VISHNU – a dynamical evolution model for heavy-ion collisions

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presented at
HI Workshop II, 2011 RHIC & AGS Annual Users’ Meeting,
Brookhaven National Laboratory, June 20–24, 2011

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*Supported by the U.S. Department of Energy (DOE)
Prologue: How to measure $\left( \frac{\eta}{s} \right)_{\text{QGP}}$

Hydrodynamics converts spatial deformation of initial state $\Rightarrow$ momentum anisotropy of final state, through anisotropic pressure gradients.

**Shear viscosity** degrades conversion efficiency

$$\varepsilon_x = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \implies \varepsilon_p = \frac{\langle T_{xx} - T_{yy} \rangle}{\langle T_{xx} + T_{yy} \rangle}$$

of the fluid; the suppression of $\varepsilon_p$ is monotonically related to $\eta/s$.

The observable that is most directly related to the total hydrodynamic momentum anisotropy $\varepsilon_p$ is the **total ($p_T$-integrated) charged hadron elliptic flow** $v_2^{\text{ch}}$:

$$\varepsilon_p = \frac{\langle T_{xx} - T_{yy} \rangle}{\langle T_{xx} + T_{yy} \rangle} \iff \sum_i \int p_T dp_T \int d\phi_p \frac{p_T^2}{dN_i} \frac{dN_i}{dy p_T dp_T d\phi_p} \cos(2\phi_p) \implies v_2^{\text{ch}}$$
Prologue: How to measure \((\eta/s)_{QGP}\) (ctd.)

- If \(\varepsilon_p\) saturates before hadronization (e.g. in PbPb@LHC (?))
  \[ v_{2}^{ch} \approx \text{not affected by details of hadronic rescattering below } T_c \]
  but: \(v_2^{(i)}(p_T), \frac{dN_i}{dyd^2p_T}\) change during hadronic phase (addl. radial flow!), and these changes depend on details of the hadronic dynamics (chemical composition etc.)
  \[ v_2(p_T) \text{ of a single particle species not a good starting point for extracting } \eta/s \]

- If \(\varepsilon_p\) does not saturate before hadronization (e.g. AuAu@RHIC), dissipative hadronic dynamics affects not only the distribution of \(\varepsilon_p\) over hadronic species and in \(p_T\), but even the final value of \(\varepsilon_p\) itself (from which we want to get \(\eta/s\))

  \[ \Rightarrow \text{need hybrid code that couples viscous hydrodynamic evolution of QGP to realistic microscopic dynamics of late-stage hadron gas phase} \]
  \[ \Rightarrow \text{VISHNU ("Viscous Israel-Steward Hydrodynamics 'n' UrQMD")} \]

(Song, Bass, Heinz, PRC83 (2011) 024912)  Note: this paper shows that UrQMD \(\neq\) viscous hydro!
s95p-PCE: A realistic, lattice-QCD-based EOS

High $T$: Lattice QCD (latest hotQCD results)

Low $T$: Chemically frozen HRG ($T_{\text{chem}} = 165$ MeV)

No softest point!
s95p-PCE: A realistic, lattice-QCD-based EOS

Huovinen, Petreczky, NPA 837 (2010) 26
Shen, Heinz, Huovinen, Song, PRC 82 (2010) 054904

Generates less radial flow than SM-EOS Q and EOS L but larger momentum anisotropy
Smooth transition leads to smaller $\delta f$ at freeze-out

$\Rightarrow$ larger $v_2$
**H$_2$O: Hydro-to-OSCAR converter**

Monte-Carlo interface that samples hydrodynamic Cooper-Frye spectra (including viscous correction $\delta f$) on conversion surface to generate particles at positions $x_i^\mu$ with momenta $p_i^\mu$ for subsequent propagation in UrQMD (or any other OSCAR-compatible hadron cascade afterburner).

Song, Bass, Heinz, PRC 83 (2011) 024912

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**Graphs:**
1. **Left Graph:**
   - Plot showing $\tau$ vs. $r$ for 200 A GeV Au+Au, $b = 0$.
   - Inset shows $dN/d\tau$ vs. $\tau$.
   - Labelled as "VISH2+1: hydro results" and "H$_2$O: statistical results".
   - Parameters: $T_{\text{dec}} = 130$ MeV, $\eta/s = 0.08$.

2. **Right Graph:**
   - Plot showing $V_2$ vs. $p_T$ for 200 A GeV Au+Au, $b = 7$ fm.
   - Lines represent $\pi$, $K$, $p$.
   - Parameters: $\eta/s = 0.08$, $T_{\text{dec}} = 130$ MeV.
   - Legend: "VISH2+1: hydrodynamic results", "H$_2$O: statistical results for 500000 events".
VISHNU: hydro (VISH2+1) + cascade (UrQMD) hybrid

Sensitivity to $H_2O$ switching temperature:

With chemically frozen EOS (s95p-PCE), $p_T$-spectra show very little sensitivity to $T_{sw}$ (Teaney, 2000):

Song, Bass, Heinz, PRC 83 (2011) 024912

$200 \, \, A \, GeV \, Au+Au, \, b = 7 \, fm$
**VISHNU: hydro (VISH2+1) + cascade (UrQMD) hybrid**

**Sensitivity to H$_2$O switching temperature:**

With chemically frozen EOS (s95p-PCE), $p_T$-spectra show very little sensitivity to $T_{sw}$

**but $v_2$ does:**

Song, Bass, Heinz, PRC 83 (2011) 024912

200 $A$ GeV Au+Au, $b = 7$ fm

![Graph](image)

Viscous hydro with fixed $\eta/s = 0.08$ generates more $v_2$ below $T_c$ than does UrQMD

$\Rightarrow$ UrQMD is more dissipative

VISH2+1 simulation of UrQMD dynamics requires $T$-dependent $(\eta/s)(T)$ that increases towards lower temperature
Is there a switching window in which UrQMD can be simulated by viscous hydro?

Unfortunately NO!

\[(\eta/s)(T)\] extracted by trying to reproduce \(v_2\) independent of switching temperature depends on \(\delta f\) input into UrQMD from hadronizing QGP

\(\Rightarrow\) \(\delta f\) relaxes too slowly in UrQMD to be describable by viscous Israel-Stewart hydro

\(\Rightarrow\) extracted \((\eta/s)(T)\) not a proper UrQMD transport coefficient

\(\Rightarrow\) UrQMD dynamics can’t be described by viscous Israel-Stewart hydrodynamics
Extraction of $\left(\frac{\eta}{s}\right)_{\text{QGP}}$ from AuAu@RHIC


All shown theoretical curves correspond to parameter sets that correctly describe centrality dependence of charged hadron production as well as $p_T$-spectra of charged hadrons, pions and protons at all centralities.

- $v_2^{ch}/\varepsilon$ vs. $(1/S)(dN_{ch}/dy)$ is “universal”, i.e. depends only on $\eta/s$ but (in good approximation) not on initial-state model (Glauber vs. KLN, optical vs. MC, RP vs. PP average, etc.)
- Dominant source of uncertainty: $\varepsilon^\text{Gl}_x$ vs. $\varepsilon^\text{KLN}_x$
- Smaller effects: early flow → increases $\frac{v_2}{\varepsilon}$ by $\sim$ few % → larger $\eta/s$
- Bulk viscosity → affects $v_2^{ch}(p_T)$, but $\approx$ not $v_2^{ch}$

• $1 < 4\pi(\eta/s)_{\text{QGP}} < 2.5$

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dominant source of uncertainty: $\varepsilon_x^{G1}$ vs. $\varepsilon_x^{KLN}$

smaller effects: 
- early flow $\rightarrow$ increases $\frac{v_{ch}^2}{\varepsilon}$ by $\sim$ few% $\rightarrow$ larger $\eta/s$
- bulk viscosity $\rightarrow$ affects $v_{ch}^2(p_T)$, but $\approx$ not $v_{ch}^2$
- e-by-e hydro $\rightarrow$ decreases $\frac{v_{ch}^2}{\varepsilon}$ by $\approx 5\%$ $\rightarrow$ smaller $\eta/s$
Global description of AuAu@RHIC spectra and $v_2$


• $(\eta/s)_{QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{QGP} = 0.16$ for MC-KLN work well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities
Global description of AuAu@RHIC spectra and $v_2$


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- A purely hydrodynamic model (without UrQMD afterburner) with the same values of $\eta/s$ does almost as well (except for centrality dependence of proton $v_2(p_T)$)
- Main difference: VISHNU develops more radial flow in the hadronic phase (larger shear viscosity), pure viscous hydro must start earlier than VISHNU ($\tau_0 = 0.6$ instead of 0.9 fm/$c$), otherwise proton spectra are too steep
- These $\eta/s$ values agree with Luzum & Romatschke, PRC78 (2008), even though they used EOS with incorrect hadronic chemical composition $\Rightarrow$ shows robustness of extracting $\eta/s$ from total charged hadron $v_2$
Pre- and postdictions for PbPb@LHC

VISHNU with MC-KLN (Song, Bass, Heinz, PRC 83 (2011) 054912)

- After normalization in 0-5% centrality collisions, MC-KLN + VISHNU (w/o running coupling, but including viscous entropy production!) reproduces centrality dependence of \(dN_{ch}/d\eta\) well in both AuAu@RHIC and PbPb@LHC

- \((\eta/s)_{QGP} = 0.16\) for MC-KLN works well for charged hadron \(v_2(p_T)\) and integrated \(v_2\) in AuAu@RHIC, but overpredicts both by about 10-15% in PbPb@LHC

- Similar results from predictions based on pure viscous hydro \(\Rightarrow\) Shen et al., arXiv:1105.3226

- but: At LHC, we see significant sensitivity of \(v_2\) to initialization of viscous pressure tensor \(\pi^{\mu\nu}\) (Navier-Stokes or zero), and it is not excluded that it may be possible to bring down \(v_2\) at LHC to the ALICE data without increasing \(\eta/s\) at higher \(T\) (requires more study)

\(\Rightarrow\) QGP at LHC perhaps a bit, but not dramatically more viscous than at RHIC!
Why is $v^\text{ch}_2(p_T)$ the same at RHIC and LHC?

Answer: Pure accident! (Kestin & Heinz EPJC61 (2009) 545)

$v^\text{ch}_2(p_T)$ increases a bit from RHIC to LHC, for heavier hadrons $v_2(p_T)$ at fixed $p_T$ decreases
(radial flow pushes momentum anisotropy of heavy hadrons to larger $p_T$)

This is a hard prediction of hydrodynamics! (See also Nagle, Bearden, Zajc, arXiv:1102.0680)
Successful prediction of $v_2(p_T)$ for identified hadrons in PbPb@LHC

Data: ALICE  
Lines: Shen et al., arXiv:1105.3226 (VISH2+1)

Perfect fit in semi-peripheral collisions, but not enough proton radial flow in central collisions $\implies$ hadronic cascade (VISHNU) may help
Back to the elephant in the room: How to eliminate the large model uncertainty in the initial eccentricity?

Zhi Qiu and U. Heinz, arXiv:1104.0650

Initial eccentricities $\varepsilon_n$ and angles $\psi_n$:

$$\varepsilon_n e^{in\psi_n} = \frac{\int r dr d\phi r^2 e^{in\phi} e(r, \phi)}{\int r dr d\phi r^2 e(r, \phi)}$$

- MC-KLN has larger $\varepsilon_2$ and $\varepsilon_4$, but similar $\varepsilon_5$ and almost identical $\varepsilon_3$ as MC-Glauber

- Angles of $\varepsilon_2$ and $\varepsilon_4$ are correlated with reaction plane by geometry, whereas those of $\varepsilon_3$ and $\varepsilon_5$ are random (purely fluctuation-driven)

- While $v_4$ and $v_5$ have mode-coupling contributions from $\varepsilon_2$, $v_3$ is almost pure response to $\varepsilon_3$ and $v_3/\varepsilon_3 \approx \text{const.}$ over a wide range of centralities (for details see arXiv:1104.0650)

$$\Rightarrow \text{Idea: Use total charged hadron } v_{3}^{ch} \text{ to determine } (\eta/s)_{QGP},$$

then check $v_{2}^{ch}$ to distinguish between MC-KLN and MC-Glauber!
Shooting the elephant

Proof of principle calculation:

- Take ensemble of sum of deformed Gaussian profiles,
  \( s(\mathbf{r}_\perp) = s_2(\mathbf{r}_\perp; \tilde{\varepsilon}_2, \psi_2) + s_3(\mathbf{r}_\perp; \tilde{\varepsilon}_3, \psi_3) \), with
  1. equal Gaussian radii \( R_2^2 = R_3^2 = 8 \text{fm}^2 \) to reproduce \( \langle r_\perp^2 \rangle \) of MC-KLN source for 20-30\% AuAu
  2. \( \tilde{\varepsilon}_2 \) and \( \tilde{\varepsilon}_3 \) adjusted such that
     - \( \bar{\varepsilon}_2, 3 = \langle \varepsilon_{2,3} \rangle_{20-30\%}^{\text{MC-KLN}} \)
     - \( \bar{\varepsilon}_2, 3 = \langle \varepsilon_{2,3} \rangle_{20-30\%}^{\text{MC-Glauber}} \)
  3. \( \psi_2 = 0, \psi_3 \) (direction of triangularity) distributed randomly

- Use \( v_2^\pi(p_T) \) from VISH2+1 for \( \eta/s = 0.20 \) with MC-KLN initial conditions for 20-30\% AuAu as “mock data”
- Fit mock \( v_2^\pi(p_T) \) data with VISH2+1 for “MC-Glauber-like” or “MC-KLN-like” Gaussian initial conditions with both elliptic and triangular deformations by adjusting \( \eta/s \)
  \( \Rightarrow (\eta/s)_{\text{KLN}} = 0.217 \pm 0.005 \) for “MC-KLN-like”,
  \( (\eta/s)_{\text{G1}} = 0.111 \pm 0.001 \) for “MC-Glauber-like”
- Compute \( v_3^\pi(p_T) \) for “MC-KLN-like” fit with \( (\eta/s)_{\text{G1}} = 0.217 \) and reproduce it with “MC-Glauber-like” initial condition by readjusting \( \eta/s \)
  \( \Rightarrow (\eta/s)_{\text{G1}}^{v_3} = 0.224 \pm 0.005 \) for “MC-Glauber-like”
- Compute \( v_2^\pi(p_T) \) for “MC-Glauber-like” initial profiles with readjusted \( (\eta/s)_{\text{G1}}^{v_3} = 0.224 \) and compare with “MC-Glauber-like” fit to original mock data \( \Rightarrow \) clearly visible (and measurable) difference!

This exercise proves: (i) Fitting \( v_3(p_T) \) data with MC-Glauber and MC-KLN initial conditions yields the same \( \eta/s \) (within narrow error band); (ii) The corresponding \( v_2(p_T) \) fits are quite different, and only one (more precisely: at most one!) of the models will fit the corresponding \( v_2(p_T) \) data.
Conclusions

- Hybrid codes (e.g. VISHNU) that couple viscous hydro evolution of QGP to microscopic hadron cascade now allow a determination of \((\eta/s)_{QGP}\) with \(O(25\%)\) precision if the initial fireball eccentricity is known to better than 5\% relative accuracy.

- With VISHNU good global fits that describe all single-particle observables for soft hadron production (spectra, elliptic flow) at all but the most peripheral AuAu collision centralities are obtained, for both MC-Glauber and MC-KLN initial conditions, by using \((\eta/s)_{QGP} = 0.08\) for MC-Glauber and \((\eta/s)_{QGP} = 0.16-0.20\) for MC-Glauber.

- Event-by-event hydrodynamics with fluctuating initial conditions yields somewhat less \(v_2/\varepsilon_2\) than single-shot hydro with smooth average initial profiles \(\Rightarrow\) this will bring \((\eta/s)_{QGP}\) from charged hadrons down by \(\sim 0.02 - 0.03\). For proton \(v_2\), event-by-event hydro matters a lot.

- While MC-Glauber and MC-KLN give \(\varepsilon_2\) that differ by 20-25\%, they give almost identical \(\varepsilon_3\) (which is not geometric but fluctuation-driven). Only one of them will be able to fit simultaneously both \(v_2\) and \(v_3\).

- This may be enable us to gain the necessary control over initial conditions to make a precise (i.e. better than factor 2) measurement of \((\eta/s)_{QGP}\).
Supplements
Global description of AuAu@RHIC spectra and $v_2$


- $(\eta/s)_{QGP} = 0.08$ for MC-Glauber and $(\eta/s)_{QGP} = 0.16$ for MC-KLN works well for charged hadron, pion and proton spectra and $v_2(p_T)$ at all collision centralities