Photon emission from strongly magnetized QCD plasma

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[X. Wang, I. Shovkovy, L. Yu, M. Huang, Phys. Rev. D 102, 076010 (2020)]

Magnetic field in HICs

- QGP produced at RHIC/LHC is magnetized
  - \(10^{18} \text{ to } 10^{19} \text{ G } \sim m_{\pi}^2 \sim (100 \text{ MeV})^2\)

Main idea

- Photon emission is not only a thermometer but also magnetometer of QGP
Thermal photons \((B = 0)\)

- The rate of the thermal emission of photons (more precisely, the energy loss rate) is

\[
k^0 \frac{d^3 R}{dk_x dk_y dk_z} = - \frac{1}{(2\pi)^3} \frac{\text{Im} \left[ \Pi^\mu_\mu(k) \right]}{\exp \left( \frac{k_0}{T} \right) - 1}
\]


- In the case of hot QCD plasma,

- Processes:
Thermal photons ($B = 0$)

- The approximate result is given by

$$\mathcal{R}_{2\rightarrow 2}: \quad E \frac{dR}{d^3p} = \frac{5}{9} \frac{\alpha \alpha_s}{2\pi^2} T^2 e^{-E/T} \ln \left( \frac{2.912 E}{g^2 T} \right)$$


- There are important corrections from bremsstrahlung and inelastic pair annihilation

- Next to leading order corrections are $\sim 100\%$

[Ghiglieri et al., JHEP 05 (2013) 010; arXiv:1302.5970]
Photon emission rate

• The expression for the rate is

\[
k^0 \frac{d^3 R}{dk_x dk_y dk_z} = - \frac{1}{(2\pi)^3} \frac{\text{Im} \left[ \Pi_{\mu}^{\nu}(k^0) \right]}{\exp \left( \frac{k^0}{T} \right) - 1}
\]

• At \( \vec{B} \neq 0 \), the imaginary part of the polarization tensor is nonzero at leading order in \( \alpha_s \)!

Physics processes

- Relevant physics processes (0\textsuperscript{th} order in $\alpha_s$):

The energy momentum conservation

\[ E_{n, p_z, f} - \lambda E_{n', p_z - k_z, f} + \eta \Omega = 0 \]

is satisfied for these $1 \rightarrow 2$ and $2 \rightarrow 1$ processes

The explicit expression for $\text{Im} \left[ \Pi_{R, \mu}^\mu (\Omega, \mathbf{k}) \right]$ is

$$
\text{Im} \left[ \Pi_{R, \mu}^\mu \right] = \sum_{f=u,d} \frac{N_c \alpha_f}{2 \pi l_f^4} \sum_{n>n'} \frac{g(n, n') \left[ \theta \left( k_-^f - |k_y| \right) - \theta \left( |k_y| - k_+^f \right) \right]}{\sqrt{[(k_-^f)^2 - k_y^2][(k_+^f)^2 - k_y^2]}} \left( F_1^f + F_4^f \right)
$$

$$
- \sum_{f=u,d} \frac{N_c \alpha_f}{4 \pi l_f^4} \sum_{n=0}^{\infty} \frac{g_0(n) \theta \left( |k_y| - k_+^f \right)}{\sqrt{k_y^2[k_y^2 - (k_+^f)^2]}} \left( F_1^f + F_4^f \right),
$$

where $g(n, n')$ and $g_0(n)$ are combinations of the Fermi-Dirac distribution functions.

The momentum thresholds are determined by

$$
k_\pm^f = \left| \sqrt{m^2 + 2n |e_f B|} \pm \sqrt{m^2 + 2n' |e_f B|} \right|
$$

Angular dependence (1)

- At small $k_T$, the emission rate is maximal at $\phi = \frac{\pi}{2}$ (i.e., perpendicular to the reaction plane)
- Effectively, this gives photon “flow” with $\nu_2 < 0$
- Note: $k_x = 0$, $k_y = k_T \cos \phi$ and $k_z = k_T \sin \phi$
Angular dependence (2)

- At large $k_T$, the emission rate is maximal at $\phi = 0$ (i.e., parallel to the reaction plane)
- Effectively, this gives photon “flow” with $\nu_2 > 0$

\[ |eB| = m_{\pi^0}^2 T = 0.2 \text{ GeV} \]

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\[ k_T = 0.2 \text{ GeV} \]
\[ k_T = 0.5 \text{ GeV} \]
\[ k_T = 0.8 \text{ GeV} \]

\[ d^2 R/(dE d\cos\theta) \]

\[ B \]

\[ \nu_2 > 0 \]

Thermal rate at $\vec{B} \neq 0$

- The photon production rate
  - decreases with energy ($k_T$) at large $k_T$
  - increases with temperature
  - goes to zero when $k_T \to 0$ (quantization effects)
  - has a peak at a small nonzero $k_T$

Nonzero elliptic “flow” ($v_2$)

Photon $v_2$ puzzle

- Most photons are produced early (before flow develops)
- Thus, $v_2$ for photons should be very small

Magnetic enhancement of $v_2$

- Estimate of $v_2$ in a hot magnetized QGP
  \[ \mathcal{R}_{2 \rightarrow 1}^{1 \rightarrow 2}: \quad v_2 \sim 20\% \]

- Noting that
  \[ \mathcal{R}_{2 \rightarrow 1}^{1 \rightarrow 2} \sim \mathcal{R}_{2 \rightarrow 3}^{3 \rightarrow 2} \]

- Naïve estimate at $p_T \sim 1$ GeV gives
  \[ 6.7\% \lesssim v_2 \lesssim 20\% \]

- A more realistic estimate should consider non-isotropic expansion & non-thermal processes
• $\vec{B} \neq 0$: photons are produced at 0th order in $\alpha_s$

(i) $q \rightarrow q + \gamma$,  
(ii) $\bar{q} \rightarrow \bar{q} + \gamma$,  
(iii) $q + \bar{q} \rightarrow \gamma$

• Photon emission has pronounced ellipticity

$-\nu_2 < 0$ at small $k_T$ ($k_T \leq \sqrt{|eB|}$)

$-\nu_2 > 0$ at large $k_T$ ($k_T \geq \sqrt{|eB|}$)

• A nonzero ellipticity of thermal emission is a “measure” of the magnetic field in collisions