Anisotropic flow analysis in ALICE at LHC

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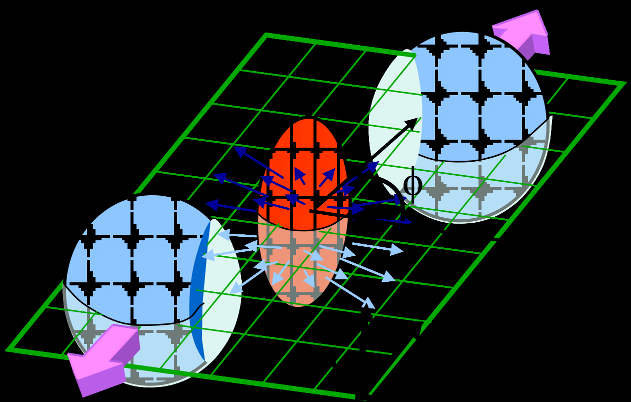
Copenhagen, 13/11/2012

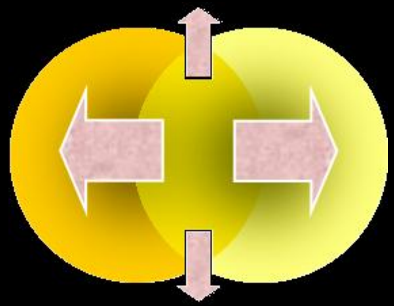
Outline

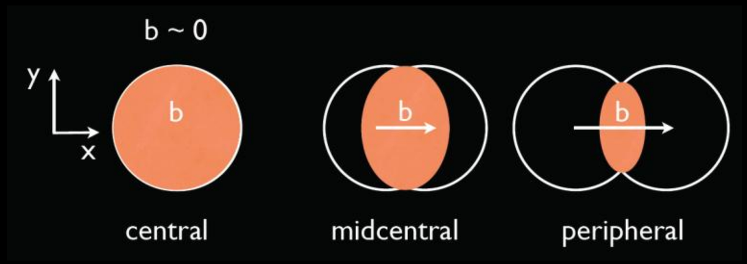
- Introduction
- How do we measure anisotropic flow?
  - Multi-particle *Q*-cumulants (QC)
- Selection of anisotropic flow results in ALICE
- Future prospects

Quick introduction to anisotropic flow

Introduction (1/3)







- Anisotropies in momentum space (S. Voloshin and Y. Zhang (1996)):

$$E\frac{d^3N}{d^3\vec{p}} = \frac{1}{2\pi}\frac{d^2N}{p_T\,dp_T\,dy}\left(1+\sum_{n=1}^{\infty}2v_n\cos\left(n\left(\phi-\Psi_{\mathrm{RP}}\right)\right)\right)$$

$$v_n = \langle\cos(n(\phi-\Psi_{\mathrm{RP}}))\rangle$$

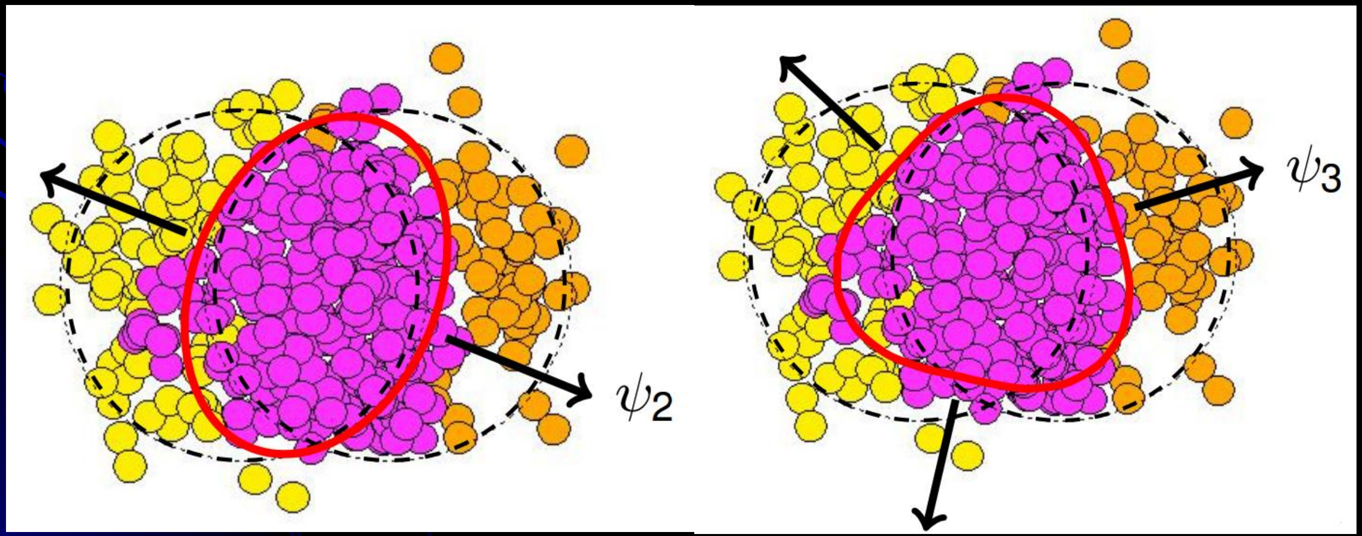
- Harmonics v_n quantify anisotropic flow
  - v_1 is directed flow, v_2 is elliptic flow, v_3 is triangular flow, etc.

Introduction (2/3)

- The paradigm has changed of late:

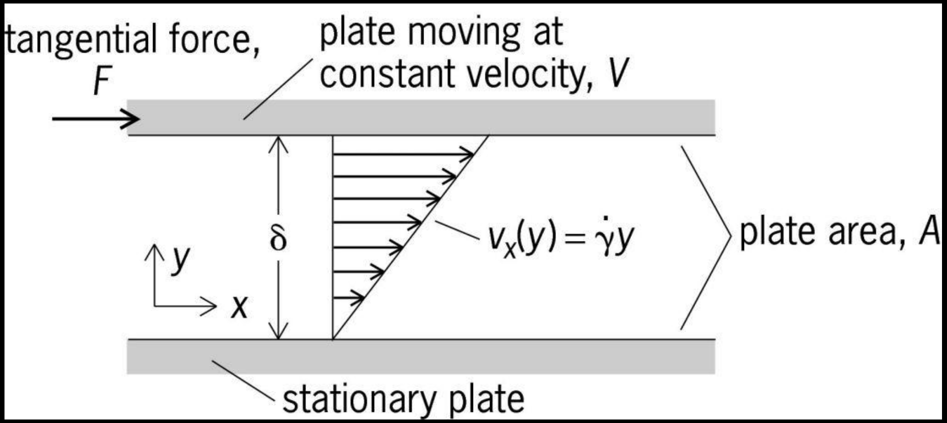
$$v_n = \langle \cos(n(\phi - \Psi_n)) \rangle$$

- We need full Fourier decompositon to also take into account effects of fluctuations => each harmonic has its own symmetry plane
  - What are these symmetry planes?



Introduction (3/3)

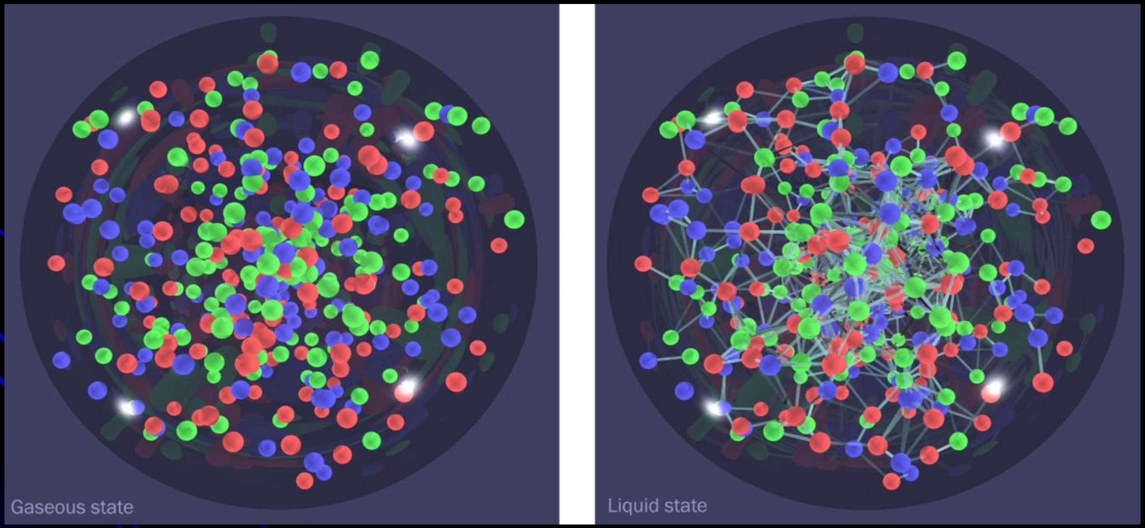
- Anisotropic flow is sensitive probe to system properties => e.g. shear viscosity
  - Perfect liquid <=> shear viscosity negligible <=> flow develops easily



- Shear viscosity characterizes quantitatively the resistance of the liquid or gas to displacement of its layers

A bit of history….

- In 2005 in Au-Au collisions at RHIC after 3 years of data taking the discovery of a new state of matter was reported
  - Expected: weakly interacting gas
  - Observed: strongly coupled liquid



How do we measure anisotropic flow?

Is it really that trivial?

- ‘Standard’ recipe (a.k.a. Event Plane method):
  - Step 1: Measure/estimate reaction (symmetry) plane(s)
  - Step 2: Take azimuthal angles of all reconstructed particles
  - Step 3: Evaluate anisotropic flow harmonics via the average

$$v_n = \langle \cos(n(\phi - \Psi_{\mathrm{RP}})) \rangle$$

…. and you are done!?!?

- However, in experimental practice the above prescription will not work
  - We cannot neither measure directly nor estimate reaction (symmetry) plane(s) reliably event-by-event
  - M. Luzum and J.-Y. Ollitrault, ‘The event-plane method is obsolete’, arXiv:1209.2323 [nucl-ex]

Anisotropic flow (exp)

- Theoretical definition not useful in practice

$$\langle v_n \rangle = \langle\langle \cos(n(\phi - \Psi_{RP})) \rangle\rangle$$

- Alternative approach: Two- and multi-particle azimuthal correlations:

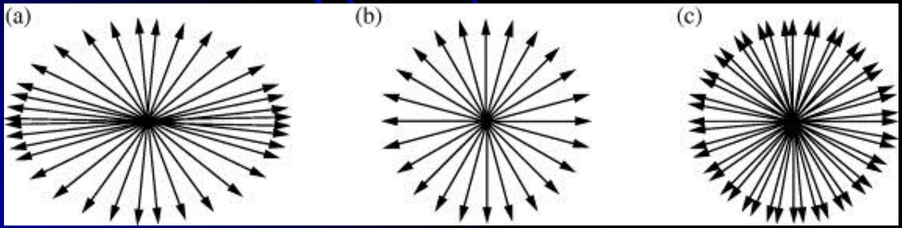
event average

particle average

$$\left\langle\!\left\langle e^{in(\phi_1-\phi_2)} \right\rangle\!\right\rangle = \left\langle\!\left\langle e^{in(\phi_1-\Psi_{RP}-(\phi_2-\Psi_{RP}))} \right\rangle\!\right\rangle$$

$$= \left\langle\!\left\langle e^{in(\phi_1-\Psi_{RP})} \right\rangle \left\langle e^{-in(\phi_2-\Psi_{RP})} \right\rangle\!\right\rangle = \left\langle v_n^2 \right\rangle$$

- Price to pay: Systematic bias due to other sources of correlations (autocorrelations, few-particle non-flow correlations, trivial anisotropy due to detector's non-uniform acceptance)



Multi-particle *Q*-cumulants can do the magic!

Q-cumulants (1/4)

- In what follows X_i will denote the general i-th random observable
- The most general decomposition of 2-particle correlation reads

$$\langle X_1X_2\rangle = \langle X_1\rangle\langle X_2\rangle + \langle X_1X_2\rangle_c$$

- By definition, the 2nd term above is 2-particle cumulant => it isolates the genuine 2-particle correlation in the system, which cannot be factorized further
- We cannot measure cumulants directly, however trivially:

$$\langle X_1X_2\rangle_c = \langle X_1X_2\rangle - \langle X_1\rangle\langle X_2\rangle$$

Q-cumulants (2/4)

- The most general decomposition of 3-particle correlation reads:

$$\begin{aligned}\langle X_1X_2X_3\rangle &= \langle X_1\rangle\langle X_2\rangle\langle X_3\rangle\\ &+ \langle X_1X_2\rangle_c\langle X_3\rangle+\langle X_1X_3\rangle_c\langle X_2\rangle+\langle X_2X_3\rangle_c\langle X_1\rangle\\ &+ \langle X_1X_2X_3\rangle_c\end{aligned}$$

- Inserting previous results for 2-particle cumulants, it follows:

$$\begin{aligned}\langle X_1X_2X_3\rangle_c &= \langle X_1X_2X_3\rangle\\ &- \langle X_1X_2\rangle\langle X_3\rangle-\langle X_1X_3\rangle\langle X_2\rangle-\langle X_2X_3\rangle\langle X_1\rangle\\ &+ 2\langle X_1\rangle\langle X_2\rangle\langle X_3\rangle\end{aligned}$$

- In this way, one can isolate cumulants recursively for any number of random observables

Ryogo Kubo, *"Generalized Cumulant Expansion Method"*

Q-cumulants (3/4)

- In the context of anisotropic flow analysis (Ollitrault *et al*)

$$X_1 \equiv e^{in\phi_1}, \qquad X_2 \equiv e^{in\phi_2}$$
$$X_3 \equiv e^{-in\phi_3}, \qquad X_4 \equiv e^{-in\phi_4}$$

- Azimuthal correlations:

$$\langle 2 \rangle \equiv \langle \cos n(\phi_1 - \phi_2) \rangle \;, \qquad \phi_1 \neq \phi_2$$
$$\langle 4 \rangle \equiv \langle \cos n(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle \;, \qquad \phi_1 \neq \phi_2 \neq \phi_3 \neq \phi_4$$

- Cumulants expressed in terms of azimuthal correlations:

$$\begin{aligned}
QC\{2\} &= \langle\langle 2 \rangle\rangle \\
QC\{4\} &= \langle\langle 4 \rangle\rangle - 2\,\langle\langle 2 \rangle\rangle^2 \\
QC\{6\} &= \langle\langle 6 \rangle\rangle - 9\,\langle\langle 2 \rangle\rangle\,\langle\langle 4 \rangle\rangle + 12\,\langle\langle 2 \rangle\rangle^3 \\
QC\{8\} &= \langle\langle 8 \rangle\rangle - 16\,\langle\langle 6 \rangle\rangle\,\langle\langle 2 \rangle\rangle - 18\,\langle\langle 4 \rangle\rangle^2 \\
&+ 144\,\langle\langle 4 \rangle\rangle\,\langle\langle 2 \rangle\rangle^2 - 144\,\langle\langle 2 \rangle\rangle^4
\end{aligned}$$

Q-cumulants (4/4)

- When only flow correlations are present in the system their contribution to QCs is well understood and quantified (neglecting e-b-e flow fluctuations):

$$
\begin{aligned}
QC\{2\} &= v^2 \\
QC\{4\} &= -v^4 \\
QC\{6\} &= 4v^6 \\
QC\{8\} &= -33v^8
\end{aligned}
$$

- Thing to note and remember: Flow contribution to QCs have a distinct signature (+,-,+,-)
  - In order to interpret dominant contribution to QCs as a flow this signature is a necessary condition (not sufficient, though)

Finally => $v_n\{2\}, v_n\{4\}, v_n\{6\}, v_n\{8\}$

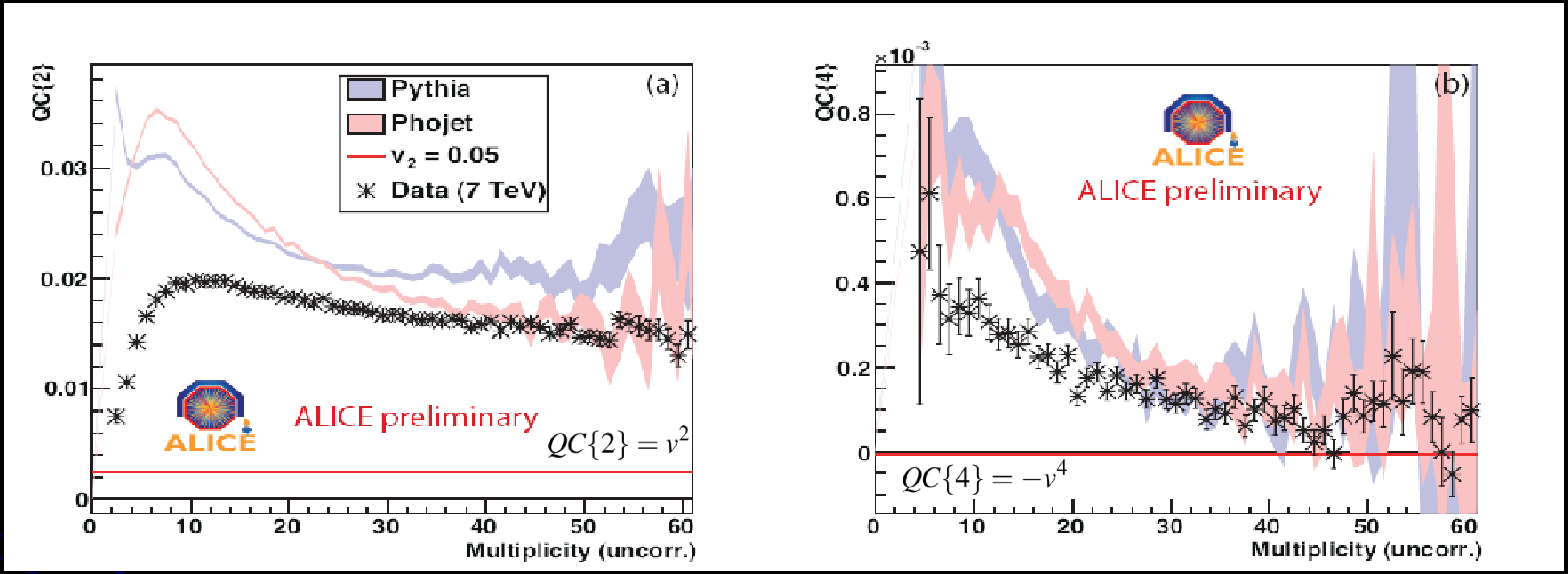
Data analysis, Part 1 (‘waiting for heavy-ions’)

pp

Elliptic flow in *pp*? (1/2)

- Effects of collectivity in high multiplicity *pp* collisions as well?
  - Various theoretical predictions indicate possible elliptic flow values between 0.03 and 0.15 in *pp* collisions @ LHC energies
- Testing the software and getting experienced with ALICE analysis framework

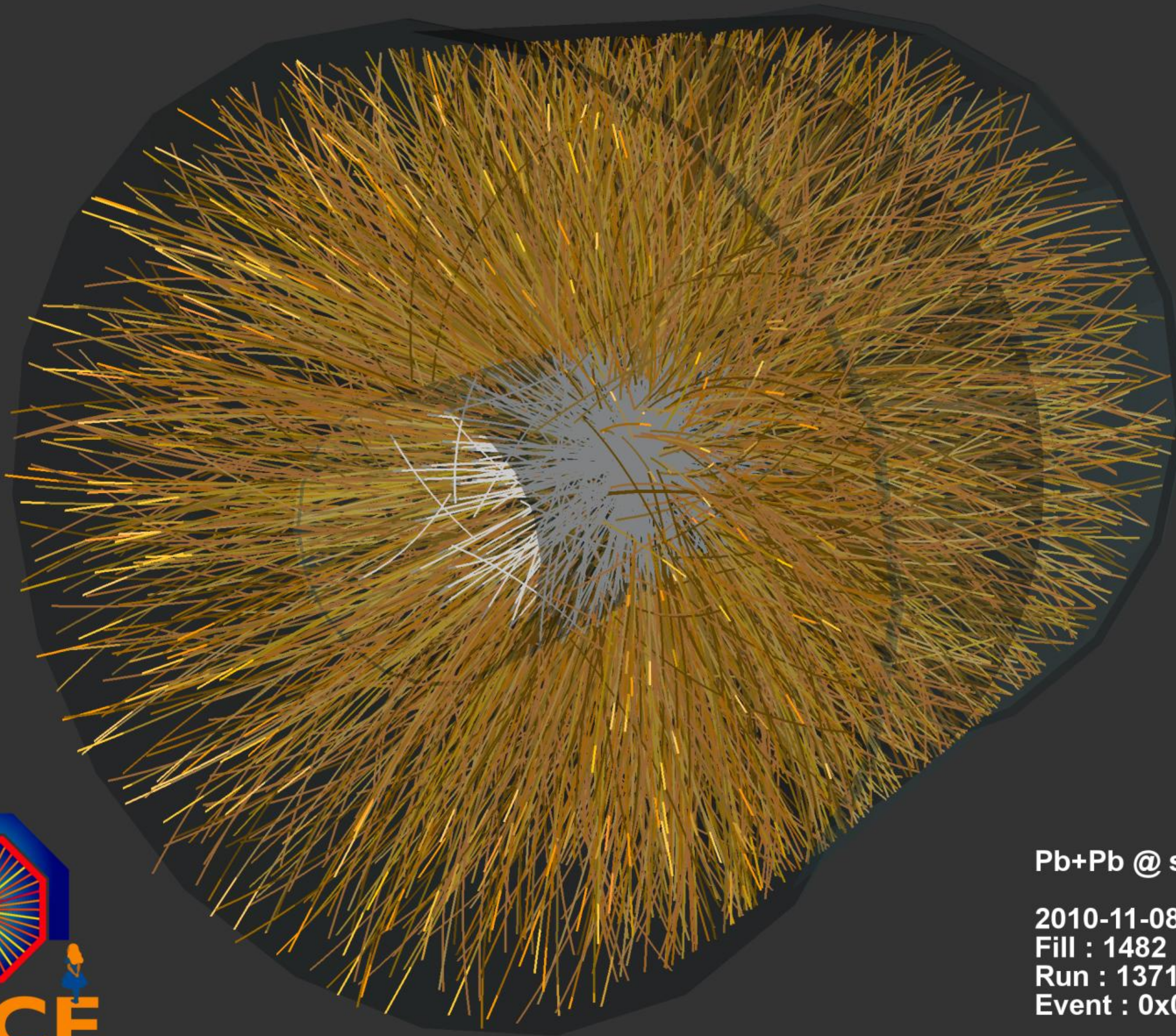
Elliptic flow in *pp*? (2/2)



- Both 2- and 4-particle correlations decrease with multiplicity: Typical for non-collective behavior
- Pythia and Phojet are overestimating the strength of the correlations (and these two generators are dominated by jets and resonances)
- 4-p cumulant comes with a “wrong sign” => its dominant contribution is not coming from flow
- Current status – We do not see elliptic flow in *pp*

Data analysis, Part 2 (‘mission accomplished’)

PbPb

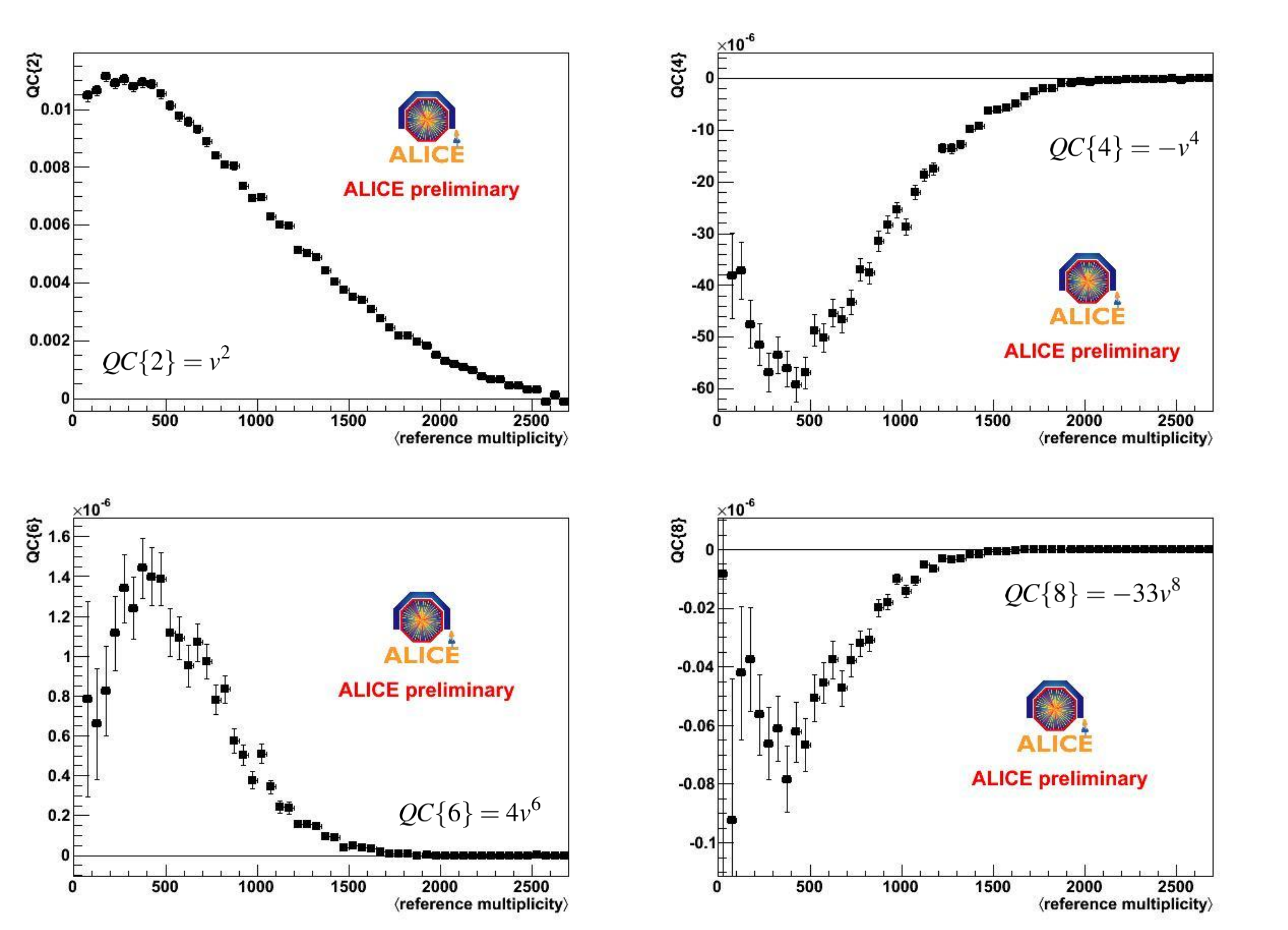


Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:29:52
Fill : 1482
Run : 137124
Event : 0x0000000042B1B693

ALICE

Flow at first sight!



Elliptic flow paper (1/3)

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)

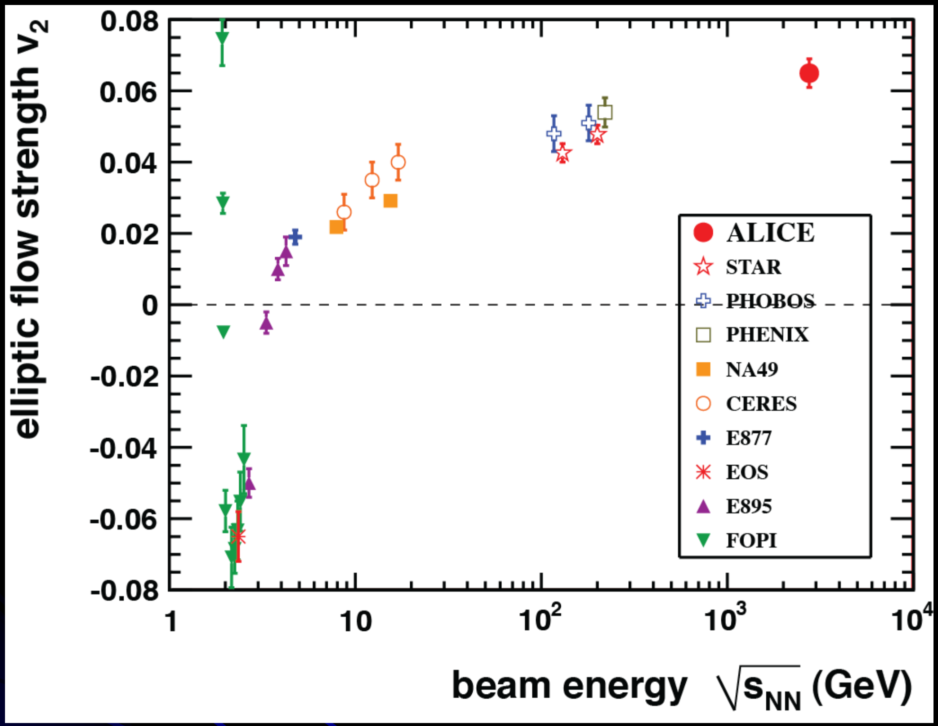
(Received 18 November 2010; published 13 December 2010)

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

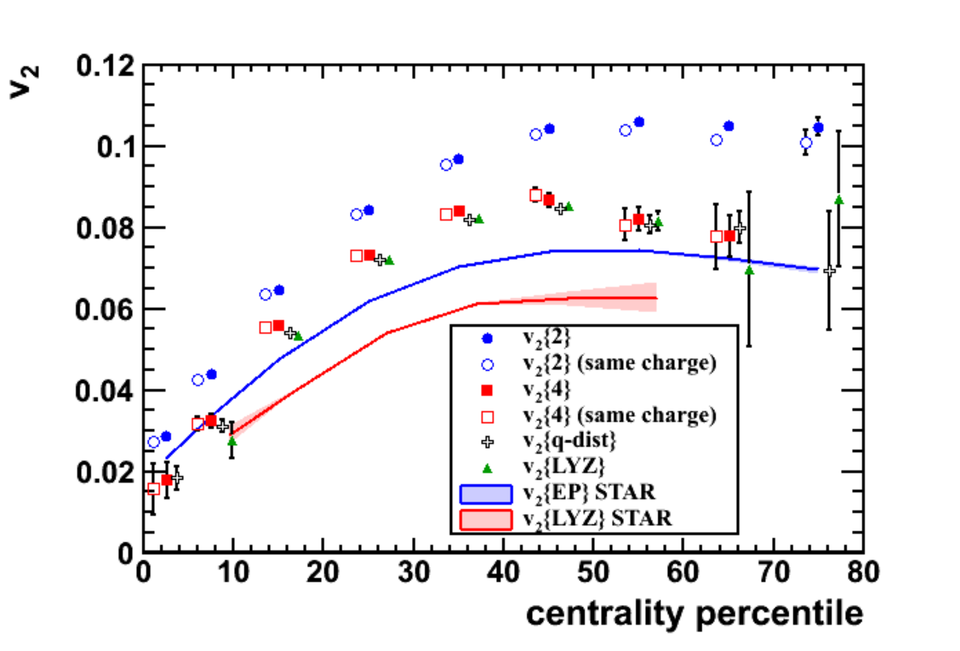
The goal of ultrarelativistic nuclear collisions is the creation and study of the quark-gluon plasma (QGP), a state of matter whose existence at high energy density is predicted by quantum chromodynamics. One of the experimental observables that is sensitive to the properties of this matter is the azimuthal distribution of particles in the plane perpendicular to the beam direction. When nuclei collide at finite impact parameter (noncentral collisions), the geometrical overlap region and therefore the initial matter distribution is anisotropic (almond shaped). If the matter scribe flow at RHIC predict an increase of the elliptic flow at the LHC ranging from 10% to 30%, with the largest increase predicted by models which account for viscous corrections [15–18] at RHIC energies. In models with viscous corrections, v_2 at RHIC is below the ideal hydrodynamic limit [12,17] and therefore can show a stronger increase with energy. In hydrodynamic models the charged particle elliptic flow as a function of transverse momentum does not change significantly [7,14], while the p_t-integrated elliptic flow increases due to the rise in

Elliptic flow paper (2/3)



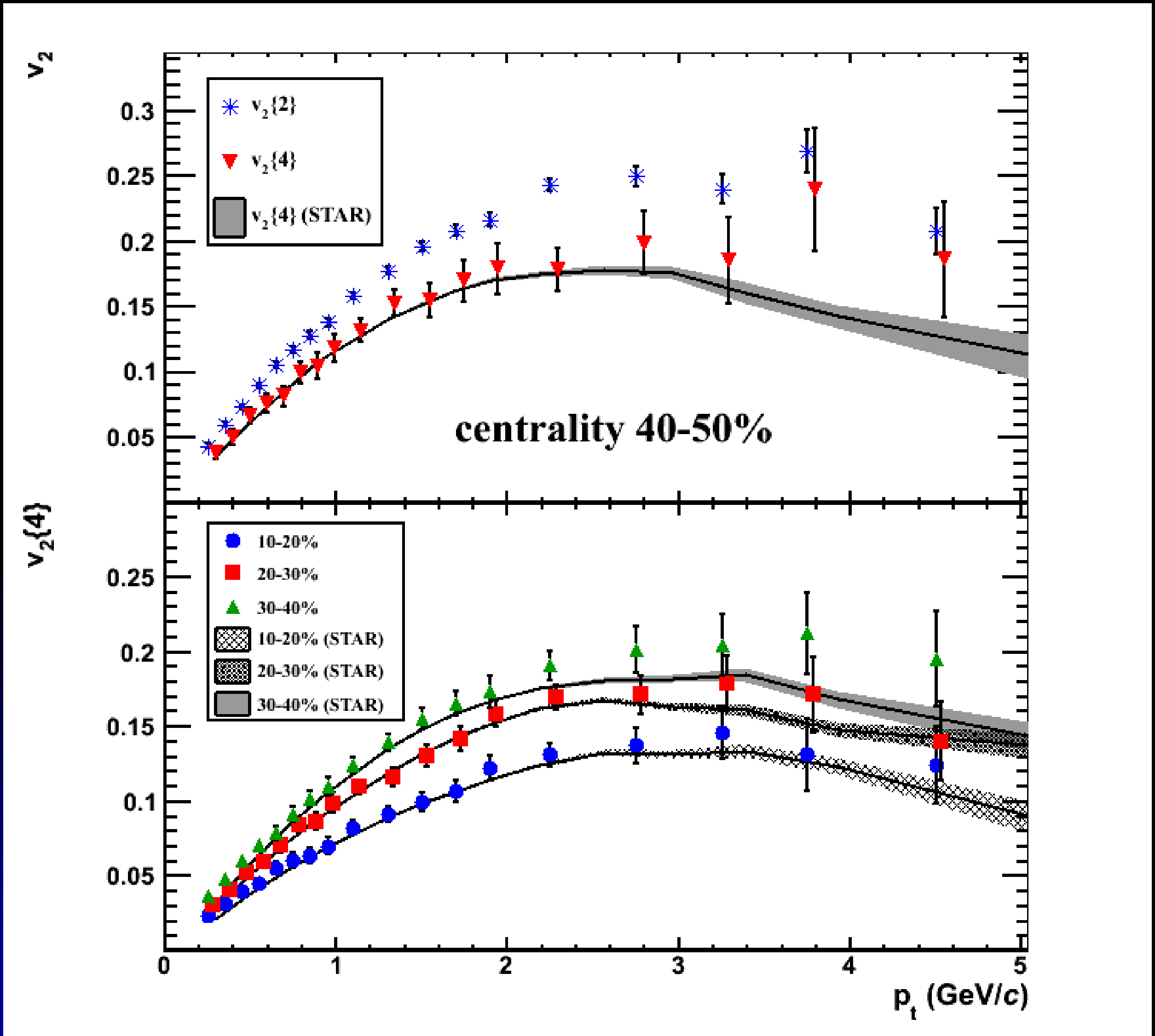
Phys. Rev. Lett. 105, 252302 (2010)

Cited by now almost 250 times!
The most cited LHC physics paper until Higgs overtook the honor ....



Elliptic flow increases by ~ 30% when compared to RHIC energies

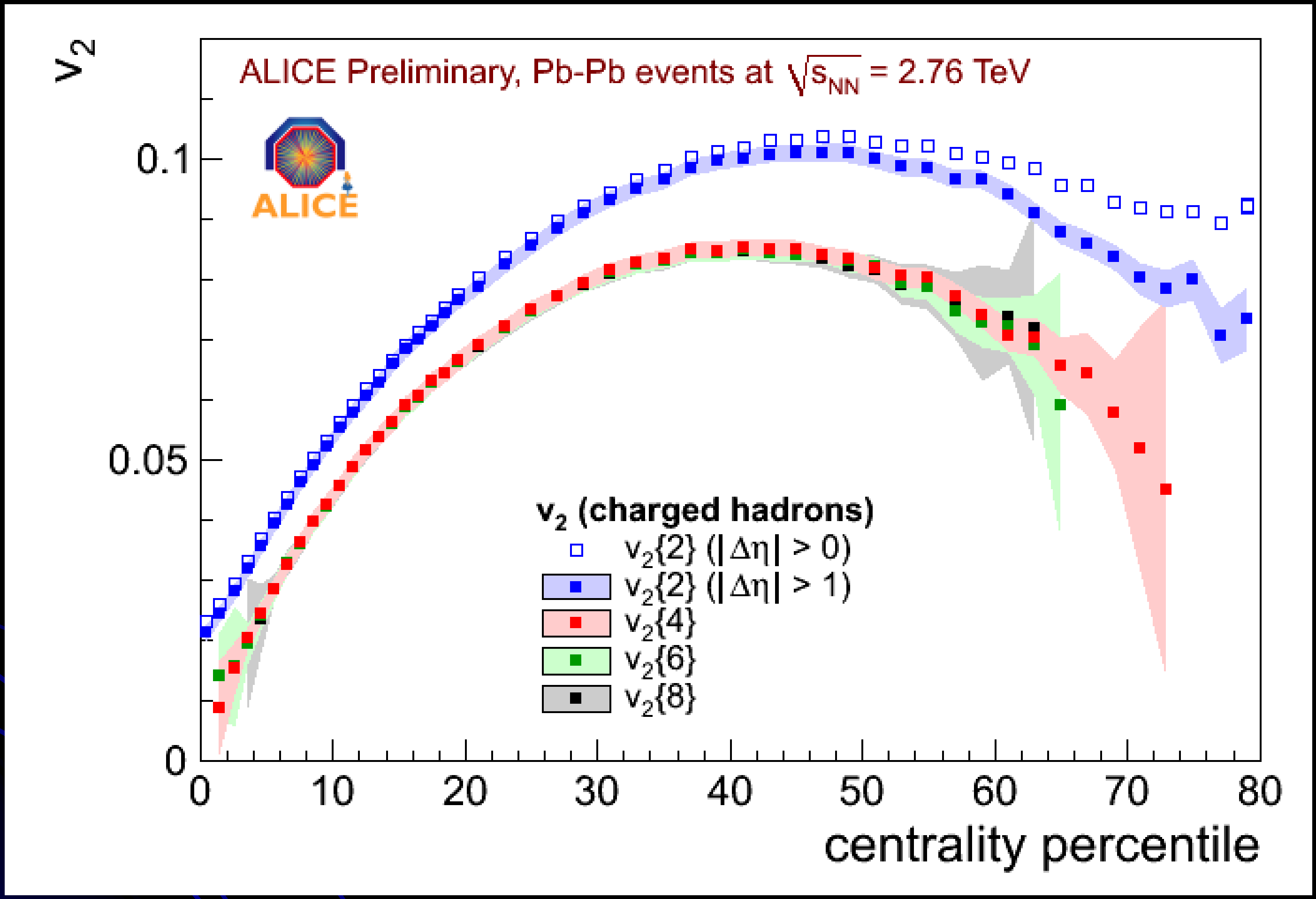
Elliptic flow paper (3/3)



Phys. Rev. Lett. 105, 252302 (2010)

p_t dependence of elliptic flow at LHC close to the one at RHIC!

Exploiting all statistics….



- The difference between 2- and multi-particle estimates is due to fluctuations in the initial geometry
- $v_2\{2\}$ might still have some non-flow bias leftover (not in the systematical uncertainty here). With eta gap non-flow is suppressed, not eliminated completely

“Higher harmonics” paper

PRL **107,** 032301 (2011) PHYSICAL REVIEW LETTERS week ending 15 JULY 2011

Higher Harmonic Anisotropic Flow Measurements of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

K. Aamodt *et al.**
(ALICE Collaboration)
(Received 19 May 2011; published 11 July 2011)

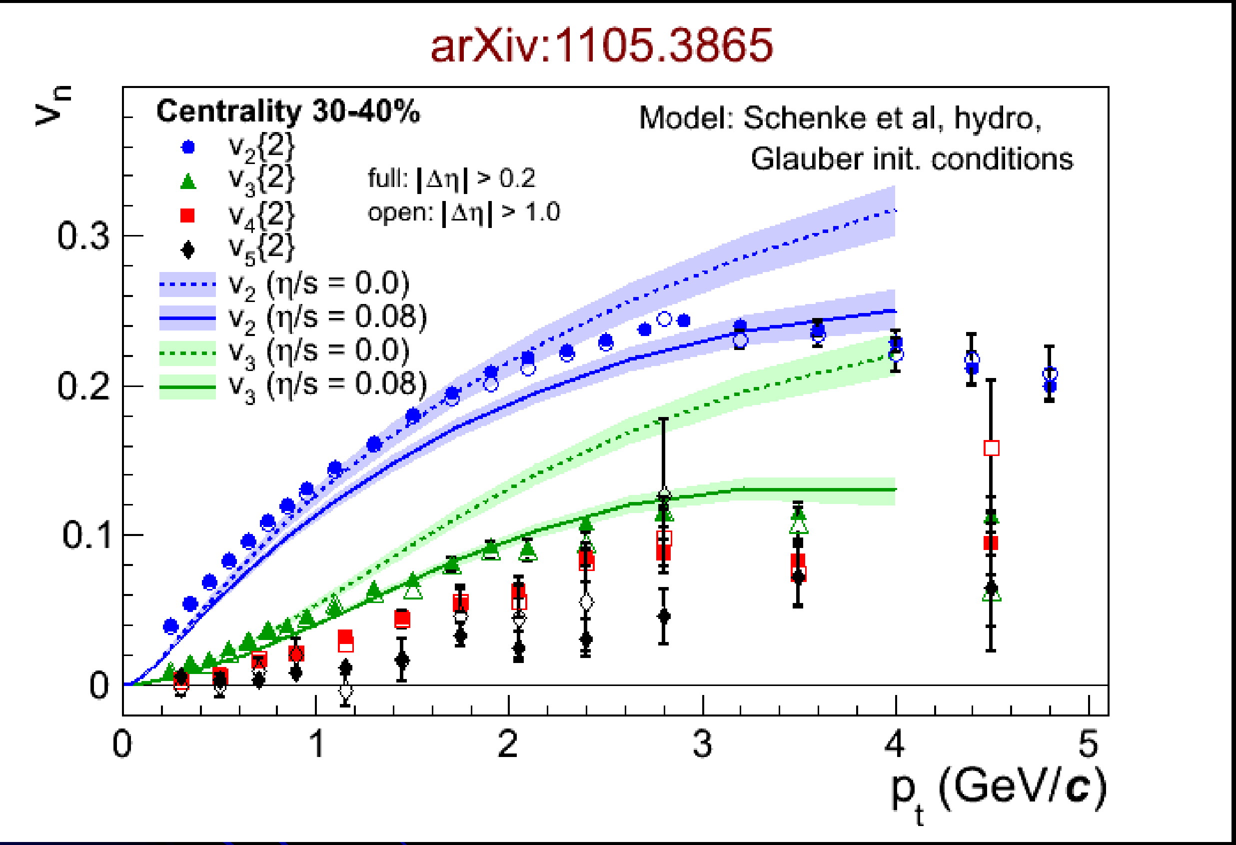
We report on the first measurement of the triangular v_3, quadrangular v_4, and pentagonal v_5 charged particle flow in Pb-Pb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV measured with the ALICE detector at the CERN Large Hadron Collider. We show that the triangular flow can be described in terms of the initial spatial anisotropy and its fluctuations, which provides strong constraints on its origin. In the most central events, where the elliptic flow v_2 and v_3 have similar magnitude, a double peaked structure in the two-particle azimuthal correlations is observed, which is often interpreted as a Mach cone response to fast partons. We show that this structure can be naturally explained from the measured anisotropic flow Fourier coefficients.

DOI: 10.1103/PhysRevLett.107.032301 PACS numbers: 25.75.Ld, 05.70.Fh, 25.75.Gz

The quark-gluon plasma is a state of matter whose existence at high-energy density is predicted by quantum chromodynamics. The creation of this state of matter in the laboratory and the study of its properties are the main goals

odd Fourier coefficients are zero by symmetry. However, due to fluctuations in the matter distribution, including contributions from fluctuations in the positions of the participating nucleons in the nuclei, the plane of symmetry

Comparison to models



Within this model overall magnitude of v_2 and v_3 seems to be fine, but the details of p_t dependence are not well described

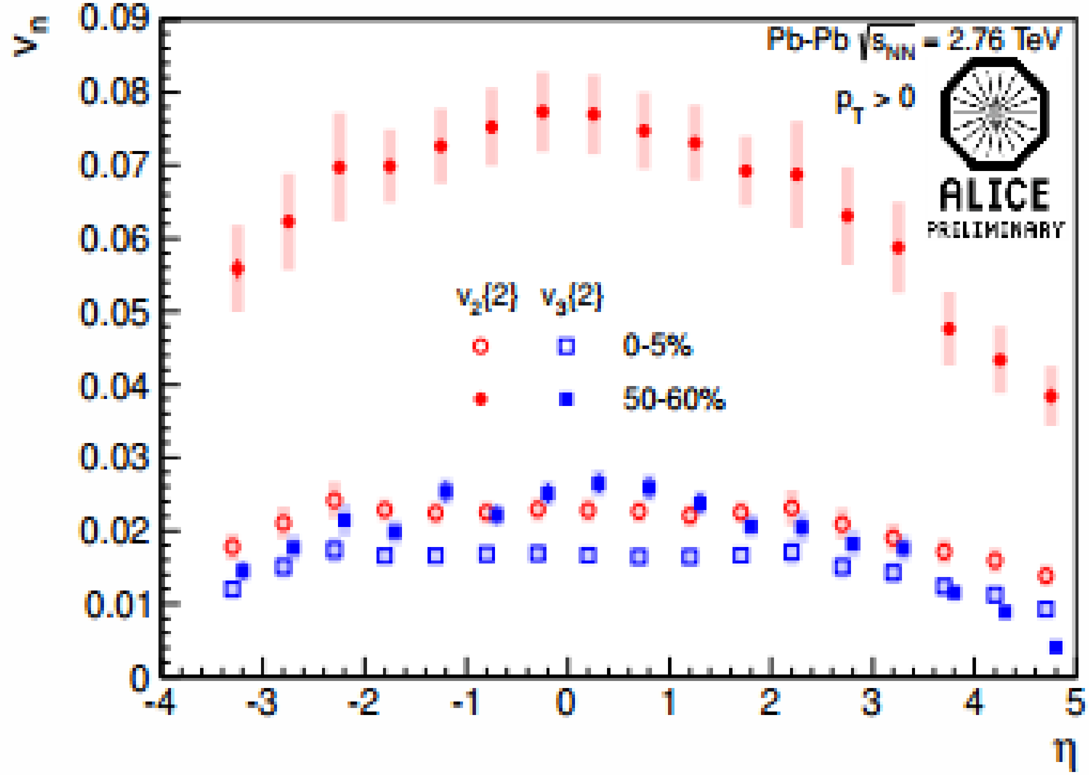
- More quantitative statement: The magnitude of $v_2(p_t)$ is described better with eta/s = 0, while for $v_3(p_t)$ eta/s = 0.08 provides a better description
- This model fails to describe well v_2 and v_3 simultaneously
- Produced matter in Pb-Pb collisions at LHC continues to behave as a nearly perfect liquid

Data analysis, Part 3
(‘QM 2012’)

Quark Matter 2012

- QM is the largest conference dedicated to relativistic heavy ion physics, and this year marked the 23rd edition
- The Discovery Center made its presence felt, with two parallel talks, a poster and large contributions to a third parallel talk
  - A. Hansen: 'Pseudorapidity dependence of the anisotropic flow with ALICE at the LHC'
  - A. Bilandzic: 'Anisotropic flow measured from multi-particle azimuthal correlations for Pb-Pb collisions at 2.76 TeV by ALICE at the LHC'
  - M. Guilbaud, H. Dalsgaard: 'Pseudorapidity density of charged particles in a wide pseudorapidity range and its centrality dependence in Pb-Pb collisions at 2.76 TeV'
  - J. J. Gaardhoje *et al* (poster): 'Morphology of High-Multiplicity Events in Heavy Ion Collisions'

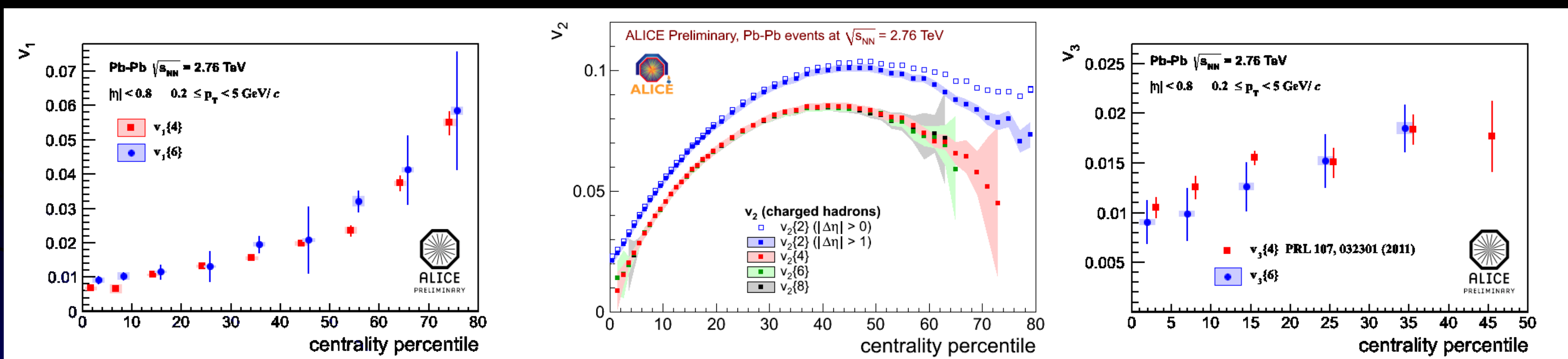
Elliptic and triangular flow with ALICE



- $v_2\{2\}$ and $v_3\{2\}$ measured over wide rapidity range: $-3.5 < \eta < 5$.
- v_2 has strong centrality dependence.
- v_3 has weaker centrality dependence (expected for flow fluctuations).

What is the p.d.f. of e-b-e flow fluctuations?

- Established experimentally that $v_n\{4\} \sim v_n\{6\}$ => p.d.f. of e-b-e flow fluctuations must have non-negligible 3rd/higher moments (when compared to the 1st/2nd moment)
  - http://echoserver.sinc.stonybrook.edu:8080/ess/echo/presentation/b189a3e6-bc07-4328-b511-82d4cfe90292



- Bessel-Gaussian function is an example of p.d.f. with $v_n\{4\} = v_n\{6\}$

Voloshin *et al*:
PLB 659, 537 (2008)

$$
\begin{aligned}
f(v) &= \frac{v}{b^2}\exp\left(-\frac{v^2+a^2}{2b^2}\right) I_0\left(\frac{va}{b^2}\right) \\
v\{2\} &= \sqrt{a^2+2b^2} \\
v\{4,6,\ldots\} &= a
\end{aligned}
$$

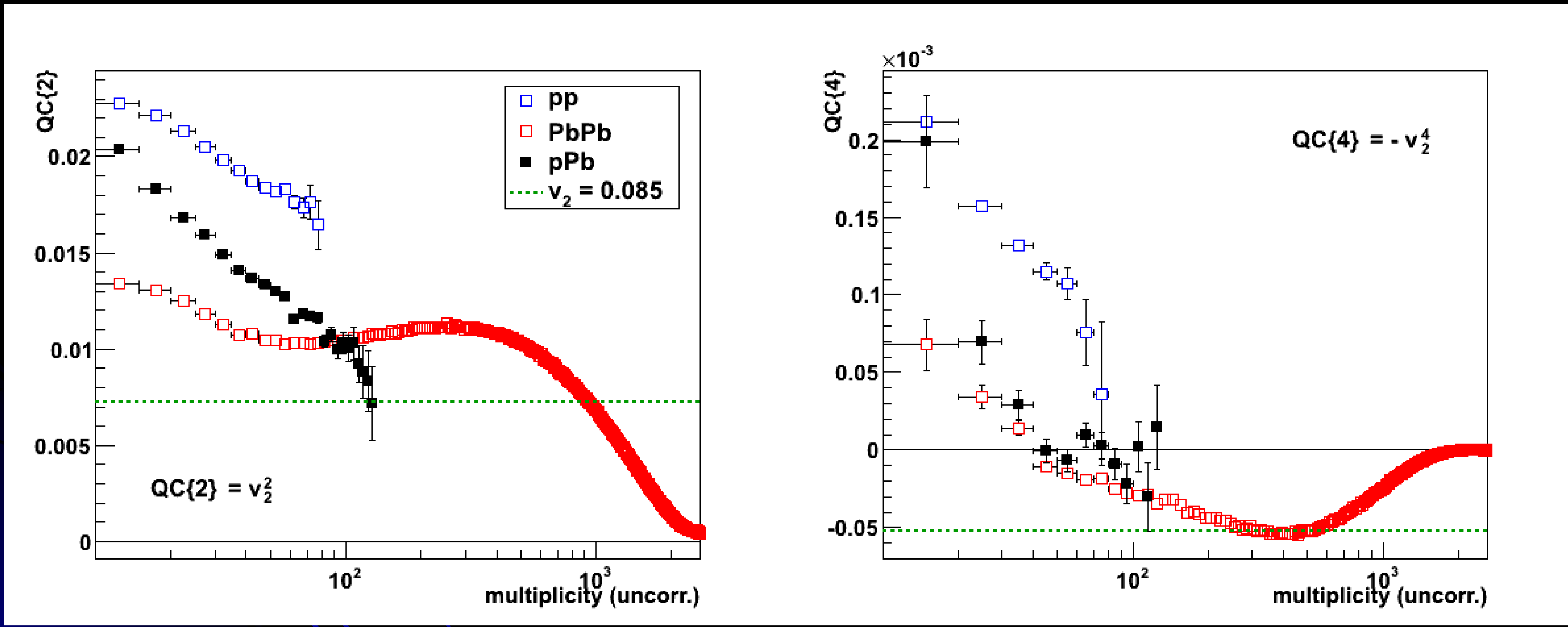
Data analysis, Part 4
('pilot pPb run')

Pilot pPb run (1/2)

- Questions: Is there any physical difference between azimuthal correlations measured in pPb, pp and most peripheral PbPb? Does anisotropic flow develops in pPb collisions?
  - Presumably, all of them are dominated by non-flow => Is there any non-trivial difference in that non-flow?
  - Example: If pPb is just a trivial pile-up of many individual pp collisions, the non-flow in pPb will be just trivially diluted non-flow measured in pp.
- Let’s see ....

Pilot pPb run (2/2)

- QC{2} and QC{4} comparison between pp, PbPb and pPb:



- What we can conclude from this?

Future prospects

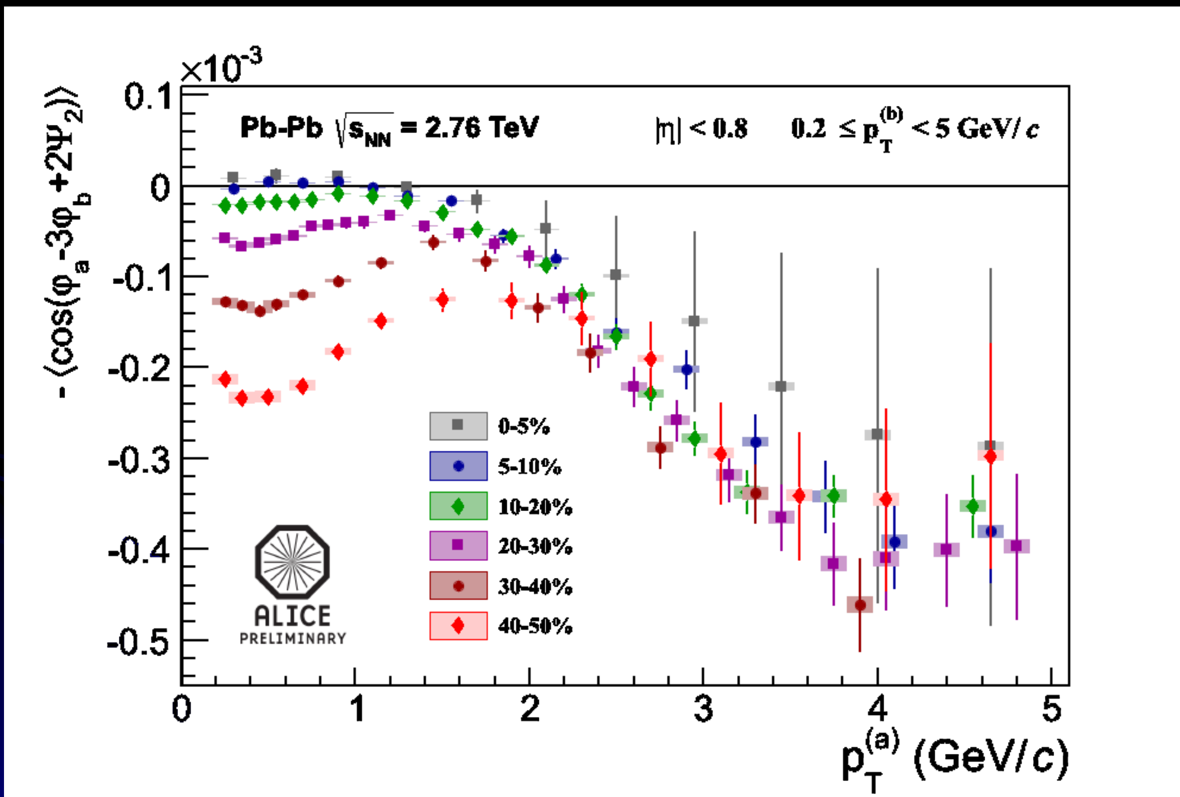
Future prospects (1/2)

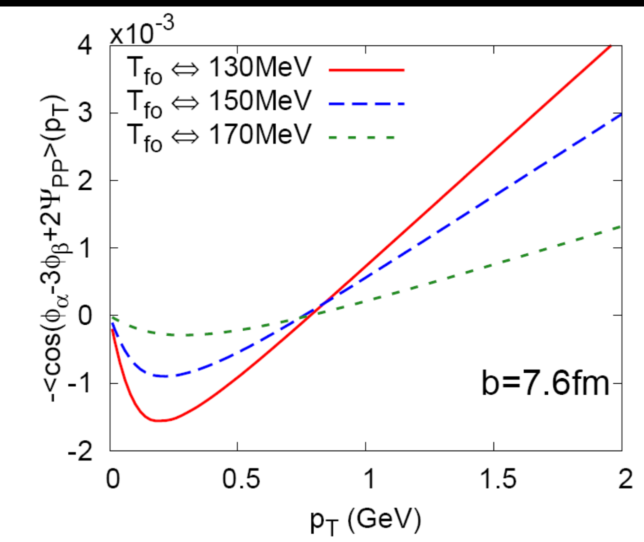
- v_n harmonics fluctuate event-by-event => are these fluctuations correlated, and can we quantify these correlations?
- Each harmonic v_n has a distinct symmetry plane => what is the relation between these distinct symmetry planes?
- Development of new azimuthal observables (so called 'mixed harmonics multi-particle correlators')
- Differential non-flow analysis in pp and pPb

Above measurements are example new measurements currently underway at Discovery center which will further clarify the properties of nuclear matter produced in ultra-relativistic collisions at LHC!

Future prospects (2/2)

$$\langle\cos(\varphi_a - 3\varphi_b + 2\varphi_c)\rangle = \langle\cos(\varphi_a - 3\varphi_b + 2\Psi_2)\rangle \times v_2$$





Teaney, Yan PRC **83**, 064904 (2011)

- Measured correlations have different structure than expected from MC Glauber + ideal hydro model calculations => challenge for theorists

Thanks!

Backup

Anisotropic flow

- Why we do not care about 'sinus terms'?
  - It is equally probable for a particle to be produced in directions φ and $-\varphi$:

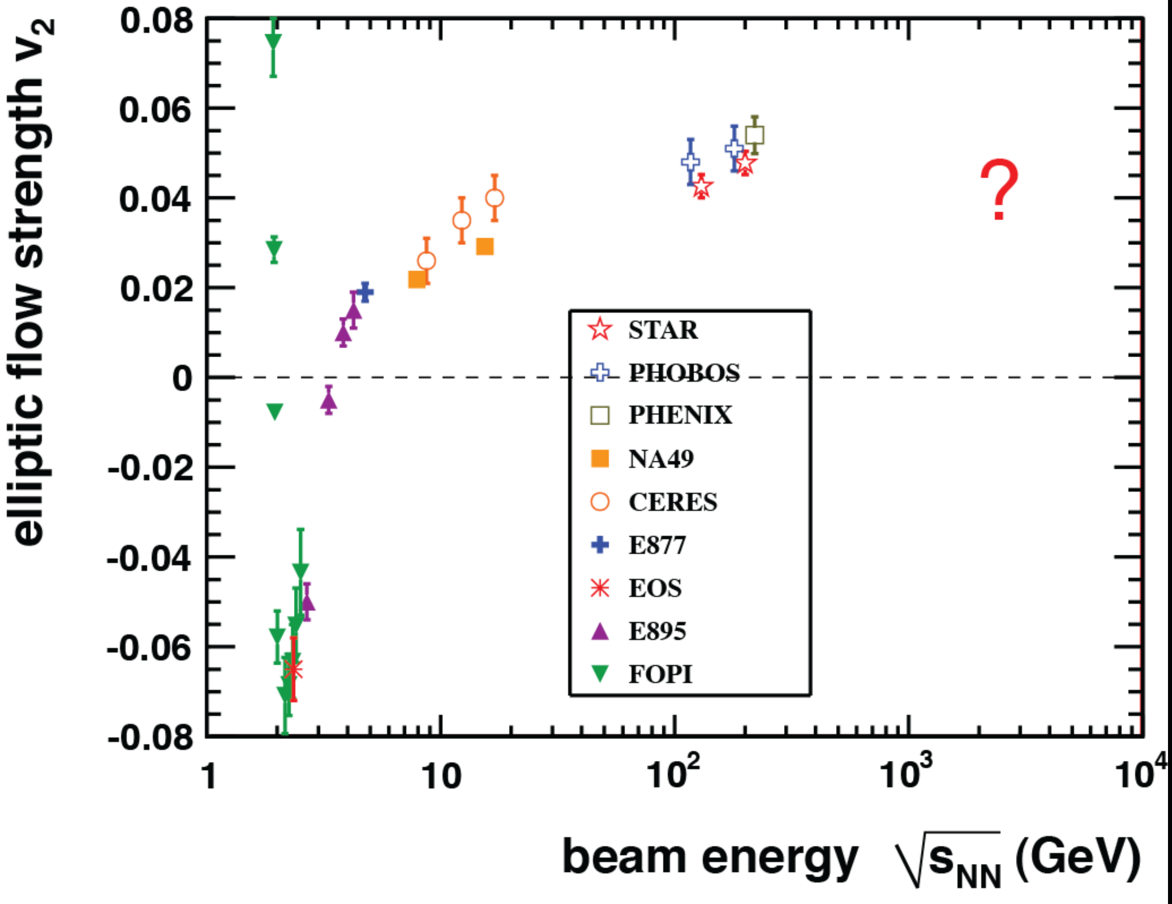
$$\sin(n\varphi) + \sin[n(-\varphi)] = \sin(n\varphi) - \sin(n\varphi) = 0$$

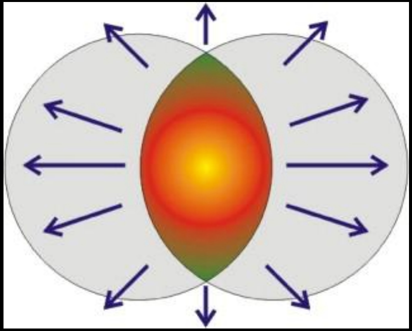
- Can 'odd cosine terms' be non-zero for ideal geometry?
  - It is equally probable for a particle to be produced in directions φ and $\varphi + \pi$:

$$\begin{aligned}
\cos(n\phi) + \cos[n(\phi+\pi)] &= \cos(n\phi) + \cos(n\phi)\cos(n\pi) - \sin(n\phi)\sin(n\pi) \\
&= \cos(n\phi) + \cos(n\phi)(-1)^n - \sin(n\phi)\cdot 0 \\
&= \cos(n\phi)\cdot(1+(-1)^n) = 0 \text{ for odd } n
\end{aligned}$$

A bit of history….

- Is the collective behavior of matter at LHC still like a perfect liquid or rather a viscous gas?





Bounce-off?
Squeeze-out?
Flow in-plane?

Autocorrelations

- We have to correlate only distinct particles, because autocorrelations are dominant and useless (really!) contribution in all averages. So:

$$\langle 2\rangle \equiv \langle\cos n(\phi_1-\phi_2)\rangle\ , \qquad \phi_1 \neq \phi_2$$

$$\langle 4\rangle \equiv \langle\cos n(\phi_1+\phi_2-\phi_3-\phi_4)\rangle\ , \qquad \phi_1 \neq \phi_2 \neq \phi_3 \neq \phi_4$$

- How to enforce above constrains in practice?
  - Brute force evaluation via nested loops? => not feasible
  - Formalism of generating functions? => only approximate

$$G_n(z) \equiv \prod_{j=1}^{M}\left(1+\frac{z^* e^{in\phi_j}+ze^{-in\phi_j}}{M}\right)$$

$$\langle G_n(z)\rangle = \sum_{k=0}^{M/2}\frac{|z|^{2k}}{M^{2k}}\binom{M}{k}\binom{M-k}{k}\left\langle e^{in(\phi_1+\cdots+\phi_k-\phi_{k+1}-\cdots-\phi_{2k})}\right\rangle$$

N. Borghini, P. M. Dinh and J.-Y. Ollitrault, "Flow analysis from multiparticle azimuthal correlations," PRC 64 (2001) 054901

Q-cumulants

- We have a new analytic results to eliminate all autocorrelations!
- Q-vector (a.k.a. flow vector) Q_n evaluated in harmonic n:

$$Q_n = \sum_{i=1}^{M} e^{in\phi_i}$$

- Key result: Analytical expressions for multi-particle azimuthal correlations in terms of Q-vectors

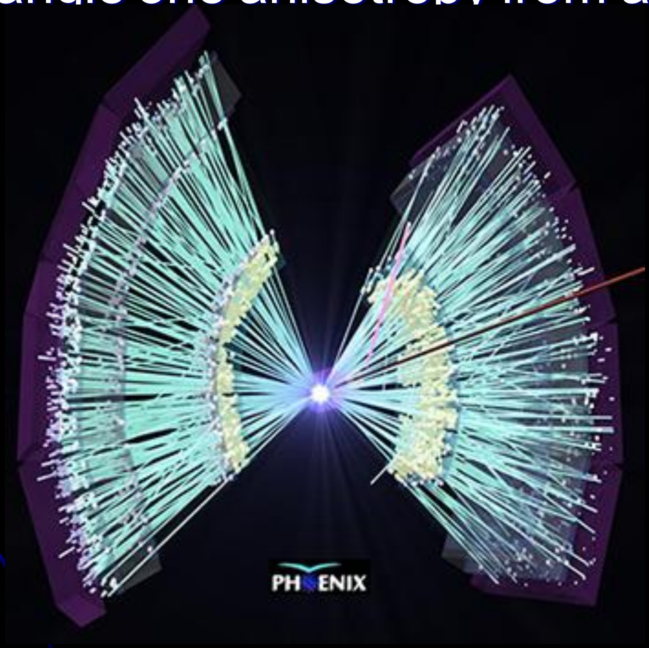
$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2 \cdot \mathbf{Re}\left[Q_{2n} Q_n^* Q_n^*\right] - 4(M-2) \cdot |Q_n|^2}{M(M-1)(M-2)(M-3)} + \frac{2}{(M-1)(M-2)}$$

R. Snellings, S. Voloshin, A.B. *“Flow analysis with cumulants: Direct calculations”*, PRC 83, 044913 (2011)

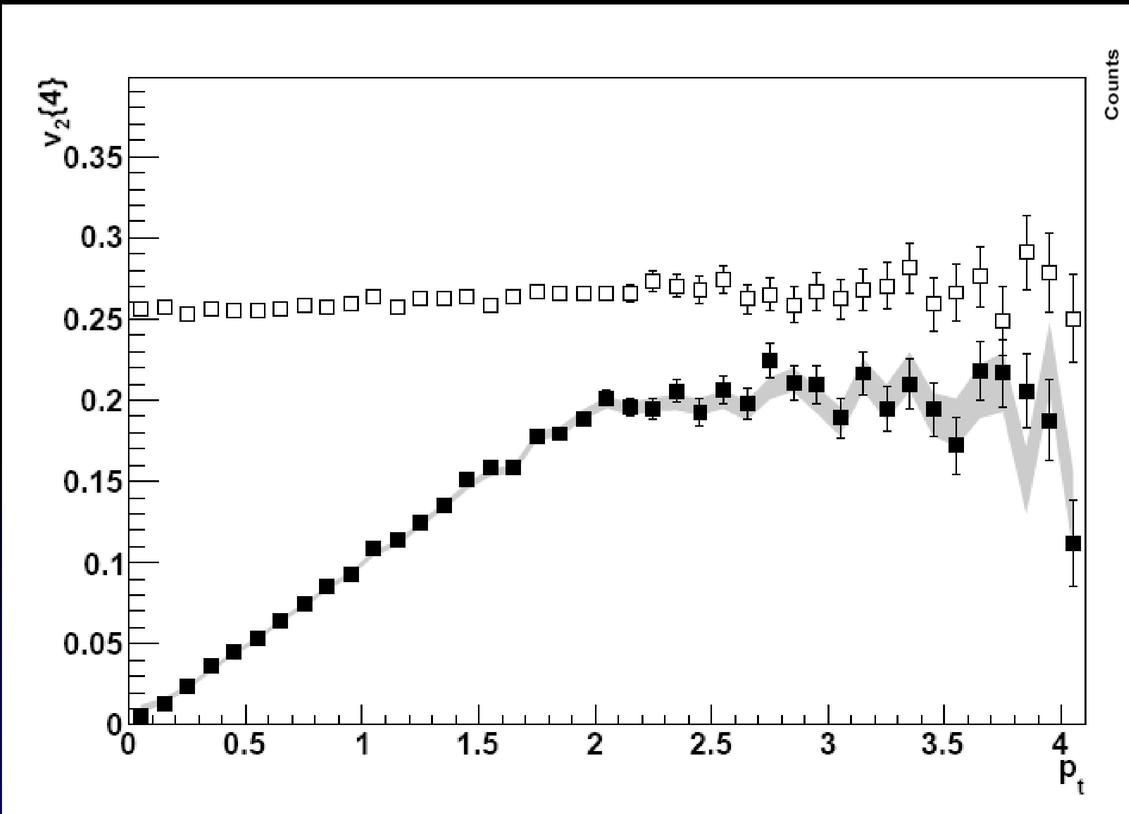
Non-uniform acceptance (1/2)

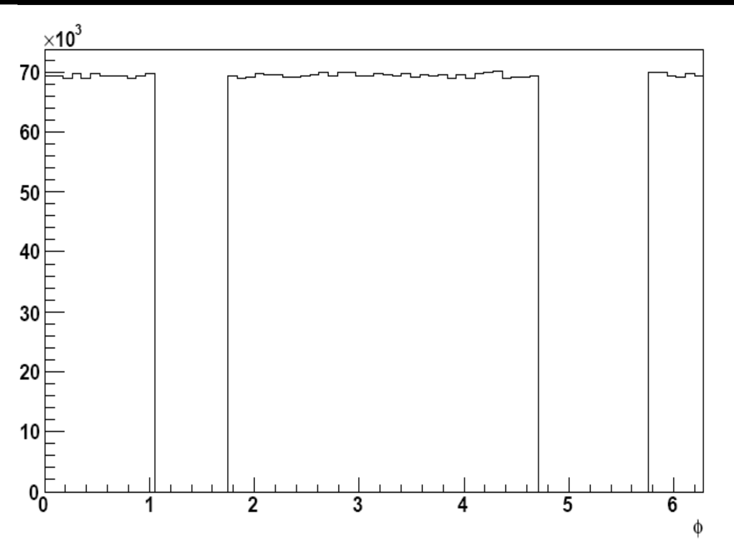
- If a detector has non-uniform acceptance in azimuthal angle, than in each event we have trivial anisotropies in momentum distributions of detected particles => this has nothing to do with anisotropic flow!
  - Can we disentangle one anisotropy from another?



Non-uniform acceptance (2/2)

- Generalized *Q*-cumulants can correct for non-uniform acceptance very well



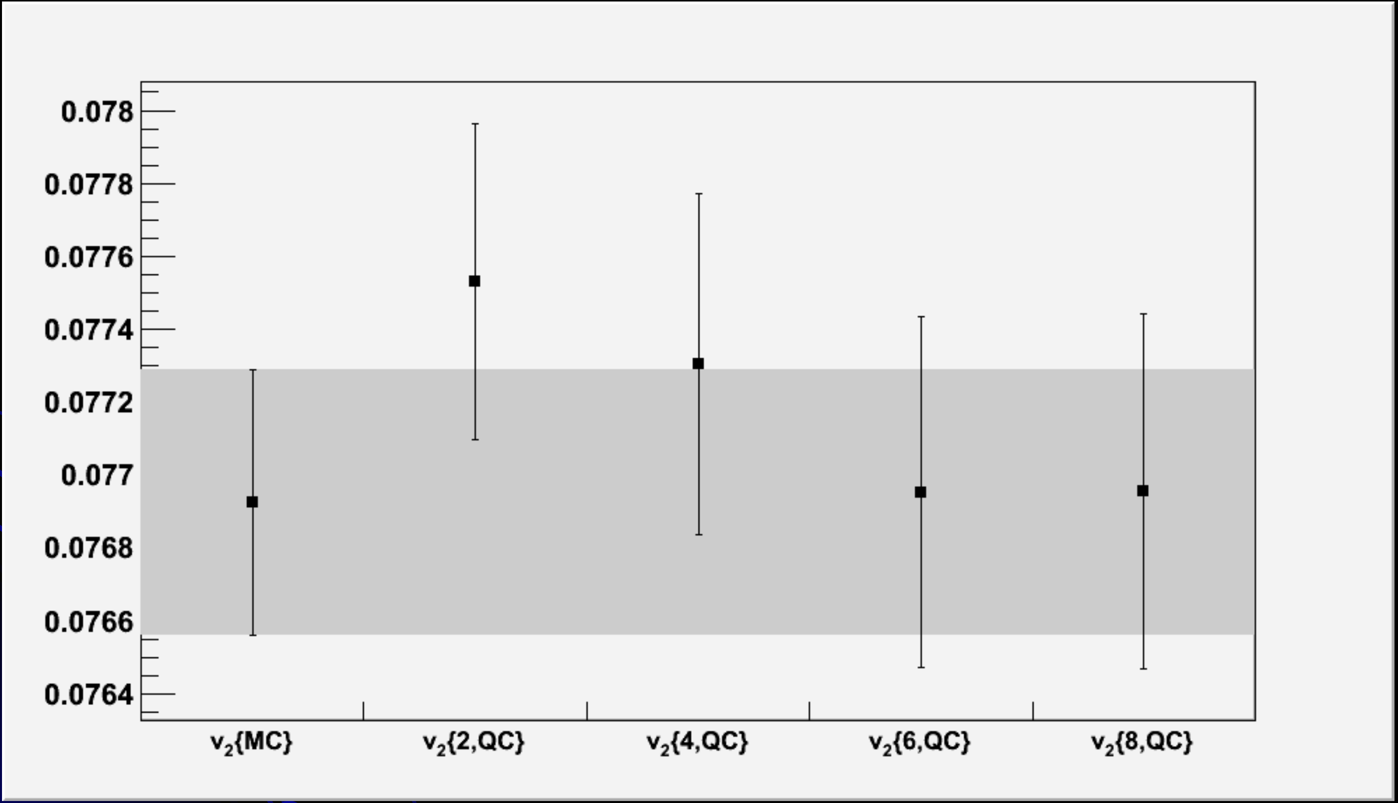


Technical details => Appendix C in R. Snellings, S. Voloshin, A.B. *"Flow analysis with cumulants: Direct calculations"*, PRC 83, 044913 (2011)

Grey band => $v_2\{MC\}$; open markers => $v_2\{4\}$ from isotropic *Q*-cumulants; filled markers => $v_2\{4\}$ from generalized *Q*-cumulants

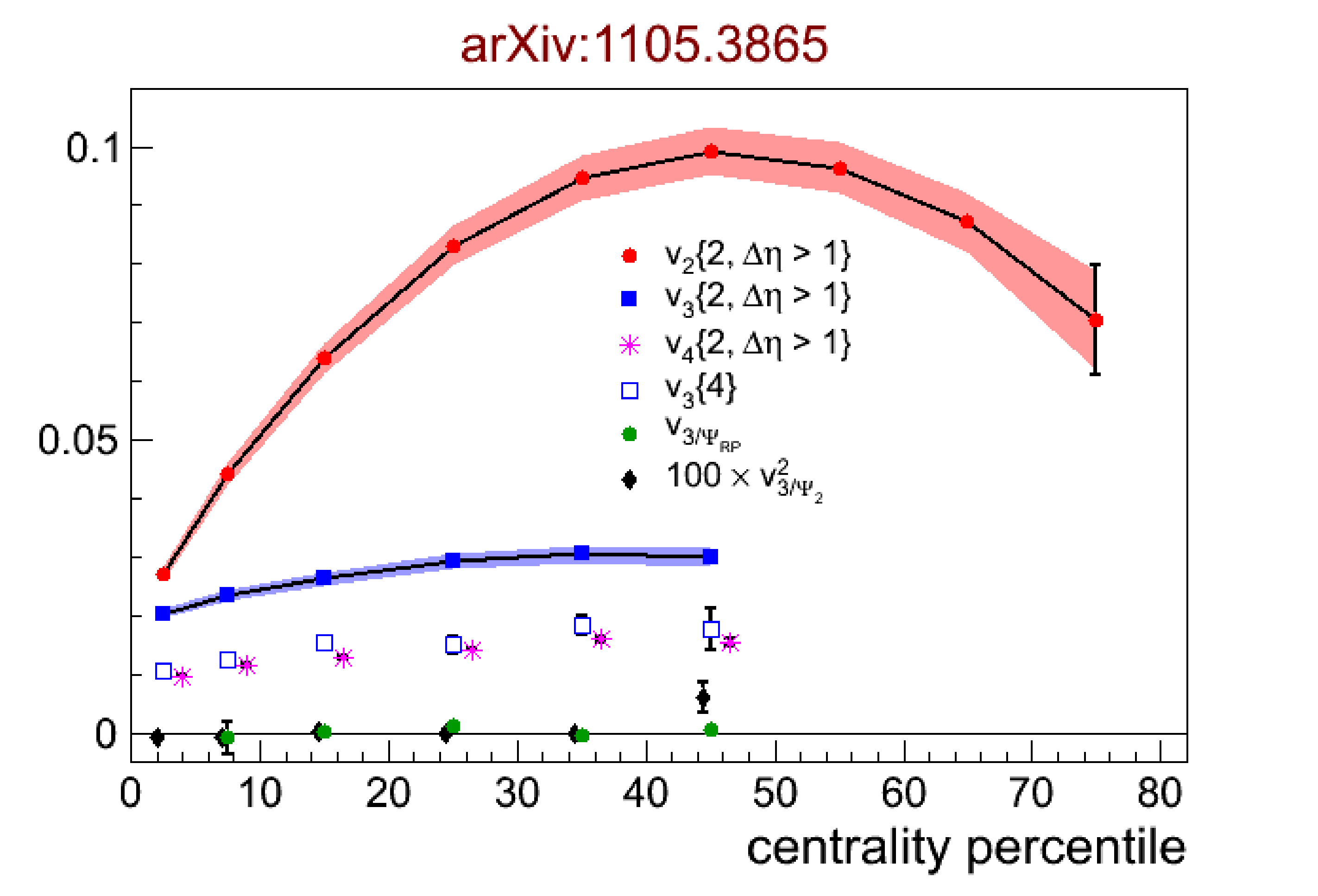
Q-cumulants

- Proof of the principle: Using Therminator events (realistic Monte Carlo generator of heavy-ion events, has both anisotropic flow and all resonances in the standard model)



In this regime multi-particle QCs are precision method

Charged particle v_3



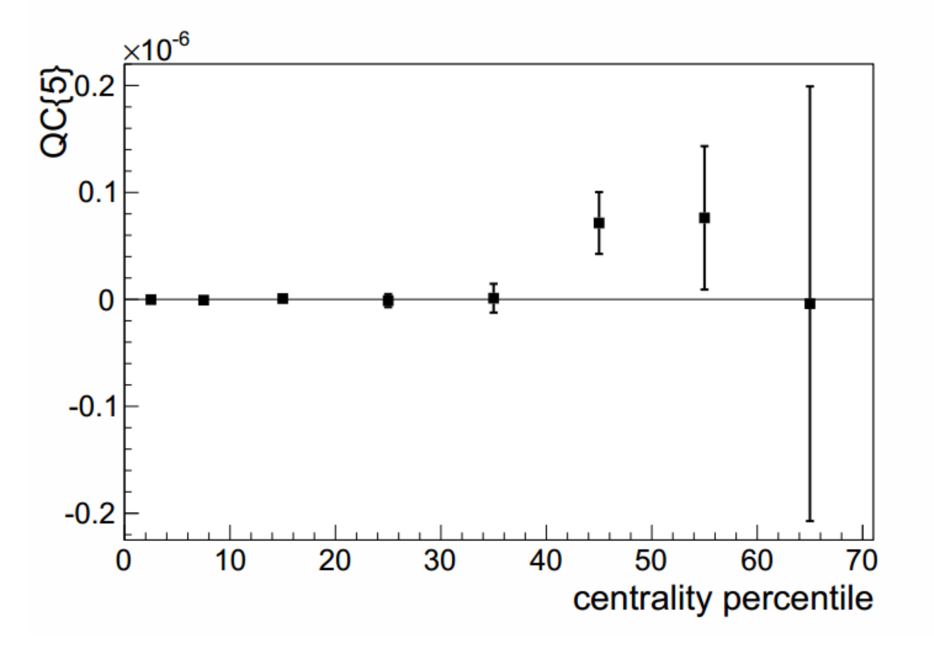
- **Phys.Rev.Lett. 107 (2011) 032301**
- v_3 is not 0 and it develops along its own symmetry plane
- Symmetry plane of v_2 is not the symmetry plane of v_3

QC{5}

- For the detector with uniform acceptance:

$$QC\{5\} = \langle\cos(3\phi_1+3\phi_2-2\phi_3-2\phi_4-2\phi_5)\rangle \overset{\text{in theory}}{=} v_3^2 v_2^3 \cos[6(\Psi_3-\Psi_2)]$$

- QC{5} *vs* centrality for the ALICE data (unofficial):

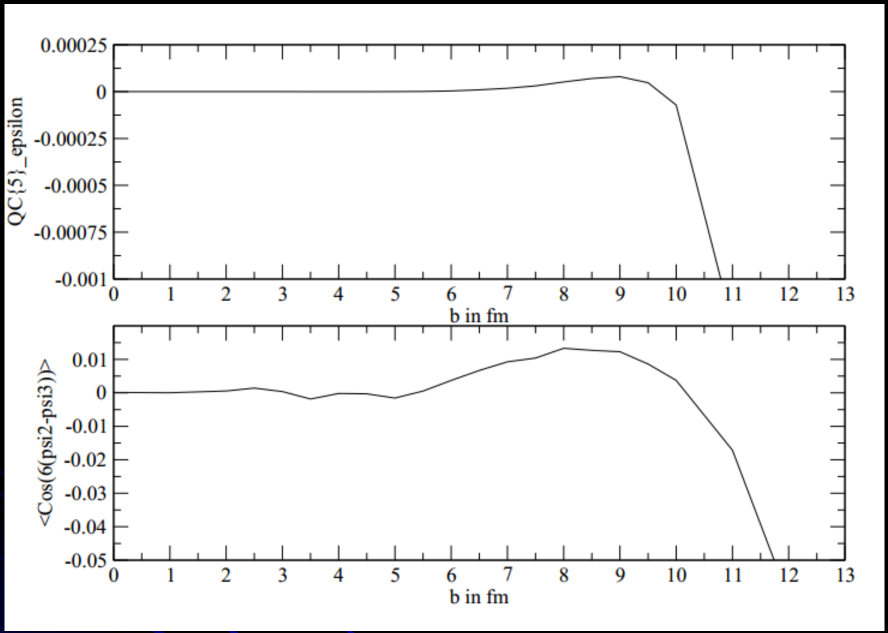


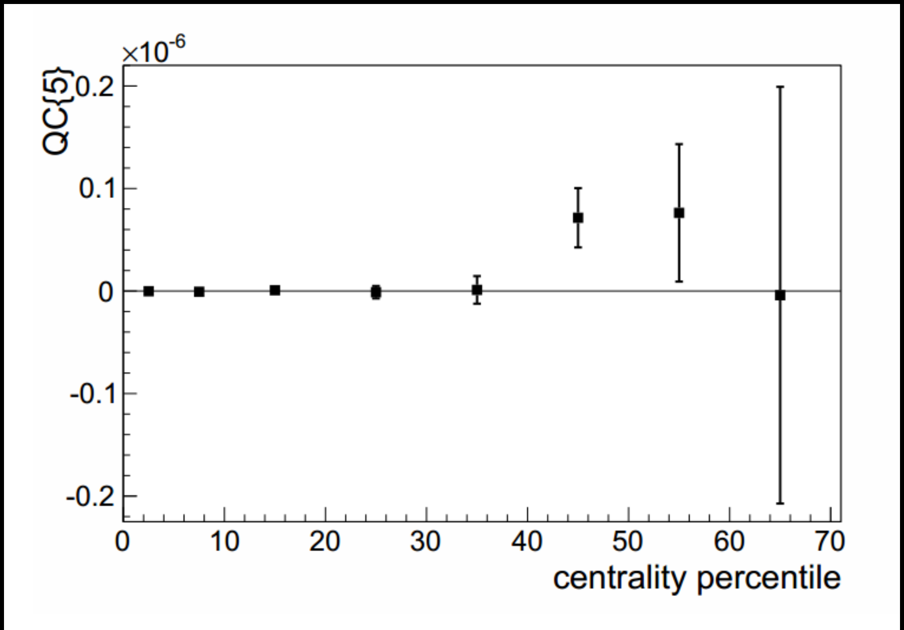
1.) For most- and mid-central events measured QC{5} is zero
2.) For most- and mid-central events v_2 and v_3 measured independently (via QC{2} and QC{4}) are not zero

⇒ <cos[6(Psi3 – Psi2)]> must be 0 in accordance with above equation, i.e. symmetry planes of v_3 and v_2 are not correlated for most- and mid-central events

QC{5}

- Feedback from the theorists (Urs Wiederman):

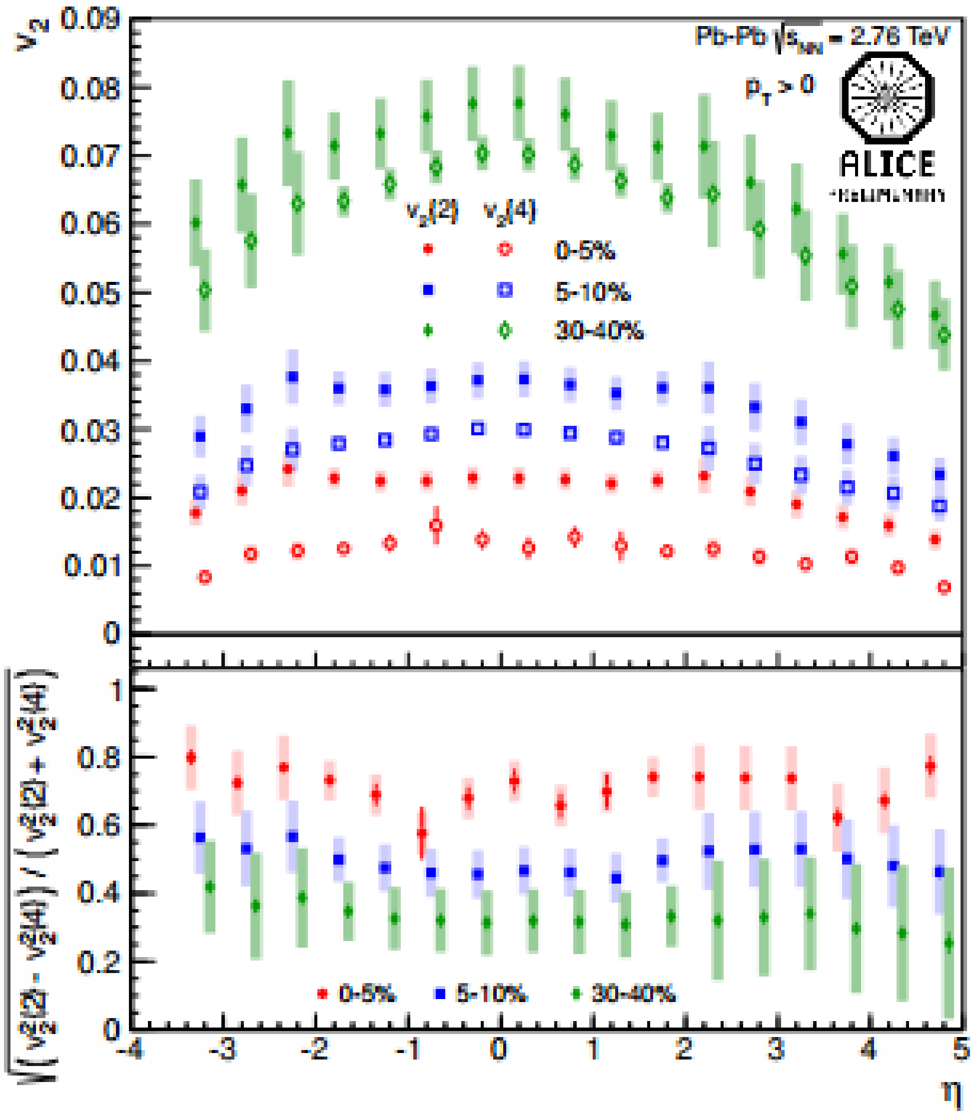




THEORY **ALICE**

- **LHS plot:** The trend of QC{5} centrality dependence (top) is consistent with direct <cos[6(Psi3–Psi2)]> calculation (bottom) by theorists in coordinate space (in coordinate space there is no nonflow)
- The trend of QC{5} centrality dependence is consistent in theory (LHS, top) and in ALICE (RHS)!

Elliptic flow fluctuations



- Difference between $v_2\{2\}$ and $v_2\{4\}$ is used to estimate flow fluctuations:
  - $\frac{\sigma_{v_2}}{\langle v_2 \rangle} \approx \sqrt{\frac{v_2^2\{2\} - v_2^2\{4\}}{v_2^2\{2\} + v_2^2\{4\}}}$.
- Fluctuations at forward rapidity are similar to fluctuations at mid-rapidity.

Few-particle non-flow

- Question: Can we suppress systematically unwanted contribution to measured azimuthal correlations which do not originate from the initial geometry?
  - Resonance decays
  - Track splitting during reconstruction
- Originally, cumulants were introduced in flow analysis by Borghini, Dinh and Ollitrault
- Studied by mathematicians and used in the other fields of physics already for a long time