Hot QCD Matter

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Lecture 1: Tools
Lecture 2: Initial conditions: partonic structure and global observables
Lecture 3: Collective flow and hydrodynamics
Lecture 4: Jets and other hard probes

What is a liquid? Look at some unusual "fluids"

1. Cornstarch+water ("oobleck", Non-Newtonian fluid) on an audio speaker:

http://youtu.be/3zoTKXXNQIU

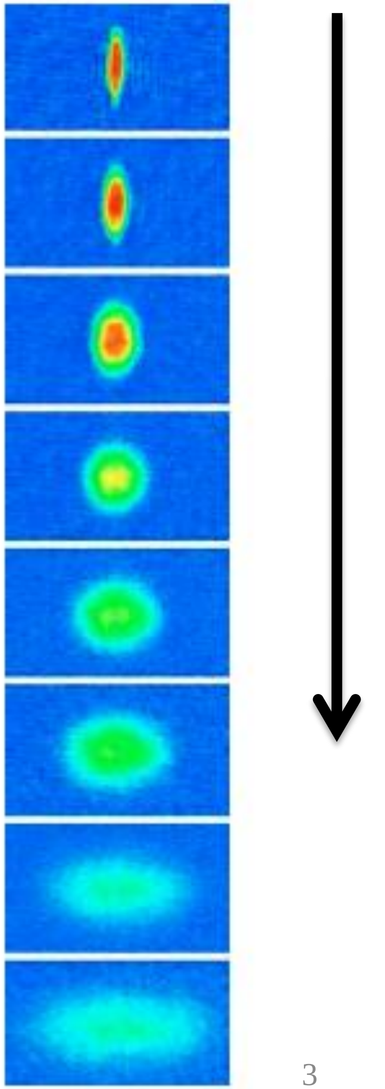
2. Stream of sand particles striking a target in symmetric geometry:

http://nagelgroup.uchicago.edu/Nagel-Group/Granular.html

Elliptic flow of a degenerate Fermi fluid

J. Thomas et al., Duke

time



Optically trapped atoms

- ➔degenerate Fermi gas
- ➔nanokelvin temperature (!)

Interactions magnetically tuned to Feshbach resonance

- ➔infinite 2-body scattering cross-section
- ➔prototypical"strongly-coupled" system

Prepare the system with spatial anisotropy and let it evolve

- ➔develops momentum anisotropy
- ➔❽elliptic flow" (remember this term)

What is hydrodynamics?

Hydrodynamics = Conservation of Energy+Momentum for long wavelength modes of excitation

What defines "long wavelengths" for dynamical systems? (early universe, heavy ion collision)

Collision rate of constituents >> expansion rate

breaks down for small or dilute systems

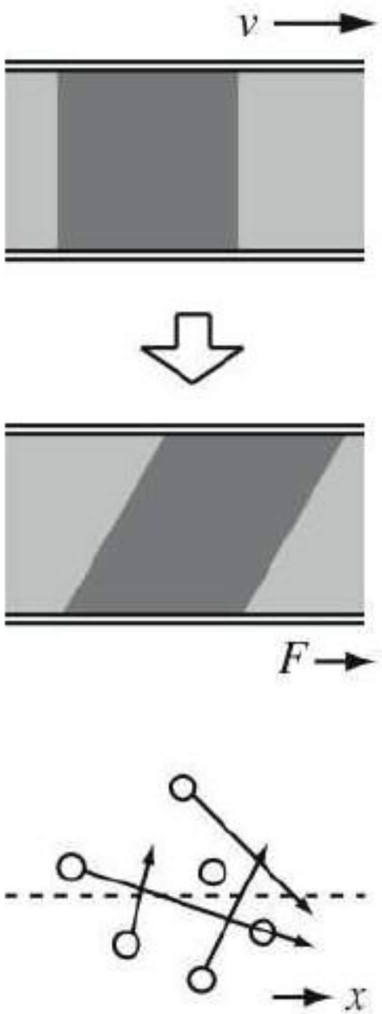
Degrees of freedom for a relativistic fluid

- fluid velocity u^μ (4-vector)
- pressure p (scalar)
- energy density e (scalar)
- General relativity: metric tensor $g_{\mu\nu}$

Quantum field theory:

- Energy-Momentum Tensor: $T^{\mu\nu}$
- Conservation of Energy+Momentum: $\partial_\mu T^{\mu\nu} = 0$

Shear viscosity in fluids



Shear viscosity characterizes the efficiency of momentum transport

Velocity of fluid element

$$\frac{F}{A} = \eta \frac{v}{L}$$

$$\eta = \rho \langle v \rangle \lambda_{mfp} \sim \frac{1}{\sigma}$$

quasi-particle interaction cross section

Comparing relativistic fluids: η/s

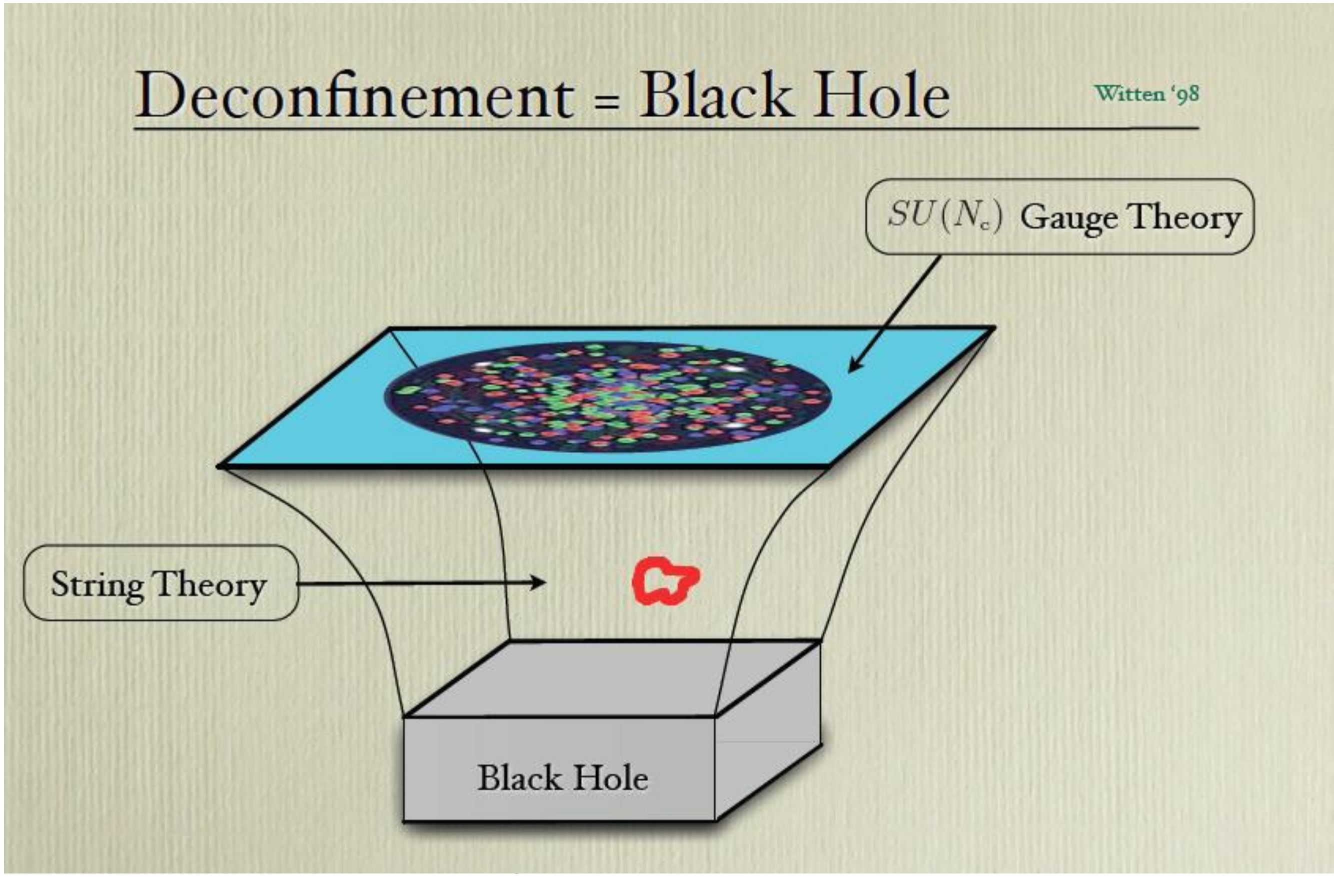
- s = entropy density
- scaling param. η/s emerges from relativistic hydro eqns.
- generalization for non-rel. fluids: η/w (w=enthalpy) (Liao and Koch, Phys.Rev. C81 (2010) 014902)

Large σ ➔small η/s
➔Strongly-coupled matter
➔"perfect liquid"

Gauge/string duality and the QGP

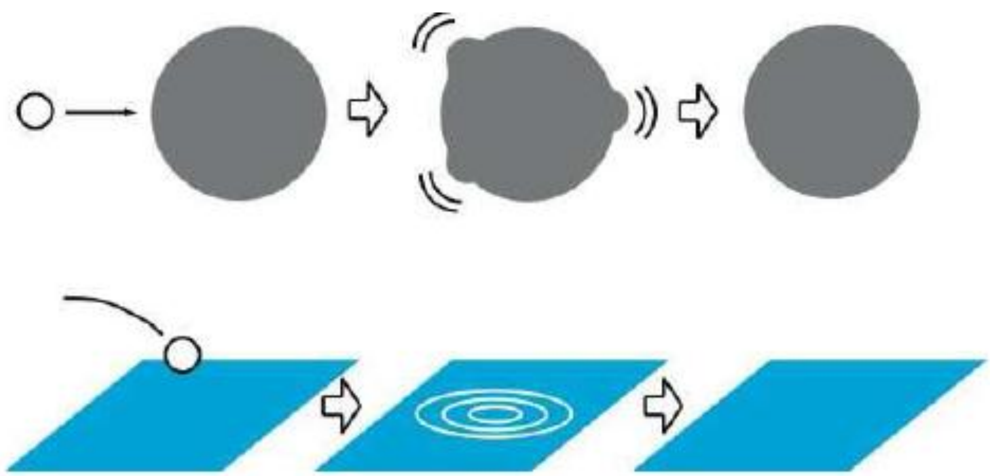
AdS/CFT correspondence (Maldacena ’97): conjecture of deep connection in String Theory between strongly coupled non-abelian gauge theories and weak gravity near a (higher-dimensional) black hole

AdS/CFT correspondence = holography



Shear viscosity and entropy in String Theory (AdS/CFT)

η/s of a black hole (M. Natsuume, hep-ph/0700120)



Shear visc. ~ cross section:

$$\eta \propto \lim_{\omega \to 0} \sigma_{BH} = Area$$

Beckenstein entropy:

$$S_{BH} = \frac{Area}{4G\hbar} k_B$$

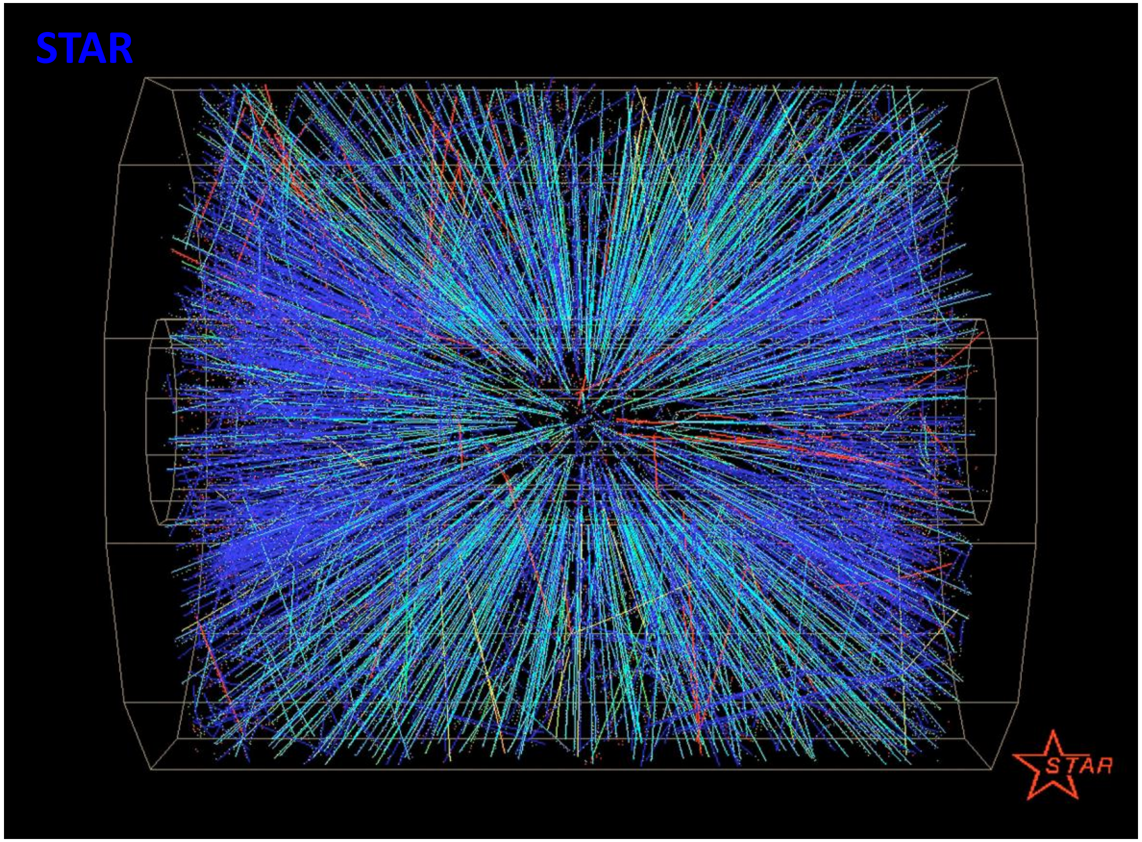
$$\Rightarrow \frac{\eta}{s} = \frac{\hbar}{4\pi k_B} \sim 0.1$$

Universal result: gauge theory plasmas with gravity duals have a universal low value η/s=1/4π at strong (‘t Hooft) coupling

Kovtun, Son and Starinets (KSS), PRL 94, 111601

(More precisely: η/s=1/4π is Leading Order result for ~infinite coupling)

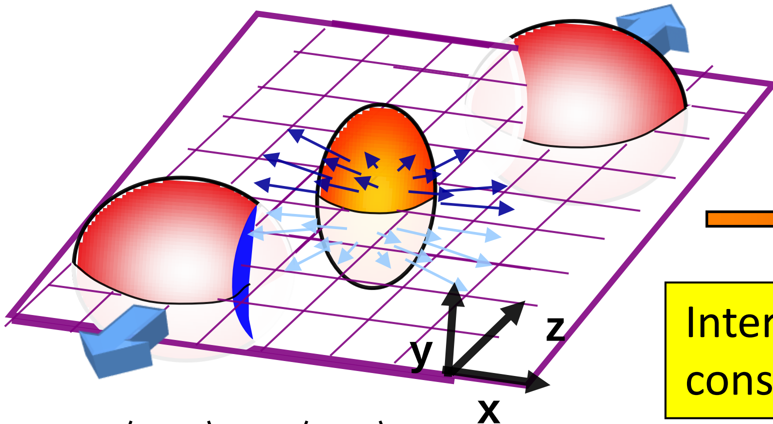
Back to nuclear collisions…

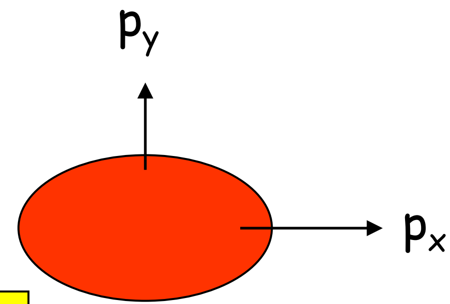


Collective Flow of QCD Matter

Initial spatial anisotropy

Final momentum anisotropy





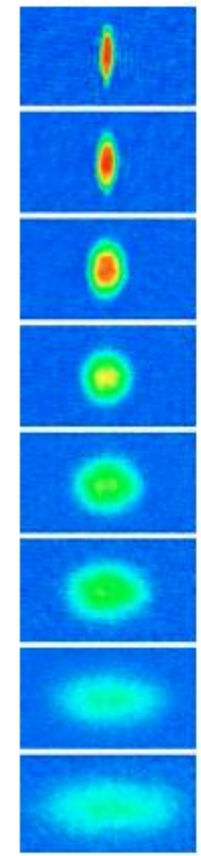
Interaction of constituents

$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

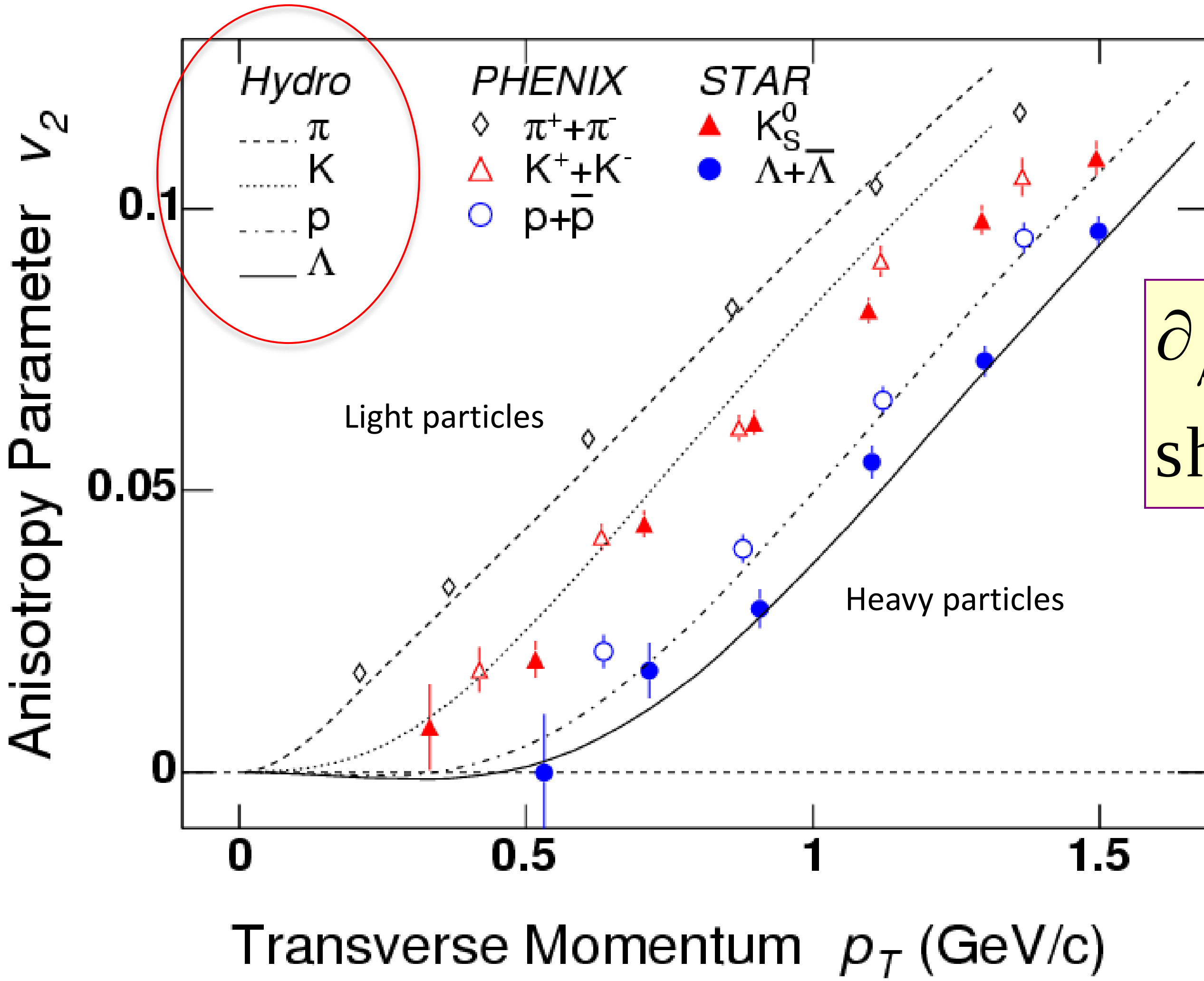
$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

Elliptic flow

$$\frac{dN}{d\phi} \propto 1 + 2v_2 cos\left[2\left(\phi - \Psi_R\right)\right] + \ldots$$



A teaser: v_2 at RHIC



v_2 is sizable: ~10% anisotropy

$$\partial_\mu T^{\mu\nu} = 0$$

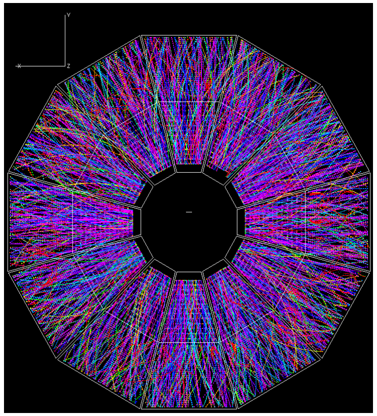
$$\text{shear viscosity}\ \eta = 0$$

Mass hierarchy vs *momentum* is characteristic of common *velocity* distribution

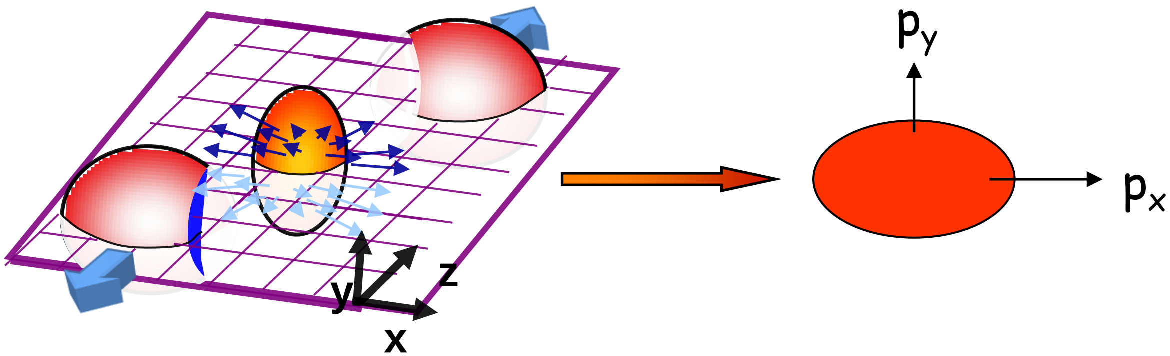
Ideal hydro: qualitative agreement but missing the details

How do we actually measure v_2?

STAR Heavy Ion event: azimuthal view in momentum space



Find momentum-weighted plane of symmetry of the event ("reaction plane" Ψ_R)



Calculate the momentum-weighted azimuthal asymmetry relative to that plane:

$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

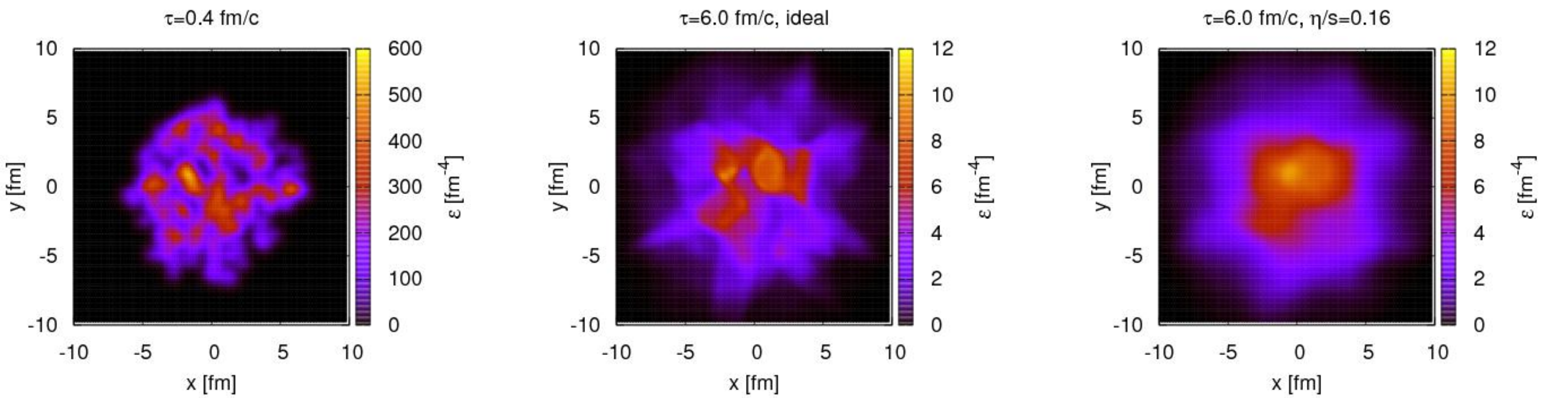
$$\frac{dN}{d\phi} \propto 1 + 2 v_2 cos\left[2\left(\phi - \Psi_R\right)\right] + \ldots$$

Wait: can it really be that simple? Actually, no.

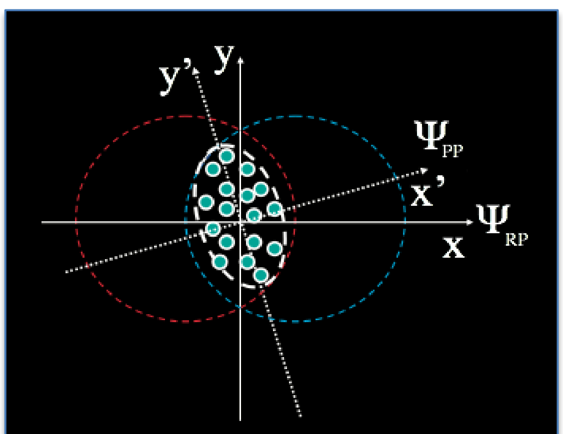
Initial state is (highly) non-uniform:

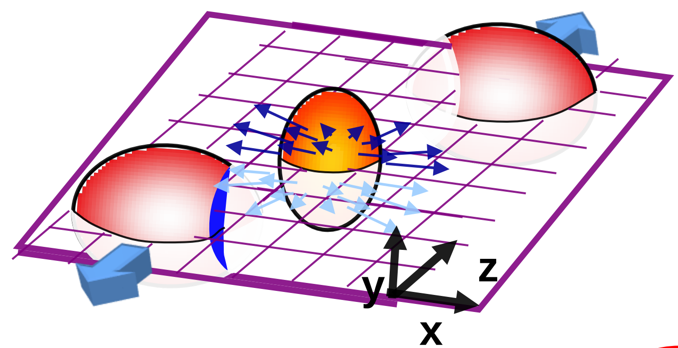
nucleon correlations, local hot spots of energy density,…

Theory calculation: Schenke, Jeon, Gale, PRL 106, 042301



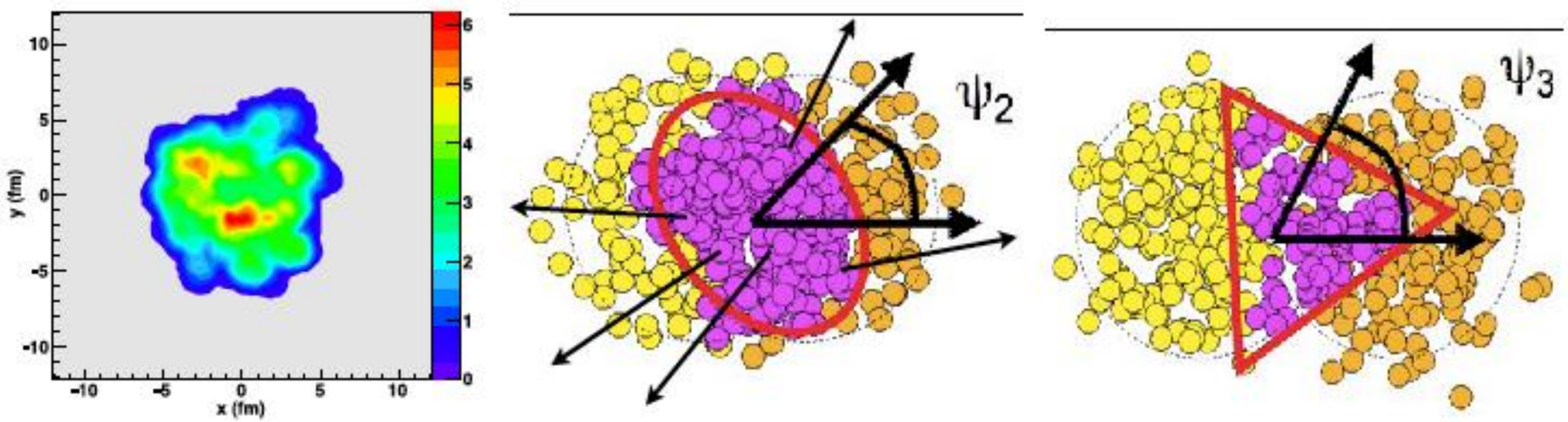
This will bias the measurement of the reaction plane orientation:





$$\frac{dN}{d\phi} \propto 1 + 2v_2 cos\left[2\left(\phi - \Psi_R\right)\right] + \ldots$$

Event shape and higher order moments



- Each event has a different initial shape and density distribution, characterized by different set of harmonic eccentricity coefficients ε_n
- Each event develops its individual hydrodynamic flow, characterized by a set of harmonic flow coefficients v_n and flow angles ψ_n
- At small impact parameters fluctuations ("hot spots") dominate over geometric overlap effects

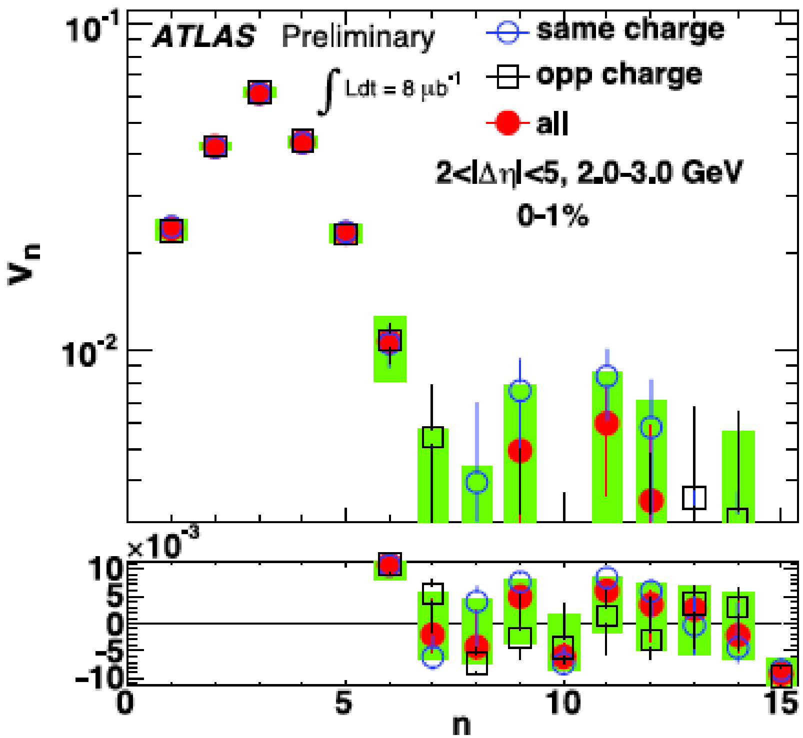
(Alver & Roland, PRC81 (2010) 054905; Qin, Petersen, Bass, Müller, PRC82 (2010) 064903)

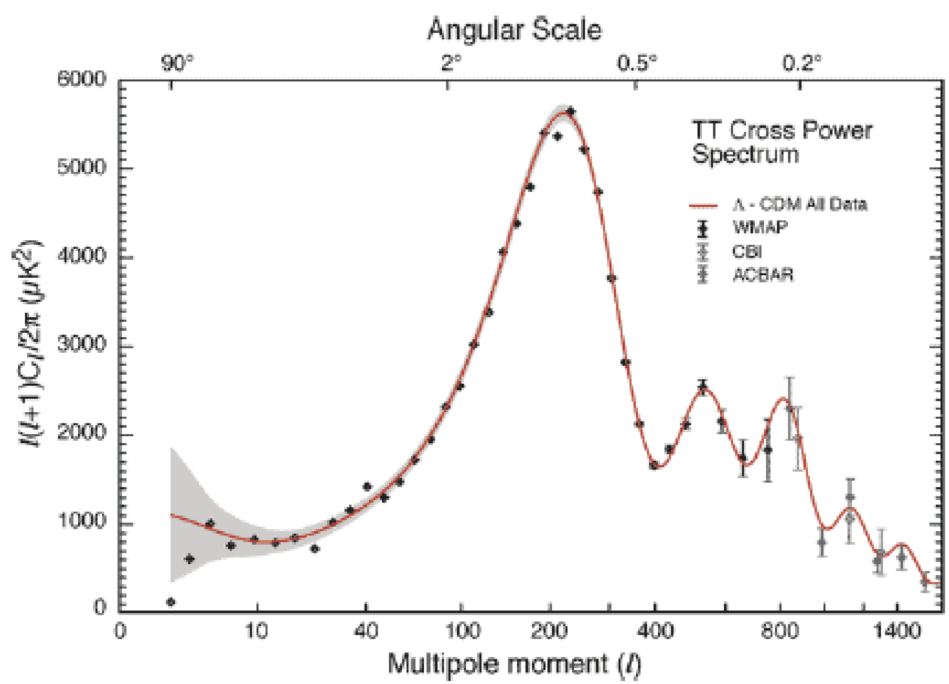
In general, expect finite values for arbitrarily high moments: v_2, v_3, v_4,…

The fluctuation "power spectrum" of the Little Bang

Mishra, Mohapatra, Saumia, Srivastava, PRC77 (2008) 064902 and C81 (2010) 034903

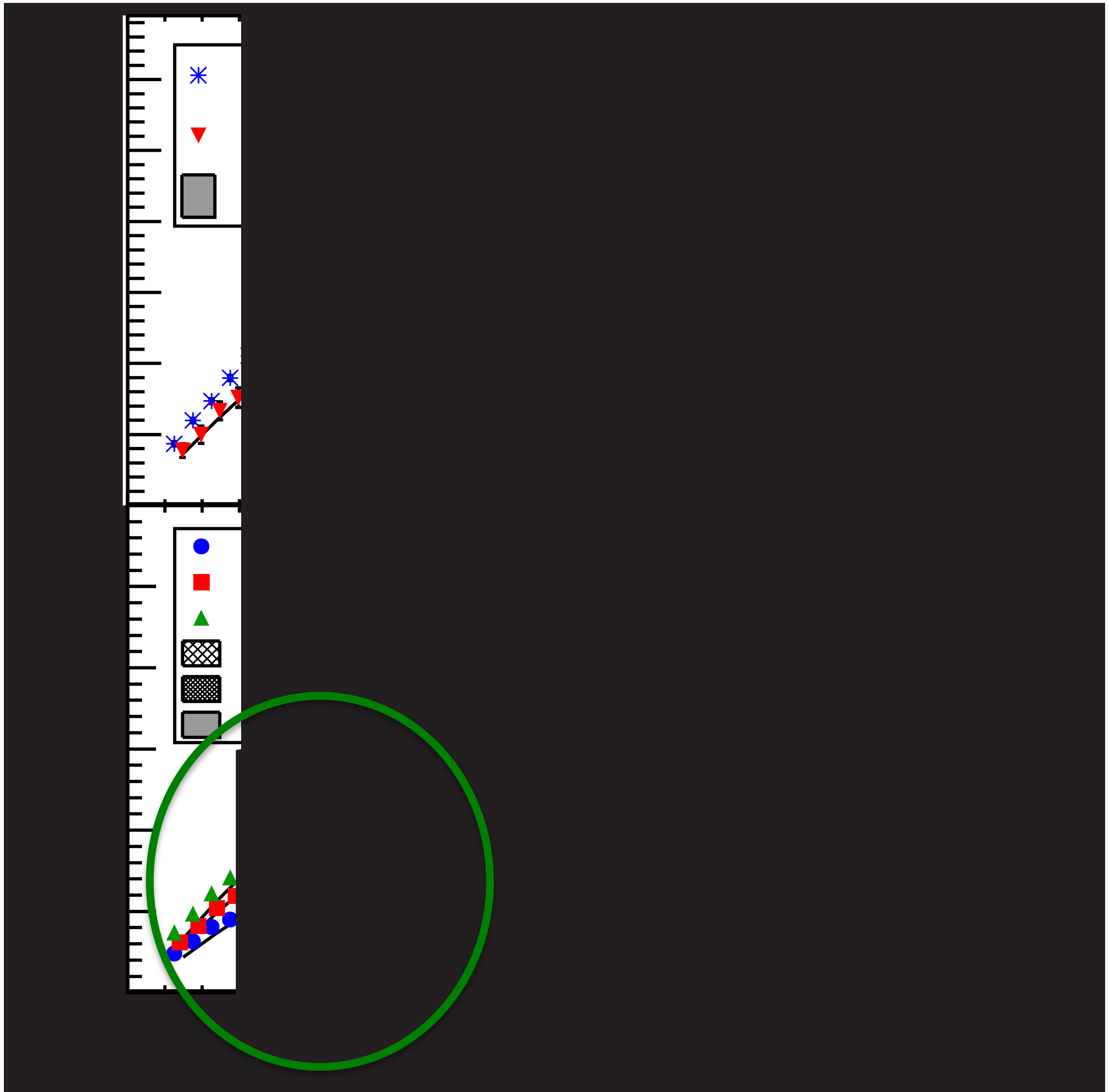
Mocsy & Sorensen, NPA855 (2011) 241, PLB705 (2011) 71





Elliptic flow v_2: LHC vs RHIC

ALICE, PRL 105, 252302 (2010)



Striking similarity of p_T-differential v_2 at RHIC and LHC – are we looking at ~similar Quark-Gluon Plasma at the two colliders?

Hydrodynamic modeling of a heavy ion collision

P. Romatschke, Quark Matter 2011

- Need initial conditions for Hydro: ϵ, u^{μ} at $\tau = \tau_0$
- Need equation of state $p = p(\epsilon)$, which gives $c_s^2 = \frac{dp}{d\epsilon}$
- Need functions for transport coefficients η, ζ.
- Need algorithm to solve (nonlinear!) hydro equations
- Need method to convert hydro information to particles ("freeze-out")

How to include viscous effects?

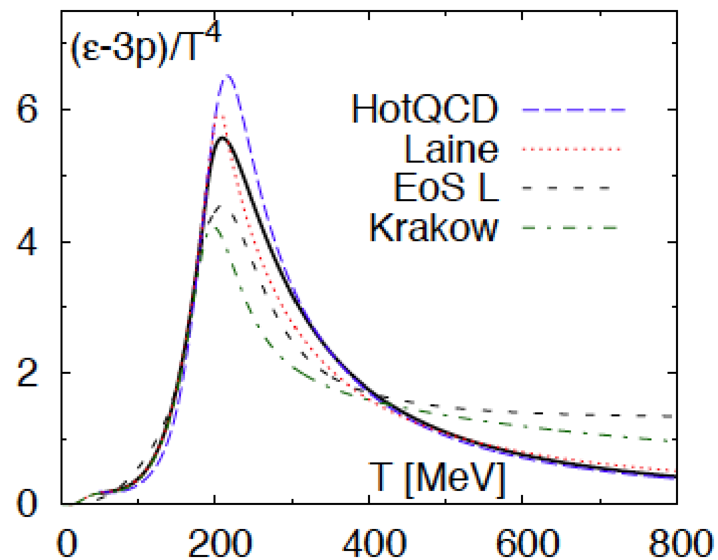
- Energy and Momentum Conservation: $\partial_\mu T^{\mu\nu} = 0$ is exact
- But $T^{\mu\nu} = T^{\mu\nu}_{\rm id}$ is approximation!
- Lift approximation: $T^{\mu\nu} = T^{\mu\nu}_{\rm id} + \Pi^{\mu\nu}$
- Build $\Pi^{\mu\nu}$: Shear viscosity adie Bulk viscosity

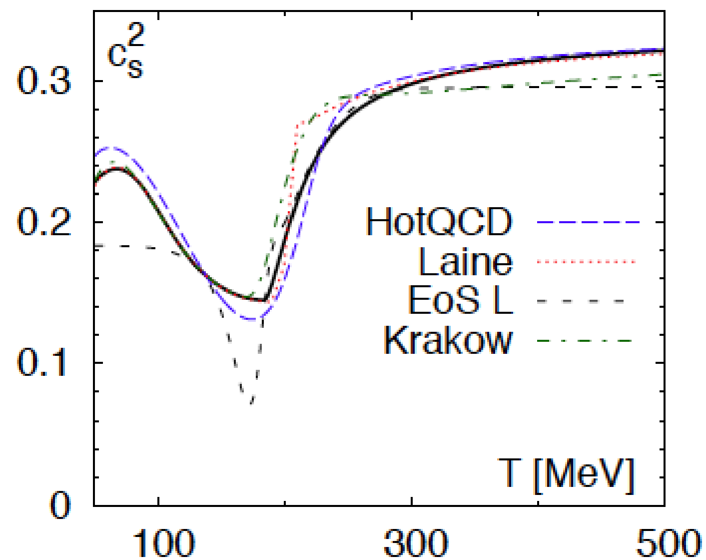
$$\Pi^{\mu\nu} = \eta \nabla^{<\mu} u^{\nu>} + \zeta \Delta^{\mu\nu} \nabla \cdot u$$

Lattice calculation of QCD Equation of State and speed of sound (c_s)

Comparison of different equations of state in hydrodynamic evolution:

P. Huovinen, P. Petreczky, Nucl.Phys.A837:26-53 (2010) see also talk by P. Huovinen, poster by W. Florkowski





Solid black: Parametrization from P. Huovinen, P. Petreczky, Nucl.Phys.A837:26-53 (2010)

HotQCD: HotQCD collaboration, Phys.Rev.D80:014504 (2009)

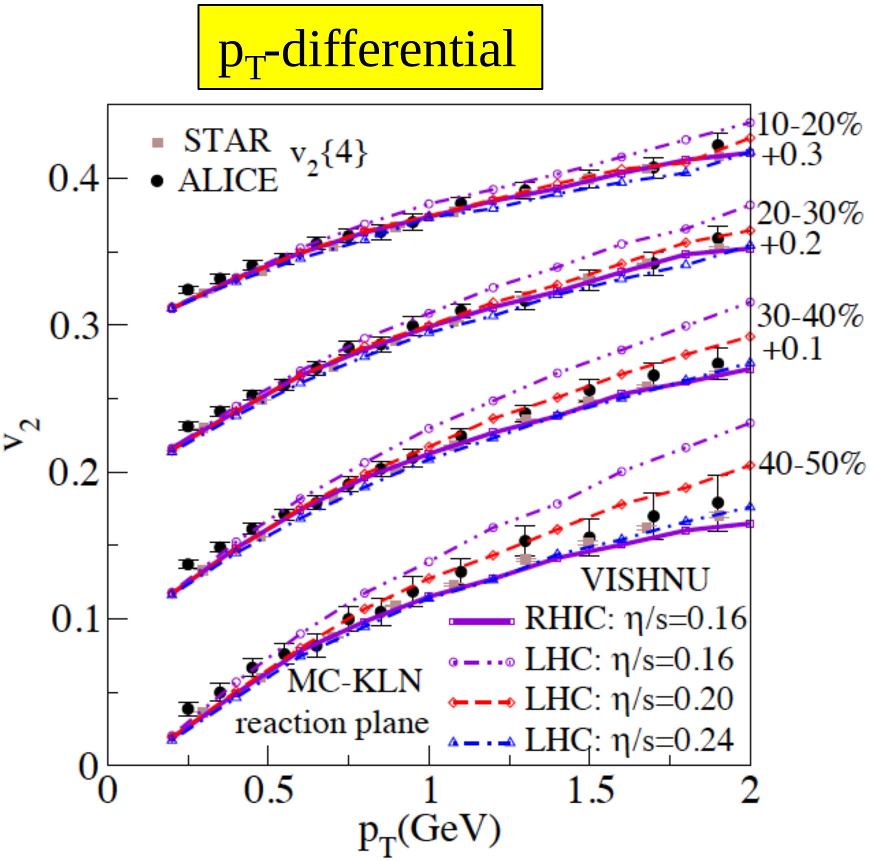
Laine: M. Laine and Y. Schröder, Phys. Rev. D73, 085009 (2006)

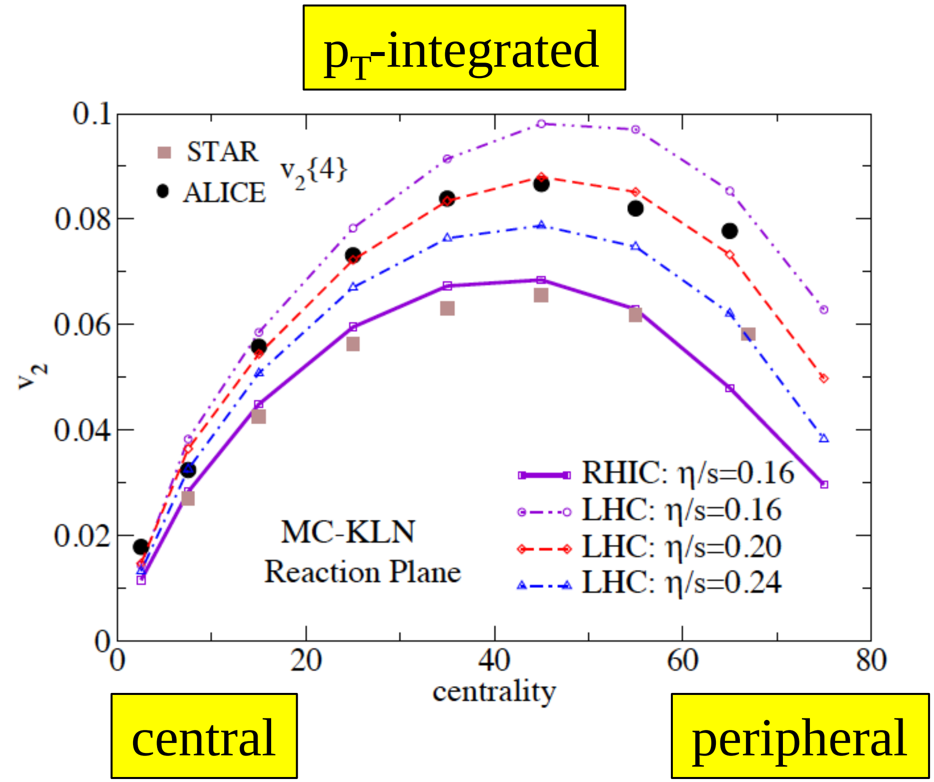
EoS L: H. Song and U. W. Heinz, Phys. Rev. C 78, 024902 (2008) using Wuppertal-Budapest results

Krakow: M. Chojnacki et al, Acta Phys. Polon. B 38, 3249 (2007) and Phys. Rev. C 78, 014905 (2008)

v_2: data vs. viscous hydrodynamic modeling

Song, Bass, and Heinz, arXiv:1103.2380

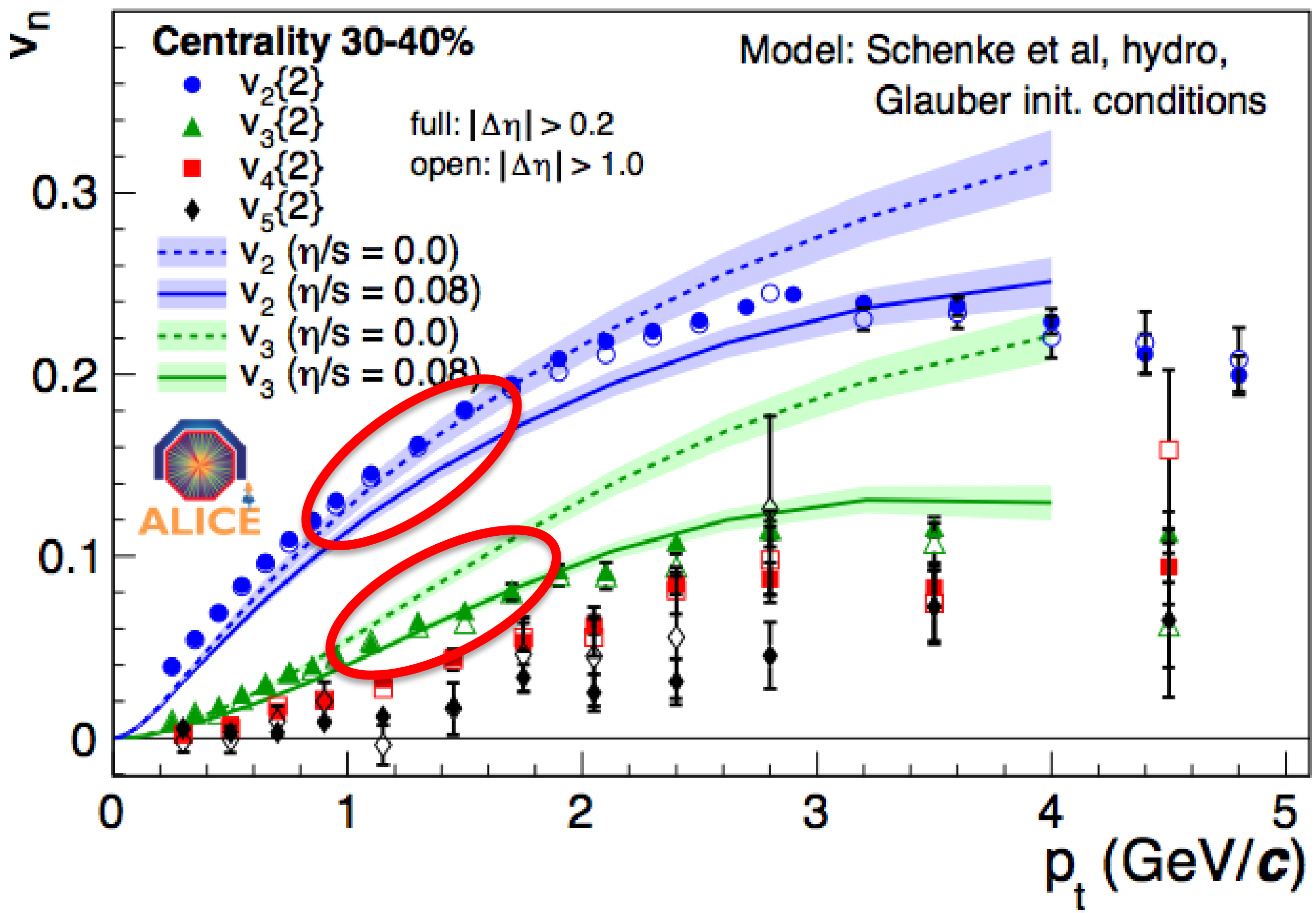




Preferred values: η/s(RHIC)=0.16, η/s(LHC)=0.20 …..????

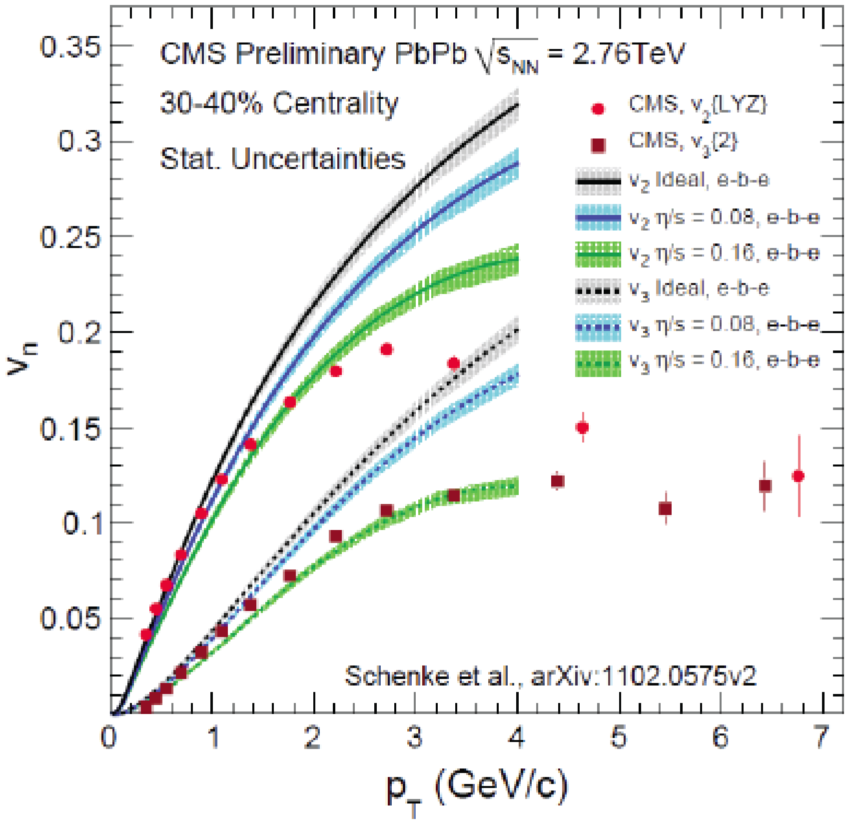
Higher harmonics

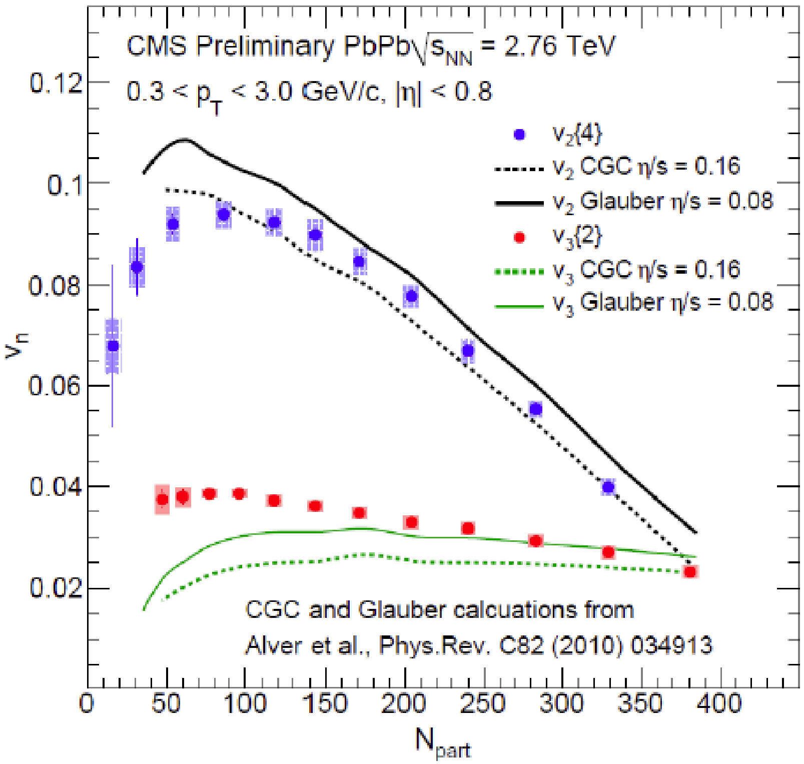
ALICE arXiv:1105.3865



ALICE: v2 and v3 have contradictory preferences for η/s
→not understood

CMS: similar ambiguities



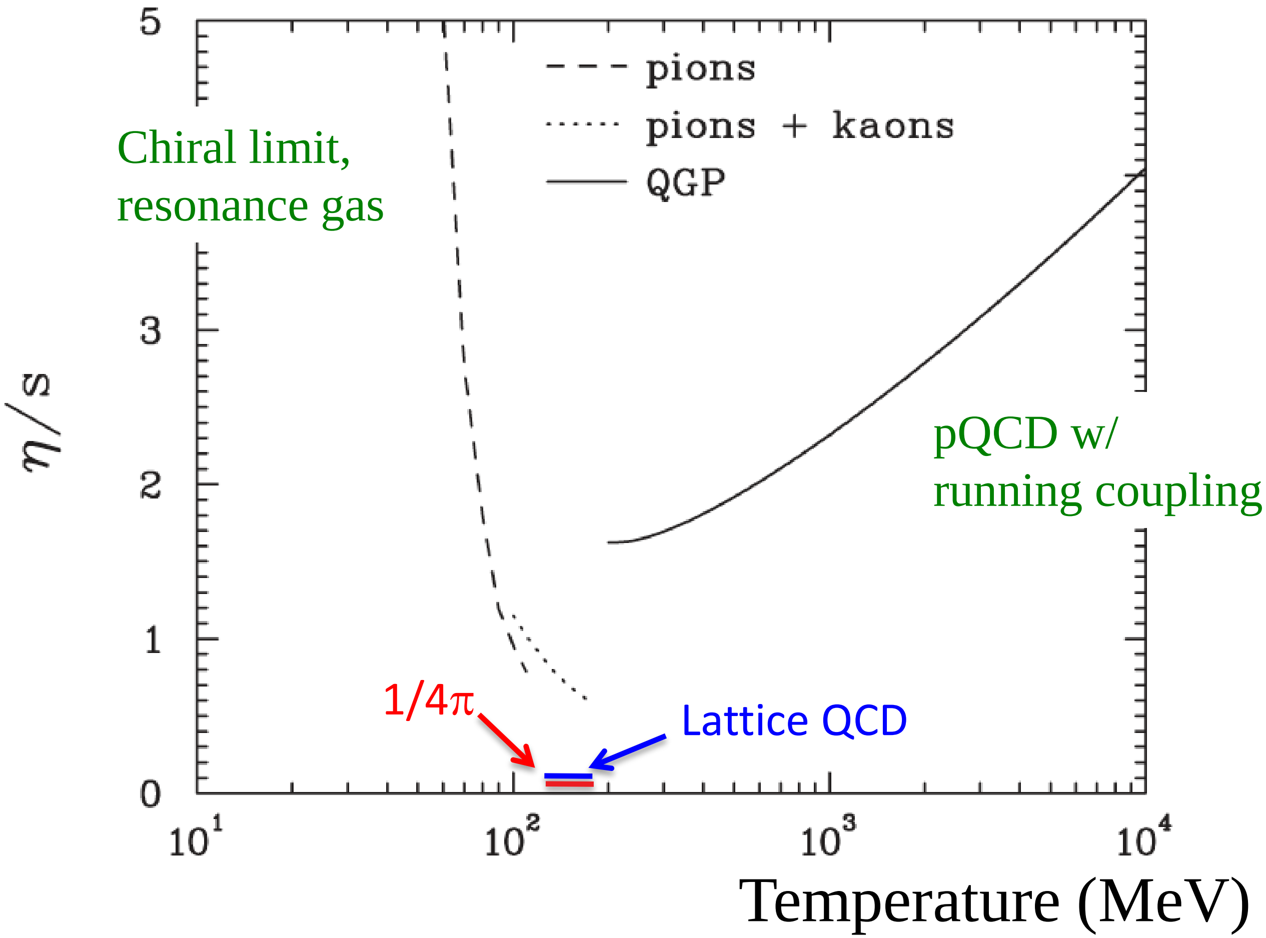


Qualitatively: η/s is within ~2-3 times 1/4π

Quantitatively: need better theoretical and experimental control for definite measurement

Shear viscosity: expectations from QCD

Analytic: Csernai, Kapusta and McClerran PRL 97, 152303 (2006)
Lattice: H. Meyer, PR D76, 101701R (2007)



If $T_{LHC} > T_{RHIC}$, expect $\eta/s(LHC) > \eta/s(RHIC)$

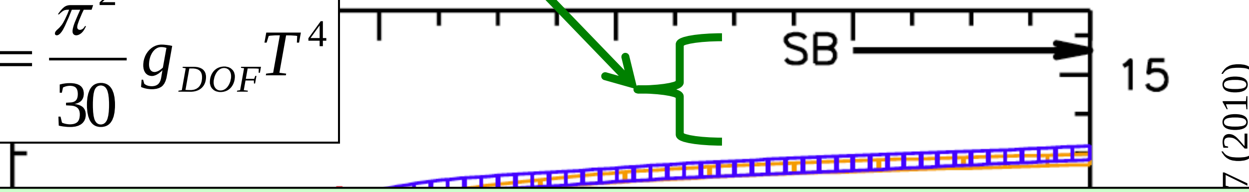
Remember this plot:

QCD calculated on the lattice (μ_B=0)

Slow convergence to non-interacting Steffan-Boltzmann limit
What carries energy - complex bound states of q+g? "strongly-coupled" plasma?

Energy density

$$\varepsilon = \frac{\pi^2}{30} g_{DOF} T^4$$



Both flow measurements and Lattice QCD calculations suggest that the Quark-Gluon Plasma at high temperature is very different than a simple gas of non-interacting quarks and gluons

Why? What are the dominant degrees of freedom ("quasi-particles")?

We don't know yet…

Cross
(like ionization of atomic plasma)

Postscript: statistical hadronization

Andronic, Braun-Munzinger, Stachel; arXiv:082.1186

Very simple static, thermodynamic model of hadron production from the Quark-Gluon Plasma:

QGP is equilibrated
Hadrons generated with thermal (Boltzmann) distributions that can be parameterized by a small number of parameters:

- Temperature
- Chemical potentials for conserved quantities: net baryon number, isospin, strangeness, charm

The basic quantity required to compute the thermal composition of hadron yields and the thermodynamical quantities is the partition function $Z(T,V)$. In the grand canonical (GC) ensemble, the partition function for a particle species i in the limit of large volume takes the following form ($k = \hbar = c = 1$):

$$\ln Z_i^{id.gas} = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \mathrm{d}p \ln[1 \pm \exp(-(E_i - \mu_i)/T)], \qquad (1)$$

Statistical hadronization: comparison of data and theory

Particle yields

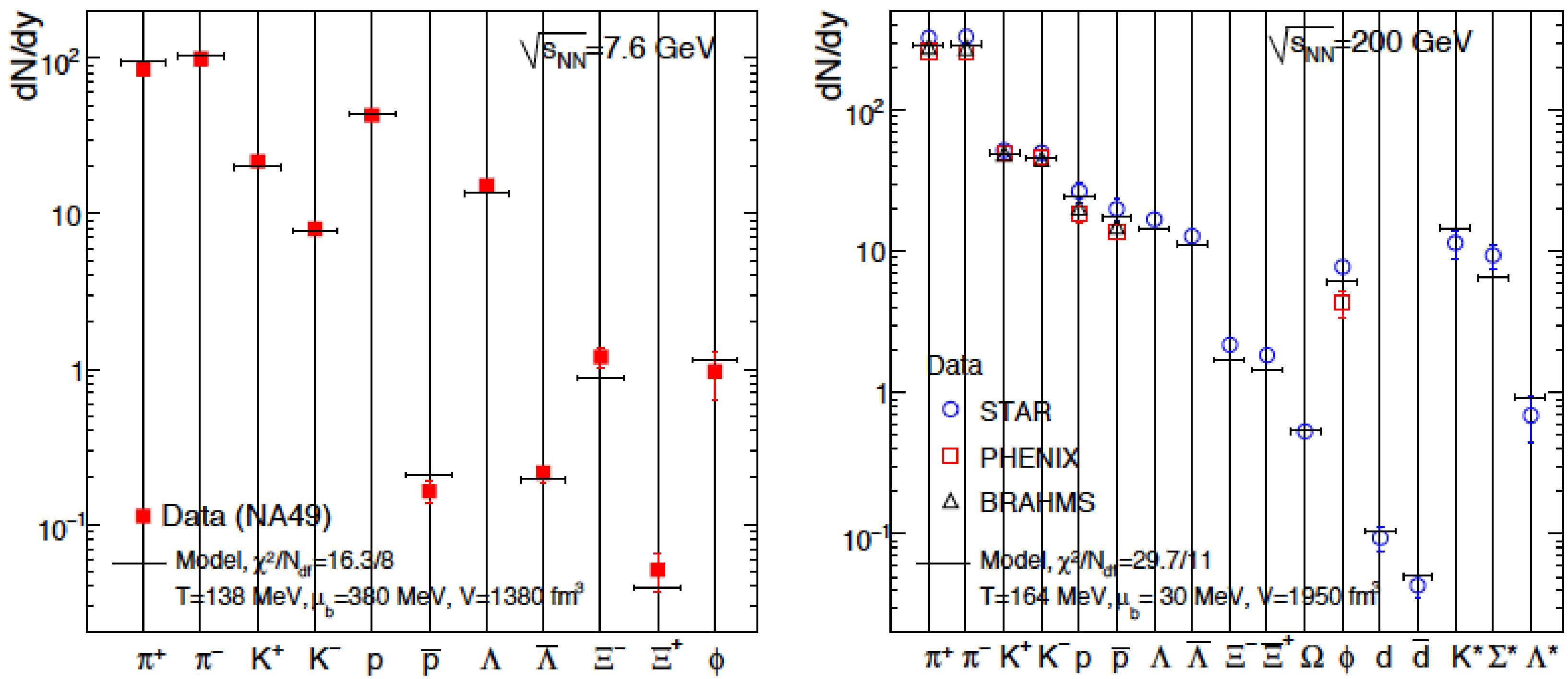


Figure 2. Experimental hadron yields and model calculations for the parameters of the best fit at the energies of 7.6 (left panel) and 200 GeV (right panel; the Ω yield includes both Ω^- and $\bar{\Omega}^+$).

Statistical hadronization: "measurement" of Temperature and μ_B

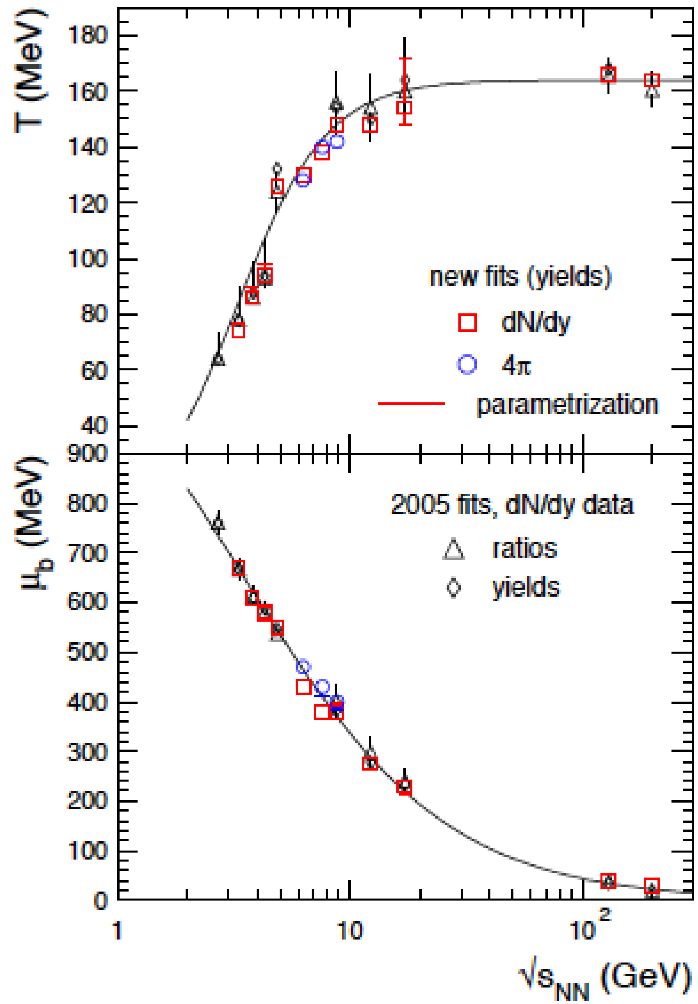
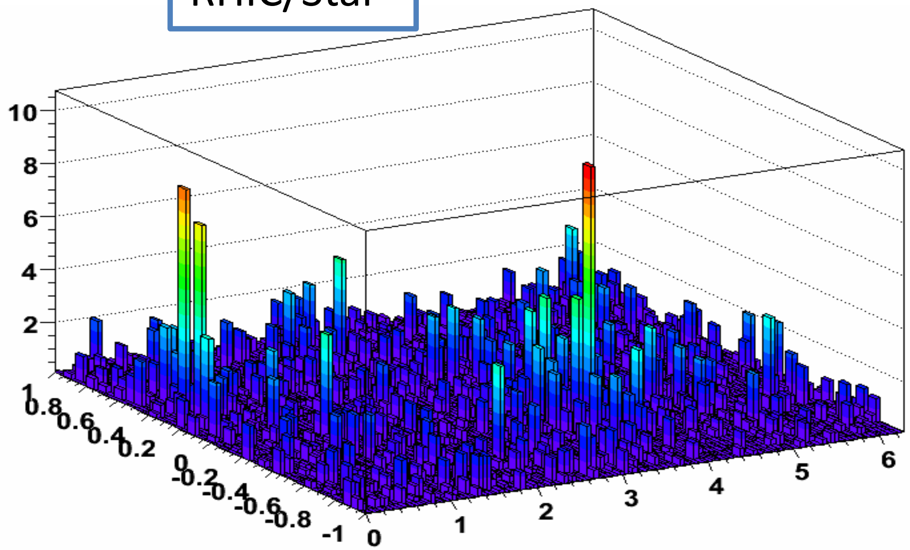


Figure 3. The energy dependence of temperature and baryon chemical potential at chemical freeze-out. The results obtained here are compared to the values obtained in our earlier study [12]. The lines are parametrizations for T and μ_b (see text).

Backup

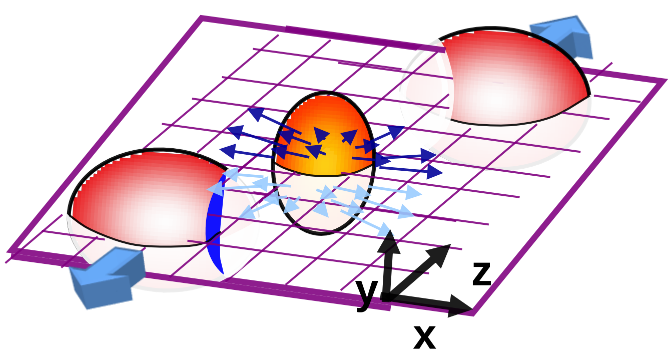
Another complication: “non-flow” from jets

RHIC/Star

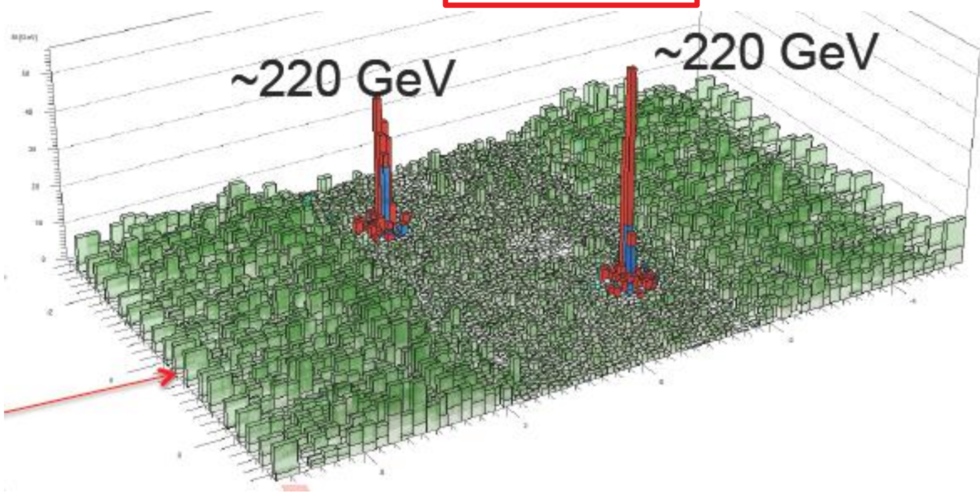


Large anisotropic contribution to momentum flow in the event

But complex and unknown correlation with reaction plane orientation

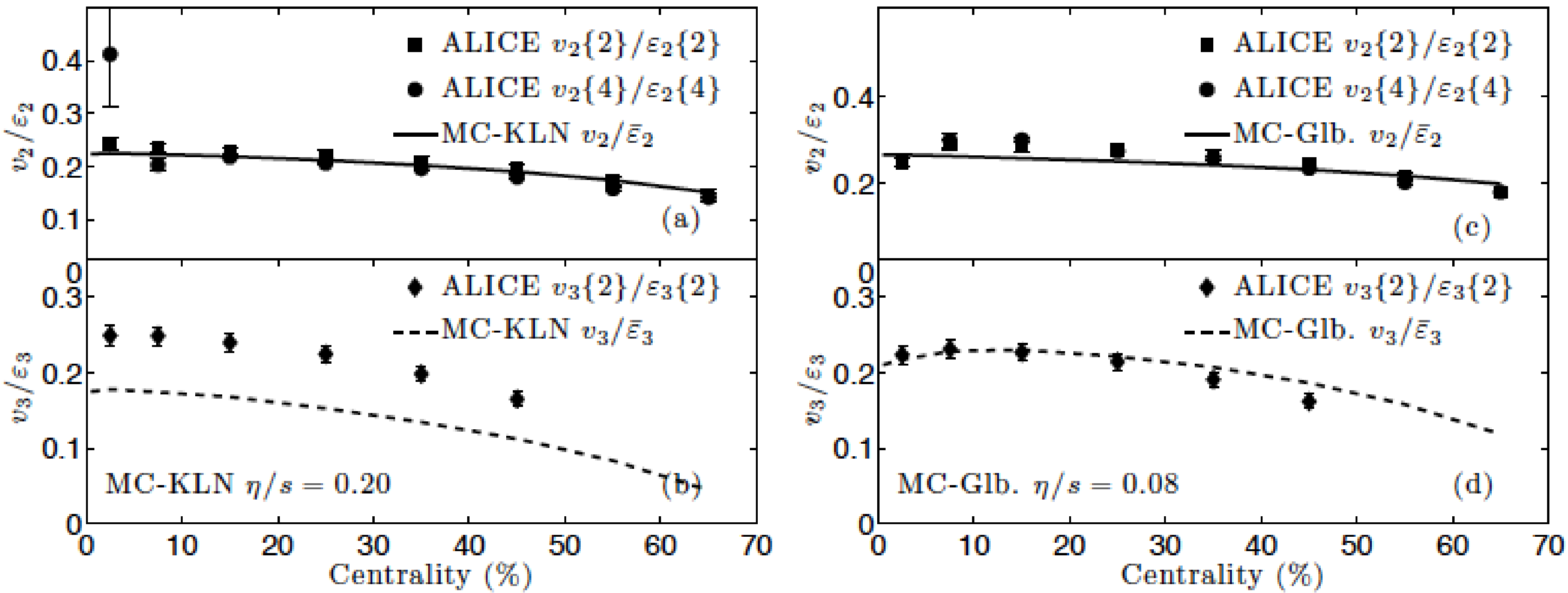


LHC/CMS



Combined v_2 & v_3 analysis: η/s is small!

Zhi Qiu, C. Shen, UH, PLB707 (2012) 151 (VISH2+1)



- Both MC-KLN with $\eta/s = 0.2$ and MC-Glauber with $\eta/s = 0.08$ give very good description of v_2/ε_2 at all centralities.
- **Only $\eta/s = 0.08$ (with MC-Glauber initial conditions) describes v_3/ε_3!**

  PHENIX, comparing to calculations by Alver et al. (PRC82 (2010) 034913), come to similar conclusions at RHIC energies (Adare et al., arXiv:1105.3928, and Lacey et al., arXiv:1108.0457)
- **Large v_3 measured at RHIC and LHC requires small $(\eta/s)_{QGP} \simeq 1/(4\pi)$** unless the fluctuations predicted by both models are completely wrong and ε_3 is really 50% larger than we presently believe!

Controlling "non-flow"

Want to remove all correlations that are not due to collective flow of many particles:

- Measure reaction plane orientation and flow signal in widely separated regions of phase space (large $\Delta\eta$ separation)

- Compare cumulants of various order: 2,4,6,…particle

    - cumulants are well-known in statistics: isolate true n-particle correlations by removing lower order correlations (e.g. n particles can be mutually correlated due to 2-particle correlations)

Methods are under good control ➔ small systematic uncertainties due to "non-flow" correlations