Thermal photon $v_3$ from event-by-event fluctuating initial conditions

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Event-by-event hydrodynamics and initial density profile


- Monte Carlo Glauber Model: two nucleons i and j from different nuclei collide when

\[(x_i - x_j)^2 + (y_i - y_j)^2 \leq \frac{\sigma_{NN}}{\pi}\]  \[\rightarrow (1)\]

- Entropy density \(s\) is distributed in the \((x, y)\) plane around the wounded nucleons using a 2D Gaussian:

\[s(x, y) = \frac{K}{2\pi\sigma^2} \sum_{i=1}^{N_{WN}} \exp\left(-\frac{(x - x_i)^2 + (y - y_i)^2}{2\sigma^2}\right)\]  \[\rightarrow (2)\]

- \(\sigma\) is a free parameter determining the size of the fluctuation.
The hotspots in the fluctuating events produce more high $p_T$ photons compared to the smooth profile.

Note: Hardening of hadron spectra from fluctuating IC is due to different reason.
Distributions of temperature in the transverse plane for 200A GeV Au+Au collisions at RHIC.

$\tau_0 = 0.17$ fm, $\sigma = 0.4$ fm

$\tau_0 = 0.17$ fm, $\sigma = 0.8$ fm

$\tau_0 = 3.0$ fm, $\sigma = 0.4$ fm

$\tau_0 = 3.0$ fm, $\sigma = 0.8$ fm

Elliptic flow of thermal photons for same event with different $\sigma$ values.

Elliptic flow of thermal photons from 200A GeV Au+Au collisions at RHIC

E-by-e calculation gives significantly larger $v_2$ for $p_T > 2.5$ GeV/c. At $p_T = 4$ GeV/c, the $v_2$(RP) is about 3 times larger than the result from smooth IC and the difference increases for larger values of $p_T$. $v_2$(PP) is even larger than $v_2$(RP).

Elliptic flow of thermal photons from 200A GeV Au+Au collisions at RHIC using fluctuating initial conditions and PHENIX direct photon data

Direct photon spectra for 200A GeV Au+Au collisions at RHIC and for 20–40% centrality bin along with prompt and thermal (FIC and SIC) contributions.

\[ v_2 = \frac{v_2^{\text{th}} \cdot dN^{\text{th}} + v_2^{\text{pr}} \cdot dN^{\text{pr}}}{dN^{\text{th}} + dN^{\text{pr}}} = \frac{v_2^{\text{th}} \cdot dN^{\text{th}}}{dN^{\text{th}} + dN^{\text{pr}}} \]

\( v_2 \) with and without the prompt photon contribution for smooth and fluctuating IC.

Thermal photon $p_T$ spectra for 2.76A TeV Pb+Pb collisions at LHC for 0–40% centrality bin.

Thermal photon elliptic flow at LHC and ALICE preliminary direct photon $v_2$

Triangular and elliptic flow of thermal photons for 0–40% central collisions of Pb nuclei at LHC

\( v_3^{(PP)} \) is non-zero, positive and its \( p_T \) dependence is qualitatively similar to the elliptic flow parameter \( v_2^{(PP)} \).
Average transverse flow velocities for different events with fixed number of wounded nucleons and $v_3(PP)$ for the same events.

Triangular flow of thermal photons for 0–40% central collisions of Pb nuclei at LHC and for size parameter 0.4 and 0.8 fm

2.76 A TeV Pb+Pb@LHC, 0-40%

$v_3 (PP), \sigma=0.4 \text{ fm}$

$v_3 (PP), \sigma=0.8 \text{ fm}$

$v_3 (RP), \sigma=0.8 \text{ fm}$

$p_T (\text{GeV/c})$
Triangular flow of thermal photons for 0–40% central collisions of Pb nuclei at LHC and formation times 0.14 and 0.6 fm/c
Summary and Conclusions:

1) Fluctuations in the initial density distribution increase the elliptic flow of thermal photons significantly in the region $p_T > 2$ GeV compared to a smooth initial state averaged profile, however not sufficient to explain the large direct photon elliptic flow.

2) Triangular flow of thermal photons calculated from event by-event hydrodynamics is significantly large and its $p_T$ dependence is qualitatively similar to the elliptic flow result.
Thank You
Direct photon spectra at RHIC and LHC

- Low $p_T$ direct photon elliptic flow measurement could provide direct constraints on QGP dynamics ($\eta/s$, $T$, $t_0$...).
- Excess of direct photon yield over $p+p$: $T_{\text{eff}} = 221 \pm 19 \pm 19$ MeV in 0-20% Au +Au; substantial positive $v_2$ observed at $p_T < 4$ GeV/c.
- Excess of direct photon yield over $p+p$ at $p_T < 4$ GeV/c: $T_{\text{eff}} = 304 \pm 51$ MeV in 0-40% Pb+Pb.
- Di-lepton $v_2$ versus $p_T$ & $M_{ll}$: probe the properties of the medium from hadron-gas dominated to QGP dominated.
Effect of centrality dependent formation time and fluctuating IC

Centrality dependent formation time is estimated from EKRT model.

<table>
<thead>
<tr>
<th>Centrality bin (%)</th>
<th>$p_0$ (GeV)</th>
<th>$A_{eff}$</th>
<th>$\tau_0$ (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 5</td>
<td>1.3945</td>
<td>193</td>
<td>0.140</td>
</tr>
<tr>
<td>20 - 30</td>
<td>1.2070</td>
<td>90</td>
<td>0.164</td>
</tr>
<tr>
<td>40 - 50</td>
<td>1.0507</td>
<td>40</td>
<td>0.188</td>
</tr>
</tbody>
</table>

The $p_T$ spectra alone are found to be insufficient to quantify the fluctuations in the IC due to uncertainties in the initial conditions.

Table from R. Paatelainen
Time evolution of thermal photons for transverse momentum values of (a) 1 GeV/c, (b) 3 GeV/c, and (c) 5 GeV/c.

Results are compared with an initial state averaged event and four different random events.

\[ R_{cp}^\gamma |_{i} = \frac{dN/d^2p_TdY|_{0-10\%}}{dN/d^2p_TdY|_{i-j\%}} \times \frac{N_{bin|_{i-j\%}}}{N_{bin|_{0-10\%}}} \]
The effect of fluctuations in the IC is more pronounced for peripheral collisions and for lower beam energies.
Thermal photons are emitted from different stages of the expanding system and thus in order to gain a better understanding it is useful to study the time evolution of $\varepsilon_p$, $\varepsilon_x$, $\langle v_T \rangle$.

\[
\varepsilon_x = \frac{\int dxdy \varepsilon(x, y)(y^2 - x^2)}{\int dxdy \varepsilon(x, y)(y^2 + x^2)},
\]

\[
\varepsilon_p = \frac{\int dxdy (T_{xx} - T_{yy})}{\int dxdy (T_{xx} + T_{yy})},
\]

\[
\langle v_T \rangle = \frac{\int dxdy \varepsilon(x, y)\gamma_T v_T}{\int dxdy \varepsilon(x, y)\gamma_T}
\]
The ratios of the emitted thermal photon yield as a function of time in a single event with different size parameters.
Elliptic flow of thermal photons for 0–40% central collisions of Pb nuclei at LHC.

$v_2$ with and without the prompt photon contribution for smooth and fluctuating IC.
This e-by-e hydrodynamic model successfully reproduces both centrality dependence and $p_T$ shape of charged particle elliptic flow.

$p_T$ spectra of positive pions for 200A GeV Au+Au collisions at RHIC calculated with averaged and fluctuating initial states with varying $\sigma$.

Elliptic flow of charged particles at different centralities with two different values of $\sigma$. 