On jet structure in heavy ion collisions

I.P. Lokhtin, A.A. Alkin, A.M. Snigirev
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

Abstract. The LHC data on jet fragmentation function and jet shapes in PbPb collisions at center-of-mass energy √s = 2.76 TeV per nucleon pair are analyzed and interpreted in the frameworks of PYQUEN jet quenching model. A specific modification of longitudinal and radial jet profiles in PbPb collisions as compared with pp data is reproduced by PYQUEN simulation with wide-angle radiative and collisional partonic energy loss taken into account.

1 Introduction

Studying the modification of jets as they are formed from energetic partons propagating through the hot and dense medium created in ultrarelativistic heavy ion collisions is a particularly useful tool for probing the produced matter’s properties. The energy loss of jet partons in deconfined medium, quark-gluon plasma, is predicted much stronger than in cold nuclear matter, and leads to so-called “jet quenching” effect (see, e.g., reviews [12] and references therein). Indirectly jet quenching was observed for the first time at RHIC experiments via measurements of inclusive high-pT hadron production in gold-gold collisions at center-of-mass energy √sNN = 200 GeV. It was manifested as the suppression of overall high-pT hadron rates and back-to-back dihadron azimuthal correlations (including the specific azimuthal angle dependence of the effect with respect to the event plane). The summary of experimental results at RHIC can be found in [8,9,10,11].

The lead-lead collision energy at LHC, √sNN = 2.76 TeV, is a factor of ~14 larger than that in RHIC, thereby allows one to probe new frontiers of super-hot quark-gluon matter. The analysis of high statistics samples of fully reconstructed jets becomes possible. The results of jet analyses of 2010 and 2011 PbPb data obtained by three LHC experiments, ALICE, ATLAS and CMS, is summarized e.g. in review [12]. The first direct evidence of jet quenching has been observed as the large, centrality-dependent, imbalance in dijet transverse energy [13,14]. It has been found using missing pT techniques that the jet energy loss spreads over low transverse momenta and large angles [14]. Then jet momentum dependence of the dijet imbalance has been studied in detail [15]. Significant transverse energy imbalance has been observed for photon+jet production in PbPb events [16]. Another direct manifestation of jet quenching is the inclusive jet production in central PbPb collisions with respect to peripheral events [17,18]. The azimuthal angle dependence of such suppression has also been measured [19]. The similar level of suppression as for inclusive jets is seen for jets from b-quark fragmentation [20]. In contrast to PbPb collisions, proton-lead data from LHC do not show jet quenching manifestation [21].

A number of theoretical calculations and Monte-Carlo simulations were attempted to reproduce some of basic features of jet quenching pattern at LHC (dijet and photon+jet imbalance, nuclear modification factors for jets and high-pT hadrons), and to extract by such a way the information about medium properties and partonic energy loss mechanisms [22,23,24,25,26,27,23,29,30,31,32,33,34,35,36,37,38,39,40,41]. The observable that allows more precise comparison between the data and theoretical models of jet quenching to be done, is the internal jet structure. The recently published experimental data on medium-modified jet structure include the measurement of jet shapes (radial profile) [42] and jet fragmentation function (longitudinal profile) [43,44]. It was suggested in [15] that it could be also of interest to study moments of jet fragmentation function.

In present paper, the LHC data on jet fragmentation function and jet shapes in PbPb collisions are analyzed and interpreted in the frameworks of PYQUEN partonic energy loss model, [16]. In the previous papers [20,27] this model was applied to analyze the dijet energy asymmetry and nuclear modification factor of inclusive hadrons.

2 PYQUEN model

PYQUEN (PYthia QUENched) is one of the first Monte-Carlo models of jet quenching [16]. PYQUEN was constructed as a modification of jet events obtained with the generator of hadron-hadron interactions PYTHIA_6.4 [37]. The details of the used physics model and simulation procedure can be found in the original paper [16]. Main features of the model are sketched below as follows.

The approach describing the multiple scattering of hard partons relies on accumulated energy loss via gluon radiation, which is associated with each parton scattering in a hot matter. It also includes the interference effect in gluon emission with a finite formation time using the modified...
radiation spectrum $dE/dx$ as a function of the decreasing temperature $T$. The model takes into account radiative and collisional energy loss of hard partons in longitudinally expanding quark-gluon fluid, as well as the realistic nuclear geometry. The radiative energy loss is treated in the frameworks of BDMS model \cite{BDMS} with the simple generalization to a massive quark case using the “dead-cone” approximation \cite{deadcone}. The collisional energy loss due to elastic scatterings is calculated in the high-momentum transfer limit \cite{peres, peres2, peres3}. The strength of partonic energy loss in PYQUEN is determined mainly by the initial maximal temperature $T^\text{max}_0$ of hot fireball in central PbPb collisions, which is achieved in the center of nuclear overlapping area at mid-rapidity. The energy loss depends also on the proper time $\tau_0$ of matter formation and the number $N_f$ of active flavors in the medium.

Another important ingredient of the model is the angular spectrum of medium-induced radiation. The simple parametrizations of the gluon distribution over the emission angle $\theta$ are included in PYQUEN. There are two basic options in the model. The first one is the “small-angle” radiation,

$$\frac{dN^g}{d\theta} \propto \sin \theta \exp \left( -\frac{(\theta - \theta_0)^2}{2\theta_0^2} \right),$$

(1)

where $\theta_0 \approx 5^\circ$ is the typical angle of the coherent gluon radiation as estimated in \cite{small_angle}. The second one is the “wide-angle” radiation,

$$\frac{dN^g}{d\theta} \propto 1/\theta,$$

(2)

which is similar to the angular spectrum of parton showering in a vacuum without coherent effects \cite{wide_angle}. The physical meaning of wide-angle radiation could be the presence of intensive secondary rescatterings of in-medium emitted gluons \cite{rescattering}. It may result in destroying the small-angle (BDMPS-like) coherence emission and significant broadening of gluon emission angular spectrum. The collisional energy loss in PYQUEN is always “out-of-cone” loss. Such lost energy is considered as “absorbed” by the medium, because the major part of “thermal” particles knocked out of the hot matter by elastic rescatterings fly outside a typical jet cone \cite{jetcone}.

The event-by-event simulation procedure in PYQUEN includes three main steps: the generation of initial parton spectra with PYTHIA and production vertexes at the given impact parameter; the rescattering-by-rescattering passage of each jet parton through a dense zone accompanied with gluon radiation and collisional energy loss; the final hadronization for jet partons and in-medium emitted gluons according to the standard Lund string scheme implemented in PYTHIA.

3 Results

PYQUEN model was applied to simulate medium-modified inclusive jet production at energy $\sqrt{s_{NN}} = 2.76$ TeV for different PbPb centralities. The radiative and collisional energy loss were taken into account. Two options for the angular spectrum of gluon radiation were considered, wide- and small-angle radiative loss. Hereafter we let call these options as “Scenario W” and “Scenario S” respectively. PYQUEN parameter values $T^\text{max}_0 = 1$ GeV, $\tau_0 = 0.1$ fm/c and $N_f = 0$ (gluon-dominated plasma) were used. Such parameter settings allow us to reproduce the LHC data on dijet transverse energy imbalance and nuclear modification factors of inclusive hadrons as wide-angle radiative and collisional energy loss are taken into account \cite{jet_suppression}.

At that PYTHIA tune Pro-Q20 was utilized. The iterative cluster finding algorithm PYCELL implemented in PYTHIA \cite{PYCELL} was applied to reconstruct final state hadronic jets within cone size $R^\text{jet} = \sqrt{\Delta \eta^2 + \Delta \phi^2} = 0.3$ with transverse energy $E^\text{jet}_T > 100$ GeV and pseudorapidity $0.3 < |\eta^\text{jet}| < 2$. The numerical results were compared with the CMS data on modification factors for jet shapes \cite{CMS} and jet fragmentation function \cite{frag} using the same kinematic cuts as in the experiment.

At first we have checked that the overall suppression of inclusive jet rates for 10% of most central PbPb events as compared to the corresponding pp collisions (scaled to the number of binary nucleon-nucleon collisions) almost does not depend on $E^\text{jet}_T$, and is found on the level \(R_{AA} \approx 0.45\pm0.5\) for “Scenario S” and \(R_{AA}^\text{jet} \approx 0.35\pm0.4\) for “Scenario W”. Such results in principle do not contradict the published ATLAS measurement of the jet suppression factor, \(R_{\text{jet}} \approx 0.5\) for 10% of most central PbPb collisions with respect to peripheral events \cite{ATLAS} (taking in mind that \(R_{\text{jet}}\) may be some larger than \(R_{AA}\)). Since no qualitative difference between “Scenario W” and “Scenario S” seen for the energy dependence of \(R_{\text{jet}}\) (only numerical difference \(\approx 20\%\) independently of \(E^\text{jet}_T\)), making unambiguous conclusions in favor of either scenario would be rather difficult.

Then we consider the jet internal structure. The radial jet profile may be characterized by the distribution of the transverse momentum inside the jet cone:

$$\rho(r) = \frac{1}{\delta r N^\text{jet}} \sum_{\text{jets}} \frac{p_T(r - \delta r/2, r + \delta r/2)}{E^\text{jet}_T},$$

(3)

where $r = \sqrt{(\eta - \eta^\text{jet})^2 + (\phi - \phi^\text{jet})^2} \leq R^\text{jet}$ is the radial distance from jet particle to the jet axis, defined by the coordinates $\eta^\text{jet}$ and $\phi^\text{jet}$. Following CMS analysis procedure \cite{CMS} the jet cone was divided into six bins with radial width $\delta r = 0.05$, and the transverse momentum of all charged particles with $p_T > 1$ GeV/c in each radial bin was summed to obtain the fraction of the total jet $p_T$ carried by these particles. Then the results were averaged over the total number of found jets, $N^\text{jet}$.

The longitudinal jet profile usually is characterized by the jet fragmentation function \(D(z)\) defined as the probability for a jet particle to carry a fraction $z$ of the jet transverse energy. Often jet fragmentation function is measured in terms of variable $\xi = \ln(1/z) = \ln(E^\text{jet}_T/p_T)$, and it normalized to the total number of jets, $N^\text{jet}$. The charged particles with $p_T > 1$ GeV/c in a jet cone were selected for the analysis \cite{CMS}.
Figure 1 shows the jet shape nuclear modification factors, \(\rho(r)(\text{PbPb})/\rho(r)(\text{pp})\), for four centralities of PbPb collisions. The specific modification of radial jet profile in the more central collisions due to a redistribution of the jet energy inside the cone is observed. It includes the excess at large radii, the suppression at intermediate radii, and unchanged (or slightly enhanced) jet core. PYQUEN (“Scenario W”) reproduces the data quite well (within the experimental uncertainties). At the same time PYQUEN (“Scenario S”) gives qualitatively very different result, such as excess at large and intermediate radii, and suppression for jet core. The similar situation appears for jet fragmentation function (figure 2). The same prominent features for the ratio of PbPb jet fragmentation function to its pp reference seen in the data and in the PYQUEN features for the ratio of PbPb jet fragmentation function (figure 2). The same prominent features for the ratio of PbPb jet fragmentation function to its pp reference seen in the data and in the PYQUEN (“Scenario W”) as well as for jet core. The similar situation appears for jet fragmentation function (figure 2). The same prominent features for the ratio of PbPb jet fragmentation function to its pp reference seen in the data and in the PYQUEN (“Scenario W”) as well as for jet core. The similar situation appears for jet fragmentation function (figure 2).

Let us discuss now the possible origin of such specific medium-modified jet structure. In-medium emitted gluons are softer than initial jet partons, and fly at some angle with respect to the parent parton direction. Thus it is quite expectable that such “additional” gluons contribute to an excess of hadron multiplicity at low transverse momenta and jet radial broadening. On the other hand, the energy loss of initial jet partons reduces a number of hadrons at high and intermediate transverse momenta, such hadrons being strongly correlated with a jet axis. Then at first glance it should result in the suppression of hadron multiplicities in a jet core and at high \(p_T\), which contradicts the data. However, in fact medium-modified jet structure at intermediate and high \(p_T\) is determined by the interplay of two effects. The first one is radial broadening and longitudinal softening due rescatterings and energy loss of jet partons. The second one is shifting down the jet energy due to “out-of-cone” energy loss. The energy loss of a jet as a whole results in the difference between the “initial” (non-modified) and final jet energies. Since more energetic jets initially are more collimated and particle \(p_T\)-spectrum in such jets is more harder, two above effects enter into competition. If the contribution of wide-angle partonic energy loss into the total loss is large enough, the decrease in the yield of jet particles at high \(p_T\) and broadening of a jet core can be compensated by significant jet energy “rescaling”, and converted into increase in the particle yield and (almost) unmodified radial profile at small radii. Such specific behavior of medium-modified jet fragmentation function at high \(p_T\) has been predicted some years ago in [55] (see also subsection 6.16.2 in [57]). The influence of measured jet fragmentation functions by the enhanced quark-to-gluon jet fraction can be also important [42].

Finally we would like refer to other recent theoretical calculations for jet structure observables in PbPb collisions at the LHC. Jet fragmentation function was calculated and compared with the data in Refs. 11, 55. JEWEL event generator 33 and hybrid strong/weak coupling jet quenching model [11] are successful in describing the basic trends seen in the data excepting low-\(p_T\) region. Hardening of the fragmentation function at high \(p_T\) in these models is a consequence of the depletion of softer jet particles. Effective 1+1 dimensional quasi-Abelian model [58] is able to reproduce low and intermediate \(p_T\)-region, and predicts unmodified fragmentation at high \(p_T\). Jet shapes were studied with YaJEM event generator [59]. It has been found that YaJEM simulation produces the jet broadening, but it is significantly stronger than in the data.

4 Conclusion
Modification of jet fragmentation function and jet shapes in PbPb collisions at \(\sqrt{s}\_\text{NN} = 2.76\) TeV with respect to the corresponding pp data has been analyzed in the frameworks of PYQUEN partonic energy loss model. Taking into account wide-angle radiative and collisional energy loss allows PYQUEN to reproduce specific medium-induced modifications of longitudinal and radial jet profiles simultaneously. Some excess in the yield of jet particles at high \(p_T\) and (almost) unmodified jet core may be explained by significant shifting down the jet energy due to “out-of-cone” energy loss. At the same time, the scenario with small-angle energy loss does not reproduce this effect.

Together with other jet observables, the medium-modified jet structure seen in most central PbPb collisions at the LHC supports the presence of intensive wide-angle partonic energy loss, and can put strong constraints on the theoretical models of jet quenching. Future LHC data collected at increased energy and luminosity are expected to deliver more precise measurements of various jet characteristics in heavy ion collisions. This will allow us to study jet quenching mechanisms and properties of hot deconfined matter in more detail.

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Fig. 1. Jet shape nuclear modification factors as a function of distance from the jet axis in PbPb collisions (four centralities) at $\sqrt{s_{\text{NN}}} = 2.76$ TeV for inclusive jets with $E_{\text{jet}} > 100$ GeV and pseudorapidity $0.3 < |\eta_{\text{jet}}| < 2$. The charged particles with $p_T > 1$ GeV/c in a jet cone $R = 0.3$ are included. The closed circles are CMS data [42], the error bars show the statistical uncertainties, and the boxes show the systematic errors. The solid and dashed histograms are simulated PYQUEN events for “Scenario W” (wide-angle radiative plus collisional energy loss) and “Scenario S” (small-angle radiative plus collisional energy loss) respectively.
Fig. 2. The ratio of jet fragmentation function in PbPb collisions (four centralities) to its pp reference at $\sqrt{s_{NN}} = 2.76$ TeV for inclusive jets with $100 < E_{\text{jet}} < 300$ GeV and pseudorapidity $0.3 < |\eta_{\text{jet}}| < 2$. The charged particles with $p_T > 1$ GeV/$c$ in a jet cone $R = 0.3$ are included. The closed circles are CMS data [43], the error bars show the statistical uncertainties, and the boxes show the systematic errors. The solid and dashed histograms are simulated PYQUEN events for “Scenario W” (wide-angle radiative plus collisional energy loss) and “Scenario S” (small-angle radiative plus collisional energy loss) respectively.