ANGULAR STRUCTURE OF ENERGY LOSSES OF HARD JET IN DENSE QCD-MATTER

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Abstract

Angular structure of radiative and collisional energy losses of a hard parton jet propagating through dense QCD-matter is investigated. 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 $\theta_0 \gtrsim 5^0 - 10^0$.

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1. Introduction

Jet production, as well as other hard processes, is considered to be an efficient probe for formation of quark-gluon plasma (QGP) [1] in future experiments on heavy ion collisions at RHIC and LHC [2]. 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 (~ 0.1 fm/c) and interacts strongly with comoving constituents in the medium.

The actual problem is to study the energy losses of a hard parton jet propagating through dense matter. We know two possible mechanisms of energy losses: (1) radiative losses due to gluon bremsstrahlung induced by multiple scattering [3, 4, 5, 6, 7, 8, 9, 10] and (2) collisional losses due to the final state interaction (elastic rescatterings) of high-p_T partons off the medium constituents [11, 12, 13]. Since the jet rescattering intensity strongly increases with temperature, formation of a super-dense and hot partonic matter in heavy ion collisions with initial temperatures up to $T_0 \sim 1$ GeV at LHC energies [14] should result in significantly larger jet energy losses as compared with the case of hadronic gas at $T_h \lesssim 0.2$ GeV or a "cold" nuclear matter, the other parameters of the medium being kept the same.

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) [15] and a monojet/dijet ratio enhancement [16] were proposed as possible signals of dense matter formation in ultrarelativistic nuclei collisions. Suppression of high-p_T particles is also considered as manifestation of jet quenching in the single-particle spectrum [17]. Another option is to perform a direct jet energy losses measurement in processes where a hard parton jet is tagged by "unquenched" strongly non-interacting particle like Z-boson [18] ($q + g \to q + Z \to q + \mu^+ + \mu^-$, $q + \overline{q} \to g + Z \to g + \mu^+ + \mu^-$) or γ-photon [19] ($q + g \to q + \gamma$, $q + \overline{q} \to g + \gamma$). The possibility that the dilepton mass spectra in the invariant mass range $1.5 \leq M \leq 2.5$ GeV/c^2 are modified due to suppression of correlated semileptonic charm and bottom decays, $D\bar{D}$ ($B\bar{B}$) $\to l^+l^-$, was recently investigated [20, 21] as a sign of large energy losses experienced by c and b quarks [22].

All the above phenomena (dijet and monojet production, $Z + jet$ and $\gamma + jet$ channels, dilepton yield) are important for extracting information about the properties of super-dense matter to be created in ultrarelativistic heavy ion collisions and are related, one way or another, with the medium-induced QCD energy losses.

Although the radiative energy losses of a high energy projectile parton have been shown to dominate over the collisional losses by up to an order of magnitude [5, 22], a direct experimental verification of this phenomenon remains an open problem. Indeed, with increasing of hard parton energy the maximum of the angular distribution of bremsstrahlung gluons has shift towards the parent parton direction. This means [3] that measuring the jet energy as a sum of the energies of final hadrons moving inside an angular cone with a given finite size θ_0 will allow the bulk of the gluon radiation to belong to the jet and thus the major portion of the initial parton energy to be reconstructed. 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.

Dependence of radiative energy losses on the angular cone size of a jet should be studied to allow a meaningful comparison with future experimental data on jet production in ultra-relativistic ion collisions. The aim of the present paper is to analyze the angular structure of radiative and collisional energy losses of hard parton jet in a dense QCD matter and to study how the radiative and collisional losses affect the total energy of a hard parton jet of a finite angular cone size.

It was recently shown [6, 7] that the radiation of energetic gluons in a QCD medium is essentially different from the Bethe-Heitler independent radiation pattern. Such gluons have formation times exceeding the mean free path for QCD parton scattering in the medium. In these circumstances the coherent effects play a crucial rôle leading to a strong suppression of the medium-induced gluon radiation. This coherent suppression is a QCD analogue of the Landau-Pomeranchuk-Migdal effect in QED. It is important to notice that, contrary to the standard gluon bremsstrahlung in hard processes where the radiation angles have a broad logarithmic distribution which is practically independent on the gluon energy ω, the coherent LPM radiation is concentrated at $\theta \sim \theta(\omega) \ll 1$ with $\theta(\omega)$ a given (E_{jet}–independent) function of the gluon energy. This induces a strong dependence of the jet energy on the jet cone size θ_0.

On the other hand, the collisional energy losses represent an incoherent sum over all rescatterings. It is also almost independent of the initial parton energy. At the same time, the angular distribution of the collisional energy loss is essentially different from that of the radiative one. The bulk of "thermal" particles knocked out of the dense matter by elastic scatterings fly away in almost transverse direction relative to the hard jet axis. As a result, the collisional energy loss turns out to be practically independent on θ_0 and emerges outside the narrow jet cone.

2. Energy losses of a jet with finite cone size: heuristic discussion

2.1 Collisional energy losses

In this section we apply simple qualitative considerations in order to analyze the angular structure of collisional losses of a hard jet in a dense matter. If the mean free path of a hard parton is larger than the screening radius in the QCD medium, $\lambda \gg \mu_D^{-1}$, the successive scatterings can be treated as independent. The dominant contribution to the differential cross section for scattering of a parton with energy E off the "thermal" partons with energy (or effective mass) $m_0 \sim 3T \ll E$ at temperature T can be written as [5, 22]

$$\frac{d\sigma_{ab}}{dt} \cong C_{ab} \frac{2\pi\alpha_s^2(t)}{t^2}, \tag{1}$$

where $C_{ab} = 9/4, 1, 4/9$ for gg, gq and qq scatterings respectively. Here t is the transfer momentum squared, α_s is the QCD running coupling constant,

$$\alpha_s = \frac{12\pi}{(33 - 2N_f)\ln(t/\Lambda^2)}, \tag{2}$$

for N_f active quark flavours, and Λ is the QCD scale parameter which is of the order of the critical temperature, $\Lambda \simeq T_c$. The integrated parton scattering cross section,

$$\sigma_{ab} = \int\limits_{\mu_D^2(\tau)}^{m_0(\tau)E/2} dt \frac{d\sigma_{ab}}{dt}, \tag{3}$$

is regularized by the Debye screening mass μ_D^2. In relativistic kinematics, $E \gg m_0$, in the rest system of the target with effective mass m_0 we get the following estimate for the transverse $p_T^{t,i}$ and longitudinal $p_L^{t,i}$ momenta of the incident and "thermal" particles: $p_T^t \simeq \sqrt{t}$, $p_L^t \simeq t/2m_0$; $p_T^i \simeq -\sqrt{t}$, $p_L^i \simeq E - t/2m_0$. Then the thermal average of the collisional energy loss due to single elastic scattering can be estimated as [1]

$$\nu = \left\langle \frac{t}{2m_0} \right\rangle = \frac{1}{2} \left\langle \frac{1}{m_0} \right\rangle \cdot \langle t \rangle \simeq \frac{1}{4T\sigma_{ab}} \int\limits_{\mu_D^2}^{3TE/2} dt \frac{d\sigma_{ab}}{dt} t. \tag{4}$$

[1]For simplicity we do not consider here the possibility of collisional losses due to soft interactions of jet partons with the collective QGP modes (plasma polarization) [11, 12], inclusion of which seems to be irrelevant for our semi-qualitative discourse.

Scattering angle θ_i of the incident parton vanishes in the relativistic limit, $\tan\theta_i = p_T^i/p_L^i \simeq \sqrt{t}/E \to 0$. The scattering angle θ_t of a struck "thermal" particle with respect to the initial direction of the fast parton can be estimated as $\tan\theta_t = p_T^t/p_L^t \simeq 2m_0/\sqrt{t}$. The minimal and maximal values of $\tan\theta_t$ are $\tan\theta_t^{max} \simeq 2m_0/\mu_D$ and $\tan\theta_t^{min} \simeq 2m_0/\sqrt{0.5m_0E}$ respectively. It is straightforward to evaluate the average $\langle\tan\theta_t\rangle$ as

$$\langle\tan\theta_t\rangle = \left\langle\frac{2m_0}{\sqrt{t}}\right\rangle \simeq \frac{6T}{\sigma_{ab}}\int\limits_{\mu_D^2}^{3TE/2} dt\frac{d\sigma_{ab}}{dt}\frac{1}{\sqrt{t}}. \tag{5}$$

Neglecting a weak $\alpha_s(t)$ dependence we obtain $\langle\tan\theta_t\rangle \simeq \frac{2}{3}\tan\theta_t^{max} \simeq 4m_0/3\mu_D$. Substituting $m_0 = 3T$ and the lowest order pQCD estimate $\mu_D^2 \cong 4\pi\alpha_s^* T^2(1+N_f/6)$ we arrive at $< \theta_t >\sim 60^0$ for $T \gtrsim 200$ MeV. This value exceeds typical cone sizes $\theta_0 \sim 10^0 - 30^0$ used to experimentally define hadronic jets. This means that the major part of "thermal" particles will fly outside the cone of the jet and thus cause the "jet energy loss".

2.2 Radiative energy loss

In [6, 7] three regimes of gluon radiation off a high energy parton in a QCD matter were discussed: the Bethe-Heitler regime of independent emission (producing energy loss $dE/dx \propto \mu_D^2$), the Landau-Pomeranchuk-Migdal regime ($dE/dx \propto \sqrt{E}$), and the factorization limit ($dE/dx \propto E$, modulo logarithms). The radiation pattern depends on the energy of the radiated gluon and on the properties of the medium.

BH regime. Small energy gluons with $\omega \lesssim E_{LPM} = \mu_D^2\lambda_g$ follow the Bethe-Heitler regime. Hereafter λ_g is the gluon mean free path. This radiation produces finite energy loss per unit length, is concentrated at large angles,

$$\omega \lesssim \mu_D^2\lambda_g\,, \quad k_t \sim \mu_D\,; \qquad \theta^{(BH)} \simeq \frac{k_t}{\omega} \gtrsim (\mu_D\lambda_g)^{-1} \equiv \theta_M \lesssim 1\,, \tag{6}$$

and therefore is similar to the collisional energy loss. Formation time of the BH gluons does not exceed the mean free path:

$$\tau_f \simeq \frac{\omega}{k_t^2} \lesssim \lambda_g\,.$$

LPM regime. Radiative energy losses are dominated by emission of relatively energetic gluons with large formation times $\tau_f \gg \lambda$. This is the domain of the coherent LPM regime. The structure of the LPM gluon spectrum can be understood, semi-quantitatively, by equating the gluon formation time with the time of gluon propagation through the medium in course of which the gluon transverse momentum accumulates according to the random walk scattering pattern:

$$k_t^2 \simeq \frac{t}{\lambda_g} \cdot \mu_D^2\,, \quad \tau_f \simeq \frac{\omega}{k_t^2} = t\,, \tag{7}$$

where we have taken μ_D to represent a typical momentum transfer to the gluon in a single scattering in the medium. This gives

$$\tau_f \simeq \lambda_g \cdot \left(\frac{\omega}{E_{LPM}}\right)^{\frac{1}{2}}, \qquad k_t \simeq \mu_D \cdot \left(\frac{\omega}{E_{LPM}}\right)^{\frac{1}{4}}. \tag{8}$$

For the radiation angle we get an estimate

$$\theta = \theta(\omega) \simeq \theta_M \cdot \left(\frac{E_{LPM}}{\omega}\right)^{\frac{3}{4}}. \tag{9}$$

Here θ_M is the characteristic angle depending on the local properties of the medium,

$$\theta_M = (\mu_D \lambda_g)^{-1}\,, \tag{10}$$

the combination that has already appeared in (6). Formally,

$$\theta_M = \frac{\sigma_g \rho}{\mu_D} \propto \alpha_s^2 \cdot \left(\rho \mu_D^3\right)\,, \tag{11}$$

where σ_g is the gluon scattering cross section and ρ the density of the scattering centers. Strictly speaking, it should be considered a small parameter in order to ensure applicability of the independent scattering picture, see above. In reality however θ_M may be numerically of the order unity since the momentum scale of the coupling α_s in (11) is small, $\alpha_s = \alpha_s(\mu_D) \lesssim 1$.

Factorization regime. Finally, for a medium of a finite size L radiation of the most energetic gluons is *medium-independent* (the factorization component). These are the gluons with formation times τ_f exceeding the time $\tau_L = L$ it takes to traverse the medium. From (8) we derive from the condition $\tau_f = \tau_L$ the maximal gluon energy in the LPM regime,

$$\omega_{(LPM)} < \left(\frac{L}{\lambda_g}\right)^2 E_{LPM} = \frac{\mu_D^2 L^2}{\lambda_g}\,.$$

The gluons that are formed outside the medium carry away a large fraction of the initial parton energy, proportional to $\alpha_s(E)$. This part of gluon radiation produces the standard jet energy profile which is identical to that of a jet produced in a hard process in the vacuum. Hereafter we shall concentrate on the *medium-dependent* effects in the angular distribution of energy and will not include the "vacuum" part of the jet profile.

3. A model for energy losses of a jet with finite cone size

We calculate the energy losses for the case which can be realized in symmetric ultrarelativistic nucleus-nucleus collisions. Following Bjorken [23] we treat the medium as a boost-invariant longitudinally expanding quark-gluon fluid, and partons as being produced on a hyper-surface of equal proper times $\tau = \sqrt{t^2 - z^2}$. Recently the radiative energy losses of a fast parton propagating through expanding (according to Bjorken's model) QCD plasma have been derived as $dE/dx|_{expanding} = c \cdot dE/dx|_{T_L}$ with numerical factor $c \sim 6$ (2) for a parton created outside (inside) the medium, T_L being the temperature at which the dense matter was left [9]. We shall denote here this radiative energy losses scenario as model I.

We can compare model I with another one which relies on an accumulative energy losses, when both initial and final state gluon radiation is associated with each scattering in expanding medium together including the interference effect by the modified radiation spectrum as a function of decreasing temperature $dE/dx(T)$ (the model II). 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, φ), the momentum transfer t in a single rescattering and space-time evolution of the medium:

$$\Delta E_{tot} = \int\limits_0^{2\pi} \frac{d\varphi}{2\pi} \int\limits_0^{R_A} dR \cdot P_A(R) \int\limits_{\tau_0}^{\tau_L} d\tau \left(\frac{dE}{dx}^{rad}(\tau) + \sum_b \sigma_{ab}(\tau) \cdot \rho_b(\tau) \cdot \nu(\tau) \right). \qquad (12)$$

Here τ_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, respectively (R_A is the radius of the nucleus). Function $P_A(R) \simeq 3(R_A^2 - R^2)/(2R_A^3)$ at $R \leq R_A$ describes the distribution of the distance R from the nuclear collision axis z to the dijet production vertex for the uniform nucleon density; $\rho_b \propto T^3$ is the density of plasma constituents of type b at temperature T; σ_{ab} is the integral cross section of scattering of the jet parton a off the comoving constituent b (with the same longitudinal rapidity).

The interval between successive scatterings, $l_i = \tau_{i+1} - \tau_i$, is determined in linear kinetic theory according to the probability density:

$$\frac{dP}{dl_i} = \lambda^{-1}(\tau_{i+1}) \cdot \exp{(-\int\limits_0^{l_i} \lambda^{-1}(\tau_i + s) ds)}, \tag{13}$$

where the mean inverse free path is given by $\lambda_a^{-1}(\tau) = \sum_b \sigma_{ab}(\tau)\rho_b(\tau)$.

The thermal-averaged collisional energy loss $\nu(\tau)$ of a jet parton due to single elastic scattering outside the angular cone θ_0 is estimated according to Eq. (4) by imposing an additional restriction on the momentum transfer $t < (2m_0/\tan\theta_0)^2$ in order to ensure $\theta_t > \theta_0$.

The energy spectrum of coherent medium-induced gluon radiation and the corresponding radiative energy loss, dE/dx, were analyzed in [7] by means of the Schrödinger-like equation whose "potential" is determined by the single-scattering cross section of the hard parton in the medium. Here we suggest a simple generalization of this result to calculate the gluon energy deposited outside a given cone θ_0. To this end we make use of the relation (9) between the gluon energy and the characteristic emission angle and mean energy $\bar{\omega}$ of radiated gluons:

$$\bar{\omega} < \omega(\theta_0) \;\equiv\; E_{LPM} \left(\frac{\theta_M}{\theta_0}\right)^{\frac{4}{3}} , \tag{14}$$

which restriction, according to (9), selects the gluons with large radiation angles, $\theta > \theta_0$.

For the quark jet we obtain [8, 10]

$$\frac{dE^{rad}}{dx} = \frac{2\alpha_s C_R}{\pi\tau_L} \int\limits_{\omega_{\min}}^{E} d\omega \left[1 - y + \frac{y^2}{2}\right] \ln\left|\frac{\sin{(\omega_1\tau_1)}}{\omega_1\tau_1}\right| , \tag{15}$$

$$\omega_1 = \sqrt{i\left(1 - y + \frac{C_R}{3}y^2\right)\bar{\kappa}\ln\frac{16}{\bar{\kappa}}} \quad \text{with} \quad \bar{\kappa} = \frac{\mu_D^2\lambda_g}{\omega(1-y)}. \tag{16}$$

Here $\tau_1 = \tau_L/(2\lambda_g)$, and $y = \omega/E$ is the fraction of the hard parton energy carried by the radiated gluon, and $C_R = 4/3$ is the quark colour factor. A similar expression for the gluon jet can be obtained by substituting $C_R = 3$ and a proper change of the factor in the square bracket in (15), see [10]. The integral (15) and analogous one for $\bar{\omega}$ are carried out over all energies from $\omega_{\min} = E_{LPM}$, the minimal radiated gluon energy in the coherent LPM regime, up to initial jet energy E.

It is worth noticing that such a treatment is approximate since it is based on the relation between the gluon radiation angle and energy which holds only in *average*. 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 [6, 7].

We also disregard the final state interaction of the hard parton and the secondary gluon in the medium after the gluon has been produced. Such interactions, even elastic, could affect the angular distribution of the emitted gluon with respect to the parent parton. As long as the radiation angles are relatively large, $\theta > \theta_0 \lesssim 1$, one would not expect the final state redistribution effects to be significant. In the case of numerically small jet cone size θ_0 an importance of the rescattering effects should be analyzed separately. However, in the limit of very small θ_0 one would not envisage large final state effects either. Indeed, with θ_0 decreasing, the energies of the relevant gluons increase, and so do the formation times. Gluons with formation times of the order of the size of the medium, $\tau_f \sim \tau_L$, have got no spare time left to interact with the medium after being radiated.

In order to simplify calculations (and not to introduce new parameters) we omit the transverse expansion and viscosity of the fluid using the well-known scaling Bjorken's solution [23] for temperature and density of QGP at $T > T_c \simeq 200$ MeV: $T(\tau)\tau^{1/3} = T_0\tau_0^{1/3}, \quad \rho(\tau)\tau = \rho_0\tau_0$. Let us remark that the transverse flow effect can play an important role in the formation of the final hadronic state at later stages of the evolution of a long-living system created in an ultrarelativistic nuclei collision. At the same time, the influence of the transverse expansion of QGP, as well as of the mixed phase at $T = T_c$, on the intensity of jet rescattering (which is a strongly increasing function of temperature) seems to be inessential for high initial temperatures $T_0 \gg T_c$ [13]. On the contrary, the presence of viscosity slows down the cooling rate, which leads to a jet parton spending more time in the hottest regions of the medium. As a result the rescattering intensity goes up, i.e., in fact an effective temperature of the medium gets lifted as compared with the perfect QGP case [13]. Also for certainty we have used the initial conditions for the gluon-dominated plasma formation in central $Pb - Pb$ collisions at LHC energies, which have been estimated perturbatively in [14] using the new HERA parton distributions: $\tau_0 \simeq 0.1$ fm/c, $T_0 \simeq 1$ GeV, $N_f \simeq 0$ [2].

[2] These estimates are of course rather approximate and model-depending. The discount of higher order α_s terms in computing the initial energy density of the mini-jet system, uncertainties of structure functions in the low-x region, and nuclear shadowing can result in variations of the initial energy density of QGP [14].

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 in the central rapidity region $y = 0$ as a function of the parameter θ_0 of a jet cone size for $T_0 = 1$ GeV and $R_A = 1.2 \cdot (207)^{1/3} \simeq 7$ fm. Let us remark that the choice of the scale for a minimal jet energy $E \sim 100$ GeV corresponds to the estimated threshold for "true" QCD-dijet recognition from "thermal" background — statistical fluctuations of the transverse energy flux in heavy ion collisions at LHC energies [24]. We can see the weak θ_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 results for the radiative energy losses in both models I and II are very similar. The radiative losses are almost independent of the initial jet energy and decrease rapidly with increasing the angular size of the jet at $\theta_0 \gtrsim 5^0$.

4. Conclusions

To summarize, we have considered the angular structure of medium-induced radiative and collisional energy losses experienced by a hard parton which is produced before the hot dense matter is formed and propagates through an expanding quark-gluon fluid. In our analysis we took into account the QCD Landau-Pomeranchuk-Migdal effect and effects of the finite volume of the medium. Although the radiative energy loss of a jet with a small cone size θ_0 can be much larger than the collisional loss, the former decreases considerably with θ_0 increasing. On the other hand, the major part of "thermal" particles knocked out of the dense matter by elastic rescatterings, fly outside a typical jet cone of $\theta_0 \sim 10^0 - 20^0$.

In our model, within the parameter range used, the coherent part of the medium-induced radiative loss dominates over the collisional loss by a factor ~ 3 at $\theta_0 \to 0$. The radiative loss due to coherent LPM gluon emission is comparable with the collisional loss at $\theta_0 \sim 8^0$, and becomes negligible at $\theta_0 \gtrsim 10^0$.

Collisional losses are likely to be significant for jets propagating through a hot gluon plasma in the conditions envisaged for central heavy ion collisions at LHC energies.

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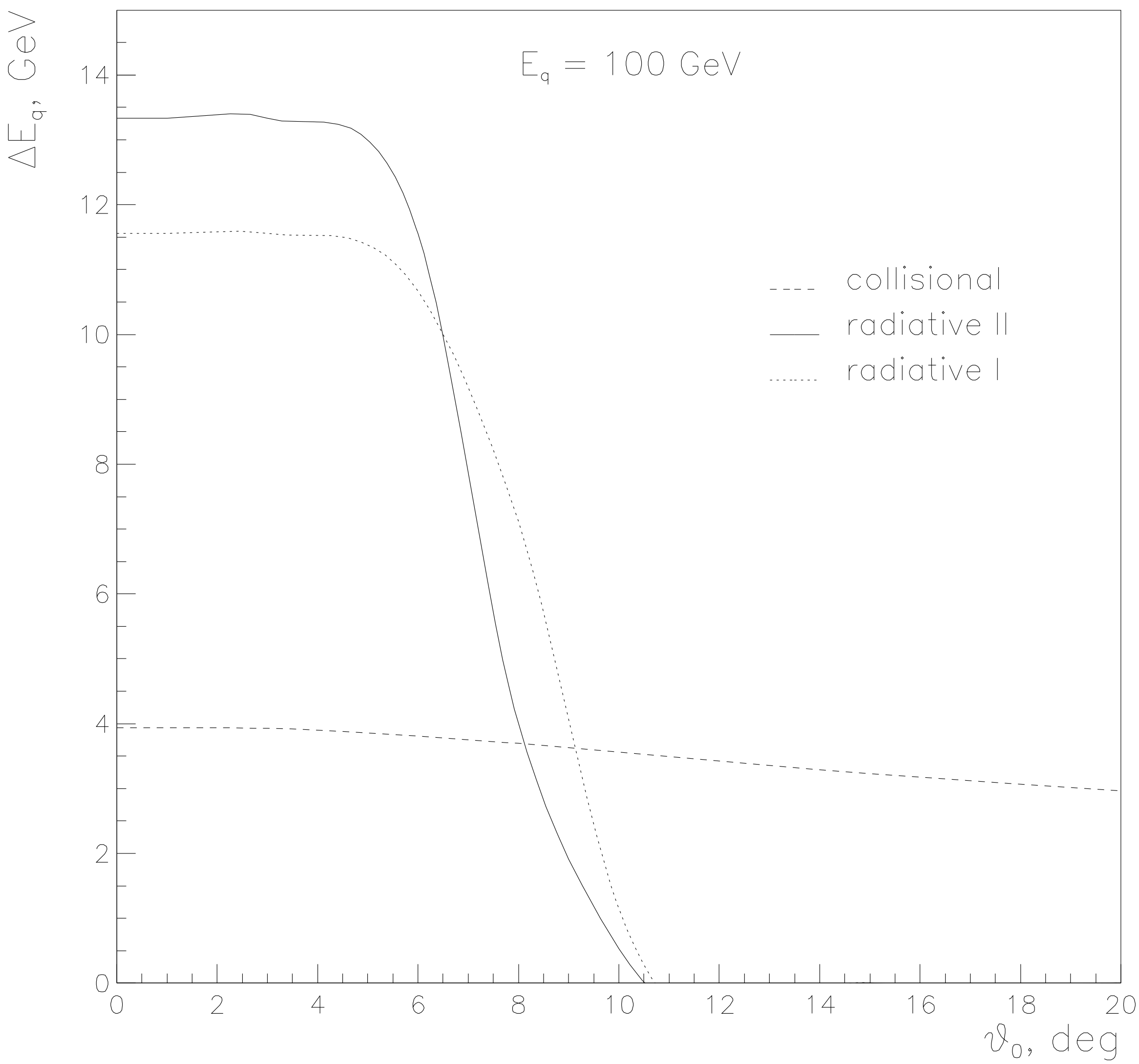

Figure 1: The average radiative (coherent medium-dependent part, the dotted and solid curves for models I and II respectively) and collisional (dashed curves) energy losses of quark-initiated jet ΔE_q with initial energy $E = 100$ GeV in the central rapidity region $y = 0$ as a function of the parameter θ_0 of a jet cone size. $R_A = 7$ fm.

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