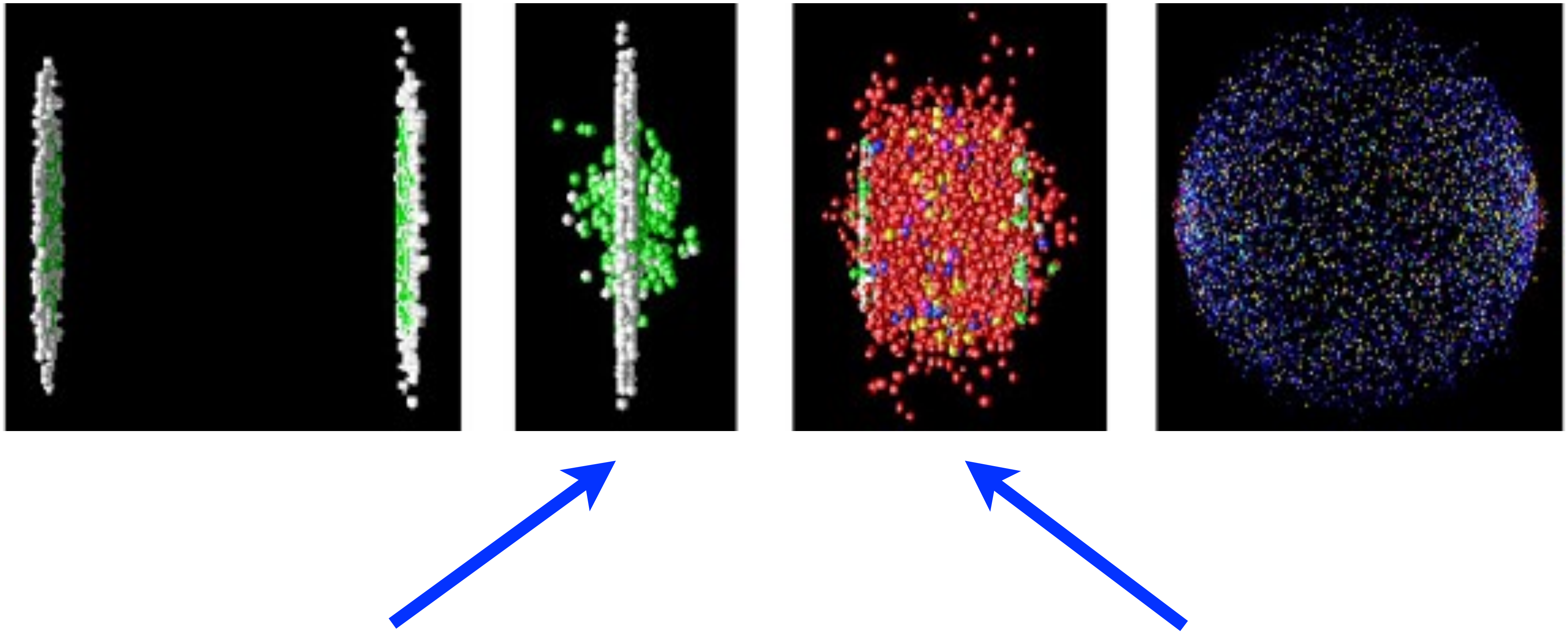
Harmonics in harmony

Jean-Yves Ollitrault (IPhT, Saclay)
Illa da Toxa, Sept.9, 2013

Nuclear collisions at the LHC



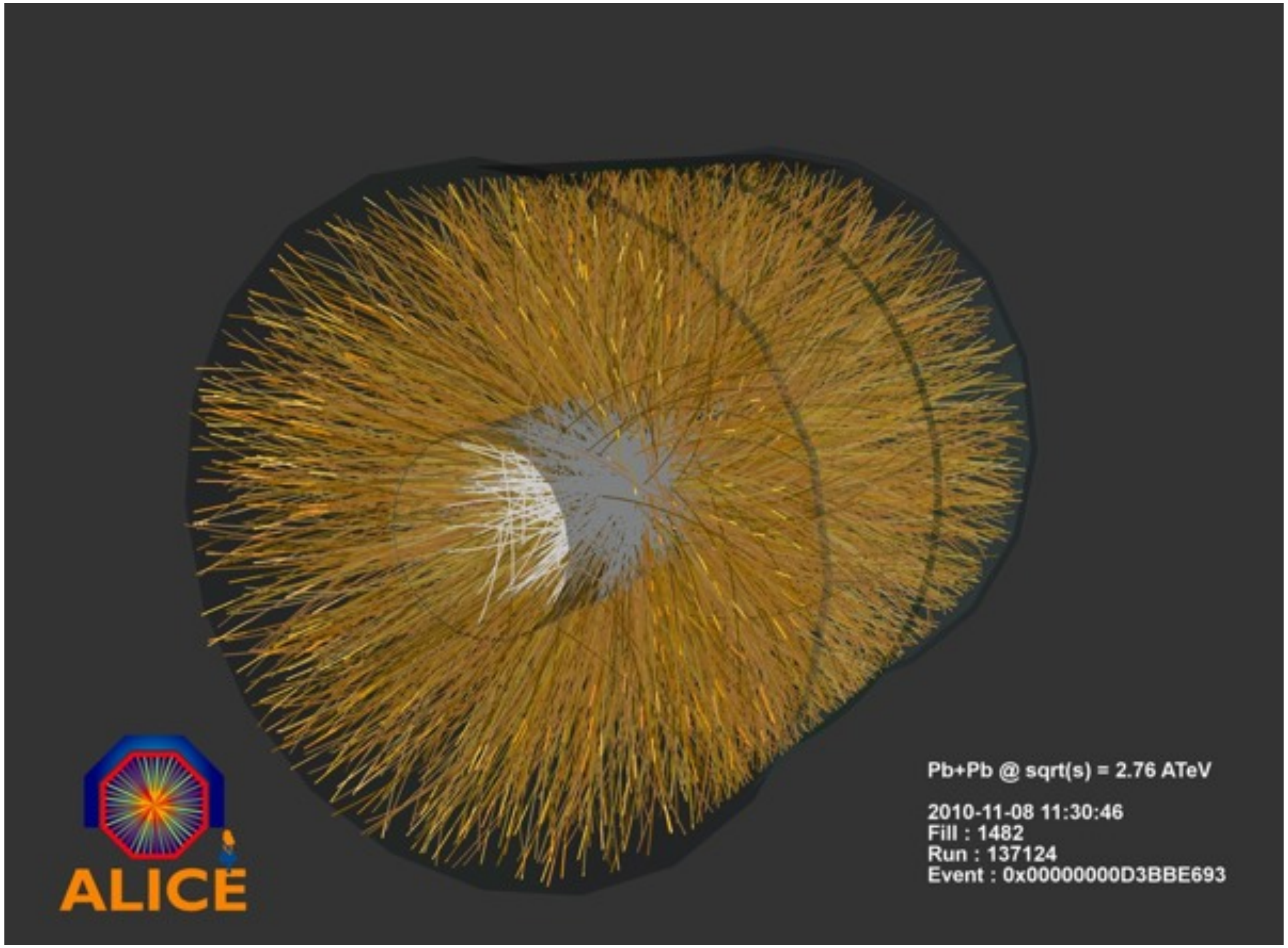
Initial stage: energy deposited in central rapidity region, thermalization

Kurkela Heller Epelbaum

Strongly-interacting expanding plasma: best described as a (macroscopic) small lump of fluid

Luzum Strickland Schenke
Niemi Flörchinger Denicol

What we see



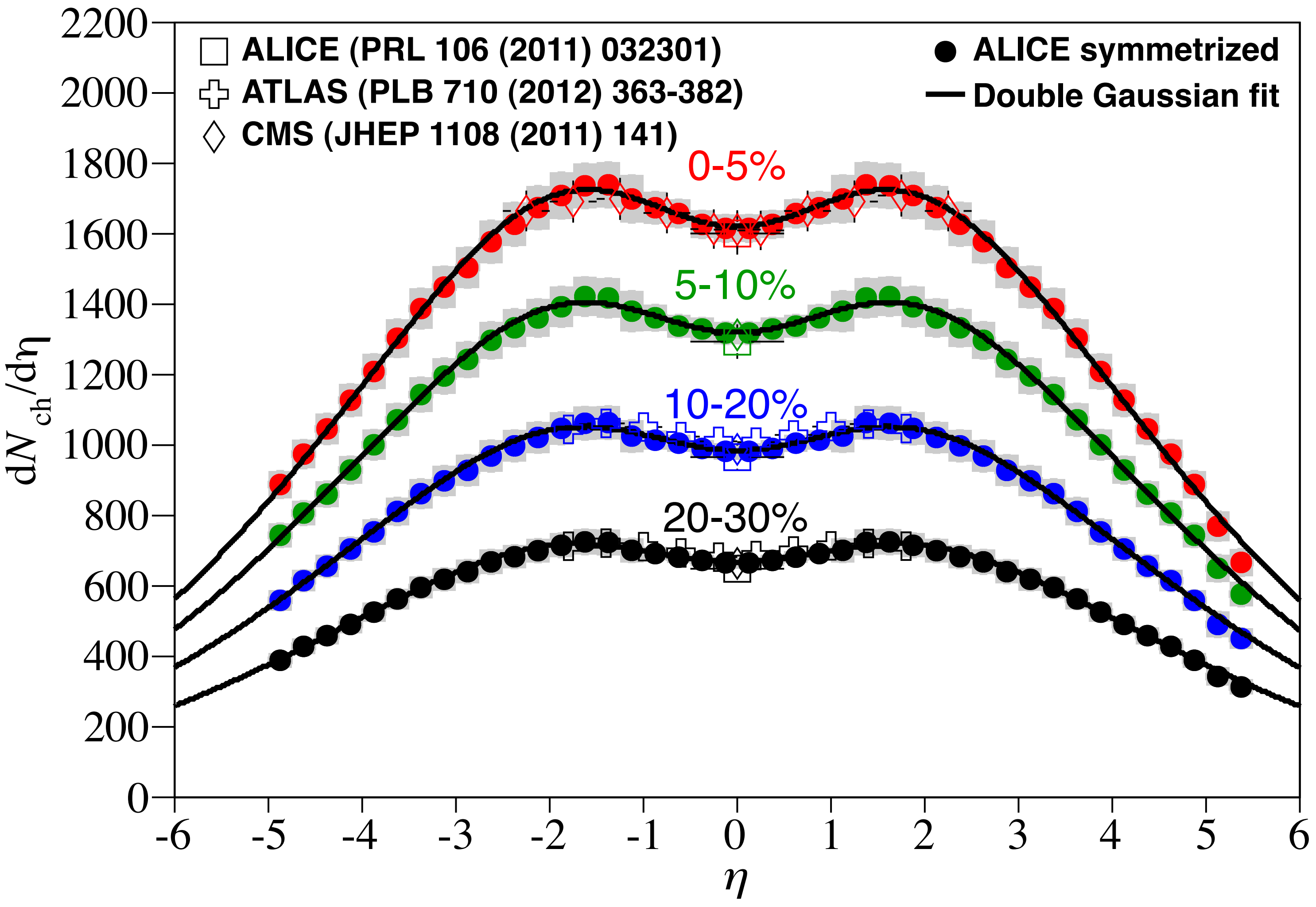
Trajectories of charged particles:

polar angle θ
(or pseudorapidity
η=-ln tan θ/2)

azimuthal angle ϕ

Counting charged particles

distribution in pseudorapidity (~polar angle)



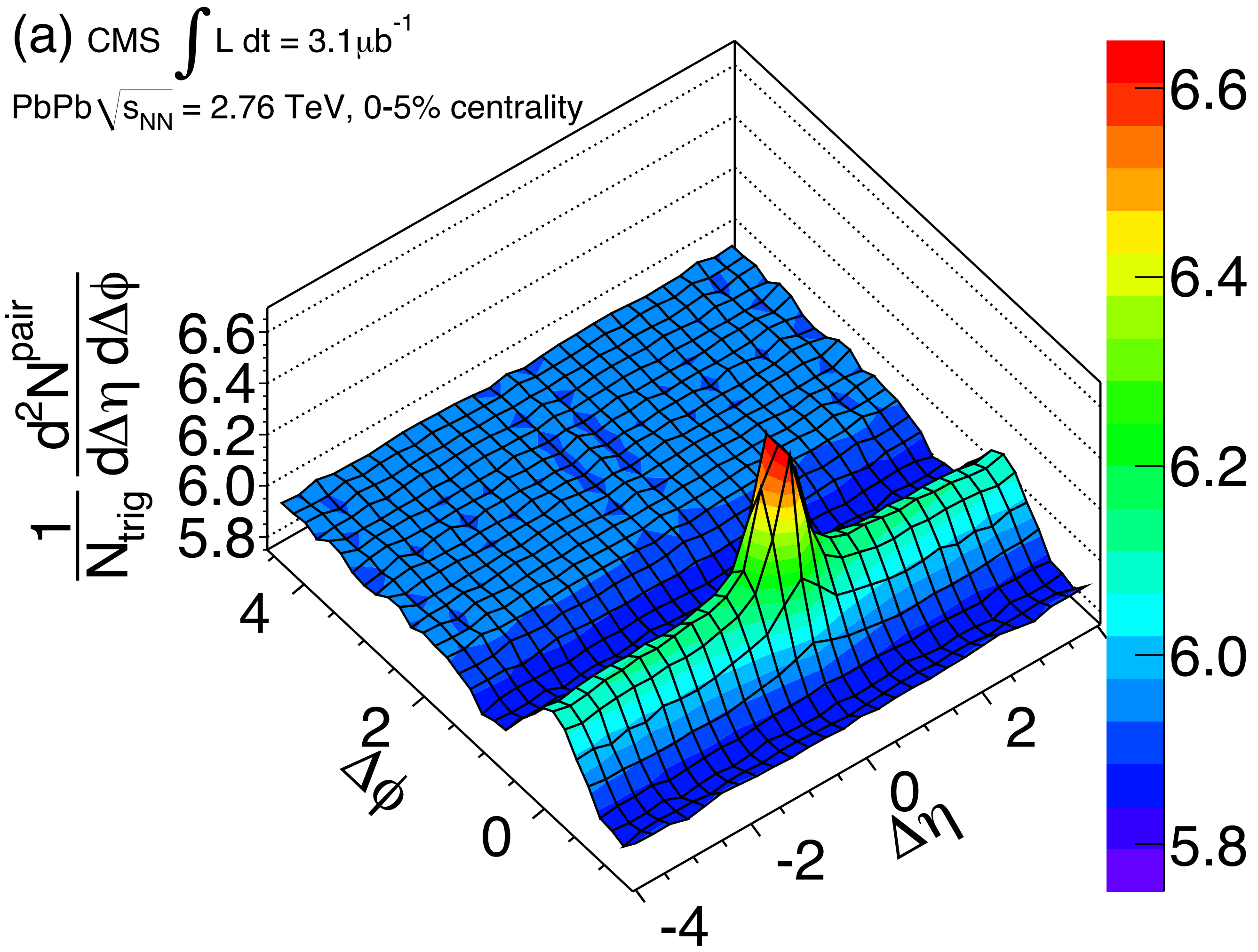
ALICE arXiv:1304.0347

Collisions classified from more central to less central in 5% bins

More central creates more particles

A central collision typically produces 25000 particles.

Observing the small fluid: counting pairs

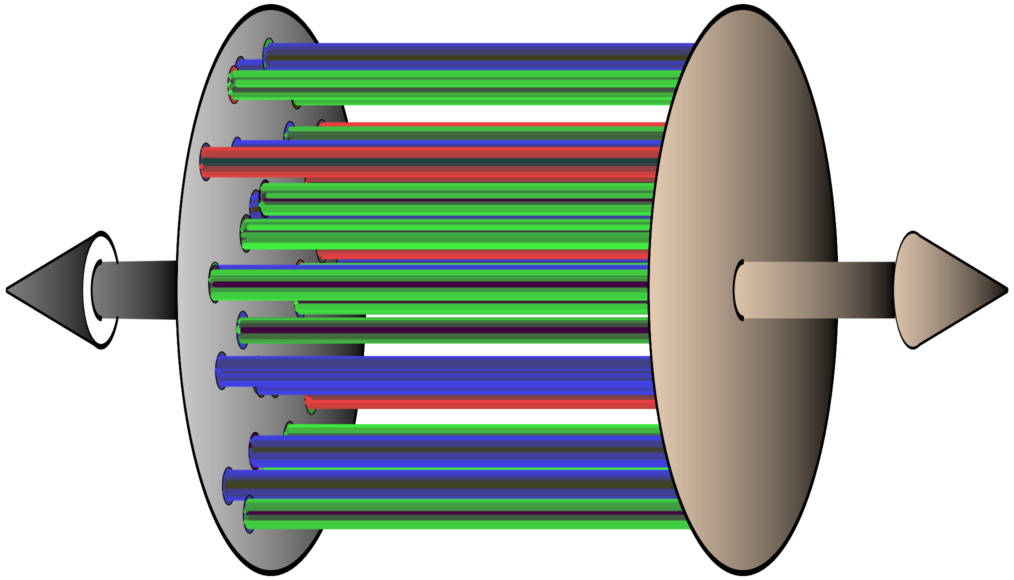


CMS arXiv:1105.2438

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

- *Ripple in a pond: cleanest signature of fluid behavior*

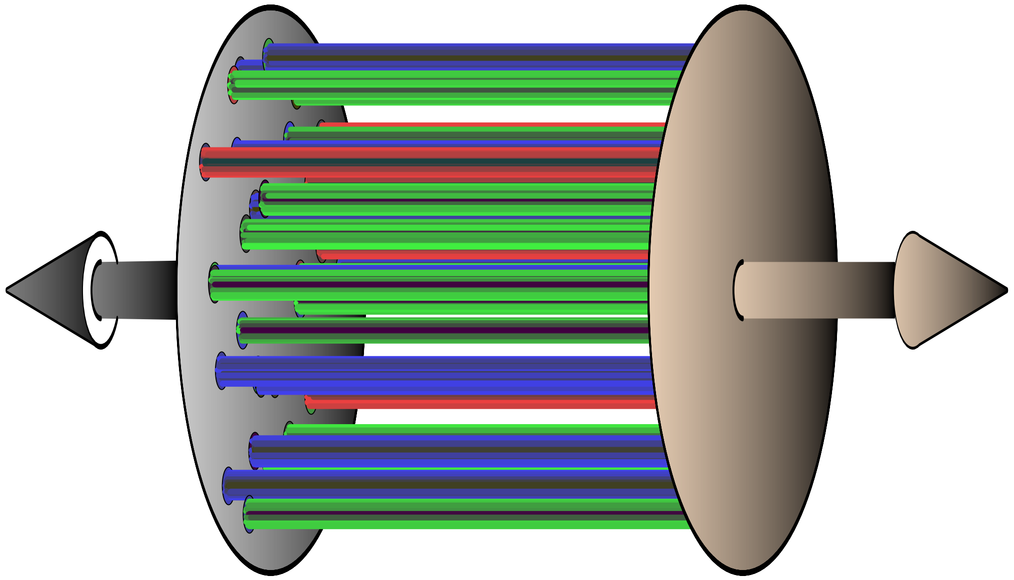
Lorentz contraction produces longitudinally-extended fluctuations

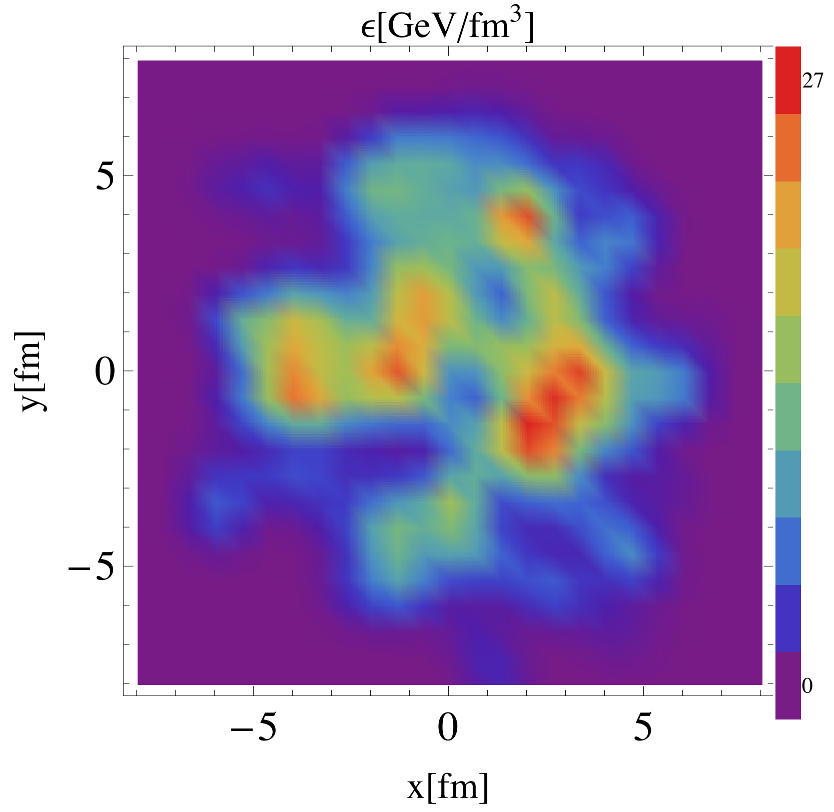


Gelis 1110.1544

- Pb nucleus=208 nucleons
- Each nucleon-nucleon collision deposits energy at the transverse location of the nucleons
- Thus the initial density profile is typically uniform longitudinally, but with a bumpy transverse profile

The fluid and its symmetries



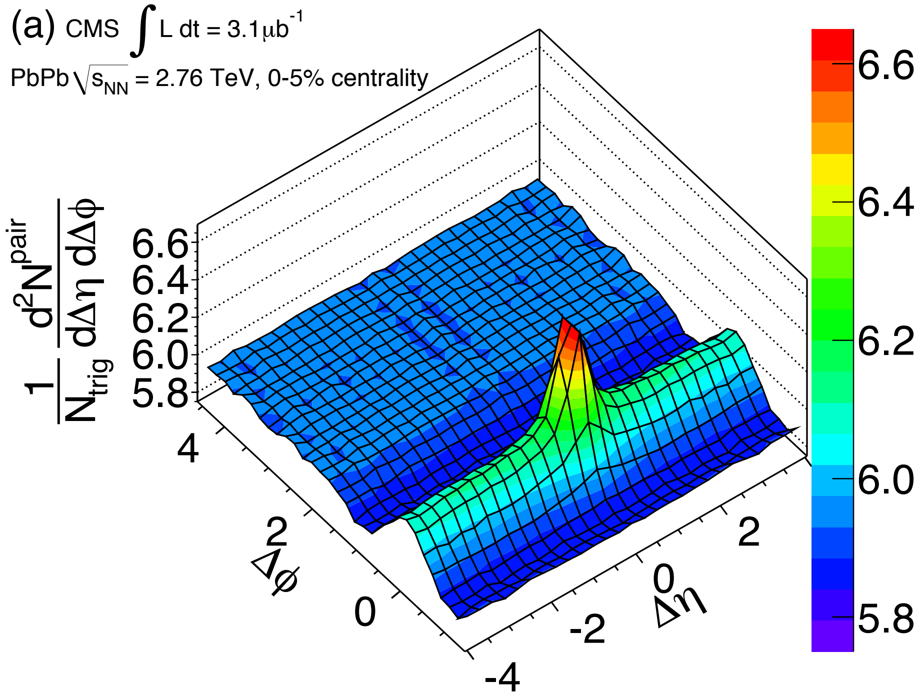


NeXSPheRIO (F. Gardim)

- The fluid has the same symmetry as the initial state: longitudinally invariant, with large transverse fluctuations.
- Transverse velocity is generated by expansion into the vacuum
- The transverse velocity of the fluid depends on the azimuthal direction φ due to transverse fluctuations

Fluid to particles

- Eventually the fluid freezes and transforms into independent individual particles
- Particle velocity = fluid velocity, plus (small) thermal motion
- Some azimuthal directions φ have more/faster particles than others due to fluctuations.
- More particles ⇒more pairs
- Explains the observed peak near Δφ=0, independent of longitudinal separation Δη



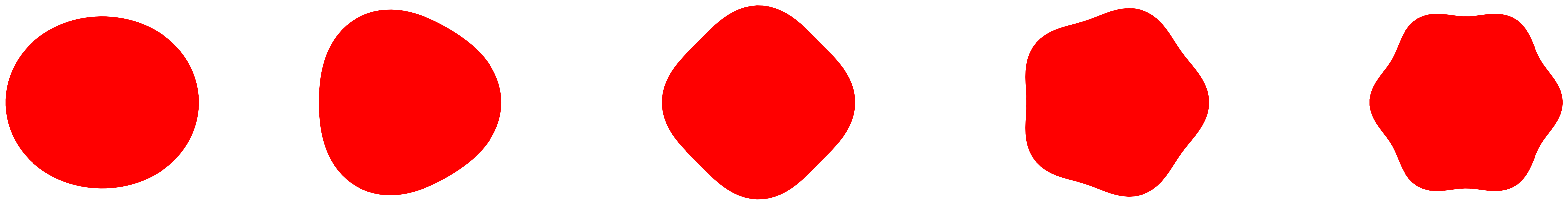
Understanding the *ripple in a pond*

- Independent particle emission from a thermal fluid
- + fluctuations in the initial state
- ⇒ Correlations between outgoing particles

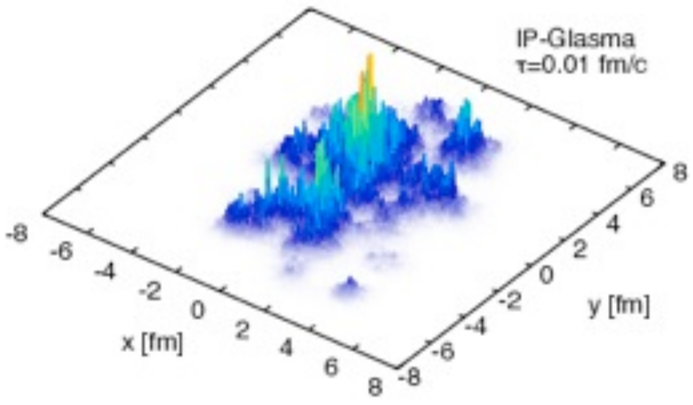
Flow harmonics

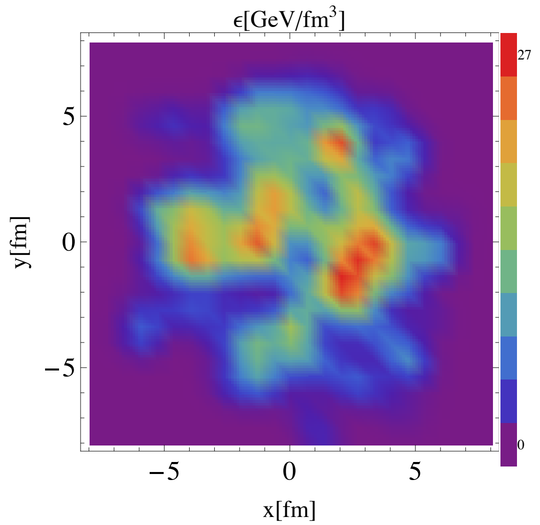
Hydrodynamics: information about flow is captured by the single-particle azimuthal (ϕ) distribution and its *complex* Fourier harmonics

$$dN/d\phi \sim \sum_n V_n\, e^{-in\phi}$$



From initial stage to flow





First strategy:

- take a particular model for initial conditions
- solve viscous hydro with these initial conditions

Difficulties:

- Numerically heavy (solve hydro event by event)
- Hydro=theory for long-wavelength modes, not reliable for short-scale structures

From initial stage to flow

Alternative strategy: symmetry arguments

- V_n is determined by a property of initial conditions which is invariant under translation and $2\pi/n$ rotation
- Construct smooth initial conditions with the same property
- Solve hydro with these smooth initial conditions

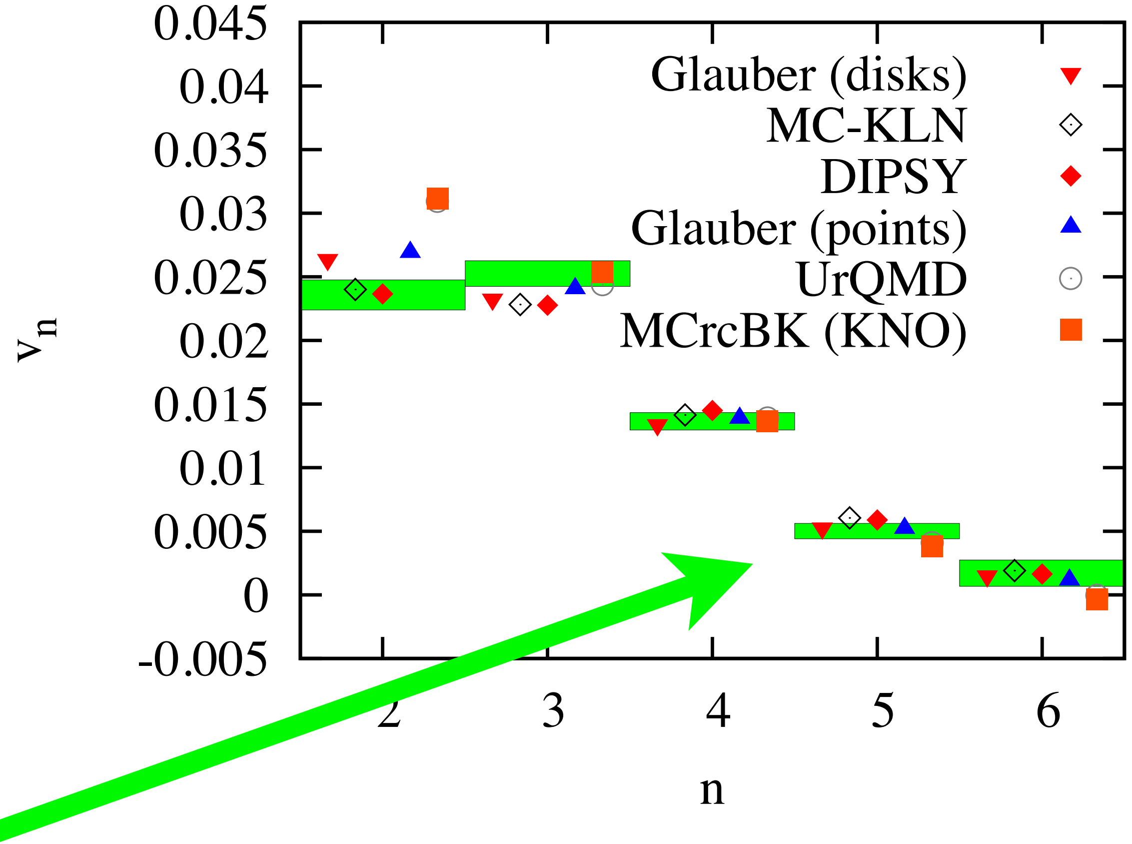
Example : Teaney and Yan's cumulants [1010.1876]

$\varepsilon_n \sim \langle r^n e^{in\varphi} \rangle$ (averaged over initial profile)

Central collisions: linear response

$V_n \propto \varepsilon_n$ (magnitude & phase) = good approximation to event-by-event hydro, better as viscosity increases *[talk by H. Niemi]*

Within this approximation, initial models+viscous hydro describe ATLAS data



Luzum JYO 1210.6010

Flow observables

- Methods used to analyze flow were devised before the importance of flow fluctuations was fully recognized (2005)
- V_n fluctuates event-to-event
- All observables are averaged over events
- Which properties of the distribution of V_n can we measure?

Good flow observables

- Perform Fourier decomposition on an event-by-event basis $Q_n=(1/N)\sum e^{in\phi}$
- Independent particle emission ⇒

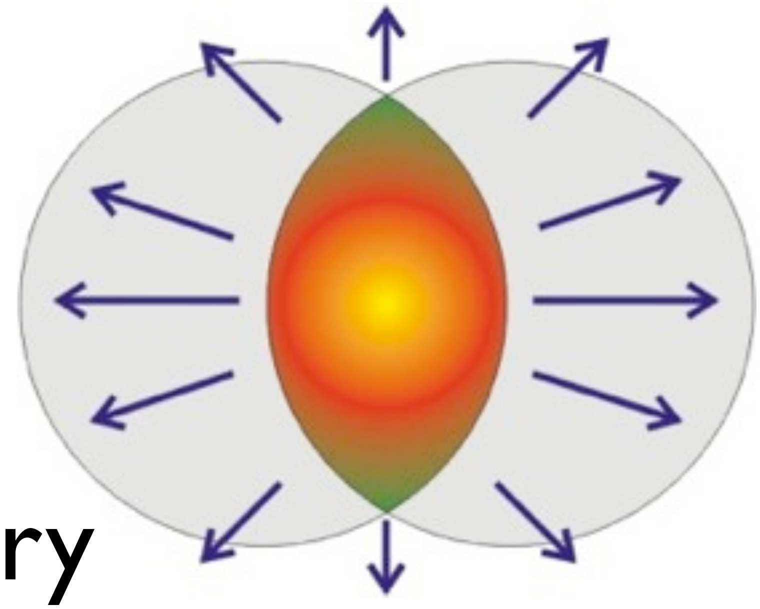
  average of product = product of averages for a fixed underlying flow.
- Good observables are products of Q_n vectors.

Good flow observables

- $\langle Q_n Q_{-n} \rangle = \langle |V_n|^2 \rangle \rightarrow$ rms v_n
- More generally, all even moments of the v_n distribution
- Mixed harmonics $\langle (Q_2)^2 Q_{-4} \rangle = \langle (V_2)^2 V_{-4} \rangle$ involve angles *and magnitudes* of V_2 and V_4.
- Not directly measurable: mean v_n, correlations between event plane angles.

Luzum JYO 1209.2323

Non-central collisions



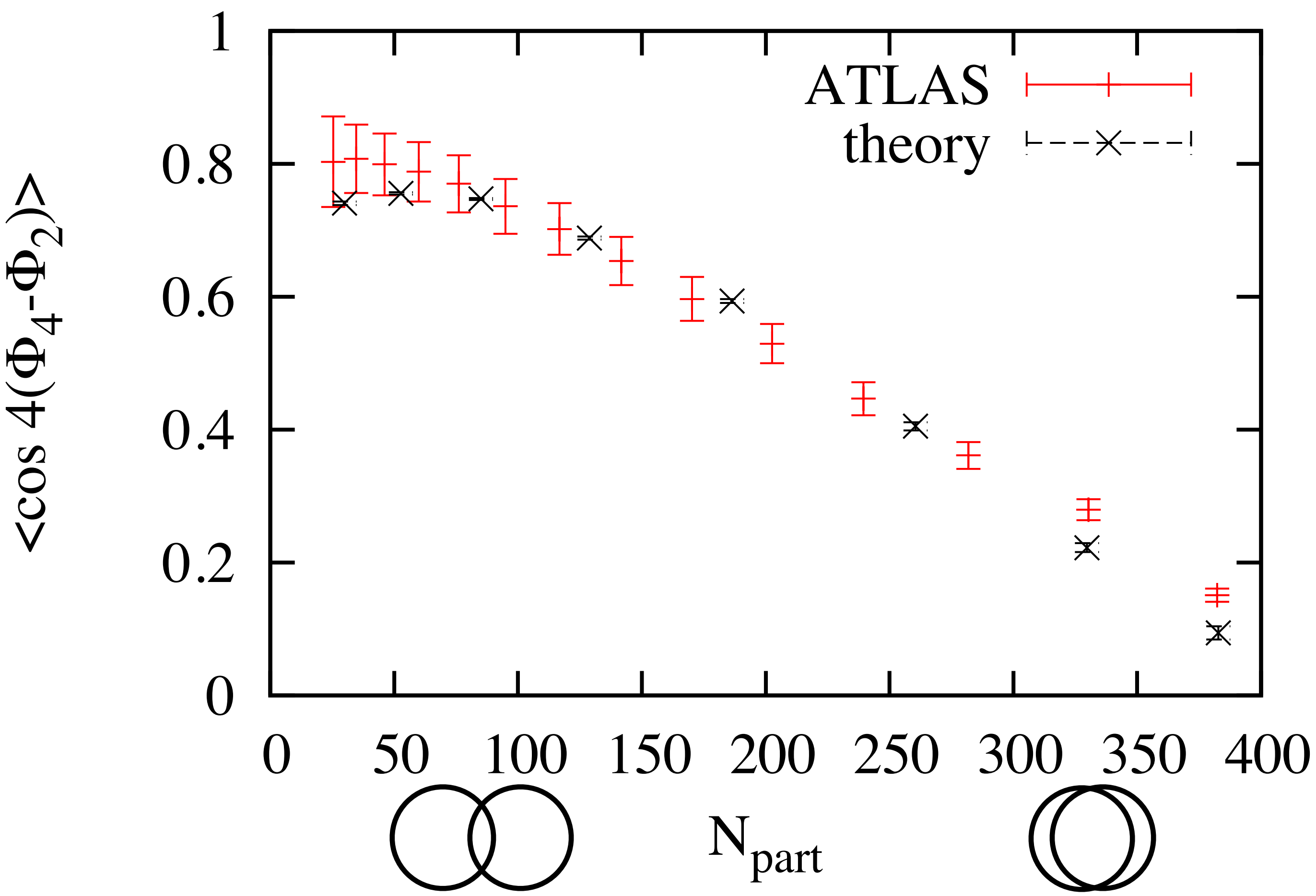
- Large elliptic anisotropy ε_2 due to average collision geometry
- Since ε_2 is large, nonlinear effects involving ε_2 are important
- $V_4 \propto (\varepsilon_2)^2$ is a better rule than $V_4 \propto \varepsilon_4$

Event plane correlators

ATLAS has measured 14 mixed correlations.

e.g., linear correlation between V_4 and $(V_2)^2$

=Large when non-linear response dominates



ATLAS 1208.1427

Bhalerao JYO Pal 1307.0980

Summary

- Flow fluctuations: a rich, new subfield of heavy-ion physics
- Hydrodynamic response to initial fluctuations not fully understood: effects of small-scale fluctuations + thermalization?
- Flow methods must be revisited to take flow fluctuations into account: new analyses needed.