Strange and Charm Quark Production in hot QCD Matter

Valeriya Mykhaylova

Collaboration and supervision: dr hab. C. Sasaki, prof. UWr; prof. dr hab. K. Redlich

Institute of Theoretical Physics
University of Wrocław

Uniwersytet Wrocławski

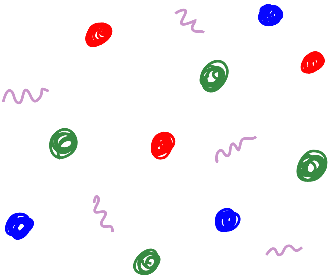
Motivation

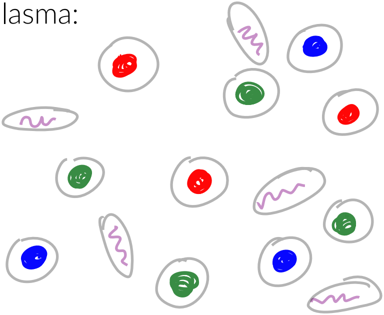
Goal: study dynamical and transport properties of the QGP

- Lattice QCD
- Holographic QCD (AdS/CFT)
- Perturbative QCD
- Relativistic hydrodynamics
- Kinetic theory in relaxation time approximation
- Effective models: quasiparticle approach
- ...

Quasiparticle model

Quark-gluon plasma:





Reality:		Effective approach:
$\sim$ massless,	$\longrightarrow$	massive,
strongly-interacting particles		weakly-interacting **quasi**particles

$\star$ similar to massive quasielectron moving freely in solid states

Quasiparticle model

Weakly-interacting quasiparticles $\to$ Kinetic theory for ideal gases:

$$P,\ \epsilon,\ s \sim \sum_i \int \frac{d^3p}{(2\pi)^3} f_i^0 \ \dots, \qquad i = g, (\underbrace{u, d}_{l}), s, (c);$$

$$f_i^0 = (\exp(E_i/T) \pm 1)^{-1}, \ \ \mu = 0;$$

\+ Dynamical quasiparticle masses:

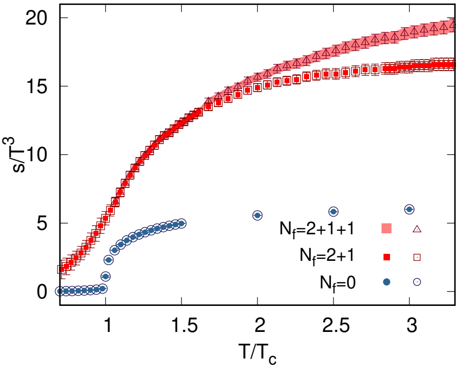
$$E_i^2[G(T), T] = p^2 + m_i^2[G(T), T]$$

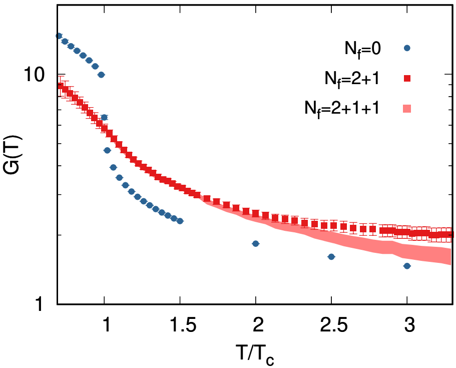
Setup:

- effective coupling $G(T)$;
- dynamical masses $m_i[G(T), T]$;
- reliable Equation of State $P(\epsilon)$ - from lattice QCD;

Effective running coupling

$$s = \sum_i \frac{d_i}{\pi^2} \int dp\, 2p^2\, \frac{\frac{4}{3}p^2 + m_i^2[G(T),T]}{E_i(T)\,T} f_i^0 \Longrightarrow G(T) \Longrightarrow m_i[G(T),T]$$



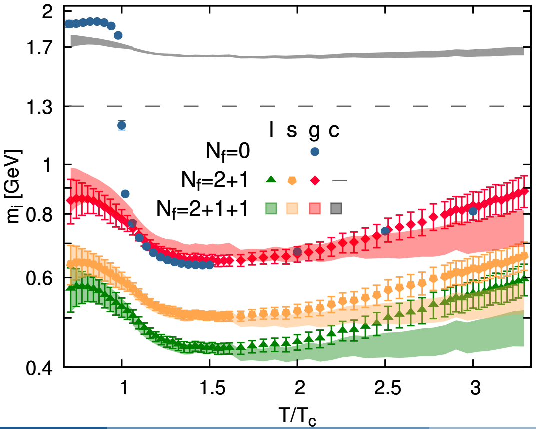


[V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 (2019) and preliminary; lQCD: Wuppertal-Budapest]

Effective Masses: $m_i[G(T), T] = \sqrt{(m_i^0)^2 + \Pi_i[G(T), T]}$

$$\Pi_g[G(T), T] = \left(3 + \frac{N_f}{2}\right) \frac{G^2(T)\, T^2}{6}$$

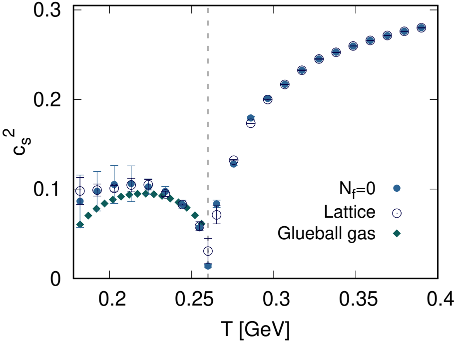
$$\Pi_{l,s,(c)}[G(T), T] = 2\left[m^0_{l,s,(c)} \sqrt{\frac{G^2(T) T^2}{6}} + \frac{G^2(T) T^2}{6}\right]$$



Quasiparticle Model: Thermodynamic Consistency

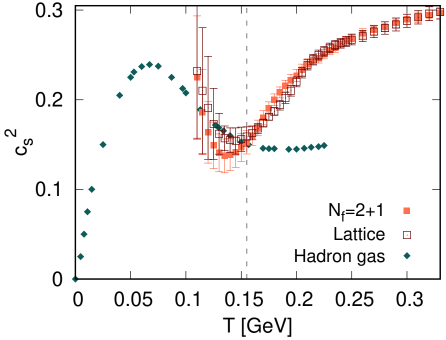
$$c_s^2 = \frac{\partial P}{\partial \epsilon} = \frac{s}{T}\left(\frac{\partial s}{\partial T}\right)^{-1}$$

Pure Yang-Mills, $N_f = 0$



[lQCD: Borsanyi et al., JHEP1207, 056 ’12; Glueball resonance gas: Meyer, PRD80 ’09]

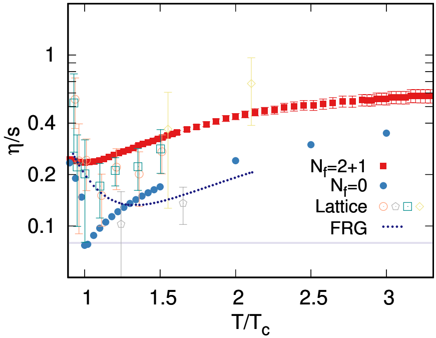
QCD, $N_f = 2 + 1$



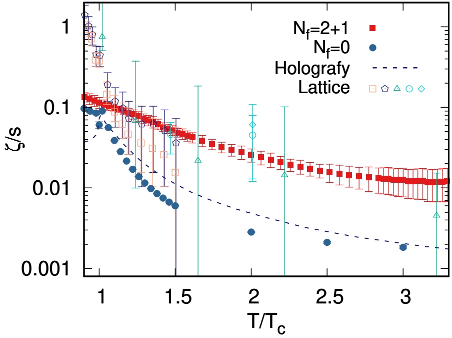
[lQCD: Borsanyi et al., PLB730 ’14; Hadron resonance gas: Castorina et al., EPJ C66 ’10]

[V.M, C. Sasaki, PRD103 ’21]

Shear and Bulk Viscosities: $N_f = 0$ vs $N_f = 2+1$



[V. M., M. Bluhm, K. Redlich, C. Sasaki, PRD100 '19]



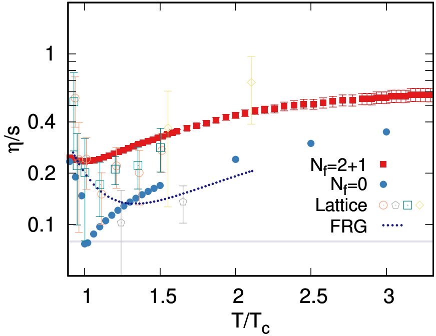
[V. M., C. Sasaki, PRD103 '21]

$$\eta = \frac{1}{15T} \sum_{i=l,s,g} d_i \int \frac{d^3p}{(2\pi)^3} \frac{p^4}{E_i^2} f_i^0 (1 \pm f_i^0) \tau_i;$$

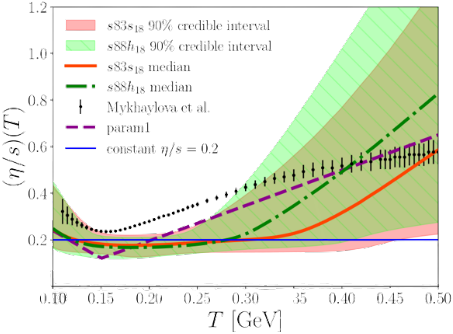
$$\zeta = \frac{1}{T} \sum_{i=l,s,g} d_i \int \frac{d^3p}{(2\pi)^3}\, f_i^0 (1 \pm f_i^0) \frac{1}{E_i^2} \left\{ \left(E_i^2 - T^2 \frac{\partial m_i^2(T)}{\partial T^2} \right) c_s^2 - \frac{p^2}{3} \right\}^2 \tau_i$$

⋆ common relaxation times τ_i

Specific Shear Viscosity



[V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 (2019)]



[J. Auvinen, K.J. Eskola, P. Huovinen, H. Niemi,

R. Paatelainen, P. Petreczky, Phys.Rev.C 102 (2020)]

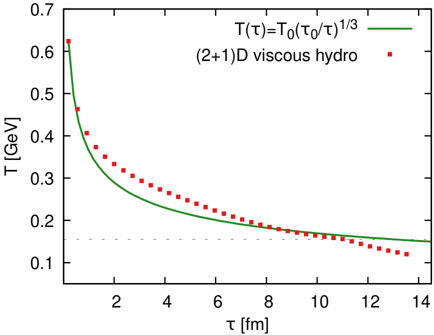
Red curve on LHS = black on RHS.

Time evolution of the QGP

1. Bjorken scaling (1D expansion): [J. D. Bjorken, PRD 27 (1983)]

$$T(\tau) = T_0 \left(\frac{\tau_0}{\tau} \right)^{1/3}$$

2. (2+1)D 2^{nd} order viscous hydro (+ η/s) [J. Auvinen et al., Phys.Rev.C 102 (2020)]



⋆ Same initial conditions for both: $\tau_0 = 0.2$ fm, $T_0 = 0.624$ GeV

Rate Equations

$N_f = 2+1$: quasiparticles (l, s, g) are in equilibrium, C quarks are not

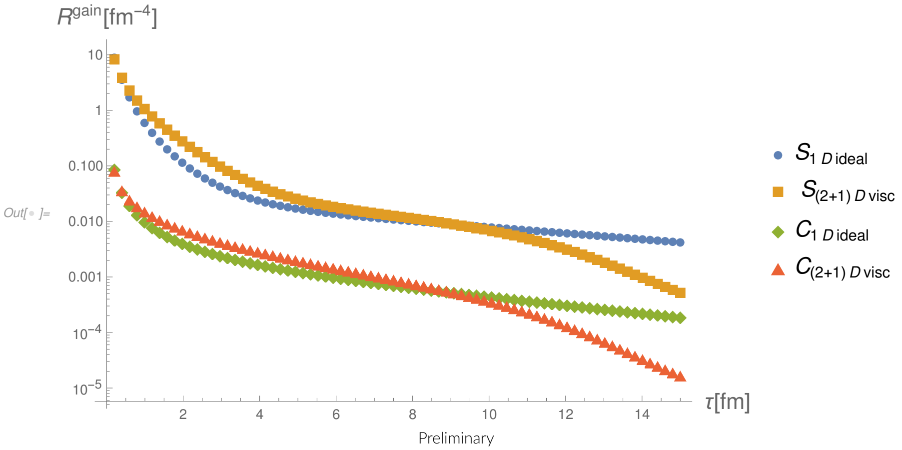
$$n_{c,Jut} = 6\int \frac{p^2}{2\pi^2}\lambda_c[\tau](e^{\sqrt{p^2+M_c^2}} + \lambda_c[\tau])^{-1}$$

$$\partial_\mu(n_{c,Jut}u^\mu) = R_c^{gain} - R_c^{loss};$$
$$\partial_\mu(n_s^0 u^\mu) = R_s^{gain} - R_s^{loss} = 0 \text{ (detailed balance)}$$

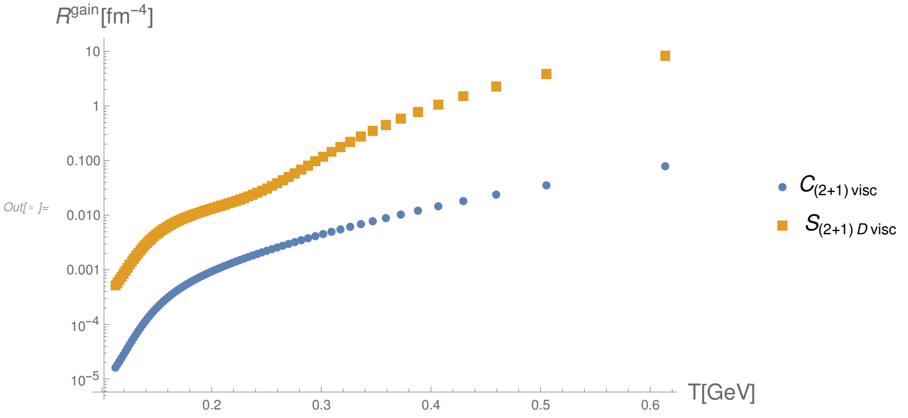
$$R_s^{gain} = \frac{1}{2}\bar{\sigma}_{gg\to s\bar{s}}\,(n_g^0)^2 + \bar{\sigma}_{q\bar{q}\to s\bar{s}}\,(n_q^0)^2 + \bar{\sigma}_{c\bar{c}\to s\bar{s}}\,n_{c,Jut}^2$$
$$R_c^{gain} = \frac{1}{2}\bar{\sigma}_{gg\to c\bar{c}}\,(n_g^0)^2 + \bar{\sigma}_{q\bar{q}\to c\bar{c}}\,(n_q^0)^2 + \bar{\sigma}_{s\bar{s}\to c\bar{c}}\,(n_s^0)^2$$

[T.S. Biro et al., PRC 48 (1993); B.-W. Zhang et al., Phys.Rev.C 77 (2008)]

Production rate of strange and charm quarks



Production rate of strange and charm quarks



Preliminary

$$R_s^{gain} = \frac{1}{2}\,\bar{\sigma}_{gg\to s\bar{s}}\,(n_g^{\mathbf{0}})^2 + \bar{\sigma}_{q\bar{q}\to s\bar{s}}\,(n_q^{\mathbf{0}})^2 + \bar{\sigma}_{c\bar{c}\to s\bar{s}}\,n_{c,Jut}^2$$

$$R_c^{gain} = \frac{1}{2}\,\bar{\sigma}_{gg\to c\bar{c}}\,(n_g^{\mathbf{0}})^2 + \bar{\sigma}_{q\bar{q}\to c\bar{c}}\,(n_q^{\mathbf{0}})^2 + \bar{\sigma}_{s\bar{s}\to c\bar{c}}\,(n_s^{\mathbf{0}})^2$$

Summary | Quasiparticle model:

- effective tool to explore the properties of hot QCD matter;
- provides $\eta/s, \zeta/s$ consistent with lQCD, AdS/CFT, hydro models, etc.;
- connects weak and strong coupling QCD regimes;
- allows analysis of the particle production;

Further developments:

$\star$ Heavy flavors, finite chemical potential, separate relaxation times …

Thank you for attention! Stand with Ukraine!