Geometrical Scaling of Direct Photons in Relativistic Heavy Ion and d+Au Collisions

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Gluon saturation and basics of geometrical scaling

We show the key results from theses papers: VK and MP, EPJC 80 (2020) [arXiv:1907.03815 [nucl-th]]; VK and MP, [arXiv:2203.16204 [nucl-th]]

Let us consider relativistic A+A, d+A, and p+p collisions

Overview of the collision geometry

Left panel: the side view of large and small system collisions

Right panel: the front view of d+Au and p+p collisions

Active transverse (interaction) area shown in colors

$S_T$ is a parameter characterizing geometrical overlap area of colliding nuclei

$S_T \sim \pi N_{\text{part}}^{2/3} / Q_0^2$

Sphere radius: $\sim N_{\text{part}}^{1/3} / Q_0$

Geometrical scaling phenomenon emerges when particles are produced in a kinematical region, where the only relevant intrinsic scale is the parton saturation momentum of a radiation source.

$$Q_{\text{sat}} = N_{\text{part}}^{1/6} Q_0 \left( \frac{p_T}{x_0 \sqrt{S_{NN}}} \right)^{-\lambda/2}$$

We have studied direct photon $p_T$-spectra related to GS.

$N_{\text{part}}$ is an important quantity in our analysis

<table>
<thead>
<tr>
<th>$W$ [GeV]</th>
<th>System</th>
<th>Centrality</th>
<th>$N_{\text{part}}$</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>Au+Au</td>
<td>c1 0-20 %</td>
<td>277.5</td>
<td>PHENIX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c2 20-40 %</td>
<td>135.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>mb 0-92 %</td>
<td>106.3</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>Au+Au</td>
<td>c1 0-20 %</td>
<td>277.5</td>
<td>PHENIX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c2 20-40 %</td>
<td>135.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c3 40-60 %</td>
<td>56.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c4 60-92 %</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>62.4</td>
<td>Au+Au</td>
<td>mb 0-86 %</td>
<td>114.5</td>
<td>PHENIX</td>
</tr>
<tr>
<td>200</td>
<td>Cu+Cu</td>
<td>c1 0-40 %</td>
<td>66.4</td>
<td>PHENIX</td>
</tr>
<tr>
<td></td>
<td></td>
<td>mb 0-94 %</td>
<td>34.6</td>
<td></td>
</tr>
<tr>
<td>2760</td>
<td>Pb+Pb</td>
<td>c1 0-20 %</td>
<td>308.0</td>
<td>ALICE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>c2 20-40 %</td>
<td>157.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>c3 40-80 %</td>
<td>45.7</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>d+Au</td>
<td>p+p</td>
<td></td>
<td>PHENIX</td>
</tr>
</tbody>
</table>

Data sets of direct photon $p_T$-spectra used in our work

Introducing the variable $W = \sqrt{S_{NN}} \times x_0$

we will further have

$$\tau = \frac{p_T}{Q_{\text{sat}}} = \frac{1}{N_{\text{part}}^{1/6}} \frac{p_T}{Q_0} \left( \frac{p_T}{W} \right)^{\lambda/2}$$

where $\lambda \approx 0.2 - 0.35$; $Q_0 \sim 1$ GeV/c; $x_0 = 10^{-3}$ for a typical value of Bjorken $x$, where the saturation effects become important
Gluon saturation and basics of geometrical scaling

Direct-photon multiplicity scaling (MS)

\[
\frac{1}{(dN_{ch}/d\eta|_{\eta \approx 0})} \frac{dN_\gamma}{d^2p_Td\eta} = \frac{1}{Q_0^2} G(p_T)
\]

G is a universal energy- and multiplicity-independent function of \( p_T \)

Direct-photon geometrical scaling (GS)

\[
\frac{1}{S_T} \frac{dN_{\gamma, ch}}{d^2p_Td\eta} = F_{\gamma, ch}(\tau)
\]

\( F_{\gamma, ch} \) is a universal energy-independent function of the scaling variable \( \tau \)

Glauber model predictions for \( S_T \) scaled by \( N_{part}^\delta \) with \( \delta = 2/3 \)

for ALICE Pb+Pb 2760 GeV simulation data as upper (green) squares

for PHENIX Au+Au 200 GeV simulation data as lower (red) circles

Direct photon \( p_T \) - spectra for various colliding nuclei and collision centrality selections at three center-of-mass energies

Direct photon \( p_T \) - spectra scaled by \((dN_{ch}/d\eta)^\alpha\)

Both MS and GS scaling laws can be related

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\[ Q_{\text{sat}} [\text{large}] = Q_0 \left( \frac{N_{\text{part}}}{n_{\text{part}}^{2/3}} \right)^{1/2} \left( \frac{p_T}{W} \right)^{-\lambda/2} \]

One-saturation scale of a large nucleus probed by a small nucleus in symmetric collisions

\[ Q_{\text{sat}} [\text{small}] = Q_0 n_{\text{part}}^{1/6} \left( \frac{p_T}{W} \right)^{-\lambda/2} \]

One-saturation scale of a small nucleus in symmetric collisions

\[ Q_{\text{sat}}^{\text{eff}} = \sqrt{Q_{\text{sat}} [\text{large}] Q_{\text{sat}} [\text{small}]} = \left( \frac{N_{\text{part}}^3}{n_{\text{part}}} \right)^{1/12} Q_0 \left( \frac{p_T}{W} \right)^{-\lambda/2} \]

Effective two-saturation scale in asymmetric collisions

\[ \tau = \frac{1}{N_{\text{part}}^{\delta/4} Q_0} \left( \frac{p_T}{W} \right)^{\lambda/2} \]

Variable \( \tau \) for large-large collision systems

(as on slide 2 for \( \delta = 2/3 \))

\[ \tau = \frac{1}{(N_{\text{part}}^3 / n_{\text{part}})^{\delta/8} Q_0} \left( \frac{p_T}{W} \right)^{\lambda/2} \]

Variable \( \tau \) for small-large collision systems

Left figure shows the illustration of geometrical scaling of direct photon \( p_T \)-spectra as ratios

1: of the A+Au scaled most central data to the A+Au scaled semi-central data

2: of the A+Au scaled most central data to the d+Au minimum bias data (with one-saturation scale and two-saturation scales)

3: of the A+Au scaled most central data to the p+p data

The figure is made at the energy \( \lambda = 0.2 \)

Direct photon \( p_T \)-spectra for various colliding nuclei and centralities at different energies

(the yield from p+p overall has smaller slope than the yields from A+A collisions)
Gluon saturation and basics of geometrical scaling

Geometrical scaling of direct photon $p_T$- spectra in large-large collision systems, as ratios

Left 1: of the Au+Au scaled most central data to the Au+Au scaled semi-central data

Left 2: of the Au+Au scaled most central data to the Au+Au scaled semi Peripheral data

Left 3: of the Au+Au scaled most central data to the Au+Au scaled peripheral data

Left 4: of the Au+Au scaled most central data to the Cu+Cu scaled most central data (orange-colored down triangles)

Right 1: of the Pb+Pb scaled most central data to the Pb+Pb scaled semi-central data

Right 2: of the Pb+Pb scaled most central data to the Pb+Pb scaled semi peripheral data

The figures are made at

$\delta = 1$ (upper both)

$\delta = 2/3$ (middle both)

$\delta = 1/3$ (lower both)

All figures are made at the same energy $\lambda = 0.2$

GS is best observed in the middle figures made at $\delta = 2/3$ and $\lambda = 0.2$
Gluon saturation and basics of geometrical scaling

Geometrical scaling of direct photon $p_T$ - spectra in large-large collision systems, as ratios

1. Of the Au+Au 200 GeV scaled most central data to the Au+Au 62.4 scaled minimum bias data

2. Of the Au+Au 200 GeV scaled most central data to the Pb+Pb 2760 GeV scaled most central data

The figures are made at
- $\lambda = 0$ (upper left)
- $\lambda = 0.1$ (upper right)
- $\lambda = 0.2$ (lower left)
- $\lambda = 0.3$ (lower right)

All figures are made at the same centrality $\delta = 2/3$

GS is best observed in the figures made at $\delta = 2/3$ and $\lambda = 0.1 - 0.2$

$\lambda = 0.2$ is very close to what has been used originally in hadronic collisions: Phys. Rev. D 92, 074036 (2015)

i) We have established GS for direct photon invariant yield data in A+A and observed a GS sign in d+Au collisions

ii) Our analysis of the p+p data is rather inconclusive, due to the large uncertainties seen in the ratio figure on slide 4

iii) New data on direct photon $p_T$ - spectra, especially, for p+p and small-large collision systems will make our analysis more complete