Nominal Lecture #2 Start

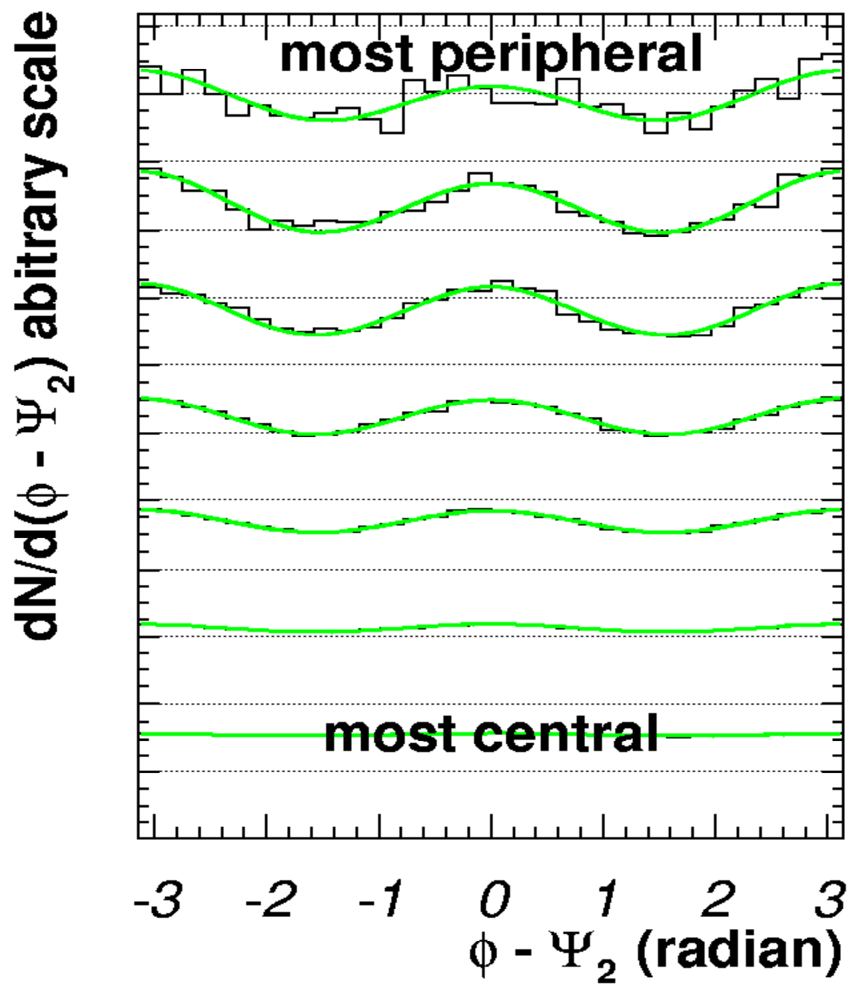
The Perfect Liquid

The Key Paradigm in the Field

What do we mean by Perfect?

What evidence is there?

Non-Central A+A Geometry



$$\frac{dN}{p_T dp_T dy d\varphi}(p_T, \varphi; b) = \frac{dN}{2\pi p_T dp_T dy}\left(1 + 2\underline{v_2}(p_T; b)\cos(2\varphi) + \ldots\right)$$

v_2 = "elliptic flow"

Always Read the Original Material

PHYSICAL REVIEW D VOLUME 46, NUMBER 1 1 JULY 1992

Anisotropy as a signature of transverse collective flow

Jean-Yves Ollitrault
Service de Physique Théorique, Centre d'Études de Saclay, F-91191 Gif-sur-Yvette CEDEX, France
(Received 19 February 1992)

We show that anisotropies in transverse-momentum distributions provide an unambiguous signature of transverse collective flow in ultrarelativistic nucleus-nucleus collisions. We define a measure of the anisotropy from experimental observables. The anisotropy coming from collective effects is estimated quantitatively using a hydrodynamical model, and compared to the anisotropy originating from finite multiplicity fluctuations. We conclude that collective behavior could be seen in Pb-Pb collisions if a few hundred particle momenta were measured in a central event.

PACS number(s): 25.75.+r, 12.38.Mh, 24.60.Ky, 47.75.+f

Article

Zeitschrift für Physik C Particles and Fields
December 1996, Volume 70, Issue 4, pp 665-671

First online: 31 March 2014

Flow study in relativistic nuclear collisions by Fourier expansion of azimuthal particle distributions

S. Voloshin, Y. Zhang

Common problem – not reading the original references…

V = Voloshin (?)

How do experiments measure v2?

An entire lecture could be on these details…

http://journals.aps.org/prc/abstract/10.1103/PhysRevC.80.014904

PHYSICAL REVIEW C

covering nuclear physics

Highlights Recent Accepted Authors Referees Search Press About

Effect of flow fluctuations and nonflow on elliptic flow methods

Jean-Yves Ollitrault, Arthur M. Poskanzer, and Sergei A. Voloshin

Phys. Rev. C **80**, 014904 – Published 10 July 2009

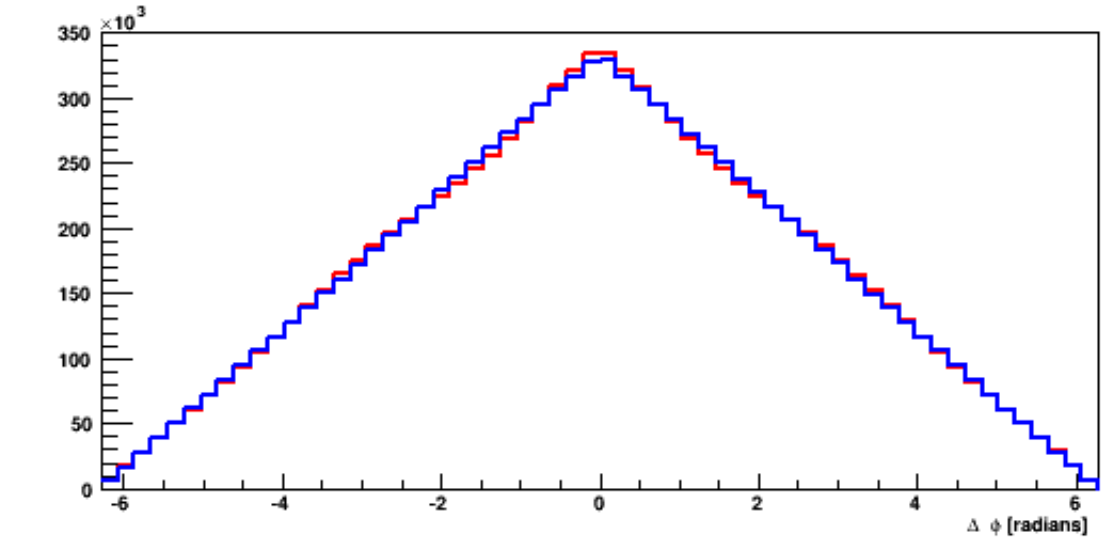
Short introduction to some experimental basics

Two Particle Correlations

Two independent particles that come from a common source distribution $1 + 2v_2\cos[2(\phi-\psi_2)]$

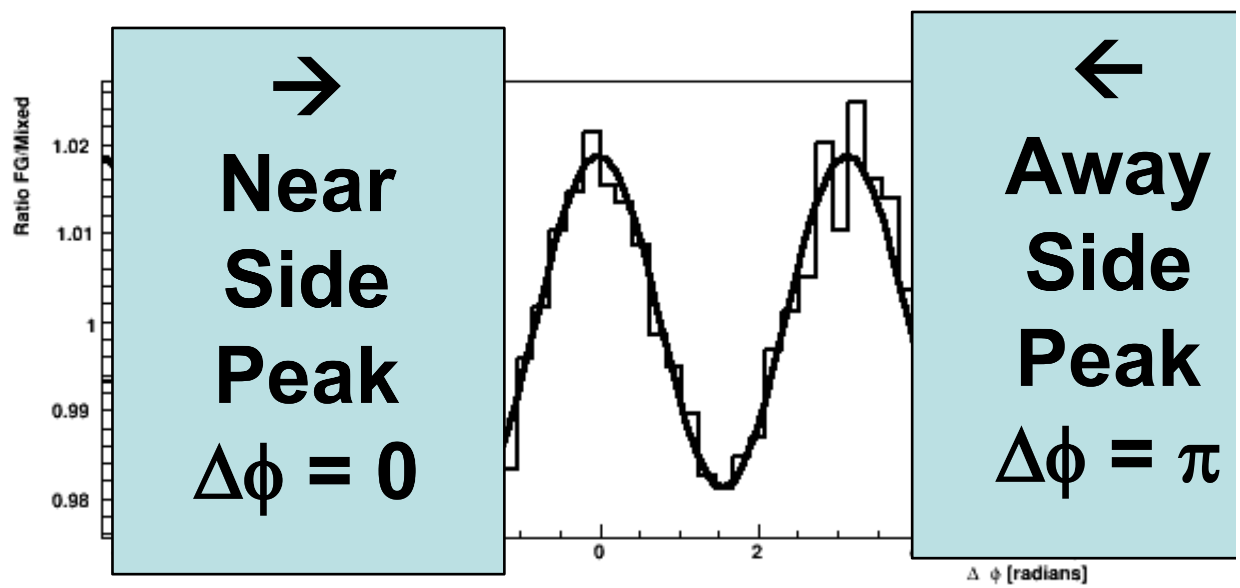
Random Case

Resulting $\Delta\phi$ Distribution



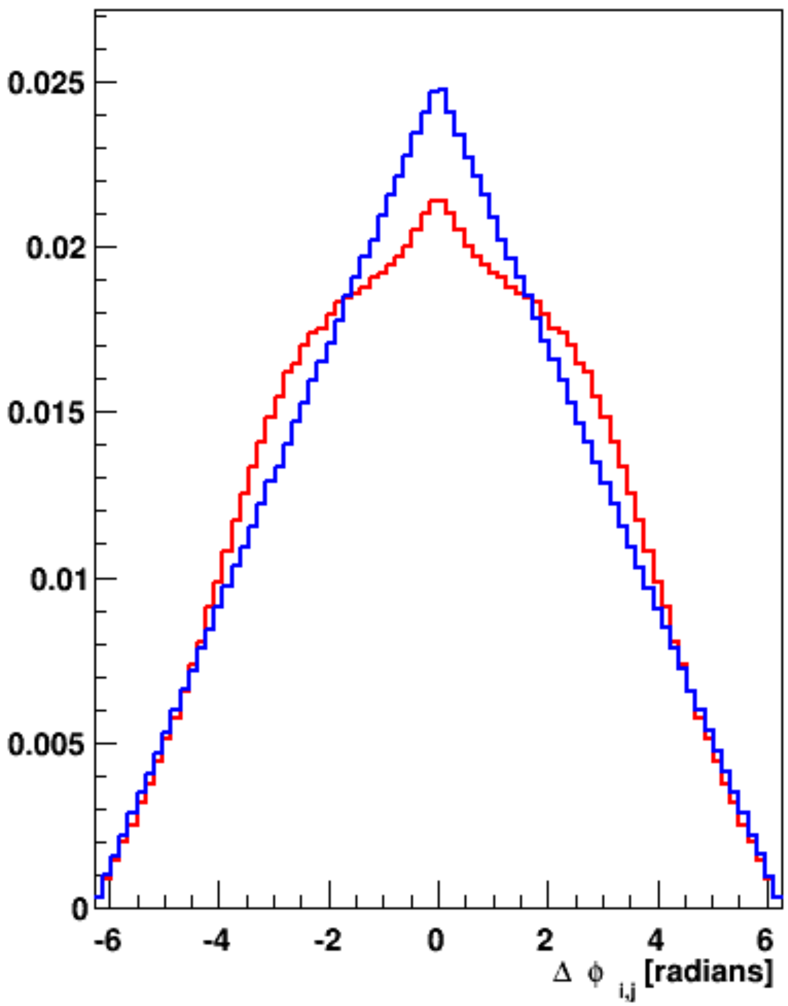
Divide the two FG/BG

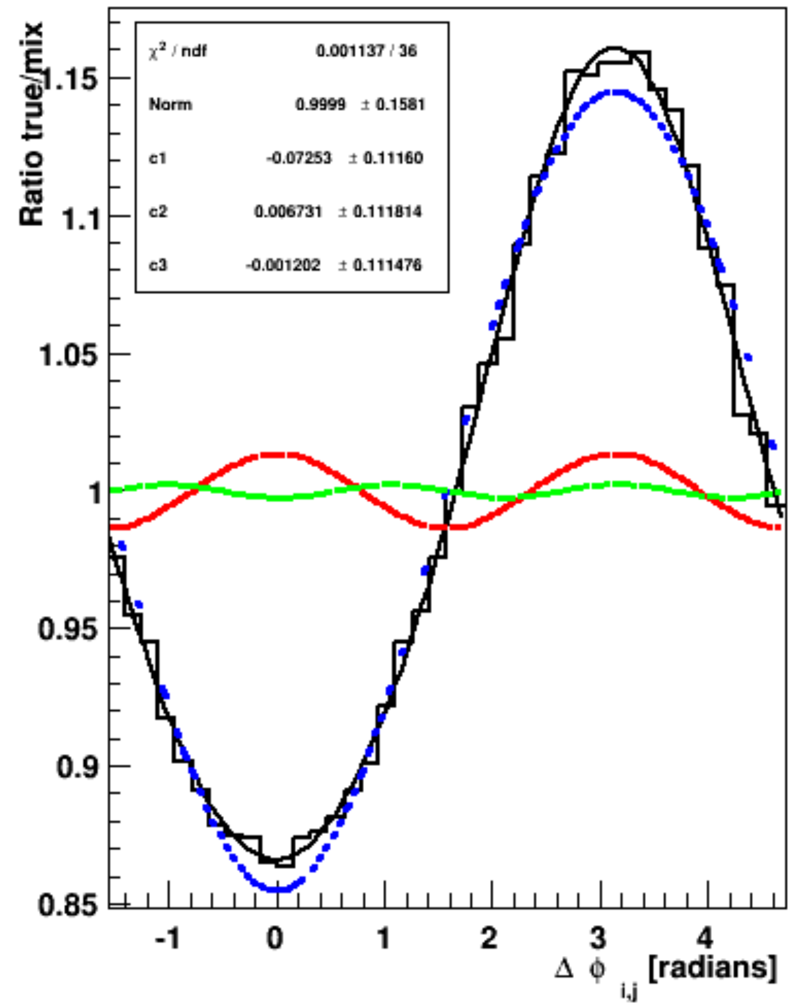
Oscillation
$1 + 2v_2^2\cos(2\Delta\phi)$



Complications and Other Contributions?

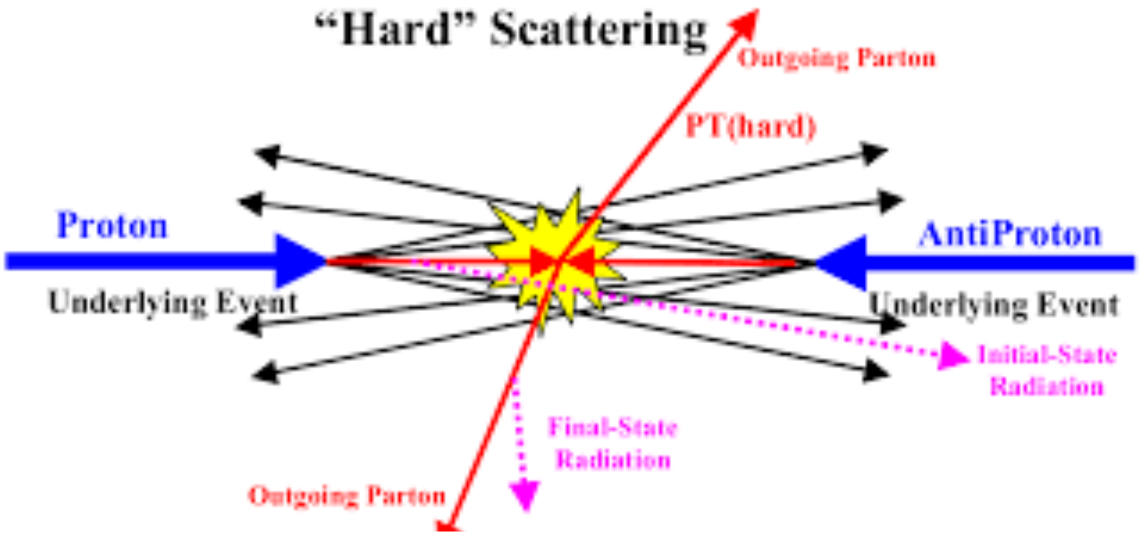
Momentum Conservation



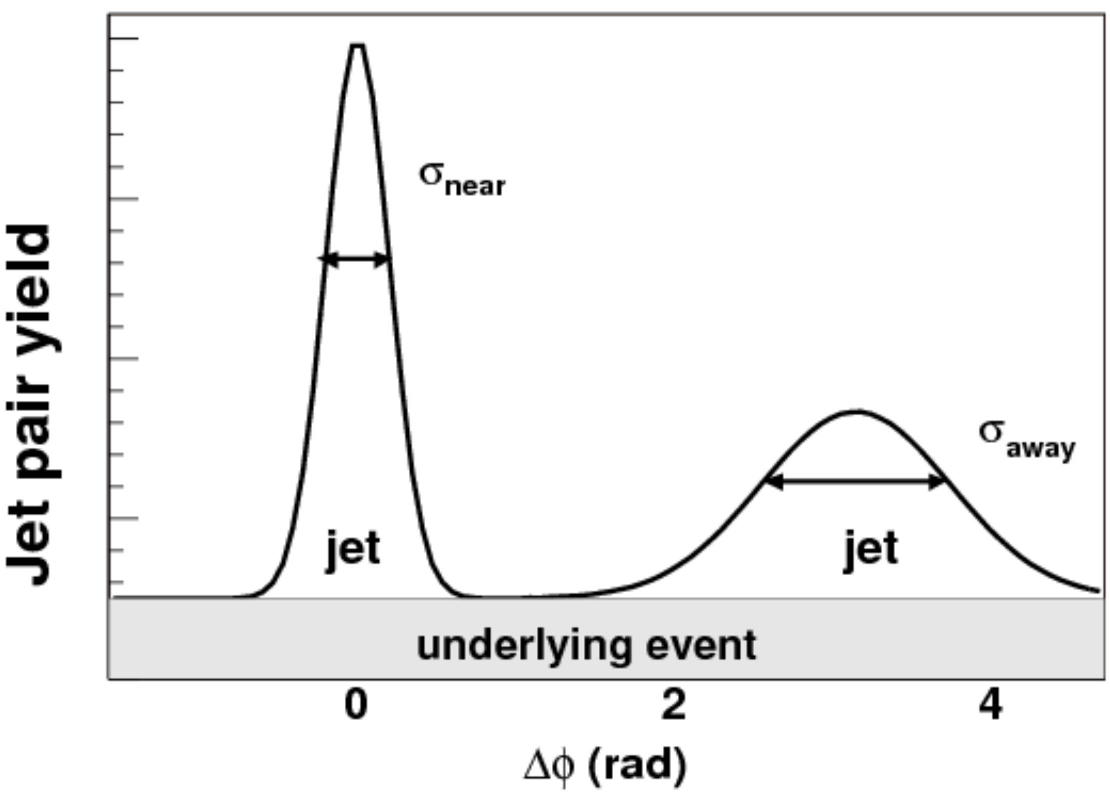


https://root.cern.ch/doc/master/classTGenPhaseSpace.html

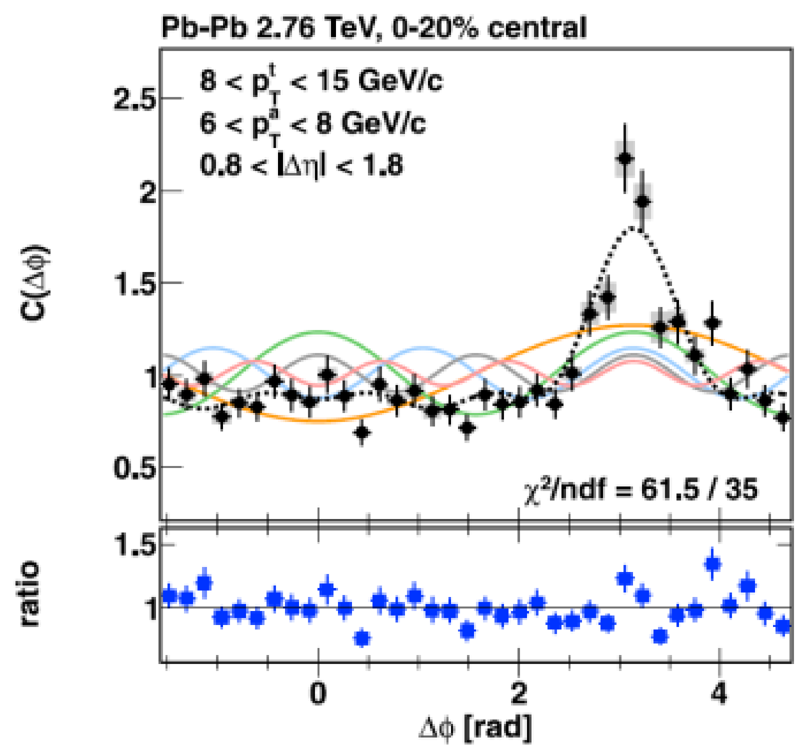
Jet Correlations



Multi-particle correlations – same jet, opposite jet, etc.



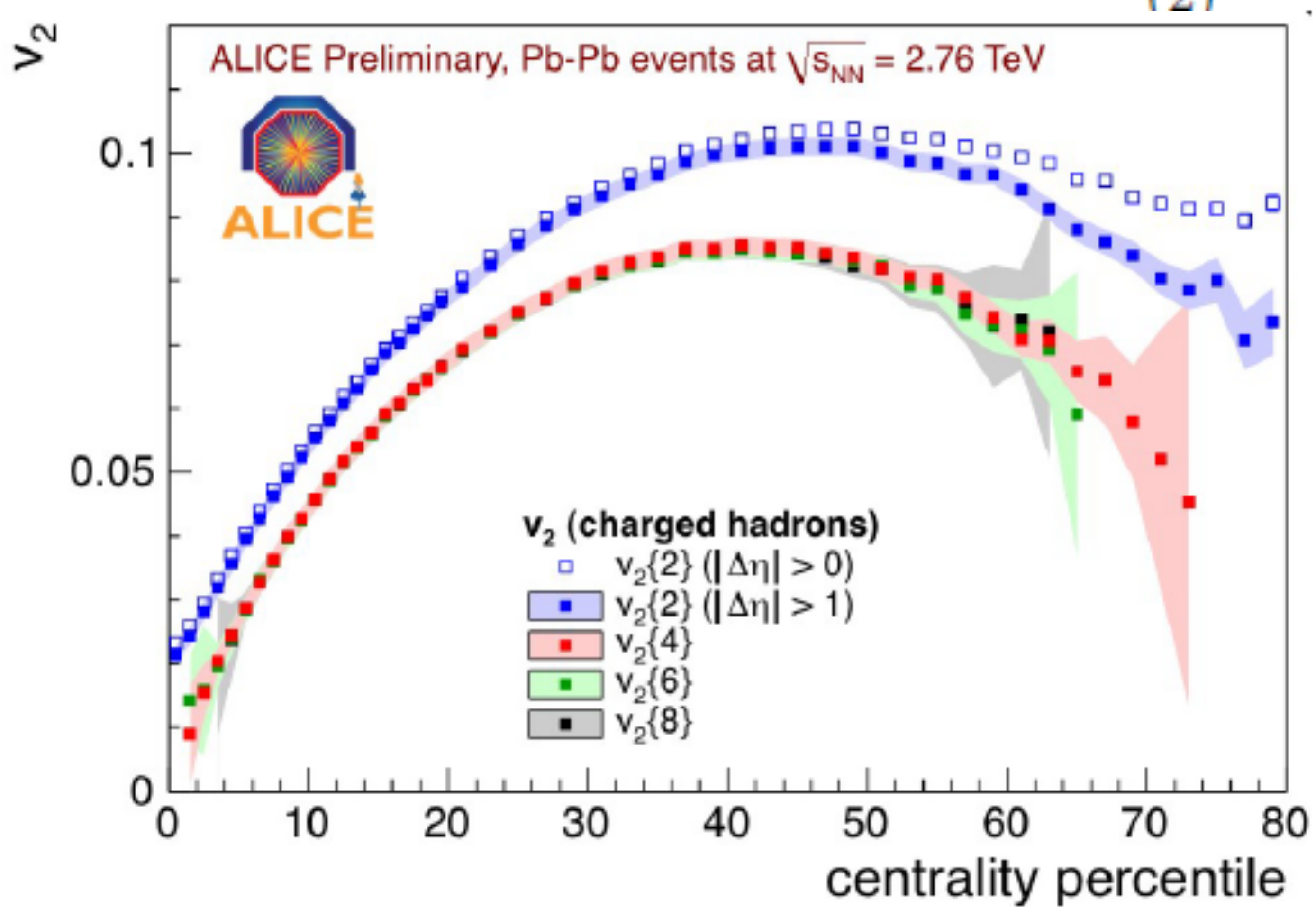
Require large pseudorapidity gap



How to Separate "Flow" and "Non-Flow"

$$v\{2\} \equiv \sqrt{\langle \cos(\phi_1 - \phi_2) \rangle}$$

$$v\{4\} \equiv \left(2\langle \cos(\phi_1 - \phi_2) \rangle^2 - \langle \cos(\phi_1 + \phi_2 - \phi_3 - \phi_4) \rangle\right)^{1/4} \quad (2)$$

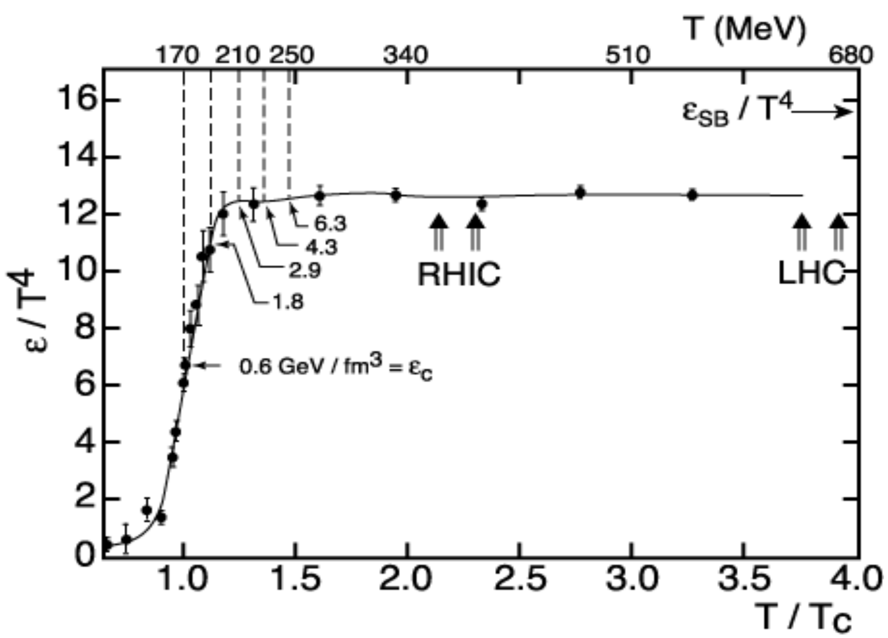


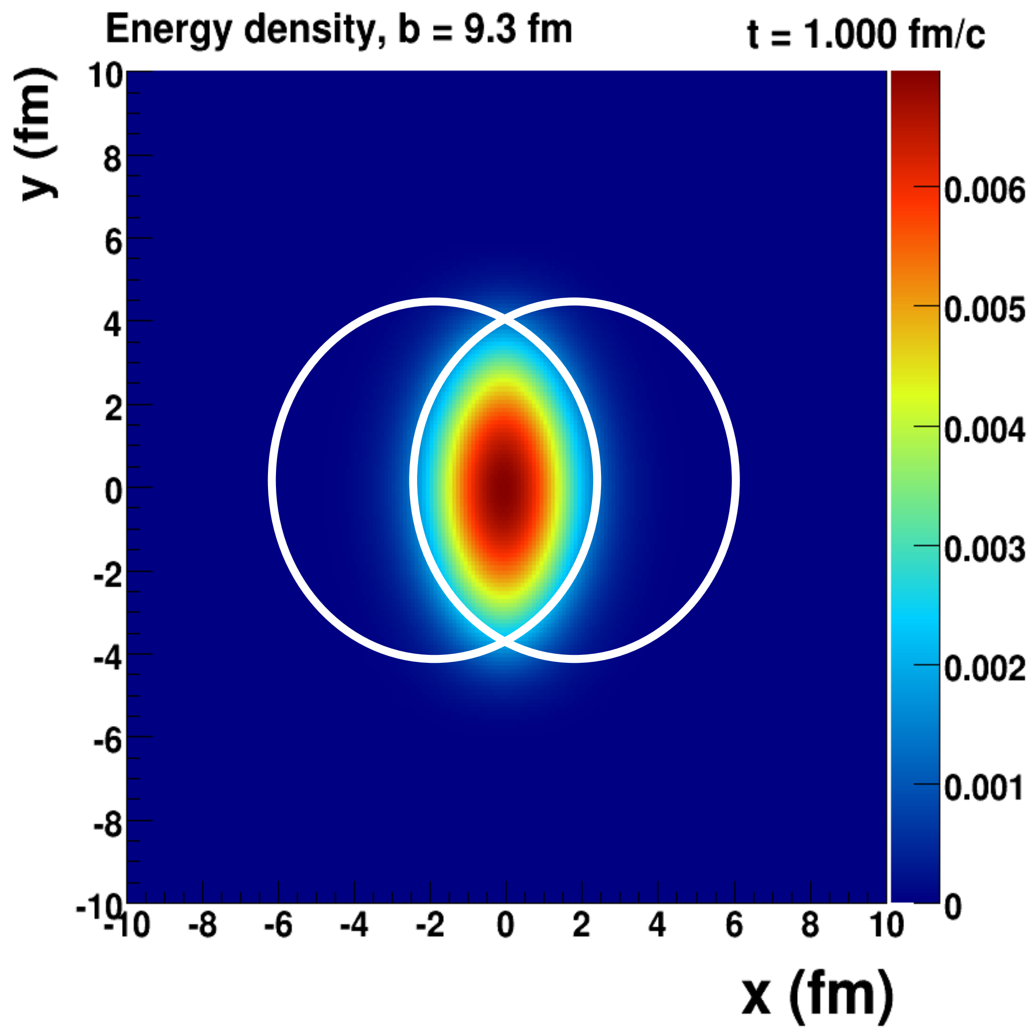
Cumulants are not "like magic"…

Ideal Hydrodynamics

Key Inputs:

- Initial Geometry
- QCD Equation of State



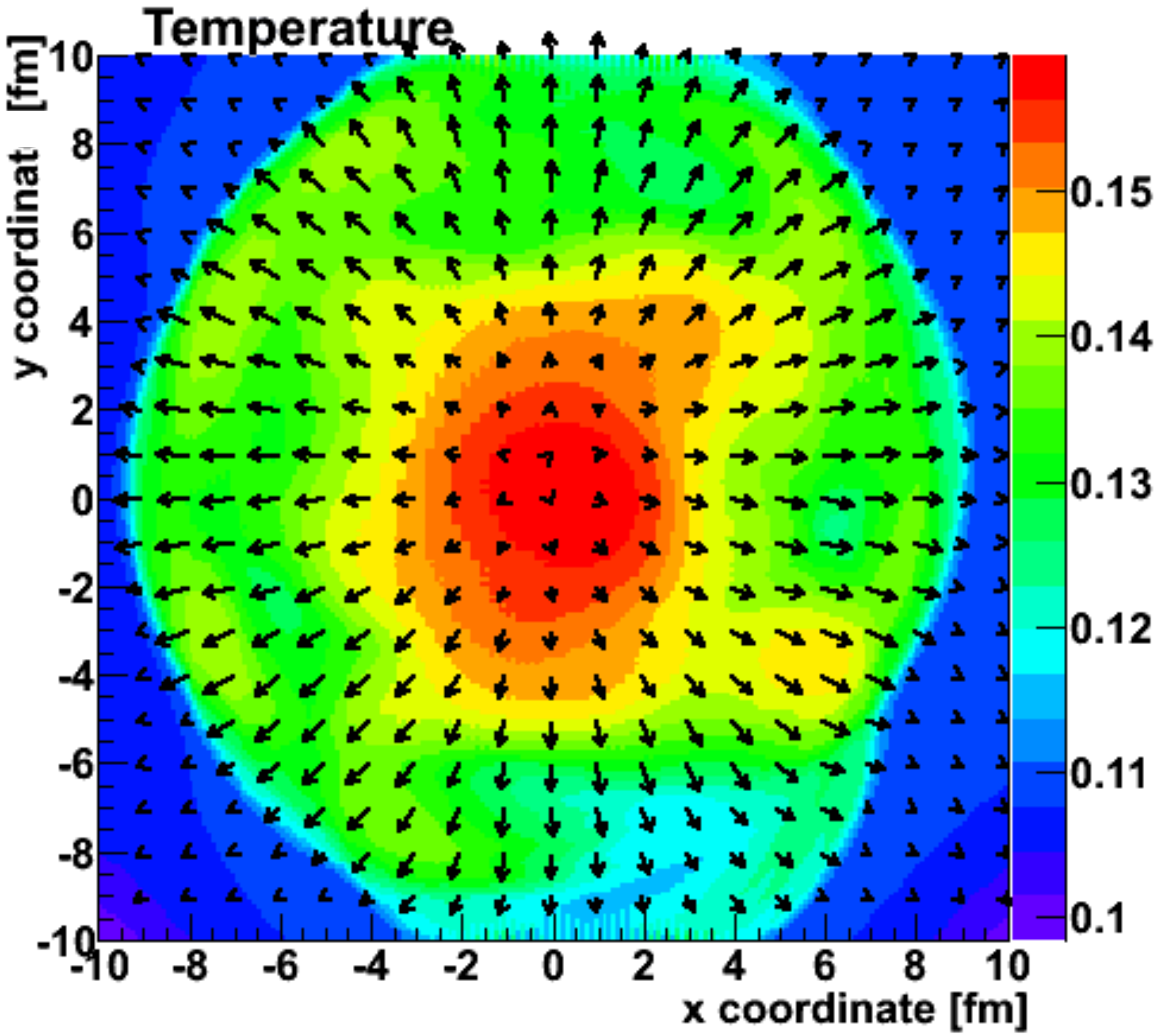


Assumes early thermalization [not proven]

Assumes no dissipation (shear/bulk viscosity = 0)

Fluid cells "freeze-out" below T_{freeze}

Isotropic hadrons in cell rest frame, then boosted



Temperature Profile + Fluid Cell Velocity Vectors

Fluid → Hadrons

Single-particle distribution in the hydrodynamic and statistical thermodynamic models of multiparticle production

Fred Cooper and Graham Frye
Phys. Rev. D **10**, 186 – Published 1 July 1974

$$E\frac{dN}{d^3p} = \int_\Sigma d\Sigma_\mu p^\mu f(T, p_\mu u^\mu, \pi^{\mu\nu}),$$

An important, but not often discussed, assumption in the calculations.

http://journals.aps.org/prd/abstract/10.1103/PhysRevD.10.186

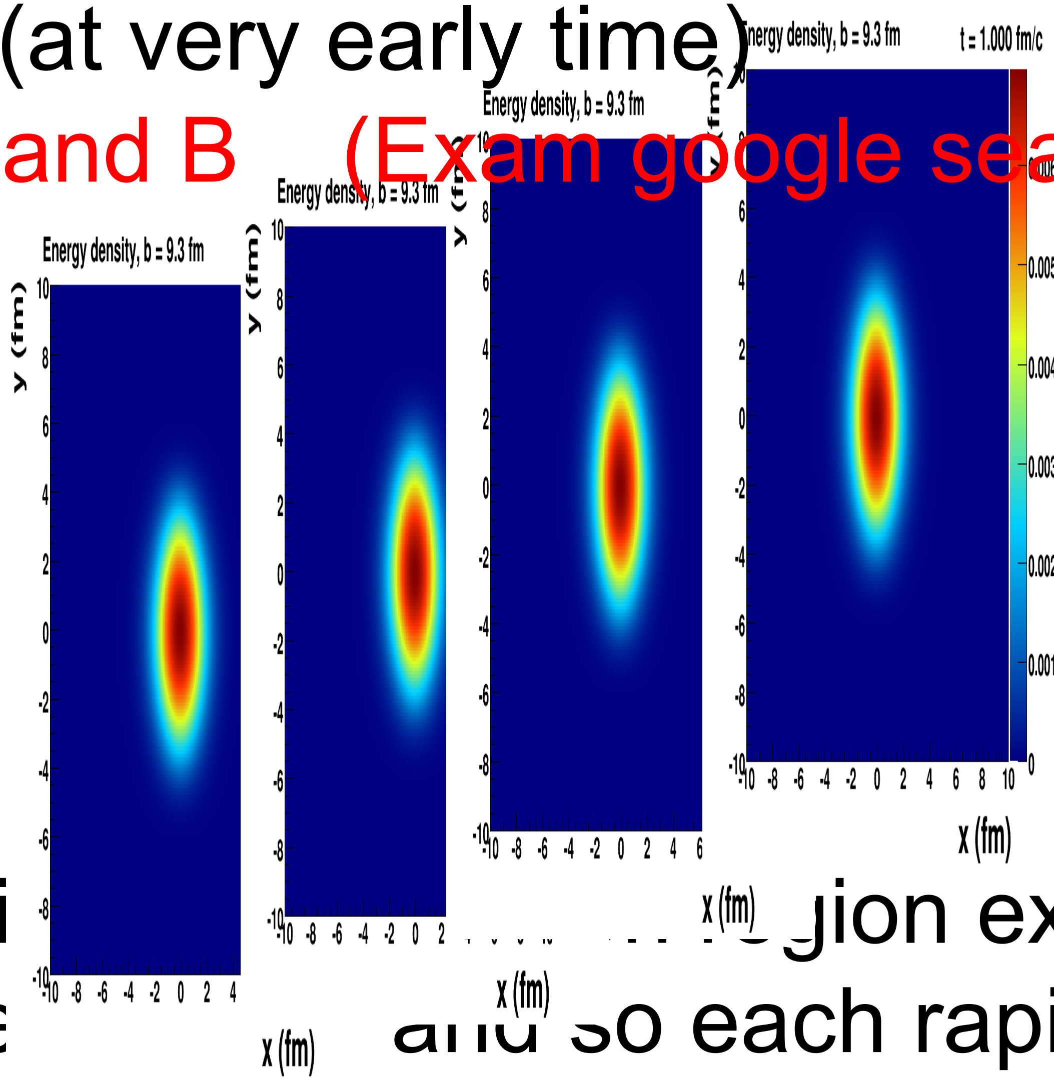
Two particles separated far in rapidity

Just like the Universe event horizon problem

A causes B (at very early time)

B causes A (at very early time)

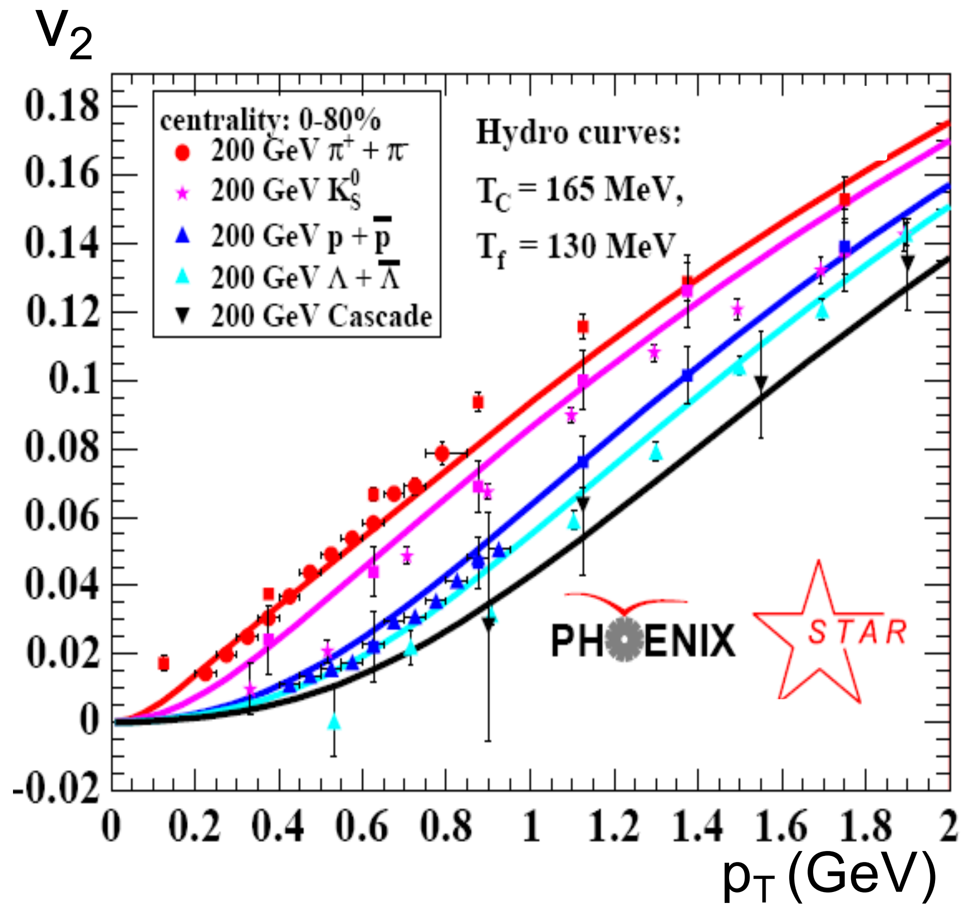
C causes A and B   (Exam google search story)

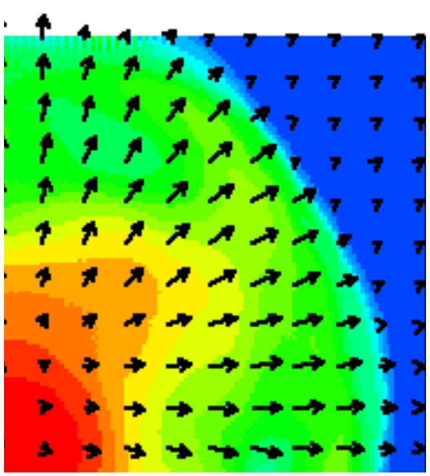


Initial elli ... gion expands at the spee ... and so each rapidity slice has approximately the same geometry.

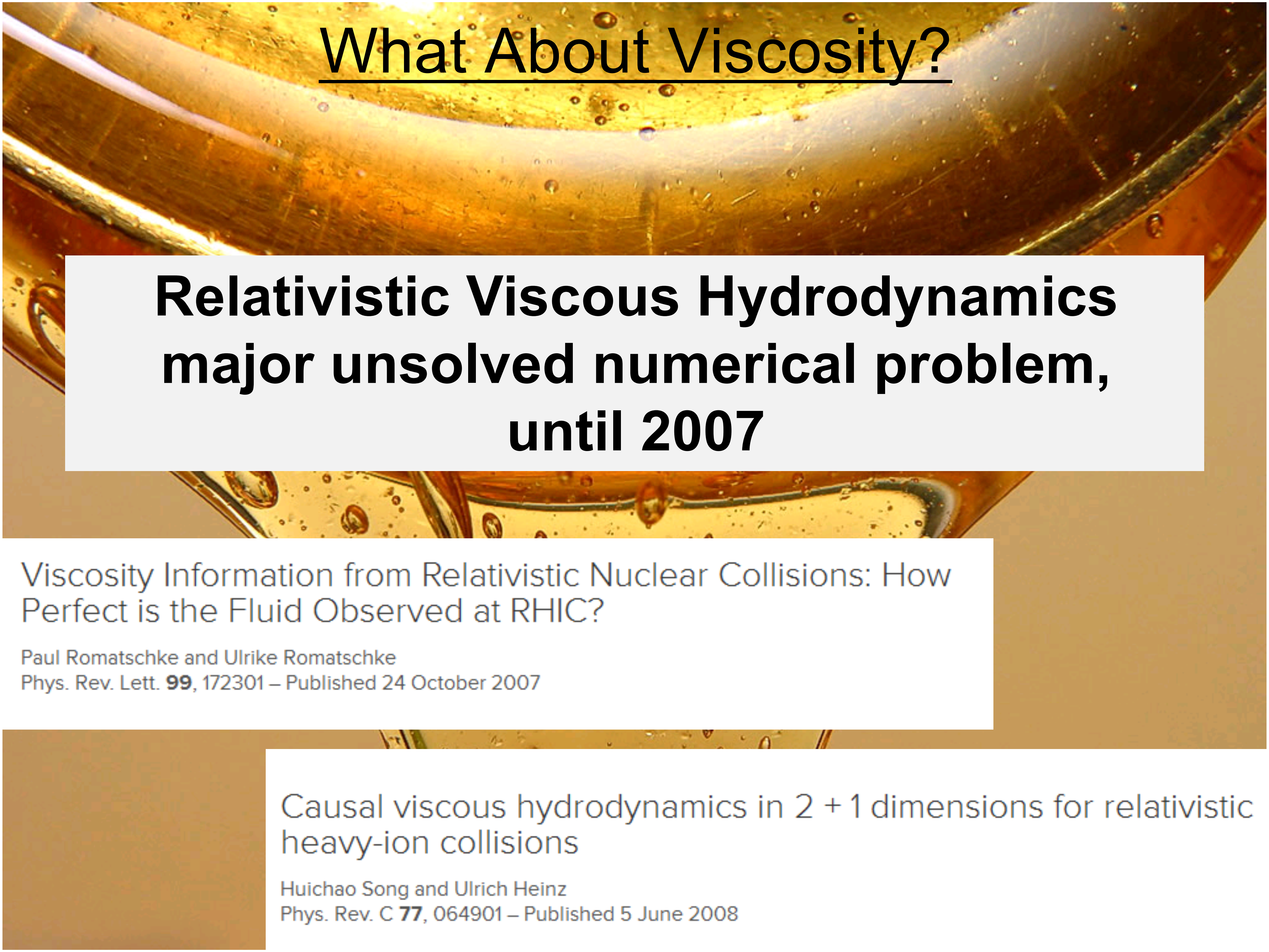
Perfect Fluidity Discovery - 2005

Agreement of ideal hydrodynamics with experimental data.





Heavier particles get a larger momentum boost from the fluid velocity and so heavier hadron v_2 pattern shifted to higher p_T.



What About Viscosity?

Relativistic Viscous Hydrodynamics major unsolved numerical problem, until 2007

Viscosity Information from Relativistic Nuclear Collisions: How Perfect is the Fluid Observed at RHIC?

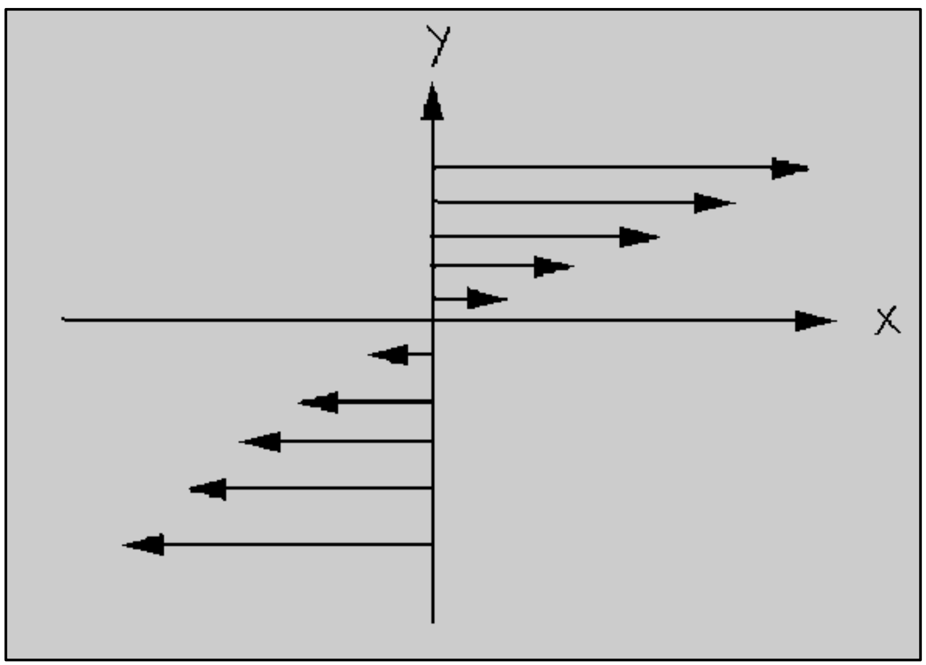
Paul Romatschke and Ulrike Romatschke
Phys. Rev. Lett. **99**, 172301 – Published 24 October 2007

Causal viscous hydrodynamics in 2 + 1 dimensions for relativistic heavy-ion collisions

Huichao Song and Ulrich Heinz
Phys. Rev. C **77**, 064901 – Published 5 June 2008

Shear Viscosity

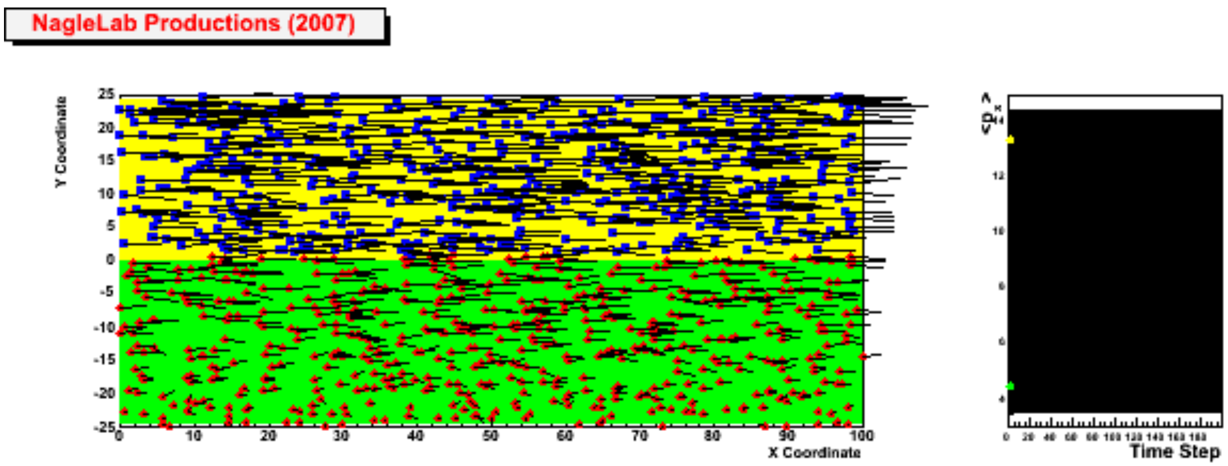
$$\frac{F_x}{A} = \qquad \frac{v_x}{y}$$



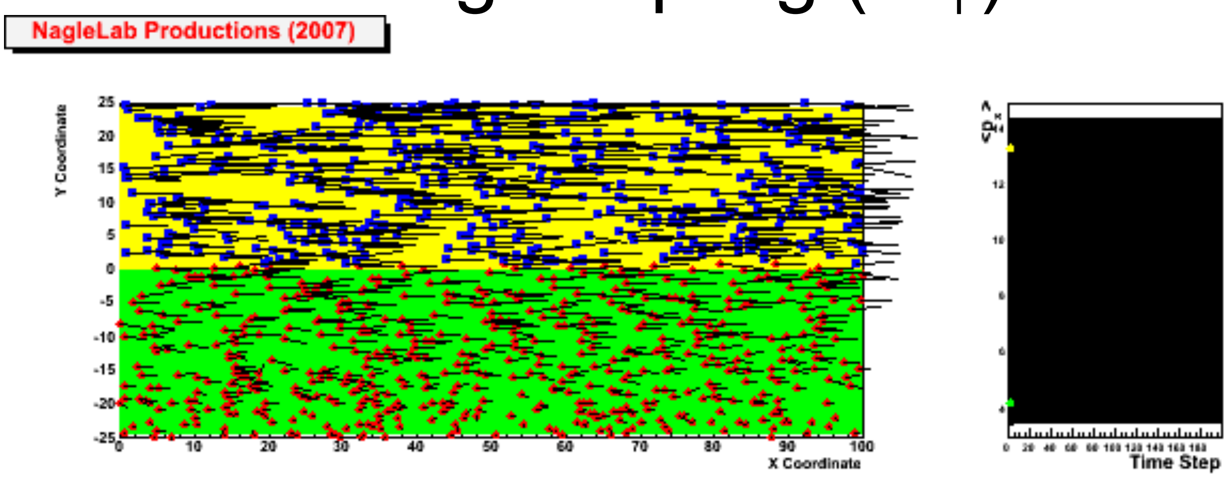
Viscosity Review

Honey – viscosity decreases at higher temperatures
viscosity increases with stronger coupling

Weak coupling (σ=0)



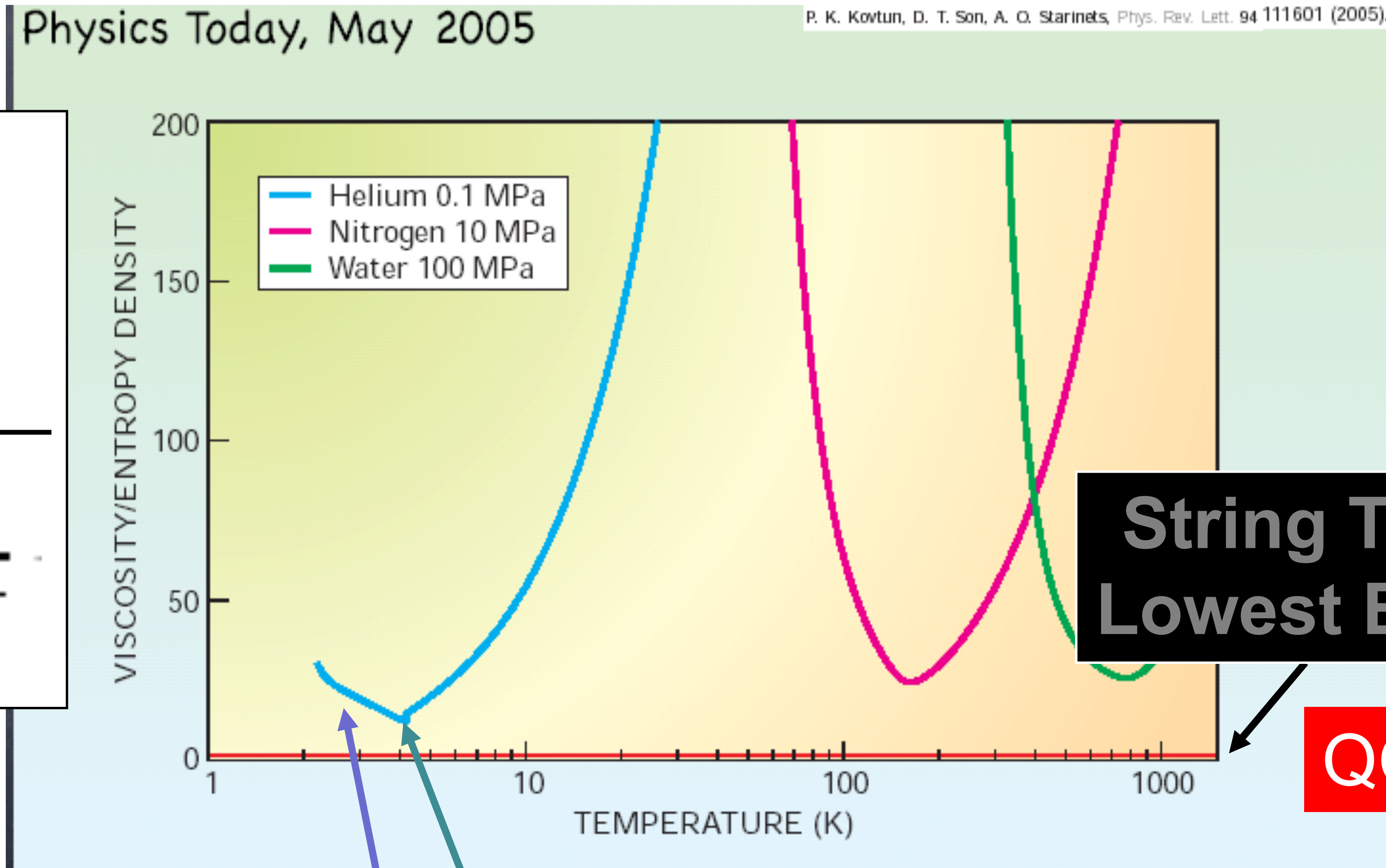
Strong coupling (σ ↑)



Inhibited diffusion
↓
Small viscosity
↓
Perfect fluid
↓
Strong Coupled QGP
(i.e. sQGP)

What is η/s for the Quark-Gluon Plasma

$$\frac{\eta / s}{1 / 4\pi}$$



String Theory Lowest Bound!

QGP?

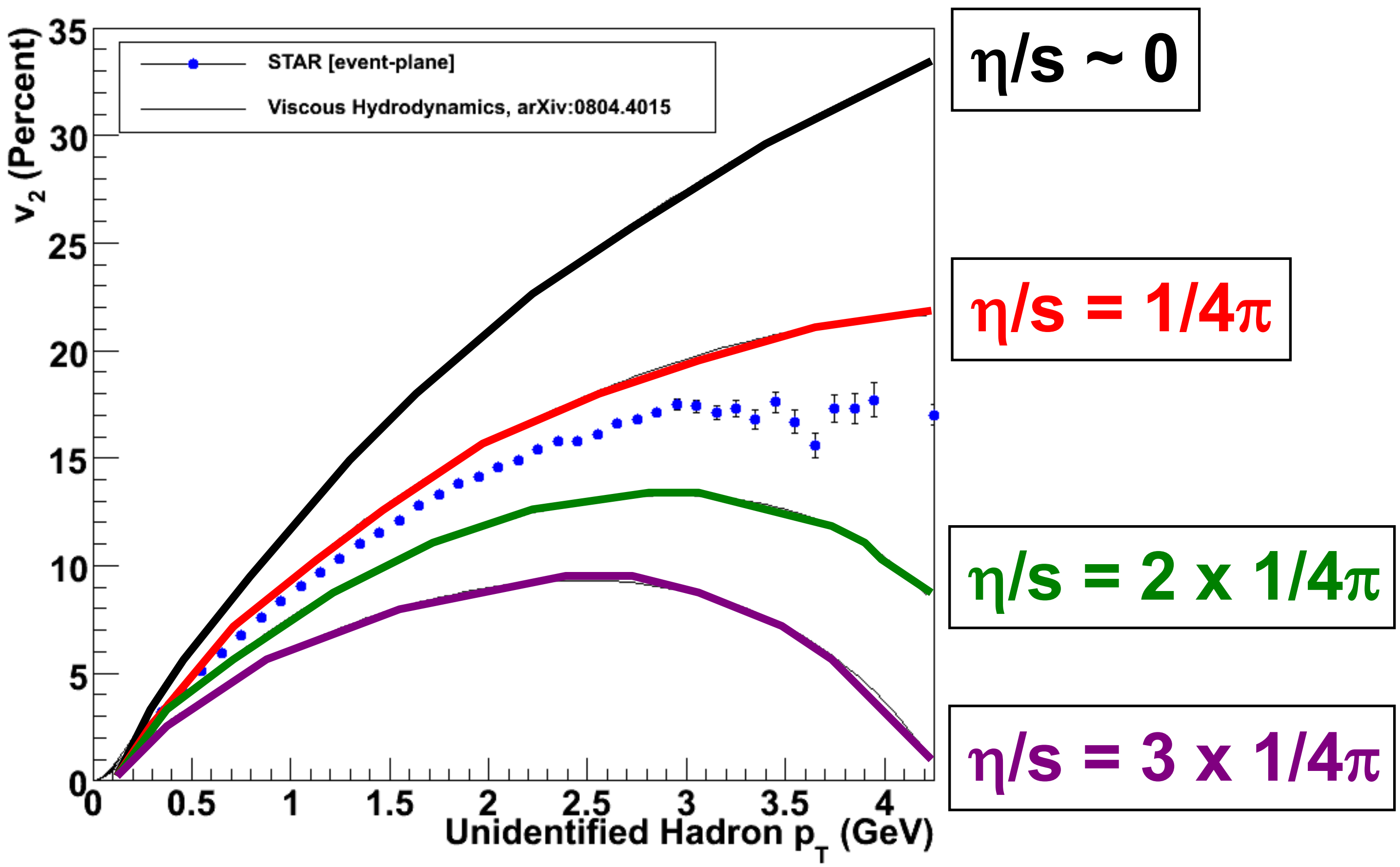
Gas-Liquid Phase Transition

Superfluidity Transition

How to Quantify QGP η/s?

Relativistic viscous hydrodynamics compared to data

Luzum, Romatschke, Phys. Rev. C78, 034915 (2008)

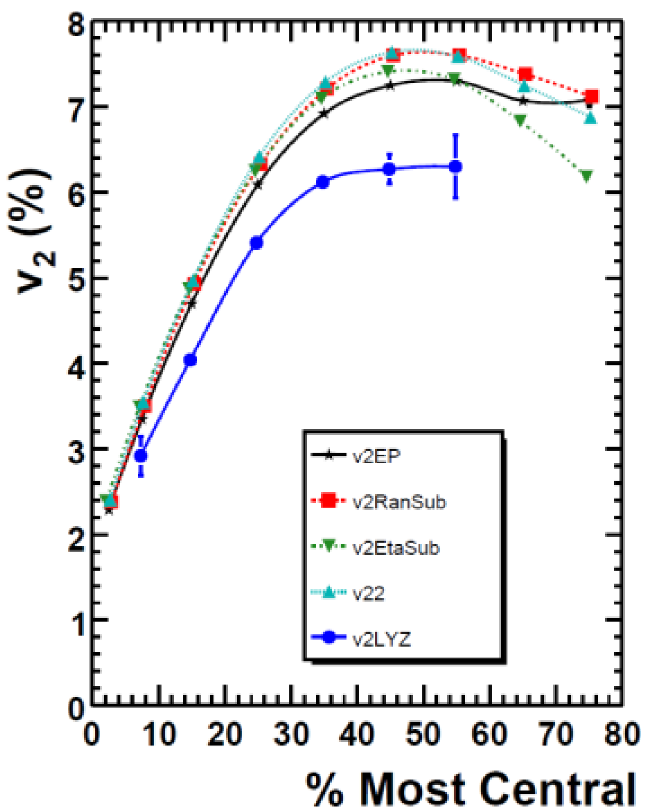


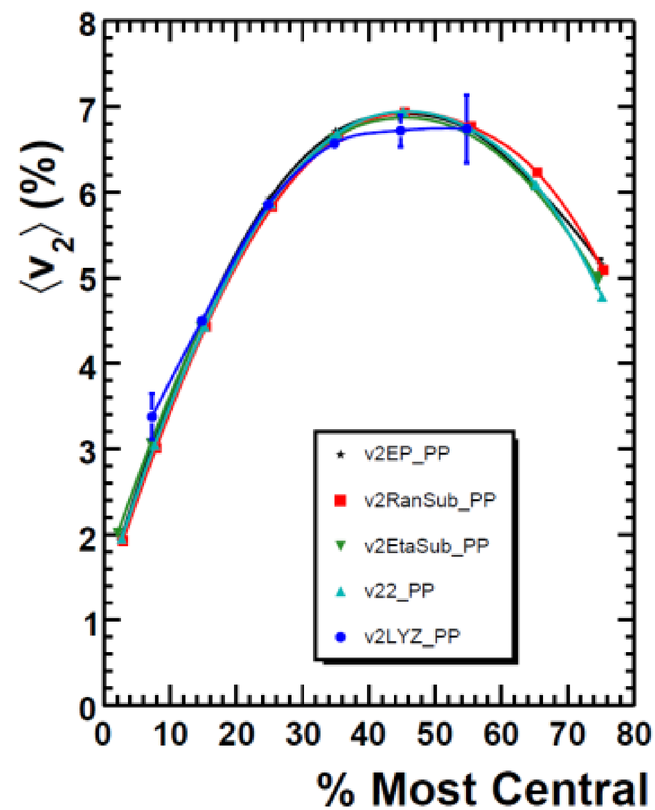
$$\frac{\ }{s} \Big/ \frac{1}{4} = 1.3 \pm 1.3\,(\text{theory}) \pm 1.0\,(\text{experiment})$$

What dominates the uncertainty?

$$\frac{}{s} \Big/ \frac{1}{4} = 1.3 \pm 1.3\,(\text{theory}) \pm 1.0\,(\text{experiment})$$

At the time, different experimental flow methods gave different v_2 results. Now these differences are understood from non-flow contributions and fluctuations.



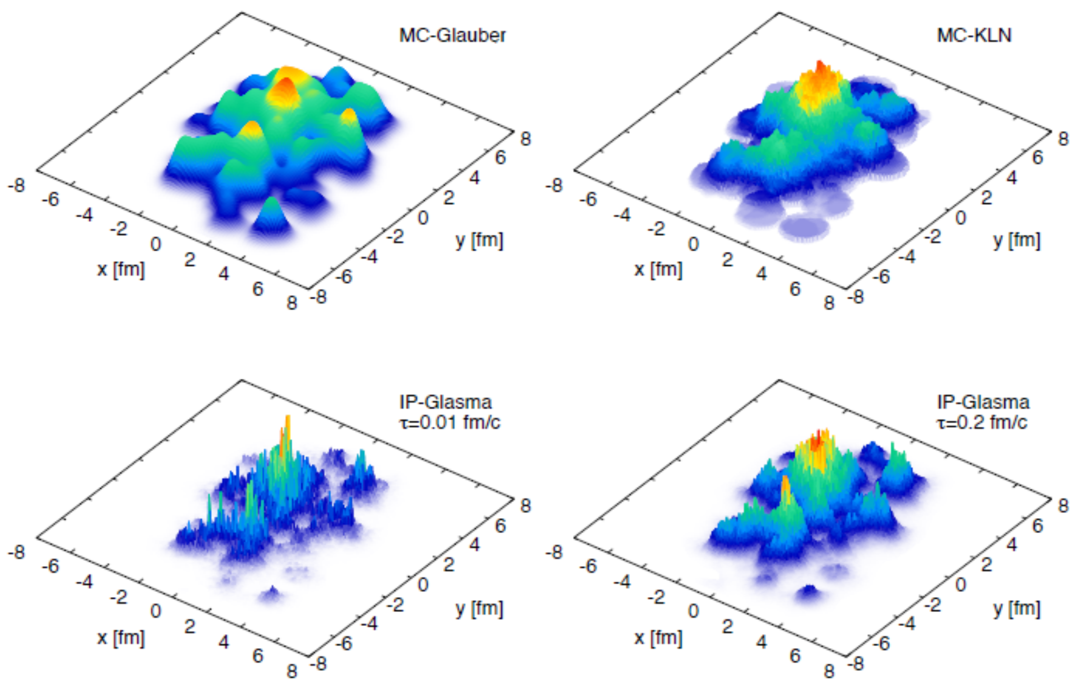


What dominates the uncertainty?

$$\frac{\quad}{s} \Big/ \frac{1}{4} = 1.3 \pm 1.3\,(\text{theory}) \pm 1.0\,(\text{experiment})$$

The v_2 you get out is directly related to the ε_2 of the initial geometry you put in.

Different initial geometry models yield 20% ε_2 differences resulting in 100% η/s differences.



Different models of the initial geometry.

Uncertainty by considering model A and model B.

Systematic Uncertainties

Systematic Errors

Joel Heinrich[1] and Louis Lyons[2]

[1]Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104; email: heinrich@hep.upenn.edu

[2]Department of Physics, University of Oxford, Oxford OX1 3RH, United Kingdom; email: l.lyons@physics.ox.ac.uk

Not much help in many practical situations…

Example: Two model inputs give different results.

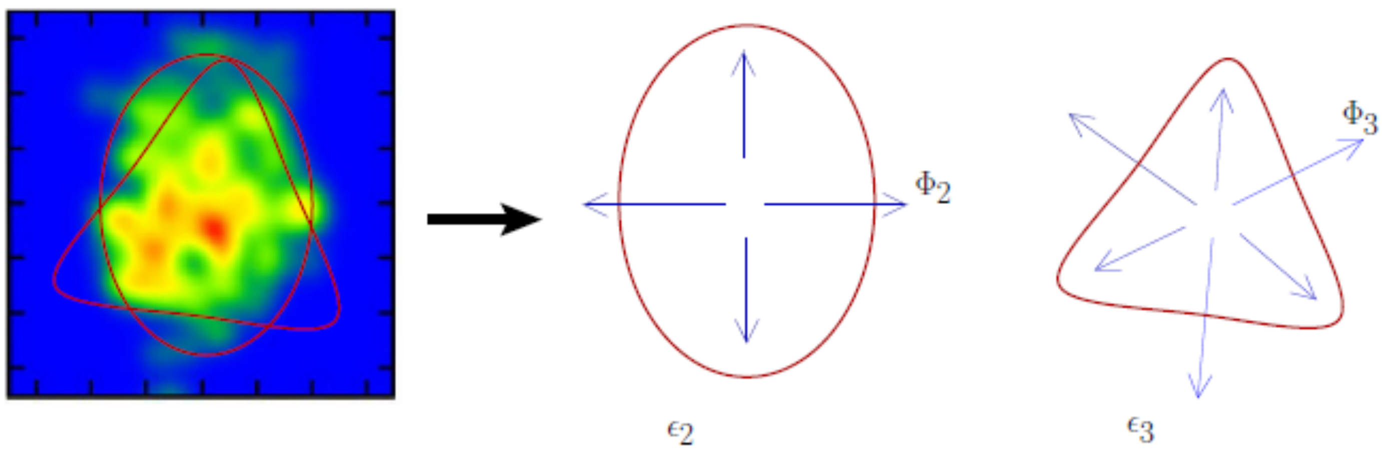
Uncertainty = 1 RMS = Difference / sqrt(12)
= Difference / 2
= Cannot determine

Alver and Roland Revolution 2010

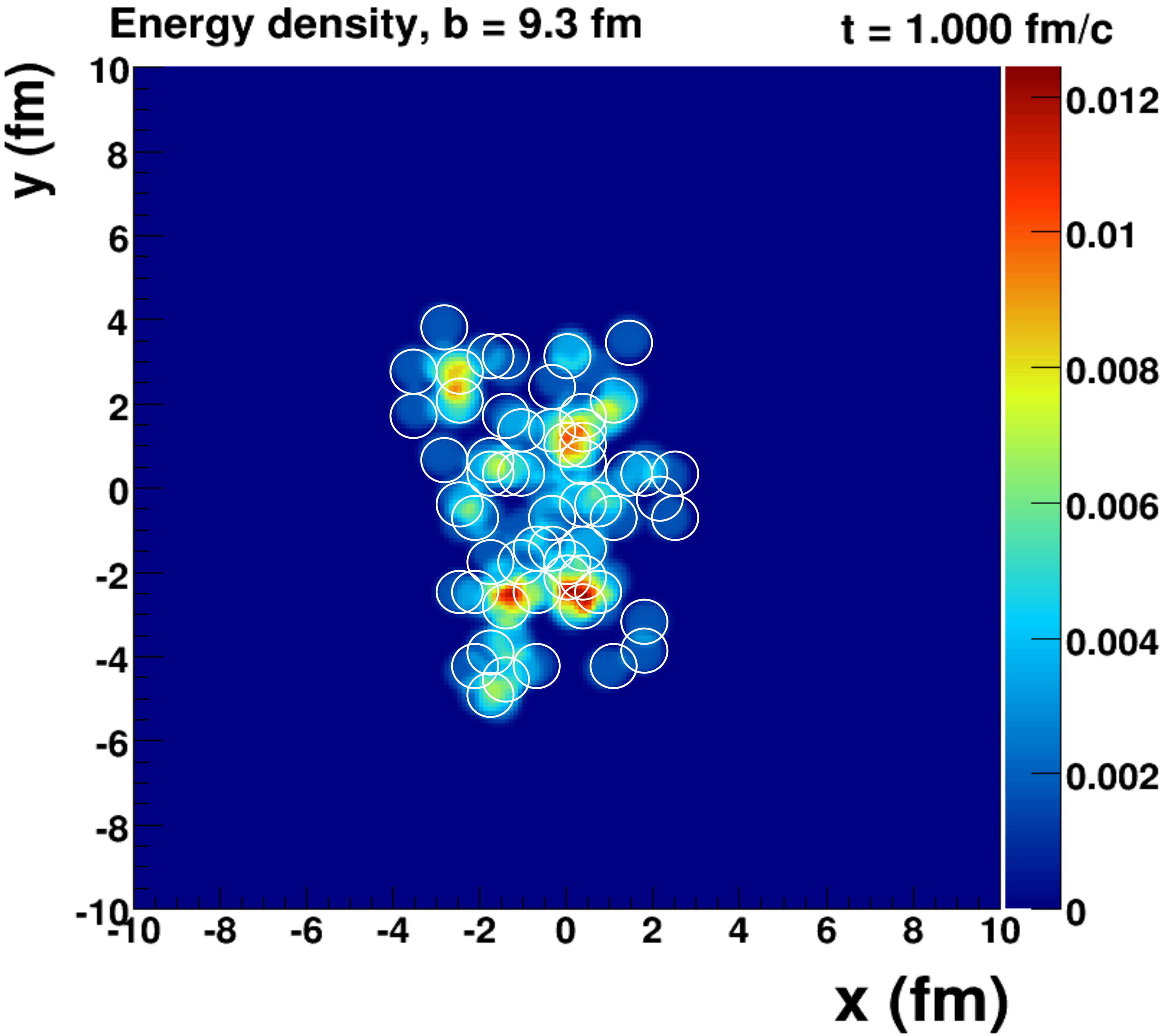
Collision-geometry fluctuations and triangular flow in heavy-ion collisions

B. Alver and G. Roland
Phys. Rev. C **81**, 054905 – Published 21 May 2010; Erratum Phys. Rev. C **82**, 039903 (2010)

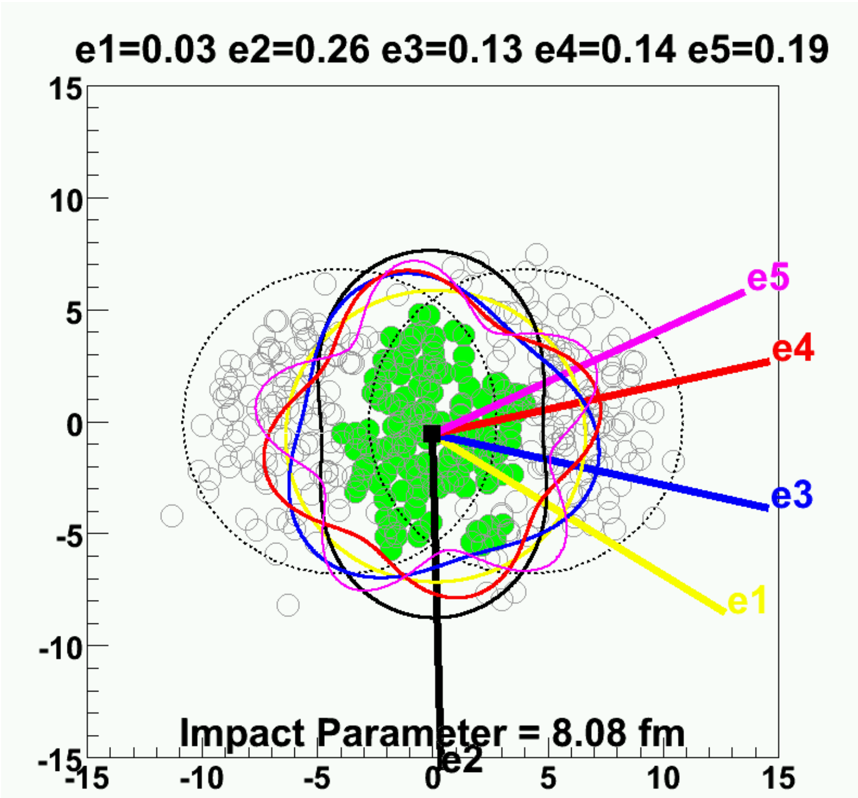
http://journals.aps.org/prc/abstract/10.1103/PhysRevC.81.054905



Fluctuations in geometry yield not only elliptical shapes, but triangular, quadrangular, etc.



Romatschke=viscous hydrodynamics, McCumber=lumpy conditions + animation



$\varepsilon_2 \approx 2 \times \varepsilon_3 \approx 2 \times \varepsilon_4$

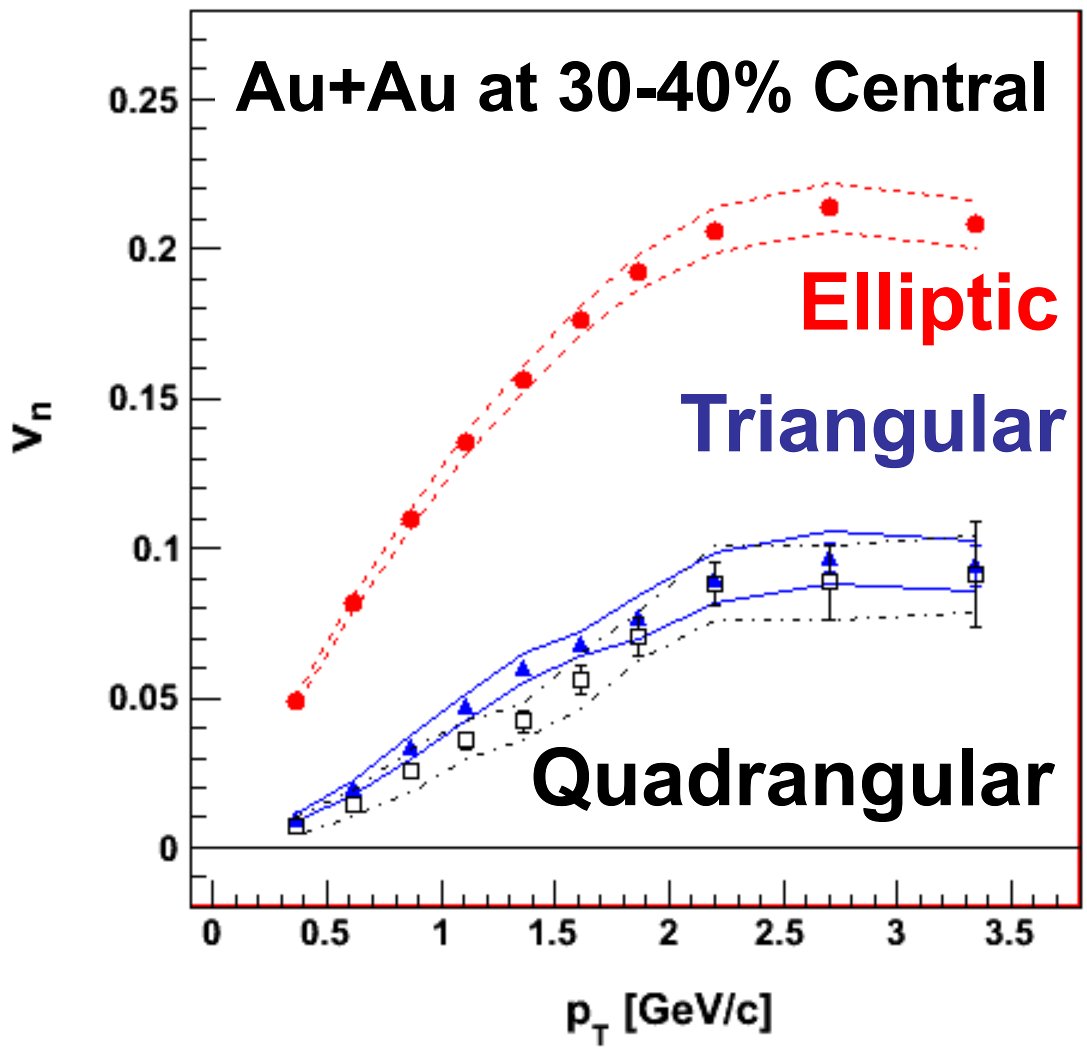
Early geometric features survive through QGP evolution because of very small dissipation

PHENIX Experiment

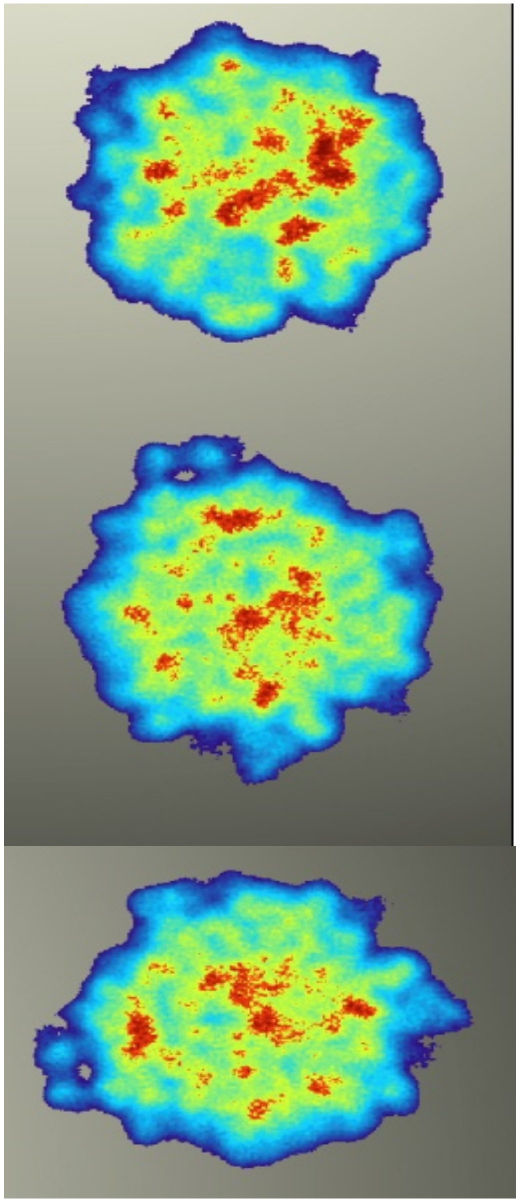
$v_2\{\Phi_2\ \text{forw.}\eta\}$

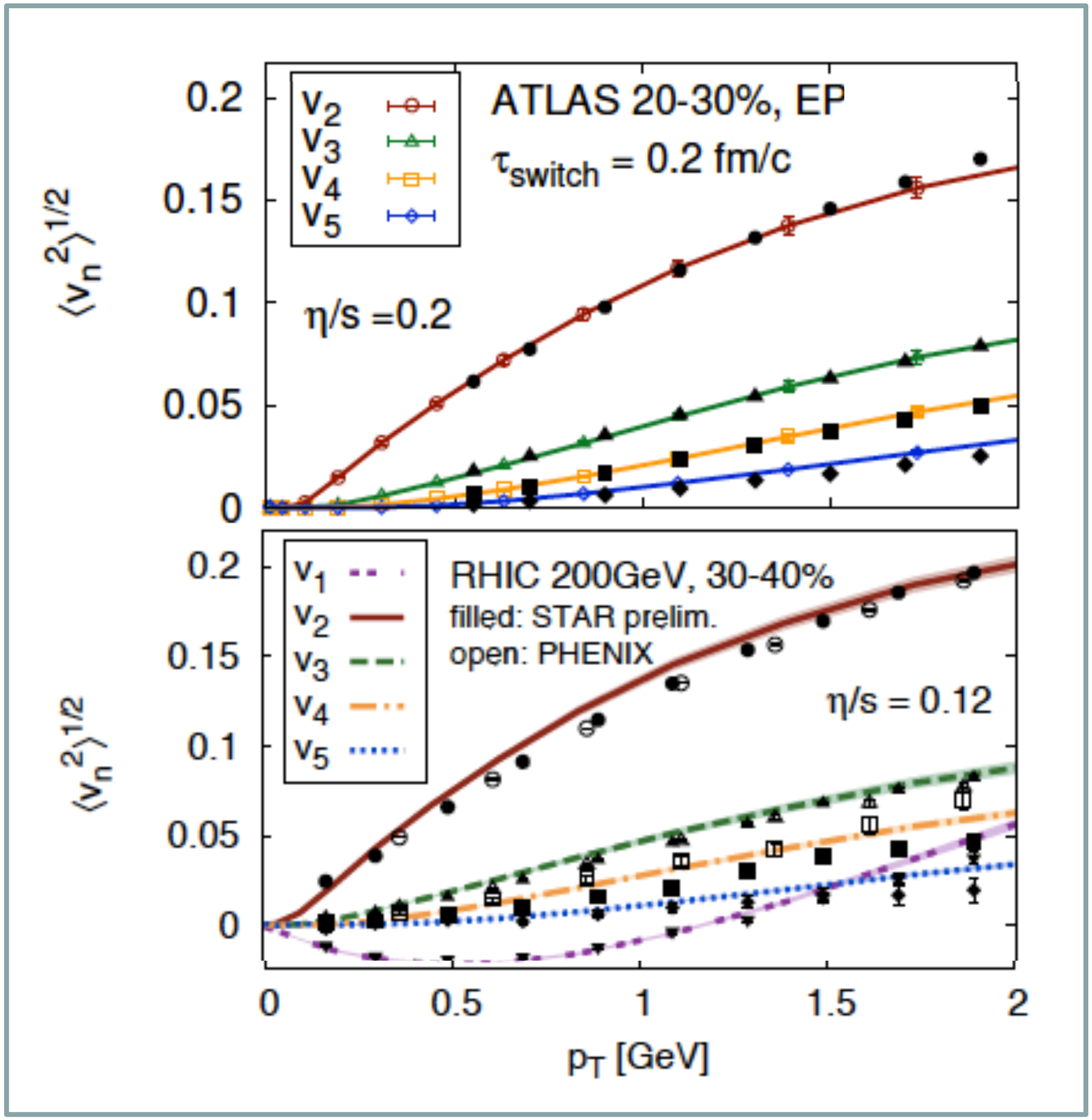
$v_3\{\Phi_3\ \text{forw.}\eta\}$

$v_4\{\Phi_4\ \text{forw.}\eta\}$



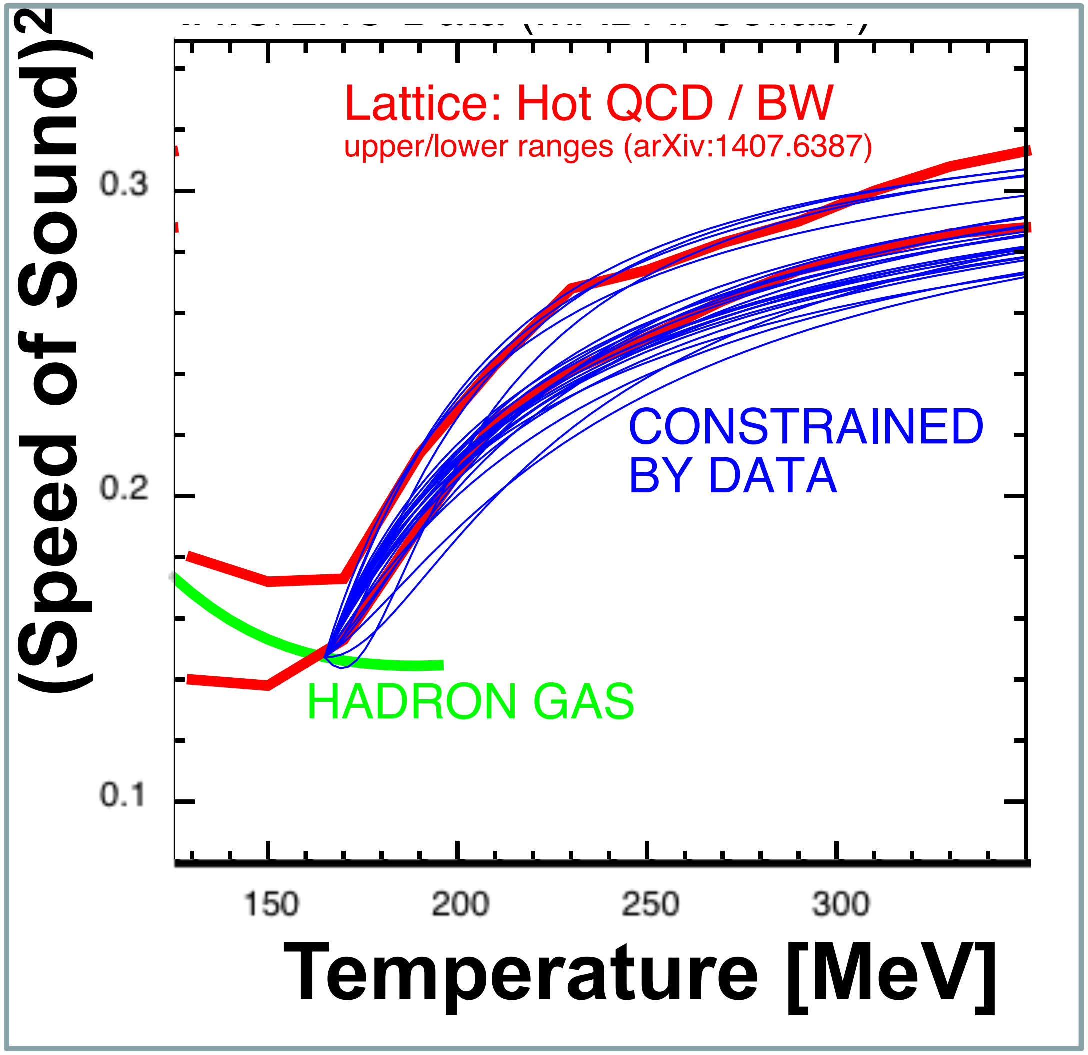
Detailed Fingerprint of Early Time





Calculation from Bjoern Schenke

Global Constraint Analysis

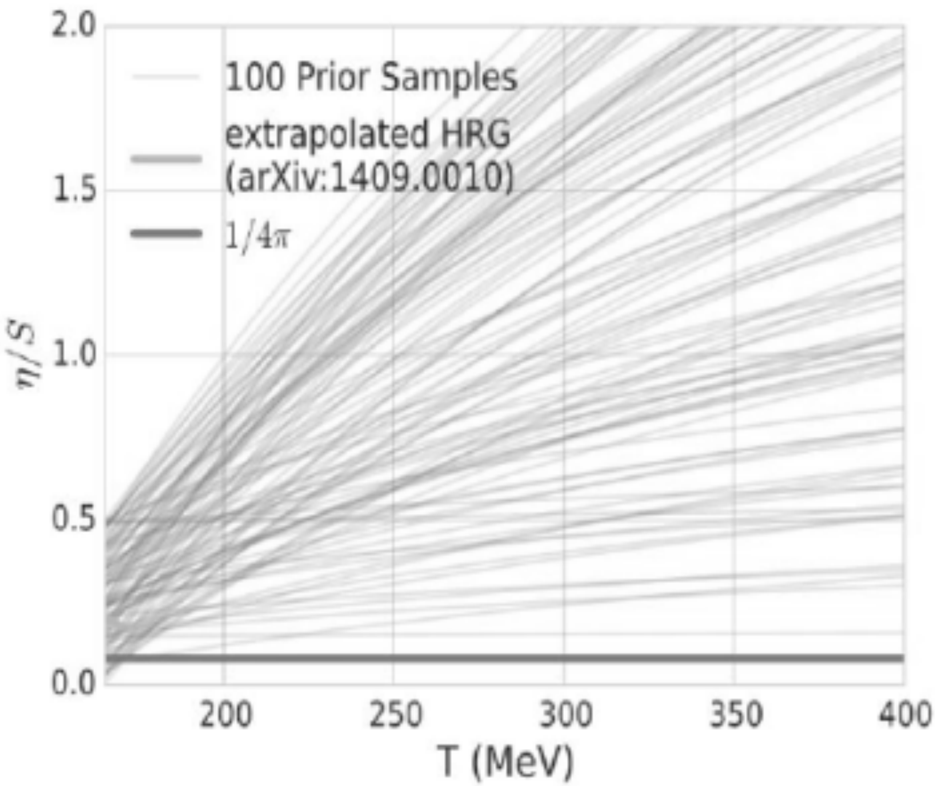


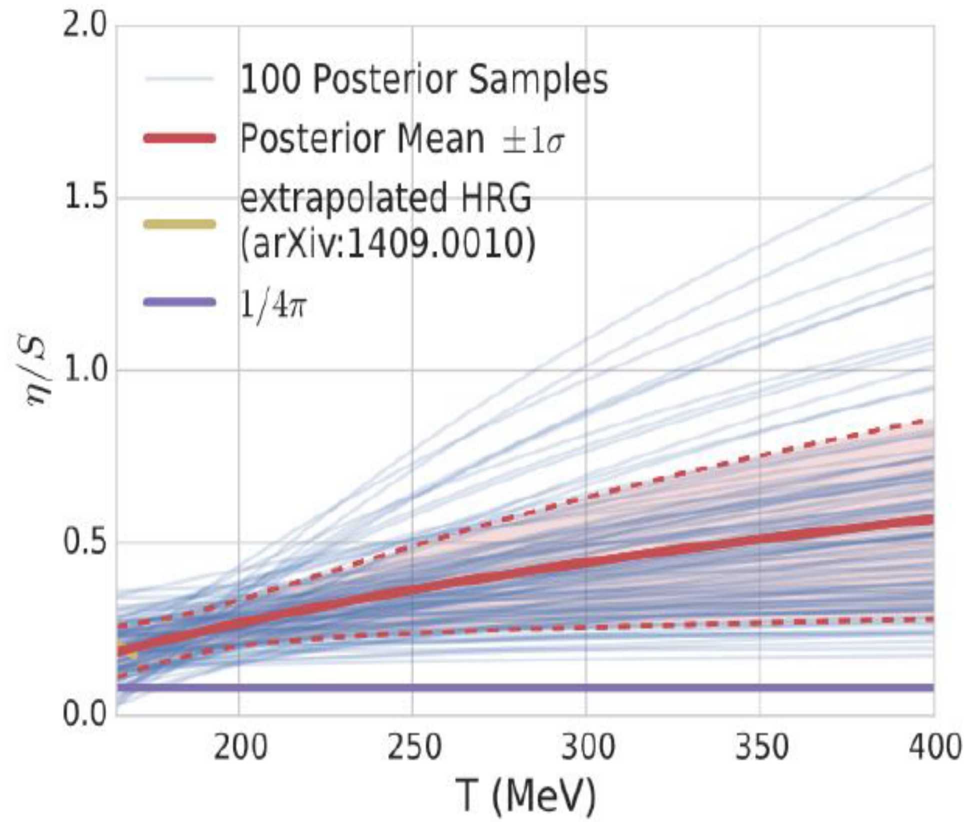
Global constraint methods using Bayesian sampling as done in Climate Modeling for example.

Includes particle spectra, elliptic flow, two-particle quantum correlations, …

Experimental confirmation of Lattice QCD Equation of State

Global Constraint Analysis





Expect η/s to increase at higher temperatures
even just from running of α_s

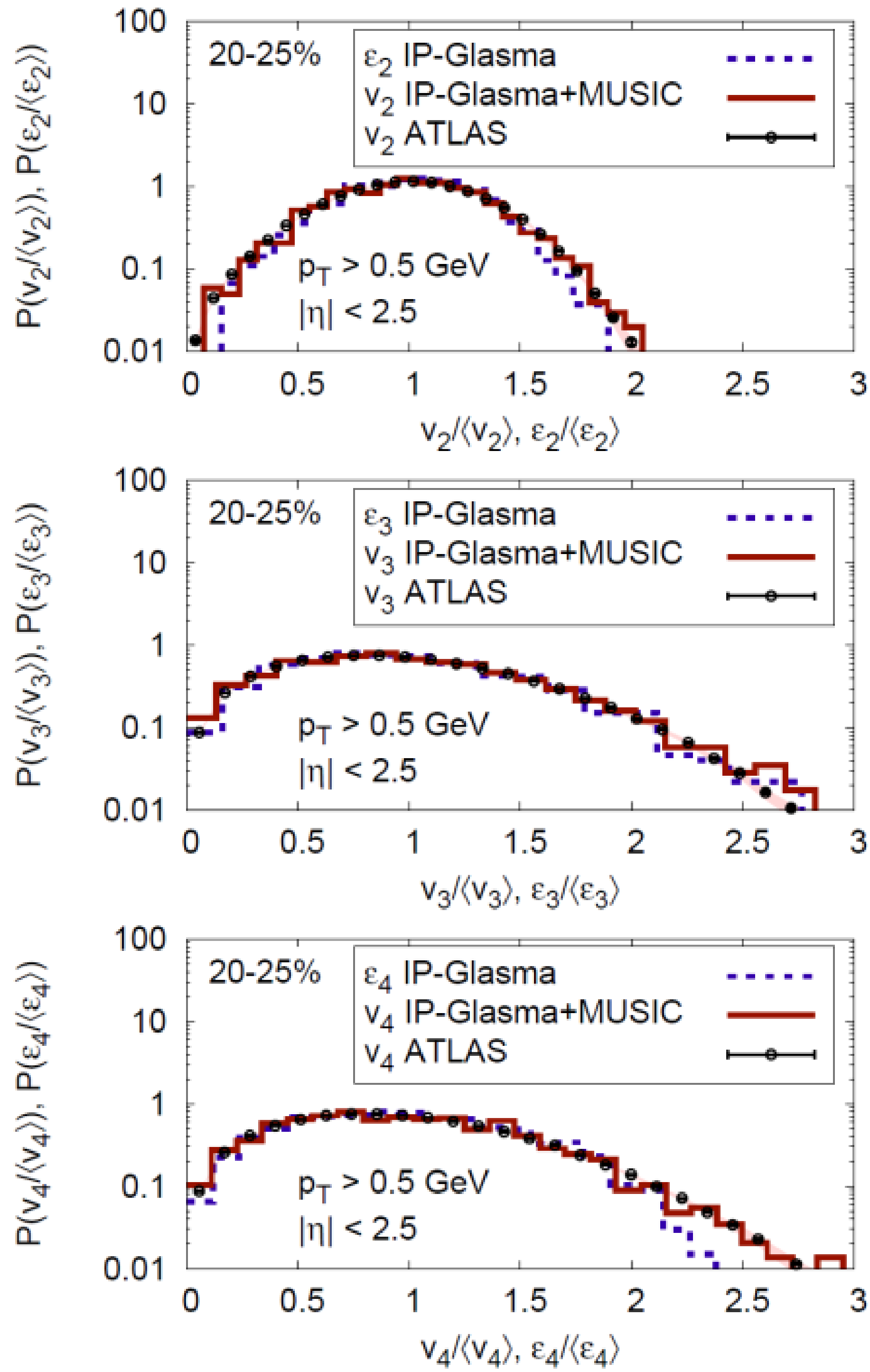
Key lesson about when and when not to include scenarios
(story of High Voltage Power Lines)…

Power of the LHC

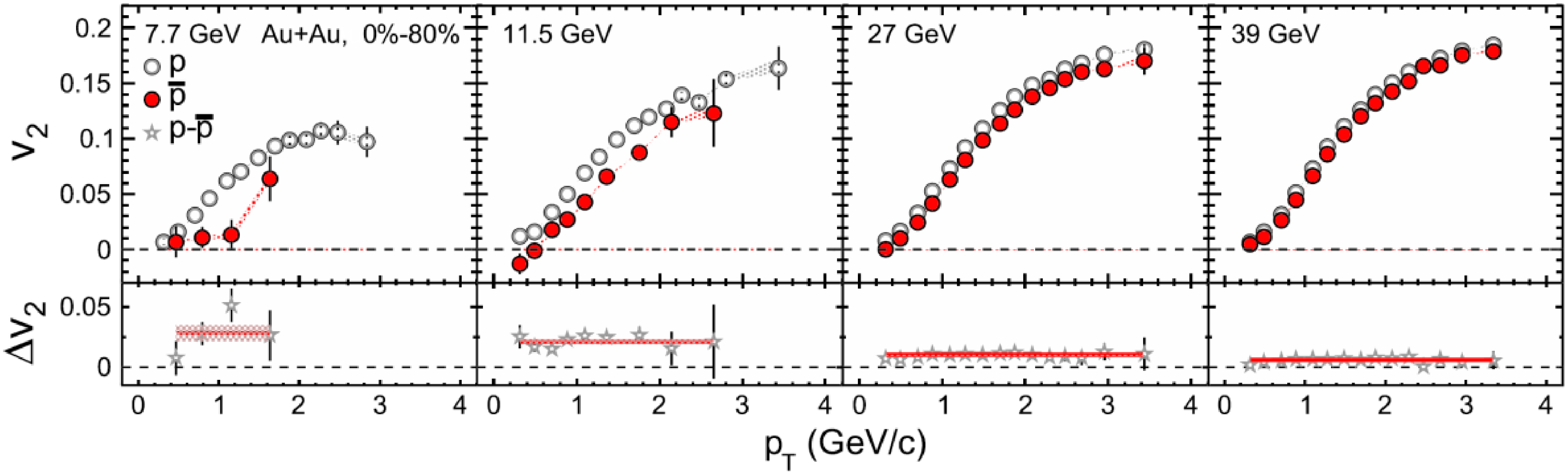
Particle production $dN/d\eta$ approximately 2.5x higher

Also ability to measure over 5 units (compare to PHENIX 0.7 and STAR 2.0)

Order of magnitude more particles per event, opens ability to measure v_2 event-by-event!



Power of RHIC – changing the energy



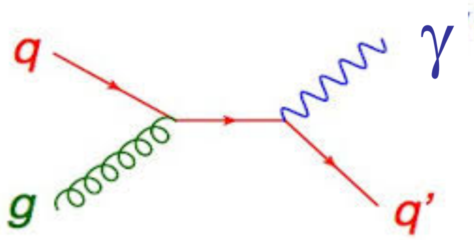
Flow of protons decreases a little at lower energies.

Anti-protons decrease much more from annihilation.

Lower collision energy, more net baryons piling up.
Larger chemical potential.
Possible change to 1st order transition!

Direct Photon Puzzle

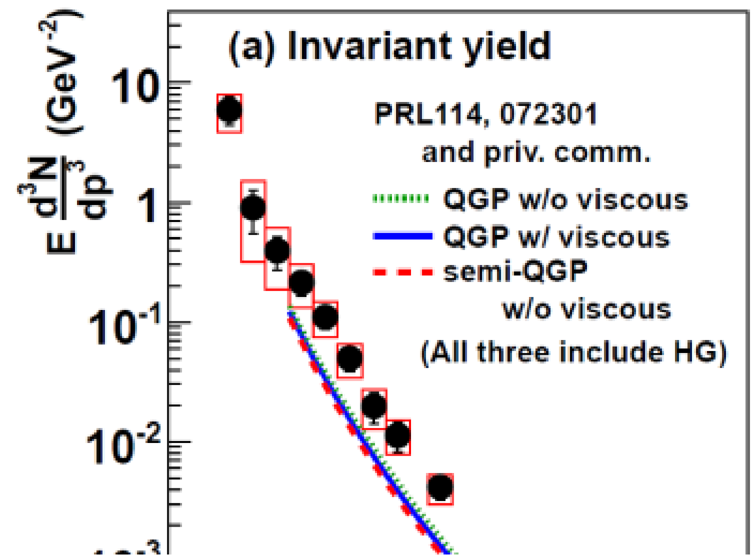
Quarks/Gluons in QGP scatter to create photons

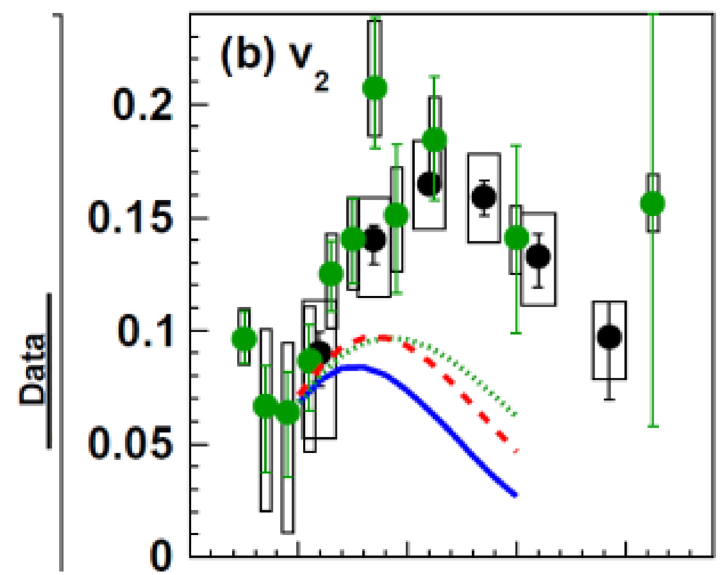


Not Black-Body because photons are not in equilibrium.
They escape giving information on QGP interior.

Hydrodynamics has local temperature of q/g and thus one can calculate the photon emission, then boost by fluid velocity.

Predict too few photons





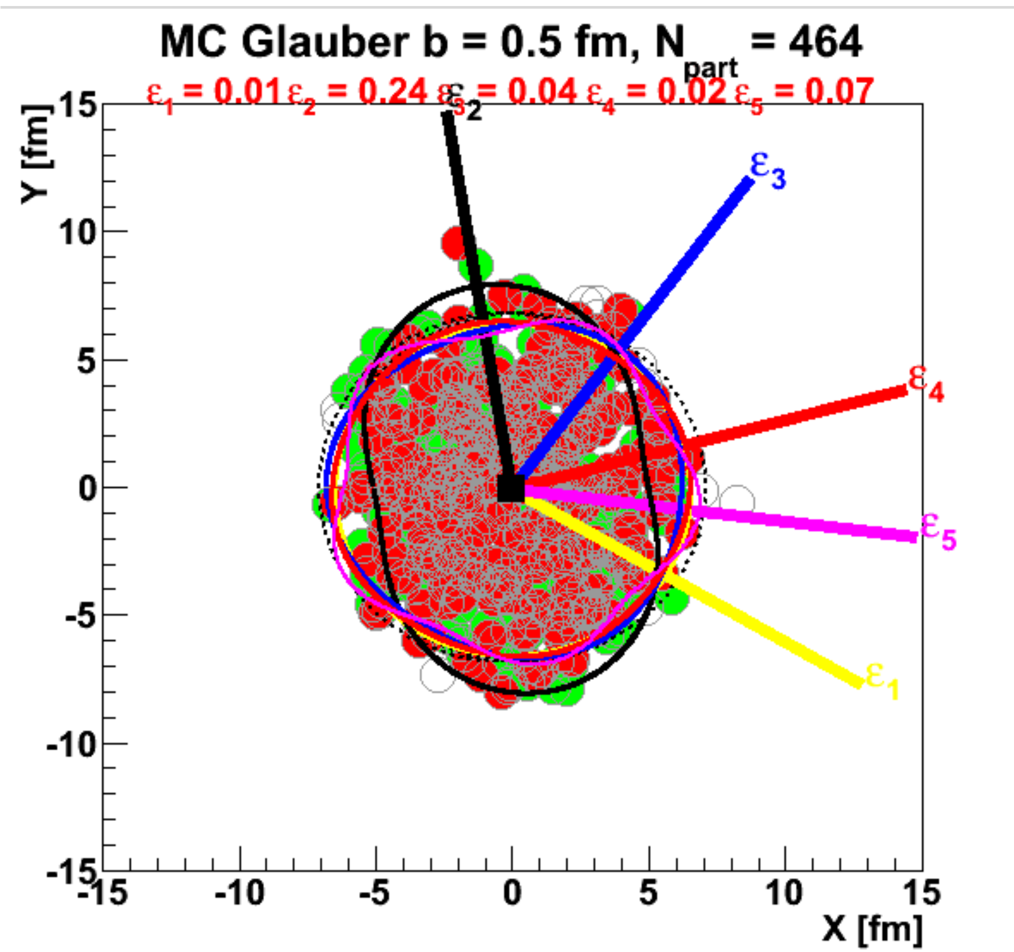
Ultra-Central Puzzle

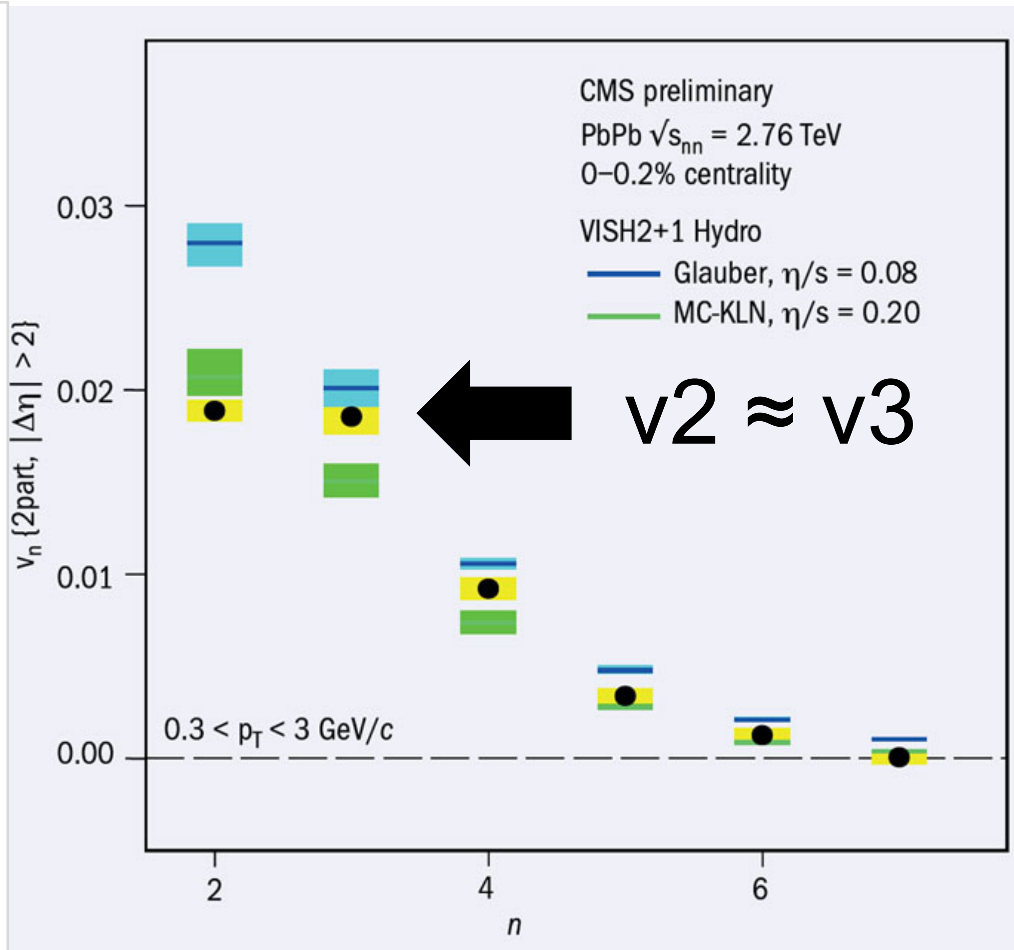
Ultra-Central A+A geometry driven by fluctuations

$\varepsilon_2 = \varepsilon_3 = \varepsilon_4 = \varepsilon_5$ (good exercise to check)

Hydrodynamics always damps finer structures

$v_2 > v_3 > v_4 > v_5$





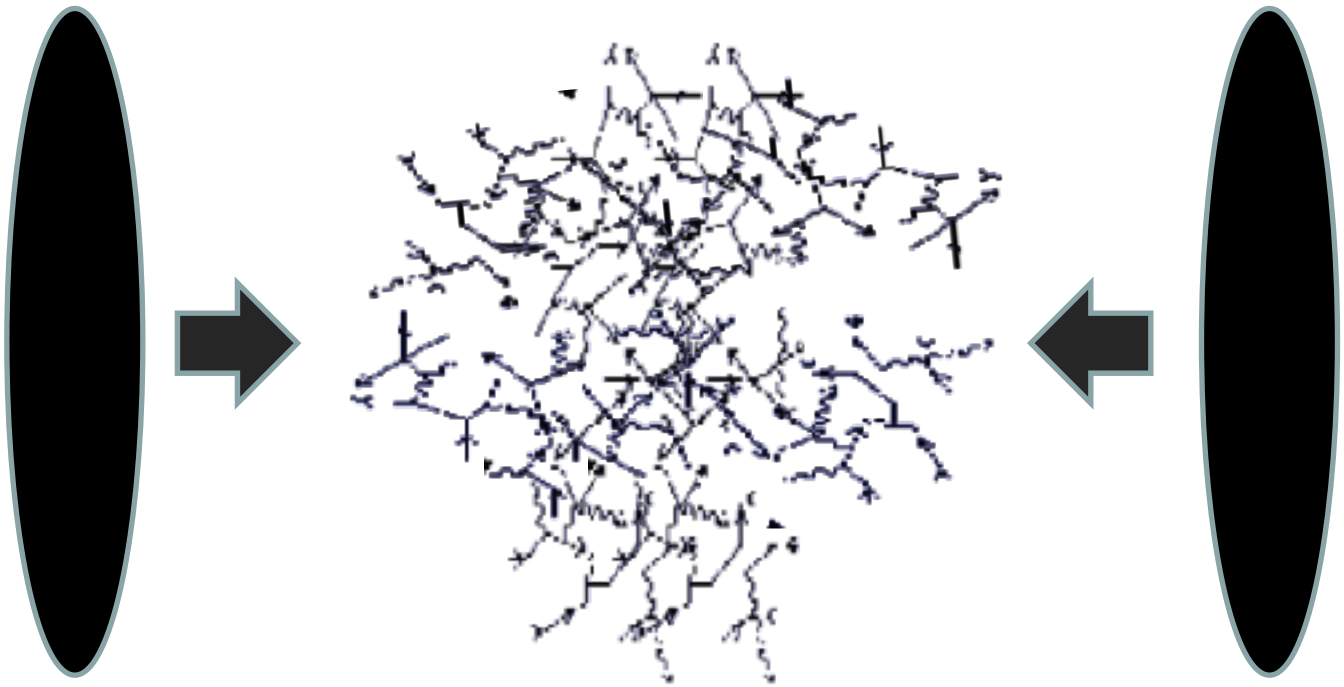
The Biggest Puzzle

In the last couple of years, many of these signatures of collectivity are now seen in proton+nucleus collisions at RHIC and the LHC, and now also in proton+proton collisions at the LHC.

The "Smallest System"
Biggest Puzzle

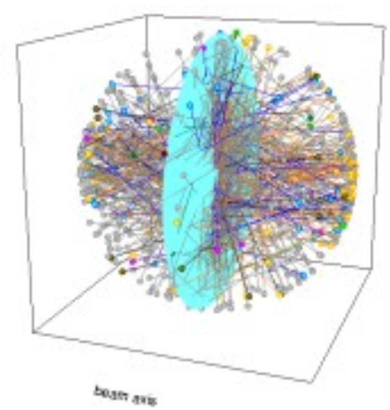
Alternatives

Alternatives to the Hydrodynamic Paradigm



Kinetic theory – well defined particles

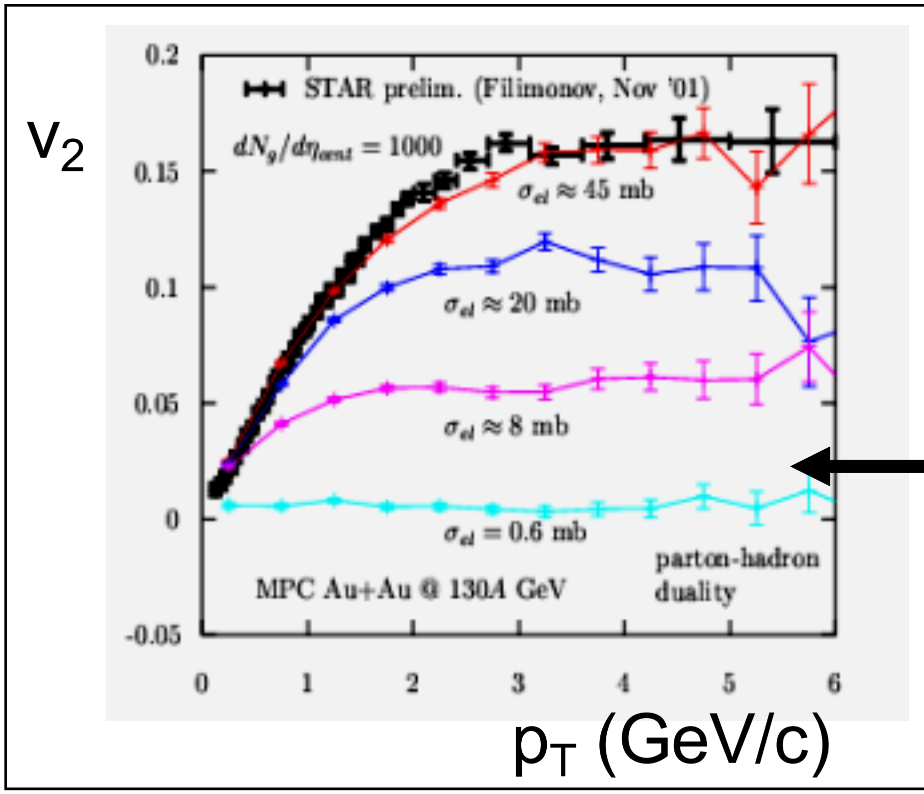
Parton cascade programs



Weak Coupled Parton Cascade

What interactions can lead to equilibration in < 1 fm/c?

Perturbative calculations of gluon scattering lead to long equilibration times (> 2.6 fm/c) and small v_2.

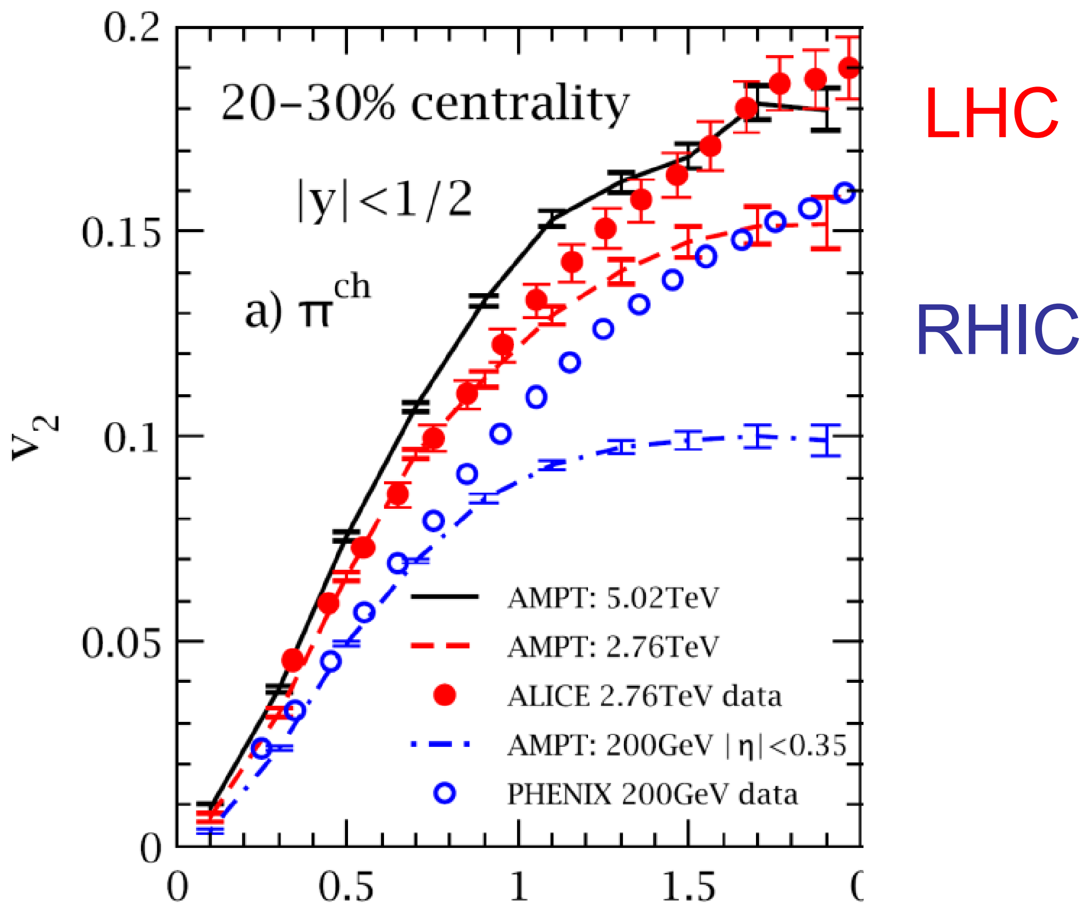


R. Baier, A.H. Mueller, D. Schiff, D. Son, Phys. Lett. B539, 46 (2002).
MPC 1.6.0, D. Molnar, M. Gyulassy, Nucl. Phys. A 697 (2002).

2-2 processes with pQCD σ = 3 mb

Early conclusion – kinetic theory will not work.

AMPT with Zhang Parton Cascade



Parton Cascade with σ=3 mb gives reasonable agreement, particularly at LHC

Why is this different from decade earlier result?

Old: 100 hadrons from 100 gluons [parton-hadron duality]
New: 100 hadrons from 200 (anti) quarks [coalescence]

Also, different p_T dependent formation time, hadronic rescattering afterwards – many knobs in the model

http://myweb.ecu.edu/linz/ampt/

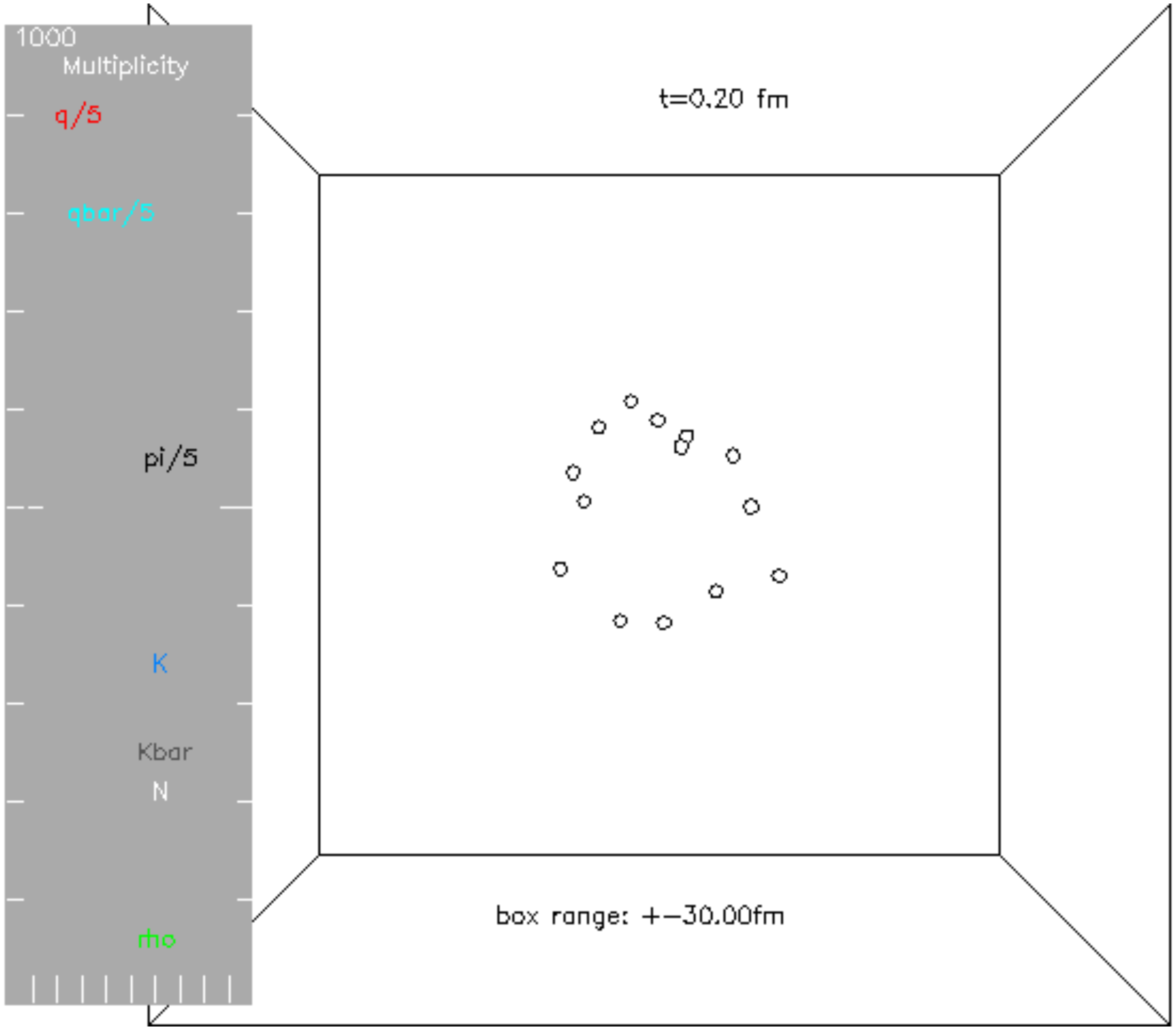
Each of the following versions contains:
the source codes, an example input file, a Makefile, a readme, a required subdirectory for storing output files, and a script to run the code.

1. ampt-v1.11-v2.11.tgz (11/2004)
2. ampt-v1.21-v2.21.tgz (10/2008)
3. ampt-v1.25t3-v2.25t3.tgz (8/2009)
4. ampt-v1.25t7-v2.25t7.zip (9/2011)
5. ampt-v1.25t7d-v2.25t7d.zip (4/2012)
6. ampt-v1.26t1-v2.26t1.zip (9/2012)
7. ampt-v1.26t4-v2.26t4.zip (8/2014)
8. ampt-v1.26t5-v2.26t5.zip (4/2015)

This readme file lists the main changes up to version v1.26t5-v2.26t5 ("t" means a version under test):

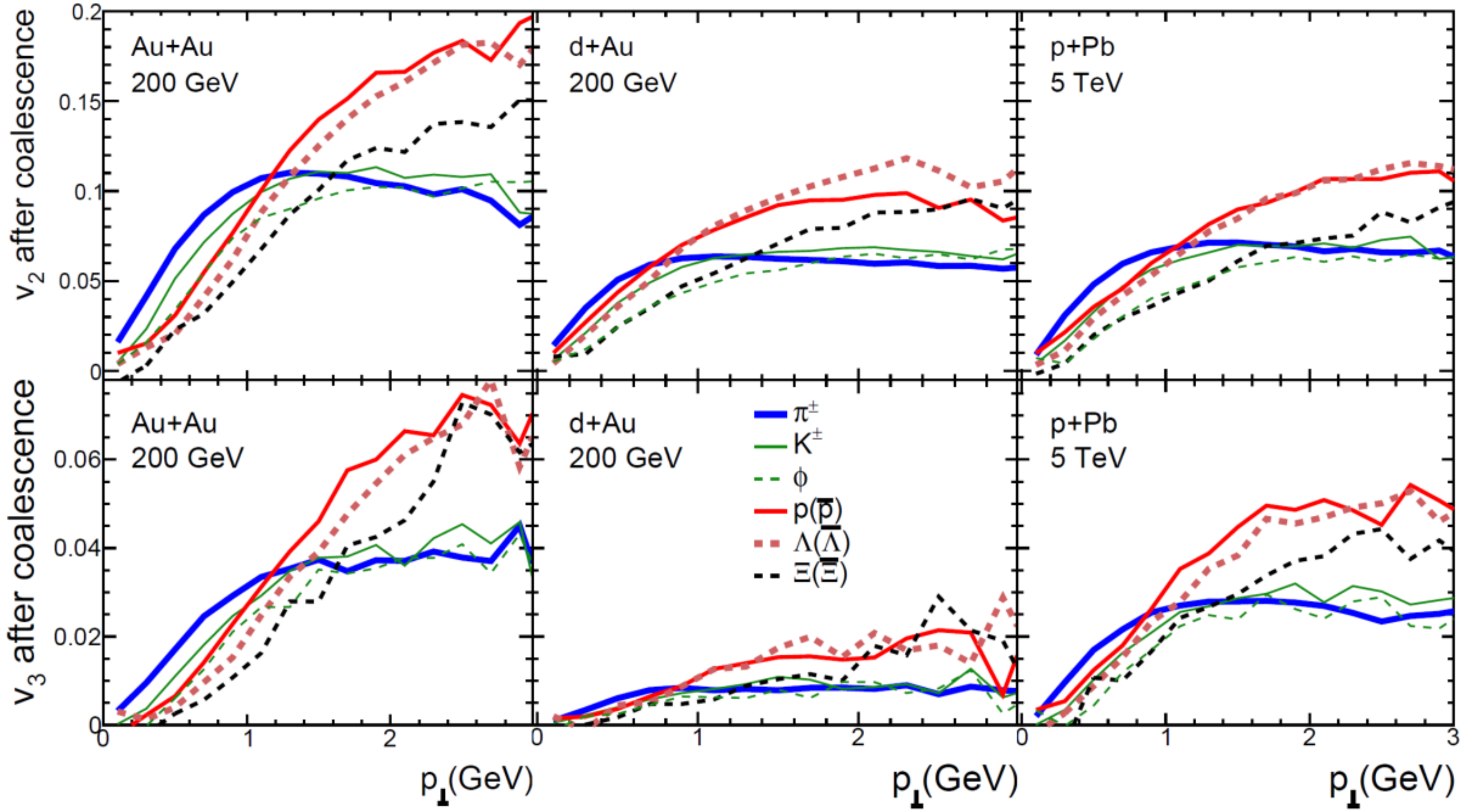
```
AMPT Users' Guide

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
4/2015 test version v1.26t5/v2.26t5:
     * Random seed for HIJING is modified in main.f, so that a different
       random seed will always lead to a different random number sequence
       (in earlier versions, an even integer leads to the same random number
       sequence as the odd integer that is bigger than it by 1).
```

AMPT with String Melting



No gluons!

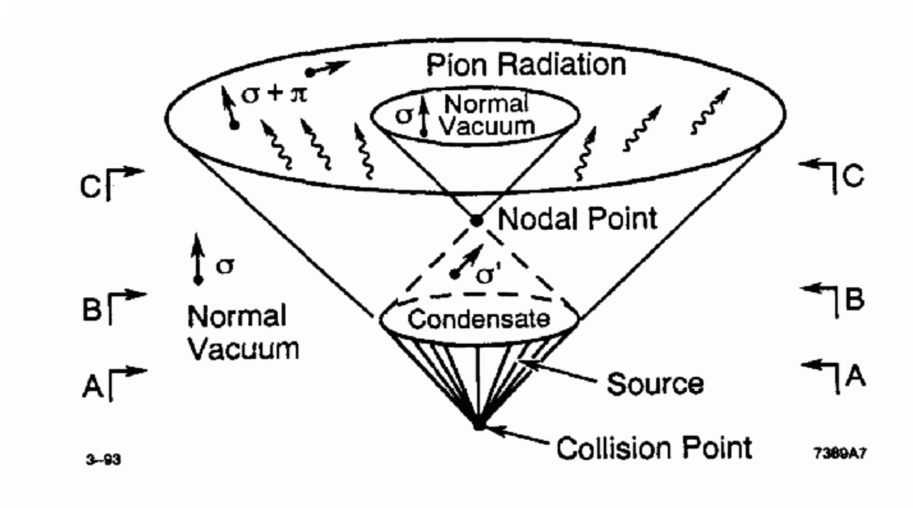
AMPT and Coalescence



Particle type flow dependence not from boost via fluid velocity, but from coalescence mechanism and hadronic re-scattering.

Small QGP

Remember your History

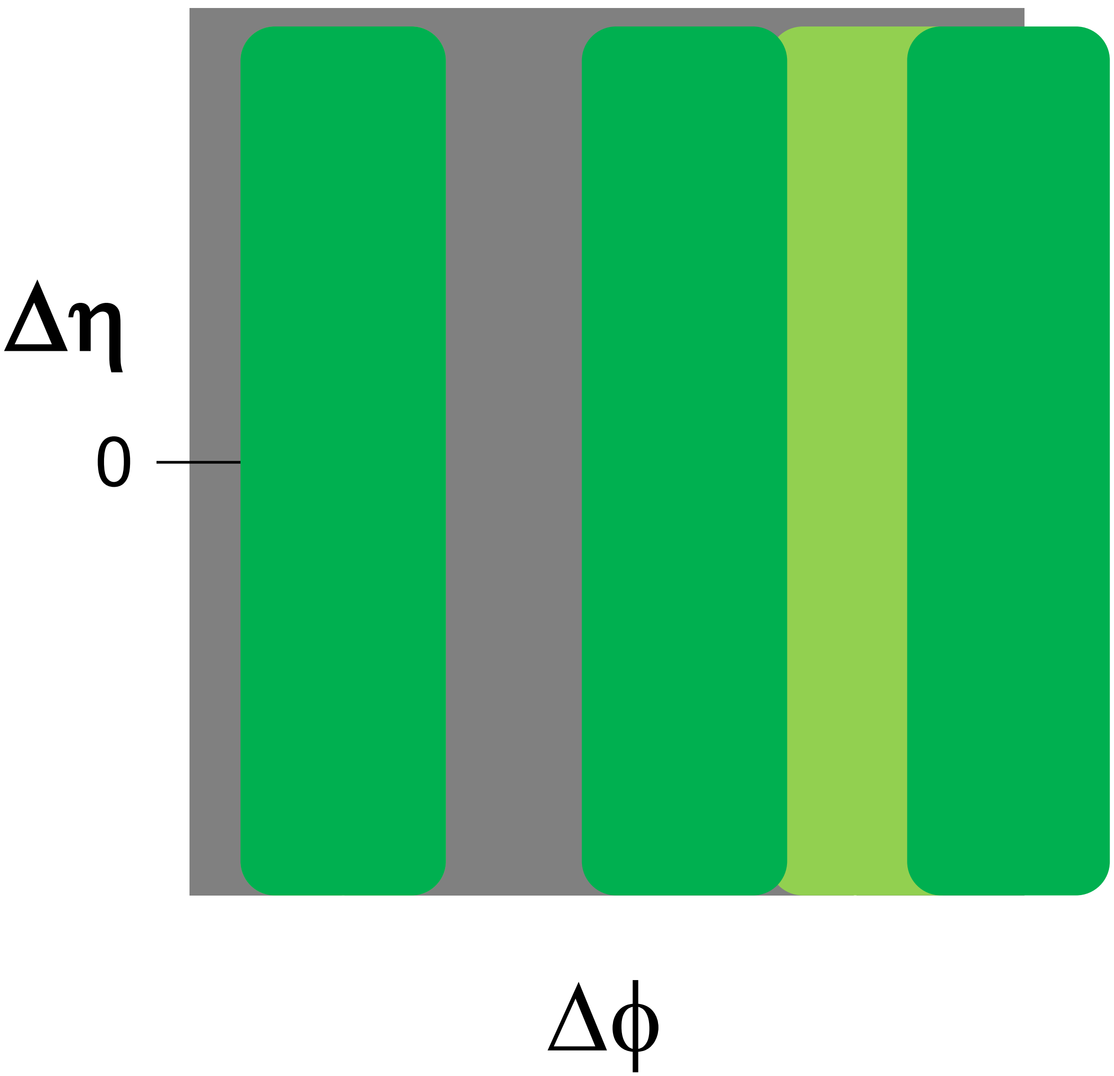


The idea about small QGP was somewhat lost, but maybe not for good scientific reasons.

No particles → think fields / disturbed vacuum

Maybe the small number of final state particles is just not relevant…

Two-Particle Correlation Basics



Jet Correlations

Same jet

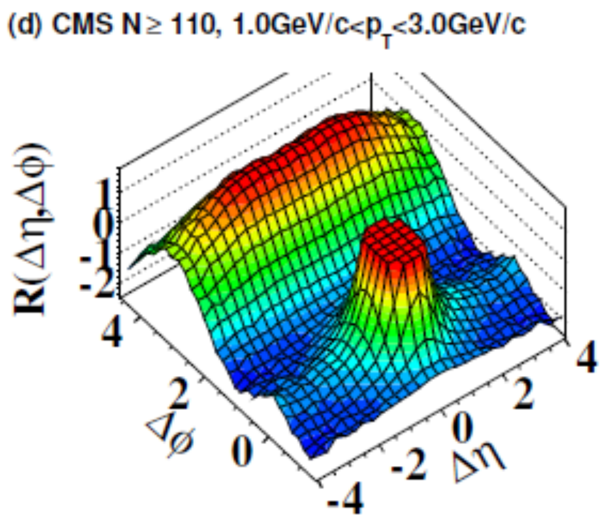
Opposing jet

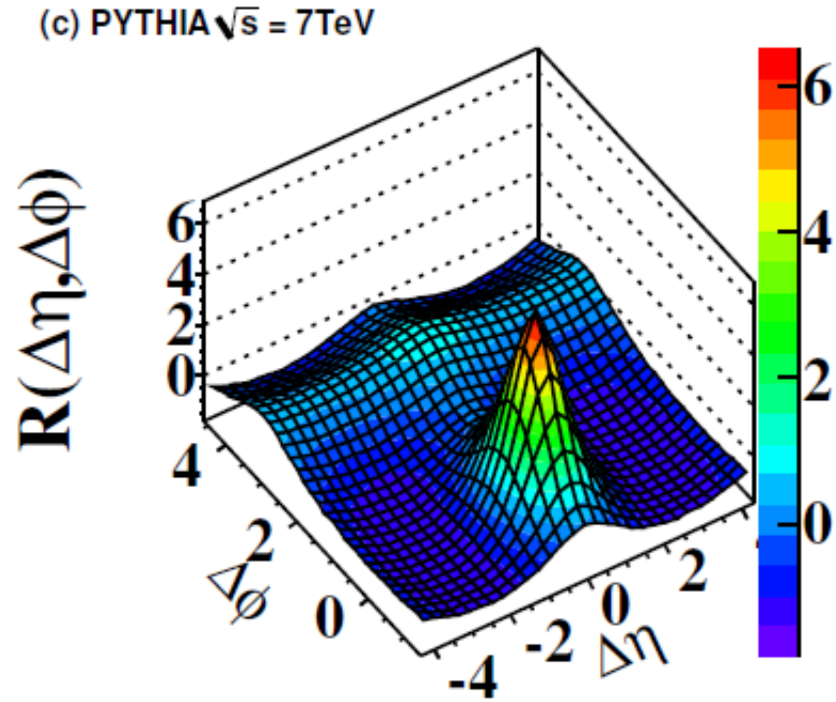
Flow Correlations…

- Elliptic (v_2)
- Triangular (v_3)

etc.

CMS Proton-Proton Hint





JHEP Journal of High Energy Physics

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September 2010, 2010:91

Observation of long-rang
correlations in proton-proton collisions at the LHC

The CMS collaboration, V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V. M. Ghete, J. Hammer, S. Hänsel, C. Hartl … show 2150 more

Open Access | Article

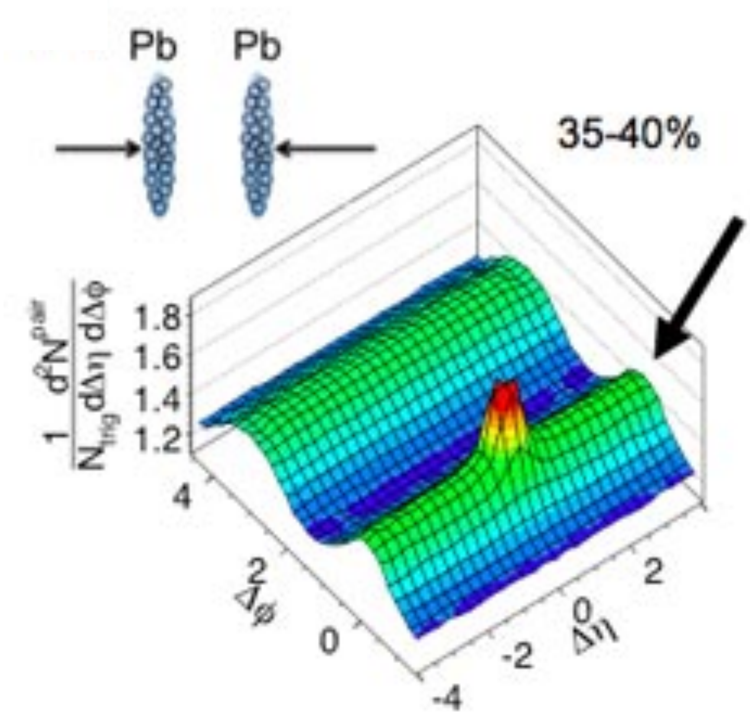
First Online: 27 September 2010

DOI: 10.1007/JHEP09(2010)091

Cite this article as:

The CMS collaboration et al. J. High Energ. Phys. (2010) 2010: 91. doi:10.1007/JHEP09(2010)091

http://link.springer.com/article/10.1007%2FJHEP09%282010%29091

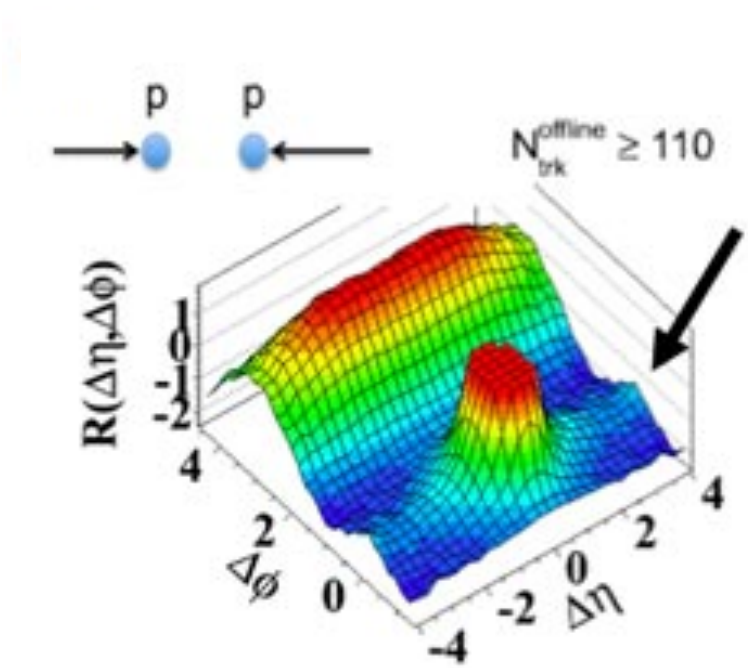


Pb+Pb at the LHC

Near side jet peak and dominant flow correlations, including long-range near-side ridge

p+p at the LHC

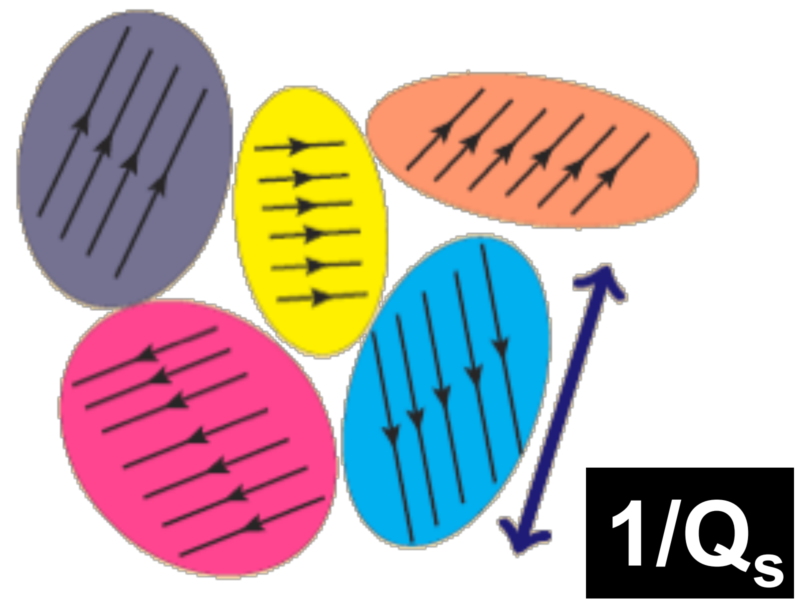
Near and away side jet peaks dominant.
And yet, clear small long-range near-side ridge



Looks Similar, but Maybe Different Origin

"Momentum Domains"
Think Color Electric Fields

Non-Geometry correlations in momentum space



$$\text{Correlation} \sim \frac{1}{{N_C}^2 Q_s^2 S_\perp}$$

Important in small systems with a finite number of these domains!