

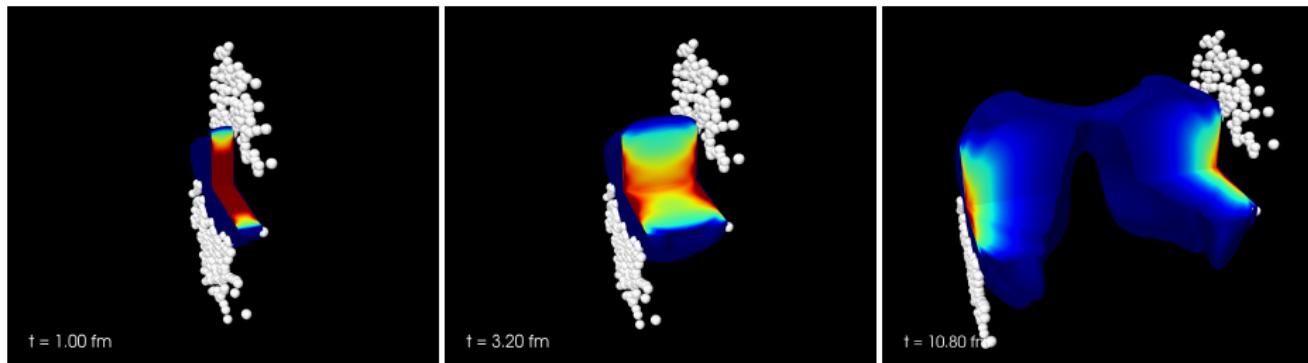
Fluid dynamical description of relativistic heavy ion collisions

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Initial Stages 2016

Search for QCD matter properties



Relativistic heavy ion collisions:

- Create small droplet of QCD fluid
- Extract limits for η/s , ζ/s , ... from experimental data

Need a complete model:

- Initial particle production
- Fluid dynamical evolution
- Convert fluid to particle spectra

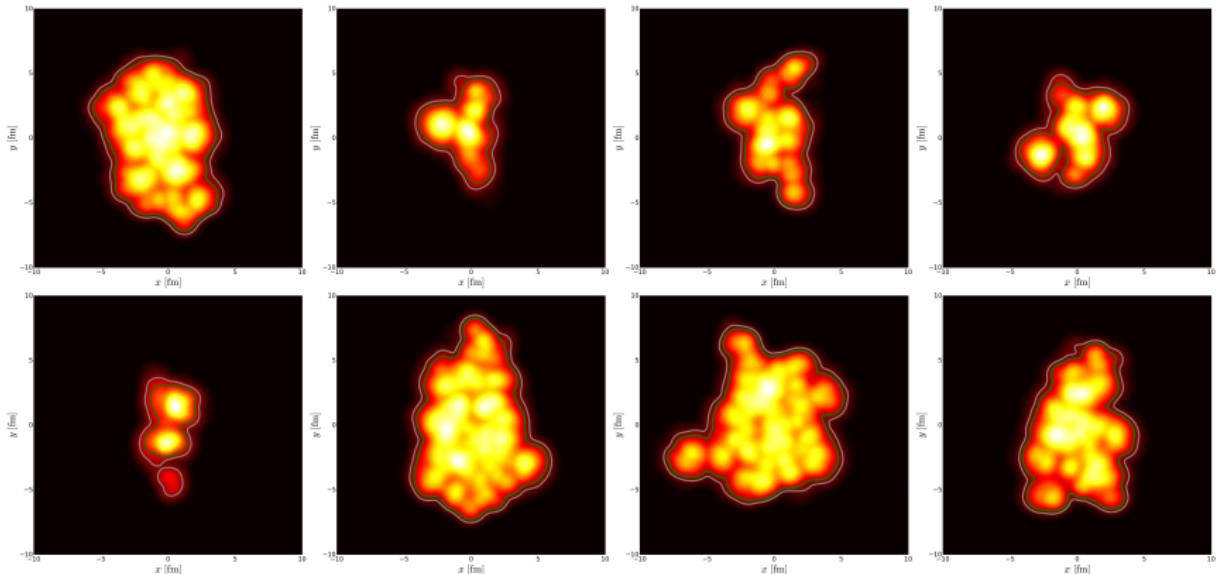
Fluid dynamics

- Fluid dynamics: power series in $\text{Re}^{-1} \sim |\pi^{\mu\nu}|/p$ and $\text{Kn} = \ell_{\text{micr}}/\text{L}_{\text{macr}}$.
- applicability: $\text{Re}^{-1} \lesssim 1$ and $\text{Kn} \lesssim 1$.
- Sufficiently close to equilibrium and gradients are sufficiently small

Fluid dynamical limit:
dynamics of the system is entirely controlled by a few macroscopic functions, $p(T)$, $\eta(T)$, ...

- All the microscopic information is integrated into these functions
- In principle can be calculated from the underlying microscopic theory

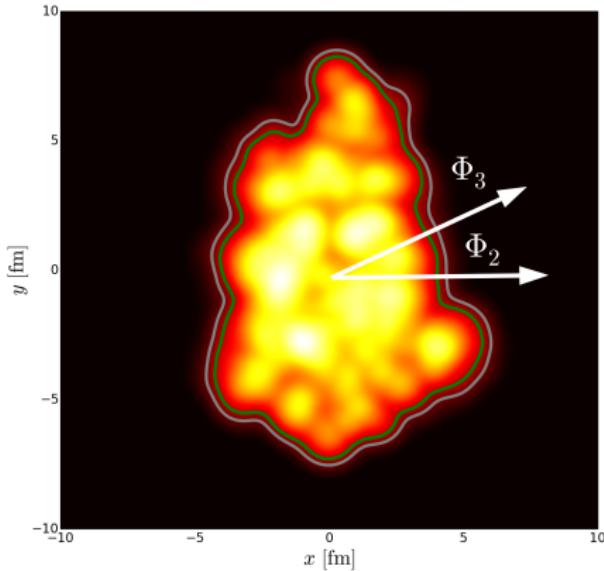
Initial states come in all shapes and sizes



Average over all events

Characterizing initial conditions

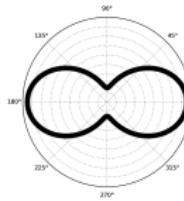
$$\varepsilon_n e^{in\Phi_n} = \{r^n e^{in\phi}\}$$



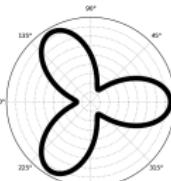
$$\{\dots\} = \int dx dy e(x, y, \tau_0) (\dots)$$

- ε_n eccentricity
- Φ_n "participant plane" angle

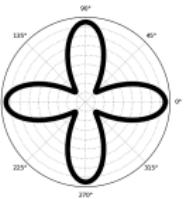
$n=2$



$n=3$



$n=4$

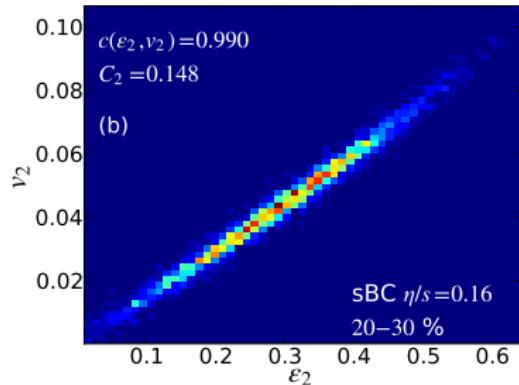
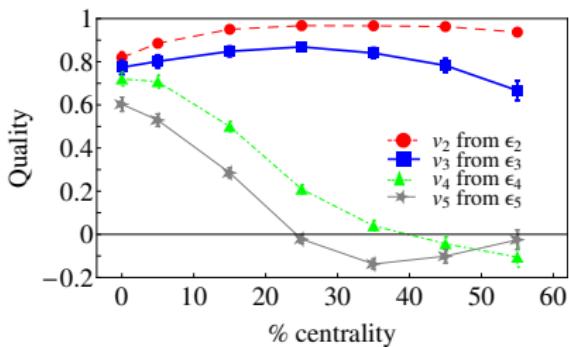


Fluid dynamics: $\varepsilon_n, \Phi_n \rightarrow v_n, \Psi_n$
(conversion efficiency depends on EoS, η/s , ...)

Flow fluctuations

Gardim, Grassi, Luzum and Ollitrault,
Nucl. Phys. A904-905 2013, 503c (2013)

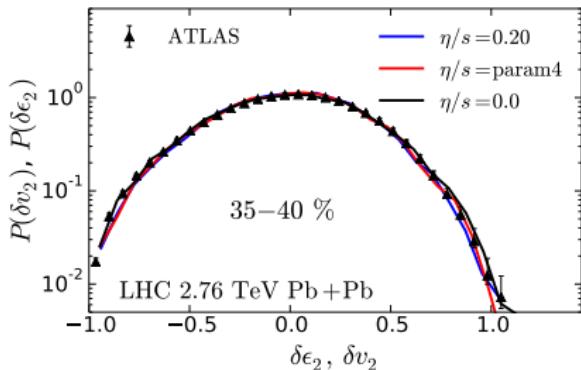
HN, Denicol, Holopainen, Huovinen, Phys. Rev. C 87,
054901 (2013)



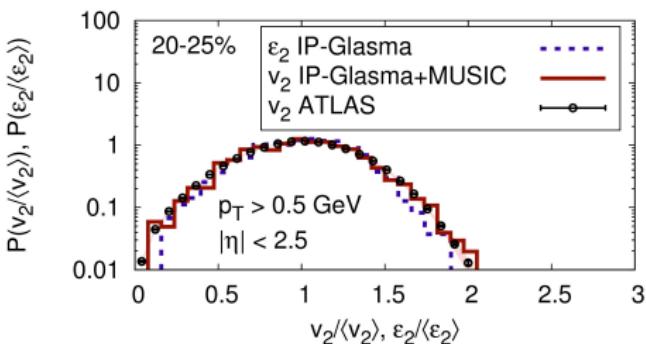
- Strong correlation between $v_{2/3}$ and $\epsilon_{2/3}$, i.e. $v_n \sim C_n \epsilon_n$
- Relative fluctuations of $\epsilon_n \rightarrow$ relative fluctuations of v_n ($n = 2, 3$)
- Probability distributions $P(v_n/\langle v_n \rangle) = P(\epsilon_n/\langle \epsilon_n \rangle)$

Fluctuations of Elliptic flow

HN, Eskola, Paatelainen, PRC 93, 024907 (2016)
 (EKRT)

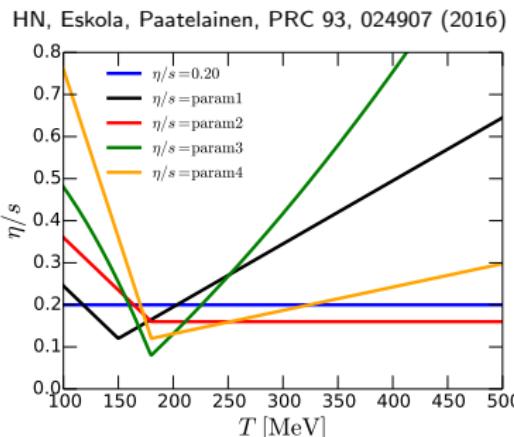
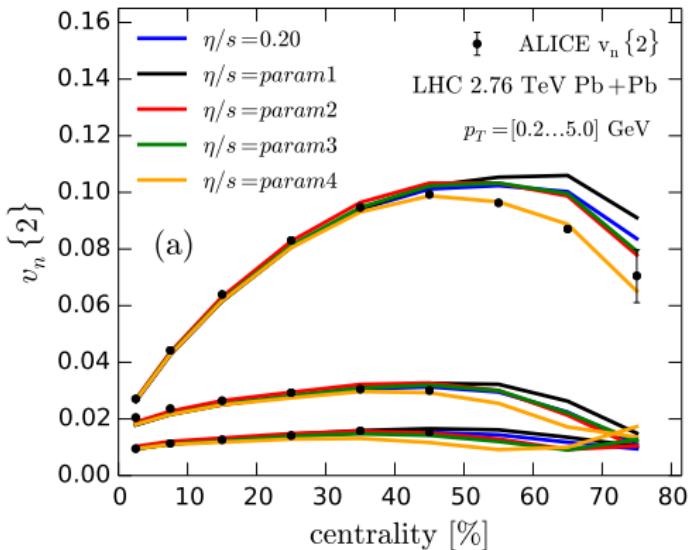


Gale, Jeon, Schenke, Tribedy, Venugopalan, Phys. Rev. Lett.
 110, 012302 (2013)
 (IP-Glasma)



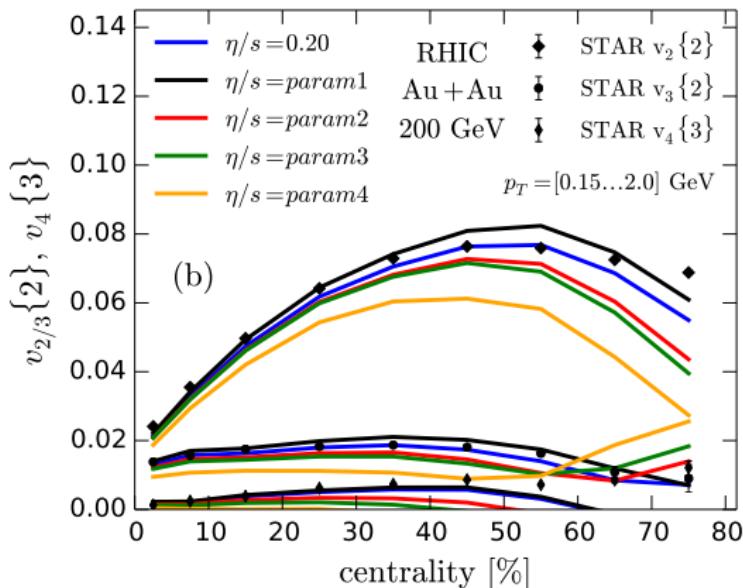
- in peripheral collisions non-linear correlation.
- Shows no sensitivity to η/s . (Note: average v_2 scaled out)
- Depend only on the initial state (good constraint)

$\eta/s(T)$ from v_n data

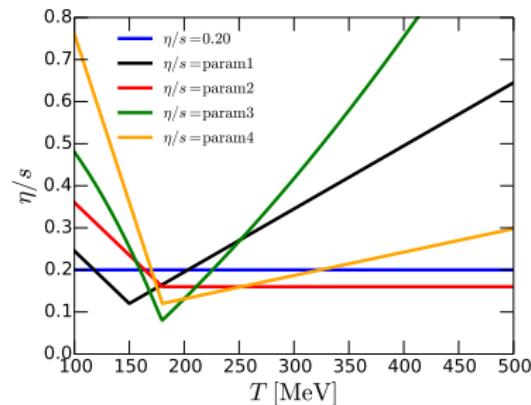


- $\eta/s(T)$ parametrizations tuned to reproduce the v_n data at the LHC.
- No strong constraints to the temperature dependence (all give equally good agreement)
- Deviations mainly in peripheral collisions, where the applicability of the framework most uncertain.

Constraints for $\eta/s(T)$ from RHIC v_n data



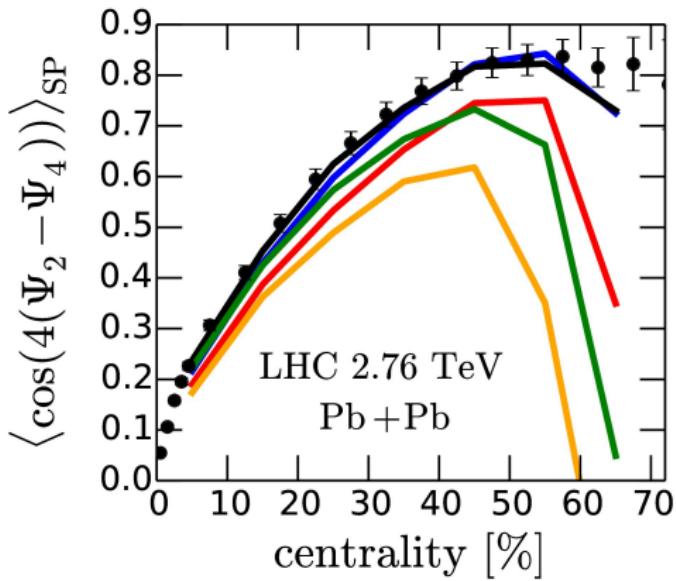
HN. Eskola, Paatelainen, PRC 93, 024907 (2016)



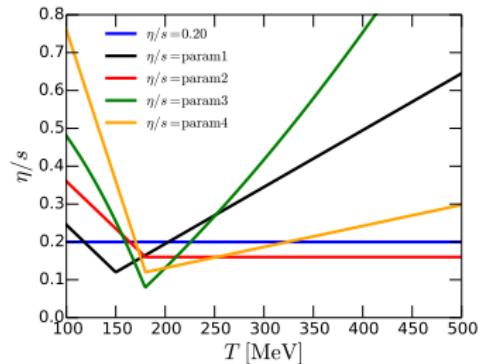
- Same $\eta/s(T)$ as at LHC.
 - Simultaneous fit constraints temperature dependence

$$v_4\{3\} \equiv \frac{\langle v_2^2 v_4 \cos(4 [\Psi_2 - \Psi_4]) \rangle_{ev}}{\langle v_2^2 \rangle_{ev}}.$$

Event-plane correlations

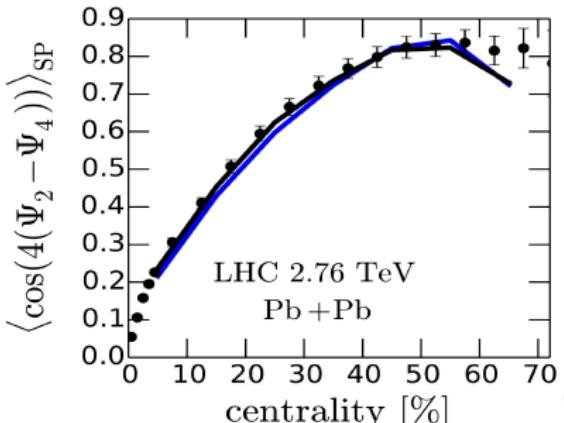
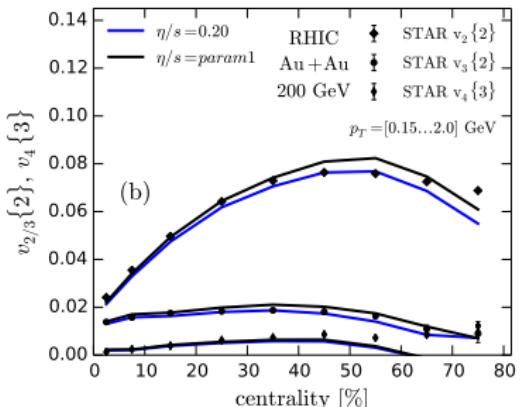
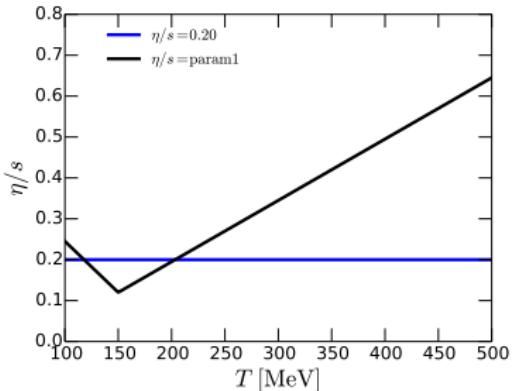
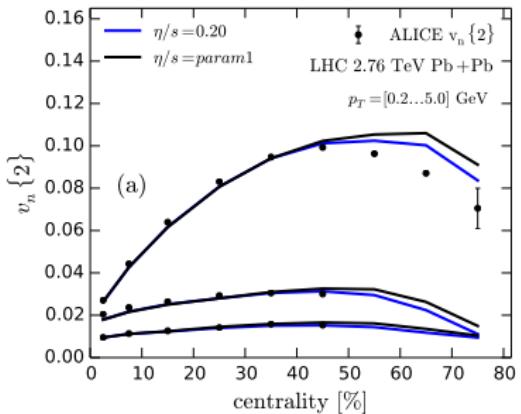


HN, Eskola, Paatelainen, PRC 93, 024907 (2016)



$$\langle \cos(k_1 \Psi_1 + \dots + n k_n \Psi_n) \rangle_{\text{SP}} \equiv \frac{\langle v_1^{|k_1|} \dots v_n^{|k_n|} \cos(k_1 \Psi_1 + \dots + n k_n \Psi_n) \rangle_{\text{ev}}}{\sqrt{\langle v_1^{2|k_1|} \rangle_{\text{ev}} \dots \langle v_n^{2|k_n|} \rangle_{\text{ev}}}}$$

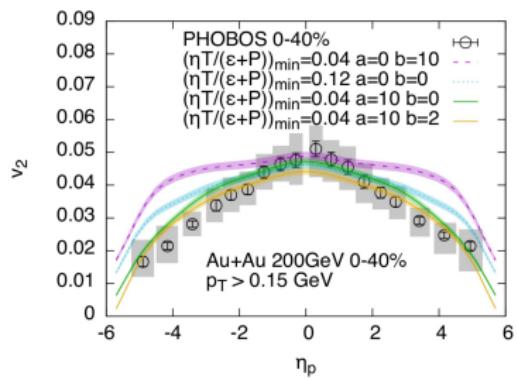
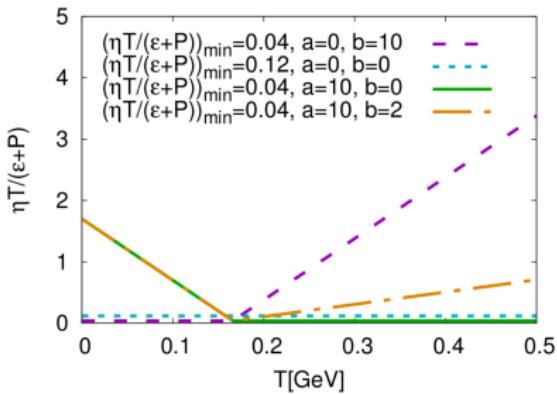
- Already from the LHC data more constraints to $\eta/s(T)$.
- Small hadronic viscosity needed to reproduce the data



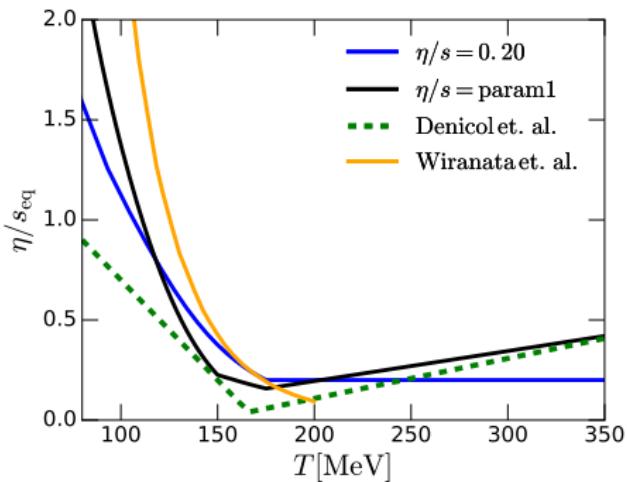
Rapidity dependent v_2

- Rapidity dependent v_2 gives constraints especially for low temperature (hadronic) η/s
- The data clearly favors large hadronic η/s

Denicol, Monnai, Schenke, arXiv:1512.01538 [nucl-th]



Temperature dependent η/s and chemistry



- Microscopic calculations of hadronic $\eta/s(T)$: strong increase with decreasing T .

Wiranata, Koch, Prakash, Wang, Phys.Rev. C88 (2013)
no.4, 044917

- EKRT (small) hadronic η/s in chemically frozen hadron gas (PCE).
- Denicol et. al. hadrons in chemical equilibrium (CE)

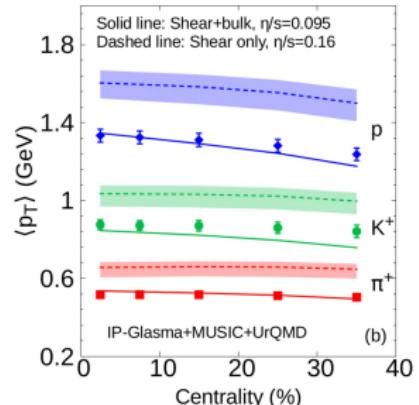
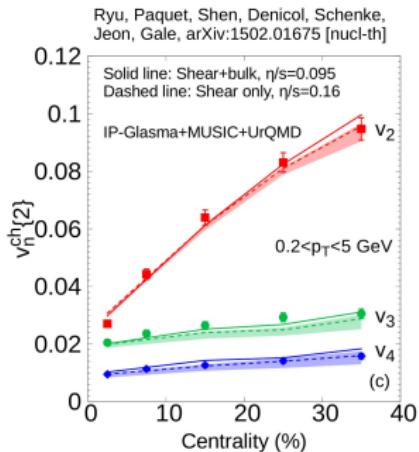
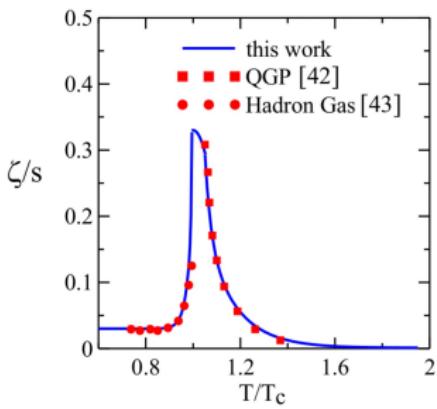
Estimate $\eta/s(T)$ in chemical equilibrium:

$$\eta/s_{\text{CE}} = (\eta/s_{\text{PCE}}) \times \left(\frac{s_{\text{PCE}}}{s_{\text{CE}}} \right)$$

using $\eta_{\text{CE}} \sim \eta_{\text{PCE}}$ (Wiranata, Prakash, Huovinen, Wang, J.Phys.Conf.Ser. 535 (2014) 012017)

Bulk viscosity

- Bulk viscosity can be large near the QCD transition
- Large bulk viscosity affects the determination of η/s
- Helps to reduce average p_T (important especially at LHC energies)

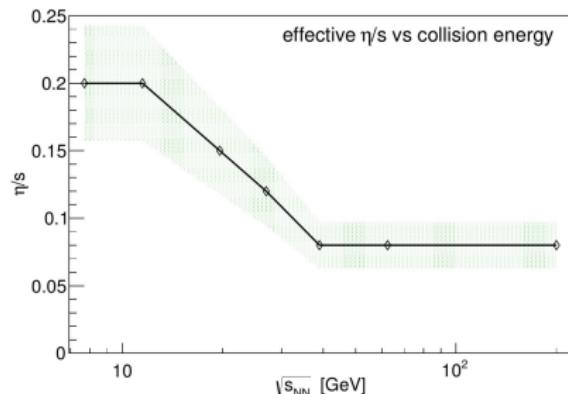
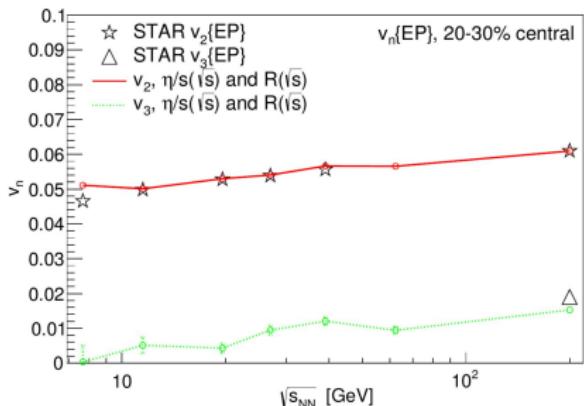


Beam Energy scan

- More constraints to the hadronic properties of the matter
- Important background in determining the QGP properties
- Here constant η/s fitted separately for each \sqrt{s}

Evidence for temperature and/or net-baryon density dependence of η/s ?

Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher, Phys.Rev. C91 (2015) 6, 064901

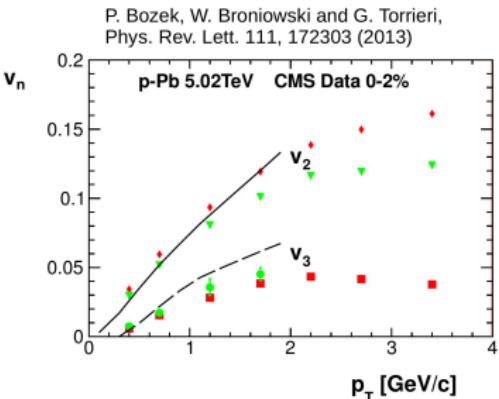
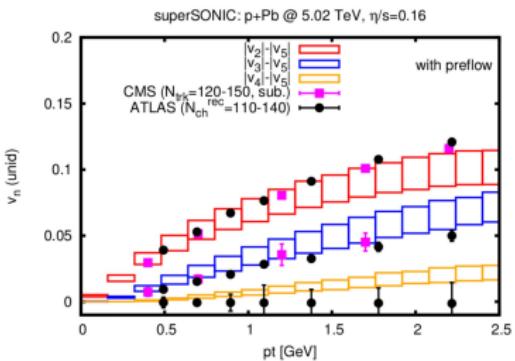


p+Pb collisions

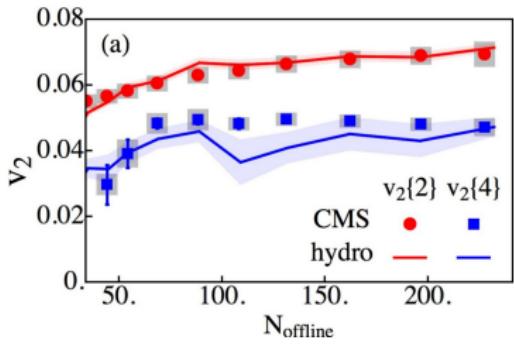
- Can be described by using hydrodynamics
 - Typically η/s small $O(0.08)$
 - Inconsistency with AA results with saturation based initial conditions
 $\eta/s \sim 0.20$

Is hydrodynamics valid?

Romatschke, Eur.Phys.J. C75 (2015) no.7, 305



Kozlov, Luzum, Denicol, Jeon, Gale, Nucl. Phys. A931 (2014)



Global fits and emulators

Hydrodynamical behavior: All the different system described by the same equation of state and transport coefficients:

$$\eta/s(T, \{\mu_i\}), \zeta/s(T, \{\mu_i\}), p(T, \{\mu_i\}), \dots$$

Different collisions at different collision energies probe different regions of temperature and densities.

Call for global analysis

Computationally very expensive
(mainly because many observables require event-by-event analysis)

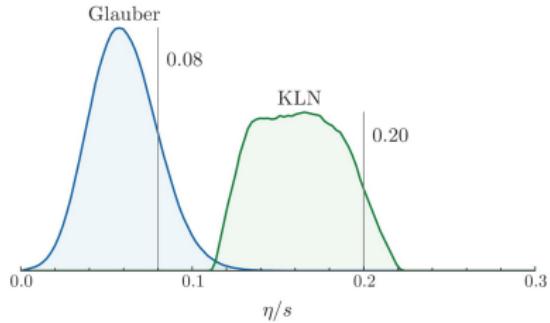
Solution: Emulators

Novak, Novak, Pratt, Vredevoogd, Coleman-Smith, Wolpert, Phys.Rev. C89 (2014) no.3, 034917

Global fits and emulators

- Calculate large number of collision events with random choices for the parameters (avoid huge number of runs)
- Emulator: (essentially) interpolate between the runs
- Start from the equal probability for each of the free parameters.
- Weight with the probability of describing the actual measurements
- Here separately for two different types of initial conditions.

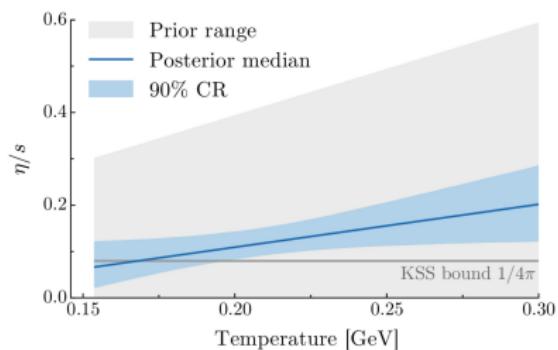
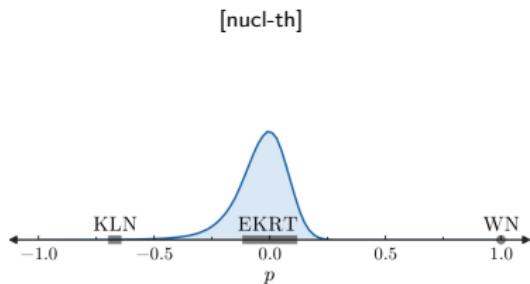
Bernhard, Marcy, Coleman-Smith, Huzurbazar, Wolpert, Bass
Phys. Rev. C91, 054910 (2015)



Global fits and emulators

- Continuous parametrization of initial states (TRENTO) from KLN to Glauber wounded nucleon model
- Temperature dependent η/s + UrQMD
- dN/dy , $\langle p_T \rangle$ and v_n (RHIC 200 GeV and LHC 2.76 TeV)

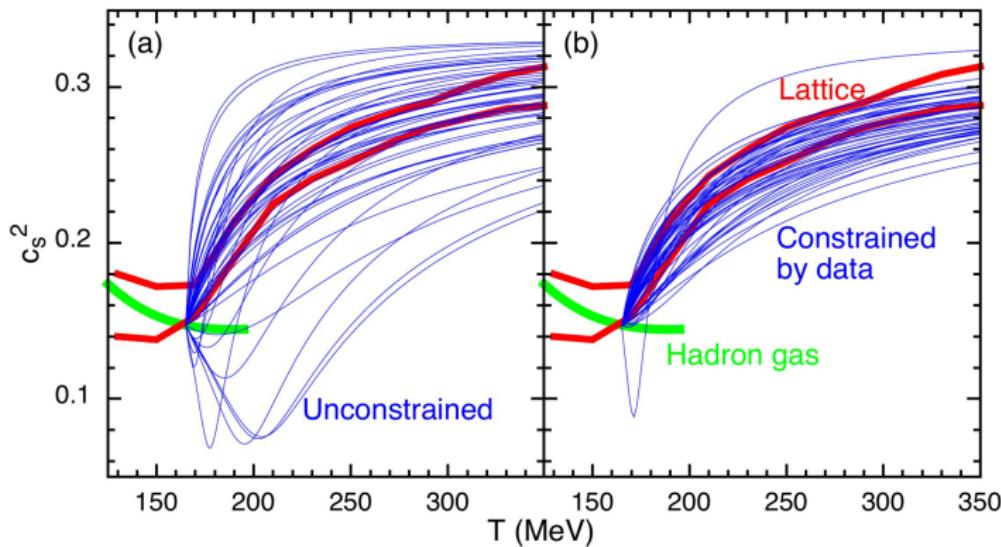
Bernhard, Moreland, Bass, Liu, Heinz, arXiv:1605.03954



Constraining the equation of state

Similar work with emphasis in constraining EoS

Scott Pratt, Evan Sangaline, Paul Sorensen, Hui Wang. Phys. Rev. Lett. 114 (2015) 202301



Summary

- The magnitude, fluctuations and correlations of the flow coefficients in wide variety of systems can be described using relativistic hydrodynamics
- At least between some systems (top RHIC energy and the LHC) it is possible to find consistent description (same EoS, transport coefficients)
- These findings suggest that we indeed create a small droplet of fluid in AA collisions, and that at least the minimum value of η/s is small
- Temperature dependence of η/s not yet so well constrained
- Applicability limits of fluid dynamics still not known (does it work in pA?)
- Bulk viscosity is not yet well constrained, but apparently non-zero
- Emulators make global statistical analysis feasible

Transient Fluid Dynamics (Israel & Stewart)

$$\pi^{\mu\nu} = 2\eta \nabla^{\langle\mu} u^{\nu\rangle}$$



$$\tau_\pi \frac{d}{d\tau} \pi^{\langle\mu\nu\rangle} + \pi^{\mu\nu} = 2\eta \nabla^{\langle\mu} u^{\nu\rangle} - c_1 \tau_\pi \pi^{\mu\nu} \nabla_\lambda u^\lambda - c_2 \tau_\pi \pi_\lambda^{\langle\mu} \sigma^{\nu\rangle\lambda} + \dots$$

- Transient: $\pi^{\mu\nu} \rightarrow 2\eta \nabla^{\langle\mu} u^{\nu\rangle} + O(2)$ with timescale τ_π
- $\pi^{\mu\nu}/p \sim \text{Re}^{-1}$ inverse Reynolds number: measures deviations from equilibrium
- $\tau_\pi \nabla_\lambda u^\lambda \sim \text{Kn}$ Knudsen number: measures separation between microscopic scales (τ_π) and macroscopic scales ($\nabla_\lambda u^\lambda = \text{volume expansion rate}$)
- $O(1) \times O(1) = O(2)$ Second order fluid dynamics
- linearly stable and causal
- c_n e.g. from kinetic theory ([Denicol,Niemi,Molnar,Rischke,PRD85(2012)114047])

Converting fluid to particles (Freeze-out)

$$e, u^\mu, \pi^{\mu\nu} \longrightarrow E \frac{dN}{d^3\mathbf{p}}$$

- Standard Cooper-Frye freeze-out for particle i

$$E \frac{dN}{d^3\mathbf{p}} = \frac{g_i}{(2\pi)^3} \int d\sigma^\mu p_\mu f_i(\mathbf{p}, x),$$

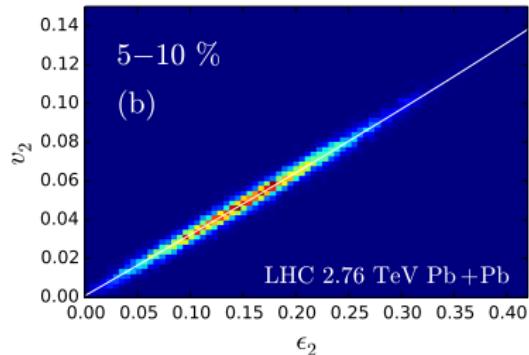
where

$$f_i(\mathbf{p}, x) = f_{i,\text{eq}}(\mathbf{p}, u^\mu, T, \{\mu_i\}) \left[1 + \frac{\pi^{\mu\nu} p_\mu p_\nu}{2T^2(e + p)} \right]$$

- Integral over constant temperature hypersurface (decoupling surface)
- Decays of unstable hadrons

(non)linear-response?

5-10 %



55-60 %

