Extracting Effective Viscosities from heavy ion collisions

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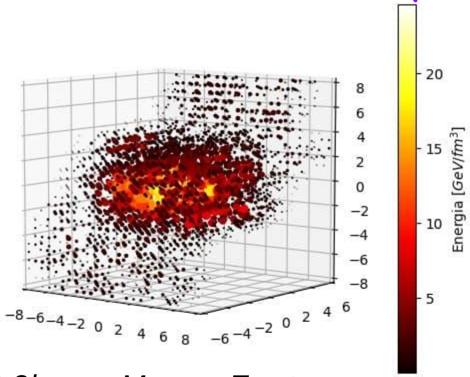
Based on 2010.11919, with J-Y. Ollitrault,
Phys. Rev. C 103, 044907 (2021)

Krakow (online) – 7 th April 2022

Relativistic Hydro and QGP

(1) Initial Conditions (QGP)



NeXus, IP-Glasma, Magma, Trento ….

Fig by L. Barbosa

(2) Hydro Evolution

$$\partial_\mu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = T_0^{\mu\nu} - \Pi^{\mu\nu}$$

Ideal → $T_0^{\mu\nu} = (e + P)u^\mu u^\nu - g^{\mu\nu} P$

Viscous → $\Pi^{\mu\nu} = \eta\sigma^{\mu\nu} + \zeta\Delta^{\mu\nu}\nabla_\lambda u^\lambda + \mathcal{O}(\partial^2)$

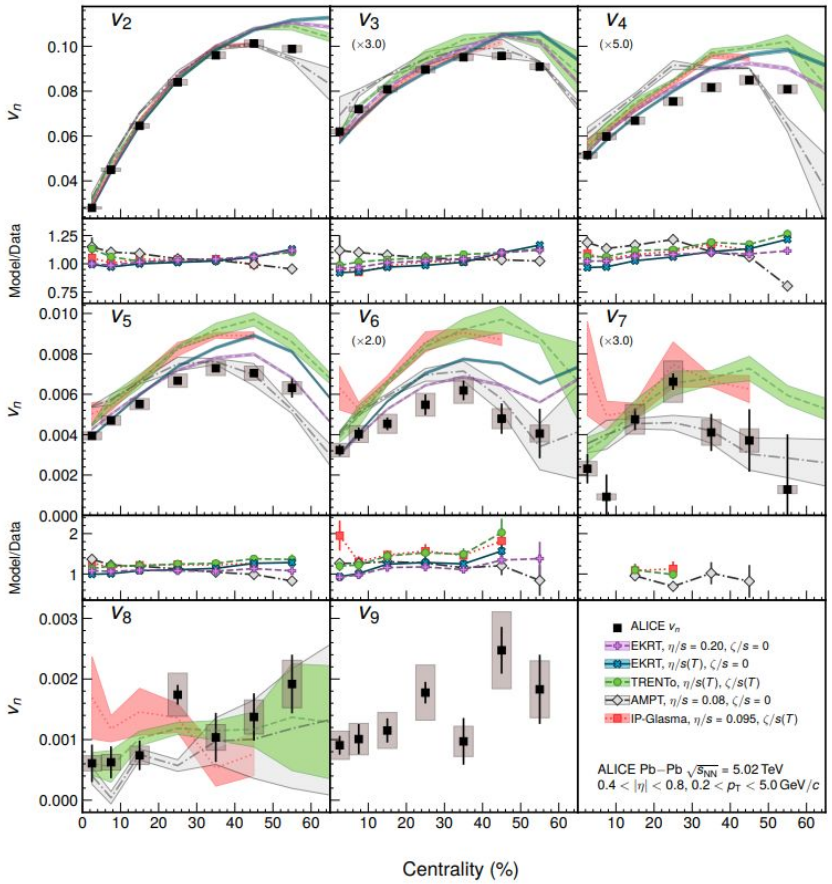
shear

bulk

(3) Hadronization:

When expanding, temperature and densities decrease, until the moment of emitting particles: Cooper-Frey, URQMD, AfterBurner ……. then we have a spectrum of emitted particles

Anisotropic flow: Experiment versus hydro



Nice agreement with data provided that viscous corrections are included.

One of the goals of heavy ion physics is to extract the viscosity from experimental data

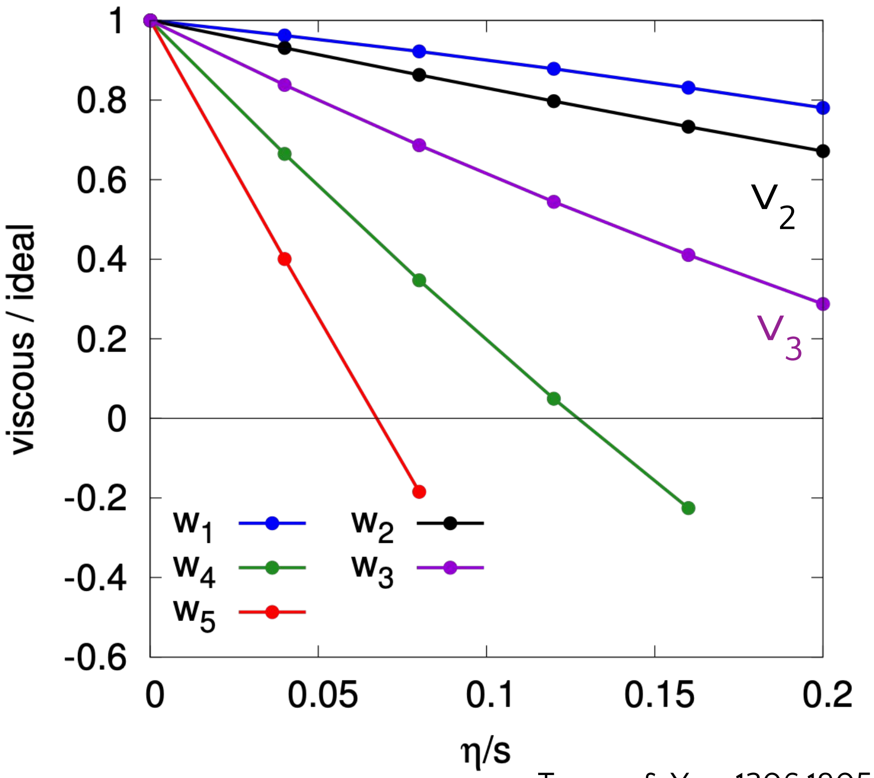
S. Acharya et al. [ALICE], JHEP 05, 085 (2020)
arXiv:2002.00633

This Talk

(1) I show that from v_2 and v_3 data at a given energy, one cannot infer the whole temperature dependence of $\left(\frac{\eta}{s}\right)$ and $\left(\frac{\zeta}{s}\right)$, but only weighted averages, which I denote by effective viscosities.

(2) I then estimate the values of these effective viscosities using first-principles QCD calculations, and compare with the values inferred from data.

Effect of CONSTANT $\frac{\eta}{s}$ on anisotropic flow



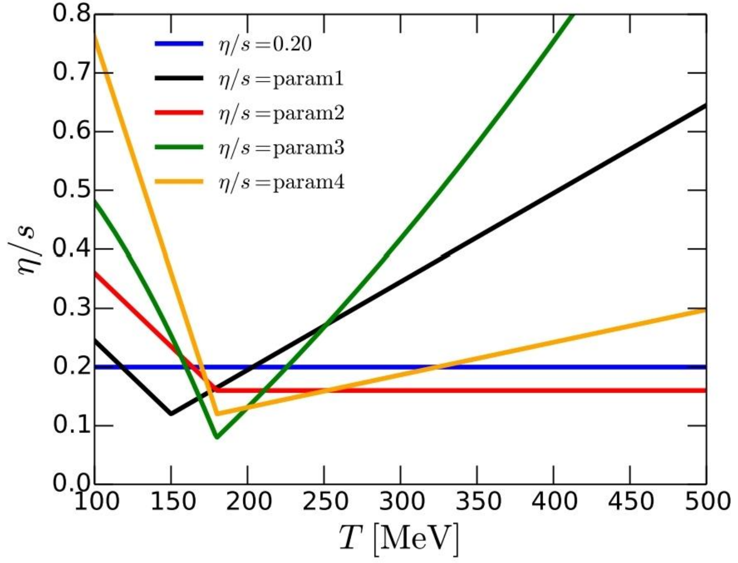
Teaney & Yan 1206.1905

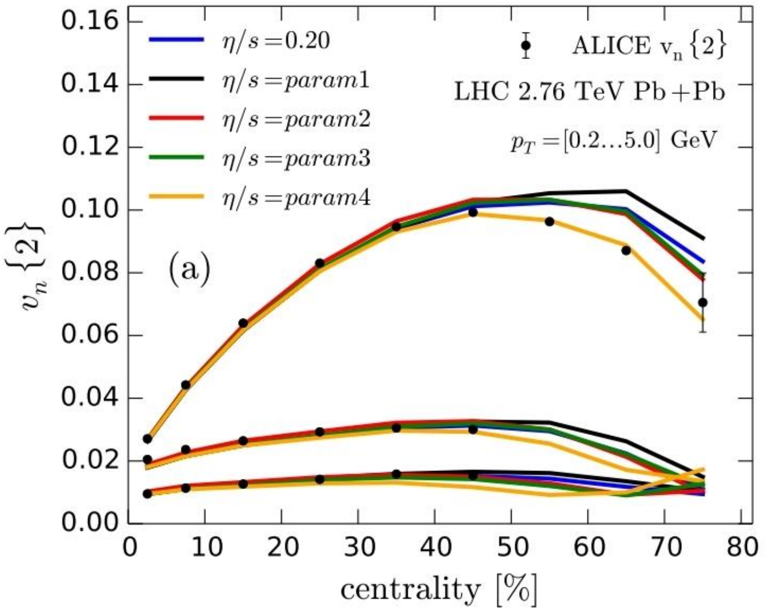
There is a decrease in the anisotropic flows , which depend on the intensity of viscosity.

The damping is approximately linear!

Effect of NOT CONSTANT $\frac{\eta}{s}$ on anisotropic flow

H. Niemi et. al PRC 93, 024907 (2016)





DIFFERENT PARAMETRIZATIONS, HOWEVER, ALMOST THE SAME V'S

F.G & JY Ollitrault PRC 103 (2021) 4, 044907

Probing viscous damping

For temperature-dependent viscosities, the condition that the damping is linear in the viscosity can be rewritten as

$$\frac{v_n(viscous)}{v_n(ideal)} - 1 \approx \int dT \left(w_n^{\eta}(T)\frac{\eta}{s}(T) + w_n^{\zeta}(T)\frac{\zeta}{s}(T) \right)$$

$$w(T) = w_f \delta(T - T_f) + \frac{a_0 + a_1 T + a_2 T^2}{1 + b_1 T + b_2 T^2 + b_3 T^3}$$

determined using viscous hydrodynamic calculations.

Freeze-out contribution: discrete

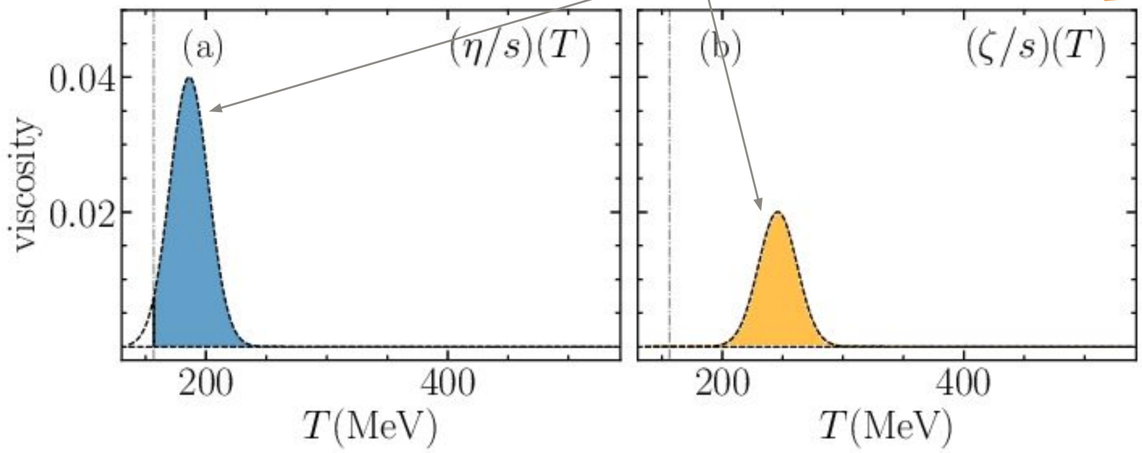
hydro contribution: smooth

Probing viscous damping

$$\frac{v_n(viscous)}{v_n(ideal)} - 1 \approx \int dT \left(w_n^{\eta}(T)\frac{\eta}{s}(T) + w_n^{\zeta}(T)\frac{\zeta}{s}(T) \right)$$

How to determine w's?

Switch on shear/bulk viscosity only in a narrow temperature interval around a temperature T_0. In this way, we isolate the effect of viscosity around T_0.

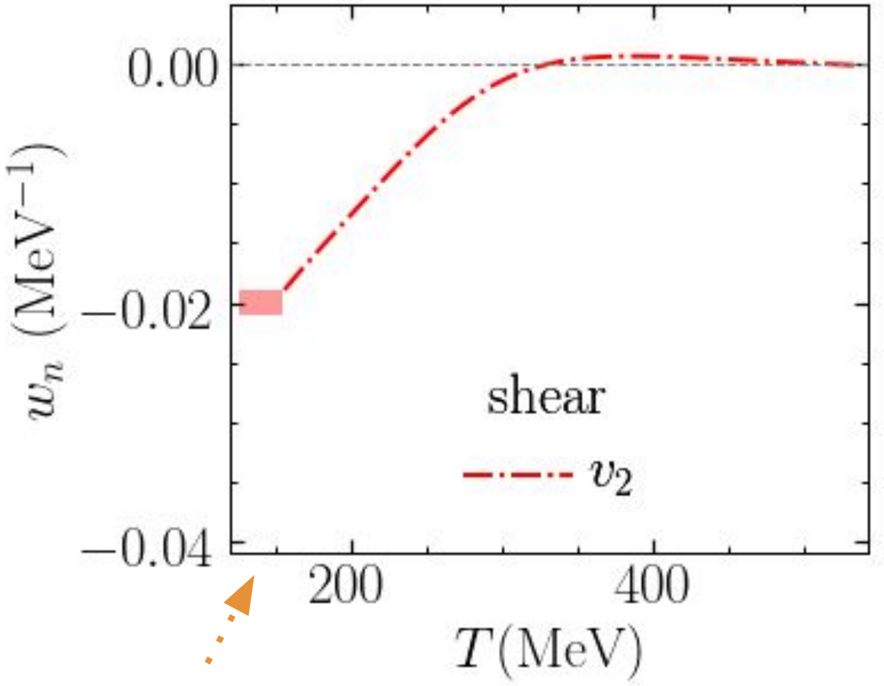


Then, repeat the calculation for values of T_0 spanning the relevant range.

Investigating the same IC (ideal and viscous), through a Gaussian parameterization.
COMPUTATION: boost invariant - MUSIC - hadrons at freeze-out after resonance decays @ LHC

Where is viscosity relevant?

Where is viscosity relevant?



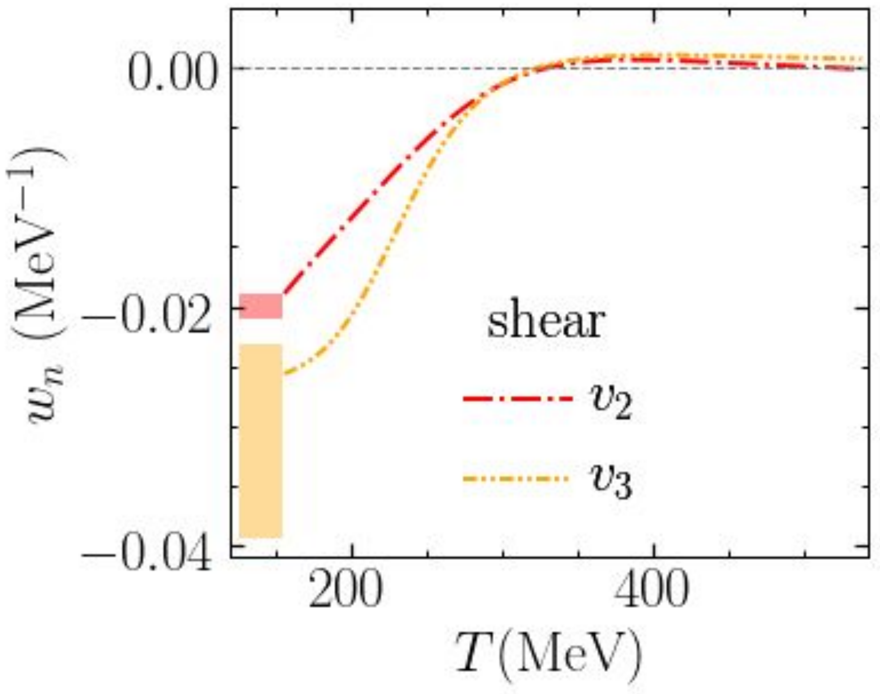
Viscous correction at Tf

$$\frac{v_n(viscous)}{v_n(ideal)} - 1 \approx \int dT\left(w_n^{\eta}(T)\frac{\eta}{s}(T) + w_n^{\zeta}(T)\frac{\zeta}{s}(T)\right)$$

SHEAR v_2

- w<0: Suppression.
- Largest in absolute value at low temperature

Where is viscosity relevant?

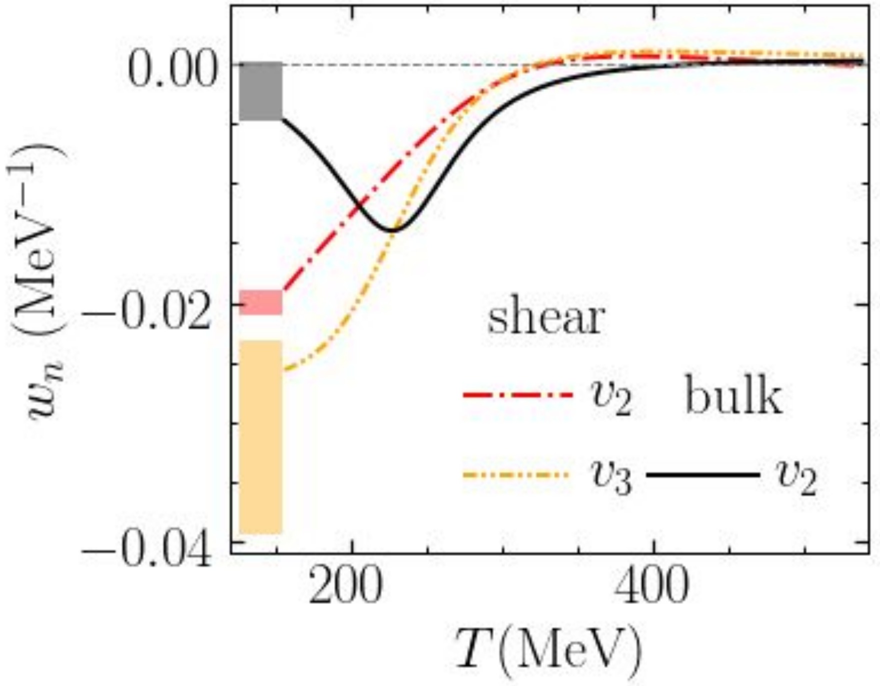


$$\frac{v_n(viscous)}{v_n(ideal)} - 1 \approx \int dT\left(w_n^{\eta}(T)\frac{\eta}{s}(T)+w_n^{\zeta}(T)\frac{\zeta}{s}(T)\right)$$

SHEAR v_3

- w<0: Suppression.
- Similar temperature dependence
- Weight larger in absolute value

Where is viscosity relevant?

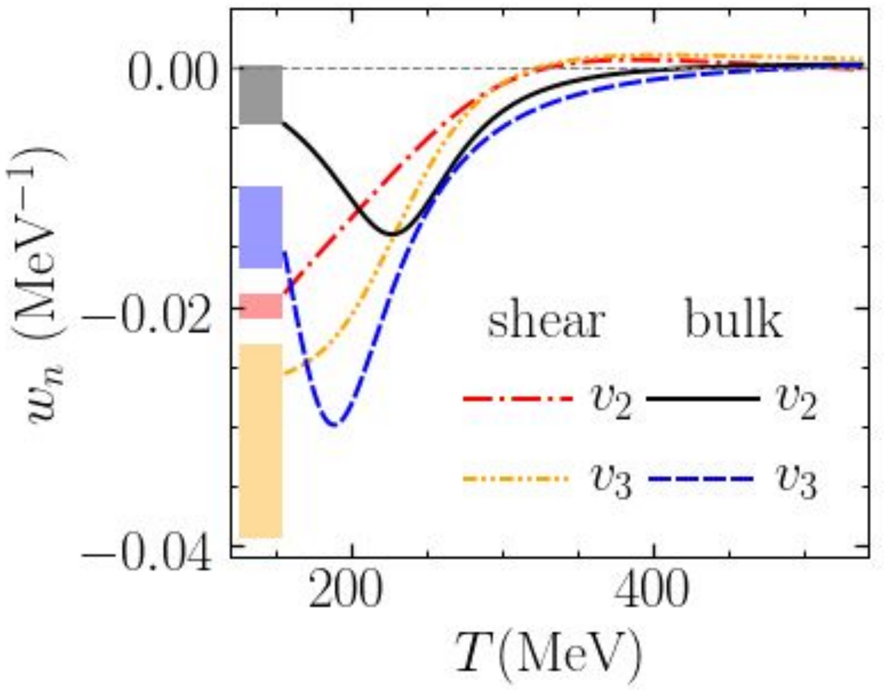


$$\frac{v_n(viscous)}{v_n(ideal)} - 1 \approx \int dT\left(w_n^{\eta}(T)\frac{\eta}{s}(T) + w_n^{\zeta}(T)\frac{\zeta}{s}(T)\right)$$

BULK v_2

- w<0: Suppression.
- Magnitude is of the same order as for shear
- Different temperature dependence. Peak around 220 MeV

Where is viscosity relevant?



$$\frac{v_n(viscous)}{v_n(ideal)} - 1 \approx \int dT(w_n^{\eta}(T)\frac{\eta}{s}(T)+w_n^{\zeta}(T)\frac{\zeta}{s}(T))$$

BULK v_3

- w<0: Suppression.
- similar temperature dependence as bulk v_2
- Peak around 200 MeV

Effective Viscosities

$$v_2(viscous) = v_2(ideal)\left(1 - 1.34\left(\frac{\eta}{s}\right)_{2,\mathrm{eff}} - 1.30\left(\frac{\zeta}{s}\right)_{2,eff}\right)$$

$$v_3(viscous) = v_3(ideal)\left(1 - 2.33\left(\frac{\eta}{s}\right)_{3,\mathrm{eff}} - 2.61\left(\frac{\zeta}{s}\right)_{3,eff}\right)$$

$$\left(\frac{\eta}{s}\right)_{n,\mathrm{eff}} = \frac{\int_{T_f}^{\infty}(\eta/s)(T)w_n^{(\eta)}(T)dT}{\int_{T_f}^{\infty}w_n^{(\eta)}(T)dT}$$

$$\left(\frac{\zeta}{s}\right)_{n,\mathrm{eff}} = \frac{\int_{T_f}^{\infty}(\zeta/s)(T)w_n^{(\zeta)}(T)dT}{\int_{T_f}^{\infty}w_n^{(\zeta)}(T)dT}$$

Effective Viscosities

$$v_2(viscous) = v_2(ideal)\left(1 \boxed{-1.34}\left(\frac{\eta}{s}\right)_{2,\mathrm{eff}} \boxed{-1.30}\left(\frac{\zeta}{s}\right)_{2,eff}\right)$$

$$v_3(viscous) = v_3(ideal)\left(1 \boxed{-2.33}\left(\frac{\eta}{s}\right)_{3,\mathrm{eff}} \boxed{-2.61}\left(\frac{\zeta}{s}\right)_{3,eff}\right)$$

$$\left(\frac{\eta}{s}\right)_{n,\mathrm{eff}} = \frac{\int_{T_f}^{\infty}(\eta/s)(T)w_n^{(\eta)}(T)dT}{\boxed{\int_{T_f}^{\infty} w_n^{(\eta)}(T)dT}}$$

$$\left(\frac{\zeta}{s}\right)_{n,\mathrm{eff}} = \frac{\int_{T_f}^{\infty}(\zeta/s)(T)w_n^{(\zeta)}(T)dT}{\boxed{\int_{T_f}^{\infty} w_n^{(\zeta)}(T)dT}}$$

Effective Viscosities

$$v_2(viscous) = v_2(ideal)\left(1 - 1.34\left(\frac{\eta}{s}\right)_{2,\mathrm{eff}} - 1.30\left(\frac{\zeta}{s}\right)_{2,eff}\right)$$

$$v_3(viscous) = v_3(ideal)\left(1 - 2.33\left(\frac{\eta}{s}\right)_{3,\mathrm{eff}} - 2.61\left(\frac{\zeta}{s}\right)_{3,eff}\right)$$

The variation of v_n due to viscosity is proportional to the sum of effective shear and bulk viscosities.

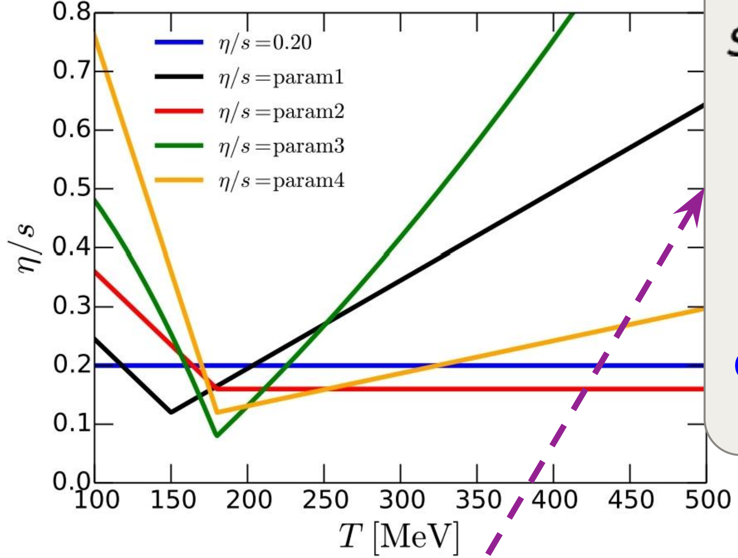
Viscous suppression is a factor ~2 larger for v_3 than v_2.

Viscous suppression for bulk is of same order as for shear

v_n data can only constrain the effective viscosity, not the whole temperature dependence.

Effective Viscosity: An Example

H. Niemi et. al PRC 93, 024907 (2016)



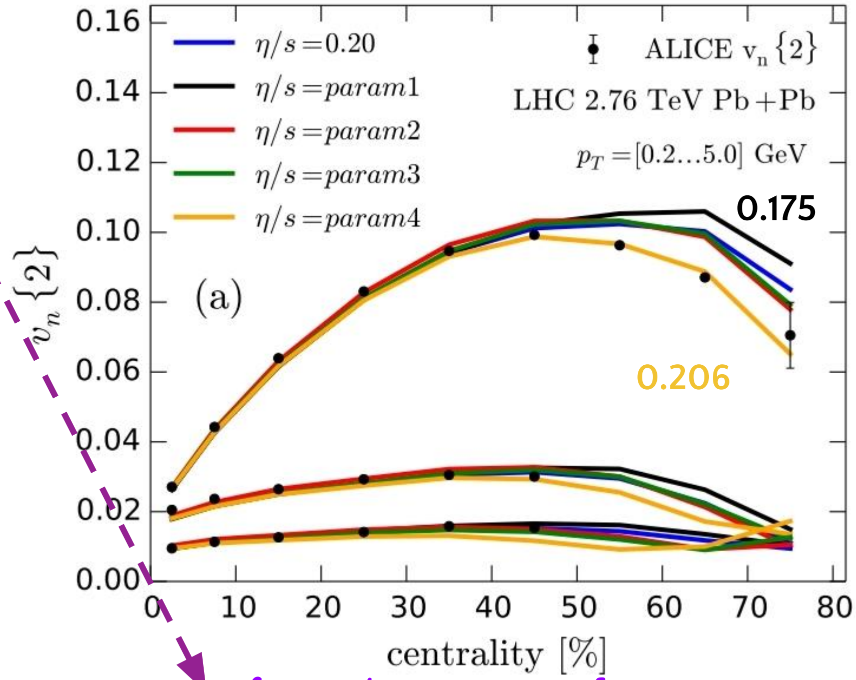
$\left.\frac{\eta}{s}\right|_{2,effec}$

0.175

0.206

0.2

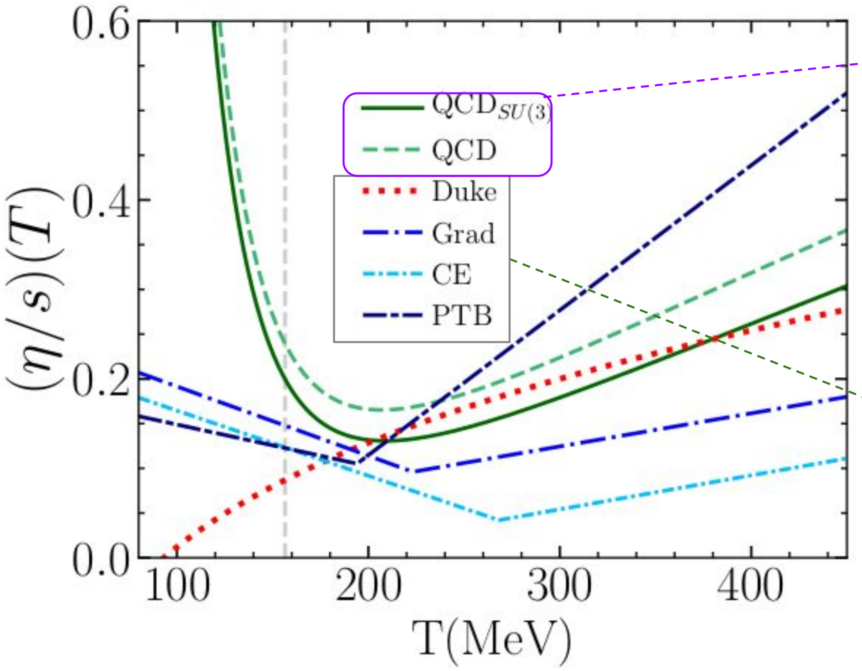
0.184



Similar Effective Viscosity

Same Anisotropic Flow

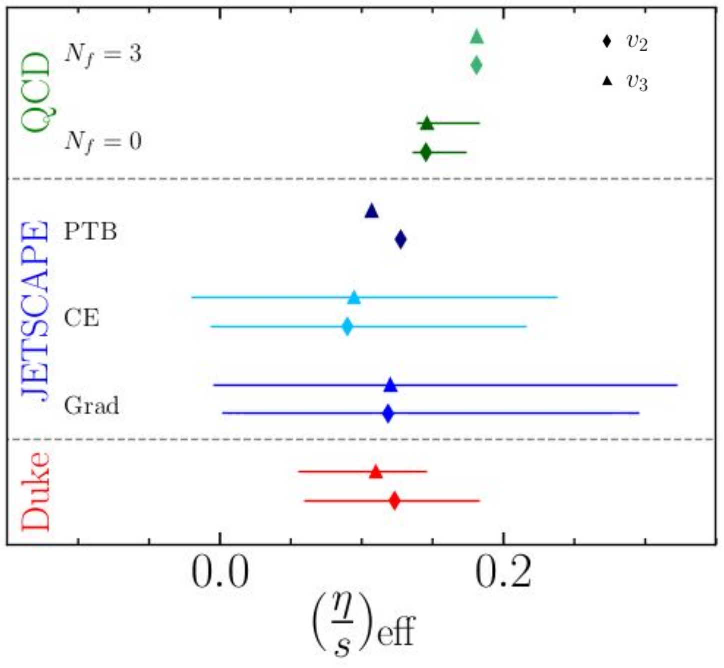
What is the expected value of the effective SHEAR viscosity in QCD?



from QCD calculations

from heavy ion data

What is the expected value of the effective SHEAR viscosity in QCD?

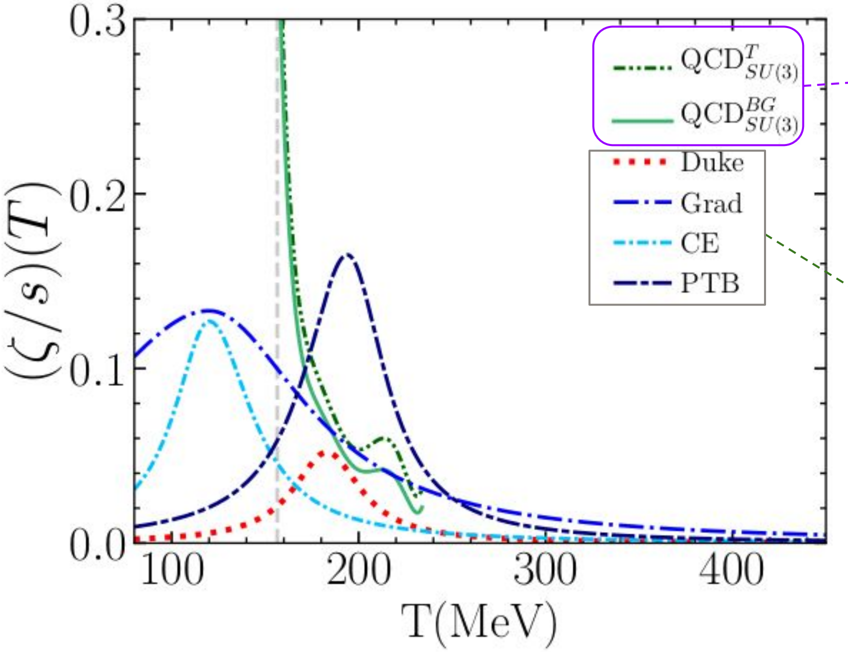


Error bars: 90% posterior

- From QCD calculations, one expects that the effective shear is essentially identical for v2 and v3

- Effective shear viscosity extracted from Bayesian analyses of heavy ion data is compatible with that from QCD calculations, but somewhat smaller

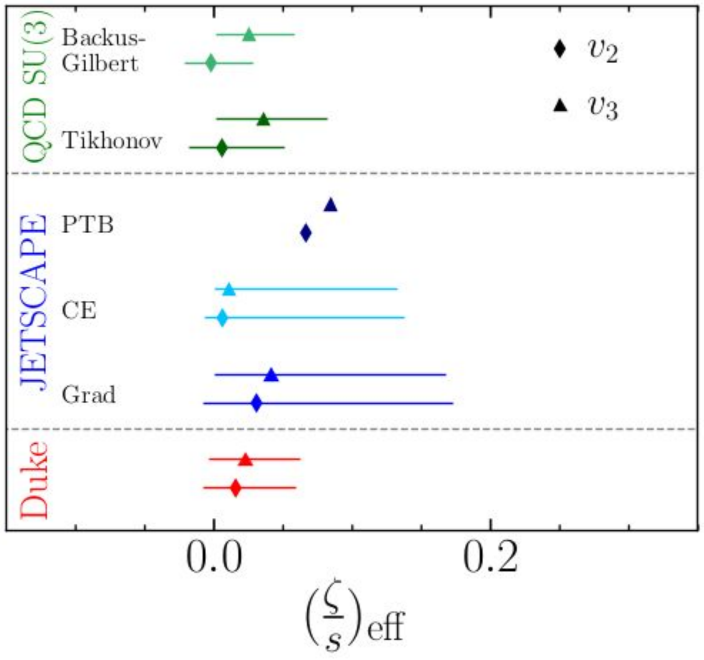
What is the expected value of the effective BULK viscosity in QCD?



from QCD calculations

from heavy ion data

What is the expected value of the effective BULK viscosity in QCD?

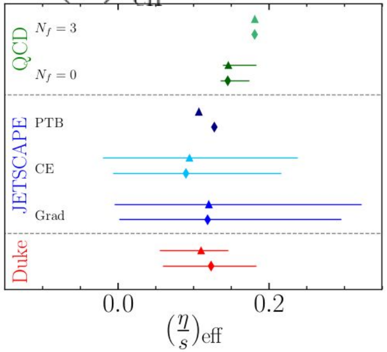


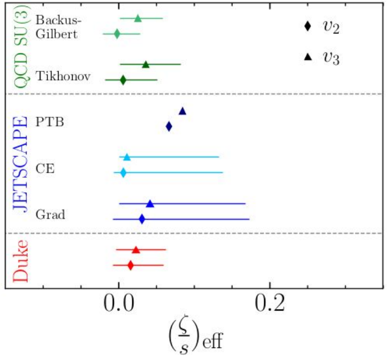
Error bars: 90% posterior

- From QCD calculations, one expects that the effective bulk is essentially identical for v2 and v3
- Effective bulk viscosity extracted from Bayesian analyses of heavy ion data is compatible with that from QCD calculations.

What we learn from effective viscosities in heavy ion physics?

$$\left(\frac{\zeta}{s}\right)_{\mathrm{eff}} \ll \left(\frac{\eta}{s}\right)_{\mathrm{eff}}$$





- Data can determine only the sum of effective shear and effective bulk.
- Effective bulk viscosity is much smaller than effective shear viscosity.

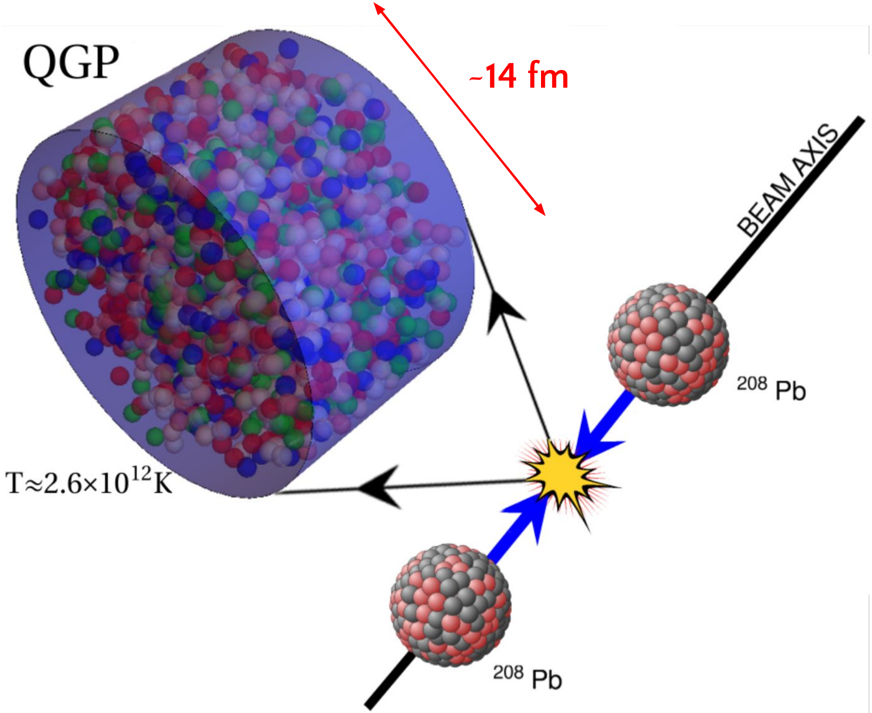
We can "only" extract the effective shear from data

Summary

- At each energy, one can, at most, extract an effective viscosity, which is a weighted average of the temperature-dependent viscosities.
- One cannot separate bulk from shear from v2 and v3 alone.
- The decrease of v2 and v3 in viscous hydrodynamics is determined by an effective viscosity, which encapsulates the detailed information contained in

  $(\eta / s)(T)$ and $(\varsigma / s)(T)$.
- The effective viscosity is likely to be almost identical for v2 and v3.
- We can "only" extract the effective shear from data

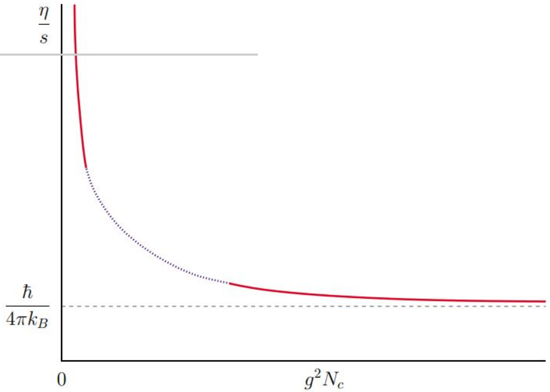
Thanks



Backup Slides

Viscosity in QCD

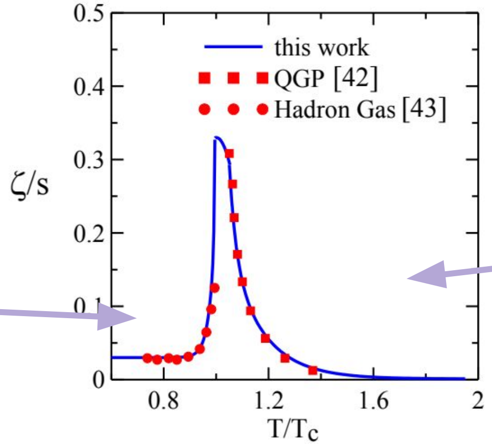
SHEAR



P.Kovtun, D.T.Son, A.O.Starinets, hep-th/0405231

Small $\frac{\eta}{s}$ typically imply strong interactions

BULK



S. Ryu, et. al. nucl-th/1502.0167

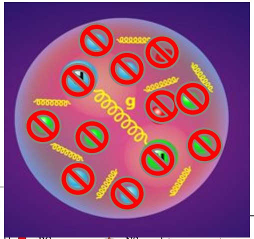
small for a dilute gas

small at high T

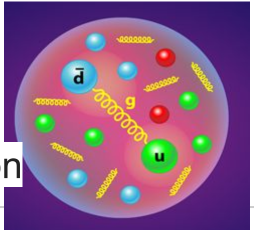
(massless quarks and gluons)

What do we know about viscosity from calculations

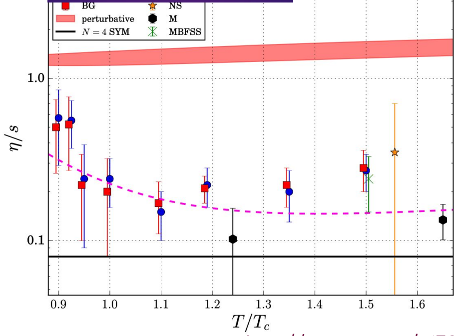
LATTICE



Functional renormalization group



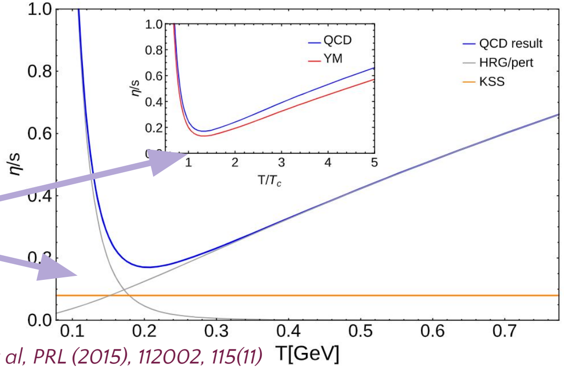
SHEAR



Astrakhantsev et al. 1701.02266

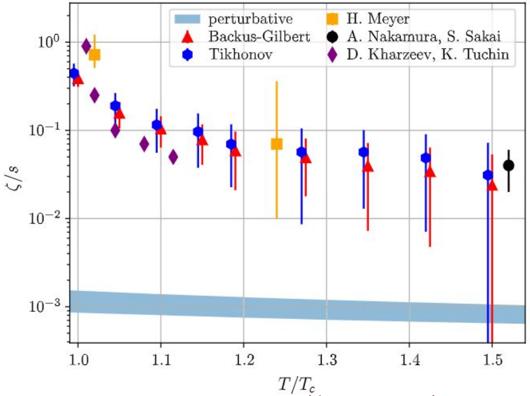
Minimum close to Tc

as expected



Christiansen et al, PRL (2015), 112002, 115(11)

BULK



Astrakhantsev et al. 1804.02382

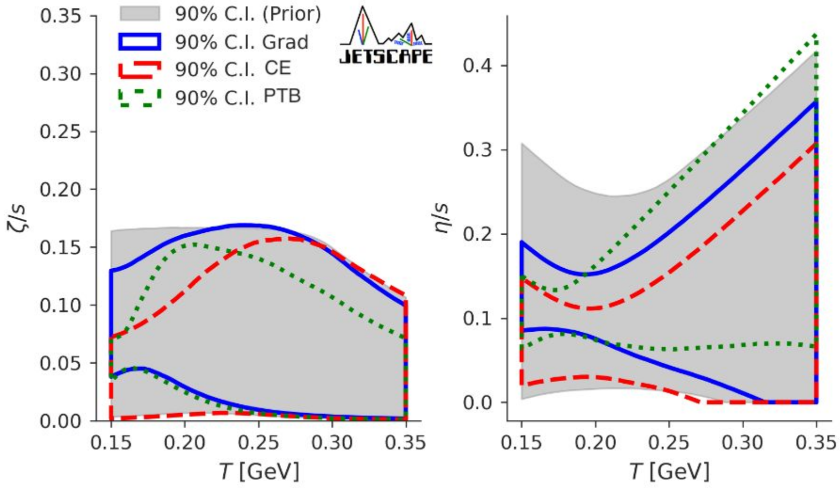
Uncertainties are large.

NOT YET

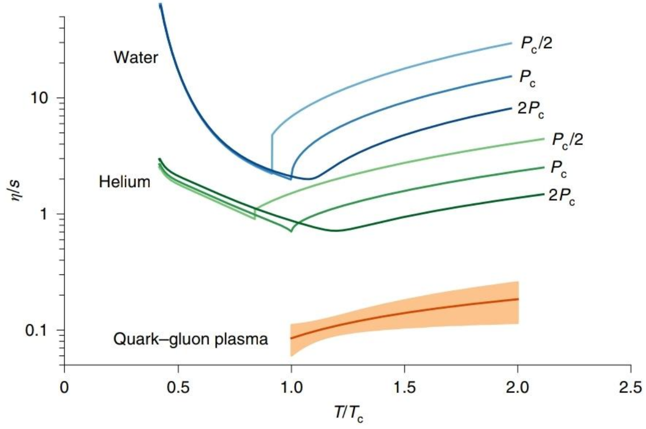
What do we know about viscosity from data

Model-to-data comparison with Bayesian inference

Everett et al. 2011.01430



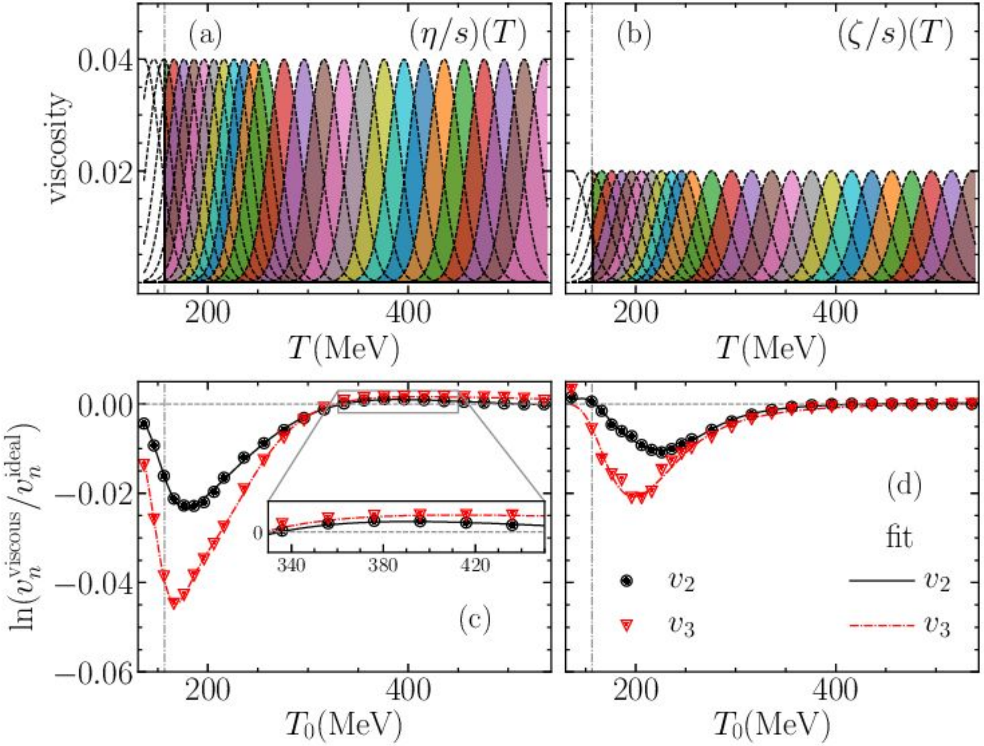
J.E. Bernhard, J. S. Moreland & S. A. Bass
Nature Physics 15, 1113 (2019)



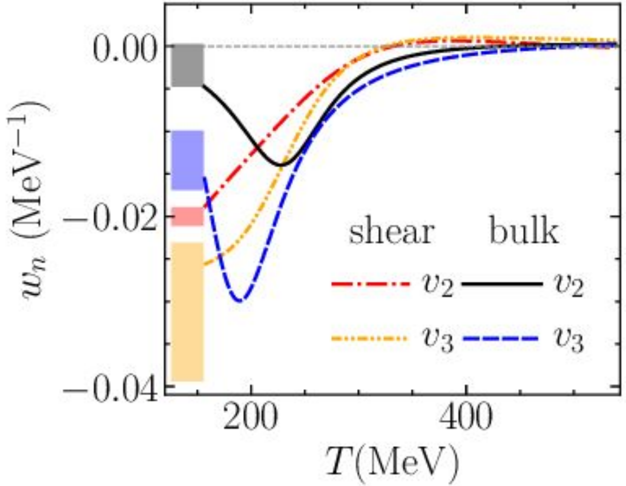
uncertainties on shear and bulk are similar in absolute value.

Almost-perfect fluid, but how viscosity affects the observable?

Results on viscosity



$$\ln \frac{v_n(viscous)}{v_n(ideal)} = \int dT \left(w_n^{\eta}(T)\frac{\eta}{s}(T) + w_n^{\zeta}(T)\frac{\zeta}{s}(T)\right)$$



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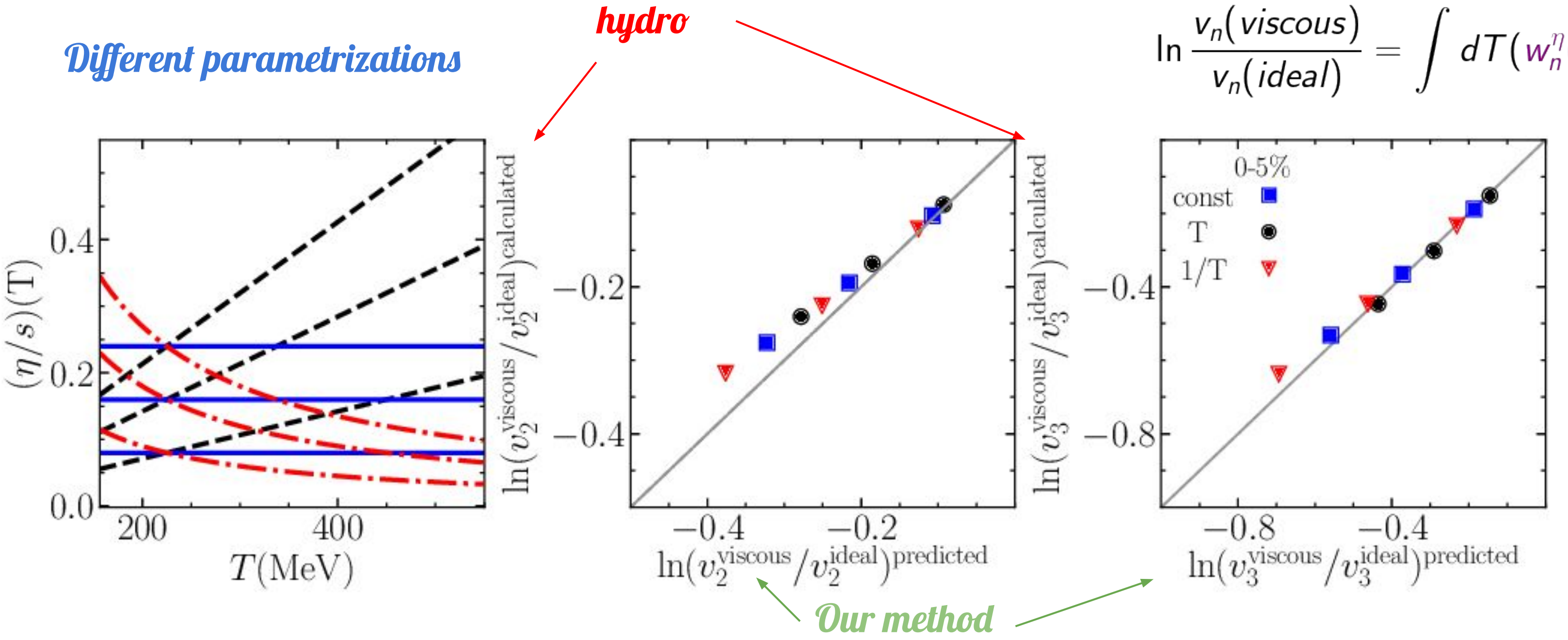
Effective Shear Viscosity

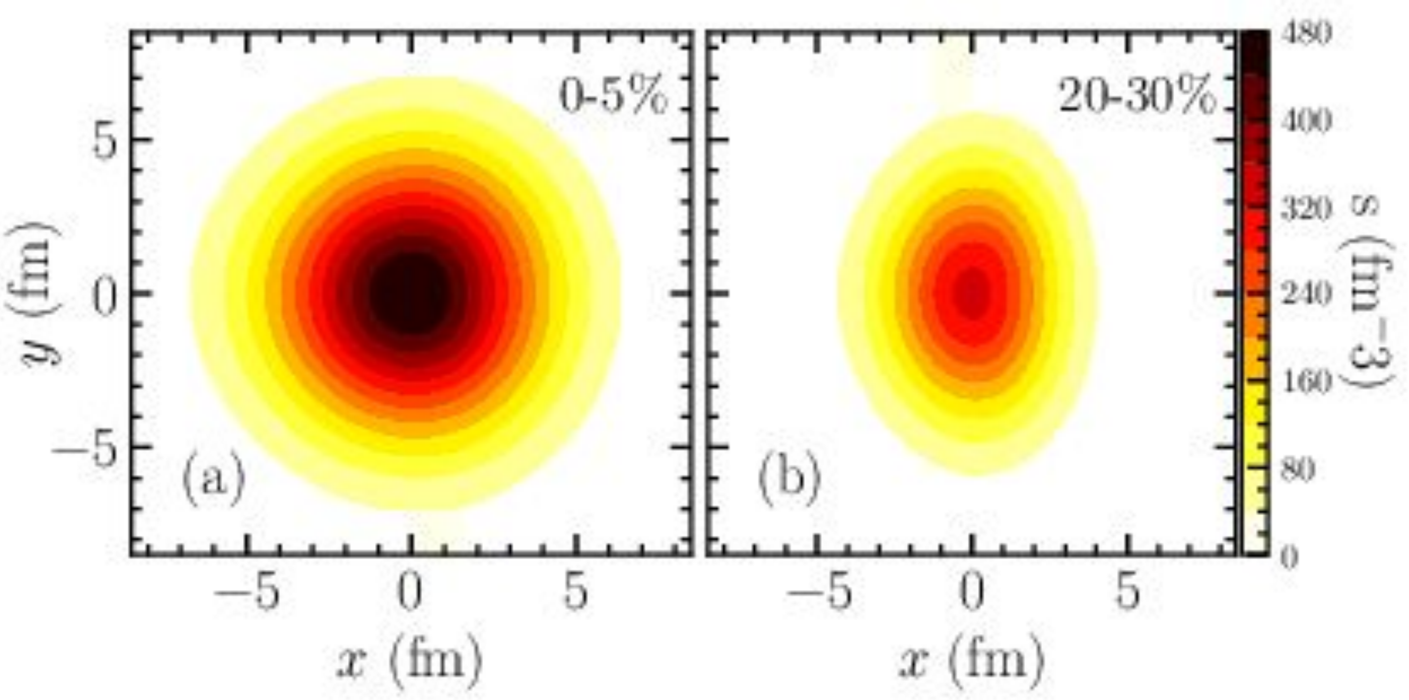
Different parametrizations

$$\ln \frac{v_n(viscous)}{v_n(ideal)} = \int dT (w_n^{\eta}(T) \frac{\eta}{s}(T))$$

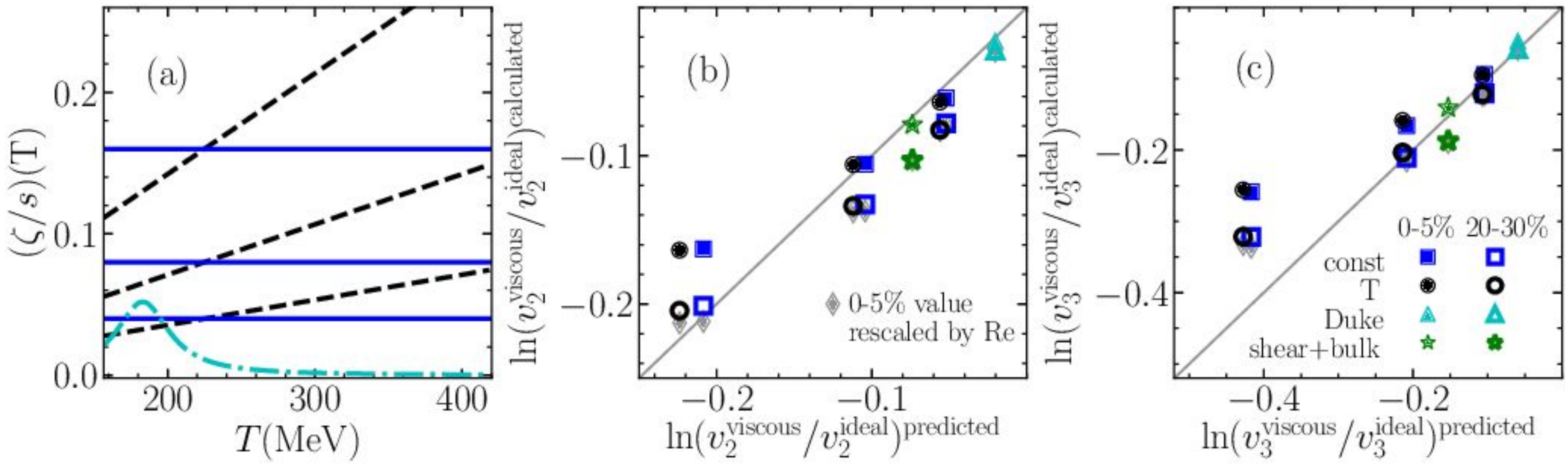


Effective viscosity is an excellent predictor !!!

IC

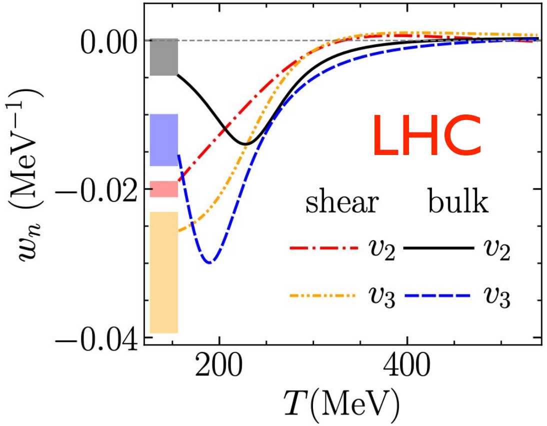


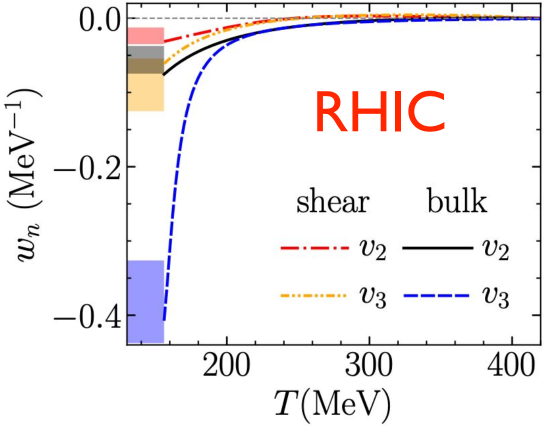
Centrality



(a)
$(\zeta/s)(T)$
0.0
0.1
0.2
200
300
400
T(MeV)
(b)
$\ln(v_2^{\rm viscous}/v_2^{\rm ideal})^{\rm calculated}$
−0.1
−0.2
−0.2
−0.1
$\ln(v_2^{\rm viscous}/v_2^{\rm ideal})^{\rm predicted}$
0-5% value rescaled by Re
(c)
$\ln(v_3^{\rm viscous}/v_3^{\rm ideal})^{\rm calculated}$
−0.2
−0.4
−0.4
−0.2
$\ln(v_3^{\rm viscous}/v_3^{\rm ideal})^{\rm predicted}$
0-5% 20-30%
const
T
Duke
shear+bulk

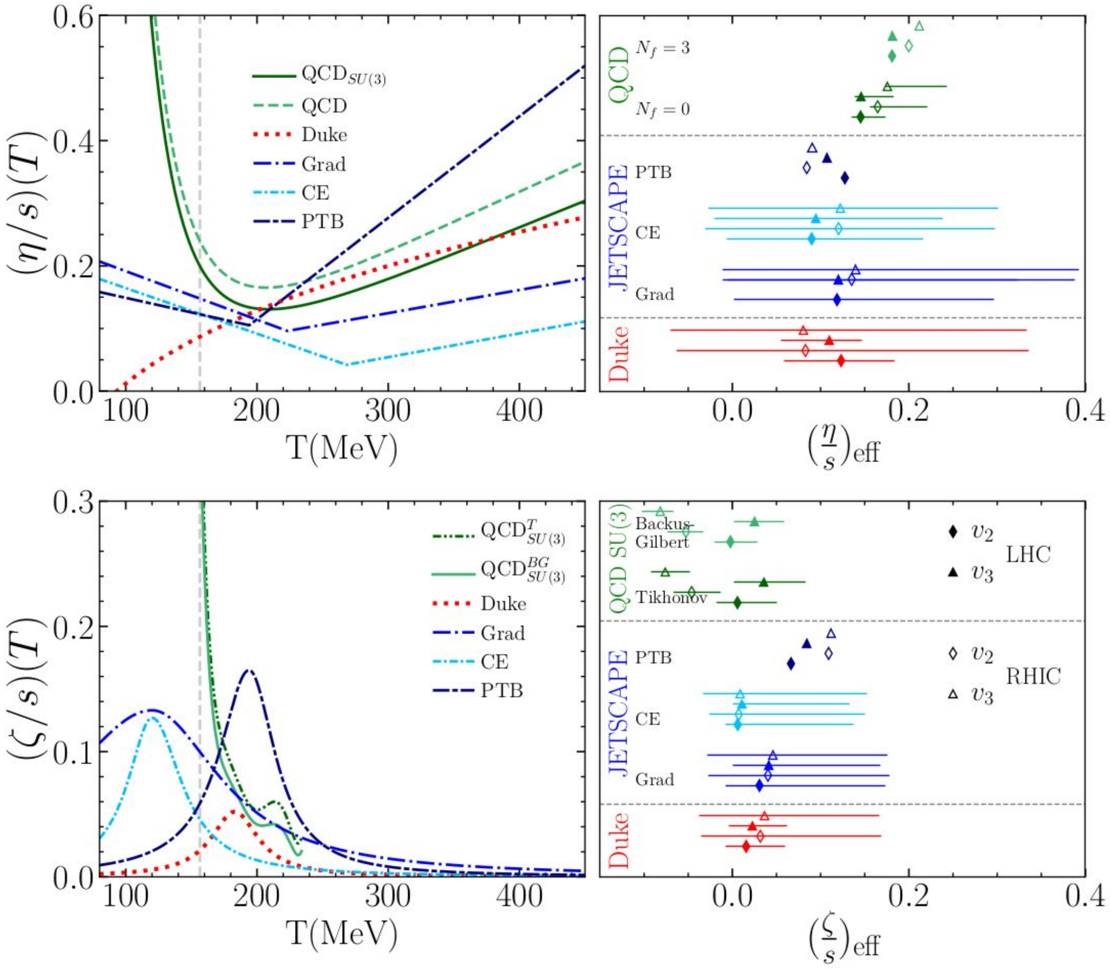
The case of RHIC





Results turn out to be different in the end.
The main difference is that freeze-out is no longer a small contribution to the viscous damping.
And it is the non-robust part. This implies that it will be harder to constrain the viscosity from RHIC data.

RHIC



QCD$_{SU(3)}$
QCD
Duke
Grad
CE
PTB
$(\eta/s)(T)$
T(MeV)
$N_f = 3$
$N_f = 0$
QCD
JETSCAPE
PTB
CE
Grad
Duke
$\left(\frac{\eta}{s}\right)_{\text{eff}}$
QCD$^{T}_{SU(3)}$
QCD$^{BG}_{SU(3)}$
$(\zeta/s)(T)$
Backus-Gilbert
Tikhonov
QCD SU(3)
v_2
v_3
LHC
RHIC
$\left(\frac{\zeta}{s}\right)_{\text{eff}}$