Temperature Dependence of Transport Coefficients of QCD in High-Energy Heavy-Ion Collisions

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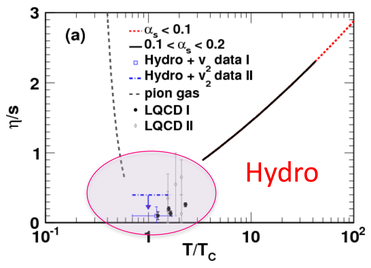
Okamoto and Nonaka, arXiv:1712.00923

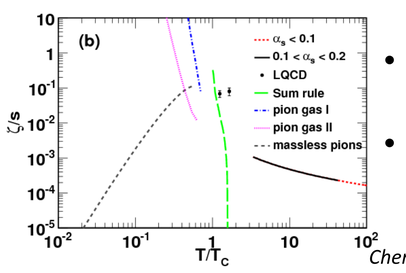
Abstract: using our developed new relativistic viscous hydrodynamics code, we investigate the temperature dependence of shear and bulk viscosities from comparison with the ALICE data; single particle spectra and collective flows at Pb+Pb$\sqrt{s_{NN}}$ =2.76 TeV collisions at the Large Hadron Collider. We find that from the comprehensive analyses of centrality dependence of single particle spectra and collective flows, we can extract the detailed information of the QGP bulk property, without being smeared by the final state interactions.

Purpose: understanding shear and bulk viscosities of QGP from quantitative analyses of the ALICE data

Current status



- Shear viscosity takes the minimum around T_c.
- Cf. η/s=1/4π AdS/CFT
- Hydrodynamic model constant η/s



- Bulk viscosity
  Temperature dependence is unclear.
- Hydrodynamic model
  vanishing ζ/s

Chen,Deng,Dong,Wang,PRC87,024910(2013)

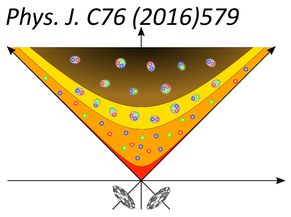
Our Phenomenological Model

Initial conditions	Hydrodynamics	Final state interactions
Fluctuations: Glauber, KLN, IP-Glasma…	QGP bulk property EoS: lattice QCD Shear and bulk viscosities	Hadron based event generator
TRENTO	New Hydrodynamics Code	UrQMD
Phenomenological model Parametrization		
Moreland et al.,PRC92,011901(2015) Ke et al.,PRC96,044192(2017)		*Bass et al., Prog.Part.Nucl.Phys.(1998) Bleicher et al., J.Phys.G25,1859(1999)*

1.Development of New Hydrodynamics code

Riemann solver in Milne coordinates

K. Okamoto, Y. Akamatsu and CN, Eur. Phys. J. C76 (2016)579

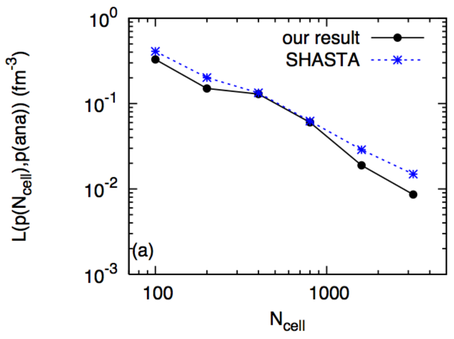


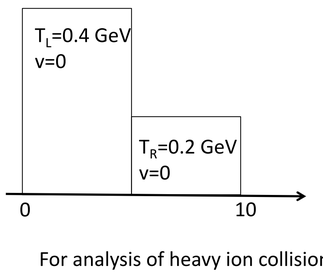
- ✓ Stable with small numerical dissipation
- ✓ Shock wave
- ✓ Strong expansion in longitudinal direction
- ✓ Conservation property

• Small Numerical Dissipation

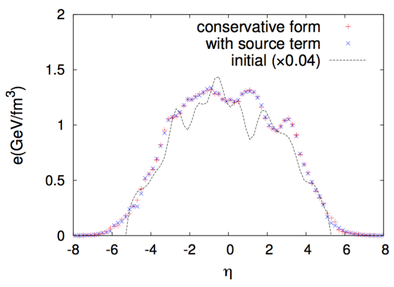
$$L(p(N_{\rm cell}),p(\text{anaytic})) = \sum_{i=1}^{N_{\rm cell}} |p(N_{\rm cell}) - p(\text{analytic})| \frac{\lambda}{N_{\rm cell}}$$

deviation from analytical solution





For analysis of heavy ion collisions
N$_{cell}$=100: dx=0.1 fm



• Numerical Tests in 1D

- ✓ Bjorken's scaling solutions
- ✓ Landau-Khalatnikov Solution (1D)
- ✓ Longitudinal fluctuations
- ✓ Conservation property

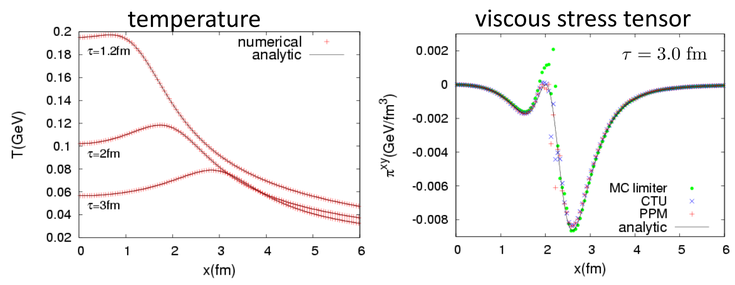
Sum of violation of conservation

	ε_E	ε_M
conservative	1.38E-09	8.59E-09
with souce	1.27E-02	5.61E-02

Akamatsu et al, JCP256,34(2014)
Okamoto, Akamatsu, Nonaka, EPJC76,579(2016)
Okamoto and Nonaka, EPJC77,383(2017)

• Gubser Flow

Marrochio et al, PRC91,014903(2015)



Our computed results show good agreement with analytical solution.

2. Analyses of the ALICE data

Okamoto and Nonaka, arXiv:1712.00923

• Shear and Bulk Viscosities

a) shear viscosity

⇩ $\eta/s = 0.17$

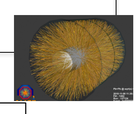
b) shear + bulk viscosities

⇩ $\eta/s = 0.17$

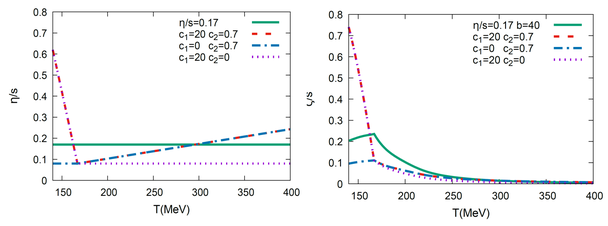
$\zeta = b\eta\left(\frac{1}{3} - c_s^2\right)^2 \quad b = 40$

ALICE Pb+Pb $\sqrt{s_{NN}} = 2.76$ TeV, LHC

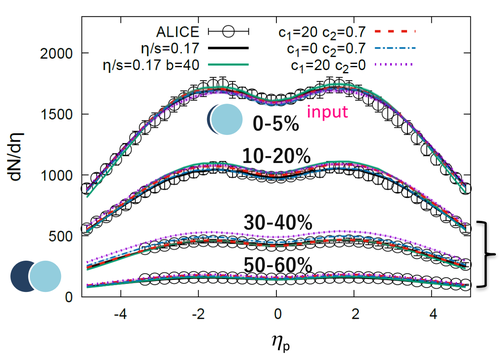
- ✓ Rapidity distributions
  central collision: parameter fixing
- ✓ P_T distributions
- ✓ Mean P_T
- ✓ Collective flow v_2, v_3

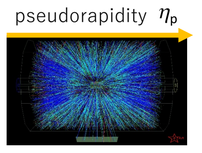


c) temperature dependent shear + bulk viscosities



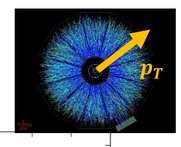
• Rapidity Distributions

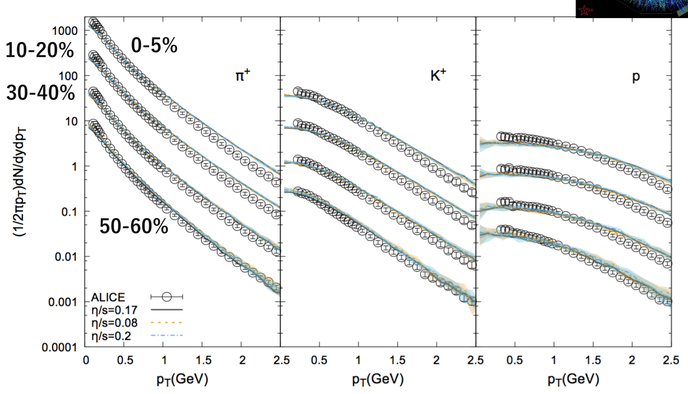




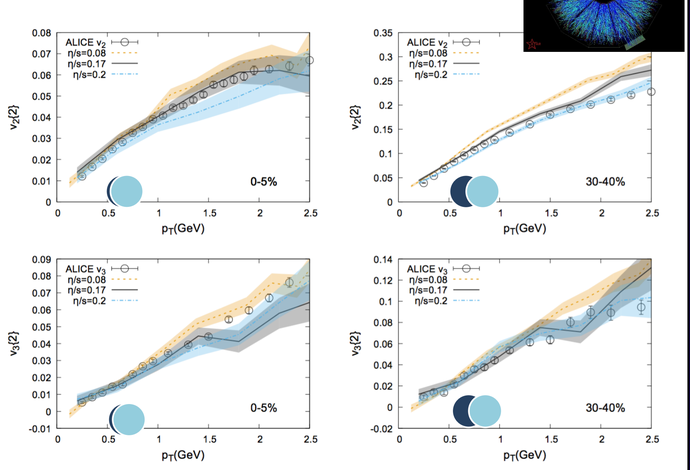
- Parameters in initial condition TRENTO are fixed from comparison with experimental data at 0-5 % centrality.

a) Constant η/s



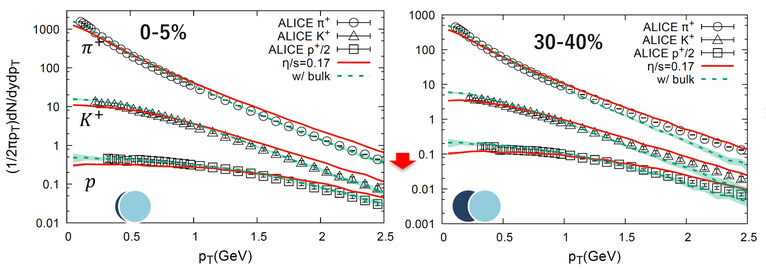


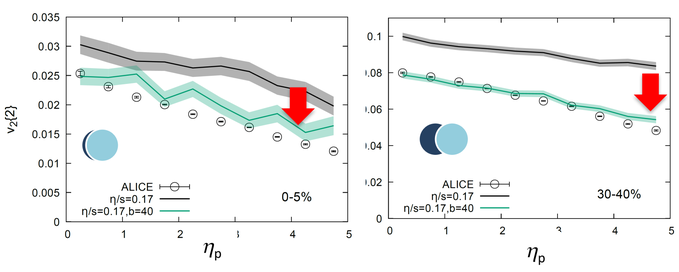
P_T spectra do not depend on η/s.



v$_2$ and v$_3$ are smaller at larger η/s. ➡ η/s=0.17

b) Shear + Bulk Viscosities

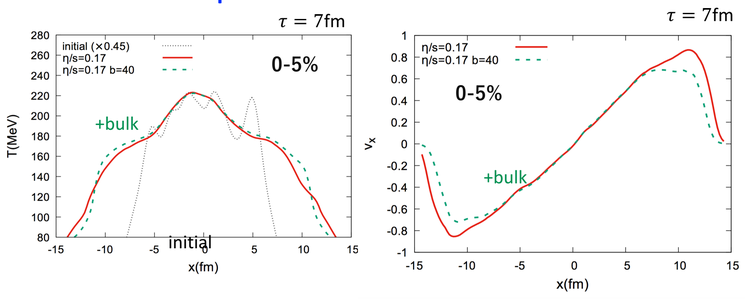




Bulk viscosity reduces the transverse expansion.
-> Slope of P_T spectra becomes steep.
-> Close to ALICE data.

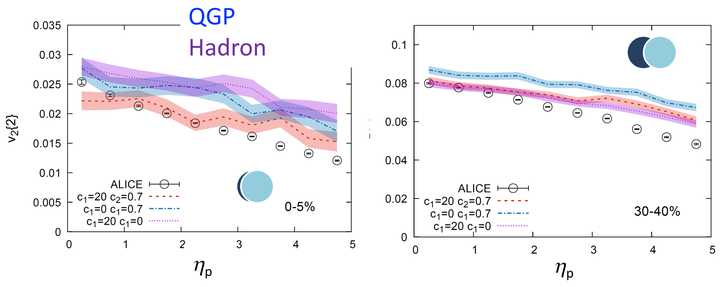
- v_n with bulk viscosity is much closer to the ALICE data. amplitude and slope
- Effect of bulk viscosity at forward rapidity is large.

Effect on expansion



Bulk viscosity is large below 200 MeV.
-> Its effect appears around T_c ~160 MeV.
-> Expansion rate decreases in lower temperature region.
-> Volume elements of fluid keep around T_c temperature longer.

c) Temperature Dependent η/s & ζ/s



- 0-5 % centrality
  η/s of QGP and hadron phases is important.
- 30-40 % centrality
  η/s of hadron phase is dominant.

Summary

- New relativistic viscous hydrodynamics code
  - –Stable with small numerical dissipation
  - –Phenomenological model : TRENTO — Hydro — UrQMD
  - –Quantitative analyses of the ALICE data
- QGP bulk property
  - –Shear and bulk viscosity
  - –Finite bulk viscosity, central dependence of $v_2(\eta_p)$
- Future works
  - –Two particle correlations (HBT), Electromagnetic probes and so on

Central dependence of $v_2(\eta_p)$ reveals temperature dependence of η/s.