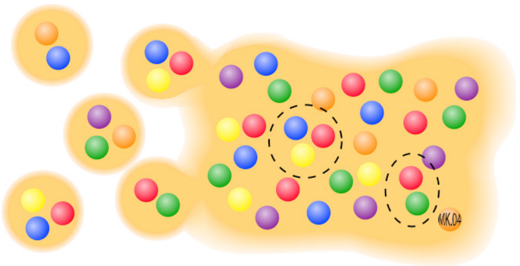
Dynamical equilibration and transport coefficients of strongly-interacting 'infinite' parton matter

Vitalii Ozvenchuk

Transport Meeting

13 December 2012

From hadrons to partons



In order to study of the phase transition from hadronic to partonic matter – Quark-Gluon-Plasma – we need a consistent non-equilibrium (transport) model with

- ☐ **explicit parton-parton interactions (i.e. between quarks and gluons) beyond strings!**
- ☐ **explicit phase transition from hadronic to partonic degrees of freedom**
- ☐ **lQCD EoS for partonic phase**

Transport theory: off-shell Kadanoff-Baym equations for the Green-functions $S^{<}_{h}(x,p)$ in phase-space representation for the partonic and hadronic phase

⇨ **Parton-Hadron-String-Dynamics (PHSD)**

W. Cassing, E. Bratkovskaya, PRC 78 (2008) 034919;
NPA831 (2009) 215;
W. Cassing, EPJ ST 168 (2009) 3

QGP phase described by

Dynamical QuasiParticle Model (DQPM)

A. Peshier, W. Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365: NPA 793 (2007)

DQPM spectral function

Basic idea: effective strongly-interacting quasiparticles

- massive quarks, antiquarks and gluons (q, q_{bar}, g) with broad spectral functions

DQPM: Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365; NPA 793 (2007)

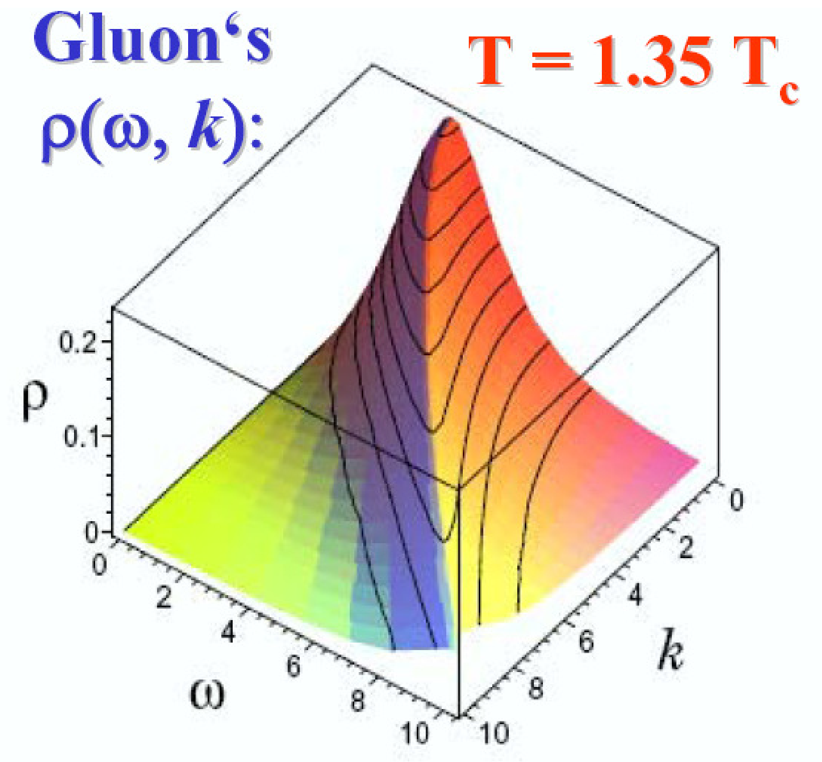
Breit-Wigner spectral function:

$$\rho(\omega, \mathbf{p}) = \frac{4\omega\Gamma}{(\omega^2 - \mathbf{p}^2 - M^2)^2 + 4\Gamma^2\omega^2} \equiv$$

$$\equiv \frac{\Gamma}{E}\left[\frac{1}{(\omega - E)^2 + \Gamma^2} - \frac{1}{(\omega + E)^2 + \Gamma^2}\right]$$

notation: $E^2 = \mathbf{p}^2 + M^2 - \Gamma^2$

- ☐ mass and width:
  - $\Rightarrow$ quasiparticle properties
- ☐ finite width:
  - $\Rightarrow$ two-particle correlations



DQPM running coupling

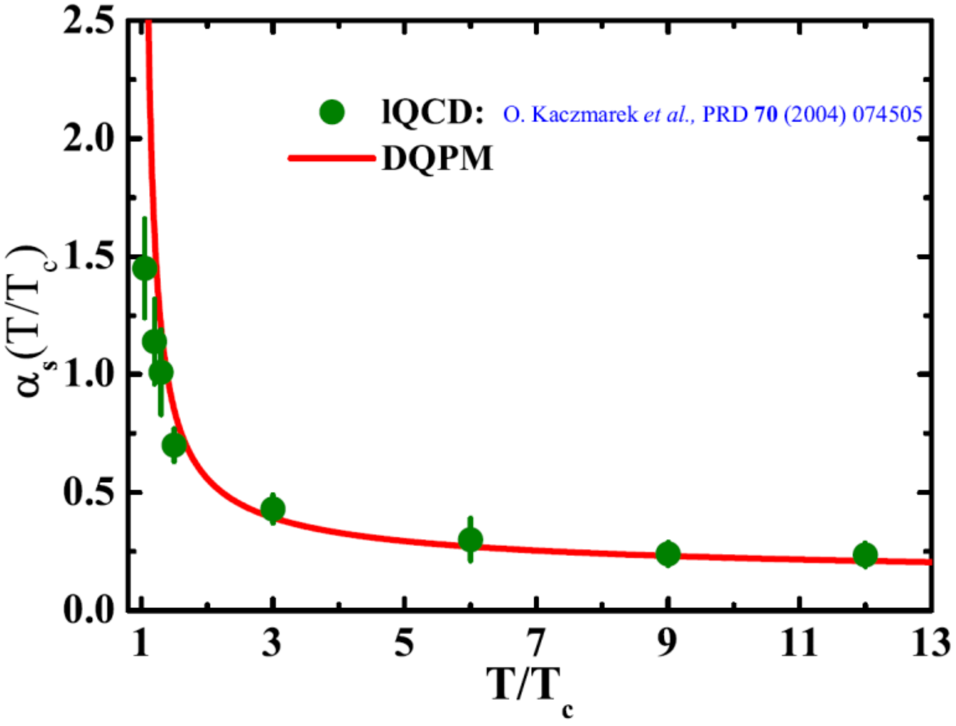
- running coupling $\Rightarrow$ fit to the lattice QCD results

lQCD: Kaczmarek *et al.*, PRD 70 (2004) 074505

$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$

- number of colors $\Rightarrow$ $N_c = 3$
- number of flavors $\Rightarrow$ $N_f = 3$
- 3 fitting parameters

$$\Rightarrow \quad \lambda = 2.42 \qquad T_s/T_c = 0.56$$
$$c = 14.4$$



DQPM mass and width

- **spectral function:** $\rho(\omega, \mathbf{p}) = \dfrac{4\omega\Gamma}{(\omega^2 - \mathbf{p}^2 - M^2)^2 + 4\Gamma^2\omega^2}$

quark (antiquark):

$$M^2_{q(\bar{q})}(T) = \frac{N_c^2 - 1}{8N_c} g^2 \left(T^2 + \frac{\mu_q^2}{\pi^2} \right)$$

$$\Gamma_{q(\bar{q})}(T) = \frac{1}{3} \frac{N_c^2 - 1}{2N_c} \frac{g^2 T}{8\pi} \ln\left(\frac{2c}{g^2} + 1 \right)$$

gluon:

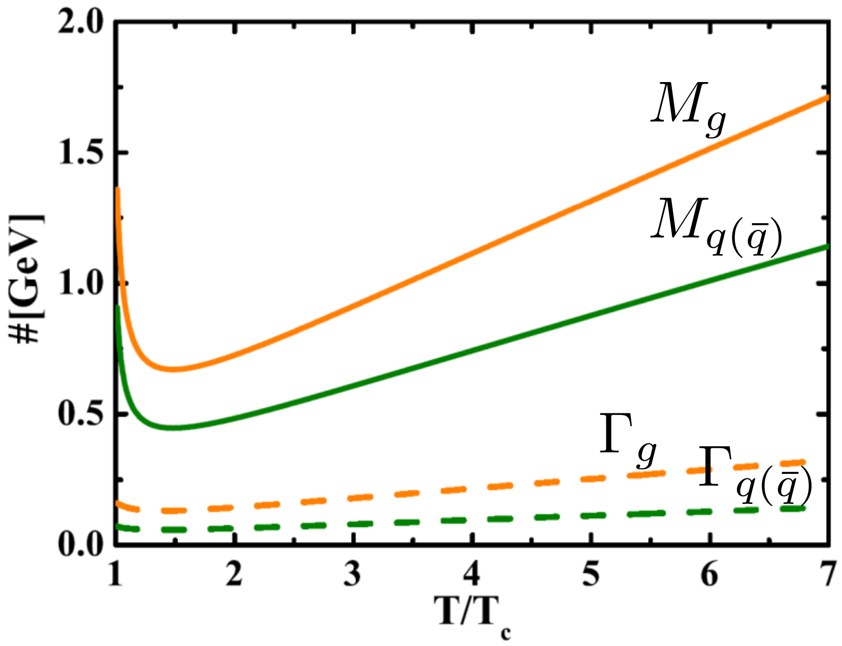
$$M_g^2(T) = \frac{g^2}{6} \left(\left(N_c + \frac{N_f}{2} \right) T^2 + \frac{N_c}{2} \sum_q \frac{\mu_q^2}{\pi^2} \right)$$

$$\Gamma_g(T) = \frac{1}{3} N_c \frac{g^2 T}{8\pi} \ln\left(\frac{2c}{g^2} + 1 \right)$$

Peshier, PRD 70 (2004) 034016

- **high temperature regime**
  $\Rightarrow$ **one-loop perturbative QCD results**

- **mass and width define quasiparticle properties**

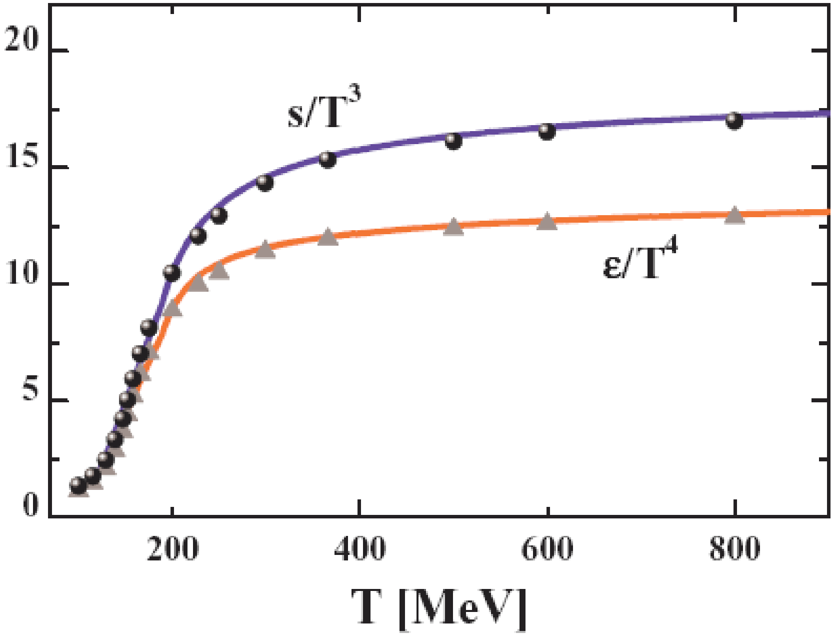


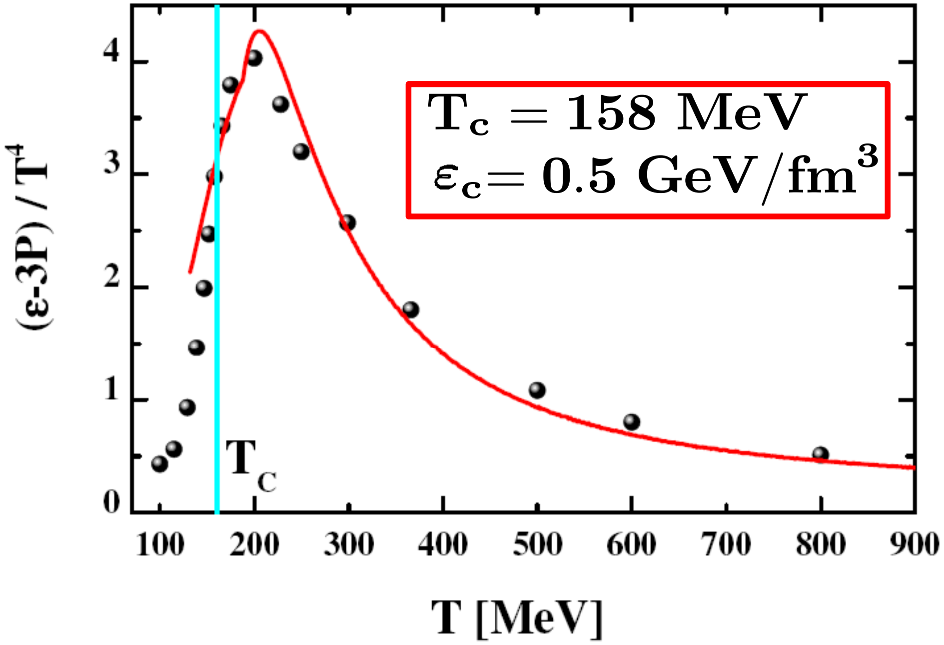
DQPM thermodynamics (N_f=3)

- ☐ **entropy:** $s = \frac{\partial P}{\partial T} \Rightarrow$ **pressure**
- ☐ **energy density:** $\varepsilon = Ts - P$
- ☐ **interaction measure:**

$$W = \varepsilon - 3P = Ts - 4P$$

lQCD: Wuppertal-Budapest group
Y. Aoki et al., JHEP 0906 (2009) 088





$T_c = 158$ MeV
$\varepsilon_c = 0.5$ GeV/fm^3

DQPM gives a good description of lQCD results !

DQPM overview

- ☐ **fit to lattice QCD results:**
  - ⇒ **thermodynamics quantities (pressure, entropy density, energy density) in equilibrium**
  - ⇒ **running coupling:**

$$\alpha_s(T) = \frac{g^2(T)}{4\pi} = \frac{12\pi}{(11N_c - 2N_f)\ln[\lambda^2(T/T_c - T_s/T_c)^2]}$$

- ☐ **DQPM provides:**
  - ⇒ **spectral function (mass and width) ⇒ off-shell quasiparticle properties**

$$\rho(\omega, \mathbf{p}) = \frac{4\omega\Gamma}{(\omega^2 - \mathbf{p}^2 - M^2)^2 + 4\Gamma^2\omega^2}$$

  - ⇒ **mean fields (1 PI) for quarks (antiquarks) and gluons as well as effective 2-body interactions (2 PI)**

Peshier, Cassing, PRL 94 (2005) 172301;
Cassing, NPA 791 (2007) 365; NPA 793 (2007)

Our goals

- ☐ study of the partonic system out of equilibrium (beyond the DQPM)
  - ○ dynamical equilibration of QGP within the non-equilibrium off-shell PHSD transport approach
  - ○ influence of the partonic elastic and inelastic cross sections;

- ☐ study of the thermal properties of equilibrated partonic system in PHSD
  - ○ transport coefficients (shear and bulk viscosities) of strongly-interacting partonic matter;
  - ○ particle number fluctuations (scaled variance, skewness, kurtosis).

Ozvenchuk, Linnyk, Gorenstein, Bratkovskaya, Cassing, arXiv: 1203.4734

Parton interactions in PHSD

❑ **degrees of freedom in PHSD:**

colored quarks (u, d, s), **antiquarks** (ubar, dbar, sbar) **and gluons**

❑ **interaction processes:**

(quasi)-elastic

$$\mathrm{q(m_1) + q(m_2) \to q(m_3) + q(m_4)}$$

$$\mathrm{q + \bar{q} \to q + \bar{q}}$$

$$\mathrm{\bar{q} + \bar{q} \to \bar{q} + \bar{q}}$$

$$\mathrm{g + q \to g + q}$$

$$\mathrm{g + \bar{q} \to g + \bar{q}}$$

$$\mathrm{g + g \to g + g}$$

inelastic

$$\left.\begin{array}{c} \mathrm{q + \bar{q} \to g} \\ \mathrm{g \to q + \bar{q}} \end{array}\right\} \Longrightarrow$$

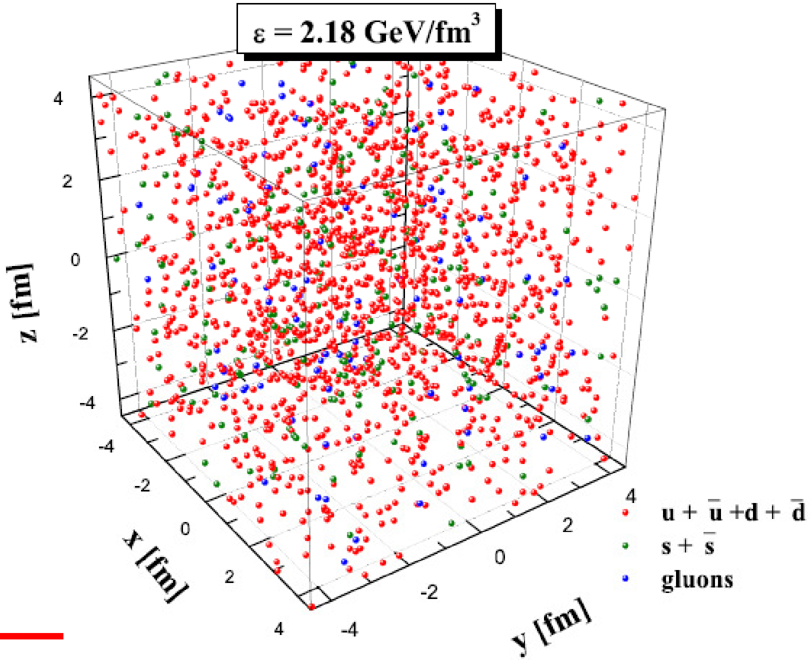
basic processes for the chemical equilibration ⇔ flavor exchange

e.g. $\Rightarrow u + \bar{u} \leftrightarrow g \ldots g \leftrightarrow s + \bar{s}$

$$\xcancel{\left.\begin{array}{c} \mathrm{q + \bar{q} \leftrightarrow g + g} \\ \mathrm{g \leftrightarrow g + g} \end{array}\right\}} \Longrightarrow$$

suppressed (<1%) due to the large mass of gluon

Initialization



☐ **cubic box:**

- ○ periodic boundary conditions;
- ○ size is fixed to 9^3 fm^3;
- ○ light and strange quarks, antiquarks and gluons;
- ○ various values for the energy density and quark chemical potential.

☐ **initialization is:**

$\Longrightarrow$ close to the thermal equilibrium with thermal distribution for the momenta;

$\Longrightarrow$ far out of the chemical equilibrium due to the strangeness suppression:

$$\boxed{N_u \div N_d \div N_s = 3 \div 3 \div 1}$$

Partial widths

- ☐ **DQPM provides the total width Γ of the dynamical quasiparticles**

$$\boxed{\Gamma_{total} = \Gamma_{elastic} + \Gamma_{inelastic}}$$

- ☐ **partial widths - (quasi)-elastic and inelastic - cannot be defined from the DQPM**

for gluons: $\Gamma_g^{DQPM}(\varepsilon) = \Gamma_{g\rightarrow q+\bar{q}}^{inelastic}(\varepsilon) + \Gamma_{gg}^{elastic}(\varepsilon) + \Gamma_{gq}^{elastic}(\varepsilon) + \Gamma_{g\bar{q}}^{elastic}(\varepsilon)$

for quarks: $\Gamma_j^{DQPM}(\varepsilon) = \Gamma_{\bar{q}q\rightarrow g}^{inelastic}(\varepsilon) + \Gamma_{jg}^{elastic}(\varepsilon) + \Gamma_{jq}^{elastic}(\varepsilon) + \Gamma_{j\bar{q}}^{elastic}(\varepsilon)$

$j = q, \bar{q}$

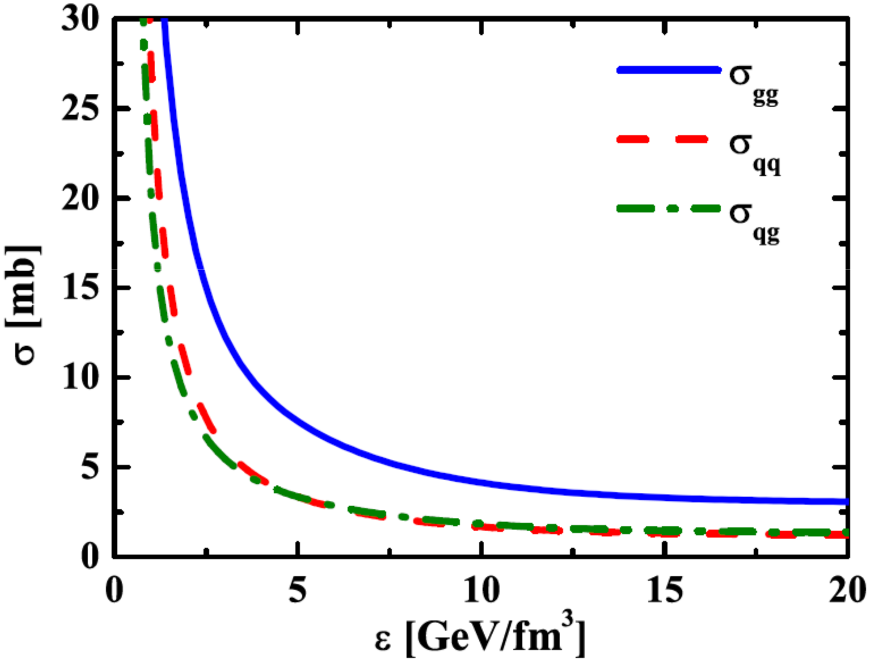
- ☐ **obtain the partial widths $\Leftrightarrow$ cross sections for different channels from the PHSD simulations in the box**

- ☐ **final check $\Longrightarrow$ reproduce the lQCD EoS within PHSD in the box**

Parton cross sections in PHSD

(Quasi)-elastic cross sections

$$\boxed{\begin{array}{c} \mathrm{q+q\rightarrow q+q} \\ \mathrm{q+\bar{q}\rightarrow q+\bar{q}} \\ \mathrm{\bar{q}+\bar{q}\rightarrow \bar{q}+\bar{q}} \\ \mathrm{g+q\rightarrow g+q} \\ \mathrm{g+\bar{q}\rightarrow g+\bar{q}} \\ \mathrm{g+g\rightarrow g+g} \end{array}} \Longrightarrow$$



Inelastic channels

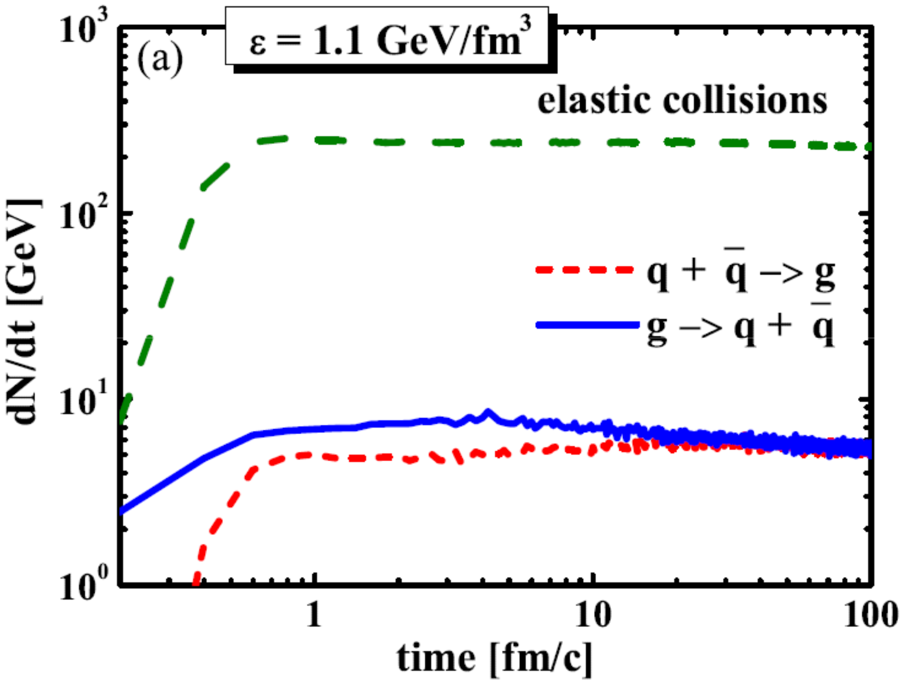
Breit-Wigner cross section

$$\boxed{\begin{array}{c} \mathrm{q+\bar{q}\rightarrow g} \\ \mathrm{g\rightarrow q+\bar{q}} \end{array}} \Longrightarrow \sigma_{q\bar{q}\rightarrow g}(\varepsilon) = \frac{2}{4}\frac{4\pi s\Gamma^2_{g\rightarrow q+\bar{q}}}{(s-M_g^2(\varepsilon))^2+s\Gamma_g^2}/P^2_{rel}$$

Detailed balance

- ❑ **reactions rates are practically constant and obey detailed balance for**
  - ○ **gluon splitting**
  - ○ **quark + antiquark fusion**
- ❑ **(quasi)-elastic collisions lead to the thermalization of all pacticle species**

$$\begin{aligned}
q + q &\rightarrow q + q \\
q + \bar{q} &\rightarrow q + \bar{q} \\
\bar{q} + \bar{q} &\rightarrow \bar{q} + \bar{q} \\
g + q &\rightarrow g + q \\
g + \bar{q} &\rightarrow g + \bar{q} \\
g + g &\rightarrow g + g
\end{aligned}$$

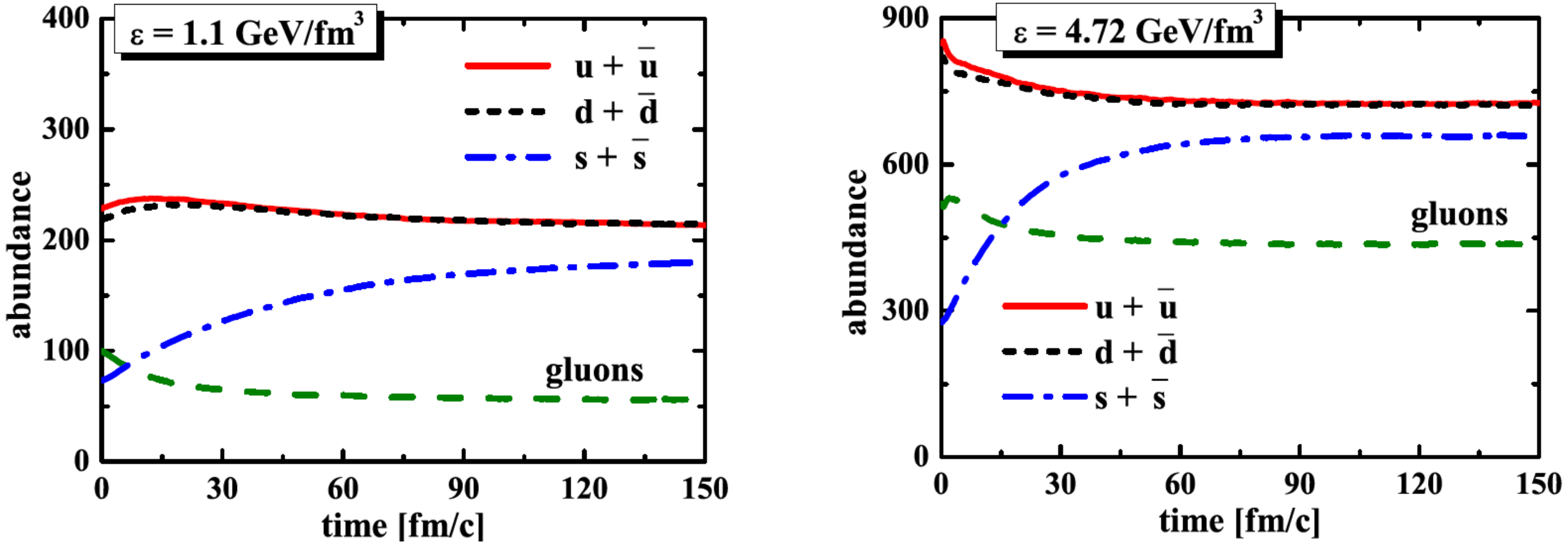


- ❑ **the numbers of partons dynamically reach their equilibrium values through the inelastic collisions**

$$\begin{aligned}
q + \bar{q} &\rightarrow g \\
g &\rightarrow q + \bar{q}
\end{aligned}$$

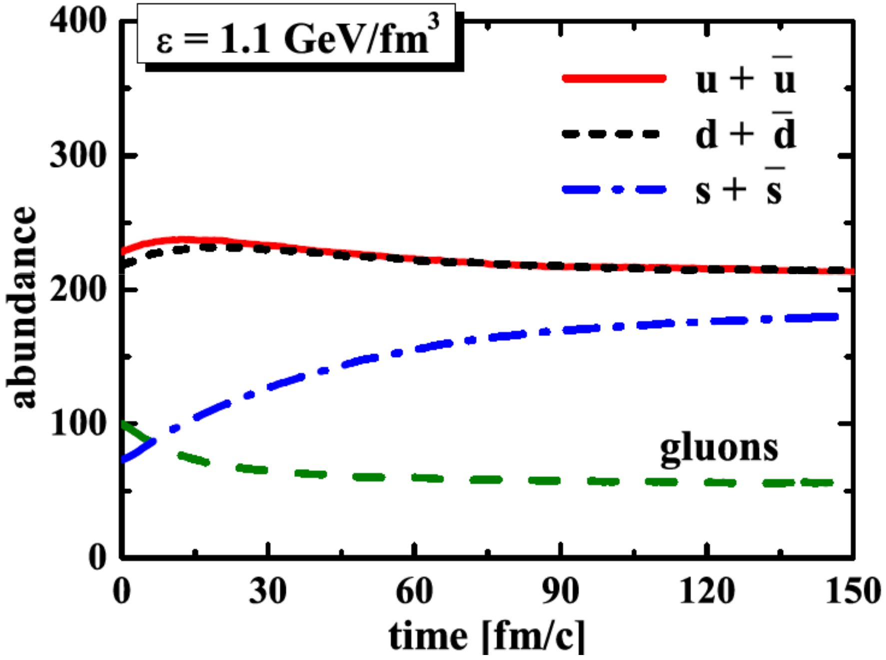
Chemical equilibrium

- ☐ **a sign of chemical equilibrium is the stabilization of the numbers of partons of the different species in time**



- ☐ **final abundancies vary with energy density**

Chemical equilibration of strange partons

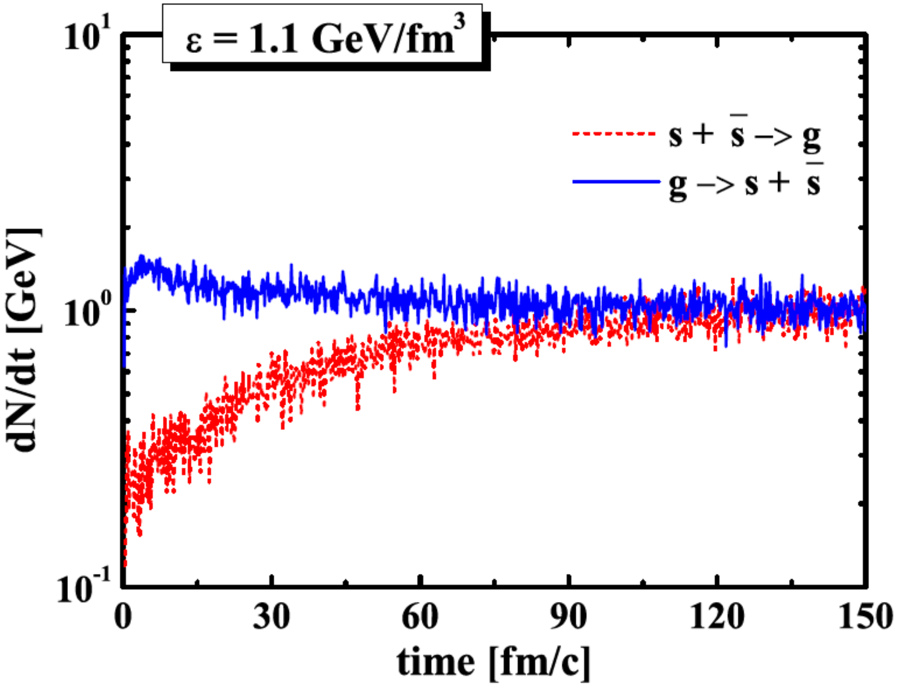


- ☐ slow increase of the total number of strange quarks and antiquarks

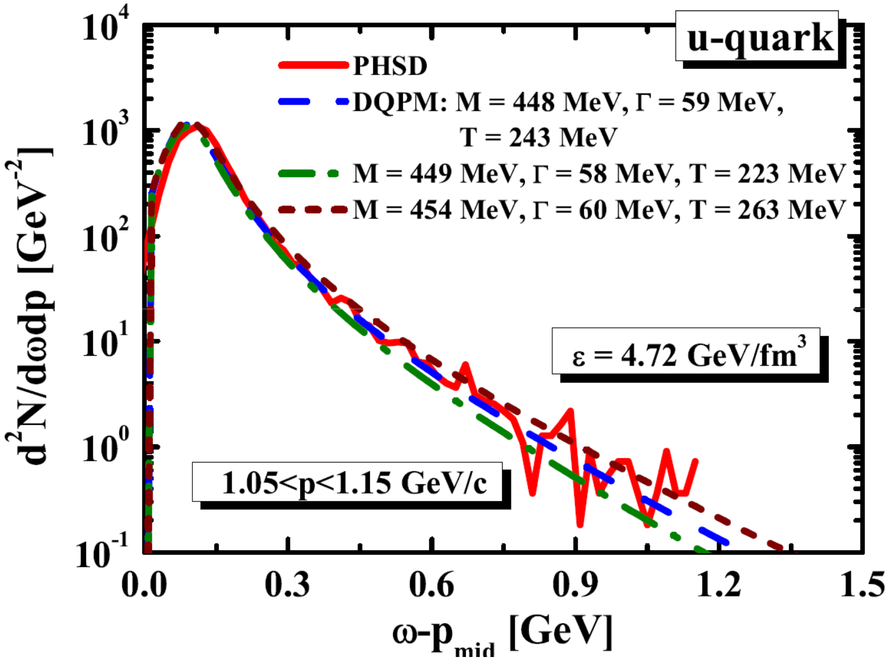
$\Rightarrow$ long equilibration times through inelastic processes involving strange partons

$$N_u \div N_d \div N_s = 3 \div 3 \div 1$$

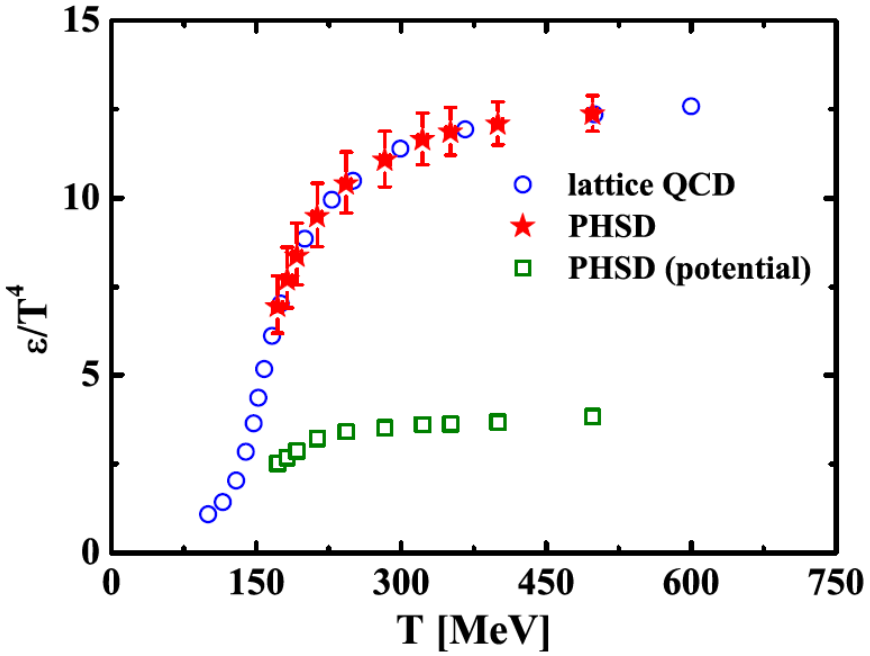
- ☐ initial rate for $s+\bar{s} \to g$ is suppressed by a factor of 9



Equation of state



$\Longrightarrow$



- ❑ **equation of state implemented in PHSD**
  - ○ **is well in agreement with the DQPM and the lQCD results;**
  - ○ **includes the potential energy density from the DQPM.**

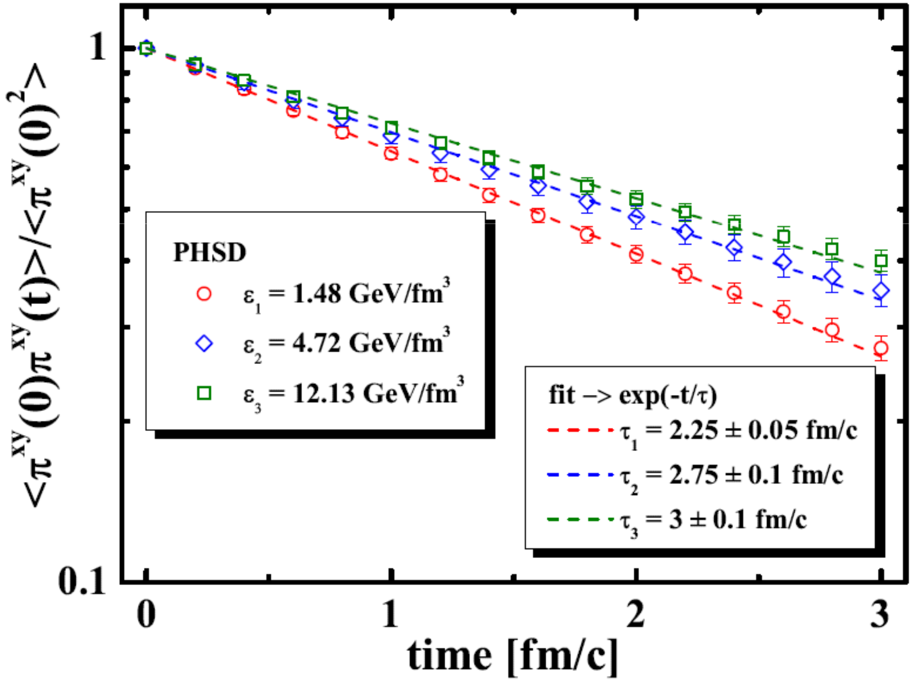
lQCD data: Borsanyi *et al.*, JHEP 1009, 073 (2010); JHEP 1011, 077 (2010)

Shear viscoty (Kubo formalism)

- **Kubo formula for the shear viscosity:**

$$\eta = \frac{1}{T}\int d^3r \int\limits_0^\infty dt \langle \pi^{xy}(\mathbf{0},0)\pi^{xy}(\mathbf{r},t)\rangle$$

Kubo, J. Phys. Soc. Japan 12, 570 (1957);
Rep. Prog. Phys. 29, 255 (1966).



- **shear component (traceless part):**

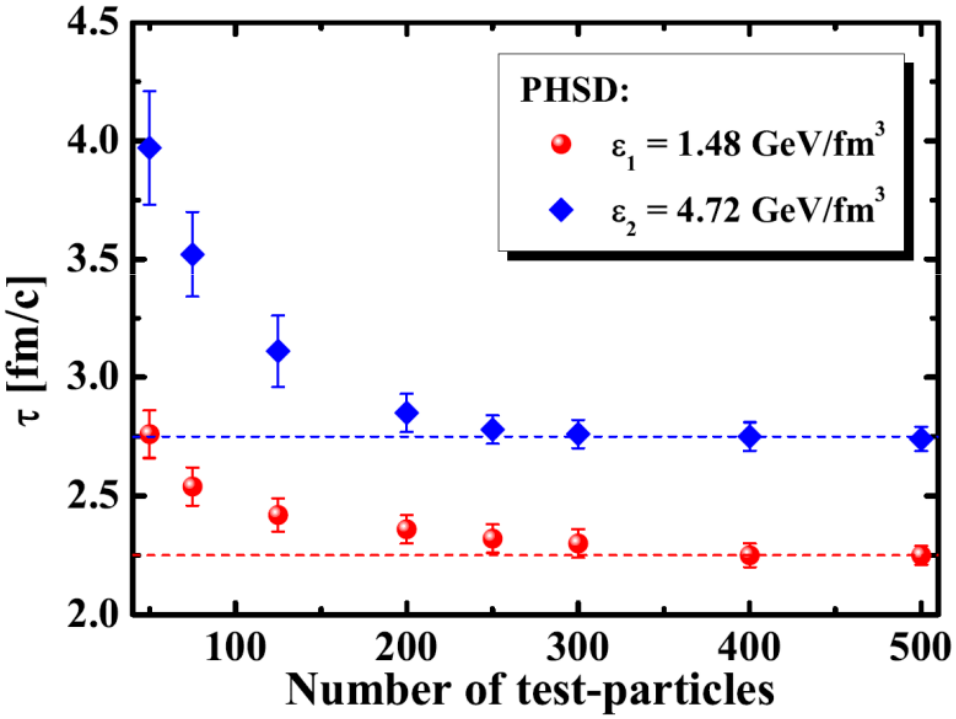
$$\pi^{xy}(\mathbf{r},t) = \int \frac{d^3p}{(2\pi)^3}\frac{p^x p^y}{E} f(\mathbf{r},\mathbf{p},t)$$

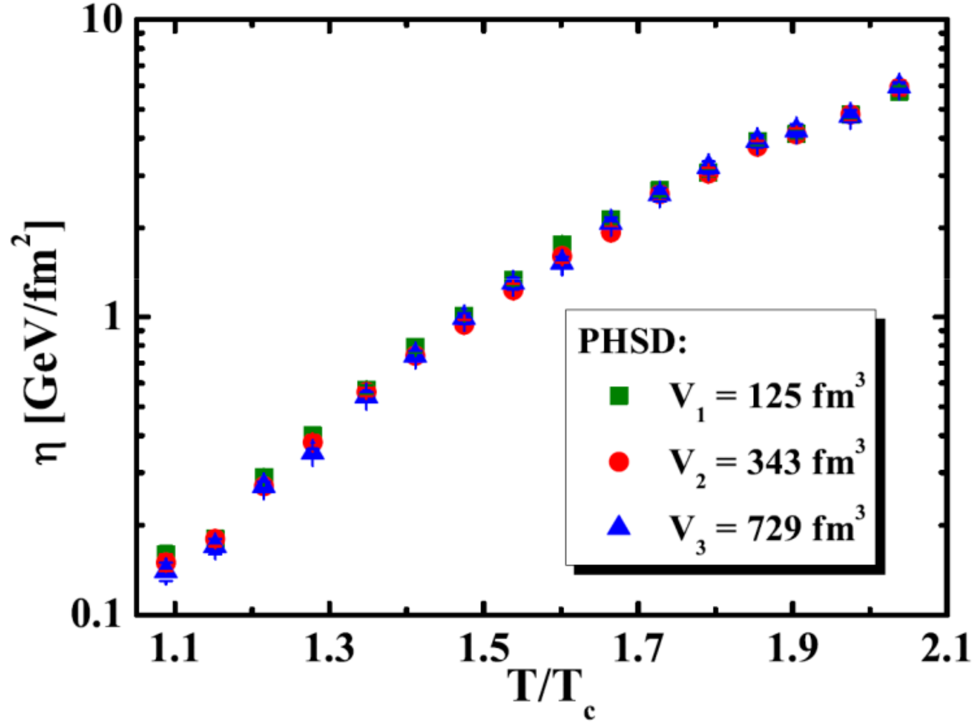
- **test-particles ansatz** $\Rightarrow \pi^{xy} = \frac{1}{V}\sum_{j=1}^{N}\frac{p_j^x p_j^y}{E_j}$

- **correlation functions are empirically found to decay exponentially in time:**

$$\langle \pi^{xy}(0)\pi^{xy}(t)\rangle = \langle \pi^{xy}(0)\pi^{xy}(0)\rangle \exp\left(-\frac{t}{\tau}\right) \quad \Rightarrow \quad \boxed{\eta = \frac{V}{T}\langle \pi^{xy}(0)^2\rangle \tau}$$

Volume and number of TP dependencies





- **relaxation time depends on the number of test-particles**

  $\Rightarrow$ **reaches the constant value for large number of TP**

- **shear viscosity does not depend on the volume of the system**

Relaxation time approximation

- **starting hypothesis:** $\boxed{C[f] = -\frac{f - f^{eq}}{\tau}}$

τ - relaxation time

$$\boxed{\tau = \Gamma^{-1}}$$

- **shear and bulk viscosities assume the following expressions:**

$$\boxed{\eta = \frac{1}{15T}\sum_a \int \frac{d^3p}{(2\pi)^3}\frac{|\mathbf{p}|^4}{E_a^2}\tau_a(E_a) f_a^{eq}(E_a/T)}$$

$$\boxed{\zeta = \frac{1}{9T}\sum_a \int \frac{d^3p}{(2\pi)^3}\frac{\tau_a(E_a)}{E_a^2}[(1-3v_s^2)E_a^2 - m_a^2] f_a^{eq}(E_a/T)}$$

Hosoya, Kajantie, Nucl. Phys. B 250, 666 (1985); Gavin, Nucl. Phys. A 435, 826 (1985); Chakraborty, Kapusta, Phys. Rev. C 83, 014906 (2011).

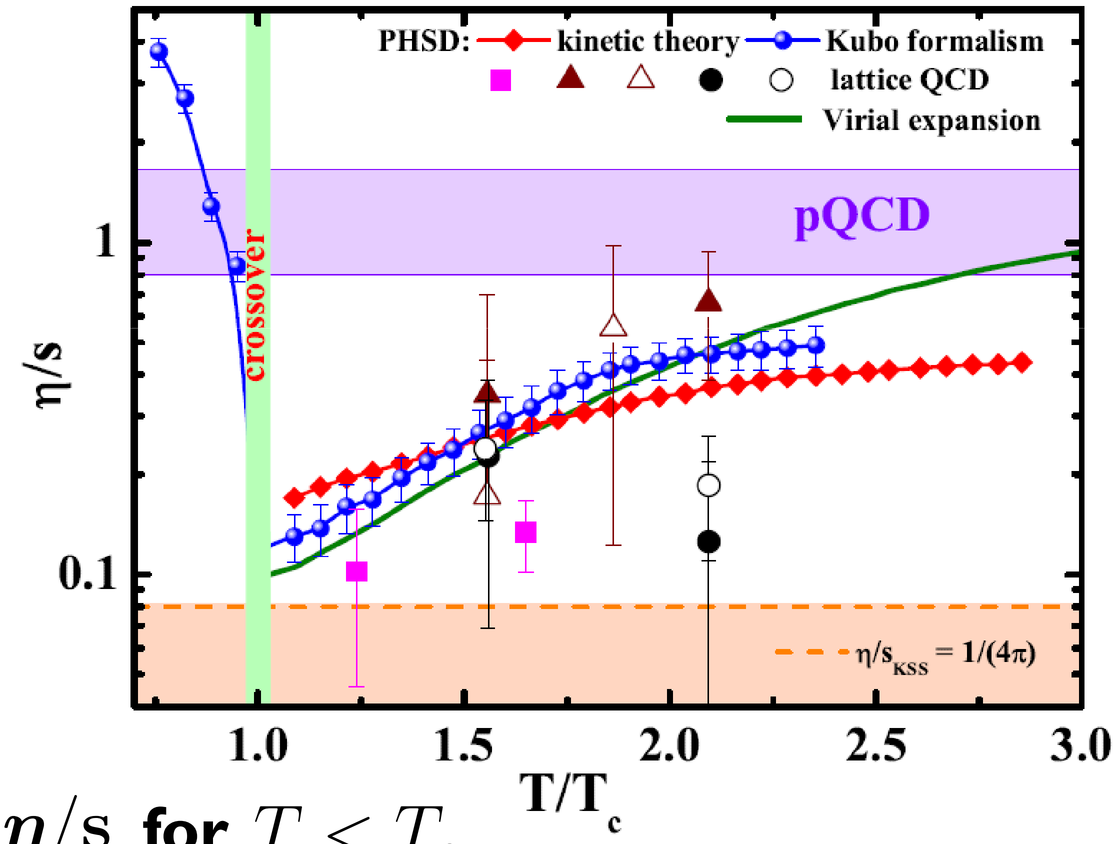
- **in numerical simulations** $\Rightarrow$ **test-particle ansatz:**

$$\boxed{\eta = \frac{1}{15TV}\sum_{i=1}^{N}\frac{|\mathbf{p}_i|^4}{E_i^2}\Gamma_i^{-1}}$$

$$\boxed{\zeta = \frac{1}{9TV}\sum_{i=1}^{N}\frac{\Gamma_i^{-1}}{E_i^2}\left[(1-3v_s^2)E_i^2 - m_i^2\right]^2}$$

Specific shear viscosity

Kubo ≈ RTA



- ☐ **minimum** close to the **critical** temperature
- ☐ **pQCD limit** at higher temperatures
- ☐ **fast increase** of the ratio η/s for $T < T_c$

  $\Rightarrow$ **lower** interaction rate of the **hadronic** system;

  $\Rightarrow$ **smaller** number of degrees of freedom (or **entropy density**).

QGP in PHSD $\Longrightarrow$ strongly-interacting liquid

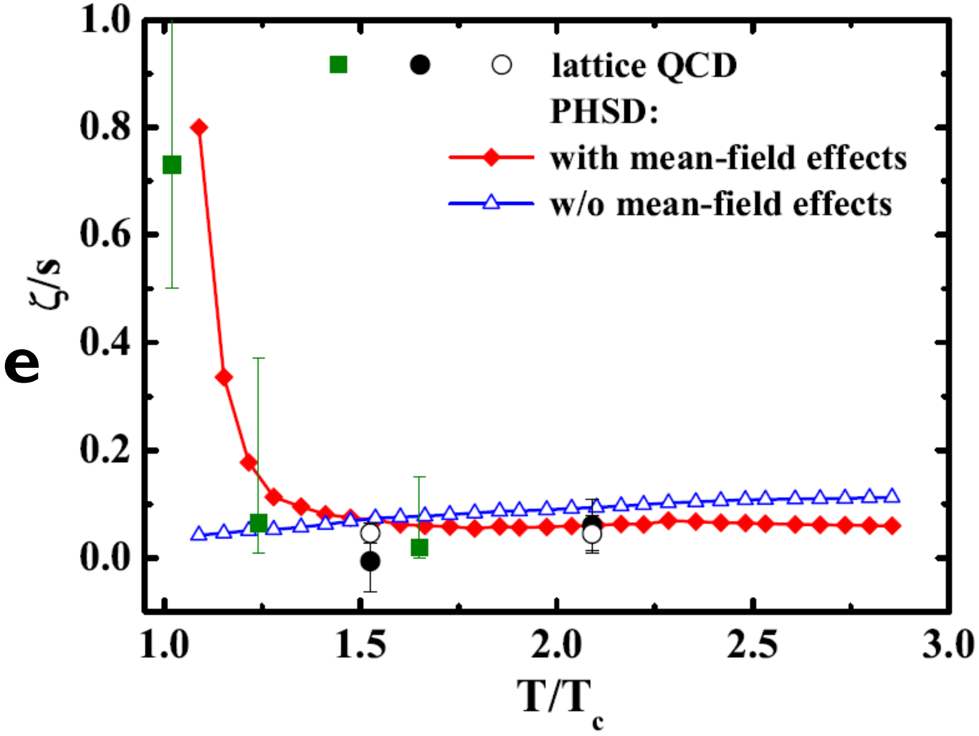
Bulk viscosity (mean-field effects)

- ❑ **bulk viscosity with mean-field effects:**

Chakraborty, Kapusta, Phys. Rev. C 83, 014906 (2011).

$$\zeta = \frac{1}{TV}\sum_{i=1}^{N}\frac{\Gamma_i^{-1}}{E_i^2}\left[\left(\frac{1}{3}-v_s^2\right)|\mathbf{p}|^2 - v_s^2\left(m_i^2 - T^2\boxed{\frac{dm_i^2}{dT^2}}\right)\right]^2$$

- ❑ **DQPM expressions for masses:** $m_q^2 = \frac{1}{3}g^2T^2, \qquad m_g^2 = \frac{3}{4}g^2T^2$

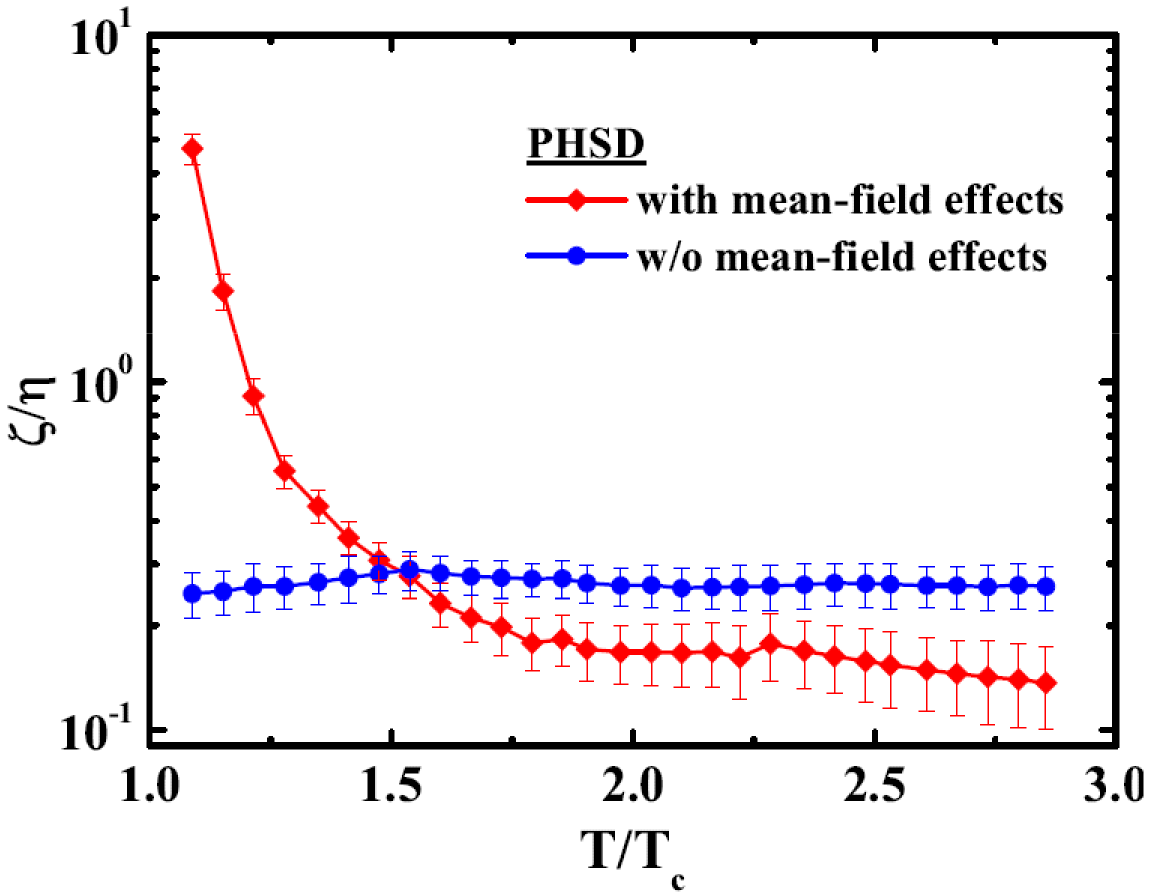


- ❑ **significant rise in the vicinity of critical temperature**

- ❑ **in line with the ratio from the lQCD calculations**

Meyer, Phys. Rev. Lett. 100, 162001 (2008);
Sakai, Nakamura, Pos LAT2007, 221 (2007).

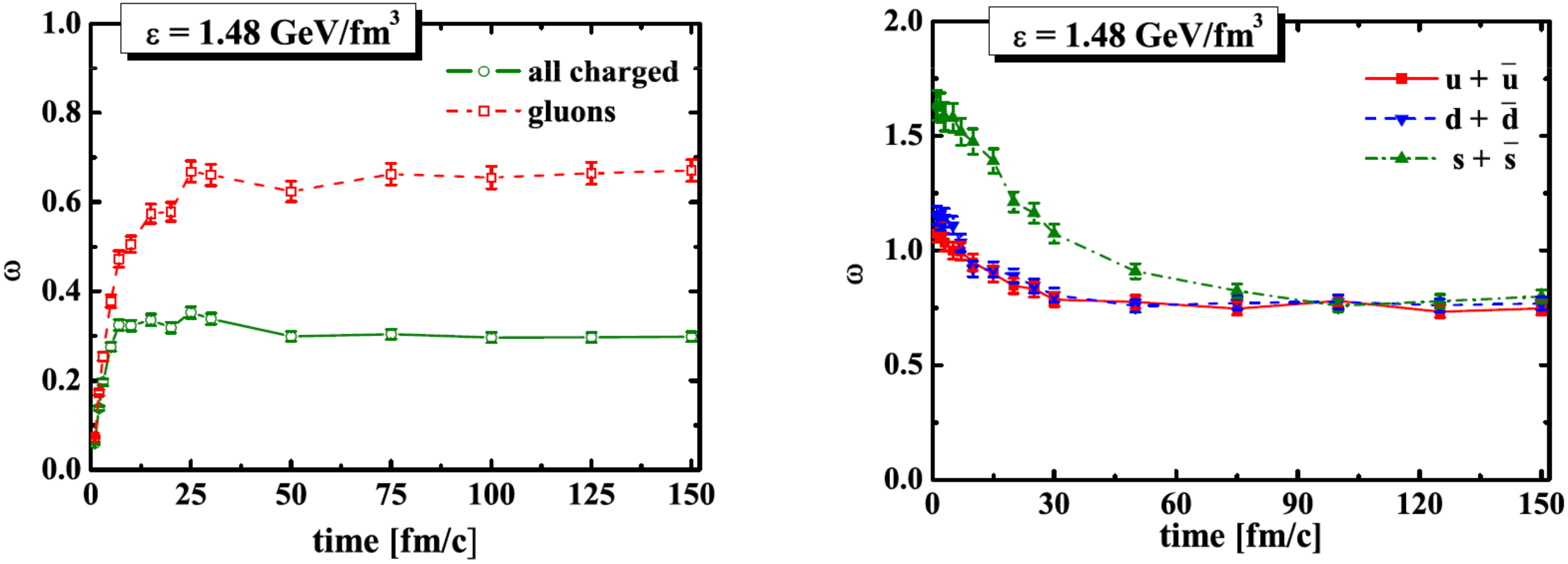
Bulk to shear viscosity ratio



- ❑ **without mean-field effects:**
  - $\Rightarrow$ **almost temperature independent behavior**
- ❑ **with mean-field effects:**
  - $\Rightarrow$ **strong increase close to the critical temperature**

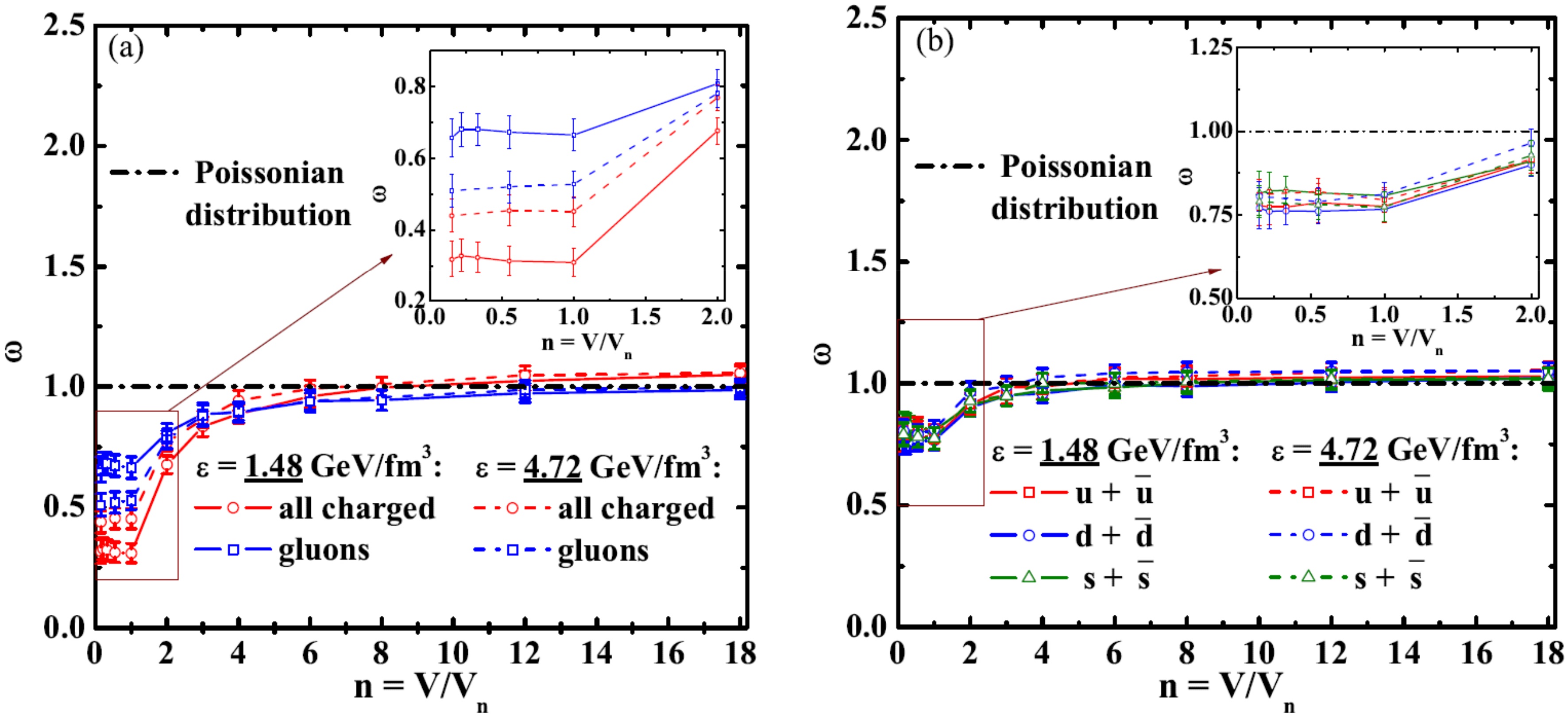
Scaled variance

- ☐ **scaled variance:** $\omega = \frac{\sigma^2}{\mu}$, $\sigma^2 = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \mu)^2$



- ☐ scaled variances reach a plateau in time for all observables
- ☐ equilibrium values are less than 1 for all observables ⇒ MCE
- ☐ particle number fluctuations are flavor blind

Cell dependence of scaled variance



- **impact** of total energy conservation in the sub-volume V_n is less than in the total volume V

  $\Rightarrow$ $\omega \cong 1$ for all scaled variances for large number of cells $\Rightarrow$ GCE

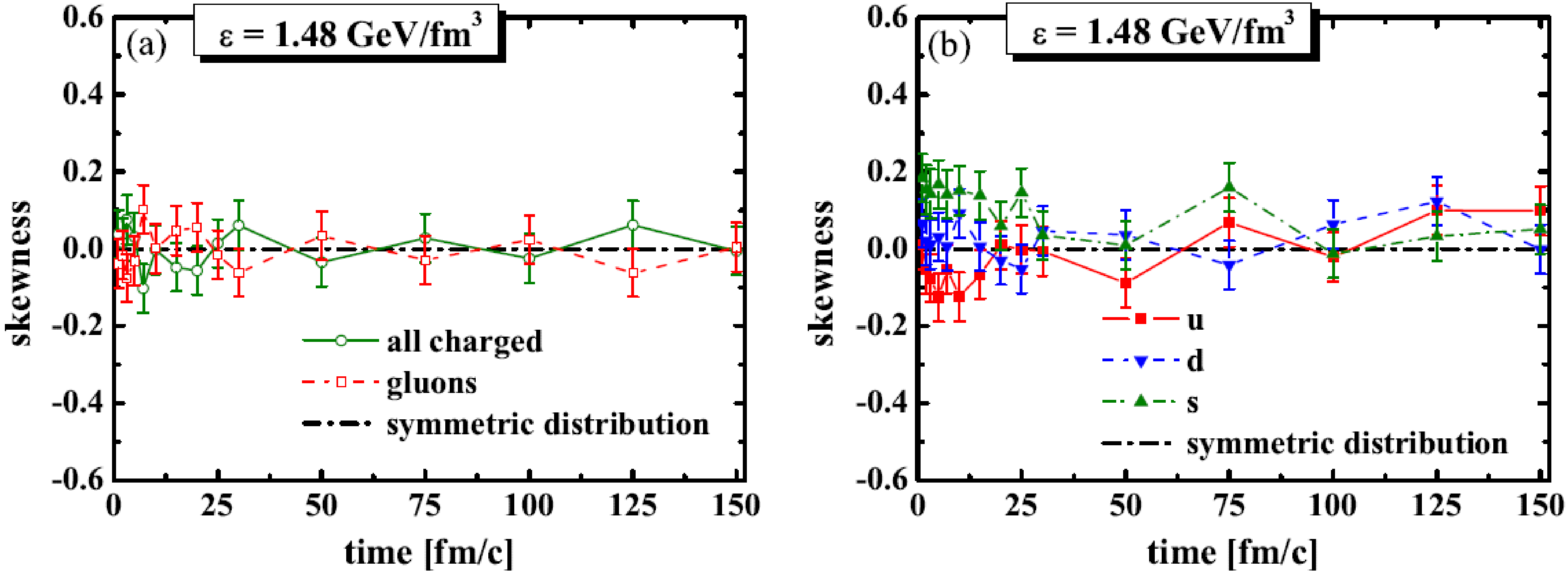
- for larger box sizes by up to about a factor of 8 ($n \approx 0.15$)

  $\Rightarrow$ scaled variances reach the continuum limit

Skewness

- ☐ **skewness:** $$g_1 = \frac{m_3}{m_2^{3/2}} = \frac{m_3}{\sigma^3}\ , \qquad m_3 = \frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^3$$

- ☐ **skewness characterizes the asymmetry of the distribution function with respect to its average value**

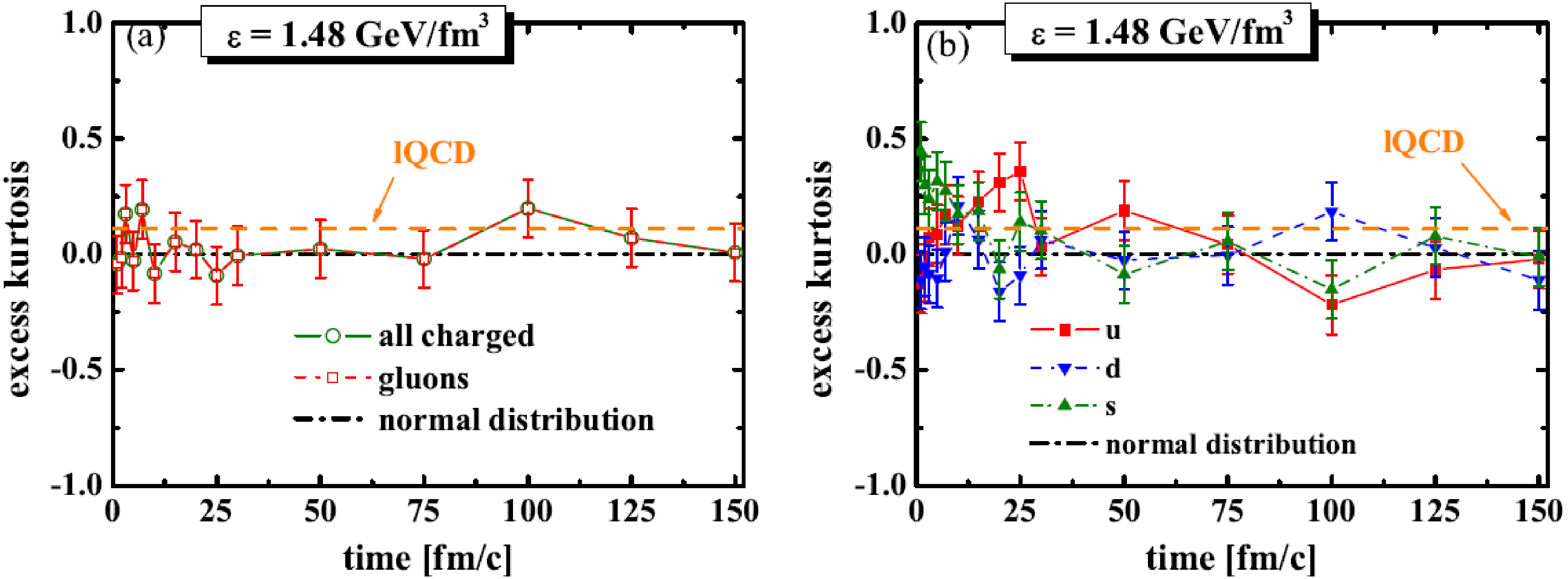


Kurtosis

- ☐ **kurtosis:** $$\beta_2 = \frac{m_4}{m_2^2} = \frac{m_4}{\sigma^4} \, , \qquad m_4 = \frac{1}{N}\sum_{i=1}^{N}(x_i-\mu)^4$$

- ☐ **kurtosis is equal to 3 for normal distribution**

$\Rightarrow$ **excess kurtosis:** $$g_2 = \beta_2 - 3$$



lQCD: Ejiri, Karsch, Redlich, Phys. Lett. B 633, 275 (2006)

Summary

- partonic systems in PHSD achieve kinetic and chemical equilibrium in time
- Kubo formalism and the relaxation time approximation show the same results for the shear viscosity to entropy density ratio
- QGP in PHSD behaves as a strongly-interacting liquid
- significant rise of the bulk viscosity to entropy density ratio in the vicinity of the critical temperature when including the scalar mean-field from PHSD
- scaled variances for the different particle number fluctuations in the box reach equilibrium values in time and behave as a in micro-canonical ensemble
- scaled variances for all observables approach the Poissonian limit (GCE) when the cell volume is much smaller than that of the total box
- skewness for all observables are compatible with zero
- excess kurtosis is compatible with lQCD results for gluons and charged particles

Back up

Initial momentum distributions and abundancies

- initial number of partons is given by: $N_{g(q,\bar{q})} = \int\limits_0^\infty \frac{d\omega}{2\pi} \int \frac{d^3p}{(2\pi)^3} f_{g(q,\bar{q})}(\omega, \mathbf{p})$

- with a 'thermal' distribution: $\boxed{f(\omega, \mathbf{p}) = C_i p^2 \omega \rho_i(\omega, \mathbf{p}) n_{F(B)}(\omega / T_{in})}$

- spectral function:

$$\rho_i(\omega, \mathbf{p}) = \frac{\gamma_i}{E_i} \left(\frac{1}{(\omega - E_i)^2 + \gamma_i^2} - \frac{1}{(\omega + E_i)^2 + \gamma_i^2} \right)$$

$$= \frac{4\omega\gamma_i}{(\omega^2 - \mathbf{p}^2 - M_i^2)^2 + 4\gamma_i^2\omega^2}$$

- Fermi and Bose distributions: $n_{F(B)} = \frac{1}{e^{(\omega-\mu)/T_{in}} \pm 1}$

- initial parameters: $\boxed{T_{in}, \mu, C_i}$

- four-momenta are distributed according to the $f(\omega, \mathbf{p})$ by Monte Carlo

Determination of mean-field parton potentials

Partonic potential energy density:

$$V := T^{-}_{00,g} + T^{-}_{00,q} + T^{-}_{00,\bar{q}} = \tilde{V}_{gg} + \tilde{V}_{qq} + \tilde{V}_{qg}$$

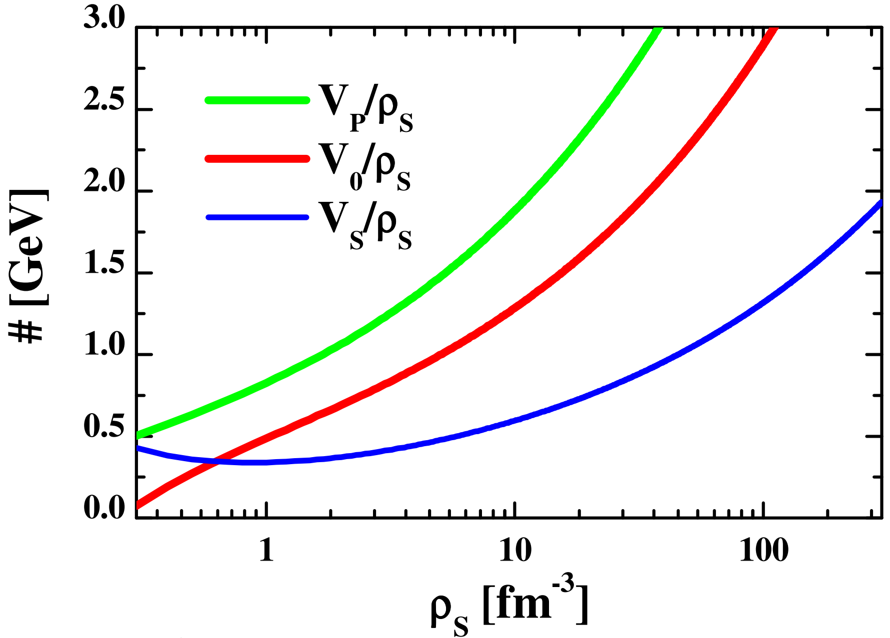
+ Constrain:

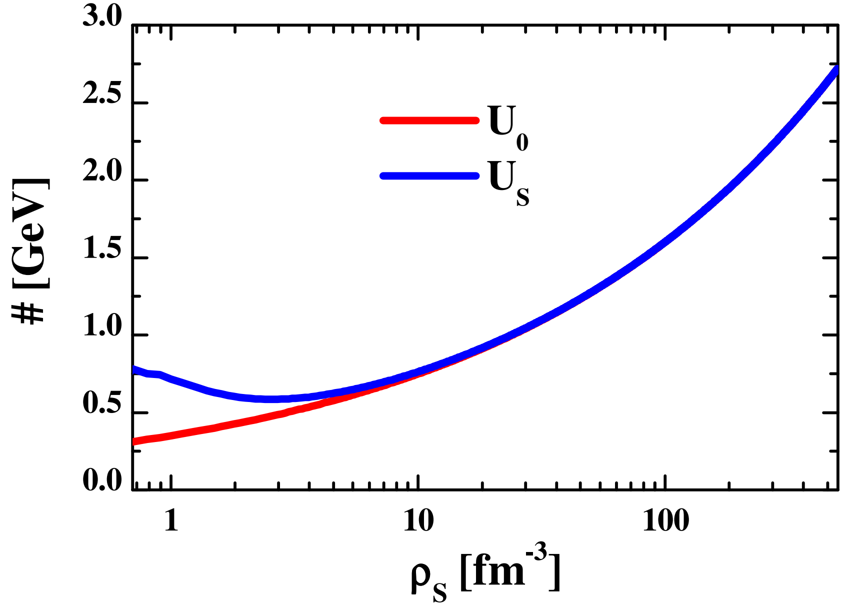
$P = \langle P_{xx} \rangle - V_s + V_0$

$\varepsilon = \langle p_0 \rangle + V_s + V_0$

Mean-field potential:

$U_s = dV_s/d\rho_s \qquad U_0 = dV_0/d\rho_0$





Parton density:

$$\rho_p = N_g^+ + N_q^+ + N_{\bar{q}}^+, \qquad N_x^+ = \tilde{Tr}_x^+ 1$$

Scalar parton density:

$$\rho_x^s \equiv N_x^s(T) = \tilde{Tr}_x^+ \left(\frac{\sqrt{P^2}}{\omega} \right), \qquad x : g, q, \bar{q}$$

→ PHSD

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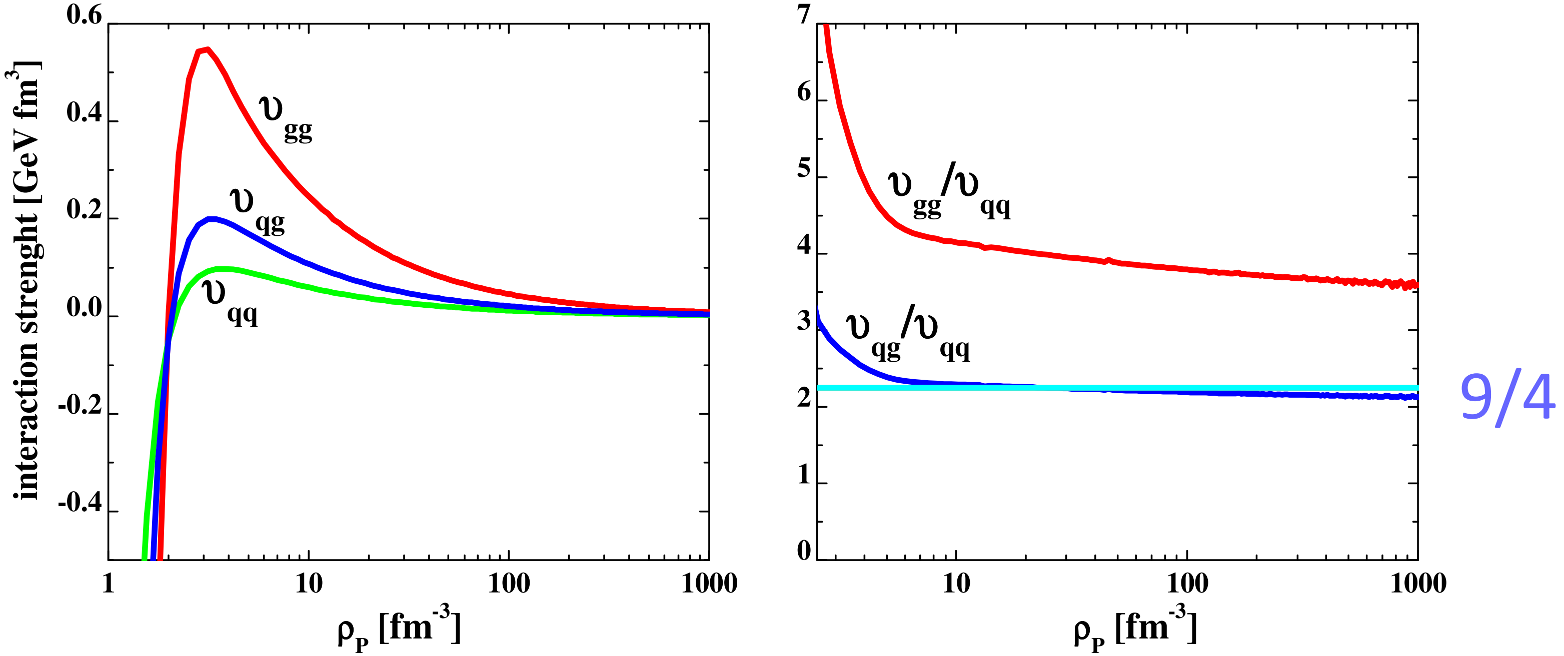
Effective 2-body interactions of time-like partons

2nd derivatives of interaction densities

$$\mathbf{v_{gg}}(\rho_\mathbf{p}) := \frac{\partial^2 \tilde{\mathbf{V}}_{\mathbf{gg}}}{\partial \mathbf{N_g^{+2}}} \approx \frac{\mathbf{1}}{\mathbf{2}} \frac{\partial^2 (\mathbf{1}-\beta-\kappa)\mathbf{V}}{\partial \rho_\mathbf{p}^2} \left(\frac{\partial \rho_\mathbf{p}}{\partial \mathbf{N_g^+}}\right)^{\mathbf{2}}$$

$$v_{qq}(\rho_p) := \frac{\partial^2 \tilde{V}_{qq}}{\partial (N_q^+ + N_{\bar{q}}^+)^2} \approx \frac{1}{2} \frac{\partial^2 (1-\beta+\kappa)V}{\partial \rho_p^2} \left(\frac{\partial \rho_p}{\partial (N_q^+ + N_{\bar{q}}^+)}\right)^2$$

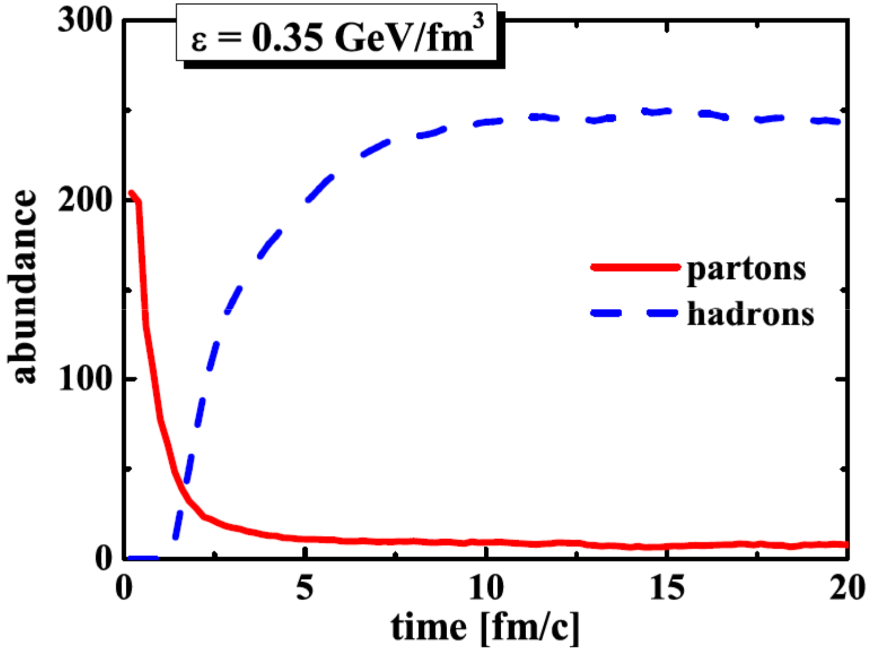
$$v_{qg}(\rho_p) := \frac{\partial^2 \tilde{V}_{qg}}{\partial (N_q^+ + N_{\bar{q}}^+) \partial N_g^+} \approx \frac{\partial^2 (\beta V)}{\partial \rho_p^2} \left(\frac{\partial \rho_p}{\partial (N_q^+ + N_{\bar{q}}^+)}\right) \left(\frac{\partial \rho_p}{\partial N_g^+}\right)$$



effective interactions turn strongly attractive below 2.2 fm^{-3} !

→ PHSD

Dynamical phase transition & different intializations

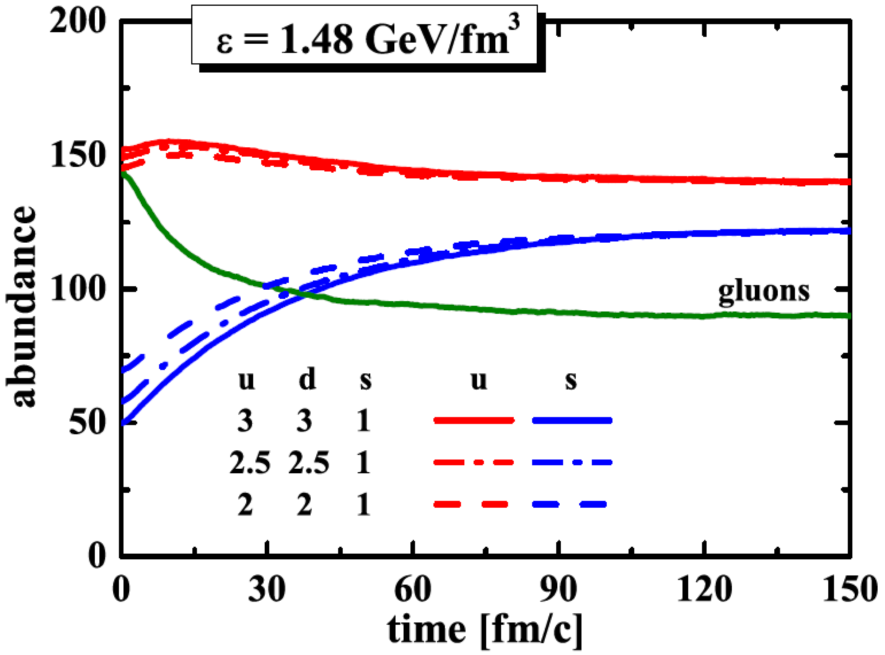


- the transition from partonic to hadronic degrees-of-freedom is complete after about 9 fm/c

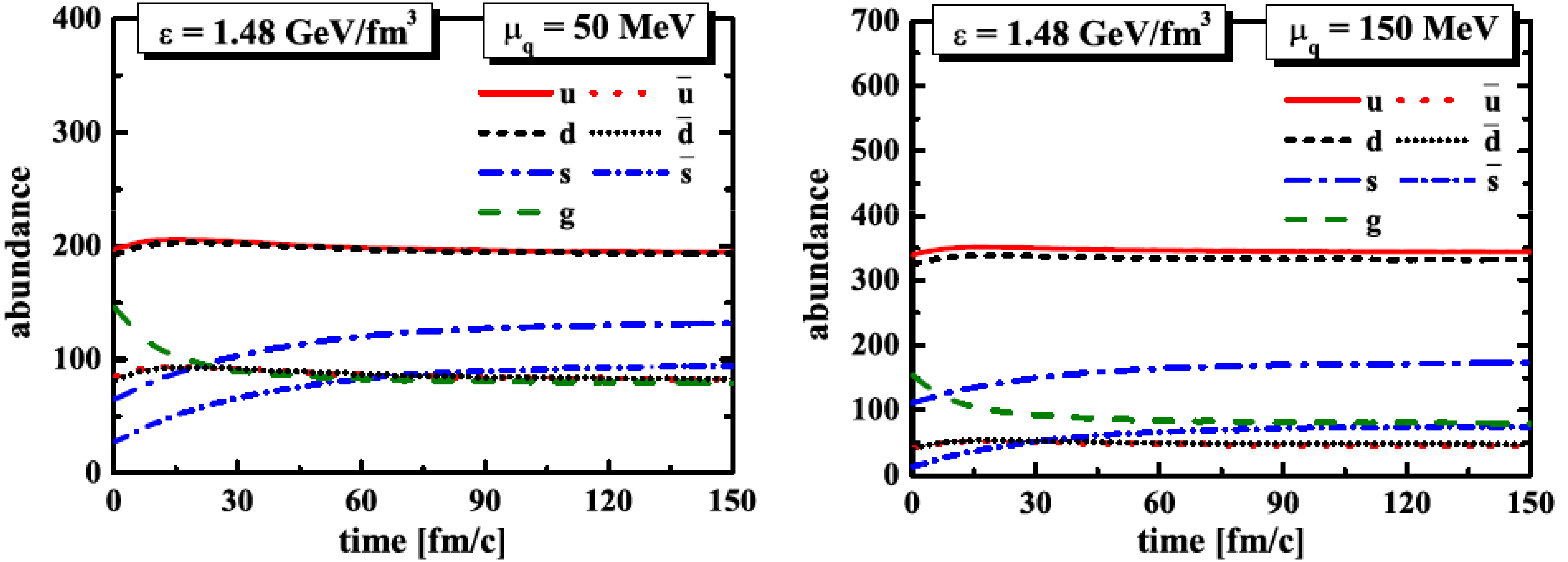
- a small non-vanishing fraction of partons – local fluctuations of energy density from cell to cell

- the equilibrium values of the parton numbers do not depend on the initial flavor ratios

- our calculations are stable with respect to the different initializations



Finite quark chemical potentials

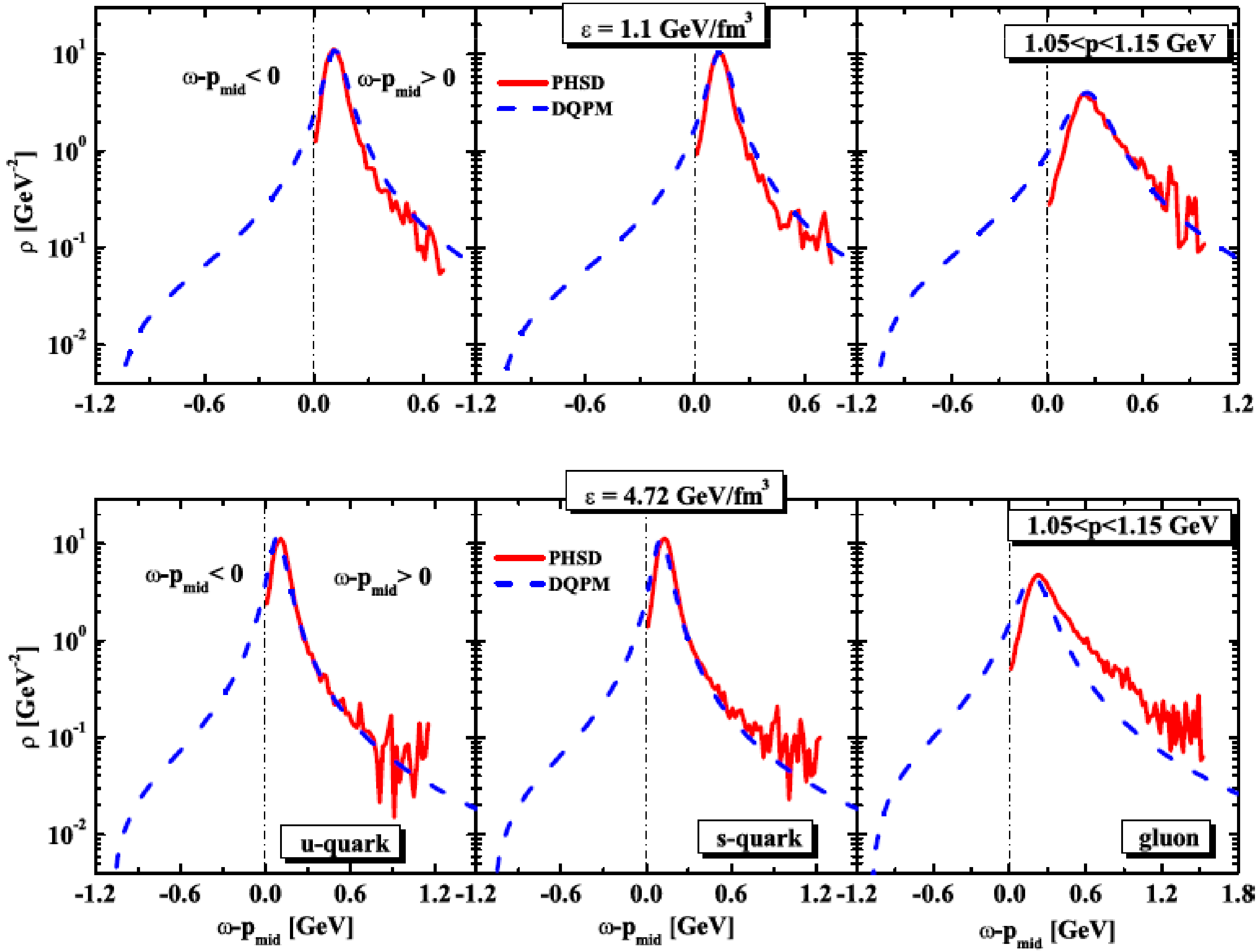


- ☐ the phase transition happens at the same critical energy ε_c for all μ_q
- ☐ in the present version the DQPM and PHSD treat the quark-hadron transition as a smooth crossover at all μ_q

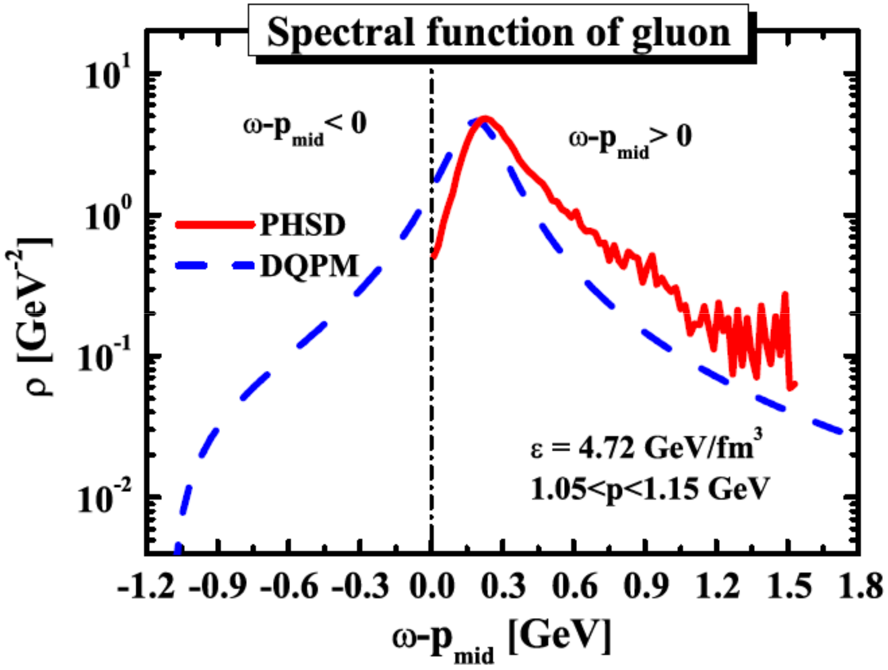
Spectral function

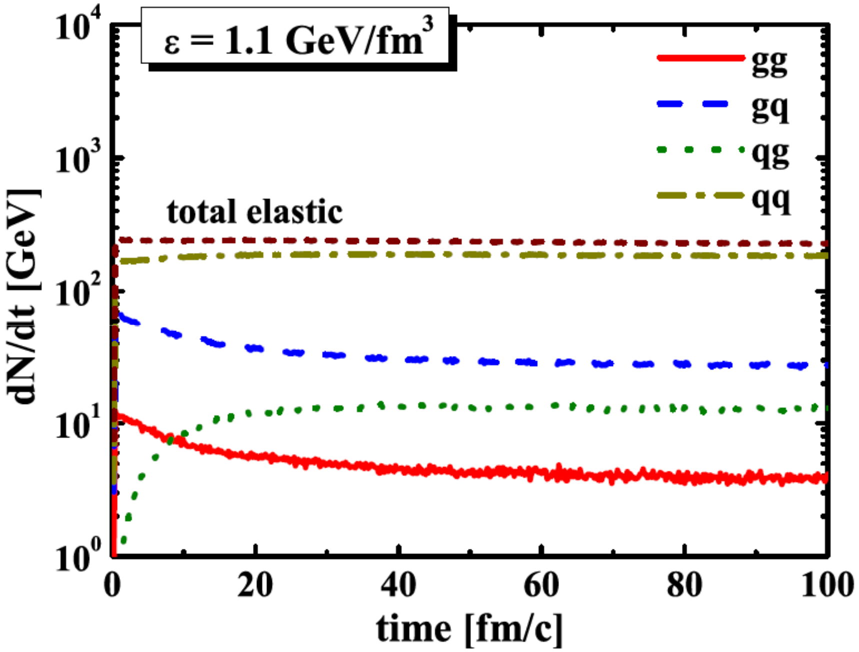
☐ the dynamical spectral function is well described by the DQPM form in the fermionic sector for time-like partons

$$\rho_j(\omega, \mathbf{p}) = \frac{\Gamma_j}{E_j}\left(\frac{1}{(\omega - E_j)^2 + \Gamma_j^2} - \frac{1}{(\omega + E_j)^2 + \Gamma_j^2}\right)$$



Deviation in the gluonic sector





- ☐ the inelastic collisions are more important at higher parton energies
- ☐ the elastic scattering rate of gluons is lower than that of quarks
- ☐ the inelastic interaction of partons generates a mass-dependent width for the gluon spectral function in contrast to the DQPM assumption of the constant width

PHSD: Hadronization details

Local covariant off-shell transition rate for q+qbar fusion
=> meson formation

$$\frac{dN_m(x,p)}{d^4x d^4p} = Tr_q Tr_{\bar{q}} \; \delta^4(p - p_q - p_{\bar{q}}) \; \delta^4\left(\frac{x_q + x_{\bar{q}}}{2} - x\right)$$
$$\times \omega_q \; \rho_q(p_q) \; \omega_{\bar{q}} \; \rho_{\bar{q}}(p_{\bar{q}}) \; |v_{q\bar{q}}|^2 \; W_m(x_q - x_{\bar{q}}, p_q - p_{\bar{q}})$$
$$\times N_q(x_q, p_q) \; N_{\bar{q}}(x_{\bar{q}}, p_{\bar{q}}) \; \delta(\text{flavor, color}).$$

using $Tr_j = \sum_j \int d^4x_j d^4p_j/(2\pi)^4$

- ❑ *$N_j(x,p)$* is the phase-space density of parton j at space-time position *x* and 4-momentum *p*
- ❑ *W_m* is the phase-space distribution of the formed ‚pre-hadrons‘: (Gaussian in phase space) $\sqrt{< r^2 >} = 0.66$ fm
- ❑ $v_{q\bar{q}}$ is the effective quark-antiquark interaction from the DQPM

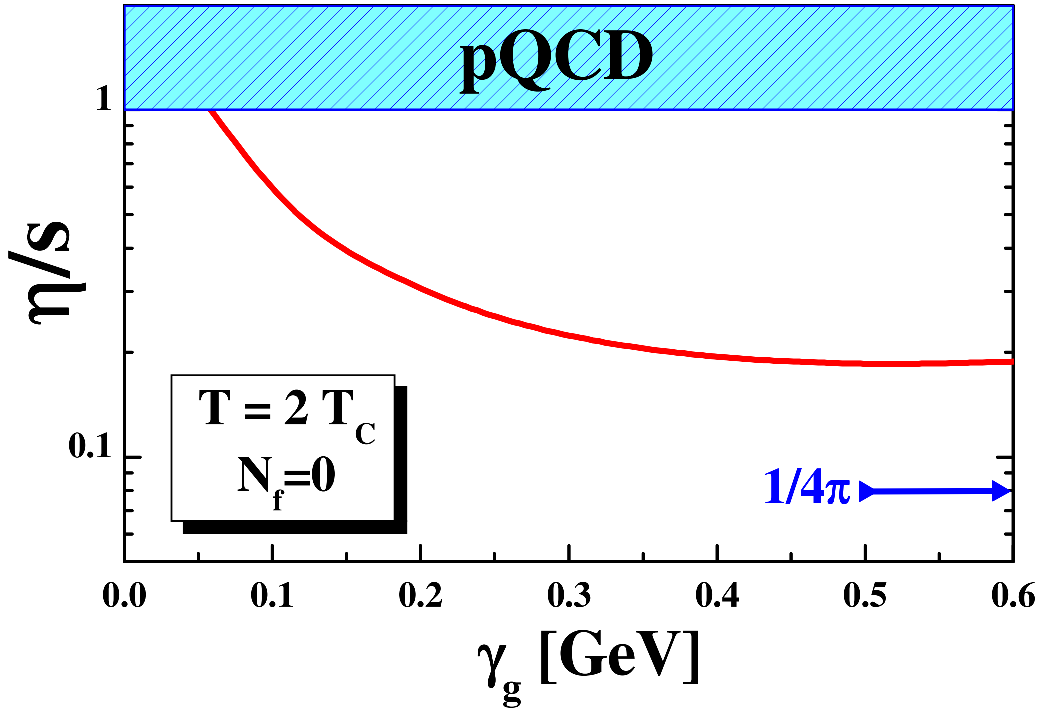
Cassing, Bratkovskaya, PRC 78 (2008) 034919; Cassing, EPJ ST 168 (2009) 3

Transport properties of hot glue

Why do we need broad quasiparticles?

shear viscosity ratio to entropy density:

$$\eta^{\mathrm{DQP}} = -\frac{d_g}{60}\int \frac{d\omega}{2\pi}\frac{d^3p}{(2\pi)^3}\frac{\partial n}{\partial \omega}\rho^2(\omega)[7\omega^4 - 10\omega^2 \boldsymbol{p}^2 + 7\boldsymbol{p}^4].$$



→ otherwise η/s will be too high!