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Jets and High-p_t Physics with ALICE at the LHC

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In central Pb–Pb collisions at the LHC at $\sqrt{s_\mathrm{NN}} = 5.5\,\mathrm{TeV}$, high rates are expected at energies at which jets can be reconstructed against the large background of the nucleus–nucleus 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. ALICE will use a combination of its central tracking system and the electromagnetic calorimeter (EMcal) to measure and trigger on jets. For lower energies, $E_\mathrm{t} < 30-50\,\mathrm{GeV}$, high-$p_\mathrm{t}$ single hadron momentum spectra, hadron correlations and γ-jet (hadron) correlations will be used to study jet modifications. The strength of ALICE lies in its low-p_t and particle identification capabilities. These allow ALICE to measure the fragmentation functions down to small momentum fractions and to determine the particle composition of jets. Hence a precise measurement of the phase space distribution of radiated gluons and the response of the medium to the jet energy deposition can be performed.

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1. Introduction

Hard strongly interacting partons produced at the initial stage of heavy ion collisions have been proposed as a tool to study the properties of the QGP [1, 2]. The partons are expected to undergo multiple interactions inside the collision region prior to hadronisation. Hereby, the energy of the partons is reduced through collisional energy loss [1, 3, 4] and medium-induced gluon radiation [2, 5, 6], the latter being the dominant mechanism in a QGP. The energy loss has been suggested to behave very differently in cold nuclear matter and in QGP, and has been postulated as a tool to probe the properties of this new state of matter. This is the main motivation for studying jets as well as high-p_t particle spectra and particle correlations in heavy-ion collisions.

Striking effects have been observed at RHIC in central Au–Au collisions among the most prominent the suppression of high transverse momentum particles [7, 8] and the suppression of back-to-back correlations [9]. They show that the jet structure is strongly modified in dense matter consistent with perturbative QCD calculations of partonic energy loss via induced gluon radiation. However, it has also been shown that these measurements alone do not strongly constrain the models of parton interactions with the medium and of the transport coefficient ($\hat{q}$) [10]. Multi-particle correlation studies or ideally full jet reconstruction would give the required sensitivity. However, in central Au–Au collisions standard jet reconstruction algorithms fail due to the large energy from the underlying event ($\approx 300\,\mathrm{GeV}$ in a cone $R_c = \sqrt{\Delta\eta^2 + \Delta\varphi^2} < 1$) and the relatively low statistically accessible jet energies ($< 30\,\mathrm{GeV}$).

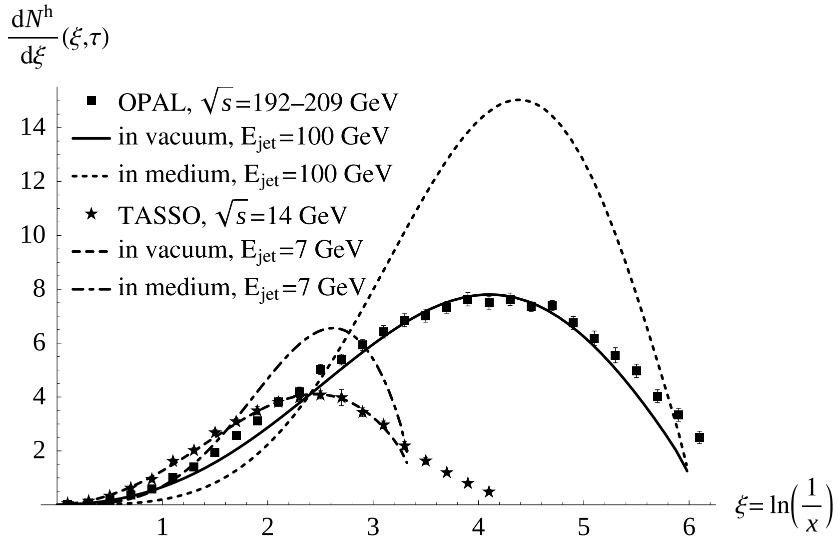

Figure 1: The single inclusive hadron distribution as a function of $\xi = \ln(E_{jet}/p^{hadron})$. Data taken from e^+e^- collision experiments TASSO and OPAL. Lines through data obtained from Modified Leading Logarithmic Approximation (MLLA) results. Dashed and dashed-dotted curves labeled 'in-medium' are calculated using the model describe in Ref. [11]. Figure taken from Ref. [11].

With the start-up of the LHC, heavy ion physics will enter into a regime where high-p_t processes contribute significantly to the A–A cross-section. In particular at the LHC for the first time high rates are expected at energies at which jets can be fully reconstructed against the high background from the underlying event at the LHC. Detailed studies of the expected modifications of the jet structure become feasible. These manifest themselves 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-energy particles with low z values [11] (Fig. 1). In addition, a broadening of the distribution of jet-particle momenta perpendicular to the jet axis, k_t, directly related to the colour density of the medium is expected [12]. The main 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]. Full reconstruction of jets is potentially free of such a bias, allowing detailed study of the induced radiation patterns.

As opposed to jet analysis at hadron colliders, the large background from the underlying events imposes limitations to the reconstruction performance. In a typical cone of size $R_c = 1$ we expect up to 2 TeV of energy from the underlying event Pb–b collision at $\sqrt{s_{NN}} = 5.5$ TeV (HIJING [14] $dN_{ch}/d\eta = 6000$). As a consequence, smaller cone sizes have to be used in heavy-ion collisions and new background subtraction techniques have to be developed for the jet energy reconstruction and for the measurements of the low-p_t part of jet structure distributions.

ALICE is a general-purpose experiment whose detectors measure mid-rapidity ($|\eta| < 0.9$) hadrons, leptons and photons [15]. Its design has been optimized to track and identify particles from very low (≈ 100 MeV) to up to fairly high (≈ 100 GeV) p_t, to reconstruct short-lived particles such as hyperons, D and B mesons and to perform these tasks in an environment with large charges particle multiplicities (up to 8000 per rapidity unit). ALICE will use a combination of its central tracking system and the electromagnetic calorimeter (EMcal) to measure and trigger on jets. Its low-p_t and particle identification capabilities will allow ALICE to measure the fragmentation functions down to small momentum fractions and to determine the particle composition of jets. Hence a precise measurement of the phase space distribution of radiated gluons and the response of the medium to the jet energy deposition can be performed.

This paper describes the ALICE capabilities to measure jets and modifications of the jet structure. We start with a discussion of the consequences of the background from the underlying nucleus-nucleus event on the jet measurements.

2. Jet reconstruction in high background environment

The amount of background energy contained in a jet cone changes drastically from hadron to heavy ion collisions. At the LHC, in a typical cone of size $R_c = 1$ we expect up to 2 TeV of energy from the underlying event. Fig. 2 shows the charged jet and background energies as a function of the cone radius R_c [16]. Jets can only be identified if the background energy E_{bg} within the cone is smaller than the signal energy. This can be achieved by decreasing the cone size ($E_{bg} \sim R_c^2$) to $R_c = 0.3 - 0.5$ and applying p_t or energy cuts on the charged hadrons or calorimeter towers.

Without modification the standard jet finders used in pp, ep and e^+e^- collisions will not work in a heavy ion environment. For this purpose a jet finder (HIJA) [17, 18] based on the UA1 cone type algorithm [19] was developed. The main modification consists in determining the mean cell energy from cells outside a jet cone. It is recalculated after each iteration of the cone jet finder and subtracted from all cells. In addition, the FastJet k_t-algorithm has been used successfully for ALICE performance studies [20].

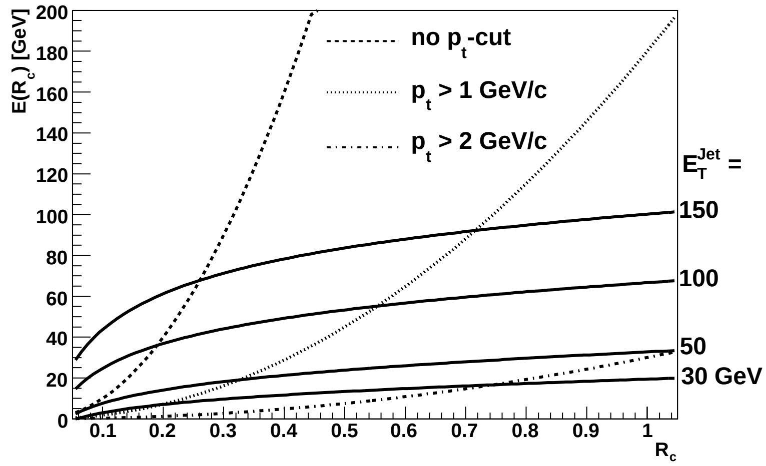

Figure 2: Charged jet energy inside a cone of radius R_c (full lines) compared to the background energy for different transverse momentum cuts (dashed lines). The background has been calculated with `HIJING` quenched $b < 5$ fm [16].

Background fluctuations

Whereas the amount of background energy limits the jet identification, the fluctuations of the background energy can deteriorate the jet energy resolution. There are three different sources of fluctuations. The first one is produced by impact parameter variations event-by-event for the same range of centrality. Their size is proportional to the jet area and can be reduced if one subtracts the background event by event. The second source are the Poissonian fluctuations of uncorrelated particles, and are proportional to the jet cone radius. However, not all particles in the background are uncorrelated since they may belong to a low-energy jet ($E_t < 20$ GeV), which can not be reconstructed over the background. This contribution increases the fluctuation level to about 30% above the Poissonian limit. Fig. 3 shows the different contributions as a function of jet cone radius for the 10% most central collisions using different p_t cuts.

Signal fluctuations

The restriction of the jet reconstruction to a smaller cone and the application of a transverse momentum cut to reduce the background from the underlying event also reduces to some extend the measured energy of the jet E_t^{meas} and increases the signal fluctuations. For a jet of 100 GeV and using a cone size of $R_c = 0.3$ for jet reconstruction the cone energy fluctuation with respect to the energy contained in $R_c = 1.0$ amounts to 18%.

Provided that instrumental resolution can be neglected one has strictly $E_t > E_t^{\mathrm{meas}}$. Now since the produced spectrum falls steeply ($d\sigma/dE_t \sim 1/E_t^{5.7}$) large deviations $E_t >> E_t^{\mathrm{meas}}$ are very unlikely and $E_t^{\mathrm{meas}} \approx E_t$. Simulations show that the ratio E_t^{meas}/E_t is 0.6 (0.7, 0.85) for jet reconstruction using leading particles, charged jets, charged particles + electromagnetic energy, respectively (Fig. 4). Also the fluctuations of the true energy for a given bin of reconstructed energy are reduced.

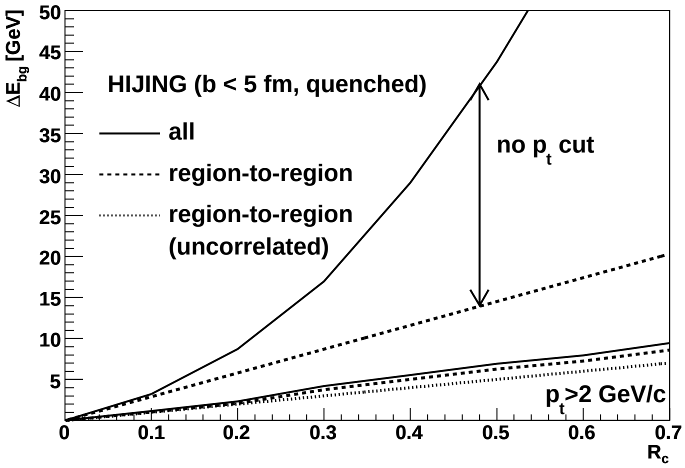

Figure 3: Different contributions to the background fluctuations as a function of the cone radius R_c for 10% central Pb–Pb collisions.

Jets reconstructed with charged particles using the ALICE central tracking system alone have unbiased fluctuations of $\Delta E_t/E_t \approx 45\%$. The trigger bias reduces these fluctuations to $\approx 30\%$. Since the dominant source of fluctuation are the charged-to-neutral fluctuations of the fragmentation the selected jets have an enhanced charged particle fraction. This means that although the overall jet reconstruction efficiency is approximately by a factor of three lower than for full jet reconstruction, most of the rare jets with high-z charged particles are selected. No bias on the measurement of jet quenching has been observed in our simulation studies (see also section 4).

Reconstruction of quenched jets

Small cone sizes and transverse momentum cuts have to be seen in the light of the measurement of quenched jets. Detailed measurement of the jet shape and fragmentation functions have been performed at hadron colliders. Monte Carlo generators have been tuned to reproduce these data and can be used to correct the measured jet energy in pp collisions. In nucleus–nucleus collisions, however, this correction is impossible without prior knowledge about the partonic energy loss.

Fig. 5 shows the result of a model calculation [21] of the modification of the jet shape $\Psi(R) = 1/N_{\rm jet}\sum_{\rm jets} E_{\rm t}(R)/E_{\rm t}(1)$. Also shown are the distributions of energy contained in low-momentum particles. As can be seen, even a relatively small transport coefficient leads to sizable increase of energy carried by low-momentum charged particles. From the experimental point of view, it is important to measure these particles in order to avoid a systematic underestimation of the parton energy. From measurements of the transverse jet structure and by comparing the jet cross-sections in pp and A–A collisions ($R^{\rm jet}_{\rm AA}(E_{\rm t})$) one has to deduce the amount of energy radiated outside the jet cone.

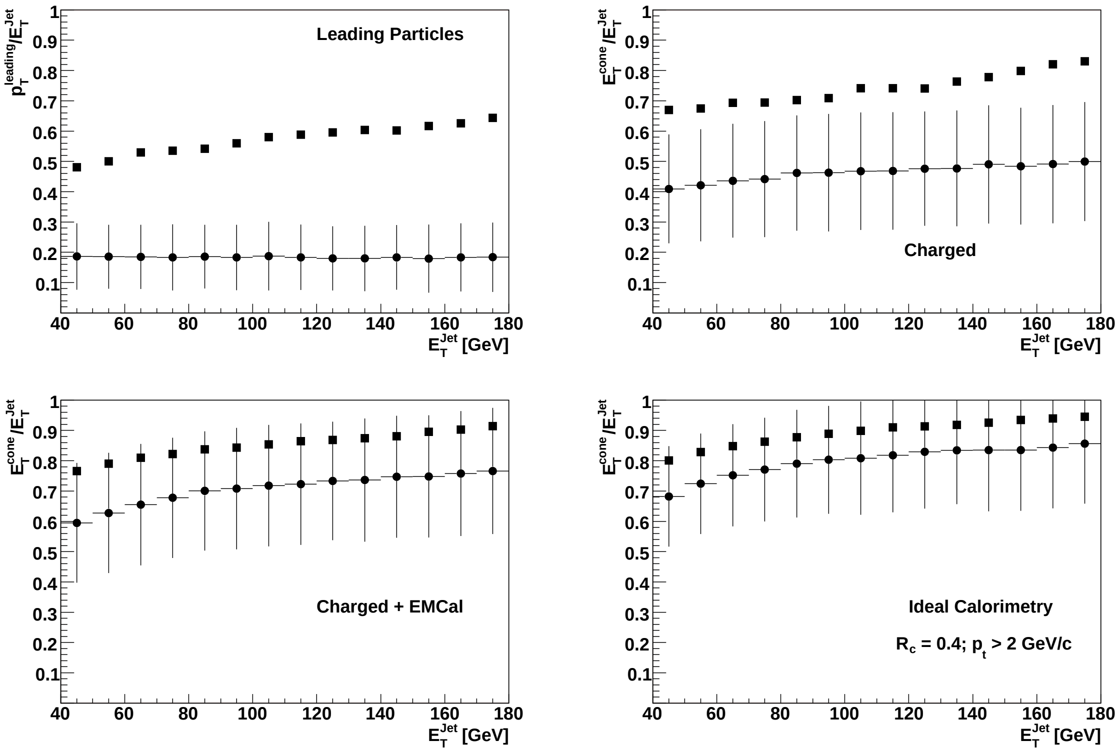

Figure 4: The ratio between cone energy and generated energy, $E_t^{\rm cone}/E_t^{\rm Jet}$, as a function of the generated energy (circles), for which the r.m.s. values are shown as error bars, and as a function of the reconstructed energy (squares). The former is equivalent to the ratio obtained from monochromatic jets whereas the latter contains the bias induced by the input spectrum. Note that for leading particles $E_t^{\rm cone} = p_t^{\rm leading}$.

3. The ALICE experiment

ALICE is a multipurpose heavy-ion experiment at the LHC [15]. It combines excellent tracking with PID, secondary vertex capabilities, electron and muon identification and a high resolution γ-spectrometer. The central tracking system covers the pseudo-rapidity range $|\eta| < 0.9$ and full azimuth. It has excellent momentum resolution for charged particles from $100\,\mathrm{MeV}/c$ to $100\,\mathrm{GeV}/c$ [16] (Fig. 6 (left)) sufficient to measure the full range of fragment momenta for the highest energy jets accessible in heavy-ion collisions. To add trigger capabilities and to improve the jet energy resolution an electromagnetic lead-scintillator sampling calorimeter (EMCal) is being constructed [22, 23]. EMCal covers the region $|\eta| < 0.7$, $\Delta\varphi = 110^\circ$ using 13k towers in Shashlik geometry with APD photo-sensor read-out. There are in total 13,000 towers each with $\Delta\eta \times \Delta\varphi = 0.014 \times 0.014$. The EMcal has a design energy resolution of $\Delta E/E = 15\%/\sqrt{E} + 2\%$.

Results of a full simulation of ALICE including EMcal indicate that the optimal resolution for $E_t = 100\,\mathrm{GeV}$ is obtained using a modified UA1 jet reconstruction algorithm [19] including event-by-event background subtraction. With a cone size of $R = 0.3$ the *rms* energy fluctuation is $\Delta E_t = 30\,\mathrm{GeV}$ for jets with $100\,\mathrm{GeV}$ in a cone $R_c = 1$ [17, 18] (Fig. 6). In case of charged jet reconstruction using TPC information only, the resolution is limited to $\approx 45\%$ mainly by charged-

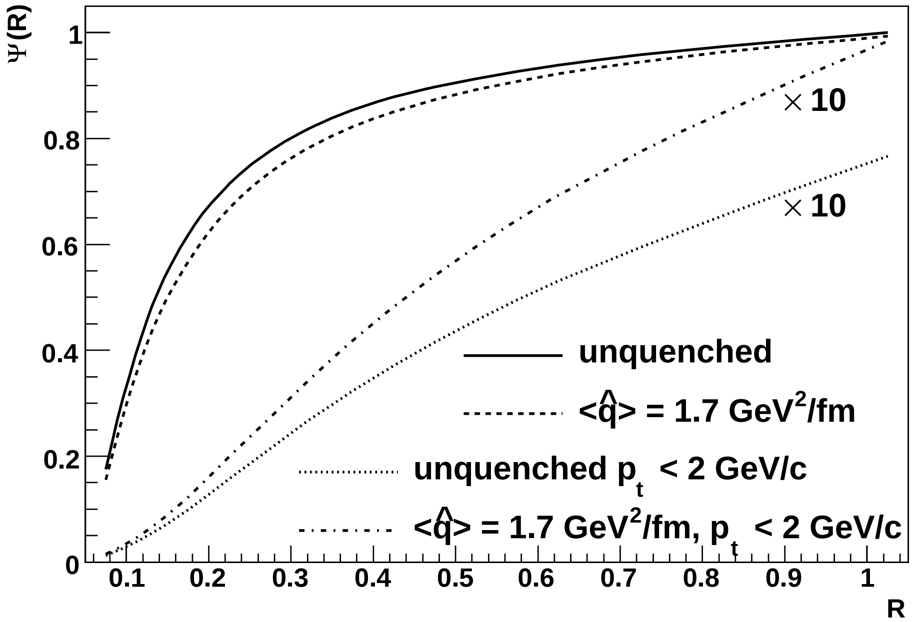

Figure 5: The jet shape $\Psi(R)$ for 100 GeV jets without in-medium energy loss (solid line) is compared with the result of AQM [21] using $\langle\hat{q}\rangle = 1.7\,\mathrm{GeV}^2/\mathrm{fm}$ (dashed line). Also shown are the corresponding distributions obtained from charged particles with $p_t < 2\,\mathrm{GeV}/c$. Figure taken from [16].

to-neutral fluctuations. In the presence of quenching, optimal resolution has to be balanced against optimising the acceptance for particles from gluon radiation. This optimisation depends also on the background particle density and is awaiting data.

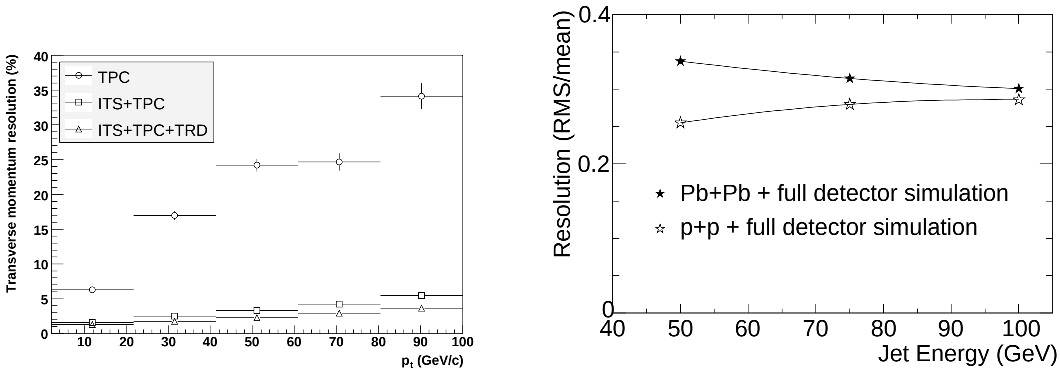

Figure 6: Left: Transverse-momentum resolution for different combinations of the ALICE tracking detectors. (central HIJING $dN_{ch}/d\eta = 6000$). Right: Jet-energy resolution using TPC and EMcal information as a function of the generated jet energy for jets embedded in central Pb–Pb collisions simulated with HIJING compared to the background free case and for an ideal detector only applying the jet reconstruction cuts ($R_c = 0.3$, $p_t > 2\,\mathrm{GeV}/c$).

The EMcal not only improves the jet energy resolution but most importantly provides a fast trigger to extend the ALICE E_t reach for jets, direct photons and electrons from heavy flavor decays. Comprehensive study of jet quenching requires an unbiased sample of high E_t jets, obtained by means of a "jet patch" trigger on total energy summed over finite phase space area. Table 1 compares the expected jet yields for on LHC year with and without the EMcal trigger. As can be seen the gains due to the trigger are substantial. In particular the important reference measurements using peripheral Pb–Pb, pPb and pp are only possible with a jet trigger.

Table 1: Jet yields in one LHC year per 20 GeV bin with and without EMcal trigger.

System	Jet Trigger ?	$N_{\rm jets}$ (125 GeV)	$N_{\rm jets}$ (175 GeV)
Pb–Pb central	y	1.1×10^4	1.7×10^3
	n	2.1×10^3	3.2×10^2
Pb–Pb peripheral	y	4.1×10^2	6.2×10^1
	n	8.0×10^0	1.0×10^0
pPb (8.8TeV)	y	2.7×10^4	4.2×10^3
	n	2.5×10^2	4.0×10^1
pp (14TeV)	y	6.9×10^5	1.0×10^5
	n	1.2×10^3	1.9×10^2

4. Simulation results

To demonstrate our jet reconstruction capabilities in a heavy-ion environment ALICE has run a Jet Data Challenge, in which jets with energies ranging from 20 to 200 GeV have been embedded into HIJING events and passed through the full detector simulation and reconstruction chain. The reconstructed jet energy spectrum and jet structure observables have been compared to to the expectation from background-free jet samples (Fig. 7). Only for cone energies below ≈ 40 GeV fake jets produced as a sum of energy from real jets and background energy influence the quality of the reconstruction.

The sample of reconstructed jets was used to obtain the fragmentation function $1/N_{\rm jet} {\rm d}N/{\rm d}\xi$. An example for $E_t^{\rm cone} > 70$ GeV corresponding approximately to jets with $E_t > 100$ GeV is shown in Fig. 7. The distribution of all particles is compared with those from signal and background particles. The low ξ region is essentially background free. At high ξ corresponding to $p_t < 2$ GeV the background dominates and has to be subtracted.

To quantify the effect of jet quenching one has to determine the nuclear modification factor by calculating the ratio between distributions obtained in central Pb–Pb collisions and pp, pA or peripheral Pb–Pb collisions ($R_{\rm AA}(\xi)$). The sensitivity of the measurement will depend crucially on the jet statistics that can be obtained for the different systems. Fig. 8 shows such ratios (central Pb–Pb over pp) in one year of LHC running for 5.5 TeV central Pb–Pb collisions (transport coefficient $\hat{q} = 50\,{\rm GeV}^2/{\rm fm}$). Error bars are due to statistical errors and the systematic uncertainty of the background subtraction. The EMCal jet triggering and reconstruction based on EMCal and tracking

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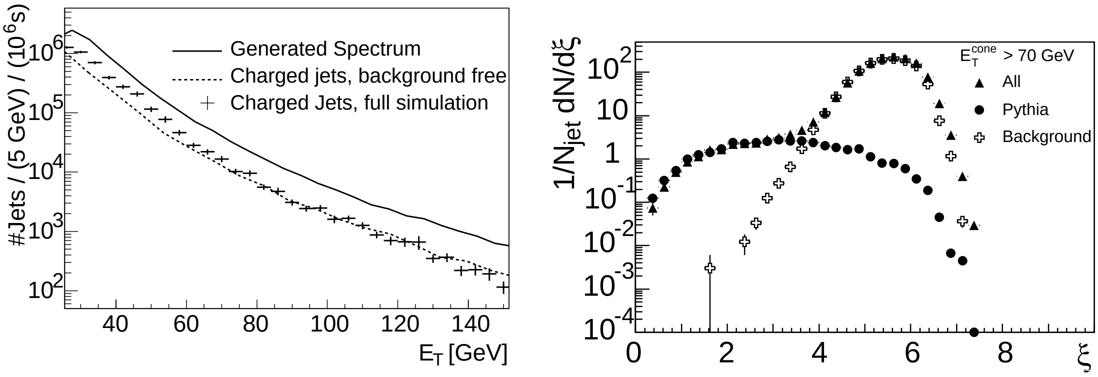

Figure 7: Left: The reconstructed jet-energy spectrum for central Pb–Pb collisions using charged tracks with $p_t > 2\,\mathrm{GeV}/c$ in a cone $R_c = 0.4$ is compared to the input spectrum (solid line) and the reconstructed jet-spectrum obtained using background-free fast simulation. The spectra are normalised to the untriggered yield for one effective month of running (10^6 s), i.e 10^7 central events. Right: Reconstructed hump-backed plateau for $E_t^{\mathrm{cone}} > 70\,\mathrm{GeV}$ and charged particles inside a cone $R < 0.4$. The spectrum is compared to the corresponding results for background free events.

is compared to minimum bias triggering and jet reconstruction based solely on charged particle tracking. Results for jet samples with two different energies 125 and 225 GeV (centre of 20 GeV bin) are shown. At both energies one observes a shift of the expected measured curve with respect to the ideal one toward smaller ξ values. It is caused by a systematic underestimation of the jet energy due to out-of-cone radiation. The average amount of out-of-cone radiation can be determined by measuring the transverse jet shapes. This will help to improve the ξ measurement. The shift is almost the same for the charged jets and the charged hadrons plus EMcal measurement. However, at the higher energy the measurements with charged jets is clearly statistics limited.

In the high-ξ region the systematic error from the background subtraction. The error bars shown correspond to $0.002B$, where B is the number of entries per bin from the background. Recent studies on the background subtraction have confirmed effects close to this magnitude [24]. Jets of true energies lower than the bin of reconstructed energy can enter the sample due to upward fluctuations of the background and true energies higher can enter due to downward fluctuations. Since there are much more jets of lower energies there is a bias toward upward fluctuations of the background. Since the background consists mainly of low-p_t particles one can expect an incomplete subtraction of the background at high ξ. The lowering of the mean true jet energy for a given sample of jets in a bin of reconstructed energy leads to a depletion of the low-ξ region.

Fig. 9 shows the ratio fragmentation functions for central Pb–Pb compared to 14 TeV pp, for $E_t^{\mathrm{jet}} \approx 116\,\mathrm{GeV}$. In the simulation of the Pb–Pb events no energy loss has been included. The bias effects explained above lead to a deviation from a ratio equal to one.

5. Di-hadron correlations from RHIC to LHC

Di-hadron correlations will be studied at LHC in an energy region where full jet reconstruction is not possible, i.e. for $E_t \lesssim 30\,\mathrm{GeV}$. As compared to RHIC one expects a harder parton $\hat{p}_t$-spectrum

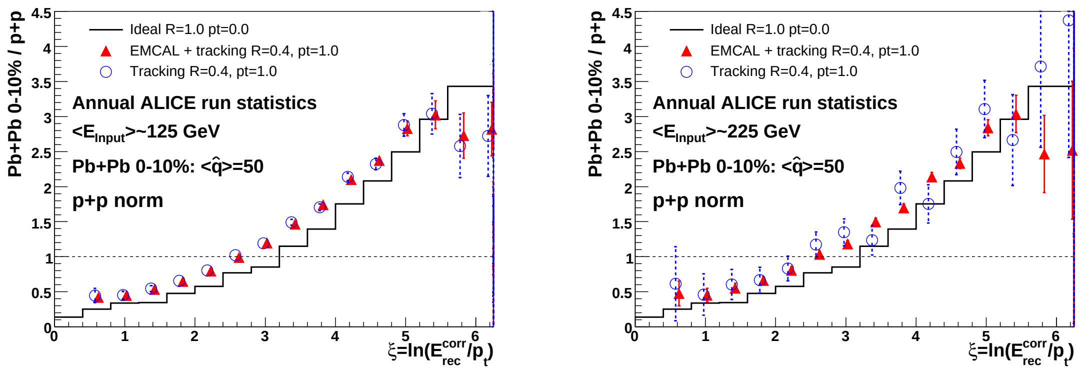

Figure 8: Ratio of fragmentation functions for central Pb–Pb compared to 14 TeV pp, for $E_t^{\rm jet} \approx 125\,\mathrm{GeV}$ (left) and $E_t^{\rm jet} \approx 175\,\mathrm{GeV}$ (right). For the Pb–Pb collisions a mean transport coefficient of $\langle \hat{} \rangle = 50\,\mathrm{GeV}^2/\mathrm{fm}$ has been assumed. [Simulations and plot P. Jacobs and J. H., Putschke]

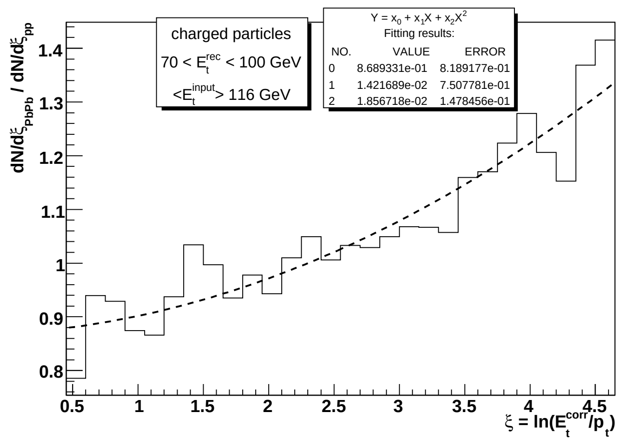

Figure 9: Ratio of fragmentation functions for central Pb–Pb compared to 14 TeV pp, for $E_t^{\rm jet} \approx 116\,\mathrm{GeV}$. Only the effect of the background on the ratio is shown.

and an increased number of high-p_t hadrons per event. In addition the increased contribution from NLO QCD processes will change the angular correlation of the hadrons. This has several consequences for the di-hadron correlation studies at LHC. For $p_t^{\rm trig} = 8\,\mathrm{GeV}/c$, the expected S/B ratio for the away-side peak is $\approx (2-5)10^{-2}$ (Fig. 10) [25] whereas the STAR experiment has demonstrated that at RHIC energies this region is essentially background free for $p_t^{\rm assoc} \approx p_t^{\rm trig}$ [27]. However, since the signal rate also increases one can expect a similar significance of the away-side peak. As explained in Refs. [28, 29] the increase in hardness of the parton p_t-spectrum with increasing centre of mass energy changes the trigger bias. As a consequence the size of the near-side peak increases relative to the away-side peak (Fig. 10).

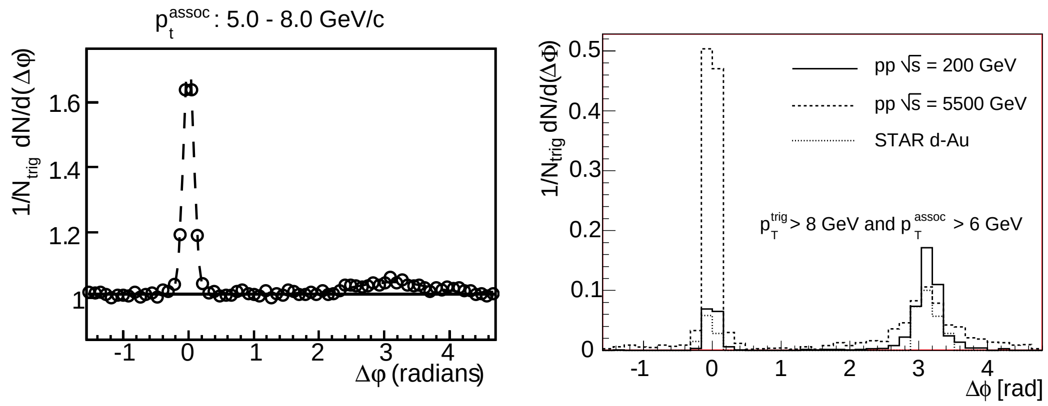

Figure 10: Azimuthal correlation function: HIJING [14] prediction for Pb–Pb at $\sqrt{s} = 5500\,\mathrm{GeV}$ for $p_t^{trig} > 8\,\mathrm{GeV}/c$ (left) and result of Pythia [26] simulations (right) for pp collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ (solid line) and $\sqrt{s} = 5500\,\mathrm{GeV}$ (dashed line).

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