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Jet physics in heavy-ion collisions at the LHC with the ALICE detector

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Abstract

In central Pb–Pb collisions at the LHC, jet rates are expected to be high at energies at which jets can be fully reconstructed over the background of the underlying event. This will open the possibility of quantifying the effect of partonic energy loss through medium induced gluon radiation, *jet quenching*, by detailed measurement of the modification of the longitudinal and transverse structure of identified jets. We will present Monte Carlo simulations strongly indicating that, in order to obtain probes sensitive to the properties of the QCD medium, it is mandatory to measure the high-p_T parton fragments together with the low-p_T particles from the radiated gluons. Hence, the excellent charged particle tracking capabilities of ALICE with $\Delta p/p < 10\%$ from 100 MeV–100 GeV combined with the proposed electromagnetic calorimeter for ALICE, EMCAL, represent an ideal tool for jet quenching studies at the LHC.

1. Introduction

ALICE is a multipurpose heavy-ion experiment at the LHC. It combines excellent tracking with PID, secondary vertex capabilities, electron and muon identification and a high resolution γ-spectrometer [1]. In the central part of the experiment, $|\eta| < 0.9$, ALICE will measure event-by-event the inclusive distribution and correlation of a wide range of flavour identified particles, whose momenta and masses are of the order of the typical energy scale involved ($T \approx \Lambda_{QCD} \approx 200$ MeV). In addition, tracking and particle identification capabilities reach far into the transverse momentum region in which particle production is expected to be dominated by hard processes, through the production and fragmentation of high transverse momentum partons. At $p_T = 100$ GeV, the momentum resolution is still better than 10%, sufficient to analyse jets with energies up to 200 GeV. As shown by the STAR experiment at RHIC [2], the combination of a TPC tracking system with an electromagnetic calorimeter is functionally equivalent to full electromagnetic plus hadronic calorimetry in a heavy-ion collision environment. Based on this concept, an electromagnetic calorimeter for ALICE (EMCAL) [3] has been proposed by the ALICE–US collaboration.

Even using a perfect calorimeter, jet resolution will be limited to ≈20% at 100 GeV due to the fluctuations of the underlying event and cone-size limitations, as will be explained below. However, energy is not the only jet observable. It is likely that the most interesting observables which can reveal the presence and kind of interactions of partons with deconfined partonic matter and the associated radiation of additional gluons, *jet quenching*, are mainly related to the structure of the jets, i.e. the phase-space distribution of particle around the jet axis: longitudinal and transverse fragmentation function and jet shape.

As compared to jet physics at RHIC there are two important new features in central Pb–Pb collisions at the LHC: The multi-jet production per event is not restricted to the mini-jet region $E_T < 2$ GeV but extends to ≈20 GeV. In addition, jet rates are high at energies, at which jets can be distinguished from the background energy of the underlying event. Hence, event-by-event reconstruction of jets with reasonable energy resolution will be possible. Since the jet production cross-section between RHIC and LHC energies grows faster than the soft multiplicity, it is evident that in the low-energy region ALICE will be able to perform the same kind of inclusive particle correlation studies as performed by the RHIC experiments [4]. Studies possible with ALICE performed using HIJING [5] as event generator can be found in [3] and [6]. Here, we concentrate on reconstructed jets.

In section 2 we will discuss the expected jet rates within the ALICE acceptance. The intrinsic jet energy resolution limits at the LHC due to background energy fluctuations, and the resolution expected for jet reconstruction in ALICE, will be presented in section 3. This is followed by a discussion of the experimental requirements for the measurement of the longitudinal and transverse jet structure as predicted by current toy Monte Carlo simulations.

2. Jet rates at the LHC

ALICE will study the whole spectrum of jet production ranging from mini-jets, $E_T > 2$ GeV, to high-E_T jets of several hundred GeV. Experimental considerations delineate four distinct energy regions, which are discussed here for the 10% most central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. In the region $E_T < 20$ GeV several jets overlap in one event within the ALICE acceptance. This means that jet identification in the traditional sense is not possible and their presence is revealed via studies of particle correlations. For $E_T < 100$ GeV the jet rate of >1 Hz is high enough so that, even with a read-out rate limited by the TPC to 20–40 Hz, an event sample of $>10^5$ jets can be collected in one effective month of running (10^6 s). For $E_T > 100$ GeV triggering will be necessary to collect jet enriched data. Considering that for a fragmentation function analysis about 10^4–10^5 jet events are needed, the statistics limit is reached at about 250 GeV.

In the absence of calorimetry, triggering on jets is only possible using a high level trigger (HLT). Presently ALICE is studying the possibility of triggering on event topologies where two or more high-p_T tracks are found in a small area of the $\eta - \phi$ plane. The search has to be performed on track candidates which are themselves the result of a HLT fast clustering and tracking procedure. The jet trigger capabilities will be improved by the addition of electromagnetic calorimetry.

3. Jet reconstruction

Charged particle multiplicities in central Pb–Pb collisions at the LHC are predicted to range from $dN_{ch}/dy = 2000$–8000. This corresponds to a total energy per unit of pseudorapidity

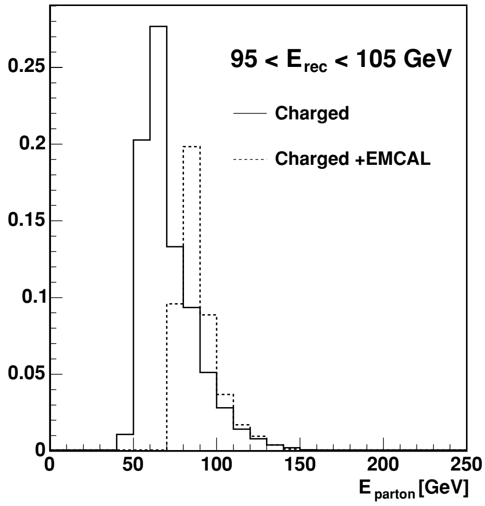

Figure 1. Selected production spectrum for reconstructed energy $95 < E_T < 105$ GeV. Reconstruction with charged particle only (solid line) is compared to charged particles + EMCAL (dashed).

of $dE_T/d\eta = 1.5$–6 TeV or to a background event energy of $E_b = 0.4$–1.6 TeV in a cone of $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.7$, the typical cone size used for jet reconstruction in pp collisions. This makes identification using large cone sizes for those jet energies accessible in Pb–Pb collisions impossible and the energy resolution is dominated by the energy fluctuations, ΔE_b, of the underlying event. Since E_b and ΔE_b are proportional to R^2 and R, respectively, identification and resolution improve for smaller cone sizes. A further reduction of the energy fluctuations can be obtained by applying a p_T cut to the charged particles. However, since $\Delta E_b > \sqrt{N(p_T)}\sqrt{\Delta p_T{}^2 + \langle p_T\rangle^2}$, the increase of the mean p_T, $\langle p_T\rangle$, and its variance Δp_T partially compensate the decrease of N.

Using a smaller cone size the measured signal energy is reduced and the out-of-cone fluctuations are increased. The intrinsic resolution limit for a 100 GeV jet fragmenting in vacuum is 23% for $R = 0.3$ and $dN/dy = 4000$ with contributions of 14% and 18% from out-of-cone fluctuations and background energy fluctuation, respectively, where background fluctuations have been simulated with HIJING. With small cone sizes, one needs to apply in addition a sizable correction factor ($\approx$1.3), to relate the measured energy to the parton energy. Since, in principle, this factor depends on the amount and phase-space distribution of radiated energy it can introduce important systematic differences between parton energies determined in pp and Pb–Pb collisions (see below).

Results of a full simulation of ALICE including EMCAL indicate that the optimal resolution for $E_T = 100$ GeV is obtained using a modified UA1 jet reconstruction algorithm [7] including event-by-event background subtraction. With a cone size of $R = 0.3$ the rms energy fluctuation is $\Delta E_T = 30$ GeV for jets with 100 GeV in a cone $R < 1$ [8]. Since the jet production cross-section varies strongly within the resolution window, the relevant quantity is not the energy resolution at a fixed parton energy, but the input production spectrum selected with a given interval of reconstructed energy (figure 1). The comparison of the reconstruction results using charged particles only to those obtained after addition of EMCAL illustrates the importance of electromagnetic calorimetry.

4. Parton energy loss observables

First evidence of parton energy loss has been observed at RHIC from the suppression of high-p_T particles (R_{AA}) [9] and suppression of back-to-back correlations [10]. However, within the LO pQCD formalism for medium-induced parton energy loss it has been shown that at very high p_T, R_{PbPb} is only weakly dependent on the transport coefficient [11]. A much higher sensitivity is expected from studies of modifications of the jet structure, i.e. the manifestation of the partonic energy loss in a decrease of the number of particles carrying a high fraction, z, of the jet energy and the appearance of radiated energy via an increase of the number of low-energetic particle with low z values. In addition, a broadening of the distribution of jet-particle momenta perpendicular to the jet axis, k_T, directly related to the transport coefficient is expected [12]. Another limitation of inclusive high-p_T particle studies is the fact that for extreme quenching scenarios one observes particle emission predominantly from the surface [13], the so-called trigger-bias. Full reconstruction of jets is potentially free of such a bias, allowing detailed study of the induced radiation patterns.

As discussed above, cone sizes smaller than the full jet cone size have to be used to identify and reconstruct jets in a heavy ion environment. Such an approach lies in between the ideal case described above and the leading particle studies which can be seen as the limit of jet-studies for very small cone sizes. To which extent limited cone sizes affect the jet-analysis at the LHC can be studied using a MC that simulates high-p_T parton production followed by a parton showering combining coherently in-medium and vacuum energy losses. At this point it should be noted that even in the absence of experimental effects complicating the analysis, there is no simple relation between the jet structure observables and the energy loss. A MC is needed to constrain the model parameters from experimental observations. In particular, the path length and hence the mean energy loss is not constant but depends on the jet production point which cannot be controlled experimentally and for the same path-length the energy loss spectrum is a combination of no energy loss, normal radiation and full quenching $\Delta E = E$.

While a full MC for partonic energy loss on solid theoretical justification does not yet exist, various phenomenological approaches still yield valuable insights. CMS (with PYQUENCH [14]) and ALICE (with AliQuench within the AliRoot simulation framework) have started efforts to use PYTHIA [15] plus afterburners acting on the final state partons as a simplified model for medium induced gluon radiation. In the case of the ALICE toy-model the amount of energy loss is simulated using the Salgado–Wiedemann quenching weights [16]. Preliminary analysis allows us to define and optimize our analysis strategy. Here some observations:

Fragmentation function. The modification of the fragmentation function $D(z) = (1/N_{jets})\mathrm{d}N_{ch}/\mathrm{d}z$, where $z = p_L/E_T$, is in principle most directly related to the energy loss. For a constant relative energy loss $\Delta E/E$ one expects a complete depletion of the region $z > 1 - \Delta E/E$. In reality the finite jet energy resolution and the finite probability to have no energy loss leads only to a suppression of high-z particles. Moreover, a systematic down-shift of the reconstructed jet energy obtained by correcting the measured energy to account for the limited cone size can partially or completely mask the softening of the fragmentation function. This situation can arise if a sizable fraction of the radiated energy is radiated outside the cone used for reconstruction. Since *a priori* the angular distribution of the radiated energy is not known, it is important to measure the fragmentation function and the jet shape under the same conditions. As an example we compare in figure 2, for different quenching scenario, an idealized bias-free measurement to a measurement performed with a reduced cone size.

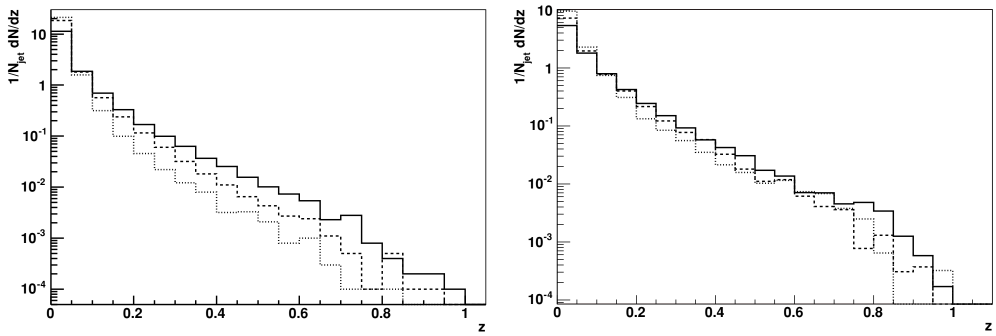

Figure 2. Fragmentation function for 100 GeV jets unquenched (solid), quenched with AliQuench (dashed) and PYQUENCH (dotted). The left distribution is obtained without the inclusion of detector effects and $R < 1$. The right plot includes the finite jet resolution and a systematic underestimation of the parton energy as described in the text.

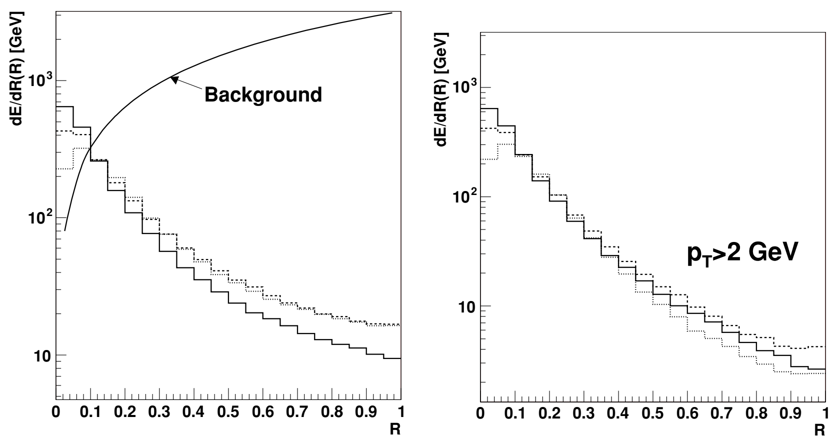

Figure 3. Energy distribution around the jet axis for 100 GeV unquenched (solid), quenched with AliQuench (dashed) and PYQUENCH (dotted). Also shown is the level of background energy for $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = 4000$. The right figure is obtained with an additional p_{T}-cut of 2 GeV.

k_{T}-Spectrum. k_{T}-broadening has been proposed as an additional very sensitive probe of the properties of dense QCD matter. The advantage of this observable is its limited sensitivity to the total jet energy. Indeed, the toy models indicate that the pure addition and fragmentation of extra gluons and the energy loss of the primary parton cannot produce a k_{T}-broadening by themselves. Since PYQUENCH simulates also the energy loss of partons from final state radiation the resulting k_{T}-distribution is even softened. As formation time is proportional to $1/(k_{\mathrm{T}}R)$ it is conceivable that such an effect exists for gluons radiated at an early time so that they see the same medium as the partons from the hard scattering. Hence it is important to map out the k_{T} spectra as a function of R. Since for constant k_{T}, $p_{\mathrm{T}} \sim 1/\theta$, low p_{T} (<2 GeV) particle tracking is needed for large R.

Jet shape. As explained above, an interpretation of the fragmentation function for jets reconstructed using small cone sizes is only possible if the jet shape defined as $\mathrm{d}E/\mathrm{d}R = 1/(N_{\mathrm{jets}}\Delta R)\sum_{\mathrm{jets}} E_{\mathrm{T}}(R - \Delta R/2, R + \Delta R/2)$ can be measured. Figure 3 compares the jet shapes for quenched and unquenched jets ($E_T = 100$ GeV) with and without a momentum cut-off of 2 GeV. For AliQuench (PYQUENCH) 10% (27%) of the jet energy is radiated outside a cone of 0.3. Most of the energy radiated at large angle is carried by relatively low-energetic particles ($p_T < 2$ GeV) it is important that this measurement can be performed without any momentum cut-off. This is only possible with the ALICE barrel tracking; the jet shape can be studied using charged particles with transverse momenta down to 100 MeV.

5. Conclusions

Monte Carlo studies of jet quenching at the LHC outlined in the preceding sections indicate that in order to obtain probes sensitive to the properties of the QCD medium it is mandatory to measure the high-p_T parton fragments together with the low-p_T fragments from the radiated gluons. In particular, experimental low-p_T capabilities are needed for measurements sensitive to the phase-space distribution of radiated gluon, the measurement of the jet shape and the k_T-distributing for $R > 0.3$. The excellent charged particle tracking capabilities of ALICE with $\Delta p/p = 1$–10% from 100 MeV to 100 GeV combined with the proposed electromagnetic calorimeter for ALICE, EMCAL, would provide an unique tool for jet quenching studies at the LHC.

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