Photon production by a quark-gluon plasma

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References:

Model:

- $T \gg$ masses
- $g \ll 1$
- equilibrium

Tool: Thermal Field Theory

$$\frac{dN^r}{dtdV d^3q^2 dv} \propto \text{Im } \Pi_{\text{Ret}}^{-\mu} (w, q)$$

- photon pol.
- tensor calculated in the thermal bath.

ex:

\[ \text{Diagram} \rightarrow \left| \begin{array}{c} \text{Diagram} \\ \rightarrow \end{array} \right| \]
Lowest order:

\[ \text{Im} \Pi_{\text{Ret}}^{\mu} (\omega, \vec{q}) \sim e^2 g^2 T e^{-\frac{\omega}{\eta T}} \]

with \( m_{\text{th}} \sim \text{thermal mass} \sim g T \)

Note: for soft photons:

\[ \text{Im} \Pi_{\text{Ret}}^{\mu} (\omega, \vec{q}) \sim e^2 g^2 \frac{m_{\text{th}}^2 T}{3} \]

phase-space suppression
Bremsstrahlung ... 

\[ \text{Im } \Pi_{\text{Ret}}^\mu \sim e^2 g^4 \frac{T^2}{m_t^2} \left[ \frac{T^3}{\omega} \Theta T \omega \right] \]

vertices \quad \uparrow 

enhancement \sim \frac{1}{g^2}

due to collinear singularities

Problem: what happens in higher orders?
Photon formation time

- Collinear singularities are controlled by the virtuality of the quarks:

\[ R = P + Q \]

\[ R^2 - M^2 \approx \frac{\omega}{P} \left[ P_1^2 + M_{\text{eff}}^2 \right] \]

with \( M_{\text{eff}} = M + \frac{Q^2}{\omega^2 P \gamma_0} \)

- Uncertainty principle:

\[ \frac{\hbar}{P} \sim 4E \sim \frac{R^2 - M^2}{2c} \sim \frac{\omega}{P \gamma_0} \left[ P_1^2 + M_{\text{eff}}^2 \right] \]
Collinear enhancement

\[ \iff \text{Small virtualities} \]

\[ \iff \text{Large formation time} \]

\[ \omega \]

\[ t_F \text{ increases} \]

\[ t_F = \text{const.} \]

\[ t_F = \infty \]

Question:

\[ t_F \text{ larger than what?} \]
Other scales of the problem

- **mean free path** of the quarks

\[ \ell_{\text{mfp}} \sim \frac{1}{g^2 T \ln \frac{1}{g}} \]

- **Range of the interactions in the medium**:

\[ \ell_{\text{elec}} \sim \frac{1}{g T} \quad \text{(Debye screening)} \]

\[ \ell_{\text{mag}} \sim \frac{1}{g^2 T} \]

\[ \ell_{\text{elec}} \sim \ell_{\text{mfp}} \sim \ell_{\text{mag}} \sim \frac{1}{(g T)^{-1}} \quad \frac{1}{(g^2 T \ln \frac{1}{g})^{-1}} \quad \frac{1}{(g^2 T)^{-1}} \]
Multiple scatterings are important if:

\[ t_F \geq 1/m_{\text{f.p.}} \]

If this condition is satisfied, higher order diagrams are important.

Question: How complicated are the topologies we must consider?
Answer: It depends on the range of the interactions.

Short-ranged interactions:

$\lambda_{\text{elec}} \ll \lambda_{\text{mfp}}$

Since $\lambda_{\text{elec}}$ is small:

is suppressed

$\Rightarrow$ only "ladder" topologies
Long-ranged interactions:

\[ d_{\text{mag}} \Rightarrow d_{\text{mfp}} \]

\[ t_F \]

\[ \Rightarrow \text{successive collisions are not independent; all topologies can contribute.} \]
\[
\begin{align*}
\text{dominate only if } t_F \text{ is very small} \\
\lambda_{\text{mag}} &> \lambda_{\text{mp}} \\
\left(\frac{g^2 T \ln \frac{1}{g}}{\beta}\right)^{-1} &> \left(\frac{g^2 T}{\beta}\right)^{-1} \\
\text{sensitivity to the mean free path} &< \text{sensitivity to the magnetic mass.}
\end{align*}
\]
How do multiple scatterings change the photon rate? (qualitative)

\[ \log(\text{Im} \Pi^\mu_\mu) \]

- Single scattering
- With multiple scatterings.
What can we calculate analytically?

- Dileptons:
  (i.e. virtual photons for which $E_p \ll m_p$).

- Photons at leading log:
  (the sensitivity to the magnetic scale seems to enter only in the subleading logs.)

- Anything beyond that is non-perturbative...