Influence of initial state fluctuations on the production of thermal photons

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Plan of the talk:

- Motivation
- Thermal photons from event-by-event fluctuating initial conditions
- Collision centrality dependence at RHIC and LHC
- Initial formation time ($\tau_0$) dependence
- Results from centrality dependent $\tau_0$ values
- Central to peripheral ratio ($R_{cp}^y$) of thermal photon yield
- Elliptic flow of thermal photons from fluctuating initial conditions
- Summary and conclusions
Event-by-event hydrodynamics and initial density profile


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

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

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

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

- \( \sigma \) is a free parameter determining the size of the fluctuation.

- Successfully reproduces both the measured centrality dependence and the \( p_T \) shape of charged particle elliptic flow upto \( p_T \sim 2 \) GeV.

Photons are especially suitable for probing fluctuations in the initial conditions.
Thermal photons from smooth and fluctuating initial density profiles

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 larger radial flow.
The effect of fluctuations in the initial conditions is more pronounced:

- for peripheral collisions than for central collisions.
- at RHIC than at LHC.
Results are sensitive to the initial formation time and size parameter

Initial formation time of the plasma \( \tau_0 \) is not known unambiguously.

The range of \( \tau_0 \) mostly used is 0.17-0.6 \( \text{fm/c} \).

\( p_T \) spectra are compared for \( \tau_0 \) values 0.17 and 0.60 \( \text{fm/c} \).

Spectra fall sharply for larger values of \( \tau_0 \).

Difficult to differentiate between enhancement due to:

- IC fluctuations
- a relatively smaller value of \( \tau_0 \).

Effect of centrality dependent formation time and fluctuating IC

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 Risto Paatelainen

<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>

A suitably normalized ratio of central to peripheral yield of thermal photons ($R^\gamma_{cp}$) can be a useful measure of the fluctuation size scale by reducing the uncertainties in the model calculation.

$R^\gamma_{cp}$ is defined as:

$$R^\gamma_{cp} |_i = \left( \frac{dN / d^2p_T dY}{dN / d^2p_T dY} \right)_{0-10\%} \times \left( \frac{N_{bin} |_{i-j\%}}{N_{bin} |_{0-10\%}} \right)$$

$R^\gamma_{cp}$ is calculated as a function of collision centrality for different values of $p_T$ and $\sigma$.

Note: we choose a different definition of $R^\gamma_{cp}$ rather than the conventional definition. The numerator is kept fixed in our case as hydrodynamics is known to work better for central collisions.
Thermal photons $R'_{cp}$ at RHIC for $\sigma$ values 0.4 & 0.8 fm

Au+Au@200 AGeV $\tau_0=0.17$ fm/c

$p_T = 1$ GeV/c

$p_T = 2$ GeV/c

$p_T = 3$ GeV/c

$p_T = 4$ GeV/c

$p_T = 5$ GeV/c

$p_T = 6$ GeV/c

$v_2(p_T)$ of thermal photons from 200A GeV Au+Au@RHIC & 20-40% centrality bin

RP: reaction plane
PP: participant plane

Larger $v_2$ from fluctuating IC for $p_T > 2$ GeV/c compared to smooth IC.

Low $p_T$ part ($< 2$ GeV/c) is not affected significantly.

$v_2(PP) = \langle \cos(2(\varphi - \psi_{PP})) \rangle_{\text{events}}$  
$v_2(RP) = \langle \cos(2\varphi) \rangle_{\text{events}}$
Comparison with the direct photon $v_2$ data from PHENIX

Our results are still well below the experimental data points.

Larger $\tau_0$ and smaller freezeout temperature increase the $v_2$ significantly, however not enough to match the data points.
Time evolution of $p_T$ spectra & $v_2(p_T)$ of thermal photons

$\tau=0.17$ fm/$c$, $\sigma=0.4$ fm

$\tau=3.0$ fm/$c$, $\sigma=0.4$ fm

RC, Holopainen, Renk, Eskola, in preparation
Summary and conclusions

- Fluctuations in the initial QCD matter density distribution lead to a significant enhancement in the production of thermal photons compared to a smooth initial state averaged profile.

- The enhancement is found to be more pronounced for peripheral collisions than for central collisions. The relative enhancement is found to be comparatively less at LHC than at RHIC for the same centrality bin.

- The \( p_T \) spectra at RHIC and LHC are found to be quite sensitive to the value of the initial formation time which may also vary with collision centralities.

- The \( p_T \) spectra alone are found to be insufficient to quantify the fluctuations in the initial density distribution due to the uncertainties in the initial conditions.

- A suitably normalized ratio of central-to-peripheral yield as a function of collision centrality and \( p_T \) can be a useful measure of the fluctuation size scale.

- Fluctuations in the IC enhance the \( v_2(p_T) \) significantly for \( p_T > 2 \text{ GeV}/c \), however not enough to explain the experimental data points.
Thank You
Results from smooth and fluctuating initial conditions.

Two very hot events and two relatively cold events are chosen for the fluctuating IC.

- **Hot events**: entropy larger than average entropy.
- **Cold events**: entropy smaller than average entropy.

The cold events produce more photons compared to the smooth IC for $p_T \geq 3$ GeV/c due to the presence of hotspots.

Ratio of photon production from fluctuating and smooth IC at different \( p_T \) as a function of the size parameter \( \sigma \).

200A GeV Au+Au@RHIC, 0-20% centrality bin

Thermal Photons

\[
\frac{\text{d}N(\text{fluctuating IC})}{\text{d}N(\text{smooth IC})} \quad \sigma (\text{fm})
\]

- \( p_T = 5 \text{ GeV/c} \)
- \( p_T = 3 \text{ GeV/c} \)
- \( p_T = 1 \text{ GeV/c} \)

$R_{\gamma_{cp}}$ for thermal photons at RHIC, size parameter 0.4 fm and $\tau_0 = 0.6$ fm/c.
Thermal photons from smooth and fluctuating IC at RHIC comparison between results from $\tau_0 = 0.17$ and $0.20$ fm/c
$R_{\gamma cp}$ as a function of $\sigma$ for different $p_T$

200A GeV Au+Au@RHIC
Thermal Photons, $\tau_0=0.17$ fm/c

$p_T=2$ GeV/c

$p_T=3$ GeV/c

$p_T=4$ GeV/c

$p_T=5$ GeV/c

$t = 0.17$ fm/c, $\sigma = 0.4$ fm

$\tau = 3.0$ fm/c, $\sigma = 0.4$ fm

$\tau = 0.17$ fm/c, $\sigma = 0.8$ fm

$\tau = 3.0$ fm/c, $\sigma = 0.8$ fm