High p_T and jet physics from RHIC to LHC

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The observation of the strong suppression of high p_T hadrons in heavy ion collisions at the Relativistic Heavy Ion Collider (RHIC) at BNL has motivated a large experimental program using hard probes to characterize the deconfined medium created. However what can be denoted as "leading particle physics" accessible at RHIC presents some limitations which motivate at higher energy the study of much more penetrating objects: jets. The gain in center of mass energy expected at the Large Hadron Collider (LHC) at CERN will definitively improve our understanding on how the energy is lost in the system opening a new major window of study: the physics of jets on an event-by-event basis. We will concentrate on the expected performance for jet reconstruction in ALICE using the EMCal calorimeter.

1. INTRODUCTION

Following an initial hard scattering in $e^+ + e^-$, $e^- + p$ and hadron collisions, high energetic partons create one (or more) high energy cluster(s) of particles moving in a same collimated direction. These kind of global objects are called "jets". Parton showering and the subsequent hadronization which lead to the particle production are known as "parton fragmentation". In ultra-relativistic heavy ion collisions (HIC), the scene of parton fragmentation is changed from vacuum to a QCD medium. These partons created before the QGP formation will first travel through the dense color medium before the "jet" formation. They are expected to lose energy through collisional energy loss and medium induced gluon radiation [9]. This is typically known as *jet quenching*. The magnitude of the energy loss depends on the gluon density of the medium (dN_g/dy) or on the number of scattering centers usually quantified

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with $\hat{q}$ the transport coefficient and on its pass length squared [10].

The measurement of the parton fragmentation products thus may yield information about the QCD medium. Even if the total jet energy is conserved, the phenomenon of quenching should change the jet fragmentation function and its structure. In the former, the manifestation of the partonic energy loss is a decrease of the number of particles carrying a high fraction of the jet energy E_{jet} (high $z = E_{hadron}/E_{jet}$ or low $\xi = \ln(\frac{1}{z})$) and an increase of the number of low-energy particles (low z or high ξ) results of the radiated energy. In the latter, a broadening of the distribution of jet-particle momenta perpendicular to the jet axis, j_T, directly related to the colour density of the traversed medium is expected [11, 12]. Such description would be the ideal scenario for the study of jet quenching under the assumption that jet measurement is possible in a heavy ion environment. Looking at RHIC Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, one can estimate that more than 350 GeV energy is included in a typical cone size $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 1$ [13], whereas a similar calculation for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV at LHC leads to an energy of the underlying event of 1.5–2.0 TeV [14]. With such numbers in mind, one easily understands that "jets" at RHIC are very complicated objects which make them impossible to disentangle from the "background". At such energies, hard scattering is better understood with single particle and few particle correlation measurements [13] (section 2).

At LHC, the picture should be quite different as 1 - the multi-jet production per event is not restricted to the mini-jet region $E_T < 2$ GeV but extended to 20 GeV, 2 - the expected jet rate at which jets can be clearly distinguished from the underlying event is high. Although some ALICE physics performances in Pb+Pb have been presented during my talk, in this paper, we will concentrate in section 3 on the $p+p$ case to show some improvements that will bring the EMCal calorimeter recently proposed as an ALICE upgrade [7, 8, 12].

2. RHIC AND THE "LEADING" PARTICLE PHYSICS

Observables such as the nuclear modification factor R_{AA} given by the ratio of A+A to $p+p$ invariant yields scaled by the nuclear geometry (T_{AB}) and two and three particle correlations have unequivocally shown at RHIC evidence for a non negligeable interaction of high energy partons with a dense color medium before hadronization [2–6, 15]. The use of the word *jet quenching* for the phenomenon which appeared consequently is a bit confusing as it is more a suppression of the production of particles with high p_T than a suppression of the "jets" themselves that is observed. It is also usually the most energetical particle (trigger) that is correlated to the associated remnants and not the jet itself. Even if this "leading particle" physics has already demonstrated its large potential to understand hard scattering processes in HIC, it has some limitations that will be briefly discussed below.

2.1. $p+p$ *Baseline and strong suppression at RHIC*

High-p_T particle production in proton–proton collisions provides the baseline "vacuum" reference to heavy-ion collisions to study the QCD medium properties. It requires the physics of such collisions to be well under control. This is now the case in the experiments STAR and PHENIX. As an illustration, PHENIX results are displayed as they presented a direct comparison of Au+Au to $p+p$ spectra. Figure 1 (top) shows the invariant π^0 yields in $p+p$ collision scaled by N_{coll} for comparison to Au+Au data [15, 16]. One can see the really good agreement with a standard Next–To–Leading (NLO) calculation [17]. Their published measurement of high p_T inclusive π^0 cross-section at $\sqrt{s_{NN}} = 200$ GeV is also well described by NLO perturbative calculations [16]. A baseline well defined, the hadron production mechanisms in N+N can be studied via their scaling behaviour with respect to $p+p$ collisions. Figure 1 shows the comparison of the $p+p$ π^0 spectrum to peripheral (top-left) and central (top-right) Au+Au collisions. Whereas the superposition of the $p+p$ scaled and peripheral spectra suggests that peripheral collisions are nothing but a superposition of nucleon–nucleon collisions, central data exhibits a clear suppression of factor 4–5. As commented previously, such observation is emphasized by looking at the ratio of Au+Au over $p+p$ scaled spectra to build the nuclear modification factor. The result of this exercise is shown in Fig. 1 (bottom) for peripheral π^0 (squares) and central ones (circles). Within error bars, peripheral to $p+p$ scaled ratio is consistent with unity, i.e. with a binary collision scaling. For central data, the suppression smoothly increases with p_T to a constant suppression factor of 4–5. Within different model interpretations, this observation would be consistent with a gluon initial density of $dN_g/dy \approx 1000$ or a transport coefficient $\hat{q} \approx 3.5$ GeV^2/fm.

2.2. *Limitations and first test of jet measurement at RHIC in* $p+p$ *collisions*

There are mainly two arguments in favour of direct jet studies justifying the fact that the "leading" particle physics present some limitations or biases. Its first main limitation is the fact that for extreme quenching scenario one observes particle emission predominantly from the surface. An increase of the in medium path length, can break the correlation of the leading particle studied with its original parent parton. For this reason, the R_{AA} exhibits small sensitivity to the medium properties [18]. This phenomenon is denoted as the *surface bias* effect. Moreover, using leading particles for the analysis, one would be biased by the fluctuations induced by the production spectrum itself. Due to its steeply falling shape with increasing E_T, the produced jet with E_T^{prod} energy will have fluctuations which will populate with a higher probability an energy part of the spectrum higher than an average reconstructed energy E_T^{rec}. Typically, the mean value of the distribution of the leading particles for a fixed jet energy is about 18%. For a given reconstructed energy interval, the lower energy jets (mainly produced) that have a harder than average longitudinal fragmentation will significantly increase the average energy fraction carried by the leading particles up to 60% (section 3.1). It is known as the *trigger bias* effect [12, 18].

Ideally, the analysis of reconstructed jets should increase the sensitivity to medium parameters by reducing the trigger bias. It will also allow to measure the original parton 4-momentum as well as the jet structure. Even if the jet reconstruction is impossible in HIC at RHIC, one can wonder to which extent jet measurement in experiments such as STAR (in $p+p$=d+Au) and ALICE (in all systems), which do not use full calorimetry but an association of charged particles from tracking and neutral particles from calorimetry, is feasible. Figure 2 (top) definitively answers this question. It presents the first measurement of reconstructed jets in $p+p$ polarized collisions at $\sqrt{s_{NN}} = 200$ GeV by the STAR experiment [19]. The inclusive differential cross section for the process $p+p \rightarrow$ jet + X versus jet p_T is compared to NLO calculations. This measurement has been obtained using a midpoint cone finder algorithm with a cone radius of R = 0.4. Both information from charged tracks in the Time Projection Chamber (TPC) (acceptance 0 < < 2 and | | < 0.3) and neutrals from lead-scintillator sampling barrel calorimeter (acceptance 0 < < 2 and 0 < | | < 1) has been stored in a grid of cell size of = 0.05 0.05. We note: 1 - the pure power law shape of the spectrum in agreement with NLO calculations, 2 - the jet p_T range covered up to 50 GeV/c. This measurement is really promising for the physics foreseen in ALICE.

A natural extension to such measurement would be to study the capabilities of heavy ion dedicated experiments to make precision measurements in order to test pQCD "*à la* CDF". The experimental measured "Humpbacked plateau" obtained by the Collider Detector at Fermilab (CDF) on di-jet events compared to the framework of the modified leading log approximation (MLLA) and to the hypothesis of local parton-hadron duality (LPHD) is presented in Fig. 2 (bottom-left and bottom-right) [20]. The distribution presented in the left figure is the jet fragmentation function in the variable . The evolution of the distribution has been studied as a function of jet energy and cone angle $_c$ around the jet axis. The MLLA evolution equations should allow an analytical description of the parton shower for gluon and quark jets insuring color coherence effect. The LPHD hypothesis assumes that hadronization is local and occurs at the end of the partons shower development, so that properties of hadrons are closely related to those of partons. MLLA+LHPD scheme views jet fragmentation as a predominantly perturbative QCD process. A possible study that can be made is illustrated in Fig. 2, right plot. A MLLA fit to these distributions or the extraction of the peak position from a gaussian fit should allow to constrain the determination of the phenomenological scale Q_{eff}, the only parameter of the model. It is then interesting to wonder to which extent such study would be accessible to the ALICE experiment. It would be necessary to first estimate if, with the expected luminosity and with the ALICE acceptance, the di-jet rate would be high enough to perform such measurement.

3. JET RECONSTRUCTION ON AN EVENT BY EVENT BASIS AT LHC ENERGIES

3.1. ALICE detectors and jet rates

ALICE is a multipurpose heavy-ion experiment [21]. Here, we will concentrate on the detectors we have used to perform jet reconstruction studies. The central tracking system (here ITS+TPC), which has good PID capabilities, makes ALICE a dedicated experiment for heavy ion studies. It covers a full azimuthal acceptance but is limited to the mid-rapididity region ($| \; | < 0.9$). Its excellent momentum resolution for charged particles covers the large range of 100 MeV/c to 100 GeV/c [12]. The capabilities of ALICE to disentangle particles with good PID down to very low p_T should lead to a very precise measurement of the number of particles inside a jet, especially at low p_T where strong modifications of the fragmentation function are expected in a HI environment. One can notice however that the tracking system is quite slow responding. It would then be necessary to include a detector with excellent trigger response. This point is one of the two arguments that have motivated the project to include an electromagnetic calorimeter (EMCal) in the ALICE apparatus. EMCal should bring trigger capabilities to ALICE and will also improve the mean reconstructed jet energy as well as its energy resolution. The proposed detector is an electromagnetic Pb-scintillator sampling calorimeter with a design energy resolution of $E{=}E = 10\%/\sqrt{E}$ and a radiation length of 20 X_0. It contains a total of around 13k towers in Shashlik geometry with a quite high granularity (= 0.014 0.014). Its main limitation is probably its not so extended (,) acceptance (| | < 0.7, 80 < < 190) [7, 8].

Figure 3 illustrates the improvement expected on the reconstructed jet energy compared to the generated one using (top left) leading particles in the reconstruction, (top right) only charged particles, (bottom left) the association of charged + neutral particles and (bottom right) an ideal calorimetry case using a cone radius R = 0.4 and a 2 GeV/c p_T cut in Pb+Pb collisions. The plots present the ratio between the reconstructed energy and the generated energy as a function of the generated energy [equivalent to what would be obtained with monochromatic jets as input] (circles) and as a function of the reconstructed energy [equivalent to what would be obtained with a full jet spectrum as input] (squares). As discussed previously, one can see first that for the leading particle case the ratio is 18% for monochromatic jets and increases to 60% due to the production spectrum bias. Then, the use of reconstructed charged jets improves the reconstructed energy and reduces the trigger bias effect. Finally, we reconstruct even higher energy using also the neutral particles in the reconstruction and the trigger bias is drastically reduced [12, 18].

ALICE will study the whole spectrum of jet production from mini-jets ($E_T < 20$ GeV) to high-E_T jets of several hundred GeV. From PYTHIA simulations over a large range of 2.5, one can note that for $E_T > 20$ GeV, 17% of the produced jets are in the ALICE fiducial region | | < 0.5 and in only 8% of these jet events the back-to-back jet-pairs are in the acceptance. For jets with $E_T > 100$ GeV, the first number increases to 26% with the same fraction of di-jets in the ALICE acceptance. With the expected average luminosity of 5 10^{26} cm ^{2}s ^{1}, the number of jets produced per effective months of running (10^6s) within the fiducial region | |<0.5 for charged jet reconstructed using ALICE central barrel tracking ITS+TPC has been estimated. For $E_T < 100$ GeV, the expected jet rate is high enough even with the limited read-out rate of the TPC so that more than 10^4 jets will be measurable. For energy jets higher than 100 GeV, triggering will be necessary to be able to perform fragmentation function analysis.

3.2. Expected p + p *performances using calorimetry*

The tools available for jet reconstruction will not be discussed in this contribution neither the expected physics performances of ALICE. For really nice discussion on these points one can already refer to the ALICE PPR II [12]. Our aim in this last part will be to concentrate on a study comparison which has been performed on jet reconstruction in p + p collisions using only charged particles (denoted as "C" in the following) and charged + neutral particles (CN) from full simulation. For such study, PYTHIA events of monochromatic jets of 50, 75 and 100 GeV have been produced and passed through the full detector simulation and reconstruction chain using GEANT3. Jets have been simulated inside the EMCal acceptance. The analysis framework of ALICE for jet reconstruction uses a seeded cone finder algorithm based on the UA1 cone finder algorithm [22]. The parameters and conditions that have been used for this study have been chosen in order to reproduce the jet finder conditions that will be used for the jet reconstruction in a HI environment. Studies have shown that in Nucleus-Nucleus collisions, because of the really large amount of background energy that is expected from the underlying event inside a jet cone as well as its fluctuations, one has to use experimental tricks to reduce the background effect in the jet finding. It appears that reducing the cone size and applying a transverse momentum cut on particles considerably reduce the background energy and eventually allow to clearly disentangle the signal energy from the background with a 40% resolution for a 100 GeV jet (R = 0.4 and p_T cut = 2 GeV/c) using charged particles only and pure MC simulations. A 30% resolution is expected from pure MC using also neutrals in the reconstruction [23].

Restricting to the p + p case, we show in Fig. 4 (left) the improvement brought by the calorimeter on the jet cone energy obtained after jet finding has been applied. Note that the reconstructed jets which have been kept in such distribution and in the following one are objects which are completely included in the EMCal acceptance. On this specific case, R = 0.4 has been used but no p_T cut has been applied on charged particles. The mean is increased from 43 GeV in the C case to 74 GeV in the CN case. The resolution defined as the ratio of RMS over Mean is also improved from 40% to less than 30%. Figure 4 (right) compares the jet energy within the cone for varying cone sizes (denoted as E_{rec} distribution) obtained after jet finding in the C and CN cases for 100 GeV jets. Note that a 1 GeV/c p_T cut has been applied and that, in the R = 1 case, part of the reconstructed jet is outside the EMCal acceptance. The error bars are the RMS of the energy distributions. E_{rec} increases with increasing R and seems to saturate around 84 GeV. Such value can be explained by detector reconstruction efficiency, the p_T cut applied, the neutral particles missed in the reconstruction outside the EMCal acceptance as well as the non measured neutrons and K^0_L.

The previous figures included only jets which were selected on geometrical criteria in order not to be biased by the EMCal edge effects on the reconstructed jet energy. Only jets whose center was chosen in a given (;) window assuring all the jets to be included in the calorimeter were kept. Keeping fixed, one can then open the accessible window to the center of jet and study how the resolution evolves consequently. This is presented in Fig. 5 (left). 3.3 rad corresponds to the calorimeter edge position in . Fig. 5 suggests that as long as the center of the jet is taken inside the EMCal acceptance, the resolution remains acceptable. It quickly becomes worse with the jet center taken outside the calorimeter. In this distribution, the first point is the limit to which a jet is completely included in the calorimeter. The last point tends to C case even if the energy distribution is a bit distorted by the neutral contribution. We eventually end-up this discussion by showing the resolutions obtained for different monoenergetic jet energies in three different cases: C with R = 0.4 (circles), CN with R = 0.4 (rectangles) and CN with R = 1 (stars). Even if the resolution is a bit worse for 50 GeV jets, we obtain a resolution lower than 40% in the C case which is really improved by the inclusion of the neutrals in the jet finding procedure. The resolution with R = 1 is a bit worse than expected for the geometrical reasons already discussed above.

4. CONCLUSION AND PERSPECTIVES

Starting from a discussion on RHIC results, we have tried to motivate the necessity to move from leading particle to jet physics to extract more information on the jet quenching phenomenon. The ALICE experiment, with its tracking and PID capabilities, will be very well equipped for such studies. A good improvement in the jet reconstruction is expected from the inclusion of the EMCal calorimeter in the ALICE apparatus. Some results obtained from full simulation in p + p have been provided to show the modifications engendered by the inclusion of neutral particles in jet finding. In a near future, we will show the improvement brought by the calorimeter on Pb+Pb collisions as well as the expected fragmentation function and its modification in a HI environment with full simulation.

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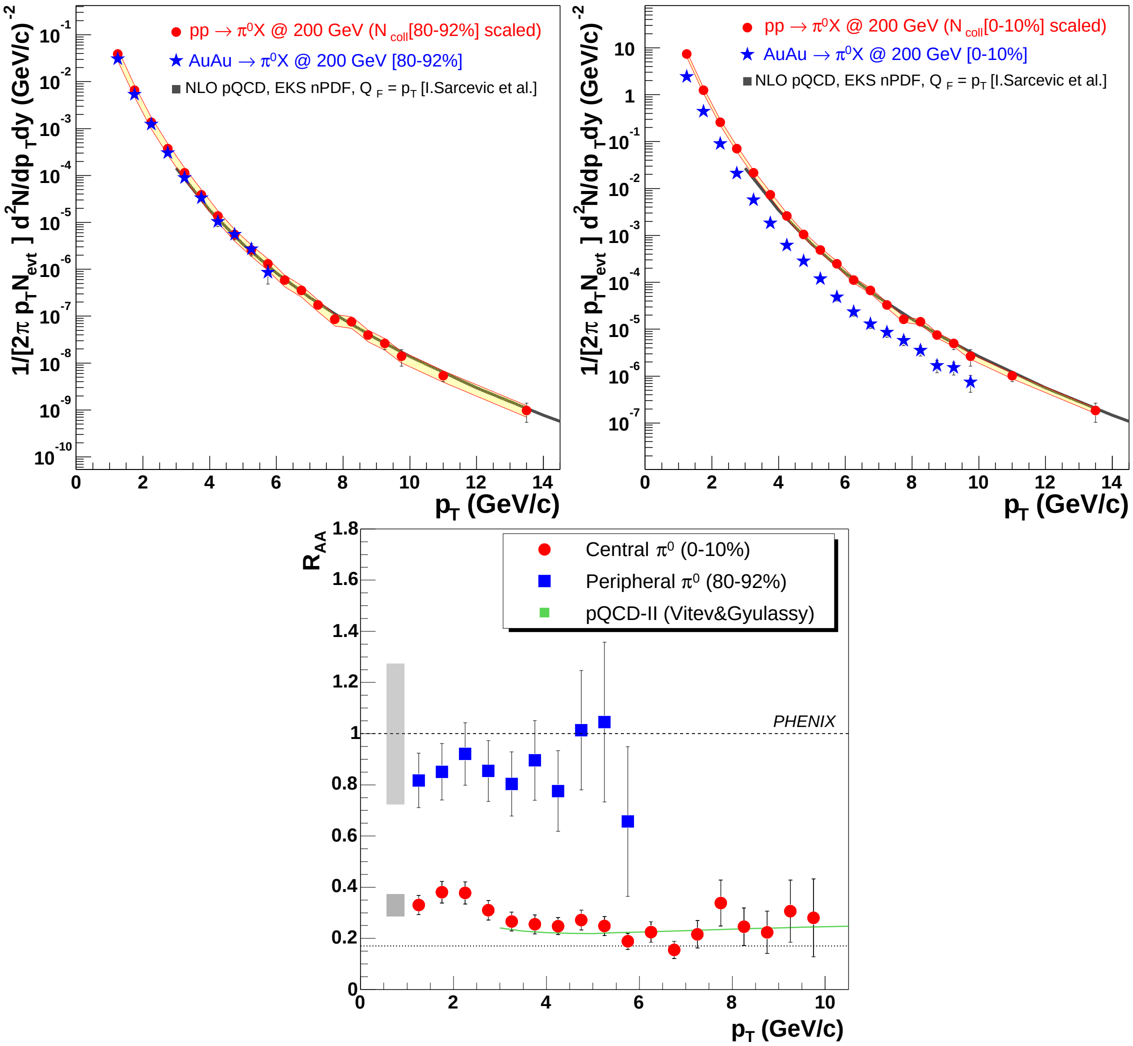

Figure 1. Top: invariant ^{0} yields measured by PHENIX in peripheral (left) and central (right) Au+Au collisions (stars), compared to the N_{coll} $p+p$ scaled ^{0} yields (circles) and to pQCD calculation (squares). Bottom: nuclear modification factor, R_{AA}, in peripheral and central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV for ^{0} measured by PHENIX [15–17].

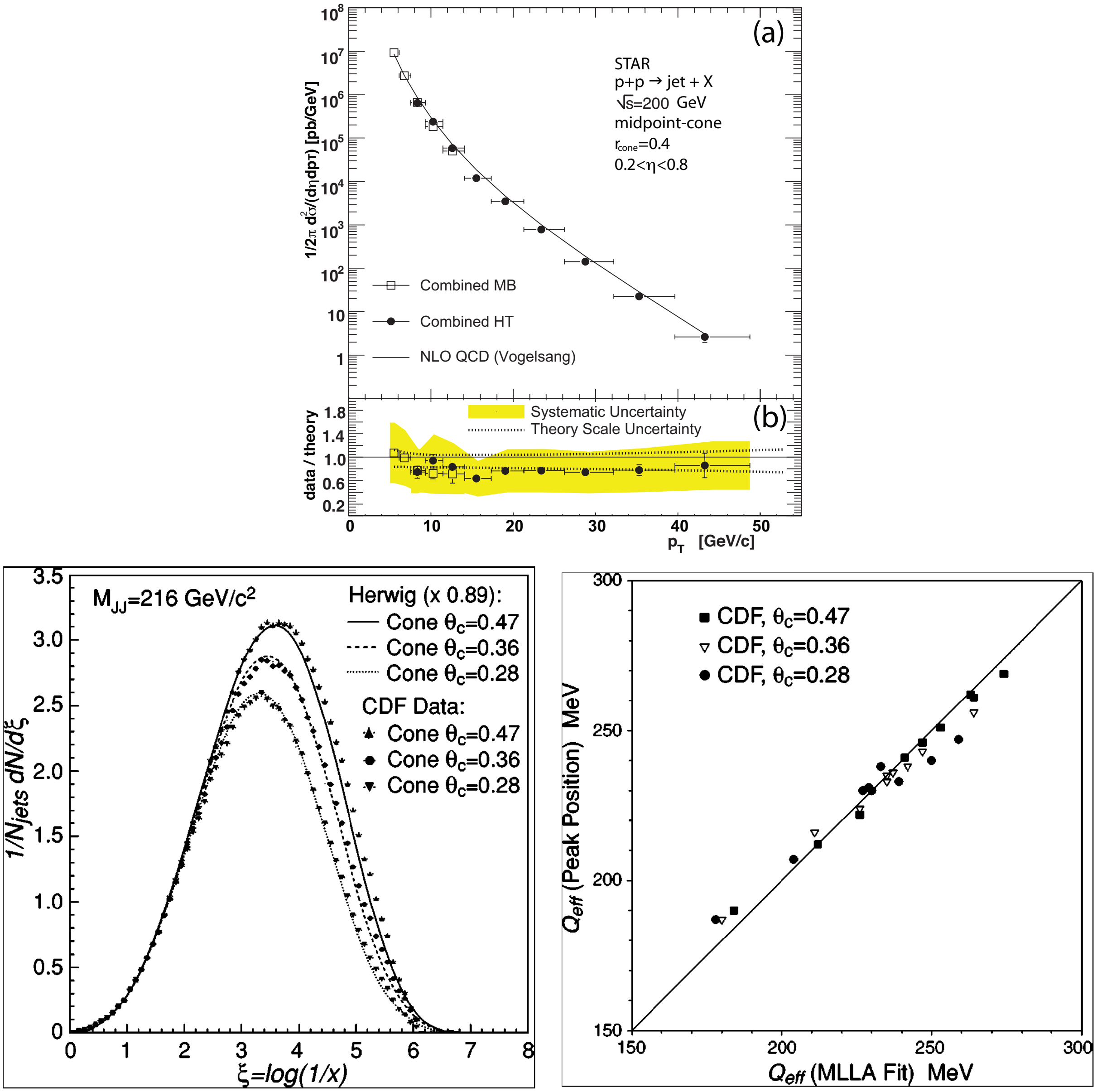

Figure 2. Top: inclusive differential cross section for $p + p \rightarrow$ jet+ X at $\sqrt{s_{NN}} = 200$ GeV versus jet p_T for a jet cone radius of 0.4 (more details in [19]) Bottom left: comparison of the inclusive momentum distribution of particles in jets in the restricted cones of size $\theta_c = 0.28$, 0.36 and 0.47 rad to HERWIG 5.6 predictions (scaled by 0.89), for dijet mass bin $M_{jj} = 216$ GeV$/c^2$. Bottom right: correlation between Q_{eff} extracted from a MLLA fit and from a Gaussian fit for peak position. Uncertainties (not shown) are dominated by the systematic errors [20].

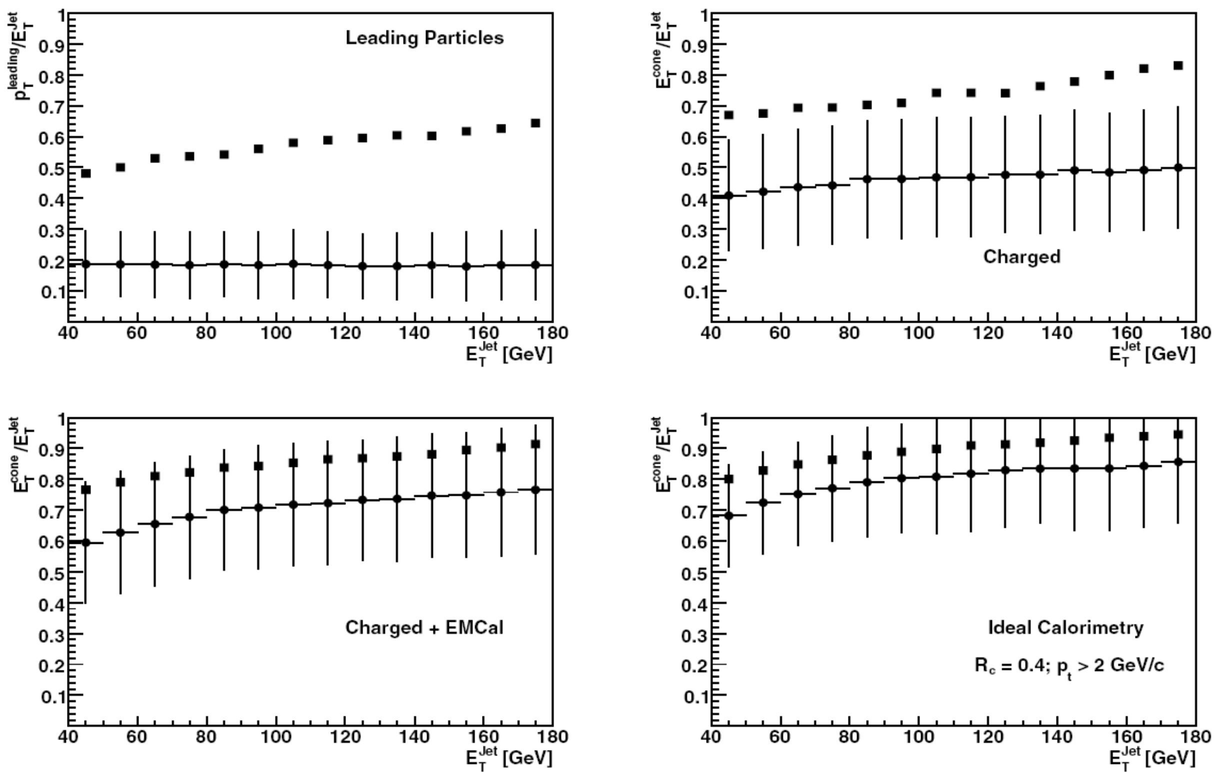

Figure 3. The ratio between reconstructed energy and generated energy, E_T^{rec}/E_T^{gen}, as a function of the generated energy (circles), for which the RMS values are shown as error bars, and as a function of the reconstructed energy (squares). The former is equivalent to the ratio obtained from monochromatic jets whereas the latter contains the bias induced by the input spectrum [12].

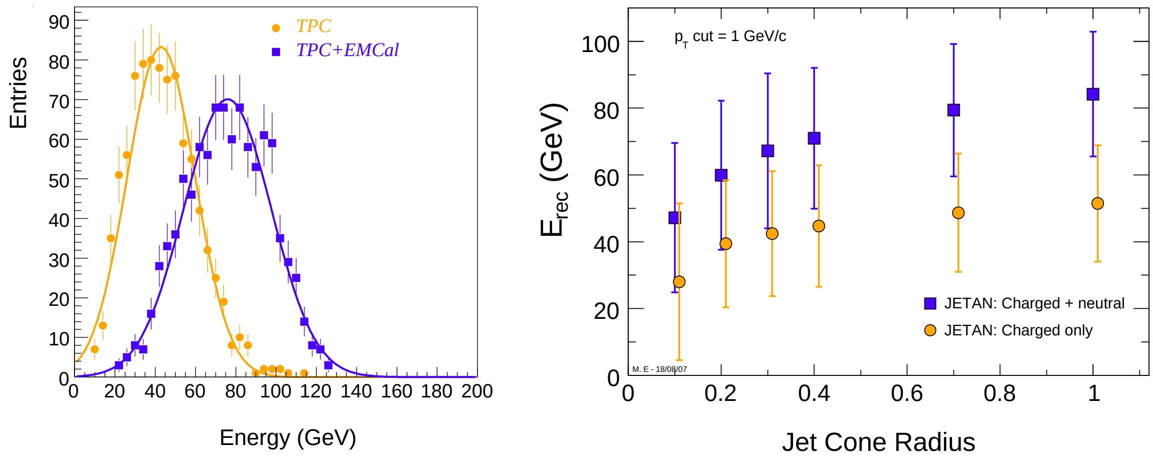

Figure 4. Left: jet cone energy obtained from the full (PYTHIA + GEANT3) detector simulation of 100 GeV jets in p+p collisions at $\sqrt{s_{NN}}$ = 14 TeV in the EMCal acceptance using charged particles only in the jet finding (circles) and charged + neutral particles, neutrons and K^0_L excepted (squares). Right: jet cone energy as a function of cone sizes for the same cases as fig. left. On this distribution, a p_T cut of 1 GeV/c has been applied on tracks.

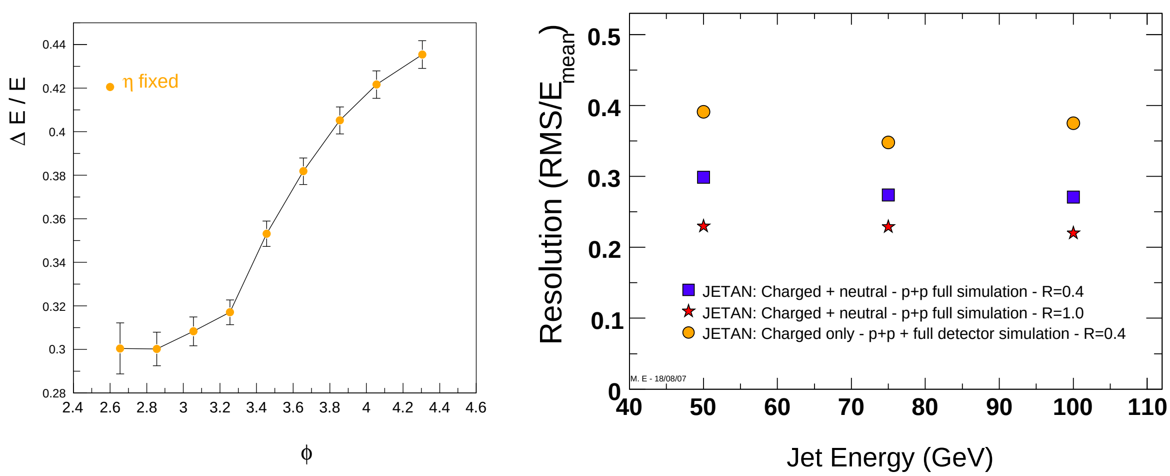

Figure 5. Left: jet energy resolution (RMS/E_{mean}) as a function of the maximum limit position of the jet center in the direction. Right: jet energy resolution of monoenergetic jets of 50, 75 and 100 GeV using only charged particles with a cone radius R = 0.4 (circles), using charged and neutral particles with R = 0.4 (squares) and R = 1.0 (stars). In the case of R = 1.0, part of the jet is outside the EMCal acceptance.