Exploring Hot Dense Matter at RHIC and LHC

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Lecture 3: Collective Flow and Hydrodynamics

“Hydrodynamic” flow in unusual systems

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

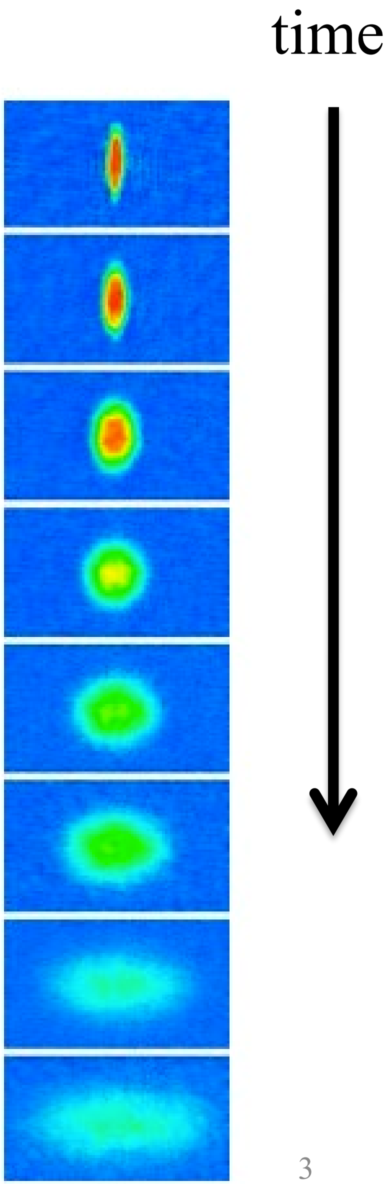
http://youtu.be/3zoTKXXNQIU

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



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” (!)

What is fluid dynamics?

Fluid dynamics = Conservation of Energy+Momentum for long wavelength modes of excitation

breaks down for small or dilute systems

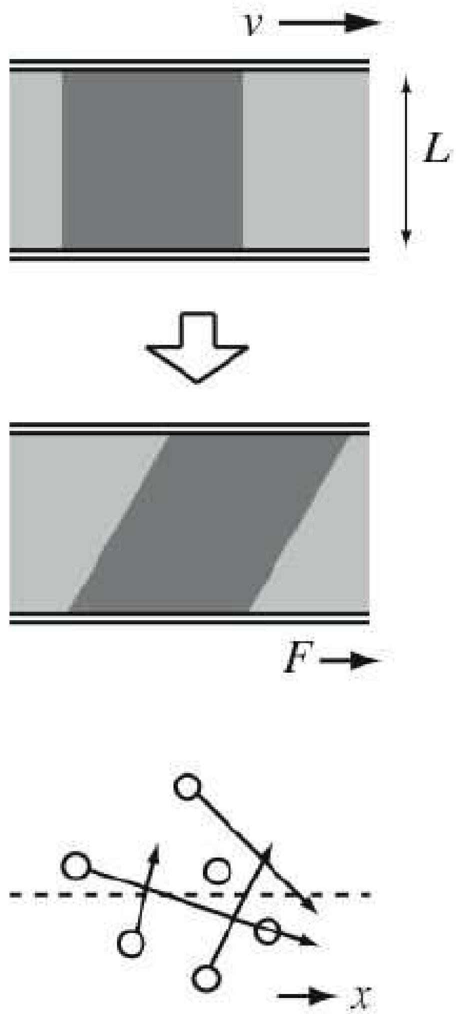
Degrees of freedom for a relativistic fluid

- 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

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

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

quasi-particle interaction cross section

Comparing relativistic fluids: η/s

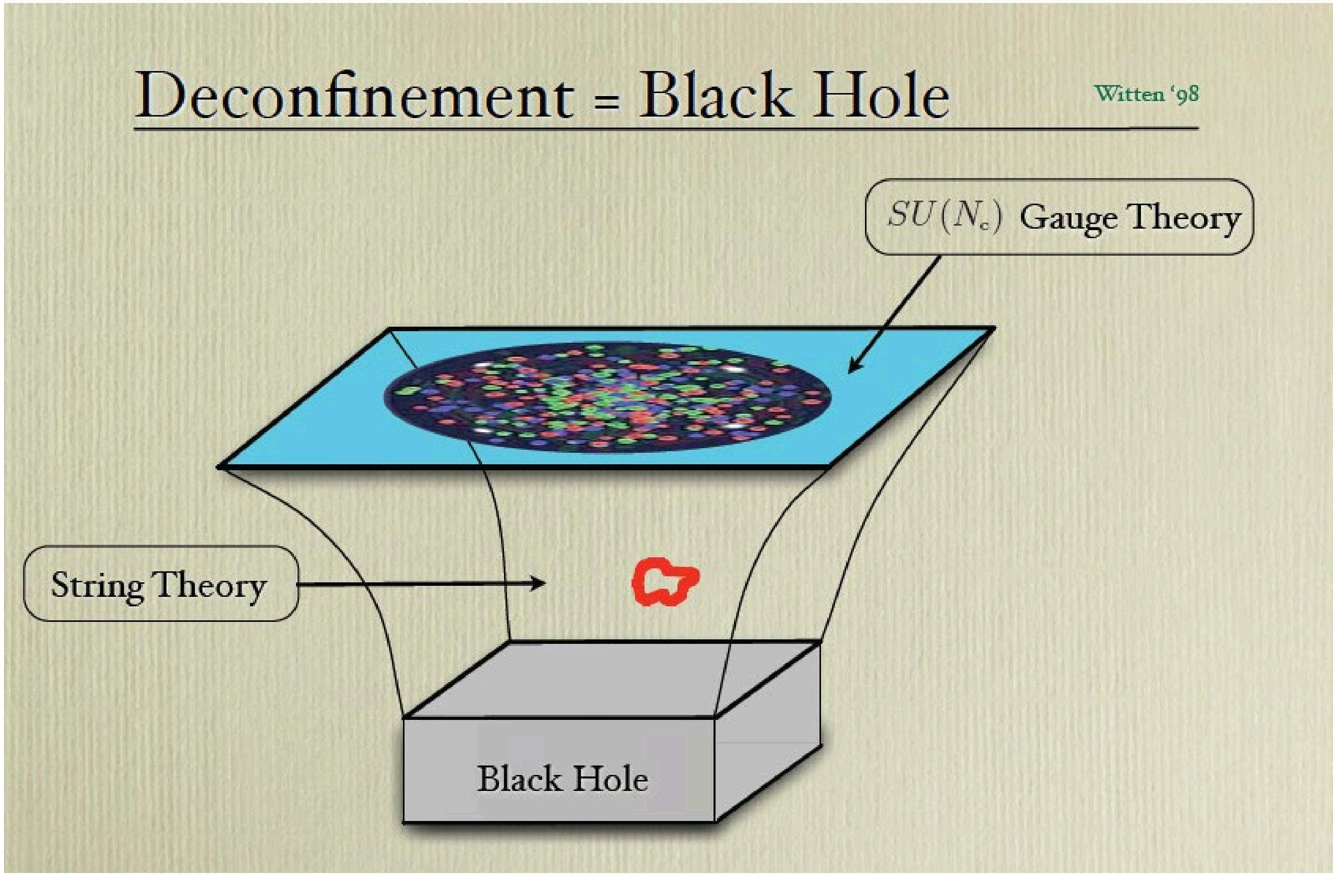
- s = entropy density
- scaling param. η/s emerges from relativistic hydro eqns.
- generalization for non-rel. fluids: η/w (w=enthalpy) (Liao and Koch, Phys.Rev. C81 (2010) 014902)

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

Gauge/string duality and the QGP

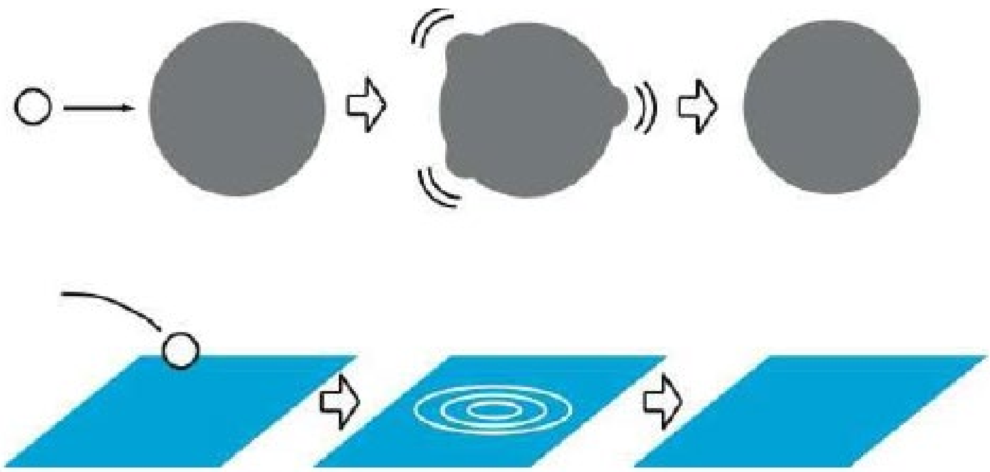
AdS/CFT correspondence (Maldacena '97): conjecture of deep connection in String Theory between strongly coupled non-abelian gauge theories and weak gravity near a (higher-dimensional) black hole

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:

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

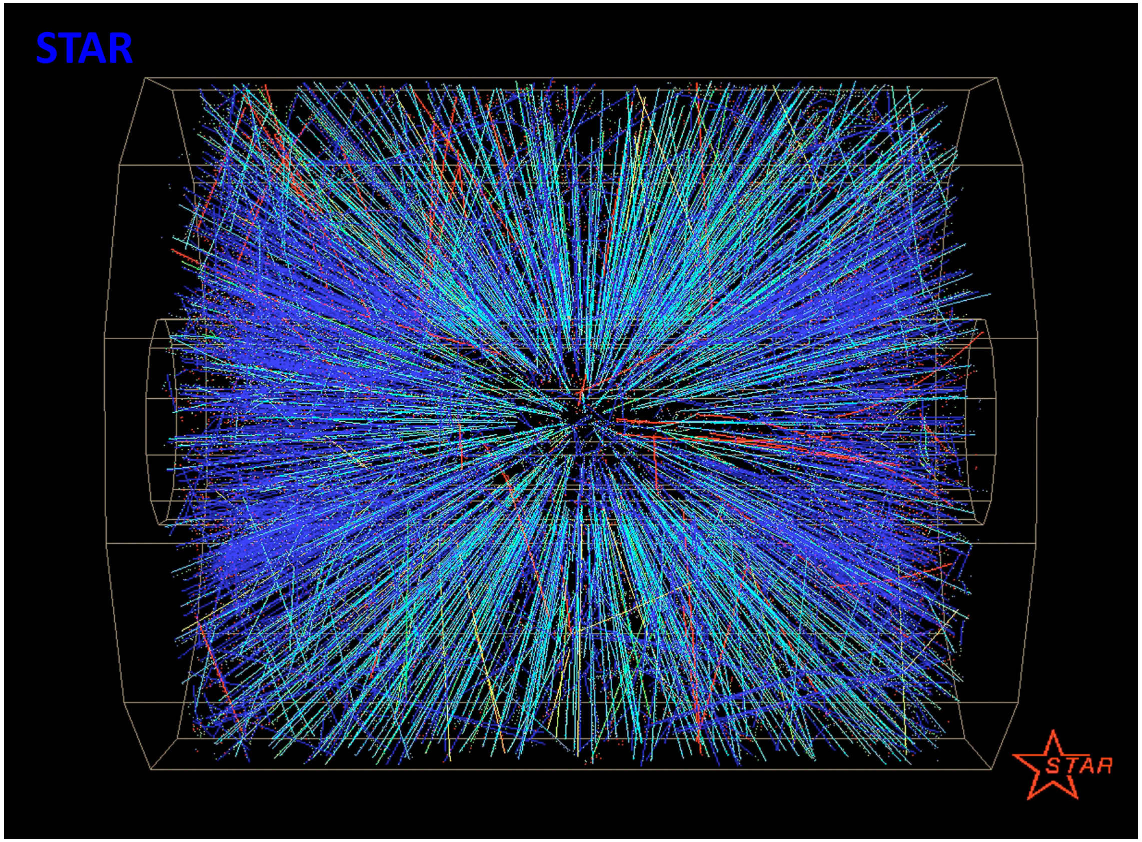
$$\Rightarrow \frac{\eta}{s} = \frac{\hbar}{4\pi k_B} \sim 0.1$$

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

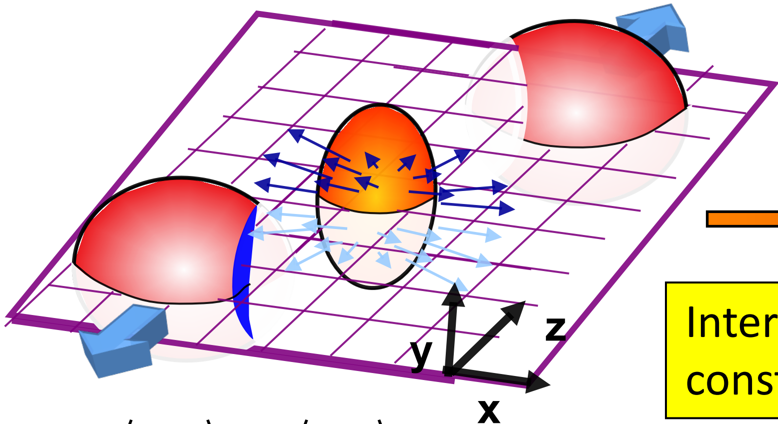
(More precisely: η/s=1/4π is only Leading Order result for infinite coupling)

Back to nuclear collisions…

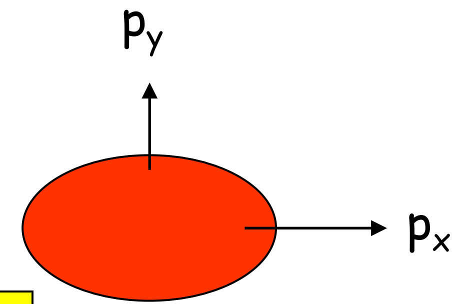


Collective Flow of QCD Matter

Initial spatial anisotropy



Final momentum anisotropy



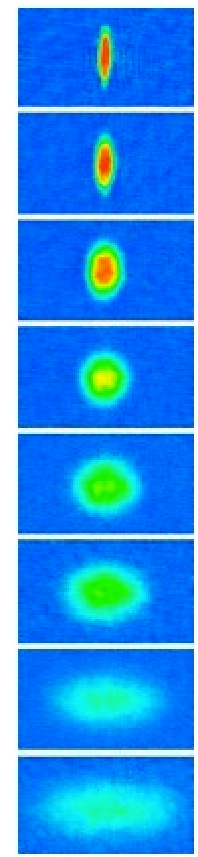
Interaction of constituents

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

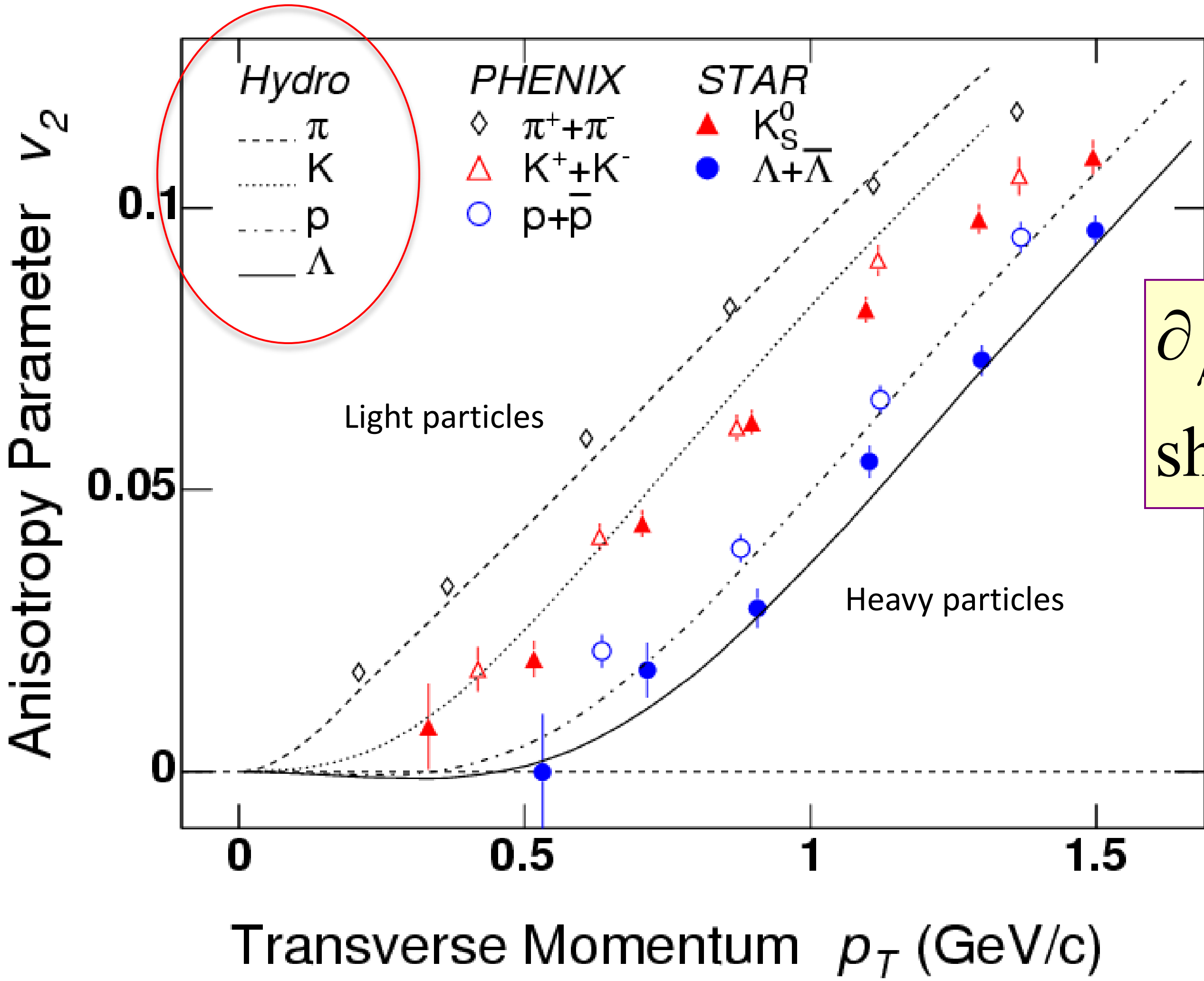
$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

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

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

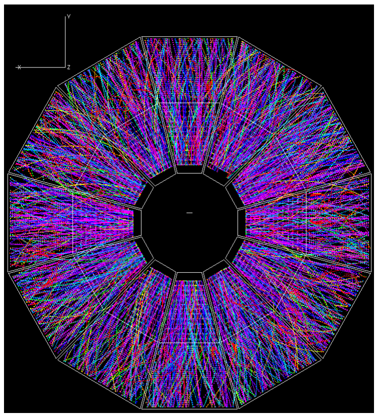
shear viscosity $\eta = 0$

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

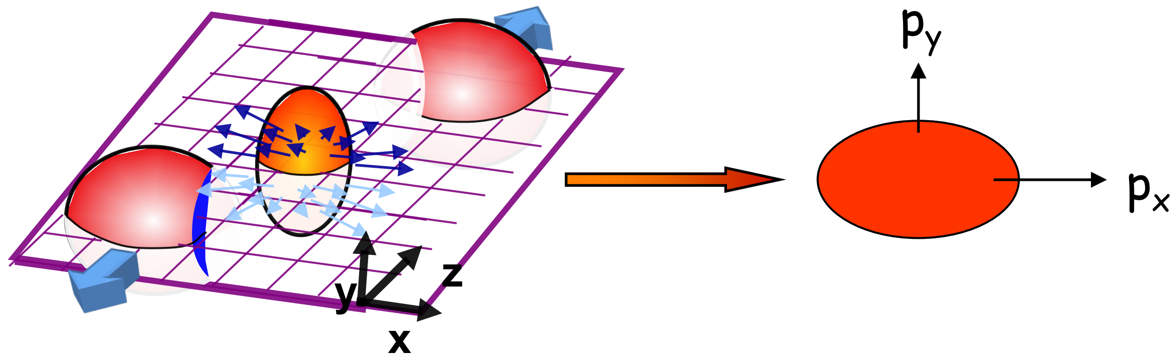
Ideal hydro: qualitative agreement but missing the details

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:

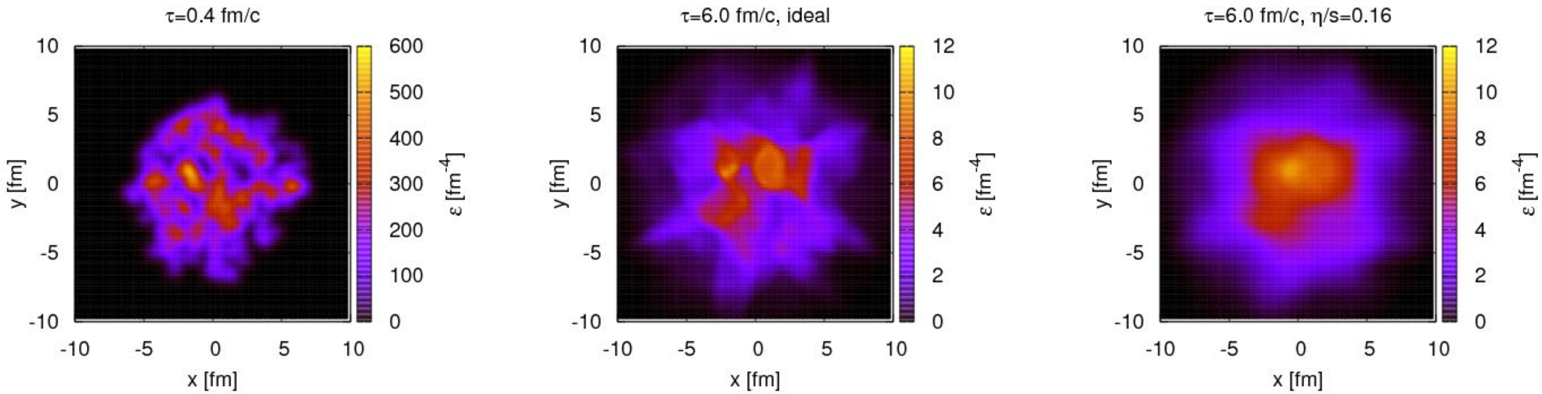
$$v_2 = \frac{\langle p_x^2 \rangle - \langle p_y^2 \rangle}{\langle p_x^2 \rangle + \langle p_y^2 \rangle}$$

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

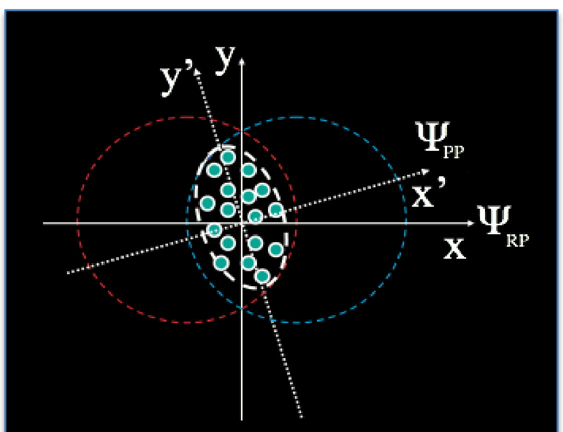
Wait: can it really be that simple? Actually, no.

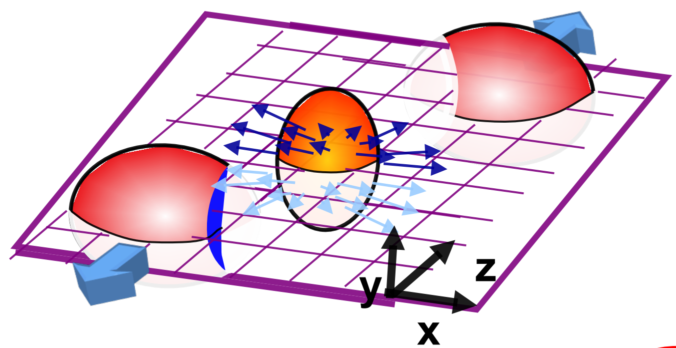
Initial state is (highly) non-uniform:
nucleon correlations, local hot spots of energy density,…

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



This will bias the measurement of the reaction plane orientation:

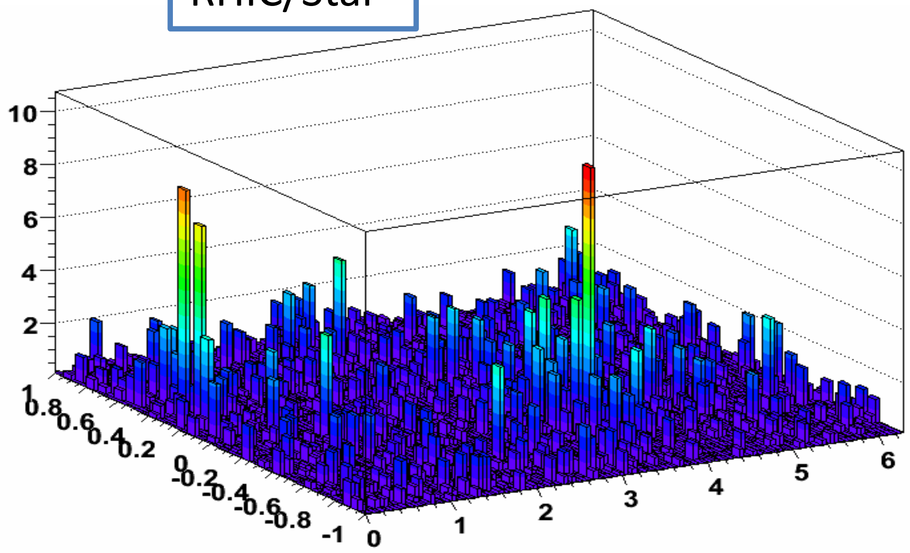




$$\frac{dN}{d\phi} \propto 1 + 2v_2 cos\left[2\left(\phi - \Psi_R\right)\right] + \ldots$$

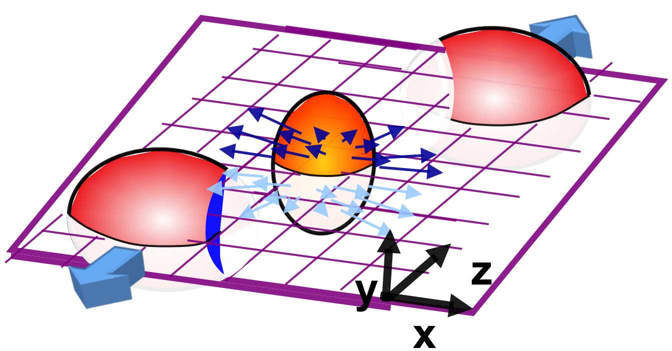
Another complication: “non-flow” from jets

RHIC/Star

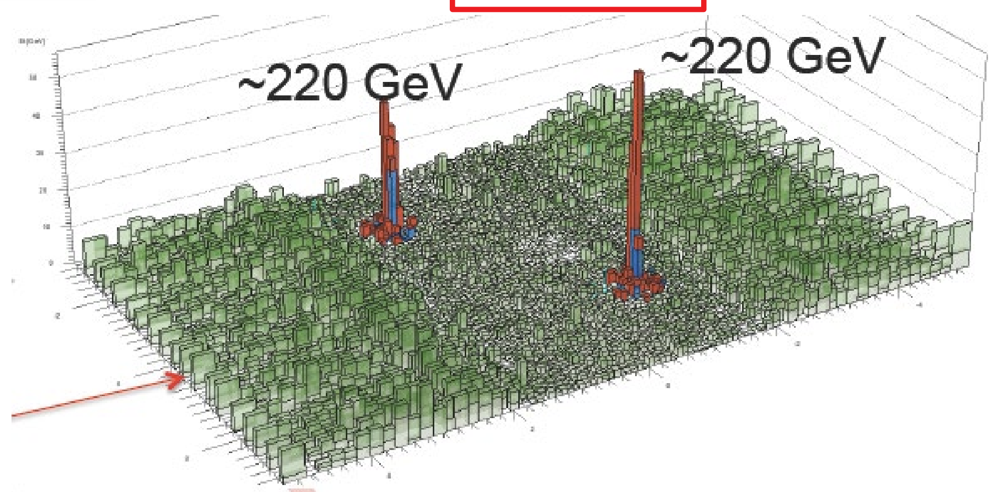


Large anisotropic contribution to momentum flow in the event

But complex and unknown correlation with reaction plane orientation



LHC/CMS



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)

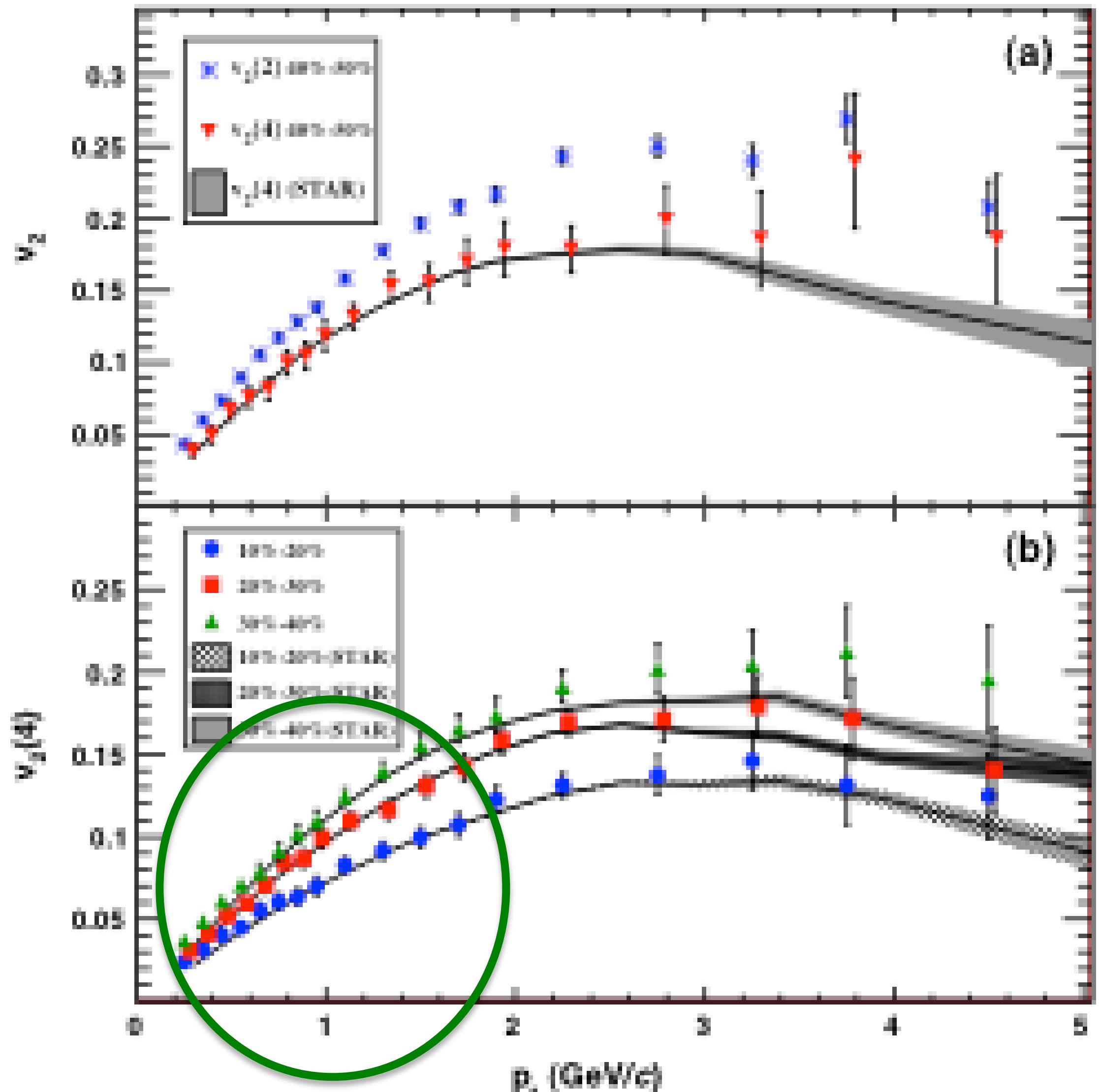
- Compare cumulants of various order: 2,4,6,…particle

  - 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

Elliptic flow v_2: LHC vs RHIC

ALICE, PRL 105, 252302 (2010)



Striking similarity of p_T-differential v_2 at RHIC and LHC

Hydrodynamic modeling of a heavy ion collision

P. Romatschke, QM11

- 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?

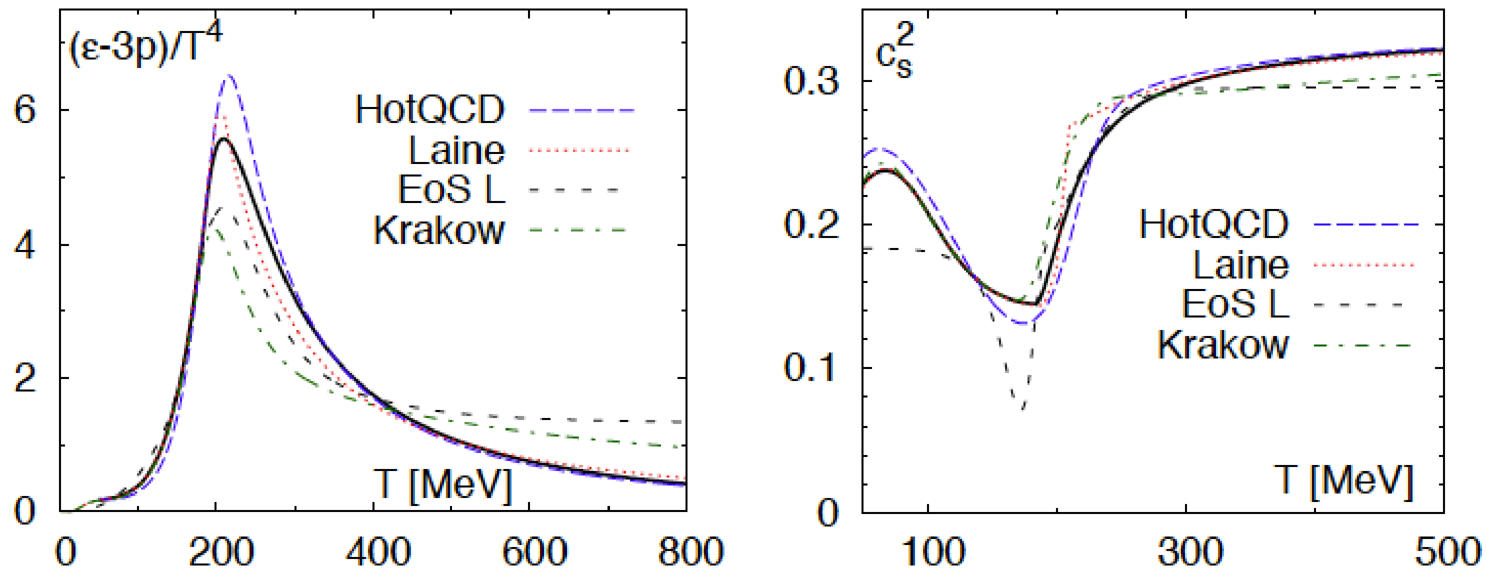
- Energy and Momentum Conservation: $\partial_\mu T^{\mu\nu} = 0$ is exact
- But $T^{\mu\nu} = T^{\mu\nu}_{\rm id}$ is approximation!
- Lift approximation: $T^{\mu\nu} = T^{\mu\nu}_{\rm id} + \Pi^{\mu\nu}$
- Build $\Pi^{\mu\nu}$: Shear viscosity radie Bulk viscosity

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

Equation of state

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)

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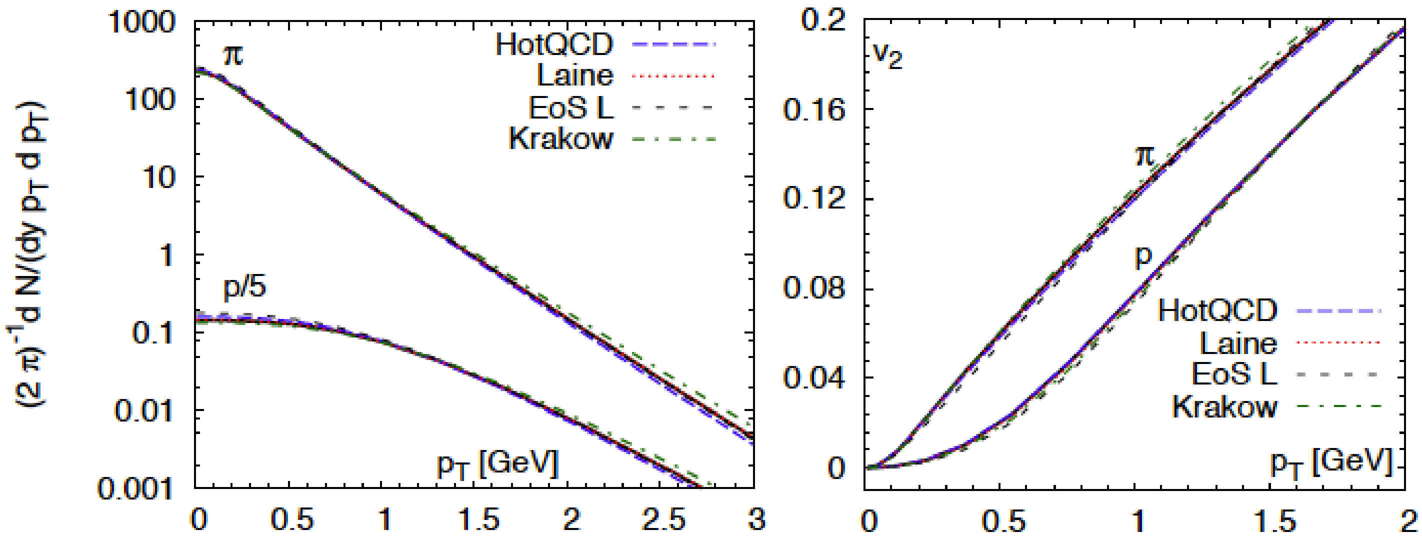


Conclusion:

"Differences in the lattice EoS parametrization in the literature are small and not observable in the p_T-differential elliptic flow."

Another more recent lattice equation of state:

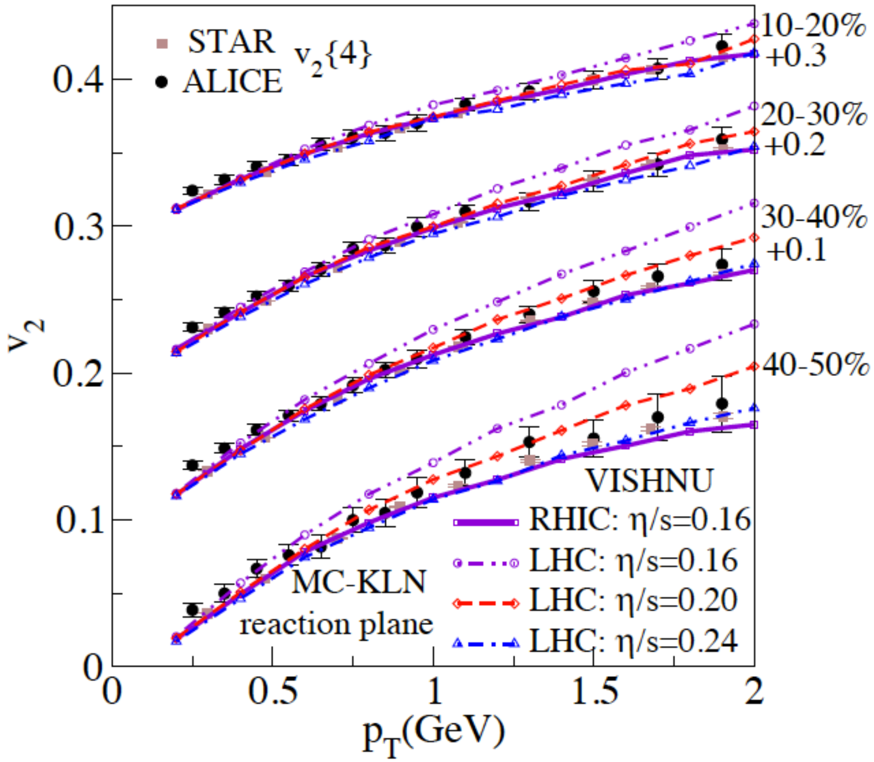
S. Borsanyi et al, JHEP 1011:077 (2010)

Wuppertal-Budapest lattice results - used in V. Roy and A.K. Chaudhuri, arXiv:1103.2870

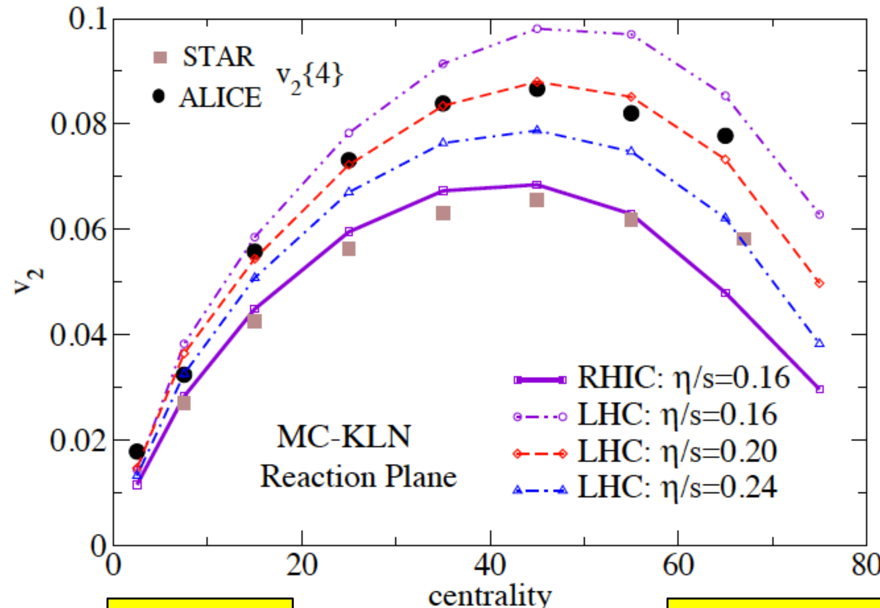
v_2: data vs. viscous hydrodynamic modeling

Song, Bass, and Heinz, arXiv:1103.2380

p_T-differential



p_T-integrated



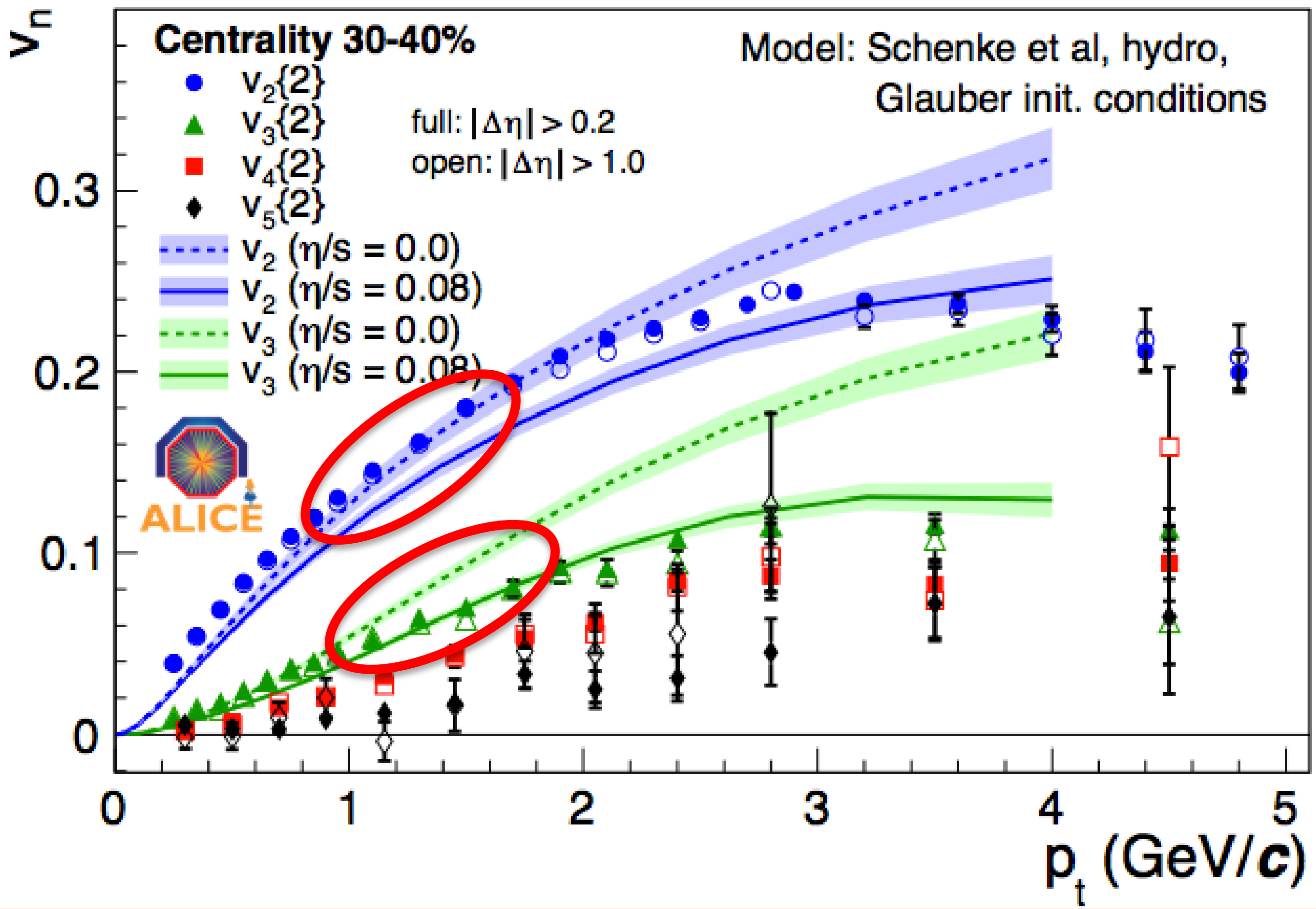
central

peripheral

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

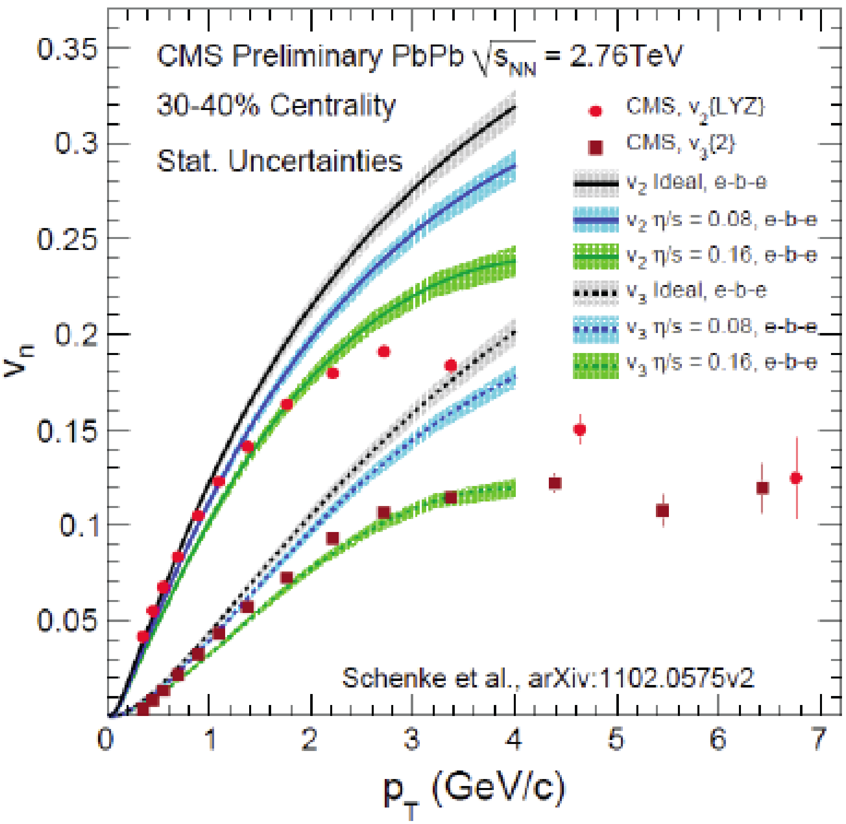
Higher harmonics

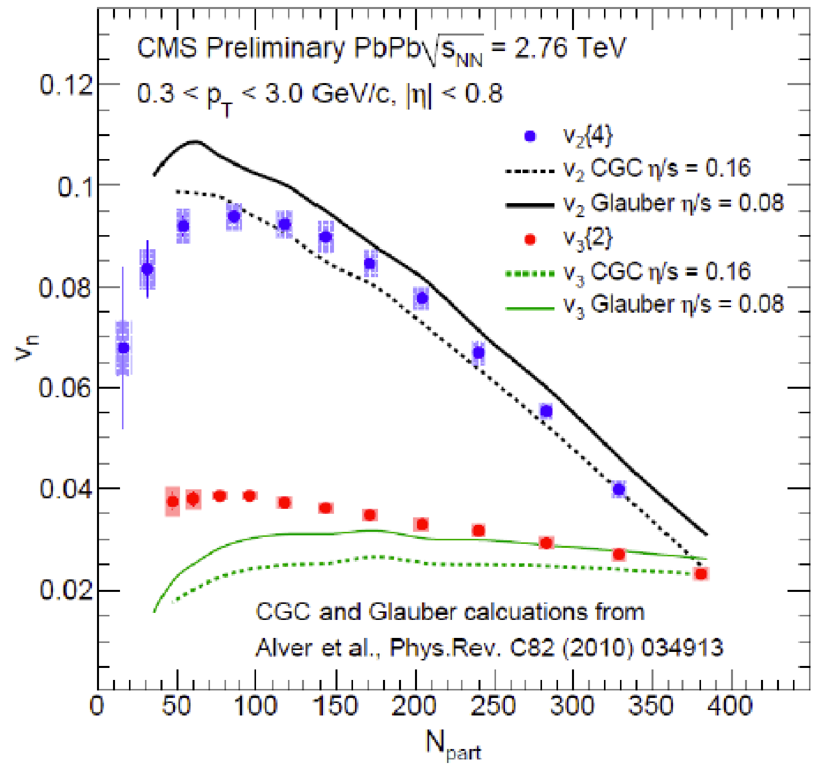
ALICE arXiv:1105.3865



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

CMS: similar ambiguities



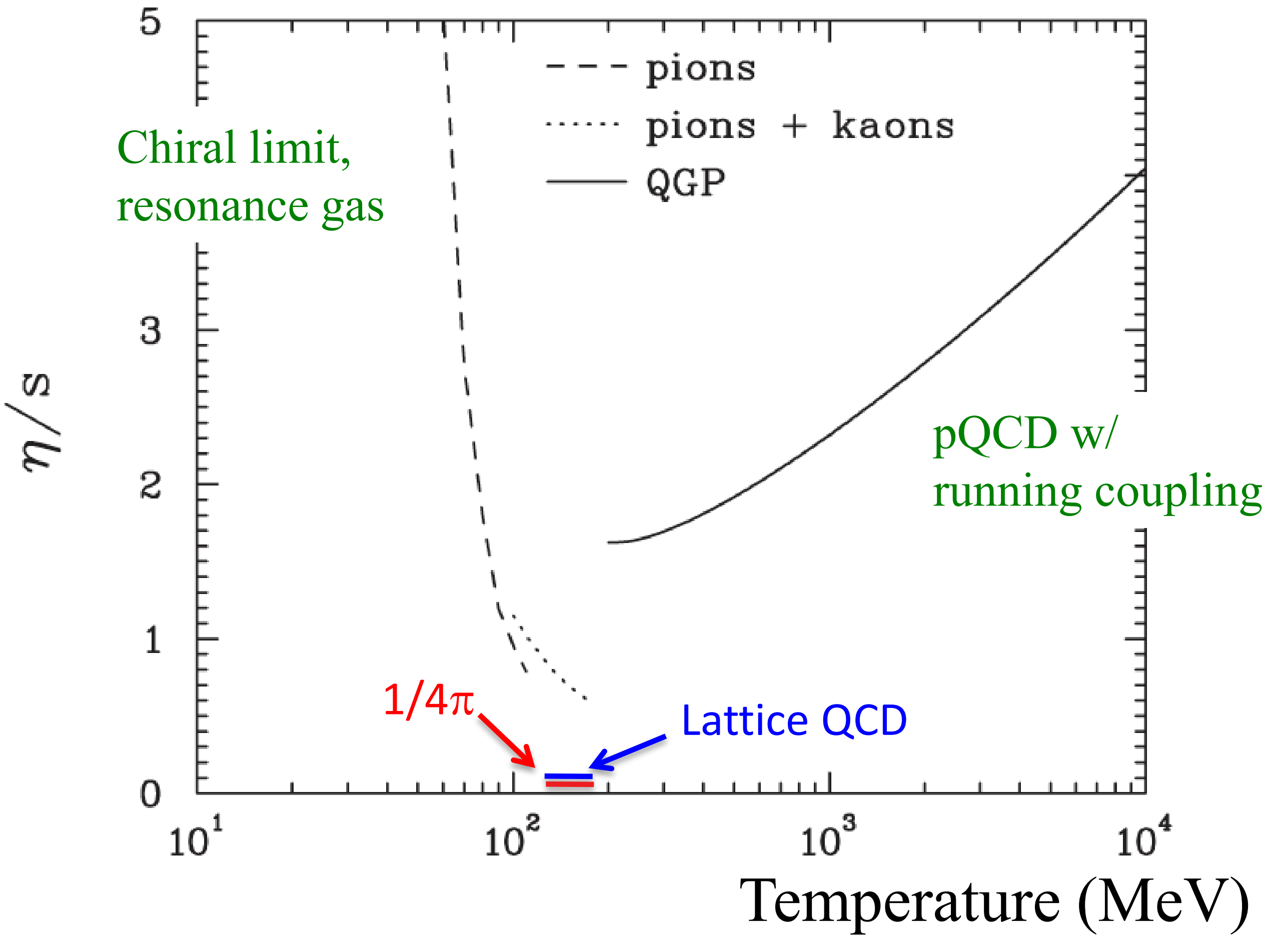


Qualitatively: η/s is within ~2-3 times 1/4π

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 $\eta/s(LHC) > \eta/s(RHIC)$

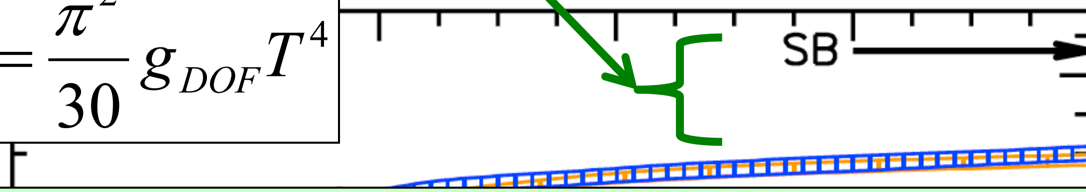
Remember this plot:

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)