LEADING ORDER PHOTON PRODUCTION IN NON-EQUILIBRIUM QGP

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1. INTRODUCTION

- Transport coefficients like shear and bulk viscosity are fundamental properties of thermal QCD.
- Photons could be an ideal probe to extract these viscosities from experimental results.
- Calculating viscous corrections boils down to using a general momentum distribution in propagators:

$$n_{B/F}(|p^0|) \to f_{g/q}(\mathbf{p})$$

E.g. n_B is the Bose-Einstein distribution.

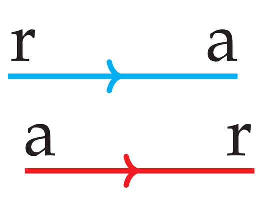
- Corrections have been calculated for two-to-two scattering diagrams [1], [2].
- We present a **first calculation of inelastic leading order channels out of thermal equilibrium.** They are just as important as two-to-two channels:
  - Off-shell pair annihilation
  - Quark bremsstrahlung
  - Coherence between different scattering sites (LPM effect)
- We focus on bulk viscous corrections where

$$f(\mathbf{p}) = f(p).$$

Our calculation applies to any isotropic momentum distribution.

2. FORMALISM

- In the real time formalism the number of degrees of freedom is doubled. Thus there are four propagators.
- In the r/a basis the bare propagators for quarks are



$$S^0_{ra} = S^0_{\rm ret} = \text{r} \rightarrow \text{a}$$
$$S^0_{ar} = S^0_{\rm adv} = \text{a} \rightarrow \text{r}$$
$$S^0_{rr} = \left(\frac{1}{2} - f_q(\mathbf{p})\right)\left[S^0_{\rm ret} - S^0_{\rm adv}\right]$$
$$S^0_{aa} = 0$$

- We need resummed propagators. In equilibrium one can use the KMS relation to get

$$S_{rr} = \left(\frac{1}{2} - n_F(p^0)\right)\left[S_{\rm ret} - S_{\rm adv}\right].$$

- Out of equilibrium we must go beyond the KMS condition and do explicit calculations.

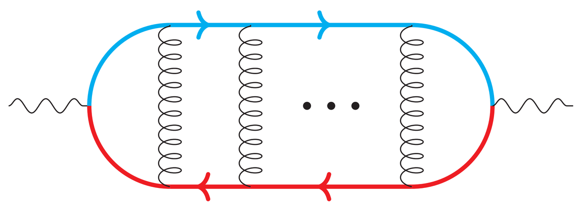
3. THE EQUILIBRIUM CASE

- Production rate of photons with momentum k is given by

$$k\frac{dR}{d^3k} \sim (i\Pi^{\gamma}_{12})^{\mu}_{\ \mu}$$

where Π^γ is the photon polarization tensor.

- The Feynman diagrams for Π^γ_{12} for the inelastic channels are

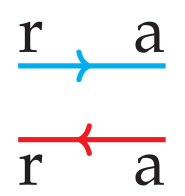


summed over all number of gluon rungs.

- Despite multiple vertices the diagrams contribute at leading order in g [3]:
  - $1/g$ enhancement for soft gluons, $P \sim gT$, in the rr propagator:

$$n_B(p^0) \sim \frac{T}{p^0} \sim \frac{1}{g}$$

  - Pinching poles from hard, on shell quarks:



$$\sim \mathcal{O}\left(\frac{1}{m^2_\infty}, \frac{1}{\Gamma}\right) \sim g^{-2}$$

m^2_∞ is the thermal mass and Γ the thermal decay width.

4. DENSITY OF SOFT GLUONS

- In a non-equilibrium medium there is also a $1/g$ enhancement from soft gluons:
- The resummed rr propagator is

$$G_{rr} = \left(\frac{1}{2} + \frac{\Pi_<}{\Pi_> - \Pi_<}\right)(G_{\rm ret} - G_{\rm adv})$$

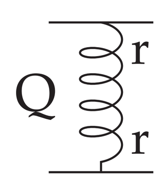
$\Pi_<$ and $\Pi_>$ are components of the gluon polarization tensor.

- Leading order diagrams give

$$\frac{\Pi_<}{\Pi_> - \Pi_<} = \boldsymbol{\Omega}\frac{T}{p^0} \sim \frac{\boldsymbol{\Omega}}{g}$$

$\boldsymbol{\Omega}[f]$ describes the resummed occupation number of soft gluons.

- Extending a sum rule from [4] we get



$$= \boldsymbol{\Omega}\, T\left[\frac{1}{\mathbf{q}^2_\perp} - \frac{1}{\mathbf{q}^2_\perp + \boldsymbol{m^2_D}}\right]$$

$\boldsymbol{m^2_D}[f]$ is the non-equilibrium Debye mass. It describes screening of chromoelecric fields.

5. DENSITY OF HARD QUARKS

- In a non-equilibrium medium we also get pinching poles.
- The resummed rr quark propagators is

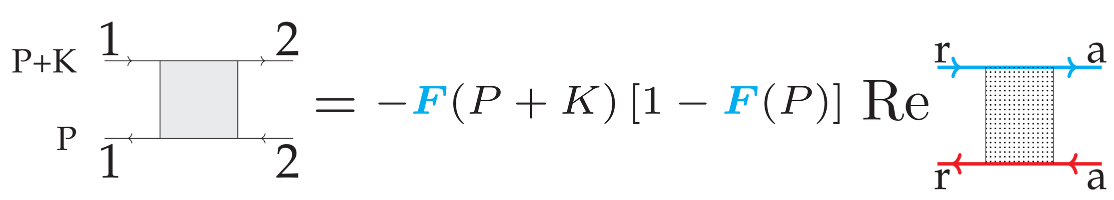
$$S_{rr} = \left(\frac{1}{2} + \frac{\Sigma_<}{\Sigma_> - \Sigma_<}\right)\left[S_{\rm ret} - S_{\rm adv}\right].$$

- For hard, on-shell quarks the resummed occupation number is

$$\boldsymbol{F} := -\frac{\Sigma_<}{\Sigma_> - \Sigma_<} = \begin{cases} f_q(p), & \text{if } p^0 > 0 \\ \underbrace{1 - f_q(p)}_{\text{Pauli blocking}}, & \text{if } p^0 < 0 \end{cases}$$

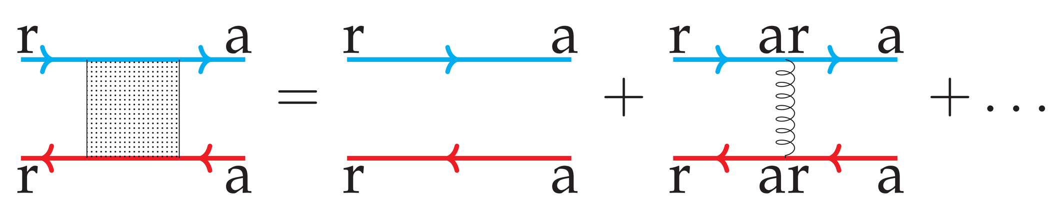
6. EVALUATING THE CHANNELS

- To get Π^γ_{12} we must sum sixteen quark four-point functions in the r/a basis.
- In equilibrium we can use the KMS condition to simplify the sum.
- Out of equilibrium our formula for S_{rr} makes the sum telescopic. Then



$$= -\boldsymbol{F}(P+K)\left[1 - \boldsymbol{F}(P)\right]\,\mathrm{Re}$$

where



- One gets a Boltzmann-like integral equation that must be solved numerically.

7. CONCLUSION

- Remarkably, the inelastic channels are fully characterized by $\boldsymbol{F}$ and three non-equilibrium constants:
  - $\boldsymbol{\Omega}$ Density of soft gluons
  - $\boldsymbol{m^2_D}$ Debye mass
  - $\boldsymbol{m^2_\infty}$ Thermal mass of quarks
- Next steps:
  - Solve the integral equation.
  - Extend to non-isotropic media (relevant for shear viscosity).
  - The tools developed can be used for non-equilibrium jet energy loss.

8. REFERENCES

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[4] P. Aurenche, F. Gelis, H. Zaraket, *JHEP*, vol. 05, p. 043, 2002 [hep-ph/0204146]