Finite lifetime effects on the photon production from a quark-gluon plasma

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Introduction and Motivation

Direct photons play an important role as electromagnetic probes from a quark-gluon plasma (QGP) created in heavy-ion collisions. It is of particular interest how non-equilibrium effects such as a finite lifetime affect the resulting photon spectra. One main result has been the occurrence of first order contributions that dominate over higher order equilibrium contributions for large photon momenta [1, 2].
Describing this phenomenon in the real time Keldysh formalism is mainly accompanied by two major problems, namely the divergent contribution from the vacuum polarization and the non-integrability of the remaining contributions in the ultraviolet domain [3, 4]. We provide an ansatz that eliminates the divergent contribution from the vacuum polarization and renders the remaining contributions UV-finite if the time evolution of the QGP is modeled in a suitable manner.

Time dependent occupation numbers

The photon production rate from a homogeneous but non-stationary emitting system reads [5, 6]:

$$k\frac{d^7n(t)}{d^4xd^3k} = \frac{1}{(2\pi)^3}\mathrm{Re}\left\{\int_{-\infty}^{t} du\; i\Pi_T^{<}(\vec{k},t,u)e^{ik(t-u)}\right\} \quad (1)$$

As in [3], we use the one-loop approximation for the photon self energy $i\Pi_T^{<}(\vec{k},t,u)$ including the processes of first order in α_e. We model the finite lifetime of the QGP via time dependent occupation numbers of the quarks

$$n_F(E) \to n_F(E,t) = f(t)n_F(E)\ , \quad (2)$$

and couple the time evolution to the interaction vertices by replacing the occupation numbers and the number of holes in $i\Pi_T^{<}(\vec{k},t,u)$ by their geometric mean from the two times t and u. If we now decompose $i\Pi_T^{<}(\vec{k},t,u)$ into the vacuum polarization and the medium contribution

$$i\Pi_T^{<}(\vec{k},t,u) = i\Pi_{T,0}^{<}(\vec{k},t-u) + i\Pi_{T,M}^{<}(\vec{k},t,u)\ , \quad (3)$$

and insert (3) into (1), we see that the vacuum polarization is evaluated on-shell and thus does not show up in the photon yield. As the occupation numbers are time dependent, the medium part of (3) is evaluated off-shell which makes the contribution of first order processes possible.

Numerical Investigations and Results

For our numerical investigations, we consider a QGP with a temperature of $T = 0.3$ GeV and model its creation by different kinds of switching functions depicted in figure 1.

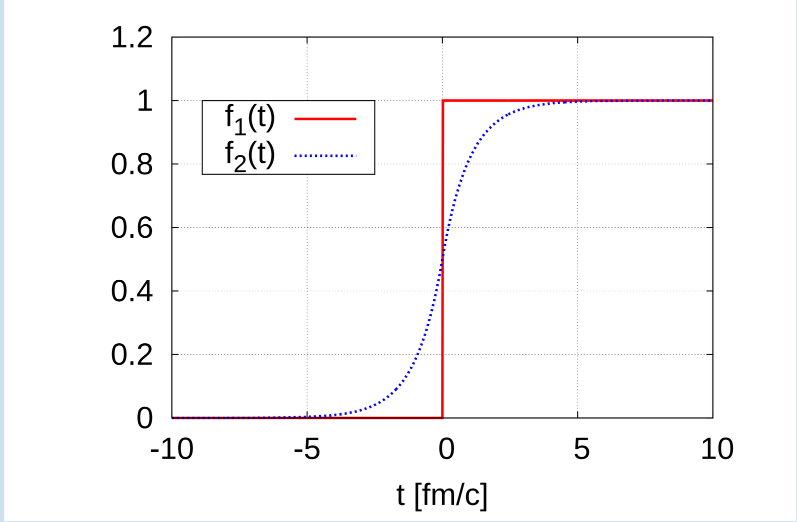

Figure 1: The QGP is switched on and maintained.

Figure 2 shows that photon spectrum decays as $\sim 1/k^3$ for an instantaneous switching and exhibits a slightly steeper decay for a finite creation time of $\tau = 1$ fm/c. The dominant contributions to the photon yield are Bremsstrahlung and a negative contribution from Pauli Blocking of the pair creation process. Both of them behave as $\sim 1/k^3$ for large k independently of $f(t)$ [7]. If we turn from an instantaneous switching to a switching over a finite time interval τ, the Bremsstrahlung contribution halves in value whereas the Pauli Blocking contribution is left unchanged [7]. This accounts for the slightly steeper decay then.

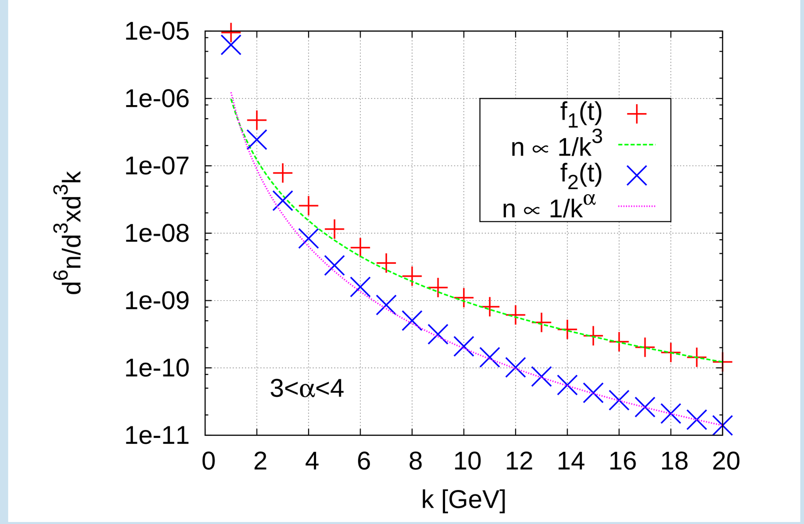

Figure 2: The photon spectrum decays as $\sim 1/k^3$ independently from $f(t)$.

However, the photon spectrum does not decay fast enough to be UV-finite. This problem can be circumvented if the QGP is also switched off again as to mimic a heavy-ion collision. The photon yield is assumed to be observed at $t \to \infty$. We adopt a creation and hadronization time of $\tau_F = \tau_H = 1$ fm/c and a lifetime of $\tau_L = 4$ fm/c. Again different switching functions $g(t)$ are compared.

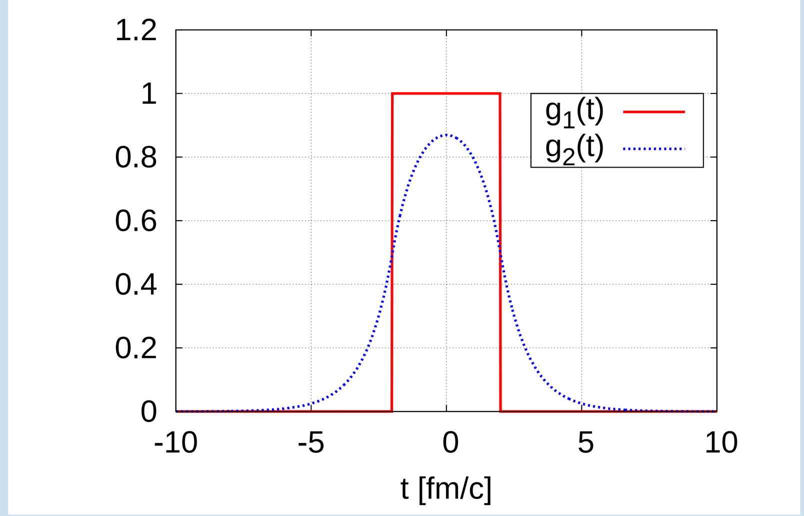

Figure 3: The QGP is switched on and off again.

Figure 4 shows that the resulting photon spectrum now is highly sensitive to the switching function $g(t)$ and becomes UV-finite if the QGP is switched on and off again over a finite time interval τ.

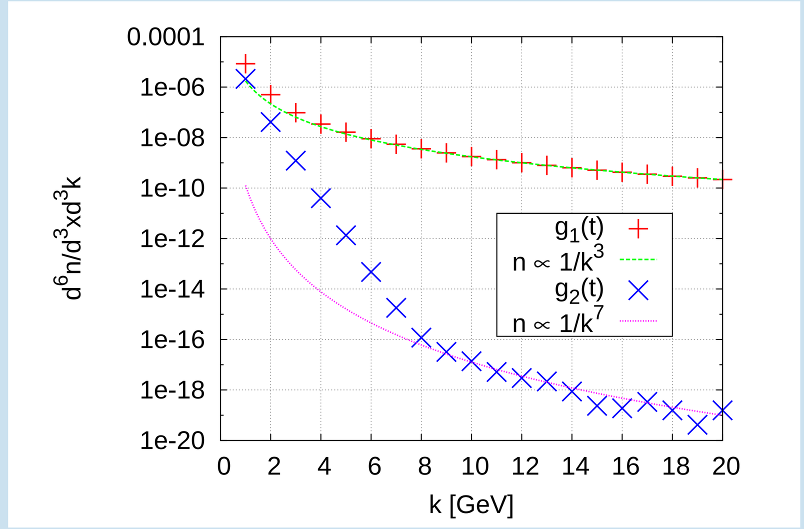

Figure 4: The decay of the photon spectrum is highly sensitive to $g(t)$.

Nevertheless, one has to keep in mind that the scenario of switching a plasma on and and off again and taking the photon yield for $t \to \infty$ is not always reasonable. If one considers photon emission from an electromagnetic plasma, for example, the photon yield can also be measured at times where the plasma is still heated up.

Yukawa-like source term

We revisit our hitherto approach by considering the Ward-Takahashi identities for photon self energy $i\Pi_{\mu\nu}^{<}(x,y)$ which result from the $U(1)$-invariance of QED:

$$\partial_x^{\mu} i\Pi_{\mu\nu}^{<}(x,y) = 0 \quad (4)$$

It can be shown that these identities are not fulfilled by our hitherto ansatz and not by [1, 2, 3] either. Therefore, we now do a first principle calculation by introducing a Yukawa-like source term in the Lagrangian of our system:

$$\mathcal{L}(x) = \mathcal{L}_{QED}(x) - g\phi(t)\hat{\bar{\psi}}(x)\hat{\psi}(x) \quad (5)$$

The source field is assumed to be classical and time dependent only. So the fermions effectively get a time dependent mass which fulfills the Ward-Takahashi identities (4).

The change of the quark mass from its constituent value m_c to its bare value m_b during the chiral phase transition in the early stage of a heavy-ion collision leads to spontaneous pair creation of quarks and antiquarks [8, 9]. We now investigate the photon emission arising from this creation process. As the electromagnetic coupling is small, we do a calculation of first oder in α_e but keep all orders in α_g.
For the case of an instant mass shift from m_c to m_b at $t = 0$, the contributions to the photon yield can be associated with first order QED-processes as well as with their interference among each other. The loop integral features a linear divergence resulting from the quark/antiquark occupation numbers decaying as $\sim 1/p^2$ for large p. As this decay behavior is an artifact from the instant mass shift [8, 9], we regulate the divergence by cutting the loop integral at $p = \Lambda_C$ in the first place. Figure 5 shows the resulting photon spectra for different values of Λ_C. As in [8, 9], we choose $m_c = 0.35$ GeV and $m_b = 0.01$ GeV.

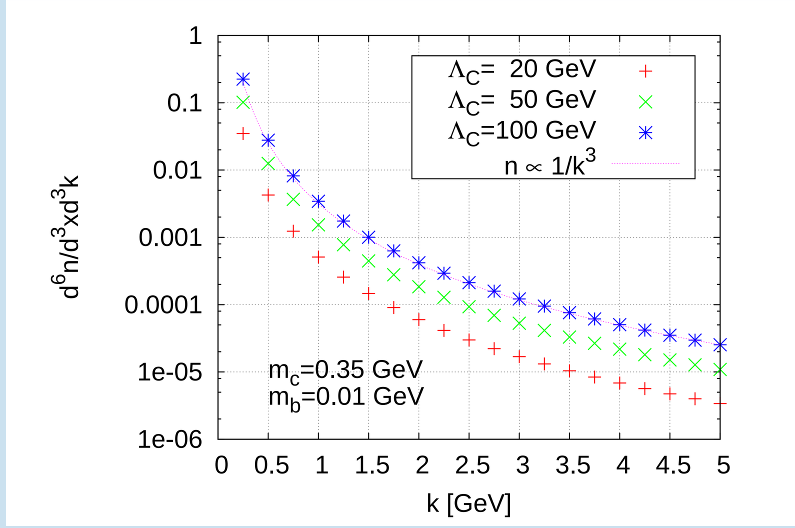

Figure 5: The photon spectrum decay as $\sim 1/k^3$ for an instant mass shift.

The photon spectra decay as $\sim 1/k^3$ for all values of Λ_C. As next step, we have to investigate if the loop integral is regulated if the mass shift takes place over a finite time interval τ and if we obtain UV-finite photon spectra then. If the latter is the case, we also have to clarify whether the problem with the UV-finiteness within the old ansatz does indeed results from a violation of the Ward-Takahashi identities (4).

Summary and Outlook

Our first ansatz of modeling the finite lifetime of the quark-gluon plasma (QGP) by time dependent occupation numbers eliminates the divergent contribution from the vacuum polarization but does not get the problem with UV-finiteness fully under control. Therefore, we work on a new ansatz where the onset of a time dependent QGP is effectively created by a change in the fermion mass. We have to investigate if we obtain UV-finite photon spectra if this change is modeled in a suitable manner. In this context, the role of the Ward-Takahashi identities also needs to be clarified.

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