Viscous corrections to photon emission in heavy-ion collisions

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Little Bang

Relativistic Heavy-Ion Collisions

- Initial energy density
- Hadronization
- QGP phase
- Hadron gas phase
- Kinetic freeze-out
- Final detected particles distributions
- Pre-equilibrium dynamics
- Viscous hydrodynamics
- Collision evolution
- Free streaming

\[ \tau \sim 0 \text{ fm}/c \quad \tau \sim 1 \text{ fm}/c \quad \tau \sim 10 \text{ fm}/c \quad \tau \sim 10^{15} \text{ fm}/c \]
Photons from Heavy-ion Collisions

time = 0.6 fm/c

Pb+Pb @ 2.76 A TeV LHC

Charged Hadrons

Thermal Photons

oversample = 10
State-of-the-art hydrodynamic modeling

Initial Condition Generators
(MC- KLN, MC- Glauber)

Hydrodynamic Simulations
(VISH2+1)

HydroInfo Package

Hydrolphoton

Thermal Photon
Emission Rates

Thermal Photon Interface

Hadrons spectra & $V_n$

Photon spectrum & $V_n$
State-of-the-art hydrodynamic modeling

Initial Condition Generators
(MC- KLN, MC- Glauber)

Hydrodynamic Simulations
(VISH2+1)

HydroInfo Package

Thermal Photon Emission Rates

Thermal Photon Interface

\[ \frac{dR}{\partial^3 q} = \Gamma_0 + \frac{\mu^\gamma q^\gamma q^\kappa}{2(e+p)} a_{\epsilon\beta} \Gamma^\epsilon_{\beta} \]

\[ E \frac{dN^\gamma}{\partial^3 p} = -d^\epsilon x q \frac{dR}{\partial^3 q} \]

Hadrons spectra & \( V_n \)

Viscous corrections

Viscous corrections

Photon spectrum & \( V_n \)
Thermal photon emission rates can be calculated by

\[
E_q \frac{dR}{d^3 q} = - \frac{d^3 p_1}{2E_1(2\uparrow)^3} \frac{d^3 p_2}{2E_2(2\uparrow)^3} \frac{d^3 p_3}{2E_3(2\uparrow)^3} \frac{1}{2(2\uparrow)^3} M^2
\]

\[
\rightarrow f_1(p_1^\mu) f_2(p_2^\mu) (1 \pm f_3(p_3^\mu))(2\uparrow)^4 \sigma^{(4)} (p_1 + p_2 - p_3 - q)
\]

With

\[
f(p^\mu) = f_0(E) + f_0(E)(1 \pm f_0(E)) \frac{\hat{q}_\mu \hat{q}_\nu}{2(e + p)} \chi \frac{p^\sigma}{T}
\]

We can expand photon emission rates around the thermal equilibrium:

\[
q \frac{dR}{d^3 q} = \Gamma_0 + \frac{\pi^{\mu\nu} \hat{q}_\mu \hat{q}_\nu}{2(e + p)} a_{\alpha\beta} \Gamma^{\alpha\beta},
\]

\[
a_{\mu\nu} = \frac{3}{2(u \cdot \hat{q})^4} \hat{q}_\mu \hat{q}_\nu + \frac{1}{(u \cdot \hat{q})^2} u_\mu u_\nu + \frac{1}{2(u \cdot \hat{q})^2} g_{\mu\nu} - \frac{3}{2(u \cdot \hat{q})^3} (\hat{q}_\mu u_\nu + \hat{q}_\nu u_\mu).
\]
Thermal photon emission rates can be calculated by

$$E_q \frac{dR}{d^3 q} = \frac{d^3 p_1}{2E_1(2\uparrow)^3} \frac{d^3 p_2}{2E_2(2\uparrow)^3} \frac{d^3 p_3}{2E_3(2\uparrow)^3} \frac{1}{2(2\uparrow)^3} |\mathcal{M}|^2$$

$$\rightarrow f_1(p_1^\mu) f_2(p_2^\mu) (1 \pm f_3(p_3^\mu))(2\uparrow)^4 \sigma^{(4)} (p_1 + p_2 - p_3 - q)$$

With

$$f(p^\mu) = f_0(E) + f_0(E)(1 \pm f_0(E)) \uparrow \mu \uparrow \nu \hat{p}_{\mu} \hat{p}_{\nu} \chi^{\downarrow \rho \downarrow \sigma} \frac{p_{\rho}}{T}$$

We can expand the thermal equilibrium:

$$\Gamma_0(q, T) a_{\alpha\beta} \Gamma^{\alpha\beta}(q, T)$$

calculated in fluid local rest frame

calculated in lab frame
Viscous Photon Emission Rates: General Formalism

\[ q \frac{dR}{d^3q} = \Gamma_0 + \frac{\hat{q} \hat{q} \hat{\epsilon} q \hat{\epsilon}}{2(e+p)} a_{\epsilon \beta} \Gamma_{\epsilon \beta} \]

Equilibrium rates

**QGP** (AMY 2001)

**Hadron Gas** (TRG 2004)

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(AMY 2001)

(TRG 2004)
\[
q \frac{dR}{d^3q} = \Gamma_0 + \frac{\hat{\mu} \hat{q} \hat{q} \hat{\mu}}{2(e + p)} a_{\varepsilon \beta} \Gamma^\varepsilon_{\beta}
\]

Equilibrium rates  off-equilibrium $\delta f$ corrections
Viscous Photon Emission Rates: General Formalism

\[ \frac{dR}{d^3q} = \Gamma_0 + \frac{\langle \mu \lessdot q \rangle \hat{q} \hat{\mu} \Gamma_{\mu\beta}}{2(e+p)a_{\mu\beta}} \]

Equilibrium rates \hspace{1cm} off-equilibrium \( \delta f \) corrections

\[
\delta f_{q dR} = 0 + \Gamma_{\mu\beta} \frac{\hat{q} \hat{\mu} a_{\mu\beta}}{2(e+p)}
\]

Self-energy
\[ \Delta = \Delta_0 + \Gamma_{\mu} \Delta_{\mu} \]

Shen, Paquet et al. (2014)
Viscous effects on photon elliptic flow

- Shear viscous suppression of photon $v_2$ is dominated by the viscous corrections to the photon emission rate.
- Photon elliptic flow is sensitive to the larger shear stress tensor at early times.
Shear viscous suppression of photon $v_2$ is dominated by the viscous corrections to the photon emission rate.

Photon elliptic flow is sensitive to the larger shear stress tensor at early times.
Definition of event-by-event $v^{\gamma, \text{dir}}_n$

$$v^{\text{dir}}_n(p_T) = \frac{R^\gamma(p_T) v^{\text{incl}}_n(p_T) - v^{\text{bg}}_n(p_T)}{R^\gamma(p_T) - 1}$$

$$R^\gamma = \frac{N^{\gamma \text{incl}}}{N^{\gamma \text{bg}}}$$

exact for a single event

8(15)
Definition of event-by-event $v_n^{Y, \text{dir}}$

$$v_n^{\text{dir}}(p_T) = \frac{R_Y(p_T) v_n^{\text{incl}}(p_T) - v_n^{\text{bg}}(p_T)}{R_Y(p_T) - 1}$$

exact for a single event

But for multiple events,

Experiment:

$$R_Y(p_T) h v_n^{\text{incl}}(p_T)i - h v_n^{\text{bg}}(p_T)i$$

$$\bar{R}_Y(p_T) = \frac{\frac{h dN_Y^{\text{incl}}}{dp_T dp_T} i}{\frac{h dN_Y^{\text{bg}}}{dp_T dp_T} i}$$

$$R_Y = \frac{N_Y^{\text{incl}}}{N_Y^{\text{bg}}}$$
Definition of event-by-event $\nu_n^{Y,\text{dir}}$

$$\nu_n^{\text{dir}}(p_T) = \frac{R_Y(p_T) v_n^{\text{incl}}(p_T) - v_n^{\text{bg}}(p_T)}{R_Y(p_T) - 1}$$

exact for a single event

But for multiple events,

Experiment:

$$\bar{R}_Y(p_T) = \frac{hdN^{Y\text{incl}} / dy p_T dp_T}{hdN^{Y\text{bg}} / dy p_T dp_T}$$

Theory:

$$h\nu_n^{\text{dir}}(p_T) = \frac{\bar{R}_Y(p_T) v_n^{\text{incl}}(p_T) - v_n^{\text{bg}}(p_T)}{R_Y(p_T) - 1}$$

$$R_Y = \frac{N^{Y\text{incl}}}{N^{Y\text{bg}}}$$
Definition of event-by-event $\nu_n^{\gamma,\text{dir}}$

$$\nu_n^{\text{dir}}(p_T) = \frac{R^\gamma(p_T) \nu_n^{\text{incl}}(p_T) - \nu_n^{\text{bg}}(p_T)}{R^\gamma(p_T) - 1}$$

But for multiple events,

Experiment:

$$\overline{R}^\gamma(p_T) = \frac{\frac{dN^{\gamma\text{incl}}}{dy dp_T dp_T} - \frac{dN^{\gamma\text{bg}}}{dy dp_T dp_T}}{\frac{dN^{\gamma\text{incl}}}{dy dp_T dp_T}}$$

Theory:

$$\overline{\nu}_n^{\text{dir}}(p_T) = \frac{R^\gamma(p_T) \nu_n^{\text{incl}}(p_T) - \nu_n^{\text{bg}}(p_T)}{R^\gamma(p_T) - 1}$$

exact for a single event
Definition of event-by-event $\nu_n^{\gamma, \text{dir}}$

$$v_n^{\gamma\{\text{SP}\}}(p_T) = \frac{\langle v_n^\gamma(p_T)v_n^{\text{ch}}\cos(n(\Psi_n^\gamma(p_T) - \Psi_n^{\text{ch}}))\rangle}{v_n^{\text{ch}\{2\}}}$$

$$v_2^{\text{dir}\{\text{SP}\}}$$
Definition of event-by-event $\nu_n^{\gamma,\text{dir}}$

$$
\nu_n^{\gamma\{\text{SP}\}}(p_T) = \frac{\langle \nu_n^\gamma(p_T)\nu_n^{\text{ch}}\cos(n(\Psi_n^\gamma(p_T) - \Psi_n^{\text{ch}})) \rangle}{\nu_n^{\text{ch}\{2\}}}
$$

$$
\bar{R}^\gamma(p_T) = \langle \nu_n^{\text{incl}\{\text{SP}\}}(p_T) \rangle - \langle \nu_n^{\text{bg}\{\text{SP}\}}(p_T) \rangle
$$

$$
\bar{R}^\gamma(p_T) - 1
$$
Definition of event-by-event $v_n^{Y,\text{dir}}$

$$v_n^{\text{dir}}(p_T) = \frac{R^Y(p_T)v_n^{\text{incl}}(p_T) - v_n^{\text{bg}}(p_T)}{R^Y(p_T) - 1}$$

exact for a single event

But for **multiple** events,

“extraction safe”

$$v_n^Y\{\text{SP}\}(p_T) = \frac{-dN^Y}{dy p_T dp_T}(p_T)v_n^Y(p_T)v_n^{\text{ch}} \cos(n(v_n^Y(p_T) - v_n^{\text{ch}}))}{\int \frac{dN^Y}{dy p_T dp_T}(p_T) v_n^{\text{ch}}\{2\}}.$$

$$v_n^{\text{dir}}\{\text{SP}\}(p_T) = \frac{R^Y(p_T)h_n^{\text{incl}}\{\text{SP}\}(p_T)i - h_n^{\text{bg}}\{\text{SP}\}(p_T)i}{R^Y(p_T) - 1}$$

**theory** ↔ **experiment**

*Poster:* J-F. Paquet, G21
Definition of event-by-event $v_n^{\gamma,\text{dir}}$

$$v_n^{\gamma}\{\text{SP}\}(p_T) = \left\langle \frac{dN^\gamma}{dp_T dp_T}(p_T) v_n^\gamma(p_T) v_n^{\text{ch}} \cos(n(\Psi_n^\gamma(p_T) - \Psi_n^{\text{ch}})) \right\rangle \frac{\left\langle \frac{dN^\gamma}{dy p_T dp_T}(p_T) \right\rangle}{v_n^{\text{ch}}\{2\}}.$$

But for $v_n^{\gamma}$, the nuclear modification factor $R_A$ is defined as:

$$R_A(p_T) = \frac{\left\langle \frac{dN^\gamma}{dp_T dp_T}(p_T) \right\rangle}{\left\langle \frac{dN^\gamma}{dp_T dp_T}(p_T) \right\rangle_{\text{background}}}.$$
Definition of event-by-event $v_n^{\gamma, \text{dir}}$

$$v_n^{\gamma\{\text{SP}\}}(p_T) = \left\langle \frac{dN^\gamma}{d\eta p_T dp_T}(p_T) v_n^{\gamma}(p_T) v_n^{\text{ch}} \cos(n(\Psi_n^{\gamma}(p_T) - \Psi_n^{\text{ch}})) \right\rangle \left\langle \frac{dN^\gamma}{d\eta p_T dp_T}(p_T) \right\rangle v_n^{\text{ch}\{2\}}.$$
Definition of event-by-event $v_{n}^{\gamma, \text{dir}}$

$$v_{n}^{\gamma}\{\text{SP}\}(p_T) = \frac{\left\langle \frac{dN^{\gamma}}{dydp_{T}}(p_T)v_{n}^{\gamma}(p_T)v_{n}^{\text{ch}}\cos(n(\Psi_{n}^{\gamma}(p_T) - \Psi_{n}^{\text{ch}})) \right\rangle}{\left\langle \frac{dN^{\gamma}}{dydp_{T}}(p_T) \right\rangle v_{n}^{\text{ch}}\{2\}}.$$
Fluctuation effects on photon elliptic flow

\begin{align*}
\text{Ideal smooth hydro } \bar{v}_2 \\
\text{Full viscous smooth hydro } \bar{v}_2 \eta/s = 0.08
\end{align*}

\text{arXiv: 1403.7558}

\text{MCGlb. 0-40\% Pb+Pb @ 2.76 A TeV}
Fluctuation effects on photon elliptic flow

Initial fluctuations increase photons’ elliptic flow

- Ideal smooth hydro \( \bar{v}_2 \)
- Full viscous smooth hydro \( \bar{v}_2, \eta/s = 0.08 \)
- Ideal ebe hydro \( v_2 \{SP\} \) **no multiplicity weight**
- Full viscous ebe hydro \( v_2 \{SP\} \) \( \eta/s = 0.08 \)

arXiv: 1403.7558

MCGlb. 0-40% Pb+Pb @ 2.76 A TeV

\[ s = 0.08 \]
Fluctuation effects on photon elliptic flow

- Initial fluctuations increase photons’ elliptic flow
- The additional photon multiplicity weighting biases e-b-e $v_2$ towards central collisions, resulting in $\sim 10-20\%$ smaller $v_2$ compared to smooth hydro
The anisotropic flows of photons show similar centrality dependence as hadron $v_n$.
• The anisotropic flows of photons show similar centrality dependence as hadron $v_n$

• The ratio $v_2/v_3$ increases with the shear viscosity

• The centrality dependence of this ratio is stronger for the MCKLN model, driven by $\gamma^2$
Event-by-Event Full Viscous Photon $v_n$

0-20% @ RHIC

MCGlb

$\mathcal{H} s = 0.08$

20-40% @ RHIC

MCKLN

Thermal + pQCD

$\mathcal{H} s = 0.20$

0-40% @ LHC

0-20% @ RHIC

20-40% @ RHIC

0-40% @ LHC

$\mathcal{H} / s = 0$.
• Current calculations still underestimate the experimental data by a factor of 3
Current calculations still underestimate the experimental data by a factor of 3.

Thermal yield is also missing in the azimuthally integrated photon spectra at low $p_T$.
EM decays of short-lived resonances (I)

Contributions from the short-lived resonances:

<table>
<thead>
<tr>
<th>reaction</th>
<th>branching ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\rho^0 \rightarrow \pi^+ + \pi^- + \gamma$</td>
<td>1%</td>
</tr>
<tr>
<td>$b_1(1235) \rightarrow \pi^\pm + \gamma$</td>
<td>$1.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>$h_1(1170) \rightarrow \pi^0 + \gamma$</td>
<td>$1.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>$a_1(1260) \rightarrow \pi^0 + \gamma$</td>
<td>$1.7 \times 10^{-3}$</td>
</tr>
<tr>
<td>$f_1(1285) \rightarrow \rho_0 + \gamma$</td>
<td>5.5%</td>
</tr>
<tr>
<td>$a_2(1320) \rightarrow \pi^\pm + \gamma$</td>
<td>$2.68 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^*(892) \rightarrow K^0 + \gamma$</td>
<td>$2.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^*(892) \rightarrow K^{\pm} + \gamma$</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K_1(1270) \rightarrow K^0 + \gamma$</td>
<td>$8.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$K_1(1400) \rightarrow K^0 + \gamma$</td>
<td>$1.6 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^*_1(1430) \rightarrow K^+ + \gamma$</td>
<td>$2.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$K^*_2(1430) \rightarrow K^0 + \gamma$</td>
<td>$9 \times 10^{-4}$</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>reaction</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$N(1440) \rightarrow p + \gamma$</td>
<td>$4.15 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N(1440) \rightarrow n + \gamma$</td>
<td>$3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N(1520) \rightarrow p + \gamma$</td>
<td>$4.15 \times 10^{-3}$</td>
</tr>
<tr>
<td>$N(1520) \rightarrow n + \gamma$</td>
<td>$4.15 \times 10^{-3}$</td>
</tr>
<tr>
<td>$N(1530) \rightarrow p + \gamma$</td>
<td>$2.25 \times 10^{-3}$</td>
</tr>
<tr>
<td>$N(1530) \rightarrow n + \gamma$</td>
<td>$2.25 \times 10^{-3}$</td>
</tr>
<tr>
<td>$N(1650) \rightarrow p + \gamma$</td>
<td>$1.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$N(1650) \rightarrow n + \gamma$</td>
<td>$8.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N(1675) \rightarrow p + \gamma$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N(1675) \rightarrow n + \gamma$</td>
<td>$7.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N(1680) \rightarrow p + \gamma$</td>
<td>$2.65 \times 10^{-3}$</td>
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<tr>
<td>$N(1680) \rightarrow n + \gamma$</td>
<td>$3.35 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N(1700) \rightarrow p + \gamma$</td>
<td>$3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N(1700) \rightarrow n + \gamma$</td>
<td>$1.2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$N(1710) \rightarrow p + \gamma$</td>
<td>$4.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N(1710) \rightarrow n + \gamma$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N(1720) \rightarrow p + \gamma$</td>
<td>$1.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$N(1720) \rightarrow n + \gamma$</td>
<td>$8 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\Delta(1232) \rightarrow N + \gamma$</td>
<td>0.6%</td>
</tr>
<tr>
<td>$\Delta(1600) \rightarrow N + \gamma$</td>
<td>$1.8 \times 10^{-4}$</td>
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<tr>
<td>$\Delta(1620) \rightarrow N + \gamma$</td>
<td>$6.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta(1700) \rightarrow N + \gamma$</td>
<td>$4.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta(1905) \rightarrow N + \gamma$</td>
<td>$2.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta(1910) \rightarrow N + \gamma$</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Delta(1920) \rightarrow N + \gamma$</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Delta(1950) \rightarrow N + \gamma$</td>
<td>$1.05 \times 10^{-3}$</td>
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<tr>
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<tr>
<td>$\Lambda(1405) \rightarrow \Lambda + \gamma$</td>
<td>$5.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Lambda(1405) \rightarrow \Sigma^0 + \gamma$</td>
<td>$2 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\Lambda(1520) \rightarrow \Lambda + \gamma$</td>
<td>$8.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\Lambda(1520) \rightarrow \Sigma^0 + \gamma$</td>
<td>2%</td>
</tr>
<tr>
<td>$\Sigma^0(1385) \rightarrow \Lambda + \gamma$</td>
<td>1.25%</td>
</tr>
<tr>
<td>$\Xi(1530) \rightarrow \Xi + \gamma$</td>
<td>4%</td>
</tr>
</tbody>
</table>
EM decays of short-lived resonances (II)

Contributions from the short-lived resonances:

- $\Delta(1232) \rightarrow N + \gamma$ 0.6%

**Graphs:**
- 2D plots showing $dN/(2\pi dP_T dp_T)$ vs. $p_T$ (GeV) for different decay channels.
- Graphs illustrating shifts and adjustments due to thermal + pQCD and thermal + pQCD + short lived decay.

Small but significant effects in the right direction.

<table>
<thead>
<tr>
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<td>$N(1710) \rightarrow n + \gamma$</td>
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</tr>
<tr>
<td>$N(1720) \rightarrow p + \gamma$</td>
<td>$1.5 \times 10^{-3}$</td>
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</tr>
</tbody>
</table>
Contributions from pre-equilibrium flow and $\mu$ $\gamma$: 

![Diagram showing contributions from pre-equilibrium flow and $\mu$ $\gamma$.]
Pre-equilibrium flow (II)

Contributions from pre-equilibrium flow and $\uparrow^\mu \downarrow$:

Free-streaming

$$f \left( \frac{d^3 p}{E} p^\mu p^\nu f \left( \xi, x, p \right) \right)$$

$$T^\mu \left( \xi, x \right) = - \frac{d^3 p}{E} p^\mu p^\nu f \left( \xi, x, p \right)$$

$$T^\mu \left( \xi, x \right) = e u^\mu$$
Pre-equilibrium flow (III)

Contributions from pre-equilibrium flow and $\pi^{\mu\nu}$:

Small but significant effects in the right direction
Pre-equilibrium flow (III)

Contributions from pre-equilibrium flow and $\pi^{\mu \nu}$:

Small but significant effects in the right direction

Poster: J-F. Paquet, G21
Conclusions

- We studied photon spectra and their anisotropic flows $v_n$ from event-by-event viscous hydrodynamic medium

$$v_n^\gamma \{SP\}(p_T) = -\frac{dN_\gamma}{dy p_T dp_T}(p_T) v_n^\gamma(p_T) v_n^{ch} \cos(n(v_n(p_T) - v_n^{ch}))$$

- **Shear viscosity** suppresses photon $v_n$. Dominant suppression comes not from flow, but from the **viscous correction to the production rates**.

- **Elliptic** and **triangular** flow of photons are **more sensitive** than hadrons to shear stress at early times and to initial state fluctuations.

- **Short-lived resonance decays** and **pre-equilibrium flow** cause measurable increase of direct photon anisotropic flow.

- Still, experimental **data** appear to **require significantly more photon rate from the late evolution stage** than in implemented in the model.

We studied photon spectra and their anisotropic flows $v_n$ from event-by-event viscous hydrodynamic medium. The shear viscosity suppresses photon $v_n$. Dominant suppression comes not from flow, but from the viscous correction to the production rates.

Elliptic and triangular flow of photons are more sensitive than hadrons to shear stress at early times and to initial state fluctuations.

Short-lived resonance decays and pre-equilibrium flows cause a measurable increase of direct photon anisotropic flow. Still, experimental data appear to require significantly more photon rate from the late evolution stage than in implemented in the model.

Conclusions

- We studied photon spectra and their anisotropic flows $v_n$ from event-by-event viscous hydrodynamic medium.

$$v_n^{\gamma} \{SP\} (p_T) = \frac{\frac{dN}{dy p_T dp_T} (p_T) v_n^{\gamma} (p_T) v_n^{ch} \cos(n( v_n^{\gamma} (p_T) - v_n^{ch}))}{\frac{dN}{dy p_T dp_T} (p_T) v_n^{ch} \{2\}}$$

- Shear viscosity suppresses photon $v_n$. Dominant suppression comes not from flow, but from the viscous correction to the production rates.

- Elliptic and triangular flow of photons are more sensitive than hadrons to shear stress at early times and to initial state fluctuations.

- Short-lived resonance decays and pre-equilibrium flows cause a measurable increase of direct photon anisotropic flow.

- Still, experimental data appear to require significantly more photon rate from the late evolution stage than in implemented in the model.

Back up
Viscous effects on photon elliptic flow

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

\[ v_2 \]

QGP

HG

\( s = 0.08 \)
Viscous effects on photon elliptic flow

$$\eta/s = 0.08$$
Viscous effects on photon elliptic flow

\[ \frac{\eta}{s} = 0.08 \]
Viscous effects on photon elliptic flow

MCGib@RHIC 0–20%
QGP photons

$\eta/s = 0.08$

QGP

HG

$\eta/s = 0.08$

Ideal

Viscous hydro + eq rates

Full viscous

$\xi_2$

0

1

$\tau - \tau_0$ (fm/c)

0

2

4

6

8

10

12

0

0.02

0.04

0.06

0.08

$\varepsilon_p = (T_0 - T_0^{\gamma})/(T_0 + T_0^{\gamma})$
Viscous effects on photon elliptic flow

MCGib@RHIC 0–20%
QGP photons

\[ \eta/s = 0.08 \]

HG photons

QGP

HG

\[ \nu_2 \]

2

10

14

10^3

0

1

2

3

4

(GeV)

0

2

4

6

8

10

12

0

0.02

0.04

0.06

0.08

\[ \varepsilon \]

\[ (T_0 - T_0^y)/(T_0 + T_0^y) \]

\[ \tau - \tau_0 \] (fm/c)
For small $g$, results from diagrammatic approach agree well with kinetic approach and AMY.

For $g = 2.0$, diagrammatic approach gives 25% larger results compared to kinetic approach; difference are due to cut-off dependence.
Viscous corrections:

For small $g$, diagrammatic approach agrees with kinetic approach

For $g = 2$, the deviations at small $k/T$ may originate from different higher order $O(g^2 T)$ contributions
Photon Emission Rates QGP vs HG

- QGP rates have very different $p_T$ dependence compared to HG rates
Photon Emission Rates QGP vs HG

- QGP rates have very different $p_T$ dependence compared to HG rates
- Estimated transition region for production rates, $T \sim 184 - 220$ MeV

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Photon Emission Rates QGP vs HG

Thermal + pQCD

$\frac{dN}{d(\Omega d\eta dp_T)}$ (GeV$^{-2}$)

$p_T$ (GeV)

$T_{sw} = 180-220$ MeV
$T_{sw} = 170-200$ MeV
$T_{sw} = 160-180$ MeV
$T_{sw} = 150-170$ MeV

$v_2$

$p_T$ (GeV)

$T_{sw} = 180-220$ MeV
$T_{sw} = 170-200$ MeV
$T_{sw} = 160-180$ MeV
$T_{sw} = 150-170$ MeV

solid line: s95p-v1

$T$ [MeV]

$100$ $250$ $400$ $550$ $700$

$10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$

$0.5$ $1.0$ $1.5$ $2.0$ $2.5$ $3.0$ $3.5$ $4.0$

$0.00$ $0.02$ $0.04$ $0.06$ $0.08$ $0.10$

• $p_T$ dependence compared to HG rates

$T \sim \mathbf{184 - 220}$ MeV

Pre-equilibrium flow effects on hadrons
Dashed: with initial flow
Solid: without initial flow
High $p_T$ photons are mostly emitted from high temperature region.

Peak photon production around $T = 165-200$ MeV due to large hydrodynamic space-time volume.
• With all available thermal emission sources, our current calculations still underestimate measured direct photon spectra at low $p_T$ at both RHIC and LHC energies.

• Additional emission sources need to be included to improve the agreement between theory and data.
State-of-the-art hydrodynamic modeling

Initial Condition Generators (MC-KLN, MC-Glauber)

Hydrodynamic Simulations (VISH2+1)

HydroInfo Package

Thermal Photon Emission Rates

Thermal Photon Interface

e-b-e VISHNU

\[ q \frac{dR}{d^3q} = \Gamma_0 + \pi^{\mu\nu} q_{\mu} q_{\nu} a_{\alpha\beta} \Gamma^{\alpha\beta} \]

\[ E \frac{dN^\gamma}{d^3p} = \int d^4x q \frac{dR}{d^3q} \]

Hadrons spectra & \( v_n \)

UrQMD

Photon spectrum & \( v_n \)
State-of-the-art hydrodynamic modeling

Initial Condition Generators (MC-KLN, MC-Glauber)

Hydrodynamic Simulations (VISH2+1)

HydroInfo Package
- $e, s, p, T,$
- $u^\mu, \pi^{\mu\nu}$

Hadrons spectra & $v_n$

Your own Jet Quenching or Heavy Quark Package