Heavy Flavor Kinetics in HIC

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Motivation

☞ Charm quarks probe the properties of the QGP

Task: study the $c\bar{c}$ production in equilibrated QGP, $N_f = 2 + 1$, two evolution scenarios:

- 1D ideal fluid (Bjorken flow)

-(2+1)D viscous QGP + $(\eta/s)(T)$

☞ Quasiparticle model

☞ Rate equation: cross sections, charm production rate

☞ Number of $c\bar{c}$ pairs in hot deconfined matter

Quasiparticle Model - Effective Approach to QCD

☞ similar to massive quasielectron moving freely in solid states

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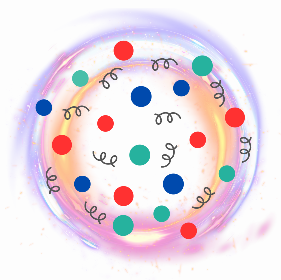
Real QGP:



strongly-interacting particles,
constant (bare) masses m_i

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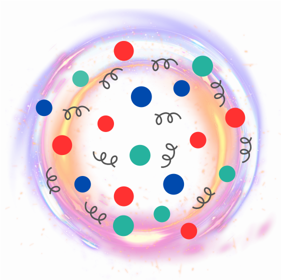

strongly-interacting particles,
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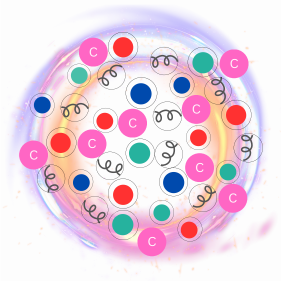
$\longrightarrow$

Effective approach:



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

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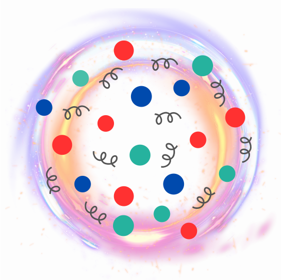

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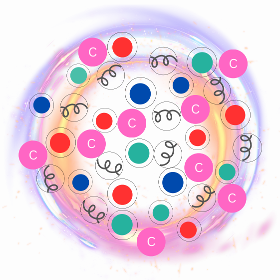

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$$m_i^{eff}[G(T), T] = \sqrt{m_i^2 + \Pi_i[G(T), T]}$$

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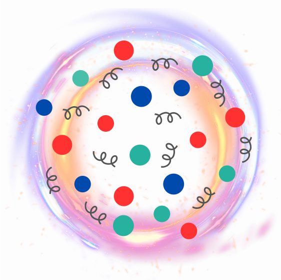

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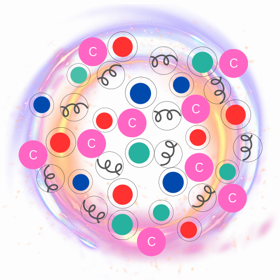

strongly-interacting particles, constant (bare) masses m_i

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

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

$G(T)$ *from lattice QCD EoS*

Quasiparticle Model

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 (Hard Thermal Loops):

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

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

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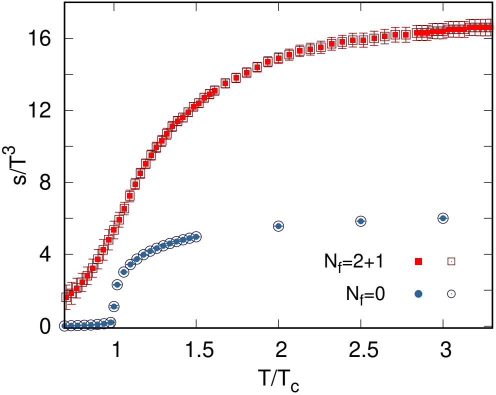
☞ effective coupling $G(T)$ – reliable thermodynamics – lattice QCD

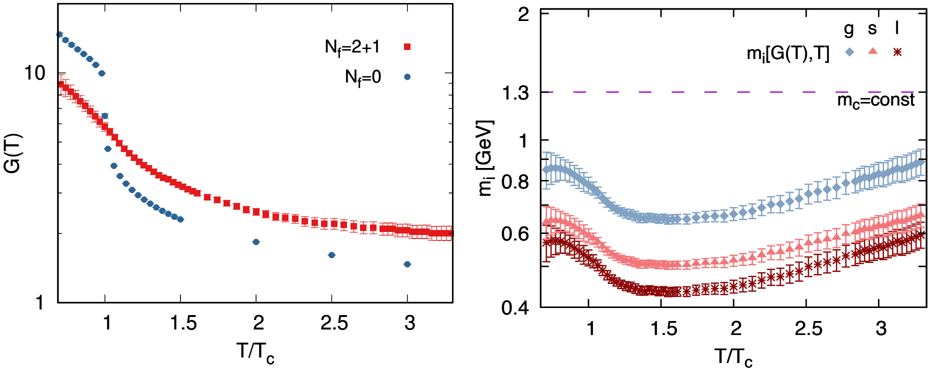
Quasiparticle Model

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

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



Effective Coupling and Masses



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

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

Charm Quark Evolution

Rate equation [Biro et al., PRC 48 '93; Zhang et al., PRC 77 '08]:
describes time/temperature evolution of the number density function

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

Applying the detailed balance:

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

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

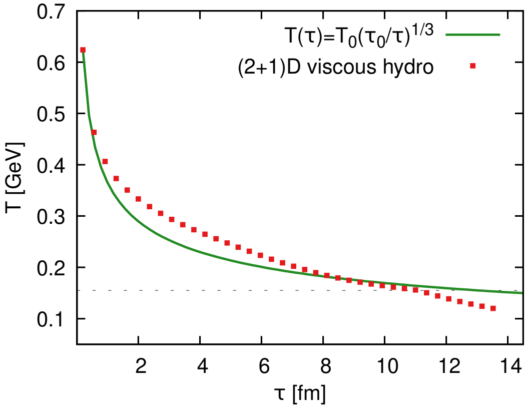
$$n_c = \lambda_c(\tau) n_c^0 \quad (8)$$

* LHS depends on the QGP evolution:

i) 1D Bjorken flow, ideal fluid;
ii) (2+1)D expansion $+(\eta/s)(T)$

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

QGP Evolution



$$T_0 = 0.624 \text{ GeV}, \tau_0 = 0.2 \text{ fm}$$

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

Thermal-Averaged Cross Sections

$$\sigma(\sqrt{s}) \rightarrow \bar{\sigma} = \langle \sigma\, v \rangle \tag{9}$$

For Boltzmann statistics:

$$\bar{\sigma}_{ab\rightarrow cd} = \frac{\int d^3p_a\, d^3p_b\, f_a\, f_b\, \sigma_{ab\rightarrow cd}\, v_{ab}}{\int d^3p_a d^3p_b\, f_a\, f_b} = \tag{10}$$

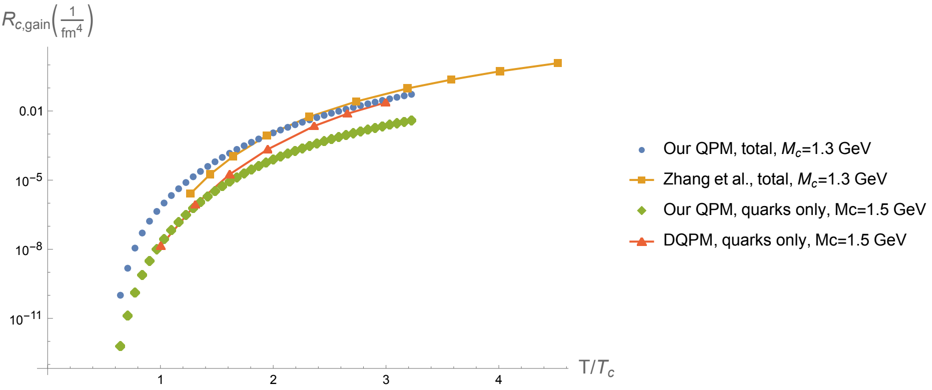
$$\left[4\frac{M_a^2}{T^2}\frac{M_b^2}{T^2}K_2\left(\frac{M_a}{T}\right)K_2\left(\frac{M_b}{T}\right)\right]^{-1}\times$$

$$\int_{\sqrt{s_0}}^{\infty} d(\sqrt{s})K_1\left(\frac{\sqrt{s}}{T}\right)\sigma_{ab\rightarrow cd}\left[\frac{s}{T^2}-\left(\frac{M_a^2}{T^2}+\frac{M_b^2}{T^2}\right)^2\right]\left[\frac{s}{T^2}-\left(\frac{M_a^2}{T^2}-\frac{M_b^2}{T^2}\right)^2\right];$$

$$\sqrt{s_0} = max[M_a + M_b, M_c + M_d]$$

P. Braun-Munzinger, K. Redlich, Eur.Phys.J.C 16 (2000), 519-525

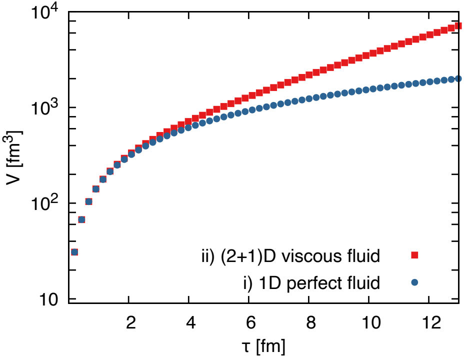
Charm Quark Production Rate



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

Volume of the QGP

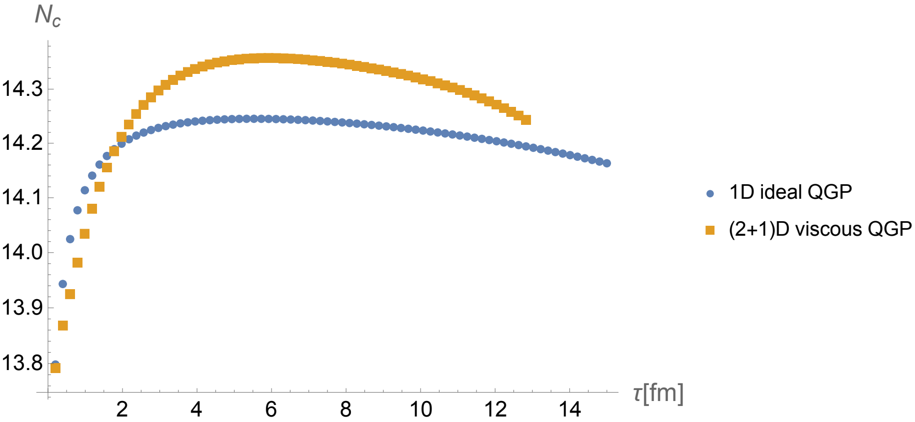
$$V(\tau) = \pi R^2 \tau \tag{11}$$



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

ii) (2+1)D viscous expansion: $R(\tau) = R_0 + (\tau - \tau_0)^2 a/2$, $a = 0.01$ fm

Charm Quark Production



$$\text{Initial charm quark number: } \frac{dN_c}{dy} = 13.8 \tag{12}$$

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.

☞ **Possibilities** – quasiquarks out of chemical equilibrium, finite μ, $N_f = 2 + 1 + 1$...