Viscosity of Quantum Liquid

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Outline

- Introduction
- Experimental Results
- Strongly Coupled Plasma
- HTL Approach
- Summary

Introduction

- Eliptic Flow
- Hydrodymamics
- New Experimental Data
- Interpretation
- What is a viscosity of QGP?

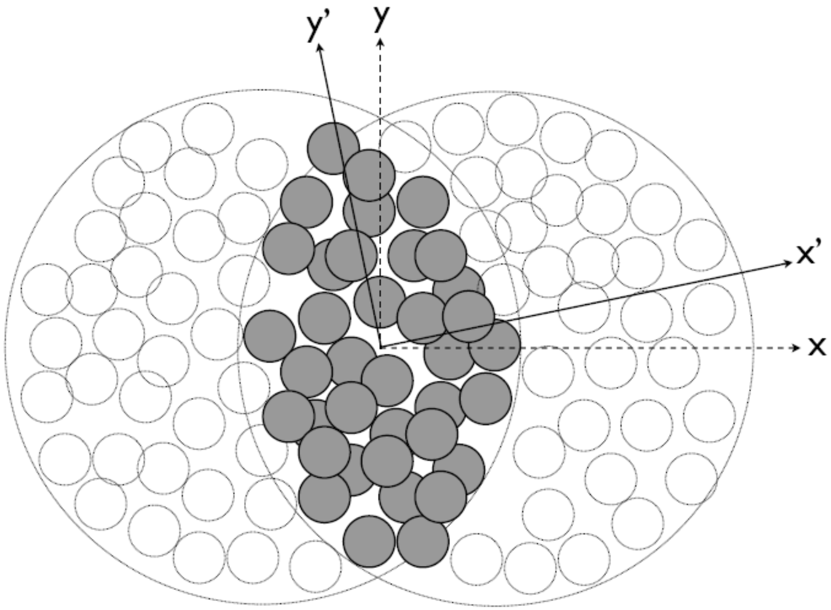
Experimental Results

Recent results of the PHOBOS collaboration

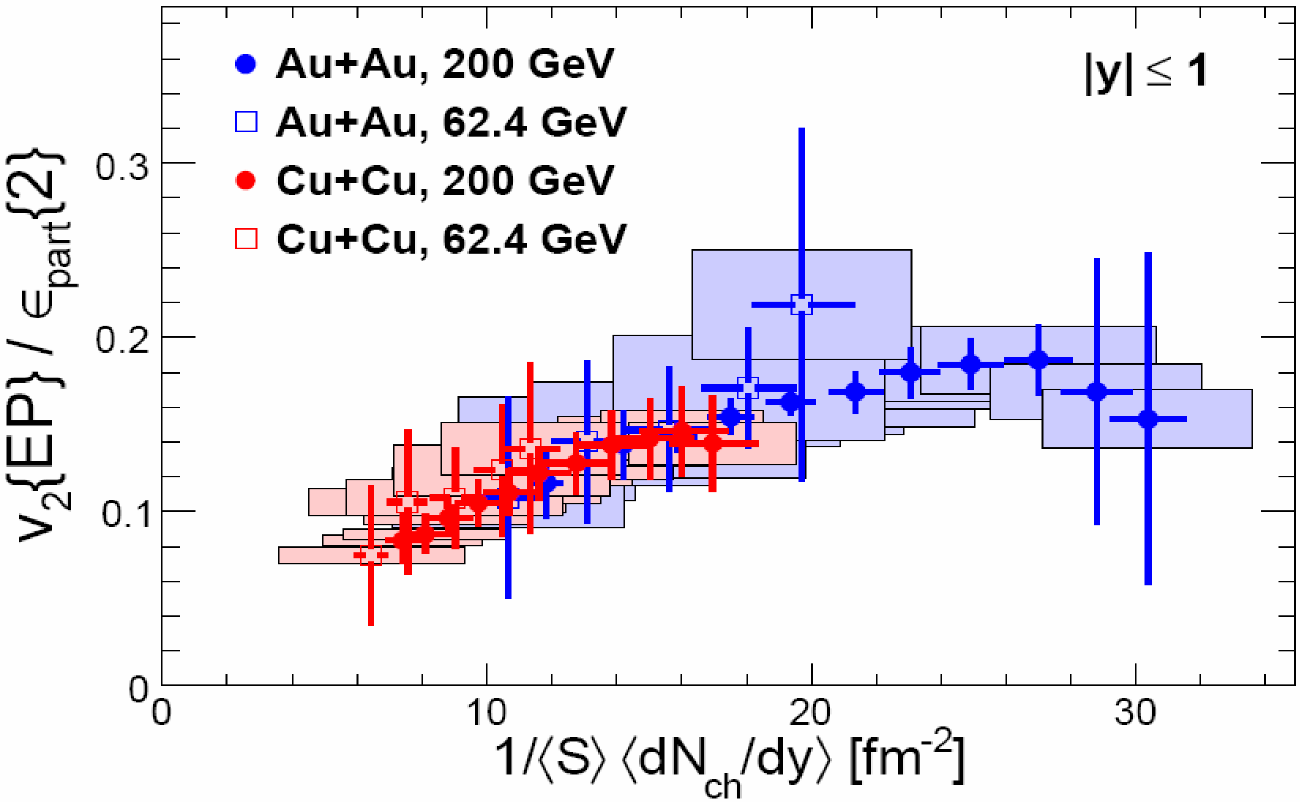
B. Alver *et al*. (PHOBOS Collaboration), Phys. Rev. C77, 014906 (2008)

participant eccentricity

$$\epsilon_{\text{part}} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$



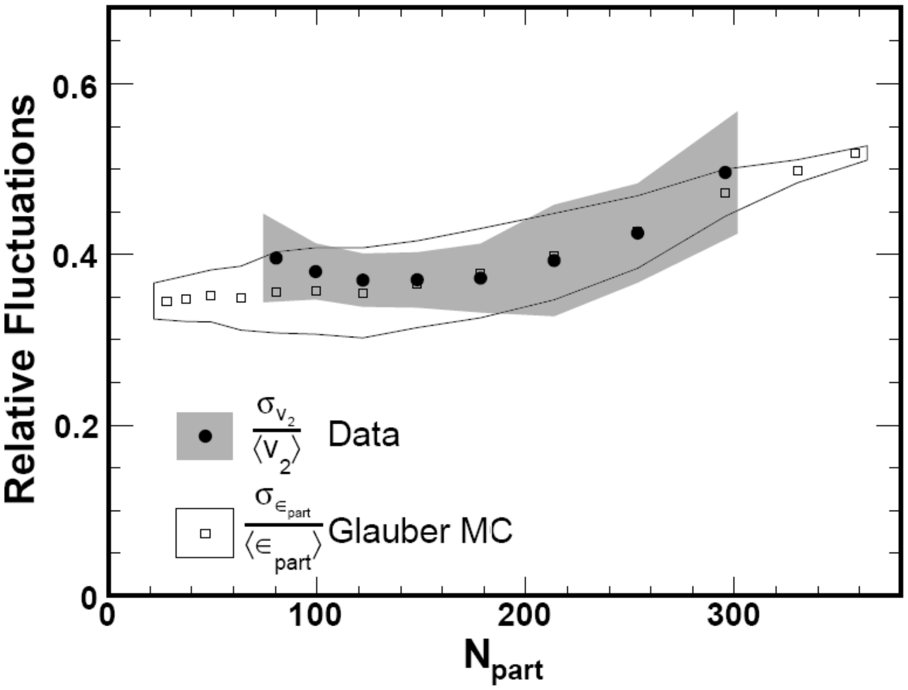
Experimental Results



Experimental Results

Au-Au collisions at 200GeV

Fluctuations of the eliptic flow reflect fluctuations in the initial state geometry and are not affected strongly by the later stages of the collision



Strongly Coupled Plasma

- G. t'Hooft's holographic principle
  - The whole information, which exists in a certain space region can be written on the border of that region.
  - Theory on the border can have at most one degree of freedom for the Planck's surface.

Strongly Coupled Plasma

- AdS/CFT correspondence
  - AdS – gravitational theory in 5D anti - de Sitter's space which has a flat 4D border.
  - CFT – Supersymmetric Yang Mills quantum field theory existing on that 4D border.

Strongly Coupled Plasma

- SYM has much more symmetries than QCD and has constant coupling constant
- Thermalization is the creation of the black holes in the 5D space
- Cooling is a movement of black holes in the 5th direction

Strongly Coupled Plasma

- Entropy is proportional to the surface of the black hole

$$s = \frac{S}{V} = \frac{\pi^2}{2} N^2 T^3$$

Gubser, Klebanov, Peet, Phys. Rev. D 54 (1996) 3915

Strongly Coupled Plasma

- Sound absorption related with the viscosity is equivalent to the capture of the gravitons by a black hole

$$\eta = \lim_{\omega \to 0} \frac{1}{2\omega} \int dt\, d\boldsymbol{x}\, e^{i\omega t} \langle [T_{xy}(x),\, T_{xy}(0)] \rangle = \frac{\pi}{8} N^2 T^3$$

Policastro, Son, Starinets, Phys. Rev. Lett. 87 (2001) 081601

Strongly Coupled Plasma

- And final result

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

HTL Approach

HTL – Hard Thermal Loops

- R.D. Pisarski, E. Braaten
- J.P. Blazoit et al..

They have proposed resummation of the perturbative expansion in the way that is gauge invariant.

HTL Approach

collaboration with

W.M. Alberico, S. Chiacchiera, A. De Pace,
H. Hansen, A. Molinari, M. Nardi,
Universta di Torino

HTL Approach

- Kubo formula relates viscosity with correlator of the energy-momentum tensor

$$\eta = \lim_{\omega \to 0^+} \eta(\omega) = -\frac{\mathrm{d}}{\mathrm{d}\omega} \mathrm{Im}\, \Pi^R(\omega)\Big|_{\omega=0^+}$$

HTL Approach

- Retarded correlator (for zero momentum)

$$\Pi^R(i\omega_l) = N_c N_f \, \frac{1}{\beta} \sum_{n=-\infty}^{+\infty} \int \frac{d^3k}{(2\pi)^3} \, k_x^2 \, \mathrm{Tr}[\gamma^2 \, S(i\omega_n, k)\gamma^2 \, S(i\omega_n - i\omega_l, k)]$$

where

$$\omega_l = 2\pi l/\beta, \; \omega_n = (2n+1)\pi/\beta, \; (\beta = 1/T)$$

are Matsubara frequencies

HTL Approach

- Spectral representation of the quark propagator

$$S(i\omega_n, k) = -\int_{-\infty}^{+\infty} d\omega \; \frac{\rho(\omega, k)}{i\omega_n - \omega}$$

$$\rho(\omega, k) = \frac{\gamma^0 - \gamma \cdot \hat{\mathbf{k}}}{2}\rho_+(\omega, k) \; + \; \frac{\gamma^0 + \gamma \cdot \hat{\mathbf{k}}}{2}\rho_-(\omega, k)$$

HTL Approach

- Expilit expresion for HTL quark spectral function

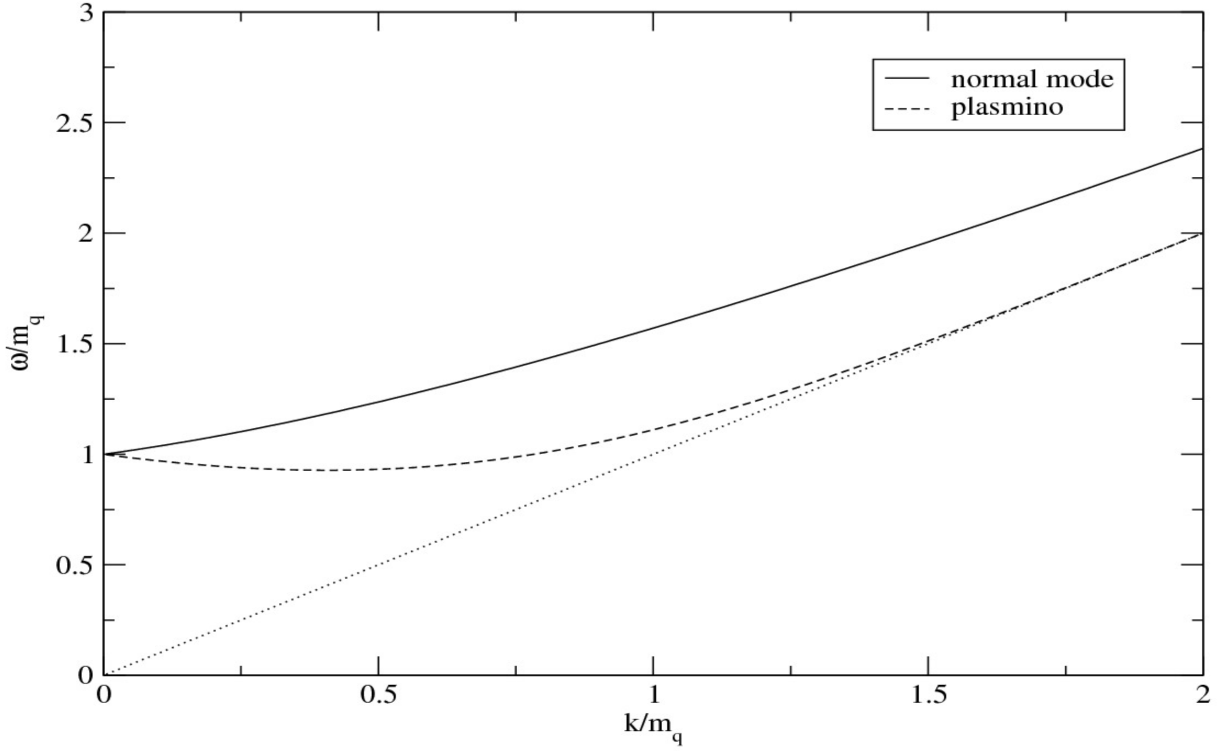
$$\rho_{\pm}(\omega, k) = 2\pi Z_{\pm}(k)[\delta(\omega - \omega_{\pm}) + \delta(\omega + \omega_{\mp})] + 2\pi\beta_{\pm}(\omega, k)\theta(k^2 - \omega^2)$$

where the quark thermal mass $m_q = g(T)T/\sqrt{6}$

and the residues of the quasi particle poles

$$Z_{\pm}(k) = \frac{\omega_{\pm}^2(k) - k^2}{2m_q^2}$$

HTL Approach



HTL Approach

- Finally

$$\eta = \frac{N_c N_f}{2T} \int \frac{d^3k}{(2\pi)^3} k_x^2 \int_{-\infty}^{+\infty} \frac{d\omega}{2\pi} (1 - f(\omega)) f(\omega) \, \mathrm{Tr} \left[\gamma^2 \rho(\omega, \mathbf{k}) \gamma^2 \rho(\omega, \mathbf{k}) \right]$$

$$\eta = \frac{N_c N_f}{60\pi^3 T} \int_0^{+\infty} dk \, k^4 \int_{-\infty}^{+\infty} d\omega (1 - f(\omega)) f(\omega) \left\{ \rho_+^2(\omega, \mathbf{k}) + \rho_-^2(\omega, \mathbf{k}) + 8\rho_+(\omega, \mathbf{k}) \rho_-(\omega, \mathbf{k}) \right\}$$

$$\eta = \eta^{QP} + \eta^{QPLD} + \eta^{LD}$$

HTL Approach

- The quasiparticle contribution

$$\eta^{QP} = \frac{N_c N_f}{60\pi^3 T} \int\limits_0^{+\infty} dk\, k^4 \int\limits_{-\infty}^{+\infty} d\omega (1 - f(\omega)) f(\omega) \left\{ (\rho_+^{QP}(\omega, \mathbf{k}) - \rho_-^{QP}(\omega, \mathbf{k}))^2 \right\}$$

$$+ \frac{N_c N_f}{60\pi^3 T} \int\limits_0^{\Lambda} dk\, k^4 \int\limits_{-\infty}^{+\infty} d\omega (1 - f(\omega)) f(\omega) \left\{ 10 \rho_+^{QP}(\omega, \mathbf{k}) \rho_-^{QP}(\omega, \mathbf{k}) \right\}$$

HTL Approach

- Let's give a finite width to the poles

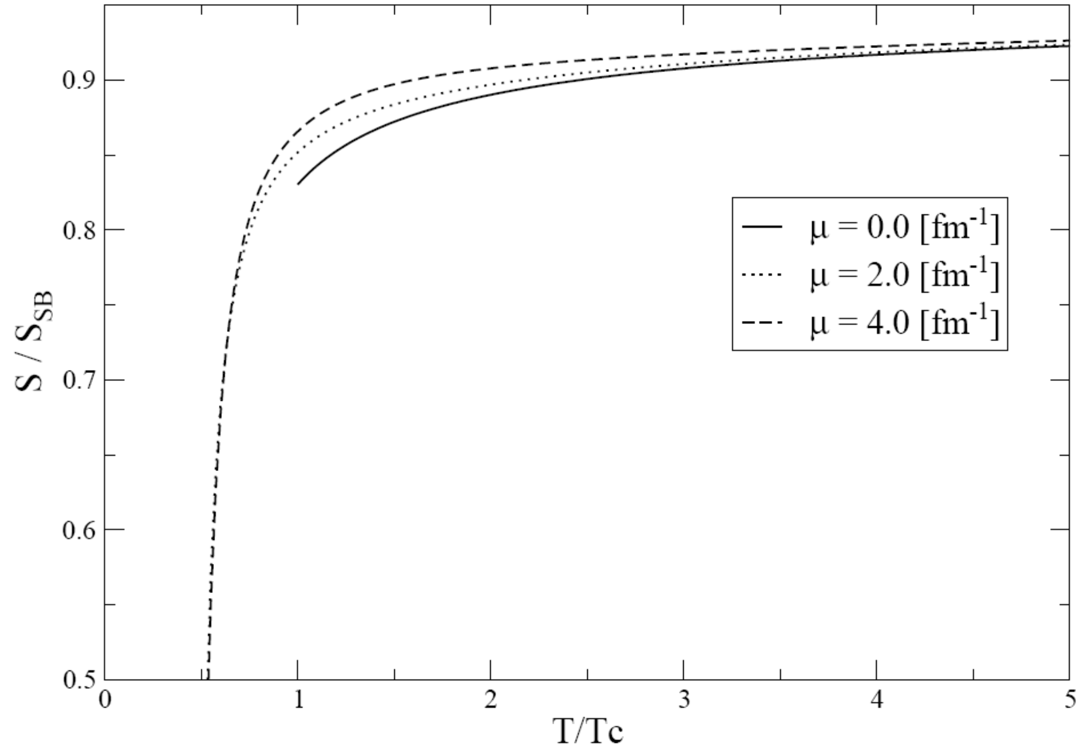
$$\rho_{\pm}^{\mathrm{QP}}(\omega,\mathbf{k}) = Z_{\pm}(k)\frac{2\gamma_{\pm}}{(\omega-\omega_{\pm}(k))^2+\gamma_{\pm}^2} + Z_{\mp}(k)\frac{2\gamma_{\mp}}{(\omega+\omega_{\mp}(k))^2+\gamma_{\mp}^2}$$

Braaten, Pisarski, Phys. Rev. D46 (1992) 1829

$$\gamma_{\pm} = a\frac{C_f g^2 T}{16\pi},$$

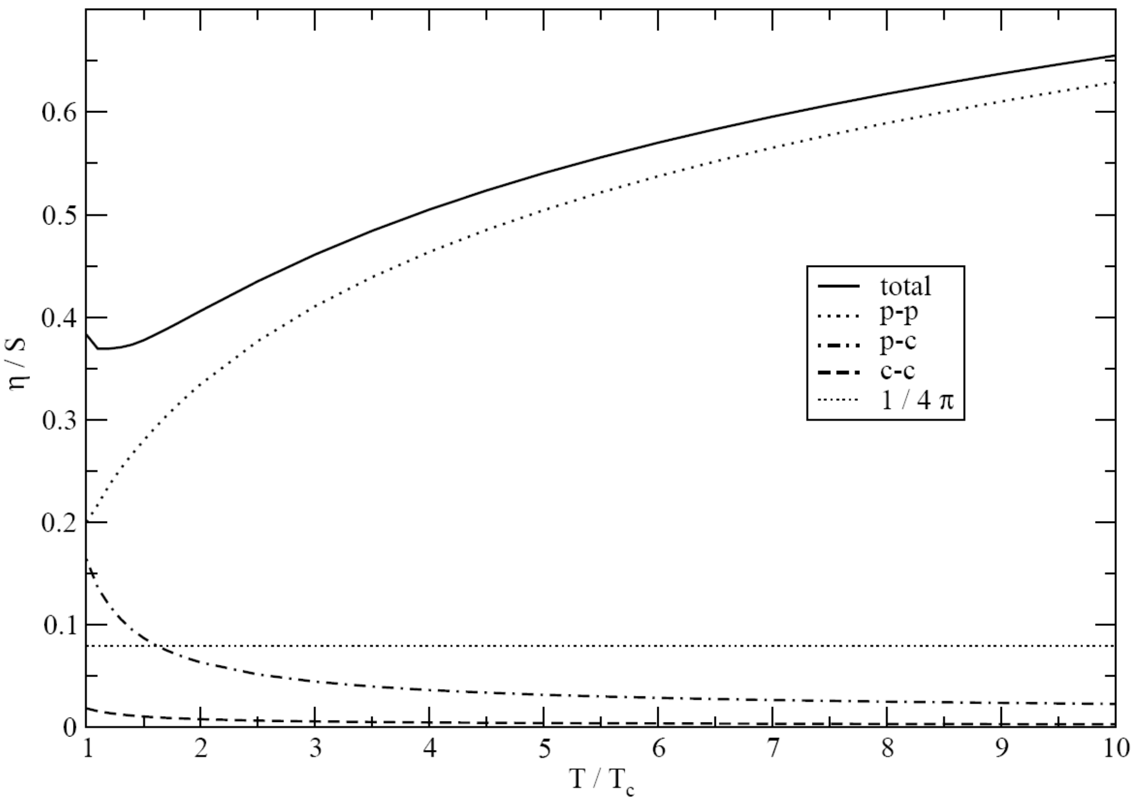
HTL Approach

- Entropy dependence on chemical potential



HTL Approach

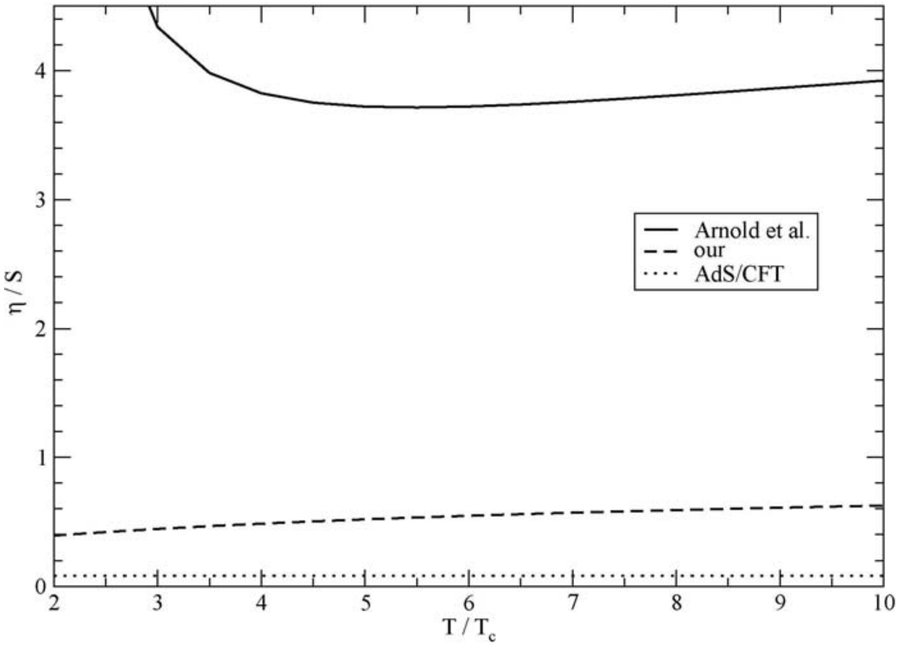
- The final results of the viscosity/entropy



Other Approach

$$\eta = 86.47\ T^3 \frac{1}{g^4} \frac{1}{\log\left[2.295\sqrt{3}/2/g\right]}$$

$$S_{SB} = \frac{74}{45}\pi^2 T^3$$



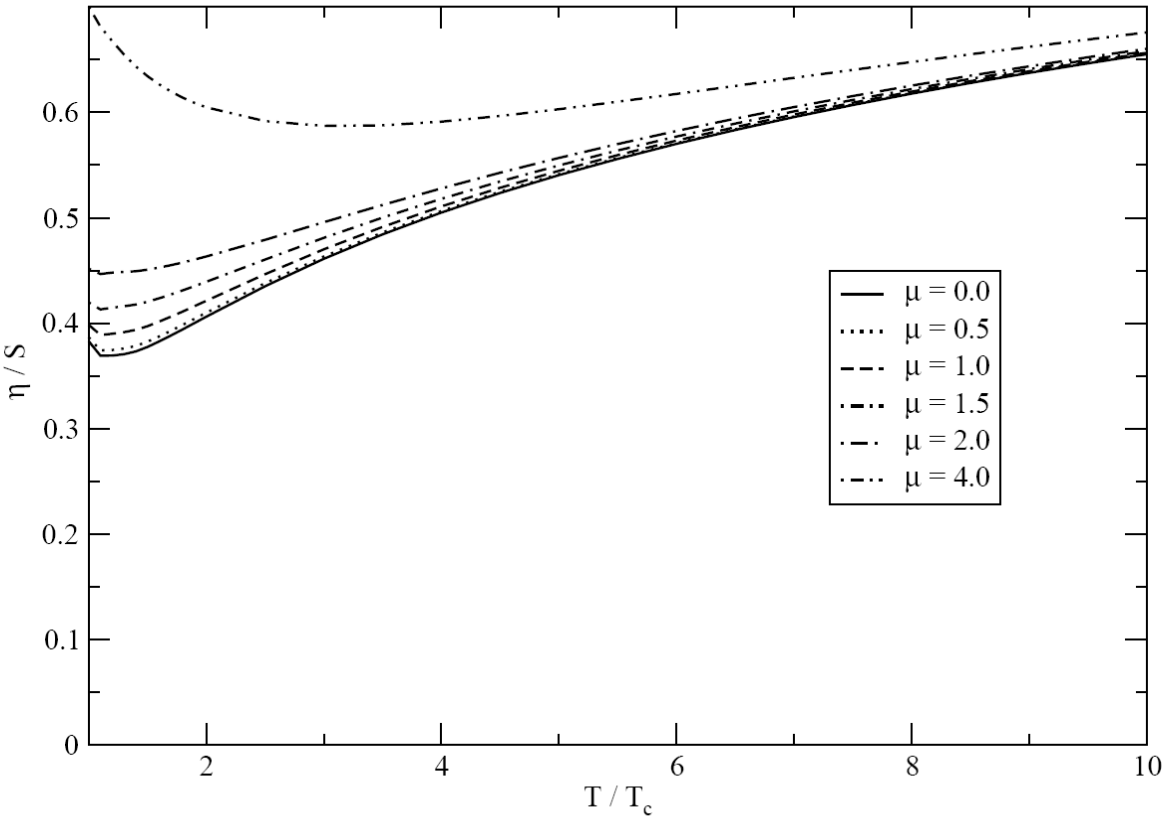
P.B. Arnold, G.D. Moore, L.G. Yaffe, JHEP05 (2003) 051

Summary

- No more problem with zero viscosity to explain the data.
- Lower bound for η/s from correspondence priciple.
- HTL, gluon contribution is needed.

HTL Approach

- Chemical potential, $\mu[\,fm^{-1}]$



HTL Approach

- Chemical potential in details, $\mu[\,fm^{-1}]$