IN-MEDIUM PARTON ENERGY LOSSES AND CHARACTERISTICS OF HADRONIC JETS IN ULTRA-RELATIVISTIC NUCLEAR COLLISIONS

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Abstract

The angular structure of collisional and radiative energy losses of a hard parton jet propagating through the quark-gluon plasma is analyzed. The possibility to observe the energy losses of quark- and gluon-initiated jets in dense QCD-matter (jet quenching) measuring the characteristics of real hadronic jets in ultra-relativistic collisions of nuclei is investigated. In particular, using calorimetric studies of jet + jet, γ + jet and Z + jet channels is discussed.
1 Angular structure of energy losses of hard jet in dense QCD-matter

Hard jet production is considered to be an efficient probe for formation of quark-gluon plasma (QGP) in future experiments on heavy ion collisions at LHC. High $p_T$ parton pair (dijet) from a single hard scattering is produced at the initial stage of the collision process (typically, at $\lesssim 0.01$ fm/c). It then propagates through the QGP formed due to mini-jet production at larger time scales ($\sim 0.1$ fm/c), and interacts strongly with the comoving constituents in the medium.

We know two possible mechanisms of energy losses of a hard partonic jet evolving through the dense matter: (1) radiative losses due to gluon "bremsstrahlung" induced by multiple scatterings and (2) collisional losses due to the elastic rescatterings of high $p_T$ partons off the medium constituents. Although the radiative energy losses of a high energy parton can dominate over the collisional losses by up to an order of magnitude, the angular distribution of the losses is essentially different for two mechanisms. Indeed, the coherent Landau-Pomeranchuk-Migdal radiation induces a strong dependence of the jet energy on the jet cone size $\theta_0$. With increasing of hard parton energy the maximum of the angular distribution of bremsstrahlung gluons shifts towards the parent parton direction. This means that measuring the jet energy as a sum of the energies of final hadrons moving inside an angular cone with a given finite size $\theta_0$ will allow the bulk of the gluon radiation to belong to the jet. Therefore, the medium-induced radiation will, in the first place, soften particle energy distributions inside the jet, increase the multiplicity of secondary particles, but will not affect the total jet energy. On the other hand, the collisional energy losses turns out to be practically independent on $\theta_0$ and emerges outside the narrow jet cone: the bulk of "thermal" particles knocked out of the dense matter by elastic scatterings fly away in almost transverse direction relative to the jet axis.

The total energy loss experienced by a hard parton due to multiple scattering in matter is the result of averaging over the dijet production vertex ($R$, $\varphi$), the momentum transfer $t$ in a single rescattering and space-time evolution of the medium:

$$\Delta E_{tot} = \int_0^{2\pi} \frac{d\varphi}{2\pi} \int_0^{R_A} dR \cdot P_A(R) \int_{\tau_0}^{\tau_L} d\tau \left( \frac{dE^{rad}}{dx}(\tau) + \sum_b \sigma_{ab}(\tau) \cdot \rho_b(\tau) \cdot \nu(\tau) \right).$$

(1)

Here $\tau_0$ and $\tau_L = \sqrt{R_A^2 - R^2 \sin^2 \varphi - R \cos \varphi}$ are the proper time of the QGP formation and the time of jet escaping from the plasma; $P_A(R)$ is the distribution of the distance $R$ from the axis of nuclei collision $z$ to the dijet production vertex; $n_b \propto T^3$ is the density of plasma constituents of type $b$ at temperature $T$; $\sigma_{ab}$ is the integral cross section of scattering of a jet parton $a$ off the comoving constituent $b$. $\frac{dE^{rad}}{dx}(\tau)$ is the radiative energy losses per unit length; $\nu(\tau) = <Q^2/2m_0>$ is the thermal average collisional energy loss of the jet parton with energy $E$ due to elastic single scattering off a constituent of the medium with energy $m_0 \sim 3T$. The scatterings can be treated as independent, if the mean free path of hard parton is larger than the Debye screening radius, $\lambda \equiv \sum_b \sigma_{ab} n_b \gg \mu_D^{-1}$.

We have suggested a simple generalization of BDPMS result for $dE/dx^{rad}$ to calculate the gluon energy deposited outside a given cone $\theta_0$, which is based on the relation between the gluon radiation angle $\theta$ and energy $\omega$ which holds only in average:

$$\bar{\theta} = \theta(\omega) \simeq \theta_M \cdot \left( \frac{E_{LPM}}{\omega} \right)^{\frac{1}{2}},$$

(2)

where $E_{LPM} = \mu_D^2 \lambda_0$ is the minimal radiated gluon energy in the coherent LPM regime and $\theta_M = (\mu_D \lambda_0)^{-1}$ is the characteristic angle depending on the local properties of the medium. Note that the problem of a rigorous description of the differential angular (transverse momentum)
distribution of induced radiation is complicated by intrinsically quantum-mechanical nature of the phenomenon: large formation times of the radiation does not allow the direction of the emitter to be precisely defined [3].

Figure 1: The average radiative (solid curve) and collisional (dashed curve) energy losses of quark-initiated jet as a function of the jet cone size $\theta_0$.

Figure 1 represents the average radiative (coherent medium-dependent part) and collisional energy losses of a quark-initiated jet with initial energy $E = 100$ GeV as a function of the jet cone size $\theta_0$. We have used scaling Bjorken’s solution [11] for temperature and density of gluon-dominated plasma $T(\tau)\tau^{1/3} = T_0\tau_0^{1/3}$, $\rho(\tau)\tau = \rho_0\tau_0$ and initial conditions, predicted to be achieved in central $Pb-Pb$ collisions at LHC energies [1]: $\tau_0 \simeq 0.1$ fm/$c$, $T_0 \simeq 1$ GeV.

We can see the weak $\theta_0$-dependence of collisional losses, at least 90% of scattered “thermal” particles flow outside a rather wide cone $\theta_0 \sim 10^0 - 20^0$. The radiative losses are almost independent of the initial jet energy and decrease rapidly with increasing the angular size of the jet at $\theta_0 \gtrsim 5^0$.

2 Jet quenching: $jet + jet$, $\gamma + jet$ and $Z + jet$ production

In a search for experimental evidences in favour of the medium-induced energy losses a significant dijet quenching (a suppression of high $p_T$ jet pairs) [12] was proposed as a possible signal of dense matter formation in ultra-relativistic nuclear collisions. Note that the dijet rate in $AA$ relative to $pp$ collisions can be studied by introducing a reference process, unaffected by energy losses and with a rate proportional to the number of nucleon-nucleon collisions, such as Drell-Yan dimuons or $Z(\rightarrow \mu^+\mu^-)$ production: $P_{dijet}^{AA}/P_{dijet}^{pp} = \left(\sigma_{dijet}^{AA}/\sigma_{dijet}^{pp}\right)/\left(\sigma_{DY}^{Z}(2)/\sigma_{DY}^{Z}(2)\right)$.

We have studied the capability of the CMS detector [3] at future LHC collider to observe the medium-induced energy losses of quarks and gluon detecting hadronic jets in heavy ion collisions [13]. The Compact Muon Solenoid (CMS) is the general purpose detector designed to run at the LHC and optimized mainly for the search of the Higgs boson in $pp$ collisions. However, a good muon system and electromagnetic and hadron calorimeters with fine granularity gives the possibility to cover important “hard probes” aspects of the heavy ion physics. At LHC ions will be accelerated at $\sqrt{s}=7 \times (2Z/A)$ TeV per nucleon pair. In the case of $Pb$ nuclei $\sqrt{s}=5.5A$ TeV and the expected average luminosity $L \approx 1.0 \times 10^{27}$ cm$^{-2}s^{-1}$. The inelastic interaction cross-section for $Pb-Pb$ collisions is about 8 b, which leads to an event rate of 8 kHz.

The jet recognition efficiency and expected production rates was studied assessing the CMS calorimeters response for the barrel part of CMS calorimeters, which covers the pseudorapidity region of $|\eta| < 1.5$. Using the selection criterion on jet shape allows getting the maximum efficiency of ”true” hard jets recognition as well as the maximum suppression of ”false” jets background at jet energy $E_T \sim 50-100$ GeV [13]. In order to test the sensitivity of the final hadronic jets to the energy losses, the three different scenarios for jet quenching due to collisional energy losses of a jet partons were studied [3]: (i) no jet quenching, (ii) jet quenching in a perfect QGP (the average collisional losses of a hard gluon $<DE_g> \approx 9$ GeV, $<\Delta E_g> = 4/9 \cdot <DE_g>$), (iii) jet quenching in a maximally viscous QGP, resulting in $<\Delta E_g> \approx 18$ GeV.
Figure 2 represents the probability of dijet yield as a function of $E_T$ in simulated central Pb – Pb collisions for CMS. The significant suppression of hard dijet yield due to energy losses (up to factor $\sim 7$, or somewhat higher if the radiative energy losses mechanism is included) can be expected. The quenching factor is almost independent of the jet energy if the losses do not depend (or depend weakly) on the energy of an initial hard parton. The expected statistics for dijet production will be large enough to make the study the dijet rates as a function of impact parameter of the collision and the transverse energy of jets. The suppression of dijet rates (jet quenching) expected to be much more stronger at very central collisions in comparison with the peripheral one’s.

Other possible signatures that could directly observe the energy losses involve tagging the hard jet opposite a particle that does not interact strongly ($q + g \rightarrow q + \gamma$ [14] and $q + g \rightarrow q + Z(\rightarrow \mu^+\mu^-)$ [15] channels). The jet energy losses should result in the non-symmetric shape of the distribution of differences in transverse momentum between the Z-boson ($\gamma$) and jet. The estimated statistics is rather low for $Z(\rightarrow \mu^+\mu^-) + \text{jet}$ channel. On the other hand, using $\gamma + \text{jet}$ production is complicated due to large background from $\text{jet} + \text{jet}$ production when one of the jet in an event is misidentified as a photon (the leading $\pi^0$). However the shape of the distribution of differences in transverse energy between the $\gamma$ and jet is well sensitive to the jet quenching effect. It seems possible to extract the background $\gamma + \text{jet}$ events from the experimental spectra using the background shape from Monte-Carlo simulation and (or) from $pp$ data.

3 Conclusions

For small angular jet cone sizes, $\theta_0 \lesssim 5^0$, the radiative energy loss is shown to dominate over the collisional energy loss due to final state elastic rescattering of the hard projectile on thermal particles in the medium. Due to coherent effects, the radiative energy loss decreases with increasing the angular size the jet. It becomes comparable with the collisional energy loss for $\theta_0 \gtrsim 5^0 – 10^0$. Relative contribution of collisional losses would likely become significant for jets with finite cone size propagating through the hot plasma under LHC conditions.

Monte-Carlo study shows that CMS detector at future LHC collider is well suited for the investigation of high transverse energy jets. Dijet production, $Z(\rightarrow \mu^+\mu^-) + \text{jet}$ and $\gamma + \text{jet}$ channels are important for extracting information about the properties of super-dense matter to be created in heavy ion collisions at LHC.
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