Fermion spectral function in a highly occupied non-Abelian plasma

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Based on:

KB, Lappi, Mace, Schlichting,
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Motivation

- Strong color fields at early times in Heavy-Ion Collisions
- Understanding interactions with fermions important:
  - ⋆ electromagnetic observables
  - ⋆ jets (energy loss, jet quenching)

For microscopic description of observables and dynamics

Spectral function $\rho(\omega, p)$ of fermions encodes interactions

- Our approach: *far from equilibrium*
  - ⋆ Highly occupied gluon plasma ($A \sim 1/g$), weak coupling ($g^2 \ll 1$)
  - ⇒ Then nonperturbative and perturbative methods available!
- Classical-statistical (CS) simulations vs. Hard thermal loops (HTL)
- Here: we develop a method to extract $\rho(\omega, p)$ in CS simulations
  - ⇒ Application to classical self-similar gluonic attractor

Method & setup

- Classical Yang-Mills (with $U_j = \exp(ia_s g A_j)$) + Dirac equation (tree-level improved Wilson Dirac operator, mode exp. $\hat{\psi} \to \phi^{u/v}$)

  Aarts, Smit (1999); Kasper, Hebenstreit, Berges (2014); Mace, Mueller, Schlichting, Sharma (2016, 2017, 2020)

$$D_\mu F^{\mu\nu} = 0\,, \qquad \partial_{t'} \phi^{u/v}_{\lambda\vec{p}}(t', \vec{x}) = -2i\gamma^0 \left(-i \not{D}^s_W[U] + m\right) \phi^{u/v}_{\lambda\vec{p}}(t', \vec{x})$$

- Start from plane waves $\phi^{u/v}_{\lambda,\vec{p}}$ at $t' = t$ and evolve for $t' > t$ to compute fermion spectral function nonperturbatively as

$$\rho^{\alpha\beta}(x, y) = \left\langle\left\langle\left\{\hat{\psi}^\alpha(t', \vec{x}), \hat{\bar{\psi}}^\beta(t, \vec{y})\right\}\right\rangle\right\rangle_\psi$$

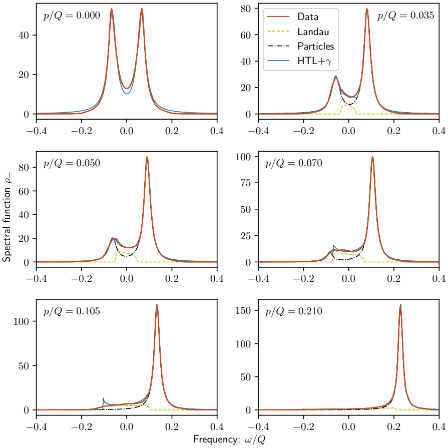
$$\rho(t', t, \vec{p}) = \frac{1}{V} \sum_{\lambda,\vec{q}} \left\langle \tilde{\phi}^u_{\lambda,\vec{q}}(t', \vec{p}) \left(\tilde{\phi}^u_{\lambda,\vec{q}}(t, \vec{p})\right)^* + \tilde{\phi}^v_{\lambda,\vec{q}}(t', \vec{p}) \left(\tilde{\phi}^v_{\lambda,\vec{q}}(t, \vec{p})\right)^* \right\rangle \gamma_0$$

  (fermion operators exp. val. $\langle . \rangle_\psi$, class. avg. over gluonic config. $\langle . \rangle$)

- Simplification due to plane wave initial cond. $\tilde{\phi}_{\lambda,\vec{q}}(t, \vec{p}) \propto \delta^{(3)}(\vec{p} - \vec{q})$

Fermion ρ in 3+1D: Comparison with HTL

$$\rho_+(t,\omega,p) \equiv \rho_V^0 + \rho_V$$



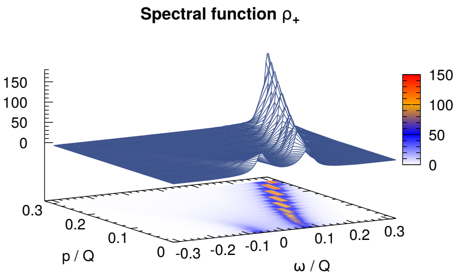
- ρ calculated at self-similar attractor $f_g(t,p) = t^\alpha f_s(t^\beta p)$
- HTL+γ: HTL Landau cut + Lorentzian quasiparticles

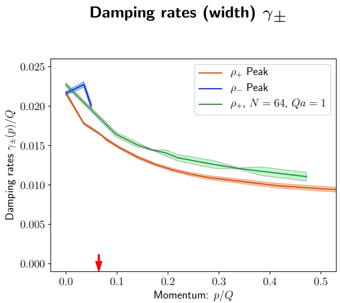
$$\rho_+^{\mathrm{HTL}}(\omega,p) = 2\pi\,\beta^{\mathrm{HTL}}(\omega,p) + \frac{2Z_+(p)\gamma_+(p)}{(\omega-\omega_+(p))^2+\gamma_+^2(p)} + \{`+` \to `-`\}$$

- Fits: $\omega_\pm(p)$, $Z_\pm(p)$, $\gamma_\pm(p)$
  - ⋆ HTL dispersions $\omega_\pm^{\mathrm{HTL}}(p)$ and residues $Z_\pm^{\mathrm{HTL}}(p)$ agree well
  - ⋆ First principles extraction of damping rates $\gamma_\pm(p)$

$\rho_V^0 = \frac{1}{4}\mathrm{Tr}(\rho\gamma^0)$, $\rho_V = -\frac{E_{\vec{p}}\,p^j}{4\,p^2}\mathrm{Tr}(\rho\gamma^j)$; 256^3 lattice, $Qa_s = 0.75$ spacing, $m = 0.003125\,Q \approx 0$

Fermion ρ in 3+1D: Main results





We find:

- Lorentzian quasiparticles + Landau cut ($\omega < p$)
- very good description by HTL+γ
- full p-dependence of $\gamma_+(t, p)$ (Arrow: mass $m_F = \left[C_F \int \frac{d^3p}{(2\pi)^3} \frac{g^2 f_g(p)}{p}\right]^{1/2}$)
- Backup: $\gamma_+(t, p{=}0) \sim m_F(t) \sim t^{-1/7}$ (vs. $\gamma_+^{\mathrm{HTL}}(t, p{=}0) \sim t^{-3/7}$)

Conclusion & Outlook

Conclusion

- We have developed a tool to extract the fermion spectral function in highly occupied plasmas nonperturbatively
- ρ (at classical attractor) well described by HTL (except for γ), first principles determination of damping rates
- Similarities to gluon spectral functions
  - ⋆ in 3+1D: consistent with HTL (KB, Kurkela, Lappi, Peuron [1804.01966])
  - ⋆ in 2+1D: $\gamma(t, p{=}0) \sim m_D(t)$ (KB, Kurkela, Lappi, Peuron [2101.02715])

Outlook: applications to heavy-ion collisions

- ρ in Bjorken expanding systems or of heavy-flavor quarks
- Effects on transport coefficients