NN2015

12th INTERNATIONAL CONFERENCE ON NUCLEUS –NUCLEUS COLLISIONS

June 21-26, 2015, Catania, Italy

Overview of Anisotropic Flow Measurements from ALICE

UNIVERSITY OF COPENHAGEN

You Zhou

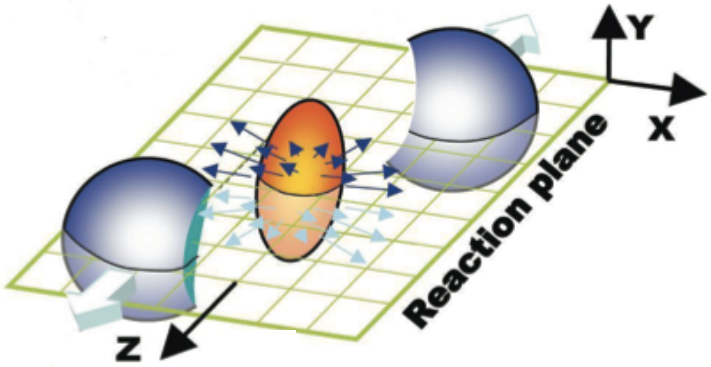
Niels Bohr Institute

(for the ALICE Collaboration)

ALICE

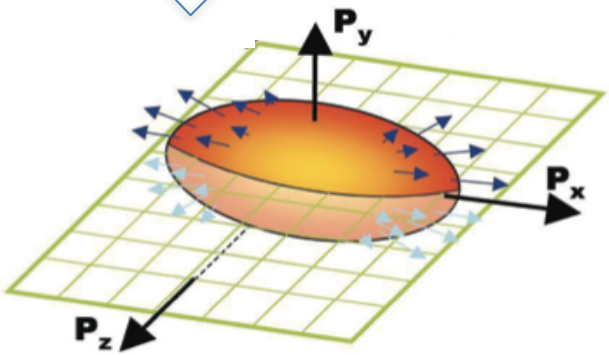
Anisotropic Flow

- "Anisotropic 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." PRD 46, 229 (1992)



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

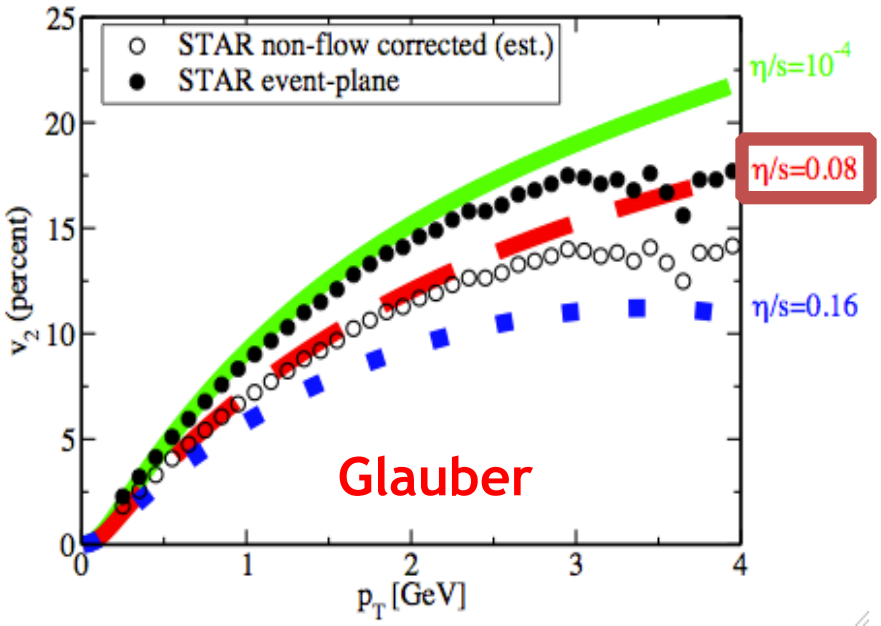
coordinate space Eccentricity

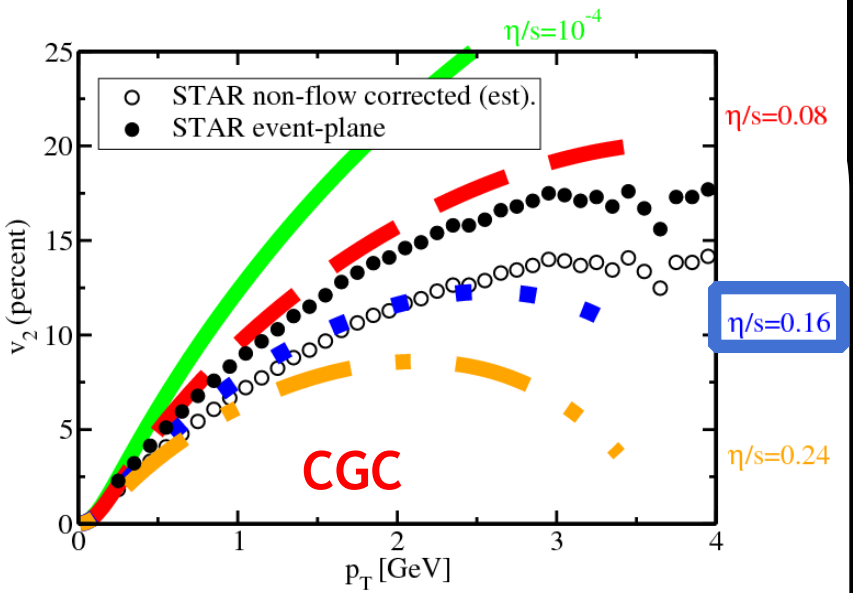


$$v_2 = \langle \cos 2 (\varphi - \Psi_{\mathrm{RP}}) \rangle$$

momentum space Elliptic Flow

Elliptic Flow

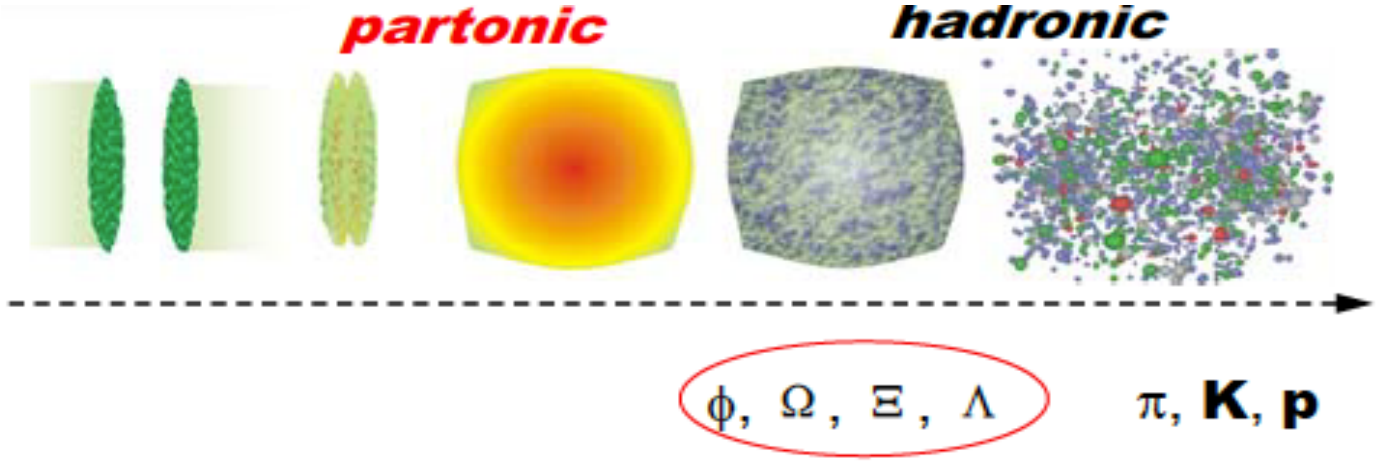




- Charged particle v_2 measurements and the comparison with hydrodynamic calculations
  - constrain the initial state model, EoS, …
  - extract the η/s, properties of the hot and dense matter (liquid)
- From charged particle v_2
  - big uncertainty of η/s (0.08 ⟺ 0.16)!!
  - model dependence of initial conditions, e.g. eccentricity ε_2 (Glauber or CGC)
- addition constraints
  - v_2 of identified particles!

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

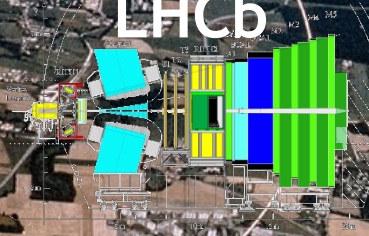


Large Hadron Collider (LHC)

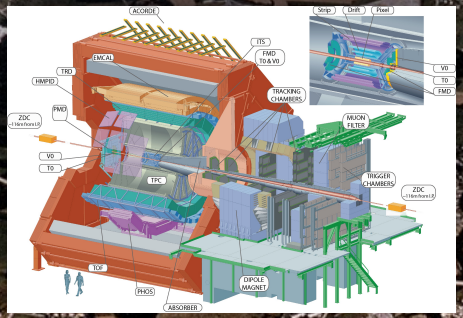
“Large Heavy ion Collider” (LHC)

CMS

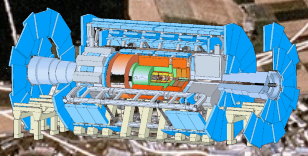
LHCb



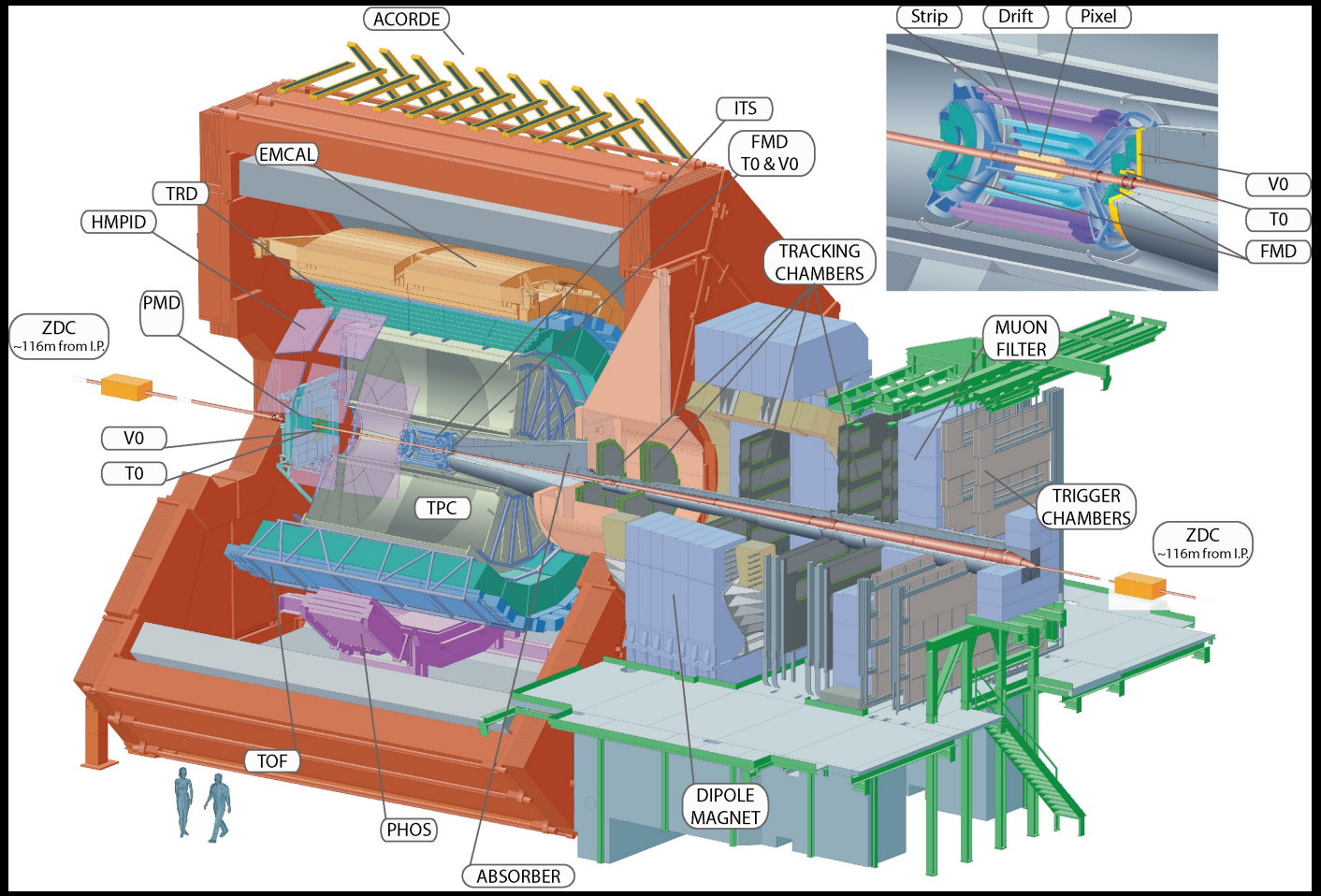
ALICE



ATLAS



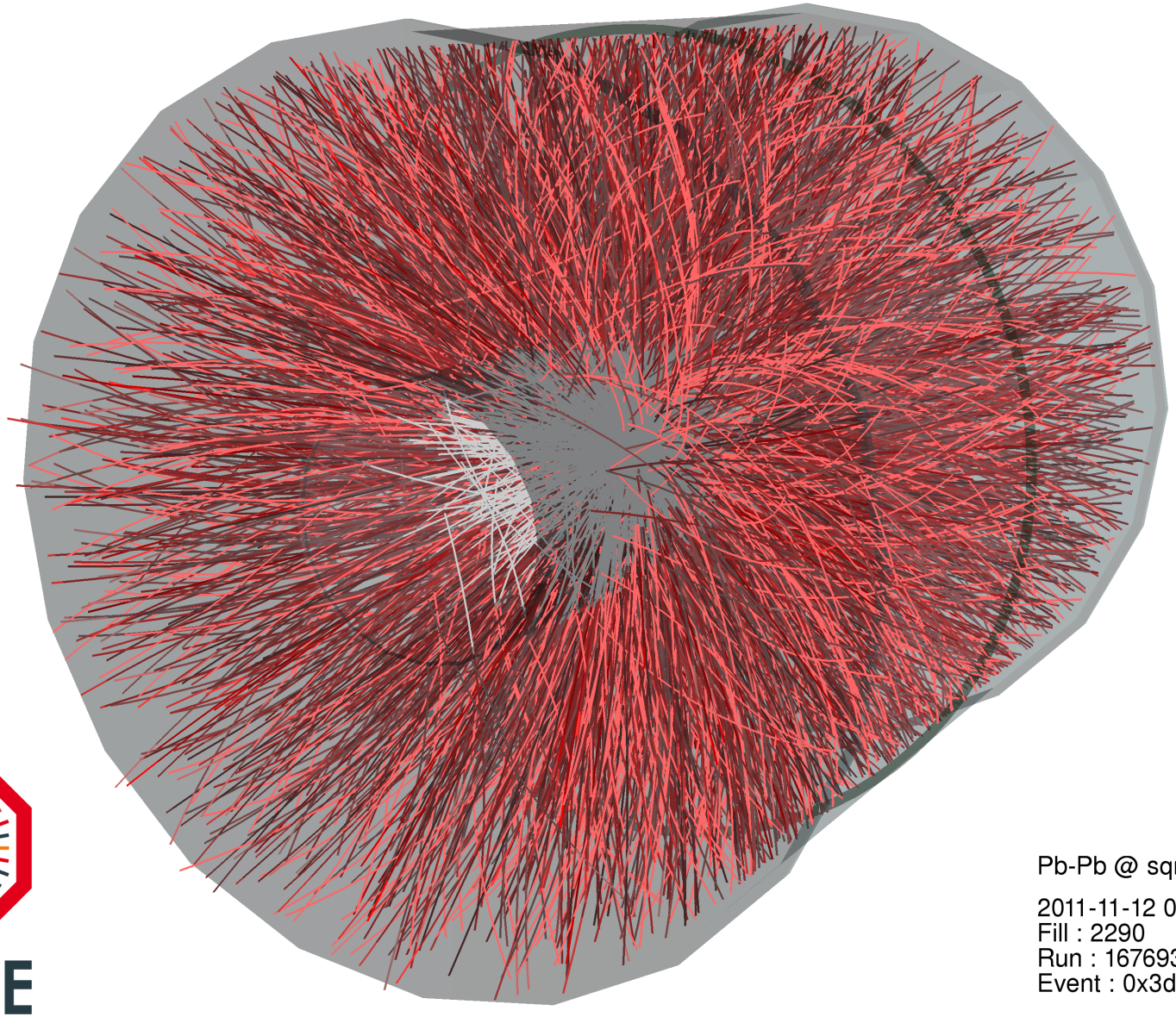
The ALICE Detector



~ 1200 people, 30 countries,

~ 150 Institutes

Pb-Pb collisions

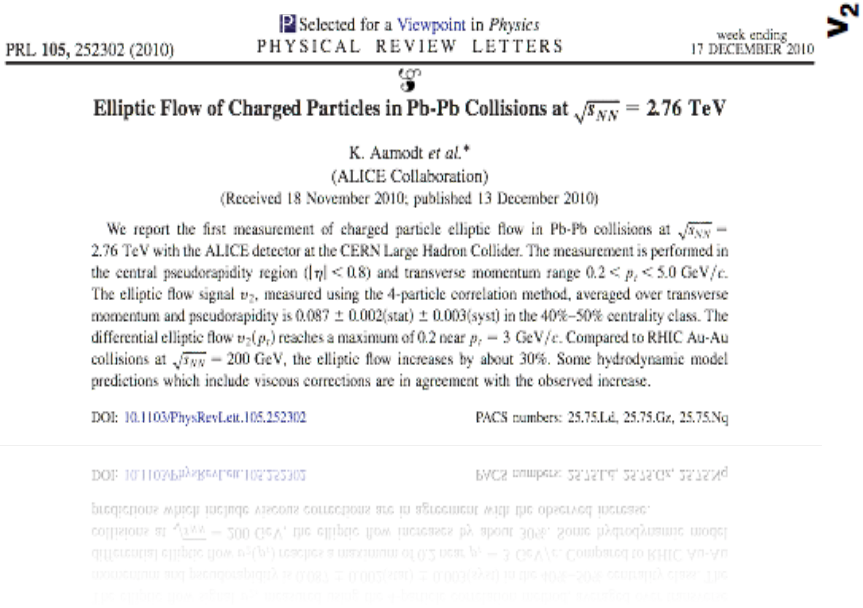


Pb-Pb @ sqrt(s) = 2.76 ATeV

2011-11-12 06:51:12
Fill : 2290
Run : 167693
Event : 0x3d94315a

ALICE
A JOURNEY OF DISCOVERY

First charged particle flow at LHC



Selected for a Viewpoint in *Physics*

PRL 105, 252302 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

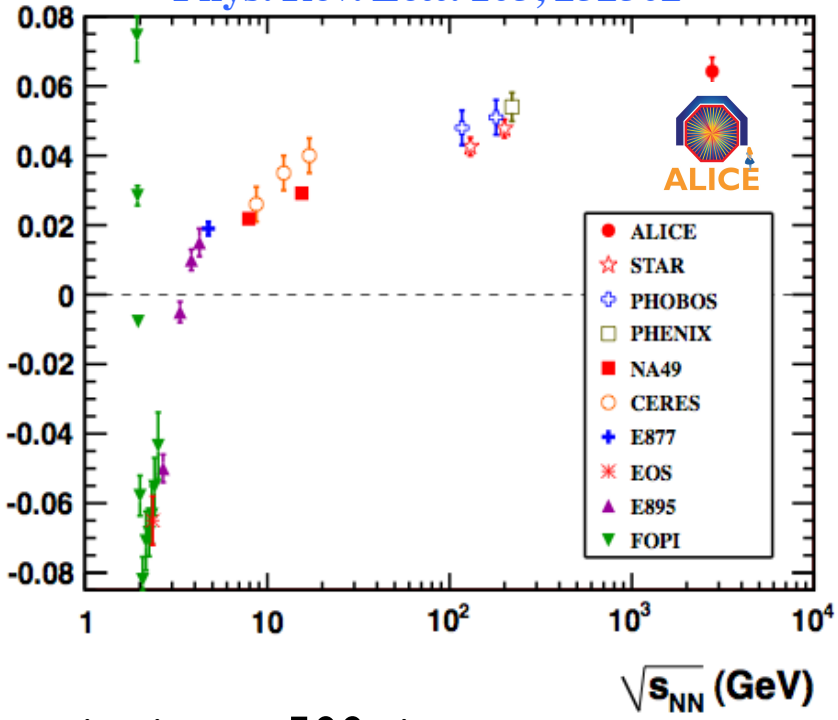
K. Aamodt *et al.**
(ALICE Collaboration)

(Received 18 November 2010; published 13 December 2010)

We report the first measurement of charged particle elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.2 < p_t < 5.0$ GeV/c. The elliptic flow signal v_2, measured using the 4-particle correlation method, averaged over transverse momentum and pseudorapidity is $0.087 \pm 0.002(\text{stat}) \pm 0.003(\text{syst})$ in the 40%–50% centrality class. The differential elliptic flow $v_2(p_t)$ reaches a maximum of 0.2 near $p_t = 3$ GeV/c. Compared to RHIC Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the elliptic flow increases by about 30%. Some hydrodynamic model predictions which include viscous corrections are in agreement with the observed increase.

DOI: 10.1103/PhysRevLett.105.252302 PACS numbers: 25.75.Ld, 25.75.Gz, 25.75.Nq

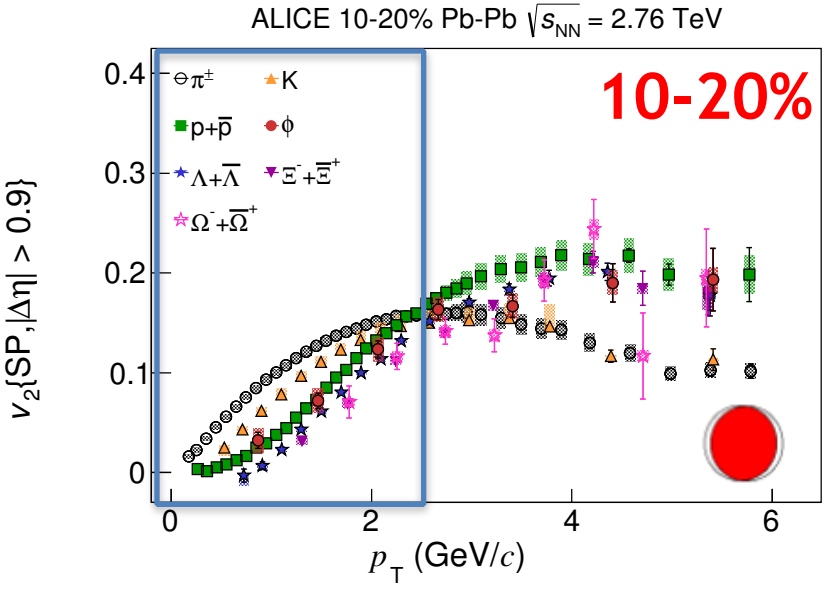
ALICE Collaboration
Phys. Rev. Lett. 105, 252302

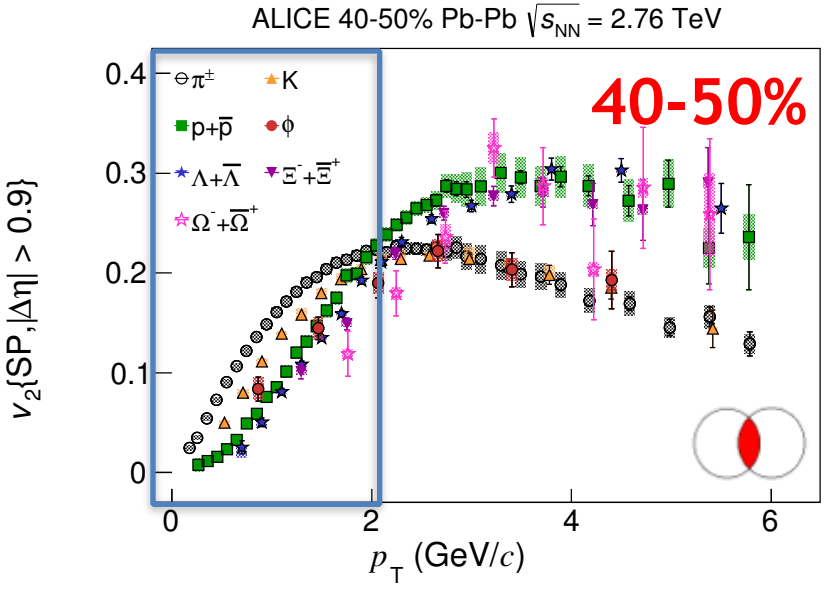


TOP cited paper at LHC for heavy ion, citations ~500 times

- CERN, November 26, 2010: 'the much hotter plasma produced at the LHC behaves as a very low viscosity liquid..'
- a 30% increase of v_2 from RHIC to LHC

Identified particle v_2 (low p_T)



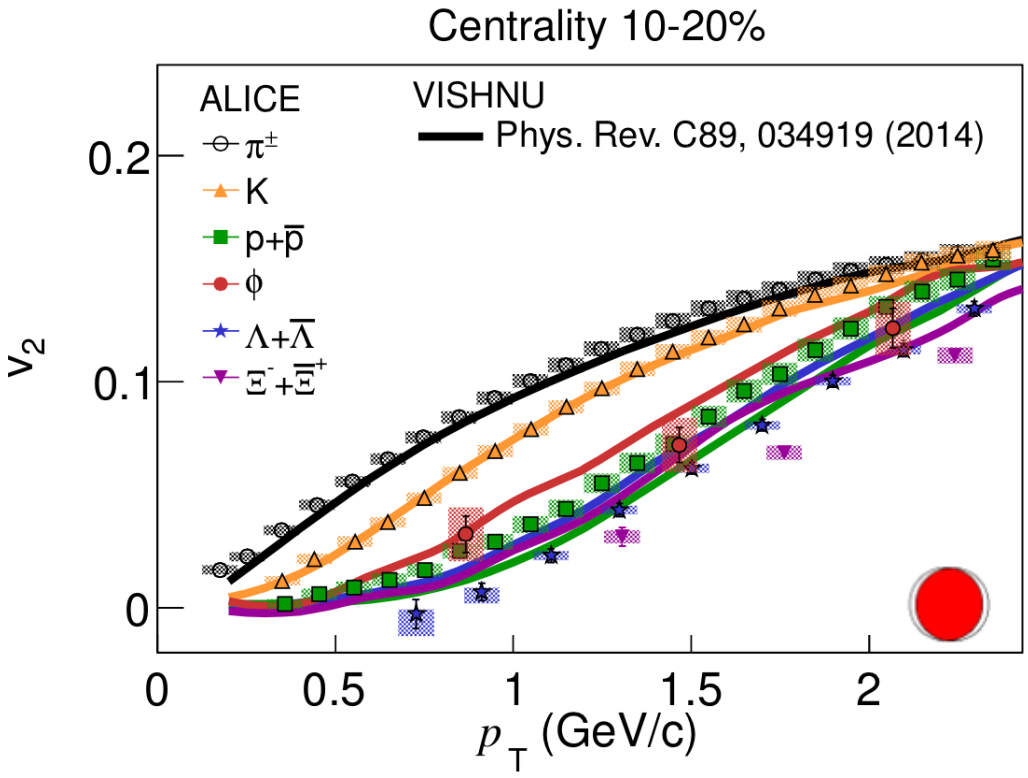


ALICE Collaboration, arXiv:1405.4632, accepted by JHEP

Low p_T (p_T < 3 GeV/c):

- exhibits mass ordering
- similar observations at RHIC energies

Comparisons with hydrodynamics

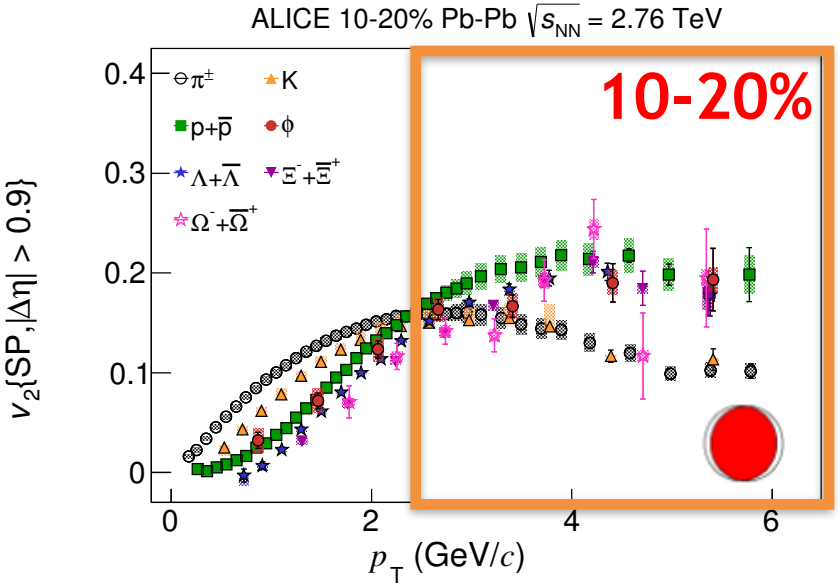


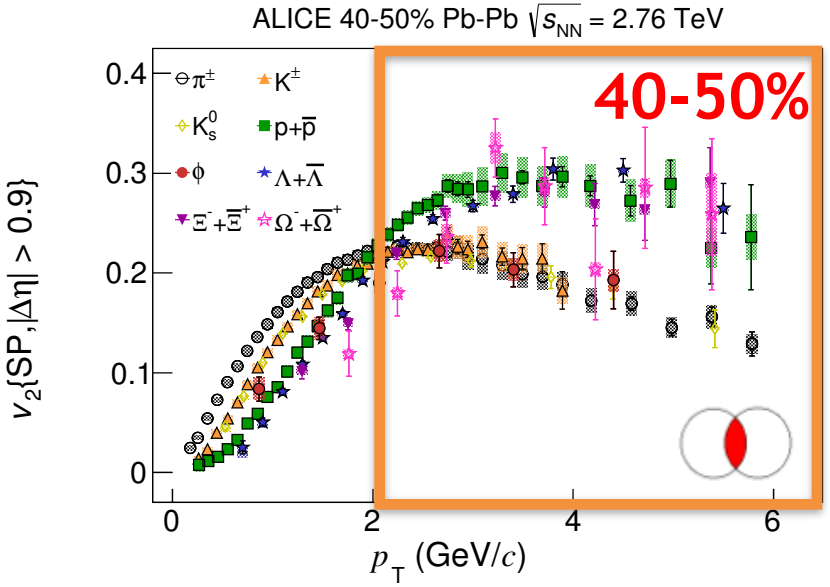
H. Song et. al.,
Phys. Rev. C 89, 034919 (2014)

VISHNU:
- viscous hydrodynamic+UrQMD
- CGC initial condition & η/s=0.16

❖ Hydrodynamic calculation qualitatively describes the PID v_2 measurements
- (multi-)strange particle v_2 do not follow the exact ordering

Identified particle v_2 (immediate p_T)

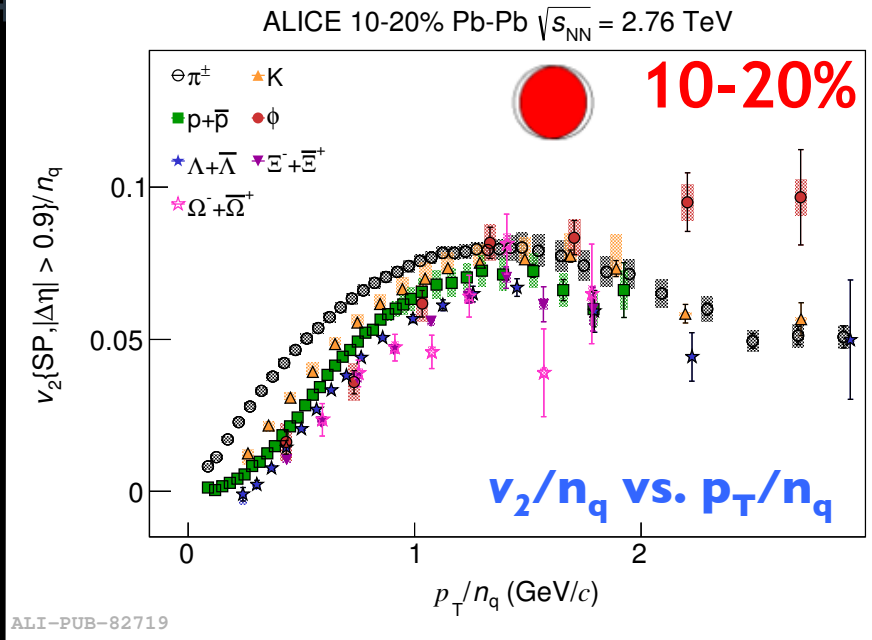


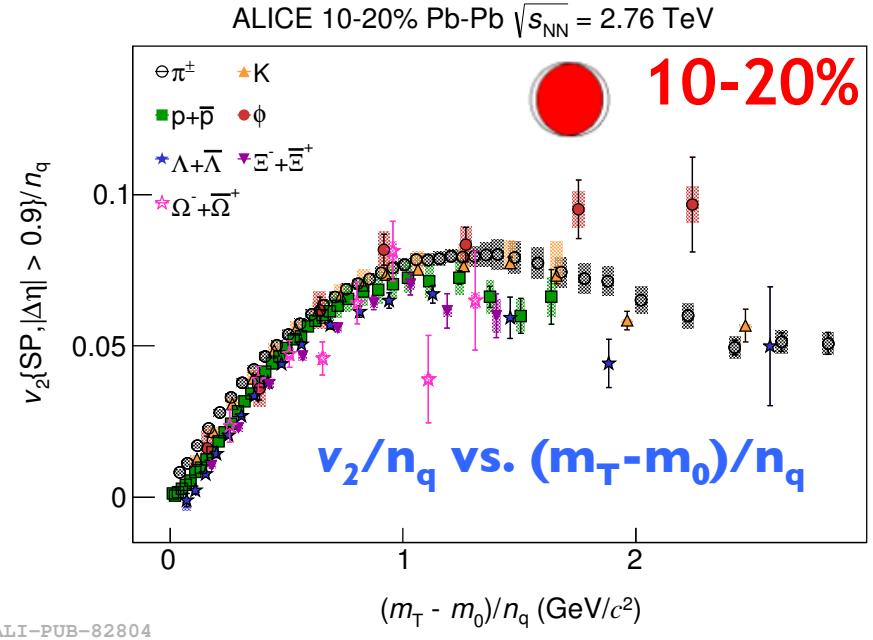


Intermediate p_T ($3 < p_T < 6$ GeV/c):

- Rough grouping based on type (mesons/baryons)
- Consistent with RHIC observations?

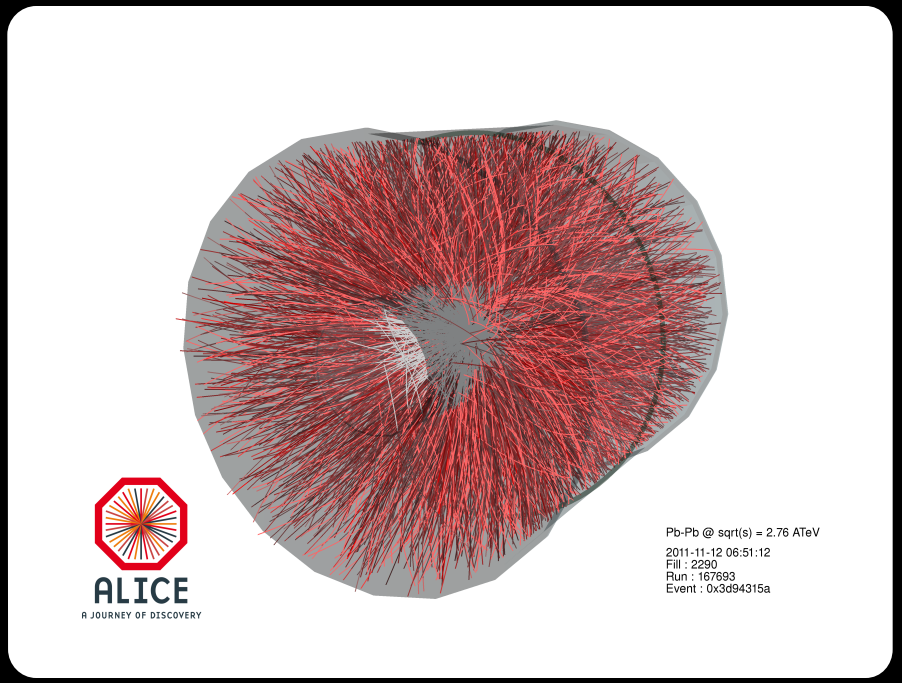
Number of constituent quark scaling



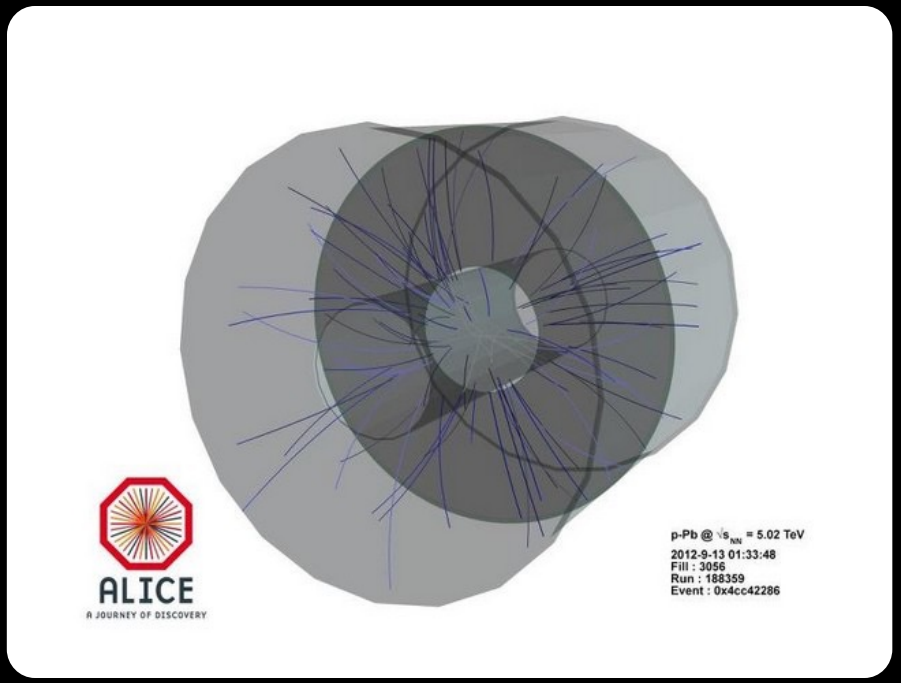


- NCQ scaling serves as a test for particle production via quark coalescence
- Neither v_2/n_q vs. p_T/n_q (n_q: number of quarks per meson/baryon) or v_2/n_q vs. $(m_T-m_0)/n_q$ gives a universal/precise scaling.

Pb-Pb collisions

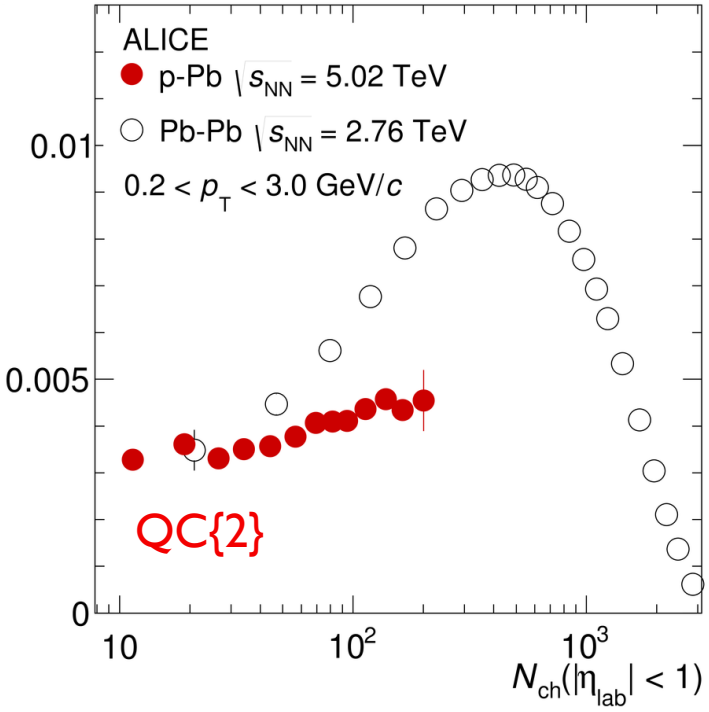


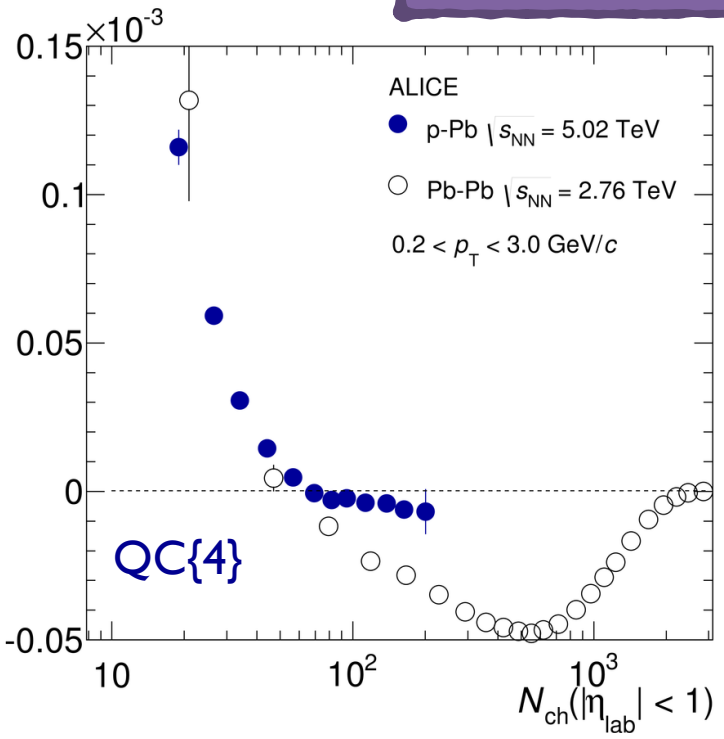
p-Pb collisions



Flow signature in p-Pb collisions

p-Pb collisions





$$QC\{2\} = v_2^2$$

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

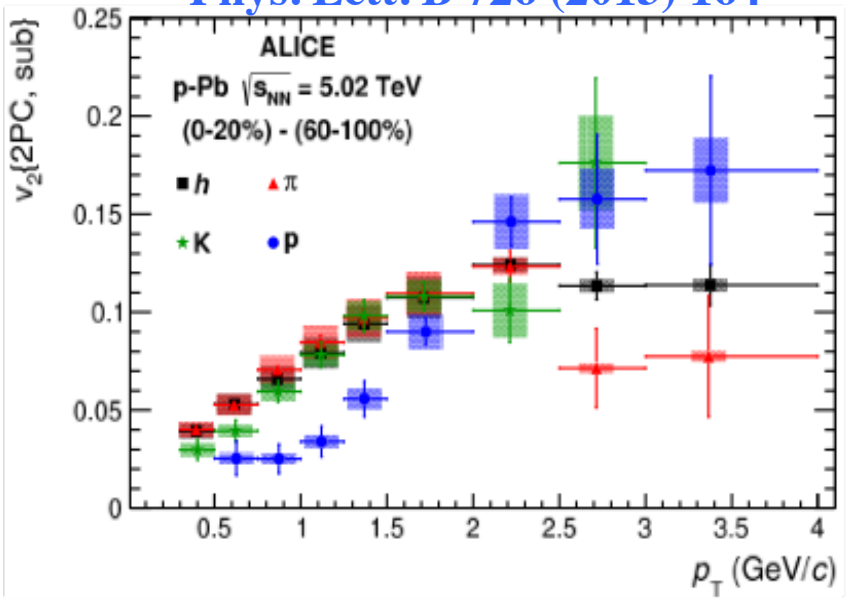
ALICE Collaboration, Phys. Rev. C 90 (2014) 054901

➢ **Flow signature**

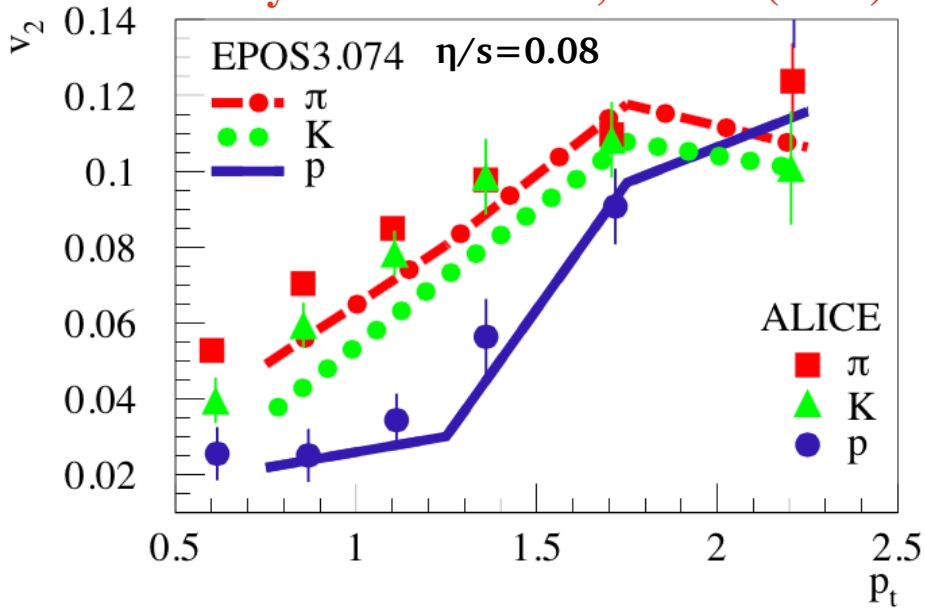
Identified particle v_2 in p-Pb

p-Pb collisions

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



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

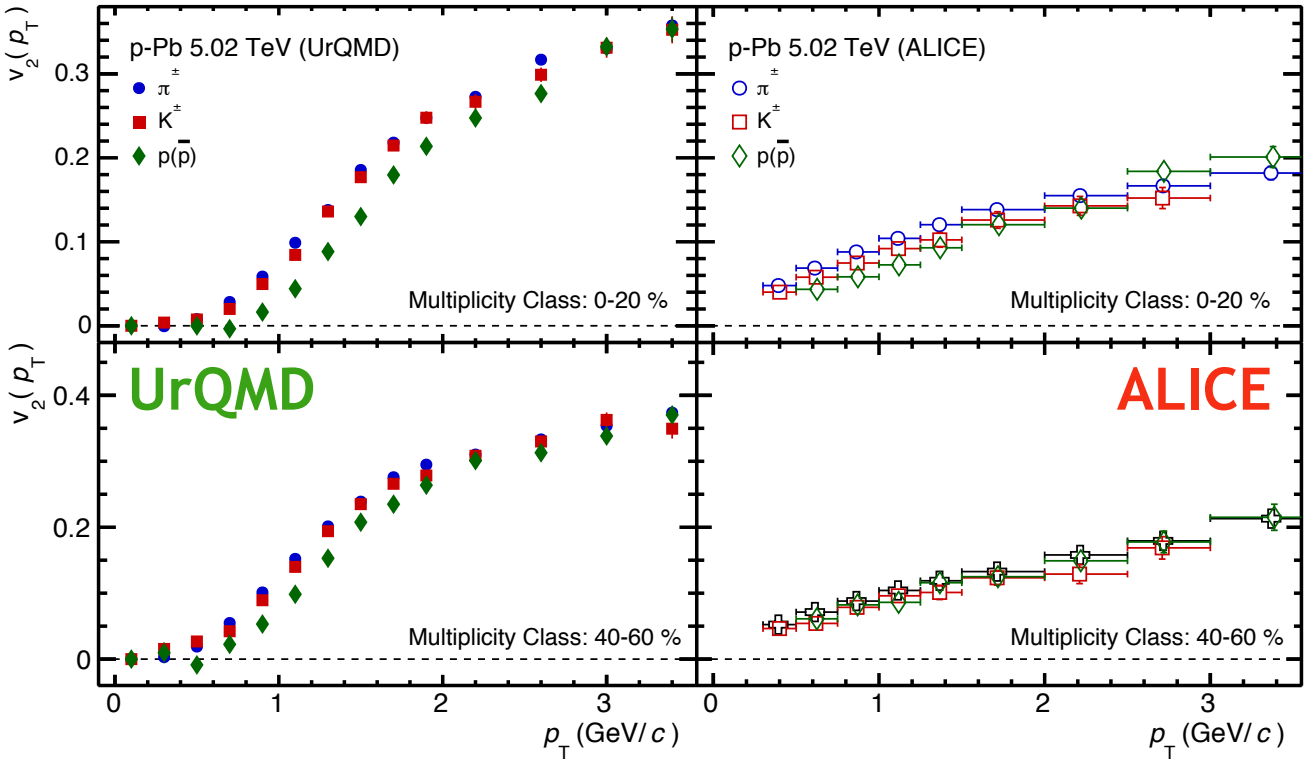


- Identified particle v_2 show mass ordering in p-Pb collisions
  - v_2 is extracted using "central - peripheral subtraction" method
  - Indication of flow (?)
  - EPOS (hydro+transport model) reproduces similar feature

Identified particle v_2 in p-Pb

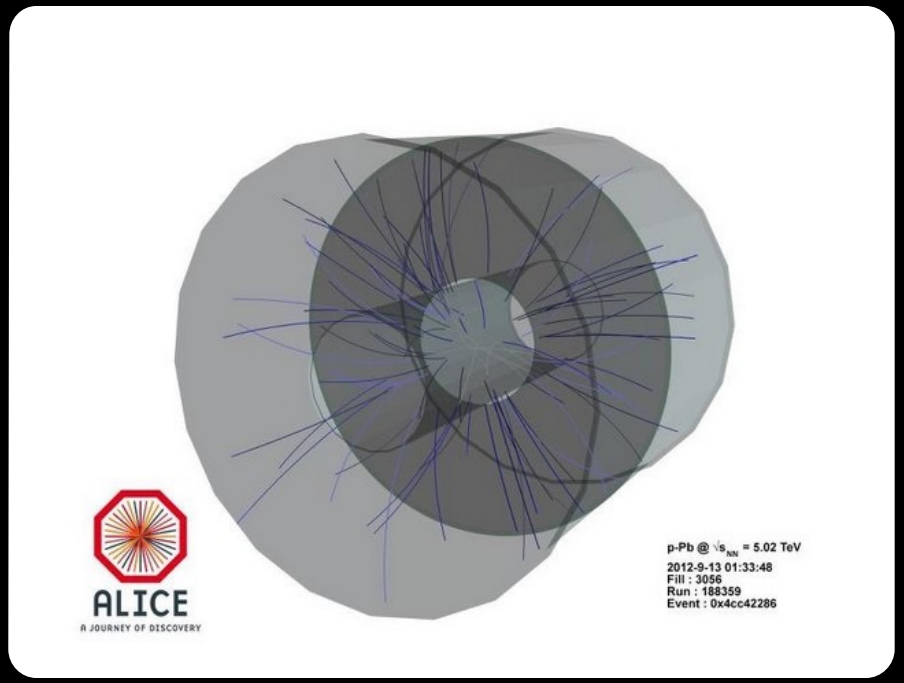
p-Pb collisions

Y. Zhou, et. al. Phys. Rev. C 91, 064908 (2015)

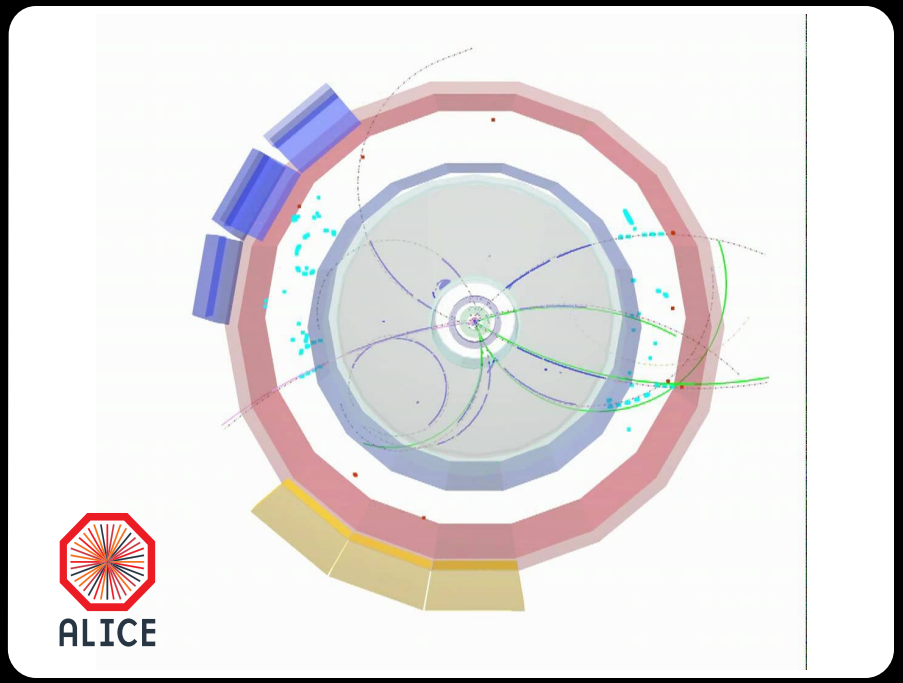


- The characteristic $v_2(p_T)$ mass-ordering of pions, kaons and protons is observed in UrQMD
  - the consequence of hadronic interactions
  - not necessarily associated with strong fluid-like expansions.

p-Pb collisions

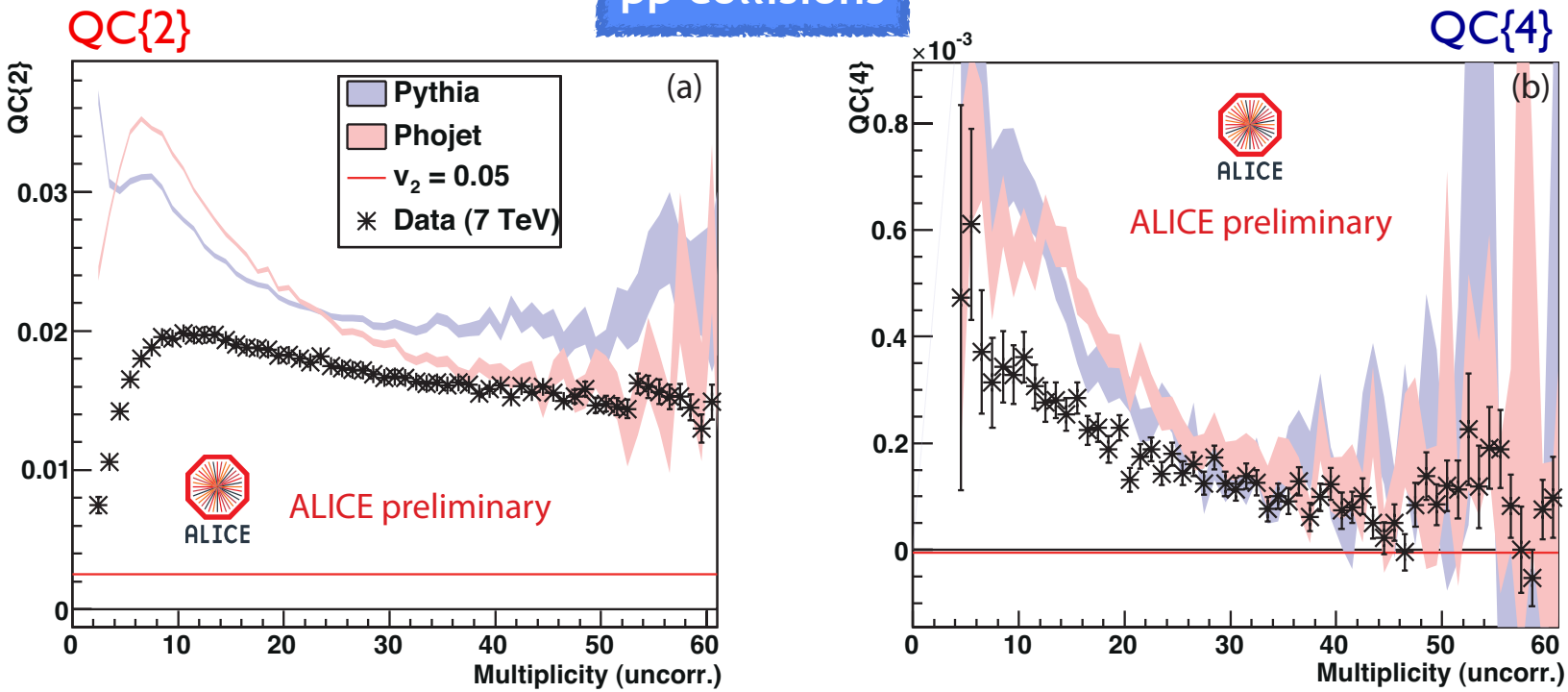


pp collisions



QC{n} in pp collisions

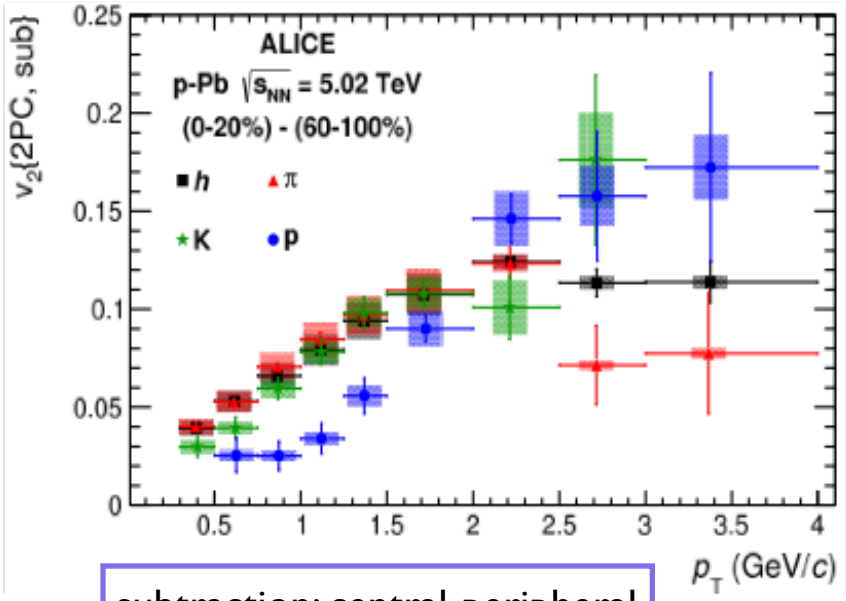
pp collisions



- For the presented multiplicity range,
  - both QC{2} and QC{4} decrease with increasing multiplicity,
  - QC{4} is positive.
  - indication of non-flow, no clear flow signature
  - Pythia and Phojet overestimate the strength of such correlations.

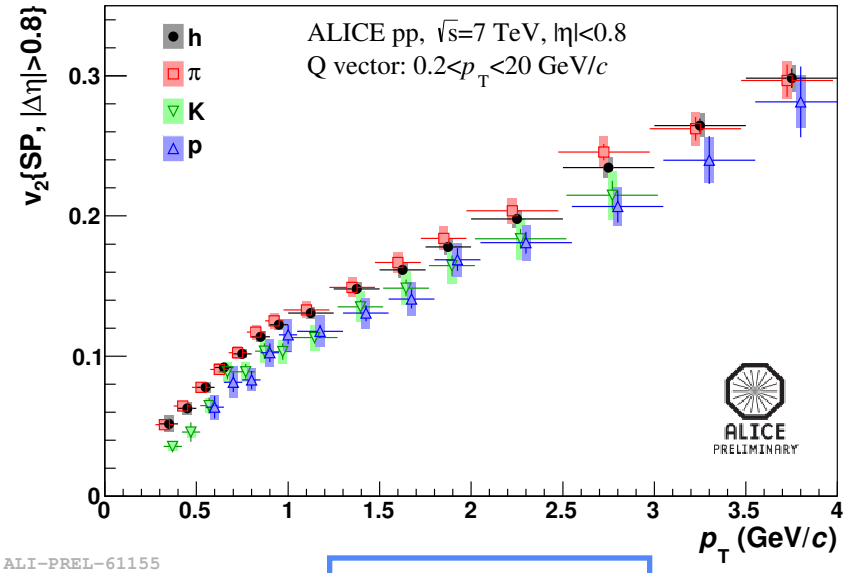
Identified particle v_2 in pp collisions

p-Pb collisions



subtraction: central-peripheral

pp collisions



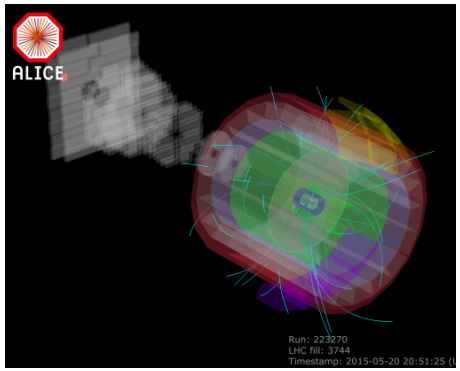
minimum bias pp

- Identified particle v_2 measurements in pp collisions
  - mass dependence (?), no crossing of v_2 of mesons and baryons
  - More hints will be obtained by analyzing high multiplicity pp events.

Summary and Outlook

- The anisotropic flow of charged and identified particles measured in Pb-Pb, p-Pb and pp collisions bring a lot of information of QGP ("perfect liquid"),
  - meanwhile some puzzles remains (flow in p-Pb and pp?)
- The LHC RUN2 program starts this month!
  - the measurements of anisotropic flow will shed new light into the properties of produced matter in these collisions.

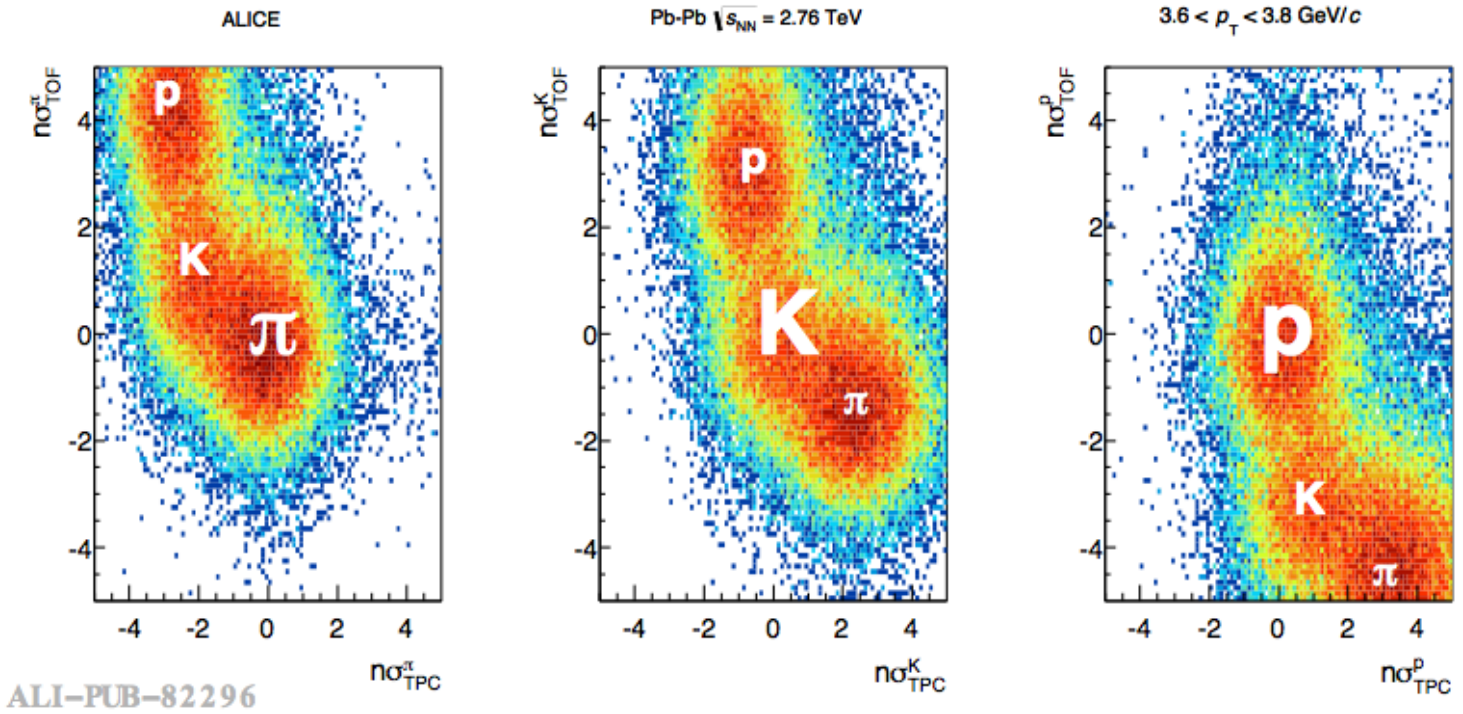
June 3rd, 2015
13 TeV pp collisions



November 2015
5.1 TeV Pb-Pb collisions

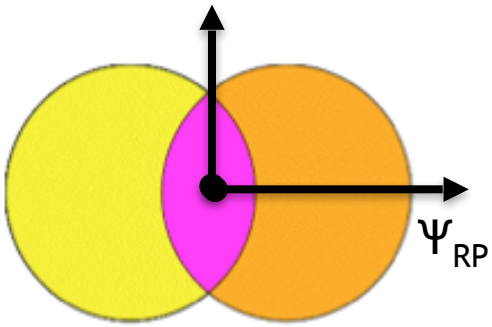
Thanks for your attention!

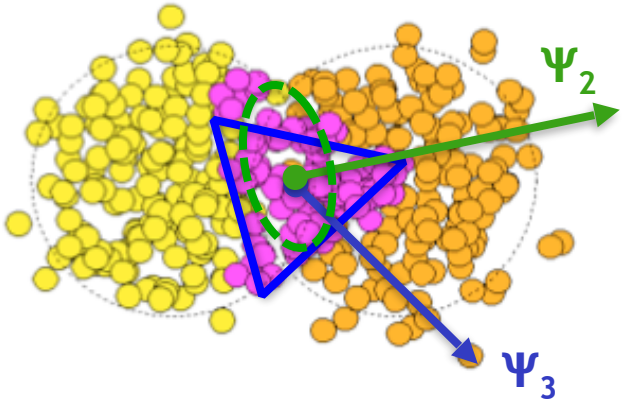
Flow Methodology I



- p, K, p: identification via combination of TPC and TOF information
  - energy loss in TPC and time of flight from TOF combined, optimized as function of p_T for purity and
  - Purity > 95% for p_T < 6 GeV/c
- Elliptic flow of p, K, p are directly measured via *Scalar Product* method with $|\Delta\eta|$ gap.

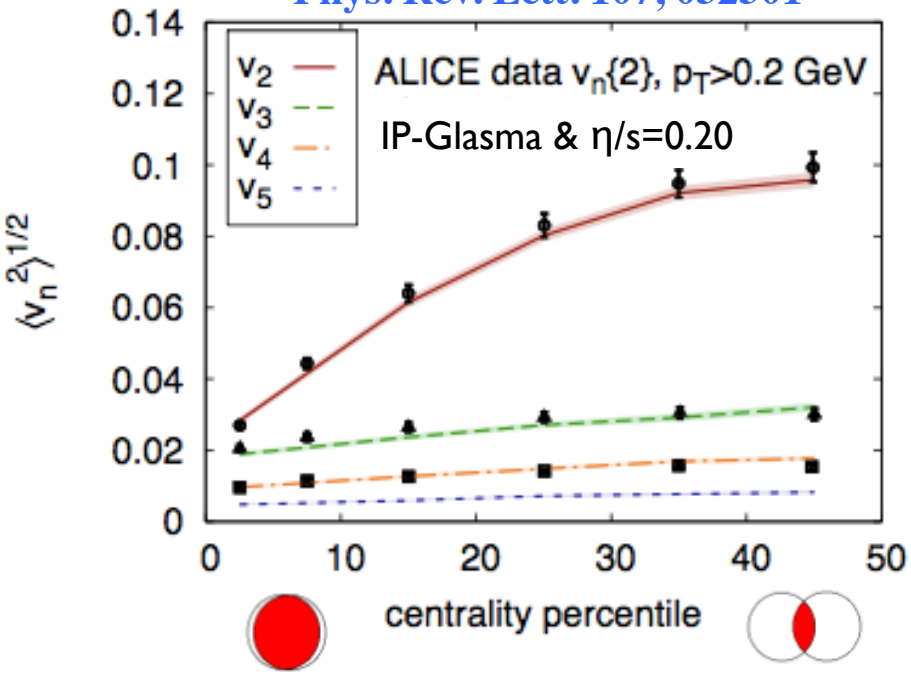
Not only v_2 but also v_3, v_4, v_5





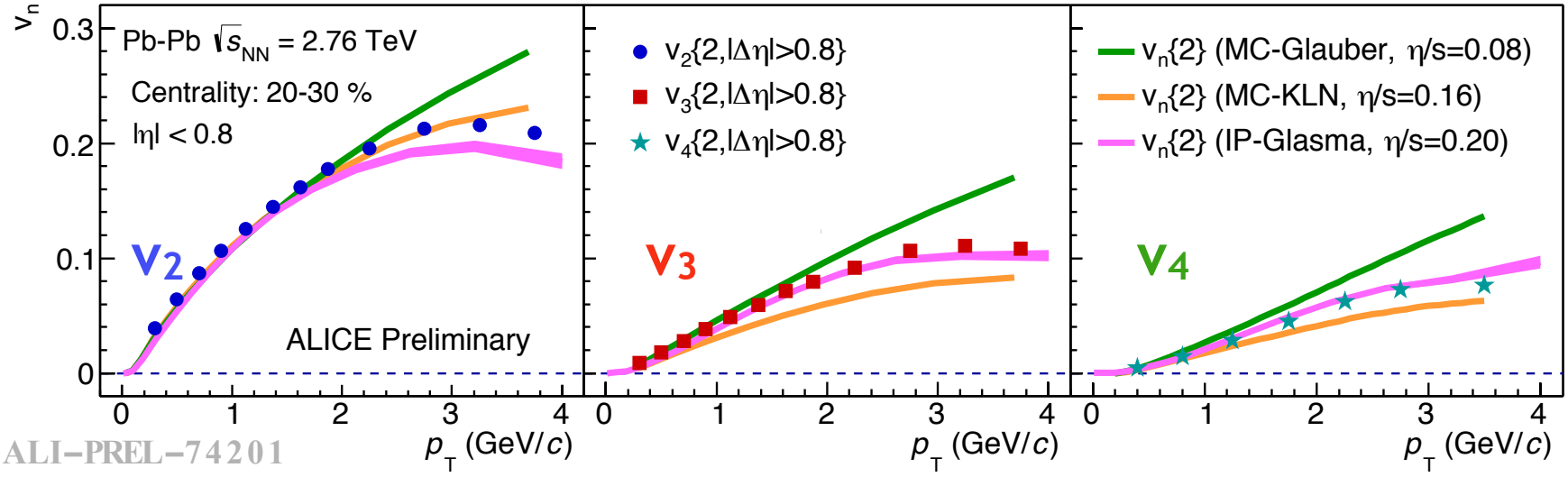
Citation>250 times

ALICE Collaboration, Phys. Rev. Lett. 107, 032301



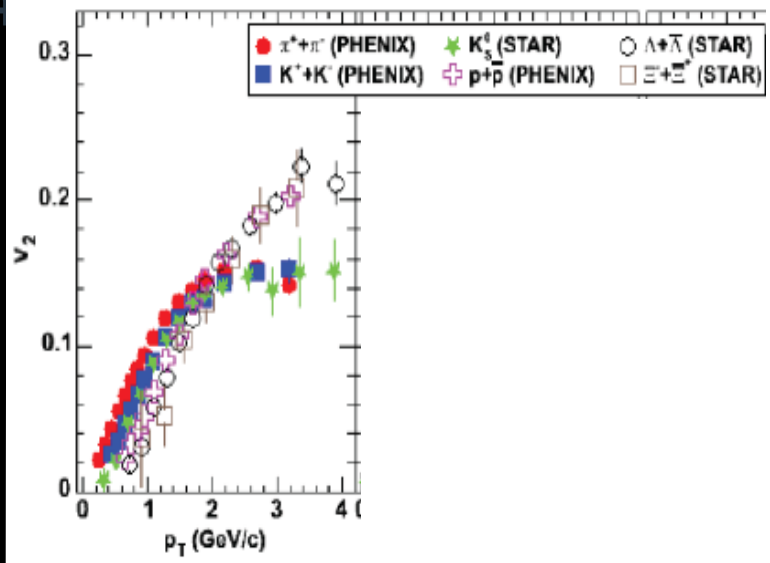
- Almost perfect matches between data and theory!
- Data prefers the IP-Glasma initial conditions and η/s = 0.20.

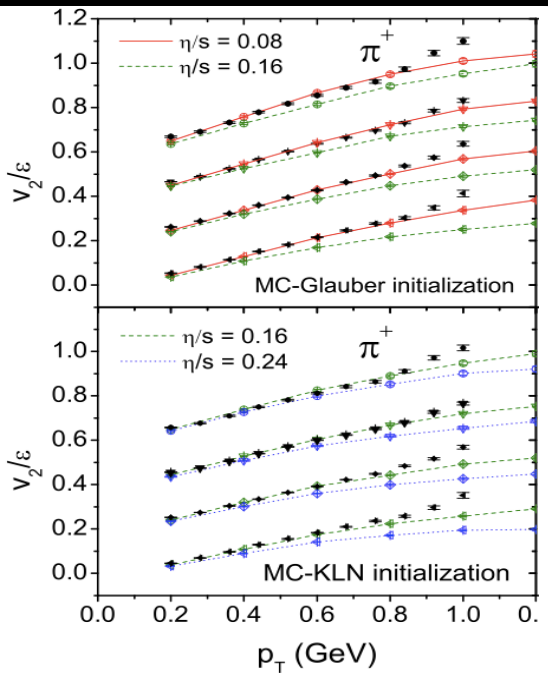
- Traditionally *Flow* analyses look for correlations w.r.t common symmetry planes over a large range in p_T.



  - Constraints on the initial state and η/s.

Lesson learned from RHIC





Experimental side:

- low p_T:

  mass ordering

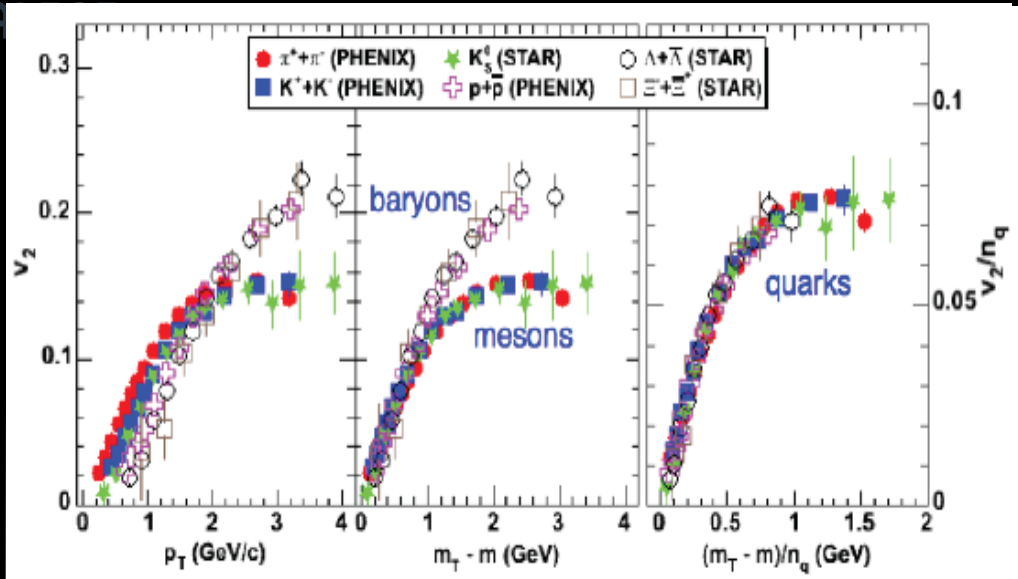
- intermediate p_T:

  Number of constituent Quark scaling (for v_2/n_q *v.s.* p_T/n_q and KE_T/n_q)

Theoretical side:

- low p_T:
  - PID v_2 reproduce by hydrodynamic calclations
  - Glauber & η/s=0.08 and CGC & η/s= 0.16 works well

Lesson learned from RHIC



Experimental side:

- low p_T:
  mass ordering
- intermediate p_T:
  Number of constituent Quark scaling (for v_2/n_q *v.s.* p_T/n_q and KE_T/n_q)

- NCQ scaling:
  - ➢ Quark Coalescence mechanism