Non-equilibrium Photon production in an external Yukawa field

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Electromagnetic probes, i.e., direct photons and dileptons provide an interesting probe for the strongly interacting, hot and dense matter, created in high-energy heavy-ion collisions. Due to their penetrating nature the transverse-momentum spectra of photons and dileptons as well as the invariant-mass spectra of dileptons provide information from the entire fireball evolution and the hot central regions of the matter. This is of particular interest in the connection with the study of the QCD phase diagram and chiral-symmetry restoration.

On the other hand, in the past there have been claims that the photon emission caused by non-equilibrium processes in the very early pre-equilibrium phase of the fireball evolution outshine the yield of the photons emitted from the equilibrated thermal sources, where medium properties are well defined in terms of an equilibrium phase diagram [1, 2, 3]. On the other hand, these studies have been challenged due to problems concerning the proper renormalization procedure used in the non-equilibrium quantum-field-theory framework [4].

In our study we use a toy model to investigate the in detail the subtleties of non-equilibrium photon production within the Schwinger-Keldysh real-time formalism, coupling quark-Dirac fields to an external homogeneous time dependent scalar field. This allows us to mimic the expected chiral-symmetry restoration by switching the effective quark mass from its constituent value of around $350\ \mathrm{MeV}$ to its current-mass value of a few MeV within a hot QGP [5]. In this framework, the problem of the quark fields coupled to this external scalar field can be solved semi-analytically.

Here, the first fundamental problem arises in how to define quark and antiquark occupation numbers. It turns out that a consistently defined particle number observable is only available in the form of counting occupation numbers for asymptotically free Fock states. Using the vacuum as the initial state in the remote past ($t \to -\infty$) we have calculated the $q\bar{q}$-pair yield in the remote future ($t \to +\infty$), by determining the corresponding Bogolyubov transformation semi-analytically.

To evaluate the photon-production yield we employed the perturbative expansion with respect to α_e and calculated the photon self-energy. In contrast to the equivalent case in thermal equilibrium where the leading $\mathcal{O}(\alpha_e)$ one-loop polarization tensor of the photon vanishes on-shell due to the time-dependence of the non-equilibrium situation, leading-order processes like the production of a photon together with a $q\bar{q}$ pair as well as bremsstrahlung and pair-annihilation processes become available.

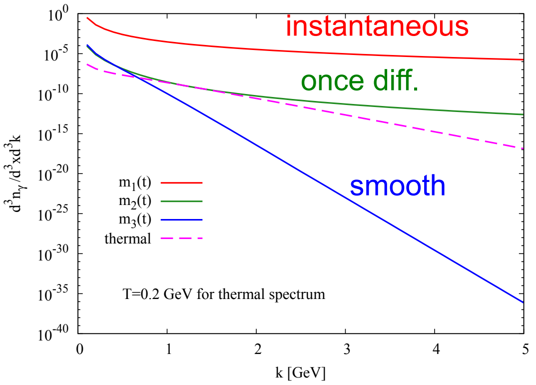

Figure 1: Photon production in a time-dependent scalar field coupled to a $q\bar{q}$ Dirac fermions. As the photon-spectral density for instantaneous mass switching is UV divergent, it has been regularized by a momentum cutoff of $\Lambda = 100\ \mathrm{GeV}$. The photon spectrum (red) is $\propto 1/k^3$ for large k. Thus the total photon number and energy density are both divergent. For a once-differentiable function the photon-spectral density is UV convergent. The results have been extrapolated to $\Lambda \to \infty$. The spectrum (green) behaves like $1/k^6$ for large momenta. So both the number and energy density are convergent. For a smooth switching function the spectrum (blue) falls off exponentially for large k and is subdominant compared to a typical thermal radiation spectrum from an equilibrated QGP (magenta).

The asymptotic photon-momentum spectra are sensitive to the choice of the mass switching function. While for instantaneous switching of the masses the photon-spectral density, $\mathrm{d}n_\gamma/\mathrm{d}^3\vec{x}\mathrm{d}^3\vec{k}$, is UV divergent, for an at least once differentiable switching function it is UV finite, and the vacuum contributions vanish when the correct Gell-Mann-Low adiabatic switching of the electromagnetic interaction is applied (for details, see Fig. 1).

References

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