Introduction to the heavy-ion session

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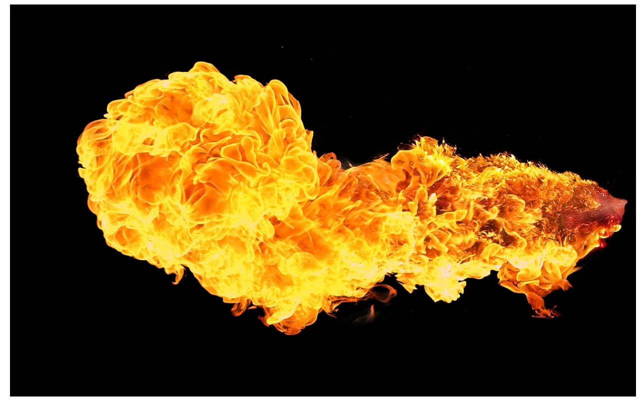
Paris, June 11, 2013

The quest for ultra-high temperatures

- Chemical reactions

  $T \sim 2\ 10^3$ K

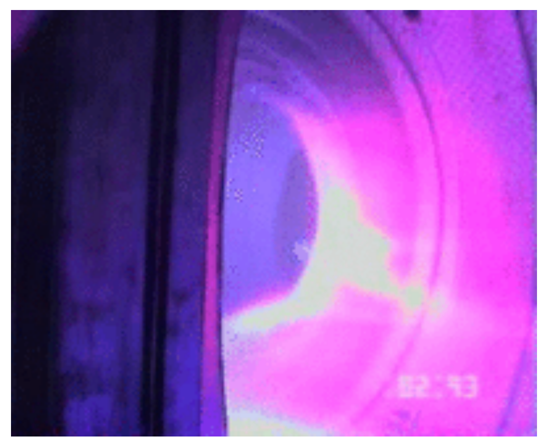
  $v \sim 10^3$ m/s



- Confined plasmas for nuclear fusion

  $T \sim 10^8$ K

  $v \sim 10^6$ m/s

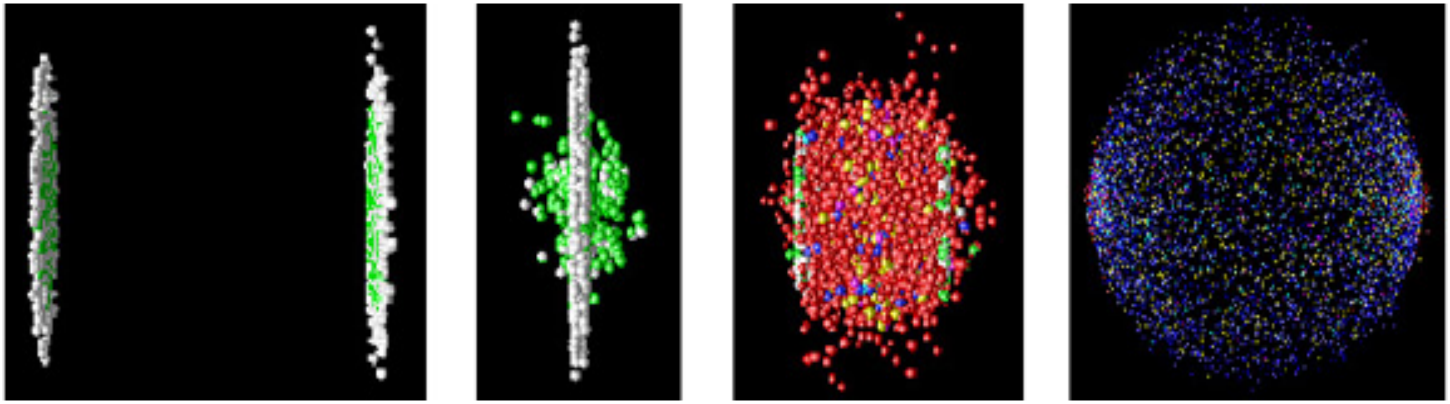


Breaking the record with accelerators

- Use the largest accelerator in the world to achieve the highest velocities: 99.9997% speed of light

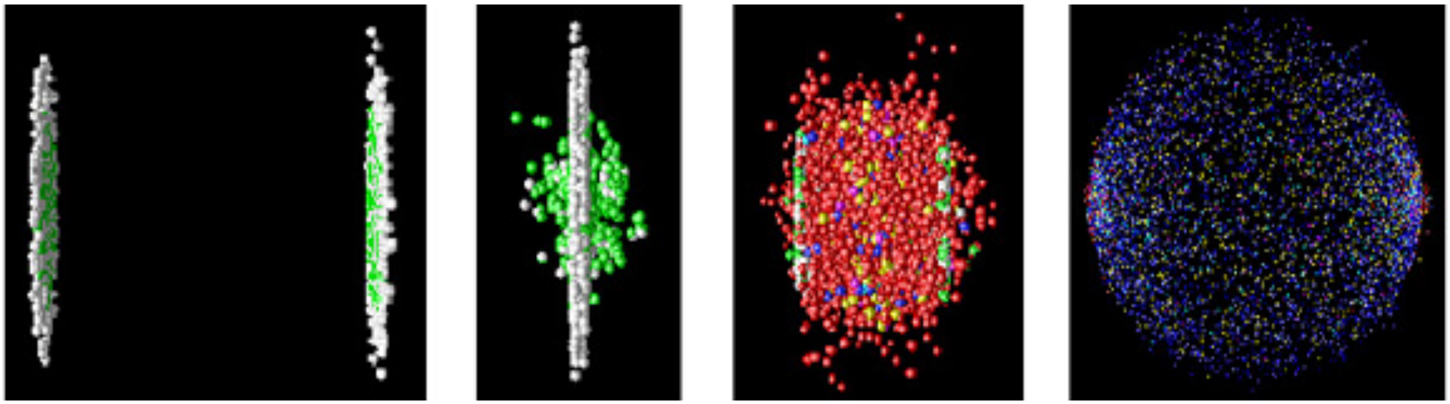
- Collide two beams of lead atomic nuclei Pb^{82+} (two runs in november 2010 and 2011)

Nuclear collisions at the LHC



- Kinetic energy of nuclei = 1500 x mass energy
- Relativistic contraction of length by factor 1500: colliding thin pancakes
- The strong interaction transfers part of incoming energy into mass energy (creation of matter) and transverse kinetic energy.

Nuclear collisions at the LHC

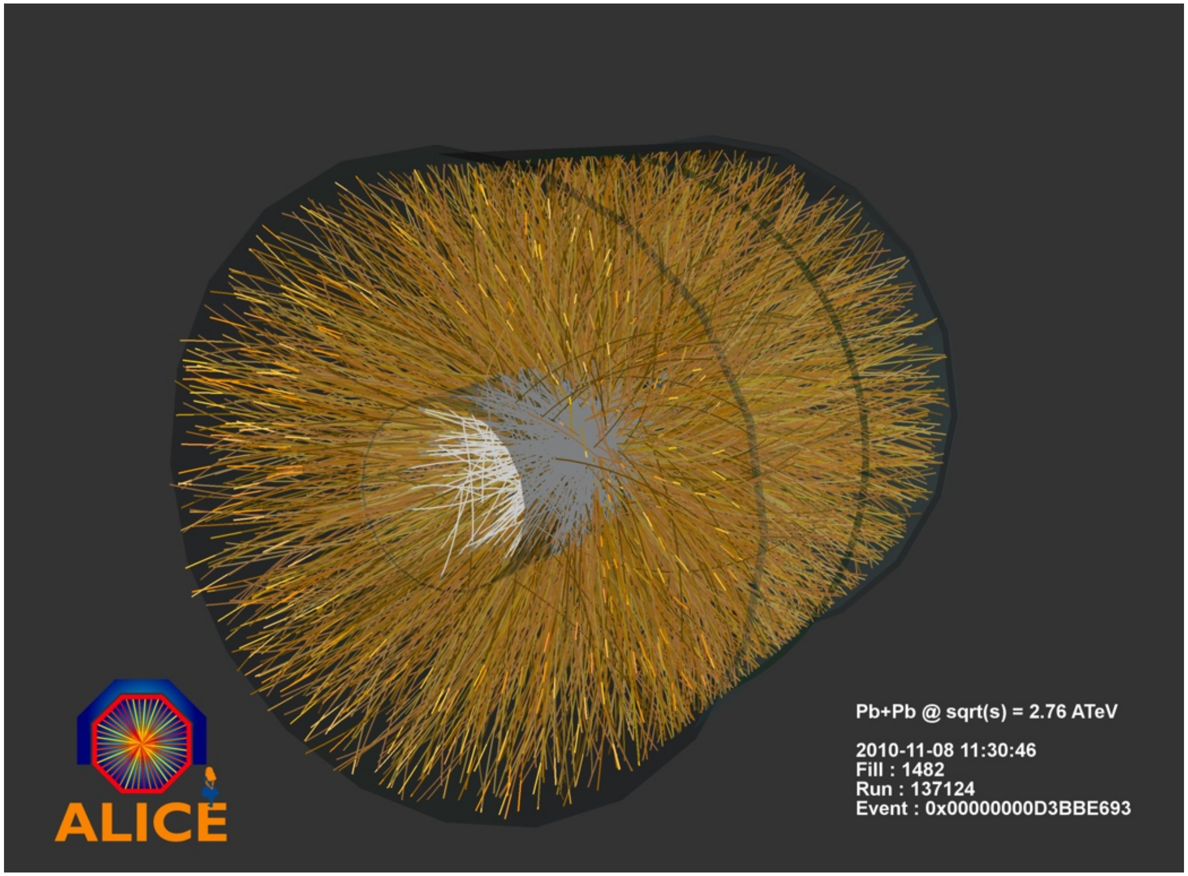


- *Something (quark-gluon plasma)* is created. It is governed by strong interactions and expands into the vacuum

- The best theoretical description is a macroscopic one: a small lump of fluid

- $T \sim 2\ 10^{12}$ K : relativistic fluid $v \sim c$

What we see



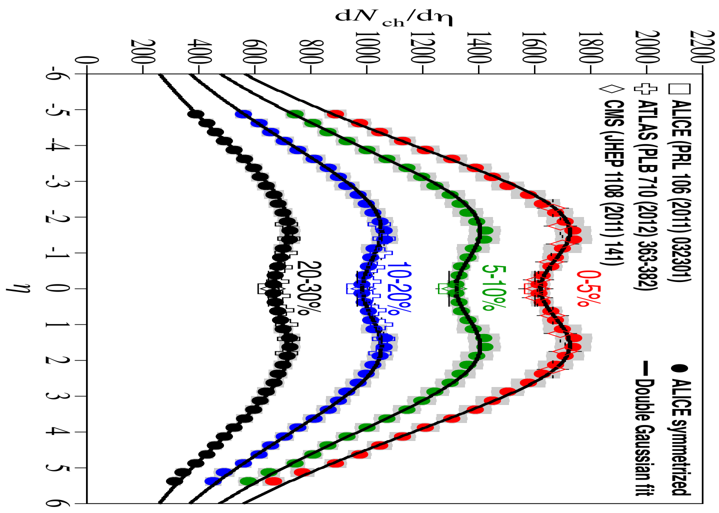
Trajectories of charged particles:

polar angle θ
(or pseudorapidity $\eta = -\ln \tan \theta/2$)

azimuthal angle ϕ

Counting charged particles

distribution in pseudorapidity (~polar angle)



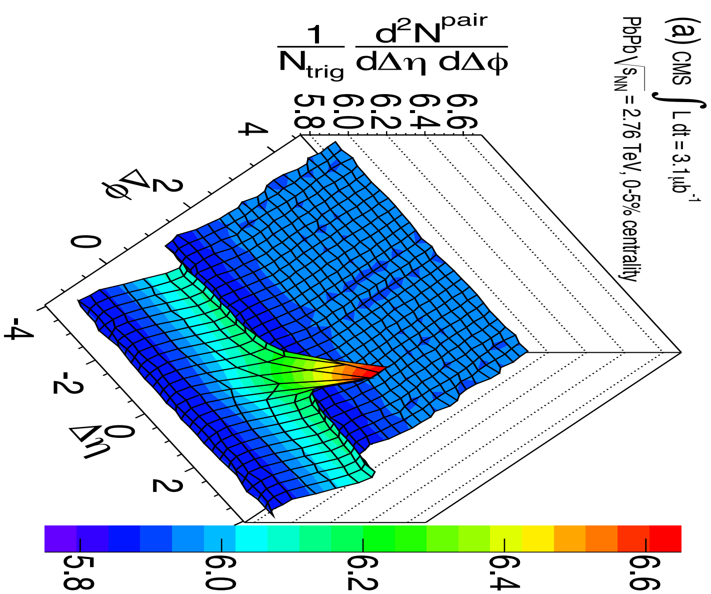
ALICE arXiv:1304.0347

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

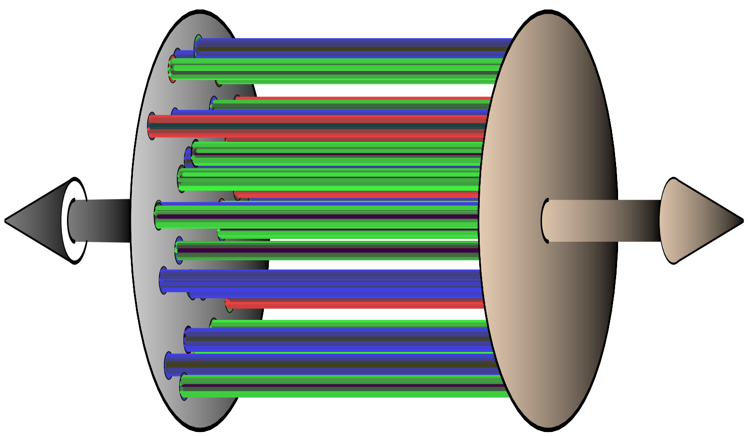


Number of pairs of particles versus relative azimuthal angle and pseudorapidity (~polar angle) in central Pb-Pb collisions

CMS arXiv:1105.2438

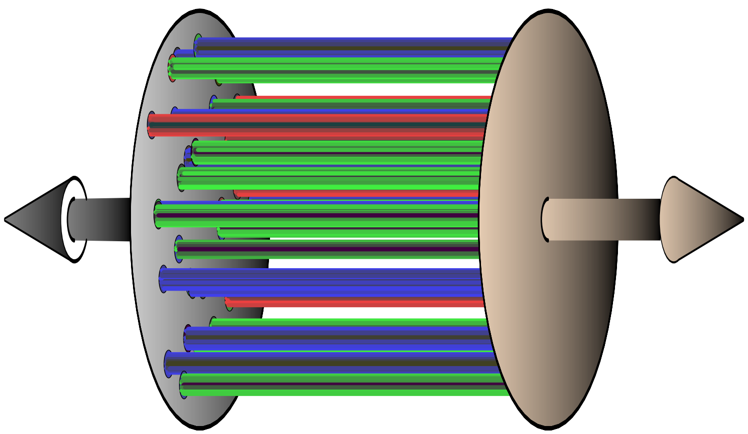
- *Ripple in a pond: cleanest signature of fluid behavior*

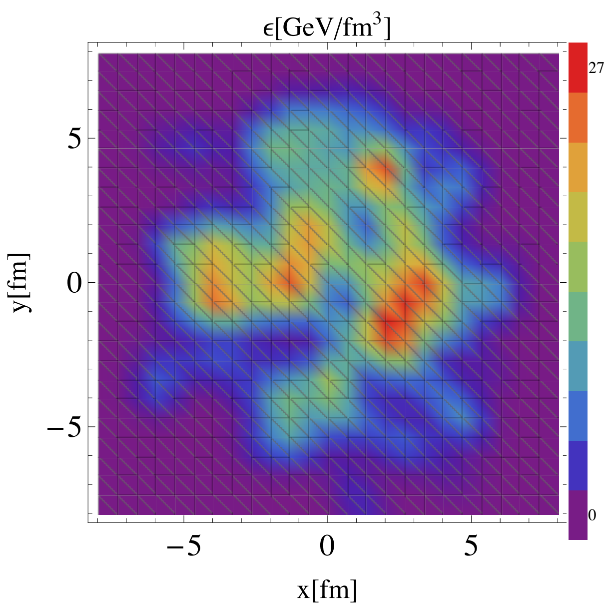
Lorentz contraction produces longitudinally-extended fluctuations



- 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



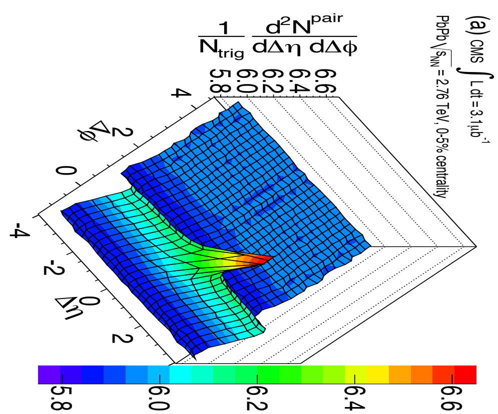


- The fluid has the same symmetry as the initial state: longitudinally invariant, with large transverse fluctuations.

- 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

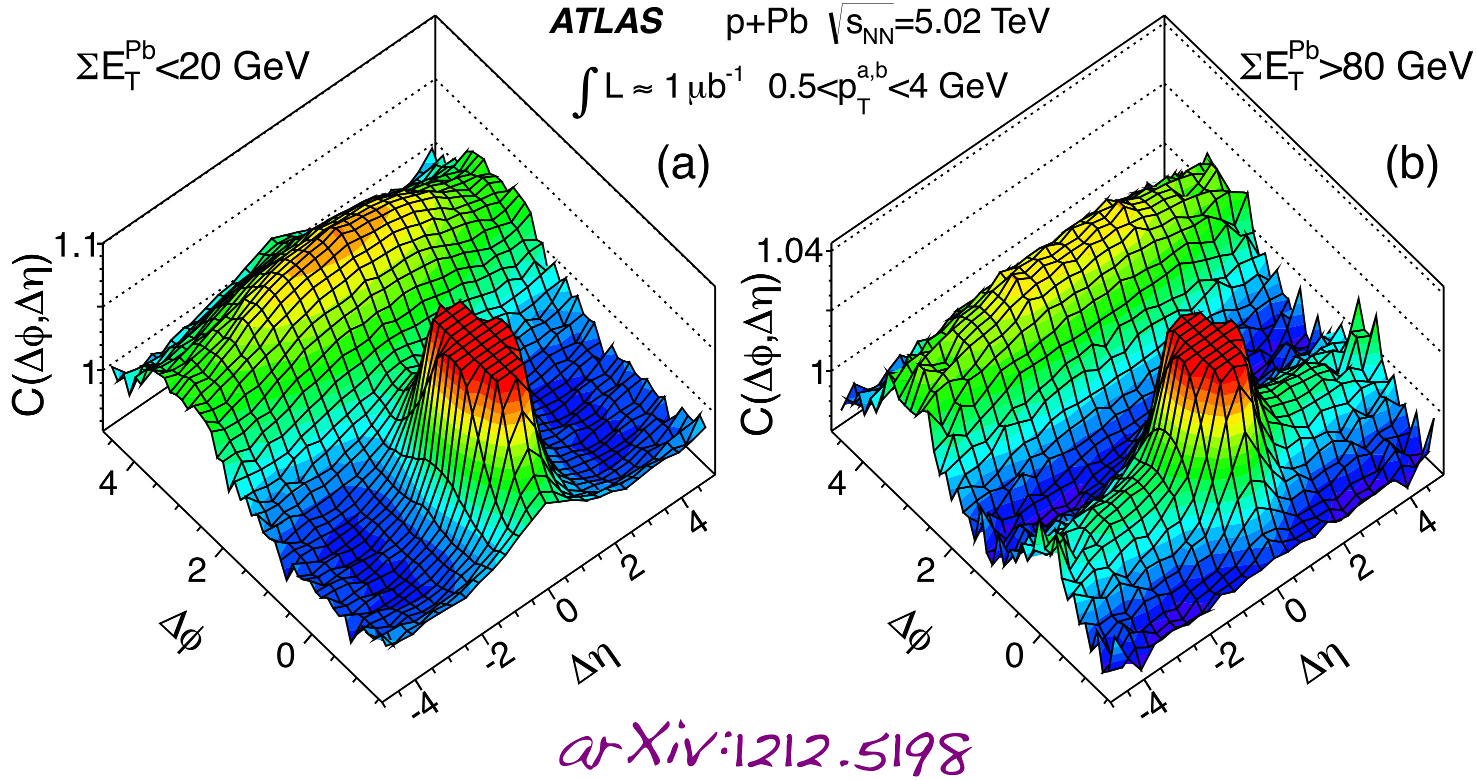


- Eventually the fluid freezes and transforms into independent individual particles
- Particle velocity = fluid velocity, plus (small) thermal motion
- Some azimuthal directions φ have more/faster particles than others due to fluctuations.
- More particles ⇒more pairs
- Explains the observed peak near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

2012: proton-nucleus collisions



Central collisions (right) also show a ridge near ΔΦ=0, similar to that observed in Pb-Pb collisions. Fluid?

Upcoming talks:
1. Initial stage

Adrian Dumitru:

Magnetic Vortices in High-Energy Heavy-Ion Collisions

Thomas Epelbaum:

The Early Stages of Heavy Ion Collisions

Upcoming talks
2. Collective flow

Experiment

Ante Bilandzic: *Anisotropic Flow in ALICE at LHC*

Jiangyong Jia: *Event-by-Event Flow and Initial Geometry at the LHC*

Theory

Wojciech Broniowski: *Collective Dynamics of the p+Pb Collisions*
Salvatore Plumari: *Anisotropic Flows and Shear Viscosity from a Beam Energy Scan*

Marco Ruggieri: *Kinetic Theory Computation of Elliptic Flow in Heavy Ion Collisions*

Upcoming talks
3. Other topics

Jet quenching

Yacine Mehtar-Tani: *Generating Functional for Jet Observables in Heavy Ion Collisions*

Quarkonium

Peter Filip: *Magnetic Quenching of Quarkonium Decay*

Strong coupling approaches

Ayan Mukhopadhyay: *AdS/CFT Imprints on the ALICE Fireball?*

Phase diagram

Hubert Hansen: *A Detailed Analysis of the Phase Diagram of QCD in the High Density and Temperature Region*

Thanks to all the speakers!

Backup

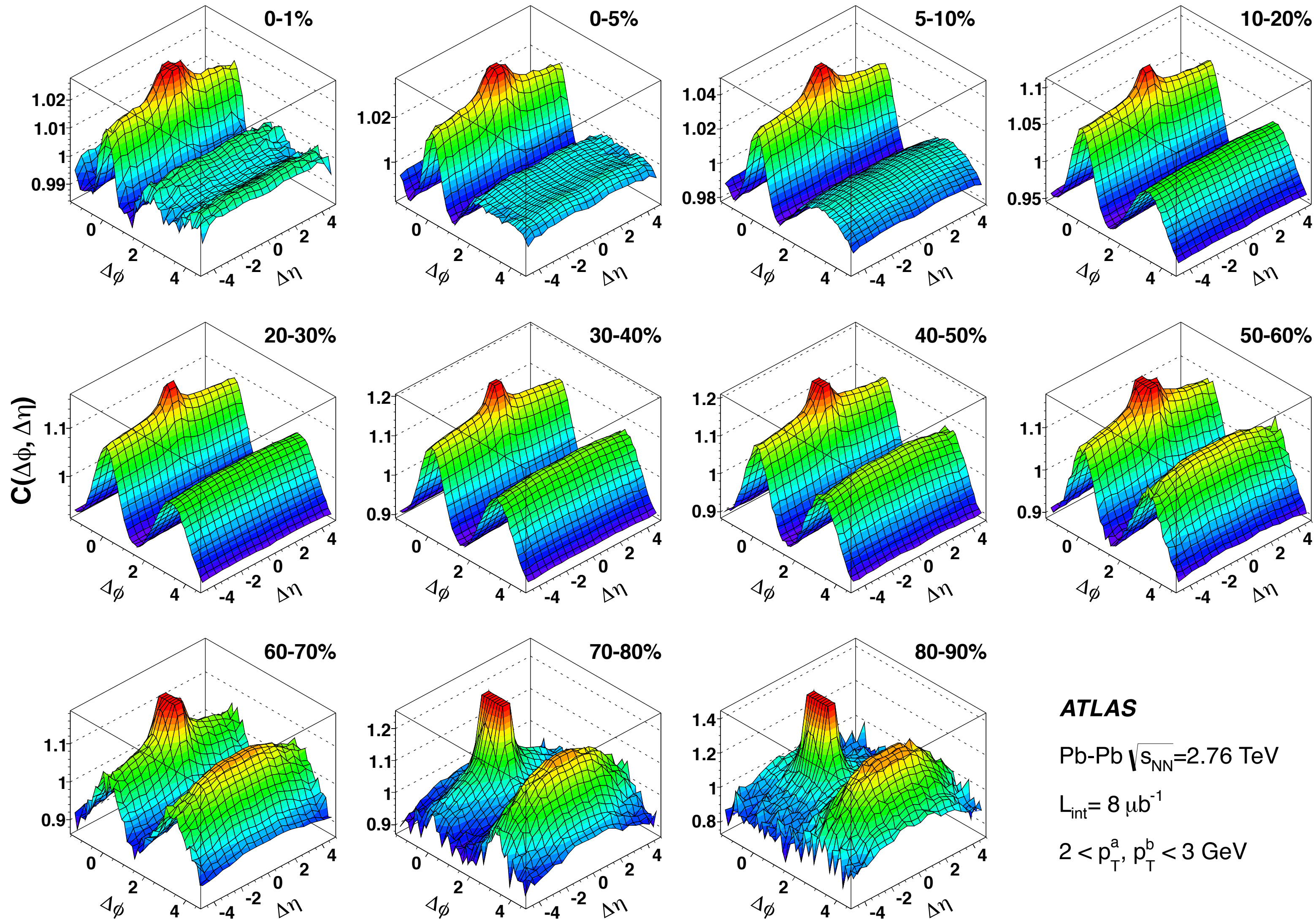
Mini bang versus big bang

- Nucleus-nucleus collisions at the LHC produce a small lump of strongly-coupled fluid expanding into the vacuum. Similar to early universe, $t \sim 10^{-6}$s
- Initial quantum fluctuations, followed by hydrodynamic expansion, explain the observed fluctuation spectrum.
- More and more phenomena observed at the LHC are explained by hydrodynamics
- Ongoing theoretical effort to understand early thermalization (Gelis, Epelbaum)

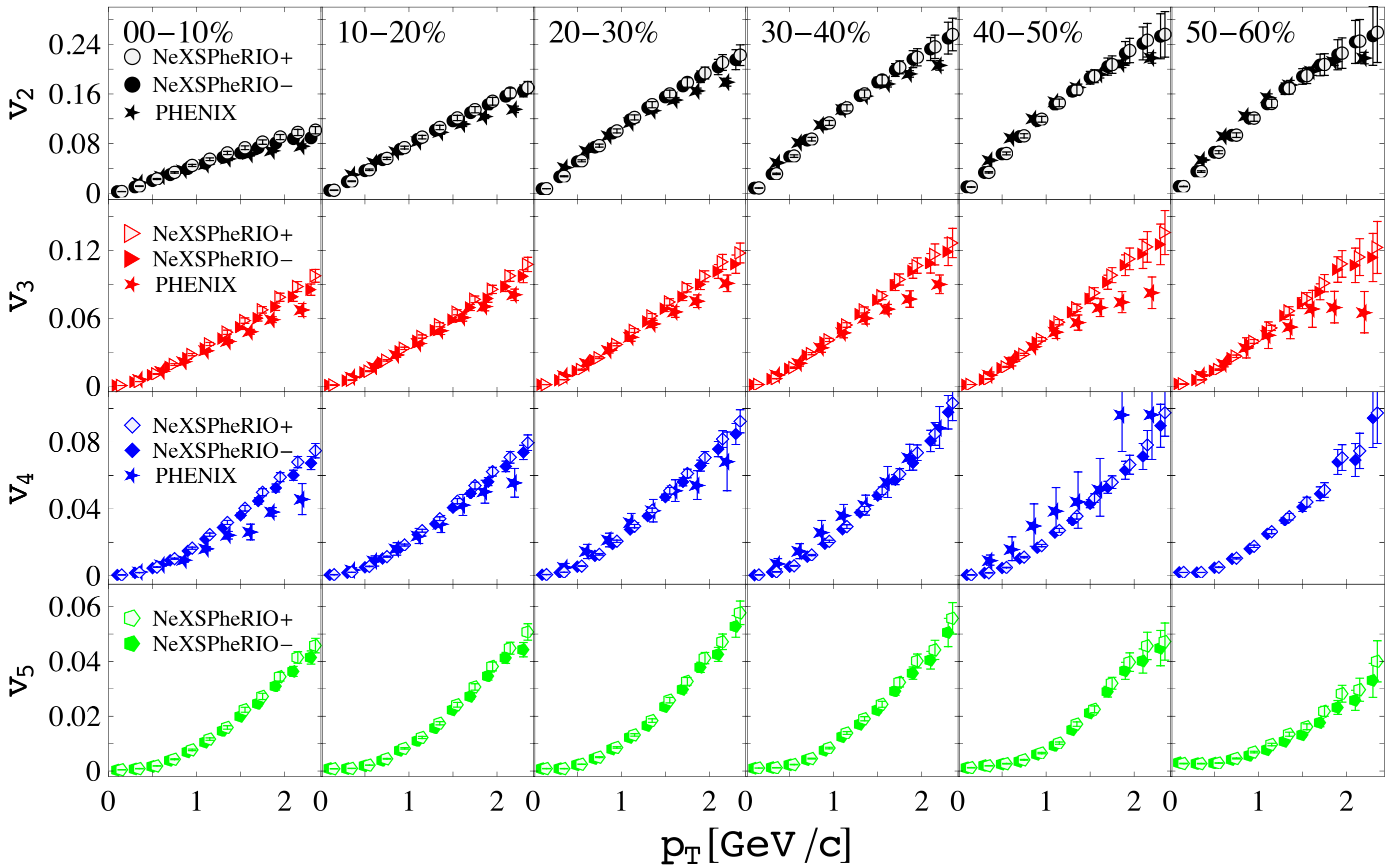
Quantitative calculations

- Observables: Fourier expansion in $\Delta\phi$ (spectrum of fluctuations v_n)
- Use some model for the initial density profile
- Solve relativistic hydrodynamics using this initial condition

ATLAS correlation data



Hydro versus v_n data



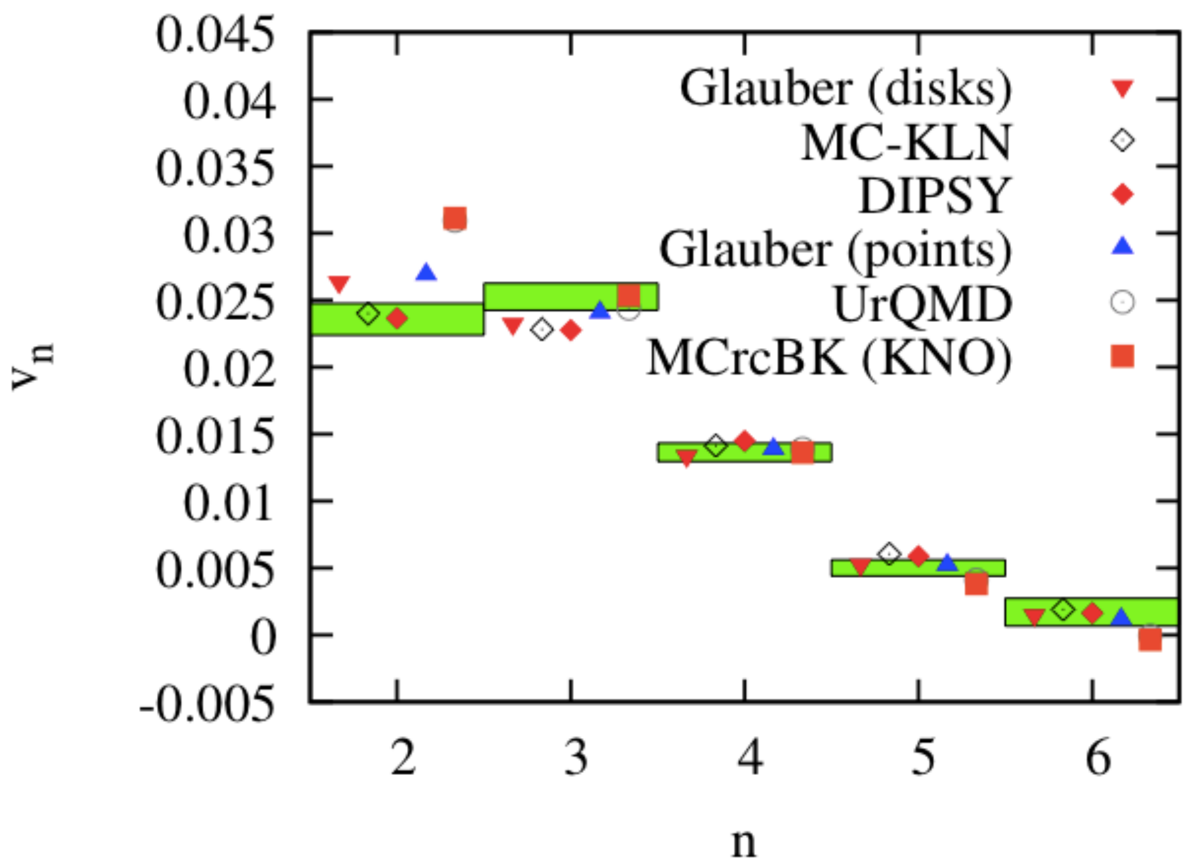
Ideal hydrodynamics, 0 viscosity

Gardim Grassi Luzum JYO, 1203.2882

Viscosity and fluctuations

- Local thermal equilibrium = ideal hydro
- Deviations from equilibrium = viscous corrections, prop. to density gradients
- Initial fluctuations ⇒ large gradients!
- Caveat : viscous hydrodynamics is not well understood in this regime.

Quantitative calculations



Luzum JYO, in preparation

Bands: ATLAS data, 1% most central

Each set of points = model for the initial density

Large n= small scale modes: damped by viscosity