

JET-MEDIUM PHOTONS AS A PROBE OF PARTON DYNAMICS*

ROUZBEH MODARRESI YAZDI^a, SHUZHE SHI^b, CHARLES GALE^a
SANGYONG JEON^a

^aDepartment of Physics, McGill University
3600 University Street, Montreal, QC, Canada H3A 2T8

^bCenter for Nuclear Theory, Dept. of Phys. and Astron., Stony Brook University
Stony Brook, New York 11794–3800, USA

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Photons resulting from jet–medium interactions offer the opportunity of studying the evolving quark distribution in a heavy-ion collision. The spectra of jet–medium photons are presented within the JETSCAPE framework for two different energy loss models, MARTINI and CUJET. Jet-medium photons can contribute significantly to the spectrum of direct photons in the intermediate p_T range.

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1. Introduction

Photons, real and virtual, are an important probe of the quark–gluon plasma. They are produced at all stages of the evolution of the plasma and have a mean-free-path larger than the size of the created medium. As such, their study and measurement can be a great tool for quantifying the properties of QGP as well as jet-energy loss. Here, we present a recent calculation of photons produced from jet interactions with the QGP using the JETSCAPE [1] framework. To that comprehensive suite, we have added CUJET [2] as a low virtuality energy loss module, thus allowing for a systematic comparison with MARTINI [3]. What follows, is a brief description of the formalisms, a discussion of jet–medium photons, and finally, the results of the simulation, a discussion, and an outlook on future work.

2. Low virtuality energy loss

CUJET implements the DGLV [4, 5] inelastic parton splitting rates, computed to leading order in the opacity expansion [2]. The calculation of the gluon-emission rates assumes that the hard probe was created at some given

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time and position inside the plasma and then evolved, scattering from a dynamical medium [2] and radiated a gluon. The calculation of DGLV rates is performed in the eikonal limit, with the jet and the radiated gluon assumed to be distinguishable from the strongly interacting medium around them. The Landau–Pomeranchuk–Migdal (LPM) effect manifests itself as a phase factor. Soft, collinear divergences are regulated by a gluon plasmon mass and the light quarks are considered massless [5]. It is also assumed that the radiated gluon does not modify the direction of travel of the incoming parton. In CUJET, collisional energy loss occurs via scattering with the QGP medium. This is done using the Thoma–Gyulassy model, where the HTL gluon propagator includes a natural IR regulator [6]. Finally, CUJET allows for the running of the strong coupling, α_s , according to the one-loop pQCD expression.

MARTINI implements the AMY–McGill formalism for radiative and elastic scattering energy loss on-shell energetic partons in a strongly interacting medium [3]. It solves a rate equation with gain and loss terms for the time-evolving parton distribution. As in CUJET, radiative energy loss is strictly collinear, with elastic scattering channels providing the momentum broadening via space-like exchanges with the medium. Unlike the DGLV model, the original AMY radiative rates, which we use in this work, do not have an explicit time dependence [3]. The reaction rates calculated with AMY are to all orders of the opacity expansion and account fully for the LPM effect. Collisional energy loss is also implemented, again using the gluon HTL propagator. Other than gluon radiation and collisional energy loss, MARTINI also includes $g \rightarrow q + \bar{q}$ radiative channel as well as conversion processes $q \rightarrow g$ and $\bar{q} \rightarrow g$. The strong coupling in radiative and elastic channels is allowed to run, using the one-loop expression for α_s .

3. Jet-medium photons

Two dominant mechanisms of jet–medium photon emission are jet bremsstrahlung and jet-photon conversion [7]. Jet bremsstrahlung has a similar structure as the jet gluon bremsstrahlung channel: the jet receives kicks from the medium and emits a photon. The differential rate for this process in MARTINI is given by

$$\begin{aligned} \frac{d\Gamma_{q \rightarrow q\gamma}^{\text{AMY}}}{dz}(p, z) &= \frac{e_f^2 \alpha_{\text{em}} P_{q \rightarrow q\gamma}(z)}{[2p z(1-z)]^2} [1 - f_q((1-z)p)] \\ &\times \int \frac{d^2 \mathbf{k}_\perp}{(2\pi)^2} \text{Re} \left[2 \mathbf{k}_\perp \cdot \mathbf{g}_{(z,p)}(\mathbf{k}_\perp) \right], \end{aligned} \quad (1)$$

where e_f is the fractional charge of quark(anti-quark) and $z \equiv k/p$ is the momentum fraction carried away by the photon. $\mathbf{g}_{(z,p)}(\mathbf{k}_\perp)$ is the solution

to the integral equation [8]

$$2 \mathbf{k}_\perp = i \delta E(z, p, \mathbf{k}_\perp) \mathbf{g}(\mathbf{k}_\perp) + \int \frac{d^2 \mathbf{q}_\perp}{(2\pi)^2} C(\mathbf{q}_\perp) \left[\mathbf{g}(\mathbf{k}_\perp) - \mathbf{g}(\mathbf{k}_\perp - z \mathbf{q}_\perp) \right], \quad (2)$$

where $q_\perp$ and $k_\perp$ are the exchanged and photon transverse momenta, respectively, $C(\mathbf{q}_\perp)$ is a scattering kernel, and δE is the energy difference between the initial and final states [8].

Conversion photons arise from soft momentum exchanges of $q(\bar{q})$ jets with the QGP medium. At leading order in the strong coupling, the process can go through either QCD Compton scattering or $q\bar{q}$ annihilation. Both processes include a Mandelstam t -channel where a soft quark is exchanged. A general property of t -channel processes is the preference of the outgoing particle to be in the same direction as the incoming owing to $1/t$ term in the matrix element and the matrix element is maximum when the relative angle is very nearly zero. As such, we can perform an approximation where the entirety of the contribution to the conversion photon rate stems from this collinear region and write the rate as

$$\frac{d\Gamma^{\gamma-\text{Conv}}}{dp dk}(p, k, T) = e_f^2 \frac{2\pi \alpha \alpha_s}{3} \frac{T}{p} \left[\frac{1}{2} \ln \frac{2pT}{m_q^2} - 0.36149 \right] \delta(p - k), \quad (3)$$

where the collinearity is made explicit by the delta function.

4. Results

Our calculations were performed using the JETSCAPE framework simulating a Pb + Pb collision at $\sqrt{s} = 2.76$ ATeV. Two sets of simulations were made using CUJET and MARTINI used as the low-virtuality energy loss modules with all other parameters held fixed. PYTHIA was used to generate the hard scattering event, performing the initial-state shower as well as handling multi-parton interactions. High virtuality partons were then handed over to MATTER [14, 15], to be further evolved down in virtuality. For the pp spectra used in the R_{AA} calculation and the tuning of the other modules in JETSCAPE Ref. [1] was used. The hydrodynamic background was provided by a VISHNU (2 + 1)D viscous hydrodynamic simulation with temperature-dependent specific shear and bulk viscosities [16]. Finally, Fast-Jet [17] was used for the jet-clustering.

Figure 1 (a) and (b) show the results of the simulation for charged hadrons and jets, respectively, for the 0–5% centrality class. We see satisfactory agreement between the two energy loss modules and the data. Despite the theoretical differences between them, the two energy loss models are nearly indistinguishable. We now turn our attention to photons. Figure 2

provides a channel-by-channel calculation of photon yield at mid-rapidity for the same colliding system as before (at 20–40% centrality) and compared to data from ALICE. The prompt, pre-equilibrium and thermal photons are taken from Ref. [18].

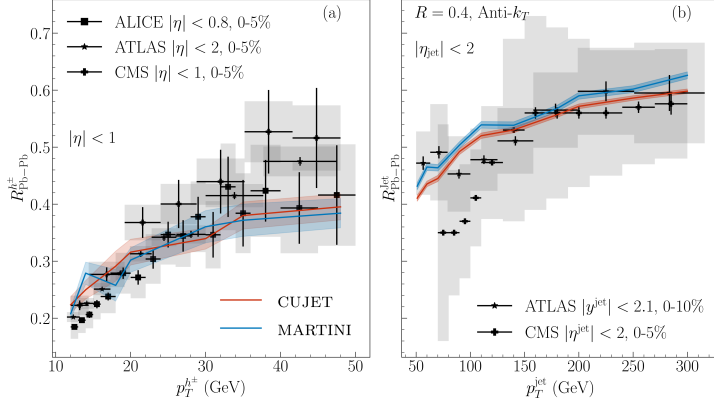


Fig. 1. Calculation of (a) charged hadron and (b) jet R_{AA} for MARTINI and CUJET for Pb + Pb collisions at $\sqrt{s} = 2.76$ ATeV. Data from [9–13].

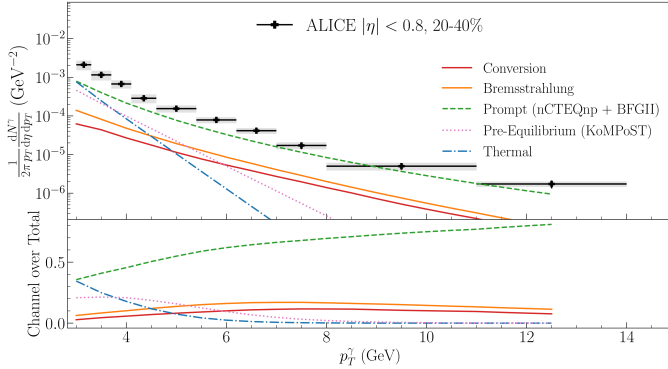


Fig. 2. Channel break down of the direct photon yield at midrapidity of 20–40% collisions of Pb + Pb at $\sqrt{s} = 2.76$ ATeV. Data from [19].

It is clear from Fig. 2 that the significance of medium sources of photons (pre-equilibrium and thermal) goes down, while that of the prompt photons goes up as we consider larger and larger values of photon p_T . The jet–medium channels contribute $\approx 30\%$ at intermediate values of photon p_T , peaking at ≈ 7 GeV. Figure 3 makes the effect of including jet–medium photons even more stark. Including photons from jet–medium interactions brings the overall curve into much better agreement with the data, particularly for the intermediate $p_T^\gamma \in [5, 8]$ GeV.

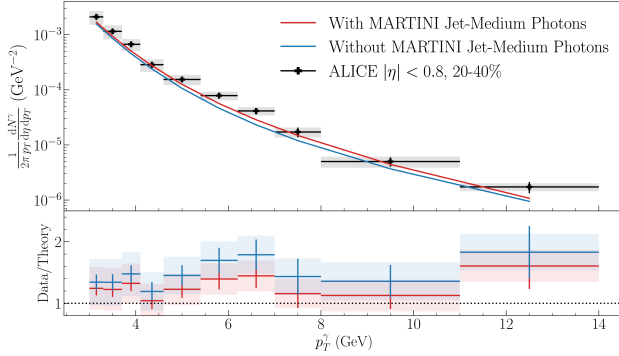


Fig. 3. Transverse momentum spectrum of direct photons, with and without jet-medium contribution. Jet-medium photons are calculated using MARTINI. Error bars and shaded regions are statistical and systematic uncertainties, respectively.

To compare the equivalent photon yield from CUJET we require a CUJET calculation of bremsstrahlung photons, which is currently being completed. Thus, we restrict the comparison to conversion photons in Fig. 4 for three centrality classes. The more peripheral collisions result in a smaller medium and lower temperatures. Given the temperature dependence of the rates of conversion photons, it is natural to see the 30–40% curves to be nearly identical. The 0–5% centrality class shows a larger difference between the two modules: conversion photon yield from MARTINI is nearly 40% larger than that of CUJET. The direct proportionality of conversion photons to the underlying $q, \bar{q}$ distribution, then, indicates a difference in the two modules and how they modify the evolving $q/\bar{q}$ distribution.

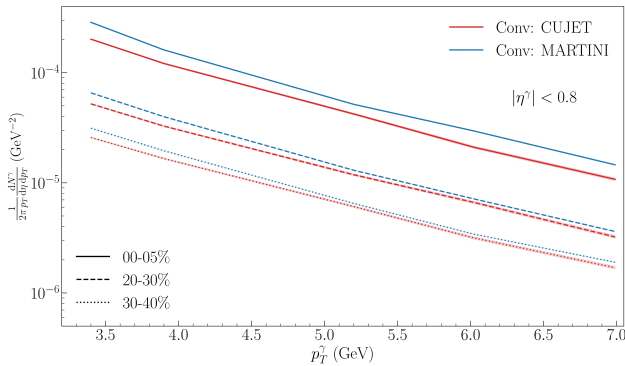


Fig. 4. Comparison of conversion photon spectra from CUJET and MARTINI, for 3 centrality classes of Pb + Pb at $\sqrt{s} = 2.76$ ATeV. See the text for details.

5. Conclusion and outlook

Jet energy loss and suppression of charged hadron yield relative to the proton–proton baseline is an important signal of the creation of QGP. In this work, we presented the results of the implementation of CUJET into JETSCAPE and a comparison of charged hadron and jet R_{AA} from CUJET and MARTINI. We further presented the first dynamic calculation of jet–medium photons in a realistic plasma and a dynamic initial jet distribution with MARTINI. The inclusion of jet–medium photons in Fig. 3 made a clear contribution to the total photon yield, bringing the theoretical curve into better agreement with the experimental measurement. We saw that the two jet–medium channels, bremsstrahlung and conversion photons, together contribute nearly $\approx 30\%$ to the total photon yield for intermediate values of photon transverse momentum. The comparison of CUJET and MARTINI in photon yield is currently limited to conversion photons only, since the former does not contain bremsstrahlung photons. We found that the difference in conversion photon yield from the two modules can be significant: 40% in central (0–5%) collisions which further motivates the usage of jet–medium photons as clean probes of energy loss models.

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