Azimuthal anisotropy of jet quenching at LHC

I.P. Lokhtin, S.V. Petrushanko, L.I. Sarycheva and A.M. Snigirev
M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear Physics
119899, Vorobievy Gory, Moscow, Russia

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.

1 Introduction
High-pT jet production and other hard processes are considered as one of the most promising tools for studying properties of super-dense and hot matter created in nucleus-nucleus 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 nonlinear phenomena, in particular, the dependence of radiative energy loss per unit distance dE/dx along the total distance traversed (see review [1] and references therein). In our previous work [2] we predicted that medium-induced parton rescattering and 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 ET ∼ 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-pT hadron spectra at RHIC was discussed in a number of papers [5, 6, 7].

2 Nuclear geometry and jet energy loss
The details of geometrical model of jet production and jet passing through a dense matter in high energy symmetric nucleus-nucleus collision can be found in [2]. The figure 1 shows the essence of the problem in the plane of impact parameter b of two colliding nuclei A–A. The initial distribution over jet production vertex B(r, ψ) in nuclear overlap zone at given impact parameter b is written as

\[ P_{AA}(r, b) = \frac{T_A(r_1) \cdot T_A(r_2)}{T_{AA}(b)}, \]

where \( r = r \cos \psi \cdot e_x + r \sin \psi \cdot e_y \) is the vector from beam axis z to vertex B; \( r_{1,2} = \sqrt{r^2 + b^2/4} \pm rb \cos \psi \) is the distance between nucleus centers \((O_1, O_2)\) and vertex B; \( T_{AA}(b) \) and \( T_A(r) \) are the standard nuclear overlap and nuclear thickness functions respectively.

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

\[ \Delta E(L, E) = \int_0^L dx \frac{dp(x)}{dx} \lambda(x) \frac{dE(x, E)}{dx}, \quad \frac{dp(x)}{dx} = \frac{1}{\lambda(x)} \exp(-x/\lambda(x)), \]

where \( x \) is the current transverse coordinate of a parton, \( dp/dx \) is the scattering probability density, \( dE/dx \) is the energy loss per unit length, \( \lambda = 1/(\sigma \rho) \) is in-medium mean free path, \( \rho \propto T^3 \) is medium

\[ ^1 \text{Talk given at 4th International Conference ‘Physics and Astrophysics of Quark-Gluon Plasma’, November 26-30, 2001.} \]
density at temperature $T$, $\sigma$ is the integral cross section of parton interaction in the medium. It is straightforward to evaluate the time $\tau_L = L$ it takes for jet to traverse the dense zone:

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

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 $r_1$, $\varphi$ is the azimuthal angle between the direction of a jet motion and vector $b$, $\varphi_0 = (\psi/|\psi|) \arccos (r^2 - b^2/4)/(r_1 r_2)$ is angle between vectors $r_1$ and $r_2$. One can see from eq.(3) that for non-central collisions, $b \neq 0$, value $\tau_L$ depends on $\varphi$: it is maximum at $\varphi = \pm \pi/2$ and minimum at $\varphi = 0$ (see fig.2 for Pb–Pb collisions and impact parameters values $b = 0, 6$ and $10$ fm).

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 \[9\]: $\tau_0 \approx 0.1$ fm/c, $T_0 \approx 1$ GeV, $N_f \approx 0$, $\rho_0 \approx 1.95 T^3$. For non-central collisions we suggest the proportionality of the initial energy density $\varepsilon_0$ 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 losses, 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 $dE/dx(T)$. For our calculations we have used collisional part of loss and differential scattering cross section from our work \[3\]; 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 \[11, 12, 13\], while the collisional energy loss turns out to be practically independent on cone size, because 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 \[14\].
3 Azimuthal anisotropy of jet spectra

Figure 3 shows the average value of medium-induced radiative (a) and collisional (b) energy loss of quark with initial transverse energy $E_T^q = 100$ GeV as a function of $\varphi$. As it might be expected, 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, of course, goes down with increasing $b$, due to reducing absolute value of mean distance traversed (and also due to decreasing initial energy density of the medium 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 4 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 PYTHIA-5.7 model [4]). The CMS kinematical acceptance for jets was taken into account: $E_{T}^{jet} > 100$ GeV, $|y_{jet}| < 2.5$. The distributions are normalized on the initial distributions of jets over $\varphi$ in Pb–Pb collisions (without any energy loss). We can see that the azimuthal anisotropy gets stronger as 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 $\theta_0(\rightarrow 0)$, while the relative contribution of collisional loss grows with increasing $\theta_0$.

In non-central collisions the jet distribution over $\varphi$ is approximated well by the following form,
$$dN/d\varphi = A(1 + B \cos 2\varphi),$$
where $A = 0.5(N_{max} + N_{min})$ and $B = (N_{max} - N_{min})/(N_{max} + N_{min}) = 2\langle \cos 2\varphi \rangle$. 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 impact parameter values, where the effect of decreasing energy loss due to reducing effective transverse size of dense zone and initial energy density of the medium is crucial and not compensated anymore by stronger non-symmetry of the volume). Other important feature is the jet azimuthal anisotropy decreases with increasing jet energy, because the energy dependence of medium-induced loss is rather weak [10, 12].

In conclusion of this section we remark, that the methodical advantage of azimuthal jet observables

Figure 3: The average medium-induced radiative (a) and collisional (b) energy loss of quark with initial transverse energy $E_T^q = 100$ GeV as a function of quark azimuthal angle $\varphi$. The curves (from top to bottom) correspond to the impact parameter values $b = 0, 6$ and 10 fm.

Figure 4: 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 $E_{T}^{jet} > 100$ GeV and $|y_{jet}| < 2.5$. The histograms (from bottom to top) correspond to the impact parameter values $b = 0, 6$ and 10 fm.
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 more ambiguous task. On the other hand, the performance of inclusive analysis of jet production as a function of azimuthal angle requires event-by-event determination of the reaction plane angle. Summarized in papers present methods of determination of the reaction plane angle are applied to study elliptic flow of soft particles in current heavy ion dedicated experiments at SPS and RHIC. The capability of CMS tracker to reconstruct momenta of all semi-hard \((p_t \gtrsim 2\text{GeV}/c)\), and especially soft \((p_t \lesssim 2\text{GeV}/c)\) charged particles is not clear at the moment. However the transverse energy flow in central CMS calorimeters should reflect the pattern of semi-hard particles flow, in particular, including any azimuthal anisotropy manifestation. Thus the determination of nuclear reaction plane angle using semi-hard particles flow (not incorporated in high-\(p_T\) jet pair) could be, in principle, possible due to two factors: \((1)\) sensitivity of semi-hard particles to the azimuthal asymmetry of reaction volume under condition that the most part of them being the products of in-medium radiated gluons \([5, 6]\); \((2)\) predicted high enough multiplicity of such particles at LHC energies (which is comparable, for example, with the total multiplicity at SPS).

4 Conclusions

The 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. We have found that the coefficient of jet azimuthal anisotropy increases almost linearly with growth of \(b\) up to \(b \sim 1.2R_A\) fm. The effect of jet azimuthal anisotropy decreases slightly with jet energy.

The methodical advantage of azimuthal jet observables is that one needs to reconstruct only azimuthal position of jet, but not the total jet energy. On the other hand, the performance of inclusive analysis of jet production as a function of azimuthal angle requires event-by-event determination of the reaction plane angle. We suggest that under LHC conditions the existing methods of determination of nuclear reaction plane angle might be applied with measuring the azimuthal anisotropy of global transverse energy flow originated from mini-jet production in non-symmetric volume of dense QCD-medium.

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