JET ENERGY RECONSTRUCTION WITH THE CMS DETECTOR

S.KUNORI

University of Maryland
College Park MD 20742, USA
E-mail: kunori@fnal.gov

The CMS calorimeter is a non-compensating calorimeter and has non-linear response to jet energy. A 4 Tesla magnetic field in a tracking volume induces extra smearing of energy measurement by the calorimeter. Various algorithm to improve the measurement have been tested. A simple mapping of the calorimeter response to jets is implemented in the trigger and more sophisticated energy flow algorithm may be used at a later stage.

1. Introduction

The CMS calorimeter has been designed for precise energy measurements of photons and electrons in the psuedorapidity interval $|\eta| < 2.6$, and moderate precision energy measurements of quarks and gluons in $|\eta| < 5.0$ through the measurement of jets of particles [1,2,3]. The central calorimeter (—$\eta| < 3$) consists of PbWO4 crystals for the electromagnetic calorimeter (ECAL) and scintillator-brass (70% Cu, 30% Zn) sampling calorimeter for the hadron calorimeter (HCAL). The forward calorimeter ($3 < |\eta| < 5$) is a quartz fiber calorimeter with iron absorber.

The response of the calorimeter to photons is quite linear versus incident energy, while the response to hadrons depends strongly on incident energy[4]. This quite different response of the calorimeter to photons and hadrons leads to a nonlinear response of the calorimeter to jet energy and a smearing effect in the energy resolution. Since the calorimeter response depends on the total energy of a jet (not the transverse energy), the transverse energy scale of jets showed a strong psuedorapidity dependence.

In order to restore the energy scale of reconstructed jets and to improve the resolution, we have studied various algorithms for correcting the jet energy. Simpler algorithms use only information from the calorimeter. More complicated algorithms require reconstructed charged tracks. In the following sections, we describe those algorithms and their performance.

2. Initial Reconstructed Jet Energy

We use the iterative cone algorithm with a cone size R=0.5 to reconstruct jets through this Monte Calro study. The energy of reconstructed jets is calculated as a simple sum of energy in ECAL and HCAL in the jet cone, i.e.

$$E_{reco} = (EC + HC) \tag{1}$$

EC and HC are reconstructed energy in ECAL and HCAL, respectively.

The energy scale of ECAL was calibrated with electrons. The energy scale of HCAL was calibrated with charged pions (E_T=30GeV) of which shower started in HCAL. Therefore, E_{reco} has a right energy scale for photons, but lower for most of pions in jets because of lower response of ECAL to hadrons.

3. Jet Energy Corrections

In order to correct the jet energy, we have tested several algorithms. All algorithms are intended to remove detector effects in jet energy reconstruction and not to make correction for parton energy. In order to translate energy of jets to energy of partons, we need additional correction for fragmentation process of partons and it is beyond the scope of this study.

3.1. *Simple map of Calorimeter Response*

The simplest correction algorithm[5] uses a form of

$$E_{corr}(E_T, \eta) = a(E_T, \eta) \times E_{reco}(E_T, \eta) \tag{2}$$

A calorimeter response function, $a(E_T, \eta) =< E_{gene} > / < E_{reco} >$ was created using a Monte Carlo QCD jet sample.

Since this approach corrected the energy scale by simply multiplying by a correction factor, it did not improve the energy resolution for individual jets, but did improve trigger turn on curves [5] and reconstruction of dijet masses by equalizing the jet energy scale in the whole range of η in the detector. For example, it provided 35% improvement in the resolution of di-jet mass for Higgs (115GeV) decaying to b-quark jets.[6]

3.2. *Use of Longitudinal Segmentation*

The CMS calorimeter has mainly two longitudinal segmentation- ECAL and HCAL. In order to improve the resolution of individual jets, our first attempt was to utilize the longitudinal segmentation.[7] We optimized two coefficients $a(E_T, \eta)$ and $b(E_t, \eta)$ in the following formula with QCD jets sample to obtain the best energy resolution.

$$E_{corr} = a(E_T, \eta) \times EC + b(E_T, \eta) \times HC \tag{3}$$

The improvement in relative resolutions before and after the correction was 4% on average in the wide range of E_T and η. For example, the resolutions before and after the correction were 14.3% and 13.6%, respectively at E_T=80GeV and η=0.2, i.e. 5% improvement in relative resolution.

The improvement was not large. This lack of improvement may be attributed to the relatively thick ECAL compartment (1.1 interaction length) without any longitudinal segmentation. In general, a calorimeter can be divided into three longitudinal sections. The first section measures mainly showers due to photons in a jet, the second section measures a mixture of showers due to photons and hadrons, and the third section measures showers due to hadrons. By optimizing a weight for the second section one can somewhat compensate a different response of calorimeter to photons and hadrons, consequently improving jet energy resolution. The thick ECAL subsumes the second section completely. Therefore, there was not much room to improve the jet energy resolution by optimizing longitudinal calorimeter weights in the CMS calorimeter.

3.3. *Use of Transverse Shower Size*

Contrary to the longitudinal segmentation, the CMS calorimeter has very fine transverse segmentation in ECAL ($\Delta\eta \times \Delta\phi$ = .0174 × .0174). We tested to separate electromagnetic clusters (*em*) and hadronic clusters (*had*) in a jet cone using the transverse shower shape in ECAL and then apply correction coefficients to *em* and *had*, separately. A preliminary result shows that the separation of *em* and *had* clusters is not clean in terms of transverse shower size in ECAL. Therefore improvement of resolution is expected to be small.[8]

3.4. *Correction for Out-of-Cone Tracks*

Relatively soft tracks can be swept away from the jet cone by 4T magnetic field. For example a track with P_T=1.6 GeV is deflected by the magnetic field by $\Delta\phi = 0.5$ radian from the original direction when it reaches the calorimeter surface. Tracks with $P_T \leq 0.8$ GeV never reaches the barrel calorimeter.

Fig. 1 shows a fraction of the energy of generated jets escaping from the jet cone in 4T field. One can see that on average about 15 % of the energy of the soft ($\sim$ 30 GeV) jets escapes from the jet cone and there are big fluctuations of this energy. Adding the energy of the out-of-cone tracks to the calorimeter jet energy removes the fluctuations and therefore improve the jet energy resolution.

Fig. 3 and Fig. 4 show the jet energy resolution and linearity as a function of the generated jet E_T. The resolution is improved significantly with addition of out-of-cone tacks(*dots* vs. *opensircles*). Also we have tested the correction using all Monte Carlo generated tracks and actually reconstructed tracks with our current track reconstruction program and found no significant difference between two cases. The efficiency of track reconstruction is 90% with a P_T cut off at 0.9GeV. This efficiency and the cut off energy are sufficient to improve the jet energy resolution.

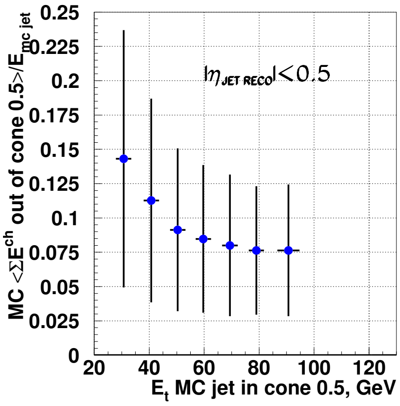

Figure 1. Fraction of energy of the generated jet escaping from the jet cone 0.5 in 4T field.

3.5. *Energy Flow Algorithm*

A considerable improvement of the calorimeter jet energy resolution using reconstructed tracks (energy flow algorithm) has been already demonstrated in a number of HEP experiments such as LEP [9], Tevatron [10], ZEUS [11], Tesla [12].

Ultimate goal of such algorithm may be expressed in the formula,

$$E_{corr} = EC_{phtons} + (EC + HC)_{neutral.h} + Tracks_{charged} \tag{4}$$

The algorithm uses ECAL to measure the energy of photons, ECAL and HCAL to measure the energy of neutral hadrons, and reconstructed tracks to measure energy of charged particles inside a jet cone.

A major issue of the algorithm is to remove energy due to charged particles and leave only energy due to photons and neutral hadrons in the calorimeter inside the jet cone. We performed the following procedure.

First we reconstructed a jet with the standard iterative cone algorithm using calorimeter energy. Then we we reconstruct tracks inside a cone R=0.5 around the jet axis and propagated them to the calorimeter surface. For tracks going out of the jet cone, we simply added the energy to the jet. For tracks stayed inside the cone, we formed a energy cluster with 3x3 crystals ($(0.017 \times 3)^2$) and 3x3 HCAL towers ($(0.087 \times 3)^2$) around the impact point of the track. Then tested a match between the track and the cluster with the following matching condition.

$$-\sigma < (Etracker - Ecalo) < 2\sigma \tag{5}$$

where $\sigma/E = 100\%/sqrt(E) + 5\%$.

If the matching condition is satisfied, we replaced the cluster energy with energy of the track. If not, subtracted an estimated calorimeter response R_{ave} from the jet energy and added the energy of the track.

We used GEANT3 to create a library of R_{ave}. The library has R_{ave} as a function of incident particle energy. R_{ave} also depends on starting point of hadronic shower. We crated it for showers started in ECAL and HCAL separately. In the correction process we identified whether a shower of unmatched track started in ECAL or HCAL by checking energy in ECAL, and applied R_{ave} accordingly.

Fig. 2 shows the number of charged tracks in the jet cone of R=0.5 on the calorimeter surface and the number of tracks which satisfied the matching condition Eq. 5 as a function of the energy of generated jets. The matching efficiency is good at low energy, but getting worse as energy increases because of more tracks overlap with photons around the core of jets.

Fig.3 and Fig.4 show the resolution and linearity of the jet energy as a function of the generated jet energy; *dots* for before and *stars* for after the full energy correction. Also shown are results with partial correction or with a simpler methods. The *opencircles* are after out-of-cone track correction. The *squares* simply replaced the energy in the calorimeter with R_{ave} without the track-cluster matching. The *triangles* used a simpler method to estimate R_{ave} [13]. Significant improvement is seen in both resolution and linearity with the correction.

4. Correction for Missing Transverse Energy

The non-linear response of the calorimeter also distorts measurement of the missing transverse energy MET. We have extended the simple jet energy correction (Eq.2) to the reconstruction of MET. We took a sum of the corrected energy of reconstructed jets plus energy outside the jets cones. For the energy outside the cone, we used the correction coefficient for low energy jets (E_T=30GeV).

Fig. 5 shows an offset of the missing transverse energy as a function of $MET(gen)$ for a sample of SUSY events. Clearly the extension of the simple

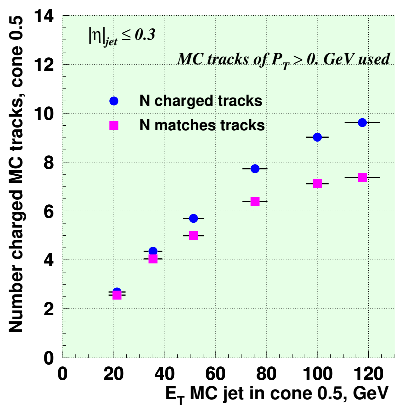

Figure 2. The number of charged particles in the jet cone R=0.5 at the calorimeter as a function of the generated jet energy: dots for all charged particles, squares for tracks satisfied the matching condition Eq.5.

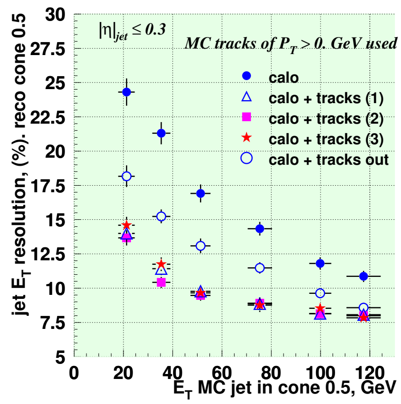

Figure 3. The jet energy resolution as a function of the generated jet E_T. *dots* for reconstruction with the calorimeter only and *stars* for with full correction. *opencircles* for correction with only out-of-cone tracks. Other two are the resolution by partial correction. (see text for more detail.)

jet energy correction restored the energy scale of missing transverse energy above MET 100GeV.

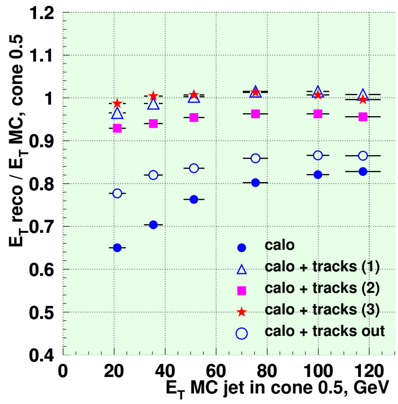

Figure 4. The jet energy scale as a function of the generated jet E_T. The definition of pointspoints are the same as Fig.3

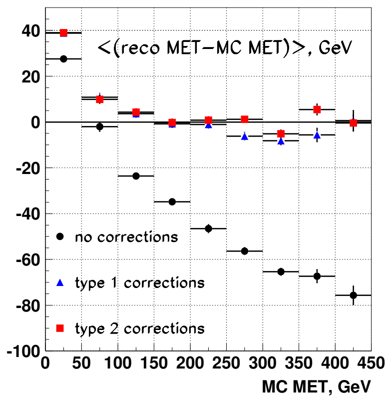

Figure 5. Offset of the missing transverse energy as a function generated missing transverse energy. The type 1 correction apply correction to only inside jet cones and the type 2 correction applied correction to both inside and outside jet cones.

5. Conclusions

We tested various algorithms to improve the jet energy scale and resolution with the CMS detector. A simple mapping of the jet response in the η-ET

space restores the jet energy scale. It has been implemented in the Level-1 jet trigger as well as the higher level trigger and offline analysis. Further improvement using only calorimeter information, namely more sophisticated use of longitudinal and transverse segmentation of the calorimeter, is found to be limited. Significant improvement is provided by combining calorimeter information and reconstructed charged tracks. The resolution of jet ET is improved from 24% to 14% at 20GeV and from 12% to 8% at 100GeV. The energy scale is accurate better than 2% in the ET range from 20GeV to 120GeV.

A jet energy correction was extended to the reconstruction of the missing transverse energy. We observed significant improvement in both the energy scale end resolution with the extension of the simple jet energy correction.

Those algorithms are still at primitive state and need to be tuned. We expect further improvement be achieved by the time we start taking data with the CMS detector.

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