QGP Viscosity & Elliptic Flow for Multi-strange Hadrons

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Shear viscosity:

\[ \partial \mu T^\mu\nu(x) = 0 \]

Bulk viscosity:

\[ T^{\mu\nu} = (e + p + \Pi)u^\mu u^\nu - (p + \Pi)g^{\mu\nu} + \pi^{\mu\nu} \]

\[ \tau_{\pi} \Delta^{\alpha\mu} \Delta^{\beta\nu} \dot{\pi}_{\alpha\beta} + \pi^{\mu\nu} = 2\eta \sigma^{\mu\nu} - \frac{1}{2} \pi^{\mu\nu} \frac{\eta T}{\tau_{\pi}} \partial_\lambda \left( \frac{\tau_{\pi}}{\eta T} u^\lambda \right) \]

\[ \tau_\Pi \dot{\Pi} + \Pi = -\zeta (\partial \cdot u) - \frac{1}{2} \Pi \frac{\zeta T}{\tau_\Pi} \partial_\lambda \left( \frac{\tau_\Pi}{\zeta T} u^\lambda \right) \]

Assume **zero net baryon density & heat conductivity** at RHIC and LHC

Input: "EOS"

\[ \varepsilon = \varepsilon(p) \]
Generic features of shear & bulk viscosities
Shear viscosity: acts against the buildup of flow anisotropy

Bulk viscosity: acts against the buildup of radial flow

The shear viscosity leads to a significant suppression of $V_2$ (Romatsche & Romatsche PRL07; Song & Heinz PLB08, PRC08; Dusling & Teaney PRC 08; Molnar & Huovinen JPG 08 … …)

Bulk viscous effects are much smaller than shear ones due to the critical slowing down near phase transition (Song & Heinz PRC09)

One can extract the QGP shear viscosity from exp data without large contaminations from bulk viscosity

Visc. suppression of elliptic flow

Song & Heinz PRC09
The shear viscosity tends to smear out the inhomogeneous structures, leading to a suppression of $V_3$ (Schenke, Jeon & Gale PRL2011, PRC2012; Qiu & Heinz PRC2011 … …)

Viscous suppression of triangular flow

Qiu & Heinz 2011

**Viscous suppression of triangular flow**
QGP viscosity at RHIC and the LHC

-results from the VISHNU hybrid model
VISHNU hybrid approach
H. Song, S. Bass, U. Heinz, PRC2011

Initial state  \[ \text{Hydro expansion of QGP or hadron gas} \]

Initial conditions  \[ \text{viscous hydro} \]

Freeze-out  \[ \text{hadron cascade} \]

**VISHNU:**
- chemical composition of HRG
- transport properties of HRG
- EoS: \( \text{(s95p-PCE)} \) \( \text{(Huovinen & Petreczky10)} \)
- switching temperature: \( T_{sw} = 165 \text{MeV} \)
- initial conditions

**Other related developments**
- 3+1 d viscous hydro + hadron cascade: Ryu et al., arXiv1210.4588
- 2+1 d vs 3+1 viscous hydro: Shen, Schenke & Heinz on going work; Vredevoogd & Pratt, PRC85,044908(2012)
V$_2$ and QGP viscosity at RHIC


The analysis uses:

- **integrated V$_2$ for all charged hadrons**: In contrast to V$_2$(Pr), it is less sensitive to bulk viscosity, $\delta f$ corrections, radial flow & chemical composition of HRG

- **corrected exp. V$_2$ data** that remove non-flow & fluc. effects
The average QGP viscosity is roughly the same at RHIC and LHC.

Please also refer to C. Gale, et al., ArXiv: 1209.5330 [nucl-th]
Initial state fluctuations, final state correlations & the QGP viscosity
Uncertainties from Initial Conditions

Main uncertainties come from initial conditions

MC-KLN, larger $\varepsilon_2$ $\rightarrow$ HIGHER value of QGP viscosity
MC-Glauber, smaller $\varepsilon_2$ $\rightarrow$ LOWER value of QGP viscosity

$1 \times (1/4\pi) \leq (\eta/s)_{QGP} \leq 2.5 \times (1/4\pi)$
MC-KLN & MC-Glauber initializations & $V_3$

Pure viscous hydro simulations:

- $v_2/\varepsilon_2$
  - ALICE $v_2\{2\}/\varepsilon_2\{2\}$
  - ALICE $v_2\{4\}/\varepsilon_2\{4\}$
  - MC-KLN $v_2/\bar{\varepsilon}_2$
- $v_3/\varepsilon_3$
  - ALICE $v_3\{2\}/\varepsilon_3\{2\}$
  - MC-KLN $v_3/\bar{\varepsilon}_3$

Qiu, Shen & Heinz 2011

- $v_2/\varepsilon_2$
  - ALICE $v_2\{2\}/\varepsilon_2\{2\}$
  - ALICE $v_2\{4\}/\varepsilon_2\{4\}$
  - MC-Glb. $v_2/\bar{\varepsilon}_2$
- $v_3/\varepsilon_3$
  - ALICE $v_3\{2\}/\varepsilon_3\{2\}$
  - MC-Glb. $v_3/\bar{\varepsilon}_3$

MC-KLN, $\eta/s = 0.20$

MC-Glb, $\eta/s = 0.08$

$V_3$ prefer lower value of QGP viscosity
MC-Glauber & MC-KLN initializations are based on fluctuation of nucleon positions.

**Theoretical Development on Initialization Models:**
- **color charge fluctuations** (IP-Glasma, correlated fluctuations)
- **multiplicity fluctuations** for local gluon numbers
- **transverse/longitudinal flow fluctuations**
- **UrQMD, AMPT, EPOS/NUSES**
  ... ... ...

**Related flow Data:**
- **elliptic flow**
- **triangular flow & higher order flow harmonics**
- **higher-order event plane correlations**
- **Event by event \(v_n\) distributions**
- **\(v_n\) in ultra-central collisions**
  ... ...

A further study of flow data in different aspects, using e-b-e VISHNU will constrain initialization models, tightening the limit on \((\eta/s)_{QGP}\)

--Please also refer the work from B. Schenke and OSU group for recent developments
Multiplicity, Spectra and elliptic flow for identified hadrons
-a nice fit for both pion and proton spectra, insensitive to QGP viscosity
RHIC: $v_2(p_T)$ for identified hadrons

LHC: spectra for identified hadrons

-a nice fit for pions, kaons and proton spectra
A very nice fit of $v_2(p_T)$ for all centrality bins at LHC from VISHNU hybrid model.
LHC: $v_2(p_T)$ for identified hadrons

A comparison between viscous hydrodynamics and VISHNU
dN/dy for identified hadrons (RHIC & LHC)

- VISHNU nicely describes the multiplicity for pions, kaons & protons
- **VISHNU** nicely describes the multiplicity for pions, kaons & protons
- B-Bbar annihilations plays an important role for a nice fit of the proton data

**VISHNU :** \( T_{ch} = 165\text{MeV} \)
dN/dy for identified hadrons (RHIC & LHC)

-VISHNU nicely describes the multiplicity for pions, kaons & protons
-B-Bbar annihilations plays an important role for a nice fit of the proton data

Statistical Model: $T_{ch} \sim 150$ MeV

(no B-Bbar annihilations!)

VISHNU: $T_{ch} = 165$ MeV
Elliptic flow for multi-strange hadrons
$v_2$ for multi-strange hadrons (LHC)

2.76 A TeV Pb +Pb collisions

-a nice description for the elliptic flow for Lambda, Xi and Omega up to 2.5 GeV!
Mass ordering of elliptic flow (LHC)

LHC : 2.76 A TeV Pb+Pb

- Roughly reproduce the mass-ordering!
Do these multi-strange hadrons decouple from the system near $T_c$?
These multi-strange hadrons are NOT that weakly coupled with the medium!
UrQMD freezeout time distributions

- Lambda freeze-out even later than pion and protons!
- Earlier freeze-out for Xi and Omega!
VISHNU vs Hydro with $T_{\text{dec}} = 165$ & 100 MeV

- Freeze-out temperature for Lambda is much below $T_c$!
- Freeze-out temperatures for Omega and xi are closer to $T_c$!
- Need more studies for firm conclusions
phi-meson
- Hadron cascade: small cross sections for phi

- Mass ordering between phi and proton are independent of collision energies, centralities & theoretical details

Preliminary
Elliptic flow for phi at the LHC

T. Hirano

3+1-d ideal hydro+JAM

200A GeV
Au+Au

VISHNU

LHC

Pb+Pb 2.76 TeV

STAR Preliminary

T. Hirano
**phi V2 in strong & weakly coupling limit**

- hydro + $T_{\text{dec}} = 165$ MeV
  - weakly coupling limit
- hydro + $T_{\text{dec}} = 100$ MeV
  - strong coupling limit

**VISHNU:**
small cross sections for phi

Neither the strongly nor the weakly coupling limit nor the cases in between (VISHNU) could explain the mass-ordering between proton & phi shown in experiment

**phi-meson puzzle!**
Summary
QGP viscosity at RHIC and the LHC

Extraction $\eta/s$ from elliptic flow data using VISHNU indicates:

\[ 1 \times (1/4\pi) \leq \eta/s \leq 2.5 \times (1/4\pi) \] (MC-Glauber; MC-KLN)

Approximately similar averaged QGP viscosity at RHIC and LHC energies

Recent developments on initialization models:
- color charge fluctuations;
- multiplicity fluctuations;
- initial flow fluctuations … …

… …

to implement e-b-e VISHNU to further study: triangular flow & higher order flow harmonics, higher-order event plane correlations e-b-e $v_n$ … …

will help us to constrain initialization models, tightening the limit on $(\eta/s)_{QGP}$

Spectra & $V_2$ for identified hadrons (& multi-strange hadrons)

- A nice description of the $p_T$ spectra and $v_2$ for pions, kaons and protons
- VISHNU with B-Bbar annihilations prefer $T_{ch}=165$ MeV
- A nice description for $v_2$ ($p_T$) for multi-strangeness at the LHC for various of centrality.
- Fails to describe the phi-$v_2$(RHIC) within the strongly, weakly coupling limit or VISHNU
Thank you
Spectra for multi-strange hadrons (RHIC)

Au + Au 200 A GeV (RHIC)

O STAR

- VISHNU

0-5%
10-20%*10^{-1}
20-40%*10^{-2}
40-60%*10^{-3}

0-5%
10-20%*10^{-1}
20-40%*10^{-2}
40-60%*10^{-3}

Preliminary
\( v_2 \) for multi-strange hadrons (RHIC)

- 10-40\%: Nice description of the experimental data.
- High statistic runs are needed in the near future!
- 0-10\%: Non-flow & fluctuation effects.
$v_2$ for multi-strange hadrons (RHIC)

-10-40%: nice description of the experimental data

-High statistic runs are needed in the near future!

-40-80%: non-flow & fluctuation effects
$v_2$ for multi-strange hadrons (RHIC)

Preliminary

- High statistic runs are needed in the near future!
- $30-40\%$ non-flow & fluctuation effects
- $70-80\%$ non-flow & fluctuation effects

$v_2 \{\text{EP}\}$ for all charged Hadrons

Non-flow & fluctuations
Mass ordering of elliptic flow (RHIC)

RHIC: 200 A GeV Au + Au

-V_{2} vs. p_{T} GeV

-Preliminary

High statistic runs are needed in the near future!
Initialization Models

- **fluctuations of nucleon positions**:
  - **MC-KLN**: (used in the VISHNU hybrid model)

- **fluctuations of color charges** (in the framework of CGC):
  - **IP-Glasma**: B. Schenke et al., arXiv:1202.6646; 1206.6805 [nucl-th]
  - **Correlated Fluctuation**: B. Muller & A. Schafer, arXiv:1111.3347 [hep-ph]

- **fluctuations of local gluon numbers** (in the framework of MC-KLN):
Pre-equilibrium dynamics

Free Streaming limit: G. Qin, et. al., Phys. Rev. C82 064903 (2010); OSU, on-going work
Hydro limit: OSU group, on-going work
Pre-equilibrium dynamics smoothes out fluctuations, reducing $\varepsilon_2, \varepsilon_3$, but building radial flow early flow & fluctuations from dynamical models:


Except IP-Glamsa, most pre-equilibrium dynamics was studied within the ideal hydro framework. Their quantitative influences on $(\eta/s)_{QGP}$ are still unknown.
In most central collisions, fluctuation effects are dominant (Geometry effects are suppressed)

- can not simultaneously fit $V_2$ and $V_3$ with single $\eta/s$ (MC-Glauber & MC-KLN)
Higher Order Event Plane Correlations

Qiu & Heinz, arXiv:1208.1200[nucl-th]

Pure $e$-$b$-$e$ viscous hydro simulations:

qualitatively reproduce the measured event plane correlations

EXP. data: [ATLAS Collaboration],
CERN preprint ATLAS-CONF-2012-049
$V_n$ & E-b-E $V_n$ distributions

C. Gale et al., arXiv:1209.4330[nucl-th]