Gluon Radiation Off Heavy Flavour Jets

TRAMBAK BHATTACHARYYA*1, SURASREE MAZUMDER1 and RAKTIM ABIR2

¹Variable Energy Cyclotron Centre, Kolkata, India ²Saha Institute of Nuclear Physics, Kolkata, India

(Received on 30 April 2014; Accepted on 4 August 2014)

It is known that gluon bremsstrahlung emission off heavy flavor jet is suppressed in the forward direction compared to that of light quark due to the mass effect ('dead cone effect'). Most of the models that address jet quenching generally assume that a jet always travels in straight eikonal path. However, once the eikonal approximation of propagation is called off and jet is allowed to bend, additional gluons popup within the so called 'depopulated' region deluging the dead cone. This color synchrotron by color charge, once wound in an ambiance of color field, seems to be more physical for better understanding of jet quenching in hot and dense deconfined quark-gluon medium.

Key Words: QCD; QGP; Heavy Quarks; Radiation; Non-Eikonality; Spectrum; Jet-Models

Introduction

When we collide two heavy nuclei with large energies in Heavy-Ion Collision (200 GeV/A in RHIC and \sim 2.76 TeV/A in LHC), partons inside nuclei are also in a Lorentz boosted frame. Now, every charge, electric or colour, in a Lorentz boosted frame acquires photons/gluons/sea quarks. This picture of imagining the field of a rapidly (but uniformly) moving charge as collection of virtual particles is called the Weizsäcker-Williams picture. This picture relies on the fact that there is a similarity between the fields of a rapidly moving charge and the fields of a pulse (Jackson, 1998). A violent collision of nuclei results in acceleration imparted to the moving charges. While the fast Fourier components of the field, whose transverse momenta $k \geq a_0$, where a_0 is the inverse acceleration time, can manage to follow the charge, the softer part is 'left behind' (Niedermayer, 1986). The Weizsäcker-Williams gluons which are now detached from the charge are regenerated along a new direction. So, there is a radiation – the vacuum radiation of highly virtual (Virtuality $Q \sim p_T$, the transverse momentum of parton) particles.

^{*}Author for Correspondence : E-mail: trambak.bhattacharyya@gmail.com

The fast particle along with the associated gluons is called the jet-shower (loosely jet); and we observe the interaction of this jet shower with the medium formed after the softer particles, produced much after the birth of the hard partons, jostle among themselves and thermalize.

There are two processes, the elastic and the radiative processes, by which the jet interacts with the medium. The radiative energy loss of a representative particle in the jet-shower, called the leading particle, calls for counting the number of gluons (n_g) emitted. The more the number of gluons given off, the more the radiative loss is. So we want the distribution of gluons for computing the energy depletion due to radiation.

Finding out the radiation distribution involves kinematics and dynamics of interaction. The dynamics is obtained by dint of the Feynman diagrams method applied for the perturbative QCD (pQCD). As far as the kinematics is concerned, we will perform all the calculations in the centre of momentum (COM) frame. The kinematic approximations widely used in calculating distribution are:

- soft approximation (energy of radiation is much smaller compared to the parent parton)
- eikonal approximation (no recoil of the leading parton due to scattering and radiation)
 and
- collinearity approximation (gluons almost graze the trajectory of the parent particle).

Dokshitzer and Kharzeev (2001) made a study of finding out radiation distribution off heavy flavours. But their study considered all the three approximations *viz.* the *soft-eikonal-collinear* approximations. They have shown the existence of a radiation-free zone (the 'dead-cone') along and around the direction of propagation of heavy quark.

The collinearity approximation in calculating the radiation distribution off heavy quarks has been removed by Raktim Abir *et al.*, (Abir *et al.*, 2012). The present study (Bhattacharyya *et al.*, 2013) removes the eikonality approximation during scattering with the bath particles and shows the absence of the deadcone when the recoil due to scattering is taken into account. The latter two calculations (Abir *et al.*, 2012; Bhattacharyya *et al.*, 2013) have shown a reduction of the respective distribution formulae to the 'Dokshitzer and Kharzeev' formula for radiation distribution off heavy quarks in proper limits.

Calculating Radiation Distribution Considering Non-Eikonality Due to Scattering

Among the interactions that a heavy flavor jet goes through as it traverses a dense medium, radiative scattering is, certainly, the dominant one in the high energy regime. The process $Q(k_1)q(k_2) \to Q(k_3)q(k_4)g(k_5)$ at $\mathcal{O}(\alpha_s^3)$ (α_s is strong coupling), which we have considered in the present work, is represented by five t

channel diagrams. In the entrance channel, k_1 and k_2 are momenta of the heavy projectile quark and light target quark respectively. k_3 and k_4 are corresponding outgoing momenta; and k_5 is the four-momentum of the emitted gluon. Scattering angle between three-vectors $\mathbf{k_1}$ and $\mathbf{k_3}$ is θ_q , whereas θ_g is the angle between the three-vectors $\mathbf{k_1}$ and $\mathbf{k_5}$. The hierarchy among various scales of momenta, considered herein, is,

$$E > q_{\perp} \gg \omega \ge k_{\perp} \gg m_{q,q} \gg \Lambda_{QCD}$$
 (1)

where E is the energy of the leading parton, q_{\perp} is the transverse momentum transfer, ω is the energy of the emitted gluon, k_{\perp} is the transverse momentum of the emitted radiation , $m_{g,q}$ are the thermal masses of the quark(q)/gluon(g),and Λ_{QCD} is cut-off scale for the perturbative QCD

The present work relaxes the approximation $E \gg q_{\perp}$, the non-eikonal approximation due to scattering. The differential gluon emission spectrum containing the recoil effect and applicable in full rapidity range is the following:

$$x\frac{dN_g}{dxdk_{\perp}^2} = \underbrace{\frac{C_A\alpha_s}{\pi} \frac{1}{k_{\perp}^2} \int_{q_{\perp}} \frac{d\sigma_{\text{el}}^{qQ \to qQ}}{dq_{\perp}^2} dq_{\perp}^2}_{GB} \underbrace{\left[\sum_{n=2,1,0} C_n e^{2(n-1)\eta_g} \left(\frac{k_{\perp}^2}{k_{\perp}^2 + x^2 M^2} \right)^n \right]}_{\mathcal{W}(x,k_{\perp}^2)}$$

$$\times \underbrace{\int_t 2\sin^2\left(\frac{t-t_i}{t_f}\right) dt}_{LPM}$$
(2)

where $d\sigma_{\rm el}^{qQ\to qQ}/dq_\perp^2=g^4/(18\pi t^2)$ is the eikonally approximated elastic cross-section of the $Qq\to Qq$ process. Variable x is defined as the ratio of light cone positive momentum carried by the emitted gluon to that of the parent heavy quark, i.e. $x=k^+/p^+=k_\perp e^{\eta_g}/\sqrt{s}$, where η_g is the rapidity of the emitted gluon expressed as: $\eta_g=-1/2\ ln\ (\tan\theta_g/2)$; and \sqrt{s} is the centre of momentum enegry. GB stands for the Gunion-Bertsch distribution (Gunion and Bertsch, 1982) and LPM stands for the Landau-Pomeranchuk-Migdal factor (Landau and Pomeranchuk, 1953; Migdal, 1956). The factor $\mathcal{W}(x,k_\perp^2)$ represents the square of the radiation current obtained by factoring out the Feynman amplitude square for the $Qq\to Qq$ process, $|\mathcal{M}_{Qq\to Qq}|^2$, from the matrix element square $|\mathcal{M}_{Qq\to Qqg}|^2$. $\mathcal{W}(x,k_\perp^2)$ is necessary for calculating the radiation distribution. For details of the calculations leading to finding out $\mathcal{W}(x,k_\perp^2)$ and for computation of the coefficients \mathcal{C}_n used in this paper, we refer to (Bhattacharyya $et\ al.$, 2013) and the appendices therein.

In Figs. 1-4 we have presented polar plots of $\mathcal{W}[\omega,\theta_g]$ (alternatively $\mathcal{W}[x,k_\perp^2]$). It is easy to espy that once $0 \le \zeta = \frac{q_\perp}{\sqrt{s}} \le 1$ (the extent of recoil due to scattering) is non-zero, so that the heavy flavor leading the jet bends, additional gluons pop-up along the direction of propagation of the outgoing heavy flavor. More the recoil is, more is the emission.

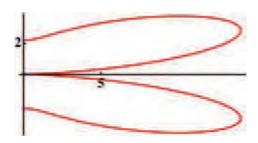


Fig. 1: Polar plot of $\mathcal{W}(\theta_g,\omega)$ (at a typical ω) with $\zeta(=q_\perp/\sqrt{s})=0$ for a 10 GeV Charm jet.

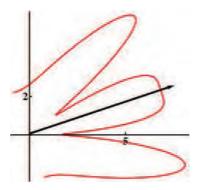


Fig. 3: Polar plot of $\mathcal{W}(\theta_g, \omega)$ (at a typical ω) with $\zeta (= q_{\perp}/\sqrt{s}) = 0.30$ for a 10 GeV Charm jet.

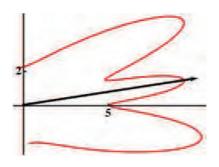


Fig. 2: Polar plot of $\mathcal{W}(\theta_g,\omega)$ (at a typical ω) with $\zeta(=q_{\perp}/\sqrt{s})=0.15$ for a 10 GeV Charm jet.

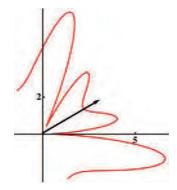


Fig. 4: Polar plot of $\mathcal{W}(\theta_g,\omega)$ (at a typical ω) with $\zeta(=q_{\perp}/\sqrt{s})=0.45$ for a 10 GeV Charm jet.

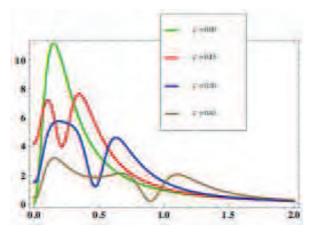


Fig. 5: Transverse momentum (of emitted gluons) (k_{\perp}) dependence of the factor $\mathcal{W}[x,k_{\perp}]$ for different $\zeta(=q_{\perp}/\sqrt{s})$.

Fig. 5 depicts the variation of $\mathcal{W}(x,k_{\perp}^2)$, which, in turn, reflects the emission spectrum, with k_{\perp} at different ζ values. The green curve represents the conventional eikonal spectrum of jet models. The red, blue and brown curves are spectrum profile corresponding to $\zeta=0.15,\ 0.30$ and 0.45 respectively. It can be shown that spectrum integrated over k_{\perp} decreases slowly with increasing non-eikonality. On the other hand, $\langle k_{\perp} \rangle$ is blue-shifted with increasing ζ values.

Conclusion

One of the main challenges of contemporary jet study initiatives is to extend the theoretical framework for jet-medium interaction in hot-dense QCD ambiance beyond soft and collinear approximations and reduce uncertainties intrinsic to the current theoretical studies. In that march, the present work removes the collinear approximation completely in single emission kernel calculation thereby probing the cloud of gluon away from the forward direction. This endeavour also removes the eikonal approximation due to scattering and hence shows the advent of a treatment which allows the jet to bend with non-negligible recoil effect from the scattering in chromo-magnetic ambiance enabling one to treat the color synchrotron radiation of color charges.

Acknowledgement

Research of the authors are supported by DAE, Govt. of India. RA is grateful to Santanu Maity for illuminating discussions.

References

- 1. Abir R, Greiner C, Martinez M, Mustafa M G and Uphoff J (2012) Soft gluon emission off a heavy quark revisited *Phys Rev* **D85** 054012 1
- 2. Bhattacharyya T, Mazumder S and Abir R (2013) Color synchrotron off heavy flavor jet deluges the dead cone, e-print: arXiv: 1307.6931
- 3. Dokshitzer Y L and Kharzeev D E (2001) Heavy-quark colorimetry of QCD matter *Phys Lett* **B519** 199
- 4. Gunion J F and Bertsch G (1982) Hadronization by Color Bremsstrahlung, Phys Rev D25 746
- 5. Jackson J D (1998) Classical Electrdynamics. John Wiley and Sons Pvt. Ltd.
- 6. Landau L D and Pomeranchuk I Y (1953) Limits of applicability of the theory of bremsstrahlung electrons and pair production at high-energies *Dokl Akad Nauk SSSR* **92** 535-536
- 7. Migdal A B (1956) Bremsstrahlung and Pair Production in Condensed Media at High Energy *Phys Rev* **103** 1811
- 8. Niedermayer F (1986) Flux tube or bremsstrahlung? Phys Rev D34 3494.