Finite lifetime effects on the photon emission from a quark gluon plasma

Frank Michler, Björn Schenke, Carsten Greiner, Hendrik van Hees and Stefan Leupold

Workshop on Solving the Two-time Kadanoff-Baym Equations. Status and Open Problems

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Outline of the talk

• Introduction and Motivation
  ► direct photons as electromagnetic probes
  ► finite lifetime effects

• Previous approaches
  ► divergent contribution from vacuum polarization
  ► remaining contributions not integrable in UV-domain

• Hitherto approach / model description
  ► time dependent occupation numbers
  ► achievements / aspects not yet under control


• New approach / first principle calculation
  ► Yukawa-like source term
  ► role of Ward Takahashi identities

• Summary and Outlook
Introduction and Motivation

- **direct access to QGP not possible**
  - experimental signatures needed
  - direct photons as electromagnetic probes
  - they leave the medium **undisturbed**
  - provide **direct insight** into the early stage of the collision

- **plasma created over finite timescale**
  - can be modeled by “switching on” of occupation numbers
  - **non equilibrium situation** occurs during creation period

- **question of interest**
  - How does the **finite lifetime itself** affect the resulting photon spectra?
Previous Approaches

  ▶ contribution of first order processes
  ▶ flattening of photon spectrum into an algebraic decay for $k > 1.5$ GeV

▶ dominance over higher order equilibrium contributions

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Previous Approaches

  - contribution from vacuum polarization **divergent**
  - attempts to “renormalize” it
  - other contributions behave as \( \sim 1/k^3 \) for large \( k \!
  - total photon number and totally emitted energy **divergent**!

  - vacuum contribution claimed to be **unphysical**
  - renormalization techniques claimed to be **ad hoc**

- **actual motivation for present investigations**
  - find an ansatz to handle mentioned problems
Hitherto approach

- photon production rate in non-equilibrium
  \[ k \frac{d^7 n}{d^4xd^3k} = \frac{1}{(2\pi)^3} \text{Re} \left\{ \int_{-\infty}^{t} du \ i\Pi_\leq_T(\vec{k}, t, u)e^{ik(t-u)} \right\} \]

- one loop ansatz for photon self energy
  \[ i\Pi_{\mu\nu}(\vec{k}, t, u) = 3 \cdot \sum_{q=u,d} e_q^2 \int \frac{d^3p}{(2\pi)^3} \text{Tr} \left\{ \gamma_\mu S_F^\leq(\vec{p} + \vec{k}, t, u)\gamma_\nu S_F^> (\vec{p}, u, t) \right\} \]

- chose model description of medium evolution
  - vacuum always persistent / medium only occurs temporarily
  - introduce time dependent occupation numbers
    \[ n_F(\omega_{\vec{p}}, t) = f(t)n_F(\omega_{\vec{p}}) \]
    \[ n_F(\omega_{\vec{p}}) \rightarrow \sqrt{n_F(\omega_{\vec{p}}, t)n_F(\omega_{\vec{p}}, u)} \]
    \[ 1 - n_F(\omega_{\vec{p}}) \rightarrow \sqrt{(1 - n_F(\omega_{\vec{p}}, t))(1 - n_F(\omega_{\vec{p}}, u))} \]
  - couple time dependence to vertices
  - keep yield an absolute square
Hitherto approach

- achievements of this ansatz
  - dynamic change from vacuum polarization to full one loop polarization
    \[
    i\Pi_T^\leq(\vec{k}, t, u) = \begin{cases} 
    i\Pi_{T,0}^\leq(\vec{k}, t - u) & \text{for } f(t), f(u) \to 0 \quad \text{vacuum} \\
    i\Pi_{T,M}^\leq(\vec{k}, t - u) & \text{for } f(t), f(u) \to 1 \quad \text{medium}
    \end{cases}
    \]
  
  - decomposition into vacuum part and medium part
    \[
    i\Pi_T^\leq(\vec{k}, t, u) = i\Pi_{T,0}^\leq(\vec{k}, t - u) + i\Pi_T^\leq(\vec{k}, t, u) - i\Pi_{T,0}^\leq(\vec{k}, t - u)
    \equiv i\Pi_{T,0}^\leq(\vec{k}, t - u) + i\Pi_{T,M}^\leq(\vec{k}, t, u)
    \]
  
  - resulting photon production rate
    \[
    k \frac{d^7 n}{d^4 x d^3 k} = \frac{1}{(2\pi)^3} \text{Re} \left\{ \int_{-\infty}^{t} du \ i\Pi_{T,0}^\leq(\vec{k}, t - u) e^{ik(t-u)} \right\} + \frac{1}{(2\pi)^3} \text{Re} \left\{ \int_{-\infty}^{t} du \ i\Pi_{T,M}^\leq(\vec{k}, t, u) e^{ik(t-u)} \right\}
    \]

- vacuum polarization evaluated onshell / no contribution
- medium contribution evaluated offshell
- contribution of 1st order processes possible
Hitherto approach

- photon rate given by convolution integrals

\[ k \frac{d^6n}{d^4xd^3k} \sim \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} i\Pi_{T,M}^{<}(\vec{k},\omega) M_R(\vec{k},\omega,t) \]

- photon self energy convoluted with weighting factor \( M_R \)

\[ M_R(k - \omega, t) \simeq f(t) \text{Re} \left\{ \int_{-\infty}^{t} du \ f(u) e^{i(k-\omega)(t-u)} \right\} \]

- \( M_R \) determines contribution from each offshell mode at time \( t \)
- time evolution entirely incorporated in \( M_R(k-\omega,t) \)

- resulting accumulated photon yield

\[ k \frac{d^6n}{d^3xd^3k} \sim \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} i\Pi_{T,M}^{<}(\vec{k},\omega) M_Y(\vec{k},\omega,t) \]

\[ M_Y(k - \omega, t) = \int_{-\infty}^{t} du \ M_R(k - \omega, u) \]
Numerical Investigations

- **properties of quark gluon plasma**
  - temperature \( T = 0.3 \text{ GeV} \)
  - formation time \( \tau_F = 1 \text{ fm/c} \)

- medium switched on and maintained

- medium switched on and off again
  - scenario for heavy ion collision
  - consider yield for \( t \to +\infty \) as observable quantity
  - assume lifetime of \( \tau = 4 \text{ fm/c} \)

- consider different switching functions
  - dependence of photon spectra on “smoothness” of switching function
Numerical Investigations
Medium switched on and maintained

• Bremsstrahlung
  ► yield grows logarithmically in time for soft photon modes
  ► yield saturates in time for hard photon modes
  ► photon spectrum behaves as as $\sim 1/k^3$ for large $k$
  ► essentially independent from $f(t)$
Numerical Investigations
Medium switched on and maintained

• Pair Annihilation
  ▶ all photon modes growing logarithmically in time
  ▶ photon spectrum thermally suppressed for large k at given time t
  ▶ properties of self energy / thermally suppressed by itself

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Numerical Investigations
Medium switched on and maintained

- Pair creation / leading order in $n_F$
  - saturation in time for all photon modes / self energy
  - negative yield / Pauli Blocking
  - entirely independent from $f(t)$
  - behaves as $\sim 1/k^3$ in UV-domain
  - same range of magnitude as contribution from Bremsstrahlung
Numerical Investigations
Medium switched on and maintained

• Pair creation / next to leading order in $n_F$
  ► again saturation in time for all photon modes
  ► behaves as $\sim 1/k^3$ in UV-domain
  ► again essentially independent from $f(t)$
  ► 2 orders of magnitude smaller than Bremsstrahlung contribution
Numerical Investigations
Medium switched on and maintained

- time dependence of total photon yield
  - remains positive at sufficiently large $t$

- photon spectrum in UV-domain
  - behaves as $\sim 1/k^3$ for $f_1(t)$
  - slightly steeper decay for $f_2(t)$
  - problem with UV-finiteness not under control
Numerical Investigations
Medium switched on and off again

- **scenario of heavy ion collision**
  - consider yield for \( t \to +\infty \) / observable quantity
  - negative contribution from pair creation vanishes
  - remaining contributions **saturate**

- **photon spectrum in UV domain**
  - highly sensitive to choice of \( g(t) \)
  - behaves as \( \sim 1/k^3 \) for instantaneous switching
  - behaves as \( \sim 1/k^7 \) for **smooth** switching

- **problems not solved but circumvented**
  - switching on and off **questionable** for photon emission from electromagnetic plasma
  - yield can also be measured at times where plasma is heated up

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New approach

• consider Ward Takahashi identity / U(1)-invariance of QED

\[ \partial_x \mu \Pi_{\mu \nu}^< (x, y) = 0 \Rightarrow \partial_t i \Pi_{0j}^< (\vec{k}, t, u) - i k^i \Pi_{ij}^< (\vec{k}, t, u) = 0 \]

▶ not fulfilled by hitherto ansatz (and not by Boyanovsky et al. either)
▶ conjectured reason for non UV-finite photon spectra

• simulate creation of QGP by Yukawa-like (mass-like) source term

\[ \mathcal{L}(x) = \mathcal{L}_{QED}(x) - g \phi(t) \hat{\psi}(x) \hat{\psi}(x) \]

▶ source field \( \phi(t) \) classical / only time-dependent
▶ time dependent mass / compatible with Ward Takahashi identities

• effective “switching on” of medium

▶ time dependent mass leads to spontaneous particle creation
▶ creation process can be controlled by varying \( \phi(t) \)
New approach

- **first principle description of photon production**
  - leading order in $\alpha_e$ / all orders in $\alpha_g$

- **photon production rate again given by**

$$k \frac{d^7 n}{d^4 x d^3 k} = \frac{1}{(2\pi)^3} \text{Re} \left\{ \int_{-\infty}^{t} du \ i\Pi_F^{\leq}(\vec{k}, t, u) e^{ik(t-u)} \right\}$$

- **photon self energy has one loop form**

$$i\Pi_{\mu\nu}^{\leq}(\vec{k}, t, u) = \int \frac{d^3 p}{(2\pi)^3} \text{Tr} \left\{ \gamma_{\mu} S_F^{\leq}(\vec{p} + \vec{k}, t, u) \gamma_{\nu} S_F^{>}(\vec{p}, u, t) \right\}$$

- Propagators obey the following equations of motion

$$\left( i\gamma^0 \partial_t + \gamma^i p_i - m - g\phi(t) \right) S_F^{>}(\vec{p}, t, u) = 0$$

$$\left( i\gamma^0 \partial_u - \gamma^i p_i + m + g\phi(u) \right) S_F^{<}(\vec{p}, t, u) = 0$$

- Kadanoff Baym equations Hatree-Fock term only
New approach
Pair production

• consider pair production during chiral phase transition
  ► model change from constituent mass $m_c$ to bare mass $m_b$

$$m(t) = \begin{cases} 
  m_c & \text{for } t \to -\infty \\
  m_b & \text{for } t \to +\infty
\end{cases}$$

► solve equation of motion for $S^<$ with time dependent mass
► project out particle number for $t \to \infty$

• consider different parameterizations of $m(t)$

• choice of parameters
  ► constituent mass $m_c = 0.35$ GeV
  ► bare mass $m_b \approx 0$ GeV
  ► change duration $\tau = 1$ fm/c
New approach
Pair production

- resulting particle spectrum
  - decay behavior highly sensitive to choice of $m(t)$
  - behaves as $\sim 1/p^2$ for $m_1(t)$
  - particle number linearly divergent
  - suppressed to $\sim 1/p^6$ for $m_2(t)$
  - particle number finite

- essentially finger exercise

- currently under investigation / next step
  - Do we get the same results for photon emission?
  - role of Ward Takahashi identities
Summary and Outlook

• photon emission from quark gluon plasma
  ▶ role of finite lifetime effects

• hitherto ansatz / model description
  ▶ model time evolution of QGP via time dependent occupation numbers
  ▶ self energy evaluated offshell / first order contributions
  ▶ achievements / problems not yet under control

• new ansatz / first principle calculation
  ▶ describe time evolution by Yukawa-like source term
  ▶ adequate to describe pair creation
  ▶ also adequate to describe photon production ?
  ▶ consider role of Ward Takahashi identities

• treatment of possible infrared singularities

• non-equilibrium quantum field theory remains challenging