Jet-Trigged Back-Scattering Photons for Quark Gluon Plasma Tomography

Sonnath De\textsuperscript{1,2}, Rainer J. Fries\textsuperscript{1}, and Dinesh K. Srivastava\textsuperscript{2}
\textsuperscript{1}Cyclotron Institute and Department of Physics and Astronomy, Texas A\&M University, College Station, TX 77845, USA and \textsuperscript{2}Variable Energy Cyclotron Center, Kolkata, India

High energy photons created from back-scattering of jets in quark gluon plasma are a valuable probe of the temperature of the plasma, and of the energy loss mechanism of quarks in the plasma. An unambiguous identification of these photons through single inclusive photon measurements and photon azimuthal anisotropies has so far been elusive. We estimate the spectra of back-scattering photons in coincidence with trigger jets for typical kinematic situations at the Large Hadron Collider and the Relativistic Heavy Ion Collider. We find that the separation of back-scattering photons from other photon sources using trigger jets depends crucially on our ability to reliably estimate the initial trigger jet energy. We estimate that jet reconstruction techniques in heavy ion experiments need to be able to get to jet $R_{AA} \gtrsim 0.7$ in central collisions for viable back-scattering signals.

I. INTRODUCTION

Electromagnetic radiation has a long history as an excellent probe in high energy nuclear collisions. The long mean free path of photons and dileptons, an order of magnitude larger than the transverse size of the colliding nuclei, allows them to carry information from the earliest stages of the collision and from deep inside the fireball to the detector systems. Over the years, several distinct sources of direct photons have been identified and calculated. They include (i) prompt photons from initial hard processes between beam partons and from jet fragmentation [1, 2], (ii) pre-equilibrium photons from the secondary scatterings between partons before the system thermalizes [3], (iii) photons from jets interacting with QGP [4, 5, 6], (iv) thermal radiation from equilibrated or near-equilibrium quark gluon plasma (QGP) [7, 8, 11], (v) photons associated with the hadronization process [12], and finally (vi) thermal photons from the hot hadronic gas phase [8, 13]. These direct photons have to be experimentally separated from a large amount of background photons from hadronic decays (most notably from neutral pions).

Thermal photons, dominant at low transverse momenta $p_T$, are supposed to act as a thermometer of the hot nuclear matter, and there is mounting evidence that the early temperatures extracted are above the critical temperature $T_c$ expected for the phase transition to quark gluon plasma [14, 15]. Photons from interactions of jets with QGP carry important complementary information. Hence it is critical to experimentally separate the contributions from different photon sources as much as possible so each can be analyzed appropriately. The list of photon sources in the previous paragraph follows a rough hierarchy of typical transverse momenta of the source, from high to low $p_T$. Jet-medium photons have been shown to make significant contributions at intermediate $p_T$ around \~{}4 GeV/c in single inclusive photon spectra both at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC), but they compete with prompt hard photons at larger $p_T$ and thermal and pre-equilibrium photons at smaller $p_T$. Hence it has been hard to confirm their existence from measurements of single inclusive photon spectra alone, much less to exploit their properties. Elliptic flow of jet-medium photons had been predicted to be negative and it was expected to serve as a telltale signature [16, 17]. However experimental studies of direct photon $v_2$ have not been able to bring conclusive evidence for the existence of jet-medium photons [18, 19].

In this work we propose to use the correlation of large momentum photons with jets in the opposite direction to measure the strength of a part of the jet-medium photon source, more precisely the photons from back-scattering kinematics. We will argue that this effectively rids the sample of photons from thermal and pre-equilibrium sources and vastly reduces the background from jet fragmentation photons. Furthermore, energy loss of the parent parton should shift back-scattering photons toward smaller momenta, exposing them compared to the remaining background source of prompt hard photons which are not affected by parton energy loss. On the other hand, energy loss of the trigger jet, and the experimental uncertainty measuring jet energies tend to wash out the signal from back-scattering photons. We will discuss these effects in detail below. Great opportunity awaits us if we successfully measure the strength of the back-scattering process. Besides having a complementary measure of parton energy loss independent of hadronic measurements (quarks will lose energy before converting into photons), one could measure the temperature of the medium ($T \sim 200$ MeV) independently using back-scatter photons with energies of tens of GeV.

Jet-medium photons have most notably been calculated in two limits: as electromagnetic bremsstrahlung to jet quenching [4, 11], e.g. in the Arnold-Moore and Yaffe (AMY) approach, and as an elastic back scattering process [3]. The latter is based on the fact that $2 \rightarrow 2$
Compton and annihilation scattering with a photon in the final state, \( q + g \rightarrow \gamma + q \) and \( q + \bar{q} \rightarrow \gamma + g \) both have a sharp peak at backward angles. In other words, when a fast quark annihilates with a slow antiquark, or Compton scatters off a slow gluon from the thermal medium, in most of the cases (Compton) or in about half the cases (annihilation) the photon created carries approximately the momentum of the fast quark. Back-scattering processes of this type are well known and are exploited in numerous ways, e.g. to create high energy photon beams.

In photon beam facilities laser photons (typically \( \sim 1 \) eV) are Compton back-scattered from a high energy electron beam (in the MeV to GeV range) to create collimated beams of MeV to GeV photons [20, 21]. The QCD Compton analogue that we use here consists of a thermal gluon (\( \sim 200 \) MeV) scattering off a quark (\( \sim 20 \) GeV) to produce a \( \sim 20 \) GeV photon. Both bremsstrahlung and back-scattering calculations are often carried out in a leading parton approximation to jets in a medium [3] however more general calculations using the parton dynamics inside a jet shower in a medium have recently become available [22].

II. Calculating Photon Sources

In Ref. [3] the rate of Compton and annihilation processes between one parton from a set of fast quarks subject to energy loss, and another from a fireball with a temperature profile \( T(x) = T(\tau, \eta, x_{\perp}) \) was calculated in the backward peak approximation (\( p_{\gamma} \approx p_{\text{fast } q} \)) to be

\[
E_\gamma \frac{dN}{dx \, d^3 p_\gamma} = \frac{\alpha \alpha_s}{4 \pi^2} \sum_{q_1} \left( \frac{e_q}{e} \right)^2 T^2(x) \times \left[ f_q(p_{\gamma}, x) + f_{\bar{q}}(p_{\gamma}, x) \right] \ln \left( \frac{3E_\gamma}{\alpha_s \pi T(x)} + C \right),
\]

where \( C = 1.916 \). Here \( \alpha \) and \( \alpha_s \) are the electromagnetic and strong coupling constant respectively. \( f_q \) is the phase space distribution of fast quarks interacting with the medium and \( e_q \) is the electric charge of a quark with the index \( q \) running over all active quark flavors. This formula is easily generalized to the rate of photons associated with a trigger jet whose energy, pseudorapidity and relative azimuthal angle, \( E_T, \eta, \phi \), fall within a trigger window \( T_j \) in \( E_T, \eta, \phi \) space. For the latter we replace the single inclusive parton distribution \( f_q(p_{\gamma}, x) \) by the parton-jet pair distribution integrated over \( T_j \),

\[
f_q^{T_j}(p_{\gamma}, x) = \frac{(2\pi)^3}{g_4 T pt} \delta(y - \eta) \rho(\tau, x_{\perp}) \times \int_{T_j} dE_T dy_j d\phi_j E_q \frac{dN}{d^3 p_q d E_T dy_j d\phi_j} \frac{dN}{d^3 p_q d E_T dy_j d\phi_j} \left| \frac{p_{\gamma}^0 - p_{\gamma} + \Delta p_q}{E_{T\gamma} = E_T + \Delta E_T} \right|.
\]

Here \( x = (\tau, \eta, x_{\perp}) \) and \( p_q \) are the position and momentum of the quark at the time of the back scatter-
JET is a longitudinally expanding, boost-invariant QGP phase. The transverse profile of the entropy density is fixed by the participant density of nucleons from a Glauber calculation. We do not expect our main conclusions to change much if transverse expansion or fluctuations in the fireball are taken into account. The normalization of the entropy density is fixed by data from RHIC and scaled up to describe multiplicity data in Pb+Pb collisions at the LHC. We will refer to different values of jet energy loss by quoting this number in plots as “raa”. Fig. 1 shows the single inclusive $R_{AA}$ for jets corresponding to values of $\hat{r}$, corresponding to $\text{raa}$ values of roughly 1.0, 0.9, 0.7 and 0.5 at 100 GeV respectively. Data from the STAR, ALICE and CMS collaborations for jet cone radii of 0.4, 0.2 and 0.4 respectively, are also shown for comparison.

Jet energy loss is much less under theoretical control. A consistent calculation can only be done with a full jet shower simulation in the medium, e.g. [22]. Here we choose a simple model of the path length and energy dependence to reproduce gross features of jet energy loss. We parameterize that the energy loss (i.e. the amount of energy outside of a given jet cone) is proportional to path length, and we add a small energy dependence, $dE_T/d\tau = -\hat{r} \ln(E_T/\Lambda)$ where $\Lambda = 0.2$ GeV. $\hat{r}$ is proportional to the local entropy density $s$ as in the case of leading parton energy loss. The linear path length dependence appears more appropriate both for the stochastic process of stripping partons off the jet cone as the jet goes through the medium, and for the large angle radiation with short formation times that plays a role as well. The normalization of $\hat{r}$ is varied to obtain different inclusive jet $R_{AA}$.

**III. RESULTS**

In order to calibrate jet energy loss we calculate the nuclear modification factor $R_{AA}$ of single inclusive jets for both central Au+Au collisions at RHIC energy and central Pb+Pb collisions at LHC energy in our jet energy loss model. This allows us to scale the normalization of the parameter $\hat{r}$ to reproduce a certain inclusive jet $R_{AA}$. We will refer to different values of jet energy loss by quoting the approximate value of $R_{AA}$ at $E_T = 30$ GeV for RHIC and $E_T = 100$ GeV at LHC, respectively. We will quote this number in plots as “raa”. Fig. 1 shows the single inclusive $R_{AA}$ for jets corresponding to values of $\text{raa}$ of roughly 1.0, 0.9, 0.7 and 0.5 for central Pb+Pb collisions at LHC and 1.0 and 0.7 for central Au+Au collisions at RHIC, respectively. We also show the data from STAR, ALICE and CMS that use rather small jet cone radii of 0.4, 0.2 and 0.4, respectively. Without a full jet shower simulation we can not make a rigorous connec-
tion between jet cone radius, jet quenching, and jet $R_{AA}$. Rather we will present our results using a set of different values of “raa” (and thus $\hat{r}$). As can be seen from the figure the lowest values of raa for both RHIC (0.7) and LHC (0.5) roughly correspond to the suppression seen in current data with small cone radii. With improving jet reconstruction techniques and larger jet cone radii larger values of “raa” might become feasible. Small jet cones in heavy ion experiments are mostly dictated by the relatively large background that needs to be subtracted. The value of $\hat{r}$ needed to reproduce raa of 0.7 at RHIC is about 0.24 GeV/fm initially in the center of head-on Au+Au collisions which corresponds to an initial energy loss of ~1.2 GeV/fm for 30 GeV jets.

We can now proceed to calculate photon spectra opposite of trigger jets in several scenarios. For this preliminary study we choose the trigger window $T_j$ for the jet to be defined as $-1 < y_j < 1$ and 30–35 GeV in $E_T$ for RHIC, and $-2 < y_j < 2$ and 60–65 GeV in $E_T$ for LHC. We define the away-side as an angle between 165 and 195 degrees in relative azimuthal angle. Let us briefly discuss the choice of trigger window. The yield of single-inclusive back-scattering photons falls faster with $p_T$ than prompt hard photons (similar to a higher twist contribution in perturbative QCD), thus the signal will become stronger with smaller $p_T$. However, experiments need to be able to reconstruct jets in a reliable manner. This puts a lower bound on the trigger window $E_T$. Our choice is an attempt to maximize the back-scattering yield while keeping jet reconstruction feasible. We would also like to make our back-scattering signals as sharply defined as possible, which is ideally achieved with very narrow trigger windows. However, uncertainties in the jet energy reconstruction put constraints on the energy resolution achieved in experiments. We have chosen a trigger window of 5 GeV for this study.

Fig. 2 shows our results for jet-triggered photon spectra in central Au+Au collisions at RHIC for scenarios with jet raa 1.0 and 0.7 at leading-order (LO) accuracy. At LO and without trigger energy loss (raa 1.0) the prompt hard photon kinematics is completely determined by the trigger jet energy and leads to a well-defined band of photons between 30 and 35 GeV in transverse momentum. Fragmentation photons generally provide a low-level background just below the trigger window (they correspond to very high-$z$ photons). We use BFG-II fragmentation function for photons [62]. The kinematic range of back-scattering photons (the signal) calculated under the same assumptions (LO, raa 1.0) and without energy loss of partons, coincide with those of prompt hard photons, as expected, although their strength is lower by about an order of magnitude. If parton energy loss is switched on with parameters determined from single hadron suppression, the back-scattering signal develops a shoulder of about 4 GeV width, indicating that quarks have lost up to 4 GeV of energy before conversion to photons. This pushes some back-scattering photon strength into the region of fragmentation photons which makes for a much better signal/background ratio just below the trigger window.

If jet energy loss is taken into account in addition, with cone radii currently available (raa 0.7), both the hard prompt photon background and the back-scattering photon spectra become slightly more diffuse and tend to be shifted to higher $p_T$ since a trigger jet measured between 30–35 GeV might have originated as a jet with larger energy. The jet triggered photon spectra thus carry fairly obvious information about the energy loss of partons and
trigger jets in their broadening around the trigger window.

These strong kinematical correlations are washed out by NLO corrections to the hard process in which another hard parton can be emitted in the final state. The effect is estimated in the lower panel of Fig. 2 where the background is now calculated at NLO accuracy and raa 1.0. We also show the back-scattering photons at LO accuracy but with a $K$ factor. Our calculation of back-scattering photons in its current form is not suitable to deal with radiative corrections as it is not clear how to treat medium induced radiation of a collinear pair of quarks that would end up in the same jet cone. However our results seem to indicate that the decorrelation of the signal with the trigger window that comes from radiative corrections to the hard process is generally weaker than the decorrelation that is induced by parton and trigger jet energy loss. This is even more the case at LHC energies where energy loss is large. Here the $K$ factor is determined from the ratio (background at NLO)/(background at LO) in the fragmentation dominated region of the background. We chose to determine $K$ at 20 GeV for RHIC and 40 GeV for LHC.

We proceed to show the results for the nuclear modification factor $R_{AA}$. Experimentally, $R_{AA}$ can be determined with smaller systematic uncertainties compared to spectra, and might thus be a more promising observable. Fig. 3 shows $R_{AA}$ as defined in Eq. 3 for central Au+Au collisions at RHIC for (i) raa 1.0 and (ii) raa 0.7 (scaled by 0.5). For comparison we also show the result one would obtain if back-scattering photons were absent (i.e. the ratio of fragmentation and prompt hard photons for Au+Au and $p+p$). The difference between the $R_{AA}$ with and without inclusion of signal, is the signature for jet-triggered back-scattering photons.

Let us understand the key features of $R_{AA}$. First, we note that the nuclear modification factor of background photons (i.e. background photons in A+A vs background photons in $p+p$) is not around 1. This is because background photons at RHIC probe hard processes with quarks in the initial wave function. In A+A those processes are suppressed due to the larger fraction of $d$ valence quarks compared to $u$ valence quarks in nuclei and their smaller electric charge. We notice that trigger jet energy loss can lead to suppression of $R_{AA}$ in the trigger window due to the shift of strength of background photons to larger energies. In fact the width of such a dip is related to the size of the typical jet energy loss. The signal of back-scattering photons on the other hand creates an enhancement in $R_{AA}$ which is peaked just below the trigger window. Both the dips in the background and the enhancement due to the signal are typical effects that will also appear at LHC. In contrast, radiative effects on the distribution of background photons in the NLO calculation generally tends to smear out an enhancement due to the signal.

Fig. 4 shows the jet-triggered photon spectrum for central Pb+Pb collisions at LHC for the 60–65 GeV trigger window discussed above. We show both signal and background for the four jet energy loss scenarios (raa 1.0, 0.9, 0.7 and 0.5) at LO kinematics with parton energy loss included. All the features discussed for the RHIC case are qualitatively present at LHC as well. However, the diffusion of signal strength both due to parton energy loss and jet energy loss is much larger than at RHIC for the raa 0.7 and 0.5 scenarios, creating shoulders up to 15–20 GeV wide on both sides of the trigger window.

Fig. 5 shows $R_{AA}$ for trigger energy loss scenarios raa 1.0, raa 0.7, and raa 0.5. The baseline suppression due to $d$ valence quarks is not present at LHC where hard processes are dominated by gluon fusion. We again find dips in the background $R_{AA}$ in the trigger window due to trigger energy loss, and enhancement in $R_{AA}$, peaked below the trigger window, from back-scattering photons.
While raa 1.0 shows a rather promising signature peak the signal for the more realistic raa 0.5 and raa 0.7 jet energy loss scenarios are small.

IV. SUMMARY AND DISCUSSION

We have, for the first time, calculated the correlation of medium-induced photon radiation from jets with trigger jets. We have focused on back-scattering photons from the Compton process. Our numerical studies indicate that there is a potential signal from back-scattering photons in the $R_{AA}$ of photons opposite of trigger jets in high energy nuclear collisions. The signal is mostly due to a downward shift of back-scattering photons in momentum due to parton energy loss before the back-scattering occurs. This reduces the background from prompt hard photons significantly. However, trigger jet energy loss and radiative corrections to the underlying hard processes tend to wash out the correlation. The decorrelation of signal and trigger due to jet energy loss dominates over those due to NLO corrections at LHC energies. With the currently used small jet cone radii and the typical trigger jet $R_{AA}$ measured at RHIC and LHC the signal is visible in our calculation, but it would be too small to be seen experimentally.

We should emphasize here that many features of our calculation are designed to establish a lower bound on the signal strength and a more detailed follow-up calcu-
loration could lead to a more promising result. Here are the main points that establish a lower bound: (i) The simple equation of state underestimates the temperature and thus the back-scattering rate. (ii) We omitted induced photon bremsstrahlung, which will generally increase the signal photon rate below the trigger window. Obviously back-scattering photons have the advantage of a rather sharp feature in $R_{AA}$, while additional yield which simply scales up $R_{AA}$ in a $p_T$-independent way will be harder to find experimentally. (iii) Photon fragmentation might happen partially or fully outside of the medium. In that case fragmentation photons are subject to energy loss which is neglected here. This effect will shift the background from fragmentation towards smaller $p_T$, effectively decreasing the background. We have also not systematically explored different kinematic cuts on the trigger jet or the photon that could possibly improve the signal over background ratio. Nevertheless we conclude that single inclusive jet $R_{AA}$ of 0.7 or larger in central collisions will likely be necessary to carry out this measurement.

Going beyond the back-scattering peak approximation in Eq. (1) leads to decorrelation of the trigger and back-scattering photon, however, it will also tend to push some of the signal strength to lower $p_T$, away from the prompt hard photon background. The net effect might thus not be simply a loss of signal due to decorrelation. In principle our proof-of-principle calculation could be improved in several ways. A full jet shower Monte-Carlo would remove the need for a leading parton approximation. It could also mimic NLO kinematics which we have only employed when final state effects leading to energy loss is absent since no consistent theory is available in that case.

One could consider the use of high-$p_T$ trigger hadrons instead of trigger jets. They will be subject to the parton energy loss and jet energy loss which leads to smearing of the back-to-back energy correlation as discussed in the jet-photon case. In addition, there is smearing due to the fragmentation of the hadron which by itself already almost completely destroys the correlation in energy with the photon on the other side, see e.g. [33]. Therefore hadron triggered photons have not been considered here.

SD is grateful to the Cyclotron Institute at Texas A&M University for their hospitality during his stay. This project was supported by the U.S. National Science Foundation through CAREER grant PHY-0847538, and by the JET Collaboration and DOE grant DE-FG02-10ER41682. SD acknowledges the financial support of DAE, India during the course of this work.

[1] J. F. Owens, Rev. Mod. Phys. 59, 465 (1987).
[2] S. Catani, M. Fontannaz, J. P. Guillet and E. Pilon, JHEP 0205, 028 (2002).
[3] P. Aurencche, M. Fontannaz, J. -P. Guillet, E. Pilon and M. Werlen, Phys. Rev. D 73, 094007 (2006).
[4] S. A. Bass, B. Muller and D. K. Srivastava, Phys. Rev. Lett. 90, 082301 (2003).
[5] R. J. Fries, B. Muller and D. K. Srivastava, Phys. Rev. Lett. 90, 132301 (2003).
[6] R. J. Fries, B. Muller and D. K. Srivastava, Phys. Rev. C 72, 041902 (2005).
[7] B. G. Zakharov, JETP Lett. 80, 1 (2004) [Pisma Zh. Eksp. Teor. Fiz. 80, 3 (2004)].
[8] J. I. Kapusta, P. Lichard and D. Seibert, Phys. Rev. D 44, 2774 (1991) [Erratum-ibid. D 47, 4171 (1993)].
[9] R. Baier, H. Nakkagawa, A. Niegawa and K. Redlich, Z. Phys. C 53, 433 (1992).
[10] P. Aurencche, F. Gelis, R. Kobes and H. Zaraket, Phys. Rev. D 58, 054003 (1998).
[11] P. B. Arnold, G. D. Moore and L. G. Yaffe, JHEP 0112, 009 (2001).
[12] G. Chen, R. J. Fries, in preparation.
[13] S. Turbide, R. Rapp and C. Gale, Phys. Rev. C 69, 014903 (2004).
[14] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 104, 132301 (2010).
[15] M. Wilde [ALICE Collaboration], Nucl. Phys. A904-905 2013, 573c (2013).
[16] S. Turbide, C. Gale and R. J. Fries, Phys. Rev. Lett. 96, 032303 (2006).
[17] S. Turbide, C. Gale, E. Frodermann and U. Heinz, Phys. Rev. C 77, 024909 (2008).
[18] A. Adare et al. [PHENIX Collaboration], Phys. Rev. Lett. 109, 122302 (2012).
[19] D. Lohner [ALICE Collaboration], J. Phys. Conf. Ser. 446, 012028 (2013).
[20] R. H. Milburn, Phys. Rev. Lett. 10, 75 (1963).
[21] F. R. Arutyunian and V. A. Tumanian, Phys. Lett. 4, 176 (1963).
[22] T. Renk, Phys. Rev. C 88, 034902 (2013).
[23] J. Pumpolin et al. JHEP 0207, 012 (2002).
[24] K. J. Eskola, H. Paukkunen and C. A. Salgado, JHEP 0904, 065 (2009).
[25] R. Rodriguez, R. J. Fries and E. Ramirez, Phys. Lett. B 693, 108 (2010).
[26] R. J. Fries and R. Rodriguez, Nucl. Phys. A 855, 424 (2011).
[27] S. Pal and S. Pratt, Phys. Lett. B 578, 310 (2004).
[28] K. M. Burke et al., Phys. Rev. C 90, 014909 (2014).
[29] M. Ploskon [STAR Collaboration], Nucl. Phys. A 830, 255C (2009).
[30] R. Reed [ALICE Collaboration], J. Phys. Conf. Ser. 446, 012006 (2013).
[31] M. Belt Tonjes [CMS Collaboration], Nucl. Phys. A 904-905, 713c (2013).
[32] L. Bourhis, M. Fontannaz and J. P. Guillet, Eur. Phys. J. C 2, 529 (1998).
[33] G. Y. Qin, J. Ruppert, C. Gale, S. Jeon and G. D. Moore, Eur. Phys. J. C 61, 819 (2009).