Elliptic flow of thermal photons in chemically non-equilibrated QCD medium

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Introduction

- **Quark-gluon plasma (QGP):** many-body system of deconfined quarks and gluons

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The QGP created in high-energy heavy ion collisions is quantified as a *relativistic fluid* with extremely small viscosity.

- Au-Au, Au-Cu (200 GeV) and U-U (193 GeV) at RHIC
- Pb-Pb (2.76 TeV) at LHC

It is a QCD phenomenon; what can an electromagnetic probe tell us?
Introduction

- Photon emission in heavy ion collisions (low $p_T$)

The hot medium is opaque in terms of QCD; transparent in terms of electromagnetism

**Hadrons**: Most of information before freeze-out is lost

**Photons**: Retain information during time evolution
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- Thermal photons (hadronic): from black-body radiation
- Thermal photons (QGP): from hard processes
- Prompt photons: from hard processes
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Decay photons
- from hadronic decay

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**Introduction**

- **Heavy-ion observable: Elliptic flow \( (v_2) \)**

\[
\frac{dN}{d\phi} = \frac{N}{2\pi} \left[ 1 + 2v_1 \cos(\phi - \Psi_1) + 2v_2 \cos(2\phi - 2\Psi_2) + 2v_3 \cos(3\phi - 3\Psi_3) + \ldots \right]
\]

- **Azimuthal anisotropy in **coordinate** space**

- **If the system is strongly interacting (= hydro-like), \( v_2 \) is large**

- **If the system is weakly interacting (= gas-like), \( v_2 \) is small**
Motivation

- Experimental results of flow anisotropy

- Hadronic $v_2$ is found to be large at RHIC & LHC
  - Nearly-ideal hydrodynamic models work well
  - An evidence for strongly-coupled QGP fluid; early equilibration ($\tau < 1$ fm/c) is suggested
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Experimental results of flow anisotropy

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- Direct photon $v_2$ is found to be large at RHIC & LHC
- Hydro models predict small $v_2$ because of the contribution from earlier stages with little anisotropy (*Note: QGP is EM transparent*)
- No definite answer so far; recognized as “photon $v_2$ puzzle”
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- Now direct photon $v_3$ is found to be large (2014)
  - The enhancement can be due to the properties of the medium
Approach of this work

Properties of the medium

- Color glass condensate (CGC): Colliding nuclei are saturated gluons
- QGP/hadronic fluid: Equilibrated quark-gluon plasma

Chemical equilibration does not necessary coincides with thermalization (cf: AM and B. Müller, arXiv: 1403.7310)
Approach of this work

- Fewer quarks + more gluons at the onset of QGP fluid

Equilibrated QGP (small $v_2$)

- Quark-gluon plasma
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Medium anisotropy develops in time evolution
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We consider: Non-equilibrated QGP

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Contribution of later stage becomes large as thermal photons are emitted in the presence of quarks; photon $v_2$ can be enhanced
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Medium anisotropy develops in time evolution
The model

- (2+1)-dimensional ideal hydrodynamic model + rate equations

- Energy-momentum conservation

$$\partial_\mu T_\mu^{\nu} + \partial_\mu T_\nu^{\mu} = 0$$

- Quark and gluon number changing processes

$$\partial_\mu N_q^{\mu} = 2r_bn_g - 2r_b \frac{n_{eq}}{n_g} n_q^2$$

$$\partial_\mu N_g^{\mu} = (r_a - r_b)n_g - r_a \frac{1}{n_{eq}} n_g^2 + r_b \frac{n_{eq}}{n_g} n_q^2$$

$$+ r_c n_q - r_c \frac{1}{n_{eq}} n_q n_g$$

$r_a$, $r_b$, $r_c$: reaction rates

$n_q^{(eq)}$, $n_g^{(eq)}$: parton densities (in equilibrium)

Late quark chemical equilibration implies $r_b < r_a$, $r_c$

as the chemical equilibration times are $\tau_i \sim 1/r_i$
Input for numerical analyses

- Hydrodynamic parameters *(Initial conditions + fluid properties)*
  - Gluon energy distribution: Kolb, Sollfrank and Heinz, PRC 62, 054909 (2000)
  - Quark energy distribution: 0 GeV/fm³
  - Initial time: 0.4 fm/c
  - Equation of state: Hadron resonance gas (mass below 2 GeV) + Parton gas (N_f = 2)
  - Chemical reaction rates: \( r_i = c_i T \) where \( c_i \) ranges are
    \[
    0.2 \leq c_b \leq 2 \ (\tau_b \sim 0.5 - 5 \text{ fm}/c) \quad \text{and} \quad 0 \leq c_{a,c} \leq 3 \ (\tau_{a,c} \sim 0.3 - \infty \text{ fm}/c)
    \]

- Photon emission rate
  - \[
  E \frac{dR^\gamma}{d^3p} = \frac{1}{2} \left( 1 - \tanh \frac{T - T_c}{\Delta T} \right) E \frac{dR^\gamma_{\text{hadron}}}{d^3p} + \frac{1}{2} \left( 1 + \tanh \frac{T - T_c}{\Delta T} \right) E \frac{dR^\gamma_{\text{QGP}}}{d^3p}
  \]
  - Turbide, Rapp and Gale, PRC 69, 014903
  - Traxler and Thoma, PRC 53, 1348

  where \( T_c = 0.17 \text{ GeV} \) and \( \Delta T = 0.017 \text{ GeV} \)
Results

- Elliptic flow of thermal photons – $c_b$ dependence

**Thermal photon $v_2$**

**Quark number density**

Late quark chemical equilibration ($\tau_{\text{chem}} \sim 1/c_b T$) leads to enhancement of thermal photon $v_2$

$$\tau_{\text{chem}} \sim 2 \text{ fm}/c$$ is motivated in an early equilibration model (AM and B. Müller, arXiv: 1403.7310) $\iff c_b = 0.5$ for $T \sim 0.2 \text{ GeV}$
Results

- Elliptic flow of thermal photons – $c_{a,c}$ dependence

Thermal photon $v_2$ is slightly enhanced for faster gluon-involved equilibration processes because quark production in early stages is suppressed due to quicker dampening of gluon overpopulation due to recombination.
Results

- Transverse momentum spectra of thermal photons

\[
\frac{1}{2\pi^2} \frac{d^3n}{dp_T^2} dy (GeV^{-1})
\]

\[
\begin{array}{c}
equilibrium \\
c_b=0.2, c_{a,c}=1.5 \\
c_b=0.5, c_{a,c}=1.5 \\
c_b=2.0, c_{a,c}=1.5
\end{array}
\]

\(p_T\) spectra is reduced by late quark chemical equilibration

Effect is limited for the chosen input; however more sophisticated photon emission rate and equation of state would be important

(Cf. Gelis et al., JPG 30, S1031)
Summary and outlook

- Thermal photon $\nu_2$ from chemically non-equilibrated QGP is investigated
  - Late quark production leads to visible enhancement of $\nu_2$, contributing positively to resolution of “photon $\nu_2$ puzzle”
  - Evolution of bulk medium from CGC to QGP is a key
  - Late gluon equilibration slightly reduces $\nu_2$
  - Net yield of thermal photons is reduced

- Future prospects include:
  - Introduction of dynamical equation of state, more realistic initial conditions, shear and bulk viscosities etc.
  - Estimation of the contribution from prompt photons
  - Other effects in non-equilibrated QGP, e.g., heavy quarks
Prompt photon $v_n$

- **Optical effects in QGP medium**

  - Transparent medium has a non-unity refractive index
  - A hot QCD medium works as a *4D lens*

  - Geometrical anisotropy ($\varepsilon_2$, $\varepsilon_3$, ...) is directly mapped onto thermal and prompt photon flow harmonics ($v_2$, $v_3$, ...)

- **Numerical analyses – prompt photon $v_n$**

  - Positive flow harmonics; not large enough w/ the model index $n^2 = 1 - a^2 T^2 / \omega^2$
    - Critical opalescence near $T_c$?
    - Semi-transparency at ultra-low momentum (determining plasma frequency of QGP)?
Vielen Dank für Ihre Aufmerksamkeit!

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