Geometrical Scaling of Direct-Photon Production in Hadron Collisions from RHIC to the LHC

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Abstract

We consider pp, dAu and AuAu production of photons at RHIC energies, and PbPb collisions at LHC energy. We show that the inclusive spectrum of photons in the transverse momentum range of 1 GeV < $p_T$ ≤ 4 GeV satisfies geometric scaling. Geometric scaling is a property of hadronic interactions predicted by theories of gluon saturation, and expresses rates in terms of dimensionless ratios of the transverse momentum to saturation momentum. We show excellent agreement with geometric scaling with the only input being the previously measured dependence of the saturation momentum upon Bjorken $x$ and centrality.

1. Introduction

The phenomenon of gluon saturation arises at high energies when the density of gluons per unit area in a hadron is large \textsuperscript{1,2,3,4}. Saturation implies the existence of a saturation momentum scale;

$$Q_{\text{sat}}^2 = \frac{\kappa}{\pi R^2} \frac{dN}{dy}, \quad (1)$$

where $R$ is the hadron size, $dN/dy$ is the gluon density per unit rapidity, and $\kappa$ is a constant of order 1. Up to effects of a running coupling constant, at very large $Q_{\text{sat}}$, the saturation momentum is the only scale for physical processes. This implies scaling relations for physical processes. In particular, geometric scaling was first discovered in deep inelastic scattering \textsuperscript{5,6}. It was later applied to high...
energy particle production in hadron-hadron scattering and explains features of $pp$ and $pA$ scattering as a function of multiplicity, as well as particle production in heavy ion collisions for fixed centrality as a function of energy [7, 8, 9, 10, 11].

In this paper, we intend to apply geometric scaling to photon production in hadron-hadron scattering at RHIC and LHC energies ($\sqrt{s_{NN}} = 200$ GeV and 2760 GeV). This is an extension of work where geometric scaling was applied to reproduce the multiplicity dependence of photon production data for AuAu collisions at RHIC [12]. This paper considers in addition $pp$ and $dAu$ collisions at RHIC energy and $PbPb$ collisions at LHC energy. The obtained agreement with experimental data indicates that geometric scaling works well for photon production.

2. Scaling

Geometric scaling is a property of particle densities. In the theory of the Color Glass Condensate, one computes these densities from an underlying theory, and in the absence of the effect of running coupling, this theory is controlled by only one scale, the saturation momentum. Therefore, in a collision with overlap area $\pi R^2$, for the production of a photon of momentum $p_T$:

$$\frac{1}{\pi R^2} \frac{d^2N}{dyd^2p_T} = F\left(\frac{Q_{sat}}{p_T}\right).$$  \hspace{1cm} (2)

The transverse overlap area $\pi R^2$ can be estimated for symmetric systems to be proportional to $N_{part}^{2/3}$. The saturation scale is given by [7]:

$$Q_{sat}^2 = N_{part}^{1/3} \left(\frac{E}{p_T}\right)^\delta$$  \hspace{1cm} (3)

with $\delta$ in the range of 0.22 to 0.28 and $E$ the center of mass energy $\sqrt{s_{NN}}$. This parameterization is consistent with fits to deep inelastic scattering [13].

The scaling relationship above will work for any function. It is convenient for us however to parameterize the functional form of the photon distribution as a power law in $p_T$. For the finite range of momenta involved, roughly $1-4$ GeV,
such a parameterization of the data is quite good. We use

\[ F \propto \left( \frac{Q_{\text{sat}}}{p_T} \right)^a = \left( \frac{N_{\text{part}}^{1/6} \cdot E^{\delta/2}}{p_T^{1+\delta/2}} \right)^a. \]  

The geometric scaling assumption can then be tested via rescaling the invariant yield only. Figure 1 shows a collection of data on direct photon production in nuclear collisions taken from \[14, 15, 16\]. All data have been fit to a power law \( A \cdot p_T^{-n} \) and different slopes are extracted for the various systems, between \( \approx 5.2 - 6.9 \). In the following a slope of \( n = 6.1 \) will be used.

The knowledge of the slope fixes the only unknown \( a \), when combining Equation (3) and (4) to extract the \( N_{\text{part}} \) dependence of the spectrum at a fixed \( p_T \):

\[ \frac{d^2N}{dydp_T} = A p_T^{-n} \propto \left( \frac{N_{\text{part}}^{1/6} \cdot E^{\delta/2}}{p_T^{1+\delta/2}} \right)^a \cdot N_{\text{part}}^{2/3} \]  

\[ \Rightarrow a = \frac{n}{1 + \delta/2} \]  

so the invariant yield roughly changes as

\[ N_{\text{part}} \frac{d^2N}{dydp_T} \approx N_{\text{part}}^{1.57} \]  

This estimate is close to the observed centrality dependence of \( N_{\text{part}}^{1.48} \) at RHIC energies \[17\]. A general scaling relation between different centralities and collision energies is given by the factor

\[ \frac{N_{\text{part}, A}^{a/6+2/3} \cdot E_A^{\delta/2}}{N_{\text{part}, A}^{a/6+2/3} \cdot E_A^{\delta/2}}. \]  

This relation has been used in Figure 2 to rescale the direct photon production in central \( Pb + Pb \) collisions at the LHC, as well as in \( pp \) at RHIC to the direct photon production in central \( AuAu \) collisions at RHIC. In particular it is remarkable that the measurement of direct photons in \( pp \) obeys the scaling over three orders of magnitude within less than a factor of two. At SPS energies \( \sqrt{s_{NN}} = 17.3 \text{ GeV} \) geometric scaling is not expected to hold, nevertheless we found that the scaled direct photon data from \[18, 19\] is also close to the universal curve in Figure 2.
3 SUMMARY AND CONCLUSIONS

For asymmetric systems, such as $dAu$, the scaling relation is more complicated, since one cannot use $N_{part}$ any more as a proxy for the geometry. E.g., in Equation (2) only the overlap matters, while $N_{part}$ is largely driven by the thickness of the larger partner. Due to the asymmetric nature of the deuteron in itself this overlap area can range between one to two times the $pp$ value. In the following the average number of participants from the deuteron $\langle N_{part}[d]\rangle = 1.6$ as calculated in [20] is used so $\pi R^2 \propto 3.2^{2/3}$. Similarly, in Equation (3) the saturation scales of the individual partners need to be considered for $d$ and $Au$.

It is thus estimated as:

$$\frac{N_{part}^{a/6+2/3}}{3.2^{2/3} \cdot 1.6^{a/12} \cdot 1.97^{a/12}}.$$

Here we have assumed that the saturation momentum for the asymmetric $dA$ collision is

$$Q_{sat}^2 = \sqrt{Q_{sat}^d Q_{sat}^A}.$$

This is the case for an emission energy of the photon large compared to the saturation momentum, which should be the case for $dAu$ collisions at RHIC energies.

3. Summary and Conclusions

Geometric scaling provides a good description of the centrality and energy dependence of nucleus-nucleus collisions. It also includes $pp$ and $dAu$ scattering. This is quite remarkable since this involves an extrapolation over several orders of magnitude in the number of nucleon participants, and because the scaling law for the saturation momentum in $dA$ collisions is different in terms of the number of nucleon participants than it is in symmetric collisions.

But how can geometric scaling work so well? It is a property of particle emission that ignores final state interactions, but one expects that the photons emitted from quarks and gluons arise from quarks and gluons that have undergone interactions. On the other hand, if there is scale invariance of the expansion, the saturation momentum will remain the only scale in the problem.
Thus until particle masses are important, or until the size of the system in the transverse direction becomes important, geometric scaling should be preserved. The former would be true if the system produces photons at an energy scale large compared to meson masses, which might be possible. The latter is more difficult, since flow measurements for photons demonstrate that they do have an azimuthal anisotropy with respect to the event reaction plane. This is conventionally associated with transverse expansion and it requires that the photons be produced at times where the size of the system is important.

So there is a mystery: How do we maintain geometric scaling in the presence of transverse flow? If this is possible, it may only be established after detailed computation that includes the effects of transverse flow. It also would probably require that the internal dynamics, if associated with early time emission of the Glasma would be different from that of the thermalized Quark Gluon Plasma. This may be possible, but again requires explicit computation.

Nevertheless, geometric scaling appears to provide an excellent description of the data. Either it implies there is something very interesting and not yet understood about the dynamics and evolution of the Glasma or thermalized Quark Gluon Plasma, or it is an accident. This result certainly encourages attempts at deeper understanding.

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Table 1: Employed $N_{part}$ values with the references to the experimental papers on the direct photon spectra and numerical values on $N_{part}$.

| $\sqrt{s_{NN}}$ (GeV) | System | $N_{part}$ | Experiment | References |
|------------------------|--------|------------|------------|------------|
| 200 $p + p$            | 2      | PHENIX     |            |            |
| 200 $Au + Au$ (0-20%)  | 280    | PHENIX     |            |            |
| 200 $d + Au$           | $N_{part}^{d} = 1.6$ | PHENIX     |            |            |
| 2760 $Pb + Pb$ (0-40%) | 233    | ALICE      |            |            |

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Figure 1: Measurements of invariant yields of direct photon production below $p_T = 5 \text{ GeV}/c$ compared to power law parameterisations.

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Figure 2: Geometrically scaled invariant yields of direct photon production below $p_T = 5$ GeV/c, the assumed common power law shape $p_T^{-6.1}$ has been fit to the PHENIX Au+Au data.
Figure 3: Comparison of scaled invariant yields of direct photon production to the power law used for the scaling (fixed slope of 6.1, fit to the PHENIX Au+Au data). The uncertainties are combined systematic and statistical uncertainties of the measurements.

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