Proc Indian Natn Sci Acad **81** No. 1 February 2015 Special Issue, pp. 217-222

DOI: 10.16943/ptinsa/2015/v81i1/48072

QCD Back-Scattering Photons in Relativistic Heavy Ion Collisions

SOMNATH DE*[1], RAINER J FRIES[2] and DINESH K SRIVASTAVA[3]

[1]*Bose Institute Indo-Fair Coordination Centre, Kolkata, India*

[2]*Texas A&M University, College Station, Texas, USA*

[3]*Variable Energy Cyclotron Centre, Kolkata, India*

(Received on 15 May 2014; Accepted on 10 June 2014)

High energy photons created from back-scattering of jets in quark gluon plasma are considered a valuable probe of the temperature of the plasma, and of the energy loss mechanism of quarks in the plasma. An unambiguous identification of this source through the measurement of single inclusive photon spectra and photon azimuthal anisotropies has not been conclusive so far. We proposed a method to identify this source by using the correlation with away-side trigger jet at large momentum. We estimate the spectra and nuclear modification factor of back-scattering photons in coincidence with trigger jets for the heavy ion collisions at the Large Hadron Collider (LHC) energy. We find the back-scattering photons cause a promising peak in nuclear modification factor which smears out by including trigger jet energy loss. Thus separating back-scattering photons from other photon sources using trigger jets depends crucially on our ability to estimate the initial trigger jet energy in experiment.

Key Words : Quark Gluon Plasma; Photons; QCD Jets; Compton Back-Scattering; Correlation; Parton Energy Loss

Introduction

The measurement of direct photons (real and virtual) holds great promise for the characterization of quark-gluon plasma (QGP) created in high energy nuclear collisions. The large mean free path (~ 100 fm) of these electromagnetic radiations which is an order of magnitude larger than the transverse size of the colliding nuclei, enable them to carry information from the earliest stages of collision. Due to electromagnetic coupling with matter ($\alpha_e/\alpha_s \sim 10^{-2}$), they are least scattered in the surrounding medium and carry the information undistorted to the detectors (Feinberg, 1976). Theoretical efforts over the last few decades have been spent to identify several sources of direct photon which constitute the entire spectrum measured in experiment

Author for Correspondence : E-mail: somvecc@gmail.com

(Chatterjee *et al*., 2010). They include; **Prompt photons:** originated from the initial hard scatterings between the beam partons and from the fragmentation of large momentum jets, **Pre-equilibrium photons:** originated from the secondary scatterings among the partons before the system achieves thermalization, **Jet-medium photons:** produced due to elastic back-scattering of high energy jets with thermalized partons of the medium, **Thermal photons:** emitted from the elastic and in-elastic scatterings of the constituents of thermalized QGP and hadronic matter.

The direct photon sources described above, follow a hierarchy in descending order of transverse momenta (p_T) of photons. However it is a challenge for experiment to separate out each contribution, in fact to distinguish direct photons from the overwhelming background of photons coming from the decay of π^0 and η mesons. In this proceeding we have discussed the importance of jet-medium photons and proposed a experimentally feasible way to separate these photons from other sources using the correlation with high energy trigger jets.

Jet-medium photons are notably produced through Compton back-scattering of fast partons or jets in the medium and the jets are preferred to produce back-to back for a leading order (LO) process. Thus we choose a jet of energy few tens of GeV and look for direct photons on the away-side in a narrow azimuthal (ϕ) sector of $\pm 15^0$. Only the hard prompt photons possess such correlation with away-side jets, thus treated as 'Background'for this measurement. Next we look for jet-medium photons having energy (E_γ) very close to trigger jet transverse energy (E_T). This will help to reduce the background from jet-fragmentation photons. In the same kinematic situation we have calculated the parton spectra which will scatter to produce jet-medium photons. The momenta of the photon-jet or the parton-jet pair are perfectly balanced in a LO kinematics. Thus the back-scattered photon signal is lying under the direct photon peak for an ideal scenario. The energy loss of partons prior to back-scattering tends to shift the signal towards low momentum region, thus makes the measurement doable (Fries *et al*., 2013). However the inclusion of trigger jet energy loss has been found to dilute the above photon-jet correlation.

Evaluation of Back-Scattered Photon Source

Jet-medium photons are produced through elastic Compton ($qg \rightarrow q\gamma$) and annihilation ($q\bar{q} \rightarrow g\gamma$) scattering in quark-gluon plasma. It is found that the cross sections of the above processes are sharply peaked either at forward or backward directions. This implies when a fast quark annihilates with a thermal anti-quark (of medium) or Compton scatters of a thermal gluon, the photon carries approximately the same momentum of the fast quark (Fries *et al*., 2003). The back-scattering phenomenon is exploited in quantum optics to produce high energy photon beams through the process $e + \gamma \rightarrow e + \gamma$ (Milburn, 1963).

The rate of production of jet-medium photons from Compton and annihilation process under the assumption of back-scattering ($\mathbf{p}_\gamma = \mathbf{p}_\mathbf{q}^{\mathbf{jet}}$ or $\mathbf{p}_{\bar{\mathbf{q}}}^{\mathbf{jet}}$) is given by (Fries *et al.*, 2003):

$$E_\gamma \frac{dN_\gamma^{total}}{d^4x d^3p_\gamma} = \frac{\alpha_e \alpha_s}{4\pi^2} \sum_{f=1}^{N_f} \left(\frac{e_f}{e}\right)^2 T^2(x) \times [f_q(\mathbf{p}_\gamma, x) + f_{\bar{q}}(\mathbf{p}_\gamma, x)] \left[\ln \frac{3E_\gamma}{\alpha_s \pi T(x)} - 1.916\right], \tag{1}$$

where f is running over all active quark flavors. It is found that the total production rate of back-scattered photons is proportional to $T^2 \ln(1/T)$, thus sensitive to the temperature of the plasma. It can also be noted that the phase space distribution of the fast quark ($f_q(\mathbf{p})$) enters linearly in the rate equation which leads to power-law behaviour of the momentum spectrum.

Now the phase-space distribution of the quark jets $f_q(\mathbf{p})$ is related to their invariant yield as (Lin and Gyulassy, 1995):

$$f_q(\mathbf{p}) = \frac{(2\pi)^3}{g_q \pi R^2 \tau p_T^q} \frac{dN^q}{d^2p_T^q dy}, \tag{2}$$

where g_q=6 is the spin-color degeneracy of the quarks and R is the transverse dimension of the fireball.

Next we consider the trigger jets whose energy (E_T), psudo-rapidity (y_j) and azimuthal angle (ϕ_j) fall within a window Γ_j. To calculate back-scattering photon associated with a trigger jet, we replace single parton distribution (Eq. 2) by parton-jet pair distribution integrated over Γ_j,

$$f_q^{\Gamma_j}(\mathbf{p}_q) = \frac{(2\pi)^3}{g_q \tau p_T} \delta(y-\eta) \rho(\tau, \mathbf{r}_\perp) \times \int_{\Gamma_j} dE_T dy_{jet} d\phi_j E_q \frac{dN}{d^3p_q dE_T dy_{jet} d\phi_j} \Big|_{\substack{\mathbf{p}_q + \Delta\mathbf{p}_q \\ E_T + \Delta E_T}} \tag{3}$$

where $r = (\tau, \eta, \mathbf{r}_\perp)$ and $\mathbf{p_q}$ are the position and momentum of the quark at the time of back-scattering. $\Delta\mathbf{p_q}$ and ΔE_T are energy lost by the parent quark and the trigger jet in the medium respectively. $\rho(\tau, \mathbf{r}_\perp)$ gives the density of hard collisions in the transverse plane.

Results

Our calculation is divided in two stages. First we have calculated the prompt photon (direct + fragmentation) spectra and the fast quark spectra at LO of strong coupling (α_s) with the code JETPHOX (Aurenche *et al.*, 2006). Next we have used the fireball model PPM (Rodriguez *et al.*, 2010) to evaluate the back-scattering photon yield while accounting for (i) the energy loss of partons and (ii) the energy loss trigger of jets. To identify the back-scattering photon signal, we propose to measure the nuclear modification of photon production around the trigger jet p_T window. The nuclear modification (R_{AA}^γ) is defined as:

$$R_{\mathrm{AA}}^\gamma(p_T) = \frac{(\text{Signal+Background})_{\mathrm{AA}}}{N_{coll} \times (\text{Background})_{\mathrm{pp}}}, \tag{4}$$

where ‘Signal’refers to the jet-medium back-scattered photons and N_{coll} is the total number of binary collisions.

For this exploratory study, we have considered central collisions of Pb nuclei at the LHC energy (2.76A TeV). First we consider no energy loss suffered by the trigger jets. The correlated yield and nuclear modification factor of back-scattered photons opposite to trigger jets of energy ($60 < E_T < 65$) GeV and psudo-rapidity $-2 < y_j < 2$ are displayed in Fig. 1.

We see that for no energy loss suffered by the leading quark, back-scattered photons are lying within the trigger jet window (blue circles). However energy loss of leading quark before back-scattering shifts the signal (red dashed line) about 10–15 GeV away from the trigger window. This causes a sharp peak in $R^{\gamma}_{\rm AA}$ just below the trigger window, could be considered as a potential signature of back-scattering photons. The nuclear modification factor of background photons (black dashed line) has also displayed in Fig. 1, which could serve as baseline for this measurement.

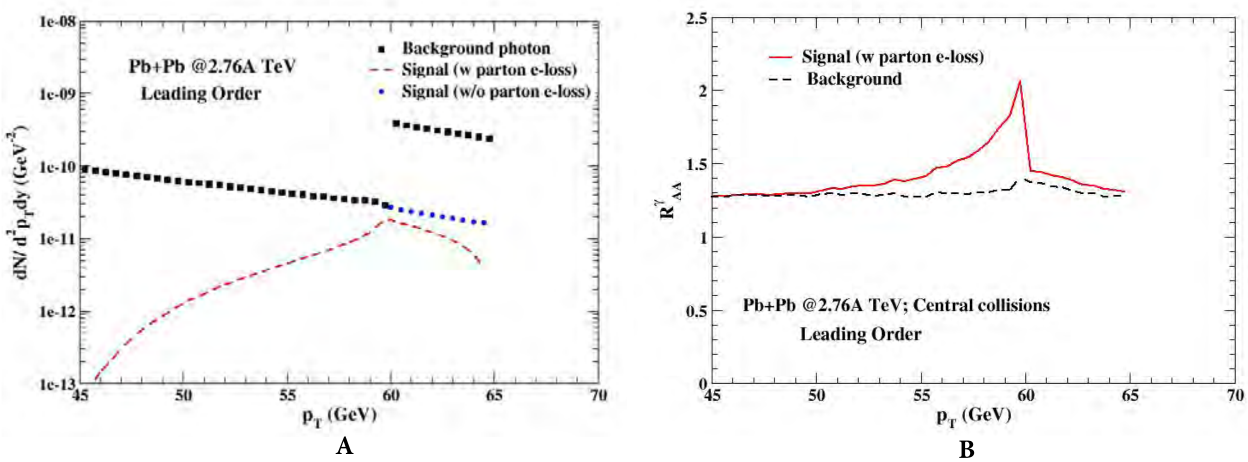
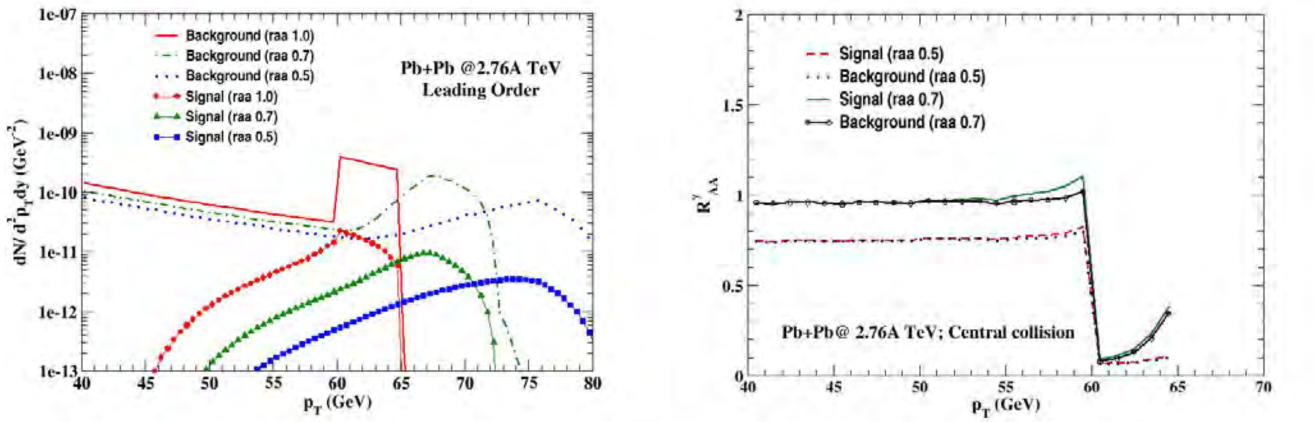


Fig. 1: Invariant yield (A) and the nuclear modification factor (B) of back-scattering photons and only background photons for central Pb+Pb collisions at LHC in opposite to 60-65 GeV trigger jets for LO kinematics

Next we consider trigger jet energy loss in our calculation which has recently been measured at LHC. We followed a simple model of the path length and energy dependence to reproduce average features of jet energy loss (De *et al.*, 2014). To calibrate our energy loss model, we have calculated the nuclear modification factor ($R_{\rm AA}$) of single inclusive jets for central Pb+Pb collisions at LHC (De *et al.*, 2014). We will refer to different jet energy loss scenarios by quoting the value of $R_{\rm AA}$ at E_T= 100 GeV. This number is mentioned in plots as “raa”.



A B

Fig. 2: Invariant yield (A) and the nuclear modification factor (B) of back-scattering photons and background photons for central Pb+Pb collisions at LHC for three different trigger jet energy loss scenarios

We have shown the back-scattering photon and the background photon spectra for three jet energy loss scenarios (raa 1.0, 0.7, 0.5) at LO kinematics in Fig. 2. We have checked that the scenario 'raa 1.0'reproduces our old result of only parton energy loss. It can be seen that both the signal and background spectra developed a shoulder$\sim$ 10-15 GeV towards large momentum side of the trigger window. This is due to the fact that a trigger jet counted in 60-65 GeV window might have originated as a jet of larger energy. We found that the energy loss suffered by trigger jets leads to suppression in $R^{\gamma}_{\rm AA}$ due to shift of background photons towards higher p_T. The back-scattering signal causes a local enhancement in $R^{\gamma}_{\rm AA}$ just below the trigger window. However this is not very distinct for the current jet reconstruction scenario (raa 0.5) used at the LHC.

Conclusions

The jet-medium back-scattered photons are found sensitive to the temperature of QGP and parton energy loss mechanism in QGP. We have shown that measuring nuclear modification factor in coincidence with the away-side leading jet offers an unique opportunity to identify these photons in experiment. However with available jet reconstruction technique used at the LHC, this is not yet feasible.

References

1. Aurenche P *et al*., (2006) Recent critical study of photon production in hadronic collisions, *Phys Rev* **D73** 094007
2. Chatterjee R, Bhattacharya L and Srivastava DK (2010) Electromagnetic Probes, *Lect Notes Phys* **785** 719

3. De S, Fries RJ and Srivastava DK (2014) Jet-triggered photons from back-scattering kinematics for quark gluon plasma tomography, *Phys Rev* **C90** 034911
4. Feinberg EL (1976) Direct Production of Photons and Dileptons in Thermodynamical Models of Multiple Hadron Production, *Nuovo Cim* **A34** 391
5. Fries RJ, De S and Srivastava DK (2013) Jet-Tagged Back-Scattering Photons For Quark Gluon Plasma Tomography, *Nucl Phys* **A904-905** 569c-572c
6. Fries RJ, Muller B and Srivastava DK (2003) High-Energy Photons from Passage of Jets through Quark-Gluon Plasma, *Phys Rev Lett.* **90** 132301
7. Lin Z and Gyulassy M (1995) Open Charm as a probe of pre-equilibrium dynamics in nuclear collisions, *Phys Rev* **C51** 2177
8. Milburn RH (1963) Electron scattering by an intense polarized photon field, *Phys Rev Lett* **10** 75
9. Rodriguez R, Fries RJ and Ramirez E (2010) Event-by-Event Jet Quenching, *Phys Lett* **B693** 108.