Outline

Viscous Hydrodynamics for RHIC: Mode d'emploi

- Collision takes place at $\tau = 0$
- $\tau \lesssim 1$ fm/c: pre-equilibrium stage, strong gradients, hydro not applicable
- $\tau \sim 1$ fm/c: start hydro evolution using models (Glauber/CGC) for initial energy density distribution
- $1\mathrm{fm/c} \lesssim \tau \lesssim 10\mathrm{fm/c}$: hydrodynamic regime
- $\tau \sim 10$ fm/c: once the last fluid element has cooled below T_{fo}, hydrodynamic regime ends and Cooper-Frye is used to calculate particle spectra
- $\tau \sim 10$ fm/c: unstable particles are allowed to decay, modifying stable particle's spectra
- $\tau \gtrsim 10$ fm/c: particles are assumed to be flying on straight lines to the detectors

Effects of Viscosity: Multiplicity

	$\frac{dN_{\pi,\mathrm{visc}}}{dy} / \frac{dN_{\pi,\mathrm{ideal}}}{dy}$	$\frac{dN_{K,\mathrm{visc}}}{dy} / \frac{dN_{K,\mathrm{ideal}}}{dy}$
$\eta/s = 0.08$	1.06	1.06
$\eta/s = 0.16$	1.12	1.12
$\eta/s = 0.24$	1.18	1.19
$\eta/s = 0.32$	1.23	1.23
$\eta/s = 0.40$	1.28	1.28

[Romatschke 07]

Viscosity generates entropy => Higher multiplicity

Effects of Viscosity: Transverse Flow

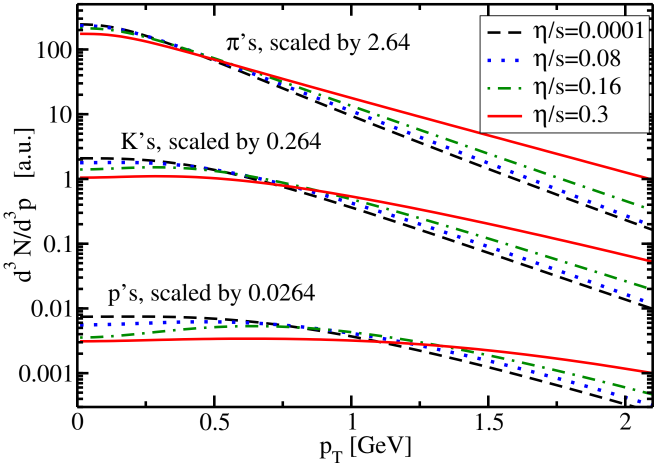
- $$T^\mu_\nu = \epsilon u^\mu u_\nu - p\Delta^\mu_\nu + \pi^\mu_\nu,$$

  therefore in local rest frame

  $$\begin{aligned} T^x_x &= p_{\rm trans,eff} = p - \Pi^x_x \\ T^\xi_\xi &= p_{\rm long,eff} = p - \Pi^\xi_\xi \end{aligned}$$

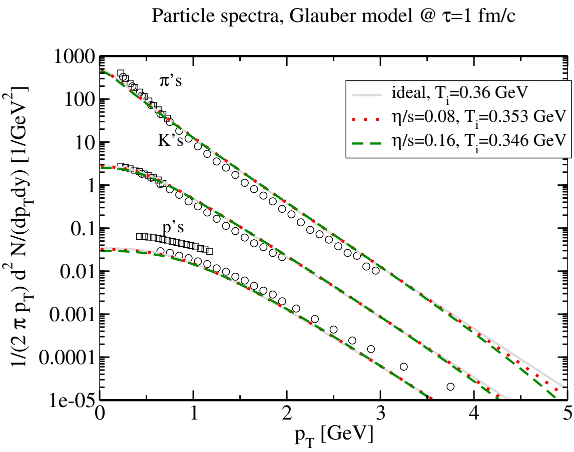
- For Bjorken flow, find $\Pi^\xi_\xi > 0, \Pi^x_x < 0$ (exercises!)
- Hydro equations $(\epsilon + p)Du^\alpha = \nabla^\alpha p$ then imply larger u^x, u^y (or u^r)
- Larger u^r means “flatter” slopes of spectra

Effects of Viscosity: Transverse Flow



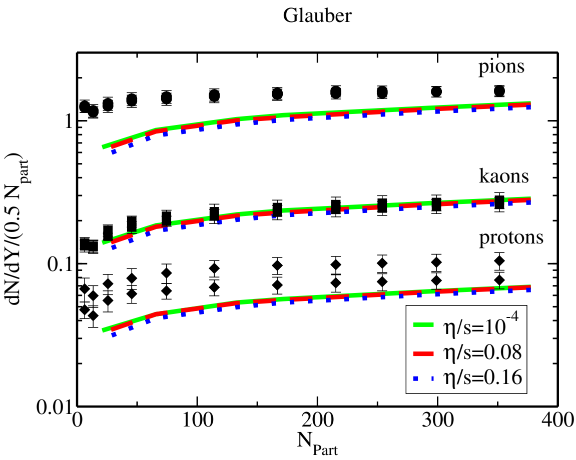
[Baier, Romatschke 06]

Effects of Viscosity: Transverse Flow



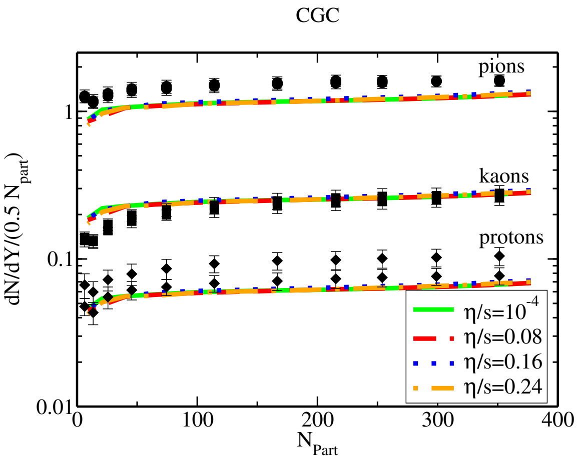
based on [Romatschke[2] 07]

Effects of Viscosity: Centrality Dependence



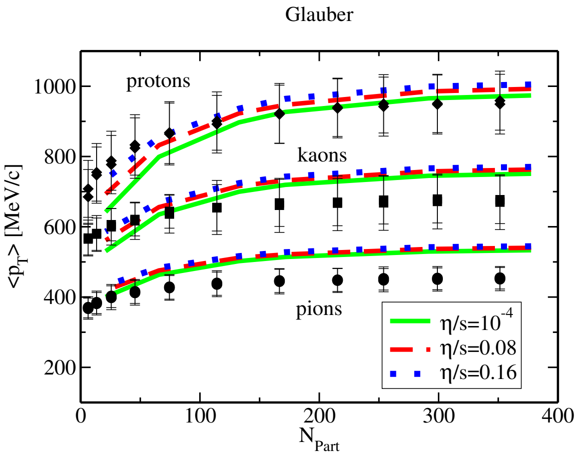
[Romatschke[2] 07]

Effects of Viscosity: Centrality Dependence



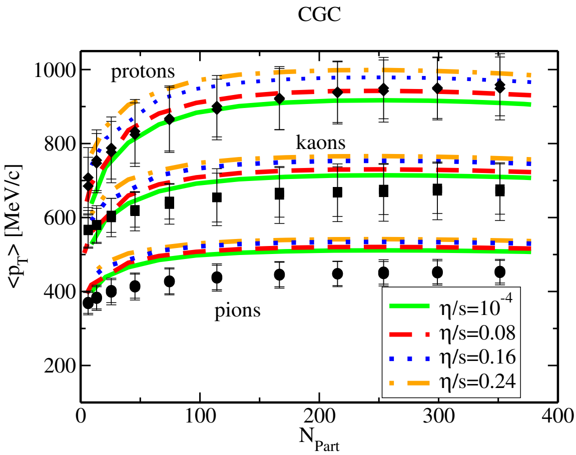
[Luzum, Romatschke 08]

Effects of Viscosity: Centrality Dependence



[Romatschke[2] 07]

Effects of Viscosity: Centrality Dependence

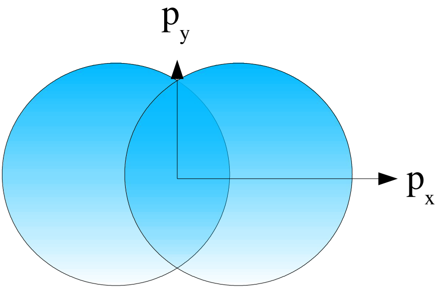


[Luzum, Romatschke 08]

Effects of Viscosity I

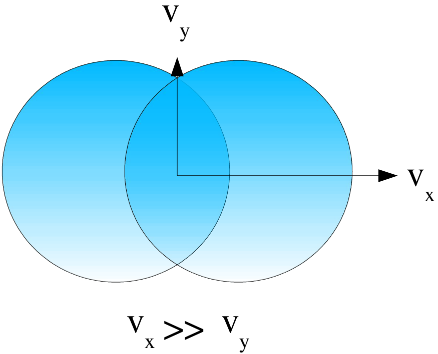
- Viscosity generates entropy (higher multiplicity)
- Viscosity generates more transverse flow (higher $< p_T >$)
- Both effects can to some extent be cancelled by reducing initial energy density and hence the system lifetime
- Viscosity does not strongly affect centrality dependence

Effects of Viscosity: Elliptic Flow



$p_x >> p_y$

Effects of Viscosity: Elliptic Flow



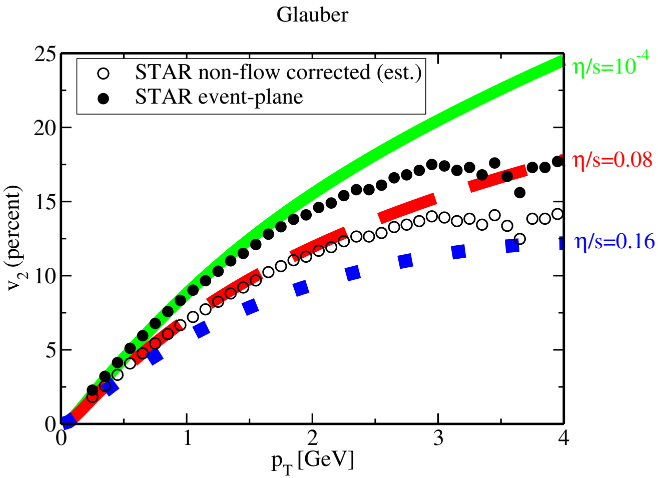
Effects of Viscosity: Elliptic Flow

- $u_x \neq u_y$ means asymmetry in angular particle distribution => elliptic flow (v2)
- In local rest frame

$$
\begin{aligned}
T^x_x &= p_{\rm x,eff} = p - \Pi^x_x \\
T^y_y &= p_{\rm y,eff} = p - \Pi^y_y
\end{aligned}
$$

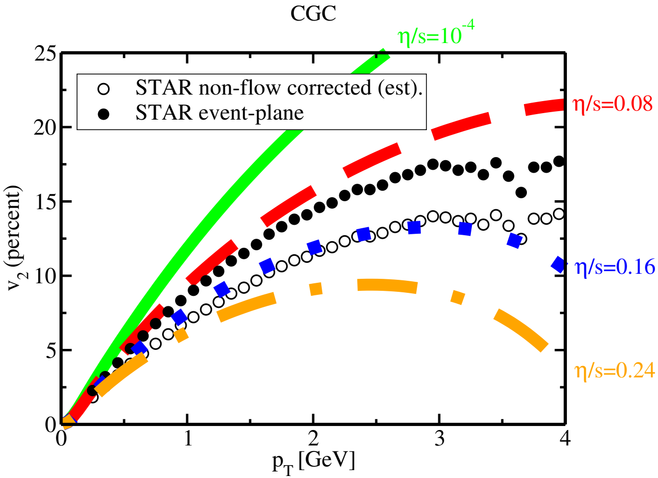
- $$\Pi^x_x \sim \eta \partial_x u^x >> \eta \partial_y u^y \sim \Pi^y_y$$
- Viscosity decreases elliptic flow

Effects of Viscosity: Elliptic Flow



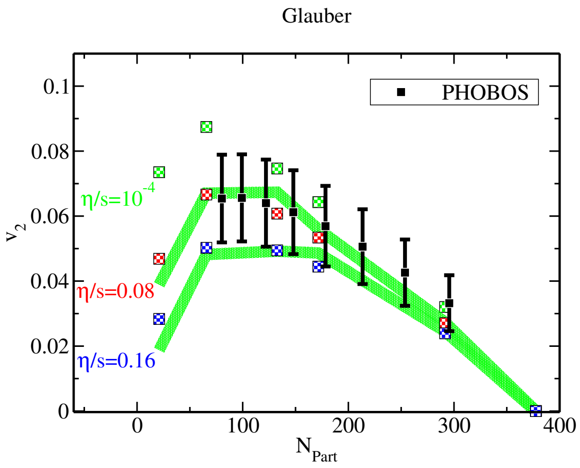
[Luzum, Romatschke 08]

Effects of Viscosity: Elliptic Flow



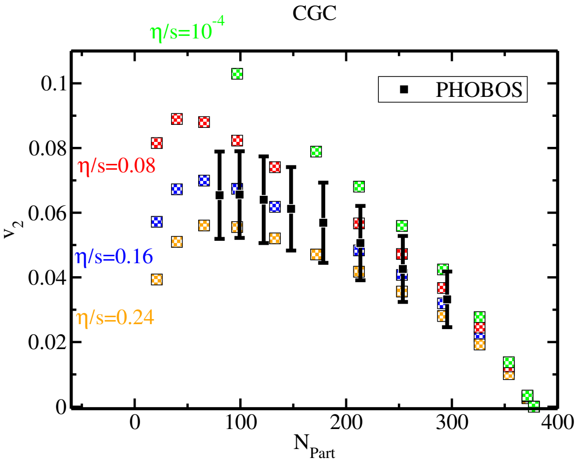
[Luzum, Romatschke 08]

Effects of Viscosity: Elliptic Flow



[Luzum, Romatschke 08]

Effects of Viscosity: Elliptic Flow



[Luzum, Romatschke 08]

Effects of Viscosity II

- Viscosity reduces momentum anisotropies (elliptic flow v_2)
- Difference in initial conditions (Glauber/CGC) give different spatial anisotropies
- Effects partly compensate
- Description of experimental data for Au+Au at $\sqrt{s} = 200$ GeV

$$\frac{\eta}{s} = 0.1 \pm 0.1(theory) \pm 0.08(experiment)$$

Outline

1. State of the Art
2. Open Problems

Finite Baryon Density

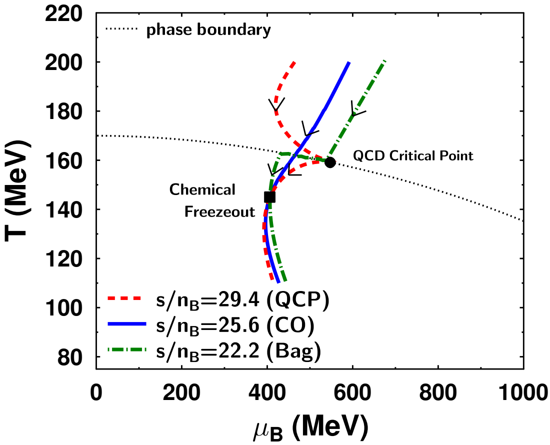
So far, all calculations for $\mu = 0$
Hydrodynamics with conserved baryon charge ($\mu \neq 0$): have to solve one additional equation for n^μ:

$$\partial_\alpha n^\alpha = 0, n^\alpha = n u^\alpha + \nu^\alpha$$

where ν^α is the flow of charge which in a first order theory is proportional to

$$\nu^\alpha \propto \partial^\alpha \frac{\mu}{T}$$

Finite Baryon Density: Why?



[Asakawa, Bass, Müller, Nonaka 08]

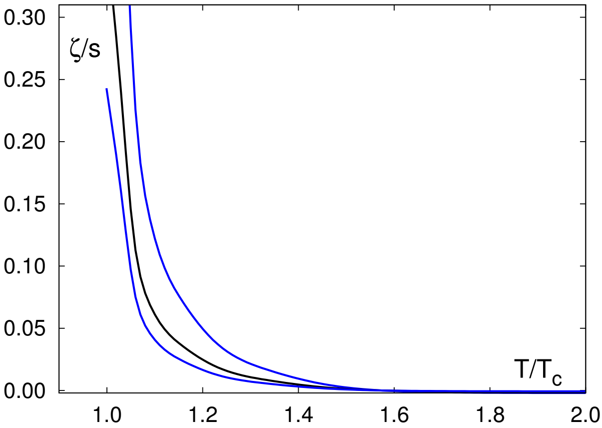
Bulk Viscosity

- So far, all calculations for $\zeta = 0$
- Hydrodynamics with nonzero ζ: loose conformal symmetry!
- But kinetic theory could give reasonable results

$$\tau_\zeta D\Pi + \Pi = \zeta \nabla_\mu u^\mu + \ldots$$

- One additional equation to solve

Bulk Viscosity: Why



[Karsch, Kharzeev, Tuchin 07]

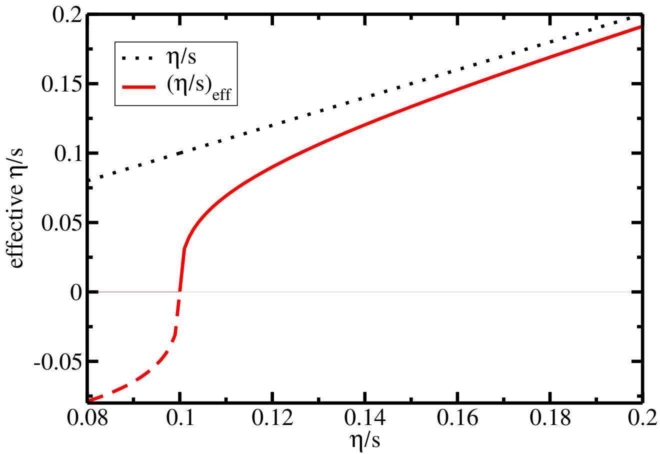
Fluid Turbulence

- Expect fluid turbulence for sufficiently large Reynolds number *Re*
- For relativistic hydrodynamics

$$Re \sim \frac{s}{\eta} T \tau$$

- Above which critical Reynolds number does turbulence set in for heavy-ion collisions?

Fluid Turbulence: Why

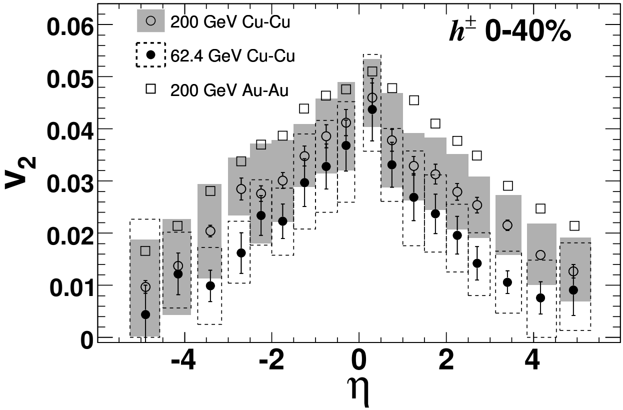


[Romatschke 07]

3d Viscous Hydro

- Existing Viscous Hydrodynamic Codes only 2+1d (assume rapidity independence)
- How does viscosity affec rapidity dependence of multiplicity/elliptic flow?

3d Viscous Hydro:Why



PHOBOS [Alver et al. 06]

The End

...many more open problems...

...which YOU could be the first to solve!

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