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Jet physics in ALICE with a proposed electromagnetic calorimeter

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Abstract. The high P_T capabilities of the ALICE experiment provided by an additional electromagnetic calorimeter are discussed in light of recent results from RHIC.

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1 Introduction

1.1 From RHIC to heavy ion collisions at the LHC

In 2007, the Large Hadron Collider (LHC) at CERN will be the highest energy accelerator operating on Earth. Its approved experimental program includes a strong heavy-ion collision component, with one dedicated heavy-ion experiment, ALICE [1], and an additional heavy-ion program in CMS [2]. Data from heavy-ion collisions at the unprecedented high LHC energies (5.5 TeV/A in Pb-Pb) will thus begin to significantly extend the Relativistic Heavy Ion Collider (RHIC) scientific program shortly after 2007. The ALICE-USA collaboration is a group of 14 U.S. institutions presently seeking support to join the ALICE collaboration and provide a significant patch of electromagnetic calorimetry to complement and extend the ALICE high P_T program. In this brief introduction, we will enumerate some of the expected features of PbPb collisions at the LHC compared to AuAu collisions at RHIC with particular emphasis on the applicability of high P_T probes as a diagnostic tool of the produced matter and give a very short discussion of our reasoning behind the choice of ALICE as the base of this proposed program.

The center of mass energy for collisions of the heaviest ions at the LHC will exceed that available at RHIC by a factor of about 30. This opens up an entirely new physics domain with exciting opportunities. Whereas the CERN SPS heavy ion program has clearly produced excited, strongly-interacting matter near the conditions for quark deconfinement [3], the heavy-ion experimental programs at RHIC and the LHC are designed to investigate the quark-gluon plasma in full detail. RHIC is the first machine that allows deep penetration into this new phase, creating a quark-gluon plasma which is sufficiently long-lived to make it accessible to a variety of specific experimental studies. A comprehensive experimental program is now underway at RHIC which foresees a broad range of systematic studies in the years to come including future upgrades to both the machine and the detectors.

Heavy-ion collisions at the even higher LHC energy, on the other hand, will explore regions of energy and particle density which are significantly beyond those available at RHIC. At LHC energies, the bulk of particle production will be dominated by collisions between very low-x virtual gluons in the incoming nuclei. The phase-space density of these low momentum gluons is expected to be saturated and gluon merging becomes important [4,5]. As a result, the effective gluon density is sharply reduced in LHC collisions, limiting in a self-consistent way the growth of the production cross section for low-P_T minijets. This qualitatively new regime of "gluon saturation" at low x and large A is presently being discussed in the context of RHIC data, but it is only expected to become centrally important to heavy ion collisions at the LHC.

In Pb+Pb collisions at the LHC, the P_T scale at which gluon saturation sets in is estimated to be around 2 GeV/c [6]. At this scale, perturbative QCD is likely to be applicable. Thus, for the first time the bulk of transverse energy and particle production as well as the initial conditions for the subsequent expansion of the hot matter formed in the reaction zone may be reliably calculated within QCD.

The energy density of the thermalized matter created at the LHC has been estimated to be 20 times higher than can be reached at RHIC, implying an initial temperature T_0 which is greater by more than a factor of 2 [7]. Due to the higher initial parton density, thermalization also occurs more rapidly, and the ratio of the quark-gluon

plasma lifetime (i.e. the time until the first hadrons begin to form) to the thermalization time accordingly in-

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creases by a factor 10. As a result, the fireballs created in heavy-ion collisions at the LHC spend nearly their entire lifetime in a purely partonic state, widening the time window available for study of the evolving quark-gluon plasma state.

A wide array of "probes" of the high density, high temperature medium produced in relativistic heavy ion collisions are presently in use at RHIC and envisioned for the LHC. In the present discussion, we will focus exclusively on the so called "hard probes" produced in high Q^2 processes. At RHIC, these high Q^2 processes in AuAu collisions include jets, or rather jet-like correlations and high P_T hadrons, charm quark and charm quarkonia production. A very much wider range of these so called 'hard probes" [8], e.g. high-P_T jets or photons, heavy quarks (b,c), quarkonia (Ψ and Υ families) and $W^{\pm}$ or Z^0 bosons will be abundantly produced in heavy ion collisions at the LHC. At the high collision energies provided by the LHC, the cross sections for very high $Q^2 > 50$ - $100\,\mathrm{GeV}^2$ processes are large enough to comfortably allow detailed experimental studies. The motivation for studying these channels at the LHC is the same as at RHIC: hard probes are created rapidly, at very early times, $\tau_{\mathrm{hard}} \sim 1/Q \leq 0.01\,\mathrm{fm}/c$, and their production can be calculated perturbatively once the nuclear structure functions are known. This time is early enough to probe the expected classical, strong field, chromodynamic stage of the collision. The bulk of the secondary matter materializes promptly and only somewhat later, at $\tau_0 \sim 1/T_0 \sim 0.2\,\mathrm{fm}/c$. The hard probes are thus embedded in this secondary matter and explore its properties by scattering and interactions on their way out. Direct evidence for this picture of hard probe scattering and interactions with the medium has already emerged from RHIC experiments [9,10]. Indeed, some of the most striking manifestations of the possible quark-gluon plasma medium effects to emerge from early RHIC measurements are found in the high-P_T sector [11]. This has led us to explore the high-P_T capabilities of the ALICE experiment and, in particular, to examine the additional capabilities that might be realized through the addition of a significant patch of electromagnetic calorimetry.

An illustration of the applicability of hard probe measurements at RHIC, is shown in Fig. 1.

This figure shows the jet-like correlations in azimuthal angle between high-P_T hadrons observed in central STAR [12] AuAu events at RHIC full energy $\sqrt{s_{NN}} = 200$ GeV compared to those seen in p+p and d+Au at the same energy. The plotted correlation is

$$D(\Delta\Phi) = \frac{1}{\epsilon N_{trig}} \frac{dN}{d\Delta\Phi}$$

where N_{trig} is the number of so called trigger particles with $4 < P_T(trig) < 6GeV/c$. The distribution shows the $\Delta\phi$-correlation between the trigger particle and all associated particles with $2 < P_T(associated) < P_T(\mathrm{trig})$. The factor ϵ is the tracking efficiency of the associated particles. Both the near and the away-side jet-like correlation of these selected high P_T hadrons is evident in the pp and dAu data but the associated hadrons of the away-side jet are absent within the precision of errors in central AuAu.

The disappearance of particles associated with the away-side jet sets in gradually with the centrality of the collision as shown in Fig. 2. The plotted quantity,

$I_{AA}(\Delta\phi_1, \Delta\phi_2)$,

is the ratio of the ϕ-integral for Au+Au of either the near-side or away-side correlation peaks, corrected for flow [13] to the same quantity for p+p. The quantities $\Delta\phi_1$ and $\Delta\phi_2$ are the limits of the ϕ-integration appropriate to the near-side and away-side correlation peaks.

Figure 2 shows that both near-side and away-side correlation peaks have approximately the same intensity for peripheral AuAu albeit slightly suppressed ($I_{AA} \approx 0.65$) compared to pp. A similar suppression compared to pp is apparent in the dAu data in Fig. 1 which signals this as a consequence of the presence of cold nuclear matter. As central collisions are approached for increasing N_{part}, the away-side peak is gradually fully quenched while the near-side correlation peak actually grows in intensity. This growth of the multiplicity of associated particles in the near-side peak is stronger for the presumably softer class of jets selected by the lower P_T (trig) selection in the right hand panel exceeding $I_{AA} \approx 1.5$.

The observation of jet-like correlations in AuAu collisions strongly suggests that the trigger particles used in the present analysis statistically select jets imbedded in the AuAu event. Indeed, further support for this conclusion comes from studies of charge sign correlations for the pp, dAu and AuAu data. The observed strength [14] of same sign versus opposite sign hadrons, within the near-side peak, in all of these systems shows the preference for opposite sign high P_T hadrons at a rate which is consistent with the dynamical charge correlations known to originate in jets from the formation of quark-antiquark pairs along the string formed by the primordial jet partons. Given the weight of evidence, therefore, the disappearance of away-side jet-like correlations in central AuAu collisions is all the more interesting.

Two extreme scenarios have been considered to account for jet suppression in RHIC data. In these, either entrance channel effects or final state effects due to the medium produced in AuAu collisions account for the disappearance of away-side jets and the suppression of inclusive high P_T hadrons in central AuAu. In the latter picture, in the final state following the hard scattering, energetic partons traversing the dense medium in the core of the collision lose the majority of their energy, and the observed jet fragments are primarily those created from partons produced near the surface and directed outwards [14]. This picture of strong partonic energy loss which has long been discussed as an essential signature of the quark-gluon plasma [15,16] has more recently evolved into a quantitative picture in which the observed parton energy loss directly measures the opacity of the medium, i.e. the hard scattering cross section times the medium's gluonic density integrated along the parton's trajectory [17,18].

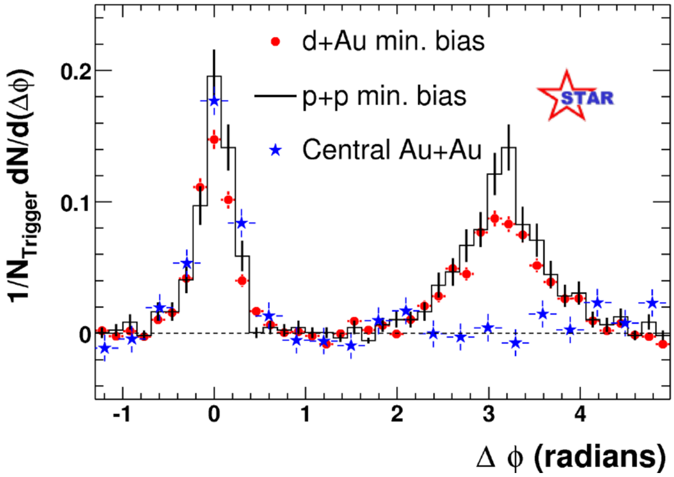

Fig. 1. Comparison of two particle azimuthal distributions for *central* d+Au collisions with those seen in p+p and Au+Au. Particles with $4 < P_T(trig) < 6GeV/c$ are correlated with all associated particles with $2 < P_T(\text{associated}) < P_T(trig)$

Alternatively, the suppression of away-side jets might result from initial-state effects prior to the hard scattering, such as the saturation of gluon densities in the incoming nuclei [19]. The present experimental situation, however, based on measurements by all four RHIC experiments, strongly favors a picture in which partonic energy loss in a dense, presumably colored medium produced in the AuAu collisions strongly suppress inclusive high P_T hadrons and quenches the energy of the away-side jets to levels undetectable in present measurements in the high multiplicity underlying AuAu event [11].

Further studies of this jet quenching phenomena and related measurements will continue at RHIC in coming runs. Clearly, attempts will be made to, among other things, quantify high P_T parton quenching as a diagnostic probe of the produced matter. In particular, it will be vital to extend the range of parton-P_T studied in these measurements using calorimetrically triggered high-P_T events to search for the eventual reemergence of the away side jet at sufficiently high P_T. In principal, this reemergence would allow a measurement of the total energy lost to the medium if it were possible to reconstruct the energy of both the near-side and away-side jet. Unfortunately, even simple estimates show that only the highest P_T jets can be reconstructed in central AuAu collisions at RHIC and only then with very poor resolution dominated by the soft background event. Other options to quantitatively characterize the energy loss at RHIC, such as the direct photon tagged γ + leading particle channel are probably multiyear measurements that will put very serious demand on integrated luminosity at RHIC.

At RHIC, two large experiments, STAR and PHENIX, and two small experiments, PHOBOS and BRAHMS, provide quite complete coverage of the available phase space with a full array of experimental tools [20]. ALICE, at the LHC, is the comprehensive heavy ion experiment integrating most of the capability of all four RHIC experiments with an array of experimental tools ideally suited to explore the properties of this long lived quark-gluon plasma state produced at the LHC [1,21]. The preceding discussion has focused on the importance of high P_T probes in the arsenal of experimental tools that has emerged from RHIC data. It might be wondered, therefore, why our attention is not drawn toward one of the other two large LHC experiments each of which feature hermetic calorimeter coverage specifically designed for high P_T measurements and each of which plans to participate in heavy ion running at some level. There are two parts to the answer, first, as we will discuss in following sections, calorimetry alone is less effective than might at first be expected in the very high multiplicity environment of LHC PbPb collisions. Second, while hard processes and their associated medium modifications will form an important part of the core program, the full array of soft physics measurements might be essential not only for a complete picture of the produced state of matter but also for any quantitative analysis of hard probes whose modifications after all will depend on the properties of the surrounding and soft bulk matter. The extreme assumption that the soft physics at the LHC will be consistent with a smooth extrapolation from the SPS and RHIC energies, while the hard physics alone will present a completely new domain misses an important connection. The system created in heavy-ion collisions undergoes a fast dynamical evolution from the extreme initial conditions to the diluted final hadronic state. The understanding of this rapidly evolving system requires a full complement of experimental input including *both* the soft and hard physics observables. The challenge of the longstanding objective of heavy-ion physics to explore the phase diagram of strongly interacting matter, to study the QCD phase transition and the physics of the Quark-Gluon Plasma state, will culminate with the heavy-ion programs at the LHC and it is of fundamental importance that we make the most complete and quantitative study possible.

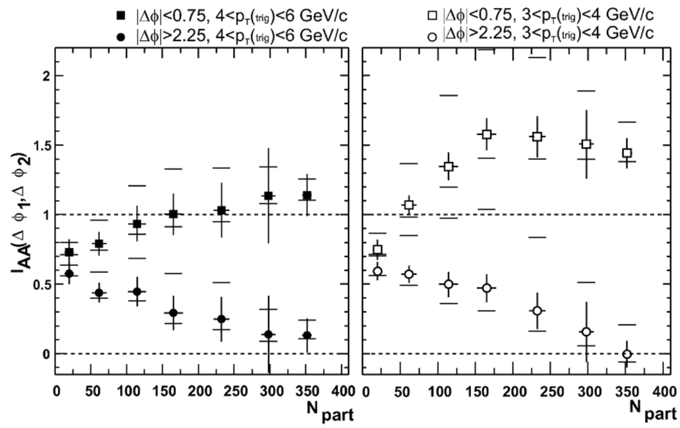

Fig. 2. Ratio of Au+Au to p+p correlation intensities for the near-side, $|\Delta\phi| < 0.75$, and away-side peaks, $|\Delta\phi| > 2.24$ radians, versus centrality as the number of participating nucleons,N_{part}. The *left* and *right* hand panels show data for $4 < P_T$ (trig)$< 6GeV/c$ and $3 < P_T$ (trig)$< 4GeV/c$ respectively

2 Jet physics with the ALICE detector at the LHC

The preceding discussion has outlined our interest in jet physics in heavy ion collisions at the LHC as providing a potentially unique opportunity to study the QCD radiation length of colored matter. In qualitative terms, beams of hard scattered partons will be used as a tomographic probe of the produced matter. These tomographic images of the QGP can be compared with pp or peripheral heavy ion measurements. In the following two sections, we will discuss the potential for such measurements in ALICE from a low P_T range that fully overlaps with ongoing measurements at RHIC, into the high P_T regime, inaccessible to RHIC, where jets can be fully reconstructed at the LHC.

2.1 Leading particles and inclusive jets in PbPb collisions at Low P_T

We begin our discussion of jet physics in ALICE in the low P_T end of the spectrum in PbPb collisions. In this P_T range, $2-30$ GeV/c, where the jet cross sections at RHIC energy are large, we have the some overlap with ongoing and future RHIC measurements. In this P_T range, however, the complexity of central heavy ion collision limits the experimental observables since jets cannot be reconstructed as distinct objects, neither at RHIC, nor the LHC. In ALICE as in STAR and PHENIX we are limited to discerning the physics of jet quenching from intermediate to high P_T inclusive spectra and angle or energy correlation studies both event-by-event and inclusively. Clearly these restrictions limit what can be unambiguously learned about jet quenching (for example no primary parton P_T can be deduced) but they provide the opportunity to complement and extend RHIC measurements to the higher temperature, denser QGP produced at LHC energies. Indeed, such measurements may provide the best means to directly compare the matter produced at RHIC with that produced at the LHC.

The physics issues in this low P_T regime, common to the LHC and RHIC, may be distinctly different from the higher P_T regime which is uniquely accessible at the LHC. For example, at lower P_T and at RHIC, parton energy loss may dominate parton propagation and complete jet absorption may be possible. At sufficiently higher P_T accessible at the LHC, this is unlikely and quenching is expected to become relativly insignificant at sufficiently high P_T. Potentially, therefore, the experimental manifestations of jet quenching may evolve considerably over the P_T range accessible at the LHC.

The physics of low P_T jets and jet quenching is unique to the ALICE experiment at the LHC. These measurements require the full power of the TPC [22] and related tracking elements along with the EMCal and the full suite of the ALICE particle identification tools to fully diagnose the correlations discussed in the following. These measurements are an essential part of our program to fully characterize parton propagation in dense colored matter over the widest possible energy range and quantify the changes in that matter from RHIC to the LHC.

It is expected and supported by RHIC measurements that in-medium modifications of the jet structure will be much stronger for low jet energies. We want to study changes of the particle momenta in these jets both parallel to the jet axis (jet quenching) and in the transverse direction (transverse heating). The challenge discussed in the following sections is to identify this physics in an environment where the individual jets can not be reconstructed.

2.1.1 Inclusive jets at low P_T

In proton-antiproton collisions in CDF at 1.8 TeV [23], evidence for low energy charged particle jet-like clusters has been seen. These charged particle jets become apparent, event by event, at a charged jet energy as low as 2 GeV with, on the average, two charged particles with $P_T > 0.5$ GeV and grow to, on the average, about 10 charged particles at a charged jet energy of 50 GeV.

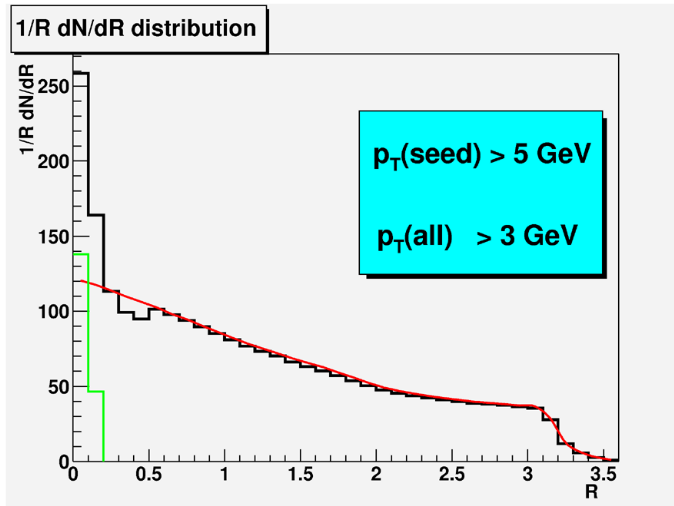

Fig. 3. $(2\pi R)^{-1}\frac{dN}{dR}$ distribution for HIJING events using the algorithm described in the text with P_{T}^{seed}= 5 GeV/c and $p_T^{all} > 3$ GeV/c. The *solid red curve* results when the leading particle direction is randomized. If this background correlation is subtracted, the minijet signal, shown in green is obtained

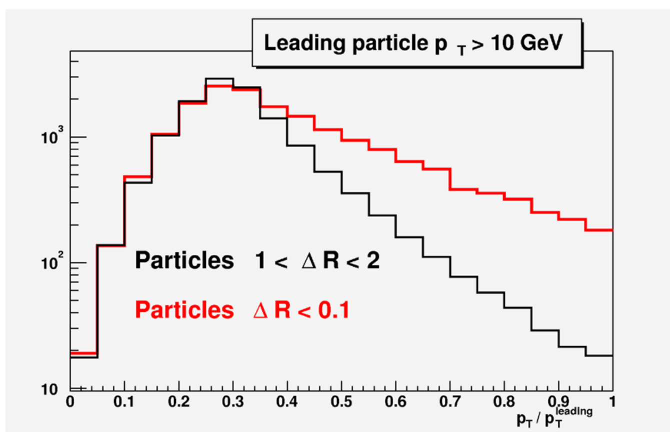

Fig. 4. "Fragmentation function" of correlated particles compared to the uncorrelated background in central PbPb HIJING events

Similar observations apply to STAR pp measurements at $\sqrt{s_{NN}} = 200\text{GeV}$ [24].

In central PbPb collisions at $\sqrt{s_{NN}} = 5.5\text{TeV}$ with a maximum anticipated rapidity density of up to 8000 charged particles per unit of rapidity, the situation will be changed significantly. It is expected, for example, that in one central PbPb collision about 100 jets with $P_T > 5$ GeV/c are produced within the acceptance of the ALICE central tracking system. The jet multiplicity decreases to an average of one per event, for $P_T > 20$ GeV/c. The individual structures of these low-P_T jets, at least at the lowest end of the scale, must dissolve into the overall event structure and are not distinguishable event by event. Nevertheless, their properties can be studied on a statistical basis, as at RHIC, using inclusive single particle spectra and multi-particle correlation given a tracking system with high, uniform tracking efficiency at low P_T as will be shown in the following Sect. [25].

2.1.2 Correlations with leading particles in ALICE

In order to study correlations with leading particles we apply an algorithm similar to the one used for the CDF and STAR charged jet analyses. Central PbPb collisions are simulated with HIJING including minijet production and analyzed using the ALICE TPC tracking parameters. All particles with a $P_T > P_{\mathrm{T}}^{seed}$are leading particle candidates P_i and are ordered according to their P_T. We start with the highest P_T candidate P_0 and record the distances R in the $\eta - \phi$ plane between all particles and P_0. If another, P_i, is found within a distance R $< R_{sep}$ it is eliminated from the list of candidates. The procedure continues with the next candidates until no candidate is left.

This algorithm is a natural extension of the cone algorithm to inclusive studies in the low-P_T jet region for heavy ions collisions. To see possible angular correlations, we plot the particle density $(2\pi R)^{-1}\frac{dN}{dR}$ as a function of R.

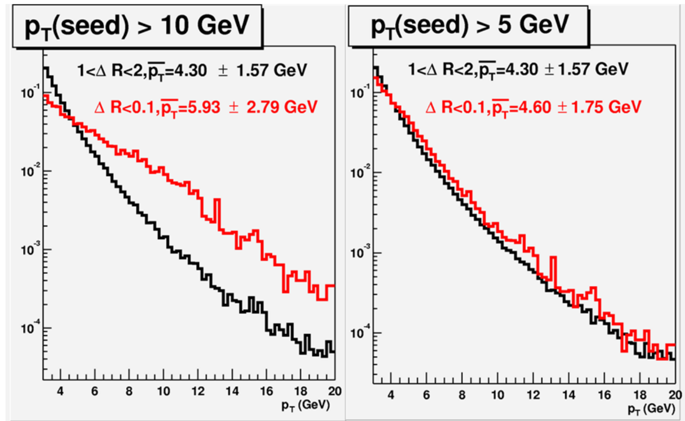

Fig. 5. P_T spectrum of correlated particles selected with P_{T}^{seed}= 10 (*left panel*) and 5 GeV/c (*right panel*). The uncorrelated background is indicated

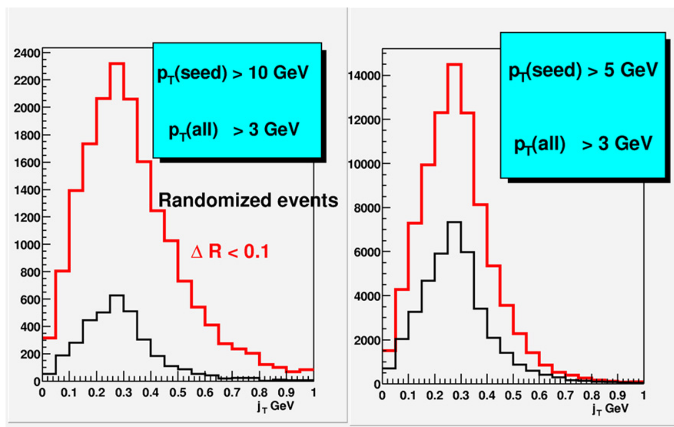

Fig. 6. Distributions of the transverse momentum of correlated particles with respect to the direction of the leading particle for seed momenta of 5 GeV/c (*left panel*) and 10 GeV/c (*right panel*). The corresponding background distribution from uncorrelated particles is also shown

Figure 3 shows such distributions for P_{T}^{seed}= 5 GeV/c with a cut on all other particles of $P_T^{all} > 3$ GeV/c. The solid red line is the corresponding distributions for randomized leading particle directions. A clear near-side correlation signal from the minijets present in the HIJING [26] calculation is visible for R<0.3

2.1.3 Fragmentation function and longitudinal momentum distributions

The distributions of the correlated particle transverse momentum normalized by the leading particle transverse momentum, $z = P_T/P_T^{leading}$, is an estimator of the jet fragmentation function. In Fig. 4 we show this distribution for particles with $R < 0.1$ in the near-side correlation. The background distribution obtained from uncorrelated particles in a guard band $1 < R < 2$ is shown as a solid black line. The signal dominates by a large factor at high z values.

The "fragmentation function" of correlated particles suffers from the fact that $P_T^{leading}$is only a rather poor estimator of the jet energy and the measured distribution can be seen as a smeared out fragmentation function. Nevertheless, since in-medium modifications of the fragmentation function are expected to be very strong for low energy jets, we expect that the quenching effect can be easily observed in the measured distribution for example by comparing central versus peripheral PbPb.

Alternatively, we may measure the associated raw P_T distributions for particles within the near-side correlation peak. These are shown in Fig. 5 for jets selected with P_{T}^{seed}= 5 and 10 GeV/c. Here it is apparent that there is substantial signal due to minijets in HIJING above the uncorrelated background. Results from STAR have suggested that the multiplicity of associated particles in very low energy jets, such as those selected here, grows with increasing centrality with the effect being stronger for lower P_T trigger particles. This suggests that P_T sensitive measurements of the type shown in Fig. 5 should exhibit very striking evolution with centrality and trigger particle P_T.

Finally, it is also of considerable interest to be able to explore the distributions of the correlated particle momentum perpendicular to the jet axis, J_T. The average particle momentum in a jet transverse to the jet axis has

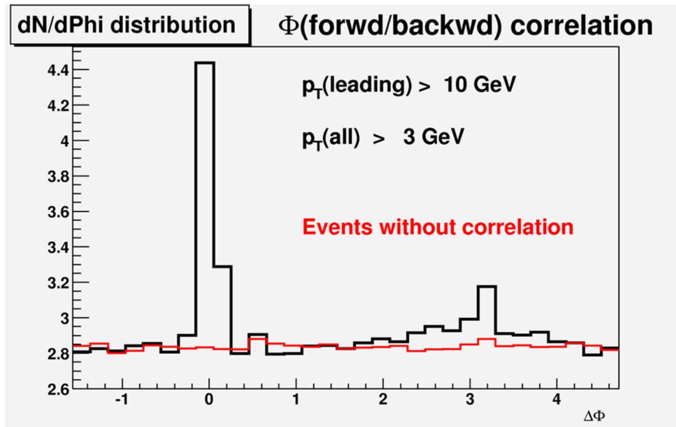

Fig. 7. Simulated ϕ correlations in the ALICE TPC for HIJING central events at LHC. Compare with the STAR results for ϕ correlations observed at RHIC showing very strong quenching of the away side jet in central collisions

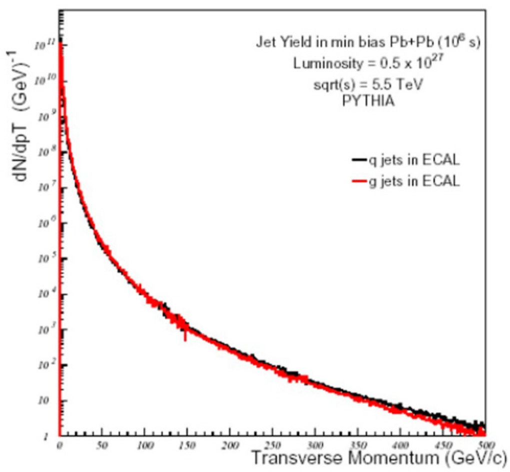

Fig. 8. Estimated inclusive jet events per GeV P_T bin per ALICE run ($10^6 s = 1.7 weeks$) at 75% efficiency for minimum bias Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$TeV . Calculations are based on PYTHIA using a k factor of 1 and CTEQ2M parton distributions without nuclear or medium modifications. The *horizontal axis* is the single jet E_T

been measured in numerous collider experiments and is relatively insensitive to the collision energy from ISR to RHIC. In the case of the associated particle correlations in PbPb presently under discussion, we take the direction of the leading particle as an estimator of the jet direction and define $J_T = p * sin(\theta_{particle}, \theta_{leadingparticle})$ for each associated particle. The resulting distributions are shown in Fig. 6. The background shown as a black line is obtained using randomized jet-directions. The signal and background have a similar shape distribution in this case. This is to be compared to the results of the previous section, where we saw that the signal has a much harder P_T spectrum compared to the uncorrelated background. Ordering of P_T in the normal jet fragmentation process in vacuum (as in the present simulations)leads to limited J_T with mean value of about $< J_T > \approx 250 - 300$ MeV/c. In this way, higher P_T particles are, on the average, therefore, closer to the jet axis.

The rather low $< J_T >$ seen here is a basic property of parton fragmentation in vacuum. Jet quenching itself, which proceeds mainly through gluon radiation, is therefore not expected to produce a significantly different J_T distribution. Post radiation processes, however, which are potentially possible as the fragmentation process proceeds inside the dense matter, may broaden the J_T distribution through an effective thermalization or partial thermalization of the of J_T distribution. It is clear that $< J_T >$ distributions may exhibit significant centrality dependence and correlation with the event plane, particularly for lower jet P_T.

2.1.4 Forward-backward correlations at low P_T in ALICE

The away side component associated with low P_T jets observed through forward- backward ϕ correlations are considerably more difficult to detect at the LHC than at RHIC. This follows from both the higher background multiplicity and from the potential for larger rapidity gaps between jets at LHC energy which correspondingly broadens the η correlation. More statistics or harder cuts are needed than for the R-correlation discussed above. In Fig. 7 we show the $\Delta\phi$ distribution for particles with $3\ GeV/c < p_T^{associated} < p_T^{leading}$ with respect to leading particles with $p_T^{leading} > 10\ GeV/c$ in HIJING events.

These results should be compared to STAR results in Fig. 1. Of course, the combinatoric background of uncorrelated particles has been subtracted in the STAR results but it has been left in Fig. 7 to better illustrate the raw signal to background ratio. In STAR, as discussed above, this analysis has shown very strong, apparently complete, quenching of the away side jet in central collisions. Our simulations show that this class of measurement is not precluded in ALICE by either the large increase in particle multiplicity or the much wider rapidity plateau compared to RHIC. Given the picture of complete absorption of these low P_T jets implied in the STAR data, it will be very important to explore the evolution of this away side quenching as a function of increasing P_T to higher P_T where full quenching should gradually disappear. Given the much larger cross sections for hard processes at the LHC, ALICE, we will be able to make these measurements beginning at the lowest P_T, comparable to ongoing measurements at RHIC, through to the very highest P_T range of interest (about 200 GeV/c) where fully reconstructed jets can be used as discussed below.

2.1.5 Low P_T jets in proton-proton collisions

The studies described above in PbPb collisions will be compared with corresponding studies in pp collisions at 14 and 5.5 TeV at the LHC. On the experimental side, as discussed above, the CDF Collaboration at Fermilab has extensively studied the properties of low P_T jets in collisions at 1.8 TeV (up to P_T=50 GeV/c of charged particle energy and in $|\eta| < 1$) measuring only the charged particles in the jets. The standard QCD Monte Carlo models describe quite well jet observables in these measurements such as the multiplicity distribution of charged particles within the leading jet (i.e. the jet with the largest energy in the event), the radial distributions of charged particles, and their transverse momentum. Surprisingly, the agreement of the Monte Carlo calculation with the data is as good at 5 GeV/c as at 50 GeV/c. ALICE will reconstruct charged particles with sufficient accuracy to allow similar measurements up to charged particle jets of $\approx$ 100 GeV/c in min bias data. In addition, charged particle identification over a wide momentum range, including π^o's, V^o's, D's and B's, will allow detailed comparisons with the QCD Monte Carlos, thus providing a benchmark for comparison of the fragmentation function of similar energy jets in heavy-ion collisions where medium effects are expected. Of course, pp measurements will be of great interest in their own right and the ALICE-USA collaboration has an extensive program that will explore the unique features of the ALICE experiment to investigate a number of issues of nuclear and nucleon structure [28].

2.1.6 Summary

The low P_T domain will be thoroughly explored at RHIC to study quenching in the QGP formed at $\sqrt{s_{NN}} = 200\text{GeV}$. In the above, we have shown that the same full suite of measurements, presently ongoing at RHIC in both STAR and PHENIX, are available at the LHC in the ALICE experiment. Of course the QGP formed at the LHC at $\sqrt{s_{NN}} = 5.5\text{TeV}$ will be quite different from that formed at RHIC which is, of course, one primary motivation of this portion of our proposed program. A direct comparison of jet quenching between STAR/PHENIX measurements and ALICE measurements will allow a unique study of the evolution of jet quenching phenomena from RHIC to the higher temperature, higher density and longer lived plasma formed at the LHC.

The above discussion has been necessarily limited in scope. A wide class of measurements involving flavor (s,c,b) tagging or exclusive tagged jets in $\gamma + jet$ and $Z^o + jet$ channels have not been discussed. For further discussion of these important possibilities see [28].

3 Jets at high P_T in ALICE

3.1 Visibility of jets in heavy ion collisions at the LHC and underlying event fluctuations

A central focus of the ALICE-USA collaboration includes the study of heavy ion collisions with the use of higher P_T jets in the range > 50 GeV/c. In combination with low P_T jet studies from correlation methods discussed above, measurements in this high P_T range complete the picture of the parton energy dependence of jet quenching phenomena and open the opportunity for investigating the new range of phenomena associated with heavy quark propagation in the dense medium. As discussed in reference to Fig. 5 and Fig. 6, the physics signature of parton energy loss in this higher P_T region will be the medium related modification of the fragmentation function as measured through the longitudinal and transverse momentum distributions of hadrons within the jet.

We will show that large transverse momentum jets are easily isolated experimentally from the background of soft particles produced in the collision.

At the LHC, the production rates for jets with P_T >50 GeV/c are many orders of magnitude larger than at RHIC allowing for systematic studies with high statistics in a clean kinematic region, far beyond the limits of the RHIC experiments. Figure 8, shows the rates for inclusive jets into the proposed ALICE-EMCal acceptance $-0.7 < \eta < 0.7$ and $\Delta\phi = 120^o$. Assuming that the 1% probability level of the fragmentation function must be measured with 5% statistical error, it is clear that the inclusive jet rates in ALICE imply a P_T reach to > 200 GeV/c for detailed studies with a jet P_T bin size of $\approx 0.1 P_T$. For nearly constant parton energy loss expected in this energy range where the asymptotic behavior of the parton dE/dx is reached, the signature of jet quenching, namely suppression of high P_T leading particles, will gradually become fractionally less significant for higher P_T jets. It is expected therefore, that there will be little compelling reasons to push beyond jets of 100-150 GeV/c in heavy ion collisions at the LHC. The region extending up to $\approx$ 150 GeV/c is sufficiently wide to allow us to observe the gradual diminution of jet quenching in the very high P_T limit. It is clear, therefore from Fig. 8 that the ALICE experiment has more than adequate jet acceptance to address the relevant physics at the LHC.

Jets of the energies discussed here are readily identified above the soft background from PbPb collisions at the LHC as seen in Fig. 9. Here we show Lego plots of the pseudo cell energy for 100 and 200 GeV/c jets embedded in central HIJING PbPb events in ALICE. The pseudo cell energy is deduced from the proposed electromagnetic calorimeter tower response and from the ALICE

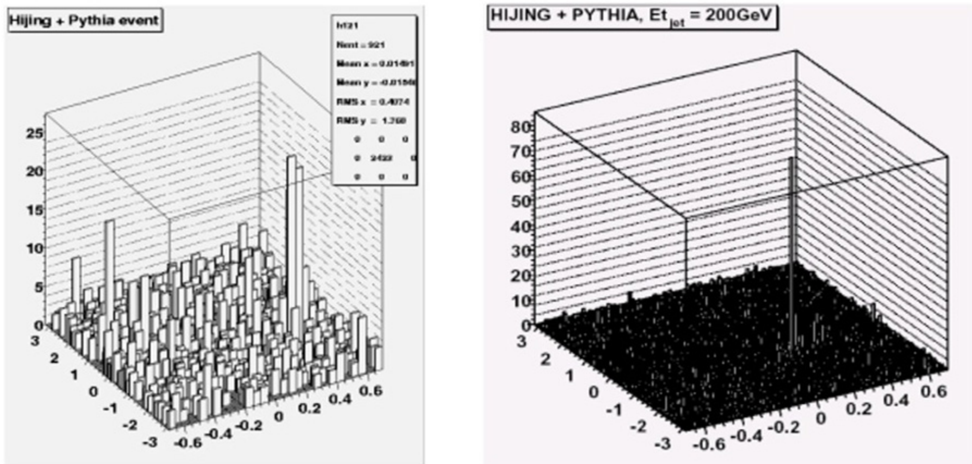

Fig. 9. Lego plots of 100 GeV/c and 200 GeV/c jets in ALICE. The energy deposited in pseudo cells is plotted versus η and ϕ. The pseudo cell energy is deduced from the calorimeter tower response and from ITS/TPC/TRD tracking. In the *right hand panel*, the cell size is chosen equal to the calorimeter tower size. For the purpose of this illustration, the calorimeter acceptance is extended through the full azimuth

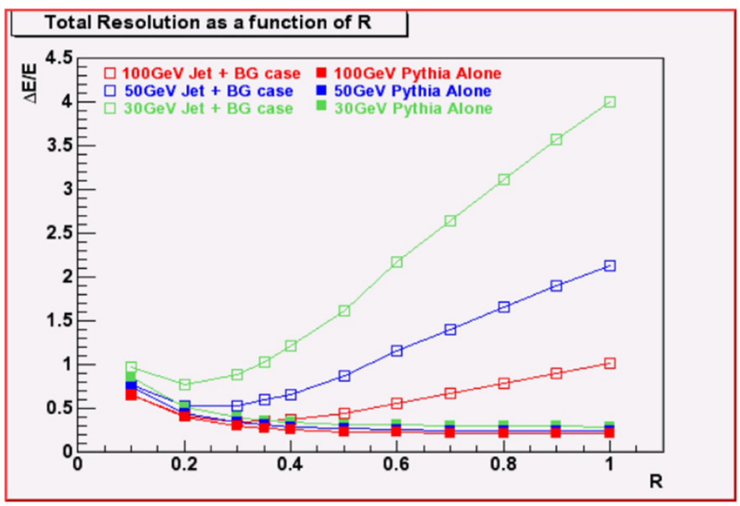

Fig. 10. Jet resolution for pure PYTHIA jets (*solid points*) and in the presence of the soft PbPb background (*open points*) as a function of cone radius used in the reconstruction algorithm. A cone radius near R $\approx$ 0.3. is optimum and the resolution rapidly deteriorates at the nominal jet radius of R=0.7

ITS/TPC/TRD tracking momentum measurement. This method of jet reconstruction follows the so called "energy flow" analysis [27].

In our approach, jet energies are reconstructed in a cone algorithm corrected for PbPb background using TPC tracks which gives the energy carried by charged hadrons and electromagnetic calorimeter tower signals corrected for the average energy deposited by charged hadrons to avoid double counting. In addition to electromagnetic energy, the calorimeter signals contain about 50%, on the average, of the energy carried by neutral hadrons. Fluctuations in both the missing neutral hadron energy and in the corrections for charged hadronic energy deposition are the principle limitations to the jet resolution achievable with this method in ALICE in pp produced jets. The resulting resolution values are rather modest compared to modern hadronic calorimeter systems. However, although it is perhaps not obvious, the combination of the TPC with an electromagnetic calorimeter as in the proposed ALICE configuration is close to the optimum jet detector in the complex PbPb environment compared to the more conventional jet measurement tools of pure hadronic calorimetry. There are two main reasons for this. First, the achievable jet resolution in PbPb collisions is dominated by fluctuations of the soft underlying background and second the basic physics sought from jet measurements in heavy ion collisions leaves very little signature in calorimetric measurements.

Our studies of jet resolution are based on HIJING simulations of the underlying event into which PYTHIA jets of selected P_T are embedded. No jets are forced, i.e. triggered, in the HIJING backgrounds. Because particle production in HIJING is based on the PYTHIA event generator, however, jets are present in our background calculations at the "zero bias" level. Because of cross section weighting, these background jets occur mainly at very low P_T. These minijet and microjet backgrounds in our analysis dominate the overall jet resolution for 50 GeV/c jets and contribute very significantly even at 100 GeV/c. This will be true of all jet measurements in the PbPb system at the LHC independent of the apparatus used to make the measurement. This bears emphasis. This effect will dominate the resolution of even ideal jet measurement systems. We emphasize further that parameterized background events, which are sometimes used to estimate detector performance issues in the LHC heavy ion environment, seriously underestimate background energy fluctuations and should not be used in connection with jet physics performance estimates. For some purposes where jet resolution, efficiency or triggerability are not a central issue, the parameterized substitutions for HIJING may be acceptable.

Consider the fluctuations of the energy contained in a cone of size R. These fluctuations limit the energy resolution of high-energy jets obtained with the cone algorithm. For uncorrelated particle production, the relation between the relative energy $\Delta E/E$ and the number of particles, N, the mean transverse momentum, $< p_T >$, and the rms width of the P_T-distribution, Δp_T, is

$$\Delta E/E = \sqrt{N}\sqrt{< p_T >^2 + \Delta p_T^2}$$

.

If correlations are present, this $\Delta E/E$ value increases, for example by a factor $\sqrt{2}$, if the multiplicity N results from N/2 clusters each of multiplicity 2. In fact, in central Pb-Pb collisions simulated with HIJING, we observe for R = 0.3, fluctuations that are by enhanced by factors of 1.5 above the expected Possonian fluctuations for uncorrelated particles, the exact value depending on the P_T-cut. Indeed, it may well be that the first information about jet quenching in the LHC plasma will come from studies of the magnitude of super-Possonian fluctuations of the underlying event in central PbPb collisions.

An important practical consequence of the soft PbPb background is the existence of an optimum cone radius for jet reconstruction. Figure 10 shows our resulting resolution for reconstructed jets of $P_T = 30$, 50 and 100 GeV/c as a function of the cone radius, R. The resolution is optimum for a cone radius of R ≈ 0.3 and is worse by a factor of ≈ 2 and ≈ 3 at the nominal jet radius of R=0.7 for jets of 100 GeV/c and 50 GeV/c respectively.

At the optimum cone size, R=0.3, the out-of-cone fluctuations are quite significant contributing about equally with background fluctuation in making the jet resolution approximately 50% worse in PbPb than in pp at R=0.7

Returning now to the potential for fully calorimetric measurements of jet quenching phenomena at the LHC: we know, partons propagating through dense matter are predicted to loose substantial energy primarily to soft gluon radiation. The higher the energy density of the medium, the more pronounced the energy loss. This process leaves its mark on the hadrons that ultimately appear as jets subsequent to the fragmentation process. Partonic energy loss prior to hadronization will affect essentially all hadronic observables and the leptonic decay products of hadronic states in jets. However, the total energy of the jet, and its spatial distribution are only very slightly modified as a result of parton energy loss [28]. The medium induced broadening of the jet, for example, reduces the energy inside the optimum R=0.3 cone by 5% and 3% respectively for jets of $P_T = 50$ and 100 GeV/c respectively [29]. It is our conclusion from this that calorimeric measurement of jet energy loss alone, as for example in direct photon/jet energy imbalance, might not be possible in the PbPb environment as a tool to study parton energy loss.

This has important implications for the experimental study of jet quenching with reconstructed calorimetric jets. Such measurements are expected to show very little sensitivity to partonic energy loss phenomena because the bulk of the partonic radiated energy remains in the useable jet cone and there is no significant observable energy loss.

While jet quenching appears to leave a negligible signature in the integrated, calorimetric, energy flow, the momentum spectra of individual hadrons are strongly modified as has already been shown at RHIC with inclusive single particle spectra. At LHC energies, jets contain many particles with momenta significantly greater than those of the underlying event so measurements sensitive to jet quenching can go well beyond the suppression of single leading particles as at RHIC. Clearly, the best signature of jet quenching at the LHC with reconstructed jets will be the longitudinal and transverse (with respect to the jet axis) distributions of individual hadrons. For our purposes in ALICE, jets are reconstructed solely to tag the primary parton energy and permit studies of the parton energy dependence of jet quenching phenomena. With reconstructed high P_T jets we consider the following observables in ALICE PbPb collisions [30]:

(A) Modification of jet fragmentation functions or the P_T distributions within jet cones: The longitudinal and transverse momentum distributions of particles within the jet cone are modified by primary parton energy loss. In the longitudinal direction, we expect a reduction in the yield of high-P_T leading particles and the enhancement in the yield of softer particles for both inclusive jets and tagged jets whose kinematics are constrained by a hard photon or Z^0 in the opposite direction. The excellent tracking properties of the ALICE TPC may be fundamental to the observation of the enhanced yield at low P_T. In the transverse direction, interaction with the medium may result in significant "transverse heating" of the J_T distribution.

(B) Baryon - Anti Baryon ratios at high P_T: Due to their higher color charge, hard gluons may loose up to approximately a factor 2 more energy than hard quarks while crossing the dense medium. Depending on the relative contribution of gluon fragmentation, this may modify the P_T dependence of the ratio of hadronic species. For example, the ratios $\bar{\Lambda}/\Lambda$ and $\bar{p}/p$ are expected to decrease at sufficiently high P_T.

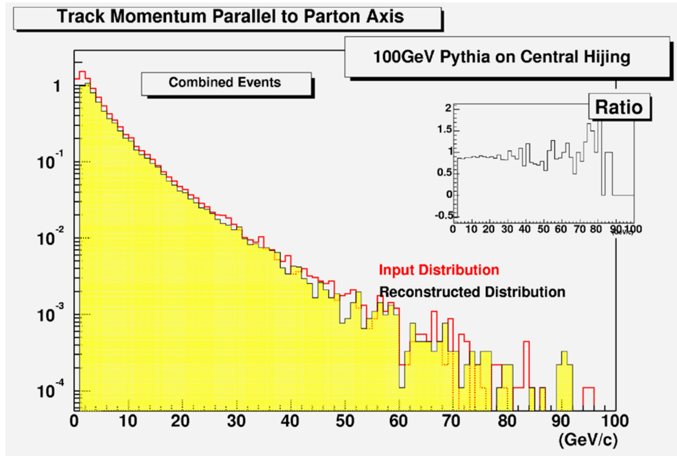

Fig. 11. Longitudinal (with respect to the jet axis) momentum, P_L , distributions for hadrons in 100 GeV/c jets in central PbPb collisions. The underlying event is calculated using HJING. Input, from PYTHIA (*red*), and output, from full detector simulations (*black*) are compared. The soft background is determined in the analysis and subtracted from these distributions

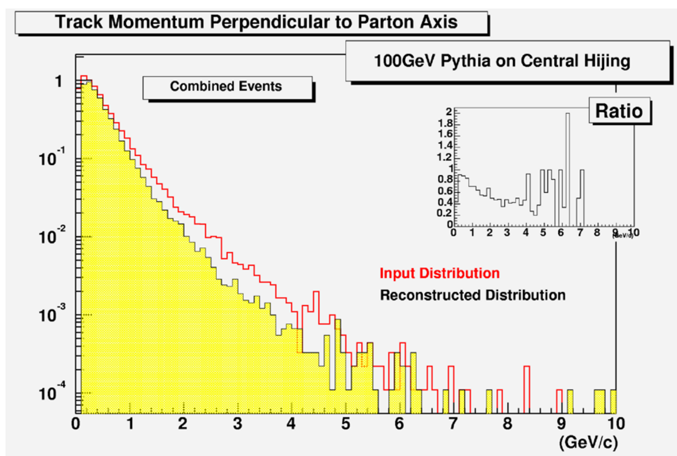

Fig. 12. Transverse (with respect to the jet axis) J_T distributions for 100 GeV/c jets in central PbPb collisions. The underlying event is calculated using HIJING. The input J_T distribution from the PYTHIA jet is compared to the reconstructed distribution from our simulations. The soft background is determined in the analysis and subtracted from these distributions

(C) The medium-induced modification of strange and heavy quark fragmentation functions: Strange (s) and heavy quark (b,c) fragmentation functions as a special case of (A), above, provide the opportunity to study the mass dependence of the energy loss mechanism. ALICE particle ID including topological ID in the inner tracker plus TPC allows unique access to jets led by strange mesons and baryons or b and c quarks.

(D) Baryon production mechanisms: Differential quenching of baryons and mesons is proving to be quite interesting at RHIC [31]. The underlying mechanism(s) which result in significant deviations from pp jet-like meson/baryon ratios (e.g. K^o/Λ) are not uniquely identified as yet but the observed systematic quenching difference between baryons and mesons is clearly not immediately consistent with conventional fragmentation of partons that have simply lost energy to the medium.

(E) The dependence of hadronic fragmentation products on the nuclear geometry: Due to the L^2 (or other) path dependence of energy loss on the in-medium path length, jet quenching phenomena are expected to show a strong and characteristic dependence on the impact parameter of the collision as well as to their orientation with respect to the reaction plane as determined, for example, from the elliptic flow pattern. In ALICE, all aspects of the program outlined above in (A) through (D) will be studied as a function of the reaction plane for reconstructed jets allowing a unique separation of the effects with path length and parton P_T. As a specific example, consider "transverse heating" of the transverse fragmentation function. If this phenomena is observed in some P_T range at the LHC then it can be expected to show substantial dependence on the collision geometry. It is important to emphasize that collision geometry can only be established with a high granularity tracking system capable of tracking to low P_T with high efficiency and negligible ghosts. Studies at RHIC have shown that a considerable "non-flow" signal contaminates $v_2$measurements based on lower order correlations such as the gross event shape [32]. Higher order correlations such as the four particle cummulant have been shown to substantially reduce the non-flow contribution to v_2. These complications can be expected to be much more serious at LHC energy and we expect that event shapes determined from calorimetric or pixel data may be strongly biased by non-flow effects.

3.2 Jet quenching in longitudinal and transverse momentum distributions within a jet

To complete this discussion we will show some simulated performance benchmarks for the reconstruction of hadron momentum distributions with respect to, and transverse to, the jet axis, P_L and J_T respectively.

In Fig. 11, we show the reconstruction of longitudinal momentum distributions for reconstructed jets with $P_T =$ 100 GeV/c in central PbPb collisions. We observe negligible interference from the underlying PbPb event over most of the range and, as shown, the input distribution is well reconstructed in the analysis. Large suppression factors typical of those seen at RHIC, or the even larger suppressions predicted by Vitev and Gyulassy [33] for LHC energies will be easily measured for specific primary parton energies with this method.

As discussed earlier in connection with low P_T jets, the J_T distributions for reconstructed jets shown in Fig. 12 are much softer than the P_L distributions and therefore are likely to be more strongly influenced by the underlying event. In the present analysis, the J_T distributions from the HIJING background and those from PYTHIA jets have essentially the same shape. Of course, our model has no physics in the transverse direction other than PYTHIA fragmentation which is identical in HIJING and in our embedded jet so we expect the signal and background to have the same shape in Fig. 12. Nonetheless, the J_T distribution is readily extracted here from fully reconstructed jets. Similar quality results are achieved for both P_L and J_T distributions for reconstructed jets with $P_T = 50$ to >300 GeV/c. A comparison of these J_T distributions in reconstructed jets with those deduced for jets in the range of 10 to 50 GeV/c from correlations studies of leading particles, will be important for discovering a possible parton P_T dependence to medium modification of the transverse properties of jets.

4 Conclusions

The measurements outlined in the preceding sections will allow a rather complete analysis of the jet quenching mechanism beginning with a precise definition of the primary parton kinematics through to the production of the final hadron momenta both along and transverse to the primary parton direction. Our program will allow the study of these kinematic distributions from quenched to unquenched jets by varying the collision centrality, system size and system energy. Using the reaction plane defined via the event-by-event elliptic flow observed in the ALICE TPC, we will directly study the path length dependence of quenching via all these observables and using fully reconstructed jets, we will produce and tag primary parton energies that span from the moderate P_T region where quenching dominates the hadron P_T distributions to very high P_T where quenching becomes fractionally insignificant in the P_T spectra. Combined with measurements for low and moderate P_T jets described in previous sections, the ALICE experiment is uniquely capable to study the full spectrum of hard parton physics in heavy ion collisions at the LHC. Finally, by extending and complementing measurements at RHIC in the low P_T regime, we hope to develop the clearest picture of the evolution of the QGP properties from RHIC to LHC energies.

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