PRAMANA
— journal of
physics

© Indian Academy of Sciences

Vol. 60, No. 5
May 2003
pp. 1045–1049

Azimuthal anisotropy of jet quenching at LHC

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Abstract. We analyze the azimuthal anisotropy of jet spectra due to energy loss of hard partons in quark–gluon plasma, created initially in nuclear overlap zone in collisions with non-zero impact parameter. The calculations are performed for semi-central Pb–Pb collisions at LHC energy.

Keywords. Quark–gluon plasma; energy loss; jet quenching; azimuthal anisotropy.

PACS Nos 12.38.Mh; 24.85.+p; 25.75.+r

High-p_{T} jet production is considered as a promising tool for studying properties of hot matter created in heavy-ion collisions at RHIC and LHC. The challenging problem here is the behaviour of colour charge in quark–gluon matter associated with the coherence pattern of the medium-induced radiation, resulting in a number of interesting non-linear phenomena (see review [1] and references therein). In our previous work [2] we predicted that medium-induced parton energy loss should result in a dramatic change in the distribution of jets over impact parameter as compared to what is expected from independent nucleon–nucleon interactions pattern. In this paper we concentrate on the phenomena related to the azimuthal dependence of jet energy loss and corresponding jet spectra in semi-central heavy-ion collisions at LHC energies, when the cross-section for hard jet production at $E_{\mathrm{T}} \sim 100$ GeV scale is large enough to study the impact parameter dependence of such processes. We consider the experimental conditions of CMS experiment at LHC [3], which can provide jet reconstruction and adequate measurement of impact parameter of nuclear collision using calorimetric information [4]. Note that the possible azimuthal anisotropy of high-p_{T} hadron spectra at RHIC was discussed in a number of papers [5–7].

The details of geometrical model of jet production in heavy-ion collisions can be found in [2]. Figure 1 shows the essence of the problem in the plane of impact parameter of two colliding nuclei A–A. The distribution over jet production vertex $B(r,\psi)$ in nuclear overlap zone at given impact parameter b is equal to $P_{AA}(\mathbf{r},b) = T_A(r_1)\cdot T_A(r_2)/T_{AA}(b)$, where $\mathbf{r} = r\cos\psi\cdot\mathbf{e_x} + r\sin\psi\cdot\mathbf{e_y}$ is the vector from beam axis z to vertex B; $r_{1,2}$ is the distance between nucleus centers (O_1,O_2) and vertex B; $T_{AA}(b)$ and $T_A(\mathbf{r})$ are the standard nuclear overlap and nuclear thickness functions respectively.

The basic kinetic integral equation for the energy loss ΔE as a function of initial energy E and path length L has the form

$$\Delta E(L,E) = \int_0^L \mathrm{d}x \frac{\mathrm{d}p(x)}{\mathrm{d}x}\lambda(x)\frac{\mathrm{d}E(x,E)}{\mathrm{d}x}, \quad \frac{\mathrm{d}p(x)}{\mathrm{d}x} = \frac{1}{\lambda(x)}\exp(-x/\lambda(x)), \quad (1)$$

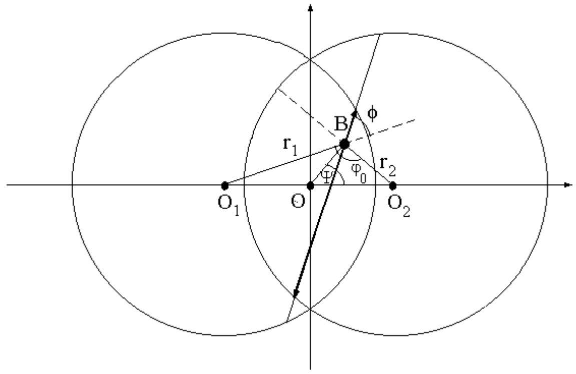

Figure 1. Jet production in high energy symmetric nucleus–nucleus collision in the plane of impact parameter **b**. O_1 and O_2 are nucleus centers, $OO_2 = -O_1O = b/2$. B is the dijet production vertex; r is the distance from the beam axis to B; r_1, r_2 are distances between nucleus centers and B.

where x is the current transverse coordinate of a parton, $\mathrm{d}p/\mathrm{d}x$ is the scattering probability density, $\mathrm{d}E/\mathrm{d}x$ is the energy loss per unit length, $\lambda = 1/\sigma\rho$ is the in-medium mean free path, $\rho \propto T^3$ is medium density at temperature T, σ is the integral cross-section of parton interaction in the medium. It is straightforward to evaluate the time $\tau_L = L$ it takes for the jet to traverse the dense zone:

$$\tau_L = \min\left\{ \sqrt{R_A^2 - r_1^2 \sin^2\phi} - r_1\cos\phi, \right.$$
$$\left. \sqrt{R_A^2 - r_2^2 \sin^2(\phi-\varphi_0)} - r_2\cos(\phi-\varphi_0) \right\}, \tag{2}$$

where $\phi = \varphi - (\psi/|\psi|)\arccos\{(r\cos\psi + b/2)/r_1)\}$ is the isotropically distributed angle which determines the direction of a jet relatively to vector $\mathbf{r_1}$, φ is the azimuthal angle between the direction of a jet and $\mathbf{b}$, $\varphi_0 = (\psi/|\psi|)\arccos(r^2 - b^2/4)/(r_1 r_2)$ is the angle between vectors $\mathbf{r_1}$ and $\mathbf{r_2}$. One can see from eq. (2) that for non-central collisions, $b \neq 0$, value τ_L depends on φ: it is maximum at $\varphi = \pm\pi/2$ and minimum at $\varphi = 0$. Since energy loss is increasing function of jet in-medium path-length, it will then depend on φ also.

In order to illustrate the azimuthal anisotropy of parton energy loss, 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 $\tau = \sqrt{t^2 - z^2}$ [8]. For certainty we used the initial conditions for the gluon-dominated plasma formation expected for central Pb–Pb collisions at LHC [9]: $\tau_0 \simeq 0.1$ fm/c, $T_0 \simeq 1$ GeV, $N_f \approx 0$, $\rho_g \approx 1.95T^3$. For non-central collisions we suggest the proportionality of the initial energy density ε_0 to the ratio of nuclear overlap function $T_{AA}(b)$ and effective transverse area $S_{AA}(b)$ of nuclear overlapping, $\varepsilon_0(b) \propto T_{AA}(b)/S_{AA}(b)$ [2].

Our approach relies on an accumulative energy loss, when 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 $\mathrm{d}E/\mathrm{d}x(T)$. For our calculations we have used collisional part of loss and differential scattering cross section from our work [2]; the energy spectrum of coherent medium-induced gluon radiation was estimated using BDMS formalism [10]. It is important to notice that the coherent LPM radiation induces a strong dependence of the jet energy on the jet cone size [10–13], while the collisional energy loss turns out to be practically independent of cone size and emerges outside the narrow jet cone [11].

Azimuthal anisotropy of energy loss goes up with increasing b, because azimuthal asymmetry of the volume gets stronger in this case. On the other hand, the absolute value of energy loss goes down with increasing b due to reducing mean path length L (and ε_0 at $b \gtrsim R_A$). Then the non-uniform dependence of energy loss on azimuthal angle results in azimuthal anisotropy of jet spectra in semi-central collisions. Figure 2 shows the distribution of jets over azimuthal angle $\varphi = \varphi_{1,2}$ for the cases with collisional and radiative loss (a) and collisional loss only (b) for $b = 0$, 6 and 10 fm (the initial jet distributions have been generated using PYTHA-5.7 model [14]). The CMS kinematical acceptance for jets was taken into account: $E_T^{\rm jet} > 100$ GeV, $|y^{\rm jet}| < 2.5$. The distributions are normalized on the initial distributions of jets over φ in Pb–Pb collisions (without energy loss). We can see that the azimuthal anisotropy gets stronger while going from central to semi-central collisions, but the absolute suppression factor reduces with increasing b. For jets with finite cone size one can expect the intermediate result between cases (a) and (b), because, as we have mentioned before, radiative loss dominates at relatively small angular sizes of jet cone $\theta_0 (\to 0)$, while the relative contribution of collisional loss grows with increasing θ_0.

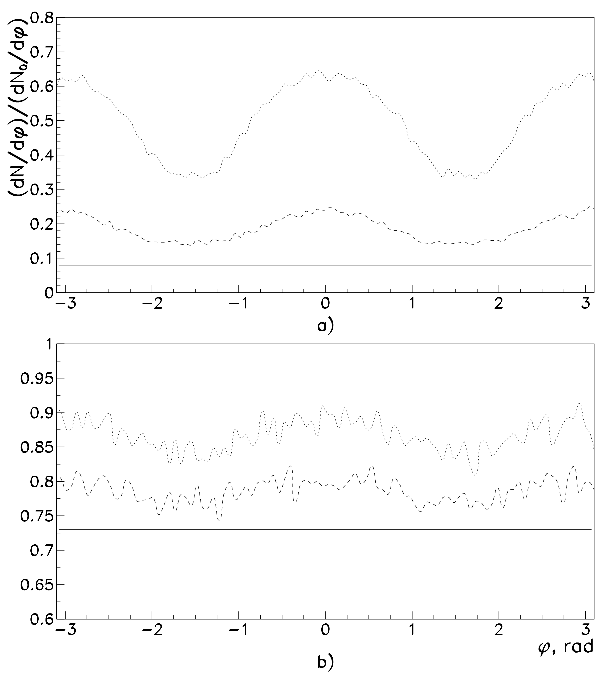

Figure 2. The distribution of jets over azimuthal angle for the cases with collisional and radiative loss (**a**) and collisional loss only (**b**). Jet kinematical acceptance is $E_T^{\rm jet} > 100$ GeV and $|y^{\rm jet}| < 2.5$. The histograms (from bottom to top) correspond to the impact parameter values $b = 0$, 6 and 10 fm.

In non-central collisions the jet distribution over φ is approximated well by the form $A(1+B\cos 2\varphi)$, where $A = 0.5(N_{\max} + N_{\min})$ and $B = (N_{\max} - N_{\min})/(N_{\max} + N_{\min}) = 2\langle\cos 2\varphi\rangle$. The average cosines of 2φ for particle flow is called as coefficient of azimuthal anisotropy v_2 [15]. In our model the coefficient of jet azimuthal anisotropy increases almost linearly with growth of b and becomes maximum at $b \sim 1.2R_A$, after that it reduces rapidly with increasing b (the domain of b values where ε_0 falls down steeply). The other important feature is that the jet azimuthal anisotropy decreases slightly with increasing jet energy, because the energy dependence of medium-induced loss is rather weak [10,12].

To summarize, an interesting phenomenon is predicted to be observed in semi-central heavy-ion collisions at LHC: the appearance of azimuthal anisotropy of jet spectra due to energy loss of jet partons in azimuthally non-symmetric volume of dense quark–gluon matter, created initially in nuclear overlap zone. The methodical advantage of azimuthal jet observables is obvious: one needs to reconstruct only azimuthal position of jet, but not the total jet energy. It can be done more easily and with high accuracy, while the reconstruction of the jet energy is a more ambiguous task [4]. On the other hand, the performance of the inclusive analysis of jet production as a function of azimuthal angle requires event-by-event determination of the reaction plane angle. The possible way of the solution in CMS conditions is using transverse energy flow in central calorimeters, which should reflect any azimuthal asymmetry of reaction volume under the condition that most part of the semi-hard particles is the product of in-medium radiated gluons [5,6]. Thus we suggest that the existing methods of determination of nuclear reaction plane angle [15] might be applied at LHC with measuring the azimuthal anisotropy of global transverse energy flow originated from mini-jet production in non-symmetric volume of dense QCD medium.

Acknowledgements

Discussions with M Bedjidian, D Denegri, P Filip, V Uzhinskii and U Wiedemann are gratefully acknowledged.

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