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Geometrical scaling of jet fragmentation photons

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Abstract

We discuss jet fragmentation photons in ultrarelativistic heavy-ion collisions. We argue that, if the jet distribution satisfies geometrical scaling and an anisotropic spectrum, these properties are transferred to photons during the jet fragmentation.

Keywords:
Photon production, Jet fragmentation, Geometrical scaling

1. Introduction

Recent photon measurements at RHIC and LHC have shown deviations between experimental data and theoretical estimates of the direct photon spectrum and its azimuthal anisotropy [1, 2, 3]. To consistently explain these deviations, much effort has been devoted to the continuous improvement of the hydrodynamic modeling [4, 5, 6].

On the other hand, it was also suggested that the photon spectra have geometrical scaling properties in a wide rage of collision energies and centralities [7]. In this contribution, we discuss the jet fragmentation processes as a possible mechanism to give rise to the geometrical scaling of photons. Assuming that the spectrum of quark jets satisfies geometrical scaling, we argue that this scaling property is transferred to the photon spectrum through collinear photon emissions. We also demonstrate that the collinear emission preserves the second harmonic coefficient $v_{\rm jet}^{(2)}$ of quark jets induced by the energy loss in a hot medium, suggesting an anisotropy of the photon spectrum close to that of quark jets.

2. Inclusive photon production in jet fragmentation

We shall begin with the photon production rate which is given by a convolution of the jet distribution $N_{\rm jet}$ and the photon production rate n_γ in the fragmentation of one quark jet as

$$\frac{dN_\gamma}{dy_\gamma d^2\boldsymbol{p}} = \int d^2\boldsymbol{k}_1 \int dy_1 \int d^2\boldsymbol{k}_2 \int dy_2 \frac{dN_{\rm jet}}{d^2\boldsymbol{k}_1 dy_1 d^2\boldsymbol{k}_2 dy_2} \cdot \frac{dn_\gamma}{dy_\gamma d^2\boldsymbol{p}}(\boldsymbol{p}, y_\gamma; \boldsymbol{k}_\perp, y_1, y_2)\,. \tag{1}$$

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The dijet distribution can be expanded into the Fourier components of the azimuthal angle $\phi_{\boldsymbol{k}}$ as

$$\frac{dN_{\rm jet}}{d^2\boldsymbol{k}_1 dy_1 d^2\boldsymbol{k}_2 dy_2} = \delta^{(2)}(\boldsymbol{k}_{1\perp} + \boldsymbol{k}_{2\perp}) f_0(k_\perp; y) \left[1 + 2v_{\rm jet}^{(2)} \cos(2\phi_{\boldsymbol{k}}) + \cdots \right], \tag{2}$$

where $f_0(k_\perp; y)$ denotes the isotropic component. We have $\boldsymbol{k}_{1\perp} = -\boldsymbol{k}_{2\perp} \equiv \boldsymbol{k}_\perp$, since dijets are produced in back-to-back configurations in the transverse plane. We assume a boost invariant distribution which depends only on the rapidity difference $y = (y_1 - y_2)/2$, and is independent of the average $y_{\rm ave} = (y_1 + y_2)/2$.

As for the photon production rate n_γ, we compute the production rate in the center-of-mass (COM) frame of each parton scattering [denoted as $d\bar{n}_\gamma/(dy'_\gamma d^2\boldsymbol{p})$], and then transform back to the COM frame of the AA collision by using the Lorentz boost along the beam axis. This boost can be implemented as $y'_{1,2} = y_{1,2} - y_{\rm ave} = \pm y$, where the upper and lower signs are for y'_1 and y'_2, respectively. Boosting also the photon rapidity as $y'_\gamma = y_\gamma - y_{\rm ave}$, we find a relation between the photon production rates as $dn_\gamma(\boldsymbol{p}, y_\gamma; \boldsymbol{k}_\perp, y_{1,2}) = \bar{n}_\gamma(\boldsymbol{p}, y_\gamma - y_{\rm ave}; \boldsymbol{k}_\perp, \pm y)$. Note also that the measure is invariant under this shift $dy_\gamma = dy'_\gamma$.

Inserting these expressions into Eq. (1), we find relations between the photon and jet spectra for the isotropic and the second-harmonic components, respectively, as

$$\frac{1}{2\pi p_\perp}\frac{dN_\gamma}{dy_\gamma dp_\perp} = 2\int d^2\boldsymbol{k}_\perp \int dy \int dy'_\gamma\, f_0(k_\perp; y) \frac{d\bar{n}_\gamma}{dy_\gamma d^2\boldsymbol{p}}(\boldsymbol{p}, y'_\gamma; \boldsymbol{k}_\perp, \pm y), \tag{3}$$

$$v_\gamma^{(2)} = \frac{\int d^2\boldsymbol{k}_\perp \int dy \int dy'_\gamma\, v_{\rm jet}^{(2)} \cos(2\phi_{\boldsymbol{k}}) f_0(k_\perp; y) \frac{d\bar{n}_\gamma}{dy_\gamma d^2\boldsymbol{p}}(\boldsymbol{p}, y'_\gamma; \boldsymbol{k}_\perp, \pm y)}{\int d^2\boldsymbol{k}_\perp \int dy \int dy'_\gamma\, f_0(k_\perp; y) \frac{d\bar{n}_\gamma}{dy'_\gamma d^2\boldsymbol{p}}(\boldsymbol{p}, y'_\gamma; \boldsymbol{k}_\perp, \pm y)}, \tag{4}$$

where we changed the integral variables from (y_1, y_2) to $(y, y_{\rm ave})$, and then shifted one of the variables as $y_{\rm ave} \to y'_\gamma = y - y_{\rm ave}$. When the jet distribution is boot invariant, i.e., independent of $y_{\rm ave}$, the photon spectrum is also independent of y_γ and thus is boost invariant.

3. Geometrical scaling of quark jets

Quark jets are produced in the initial $2 \to 2$ hard processes, and the $N_{\rm coll}$-scaled yield is given by

$$\frac{dN_{\rm jet}}{dy_1 dy_2 d^2\boldsymbol{k}_\perp} = \frac{N_{\rm coll}}{\sigma_{NN}} \cdot x_1 f_1(x_1) \cdot x_2 f_2(x_2) \cdot \frac{d\sigma}{d\hat{t}}, \tag{5}$$

where $f_1(x_1)$ and $f_2(x_2)$ are the parton distribution functions (PDFs) in the incident nuclei, and $d\sigma/d\hat{t}$ is the differential hard-scattering cross section. The leading order hard-scattering cross sections and the gluon dominant PDF tell us that the gluon Compton scattering is the dominant $2 \to 2$ process for the quark jet production. Therefore, the rapidity y_2 corresponds to that of a gluon.

Now, we assume that the PDFs are governed by only one mass scale, that is, the saturation momentum Q_s, and examine the parametric dependence of the jet distribution on this scale. Let us see how a product of the overlap function $N_{\rm coll}/\sigma_{NN} \sim N_{\rm part}^{4/3}/\sigma_{NN}$ and the hard-scattering cross section $\sim k_\perp^{-4}$ behaves. In ultrarelativistic heavy-ion collisions, incident nuclei are highly Lorentz-contracted, and each gluon occupies the average transverse area $Q_{\rm sat}^{-2}$. Counting the number of nucleons contained in the reaction zone with a transverse area S, we have $N_{\rm part}^{2/3} \sim S/\Lambda_{\rm QCD}^{-2}$. On the other hand, $N_{\rm part}$ is proportional to atomic number A as $N_{\rm part} \sim A$. The number of partons in a nucleus is also proportional to A, and is alternatively written as the ratio of the transverse nuclear size to the average area occupied by a gluon. Therefore, we have $A \sim (\Lambda_{\rm QCD}^{-1} A^{1/3})^2/Q_{\rm sat}^{-2}$. Eliminating A, we find $N_{\rm part}^{2/3} \sim (Q_{\rm sat}^2/\Lambda_{\rm QCD}^2)^2$. Combining the two expressions for $N_{\rm part}$, we obtain $k_\perp^{-4} N_{\rm coll}/\sigma_{NN} \sim k_\perp^{-4}(N_{\rm part}^{2/3})^2 \Lambda_{\rm QCD}^2 \sim k_\perp^{-4}(S\Lambda_{\rm QCD}^2)(Q_{\rm sat}^2/\Lambda_{\rm QCD}^2)^2 \Lambda_{\rm QCD}^2 \sim S(Q_{\rm sat}/k_\perp)^4$, which does not explicitly depend on $\Lambda_{\rm QCD}$. Then we expect that the quark jet distribution shows geometrical scaling:

$$\frac{1}{S}\frac{dN}{dy_1 dy_2 d^2\boldsymbol{k}_\perp} = \mathcal{N}_{\rm jet}\, g(y) \left(\frac{Q_{\rm sat}}{k_\perp}\right)^\alpha, \tag{6}$$

with an exponent α. The distribution $g(y)$ with respect to the rapidity of jets in their COM frame y defined above is informed from the hard-scattering cross section, and the normalization constant $\mathcal{N}_{\rm jet} \sim O(\alpha_s^2)$ is determined from pQCD calculation.