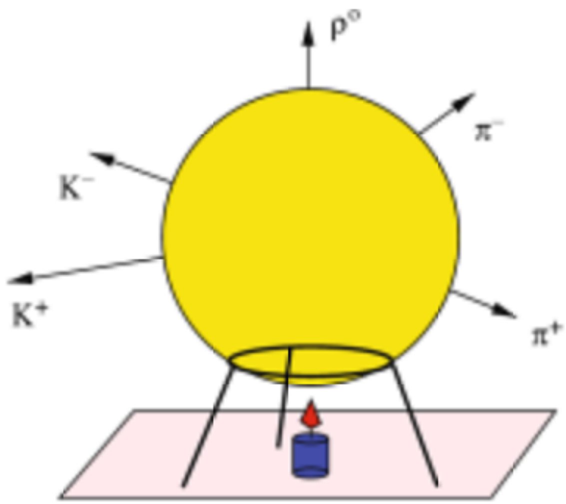
Heavy Ion Physics
Lecture 4: Elliptic Flow and Correlations

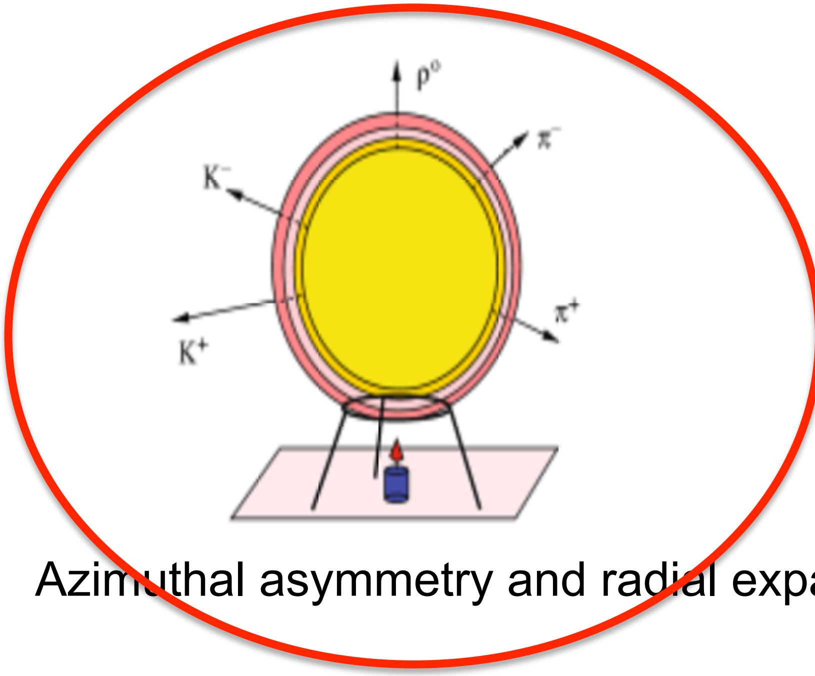
HUGS 2015

Bolek Wyslouch

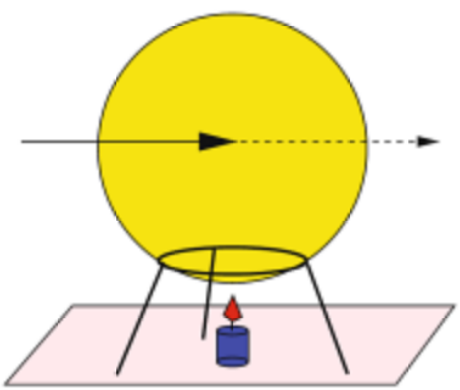
Techniques to study the plasma



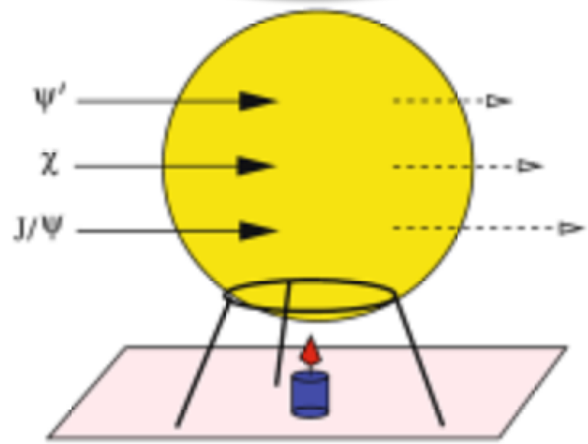
Radiation of hadrons



Azimuthal asymmetry and radial expansion



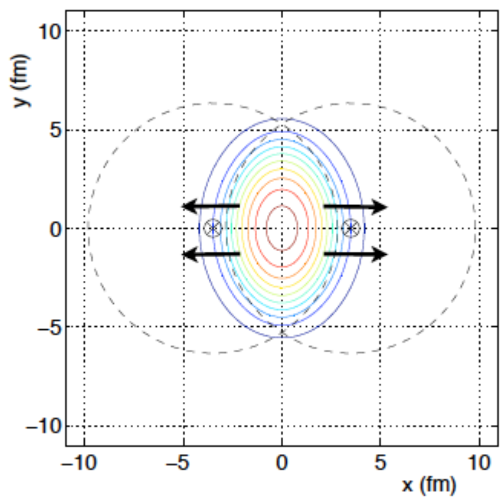
Energy loss by quarks, gluons and other particles



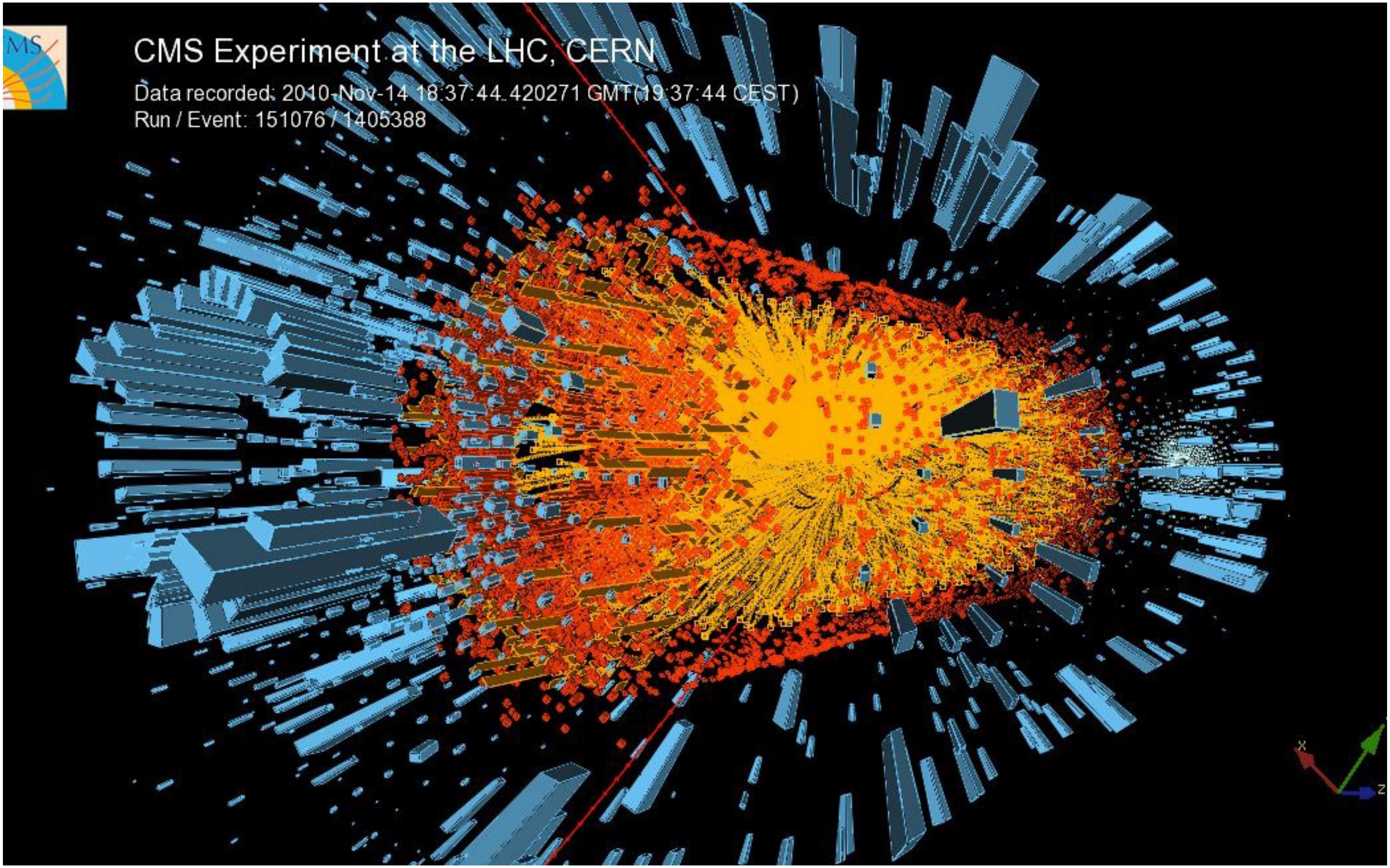
Suppression of quarkonia

Azimuthal asymmetry and radial expansion

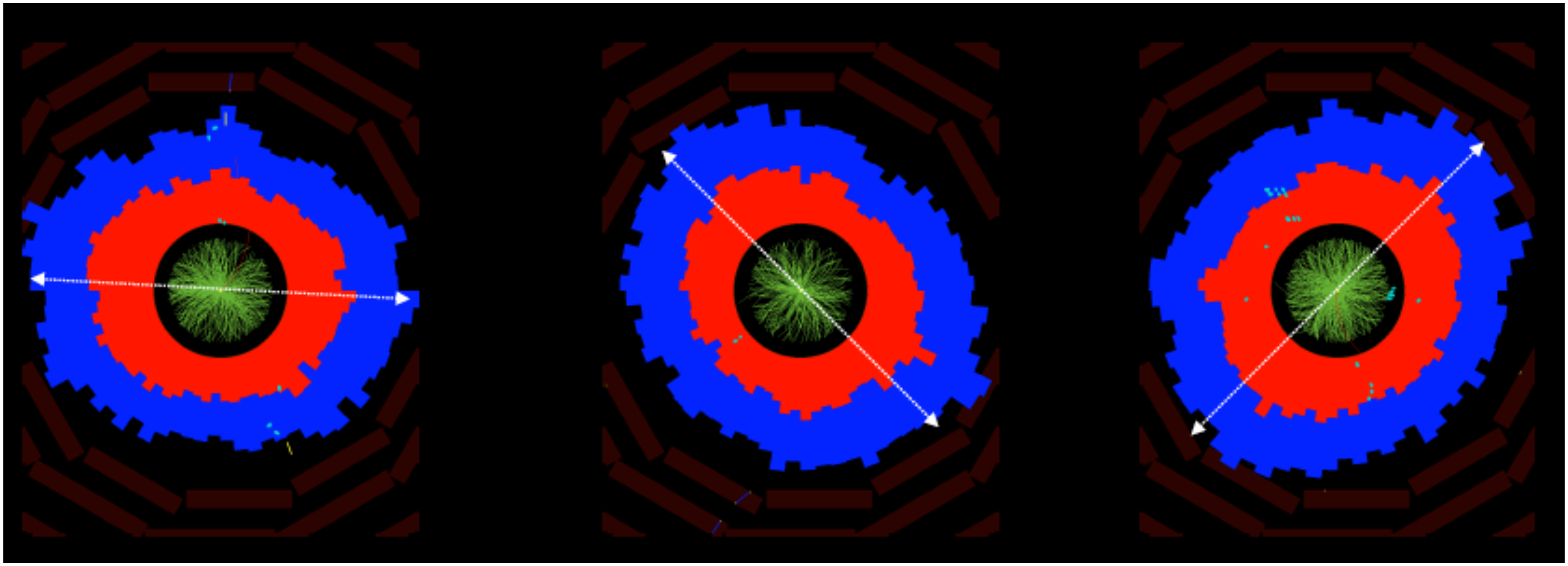
- Exploit the fact that there are many peripheral collisions that are azimuthally asymmetric



- The pressure in the hot drop of strongly interacting fluid affects the momentum of emitted particles

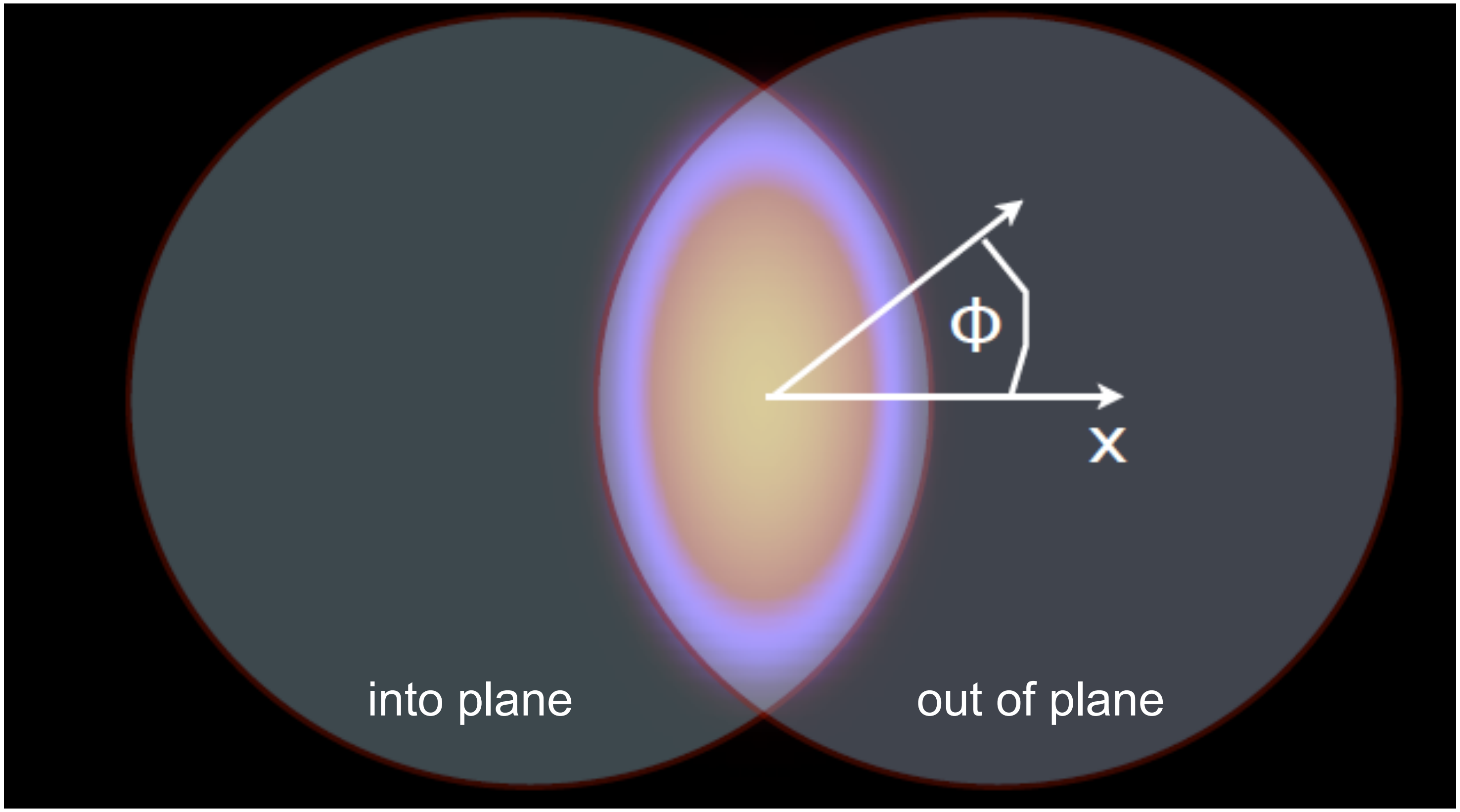

CMS Experiment at the LHC, CERN
Data recorded: 2010-Nov-14 18:37:44.420271 GMT(19:37:44 CEST)
Run / Event: 151076 / 1405388

Energy in CMS calorimeters



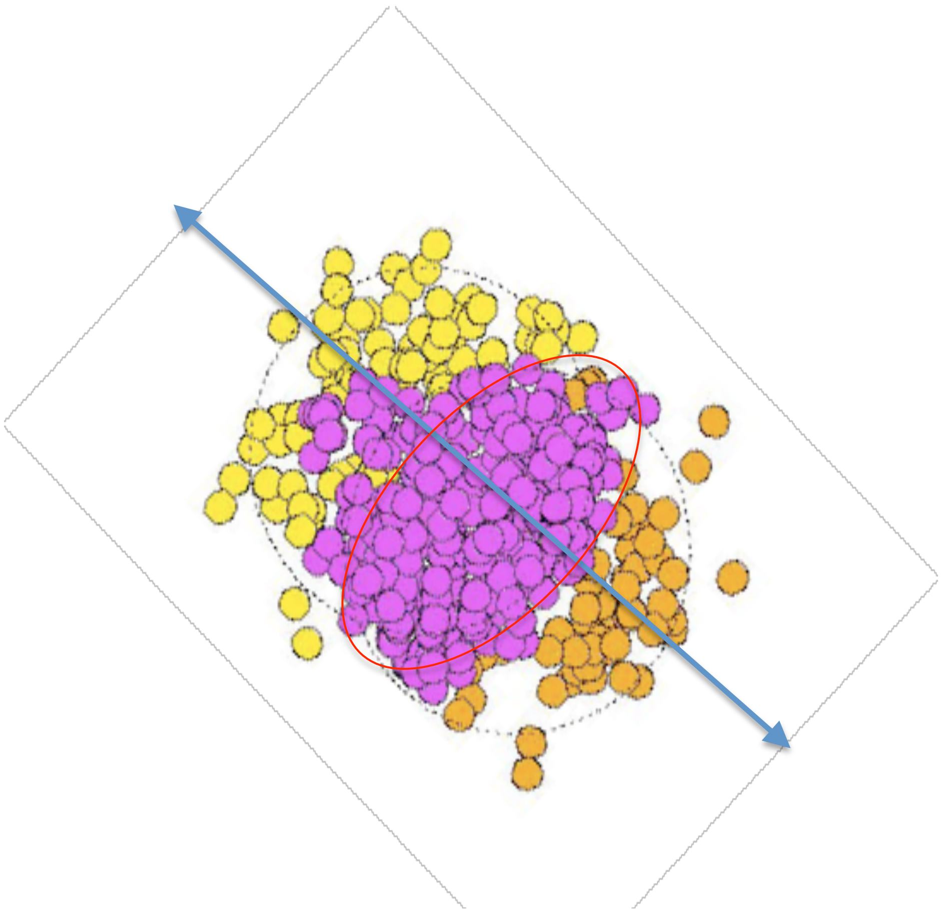
- Particles are emitted in preferred direction
- Energy/momentum modulation of ±15%
- Visible with naked eye!
- Why? (and what can we learn from this?)

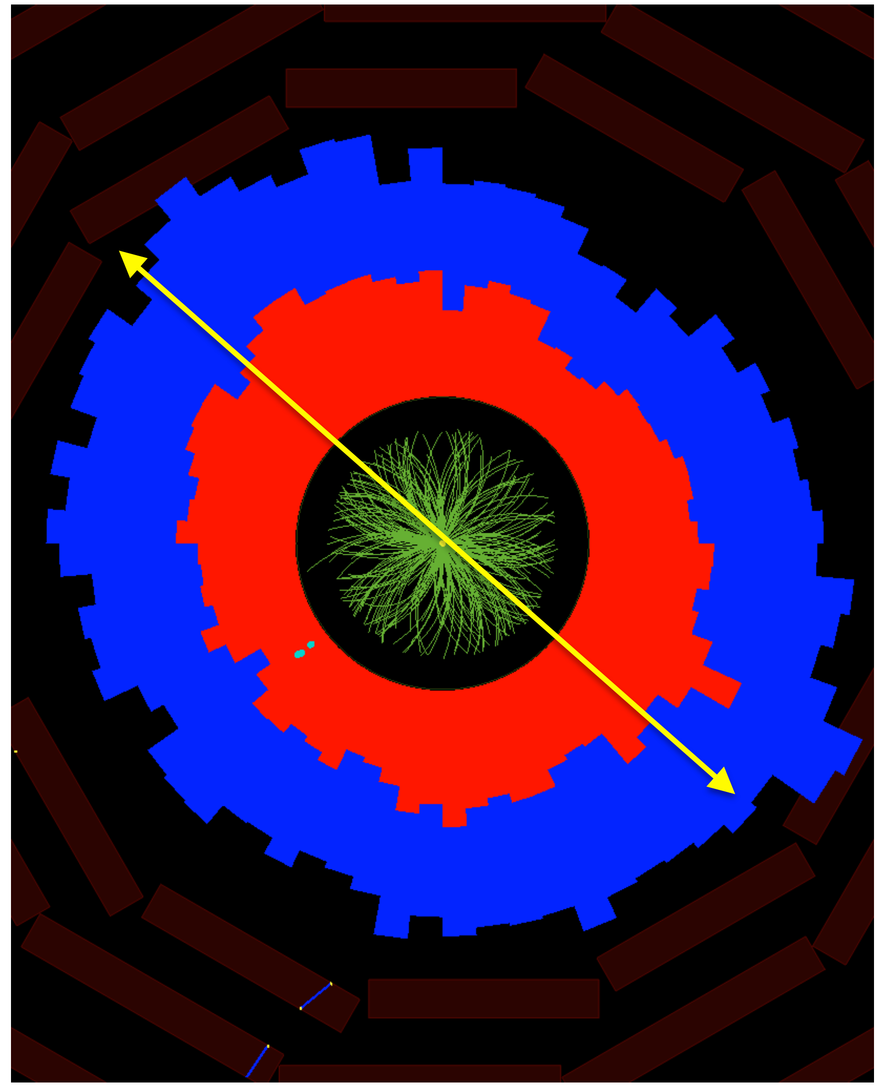
Non-central collision



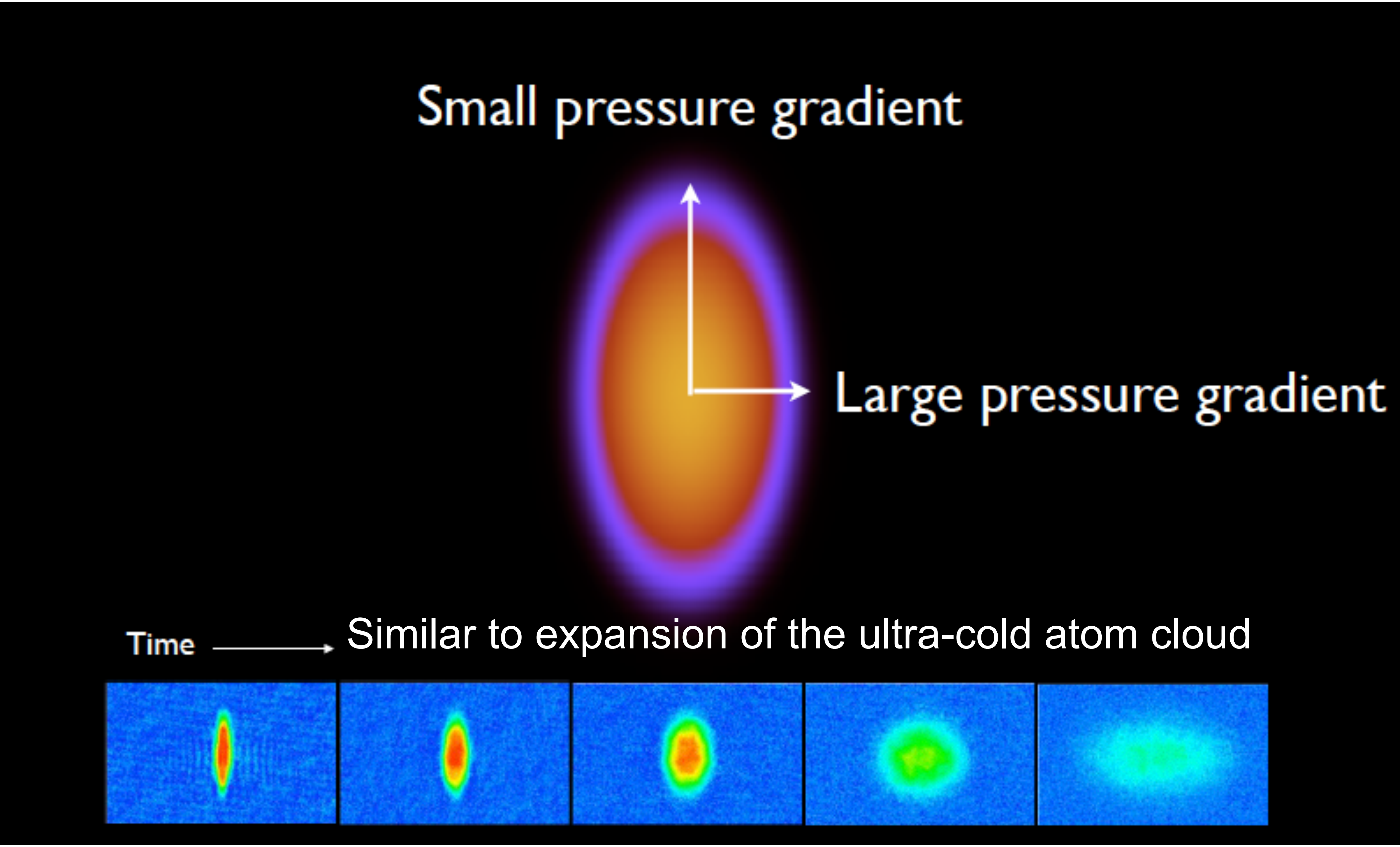
- Initial overlap of the two ions is asymmetrical in azimuth φ
- Note that in this cartoon the interaction region is nice and symmetric…

Initial shape vs momentum anisotropy

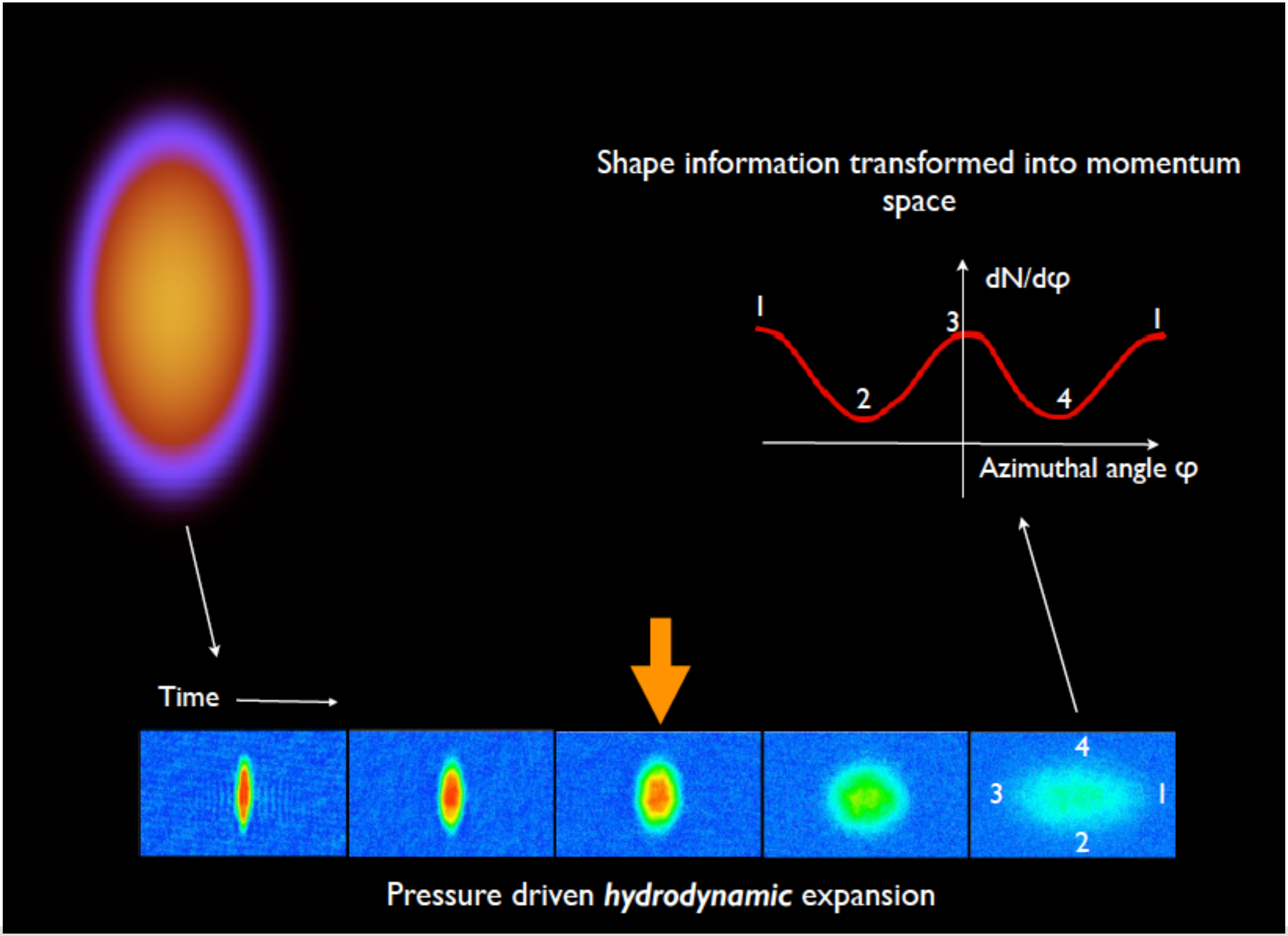




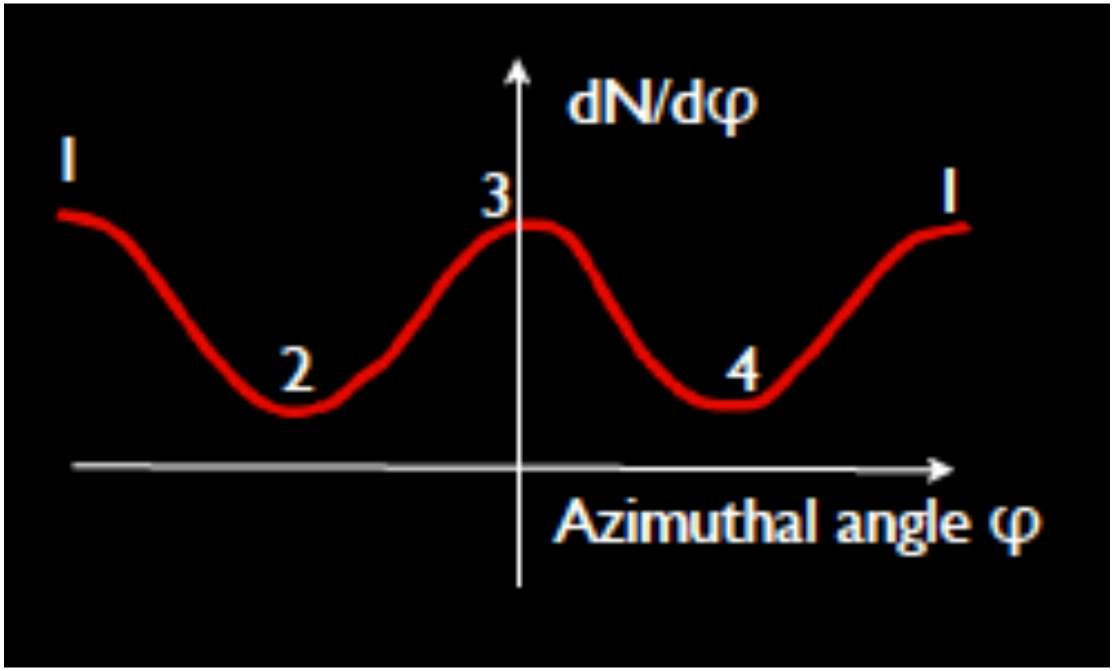
Emission of particles from lenticular hot region



Azimuthal particle distribution (p_T dependent)



Quantify the strength of the azimuthal effects



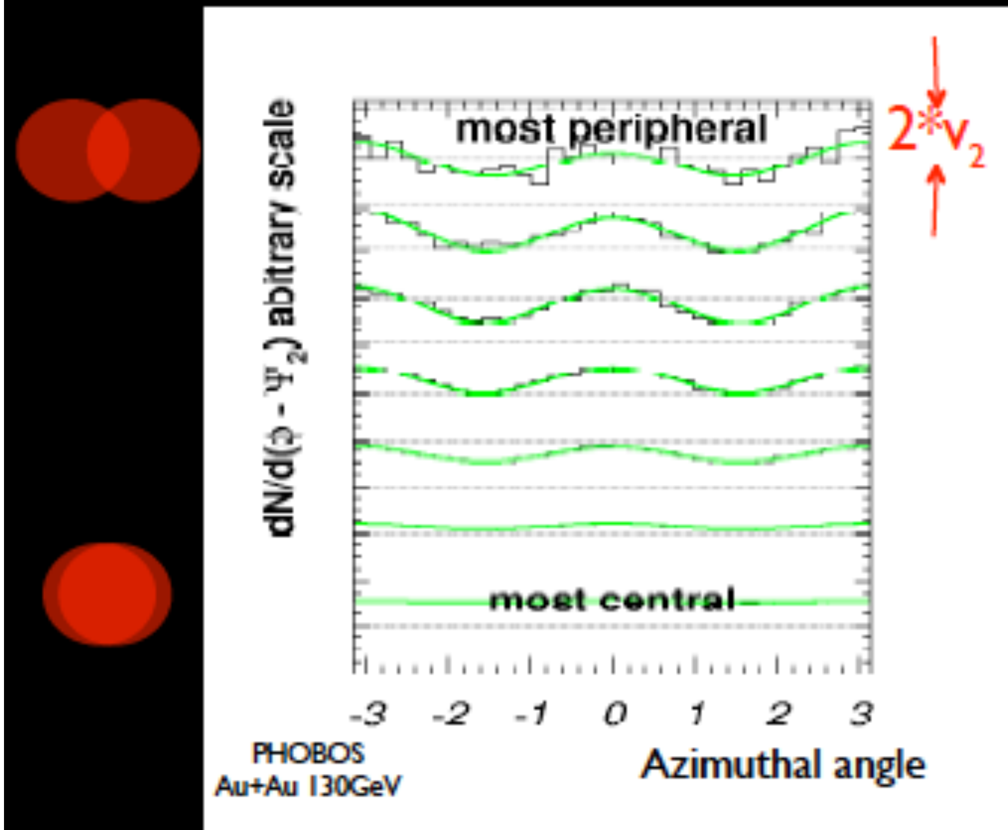
$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi)]\right)$$

- Fourier expansion, usually dominated by v_2, so-called elliptic flow

First results from RHIC in 2000

Azimuthal distribution

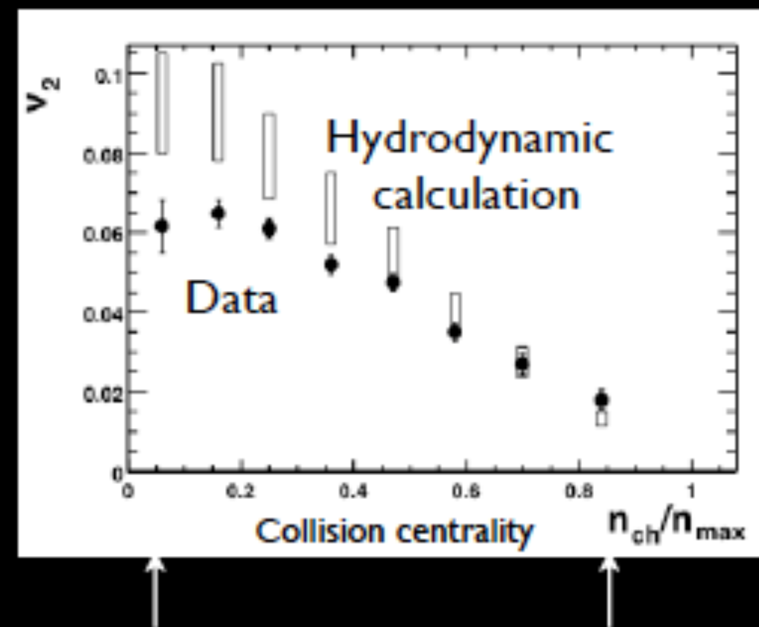
$dN/d\varphi = 1 + 2\, v_2 \cos(2(\varphi - \varphi 0))$



"Elliptic Flow"
is clearly seen

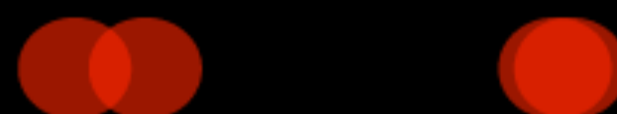
"Elliptic Flow"

STAR PRL 2000



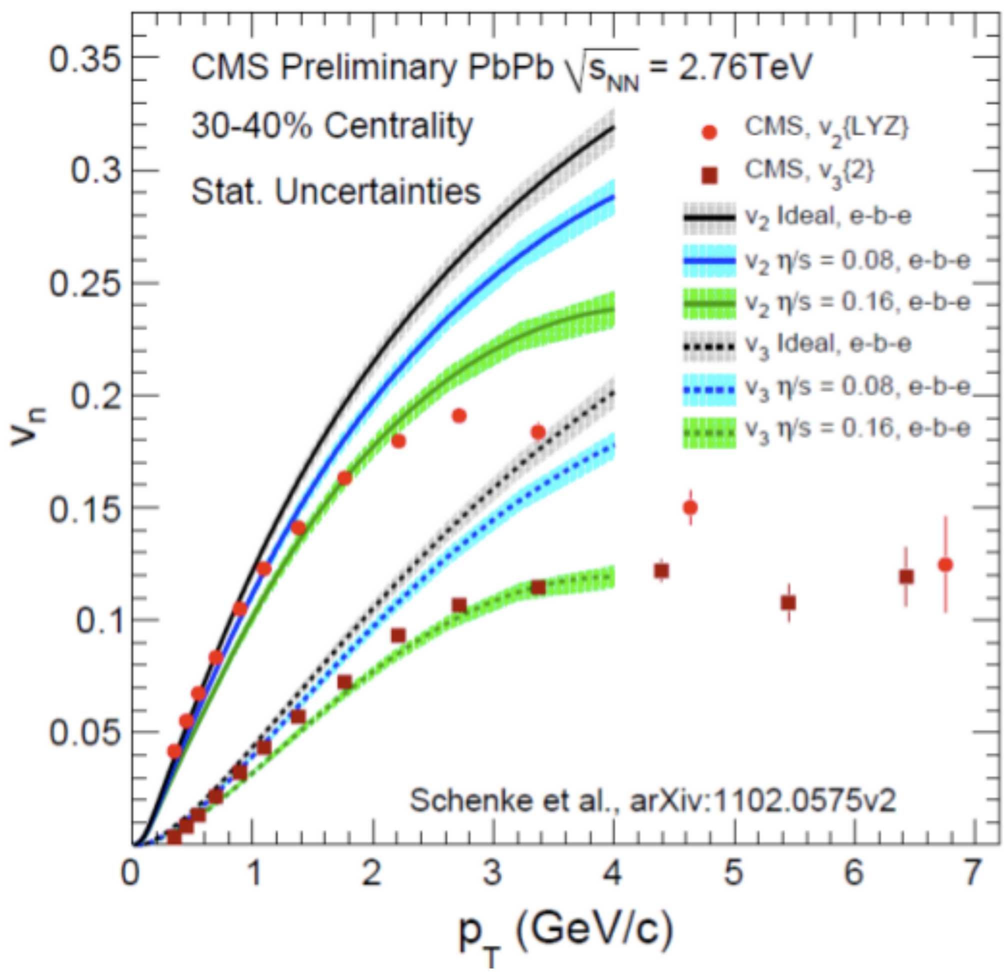
Peripheral collisions

central collisions



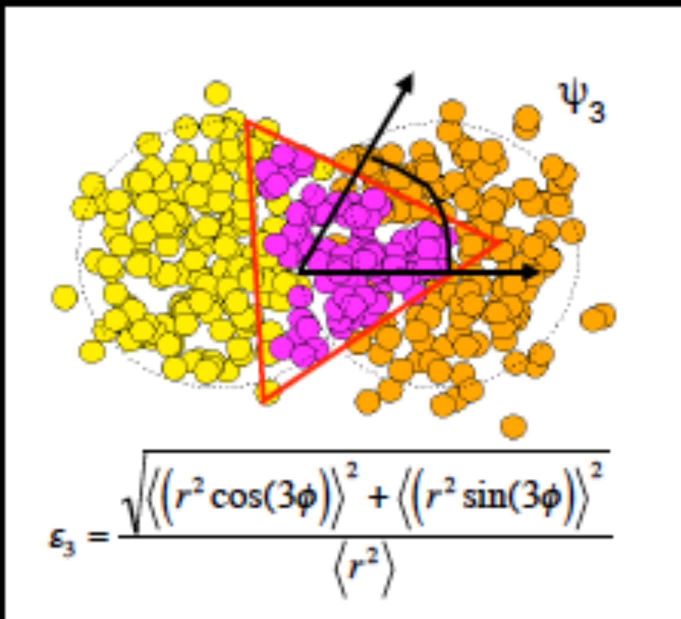
Close to "ideal hydrodynamics"

Momentum dependence of elliptic flow



- The "translation" between coordinate and momentum asymmetries carries information about shear viscosity of the fluid
- η/s is the relevant parameter in hydrodynamic theory (s is entropy density)
- Elliptic flow is a very large affect. At p_T=3 GeV v_2=0.2 modulation (min/max)=2.3!

Higher Fourier coefficients

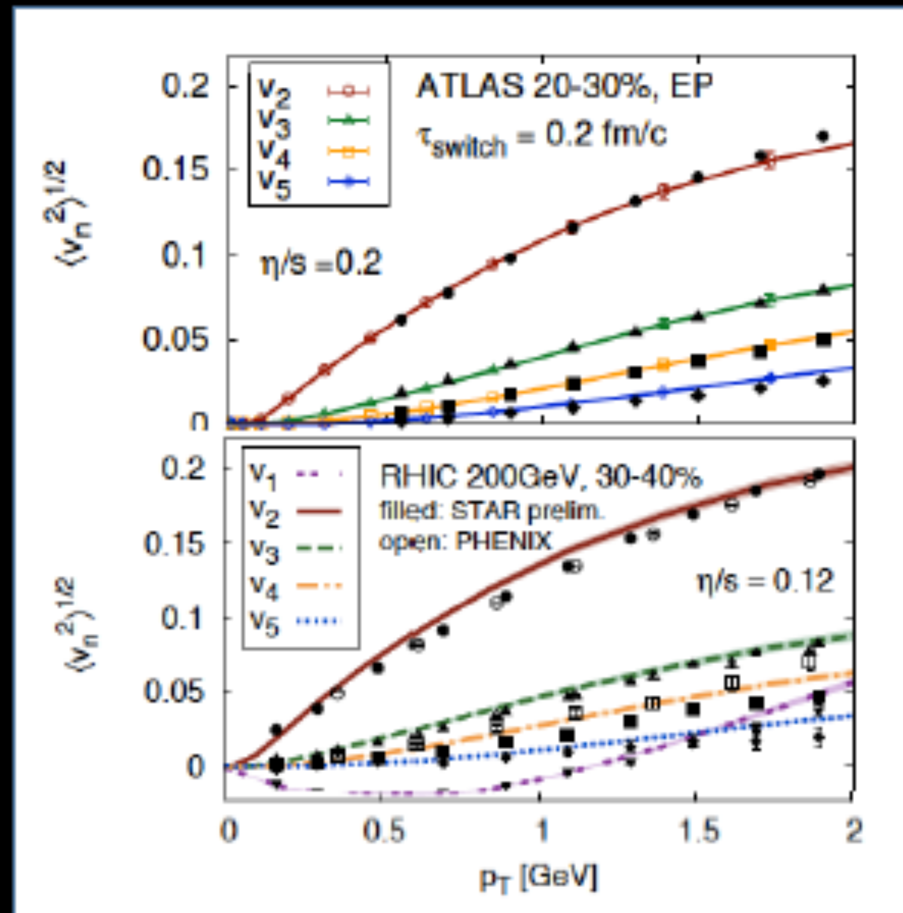


Alver, Roland
Phys.Rev.C81:054905,2010

Mishra et al arXiv:0711.1323
Takahashi et al, arXiv:0902.4870
Sorensen, arXiv:1002.4878

Fluctuations in the initial geometry induces higher order Fourier components, in particular "triangular flow" v_3

Bjoern Schenke et al
Phys.Rev. C85 (2012) 024901

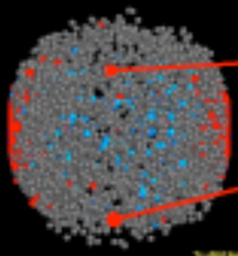


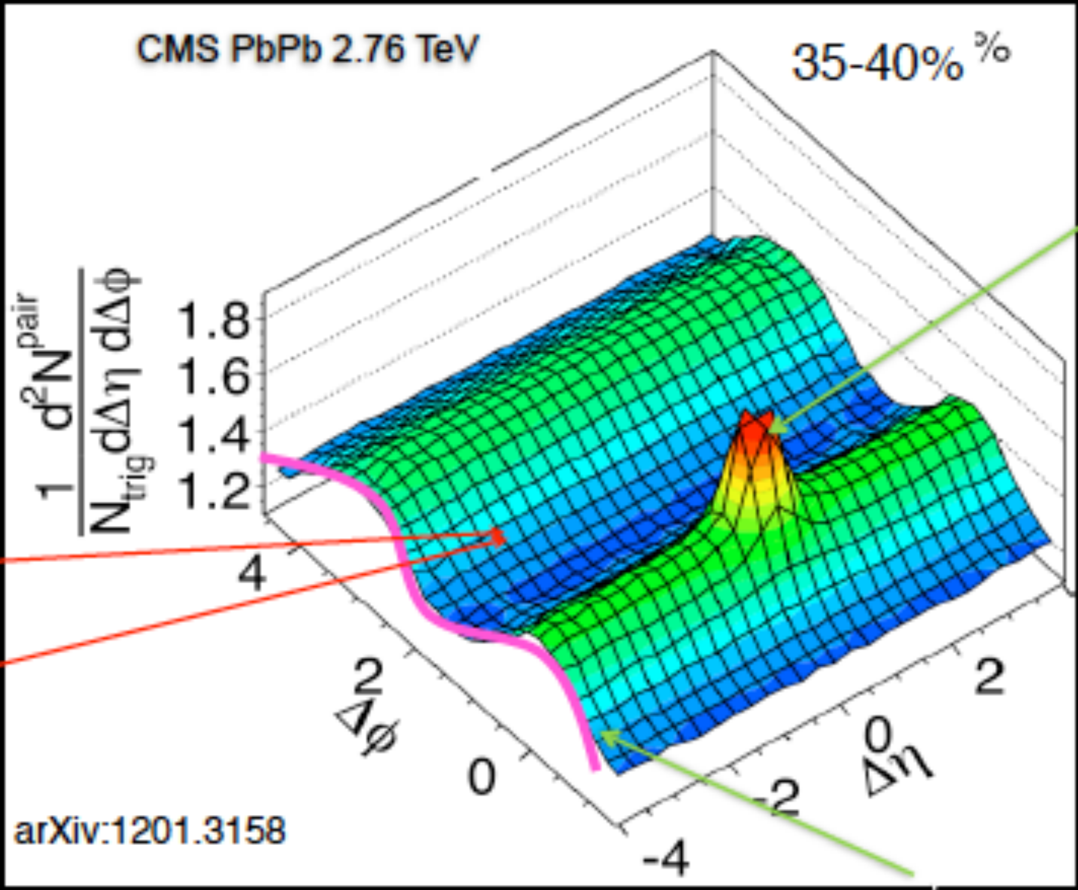
Single calculation describes Fourier coefficients at RHIC and LHC (2012)
(small change in η/s from RHIC to LHC)

Two particle correlation

35-40% peripheral

Event





Pair of particles:

p_T^{trig}: 4–6 GeV/c

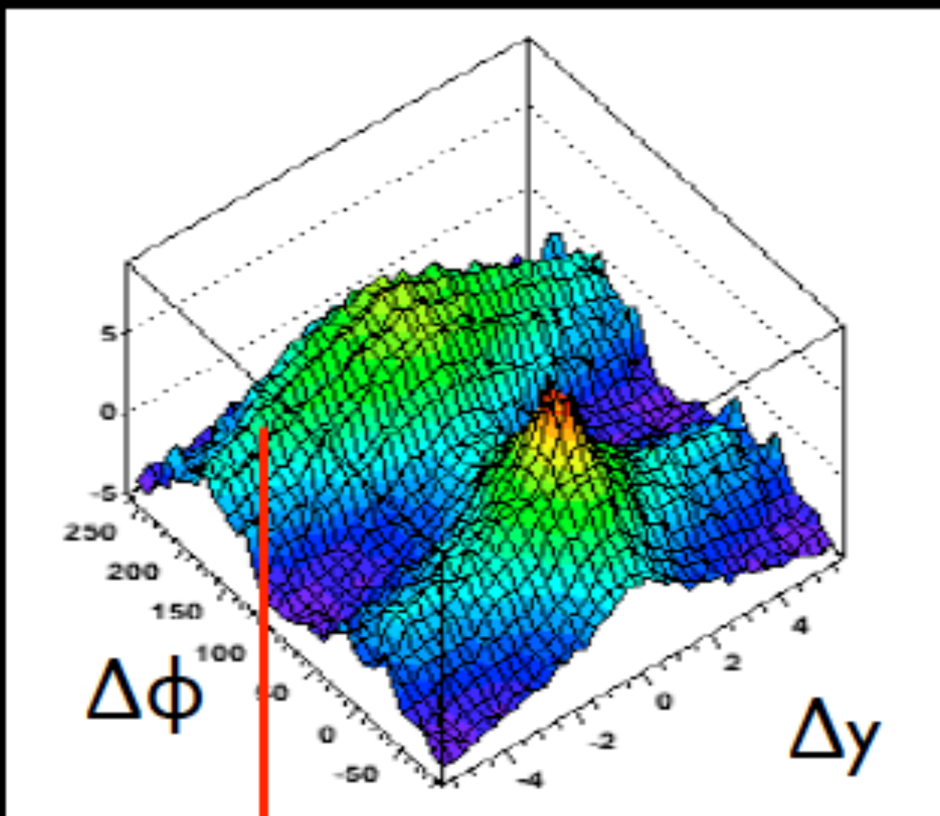
p_T^{assoc}: 2–4 GeV/c

$$\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2v_2^2 \cdot \cos 2\Delta\phi$$

Elliptic flow is long range in η ⇨ Initial condition (geometry)

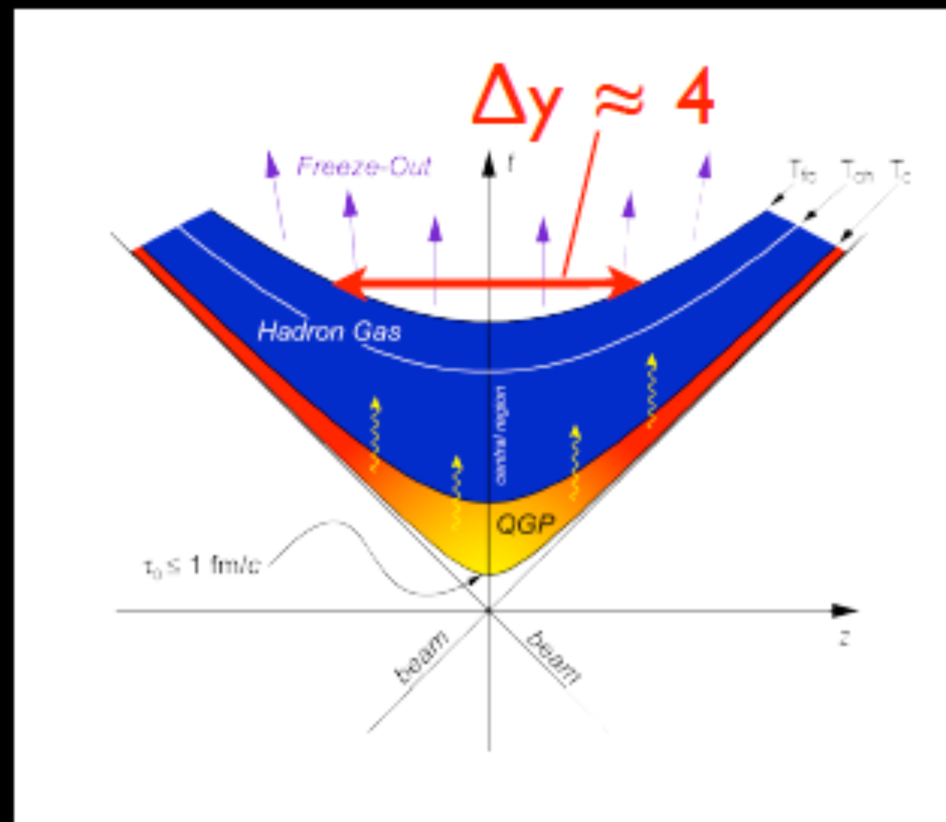
Elliptic flow and geometry of collision

Two-particle correlation function in relative azimuthal angle and relative rapidity



Strong flow correlation at $\Delta y \approx 4$

Space-time evolution of collision



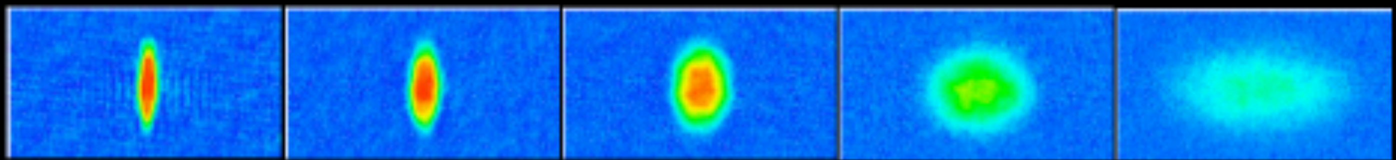
Large rapidity gap correlations have to be established in initial stage (geometry)

Shear Viscosity

Pitch drop experiment:
8 drops since 1927,
last drop in Nov 2000

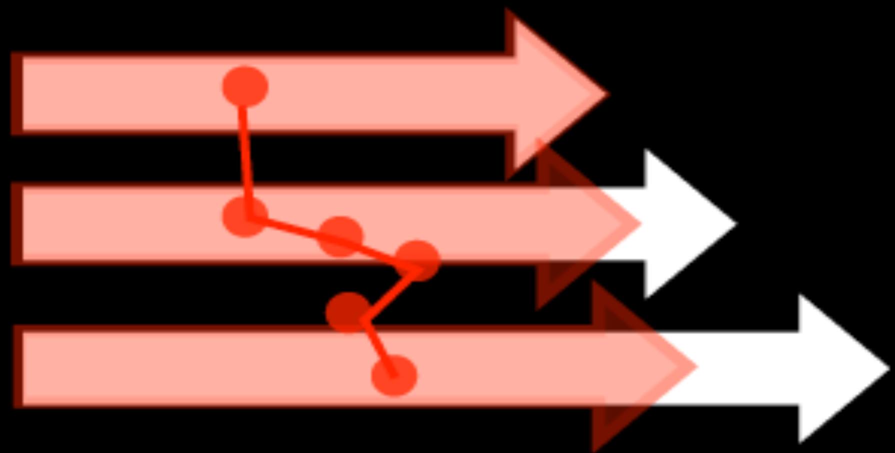
Honey

Superfluid helium



Ultracold fermionic atoms at Feshbach Resonance
Very dilute, but very large x-section

Viscosity



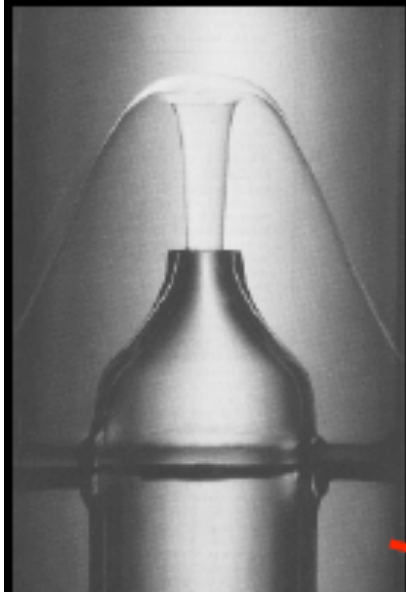
Shear viscosity: Momentum transport across fluid reduces gradients → less elliptic flow

To compare systems: Divide by density → η/s

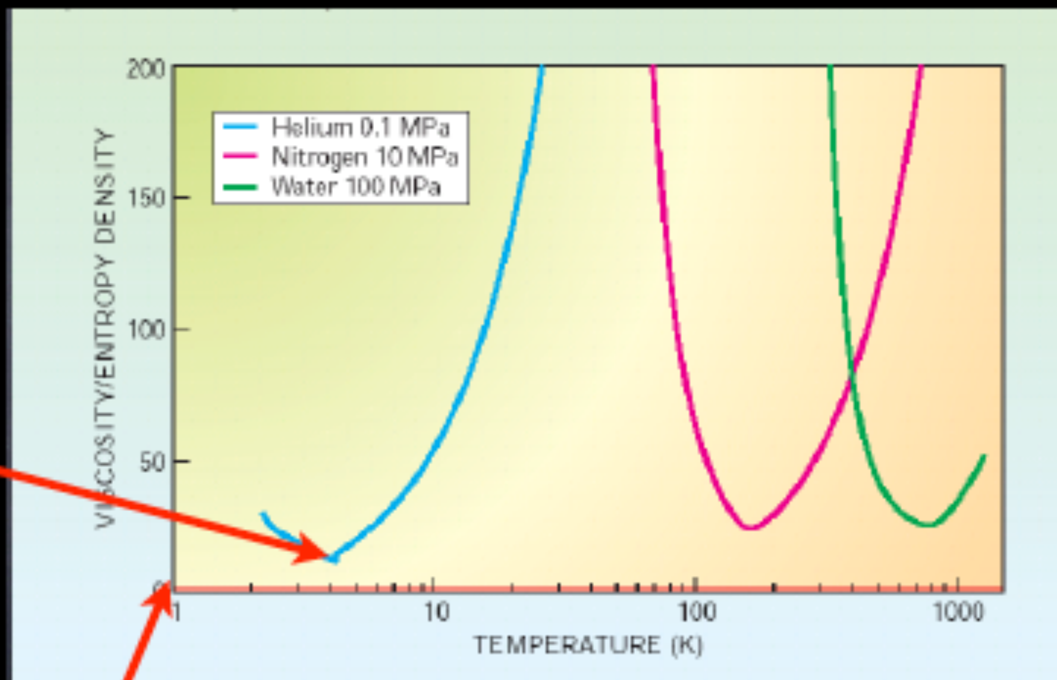
Weakly interacting gas: Large η/s

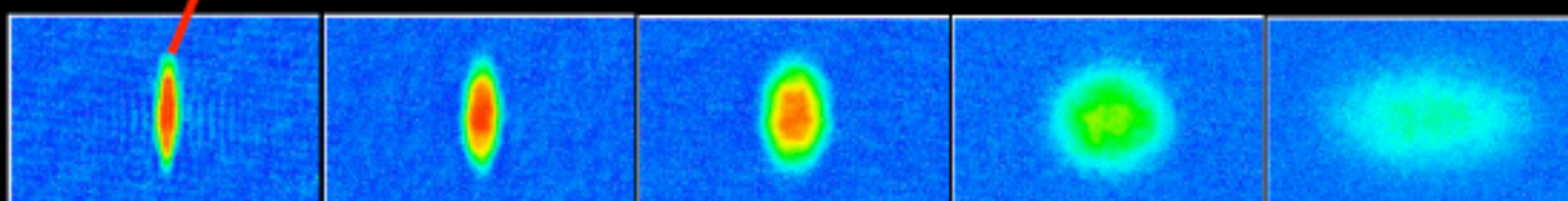
Shear viscosity championships

$\eta/s \sim$
$O(\text{bazillon}) \times 1/4\pi$



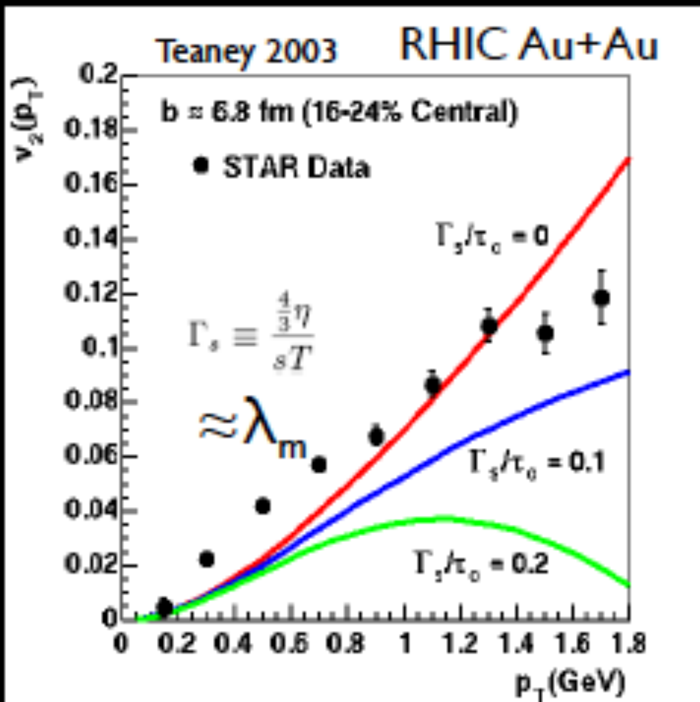
$\eta/s \sim$
$O(100) \times 1/4\pi$

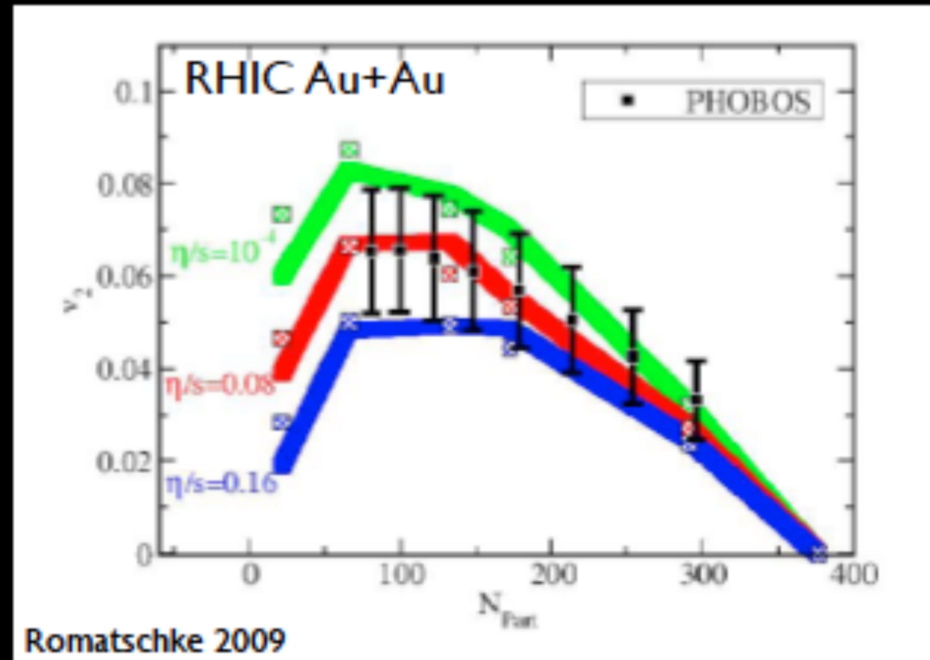




$\eta/s \sim O(\text{few}) \times 1/4\pi$

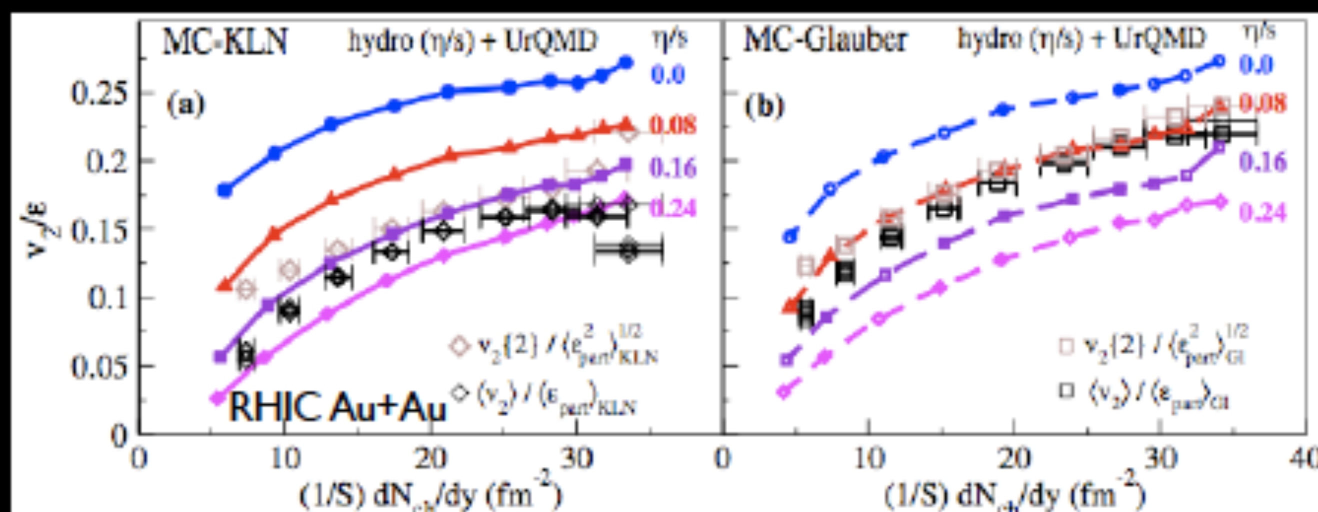
How well does QGP liquid flow?





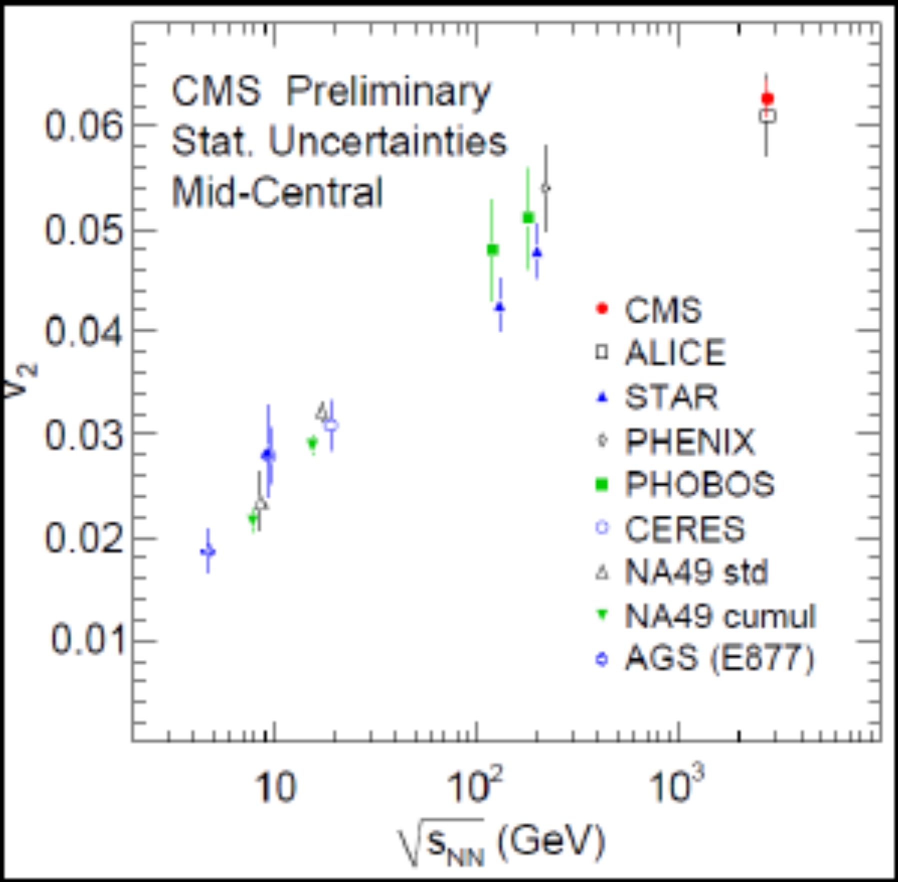
$1/4\pi < \eta/s < 2.5 \times 1/4\pi$

Large contribution to uncertainty from initial geometry



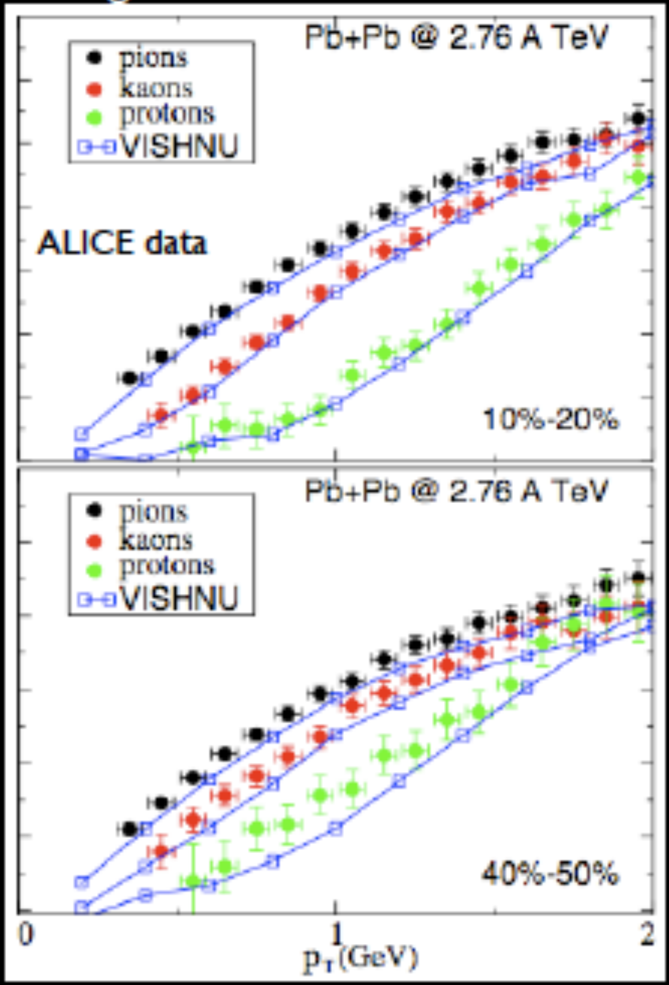
Heinz et al, 2011

What about the LHC?



Elliptic flow 10% larger at LHC: Stronger initial push due to higher density

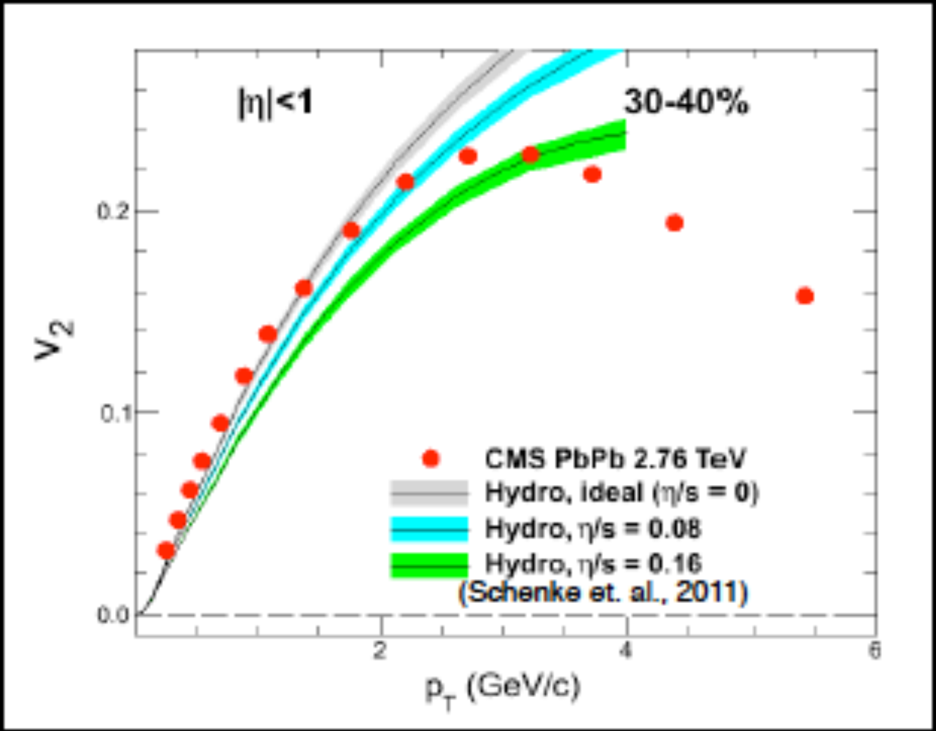
Song, Heinz et al, PANIC 2011



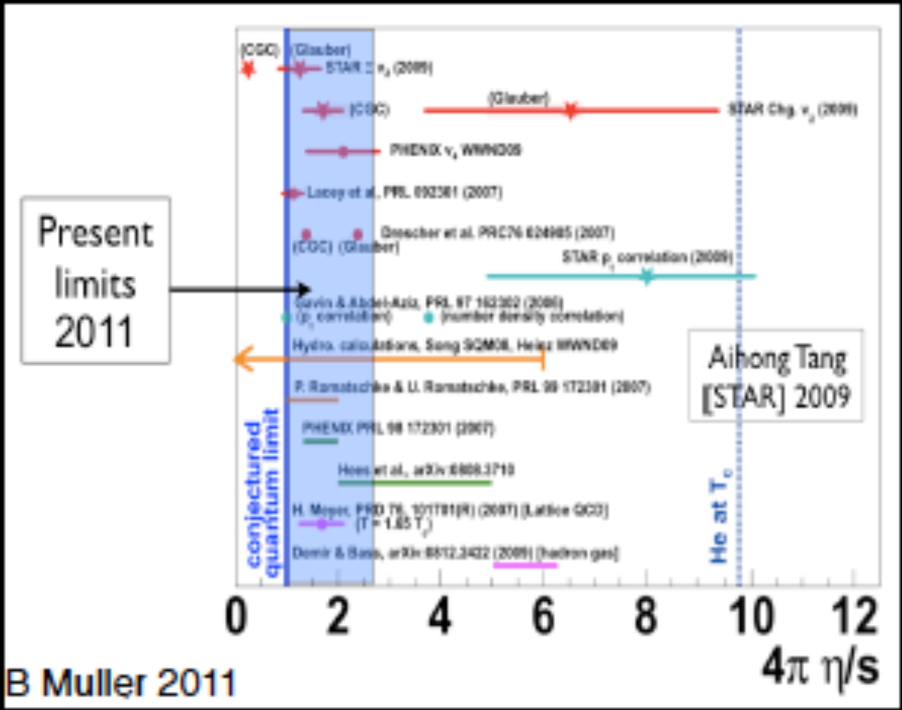
Comparison to state-of-the-art hydro calculations suggests: $\eta/s_{(LHC)} \sim \eta/s_{(RHIC)}$

How perfect is it? - Viscosity

Viscous hydrodynamics:



World's efforts on η/s of sQGP



Main uncertainties, e.g.:

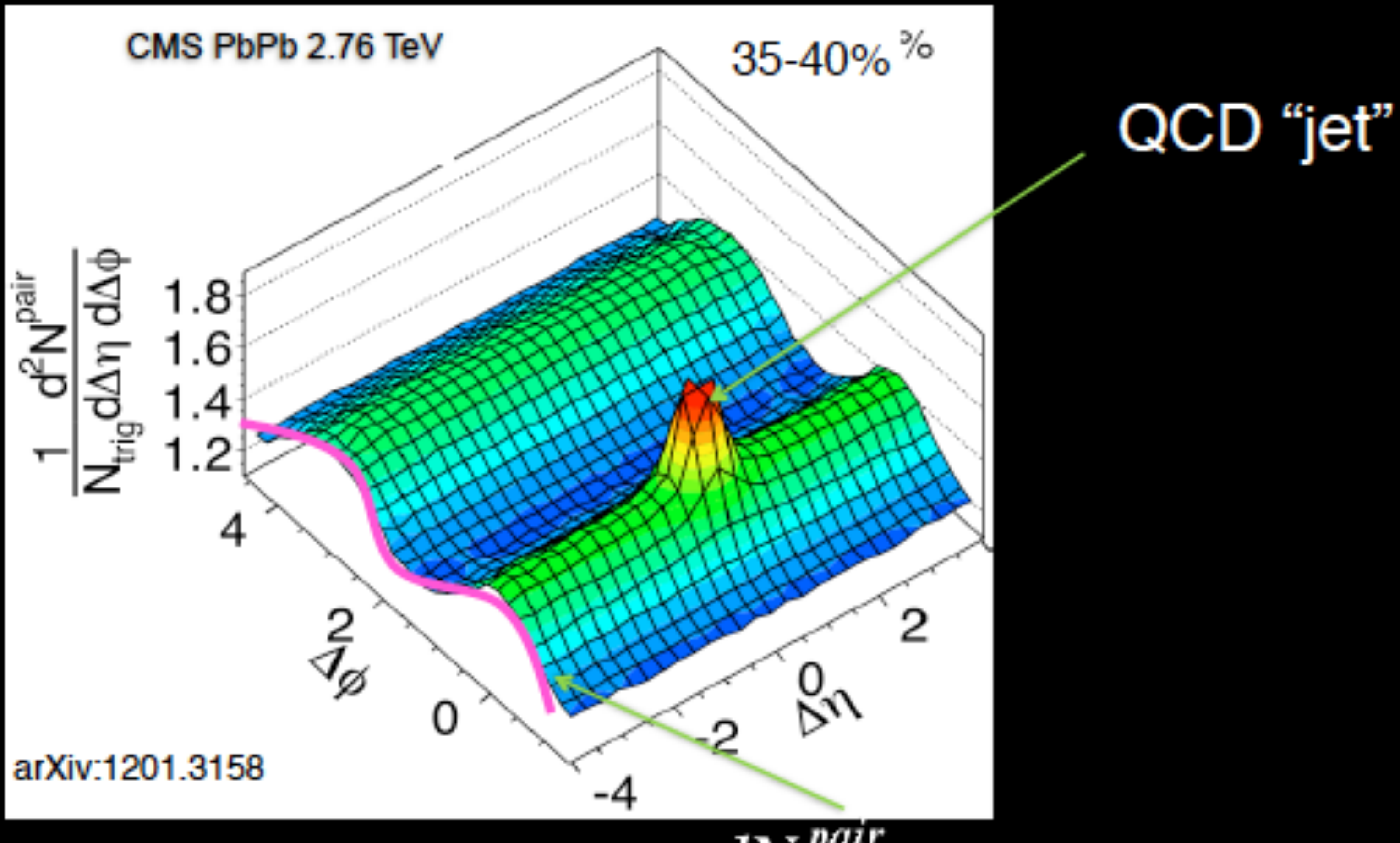
- Initial condition (eccentricity)
- Thermalization time

Current best estimate:

η/s ~ 0.08 – 0.20

Beyond elliptic flow

35-40% peripheral

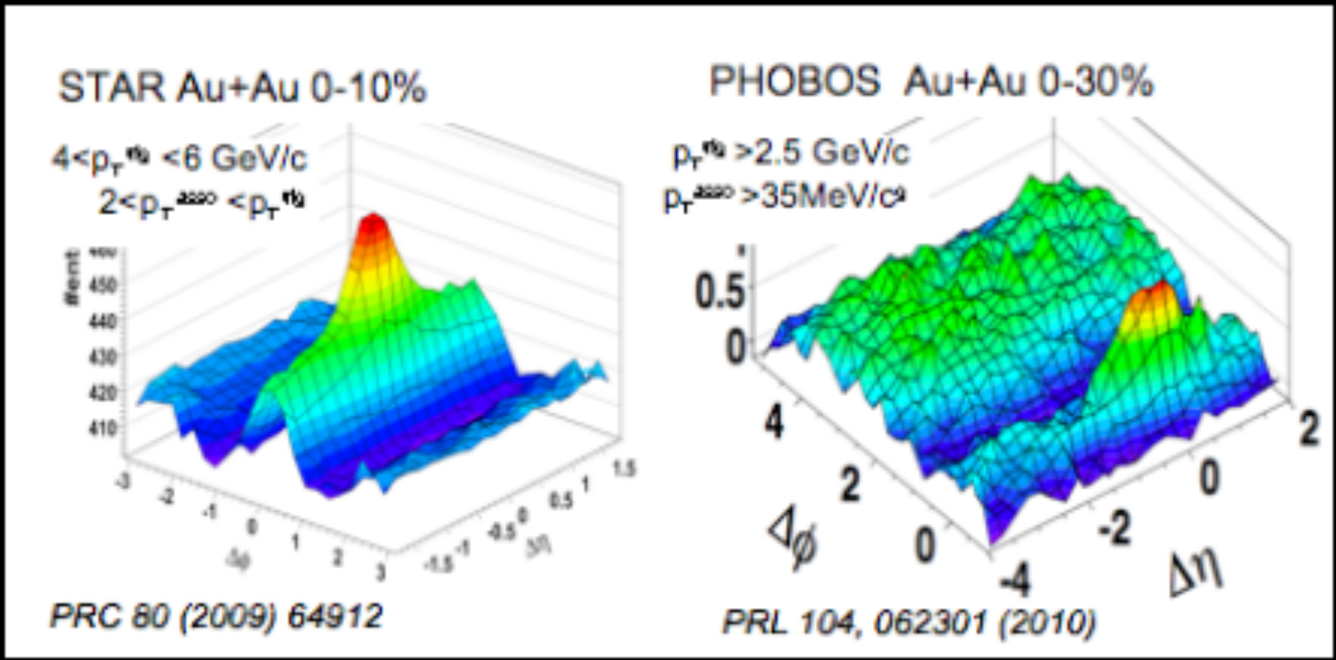


$$\frac{dN^{pair}}{d\Delta\phi} \sim 1 + 2v_2^2 \cdot \cos 2\Delta\phi$$

What remains after subtracting the elliptic flow correlations?

"Ridge" puzzle at RHIC

"Ridge" structure at RHIC (elliptic flow subtracted)

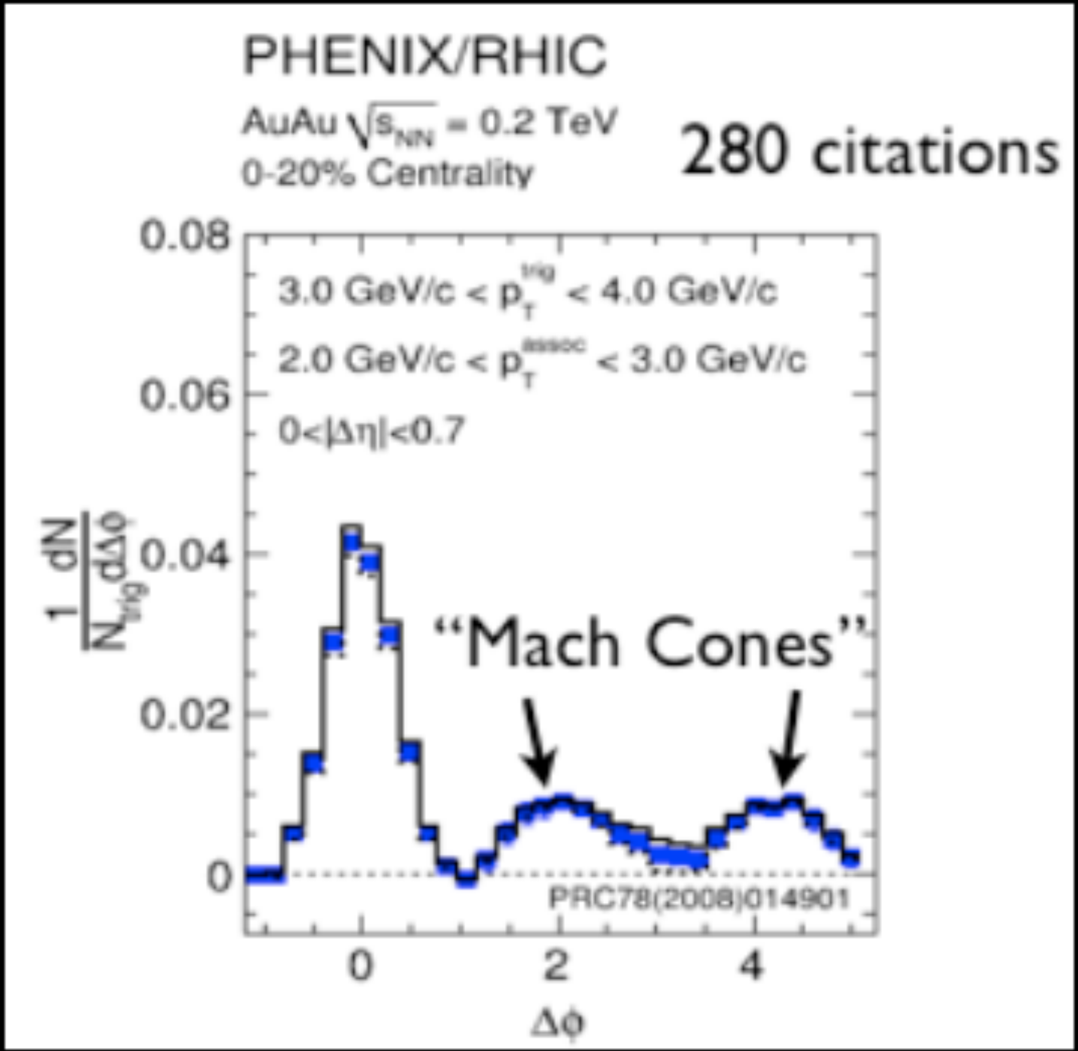


Numerous models:

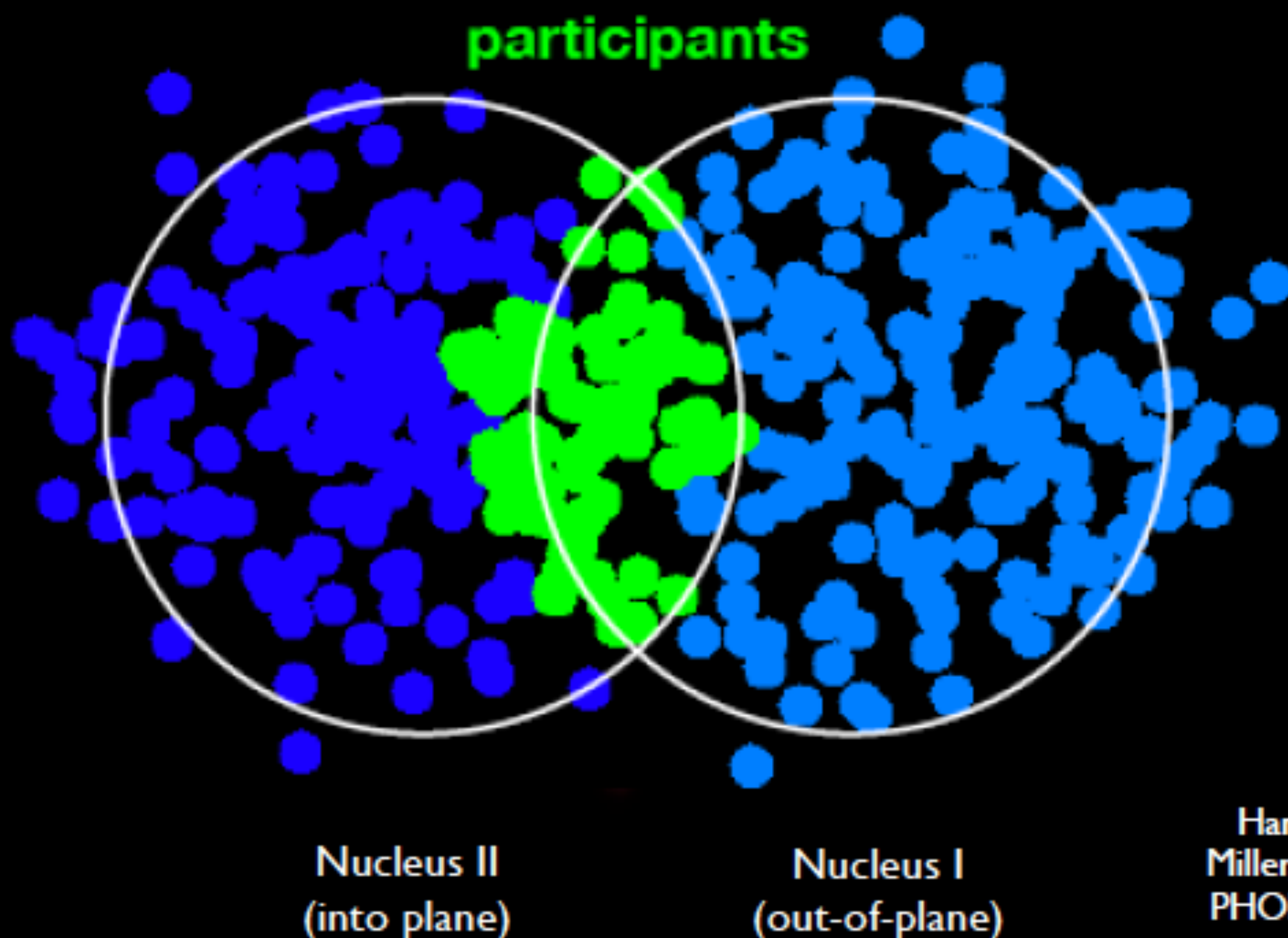
- *In medium radiation + longitudinal flow*
- *Turbulent color fields*
- *Recomb. of thermal & shower partons*
- *Momentum kick*
- *Transverse flow boost*
- *Glasma tube*
- ...

But wait, there's more....

"Mach cone" structure at +/- 120 deg to high pT particles

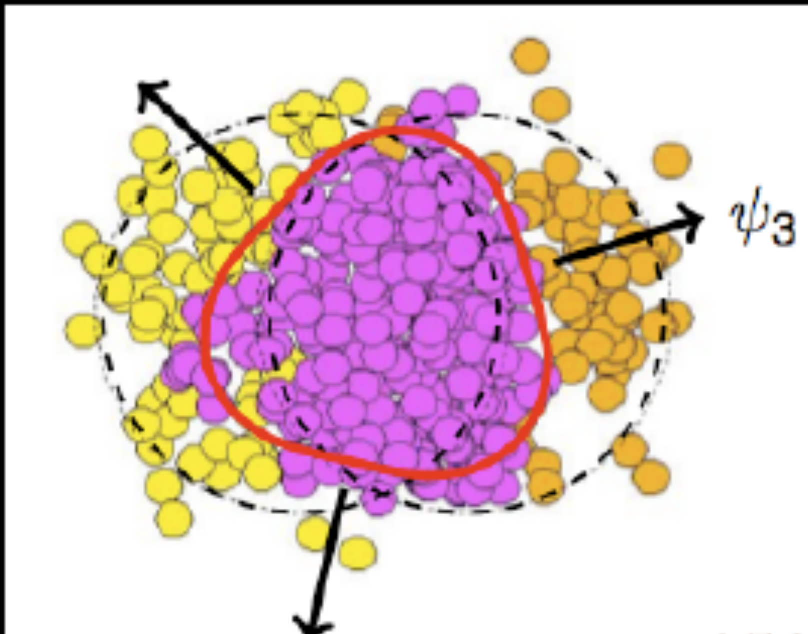


Re-thinking initial conditions



Hama et al, 2000
Miller, Snellings, 2003
PHOBOS coll., 2005

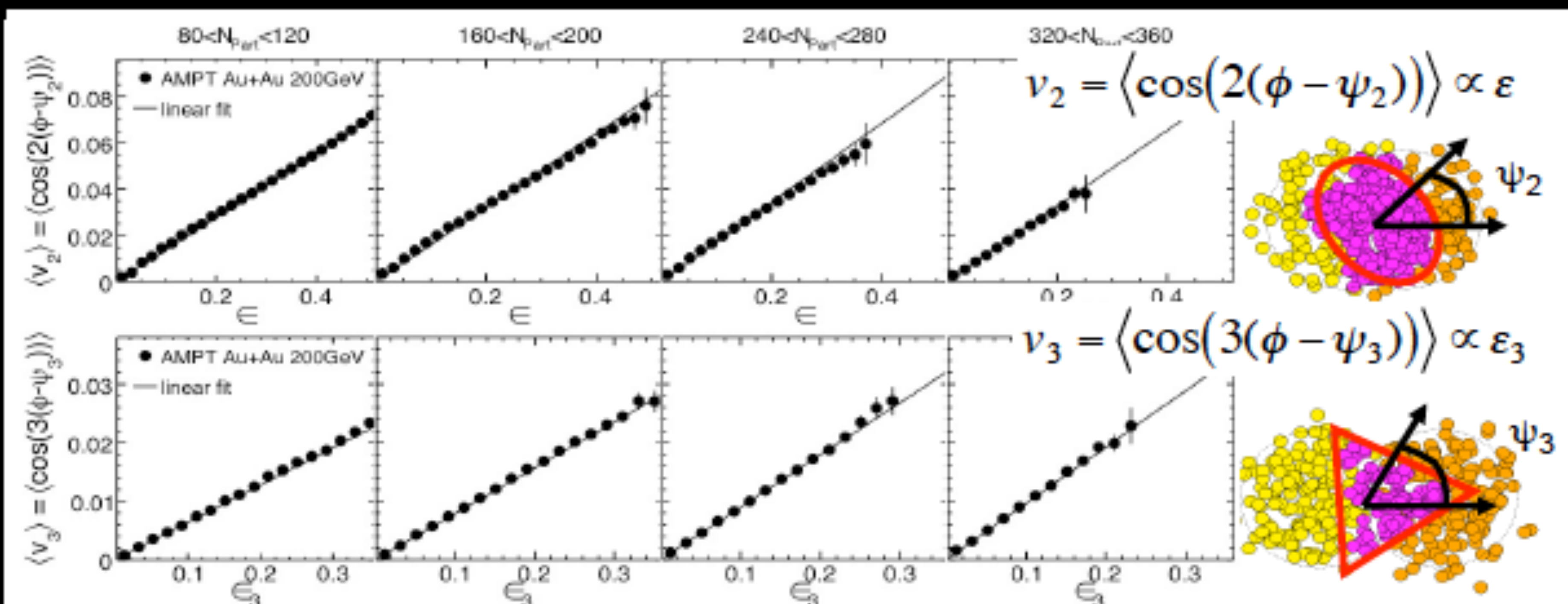
Nuclei consist of finite number of protons and neutrons

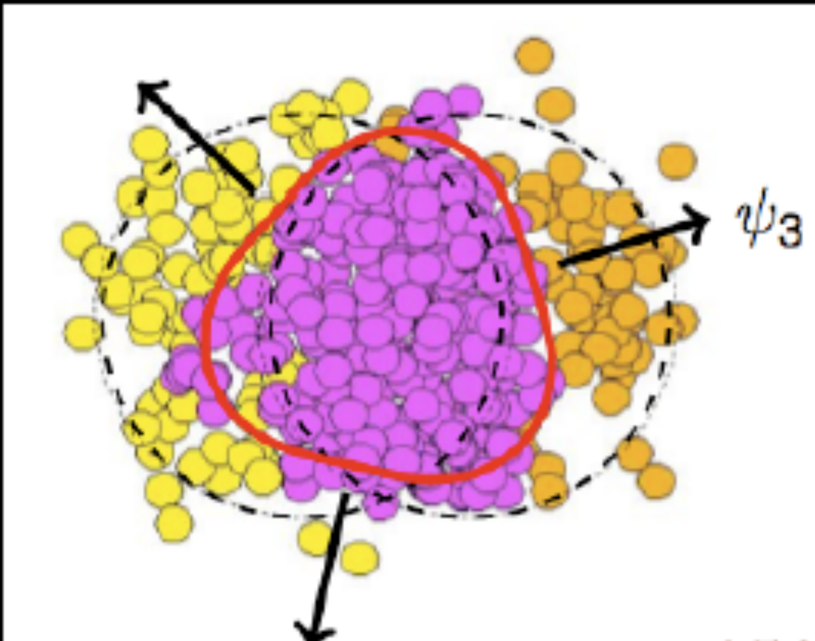


B. Alver, GR (2010)

Suggested the existence of "triangular flow" v_3 in analogy to "elliptic flow" v_2

v_3 driven purely by fluctuations
v_3,v_4,v_5 more sensitive to viscosity

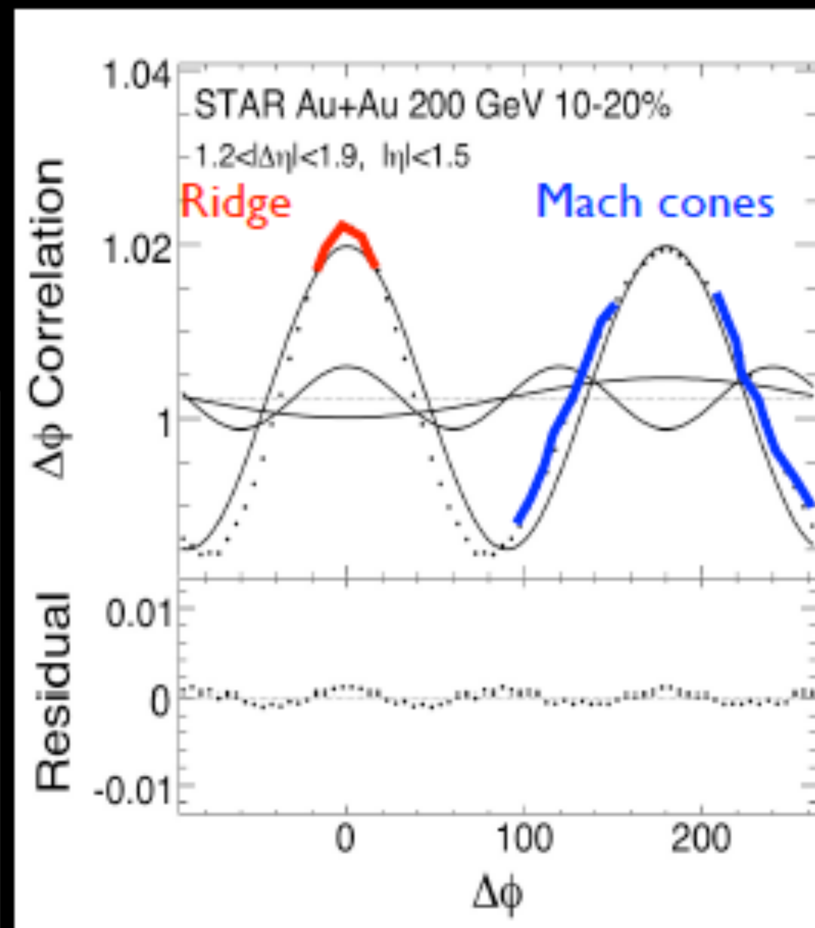




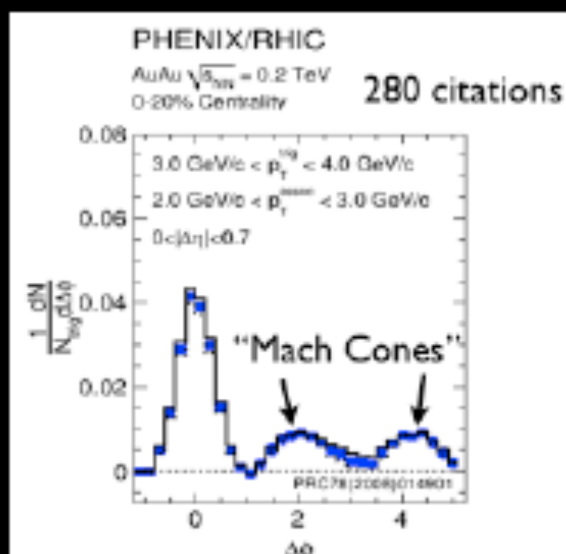
B. Alver, GR (2010)

Fluctuations in shape induce higher Fourier coefficients (e.g. v_3)

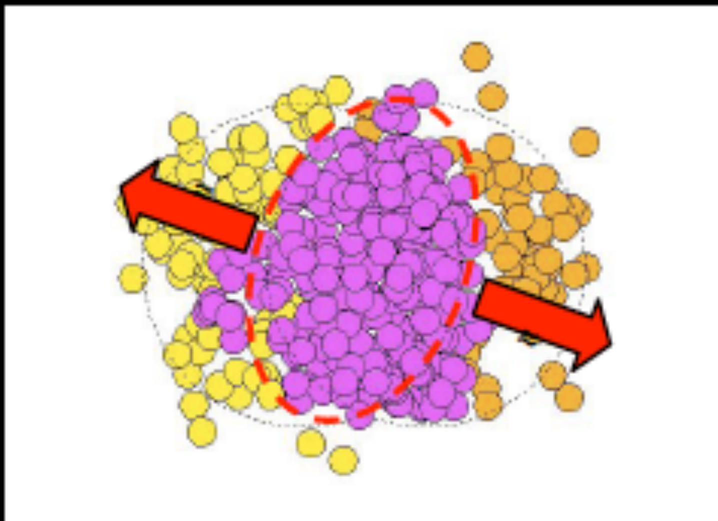
Adding v_3 explained previously mysterious features of azimuthal particle correlations (“ridge”, “mach-cones”)

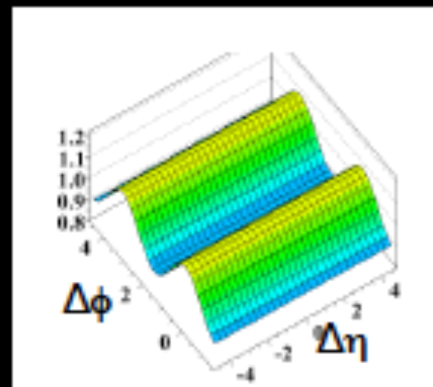


Hama et al (2009) Sorensen (2010) Alver, GR (2010)



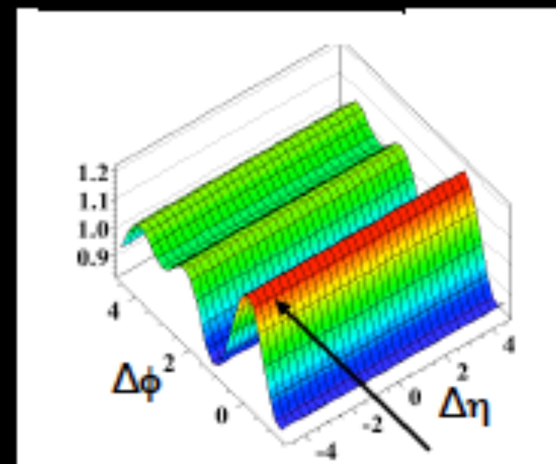
Elliptic flow (v_2)





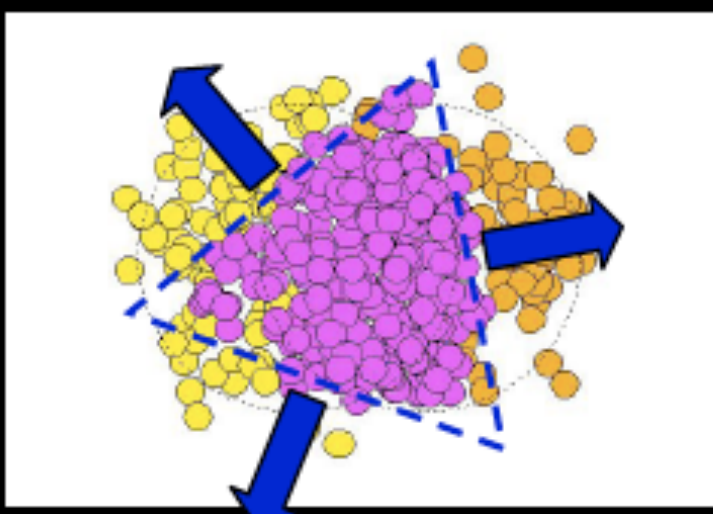
~ $v_2^2 \cos(2\Delta\phi)$

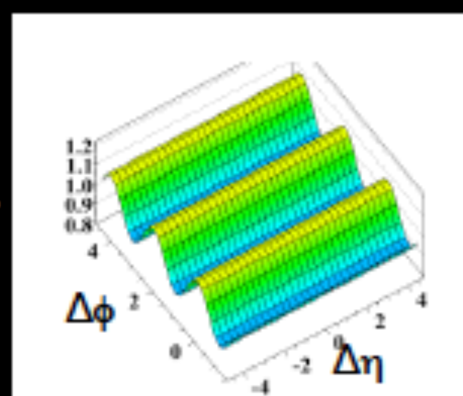
Add v_2^2 and v_3^2



"Ridge"?

Triangular flow (v_3) from fluctuating initial condition

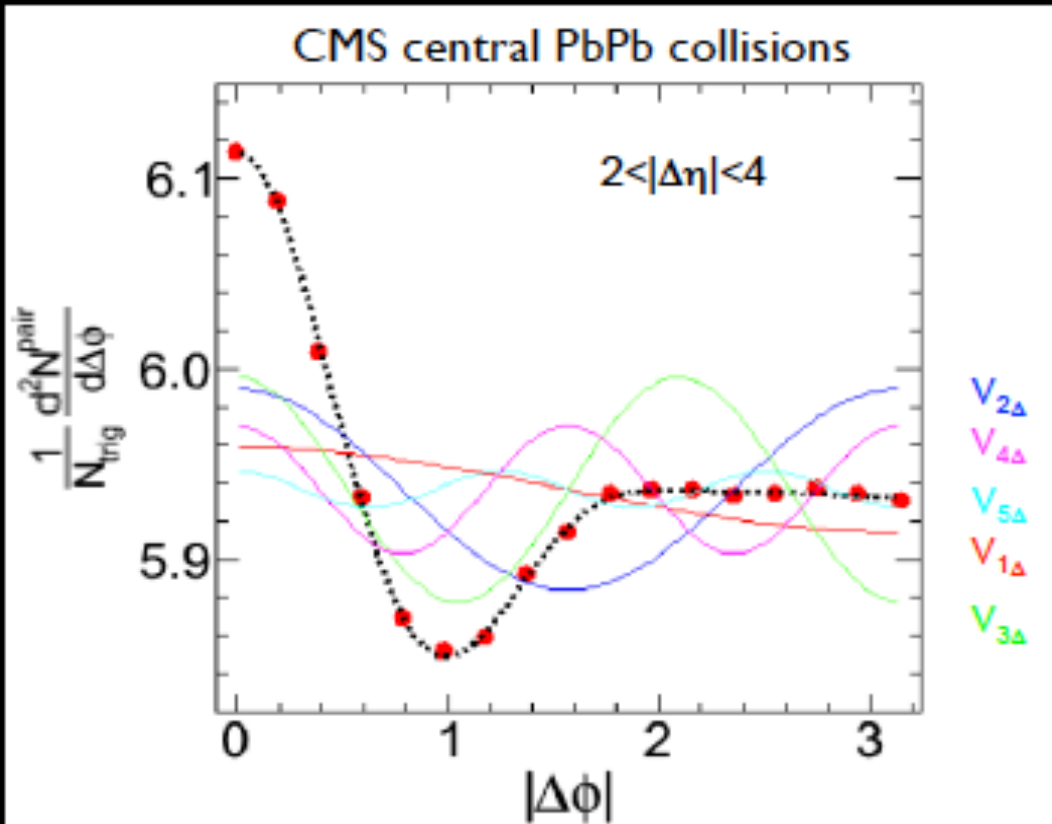


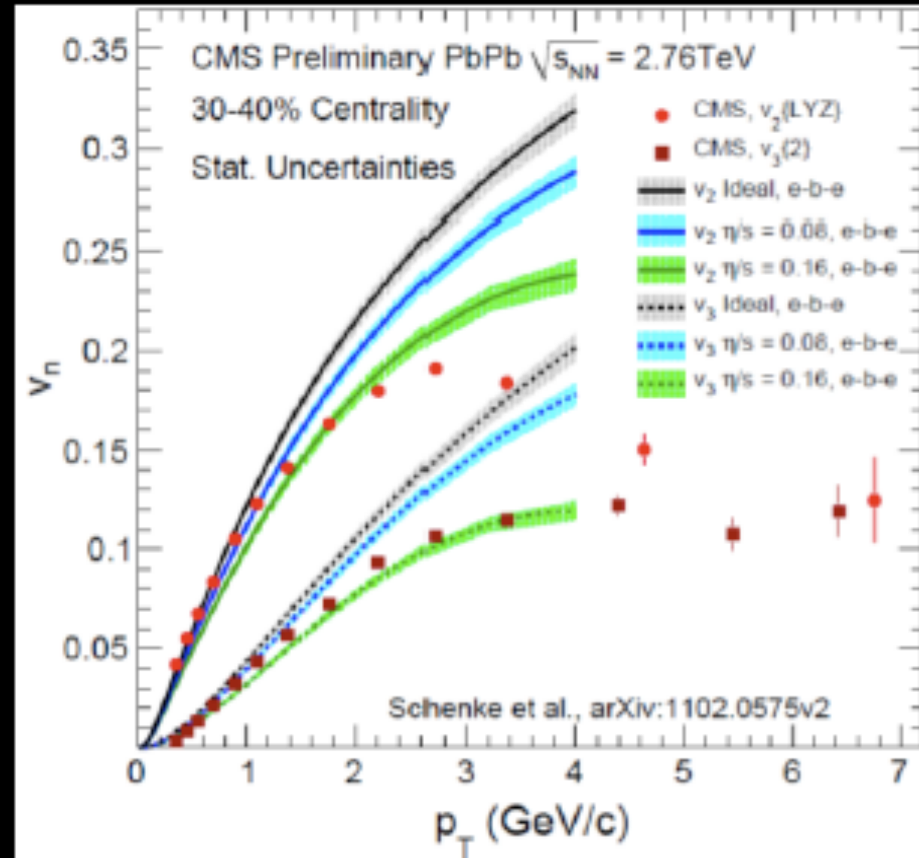


~ $v_3^2 \cos(3\Delta\phi)$

Explained?

Confirmation at the LHC!





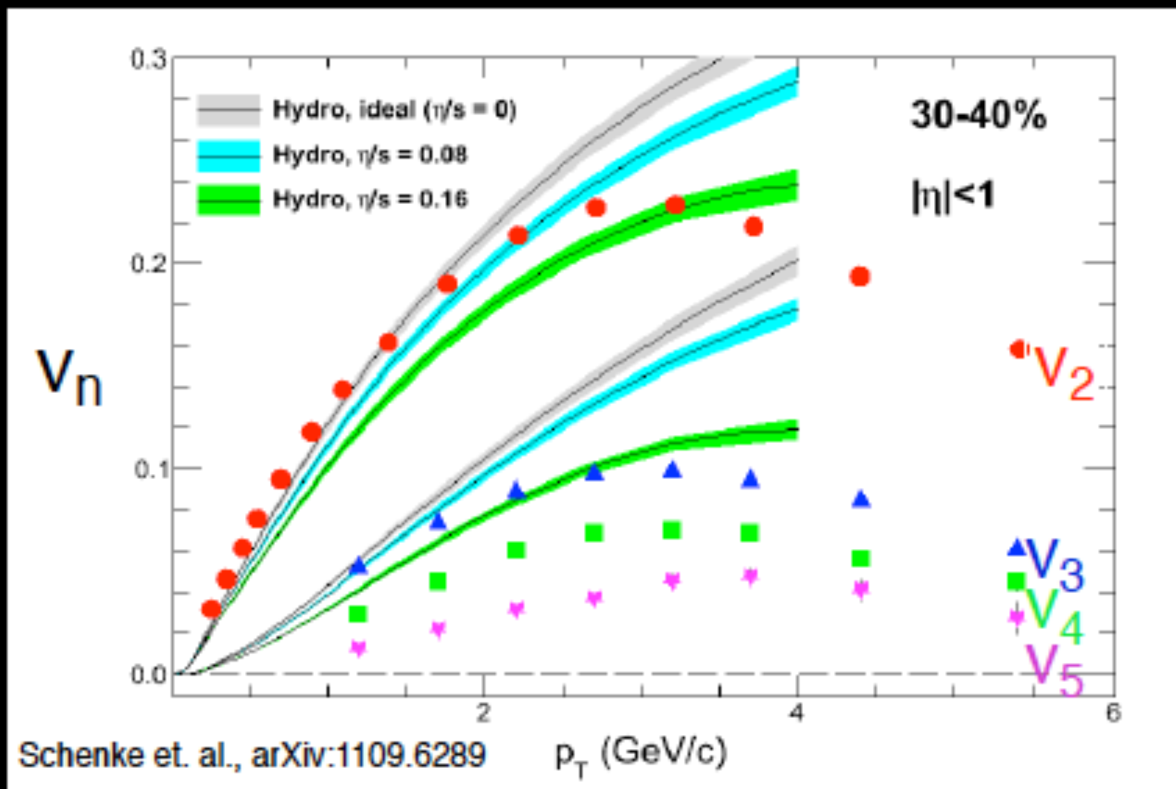
Azimuthal correlations for central collisions (driven by shape fluctuations) show higher order Fourier components

Proof is in the pudding: Full e-by-e viscous hydro calculations can describe v_3

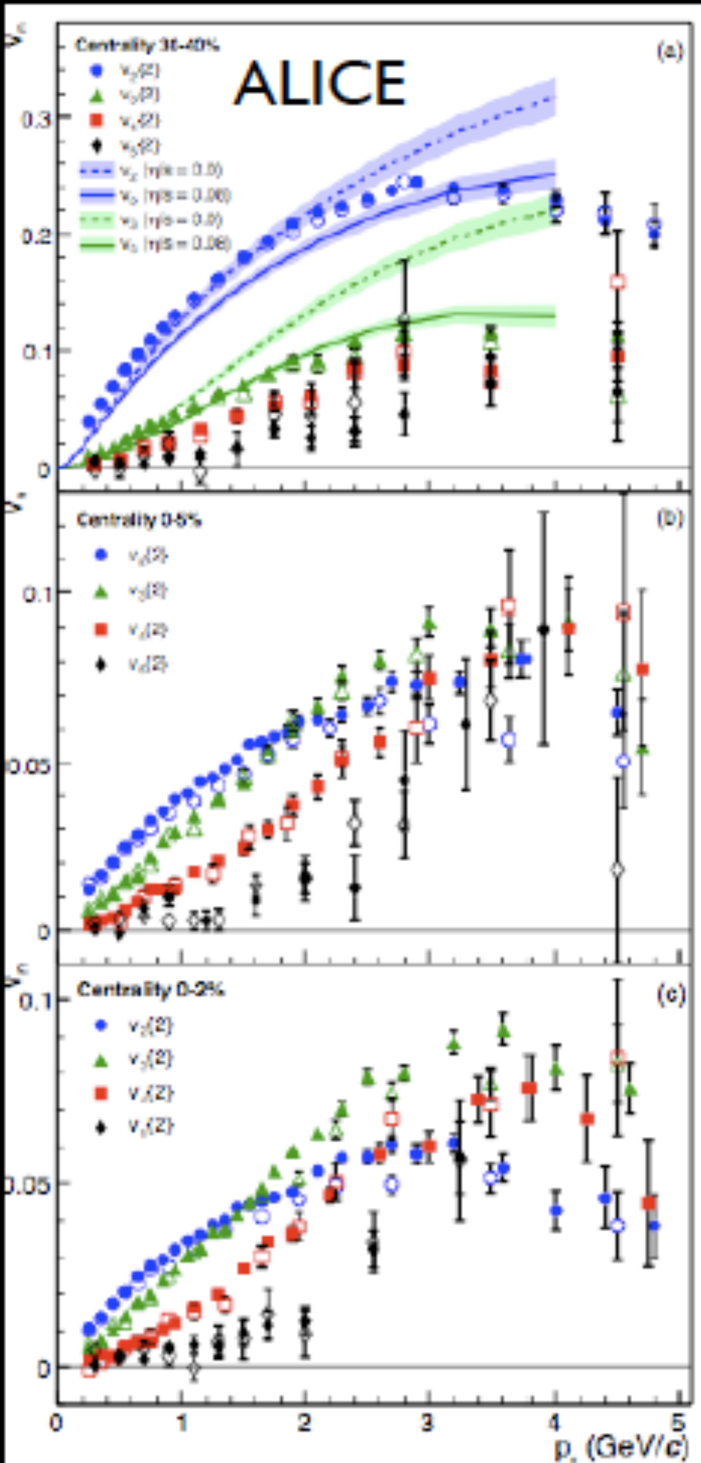
(but many functions can be Fourier-decomposed...)

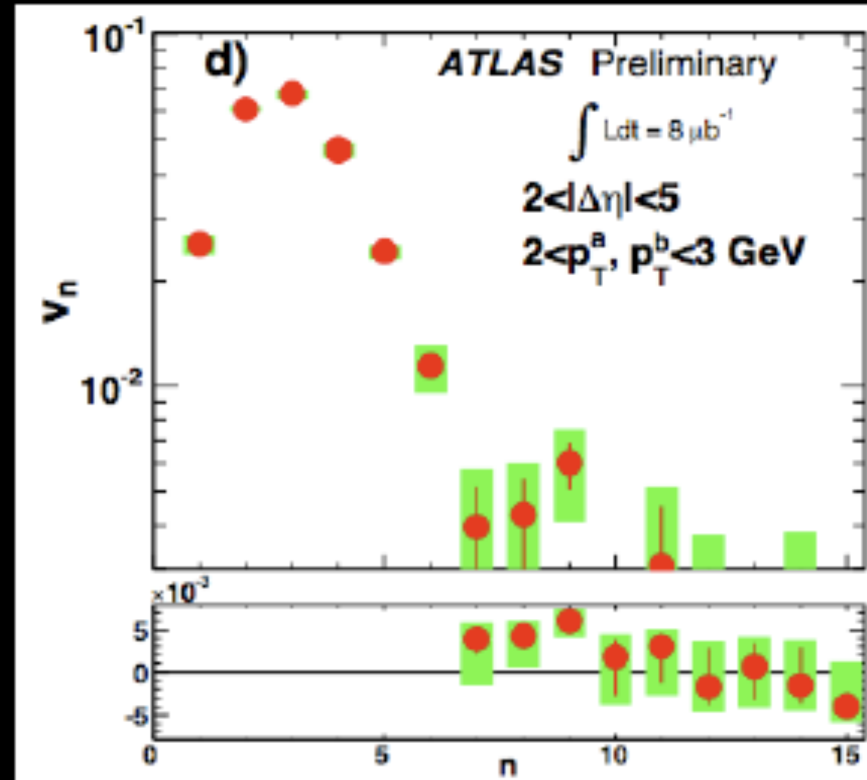
Inputs to hydrodynamics calculation:

- Initial condition (Glauber, color glass condensate etc.)
- Viscosity (η/s)
- Thermalization time

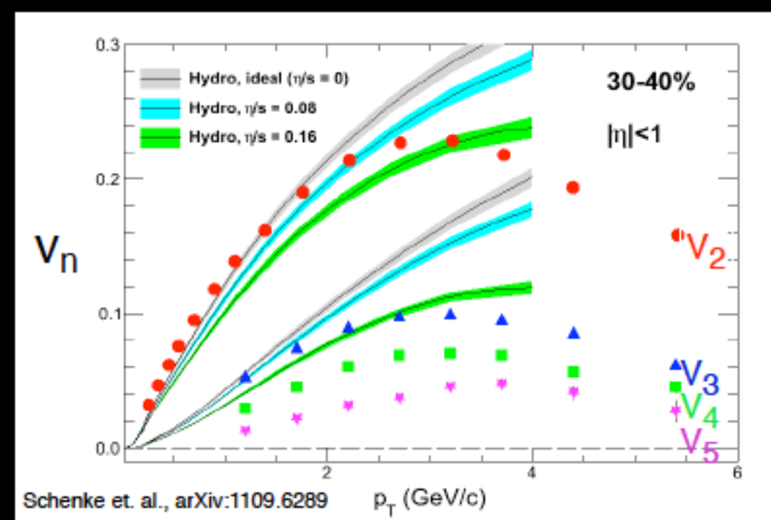


- Measure all vn to over-constrain the models

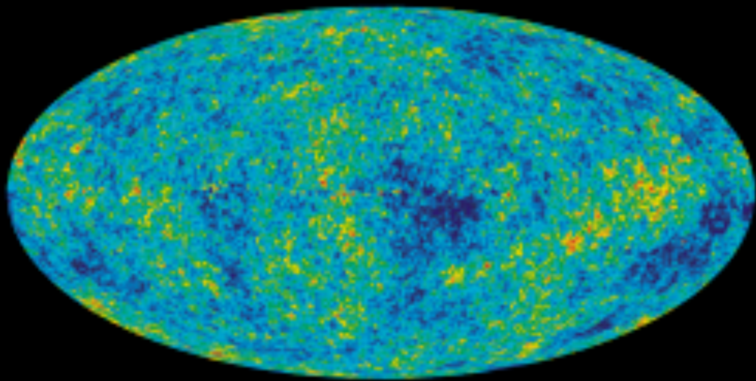




Fourier coefficients for central PbPb

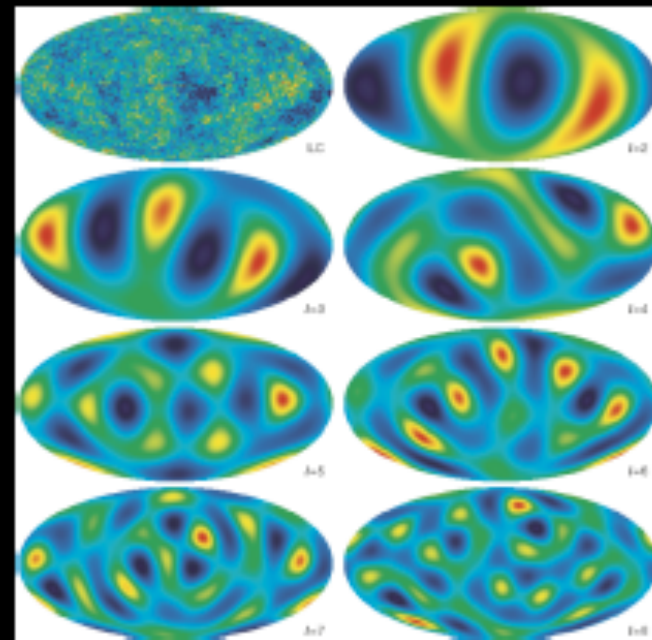


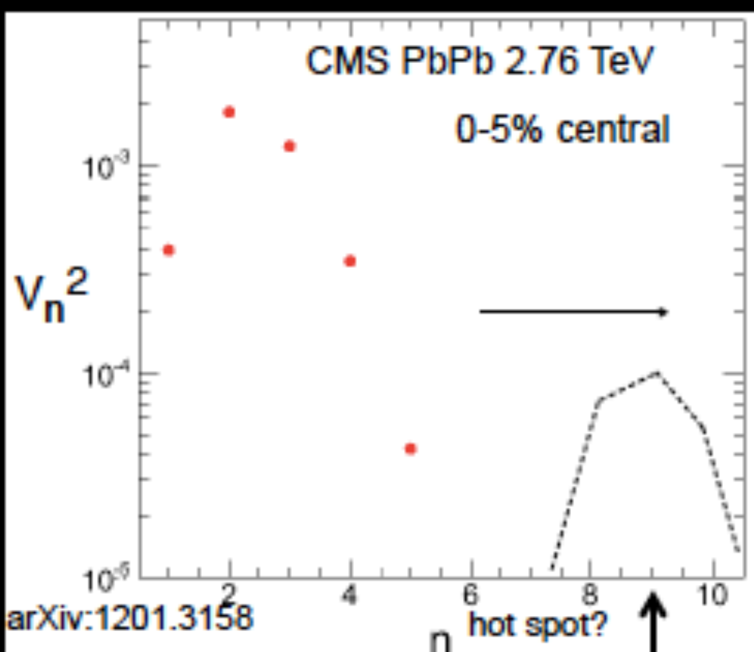
Why v_n matters?



WMAP, Astrophys.J.Suppl.170:288,2007

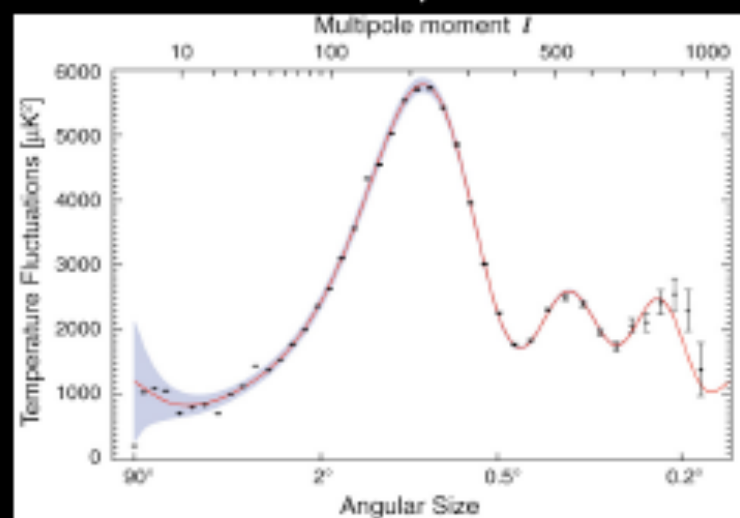
Harmonic decomposition





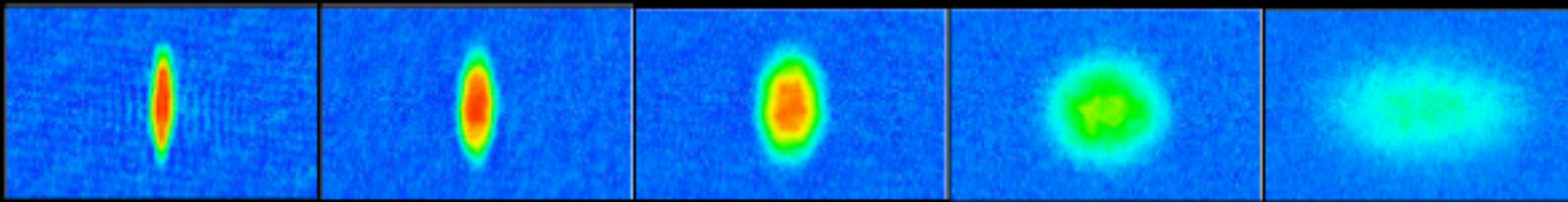
Shuryak, arXiv:1106.3243

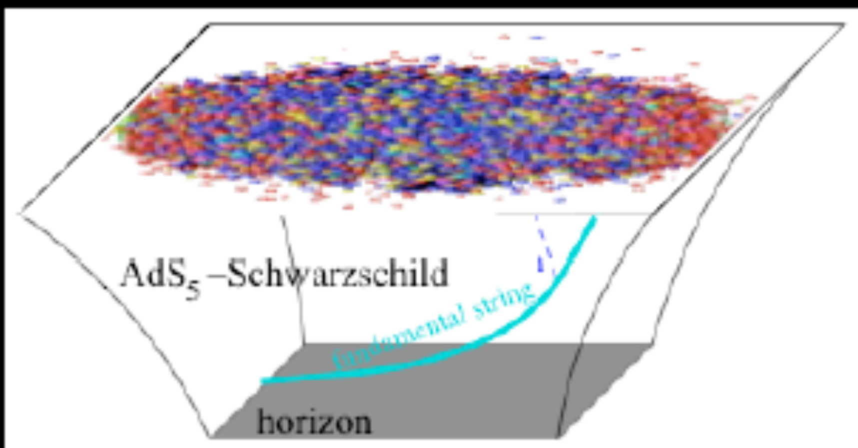
Finer-scale structure



Probe the small scale fluctuations!

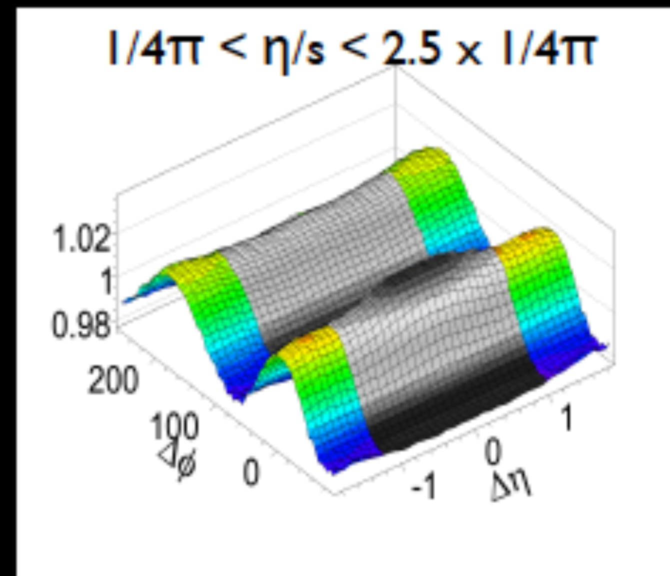
Ultra-cold atoms at Feshbach resonance





CFT in strong coupling limit

$$\frac{\eta}{s} \approx \frac{\hbar}{4\pi}$$



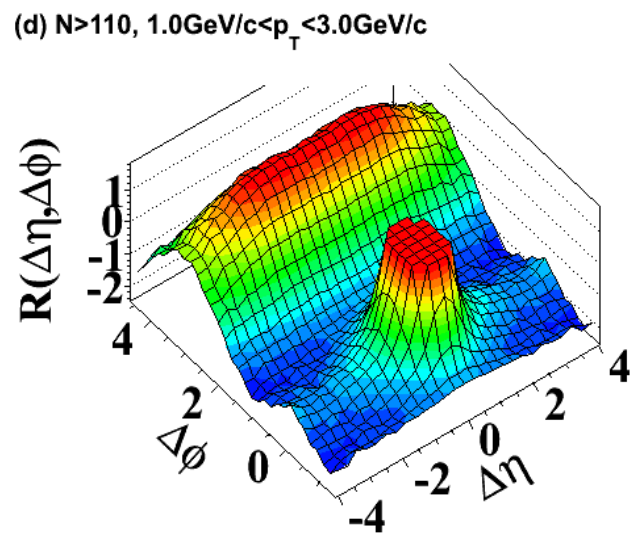
Quark-Gluon Plasma in heavy-ion collisions

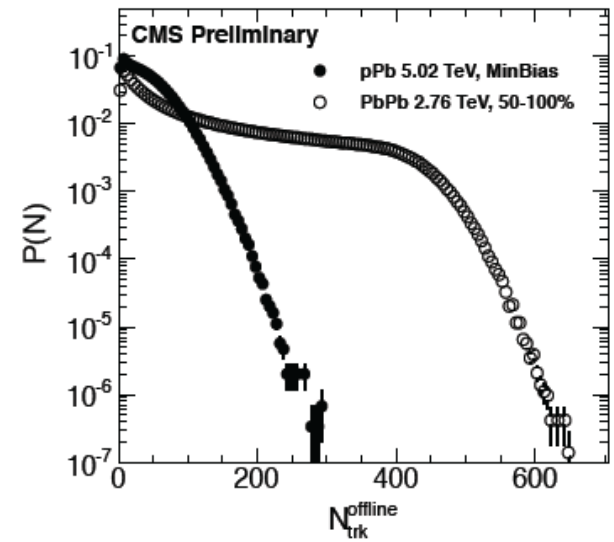
QCD matter at 10^{12}K, an atomic gas at 10^{-9}K and a black hole in 5D AdS share fundamental dynamical properties

Universal nature of strongly coupled systems?

To be understood: the "ridge" at LHC

- Early observation in high multiplicity 7 TeV pp collisions
  - Origin still unclear
- Then seen in PbPb collisions, reminiscent of RHIC
  - Believed to arise from collective flow
- Now confirmed in pPb collisions
  - Is it collective flow? CGC?
  - Tool: highest pPb multiplicity (<0.0003%) ≈ 55-60% PbPb centrality





To be understood: Triangular flow

- Remarkable similarity in the v_3 signal as a function of multiplicity in pPb and PbPb