Heavy Flavor Kinetics in Hot QCD

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Outline

- ☞ Task: thermal production of $c\bar{c}$ in the QGP
- ☞ Quasiparticle model
- ☞ QGP hydrodynamics: 1D perfect vs (2+1)D viscous
- ☞ Rate equation & $c\bar{c}$ production rate
- ☞ $N_{c\bar{c}}(\tau)$ in hot deconfined matter

Quasiparticle Model - Effective Approach to QCD

☞ similar to massive quasielectron moving freely in solid states

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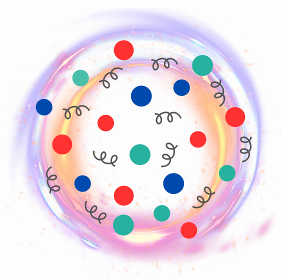
Real QGP:



strongly-interacting particles,
constant (bare) masses m_i

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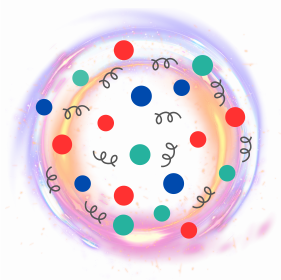

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$\longrightarrow$

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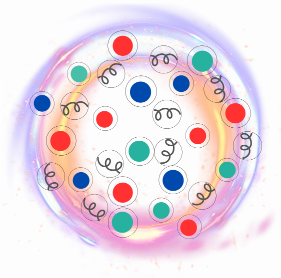

weakly-interacting **quasi**particles, dynamical $m_i^{eff}[T, G(T)]$

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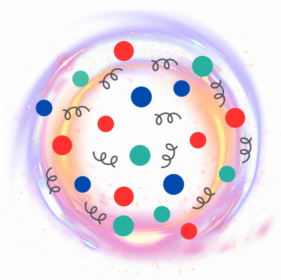

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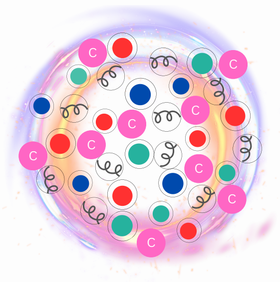

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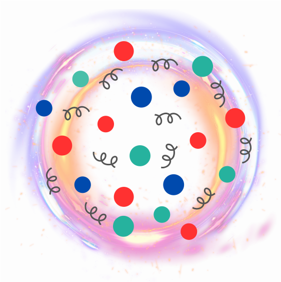

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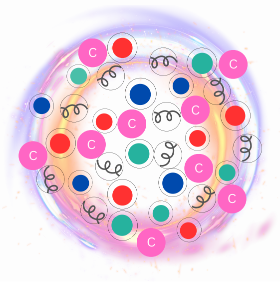

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$$m_i^{eff}[G(T), T] = \sqrt{m_i^2 + \Pi_i[G(T), T]}$$

Quasiparticle Model - Effective Approach to QCD

Quasiparticles are „dressed” with effective masses $m_i[G(T), T]$:

$$m_i[G(T), T] = \sqrt{(m_i^0)^2 + \Pi_i[G(T), T]} \tag{1}$$

Self-energies Π_i from pQCD - HTL (Hard Thermal Loops):

[M. Bluhm et al. EPJ C 49 (2007), R. D. Pisarski, Nucl. Phys. A 498 (1989)]

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

$$\text{quarks: } \Pi_{l,s}[G(T), T] = 2\left[m_{l,s}^0 \sqrt{\frac{G^2(T)T^2}{6}} + \frac{G^2(T)T^2}{6}\right] \tag{3}$$

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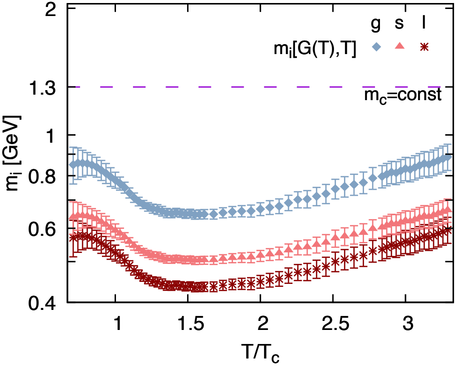
☞ Effective coupling $G(T)$ – reliable thermodynamics – lattice QCD

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

Quasiparticle Model

$$s(T) \simeq \sum_{i=g,l,s,..} \int d^3p \left([1 \pm f_i^0] \ln[1 \pm f_i^0] \mp f_i^0 \ln f_i^0\right) = \text{lattice data} \rightarrow G(T)$$

$$f_i^0(E_i): \quad E_i[G(T), T] = \sqrt{p^2 + m_i^2[G(T), T]} \tag{4}$$



[V.M, Acta Phys.Polon.Supp. 17 (2024), V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 (2019);

lattice: S. Borsanyi, et al., Phys. Lett. B 730 (2014) (Wuppertal-Budapest)]

Rate Equation

describes time/temperature evolution of the number density function:

[Biro et al., PRC 48 '(1993); Zhang et al., PRC 77 (2008)]

$$\partial_\mu \left(n_c u^\mu\right) = R_{l\bar{l}\to c\bar{c}} + R_{s\bar{s}\to c\bar{c}} + R_{gg\to c\bar{c}} - R_{c\bar{c}\to l\bar{l}} - R_{c\bar{c}\to s\bar{s}} - R_{c\bar{c}\to gg} \tag{5}$$

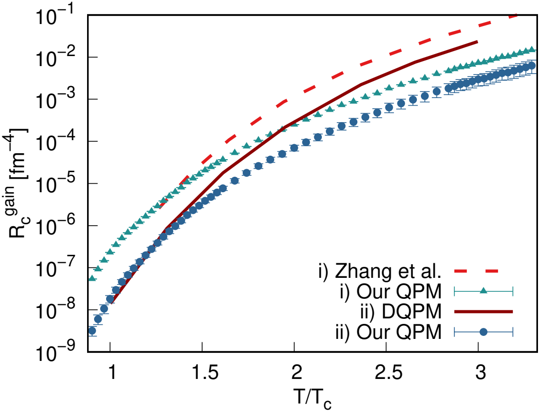
Applying the detailed balance:

$$\partial_\mu(n_c u^\mu) = \left[\bar{\sigma}_{l\bar{l}\to c\bar{c}} \, (n_l^0)^2 + \bar{\sigma}_{s\bar{s}\to c\bar{c}} \, (n_s^0)^2 + \frac{1}{2}\bar{\sigma}_{gg\to c\bar{c}} \, (n_g^0)^2\right] \times \left(1 - \frac{n_c^2}{(n_c^0)^2}\right) \tag{6}$$

$$n_i^0 = d_i \int d^3p \, f_i^0[E_i(T)] \tag{7}$$

$$R_c^{gain} = \left[\bar{\sigma}_{l\bar{l}\to c\bar{c}} \, (n_l^0)^2 + \bar{\sigma}_{s\bar{s}\to c\bar{c}} \, (n_s^0)^2 + \frac{1}{2}\bar{\sigma}_{gg\to c\bar{c}} \, (n_g^0)^2\right] \tag{8}$$

Charm Quark Production Rate



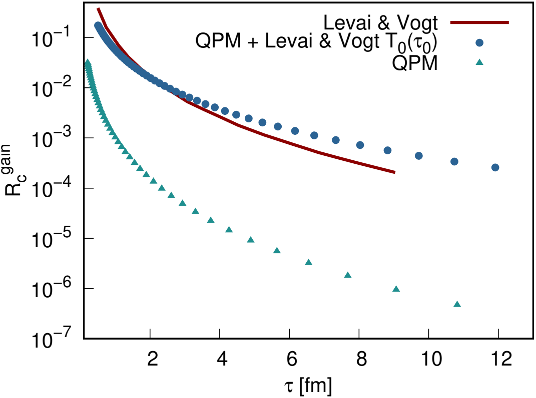
i) $M_c = 1.3$ GeV, Total rate

ii) $M_c = 1.5$ GeV, Production rate from quarks only

[DQPM: T. Song, I. Grishmanovskii, O. Soloveva, E.Bratkovskaya, arXiv:2404.00425 (2024);
Zhang et al., Phys. Rev. C 77 (2008)

Charm Quark Production Rate

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



Levai & Vogt: Total rate for $M_c = 1.2$ GeV, $T_0 = 0.82$ GeV, $\tau_0 = 0.5$ fm;

QPM: Total rate for $M_c = 1.3$, $T_0 = 0.624$ GeV, $\tau_0 = 0.2$ fm.

[V.M., C. Sasaki, K. Redlich: to appear on ArXiv; P. Levai and R. Vogt, PRC 56 (1997)]

Rate Equation

$$\partial_\mu (n_c u^\mu) = \left[\bar{\sigma}_{l\bar{l}\to c\bar{c}}\,(n_l^0)^2 + \bar{\sigma}_{s\bar{s}\to c\bar{c}}\,(n_s^0)^2 + \frac{1}{2}\bar{\sigma}_{gg\to c\bar{c}}\,(n_g^0)^2\right] \times \left(1 - \frac{n_c^2}{(n_c^0)^2}\right) \tag{9}$$

$$n_c[T(\tau)] = ? \tag{10}$$

* LHS depends on the QGP evolution:

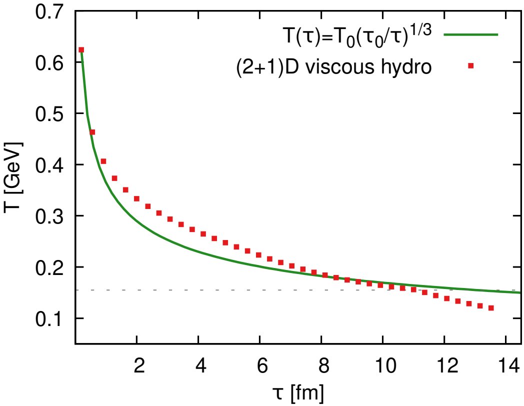
i) 1D Bjorken flow, ideal fluid: no dissipation,

$$T = T_0 \left(\frac{\tau}{\tau_0}\right)^{-1/3} \tag{11}$$

ii) (2+1)D expansion, viscous fluid + $(\eta/s)(T)$

[V.M., M. Bluhm, K. Redlich, C. Sasaki, PRD100 '19; Auvinen, Eskola, Huovinen, Niemi, Paatelainen, Petreczky, PRC 102 '20]

QGP Evolution: 1D vs (2+1)D

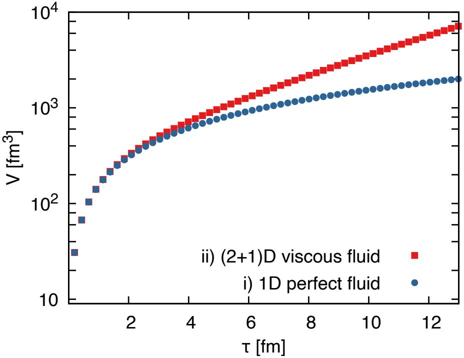


Common initial conditions: $T_0 = 0.624$ GeV, $\tau_0 = 0.2$ fm.

[Auvinen, Eskola, Huovinen, Niemi, Paatelainen, Petreczky, PRC 102 '20]

Volume of the QGP

$$V(\tau) = \pi R^2 \tau \tag{12}$$

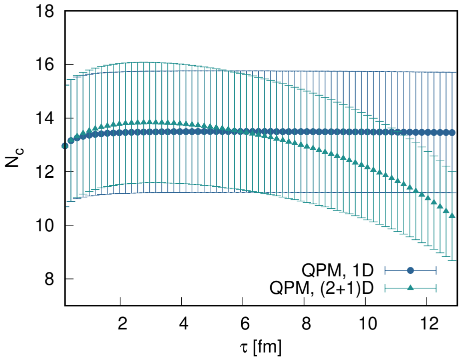


i) 1D ideal Bjorken dynamics: $R = R_0 = 7$ fm

ii) (2+1)D viscous expansion: $R(\tau) = R_0 + (\tau - \tau_0)^2 a/2$, $a = 0.07\ \text{fm}^{-1}$

[P. Braun-Munzinger, K. Redlich, EPJ C 16 (2000), Zhang et al., Phys. Rev. C 77 (2008)]

Charm Quark Evolution



$$\text{1D: } \tau_{\text{fin}} \simeq \mathbf{13} \text{ fm} \quad \text{vs} \quad \text{(2+1)D: } \tau_{\text{fin}} \simeq \mathbf{11} \text{ fm}$$

$$\text{Initial charm quark number: } \frac{dN_c}{dy} = 12.95 \pm 2.27 \tag{13}$$

(rapidity density for most central Pb-Pb collisions at $\sqrt{s} = 5.02$ TeV)

[Andronic, Braun-Munzinger, Koehler, Mazeliauskas, Redlich, Stachel, Vislavicius, JHEP 07 '21]

Summary

☞ **Quasiparticle model** – effective well-established tool connecting non-perturbative and perturbative QCD regimes.

☞ **Charm quarks** – minor thermal production in both ideal 1D- and viscous (2+1)D-expanding plasma, consistent with SHM predictions.

☞ **Possibilities** – quasiquarks out of chemical equilibrium, finite μ, ...

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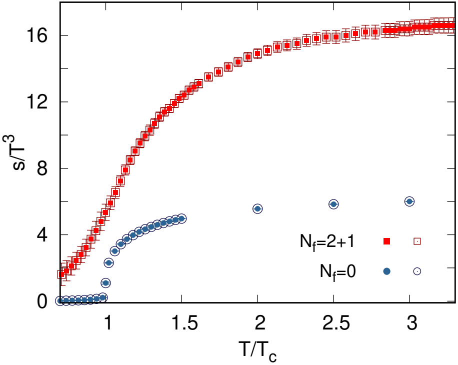
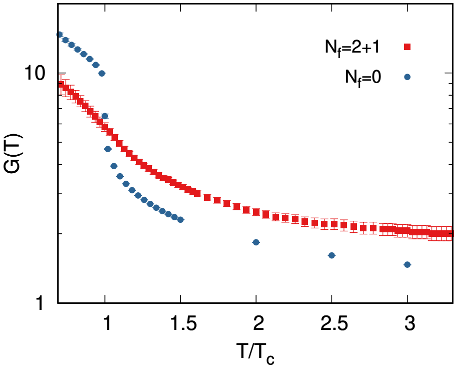
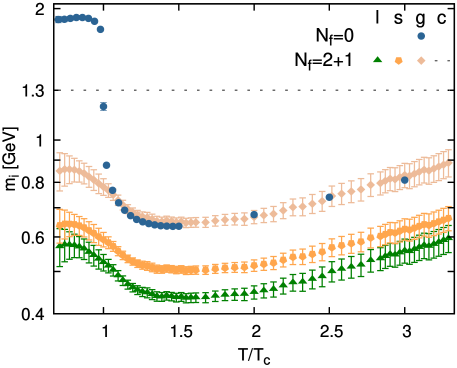


[V.M, M. Bluhm, C. Sasaki, K. Redlich, PRD 100 (2019); lattice: S. Borsanyi, et al., Phys. Lett. B 730 (2014) (Wuppertal-Budapest)]

Effective Coupling and Masses





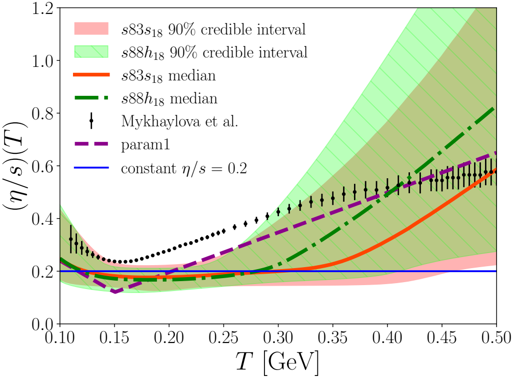
$$\mathrm{m}_i[G(T), T] \gg m_l^0 = 5\ \mathrm{MeV},\ m_s^0 = 95\ \mathrm{MeV}$$

[V.M., M. Bluhm, K. Redlich, C. Sasaki, PRD100 (2019), V.M. C. Sasaki, PRD 103 (2021)]

Shear Viscosity

(reaction to flow) [Hosoya, Kajantie, NPB250 ’85]

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



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