Tomography of high-energy nuclear collisions with photon-hadron correlations

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Within the next-to-leading order (NLO) perturbative QCD (pQCD) parton model, suppression of away-side hadron spectra associated with a high \( p_T \) photon due to parton energy loss is studied in high-energy heavy-ion collisions. Dictated by the shape of the \( \gamma \)-associated jet spectrum in NLO pQCD, hadron spectra at large \( z_T = p_T^{\gamma}/p_T^{h} \gtrsim 1 \) are more sensitive to parton energy loss and therefore are dominated by surface emission of \( \gamma \)-associated jets, whereas small \( z_T \) hadrons mainly come from fragmentation of jets with reduced energy which is controlled by the volume emission. These lead to different centrality dependence of the \( \gamma \)-hadron suppression for different values of \( z_T \). Therefore, a complete measurement of the suppression of \( \gamma \)-triggered hadron spectra, including its dependence on the orientation of the \( \gamma \)-hadron pair with respect to the reaction plane, allows the extraction of the spatial distribution of jet quenching parameters, achieving a true tomographic study of the quark-gluon plasma in high-energy heavy-ion collisions.

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Jet quenching \cite{1} or suppression of large \( p_T \) hadrons, caused by parton energy loss due to strong interaction between jets and the dense medium, has become a powerful tool for the study of properties of the quark-gluon plasma \cite{2} in high-energy heavy-ion collisions. Experimental studies of jet quenching include suppression of single \cite{3} \cite{4}, dihadron (back-to-back) \cite{5} and \( \gamma \)-hadron spectra. The strong suppression of large \( p_T \) single hadron spectra and its centrality dependence at the Relativistic Heavy-ion Collider (RHIC) \cite{3} \cite{5}, indicate a picture of surface emission of jets. Most of jets, initially produced at the center of collisions, undergo large amount of energy loss and do not contribute to the final observed large \( p_T \) hadron spectra. High \( p_T \) dihadrons, on the other hand, come not only from jet pairs close and tangential to the surface of the dense medium but also from punch-through jets originating from the center of the system \cite{6}, leading to their increased sensitivity to the initial gluon density as compared to single hadrons.

We will focus in this paper on the study of \( \gamma \)-triggered away-side hadron spectra in heavy-ion collisions within the next-to-leading order (NLO) perturbative QCD (pQCD) parton model. Since a photon does not interact in QCD with the dense medium, its energy approximately reflects that of the initial jet in \( \gamma \)-jet events prior to jet propagation through the medium. One can therefore study the medium modification of the full jet fragmentation function (FF) \cite{7} \cite{8}. By selecting \( \gamma \)-hadron pairs with different values of \( z_T = p_T^{\gamma}/p_T^{h} \), which could be larger than 1 due to radiative correction in NLO pQCD, one can effectively control hadron emission from different regions of the dense medium and therefore extract the corresponding jet quenching parameters.

Within pQCD parton model, the NLO corrections \((\alpha_s \alpha_s^2)\) to photon and photon-hadron production cross sections include 1-loop corrections to \( 2 \to 2 \) tree level processes and \( 2 \to 3 \) tree level contributions which have two-cutoff parameters, \( \delta_s \) and \( \delta_c \), to isolate the soft and collinear divergences in the squared matrix elements \cite{9} \cite{10}. This results in a set of two-body and three-body weights that depend on the cut-offs. The dependence cancels when the weights are combined in the calculation of physical observable, such as inclusive photon and photon-hadron cross sections. In this paper, we will use a Monte Carlo implementation \cite{10} of the NLO pQCD calculation for the invariant cross section of photon and photon-hadron production.

Photon production in pQCD includes direct photons from the Compton and annihilation subprocesses and bremsstrahlung photons from jet fragmentation in high-energy \( p + p \) collisions. Since the bremsstrahlung photons are always accompanied by nearly collinear hadrons, an isolation-cut can be applied on the photon signal to suppress bremsstrahlung-like photons both in theory \cite{10} and experiments \cite{11}. Even though such isolation-cut cannot eliminate fragmentation contributions, it can significantly reduce the fraction of fragmentation photons to about less than 10% for \( p_T^{\gamma} > 7 \) GeV/c. For the study of \( \gamma \)-hadron correlation in this paper, we will focus mainly on photons with isolation cuts. Therefore, we can neglect those photons that are produced via induced bremsstrahlung \cite{12}, jet-photon conversion \cite{13} and thermal production \cite{14} \cite{15} in high-energy heavy-ion collisions.

To take into account parton energy loss in \( \gamma \)-hadron correlation in high-energy heavy-ion collisions, we will use an effective form of medium modified FF’s as in previous studies \cite{6} \cite{16} with an average energy loss,

\[
\Delta E \approx \left( \frac{dE}{dL} \right)_{\text{1d}} \int_{\tau_0}^\infty d\tau \frac{\tau - \tau_0}{\tau_0 \rho_0} \rho_\gamma(\tau, \mathbf{b}, \mathbf{r} + \mathbf{n}\tau),
\]

(1)

for a quark (gluon energy loss is 9/4 of a quark) produced
at a position $r$ and traveling along the direction $n$, where,

$$
\langle \frac{dE}{dL} \rangle_{1d} = \epsilon_0 (E/\mu_0 - 1.6)^{1.2}/(7.5 + E/\mu_0) \tag{2}
$$

is the parameterized average quark energy loss per unit length in a 1-d expanding medium with an initial average gluon density $\rho_0$ at time $\tau_0$. The parameter $\epsilon_0$ is the initial quark energy loss per unit distance and is proportional to $\rho_0$. A hard-sphere nuclear overlap geometry is used as in previous studies $[6,10]$, which differs at most about 10% from a Wood-Saxon geometry.

We will use the KKP parameterization $[18]$ for parton FF’s in vacuum. The parton distributions per nucleon inside a nucleus are assumed to be factorizable into parton distributions in a nucleon given by the CTEQ6M parameterization $[19]$ and a nuclear modification factor $[20]$, including the isospin dependence. In the following, we will use values of the energy loss parameters ($\epsilon_0 = 1.68$ GeV/fm, $\mu_0 = 1.5$ GeV and $\tau_0 = 0.2 \text{ fm}/c$) as determined from a simultaneous fit to the suppression of both single and dihadron spectra $[6]$, except when specified.

For the study of $\gamma$-hadron spectra we follow Ref. $[7]$ and define the $\gamma$-triggered FF as,

$$
D_{AA}(z_T) = \frac{\int d\phi dp_T^\gamma d\gamma dy h dp_T^\gamma \frac{d\gamma}{dp_T^\gamma} \frac{d^3A}{d^3p_T^\gamma} \frac{d\gamma}{dp_T^\gamma} \frac{d^3A}{d^3p_T^\gamma}}{\int dp_T^\gamma d\gamma \frac{d^3A}{d^3p_T^\gamma} \frac{d\gamma}{dp_T^\gamma} \frac{d^3A}{d^3p_T^\gamma}}, \tag{3}
$$

where $z_T = p_T^\gamma/p_T^\gamma$ and $-\pi/2 < \phi < \pi/2$ is the azimuthal angle between the triggered $\gamma$ and the associated hadron on the away-side. The above $\gamma$-triggered FF is a sum of FF’s of the away-side jets (quark and gluon) weighted with the fractional $\gamma$-jet production cross sections and convoluted with the transverse momentum smearing due to NLO processes, which can be exploited to explore different limit of jet quenching as we will discuss later. The hadron-triggered FF’s have been similarly defined for the study of dihadron spectra $[6,16]$ by replacing photons with triggered hadrons in the above equation.

Shown in the upper panel of Fig. $1$ are the calculated $\gamma$-triggered FF’s in $p+p$ collisions at the RHIC energy as compared to PHENIX preliminary data. They agree very well for different values of $p_T^{\gamma}$. In the lower panel of Fig. $1$ we show the $\gamma$-triggered FF in central $Au+Au$ (solid) for $8 < p_T^{\gamma} < 16 \text{ GeV}/c$ as compared to $p+p$ (dashed) collisions. With the same energy loss parameters as determined by the single and dihadron suppression $[6]$, the NLO pQCD results agree with the STAR preliminary data very well. Also shown are the calculated hadron-triggered FF’s as compared to the experimental data, which are larger than the $\gamma$-triggered FF’s. This is mainly because the fraction of gluon jets associated with a hadron trigger at this range of $p_T^{\gamma}$ is larger than $\gamma$-triggered jets and the hadron yield of gluon jets is larger than that of quarks. Note that the average initial jet energy associated with a trigger hadron is larger than that associated with a direct photon for the same value of $p_T^{\gamma}$ due to parton fragmentation. We also show in the lower panel the uncertainty, mainly from the scale dependence of the FF’s, of NLO pQCD results for $p+p$ due to the choice of factorization scale $\mu$. Here $M$ is the invariant mass of the dihadron. We will use $\mu = 0.5 p_T^{\gamma}$ for $\gamma$-hadron spectra in this paper unless specified.

To quantify the suppression of hadron and $\gamma$-triggered FF’s in central $Au+Au$ relative to $p+p$ collisions due to jet quenching, as seen in Fig. $1$, one defines the nuclear modification or suppression factor,

$$
I_{AA} = D_{AA}/D_{pp}, \tag{4}
$$

for both hadron and $\gamma$-triggered FF. Shown in the upper panel of Fig. $2$ are the calculated nuclear modification factors both in LO (dashed) and NLO (solid) for different values of the energy loss parameter $\epsilon_0$. As compared to the same study of the hadron-triggered FF $[6]$, $I_{AA}(z_T)$ for $\gamma$-triggered hadron spectra at small $z_T \leq 0.6$, which are dominated by volume emission, is more sensitive to the energy loss parameter $\epsilon_0$ and therefore provides a better phenomenological constraint on the medium proper-
ties when compared to experimental data.

In the LO pQCD calculation, transverse momentum of the
associated jet is balanced exactly by the direct photon
in tree $2 \rightarrow 2$ processes. This limits $z_T = p_{TJ}^2 / p_{Tq}^2 \leq 1$. In
NLO, however, the initial jet energy can exceed $p_{TJ}^2$ due to
radiative correction or broadening in the initial state and
therefore leads to hadrons with $p_{TJ}^2 > p_{Tq}^2$ or $z_T > 1$. In
this region, the $\gamma$-triggered FF is mainly determined by
the tail of the radiative broadening which falls sharply
as a function of the jet transverse momentum. Therefore,
contributions to the final associated hadron spectra
$D_{AA}(z_T)$ ($z_T > 1$) from $\gamma$-triggered jets with even a small
amount of energy loss will be suppressed. Only those jets
from surface emission that escape from the medium with-
out energy loss will contribute, whose FF’s are the same
as in the vacuum. Therefore, the nuclear modification
factor $I_{AA}(z_T)$ in this region is mainly determined by the
thickness of the corona of the surface emission. On the
other hand, jets that have lost finite amount of energy
before fragmenting into hadrons will contribute to the
$\gamma$-triggered FF in the region $z_T < 0.6$ where the nuclear
modification factor $I_{AA}(z_T)$ is controlled by volume emis-
sion of jets and is therefore more sensitive to the variation
of the energy loss parameter. The value and $z_T$ depen-
dence of $I_{AA}(z_T)$ in $0.6 < z_T < 1.4$ are determined by the
competition of the two mechanisms of hadron emission.
One can, therefore, determine the jet energy loss param-

ter from different spatial regions in heavy-ion collisions
by measuring the effective $\gamma$-triggered FF in the whole
range of $z_T$, possibly also for different orientation of the
$\gamma$-hadron pair with respect to the reaction plane, achiev-
ing a true tomographic study of the dense medium. For
precision studies one should also consider the effect of in-
trinsic transverse momentum broadening via systematic
analysis of $p + p$ and $p(d) + A$ collisions [7].

The suppression factors $I_{AA}$ for both hadron (dashed)
and $\gamma$-triggered (solid) FF’s in central $Au + Au$ collisions
at the RHIC energy are compared with the STAR data in
the lower panel of Fig. 2. The stronger dependence of $I_{AA}$
for $\gamma$-hadrons on $z_T$ is due to the dominance of volume
emission at small $z_T$. The similarity in value between
$I_{AA}$ for dihadron and $\gamma$-hadron spectra at $z_T \approx 0.4 - 1.0$,
despite of their different trigger biases, is partially due to
the competition between the larger gluon jet fraction
(bigger energy loss) and larger initial jet energy (more
penetration) associated with a hadron trigger.

To further illustrate the above picture of volume and
surface emission of $\gamma$-triggered jets and their contribu-
tions to the effective $\gamma$-triggered FF at different values of

FIG. 2: (color online). (upper panel) LO and NLO pQCD
results for the suppression factor for $\gamma$-triggered hadrons in
central $Au + Au$ collisions at RHIC energy with different val-
ues of energy loss parameter $x_0$. (lower panel) NLO results
for $\gamma$-triggered hadrons are compared to dihadron suppression
together with STAR data [21].

FIG. 3: (color online). Transverse spatial distributions of the
initial $\gamma$-jet production vertexes that contribute to the final
observed $\gamma$-hadron pairs along a given direction (arrows) with
$z_T \approx 0.9$ (upper panel) and $z_T \approx 0.3$ (lower panel).
FIG. 4: (color online). $N_{part}$ dependence of $I_{AA}$ for $\gamma$-triggered FF in $Au + Au$ collisions at the RHIC energy. The data are from $^{[21]}$. $p_T^{h}$ in NLO pQCD calculation is chosen as $p_T^{h} = 2, 4, 6, 8, 10 \text{ GeV/c}$, respectively (from top to bottom).

$z_T$, we plot in Fig. 3 the spatial transverse distribution of the initial $\gamma$-jet production vertexes that contribute to the final $\gamma$-hadron pairs with given values of $z_T$. The color strength represents the $\gamma$-hadron yield from the fragmentation of the $\gamma$-triggered jets after parton energy loss. The $\gamma$-hadron yields with arbitrary scale are given by Eq. (3). The inserted panels are projections of the contour plots onto $y$-axes with (solid) and without energy loss (dashed). For $z_T \approx 1$ (upper-panel), contributions to the final observed $\gamma$-hadron pairs indeed come mostly from the surface. Contributions from $\gamma$-triggered jets from the center or the same side of the trigger photon are mostly suppressed. However, for small $z_T \approx 0.3$ (lower-panel), contributions to the effective $\gamma$-triggered FF are seen to come from mostly the whole volume, except near the surface on the side of the trigger photon.

These pictures of volume and surface emission of $\gamma$-hadron pairs in heavy-ion collisions will lead to different centrality dependence of the suppression factor $I_{AA}(z_T)$ for different values of $z_T$. Shown in Fig. 3 are $I_{AA}$ for $\gamma$-triggered hadron spectra as functions of the participant number $N_{part}$ in $Au + Au$ collisions at the RHIC energy for different values of $z_T$ as compared to the STAR preliminary data. For small values of $z_T < 0.6$, the $\gamma$-triggered hadron yield is dominated by volume emission and therefore the centrality dependence of $I_{AA}$ is weaker than that in the region $z_T \geq 1$ where surface emission is the dominant production mechanism.

In summary, high $p_T$ $\gamma$-hadron correlations are studied within the NLO pQCD parton model with modified parton FF’s due to jet quenching in high energy heavy-ion collisions. We demonstrated that volume (surface) emission dominates the $\gamma$-triggered hadrons spectra at small $z_T < 0.6$ (large $z_T \geq 1$) due to the underlying jet spectra in the NLO pQCD. This will enable one to extract jet quenching parameters from different regions of the dense medium via measurement of the nuclear modification factor of the $\gamma$-triggered FF in the whole kinetic region, including $z_T \geq 1$, achieving a true tomographic study of the dense medium.

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