Eur. Phys. J. C (2005)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02211-4

THE EUROPEAN
PHYSICAL JOURNAL C

Jet physics at the LHC with ALICE

A. Morsch[a] on behalf of the ALICE Collaboration

CERN, Switzerland, European Organization for Nuclear Research

Received: 14 February 2005 / Revised version: 2 March 2005 /
Published online: 8 July 2005 – © Springer-Verlag / Società Italiana di Fisica 2005

Abstract. In central Pb-Pb collisions at the LHC, jet rates are expected to be high at energies at which ALICE can reconstruct jets over the background of the underlying event. This will open the possibility to quantify 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. 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 combined with the proposed electromagnetic calorimeter for ALICE, EMCAL, represent an ideal tool for jet quenching studies at the LHC.

PACS. 25.75.Nq, 24.85.+p, 13.87.-a

Electronic Supplementary Material: Supplementary material is available in the online version of this article at http://dx.doi.org/10.1140/epjc/s2005-02211-4

1 Introduction

High-p_T partons produced in the initial stage of a nucleus–nucleus collision are expected to undergo multiple interactions inside the collision region prior to fragmentation and hadronisation. In particular, in a quark-gluon plasma (QGP) partons will loose energy through medium induced gluon radiation. These interactions give rise to modifications of the structure of the produced jets which probe the properties of the QGP. This is the main motivation for studying jets as well as high-p_T particle spectra and particle correlations in heavy ion collisions.

First evidence of parton energy loss has been observed at RHIC from the suppression of high-p_T particles [1,2] and the suppression of back-to-back correlations [3]. 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.

In the central part of the experiment, $|\eta| < 0.9$, ALICE [4] will measure event-by-event the inclusive distribution and correlation of a wide range of flavor 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/c, 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 [5], 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) [6] has been proposed by the ALICE-US collaboration. EMCAL covers the region $|\eta| < 0.7$, $60^\circ < \Phi < 180^\circ$ and has an expected energy resolution of $\Delta E/E = 15\,\mathrm{GeV}/\sqrt{E}$.

In the following we will briefly discuss jet rates, jet reconstruction and jets structure observables. More details can be found in [7,8].

2 Jet rates and jet reconstruction at the LHC

ALICE will study the whole spectrum of jet production ranging from mini-jets, $E_T \approx 2 - 20$ GeV, to high-E_T jets of several hundred GeV. For $E_T < 20$ GeV several jets overlap in one central Pb-Pb collision 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, $6 \cdot 10^5$ jets are produced per month of running (10^6 s).

[a] e-mail: morsch@mail.cern.ch

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.

Charged particle multiplicities in central Pb-Pb collisions at the LHC are predicted to range from $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}y = 2000$ to 8000. This corresponds to a total energy per unit of pseudo-rapidity of $\mathrm{d}E_{\mathrm{T}}/\mathrm{d}\eta = 1.5$–6 TeV or to a background event energy of $E_{\mathrm{b}} = 0.4$–1.6 TeV in a cone of $R < 0.7$, 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. 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 $\mathrm{d}N/\mathrm{d}y = 4000$ with contributions of 14 % and 18 % from out-of-cone fluctuations and background energy fluctuation, respectively, where background fluctuations have been simulated with HIJING [9]. Results of a full simulation of ALICE including EMCAL indicate that the optimal resolution for $E_{\mathrm{T}} = 100$ GeV is obtained using a modified UA1 jet reconstruction algorithm including event-by-event background subtraction [5,10,11]. With a cone size of $R = 0.3$ the *rms* energy fluctuation is $\Delta E_{\mathrm{T}} = 30$ GeV for jets with 100 GeV in a cone $R < 1$.

3 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}) and suppression of back-to-back correlations. 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 medium transport coefficient [12,13]. A much higher sensitivity is expected from studies of modifications of the longitudinal and transverse jet structure [14]. 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 [15,16]. Full reconstruction of jets is potentially free of such a bias, allowing detailed studies of the induced radiation patterns.

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 effect the jet-analysis at the LHC can be studied using a Monte Carlo that simulates high-p_{T} parton production followed by a parton showering combining coherently in-medium energy loss and vacuum radiation.

While a full Monte Carlo for partonic energy loss on solid theoretical justification does not yet exist, various phenomenological approaches yield valuable insights. CMS (with *PYQUENCH* [17]) and ALICE (with *AliQuench* within the AliRoot simulation framework) have started efforts to use PYTHIA [18] plus afterburners acting on the final state partons as a simplified model for medium induced gluon radiation. In the ALICE toy-model for each parton produced in a hard collision the energy loss ΔE is determined from a probability density function using the Salgado-Wiedemann Quenching Weights [19]. This depends on the medium transport coefficient, the parton energy E_p, the parton type and the in-medium path-length. Partons from the hard scattering produce further partons in a parton shower. The momentum component parallel to the initial parton of each final state parton is reduced by a factor $x = 1 - \Delta E/E_p$ keeping the transverse component constant. Total energy and momentum are conserved by putting additional gluons on the PYTHIA stack. The additional number of gluons is calculated from $N_g = 1 + x/(1-x)$. Preliminary analysis using the toy models allows us to define and optimise our analysis strategy. Here are some observations:

Fragmentation function: The modification of the fragmentation function $D(z) = (1/N_{\mathrm{jets}})\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}z$, where $z = p_{\mathrm{hadron}}/p_{\mathrm{Jet}}$, 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 Fig. 1, for different quenching scenarios, an idealised bias-free measurement to a measurement performed with a reduced cone size.

k_{T}-Spectrum: Broadening of the distribution of jet particle momenta perpendicular to the jet-direction, k_{T}, 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. Furthermore, gluons from final state radiation produced at an early time see the same medium as the partons from the hard scattering and should be also suppressed. As formation time is proportional to $1/(k_{\mathrm{T}}R)$ it is important to map out the k_{T} spectra as a function of R to look for such an effect. Since for constant k_{T}, $p_{\mathrm{T}} \sim 1/\theta$, low-$p_{\mathrm{T}}$ (< 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.

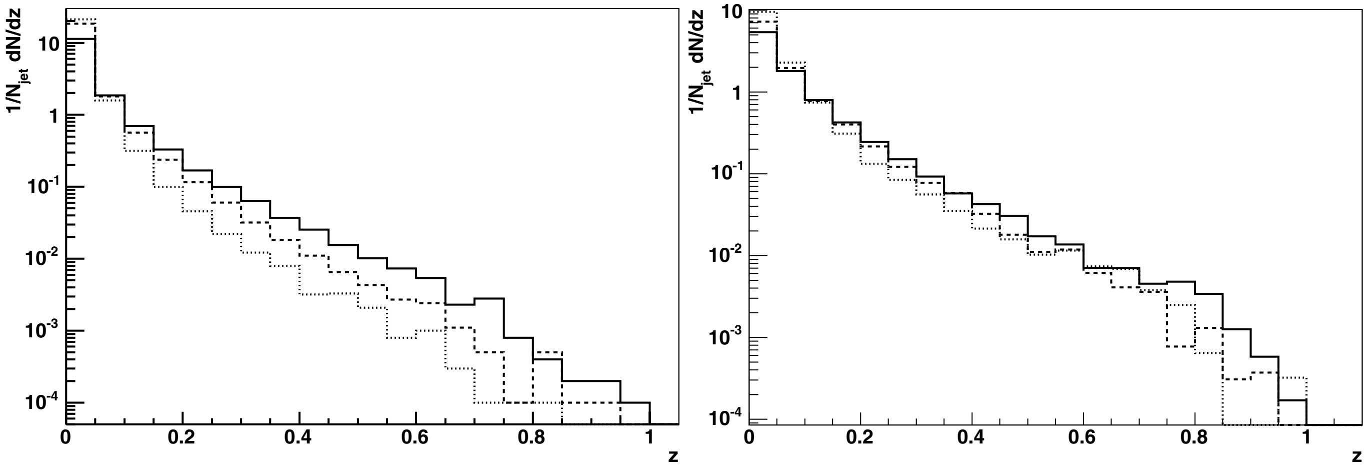

Fig. 1. Fragmentation function for 100 GeV jets unquenched (solid), quenched with AliQuench (dashed) and PYQUENCH (dotted). The left distribution is obtained without inclusion of detector effects and $R < 1$. The right plot includes the finite jet resolution and a systematic underestimation of the parton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

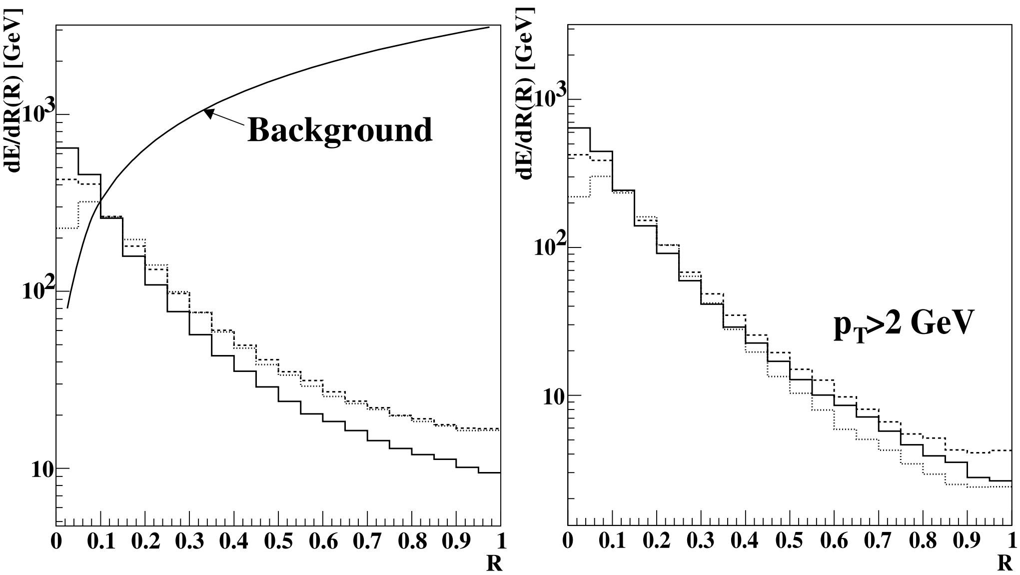

Fig. 2. Energy distribution around the jet axis for 100 GeV unquenched (solid), quenched with AliQuench (dashed) and PYQUENCH (dotted). Also shown is the level of background energy for $\mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta = 4000$. The right figure is obtained with an additional p_{T}-cut of 2 GeV/c

Figure 2 compares the jet shapes for quenched and unquenched jets ($E_{\mathrm{T}} = 100$ 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 $R = 0.3$. Most of the energy radiated at large angle is carried by relatively low-energetic particles ($p_{\mathrm{T}} < 2$ GeV/c) 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/c.

Photon-tagged jets: An attractive method to obtain an unbiased measurement of the jet energy is to tag jets with prompt photons emitted in a direction opposite to the jet direction [20, 21]. On one hand, this coincidence technique will help to localize the jet and on the other hand to determine the jet energy by measuring the photon energy. In ALICE, jets will be reconstructed as described before and the away-side photons will be detected by PHOS. Identification of prompt photons over the background of photons from π^0 decays is possible for $E_\gamma > 20$ GeV. The relatively small cross-section for prompt photon production and the acceptance of the PHOS ($200° < \Phi < 340°$, $|\eta| < 0.2$) limit this study to $E_{\mathrm{T}} \lesssim 50$ GeV.

4 Conclusions

Experiments at RHIC have shown that jet modifications can be studied by analysing inclusive spectra of identified particles and particle correlations. These studies need excellent low-p_T and PID capabilities. ALICE is well prepared to extend these studies to heavy ion collisions at the LHC. In addition, in 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 to quantify 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.

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 gluons, the measurement of the jet-shape and the k_T-distribution for $R > 0.3$. The excellent charged particle tracking capabilities of ALICE with $\Delta p/p = 1$–$10\,\%$ from 100 MeV/c to 100 GeV/c combined with the proposed electromagnetic calorimeter for ALICE, EMCAL, would provide an unique tool for jet quenching studies at the LHC.

References

1. K. Adcox et al, Phys. Rev. Lett. **88**, 022301 (2002)
2. C. Adler et al, Phys. Rev. Lett. **89**, 202301 (2002); J. Adams et al, Phys. Rev. Lett. **91**, 172302 (2003)
3. C. Adler et al, Phys. Rev. Lett. **90**, 082302 (2003)
4. ALICE Collab., Technical Proposal CERN/LHCC/95-71 (1995); ALICE Collab., Physics Performance Report Volume 1 CERN/LHCC 2003-049 (2003).
5. W.B. Christie and K. Shestermanov, STAR Note 196 (1995); T. Henry, J. Phys. G: Nucl. Part. Phys. **30**, S1287 (2004)
6. T.M. Cormier, Eur. Phys. J **C34**, s01 333 (2004)
7. A. Morsch, Jet Physics with the ALICE Detector. In: CERN Yellow Report on Hard Probes in Heavy Ion Collisions at the LHC, CERN-2004-009, eds. M. Mangano, H. Satz and U. Wiedemann (2004).
8. A. Morsch, J. Phys. G: Nucl. Part. Phys. **31** (2005) (to be published)
9. X.N. Wang, N. Gyulassy, Phys. Rev. **D44** (1991) 3501; M. Gyulassy, X.N. Wang, Comp. Phys. Comm. **83**, 307 (1994)
10. G. Arnison et al., Phys. Lett. **132B**, 214 (1983).
11. S. Blyth, J. Phys. G: Nucl. Part. Phys. **30**, S1155 (2004)
12. K.J. Eskola, H. Honkanen, C.A. Salgado, U.A. Wiedemann, Nucl. Phys. **A747**, 511 (2005)
13. A. Dainese, C. Loizides, G. Paic, Eur. Phys. J. **C38**, 461 (2005)
14. C.A. Salgado, U.A. Wiedemann, Phys. Rev. Lett. **93**, 042301 (2004)
15. E.V. Shuryak, Phys. Rev. **C66**, 027902 (2002)
16. B. Muller, Phys. Rev. **C67**, 061901 (2003)
17. I.P. Lokhtin, A.M. Snigirev, Eur. Phys. J **C16**, 527 (2000); I.P. Lokhtin, A.M. Snigirev, arXiv:hep-ph/0406038 (2004)
18. T. Sjostrand et al., Comp. Phys. Comm. **135**, 238 (2001)
19. C.A. Salgado, U.A. Wiedemann, Phys. Rev. **D68**, 014008 (2003)
20. X.N. Wang, Z. Huang, I. Sarcevic, Phys. Rev. Lett. **77**, 231 (1996)
21. G. Conesa et al., ALICE Internal Note ALICE-INT-2004-024 (2004)