CHARM QUARK PRODUCTION IN HOT QCD

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We investigate the time and temperature evolution of charm quarks in the deconfined matter with $N_f = 2+1$ assuming the perfect fluid scenario and comparing it to the viscous one with the shear viscosity taken into account. The topic is approached from the quasiparticle perspective with the calculations performed in kinetic theory under the relaxation time approximation.

QUASIPARTICLE APPROACH

The model effectively describes the QGP as a system of weakly interacting massive quasiparticles, with the interactions encoded in their dynamical masses through the temperature-depending coupling $G(T)$. The latter resembles the perturbative coupling in the high-temperature regime, while covering the non-perturbative QCD nature close to T_c [2]. $G(T)$ has been deduced from the lattice entropy density [3], by postulating that the entropy density s determined for the ideal fluid of massive quasiparticles,

$$s = \sum_{i=g,l,s,(c)} \frac{d_i}{\pi^2}\int dp\, 2p^2\, \frac{\frac{4}{3}p^2 + m_i^2[G(T),T]}{E_i(T)T} f_i^0 \Longrightarrow G(T) \Longrightarrow m_i[G(T),T], \qquad (1)$$

precisely corresponds to the lQCD data, see Fig. 3. Here d_i are degeneracy factors, f_i are equilibrium Fermi-Dirac (Bose-Einstein) distributions, and $m_i[G(T),T]$ are effective quasiparticle masses. As the particle of type i with the bare mass m_i^0 propagates through the medium and interacts with other constituents, it becomes dressed by the dynamically generated self-energies $\Pi_i[G(T),T]$ [1], therefore its total effective mass becomes

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

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

$$\Pi_{l,s,(c)} = 2\left[m^0_{l,s,(c)}\sqrt{\frac{G^2(T)T^2}{6}} + \frac{G^2(T)T^2}{6}\right], \qquad (4)$$

$$m_l^0 = 0.005 \text{ GeV},\ m_s^0 = 0.095 \text{ GeV},\ m_c^0 = 1.3 \text{ GeV}.$$

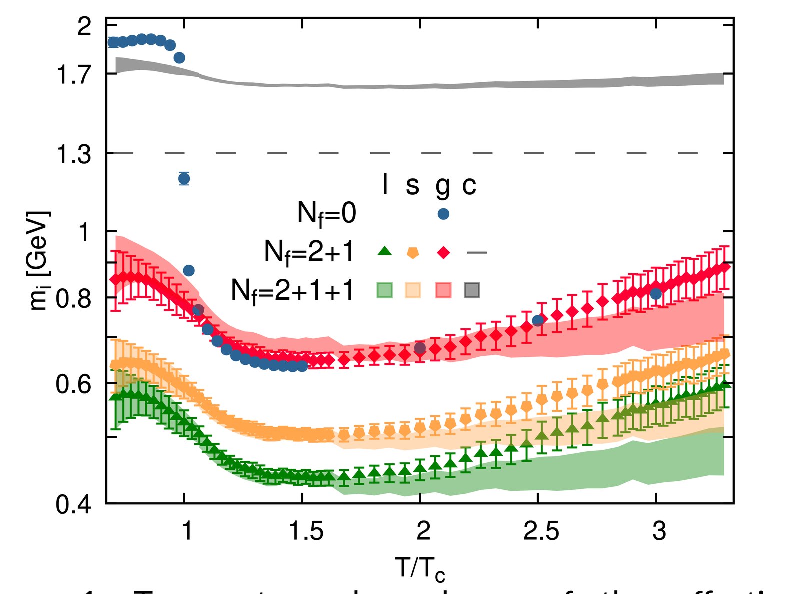

Figure 1: Temperature dependence of the effective masses m_i in hot QCD with different quark content.

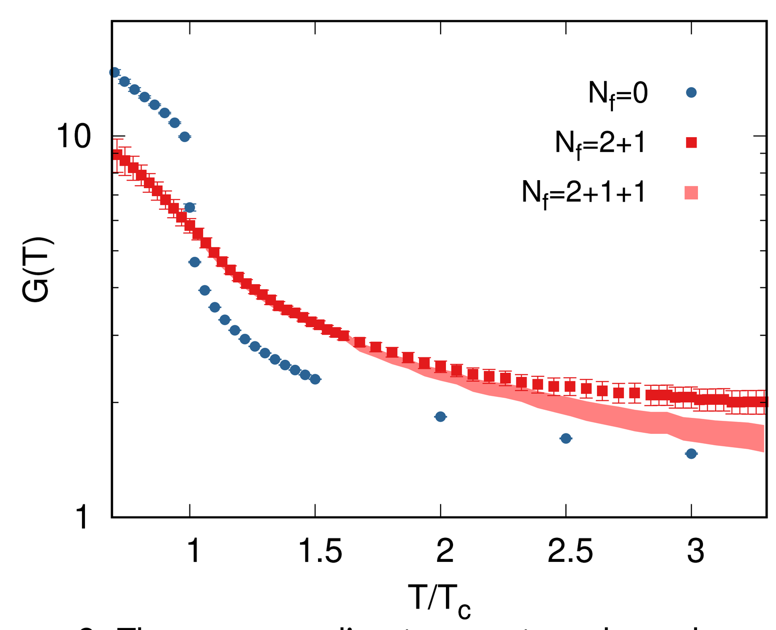

Figure 2: The corresponding temperature dependence of the effective coupling $G(T)$ deduced from the lattice entropy density for different numbers of quark flavors.

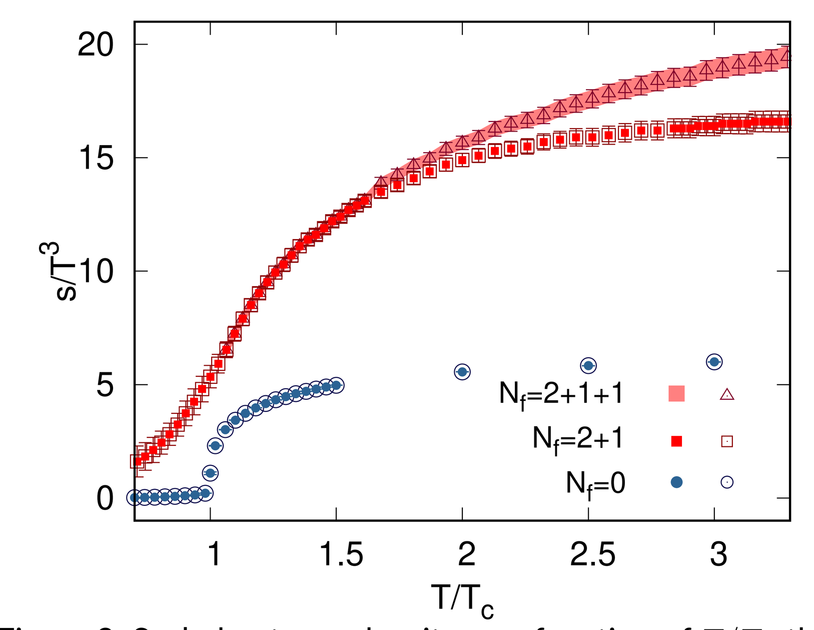

Figure 3: Scaled entropy density as a function of T/T_c: the QPM results (full bullets) overlap with the original lattice data (open bullets) for different N_f.

TRANSPORT PARAMETERS

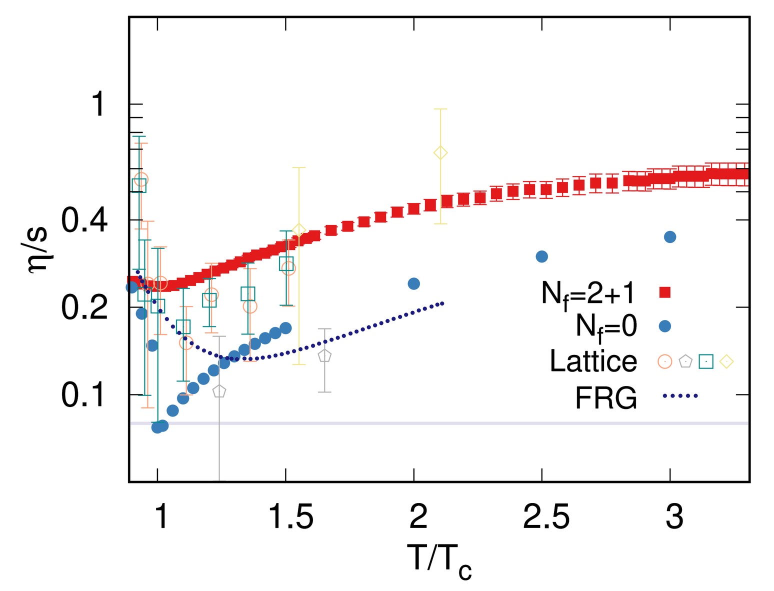

Figure 4: Specific shear viscosity η/s as a function of T/T_c obtained in the QPM (full bullets) in comparison to the available lattice data (open symbols) and the FRG outcome (dotted line) [1].

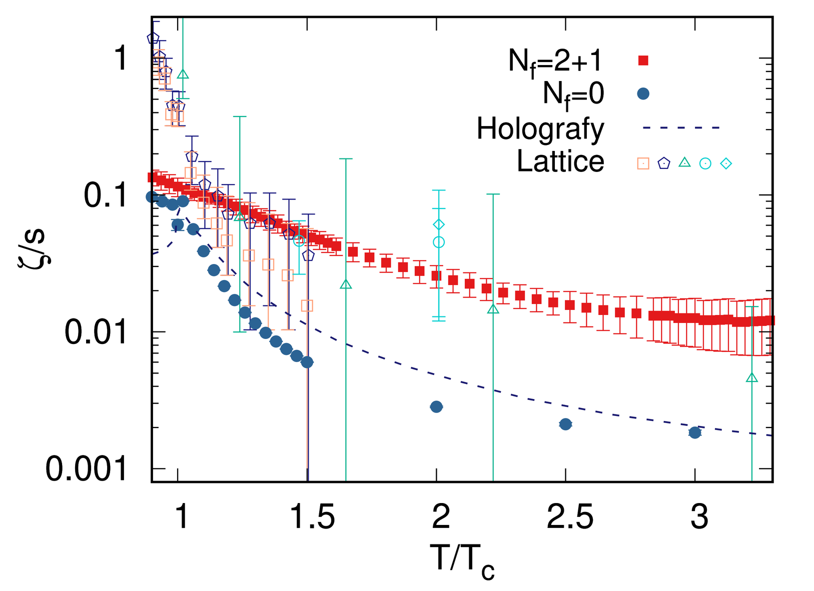

Figure 5: Specific bulk viscosity ζ/s as a function of the scaled temperature T/T_c computed in the QPM (full symbols) is compared with the lattice QCD results (open symbols) and AdS/CFT correspondence (dashed line) [2].

The QPM successfully describes the bulk properties of the deconfined matter, which we have shown by computing the shear and bulk viscosities of the QGP with $N_f = 0$ and $N_f = 2+1$, using

$$\eta = \frac{1}{15T}\int \frac{d^3p\, \vec{p}^{\,4}}{(2\pi)^3}\Big\{\sum_{i=l,s,g}\frac{d_i}{E_i^2}\tau_i f_i(1 \pm f_i)\Big\}, \qquad (5)$$

$$\zeta = \frac{1}{T}\int \frac{d^3p}{(2\pi)^3}\Big\{\sum_{i=l,s,g} d_i f_i(1 \pm f_i)\frac{\tau_i}{E_i^2}\Big\{\Big(E_i^2 - T^2\frac{\partial m_i^2}{\partial T^2}\Big)c_s^2 - \frac{p^2}{3}\Big\}^2, \qquad (6)$$

where c_s is the speed of sound and τ_i is the relaxation time, different for each particle species.

The results presented in Fig. 4, 5 agree with the available lattice QCD data and other approaches.

TIME EVOLUTION OF THE QGP

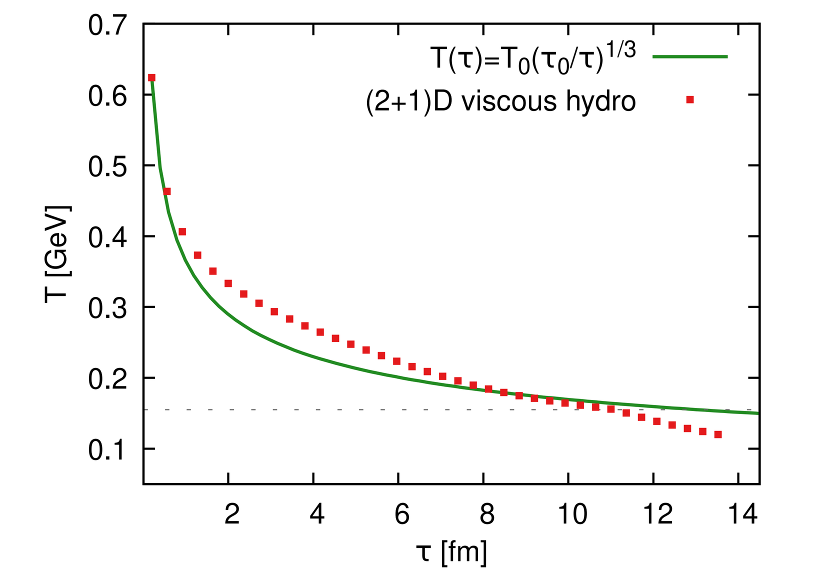

Figure 6: Temperature as a function of time τ shown from the initial point at which the fireball is created – $\tau_0 = 0.2$ fm, $T_0 = 0.624$ GeV. The pseudocritical temperature $T_c = 0.155$ GeV is shown by the dashed line.

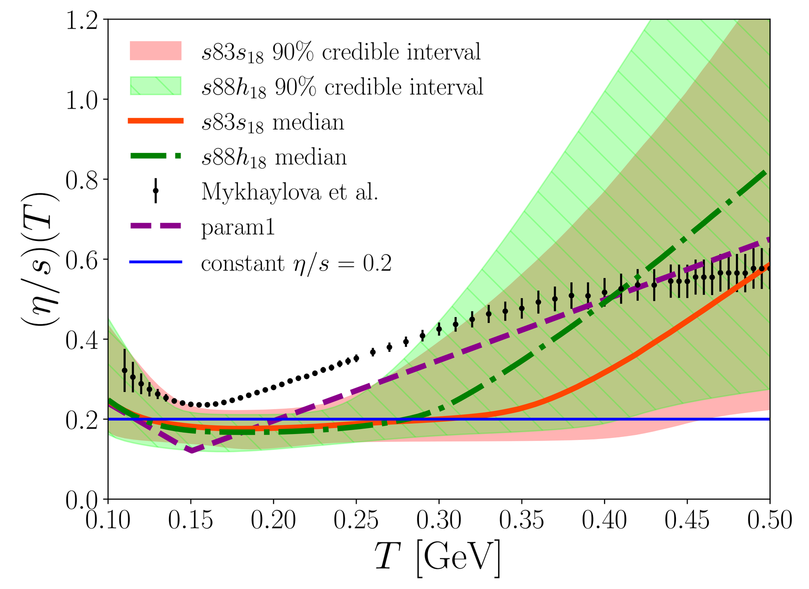

Figure 7: Temperature dependence of the shear viscosity in the QPM (black symbols) juxtaposed with the results obtained in hydrodynamic simulations for different parametrizations. Figure credit: [4].

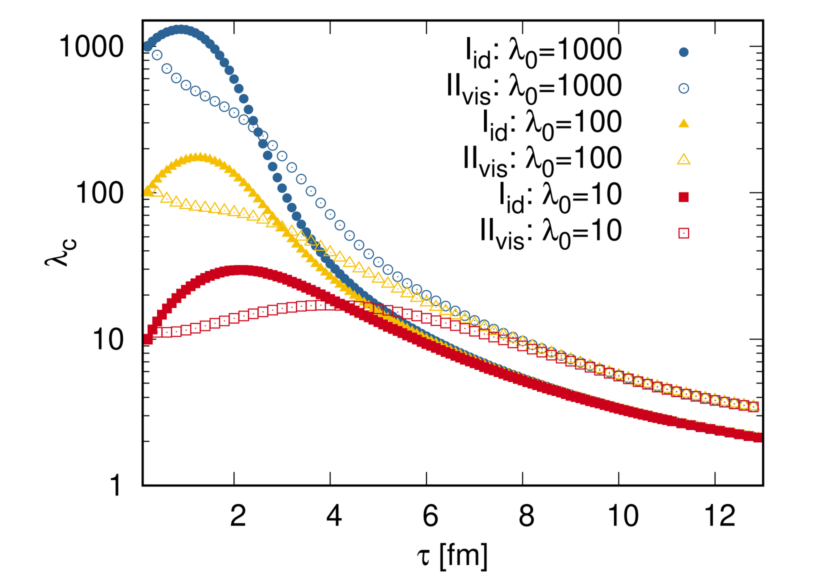

Figure 8: (Preliminary) Time evolution of the charm quark fugacity λ in ideal (expansion scheme I) vs viscous (expansion scheme II) fluid and arbitrary values of the initial charm fugacity λ_0.

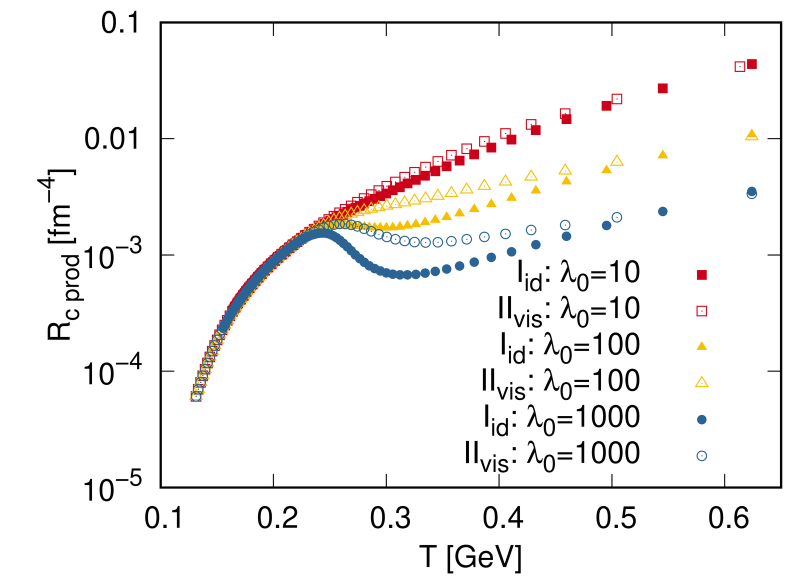

Figure 9: (Preliminary) Temperature dependence of the charm quark production rate $R_{c\ prod}$ in the ideal (I_{id}) vs viscous (II_{vis}) fluid with different values of the initial charm fugacity λ_0.

To explore how charm quark production rate changes with temperature and time, we compare two different descriptions of the QGP evolution:

I$_{id}$: Longitudinal expansion of perfect fluid described by Bjorken scaling [5]: $T(\tau) = T_0\left(\frac{\tau_0}{\tau}\right)^{1/3}$,

II$_{vis}$: (2+1)-dimensional expansion of viscous fluid, described by 2^{nd} order viscous hydrodynamics with specific shear viscosity η/s computed in the QPM (see Fig. 4 or Fig. 7).

The results for the time dependence of the QGP temperature are shown in Fig. 6. Despite a clear difference between the descriptions, one observes a slight numerical agreement of the curves when the same initial conditions are applied.

PRODUCTION RATE OF CHARM QUARKS

In the QGP with $N_f = 2+1$ quark flavors being in equilibrium, charm quarks are considered as „obstacles" which do not contribute to the EoS. The production of charm quarks is described by the rate equation in the rest frame of the co-moving element [6]

$$\partial_\mu(n_c u^\mu) = \frac{\partial n_{c\bar{c}}}{\partial \tau} + \frac{n_{c\bar{c}}}{\tau} = \overbrace{\Big(R_{l\bar{l}\to c\bar{c}} + R_{s\bar{s}\to c\bar{c}} + R_{gg\to c\bar{c}}\Big)}^{R_{c\ prod}}\Big(1 - \frac{(n_c[\lambda_c])^2}{(n_c^0)^2}\Big), \qquad (7)$$

$$n_c[\lambda_c] = d_c\int\frac{d^3p}{(2\pi)^3}\lambda_c\Big(e^{\sqrt{p^2+M_c^2}/T} + \lambda_c\Big)^{-1} \qquad (8)$$

where $n_c[\lambda_c]$ is Juttner number density, n_c^0 is number density of charm quarks in equilibrium ($\lambda_c = 1$). $R_{l\bar{l}\to c\bar{c}} = \bar{\sigma}_{l\bar{l}\to c\bar{c}} n_l n_{\bar{l}}$ is an example of the production rate of charm quarks from light quarks with $\bar{\sigma}_{l\bar{l}\to c\bar{c}}$ being a thermal-averaged in-medium cross section.

Fig. 8 illustrates the charm fugacity λ_c, quantifying how far they are from the chemical equilibrium. In comparison to Fig. 6 we now see a clear difference in the time-evolution of the quantity at early times ($\tau \sim 0.2-4$ fm, $T \sim 0.6-0.25$ GeV). Later, the solutions for ideal and viscous scenarios coincide, which may indicate a universal hydrodynamic attractor observed in the AdS/CFT correspondence [7]. $\lambda_c \neq 1$ around T_c, i.e. the charm quarks do not equilibrate before the plasma hadronizes.

Fig. 9 shows the charm quark production rate as a function of temperature. As it is expected that $R_{c\ prod}$ increases with T exponentially, we conclude that it is favorable for the initial fugacity value to be below $\lambda_0 = 100$. At around $T \sim 0.25$ GeV, all solutions for the charm quark production rate overlap with each other, and the difference in λ_c values for ideal and viscous cases becomes suppressed by the quasiparticle masses.

References

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Acknowledgments

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