Shear viscosity of the quark-gluon plasma

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(Work in progress with Jean-Yves Ollitrault)

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QUESTION:

What is the shear viscosity of the quark gluon plasma?

GOAL

- Determine the best way to extract $\eta/s$ from data
- Obtain a reliable value and systematically quantify the uncertainty
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η/s FROM FLOW (HISTORICAL)

“Glauber” initial conditions

“CGC” initial conditions

Best extraction of η/s by comparing viscous hydro to flow data

Largest uncertainty from unknown initial condition

**Initial eccentricity**

- Early-time physics is not well known
- Different initial physics $\Rightarrow$ different eccentricity $\varepsilon_2$
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Initial eccentricity

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Initial eccentricity

- Early-time physics is not well known.
- Different initial physics $\implies$ different eccentricity $\varepsilon_2 \propto v_2$.
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Different initial physics $\Rightarrow$ different eccentricity $\varepsilon_2 \propto v_2$
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Different initial physics $\implies$ different eccentricity $\varepsilon_2 \propto \nu_2$
Early-time physics is not well known

Different initial physics $\Rightarrow$ different eccentricity $\varepsilon_2 \propto v_2$

Central collisions less sensitive to differences in initial physics
Extracting $\eta/s$ from $v_n$ in central collisions

NEW MEASUREMENTS OF CENTRAL COLLISIONS FROM ATLAS AT LHC

- Extract $\eta/s$ from $p_T$-integrated $v_n$ in ultra-central LHC collisions:
  - Minimizes uncertainty from initial conditions
  - LHC collisions more sensitive to viscosity in QGP phase
- $v_n \propto \varepsilon_n$ in central collisions (even for $n > 3$)
  (see F. Gardim, Friday 6D)
Extracting \( \eta/s \) from \( v_n \) in central collisions

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**OUR HYDRO SETUP**

- 2+1d, 2nd order conformally invariant viscous hydro
- Constant $\eta/s$
- With or without separate chemical and kinetic freeze out
- Can directly test effects of:
  - As many models for initial conditions as we can get our hands on
  - Thermalization time, initialization of shear tensor, viscous correction to freeze out distribution function, second order transport coefficients, equation of state, chemical freeze-out, etc.
- Not directly tested in this work:
  - Longitudinal dynamics / fluctuations
  - Bulk viscosity
  - Hydro afterburners
  - Full event-by-event analysis
η/s FROM ULTRA-CENTRAL COLLISIONS

**Procedure**

- Calculate integrated $v_n/\varepsilon_n$ versus $\eta/s$ in hydrodynamics
- Calculate r.m.s. $\varepsilon_n$ from Monte-Carlo models of initial conditions
  \[ \Rightarrow v_n(\eta/s) \]
- Extract best-fit value for $\eta/s$ from $v_2-v_6$ in 0–1% central collisions
- Vary all parameters and determine effect on extracted $\eta/s$
  \[ \Rightarrow \text{uncertainty in } \eta/s \]
- Estimate uncertainty from other sources
- \[ \Rightarrow \text{measurement of } \eta/s \text{ with error bar} \]
A simultaneous fit of $v_2$–$v_6$ gives a preferred extracted $\eta/s$ for each initial condition.

Range of results quantifies uncertainty.
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Range of results quantifies uncertainty.

Uncertainty due to initial $\varepsilon_n$: $\sim \pm 0.05$
Systematic (plus statistical) experimental error: \( \delta \nu_2 / \nu_2 \simeq 5\% \), \( \delta \nu_3 / \nu_3 \simeq 4\% \), \( \delta \nu_4 / \nu_4 \simeq 5\% \), \( \delta \nu_5 / \nu_5 \simeq 12\% \), \( \delta \nu_6 / \nu_6 \simeq 61\% \)

Uncertainty due to experimental error: \( \sim \pm 0.02 \)
**Viscous correction to distribution function $\delta f$**

- From fluid d.o.f. to particles: $f(p, x) = f_{equil} + \delta f$
- Uncertainty due to momentum dependence of $\delta f$: $\pm 0.015$
SECOND ORDER TRANSPIRE COEFFICIENTS: $\tau\Pi$

- $\tau\Pi = 2\frac{\eta}{sT} \times C$

- Israel-Stewart: $C = 3$
- SYM: $C = 2 - \log(2) \simeq 1.3$
- Uncertainty due to 2nd order transport coeff.: $\pm 0.005$
Equation of State

Uncertainty due to equation of state: ±0.01
Uncertainty due to initialization of shear tensor: $< \pm 0.005$
THERMALIZATION TIME $\tau_0$

- Uncertainty from $\tau_0 \pm 0.03$
**INITIAL FLOW**

- Uncertainty from initial flow ± 0.04
Systematic Uncertainty for $\eta/s$

(Preliminary!)

- Experimental uncertainties ±0.020
- Initial eccentricity ±0.050
- Thermalization time ±0.030
- Initialization of shear tensor ±0.005
- Initial flow ±0.040
- Equation of State ±0.015
- Second-order transport coeff. ±0.005
- Viscous correction to f.o. distribution ±0.015
- Chemical freeze out ±0.015

(Preliminary!)
**Bounds: Hydro Run with Largest (Smallest) $\eta/s$**

**Lower Bound:**
- Data + uncert.
- MC-KLN I.C.s
- $\tau_0 = 1$ fm
- $u_0^i = 0$
- $\Pi_0^{\mu\nu} = 0$
- BMW EOS
- $\tau_\pi = \frac{6\eta}{sT}$
- $\delta f \propto p$

**Upper Bound:**
- Data $-$ uncert.
- MCrcBK (w NB)
- $\tau_0 = 0.5$ fm
- $u_0^i = \frac{-\tau}{2} \partial^i \ln s$
- $\Pi_0^{\mu\nu} = $ Nav. St.
- $s95p-PCE165$
- $\tau_\pi = \frac{2.6\eta}{sT}$
- $\delta f \propto p^2$
Next step: estimate uncertainty from other sources and add to error band

- Bulk Viscosity $\sim \pm 0.010$
- $v_n/\varepsilon_n = \text{constant} \sim \pm 0.010$
- Deviation from boost-invariance / longitudinal fluct. $\sim \pm 0.005$
- Freezing out with (PCE +) Cooper-Frye $\sim \pm 0.010$
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**Final Result:**

$0.07 \leq \eta/s \leq 0.43$
SYSTEMATIC UNCERTAINTY FOR $\eta/s$

(Preliminary!)

- Experimental uncertainties $\pm 0.020$
- Initial eccentricity $\pm 0.050$
- $v_n/\varepsilon_n = \text{constant}$ $\sim \pm 0.010$
- Thermalization time $\pm 0.030$
- Initialization of shear tensor $\pm 0.005$
- Initial flow $\pm 0.050$
- Equation of State $\pm 0.015$
- Second-order transport coeff. $\pm 0.005$
- Bulk Viscosity $\sim \pm 0.010$
- Deviation from boost-invariance / longitudinal fluct. $\sim \pm 0.005$
- Viscous correction to f.o. distribution $\pm 0.015$
- Other aspects of freeze out $\sim \pm 0.025$

(Preliminary!)
SUMMARY

- Flow in central heavy-ion collisions are less sensitive to early-time dynamics
- Focusing on ultra-central collisions reduces systematic uncertainty in viscosity extraction
- First extraction of $\eta/s$ with comprehensive study of systematics, reliable error bar:
  - $0.07 \leq \eta/s \leq 0.43$ (preliminary!!)
- Largest single source of uncertainty still initial conditions
- Many less significant sources of error are more important in aggregate; almost all have clear potential for improvement
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Largest *single* source of uncertainty still initial conditions

Many less significant sources of error are more important in aggregate; almost all have clear potential for improvement
P. H. Frampton & T. Stelbovics

Extracting Shear Viscosity: Recent Results

\( \varepsilon_n \) FROM A FEW MODELS

Graph showing the r.m.s. \( \varepsilon_2 \) as a function of centrality for different models:
- Glauber (disks)
- MC-KLN
- DIPSY
- Glauber (points)
- UrQMD
- MCrcBK (KNO)

The graph compares the results from these models across different centrality values, illustrating how the shear viscosity changes with varying levels of collision centrality.
$\varepsilon_n$ from a few models
**Extracting Shear Viscosity**

Recent Results

\( \varepsilon_n \) FROM A FEW MODELS

![Graph showing the r.m.s. \( \varepsilon_4 \) as a function of centrality for different models: MCrcBK (KNO), UrQMD, DIPSY, Glauber (points), Glauber (disks), MC-KLN.](image-url)

- **MCrcBK (KNO)**: Light blue dashed line
- **UrQMD**: Red line with plus symbols
- **DIPSY**: Purple dotted line
- **Glauber (points)**: Green dash-dotted line
- **Glauber (disks)**: Blue dotted line
- **MC-KLN**: Black solid line

This graph compares the predictions of various models for the shear viscosity as a function of centrality.
$\varepsilon_n$ FROM A FEW MODELS

![Graph showing viscosity results from different models]

- MCrcBK (KNO)
- UrQMD
- DIPSY
- Glauber (points)
- Glauber (disks)
- MC-KLN

The graph compares the r.m.s. $\varepsilon_5$ as a function of centrality for different models.
Extracting shear viscosity recent results

$\varepsilon_n$ from a few models

![Graph showing r.m.s. $\varepsilon_6$ vs. centrality for different models: MCrcBK (KNO), UrQMD, DIPSY, Glauber (points), Glauber (disks), and MC-KLN.](image)
SELECTING CENTRALITY (EXAMPLE FROM PHOBOS GLAUBER)

Correct binning in centrality is important for very central collisions.
Central Dependence of $\varepsilon_n$ (ALICE arXiv:1105.3865)

- Centrality dependence of $v_2$ $\Rightarrow$ centrality dependence of $\varepsilon_2$
- $\Rightarrow$ intrinsic eccentricity
EXTRA SLIDES

$\frac{v_3}{\epsilon_3}$ vs $\eta/s$

- $v_3$ is the shear viscosity
- $\epsilon_3$ is the third-order shear viscosity
- $\eta$ is the shear viscosity
- $s$ is entropy density