Scrutinizing ALICE data on pair correlations

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Heavy-ion seminar,
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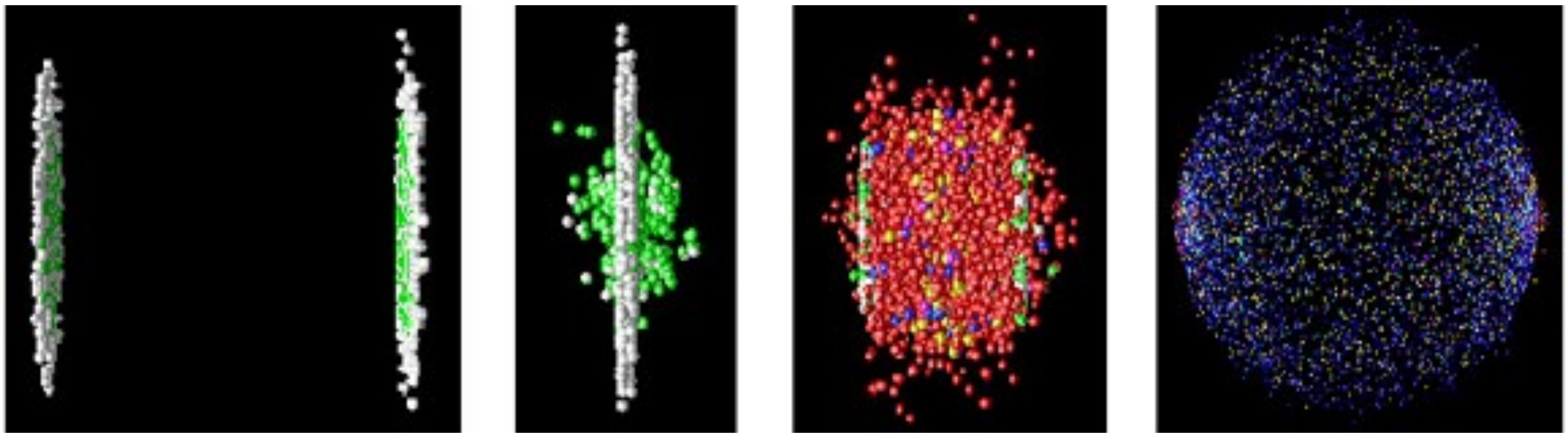
Fernando Gardim, Frédérique Grassi, Matt Luzum, JYO,
arXiv:1211.0989

Nuclear collisions at the LHC



- A central Pb-Pb collision at the LHC produces ~25000 particles, mostly pions.
- The best description we have of this strongly-coupled system is: a small lump of fluid expanding into the vacuum.

Motivations

- Relativistic hydrodynamics: the only theory for the strongly-coupled quark-gluon plasma out of equilibrium.
- An important question for LHC heavy-ion physics is therefore: how far can we go in interpreting data with hydro?
- Over the last 12 years, the scope of hydrodynamics has broadened.

Outline

- Modeling a collision with hydro
- A close look at pair correlations
- Conclusions and perspectives

Modeling a collision with hydro

- Initial conditions: typically from a Monte-Carlo event generator
- Thermalization transforms the single event into a thermal ensemble, aka *hydro event*
- Solve for expansion using equations of relativistic hydrodynamics
- Transform the fluid into independent particles
- The fluid is continuous: in every event, we can compute accurately single-particle spectra, i.e., the probability distribution of transverse momentum p_t, pseudorapidity η, azimuthal angle φ

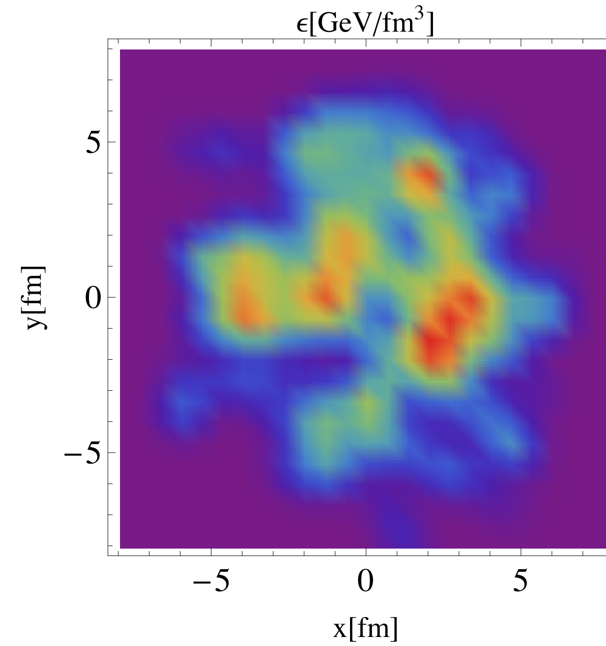
Anisotropic flow in hydro

Fourier expansion of φ *probability distribution* at fixed p_t and η

$$2\pi\, dN/d\varphi = 1 + 2 \sum v_n(p_t,\eta) \cos(n(\varphi - \psi_n(p_t,\eta)))$$

also written as: $V_n(p_t,\eta) \equiv v_n(p_t,\eta) e^{in\psi_n(p_t,\eta)} = \{e^{in\varphi}\}$

V_n is well defined in hydro (only)



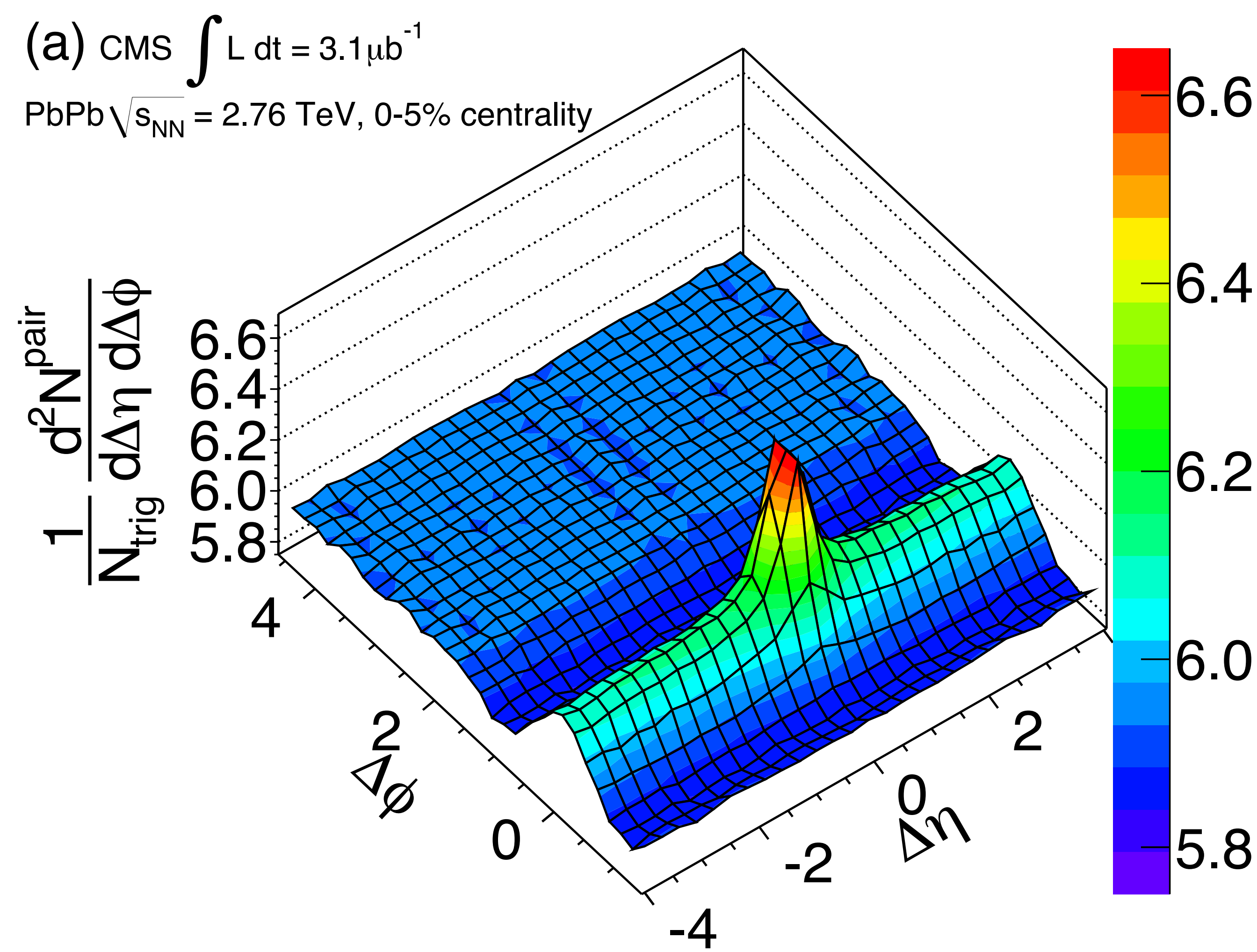
With initial state fluctuations:

- Odd harmonics at midrapidity: V_1 (directed flow) and V_3 (triangular flow) in addition to V_2 (elliptic flow).
- Each harmonic has its own phase ψ_n which may depend on p_t and η

Flow in data

- *Anisotropic flow is not an observable*
- The number of particles in a single event is too small to measure $V_n(p_t,\eta)$, or even the integrated v_n
  statistical error is typically 50% for event-by-event v_2, 100% for event-by-event v_3.
- Anisotropic flow can only be measured through event-averaged azimuthal correlations between particles.

Observing the small fluid: correlations



CMS arXiv:1105.2438

Number of pairs of particles versus relative azimuthal angle and pseudorapidity (~polar angle) in central Pb-Pb collisions at LHC

- *Long-range azimuthal correlation ~ ripple in a pond*

New data at the LHC

ALICE 1109.2501

- ALICE has measured for the first time the full 2-particle correlation matrix

$$V_{n\Delta}(t,a) \equiv \langle \cos n(\varphi_t - \varphi_a) \rangle = \langle e^{in(\varphi_t - \varphi_a)} \rangle$$

versus p_t of trigger and associated particles.

- A simple, transparent analysis, yet containing a lot of new, non-trivial information.
- Double-differential analysis: requires much more statistics than other flow analyses

Correlation matrix in hydro

- In a single event, particles are emitted independently:

$$V_{n\Delta}(t,a)=\{e^{in(\varphi_t-\varphi_a)}\}= \{e^{in\varphi_t}\} \{e^{-in\varphi_a}\}=V_n(t)V_n^*(a)$$

- The correlation matrix factorizes, which implies

$$| V_{n\Delta}(t,a) | = \sqrt{V_{n\Delta}(t,t)V_{n\Delta}(a,a)}$$

Correlation matrix in hydro

- After averaging over hydro events,

$$V_{n\Delta}(t,a) = \langle V_n(t) V_n^*(a) \rangle$$

- The correlation matrix no longer factorizes, but
  - Diagonal elements are positive: $V_{n\Delta}(t,t) = \langle |V_n(t)|^2 \rangle$
  - Non-diagonal elements measure the linear correlation between $V_n(t)$ and $V_n(a)$ and satisfy a triangular inequality, (instead of equality implied by factorization)

$$|\, V_{n\Delta}(t,a)\, | \leq \sqrt{V_{n\Delta}(t,t) V_{n\Delta}(a,a)}$$

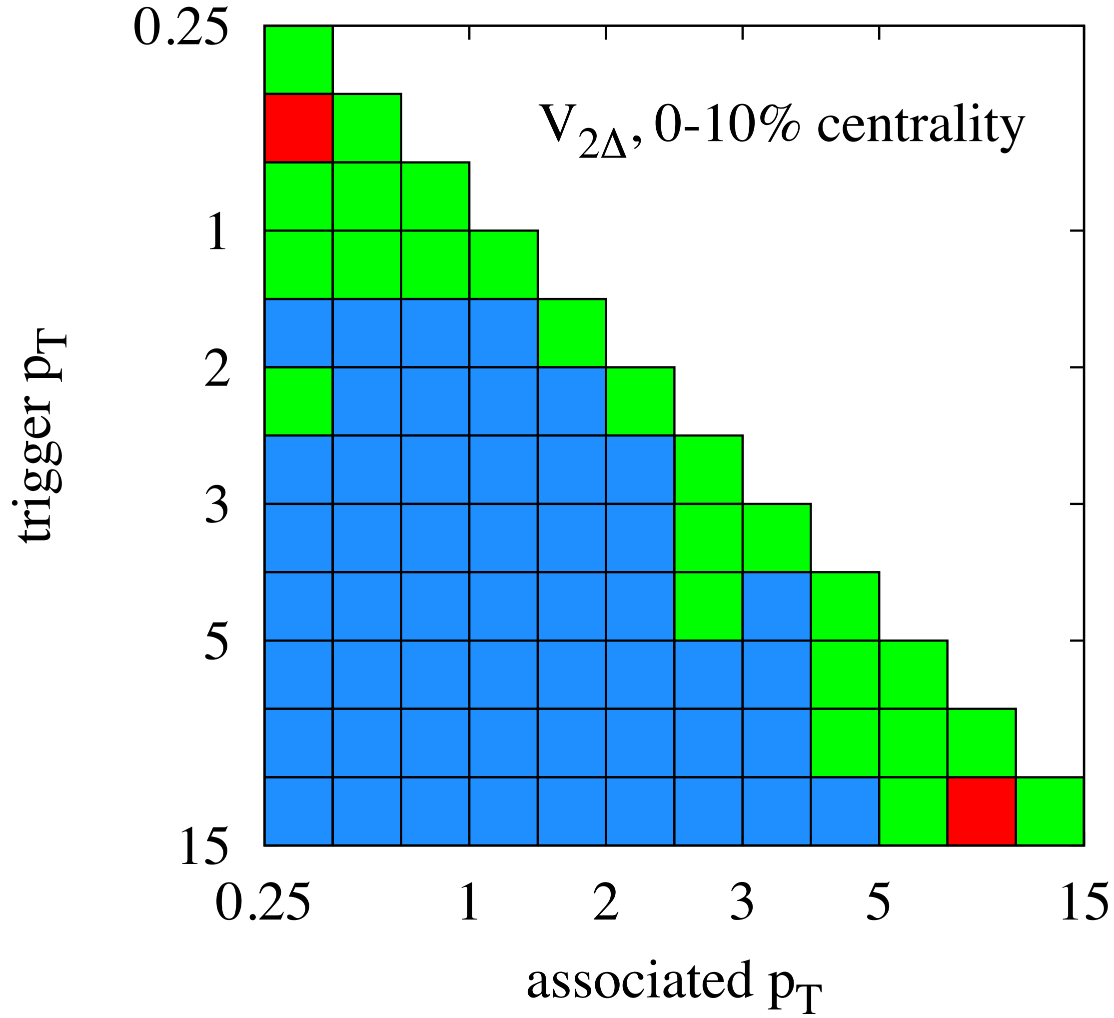
Gardim, Grassi, Luzum, JYO, 1211.0989

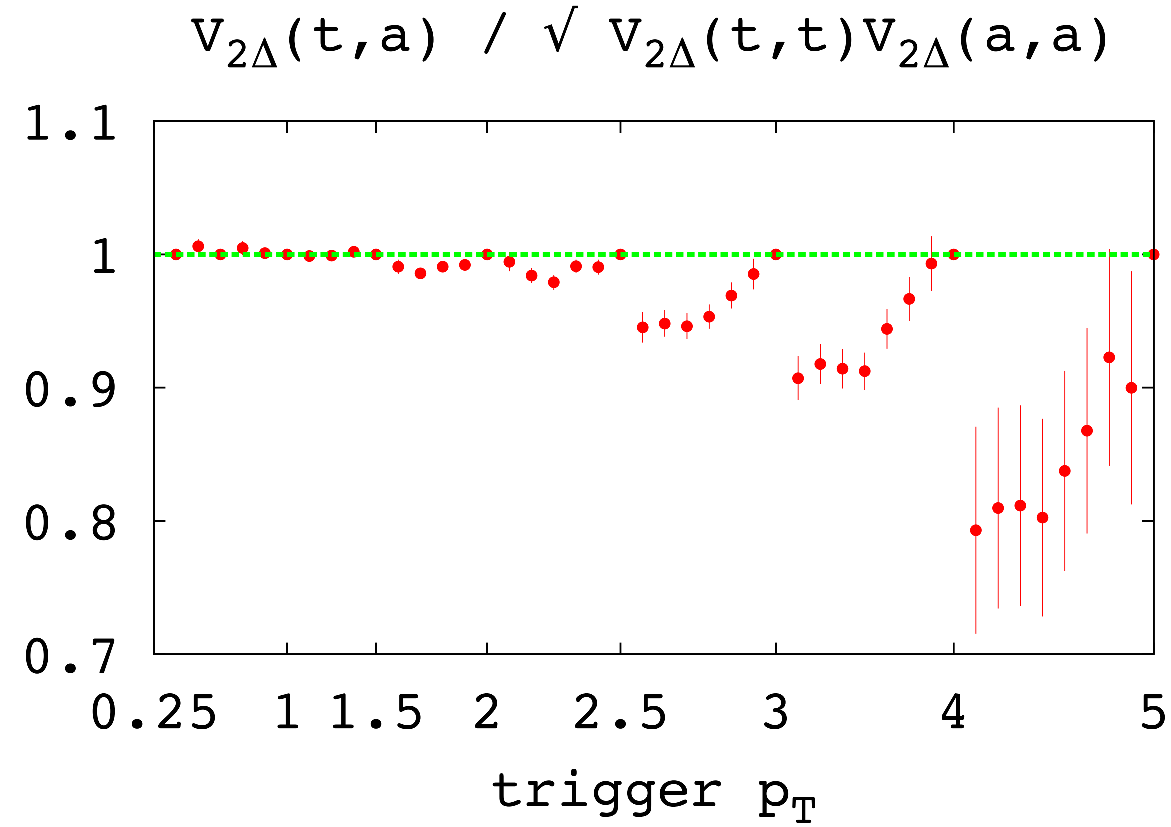
Are data compatible with flow?

Do data for $V_{n\Delta}$ show

- Factorization?
- Strict inequality, i.e. flow fluctuations?
- Breaking of inequalities (i.e. nonflow)?

Is $V_{2\Delta}$ compatible with elliptic flow?





Colors mean:

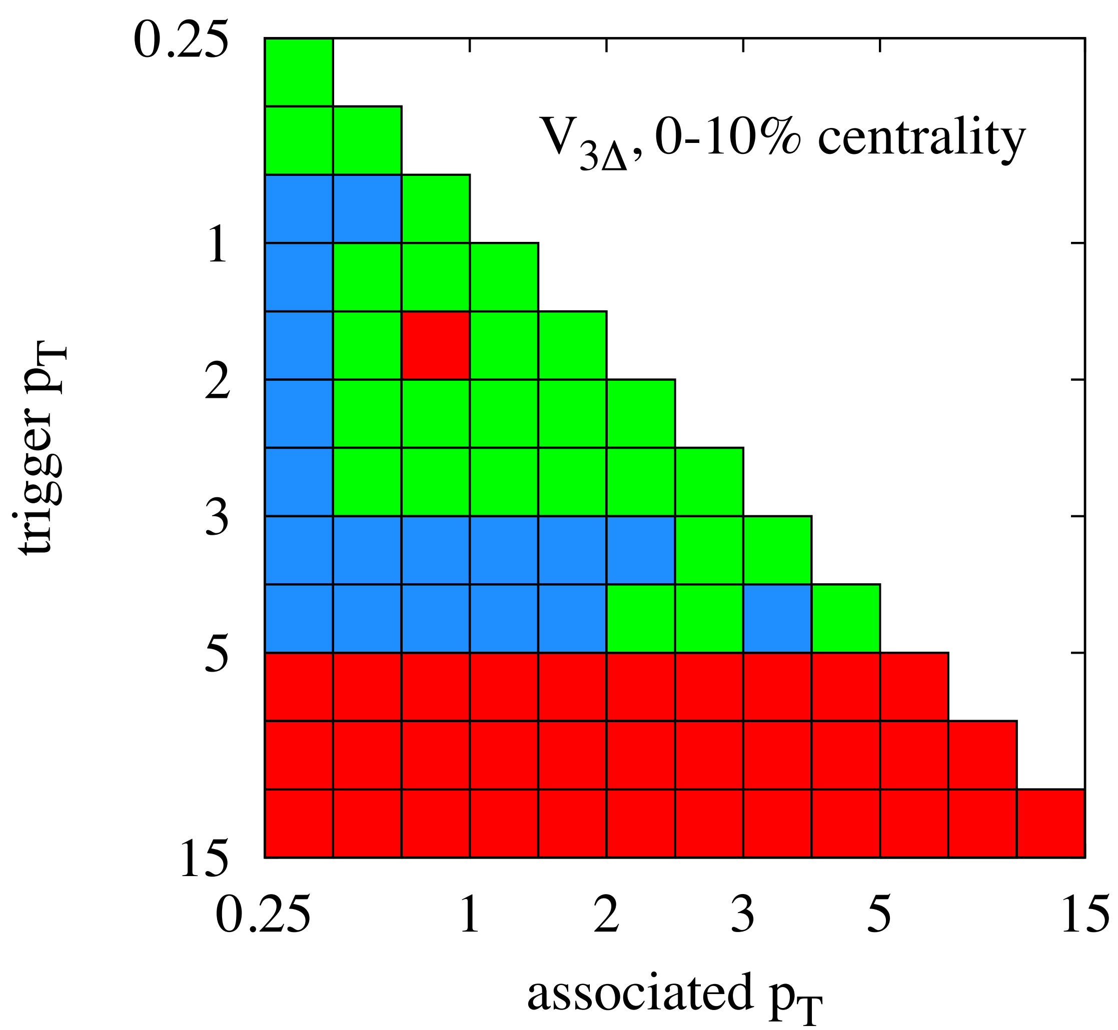
Factorization OK

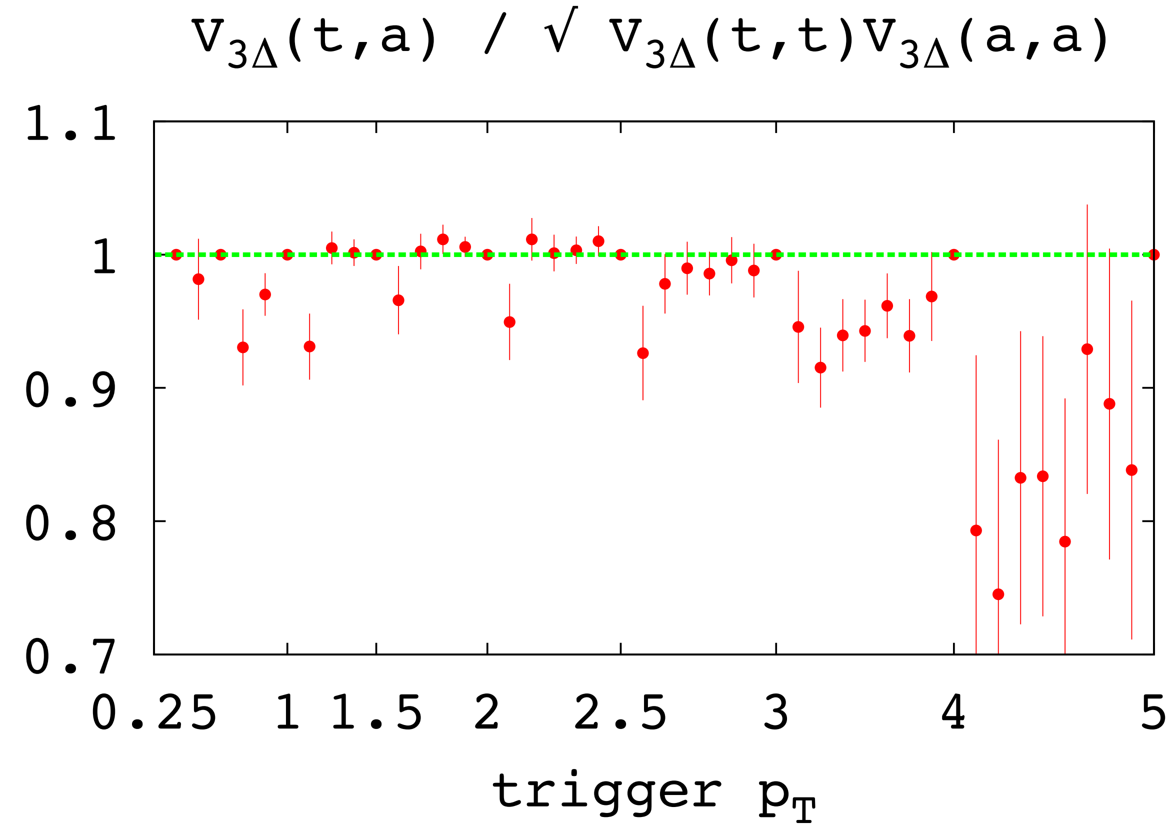
Strict inequality

Nonflow

Data everywhere compatible with flow, with evidence of flow fluctuations

Is $V_{3\Delta}$ compatible with triangular flow?





Colors mean:

Factorization OK

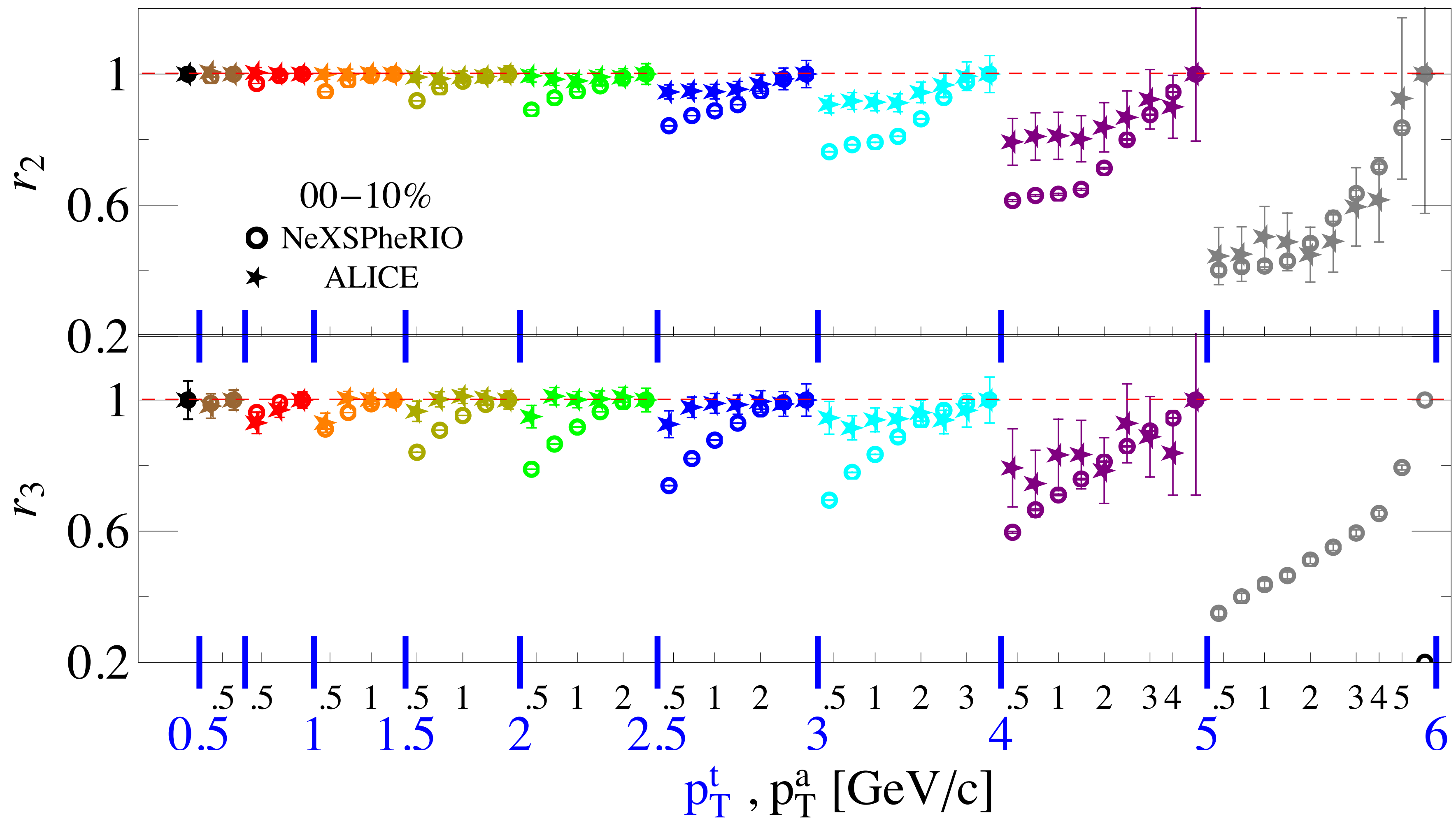
Strict inequality

Nonflow

Evidence for nonflow at high p_t. Can be explained by away-side jet

Can hydro reproduce the observed breaking of factorization?

Gardim, Grassi, Luzum, JYO, 1211.0989



- Yes. Fluctuations induce decoherence of angular correlations
- This ideal hydro calculation (for RHIC) seems to *overpredict* breaking of factorization

Conclusions

- The old picture of elliptic flow in the reaction plane is not wrong, but there is **much more** we can do with flow
- The price to pay is that we must move the boundary between theory and experiment.
- Experiments measure correlations
- The separation of correlations into flow + nonflow is a model-dependent issue: belongs to theory.
- Flow = how much we can understand within hydro.

Perspectives

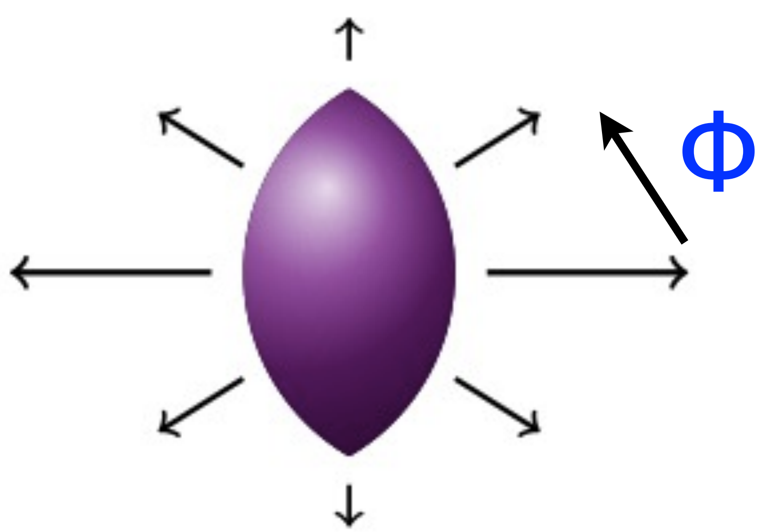
- The physics of flow is now much richer than it used to be
- Not just elliptic flow but all harmonics
- Not just single particle flow, but the detailed structure of 2-particle correlations (studied as a function of pt but the rapidity structure is as important)
- And a large number of upcoming measurements of higher-order, mixed correlations
- Beyond independent particles: fluctuations and correlations in hydro

Kapusta, Müller, Stephanov, 1112.6405

Bozek & Broniowski 1204.3580

Backup slides

2000

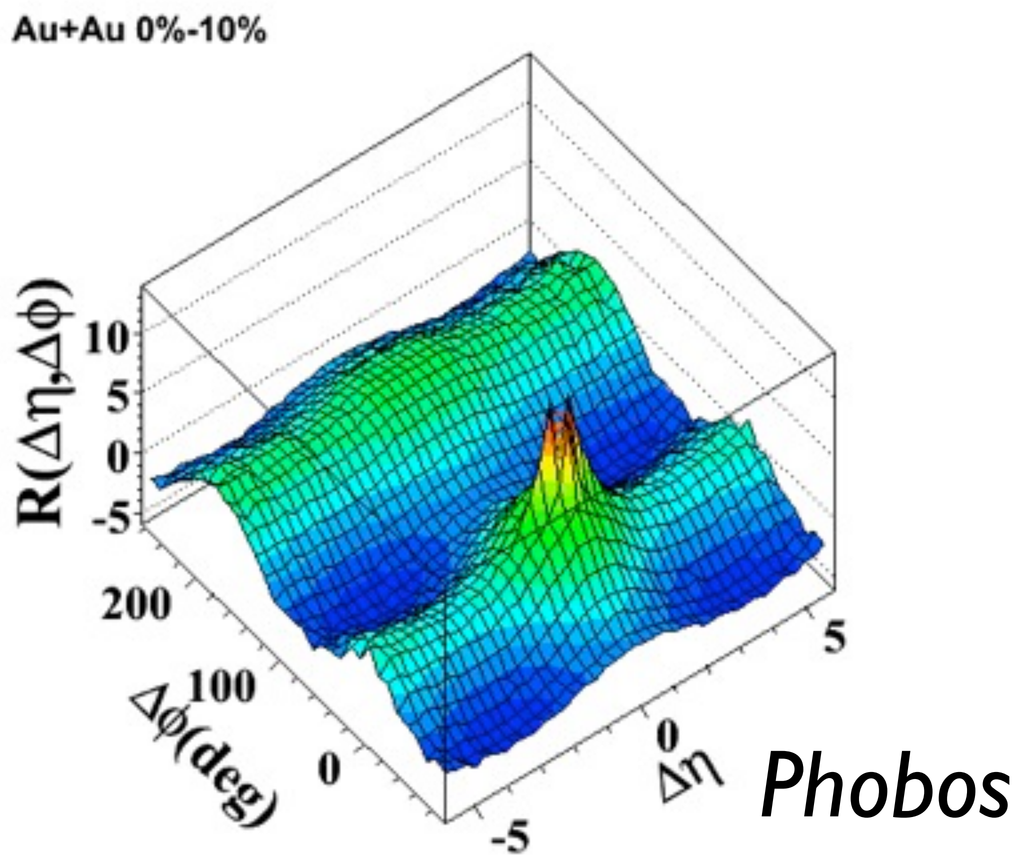


- Elliptic flow is created due to the almond shape of the overlap area of semi-central collisions. It develops in the reaction plane.
- Only hydro is able to reproduce elliptic flow quantitatively

STAR nucl-ex/0009011, 483 citations

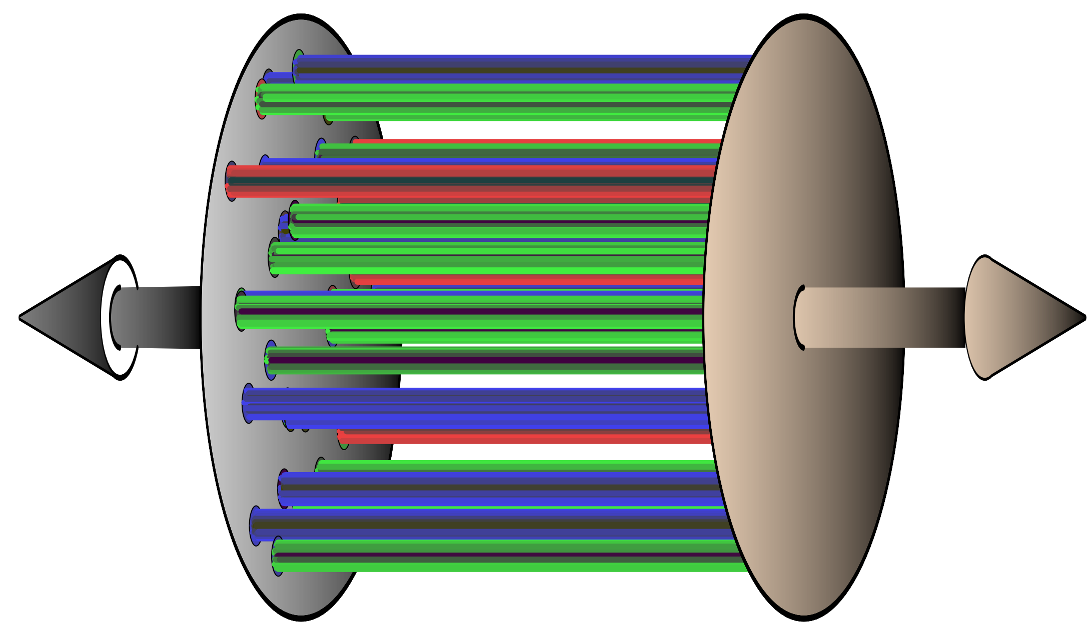
2005

Soft ridge (STAR)



The near-side peak is narrower than the away-side peak: there are other correlations than just flow

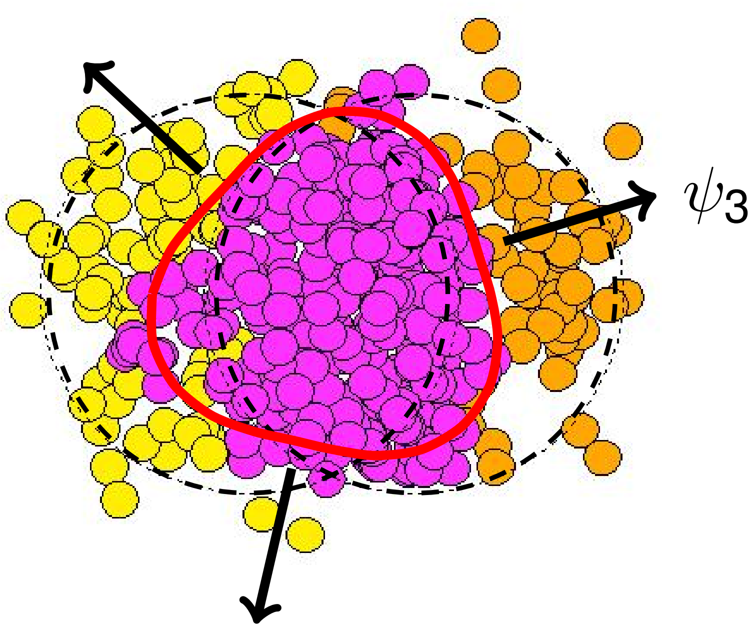
Initial fluctuations (PHOBOS)



Fluctuations of the initial geometry must be taken into account in order to describe the observed elliptic flow

2010

If initial fluctuations are properly taken into account, then the soft ridge is just flow



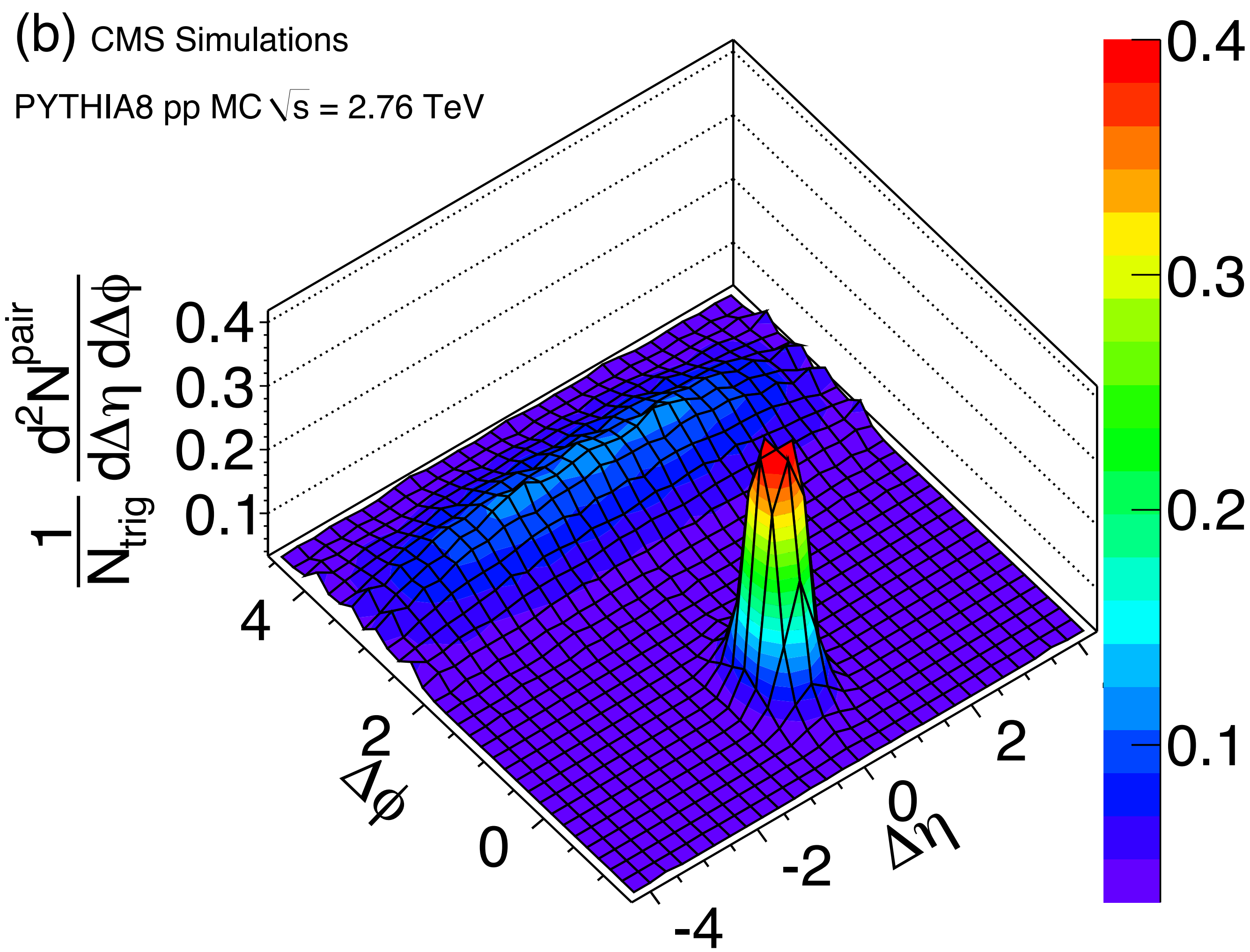
Triangular flow breakthrough

Alver and Roland, 1003.0194

2012

Where are we now?

Observing the small fluid: correlations



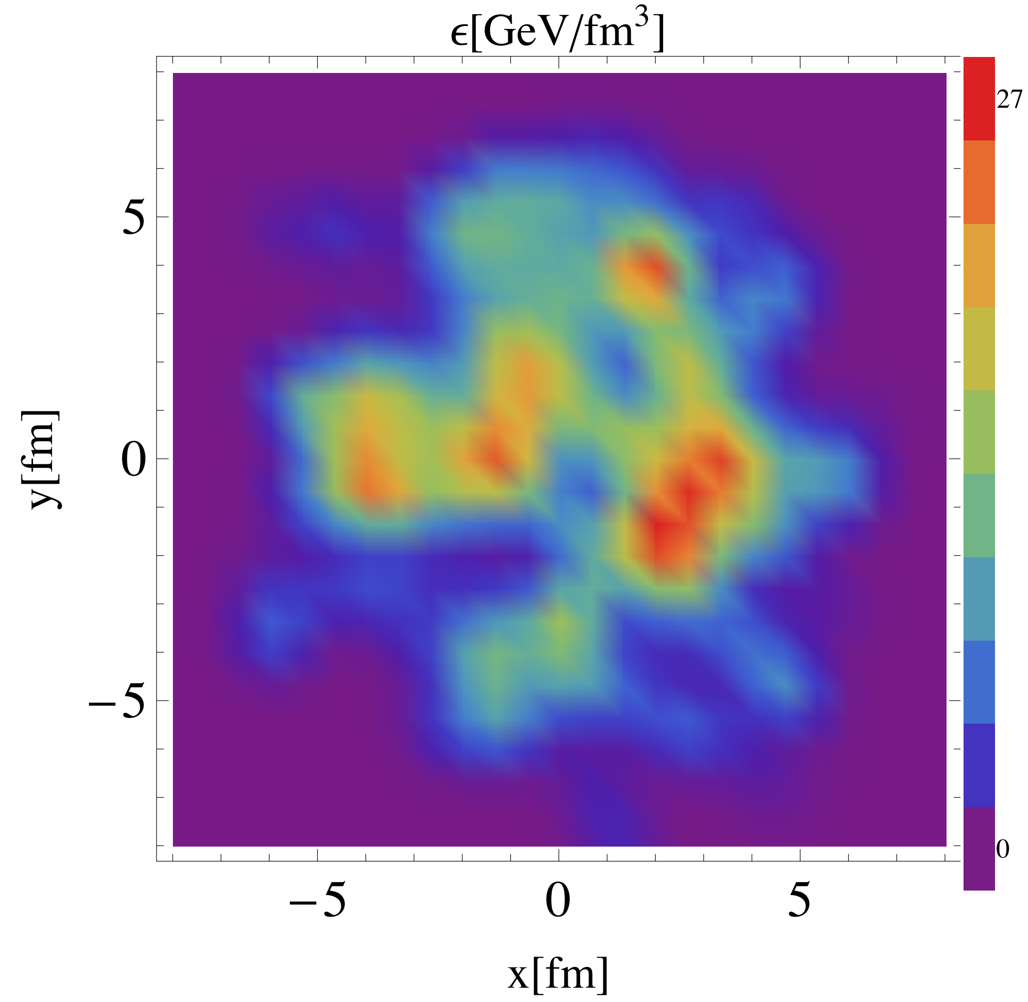
CMS arXiv:1105.2438

Number of pairs of particles versus relative azimuthal angle and pseudorapidity (~polar angle) in proton-proton collisions at LHC

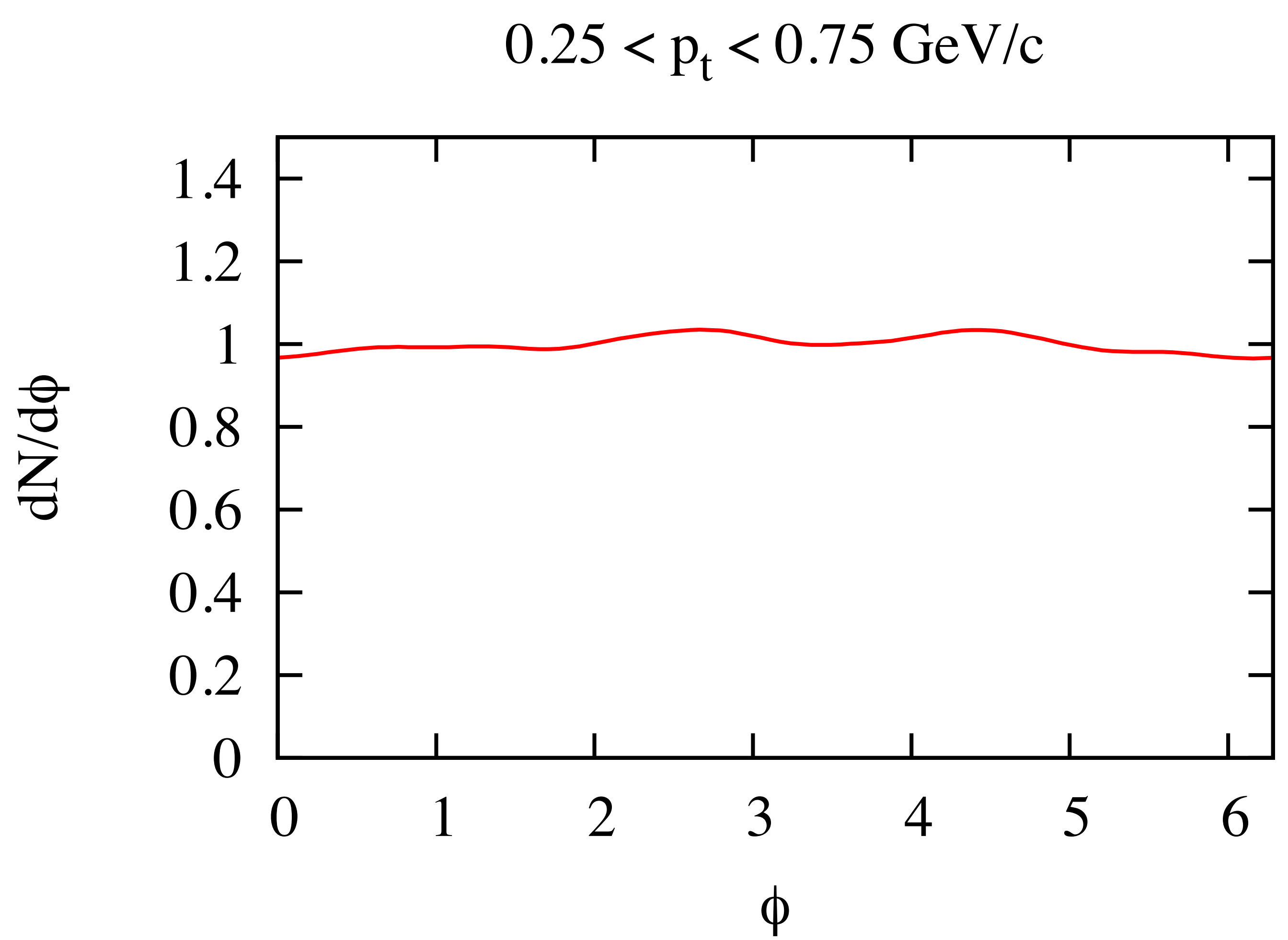
(actually not real data, but PYTHIA simulation)

A close look at a hydro event

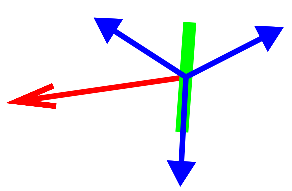
- A random central Au-Au collision at top RHIC energy, initial conditions from NeXus event generator
- These initial conditions are evolved through ideal hydrodynamics.
- Compute distribution of charged particles near midrapidity.
- See how the φ distribution evolves with p_t.



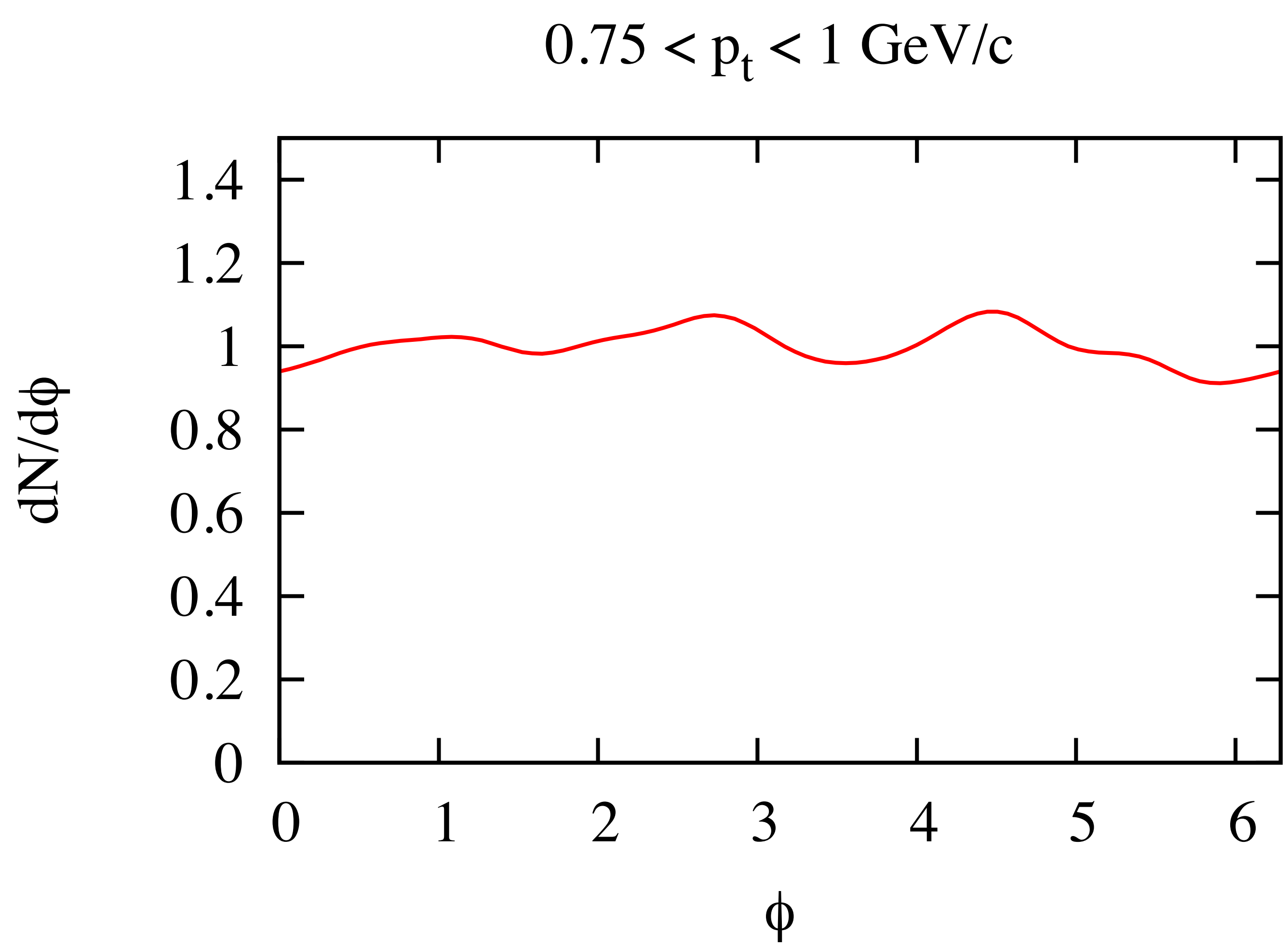
A close look at a hydro event



Fourier decomposition → magnitude and directions of directed, elliptic and triangular flows, all at the % level at low p_t.



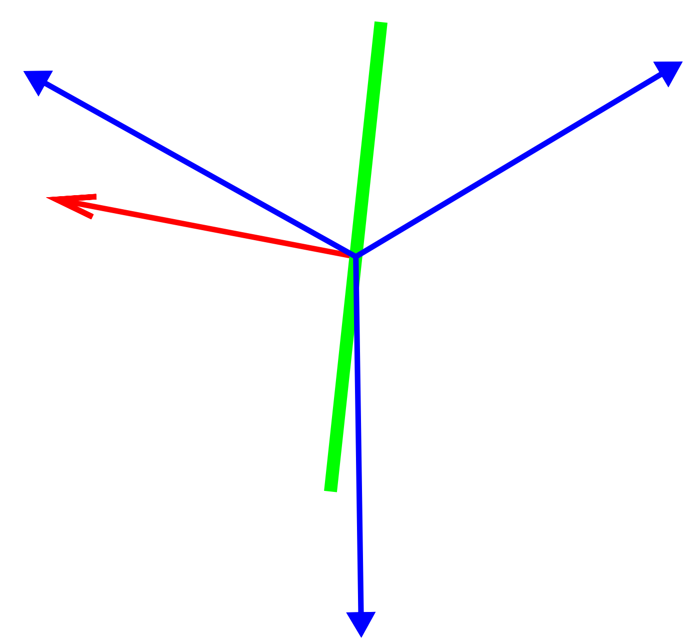
A close look at a hydro event



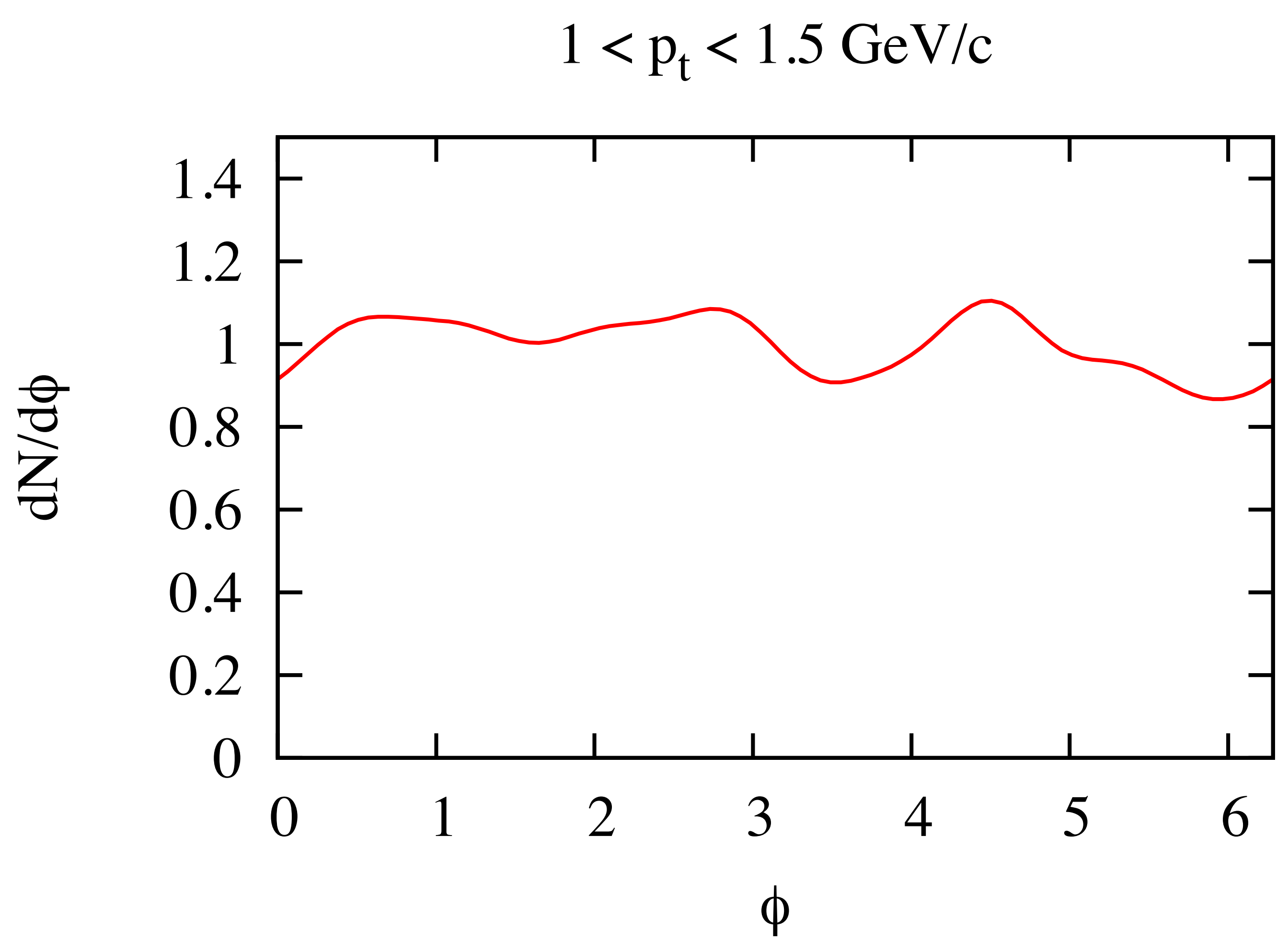
As p_t increases, anisotropic flow increases.

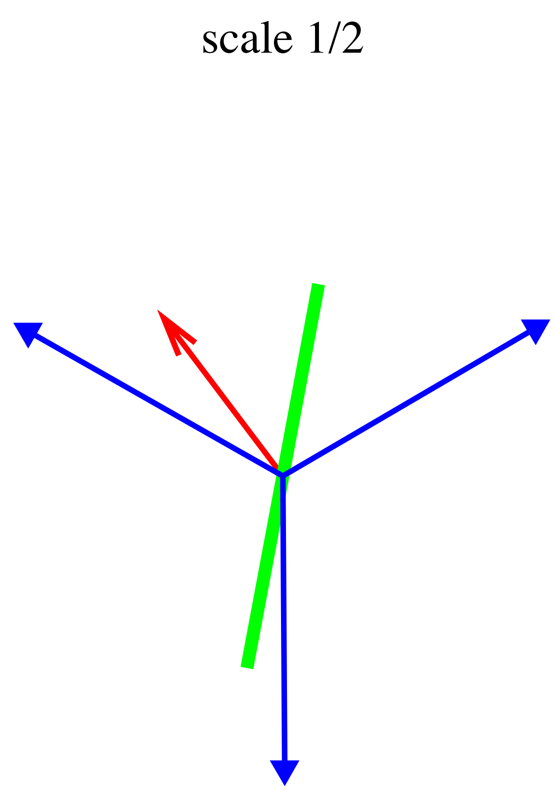
ψ_2 and ψ_3 change mildly ,

ψ_1 rotates more strongly

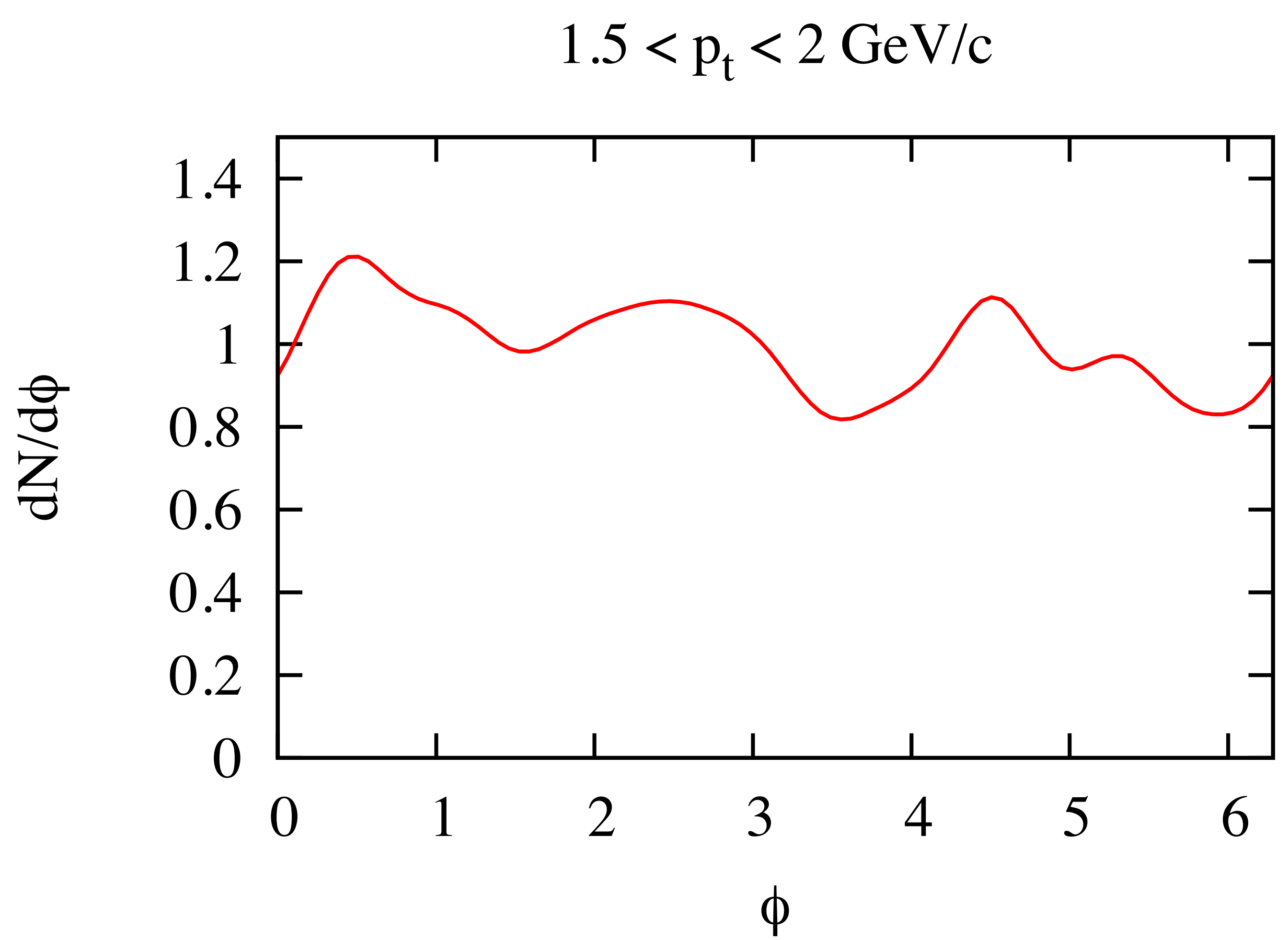


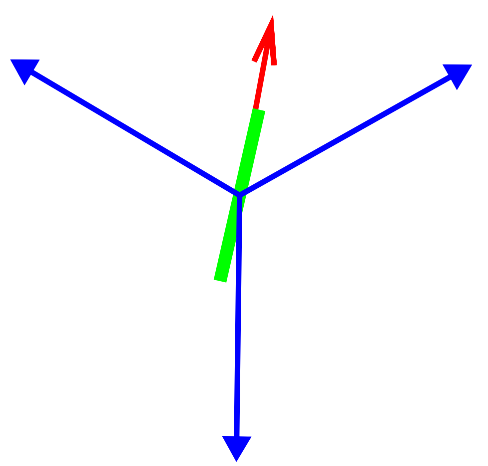
A close look at a hydro event



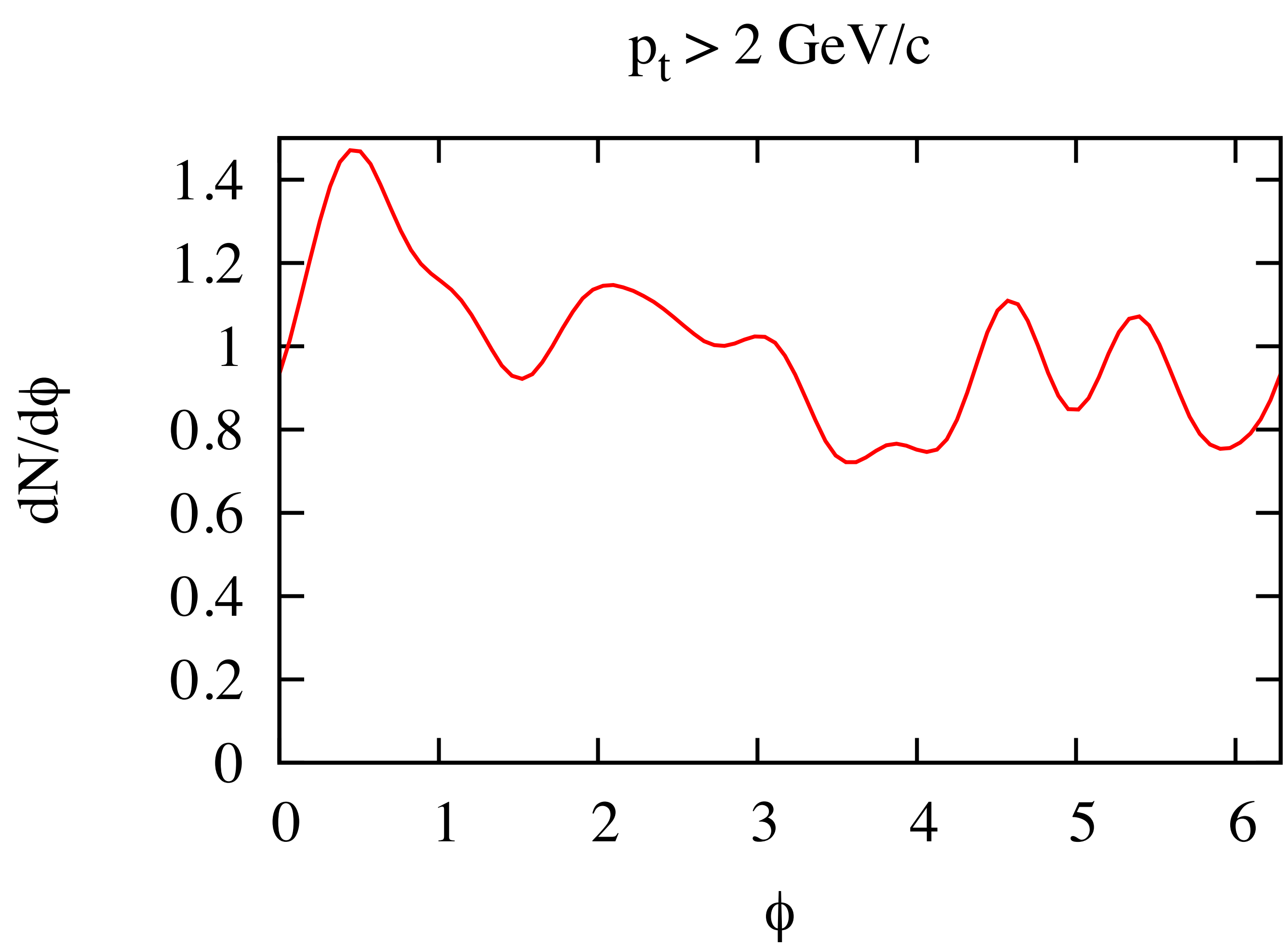


A close look at a hydro event



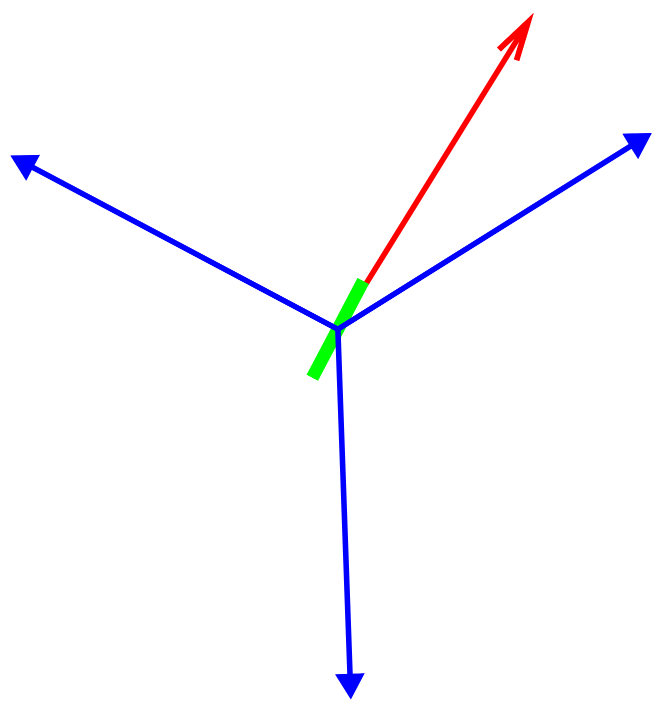


A close look at a hydro event



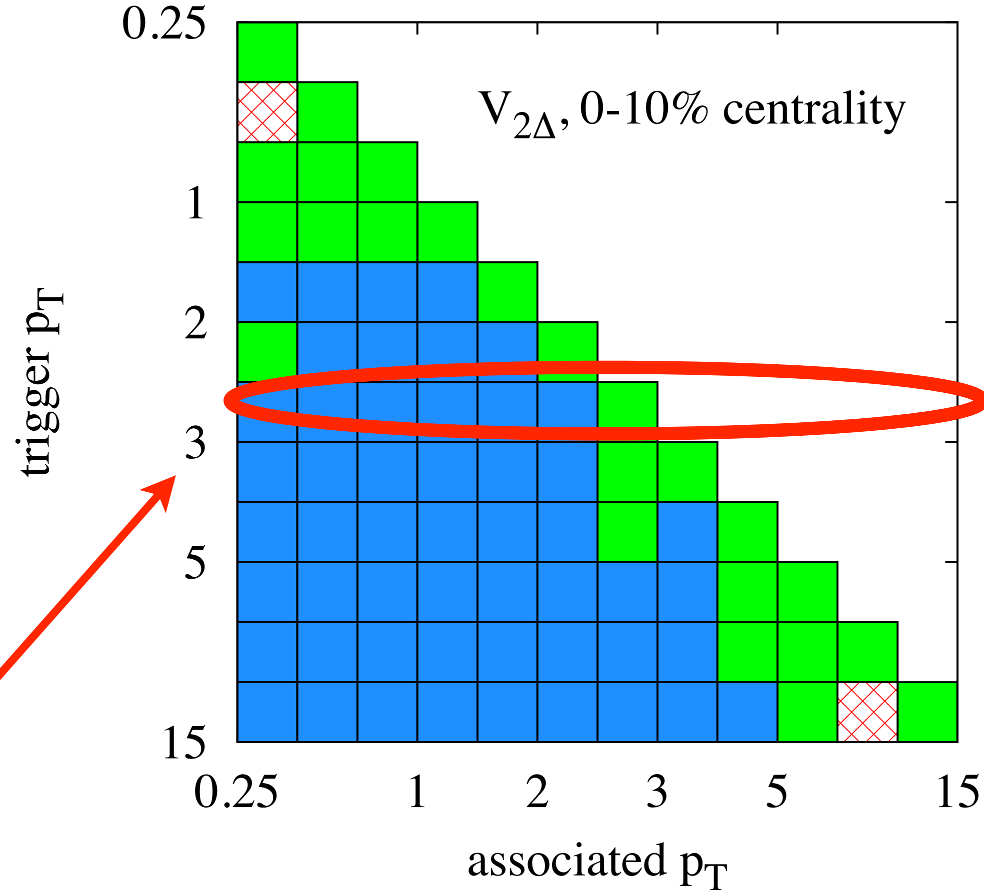
ψ_1 rotates by π between low p_t and high p_t, because the total transverse momentum $\int p_t\, v_1 e^{i\psi_1} \sim 0$.

scale 1/4

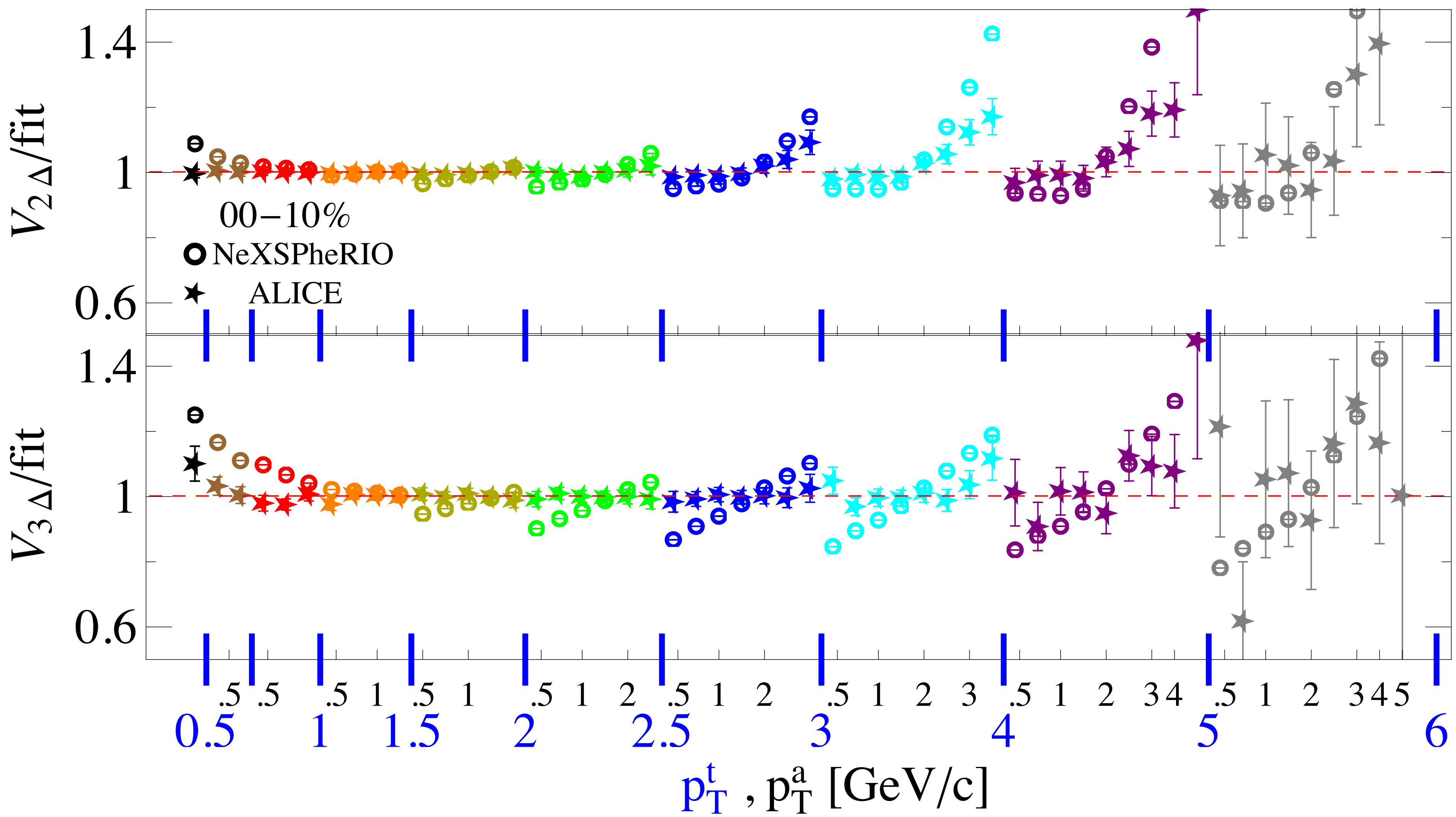


Single-particle anisotropic flow

- Most analyses so far: analyses of "single-particle" v_n
- Theorists are often confused by this misleading terminology
- It is again a correlation: a single particle correlated with all particles in an "event-plane" detector.
- Amounts to averaging the correlation matrix over a line



Factorization also breaks down in hydro



Fit correlation matrix to $v_n^t.v_n^a$, then take ratio of correlation to fit

Gardim, Grassi, Luzum, JYO, 1211.0989