Quasiparticle approach to strangeness and charm quark production in hot QCD

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V. M., C. Sasaki, Phys.Rev.D 103 (2021) [arXiv:2007.06846]
V. M., M. Bluhm, C. Sasaki, K. Redlich, Phys.Rev.D 100 (2019) [arXiv:1906.01697]

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Outlook

- Quasiparticle Model
- Shear viscosity of the QGP: η/s
- Time evolution of the QGP: $T(\tau)$
- Strange and charm quark production rates: $N_f = 2 + 1\ (+1)$

Motivation

Dynamical properties of QGP can be studied by:

- Lattice QCD
- Perturbative QCD
- AdS/CFT
- Effective models
- Green-Kubo formalism
- Kinetic theory
- $\cdots$

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Dynamical properties of QGP can be studied by:

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- Perturbative QCD
- AdS/CFT
- Effective models
- Green-Kubo formalism
- Kinetic theory + Lattice QCD EoS
- ...

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Particles propagate through the medium and become dressed with

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$\Longrightarrow$ Weakly-interacting massive particles with interactions encoded in $m_i[G(T), T]$:

$$P, \; \epsilon, \; s \sim \sum_i \int \frac{d^3p}{(2\pi)^3} f_i^0 \; \ldots;$$

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

$$E_i[G(T), T] = \sqrt{p^2 + m_i^2[G(T), T]}.$$

Effective coupling $G(T)$ extracted from LQCD entropy density

Quasiparticle Model: Effective Masses

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

$$m_i^2[G(T),T] = (m_i^0)^2 + \Pi_i[G(T),T]\,;$$

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[R. Pisarski, NPA498 '89; M. Bluhm et al., EPJC49 '07]

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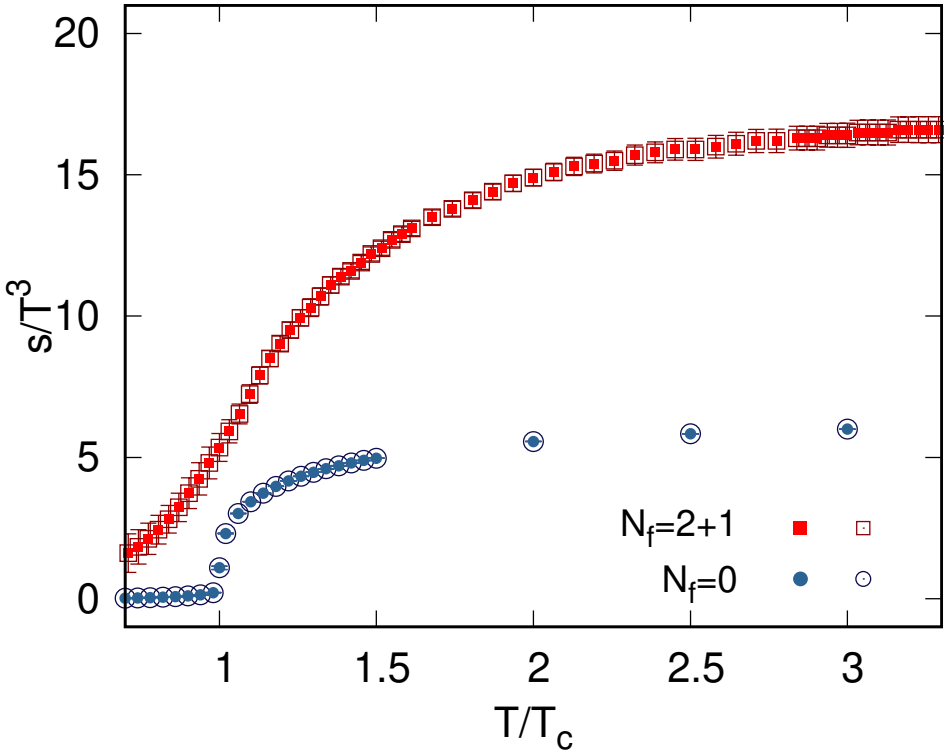

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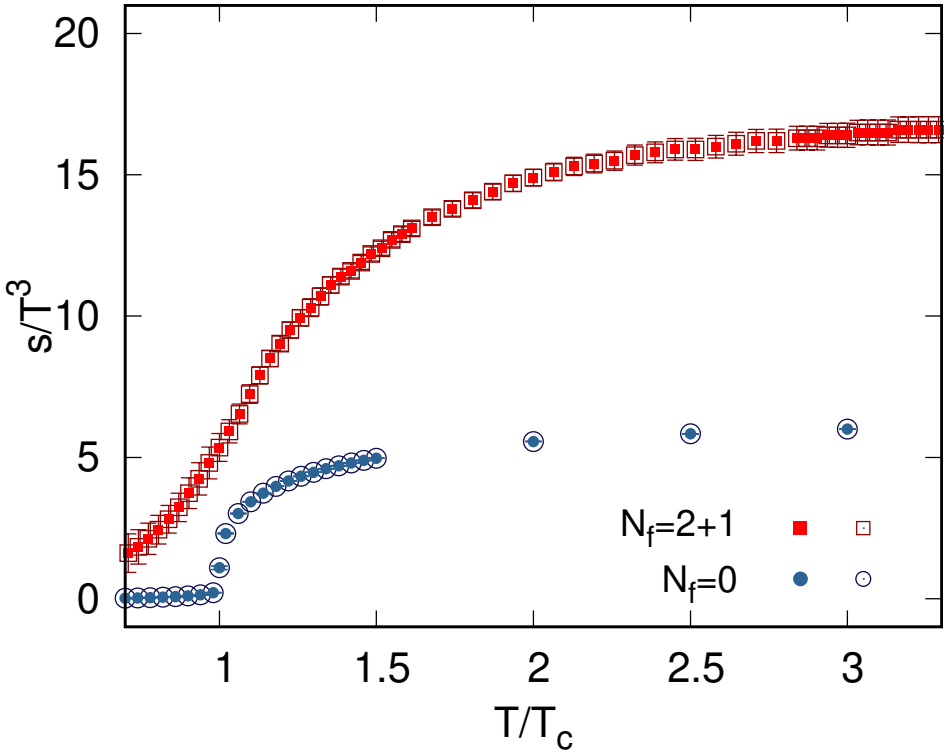
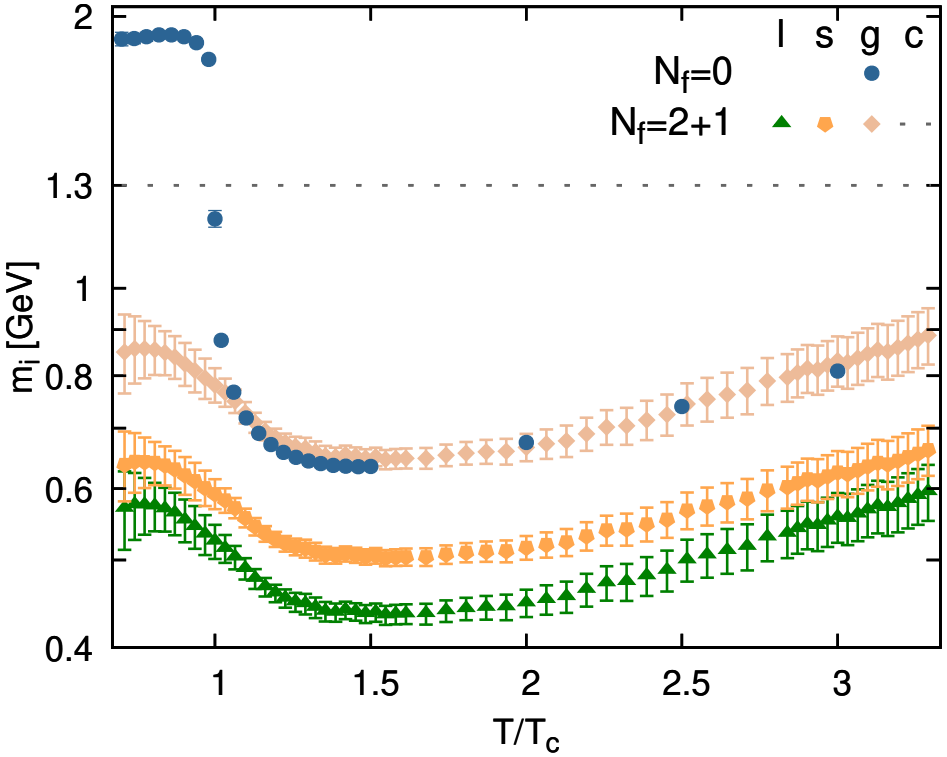


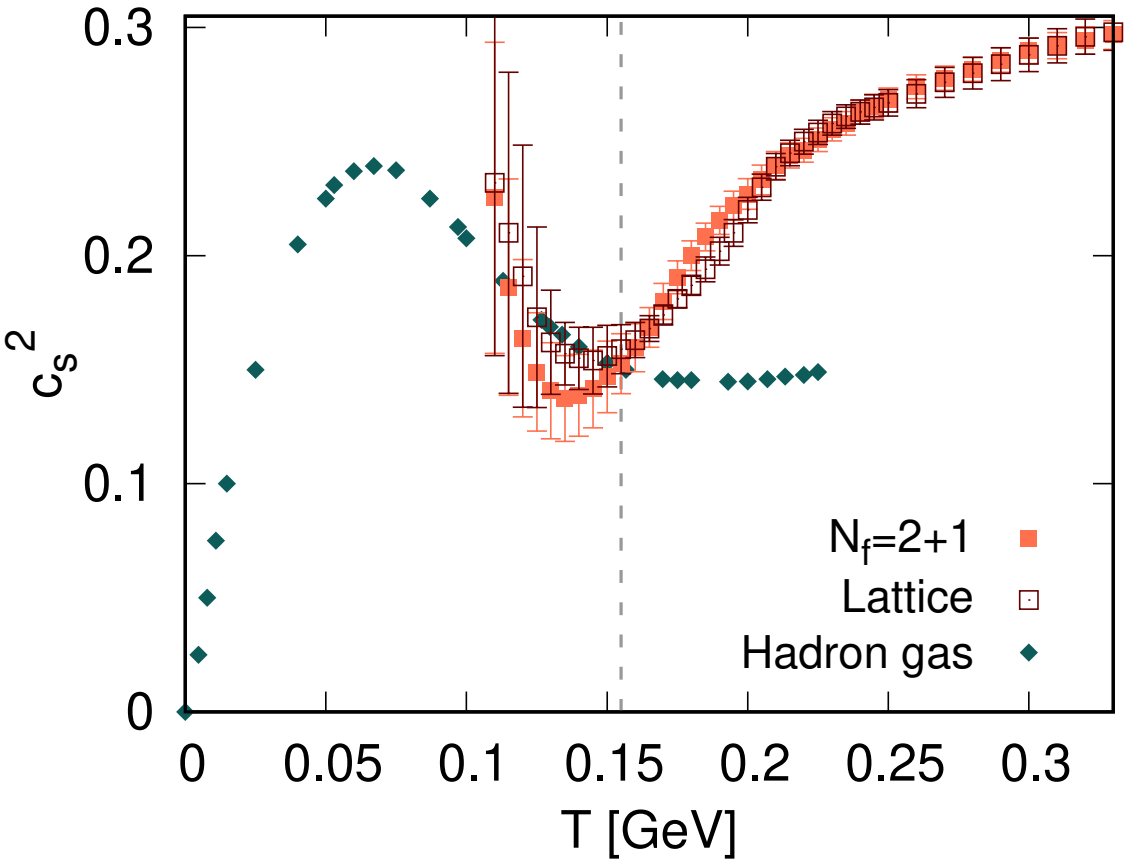


[V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 (2019); lQCD: Borsanyi et al., JHEP1207, 056 (2012); Phys. Lett. B 730 (2014)]

Quasiparticle Model: Thermodynamic Consistency

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

QCD with $N_f = 2+1$



[V.M and C. Sasaki, PRD 103 (2021); lQCD: Borsanyi et al.,PLB730 (2014); HRG, m<2.5 GeV: Castorina et al., EPJ C66 (2010)]

Kinetic Theory: Relaxation Time Approximation

$$T^{\mu\nu}_{eq}(f_0) \to \Delta T^{\mu\nu}(\delta f)$$

$$\delta f \sim \tau^{-1} \text{ from Boltzmann equation}$$

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$\Rightarrow$ strange quarks in $N_f = 2+1$ QGP:

$$\tau_s^{-1} = n_l\,\bar{\sigma}_{sl\to sl} + n_{\bar{l}}\,\bar{\sigma}_{s\bar{l}\to s\bar{l}} + n_s\,\bar{\sigma}_{ss\to ss} + n_{\bar{s}}\,\bar{\sigma}_{s\bar{s}\to s\bar{s}} + n_g\,\bar{\sigma}_{sg\to sg} +$$

$$(n_c\,\bar{\sigma}_{sc\to sc} + n_{\bar{c}}\,\bar{\sigma}_{n\bar{c}\to s\bar{c}})$$

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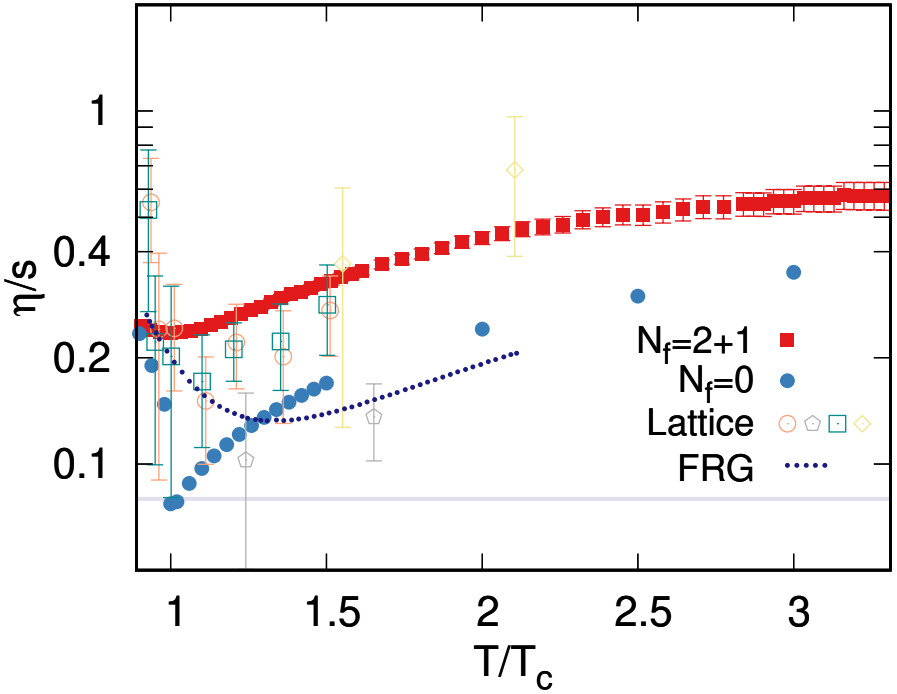
$(n_c\,\bar{\sigma}_{sc\to sc} + n_{\bar{c}}\,\bar{\sigma}_{n\bar{c}\to s\bar{c}})$

Shear viscosity:

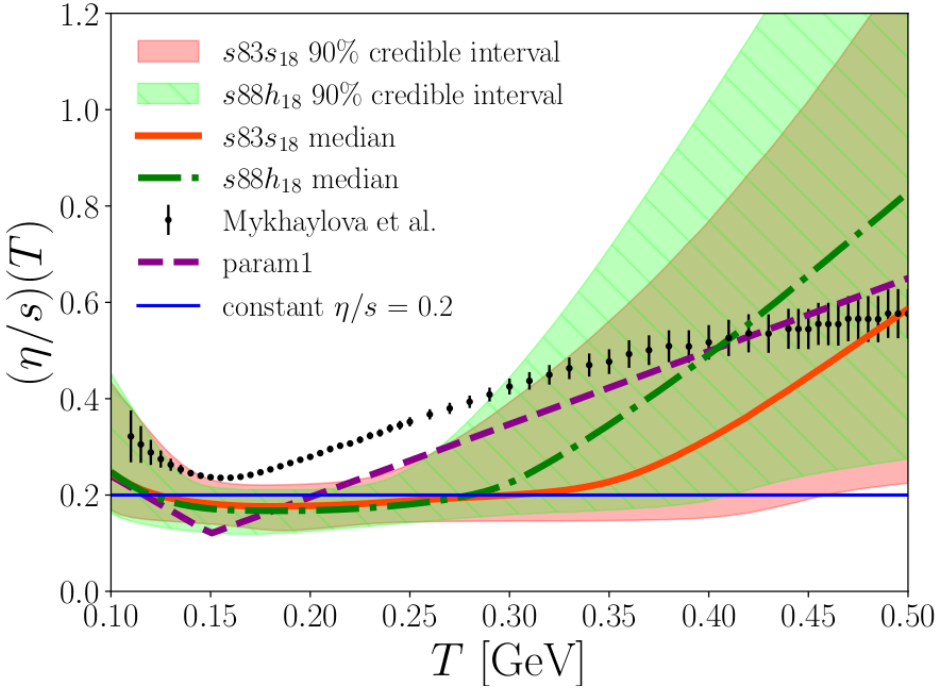
[Hosoya, Kajantie, NPB250 (1985)]

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

Specific Shear Viscosity



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



[J. Auvinen et al., Phys.Rev.C 102 (2020)]

Time evolution of the QGP: $T(\tau) = ?$

For longitudinally expanding boost-invariant medium ($\zeta = 0$)

$$\frac{\partial \epsilon}{\partial \tau} + (\epsilon + P)\frac{1}{\tau} = \frac{\Phi}{\tau}$$

1. Ideal fluid: $\Phi = 0 \quad \Rightarrow \quad s(\tau) \cdot \tau = s_0(\tau_0) \cdot \tau_0$
2. Bjorken scaling solution: [J. D. Bjorken, PRD 27 (1983)]

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

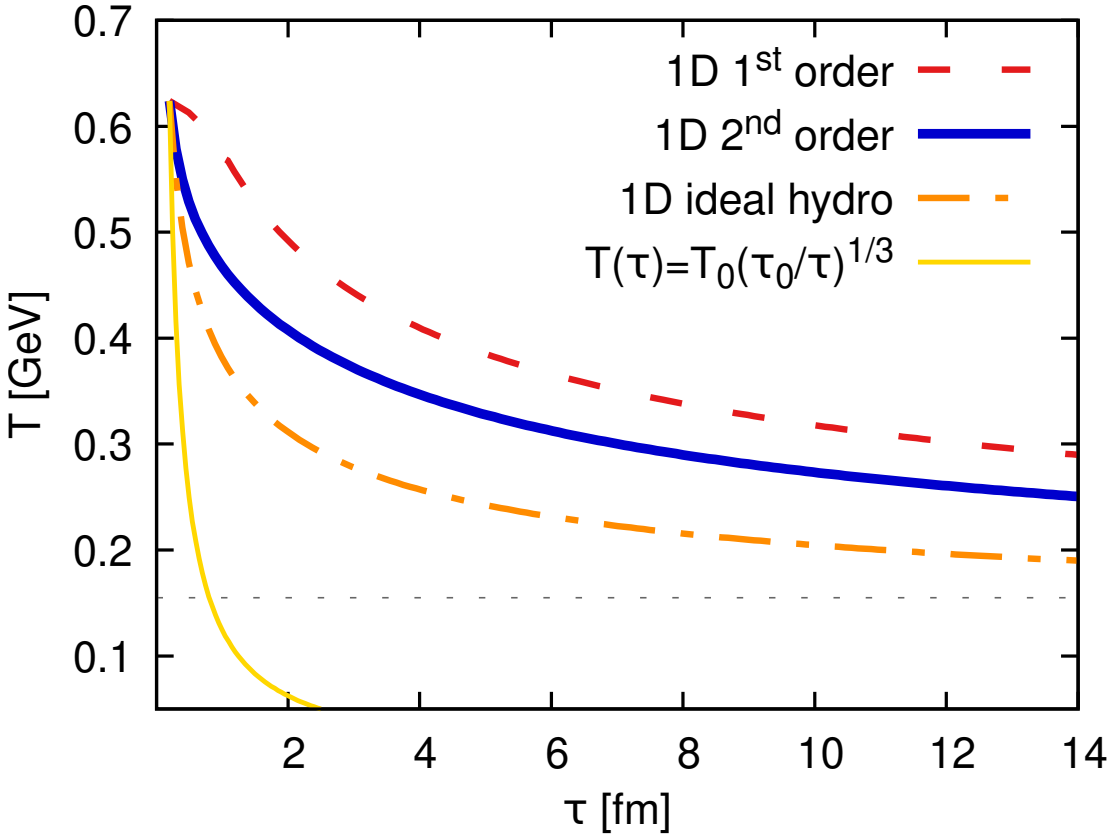
3. First-order hydro: $\Phi = 4\eta/3\tau$
4. Second-order hydro [A. Muronga PRL 88 (2002)]:

$$\frac{\partial \Phi}{\partial \tau} = -\frac{\Phi(\epsilon + P)}{5\eta} - \frac{4\Phi}{3\tau} + \frac{4(\epsilon + P)}{15\tau}$$

⋆ Same initial conditions for all: $\tau_0 = 0.2$ fm, $T_0 = 0.624$ GeV
[J. Auvinen et al., Phys.Rev.C 102 (2020)]

$T(\tau)$ for $N_f = 2 + 1$

Initial conditions: $\tau_0 = 0.2$ fm, $T_0 = 0.624$ GeV



[Preliminary]

$T(\tau)$ for $N_f = 2 + 1$

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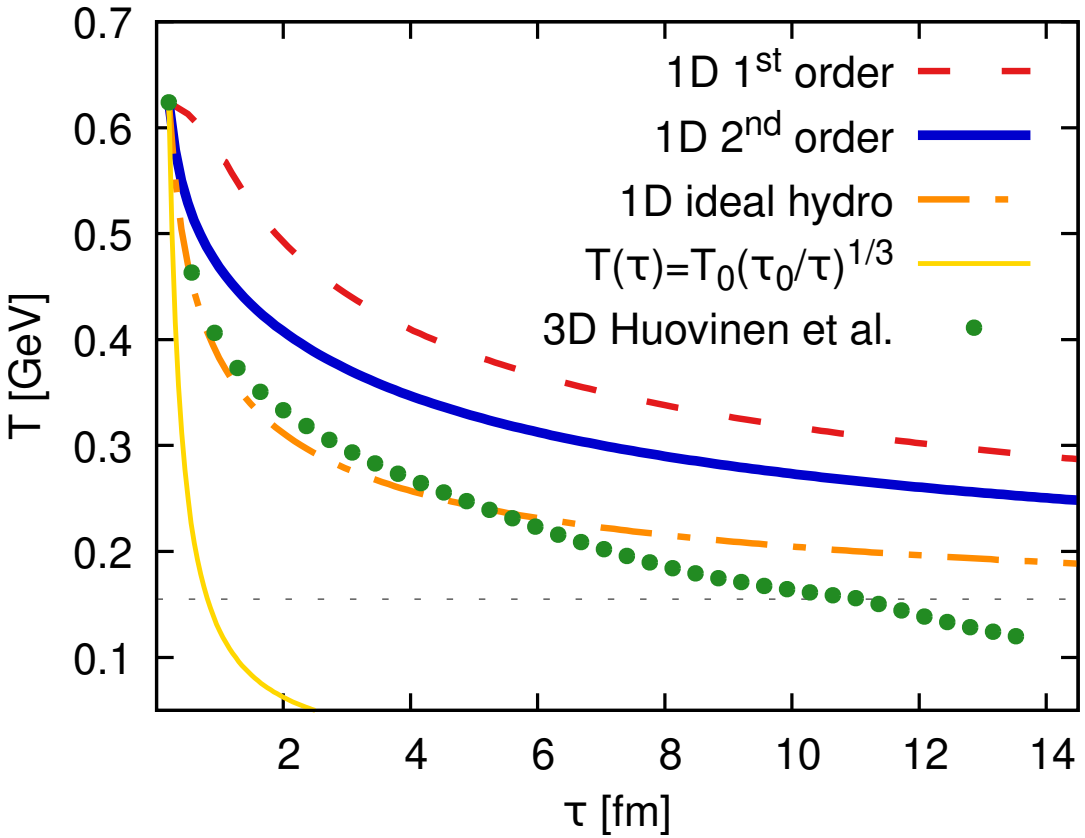


3D: not boost invariant, η/s from quasiparticle model

[Preliminary]

Strange and charm quark rate equations

$$\partial_\mu (n_{s(c)}\, u^\mu) \overbrace{=}^{u^\mu=(1,\vec{0})} \frac{dn_{s(c)}}{d\tau} = R^{gain}_{s(c)} - R^{loss}_{s(c)} = R^{tot}_{s(c)}$$

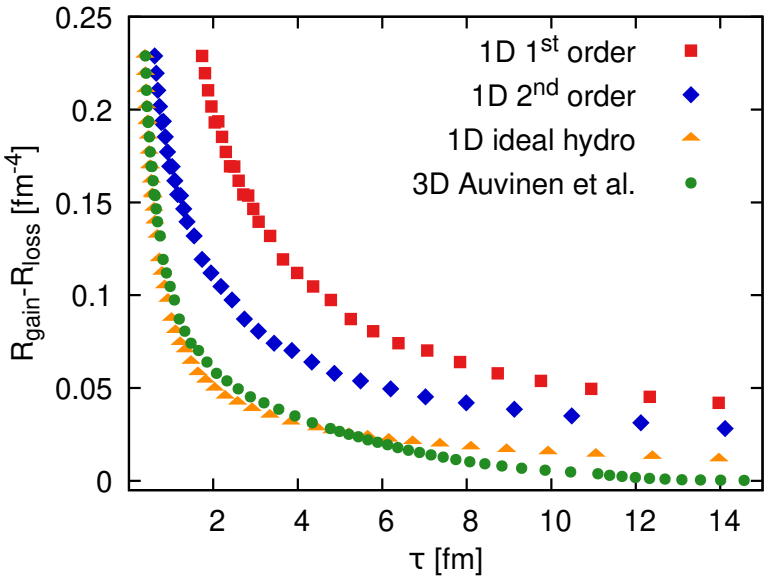
Strange quarks:

$$R^{tot}_s = \frac{1}{2}\,\bar{\sigma}_{gg\to s\bar{s}}\, n_g^2 + \bar{\sigma}_{q\bar{q}\to s\bar{s}}\, n_q^2 + \bar{\sigma}_{c\bar{c}\to s\bar{s}}\, n_c^2 - \left(\frac{1}{2}\,\bar{\sigma}_{s\bar{s}\to gg} + \bar{\sigma}_{s\bar{s}\to q\bar{q}} + \bar{\sigma}_{s\bar{s}\to c\bar{c}}\right) n_s^2$$

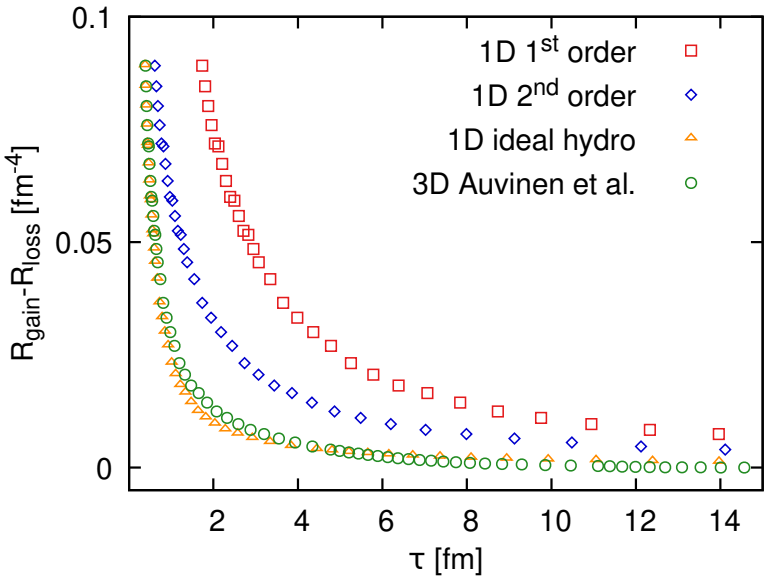
[T.S. Biro et al., PRC 48 (1993); J. Rafelski et al., Acta Phys.Polon.B 27 (1996); P. Koch et al., Phys. Rep. 142(4) (1986); T.Matsui et al., PRD 34(4) (1986)]

Time evolution of production rates, $N_f = 2 + 1$

Strange



Charm

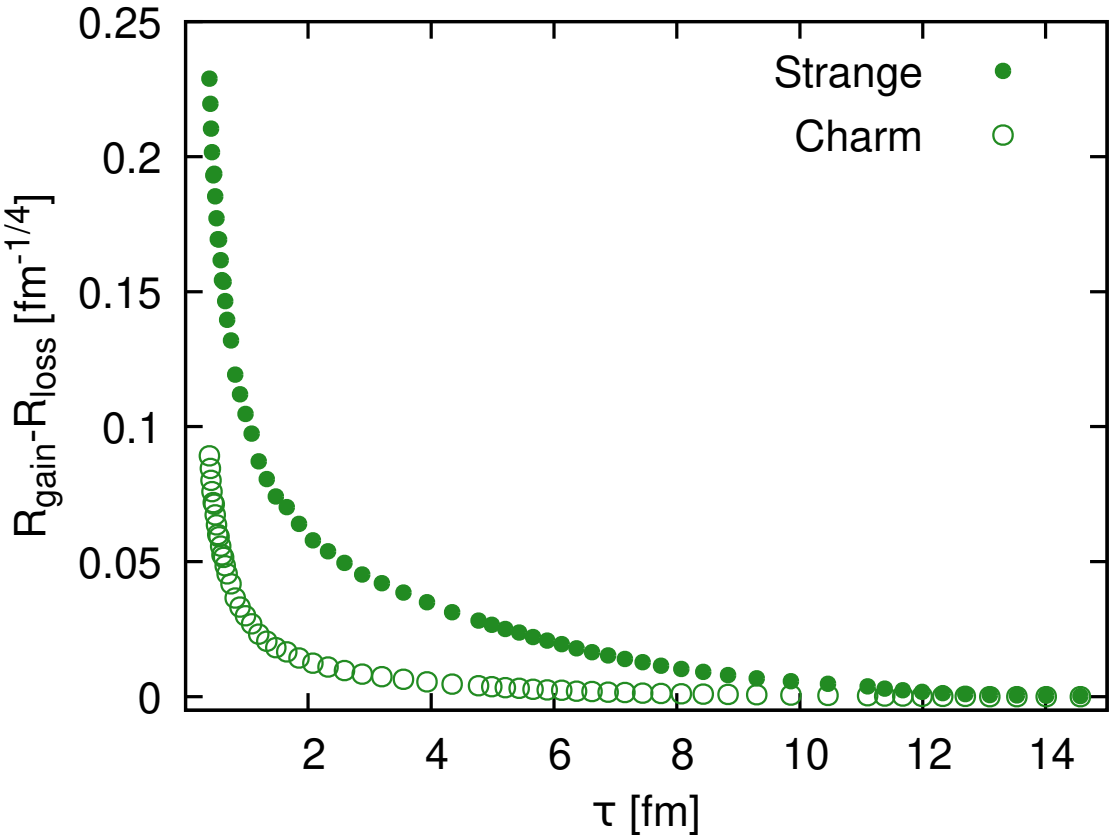


Preliminary

Time evolution of production rates, $N_f = 2 + 1$

Time evolution specified by 3D hydro simulations:

[J. Auvinen et al., Phys.Rev.C 102 (2020)]

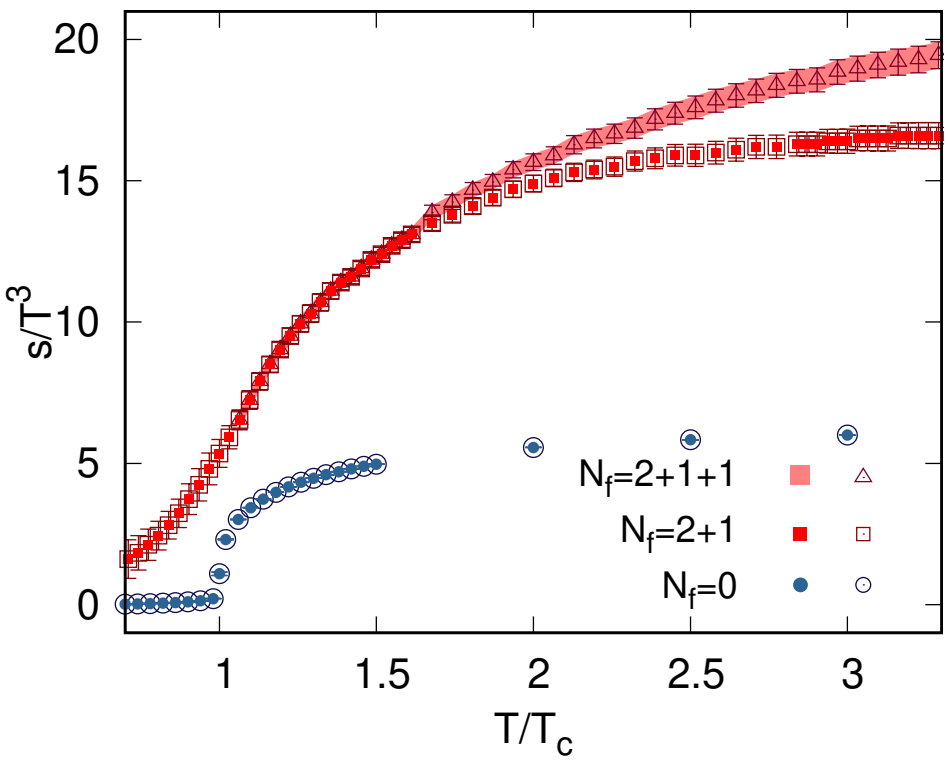


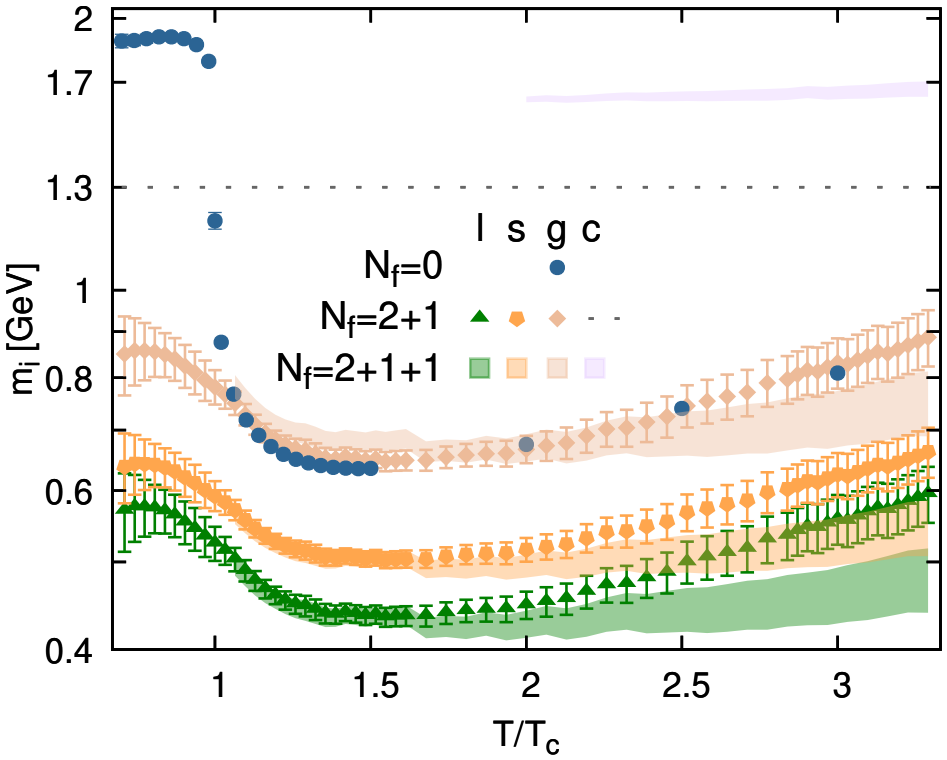
Preliminary

Quasiparticle model with thermalized charm quarks: $N_f = 2+1+1$

Charm quarks contribute to EoS at $T \geq 300$ MeV ($\simeq 2T_c$)

[Sz. Borsanyi et al., Nature 539 (2016)]

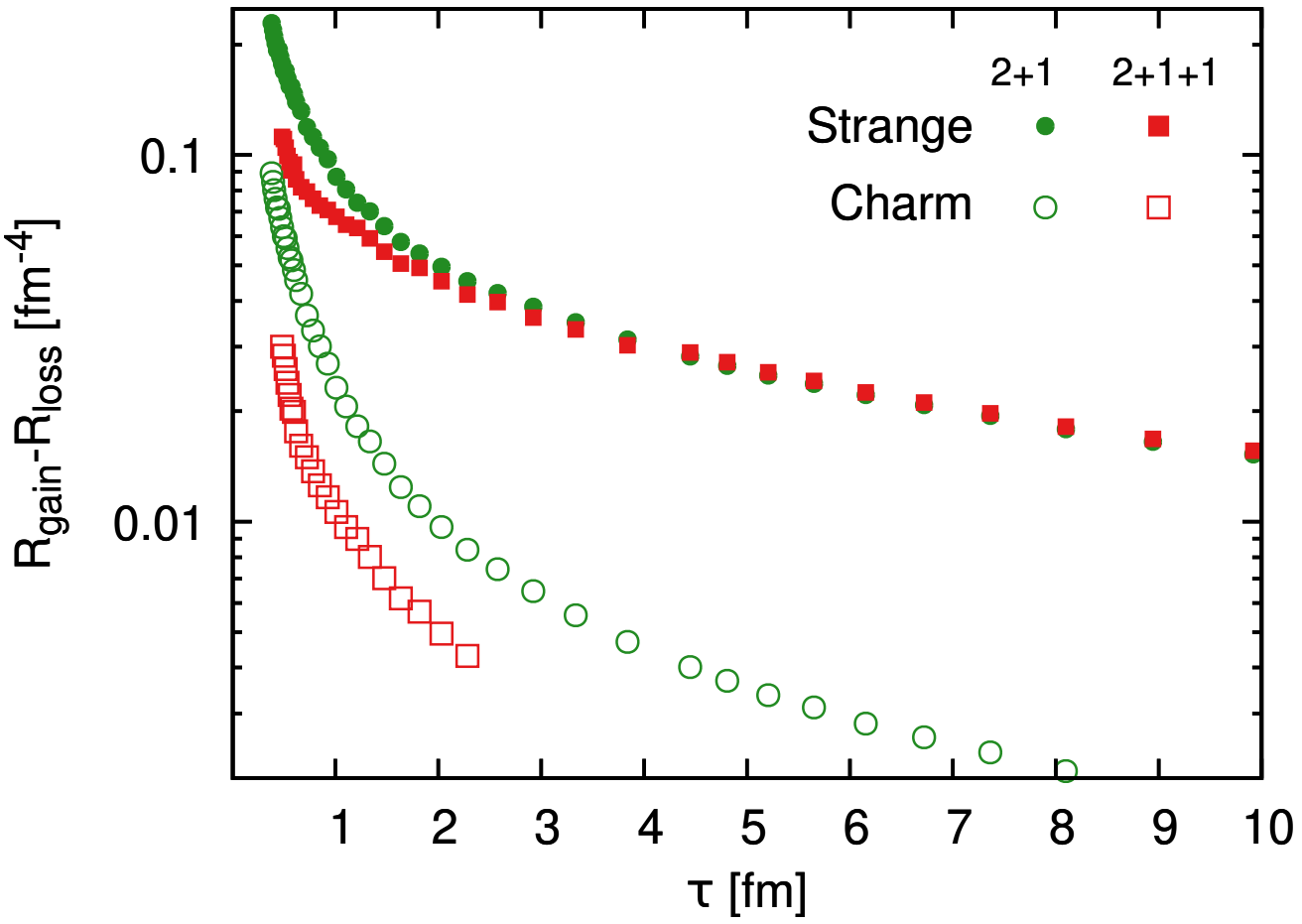




Preliminary

1D ideal QGP evolution

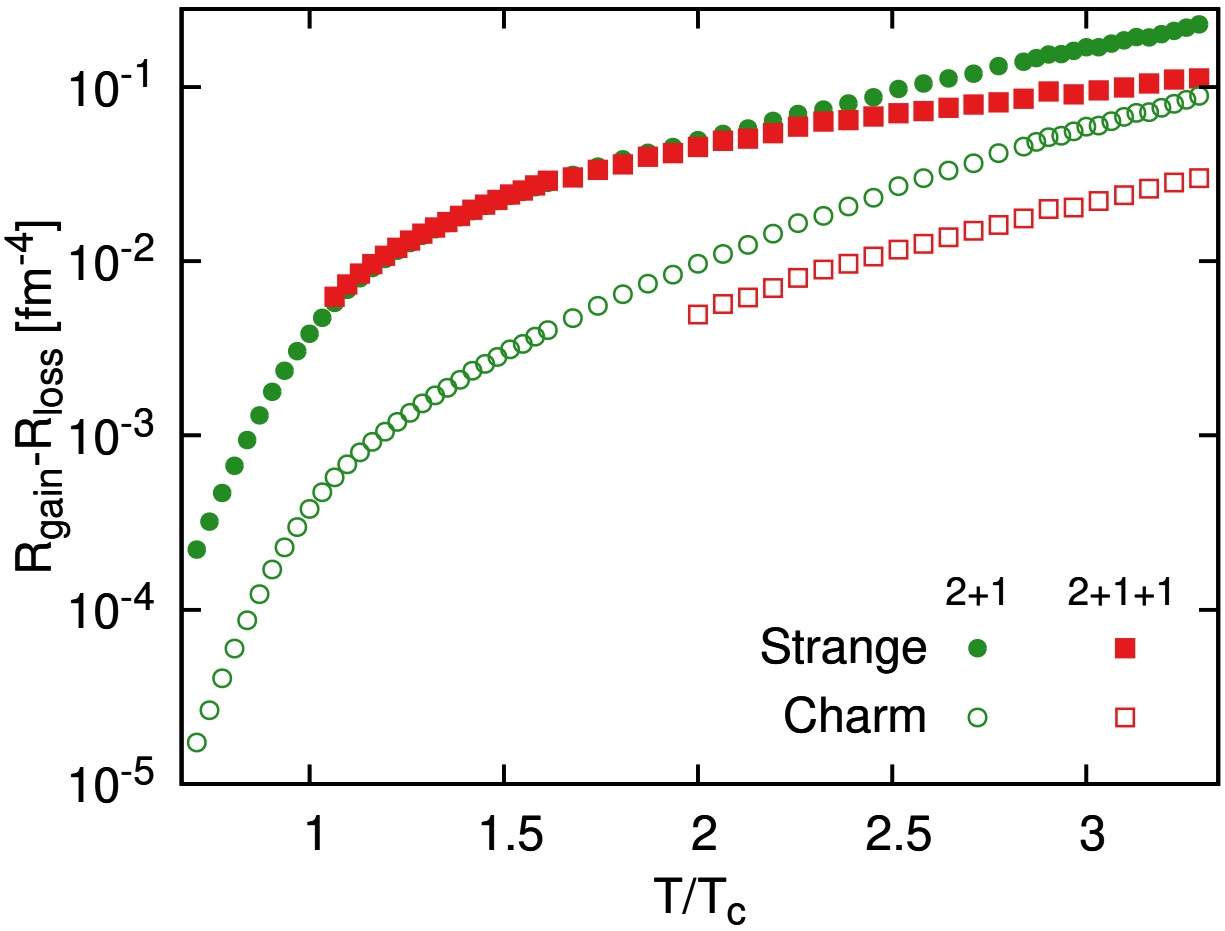
$N_f = 2 + 1$ vs $N_f = 2 + 1 + 1$



Preliminary

Temperature evolution of the particle production

$N_f = 2+1$ vs $N_f = 2+1+1$



Preliminary

Summary

Quasiparticle Model:

- consistent with lattice EoS;
- accommodates non-perturbative effects around T_c;
- corresponds to the pQCD expectations at high T;
- gives transport parameters consistent with other approaches;
- phenomenological study of QCD for different N_f;

Perspectives: $\mu \neq 0$, magnetic field, anisotropy, higher-order cross sections, more inelastic scatterings, B flavor, hadronic phase...