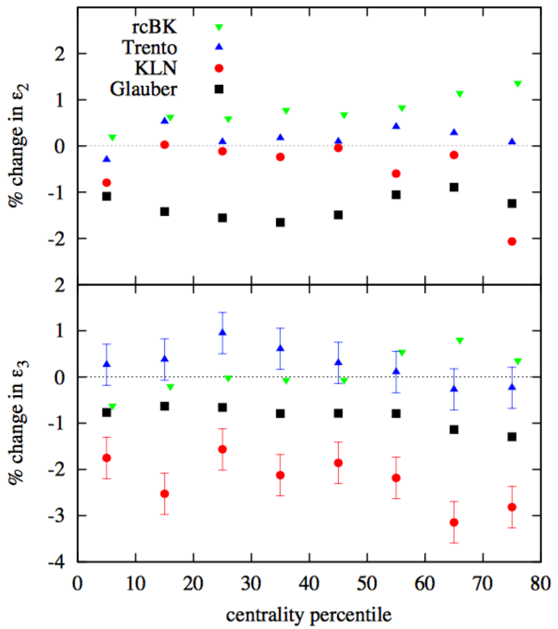


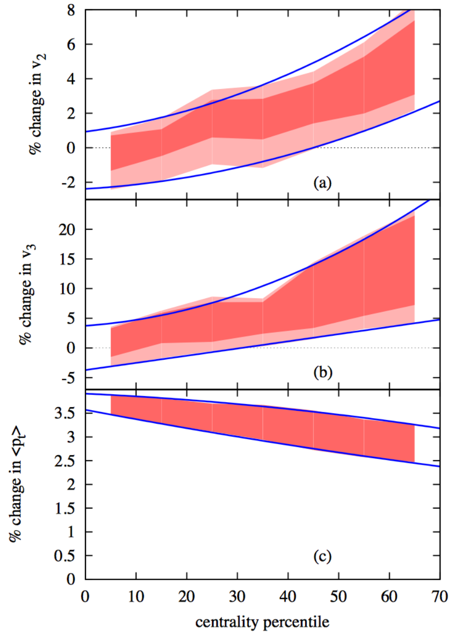
- **Pb-Pb 2.76 TeV: 2010, 2011**
- **Pb-Pb 5.02 TeV: 2015**

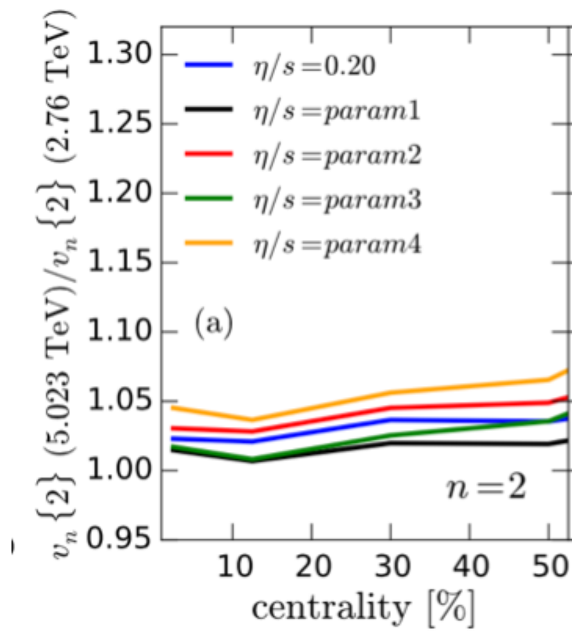
Theoretical predictions

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

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





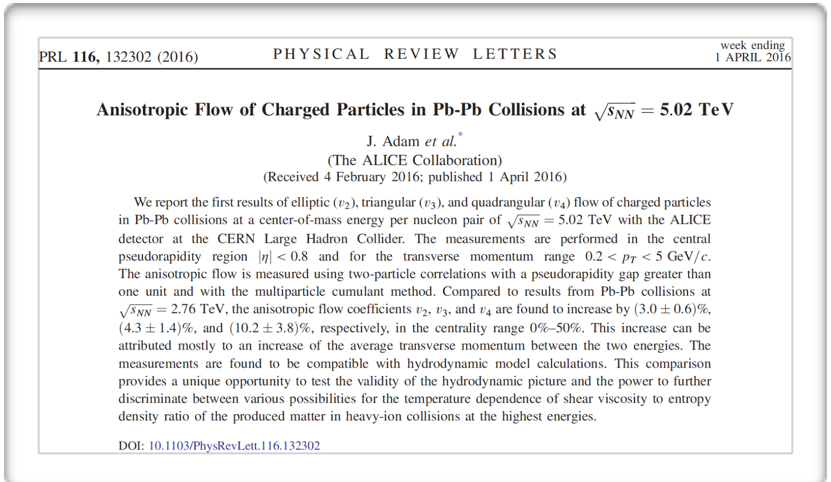


- For all centralities and every model, the change from 2.76 TeV to 5.02 TeV is between -2% and 2% for ε_2 and between -3% and 1% for ε_3.
- v_2 and v_3 should see the largest increases in peripheral collisions, while in central collisions they will show little increase
- The increasing of v_n from 2.76 TeV to 5.02 TeV is sensitive to the detailed setting of η/s(T), a new constraint on the η/s(T)

Anisotropic flow at 5.02 TeV

ALICE Collaboration PRL 116, 132302 (2016)

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



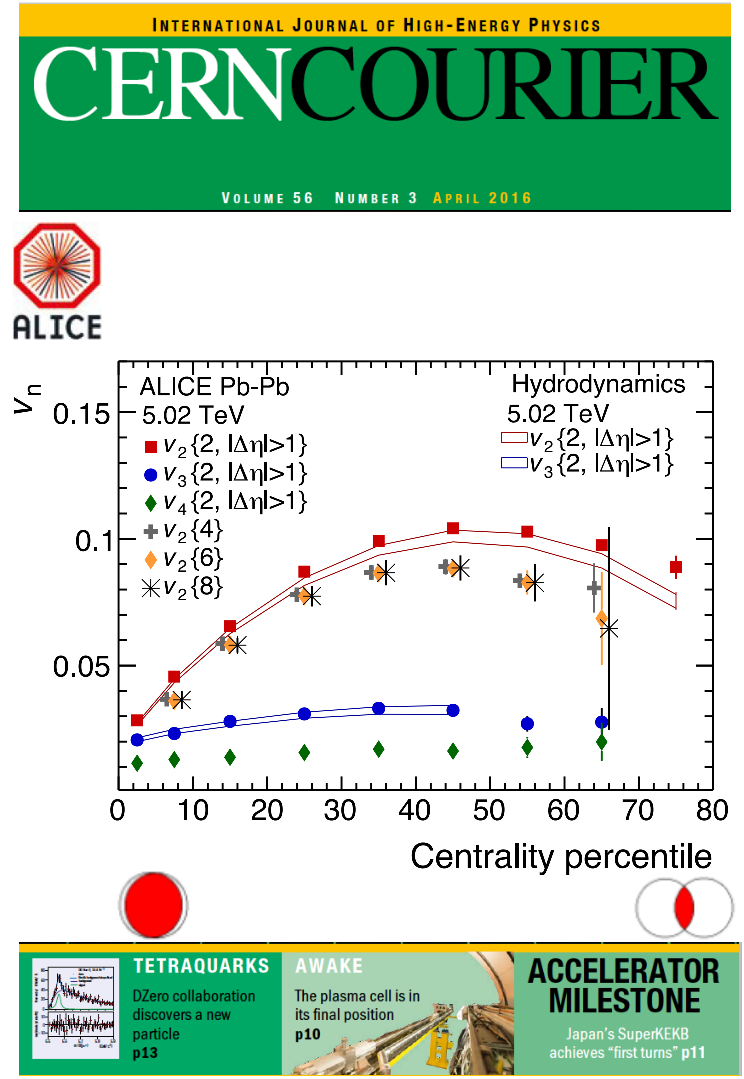
PRL **116,** 132302 (2016) PHYSICAL REVIEW LETTERS week ending 1 APRIL 2016

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.

DOI: 10.1103/PhysRevLett.116.132302

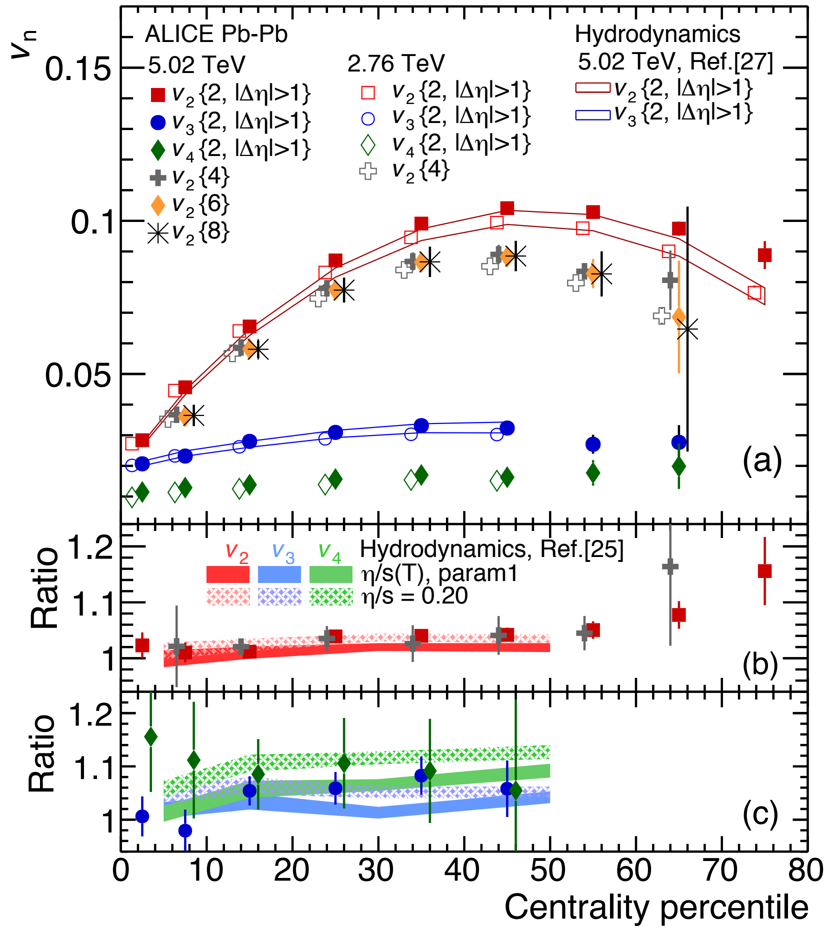


- Anisotropic flow v_n
  - agrees with hydrodynamic predictions with the best knowledge of initial conditions and η/s.
  - provides a unique opportunity to test the validity of the hydrodynamic framework.

v_n from 2.76 to 5.02 TeV

ALICE Collaboration
PRL 116, 132302 (2016)

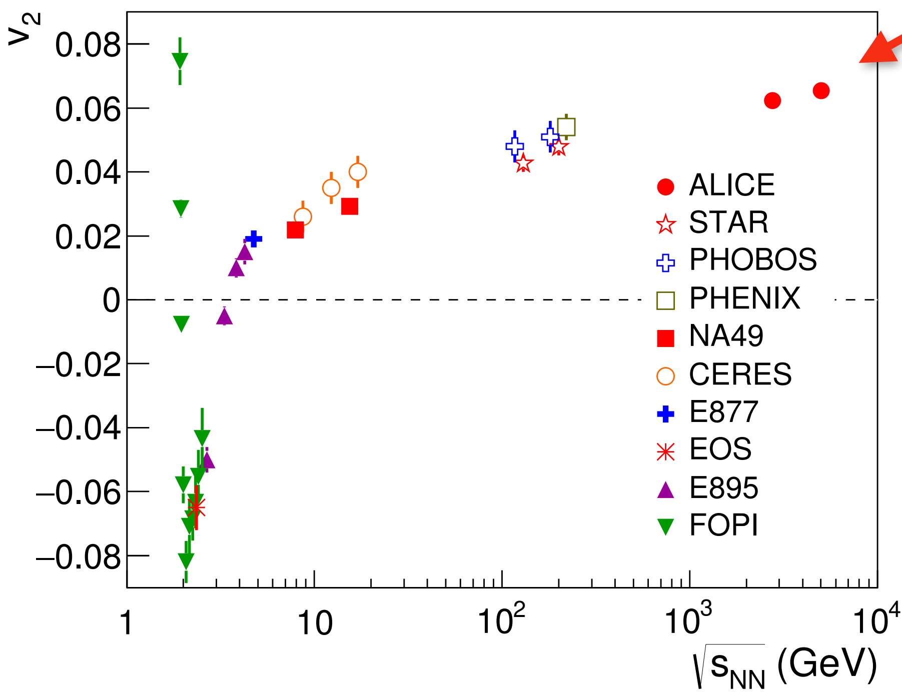
Ref [27]: **J. Noronha-Hostler et al., PRC93 (2016) 034912**
Ref [25]: **H. Niemi et al, PRC 93, 014912 (2016)**



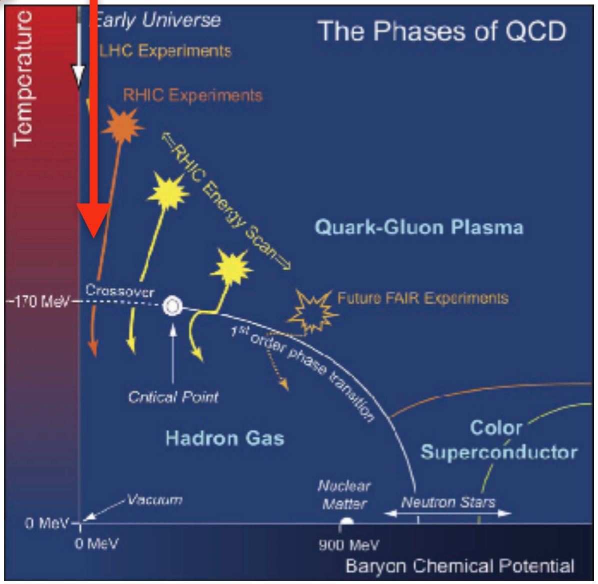
- The anisotropic flow coefficients v_2, v_3 and v_4 are found to increase by (3.0±0.6)%, (4.3±1.4)% and (10.2±3.8)%, respectively, in the centrality range 0-50%, mainly due to the increase of $\langle p_T \rangle$
- None of the ratios 5.02 TeV/2.76 TeV of flow harmonics exhibit a significant centrality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

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

ALICE Collaboration, PRL 116, 132302 (2016)



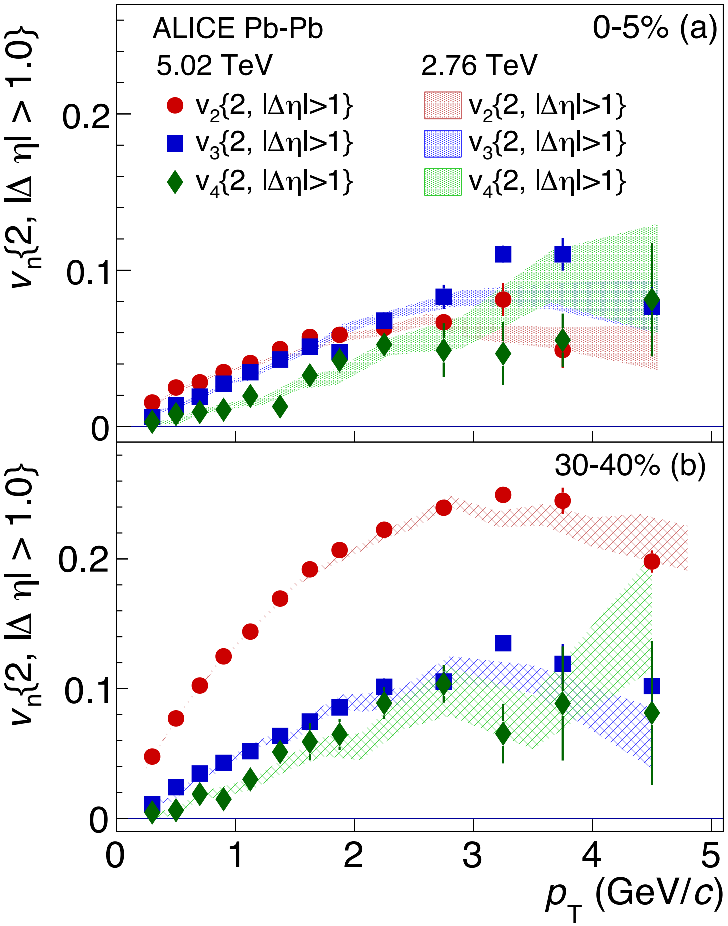
Pb-Pb 5.02 TeV



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

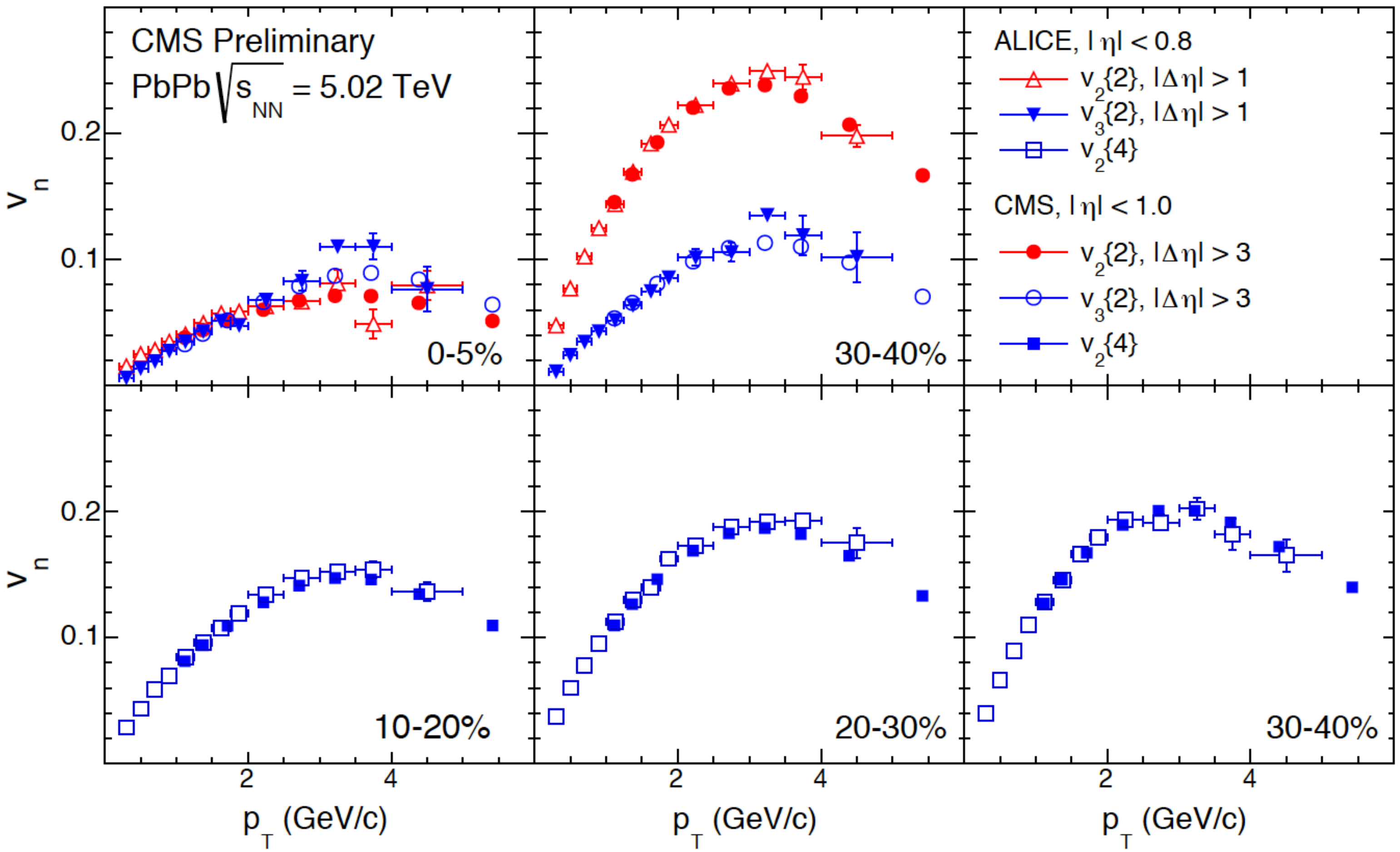
p_T differential flow

ALICE Collaboration
PRL 116, 132302 (2016)



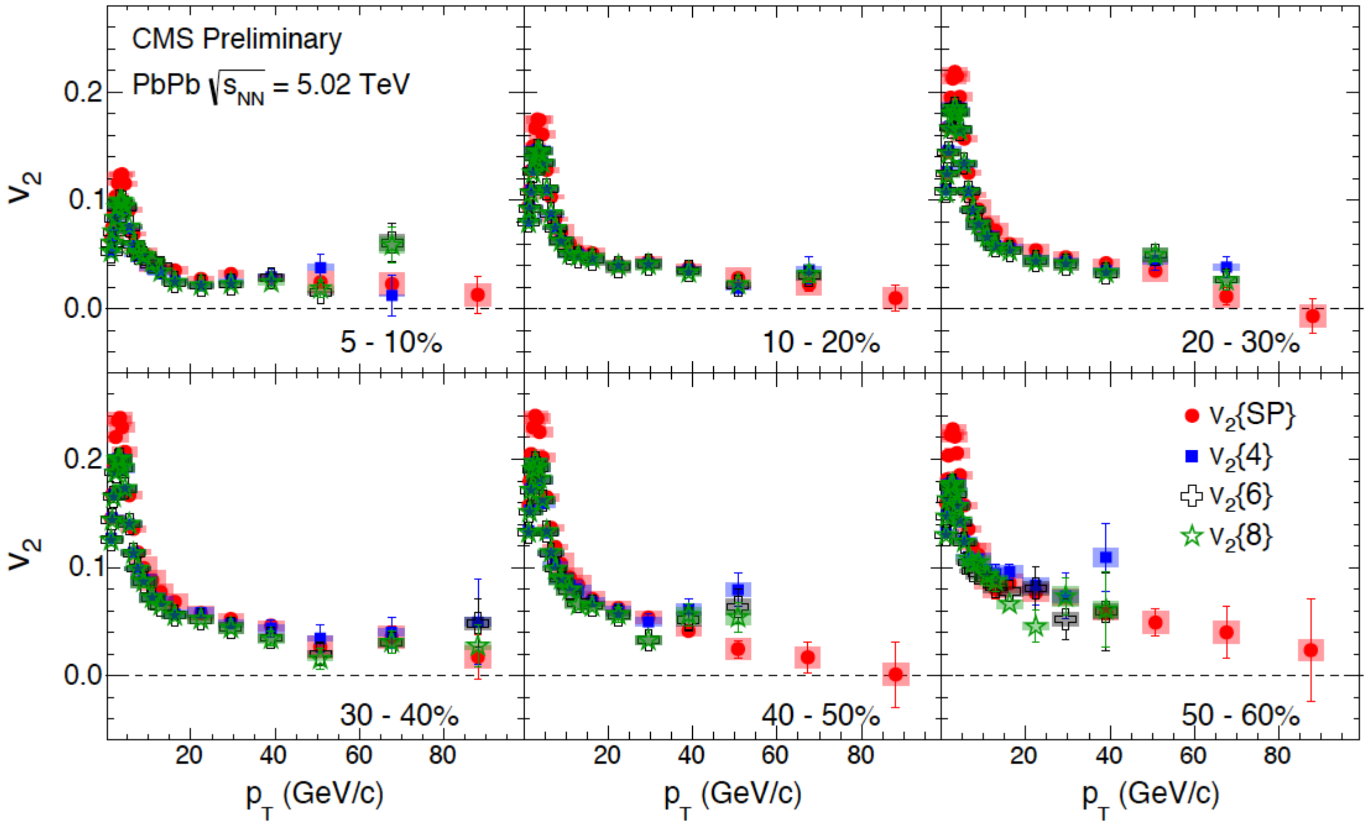
- For the 0–5% centrality class, at $p_T > 2$ GeV/c, $v_3\{2\}$ is observed to be larger than $v_2\{2\}$, while $v_4\{2\}$ is compatible with $v_2\{2\}$
- For the 30–40% centrality class $v_2\{2\}$ is higher than $v_3\{2\}$ and $v_4\{2\}$ for the entire p_T range measured: no crossing
- Comparable results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

Comparisons between experiments



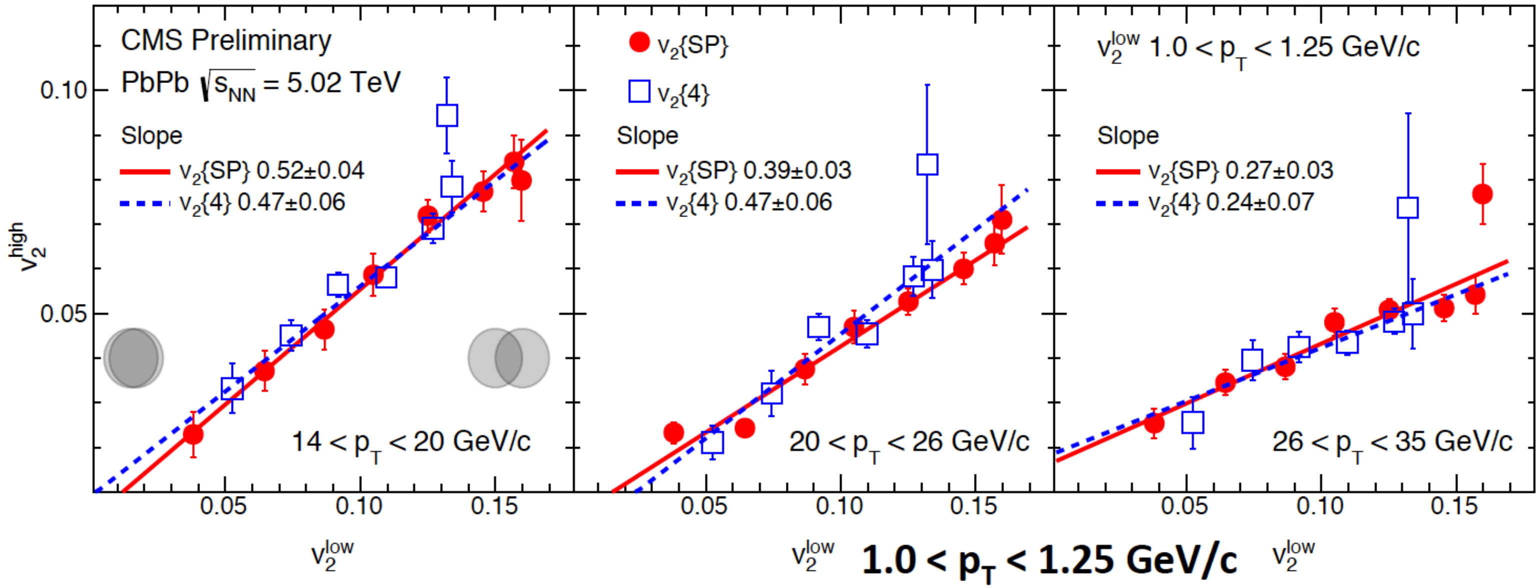
❖ Good agreements between ALICE and CMS.

v_2 at high p_T



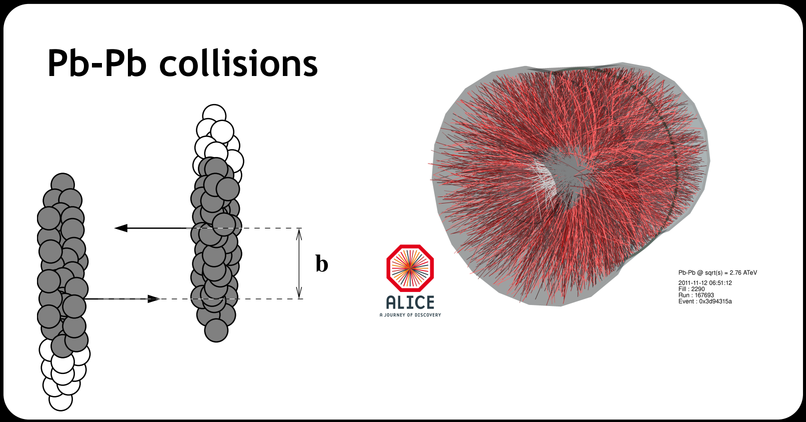
- measure multi-particle $v_2\{4,6,8\}$ up to 100 GeV/c
  - $v_2\{4,6,8\}$ seems converge with $v_2\{SP\}$ at high pT
  - Collective nature of high p_T particles

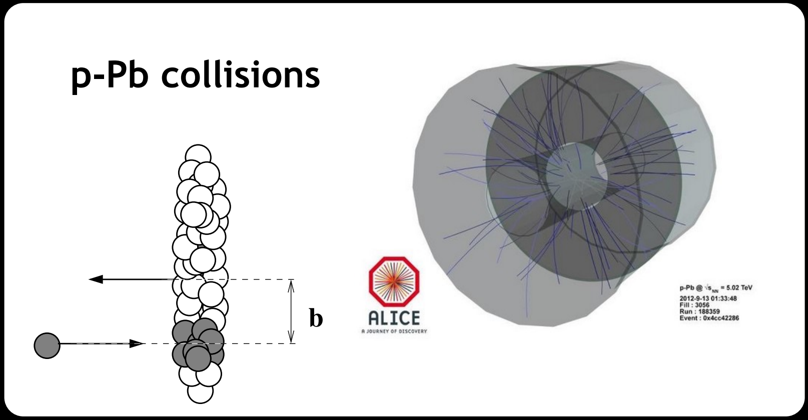
v_2 from low and high p_T

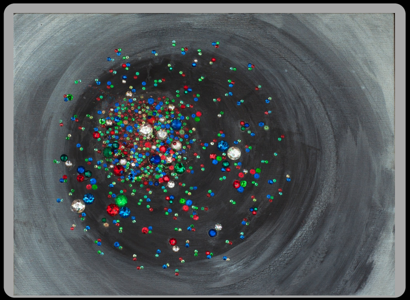


- High p_T v_2 strongly correlated with low p_T v_2
  - Suggest on of same origin of the correlations (?)
- Slope decrease while increasing p_T

QGP in small systems?







Hot Quark-Gluon Plasma (QGP)

QGP ??

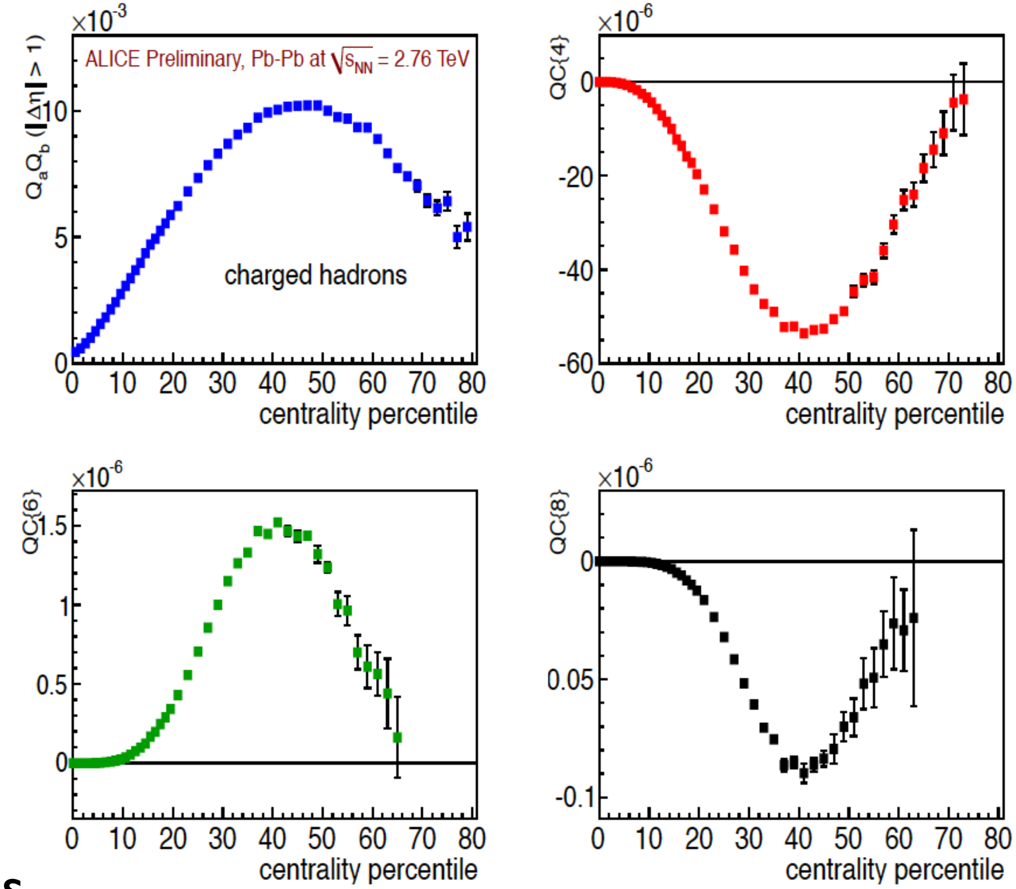
multi-particle cumulants in AA

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

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

$$QC\{6\} = v_n^6$$

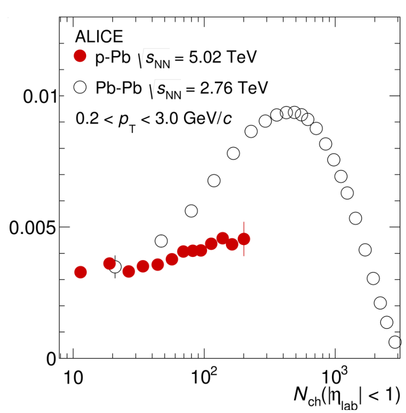
$$QC\{8\} = -v_n^8$$

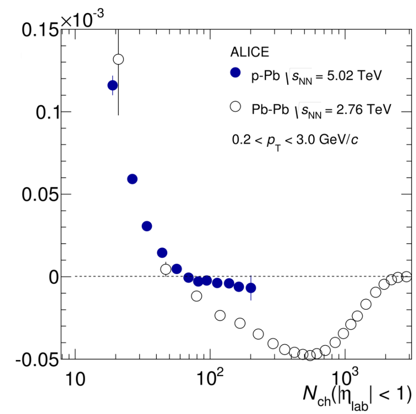


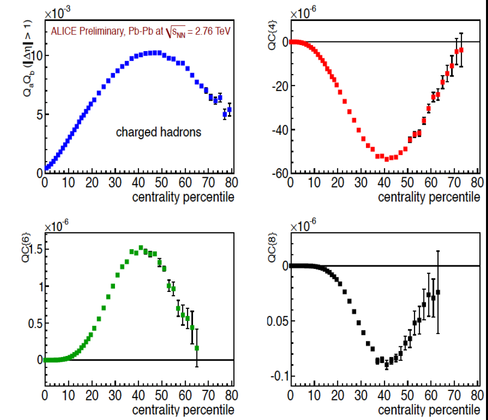
- Lesson from AA collsions, Flow signal:
  +, -, +, - signs for cumulants

multi-particle cumulants in AA, pA and pp

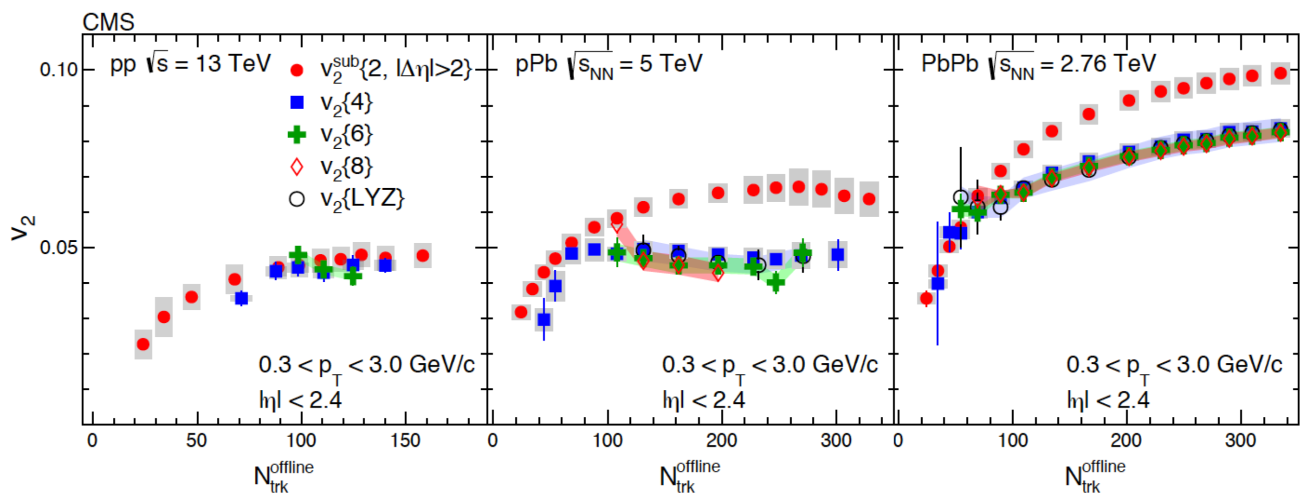
ALICE
PRC 90, 054901 (2014)







CMS:
1606.06198

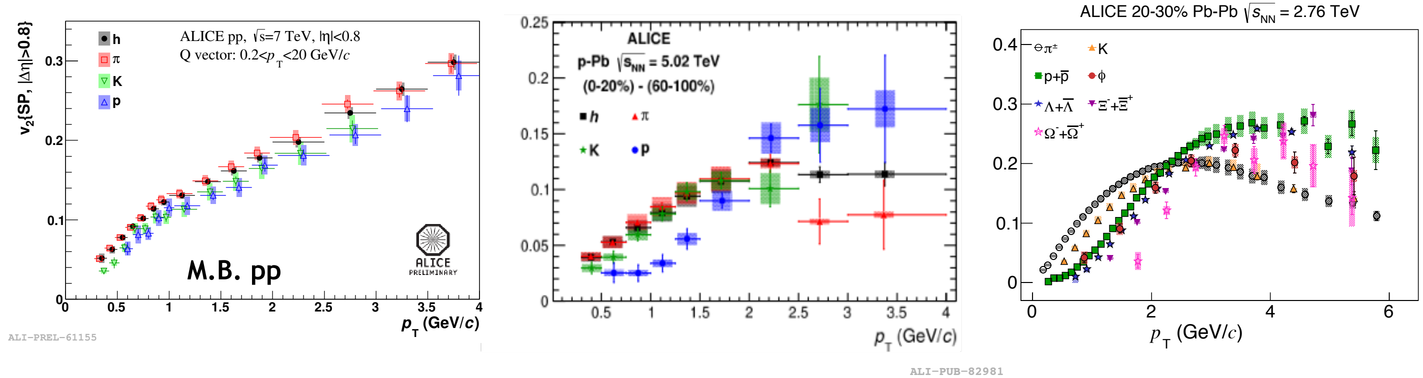


❖ $v_2\{2\} \geq v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{LYZ, \infty\}$

- Collectivity in any hadronic systems (?)

identified particle v_2 in pp, pA, AA

ALICE,
JHEP 06 (2015) 190
PLB 726 (2013) 164



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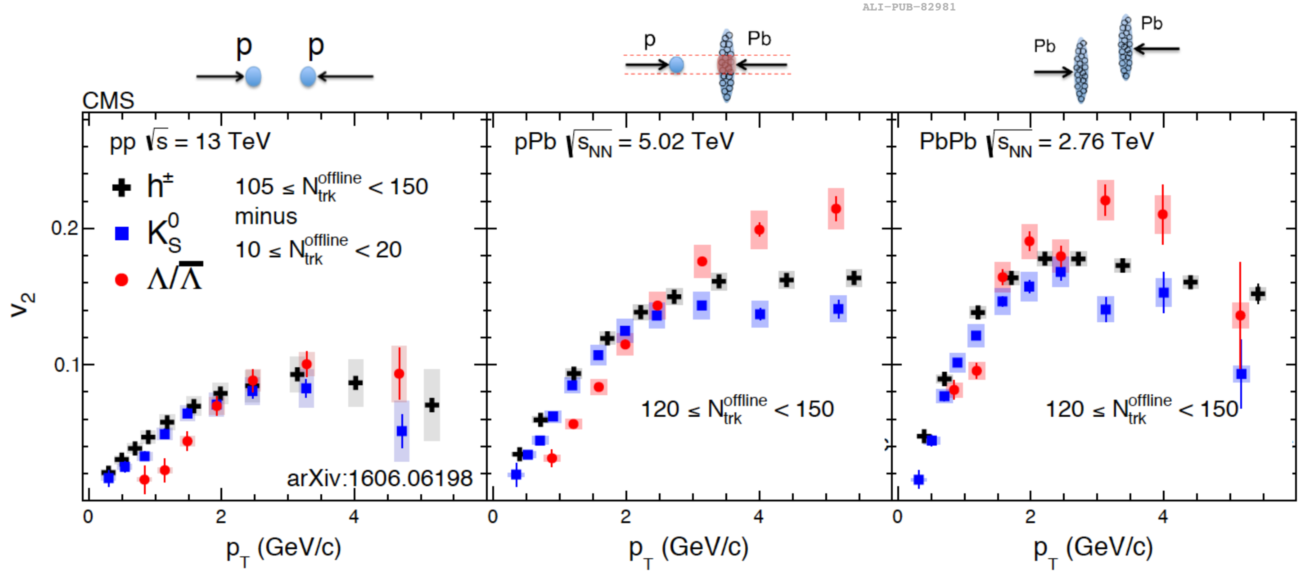


- Anisotropic flow of identified particles
  - mass ordering at low p_T
  - NCQ scaling at immediate p_T
  - Evidence of collectivity in small system ?

Summary

- The anisotropic flow measured at the LHC open new possibilities for investigation of the initial conditions in heavy-ion collisions.

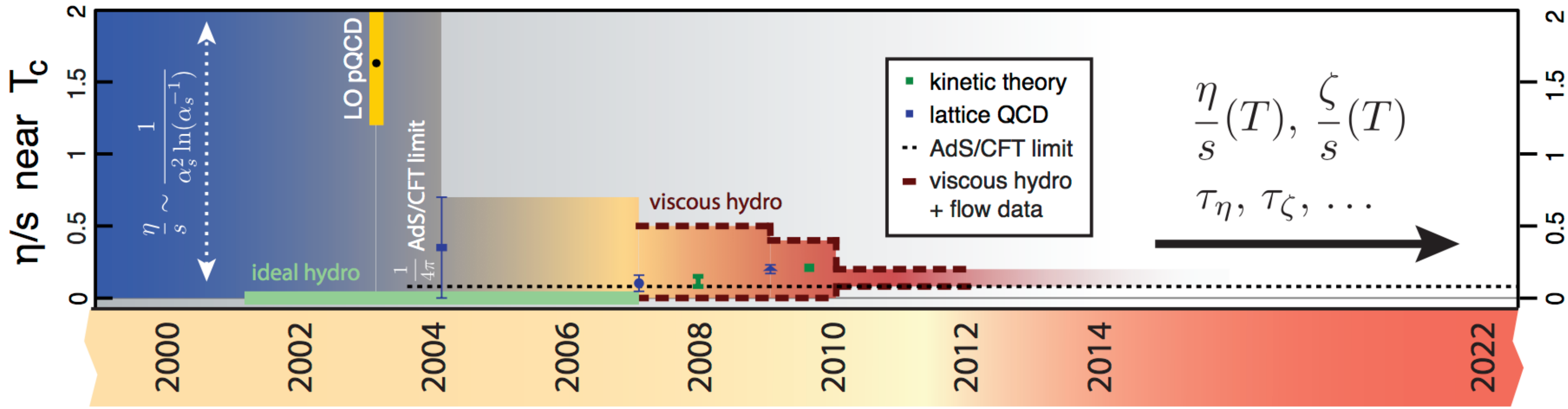
	MC-Glauber	*MC-KLN*	*MC-AMPT*	*IP-Glasma*	*EKRT*
v_2	✓	✓	✓	✓	✓
v_n	✗	✗	✓	✓	✓
v_n-v_m	✗	✗	✗	?	✗
Ψ_n-Ψ_m	✗	✗	?	✓	✓

- The LHC RUN2 program provides new opportunities
  - Pb-Pb 5.02 TeV, p-Pb 8 TeV, 5.02 TeV, pp 13 TeV
  - the anisotropic flow measurements will shed new light into the properties of produced QGP.

Thanks for your attention!

Summary

- The anisotropic flow measured at the LHC open new possibilities for investigation of the eta/s of the created matter in heavy-ion collisions.



- The LHC RUN2 program provides new opportunities
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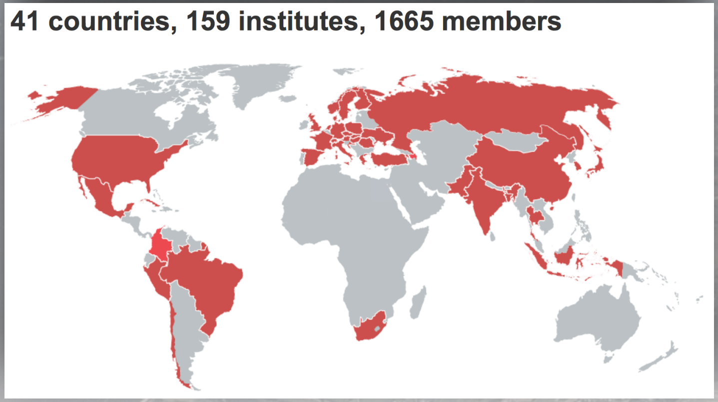
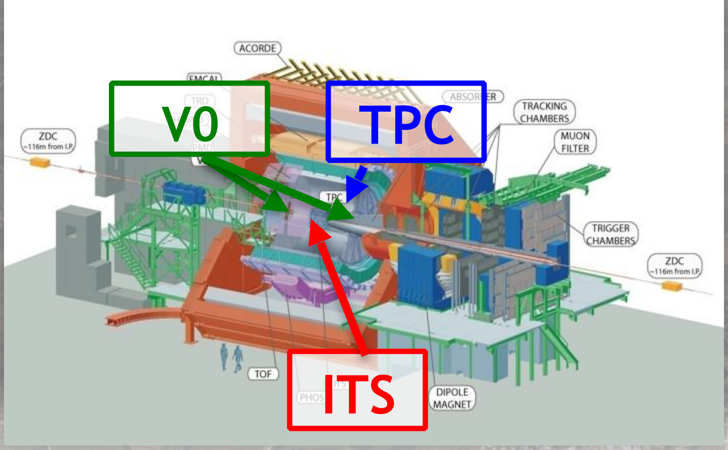
Thanks for your attention!

	MC-Glauber	*MC-KLN*	*MC-AMPT*	*IP-Glasma*	*EKRT*
v_2	✓	✓	✓	✓	✓
v_n	✗	✗	✓	✓	✓
v_n-v_m	✗	✗	✗	?	✗
ψ_n-ψ_m	✗	✗	?	✓	✓
χ_n	✗	✗	?	?	?

backup

ALICE Collaboration





❖ Detectors used:

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

❖ Data Samples:

- 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)?

Anisotropic flow at 5.02 TeV

ALICE Collaboration
PRL 116, 132302 (2016)

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

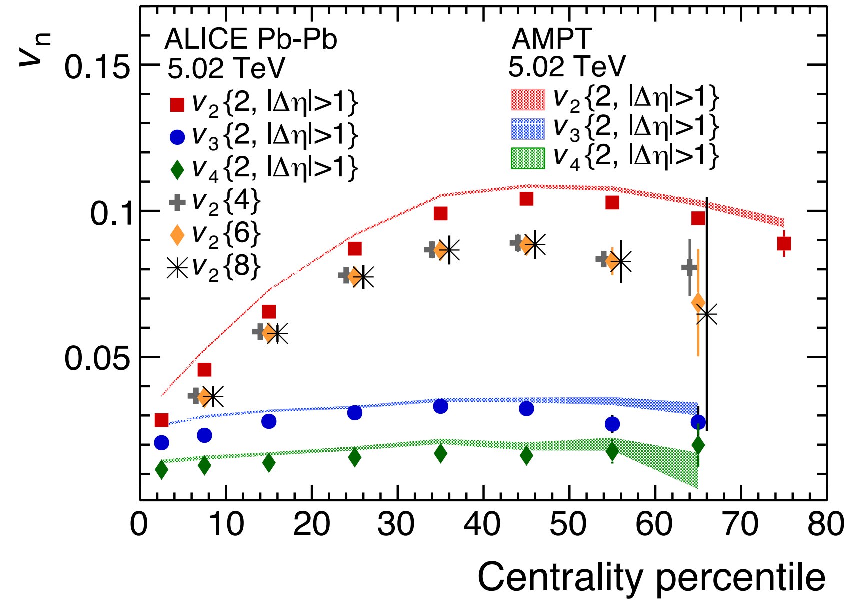
Anisotropic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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 $(3.0 \pm 0.6)\%$, $(4.3 \pm 1.4)\%$, 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.

DOI: 10.1103/PhysRevLett.116.132302

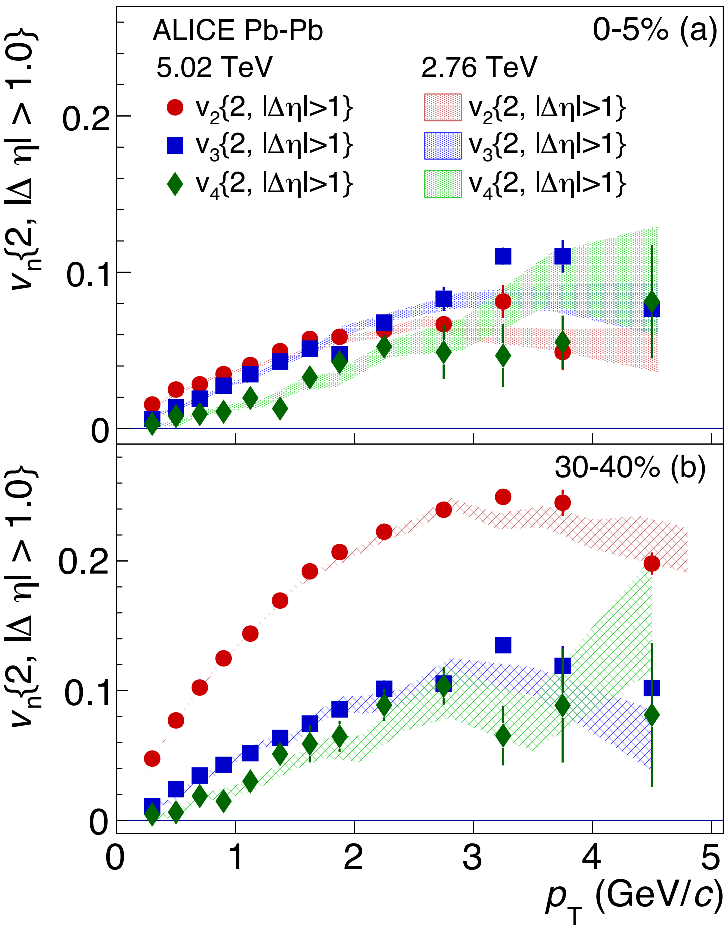
AMPT: **Z. Feng et al. (Wuhan group), arXiv:1606.02416**



- 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

p_T differential flow (I)

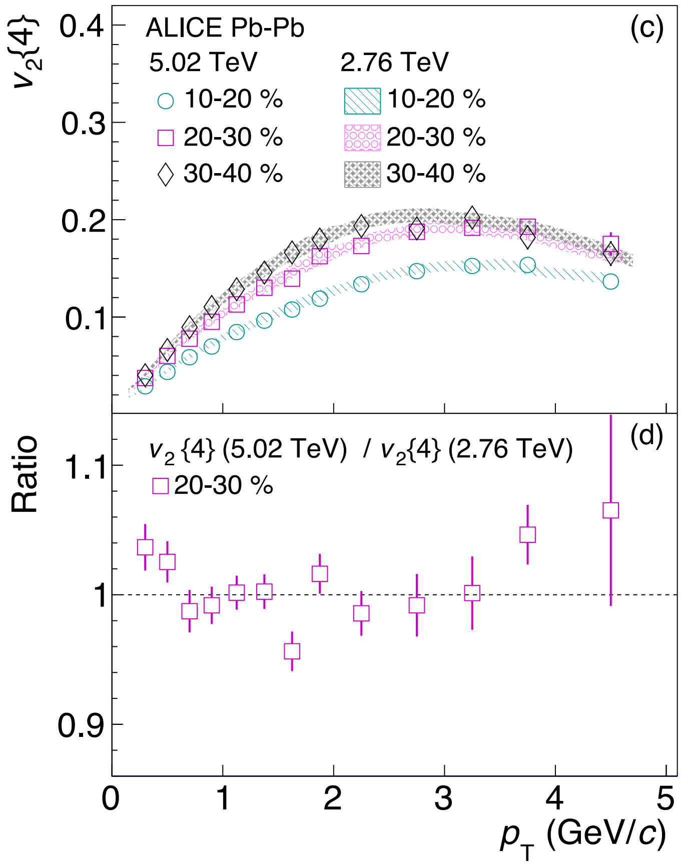
ALICE Collaboration
[PRL 116, 132302 (2016)]



- 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)



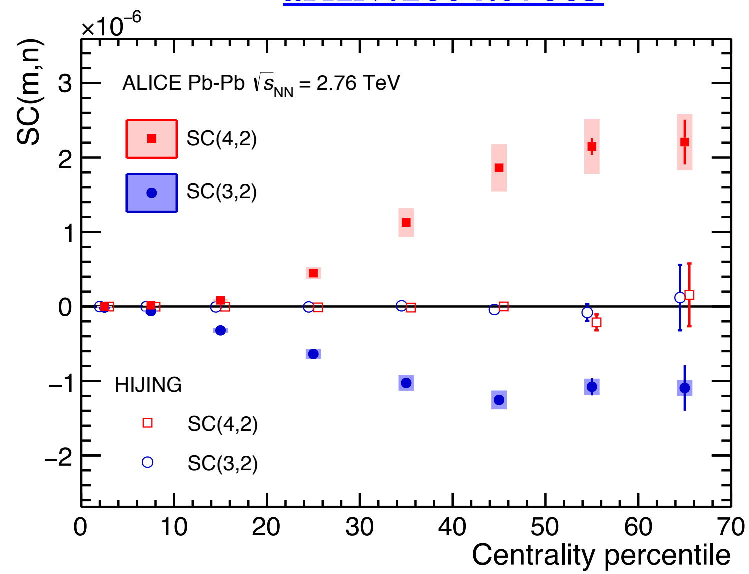
- $v_2\{4\}$ decreases from mid-central to central collisions over the entire p_T range
- ratio of $v_2\{4\}$ (5.02 TeV)/$v_2\{4\}$ (2.76 TeV) indicates there is no change in the p_T dependence between both energies

Correlations between v_m and v_n

❖ New observable: ***SC(m,n)***, measures the correlations of v_m and v_n

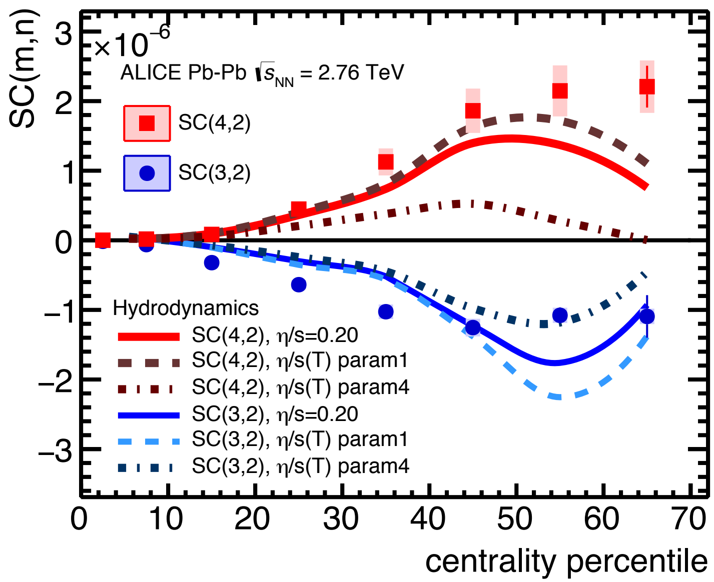
- $SC(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$
- Details see: [Phys. Rev. C 89, 064904 (2014)]
- It is found that $\langle v_m^2 v_n^2 \rangle > 0$ and $\langle v_m^2 \rangle \langle v_n^2 \rangle > 0$ in HIJING, but SC(m,n) are compatible with zero
  - SC measurements 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.

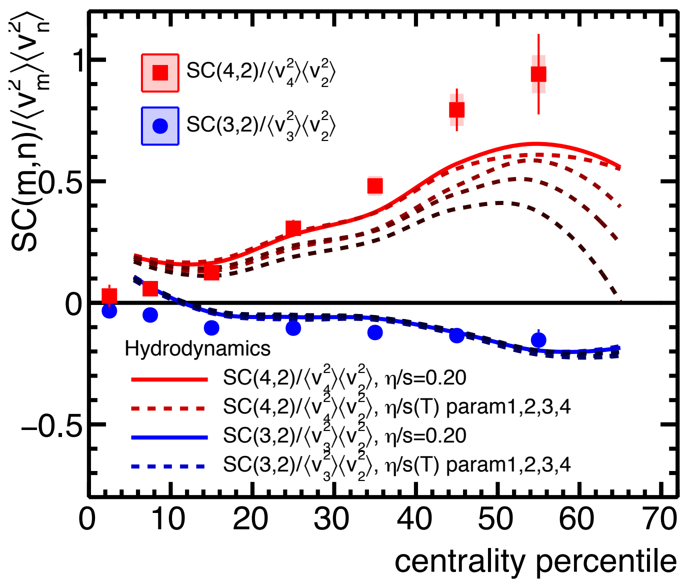
ALICE Collaboration, [arXiv:1604.07663]



Correlations between v_m and v_n

ALICE Collaboration, arXiv:1604.07663





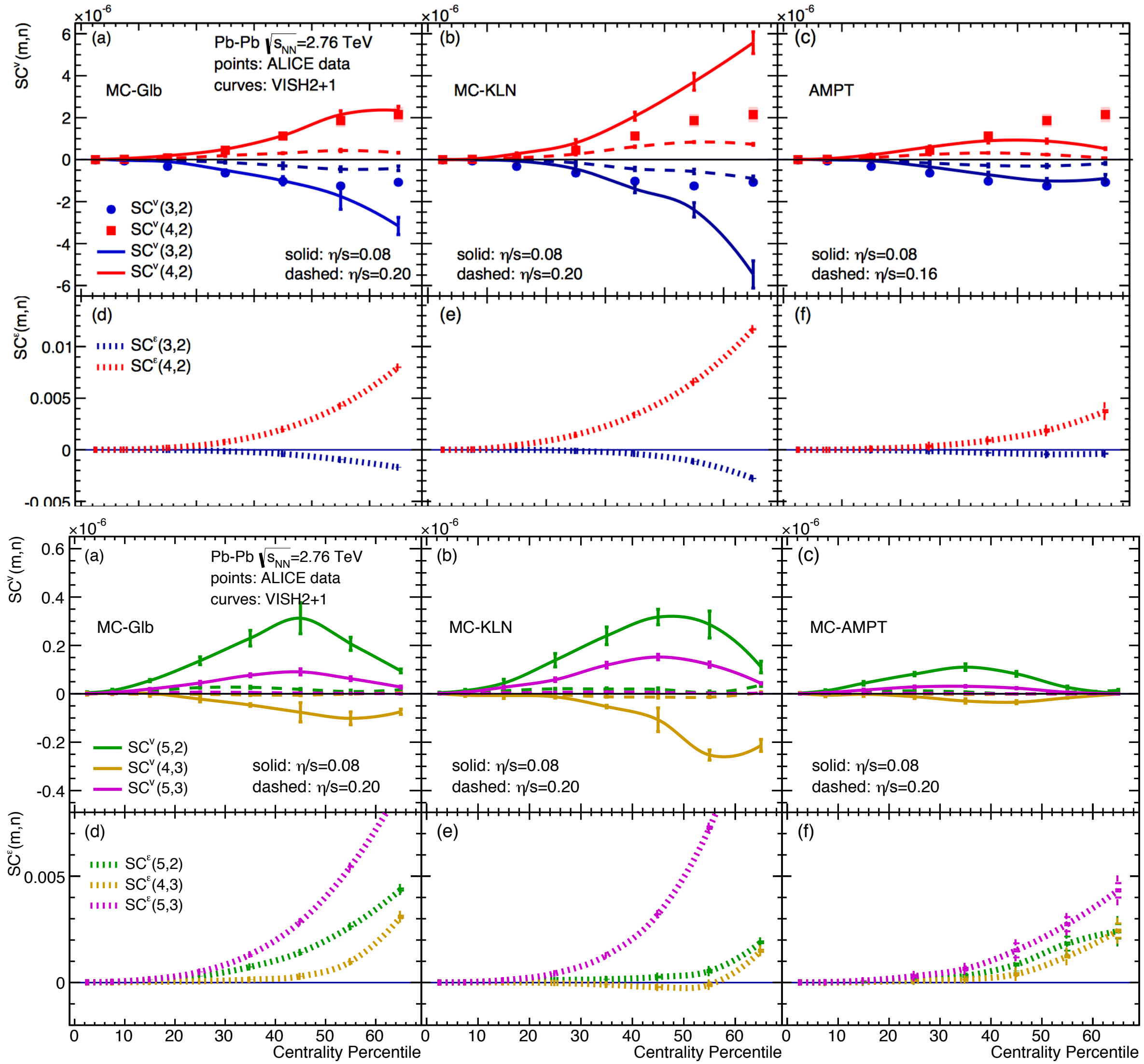
❖ Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations

- 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.

SC(m,n) from VISH2+1

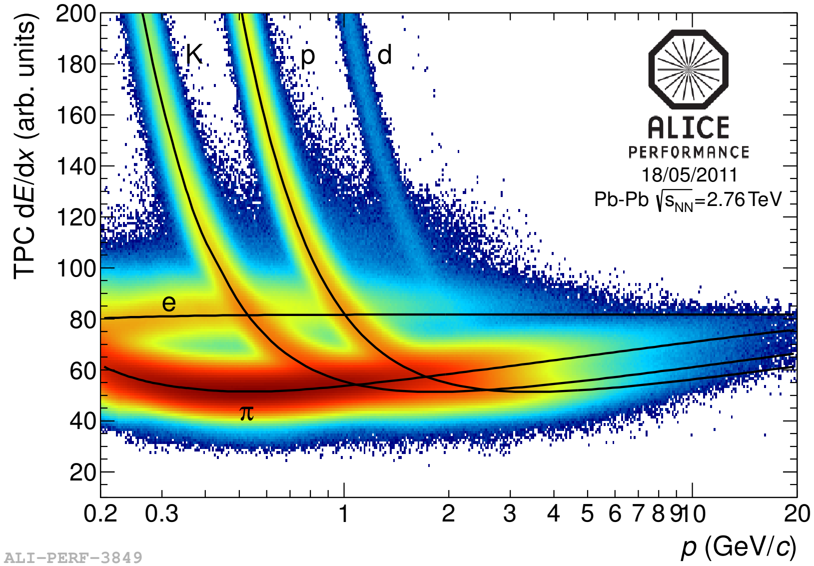


X.-R. Zhu et. al, IS2016

particle identification

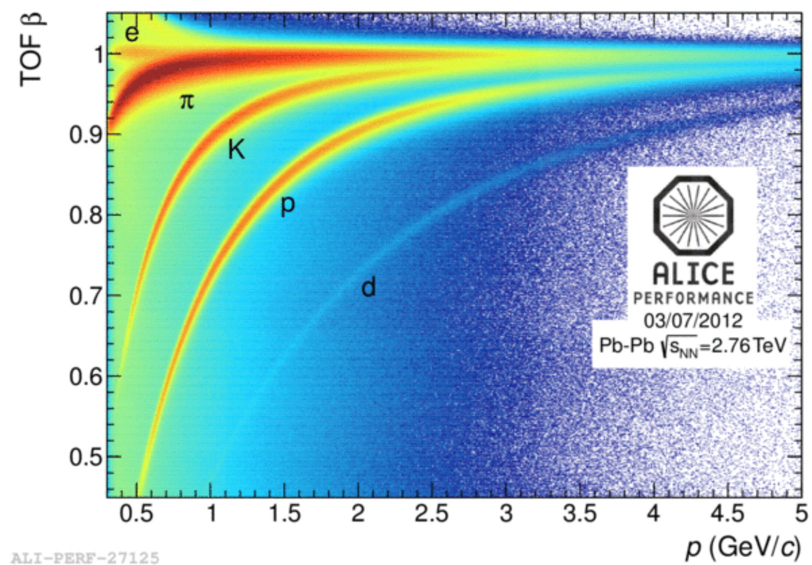
Time Projection Chamber (TPC)

dE/dx : the specific energy loss
Resolution: σdE/dx ≈ 5%



Time of Flight (TOF)

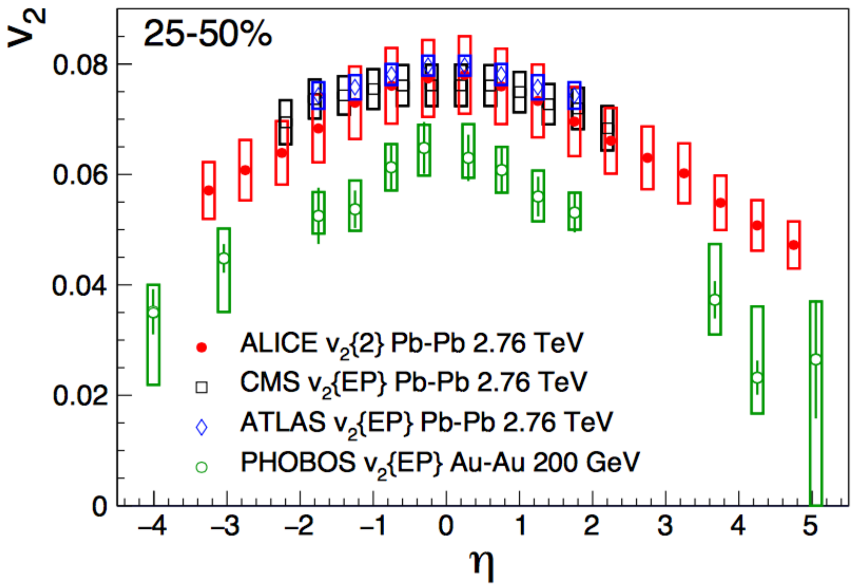
β=Track length/arrival time
Resolution: σTOF ≃ 86 ps

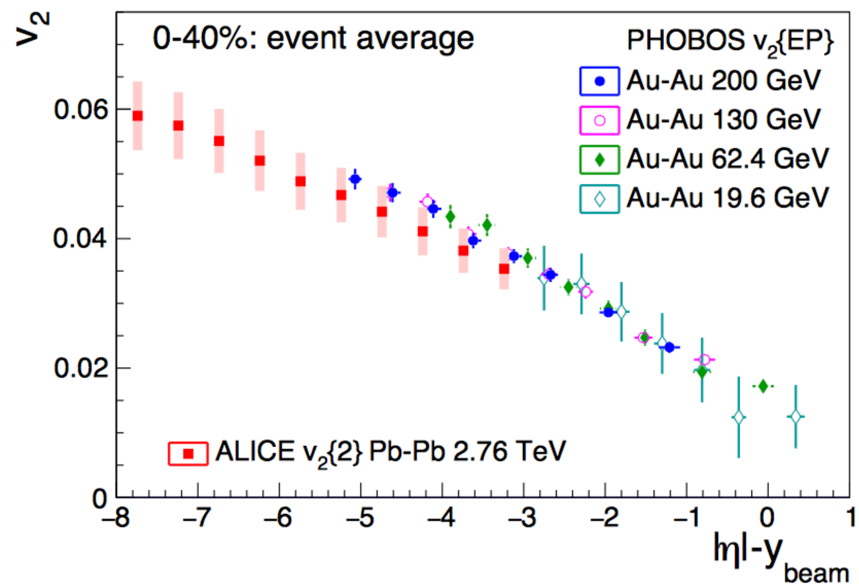


Bayesian PID (arXiv:1602.01392):

- Input quantities: <dE/dx>, β
- Identification Probability > 90%

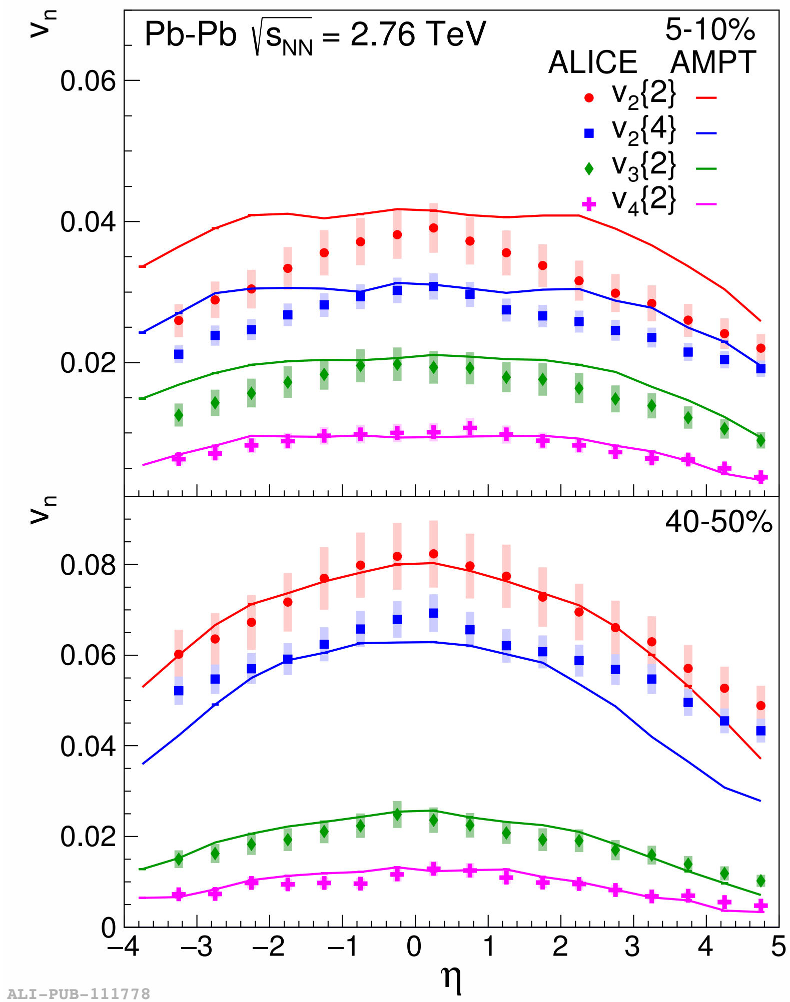
Pseudorapidity dependence of v_n





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

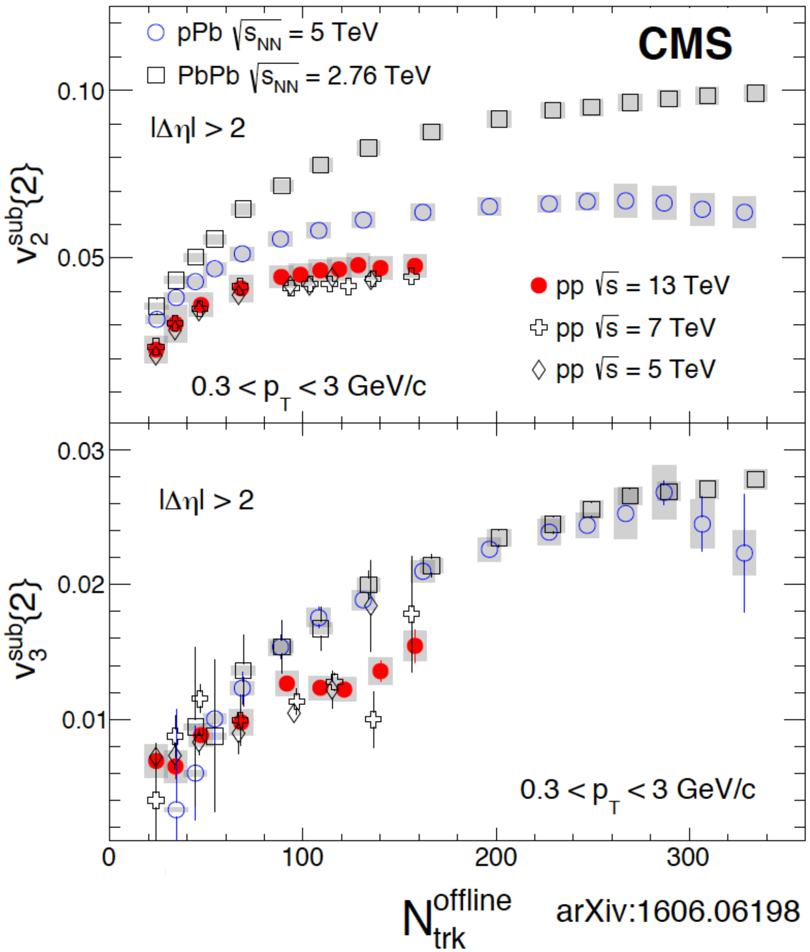
Pseudorapidity dependence of v_n



ALICE Collaboration, arXiv: 1605.02035
submitted to PLB

AMPT:

- A multiphase transport (AMPT) model with a so-called string melting scenario is used for comparisons.
- Good agreements of anisotropic flow from AMPT and data are observed in 40-50\% centrality class, except $v_2\{4\}$ at forward pseudorapidity.
- In more central collisions, AMPT overestimate v_2 and v_3 nevertheless agrees with v_4 measurements.

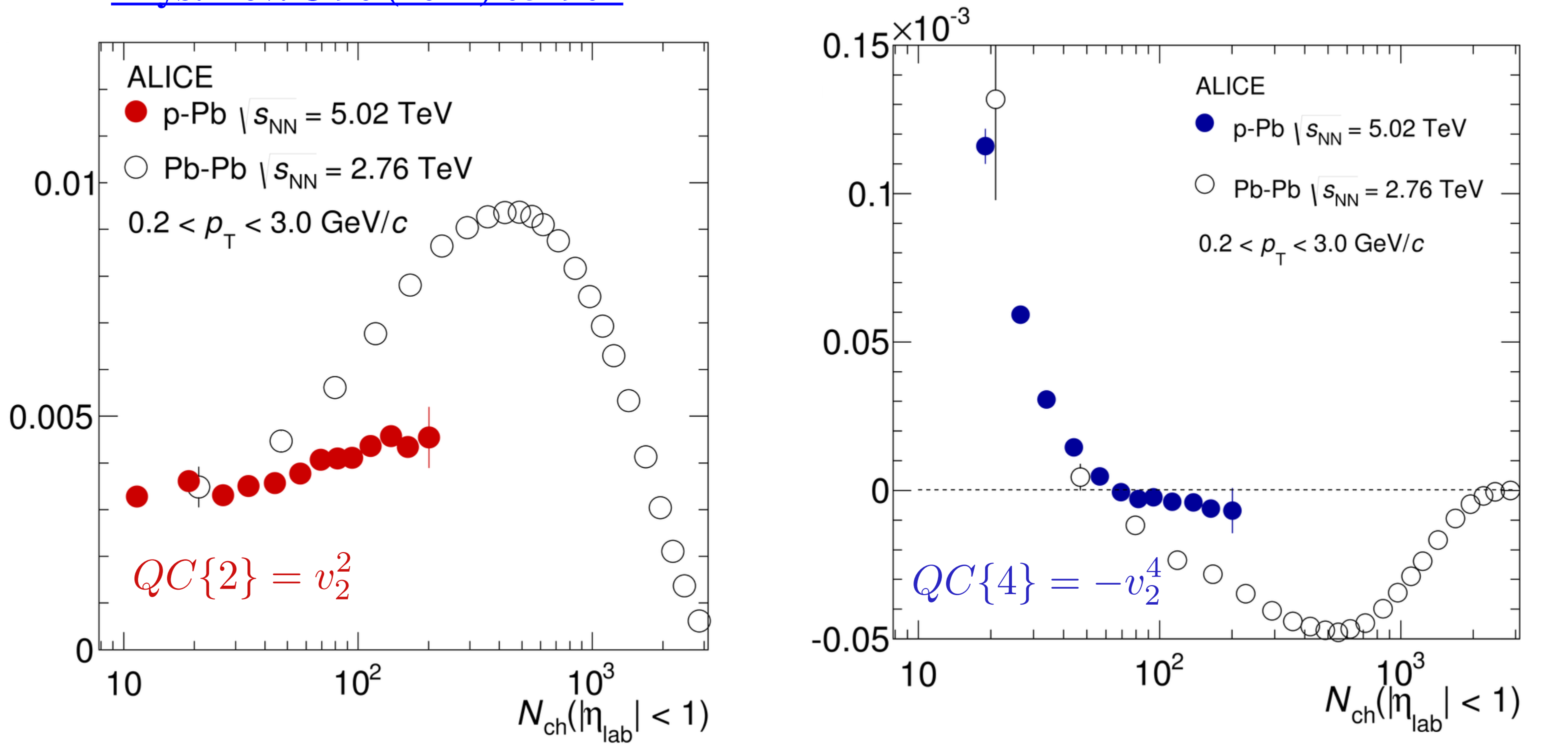


pPb $\sqrt{s_{NN}}$ = 5 TeV
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
CMS
|Δη| > 2
pp $\sqrt{s}$ = 13 TeV
pp $\sqrt{s}$ = 7 TeV
pp $\sqrt{s}$ = 5 TeV
0.3 < p_T < 3 GeV/c
$v_2^{sub}\{2\}$
$v_3^{sub}\{2\}$
$N_{trk}^{offline}$
arXiv:1606.06198

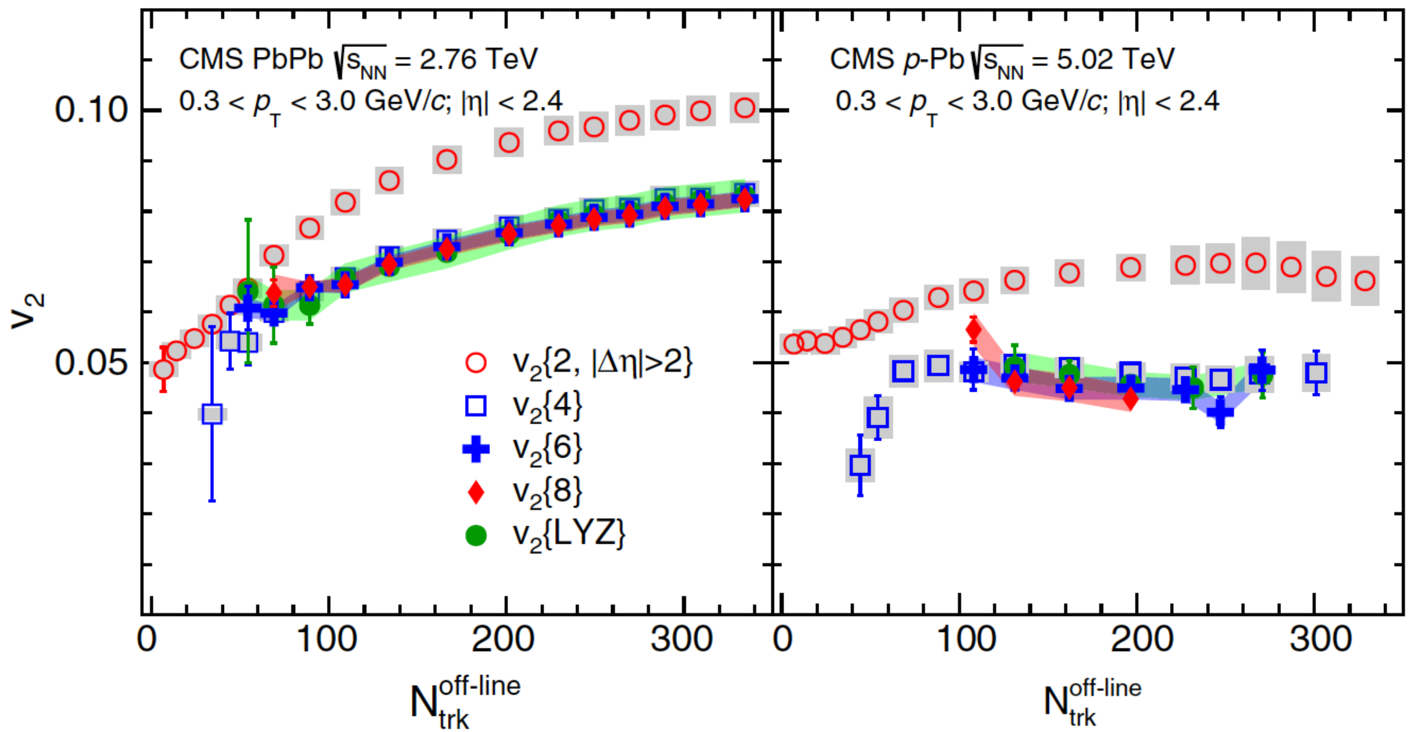
multi-particle correlations: p-Pb

p-Pb collisions

ALICE Collaboration,
Phys. Rev. C 90 (2014) 054901



❖ Positive QC{2} and negative QC{4} observed in p-Pb collisions
- signature of collective behavior
- hard to reproduce in models without QGP



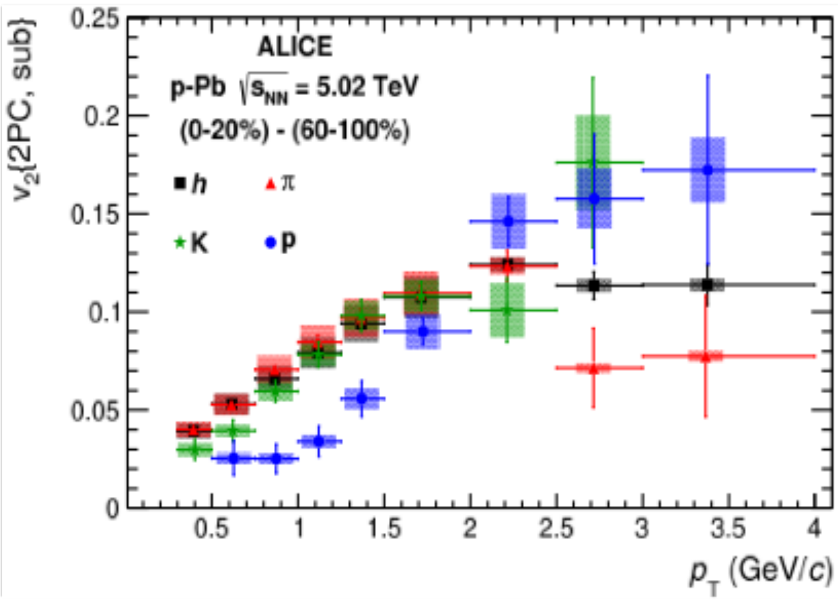
❖ Flow signal from multi-particle correlations in p-Pb collisions

- very similar with what observed in Pb-Pb, $v_2\{2\} > v_2\{4\} \simeq v_2\{6\} \simeq v_2\{8\}$

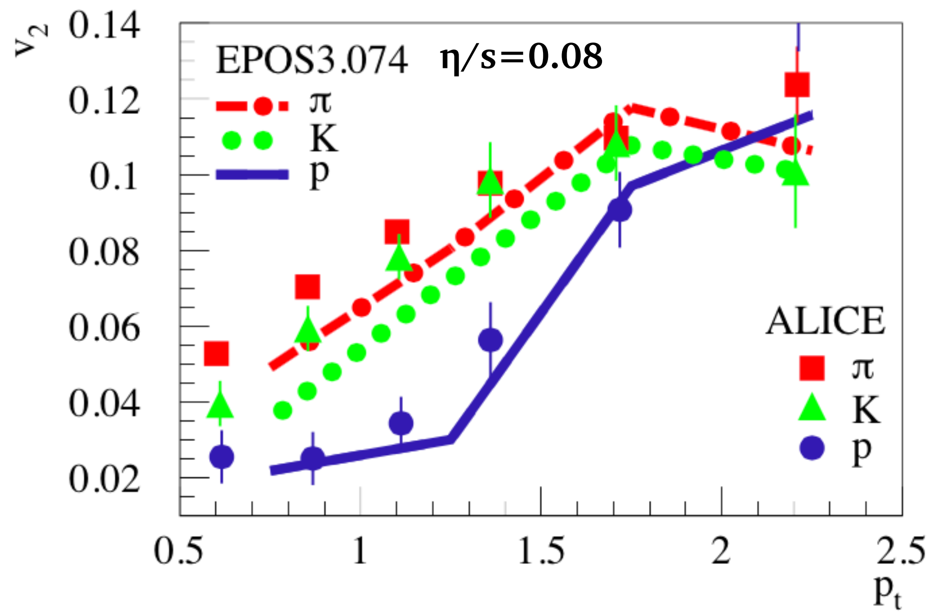
identified particle v_2 in p-Pb

p-Pb collisions

ALICE Collaboration,
Phys. Lett. B 726 (2013) 164



K. Werner, et. al.,
Phys. Rev. Lett. 112, 232301 (2014)

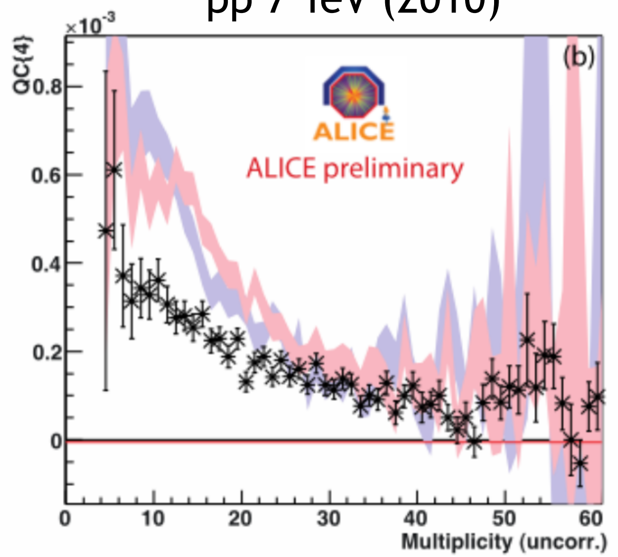


- Identified particle v_2 shows mass ordering in high multiplicity p-Pb collisions
  - similar feature as observed in Pb-Pb collisions
    - indication of anisotropic flow (?)
  - EPOS (hydro+transport model) reproduces similar feature

multi-particle correlations: pp

pp collisions

pp 7 TeV (2010)



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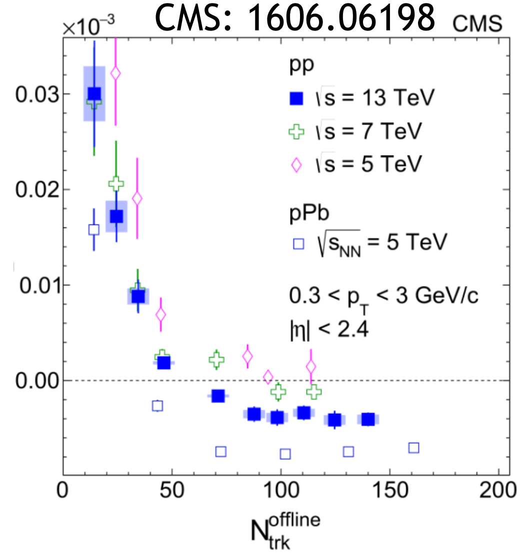
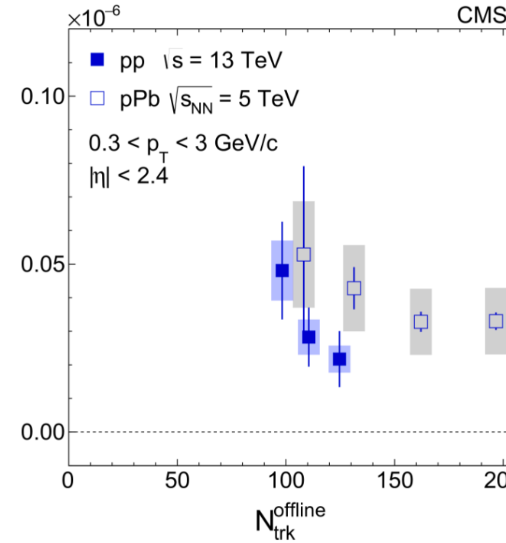




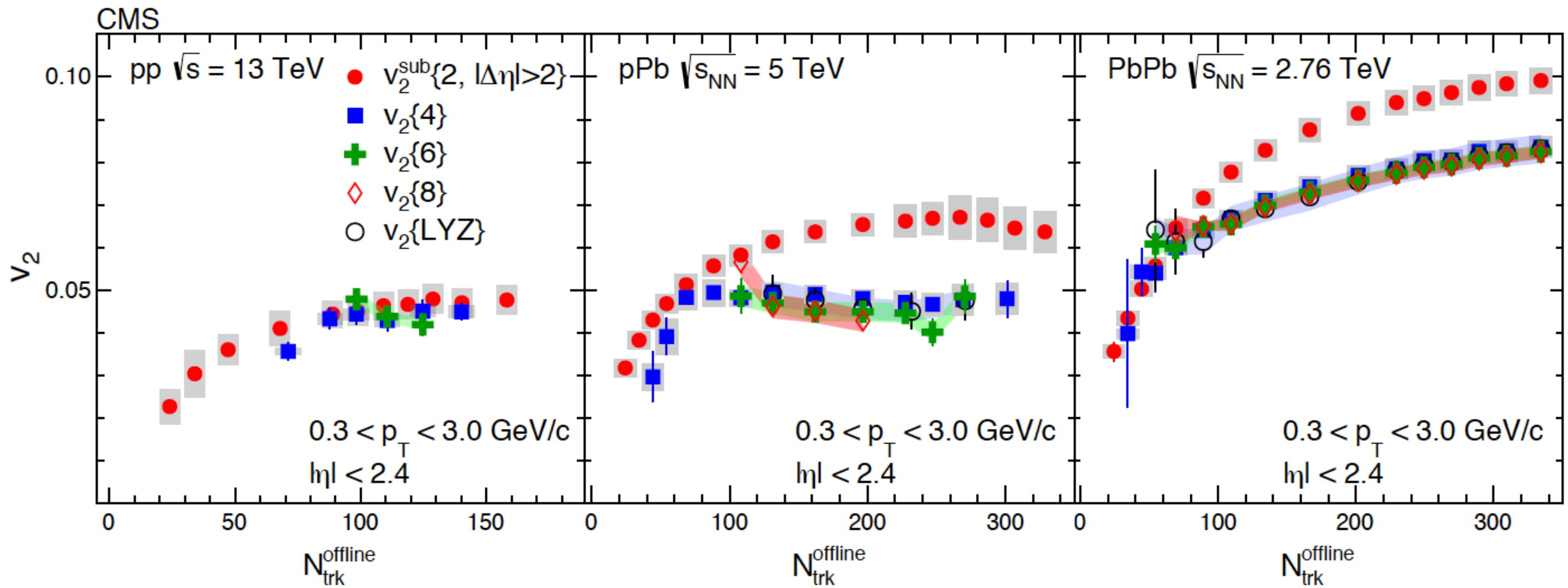
$QC\{4\} = -v_2^4$

$QC\{4\} = -v_2^4$

$QC\{6\} = v_2^6$

- Anisotropic flow produced in (high multiplicity) pp collisions?
  - negative QC{4} and positive QC{6} -> signal of flow in pp (QGP in pp?)
  - other mechanism?

multi-particle cumulants in AA, pA and pp

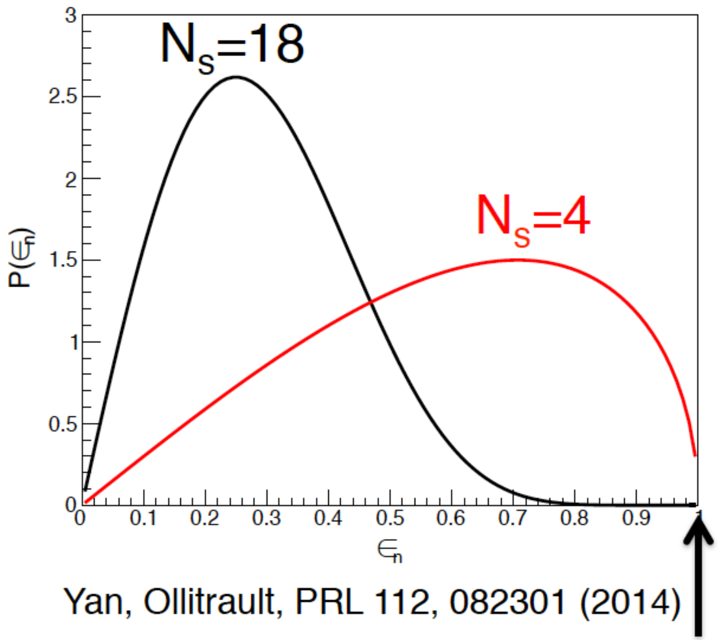


- $v2\{2\} \geq v2\{4\} \approx v2\{6\} \approx v2\{8\} \approx v2\{LYZ, \infty\}$
  - Collectivity in any hadronic systems (?)

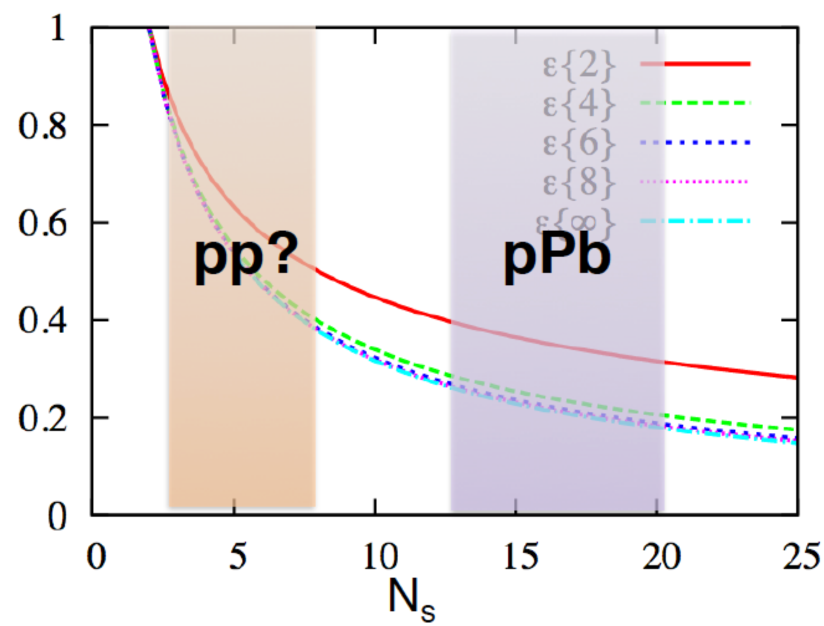
smaller fluctuations in pp ??

Fluctuation-driven ε_n

$$P(\varepsilon_n) = 2\alpha\varepsilon_n(1-\varepsilon_n^2)^{\alpha-1}, \alpha = (N_s - 1)/2$$



Yan, Ollitrault, PRL 112, 082301 (2014)



$$\frac{v_n\{4\}}{v_n\{2\}} = \frac{\varepsilon_n\{4\}}{\varepsilon_n\{2\}} = \left(\frac{2}{1+N_s/2}\right)^{1/4}$$

- suggest smaller N_s in pp ?

identified particle v_2 in pp

p-Pb collisions

pp collisions

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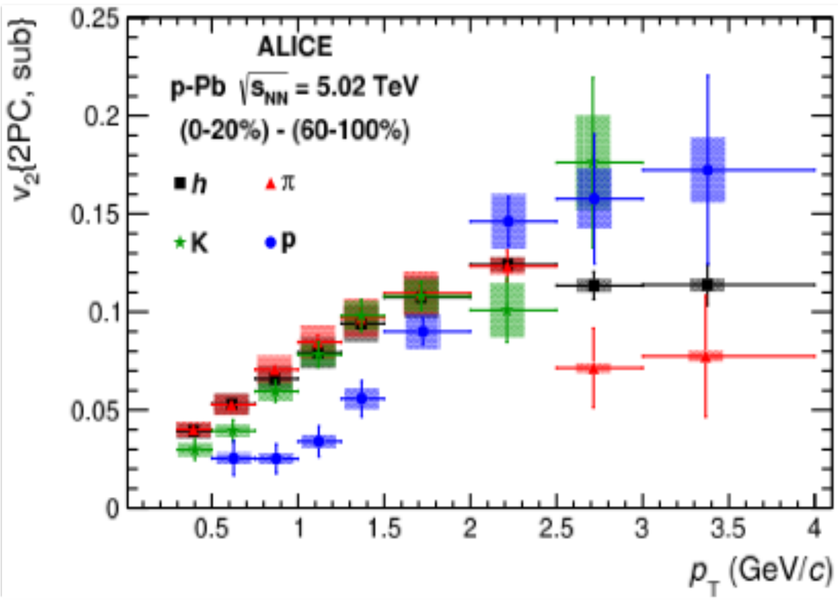
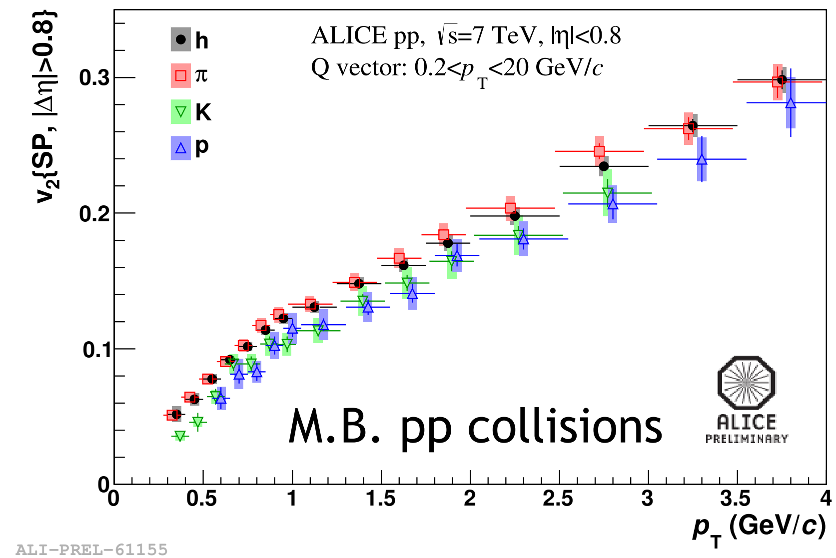
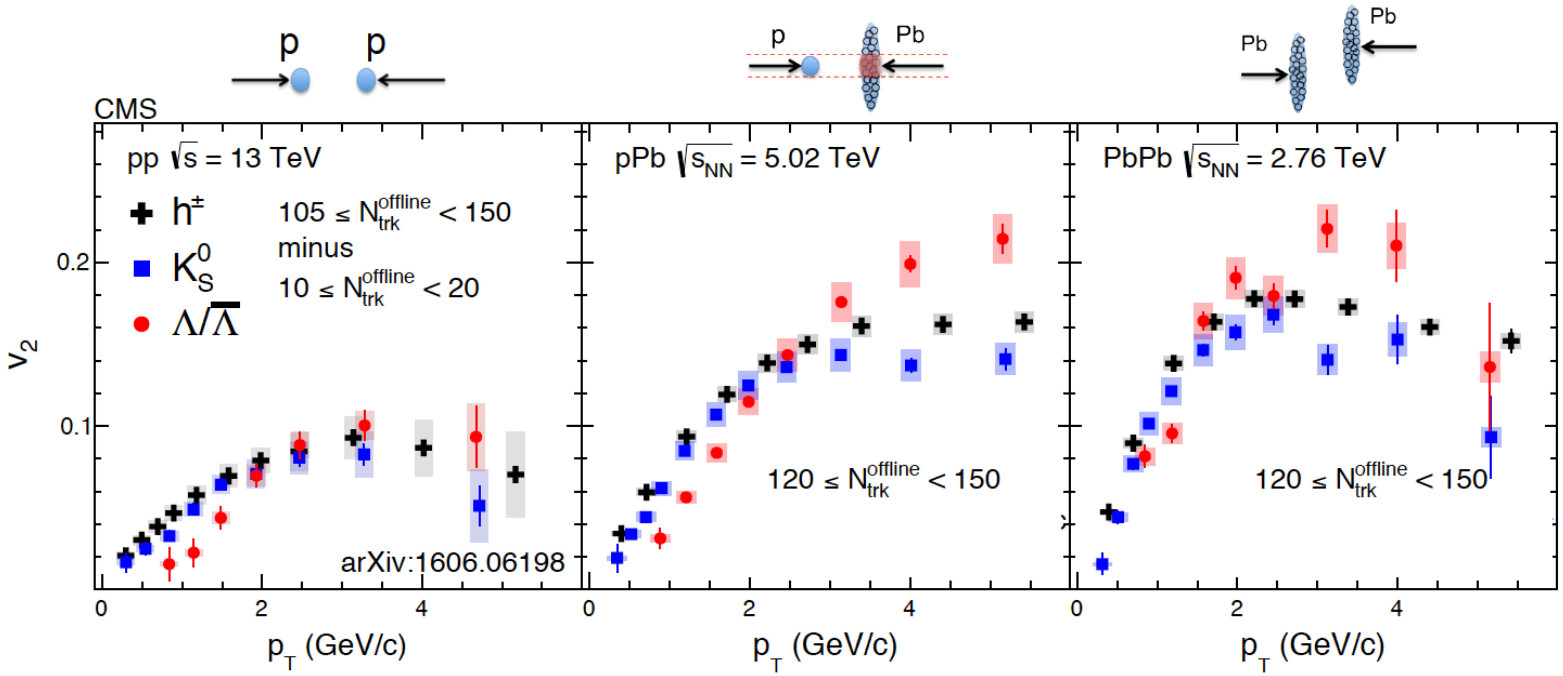




- ❖ Anisotropic flow produced in (high multiplicity) pp collisions?
  - will PID v_2 in high multiplicity pp collisions show any indication?

identified particle v_2 in pp, pA, AA



CMS: **1606.06198**

❖ Anisotropic flow of identified particles
- mass ordering at low p_T
- NCQ scaling at immediate p_T
- Evidence of collectivity in small system ?