High $p_T$ correlations of $\gamma$ and charged hadrons at RHIC

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Abstract. Prompt photon production in ultra-relativistic heavy-ion collisions provides a calibrated probe for the study of the properties of high energy density QCD matter. Especially interesting are the measurements of $\gamma$-tagged jets where the hard scattering scale is known and can be used to determine the partonic energy loss in the dense matter. We discuss the potential of $\gamma$-jet measurements at the Relativistic Heavy Ion Collider (RHIC) and argue that the observed suppression of the away-side correlations for di-jet production in central Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV should significantly reduce the backgrounds for the $\gamma$-jet coincidence measurements.

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1. Introduction

In hadronic collisions, direct photons (those that do not come from hadronic decays, such as $\pi^0 \to \gamma + \gamma$ and $\eta \to \gamma + \gamma$) result from parton-parton scatterings with large momentum transfer. They are predominantly produced from quark-antiquark annihilation ($q + \bar{q} \to g + \gamma$) and quark-gluon Compton scattering ($q + g \to q + g + \gamma$). Additional non-hadronic-decay component comes from the processes in which a photon is radiated off a quark: $q + X \to q + X + \gamma$ (bremsstrahlung photons). The measured direct photon cross section in high-energy hadronic collisions is well reproduced in the leading and next-to-leading order perturbative QCD calculations [1, 2]. In ultra-relativistic heavy-ion collisions, thermal direct photons are expected to be produced in the Quark-Gluon Plasma (QGP) phase [3]. Rates of thermal photons are predicted to be sizeable up to transverse momenta $p_T \sim$3-4 GeV/c [4] and their measurements are highly desirable to infer the temperature achieved in the nucleus-nucleus collisions. It was also suggested that partons produced in hard scatterings may interact with a thermalized parton from the QGP, resulting in a hard+thermal component in photon production, which may extend to higher...
transverse momenta [5].

Non-thermal photons from hard scatterings in heavy-ion collisions are also of high interest as they are produced very early in the collision and escape the hottest and densest stage without further interaction. The measurements of single-particle inclusive spectrum of prompt photons at high $p_T$ can test the expected scaling of particle yields in hard processes with the number of inelastic nucleon-nucleon collisions [6].

Energetic partons propagating through the medium are predicted to lose energy via induced gluon radiation, with the energy loss depending strongly on the color charge density of the created system and the traversed path length [7]. Strong suppression relative to $p+p$ collisions of inclusive hadron yields at high $p_T$ measured in central Au+Au collisions [8,9,10,11] is believed to arise from final-state interactions in the dense medium that is created at RHIC [12,13,14,15]. The observed suppression is well described by the pQCD calculations invoking partonic energy loss (“jet quenching”). However, since the yield of produced hadrons at a fixed $p_T$ results from the convolution of the parton production cross section and fragmentation function, suppression of single-particle spectra is not an ideal observable to measure directly the modification of the fragmentation function for a given energy scale. A much better tool to study jet energy loss is provided by the measurements of $\gamma$-jet coincidences, where the inclusive jet fragmentation function can be extracted from the differential $p_T$-spectrum of charged particles in the direction opposite to a tagged direct photon [16].

The STAR detector at RHIC [17] has demonstrated excellent charged particle tracking capability provided by the large acceptance ($|\eta|<1.3$, $2\pi$ in azimuth) Time Projection Chamber [18]. Neutral particle ($\gamma, \pi^0$) detection in STAR can be performed in full azimuth and $|\eta|<1, 1<\eta<2$ ranges covered by the Barrel [19] and Endcap [20] segmented electromagnetic calorimeters. We have employed the PYTHIA event generator (v. 6.131) [21] run with default parameters for $p+p$ collisions at $\sqrt{s}=200$ GeV to study the feasibility of measuring $\gamma$-tagged jets using the STAR detector.

2. Spectra of direct photons

First we would like to establish how well the PYTHIA model describes the experimental data on prompt photon production at RHIC energies. Measurements of cross section for $\pi^0$ [22] and direct $\gamma$ production [23,24] in $p+p$ collisions at $\sqrt{s}=200$ GeV were reported by the PHENIX collaboration. Figure 1 shows the measured cross sections compared to our PYTHIA calculations. The model reproduces the data quite adequately, somewhat underestimating the measured $\pi^0$ yields at low $p_T$, but shows a better agreement at higher transverse momenta. In the model, $\pi^0$ cross section dominates over prompt photon production up to $p_T \sim 25$ GeV/c. So-called isolation cuts which set a limit on the total energy or number of particles in a cone around the photon are usually used to reduce the decay photon
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Fig. 1. Measured cross section and PYTHIA calculations for $\pi^0$ (open symbols from [22], dashed line) and direct-photon (solid symbols from [23], solid line) production in $p+p$ collisions at $\sqrt{s}=200$ GeV.

3. Jets tagged by direct photons

Hard scattered partons fragment into a high energy cluster (jet) of hadrons which are distributed in a cone of size $\Delta \eta \sim \Delta \phi \sim 0.7$ in pseudorapidity and azimuth. Correlations of high $p_T$ hadrons were successfully used for the identification of jets on a statistical basis in Au+Au and $p+p$ collisions at RHIC [26, 27]. The relative azimuthal angle distributions of di-hadrons reveal jet-like correlation characterized by the peaks at $\Delta \phi = 0$ (near-side correlations) and at $\Delta \phi = \pi$ (back-to-back).
Fig. 2. Measured inclusive spectra and scaled PYTHIA calculations for $\pi^0$ (open symbols from [10], dashed line) and direct-photon (solid symbols from [25], solid line) production in central Au+Au collisions at $\sqrt{s}=200$ GeV.

Direct photons produced in hard scatterings are accompanied by a jet of hadrons in the azimuthal direction opposite to that of the photon. High $p_T$ $\gamma$-hadron relative azimuthal angle distributions are then expected to produce only away-side correlations.

Figure 3 shows the PYTHIA calculations of the relative azimuthal angle distributions between photons with $p_T>10$ GeV/c and charged hadrons with $5<p_T<10$ GeV/c in $p+p$ collisions at $\sqrt{s}=200$ GeV (photons and charged hadrons were taken within $|\eta|<1$ corresponding to the STAR experimental acceptance). Left panel of Figure 3 shows the distributions normalized separately for hadronic decay, direct, and bremsstrahlung photon triggers. Photons coming from hadronic decays (mostly $\pi^0$'s) are correlated to the charged hadrons on the near and away sides. Their correlation is stronger (larger associated hadron multiplicity) than that of direct photons, since hadronic decay photons originate from higher $p_T$ neutral pions, which in turn come from fragmentation of yet higher $E_T$ partons. In the $\gamma$-jet measurements, bremsstrahlung photons are background to the study of the processes where energy of the photon precisely characterizes the momentum transfer $Q^2$ of the hard scattering. In PYTHIA, photons coming from the processes involving initial/final state radiation contribute 40-50% to the total yield of prompt photons in the range $p_T=6$-12 GeV/c, in agreement with the NLO pQCD calculations [29]. Their correlation with the high $p_T$ charged hadrons is predicted to be weaker than that of the true direct photons. Right panel of Figure 3 shows the distributions normalized to the total number of photon triggers from all sources. The direct $\gamma$-jet correlations are predicted to contribute less than 20% to the total $\gamma$-charged distribution in $p+p$. 
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Fig. 3. PYTHIA calculations of the relative azimuthal angle distributions between photons with $p_T>10$ GeV/c and charged hadrons with $5<p_T<10$ GeV/c in $p+p$ collisions at $\sqrt{s}=200$ GeV. Left panel: distributions are normalized separately for hadronic decay, direct, and bremsstrahlung photon triggers. Right panel: distributions are normalized to the total number of photon triggers.

In central Au+Au collisions, dihadron correlations are strongly affected by in-medium effects. Correlations of high $p_T$ hadrons at small relative angles are seen to be essentially unaffected by the medium (the strength of the near-side correlations is consistent with that measured in $p+p$ and $d+Au$ collisions). In sharp contrast, the away-side (back-to-back) correlations are strongly suppressed in the most central Au+Au collisions [14, 27]. Back-to-back suppression also varies with azimuthal orientation of the jets relative to the reaction plane for non-central Au+Au collisions, exhibiting larger suppression of the back-to-back correlations for the out-of-plane trigger particles than for in-plane [28]. These observations are naturally predicted by jet quenching models, where the energy loss of a parton depends on the density of and distance traveled through the medium. The high $p_T$ trigger biases the initial production point to be near the surface so the near-side correlations should be similar to those seen in $p+p$ collisions. The away-side correlations are suppressed in the dense medium, and more suppressed when the trigger hadron is emitted perpendicular to the reaction plane.

For $\gamma$-jet processes in heavy-ion collisions, there is no bias in the initial production point as direct photons are expected to escape the medium without interaction. The accompanying back-to-back parton will travel through the medium and, in jet quenching models, will lose energy, resulting in the suppression of the away side correlations with respect to the reference nucleon-nucleon system. This suppression, however, should be smaller than that in the case of di-jet production, where the away side parton propagates through the largest distance through the dense medium. In [27], the suppression of the away-side di-hadron correlations has been quantified using $I_{AA}$ parameter. Similarly to the nuclear modification factor $R_{AA}$, taken as the ratio of single-particle yields measured in $AA$ collisions to the geometry-scaled yields measured in nucleon-nucleon collisions, $I_{AA}$ is defined as the ratio of the di-hadron correlation strength measured in $AA$ to the reference $p+p$ data.
$I_{AA}$ for the away-side correlations was found to be smaller or comparable to $R_{AA}$, indicating that the away-side jets might be suppressed more strongly than single-inclusive $p_T$-distributions, in agreement with the premise of the surface emission bias. Recently, a simple medium induced jet absorption model incorporating realistic nuclear geometry was used to quantitatively describe the centrality dependence of the observed suppression of the high $p_T$ hadron yield and of the back-to-back angular correlations [30]. We performed very similar calculations shown in Figure 4. In the jet absorption model, the geometry of the two overlapping nuclei with

![Diagram](image-url)

**Fig. 4.** Measurements of the nuclear modification factor $R_{AA}$ (triangles, $\pi^0$'s with $p_T>4$ GeV/c, from [10]) and away-side suppression factor $I_{AA}$ (circles, charged hadrons with $p_T^{trig}=4-6$ GeV/c and $2<p_T^{assoc}<p_T^{trig}$ GeV/c, from [27]) in Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV compared to different jet absorption model scenarios as a function of the impact parameter $b$ normalized by the nuclear diameter $2R_A$. The Woods-Saxon density distribution is calculated using a Monte Carlo Glauber approach. Jet energy loss is modeled using an absorption coefficient and the matter integral along the path of the parton, parameterized for the different dependencies of the absorption on the path length. Parameterizations assuming the $l^2$-dependence of the absorption on the path length $l$ describe the experimental data quite well (Figure 4). A generic prediction of the model is that the back-to-back correlations are more suppressed than the single-particle production, by as much as a factor of 2. If this holds true, the $\gamma$-jet measurements at RHIC should be easier to perform. Since there is no initial production “surface” or “skin” bias associated with selecting $\gamma$-triggers, the $\gamma$-accompanying jet will be suppressed by a single-particle rate, which is less than the di-hadron suppression rate for jet-jet processes. It is illustrated in Figure 5 where we show the distributions from the right panel of Figure 3, but with hadronic $\gamma$ production scaled by the $\pi^0$-suppression factor of 0.2, and assuming a
Fig. 5. Scaled distributions from the right panel of Figure 3. The distributions are normalized to the total number of hadronic+direct photon triggers.

back-to-back suppression factor of 0.1 for the away side. For the direct $\gamma$ distribution, the back-to-back suppression is assumed to be equal to the $\pi^0$-suppression factor. For the selected $p_T$-ranges of the trigger photon $p_T^{trig}>10$ GeV/c and associated charged hadron $p_T^{assoc}=5-10$ GeV/c, the combinatorial background even in the most central Au+Au collisions is expected to be negligible, considering the product of the single-particle per-event yields at those transverse momenta. On the other hand, the partonic energy loss is predicted to only weakly depend on the energy of the parton. Assuming that the di-hadron back-to-back suppression is twice the single-particle suppression and using PYTHIA to simulate the jet fragmentation at $\sqrt{s}=200$ GeV, we estimate that up to 70% of the $\gamma$-charged back-to-back azimuthal correlations in central Au+Au collisions may come from direct $\gamma$-jet events. The situation can further be improved using higher $p_T$ for the trigger photon and associated hadrons. Considering the integrated luminosity achieved in the last RHIC run of Au+Au collisions at $\sqrt{s_{NN}}=200$ GeV, and using the PHENIX measured and PYTHIA-extrapolated cross section for direct photon production, we conclude that the exploratory $\gamma$-jet measurement may already be achievable with the STAR data on tape.

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