Electromagnetic probes of strongly magnetized quark-gluon plasma

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[X. Wang and I. Shovkovy, work in preparation]
Magnetic field in HICs

- QGP produced at RHIC/LHC is **hot** and **magnetized**

\[ T \sim 350 \text{ MeV} \quad \text{and} \quad B \sim m^2_\pi \sim 10^{18} \text{ G to } 10^{19} \text{ G} \]

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**General proposal:**

- Electromagnetic probes serve not only as a **thermometer** but also as a **magnetometer** of QGP
Photon emission at $B = 0$

- Compare with the rate of thermal photon emission at $B=0$

\[ \text{Im}[\Pi^\mu_{R,\mu}(\Omega, k)] = \] 

\[ + \] 

\[ + \]

- Processes ($2 \rightarrow 2$):

\[ q \] 
\[ \gamma \] 
\[ g \] 
\[ q \] 
\[ \gamma \] 
\[ g \]

\[ \bar{q} \] 
\[ g \] 
\[ + \cdots \]

- The approximate result is given by

\[ \mathcal{R}_{2\rightarrow2} : \quad E \frac{dR}{d^3p} = \frac{5}{9} \frac{\alpha \alpha_s}{2\pi^2} T^2 e^{-E/T} \ln \left( \frac{2.912 E}{g^2 T} \right) \]
Data for direct photons (ALICE)

- Thermal radiation consistent with $T_{\text{eff}} = 304$ MeV
- There is a substantial $\nu_2$
  (larger than models predict)
Data for direct photons (PHENIX)

- Also, a large $\nu_2$ for direct photons is observed (larger than theoretical models predict)

Photon emission rates

• The expression for the rate is

\[
\Omega \frac{d^3 R}{d^3 k} = - \frac{1}{(2\pi)^3} \frac{\text{Im}[\Pi^\mu_{R,\mu}(\Omega, k)]}{\exp(\frac{\Omega}{T}) - 1}
\]


• At \( \vec{B} \neq 0 \), the imaginary part of the polarization tensor

\[
\text{Im}[\Pi^\mu_{R,\mu}(\Omega, k)] = \left\langle \begin{array}{c} k \\ n', p_z - k_z \end{array} \right| \left\langle \begin{array}{c} k \\ n, p_z \end{array} \right\rangle
\]

is nonzero at leading order in \( \alpha_s \)!

October 13, 2021
Igor Shovkovy @ Fall 2021 DNP Meeting
Physics processes

• Relevant physics processes \((0^{\text{th}}\ \text{order in } \alpha_s)\):

\[
\begin{align*}
\text{(a)} & \quad n > n' & \quad q & \quad (n', p_z - k_z) & \quad q \rightarrow q + \gamma \\
\text{(b)} & \quad n < n' & \quad \bar{q} & \quad (n', p_z - k_z) & \quad \bar{q} \rightarrow \bar{q} + \gamma \\
\text{(c)} & \quad (n, p_z) & \quad (n', p_z - k_z) & \quad \gamma \rightarrow \gamma + k 
\end{align*}
\]

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


Angular dependence (1)

- At very small $k_T$, the emission rate is maximal at $\phi = \frac{\pi}{2}$ (i.e., emission perpendicular to the reaction plane).
- Effectively, this gives photon “flow” with $v_2 < 0$.

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

\[ d^2R/\text{d}k \text{d}c/\cos(\theta) / m_{\pi^0}^2 \]

\[ k_T = 0.02 \text{ GeV} \]
\[ k_T = 0.05 \text{ GeV} \]
\[ k_T = 0.08 \text{ GeV} \]

\[ v_2 < 0 \]


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 $v_2 > 0$.


$v_2 > 0$
Nonzero elliptic “flow” ($\nu_2$)


Dilepton emission rates

- The expression for the rate is

\[
\frac{dN}{d^4xd^4k} = -\frac{\alpha}{12\pi^4} \frac{n_B(\Omega)}{k^2} \left(1 + \frac{2m_l^2}{k^2}\right) \left(1 - \frac{4m_l^2}{k^2}\right)^{1/2} \text{Im} \left[ \Pi^\mu_\nu (\Omega, k) \right]
\]

where

\[
\text{Im}[\Pi^\mu_\nu (\Omega, k)] = \text{Im} \left[ \Pi^\mu_{R,\mu} (\Omega, k) \right]
\]

- Compare with the B=0 rate (Born approximation):

\[
\frac{dR_{Born}}{d^4xd^4k} = \frac{5\alpha^2 T}{18\pi^4 K} n_B(\Omega) \ln \left( \frac{\cosh \frac{\Omega+K}{4T}}{\cosh \frac{\Omega-K}{4T}} \right)
\]

[Wang, Shovkovy, in preparation]

[Cleymans, Fingberg, and Redlich, Phys. Rev. D 35, 2153 (1987)]
Spectrum ($T = 350$ MeV, $eB = m^2_{\pi}$)

$T = 0.35$ GeV, $|eB| = m^2_{\pi}$

$\frac{dR}{kTdkTdy}$ (GeV$^2$)

invariant Mass (GeV)

[Wang, Shovkovy, in preparation]
$V_2 \left( T = 350 \text{ MeV}, eB = m^2_{\pi} \right)$

![Graph showing $V_2$ for different temperatures $kT$]
Summary

• $\vec{B} \neq 0$: photons are produced at 0\textsuperscript{th} order in $\alpha_s$

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

• Photon emission has pronounced ellipticity

  $v_2 < 0 @ k_T \lesssim \sqrt{|eB|}$  &  $v_2 > 0 @ k_T \gtrsim \sqrt{|eB|}$

• Dilepton emission is anisotropic, with possible $v_2 > 0$

• A nonzero ellipticity of photon & dilepton (?) emission are indirect “measures” of the magnetic field in collisions