Jet reconstruction in heavy ion collisions (emphasis on Underlying Event background subtraction)

M. Estienne[1]
[1]SUBATECH, Ecole des mines, Université de Nantes, CNRS/IN2P3
4 rue Alfred Kastler - BP 20722, 44307 Nantes Cedex 3, FRANCE

Abstract
A modification of the internal structure of jets is expected due to the production of a dense QCD medium, the Quark Gluon Plasma, in heavy-ion collisions. We discuss some aspects of jet reconstruction in $p + p$ and $A + A$ collisions and emphasize the dramatically increased contribution of the underlying event in nucleus-nucleus collisions as compared with the vacuum case. We conclude with its consequences on the full jet spectrum and fragmentation function extraction at LHC.

1 Motivations for jet studies

1.1 The phenomenon of jet energy loss in heavy-ion collisions

Non-perturbative lattice QCD calculations indicate that a deconfined state of matter, the Quark Gluon Plasma (QGP), may exist at very high temperatures and energy densities. This state of matter is expected to be formed in the heart of an ultra-relativistic heavy-ion collision, when the energy density is the largest. Since 2000, the Relativistic Heavy-Ion Collider (RHIC) has collected impressive results, which has led to the discovery of a new state-of-matter of very small viscosity [1]. Among the observables which have led to such a conclusion, the jet quenching effect is one of the most relevant as it has highlighted the production of a dense medium in interaction. One of the first computations of the radiative energy loss of high-energy quarks in a dense medium was proposed by Gyulassy et al. [2, 3] in the early nineties. Since then many approaches have been developed to determine the gluon radiation spectrum of a hard parton undergoing multiple scattering [4–7]. The experimental consequence of these processes is a significant suppression of large transverse momentum (p_T) hadrons in heavy-ion collisions (HIC) highlighted through the measurement of the nuclear modification factor or two and three particle correlations [8, 9]. Even though we can nowadays claim that a dense medium has indeed been produced and somehow characterized, a plethora of questions remains: does energy loss result from few strong scatterings in the medium or multiple soft ones ? How does it depend on the medium-length ? What is the energy loss probability distribution of the partons ? They motivate the necessity to call for some more discriminating, and differential observables to characterize the QGP.

Moreover, the “leading particle” physics which has been studied at RHIC until 2008 presents some limitations known as *surface* and *trigger* biases [10,11]. Ideally, the analysis of reconstructed jets on an event by event basis should increase the sensitivity to medium parameters by reducing the trigger bias and improve our knowledge of the original parton 4-momentum.

1.2 Jets in a heavy-ion collision and the Underlying Event background

In QCD, jets are defined as cascades of partons emitted from an initial hard scattering followed by fragmentation. In HIC, parton fragmentation is modified relative to the vacuum, due to the presence of the hot QCD medium. After the overlap of the two incoming nuclei, the quarks and gluons produced in the initial nucleon-nucleon ($N + N$) hard scatterings propagate through the dense color field generated by the soft part of the event. Consequently, the medium should affect the fragmentation process of hard partons and has drastic effects on the jet structure itself. (i) A softening of the fragmentation function is expected leading to the suppression of production of high p_T particles as well as a numerous production of soft particles. A first attempt to model medium-modification fragmentation processes by Borghini & Wiedemann was the determination of the single inclusive hadron spectrum inside jet - known as Hump-Backed Plateau (HBP) - in HIC [12]. This aspect will be addressed in section 4 at the level of the experiment. (ii) A jet broadening (inducing out-of-cone radiations) is expected as one should observe a redistribution of the particles inside the jet relatively to its axis. A modification of the transverse shape of the jet (k_T spectrum) or its particle angular distribution can be studied [13]. (iii) In case of sufficiently strong energy loss scenarii, it could have consequences on the jet reconstruction itself and reduce the expected jet rate. (iv) As di-jet pairs have different path lengths in medium and as energy loss is a stochastic process, the di-jet energy imbalance should be increased and acoplanarity induced.

Ideally, a direct measurement of these modifications should be possible. However, the picture is more complicated due to the presence of the soft Underlying Event (UE). The UE and its fluctuations will induce important bias on the jet identification. It will be extensively discussed in section 3. The expected jet reconstruction performances in $p+p$ in the ALICE experiment are first discussed in section 2. Note that the jet energy-scale, one of the main sources of uncertainty in any jet spectrum measurement will not be discussed here. ATLAS and CMS results will not be commented either. More information can be found elsewhere [14].

2 Jet reconstruction performances with calorimetry

2.1 Experimental apparatus and tools

Full jet measurement in heavy-ion experiments has become possible very recently thanks to the insertion of an electromagnetic calorimeter (EMC) in the STAR experiment at RHIC [15, 16]. STAR has demonstrated the feasibility of such measurement combining its charged particle momentum information from its Time Projection Chamber (TPC) and the neutral one from the EMC, publishing the first measurement of the inclusive jet spectrum for the process $p + p$ (both polarized) $\rightarrow$ jet + X at $\sqrt{s} = 200$ GeV with a 0.2 pb^{-1} integrated luminosity [15]. The spectrum of pure power law shape is in agreement with NLO calculations (within the error bars).

As STAR, ALICE is a multipurpose heavy-ion experiment [17]. Its central barrel mainly equipped of a large TPC and a silicium inner tracking system covers a full azimuthal acceptance but is limited to the midrapididity region ($|\eta| < 0.9$). It has a large p_T coverage ($\sim$ 100 MeV/c to $\sim$ 100 GeV/c) with a $\delta p_T/p_T$ resolution of few percents (still below 6% at 100 GeV/c) [10]. The capabilities of ALICE to disentangle particles down to very low p_T, where strong modifications of the fragmentation function are expected, should lead to a very precise measurement of the number of particles inside a jet. More recently, the insertion of an electromagnetic calorimeter to collect part of the neutral information and to improve the trigger capabilities of ALICE has been accepted as an upgrade. The EMCal is a Pb-scintillator sampling EMC ($|\eta| < 0.7, 80^\circ < \phi < 190^\circ$) with a design energy resolution of $\Delta E/E = 11\%/\sqrt{E}$ and a radiation length of $\sim 20\ X_0$ [18]. It contains ~13k towers in Shashlik geometry with a quite high granularity ($\Delta\eta\times\Delta\phi = 0.014\times0.014$). The official ALICE jet finder is a UA1 based cone algorithm which has been modified in order to include the neutral information during the jet finding procedure.

2.2 Jet signal degradation and energy resolution in $p + p$ collisions

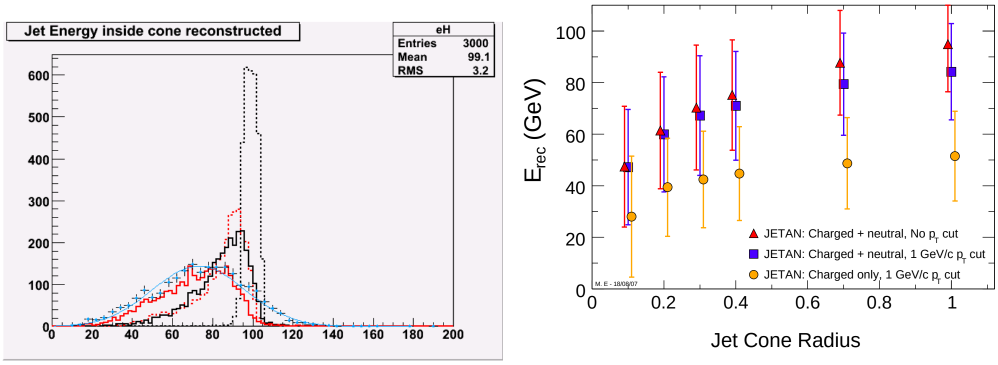

Fig. 1: Left: cone energy of 100 GeV jets reconstructed with PYCELL with $R = 1$ (dark dashed line), with the ALICE cone finder with detector inefficiencies and acceptance included in the simulation with $R = 1$ (red dashed), without detector effects but $R = 0.4$ (dark full), with both effects (red full). The markers shows the result from a full simulation. Right: cone energy of 100 ± 5 GeV fully simulated jets vs R for the three cases described in the text.

Jet reconstruction is highly influenced by the high multiplicity of an event and by the charged-to-neutral fluctuations for jets in which the neutral fraction (or part of it) can not be measured. Due to its detector configuration, ALICE will be able to reconstruct two types of jets. Using the charged particle momentum information, the production of *charged jets* will be studied. As the charged particle plus EMCal configuration is almost blind to neutrons and K_L^0, ALICE will also measure *charged+neutral jets* but will miss part of the neutral energy. In both cases and in elementary collisions, the charged-to-neutral fluctuations which dominate will give rise to a low energy tail in the reconstructed jet energy. Such effects should be enlarged by limited detector acceptance and inefficiency and analysis cuts which cause other types of fluctuations. To get a basic and qualitative understanding of the signal fluctuations for jets reconstructed in $p + p$ collisions at LHC, we have undertaken a fast simulation of 100 ± 5 GeV jets using PYTHIA as event generator for different cuts and detector configurations. Such features are illustrated in Fig. 1 (left) which shows the distribution of the jet energy reconstructed in a cone of radius R and compared with the result from a full detector simulation described below.

Jets were first reconstructed with a simple jet finder available in PYTHIA (PYCELL) with $R = 1$ using the momentum and energy information from charged and neutral particles (neutrons and K_L^0 excluded) (full black line). For the sample of simulated events which include detector acceptance cuts and reconstructed track inefficiency (not studied separately here), keeping R=1 for the jet reconstruction, one or several of the leading jet particles are not reconstructed and do not contribute to the cone energy. It leads to its broadening and a low energy tail (red dashed curve). The use of a limited cone radius during the jet finding procedure enhances collimated jets and also leads to a low energy tail of the cone energy distribution (black dashed line). The full red curve shows the combination of all the effects on the reconstructed jet energy keeping the jets which center falls inside the EMCal acceptance. The reconstructed energy results in an almost gaussian response function of resolution defined as $\Delta E/E = r.m.s./<E>$ of $\sim$ 33%. It can be improved selecting only the jets fully contained in the EMCal as discussed below.

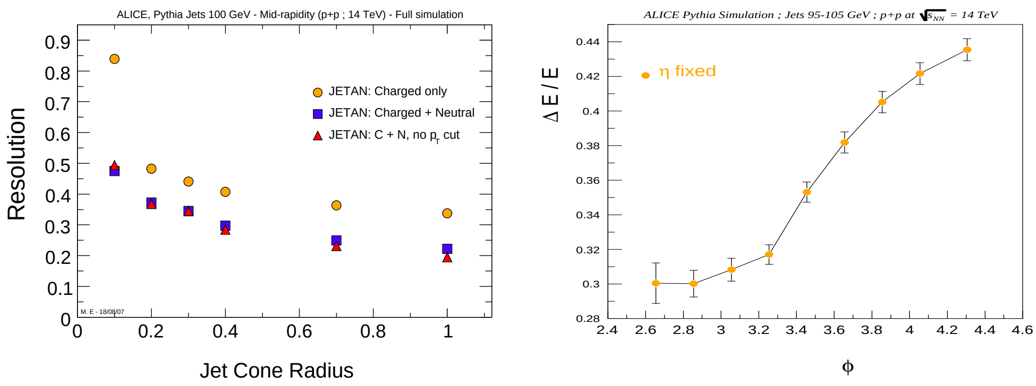

Fig. 2: Left: jet energy resolution of 100 GeV jets from a full ALICE simulation vs R for the three cases described in the text. Right: jet energy resolution as a function of the accepted ϕ window of the center of the jet reconstructed.

In the following, we present results obtained with a complete simulation and reconstruction chain using PYTHIA as event generator and GEANT3 for the detector responses for the generation of monoenergetic jets of $50, 75$ and 100 ± 5 GeV. The $\pm$5 GeV uncertainty on the simulated jet energy will be implicit below. Figure 1 (right) presents the cone energy reconstructed vs cone radius in three experimental conditions: with charged particles only and 1 GeV/c p_T cut on their momentum (circles), with charged plus EMCal configuration and 1 GeV/c p_T cut (squares) and with charged plus EMCal without p_T cut. The error bars are the r.m.s. of the energy distributions. Figure 2 (left) shows the same study but for the resolution. As already discussed, reconstructing jets from charged particles only enhances the number of jets with a larger than average charged particle fraction. Increasing R of course increases the mean reconstructed energy and improves the resolution but one reconstructs at best an energy below 50% of the input energy. These charged-to-neutral fluctuations lead to a resolution of $\sim 40\%$ for $R = 0.4$, improved to 30% by the inclusion of neutral particles in the jet finding procedure. For $R = 1$, in the case charged + neutral without p_T cut, the resolution is at best of 20% but part of the neutral information is lost as the jet is not fully collected within the calorimeter. The impact of the finite energy resolution on the full reconstructed jet spectrum will be quickly discussed in section 4.1.

The limited EMCal acceptance effect on the resolution of the reconstructed jet energy has been studied previously [19]. We have shown that as long as the jet center is taken inside the EMCal, even if part of its energy is outside it, the resolution is still close to 30%. As long as the center of the jet can be taken outside the EMCal acceptance, the resolution degrades and asymptotically reaches the charged particles only case in the full TPC acceptance (Fig. 2 (right)).

3 The underlying event in $A + A$ collisions

3.1 The background in $A + A$ collisions

Jet reconstruction in HI collisions is more complicated than in elementary systems as the UE dramatically changes. The reconstruction is dominated by the influence of the high multiplicity. A rough assessment of the energy of the UE inside R = 1 at RHIC based on $dE_T/d\eta = 660$ GeV at mid-rapidity [20] gives $E_{UE} = 1/(2\pi) \times \pi R^2 \times dE_T/d\eta \sim$ 330 GeV. A linear or logarithmic extrapolation of the charged particle rapidity density from the available data at FOPI, SPS and RHIC [20] allows to estimate an E_{UE} between 500 GeV and 1.5 TeV at LHC. In the extreme case, the UE is a 4-fold higher than at RHIC however the growth of the cross-section for hard processes is more dramatic. The substantial enhancement in the jet cross-section significantly improves the kinematics reached for jet measurement at LHC allowing the reconstruction of high-energy jets above the uncorrelated background on an event by event basis with good statistics.

Not only the multiplicity differs from $p{+}p$ collisions but the physics phenomena. First, the simple fact that the impact parameter varies event-by-event for a given centrality class implies some fluctuations in the UE ($\propto R^2$). All the well known correlations to the reaction plane and the azimuthal correlations between two and three particles at momenta below 10 GeV/c drag some structures inside what can be denoted as background for our jet studies. They are region-to-region fluctuations and are proportional to R. Moreover, the main sources of region-to-region fluctuations are the Poissonian fluctuations of uncorrelated particles also proportional to R. To optimize the jet identification efficiency, the signal energy has to be much larger than the background fluctuations ΔE_{bckg}. The energy of the UE and its fluctuations inside a given cone can be considerably reduced by simply reducing R in the jet finding procedure and applying a 1 or 2 GeV/c p_T cut on charged hadrons [10, 21]. However, they both imply some signal fluctuations whose effects have been discussed above. The jet finding procedure in a HI environment is thus essentially based on two steps. First, a p_T cut and a limited R are applied. Then, during the iteration procedure in the jet finding algorithm which has been optimized accordingly, the remaining energy of the UE outside the jet cone is estimated statistically or event by event and is subtracted from the energy of the jet inside its area at each iteration. Note that the use of a p_T cut is potentially dangerous for a quenching measurement [16] so that new background subtraction technics based on jet areas should be prefered and investigated to improve our measurement [22].

3.2 Understand the background fluctuations

The validity of our background subtraction procedure applied in the EMCal acceptance has been tested on three simulated data sets [23]. The full PYTHIA simulation of 100 GeV jets at $\sqrt{s} = 14$ TeV has been used to mimic $p{+}p$ collisions. Similarly, we processed full Minbias and Central HIJING simulations at $\sqrt{s_{NN}} = 5.5$ TeV to reproduce $Pb + Pb$ events at LHC in the EMCal acceptance in which we embed PYTHIA events to simulate the hard processes. The small change in the event multiplity between $p{+}p$ and $Pb{+}Pb$ Minbias collisions does not extensively increase the fluctuations in Minbias, unlike Central compared with Minbias where a factor of $4 - 5$ in the

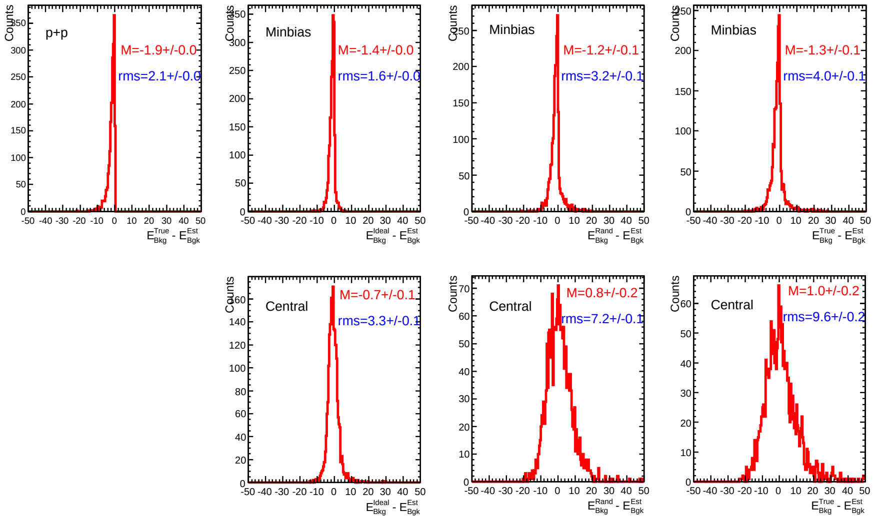

Fig. 3: $E^{X}_{bgk} - E^{Est}_{bgk}$ for $p+p$, $Pb+Pb$ Minbias and Central collisions obtained from a full ALICE simulation. E^{X}_{bgk} has been extracted in three X cases presented in the text.

multiplicity is expected to drive an increase of a factor of $2-2.2$ in the fluctuations.

The later assertion has been tested and part of the obtained results are presented in Fig. 3. We define the total fluctuations as $\Delta E_{Tot} = \Delta E_{Sig} + \Delta E_{Bkg}$ (1). One can estimate the variations of fluctuations between Minbias and Central knowing the $p+p$ case. $\Delta E_{Bkg} = E^{X}_{Bkg} - E^{Est}_{Bkg}$ has been estimated from three different methods X, using an (η, ϕ) grid filled with the HIJING particle information output where the background energy inside a cone of radius R is estimated by summing the energy (i) of all cells inside the grid and scaling the total energy to the jet cone size ($X = Ideal$) ; (ii) inside the cone taken randomly in the grid ($X = Rand$) ; (iii) inside the cone centered on the jet axis (beforehand found by the jet finder) ($X = True$). The distributions are presented in the 6 right pannels of Fig. 3 for the $Ideal$ (left), $Rand$ (center) and $True$ (right) cases respectively, and for Minbias (top) and Central (bottom) collisions. The same exercise has been applied on a grid only filled with $p+p$ events. The distribution of $\Delta E_{Bkg} = E^{True}_{Bkg} - E^{Est}_{Bkg}$ is presented in the most left hand panel. The mean value obtained for the distributions of Minbias data are systematically negative. Clearly the jet algorithm over-estimates the background compared with the three cases due to out-of-cone signal fluctuations which does dominate as emphasized in the $p+p$ case. Going from the $Ideal$ to the $True$ case, the region-to-region fluctuation effects increase the r.m.s. These fluctuations are less pronounced in the $Ideal$ case which gives a mean value of the background event by event. From Minbias to Central data, a factor of $2-2.2$ in the r.m.s. is observed, as expected, validating our background subtraction method. In Central, the fluctuations are thus dominated by the event multiplicity. It is indeed observed in the mean values which become positive with a large positive tail from the $Ideal$ to the $True$ cases. In Central data, the background is thus under-estimated by the jet algorithm so that the final cone energy is over-estimated.

3.3 Expected performances in $Pb + Pb$ collisions at LHC

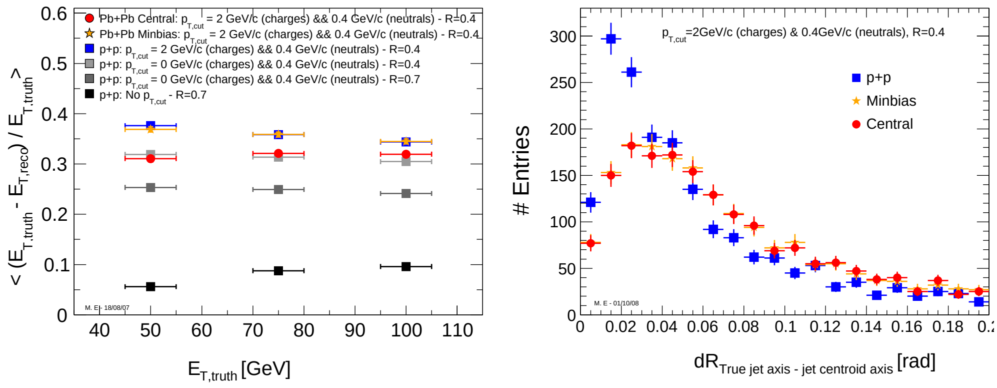

Fig. 4: Left: jet reconstruction efficiency as a function of $E_{T,truth}$ for the cases quoted in the top left legend of the figure. Right: distance in η-ϕ space between the directions of the reconstructed jet axis and the true one in $p + p$ (squares), $Pb + Pb$ Minbias (stars) and $Pb + Pb$ Central (circles) collisions.

Figure 4 (left) presents what is defined as the "jet reconstruction efficiency" ($(E_{T,truth} - E_{T,reco})/E_{T,truth} = 1 - Efficiency$) as a function of the input jet energy, $E_{T,truth}$, for the 3 input jet energies $50, 75$ and 100 ± 5 GeV. The Minbias and Central $Pb+Pb$ cases are compared with the $p+p$ one for which a systematic study of the analysis cuts has also been performed. Jets have been reconstructed using the ALICE UA1 cone finder including both charged and neutral particles. The efficiency obtained without p_T cut and $R = 0.7$ (black squares) smoothly increases when the input jet energy increases and reaches 10% for 100 GeV jets. It is enhanced by a factor of 3 to 5 after the application of a p_T cut of 0.4 GeV/c on neutral particles (dark grey squares). The reduction of R to 0.4 (light grey squares) increases the efficiency (which becomes flat vs $E_{T,truth}$) to $\sim 30\%$ as less input jet energy is reconstructed. The efficiency worsens moreover when a p_T cut on the charged particles is applied (blue squares) as part of the signal is again cut. In these cases the reconstructed energy is under-estimated by the algorithm and the out-of-cone fluctuations from the signal dominate. As expected in Fig. 3, no significant discrepancies between $p + p$ and $Pb + Pb$ Minbias data samples (stars) are observed whereas the efficiency in Central (circles) is improved because the background subtraction procedure over-estimates the cone energy and the background fluctuations dominate. In Minbias, both effects compensate.

In order to understand how the fluctuations affect the jet reconstruction, the distributions of the reconstructed jet axis minus the input jet axis have been studied in the 6 previous cases. Both the p_T and radius cuts on $p + p$ data affects a bit the jet reconstructed axis but the effect is small. Figure 4 shows the distributions for the Minbias and Central cases compared with the $p+p$ one. It clearly shows that the reconstructed jet axis in both cases is biased. Using a small radius, the jet algorithm maximizes the energy by shifting the jet (centroid) axis. In the different systems studied, the evolution of the expected jet energy and angular resolutions versus $E_{T,truth}$ and the system multiplicity are presented in Fig. 5 (left) and (right). The jets have been reconstructed using a p_T cut of 1 GeV/c and $R = 0.4$. All the jets which centers lied inside the EMCal accep-

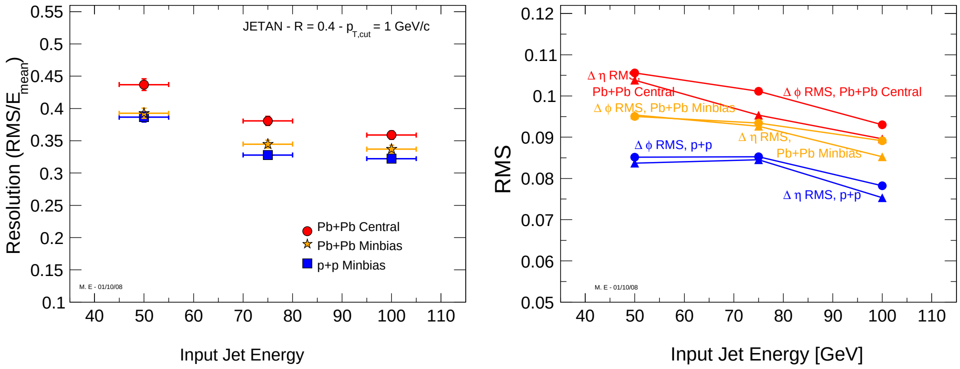

Fig. 5: Left: jet energy resolution versus the input jet energy of $50, 75$ and 100 ± 5 GeV for $p+p$ (squares), $Pb+Pb$ Minbias (stars) and $Pb+Pb$ Central (cirles) collisions. Right: resolutions in η and ϕ of the jet direction.

tance were considered. The reconstructed energy resolution worsens from 100 GeV to 50 GeV jets in the 3 systems. Contrary to the jet reconstruction efficiency, the energy resolution degrades as expected from $p+p$ to $Pb+Pb$ Central because of background fluctuations. For 100 GeV jets, we obtain an energy resolution in $p+p$ of $\Delta E_{p+p} \sim 32.5\%$. The Minbias one allows to estimate the Central one to $\Delta E_{Cent} \sim 35.8\%$ using equation (1) in agreement with the resolution of 36.4% obtained in Fig. 5 (left) validating our background subtraction method. Figure 5 (right) presents the r.m.s. of the distributions $\Delta\eta = \eta_{truth} - \eta_{reco}$ (triangle) and $\Delta\phi = \phi_{truth} - \phi_{reco}$ (circle). An accurate reconstruction of the jet direction in the three systems is obtained though it is slightly deteriorated from p+p to Minbias and Central. Indeed, the dominating background fluctuations maximize the jet energy by shifting its reconstructed direction as observed in Fig. 5.

4 Full jet spectrum and fragmentation function

4.1 A smeared jet spectrum

The results presented so far do not take into account the jet cross section distribution as $1/p_T^{\alpha}$ with $\alpha \sim 5.7$ and beyond at LHC. We note that within a 1σ fluctuation of the energy the jet production cross section varies by almost twofold [10]. Therefore, it is essential to take into account the production spectrum to truly evaluate the meaningful jet energy resolution and reconstruction efficiency. In particular, jets in the low energy tail of the resolution function are buried below lower energetic jets with much higher production cross section and, hence, the amount of jets in these tails is a measure of the reconstruction inefficiency.

In order to extract the jet production spectrum, 12 bins of p_{T-hard} from 40 to 220 GeV have been simulated with PYTHIA 6.2 CDF Tune A in the 2→2 processes. The simulated data have then been treated in the full detector chain of GEANT3 before reconstruction using the official ALICE jet finder including calorimetry. The same simulation including a heavy ion background using the HIJING generator has been produced. The mean reconstructed jet energy has then been corrected, on the average, looking at the ratio of the reconstructed over generated jets as a function of the reconstructed jet energy. This correction does not take into account the smearing of the spectrum which is amplified from $p+p$ to $Pb+Pb$ collisions. Indeed, in a heavy ion UE and due to the steeply falling shape of the input spectrum, even more contributions at low p_T populate the higher energetical part of the reconstruted jet spectrum increasing its smearing. This of course will have to be taken into account in a meaningful comparison of the $N+N$ and $A+A$ data. In the present paper, an average correction has been applied on the jet reconstructed energy so that the results presented below on the HBP are still biased by the smearing effect.

4.2 Background and quenching effects on the fragmentation function

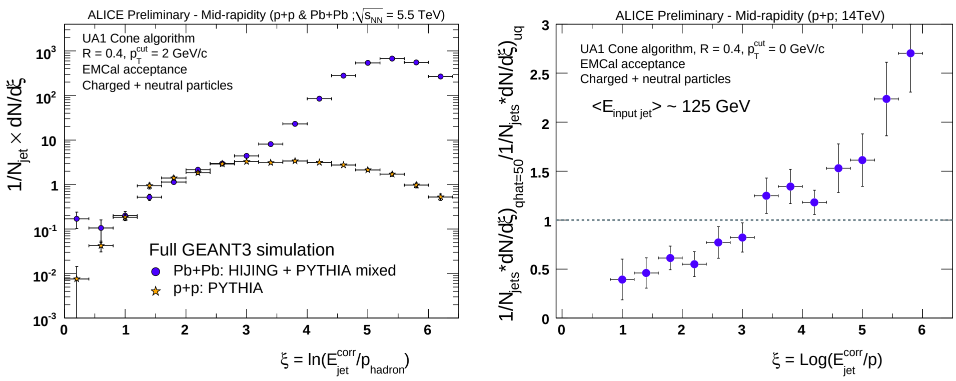

Fig. 6: Left: Hump-backed plateau in $p+p$ (stars) and $Pb+Pb$ collisions not background subtracted (circles) as a function of ξ at $\sqrt{s_{NN}} = 5.5$ TeV. Right: ratio of the HBP obtained in a $p+p$ quenched scenario over a non quenched one vs ξ in $p+p$ collisions at $\sqrt{s_{NN}} = 14$ TeV.

Radiation phenomena in QCD and how they are modified in a dense medium should be accurately probed by understanding how the energy is distributed inside jets. Therefore, it strongly motivates the study of the distribution of hadrons inside jets: the HBP. Moreover, it offers a particular window of study on the hadronisation phenomenon badly understood today. It is important to understand the effects of the heavy ion UE on its extraction. The domain of interest of such distribution is for the ξ region dominated by the production of soft particles which come from the gluon radiation emission in a quenching scenario. For jets of energy $70-100$ GeV, this region turns out to be for a ξ above ~ 3. Figure 6 (left) presents the modified fragmentation function $1/N_{jet} \times dN/d\xi$ as a function of $\xi = ln(E_{jet}^{Corr}/p_{hadron})$ in $p+p$ and $Pb+Pb$ collisions at $\sqrt{s_{NN}} = 5.5$ TeV. The full jet spectra have been considered here. In a first step, no quenching scenario has been included in these simulations in order to understand how the soft background of the UE by itself modifies the expected fragmentation function. As seen in Fig. 6, the soft emission drastically twists (more than 2 orders of magnitude) the HBP, increasing the number of entries in the high ξ region giving rise to a distortion of the distribution. In order to go a step further in the comparison of $p+p$ and $Pb+Pb$ HBP, the data have to be background subtracted. Despite a good background subtraction, the data for $\xi > 5$ will not be exploitable anymore as dominated by too large error bars. This background subtraction procedure and the results associated are not presented here.

Instead, we have chosen to show the ratio of two HBP obtained in $p+p$ collisions at $\sqrt{s} = 14$ TeV with and without quenching scenario to show the sensitivity one should expect vs ξ. For such a distribution we assume a perfect background subtraction procedure. Without specific trigger bias in the data selection and for jets of 125 GeV, one obtains a ratio which increases with ξ increasing with a value below one for a $\xi \sim 3$ and above one after. Both amplitudes below and above this ξ limit, as well as the exact ξ position of a ratio equals to unity should allow us to quantify the strengh of the quenching scenario.

5 Conclusion

Technical aspects for jet reconstruction in $p+p$ and $A+A$ collisions have been discussed. More specifically, the expected performance for jet physics studies in ALICE have been presented. The observation of some modifications of the jet structure in $Pb+Pb$ collisions at LHC will be possible for ξ up to ~ 5 where we expect to see a clear distortion of the HBP due to the soft emission generated by gluon radiation over the soft background of the UE.

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