Photon and Dilepton Production in Semi-QGP and its effect on elliptic flow

Daisuke Satow (ECT*, 🇧🇪)


<table>
<thead>
<tr>
<th>Theoretical side</th>
<th>Collaborators</th>
<th>Phenomenological side</th>
</tr>
</thead>
<tbody>
<tr>
<td>D. S. Yoshimasa Hidaka (RIKEN, 🇯🇵)</td>
<td>Charles Gale</td>
<td>Sangyong Jeon</td>
</tr>
<tr>
<td>Shu Lin (RIKEN-BNL, 🇺🇸)</td>
<td>Jean-Francois Paquet</td>
<td>Gojko Vujanovic</td>
</tr>
<tr>
<td>Robert Pisarski (BNL, 🇺🇸)</td>
<td>(McGill U. 🇨🇦)</td>
<td></td>
</tr>
</tbody>
</table>
Outline

- Introduction: Electromagnetic Probe, Semi-QGP
- Dilepton Production
- Photon Production
- Effect on Photon $\nu_2$
Electromagnetic Probe

Electromagnetic probe (lepton, photon) is phenomenologically important because

- Once generated, it goes out without interacting with medium.
- It reflects the microscopic properties of medium like quark spectrum.
- It also reflects the macroscopic properties like elliptic flow.

![Diagram of electromagnetic probe](image)
Electromagnetic Probe

**Photon $v_2$ puzzle**: theory prediction of $v_2$ is much smaller than experimental data (factor 2~4)

![Graph showing photon $v_2$ puzzle]

Theory: Rupa Chatterjee et al., PRC **88**, 034901 (2013)
One possible solution: considering (partial) confinement effect
Effect of confinement

In QGP, Polyakov loop is used as (quasi) order parameter of deconfinement transition.

\[ l \equiv \frac{1}{N_c} \text{Tr} \left\langle \mathcal{P} \exp \left( \int_0^\beta d\tau g A^0(\tau, \vec{x}) \right) \right\rangle \]

\[ l=1 \quad \rightarrow \quad \text{Deconfined} \]

\[ l=0 \quad \rightarrow \quad \text{Confined} \]
Semi-QGP

It is necessary to consider effect of nontrivial $l$ even in QGP phase.

(Semi-QGP)

$Lattice QCD: A. Bazavov et al., PRD 80, 014504 (2009)$
Simple model to analyze effect of Polyakov loop in perturbative computation:

**QCD Lagrangian + background gluon**

(quark $\psi$, gluon fluctuation $a$) \hspace{1cm} (A_0)

\[
\mathcal{L}[a, \psi, \bar{\psi}] = i \sum_{j=1}^{N_f} \bar{\psi}_j \Phi[a] \psi_j - \frac{1}{4} F^{\mu\nu}[a] F^a_{\mu\nu}[a] \\
A_0 \rightarrow A_0 + a_0 \\
(A_0)^{ab} = \frac{\delta^{ab} Q^a}{g} = (Q, -Q, 0)/g
\]

cf: PNJL model: integrate out gluon

After removing perturbative correction to $l$, background gluon is obtained from $l$ obtained from lattice calculation.

$$l(Q = 0) = 1 + \delta l(Q = 0)$$  
**assumption**  

$$\delta l(Q = 0) = \frac{g^2 C_f m_D}{8\pi T}$$

($g$: running coupling at one-loop  
$m_D$: Debye mass of gluon at one-loop)

$$l = \frac{1 + 2 \cos \beta Q}{3}$$

**Polyakov loop after subtraction**
Semi-QGP

Fourier transformation

\[
\bar{\psi} \gamma^0 (\partial_0 + i g A_0) \psi \quad \rightarrow \quad -\bar{\psi}_a \gamma^0 (E - i Q_a) \psi_a
\]

imaginary chemical potential coupled with color charge

quark distribution:

\[
\frac{1}{e^{\beta (E - i Q_a)} + 1}
\]

gluon distribution:

\[
\frac{1}{e^{\beta (E - i Q_a + i Q_b)} - 1}
\]
Statistical Confinement

\[ \frac{1}{N_c} \sum_a \frac{1}{e^{\beta(E-iQ_a)} + 1} \xrightarrow{\text{confinement phase}} \frac{1}{e^{\beta N_c E} + 1} \]

*T* is scaled by *N_c* in confined phase.

(Distribution is suppressed: **statistical confinement**)
Statistical Confinement

Ratio of quark distribution function to that at deconfined phase

\[
\frac{1}{N_c} \sum_a \frac{1}{e^{\beta(E - iQ_a)} + 1} = \frac{1}{e^{\beta E} + 1}
\]

\(N_c=3, \; E=T\)

Value at confined phase

\[
\frac{1}{e^{\beta N_c E} + 1}
\]

It decreases as \(l\) becomes small.
Dilepton Production

$2 \rightleftharpoons 2$ scattering (pair annihilation)

Distribution function is modified

$q (iQ_a)$

$q (-iQ_a)$

$l$

$\bar{l}$
Dilepton Production — Result

\[ \frac{d\Gamma}{d^4p} = f_{\Pi}(Q) \frac{d\Gamma}{d^4p} \bigg|_{Q=0} \]

\[ f_{\Pi}(Q) \equiv \tilde{f}_{\Pi}(Q)/\tilde{f}_{\Pi}(0) \]

\[ \tilde{f}_{\Pi} = 1 - \frac{2T}{3p} \ln \frac{1 + 3e^{-p_+/T} + 3e^{-2p_+/T} + e^{-3p_+/T}}{1 + 3e^{-p_-/T} + 3e^{-2p_-/T} + e^{-3p_-/T}} \]

\[ p_{\pm} = \frac{E \pm p}{2} \]

\[ \frac{d\Gamma}{d^4p} \bigg|_{Q=0} = \frac{\alpha_{em}^2}{6\pi} n(E) \left( 1 - \frac{2T}{p} \ln \frac{1 + e^{-p_-/T}}{1 + e^{-p_+/T}} \right) \]

\[ n(k^0) \equiv (e^{\beta k^0} - 1)^{-1} \]

Not suppressed, even slightly enhanced!
(Naively, confinement reduces chance of 2\(\leftrightarrow\)2 scattering, thus suppresses dilepton production)

No significant modification the production rate and \(v_2\) of dilepton
Physical Interpretation of Dilepton Enhancement

(Opposite imaginary chemical potentials)
Mesonic, Color Singlet

Boltzmann approximation: \( e^{-\beta(E_1 - iQ_a)} \times e^{-\beta(E_2 + iQ_a)} = e^{-\beta(E_1 + E_2)} \)

The phases cancels, NO suppression due to Polyakov loop!!
Photon Production

2\leftrightarrow2 scattering

(pair annihilation) 

(Compton scattering)
Photon Production

Color structure (double line notation)

Distribution function is modified

(iQ_a)

(-iQ_b)

Two independent color indices.
Photon Production — Result

\[ (E >> T) \]

\[ E \frac{d\Gamma}{d^3p} \bigg|_{Q \neq 0} = f_\gamma(Q) \left. E \frac{d\Gamma}{d^3p} \right|_{Q=0} \]

\[ E \frac{d\Gamma}{d^3p} \bigg|_{Q=0} = \frac{\alpha_{em} \alpha_s}{3\pi^2} e^{-E/T} T^2 \ln \left( \frac{E}{g^2T} \right) \]

\[ f_\gamma(Q) = 1 - 4q + \frac{10}{3} q^2 \quad q = \frac{Q}{2\pi T} \]

Suppressed.
Interpretation of Photon Production Suppression

Pair Annihilation:

Boltzmann approximation:

Due to the Bose Enhancement in final state, the phases do not cancel, and the process is suppressed!!
Interpretation of Photon Production Suppression

Compton Scattering:

\[ n_f^{(iQ_a)} \rightarrow (-iQ_a) \]
\[ n_b^{(iQ_b)} \rightarrow (-iQ_b) \]

Boltzmann approximation:
\[ \frac{1}{N_c^2} \sum_{a,b} e^{-\beta(E_1-iQ_a)} \times e^{-\beta(E_2-iQ_a+iQ_b)} \times 1 = e^{-\beta(E_1+E_2)} \times l \]

Proportional to \( l \) instead of \( l^2 \) (pair annihilation).
The two processes have different \( l \) dependence.
LPM contribution


When $Q_a=0$, LPM diagram is as large as 2 to 2 one.

In QGP

\[
\frac{1}{e^{\beta E} - 1} \simeq \frac{T}{E} \gg 1 \quad (E \sim gT)
\]
LPM contribution is suppressed

In semi-QGP

\[
\frac{1}{e^{E-i(Q_a-Q_b)}-1} \left( \begin{array}{c}
\frac{T}{E} \gg 1 \quad (a=b) \\
\sim 1 \quad (a \neq b)
\end{array} \right)
\]

LPM diagram is suppressed by $1/N_c$. 
Hydrodynamic Simulation (MUSIC)

Each stage of heavy ion collision produces dilepton, so we need to sum all the contributions.

Use hydrodynamic simulation (MUSIC)
Hydrodynamic Simulation (MUSIC)

Collision → QGP → Hadron Gas → Freeze Out

our result in semi-QGP
result in massive Yang-Mills


B. Schenke, S. Jeon, and C. Gale, PRC 82, 014903 (2010)
Effect on Photon Yield

Calculation with Hydrodynamics (MUSIC):

QGP Photon is suppressed.
(which makes the deviation from experimental data larger...)

\[
\frac{1}{2\pi} \frac{dN}{dp_T dy} \text{ [GeV}^2]\]

\[
p_T \text{ [GeV]} \]

\[
10^{-2} \quad 10^{-3} \quad 10^{-4} \quad 10^{-5} \quad 10^{-6} \quad 10^{-7} \quad 10^{-8} \]

- semi-QGP
- QGP
- HM+semi-QGP
- HM+QGP
Effect on Elliptic Flow ($v_2$)

$v_2$ increases by factor $\sim 2$.

$$v_2 = \frac{A_{QGP}v_2^{QGP} + A_{Hadron}v_2^{Hadron}}{A_{QGP} + A_{Hadron}}$$
Effect on Elliptic Flow ($v_2$)

$v_2$ increases by factor ~2.

Since hadron photon has large $v_2$, reducing QGP photon makes total $v_2$ larger.

Possible solution of $v_2$ puzzle
Summary

• We calculated the production rates of dilepton and real photon by using a model which takes into account the Polyakov loop effect in perturbative QCD calculation.

• We found that the photon production rate is suppressed while the dilepton production is enhanced in this model.

• We saw that the LPM effect is suppressed in large $N_c$ compared with 2 to 2 scattering.

• We found that the Polyakov loop effect increases total $v_2$, which suggests that considering this effect can be a possible solution of photon $v_2$ problem.