Heavy Quark Spectral Functions and Momentum Broadening in a highly occupied non-abelian plasma off-equilibrium

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Work in preparation in collaboration with Sören Schlichting & Sayantan Sharma

From first-principles QCD to experiments, ECT* Trento

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- Studying the dynamics of heavy quarks in presence of such highly occupied gauge fields in the pre-equilibrium stage could be an excellent probe in understanding the approach to thermalization in such systems.

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- Studies involving charm quarks inside a glasma have been performed primarily in the infinite-mass limit using electric field (EE) correlators until now.
- Our goal is to study heavy quark dynamics using relativistic fermion fields and perform a comparative analysis with light quarks under out-of-equilibrium conditions.

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- We observed that in-medium effects on the quark dynamics dictate the validity of various approximation schemes to study quark momentum broadening and diffusion.
- Reliable results for heavy quark momentum diffusion coefficient from our analysis to appear soon.

Initial Conditions: Non-abelian plasma in the self-similar regime

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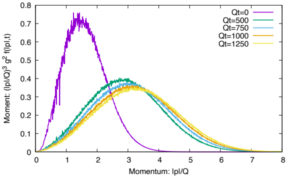
- We consider the following initial phase-space distribution of the gluons,

$$g^2 f_g(p) = n_0 \frac{Q}{p} e^{-\frac{p^2}{2Q^2}}$$

where $n_0/g^2 >> 1$.



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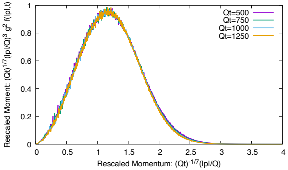

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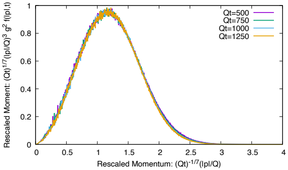

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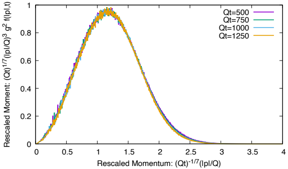

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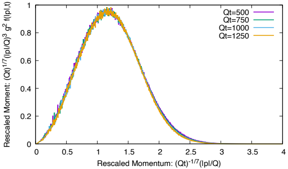

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- We have chosen a wide set of quark masses,
  $m/Q = 0.0012,\ 0.012,\ 0.12,\ 0.24,\ 0.4,\ 1.2,\ 2.4,\ 3.6,\ 4.8$.
  For $Q \sim 1GeV$, the choice of $m/Q = 1.2$ represents a charm quark.

Calculating Quark Spectral Functions

- Quark spectral function, in terms of quark fields, is defined as

$$\rho^{\alpha\beta}(x,y) = \left\langle \left\{ \hat{\psi}^{\alpha}(x), \hat{\bar{\psi}}^{\beta}(y) \right\} \right\rangle$$

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- In general, it can be decomposed into the following parts

$$\rho = \rho_S + i\gamma_5 \rho_P + \gamma_\mu \rho_V^\mu + \gamma_\mu \gamma_5 \rho_A^\mu + \frac{1}{2}\sigma_{\mu\nu}\rho_T^{\mu\nu}$$

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- Here, for example, the vector component of the spectral function ρ_V can be extracted as

$$\rho_V^0 = \frac{1}{4}Tr(\rho\gamma^0), \;\; \rho_V = -\frac{E_{\mathbf{p}}p^j}{4p^2}Tr(\rho\gamma^j)$$

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- Fermionic field, in terms of creation (b), annihilation operators (d) and fermionic wavefunctions (ϕ's)

$$\Psi(t', \mathbf{x}) = \frac{1}{\sqrt{N^3}} \sum_{\lambda, \mathbf{p}} \left(\phi^{u}_{\lambda,p}(t', \mathbf{x}) b_\lambda(t' = 0, p) + \phi^{v}_{\lambda,p}(t', \mathbf{x}) d^{\dagger}_{\lambda}(t' = 0, p) \right)$$

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- Using the above mode function expansion, we obtain the spectral function as in

$$\rho^{\alpha\beta}(x,y) = \sum_{\lambda,\mathbf{p}} \Big(\phi^{u,\alpha}_{\lambda,\mathbf{p}}(x^0,\mathbf{x}) (\phi^{u,\gamma}_{\lambda,\mathbf{p}}(y^0,\mathbf{y}))^* + \phi^{v,\alpha}_{\lambda,\mathbf{p}}(x^0,\mathbf{x}) (\phi^{v,\gamma}_{\lambda,\mathbf{p}}(y^0,\mathbf{y}))^* \Big) \gamma_0^{\gamma\beta}$$

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- Hence, we need to only evolve ϕ's for a specific momentum mode and plug it in the above expression to obtain spectral functions.

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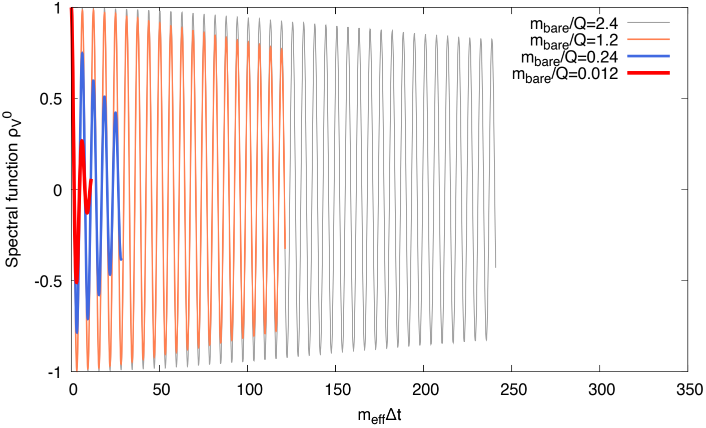
- For light quarks with zero momenta ($p = 0$), expression for the HTL spectral function simplifies to

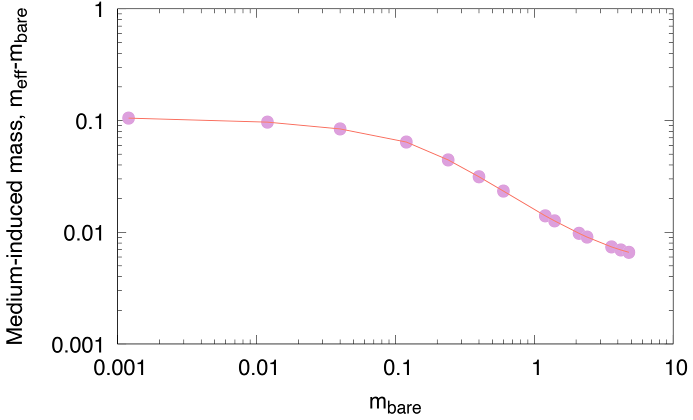
$$\mathrm{Re}\rho_V^0(t, p=0) \approx e^{-\gamma(m_{eff}, p=0)t} \cos[\omega(m_{eff}, 0)t]$$

Lattice Results: quark spectral function across a mass range



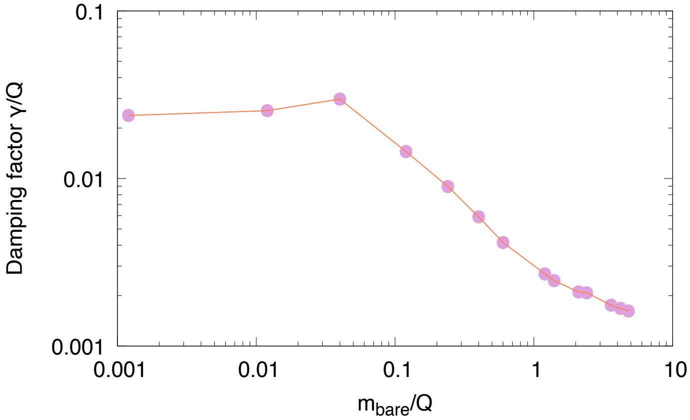
In-Medium effects on the mass of quark quasi-particles

- We obtain effective mass (m_{Eff}) via fit to spectral function and subtract the bare mass to obtain medium-induced mass → medium modification decreases from $> 99\%$ to $< 0.1\%$ from light to heavy



Quark Spectral Functions: Variation of γ with m_{bare}

- Lifetime of quasi-particles increases $> 10\times$ going from light to heavy



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- In this regime, the validity of Boltzmann equation can be thus justified.
- Intermediate $m_{bare}/Q \approx 1.2$, i.e. close to charm mass lies in the transient region $\implies$ may have enough time to diffuse but has to be evolved relativistically to capture the correct dynamics.

Momentum Broadening: How do we calculate it?

- The fermion field at a time t in terms of time-evolved creation and annihilation operators can be defined as,

$$\Psi(t,\mathbf{x}) = \frac{1}{\sqrt{N^3}} \sum_{\lambda,\mathbf{p}} \Big(u_\lambda(p)\ b_\lambda(t,p) e^{-ipx} + v_\lambda(p) d_\lambda^\dagger(t,p) e^{+ipx} \Big)$$

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- Inverting the above expression using the orthonormality of Dirac spinors, we get

$$\begin{aligned} b_{\lambda'}(t,q) &= \sum_{\mathbf{x}} u_{\lambda'}^\dagger(q) \Psi(t,\mathbf{x}) e^{+iqx} \\ &= u_{\lambda'}^\dagger(q) \tilde{\Psi}(t,\mathbf{q}) \end{aligned}$$

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- We start with a single quark in a fixed momentum (P) and spin polarization (s) mode and let it evolve in the background of gauge fields. The quark field after a time t' is

$$\Psi(t', \mathbf{x}) = \frac{1}{\sqrt{N^3}} \sum_{\lambda, \mathbf{p}} \left[\phi^{u}_{\lambda,p}(t', \mathbf{x}) b_\lambda(t' = 0, p) + \phi^{v}_{\lambda,p}(t', \mathbf{x}) d^\dagger_\lambda(t' = 0, p) \right]$$

with initial conditions

$$\langle b^\dagger_\lambda(t = 0, p) b_{\lambda'}(t = 0, p') \rangle = \delta_{\lambda\lambda'} \delta(p - p') \delta_{\lambda s} \delta(p - P)$$

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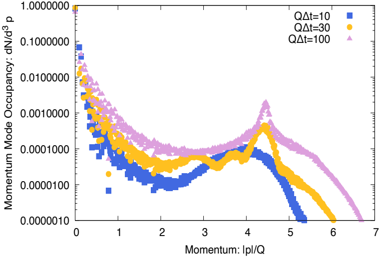
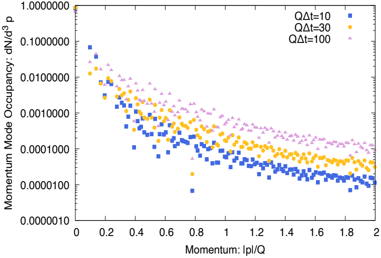
- Momentum mode occupancy is then calculated as,

$$\frac{dN}{d^3 q} = \sum_{\lambda'} \langle b^\dagger_{\lambda'}(t', \mathbf{q}) b_{\lambda'}(t', \mathbf{q}) \rangle = \sum_{\lambda'} |u^\dagger_{\lambda'}(q) \tilde{\phi}^u_s(t', P)|^2$$

Momentum Broadening: Lattice Results

- For quark mass $m/Q = 1.2$, momentum broadening profiles at different times come out to be





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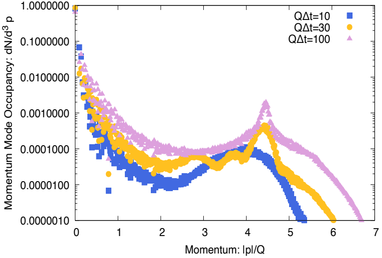

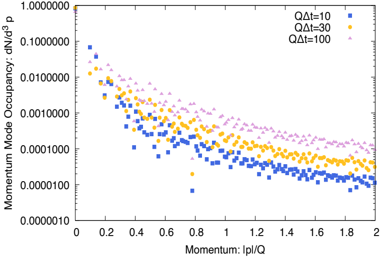

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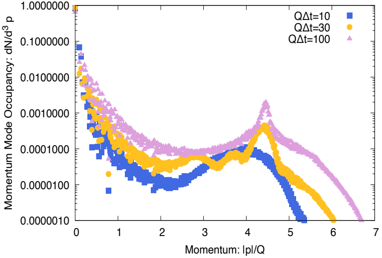

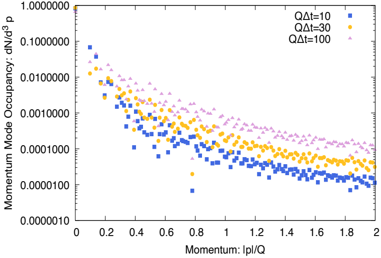

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- But more analysis is needed to get a better understanding and reliable estimates for the momentum diffusion coefficient (Work going on).

Summary and Outlook

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- We have also set up the formalism to study heavy quark momentum broadening and extraction of heavy quark momentum diffusion coefficient.
- The immediate goal is to provide reliable estimates of heavy quark momentum diffusion coefficient in the pre-equilibrium stage (especially charm, in the context of HICs) and possibly relate it to experimental observations of charm collectivity.

Thanks :)

Brief HTL calculation for heavy quarks with soft momenta

$$\rho_+^{HTL+\gamma}(\omega, p) = 2\pi\beta_+(\omega/p, p) + 2\Big[\frac{Z_+(p)\gamma_+(p)}{(\omega - \omega_+(p))^2 + \gamma_+^2(p)} + \frac{Z_-(p)\gamma_-(p)}{(\omega + \omega_-(p))^2 + \gamma_-^2(p)}\Big]$$

where

$$\beta_+(x, p) = \frac{m_f^2}{2p}(1-x)\theta(1-x^2)\Big[\Big(p(1-x) + \frac{m_f^2}{2p}[(1-x)ln\Big|\frac{x+1}{x-1}\Big| + 2]\Big)^2 + \frac{\pi^2 m_f^4}{4p^2}(1-x)^2\Big]^{-1} \text{with } x = \omega/p$$

Brief HTL calculation for heavy quarks with soft momenta

For the limit $m >> p \implies \omega >> p$,

$$\beta_+(x,p) \simeq \frac{p^2}{\pi^2 m_f^3} \to 0$$

$$Z_\pm(p) \simeq \frac{1}{2} \pm \frac{p}{3m_f} \to \frac{1}{2}$$

$$\omega_\pm \simeq m_f \pm \frac{p}{3} \to m_f$$

$$\rho_+^{HTL+\gamma}(\omega,p) = \frac{1}{2}\left[\frac{\gamma_+(0)}{(\omega - m_f)^2 + \gamma_+^2(0)} + \frac{\gamma_-(0)}{(\omega + m_f)^2 + \gamma_-^2(0)}\right]$$

Taking Fourier transform to go from frequency domain to real-time domain, we obtain

$$\rho_+^{HTL+\gamma}(t,p) = \int d\omega \rho_+^{HTL+\gamma}(\omega,p) \approx e^{-\gamma(0)t} cos(m_f t)$$

Spectral Function Plots Zoomed