The Influence of the Underlying Event on Jet Measurements in Heavy Ion Collisions

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Abstract. We present a study of the performance of jet reconstruction algorithms for Pb+Pb collisions at $\sqrt{s_{NN}} = 5.52$ TeV based on a full GEANT simulation of the ATLAS detector. It is shown that ATLAS can provide measurements that are sensitive to different in-medium energy loss scenarios leading to the jet quenching. The capability of measurements of fragmentation function and $j_T$ distribution are presented. We concentrate on some biases in these measurements that might be due to the detector effects or to the choice of a jet finding algorithm.

1. Introduction
Measurements of jets and their properties in heavy ion collisions provide information about the jet quenching phenomenon that is predicted for heavy ion collisions and already measured at RHIC. The jet quenching means that a hard parton, before fragmenting into a jet of hadrons, deposits a significant fraction of its energy in the medium, leading to a change of jet energy distribution and particle multiplicity inside a jet. At RHIC experiments the jet quenching phenomenon has been clearly established in the measurement of single- and di-hadron spectra [1]. Due to the limited $p_T$ reach of these measurements and the large soft background, they suffer from biases towards particles that escape the medium having lost little energy. In contrast, the high center-of-mass energy and large rates for high-$p_T$ jets at the LHC will make full jet measurements possible over a wide range of jet energies. In these proceedings we present capabilities of the ATLAS detector [2] to measure jets and their properties in heavy ion collisions, focusing on the problems related to the choice of the jet finding algorithm, the impact of the underlying event on the jet energy resolution, and the feasibility of measuring the jet internal structure.

2. Choice of the jet finding algorithm
The jet finding in Pb+Pb collisions at LHC will have to deal with a substantial contribution from the underlying event. The underlying event multiplicity in Pb+Pb collisions at the LHC energies is not precisely known. The existing models predict very different values of $dN_{ch}/d\eta = 1000−6000$ in the most central Pb+Pb collisions. For the jet studies, not only the underlying event multiplicity is important, but also the event-by-event fluctuations in the calorimeter energy deposits. Left plot of Fig. 1 illustrates the difference in energy deposition per one calorimeter
tower\(^1\) between two event generators, HIJING [3] and HYDJET [4] simulated with the same impact parameter range of 0\(−\)3 fm. It is visible that the difference in the mean and in the width of distributions is quite sizable.

Bearing in mind these facts we decided to test a general performance of the jet finding algorithms with respect to a presence of the calorimeter background using a simple toy-model based on a random generation of the calorimeter background energy with Poisson-like distributions. This allows us to easily vary the size of the fluctuations in the background as well as the mean deposited energy. The background was then merged with the fully reconstructed PYTHIA [5] jets at the level of calorimeter towers. PYTHIA di-jet events with energy in the range of 30\(−\)80 GeV have been used. The extreme case of the largest mean of the deposited energy \((\langle E_T, bkg \rangle \approx 3 \text{ GeV per a calorimeter tower})\) and the largest size of fluctuations \((\sigma(E_{T, bkg})/\langle E_{T, bkg} \rangle \approx 33\%\) resembles the properties of the underlying event simulated by unquenched HIJING in the most central Pb+Pb collisions \((dN_{ch}/d\eta = 2700, b = 2 \text{ fm})\) at \(\sqrt{s_{NN}} = 5.52 \text{ TeV}\). Events with and without the background were reconstructed using the jet finding algorithms implemented in FastJet package [6]. The mean value of the background has been subtracted after the jet reconstruction from each tower belonging to a given jet. The middle plot of Fig. 1 illustrates the relative difference in the transverse energy of clean PYTHIA jets and jets reconstructed in the presence of the background, both reconstructed using the \(k_T\) algorithm with the distance parameter \(R = 0.4\). The \(x\)-axis shows the mean transverse energy of the calorimeter tower background, the \(y\)-axis shows the relative size of fluctuations in the background. One can see that \(k_T\) algorithm underestimates the jet energy in the presence of a sizeable background. This underestimation becomes larger for higher backgrounds. Jet energy scale, \(\Delta E_T/E_T\), is shifted by as much as 20\% for the background with the highest mean and the highest size of fluctuations. The underestimation of the jet energy is due to the fact that a softer part of a jet may preferably be clustered to the background rather than to a jet. This is reflected by the fact that with increasing calorimeter tower background the number of towers that are assigned to a jet by the \(k_T\) algorithm is decreasing. This is not the case for the anti-\(k_T\) algorithm or iterative cone algorithm where the number of towers remains almost constant across the phase space of different calorimeter tower backgrounds (see the left plot of Fig. 1). It was found that similarly to \(k_T\) also the Cambridge/Aachen algorithm suffers from the underestimation of the jet

1 Calorimeter tower of the ATLAS detector has a size of \(\Delta \eta \times \Delta \phi = 0.1 \times 0.1\).
Figure 2. Comparison of the particle-level (open circles) fragmentation functions (left) and $j_T$ distributions (middle) and the reconstructed distributions after the background subtraction and after the corrections on tracking efficiency and jet position resolution (closed circles) for the most central HIJING Pb+Pb collisions. The subtracted background distributions are shown separately (triangles). Right: Charged particle multiplicity measured as a function of the distance from the jet axis for different jet finding algorithms.

energy. In addition, it was also found that the jet position resolution and jet energy resolution is $\sim 2 - 6$ times better for the anti-$k_T$ and iterative cone algorithm than in the case of $k_T$ and Cambridge/Aachen algorithms.

We may conclude that the anti-$k_T$ algorithm and iterative cone algorithm exhibit better performance in terms of the jet energy scale, jet energy resolution, and jet position resolution as compared to the $k_T$ and Cambridge/Aachen algorithms. More details about the expected performance of the jet reconstruction in heavy-ion collisions can be found in Refs. [7, 8, 9].

3. Jet energy resolution

One of the basic variables used to evaluate the performance of the jet reconstruction is the jet energy resolution. Relative jet energy resolution of jets measured in the calorimeter can be written as $\sigma(E_T)/E_T = \sqrt{\sigma_b(E_T)} + p_1 + p_2$ [10]. The first term in the formula is the stochastic term which is an internal characteristic of a calorimeter and which describes the response to a particle showering that develops as a stochastic process. The second term is the noise term which reflects the calorimeter noise and/or underlying event fluctuations. The last term is the constant term which accounts for various instrumental effects and which can usually be neglected. In the Pb+Pb collisions the contribution of the underlying event to a jet is large. The energy deposition from the underlying event does not depend on the jet energy, thus it is reflected by the noise term which scales as $1/E_T$ for the relative jet energy resolution $\sigma(E_T)/E_T$. The size of the noise term is measured in units of energy by the constant $p_1$. The value of the constant $p_1$ is proportional to the size of a jet and its upper limit can be obviously estimated as $p_1 = \sqrt{A \sigma_b^2(E_T)}$, where $\sigma_b(E_T)$ is the root-mean-square of the underlying event energy deposition in a unit calorimeter area (i.e. in one calorimeter tower) and $A$ is the area of a jet in these units (i.e. the number of towers that form a jet). In the case of HIJING background $p_1 \approx 15$ GeV at midrapidity, in the case of HYDJET $p_1$ is only 11 GeV. Thus, once we know a realistic size of the underlying event fluctuations we can estimate the jet energy resolution.

4. Jet internal structure

The high center-of-mass energy and large rates of high-$p_T$ jets at the LHC will make full jet measurements possible even in the heavy ion environment. Particularly interesting are measurements of fragmentation function and $j_T$ distribution. The fragmentation variable, $z$ is the longitudinal fraction of the jet momentum carried by a particle, $z = (\vec{p}_{jet} \cdot \vec{P}_{particle})/|\vec{p}_{jet}| \approx$
\[ p_{T,\text{particle}} \cos R / p_{T,\text{jet}}, \] where \( R = \sqrt{\Delta \eta^2 + \Delta \phi^2} \) is the opening angle between jet axis and position of a particle in \( \eta \times \phi \) space. The fragmentation function is then defined as \( D(z) = 1/N_{\text{jet}} \frac{dN}{dz} \).

The transverse momentum of particles with respect to the jet axis, \( j_T \), is defined as \( j_T = |\vec{p}_{\text{jet}} \times \vec{p}_{\text{particle}}| \approx p_{T,\text{particle}} \sin R \). The fragmentation functions and \( j_T \) distributions are expected to be modified in heavy ion collisions compared to \( p+p \) collisions and provide a direct information on the properties of the hot QCD medium created in heavy ion collisions [11].

Fig. 2 compares the truth fragmentation function and \( j_T \) distribution computed using charged particles and truth jets with the reconstructed distributions computed using tracks. The background distributions that are subtracted are also shown. For the reconstruction, the most central HIJING collisions (\( b = 2 \) fm, \( dN_{\text{ch}}/d\eta = 2700 \)) were used. The transverse momentum cut used for particles and tracks is \( p_T \geq 2 \) GeV/c. Jets were reconstructed using the iterative cone algorithm. The energy of generated jets is between 70 GeV and 140 GeV. The correction for tracking efficiency of 70% as well as the position resolution correction have been applied. As one can see there is a good agreement between the truth and reconstructed fragmentation function and \( j_T \) distribution.

One of the measurements sensitive to the in-medium modifications of jets is the measurement of particle multiplicity as a function of the distance from the jet axis. The right plot of Fig. 2 shows the particle multiplicity measured as a function of the distance from the jet axis (\( r \)) for \( p+p \) PYTHIA simulated minimum-bias events at \( \sqrt{s} = 900 \) GeV with jets reconstructed using different jet finding algorithms (anti-\( k_T \), \( k_T \), and Cambridge/Aachen algorithms with \( R = 0.4 \), and SISCone algorithm with \( R = 0.4 \) and split-merge fraction of 0.75). One can see that the multiplicity evolution with \( r \) depends on the choice of the jet finding algorithm. Particularly noticeable is a dip at around \( r = R = 0.4 \) present in the multiplicity of particles obtained from the anti-\( k_T \) algorithm. This effect shows that the anti-\( k_T \) optimizes the jet axis with respect to the jet periphery that is defined by the distance parameter \( R \). This effect, if seen in the heavy ion data, could be miss-interpreted as a Mach cone. Clearly it is important to use different jet finding algorithms.

More details on the measurement of the jet internal structure can be found in Ref. [12].

5. Summary

ATLAS can provide measurements of jets and their properties that are sensitive to different energy loss mechanisms in the presence of the heavy ion environment. We are looking forward to collect first heavy ion data in the fall of 2010.

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