QCD and heavy ion collisions: phenomenological aspects

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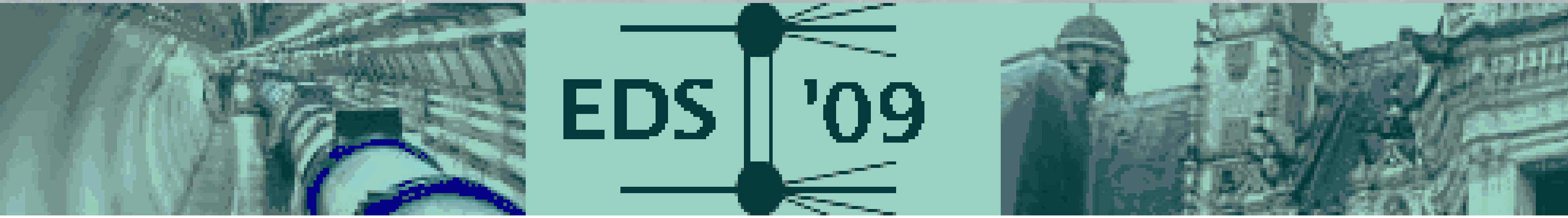
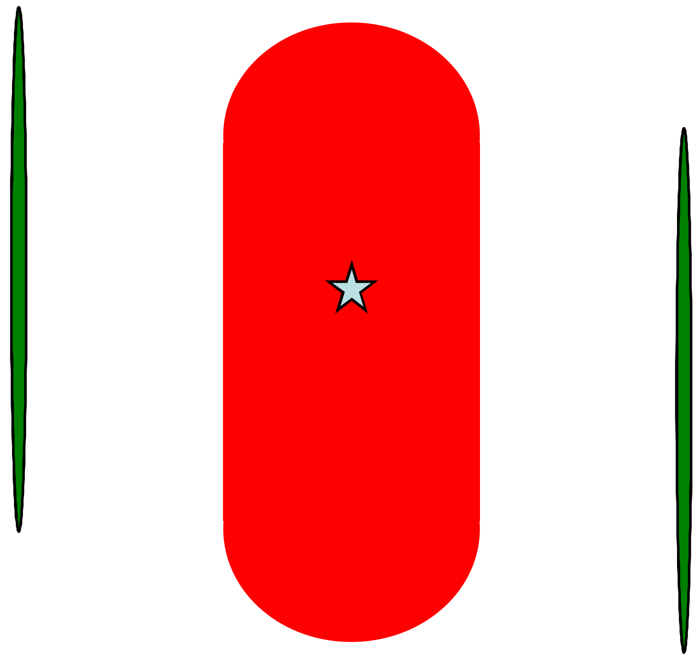
CERN, July 2, 2009



A nucleus-nucleus collision at RHIC



Two Lorentz-contracted nuclei collide

☆ Hard processes, accessible to perturbative calculations

High-density, strongly-interacting hadronic matter is created and expands, and eventually reaches the detectors as hadrons

Outline

- Do heavy ion collisions tell us anything about hot QCD?

  An example : estimating the viscosity of hot QCD from RHIC data (2009)

- Are perturbative approaches to the initial stage of heavy-ion collisions relevant to phenomenology?

  Two examples :

  1. The initial energy density profile
  2. Correlations and fluctuations

Why viscosity? (1/2)

Fluid dynamics = only well-controlled description of an expanding, strongly-interacting system.

Macroscopic description: systematic gradient expansion

$$\partial_\mu((\epsilon+P)u^\mu u^\nu - Pg^{\mu\nu}) + \eta\, \partial_\mu \partial_\rho \ldots + \partial_\mu \partial_\rho \partial_\sigma \ldots = 0$$

ideal viscous

$\sim 1/R$ $\sim 1/R^2$ where R = system size

A large system expands as an ideal fluid

Is a Au (or Cu) nucleus large enough ? Not sure…

Or, equivalently, is the viscosity η small enough ?

Why viscosity? (2/2)

The stronger the interactions, the smaller the viscosity η

So it may well be small in strongly-coupled QCD… but lattice QCD is not yet able to give a reliable estimate of η

An exact result for supersymmetric N=4 gauge theories at strong coupling, and it might be a universal lower bound $\eta/s=1/4\pi$ (s=entropy density)

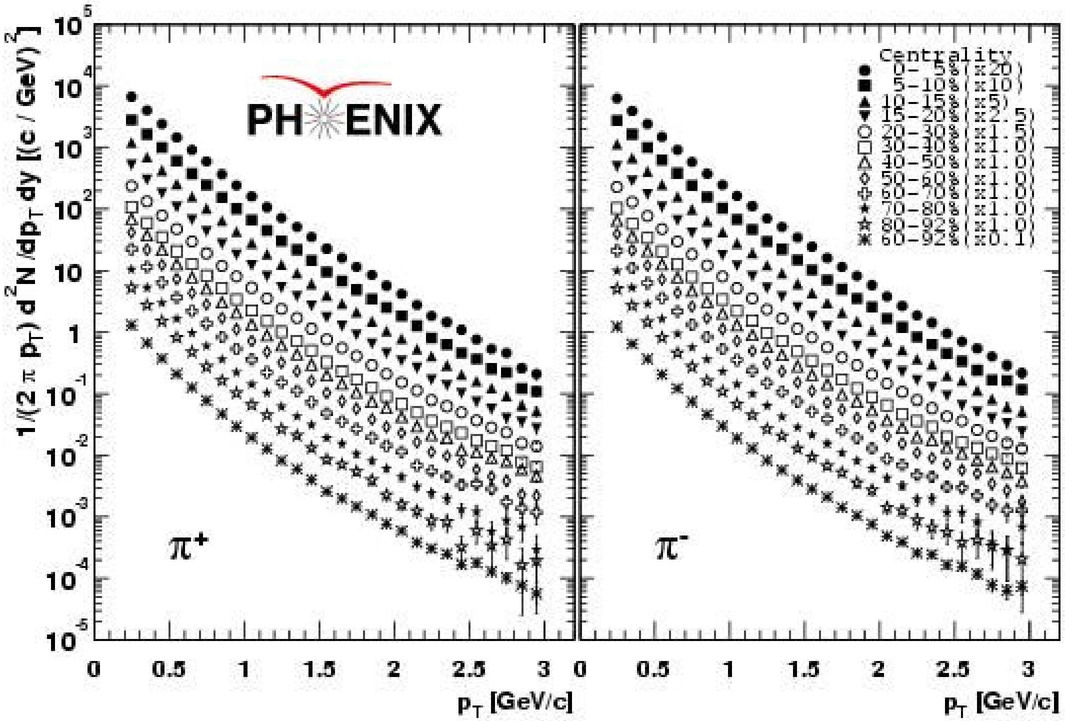
Kovtun Son Starinets hep-th/0405231

How close is the QCD η to the string theory prediction?

A simple (non-standard) test of ideal-fluid behaviour

Ideal hydrodynamics $\partial_\mu T^{\mu\nu}=0$ is scale invariant : $x^\mu \rightarrow \lambda x^\mu$ is still a solution.

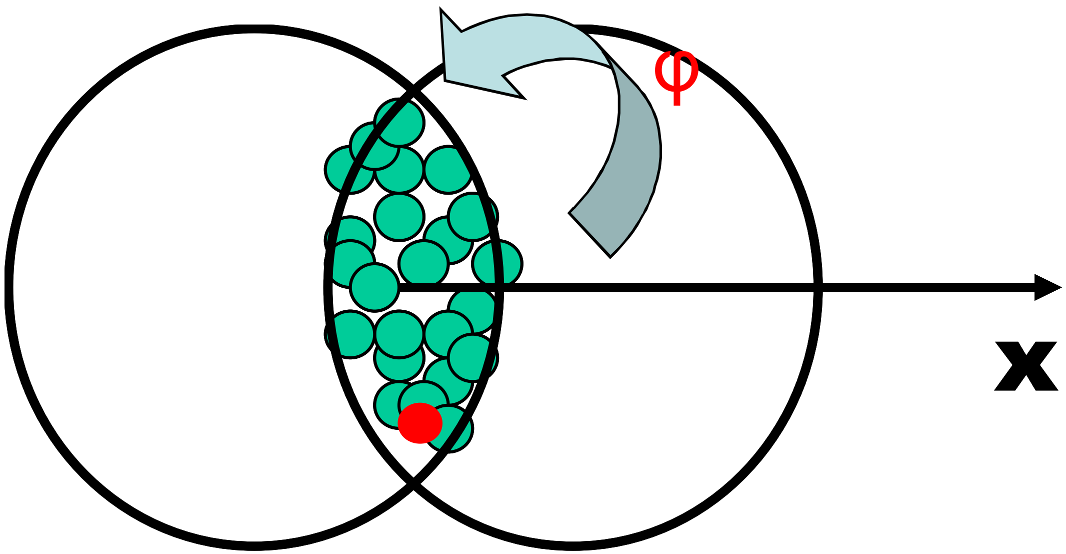
Scale invariance can be tested by varying the size of the colliding nuclei (Cu-Cu versus Au-Au) or the centrality of the collision (peripheral<central)



Pt spectra are centrality independent to a good approximation, and this is also true in ideal hydro.

A more specific observable: elliptic flow

Non-central collision seen in the transverse plane: the overlap area, where particles are produced, is not a circle.



A particle moving at φ=π/2 from the x-axis is more likely to be deflected than a particle moving at φ=0, which escapes more easily.

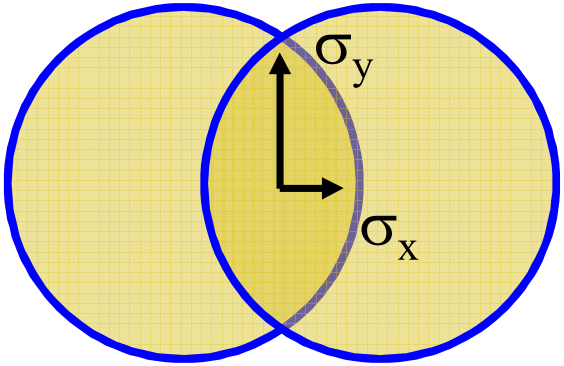
$$\frac{dN}{d\varphi} = \frac{1}{2\pi}(1 + 2v_1 \cos\varphi + 2v_2 \cos 2\varphi + ...)$$

Initially, particle momenta are distributed isotropically in φ. Collisions result in positive v_2.

Eccentricity scaling

v_2 scales by construction like the eccentricity

ε of the initial density profile, defined as :

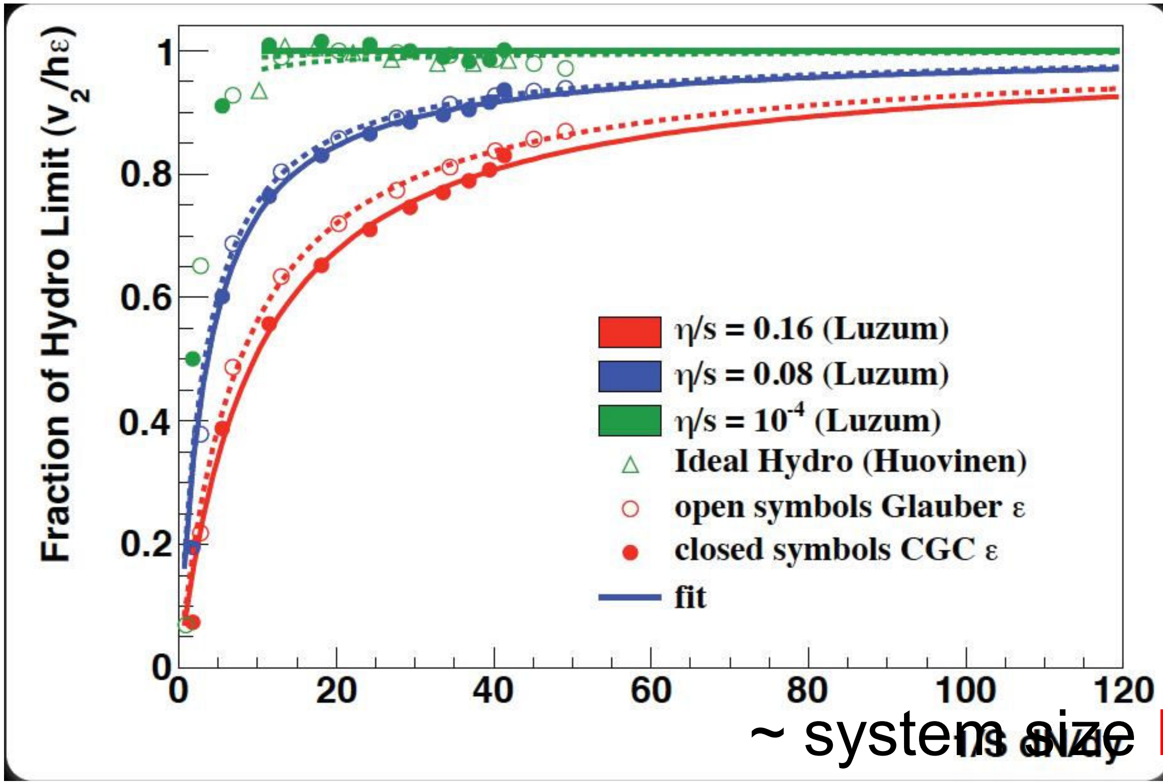


$$\varepsilon = \frac{\sigma_y{}^2 - \sigma_x{}^2}{\sigma_y{}^2 + \sigma_x{}^2}$$

This eccentricity depends on the collision centrality, which is well known experimentally.

- In ideal hydro, v_2/ε must be independent of system size R
- Viscous corrections are expected to scale like -η/R.

Test of the scaling: numerical viscous hydro (from R. Snellings, talk at QM'09)



~ system size R

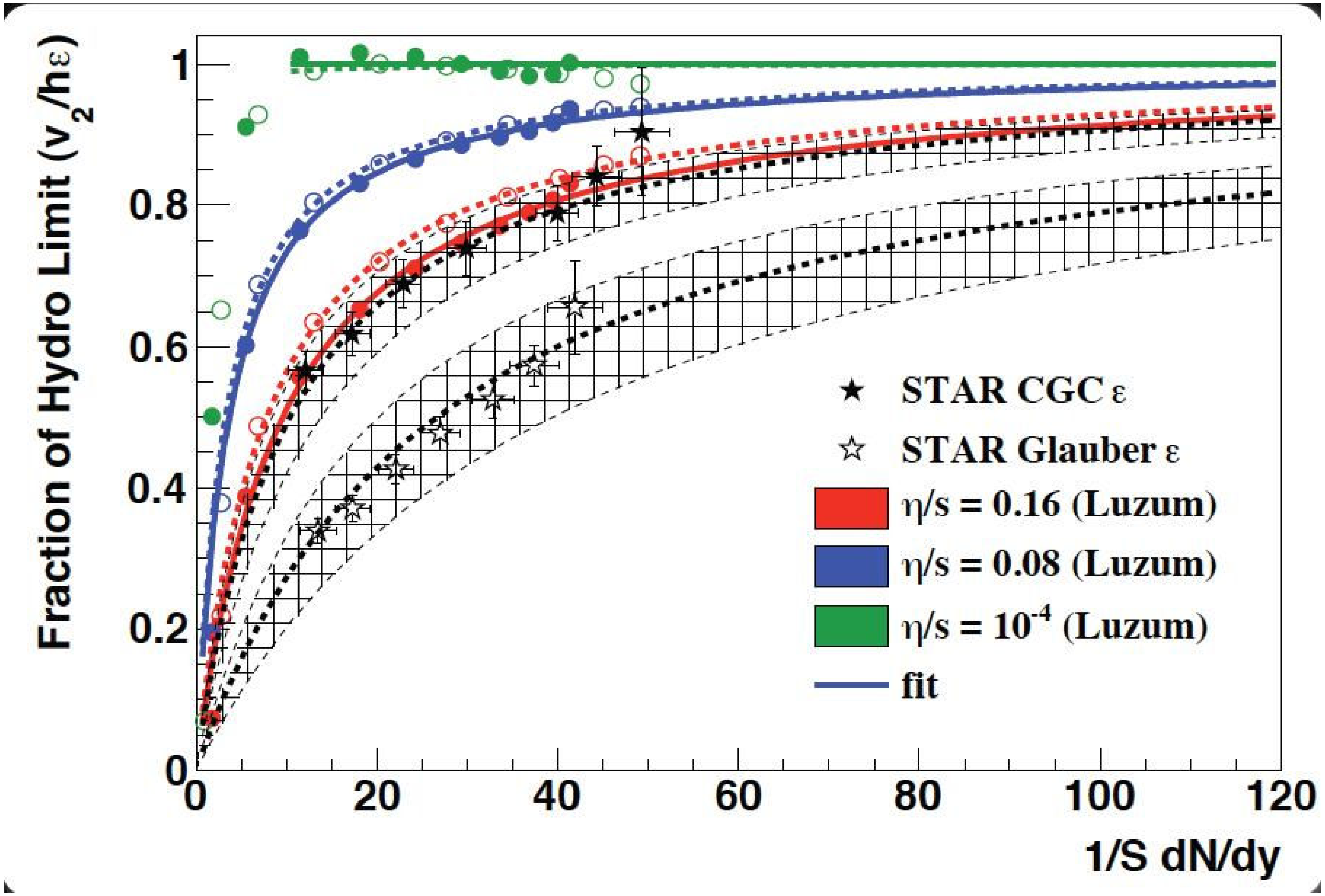
Lines: fits using $(1+\alpha/R)^{-1}$,

α = fit parameter

Deviations to v_2/ε=constant clearly scale like η/R

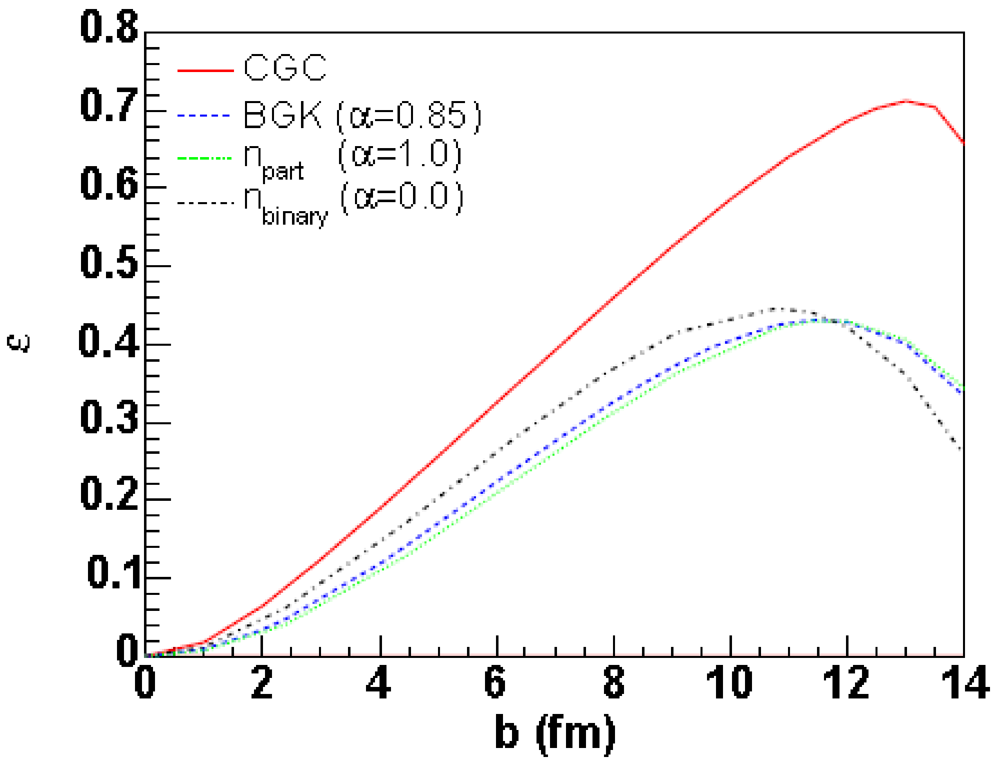
A direct way of estimating the viscosity η experimentally !

Testing the scaling on RHIC data
(R. Snellings, QM'09)



Caveat: v_2 is measured, ε comes from a model!

How well do we know the initial eccentricity?

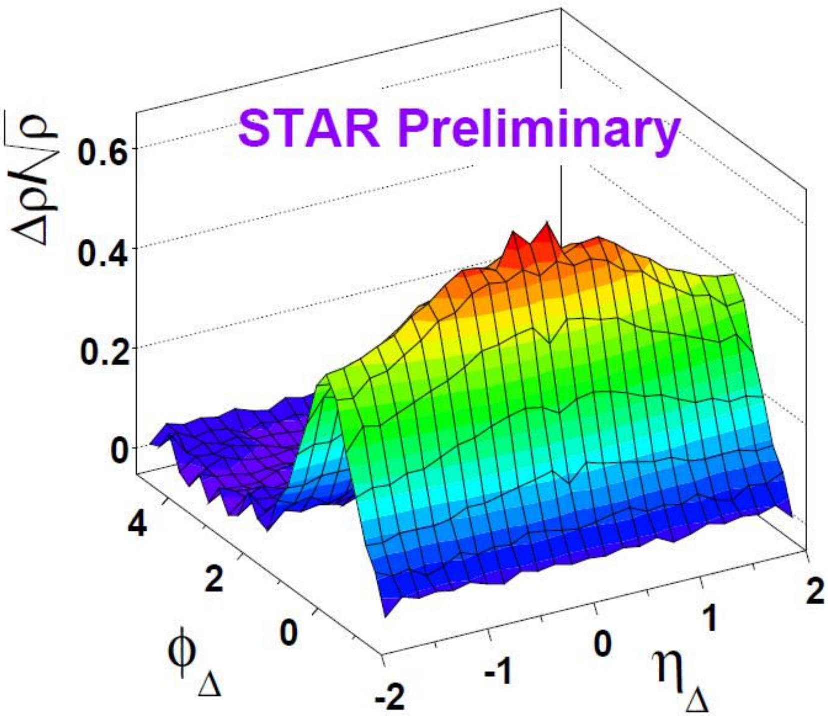


The initial eccentricity is strongly model-dependent! We need a good control of initial conditions

Drescher Dumitru Hayashigaki Nara, nucl-th/0605012

Beyond single-particle spectra: correlations

2-particle correlations look different in nucleus-nucleus, compared to proton-proton collisions

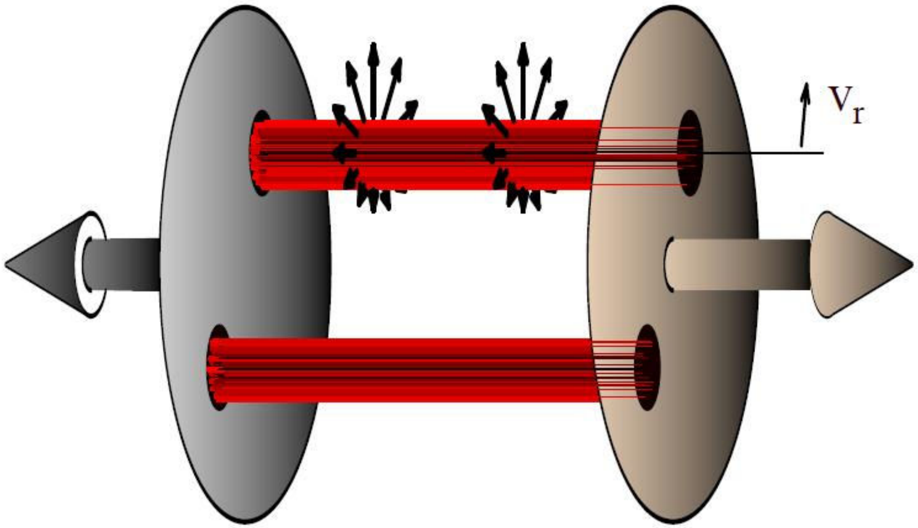


Wider in rapidity, narrower in azimuth:

A ridge rather than a circle in p-p.

Hydro does not create such correlations: they must be present initially

Correlations in the color-glass condensate



The chromo E and B fields form flux tubes, elongated in rapidity, after the collision.

Their size is determined by the saturation scale

Flux tubes eventually decay into particles, which are boosted by the flow, resulting in a narrower azimuthal width

Dumitru Gelis McLerran Venugopalan 2008

Conclusions

- Fluid dynamics is the most promising approach to describe the bulk of particle production in heavy-ion collisions.
- In 2005, the « perfect liquid » picture was popular. Now, we have learned that viscous corrections are important : elliptic flow is 25 % below the «ideal hydro », even for central Au-Au collisions !
- The phenomenology of heavy-ion collisions has made a lot of progress in the last few years: we now have quantitative relations between observables and properties of hot QCD.
- It is crucial to have a better control on the initial stage of the collision: although thermalization loses memory of initial conditions, so that the detailed structure of the initial state is lost, but nontrivial information remains through global quantities and correlations.

Backup slides

Dimensionless numbers in fluid dynamics

They involve intrinsic properties of the fluid *(mean free path λ, thermal/sound velocity c_s, shear viscosity η, mass density ρ)* as well as quantities specific to the flow pattern under study (characteristic size R, flow velocity v)

Knudsen number $K = \lambda / R$

$K \ll 1$: local equilibrium (fluid dynamics applies)

Mach number $Ma = v / c_s$

$Ma \ll 1$: incompressible flow

Reynolds number $R = Rv / (\eta / \rho)$

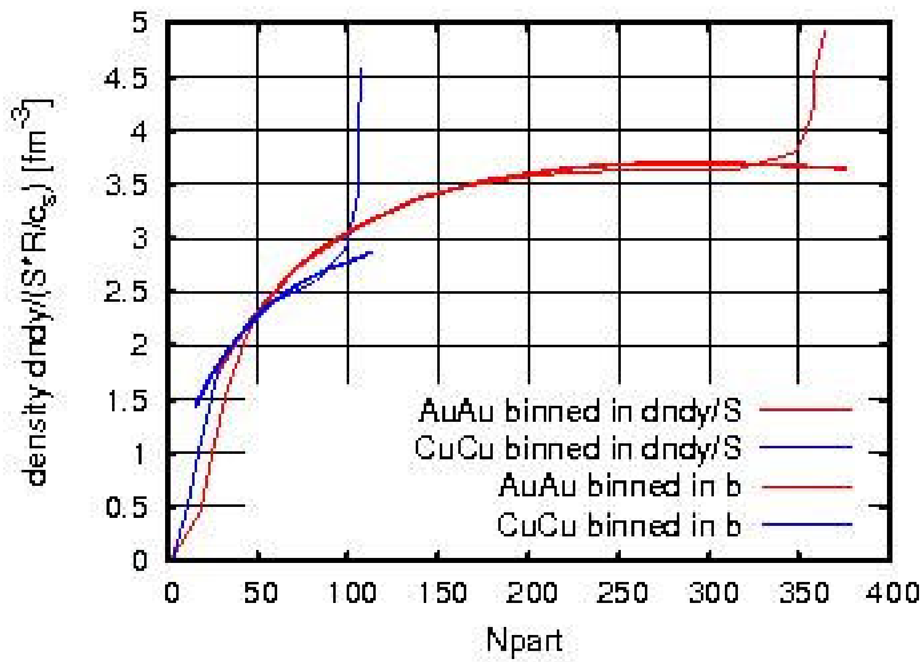
$R \gg 1$: non-viscous flow (ideal fluid)

They are related ! Transport theory: $\eta/\rho \sim \lambda c_s$ implies $R * K \sim Ma$

Remember: compressible+viscous = departures from local eq.

Particle densities per unit volume at RHIC
(MC Glauber calculation)

The density is estimated at the time $t=R/c_s$
(i.e., when v_2 appears), assuming 1/t dependence.

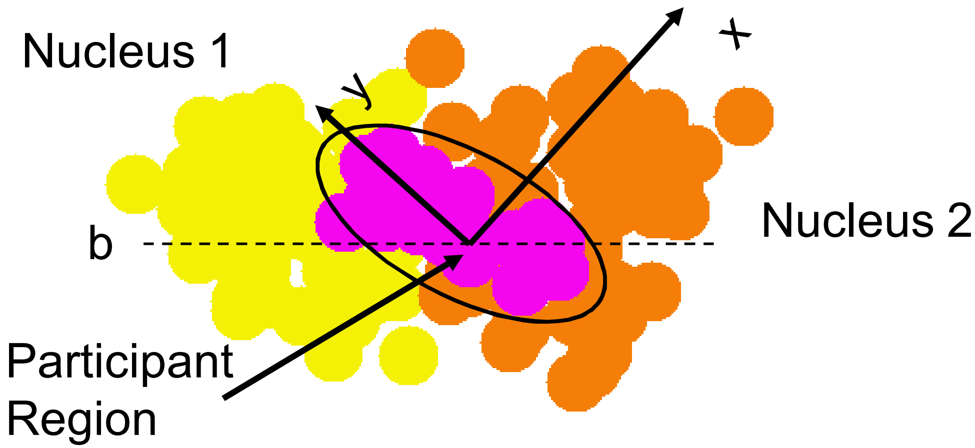


H-J Drescher
(unpublished)

The effective density that we see through elliptic flow depends little on colliding system & centrality !

Estimating the initial eccentricity

Until 2005, this was thought to be the easy part.
But puzzling results came:
1. v_2 was larger than predicted by hydro in central Au-Au collisions.
2. v_2 was much larger than expected in Cu-Cu collisions.
This was interpreted by the PHOBOS collaboration as an effect of fluctuations in initial conditions
[Miller & Snellings nucl-ex/0312008]



In 2005, it was also shown that the eccentricity depends significantly on the model chosen for initial particle production.
We compare two such models, Glauber and Color Glass Condensate.

PHOBOS data for v2

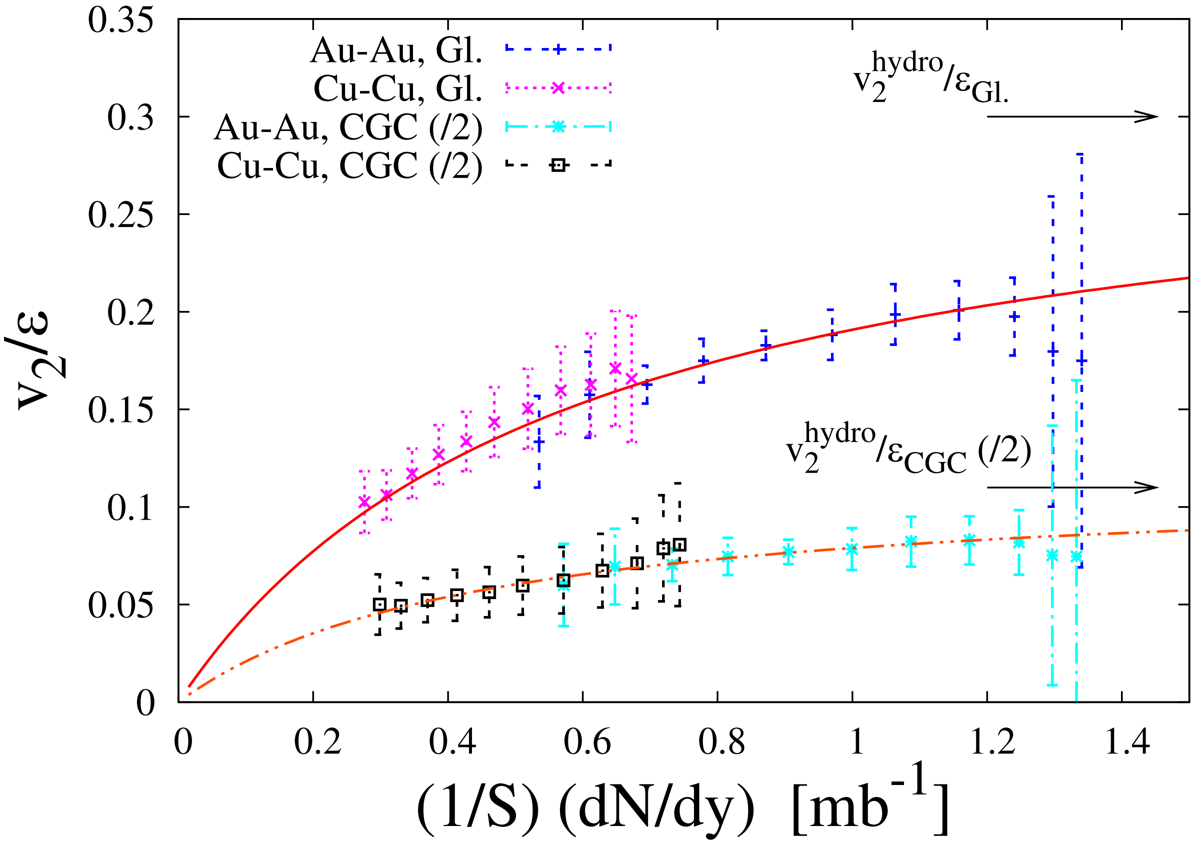
1. Phobos data for v_2
2. ε obtained using Glauber or CGC initial conditions +fluctuations
3. Fit with

$v_2 = \alpha\, \varepsilon/(1+1.4\, K)$

assuming

$1/K = (\sigma/S)(dN/dy)$

with the fit parameters σ and α.



K~0.3 for central Au-Au collisions

v_2 : 30% below ideal hydro!