# CMS Jet and Missing $E_T$ Commissioning

**V. Daniel Elvira**[*†]

*Fermi National Accelerator Laboratory*
*Batavia, Illinois, USA*
*E-mail:* daniel@fnal.gov

We describe how jets and $E_T$ are defined, reconstructed, and calibrated in CMS, as well as how the CMS detector performs in measuring these physics objects. Performance results are derived from the CMS simulation application, based on Geant4, and also from noise and cosmic commissioning data taken before the first collision event was recorded by CMS in November 2009. A jet and $E_T$ startup plan is in place which includes a data quality monitoring and prompt analysis task force to identify and fix problems as they arise.

[*]Speaker.

[†]representing the CMS Collaboration

## 1. Motivation to Measure Jets and Missing $E_T$ at the LHC

Jets will be omnipresent at the LHC *pp* Collider, where gluon and sea quark scattering dominates and there is a large phase space for gluon emission. The jet cross section at a 10 TeV center-of-mass energy is about five orders of magnitude larger than at the Tevatron, yielding about 10 thousand events with jets higher than 1 TeV in $p_T$ for an integrated luminosity of 1 fb$^{-1}$. It is hard to think of any physics measurement which does not involve jets either as signal or background, from tests of Quantum Chromodynamics (QCD) to Standard Model (SM) $W/Z$ boson and top production, as well as searches for quark compositeness or Supersymmetry (SUSY) [1].

Experimentally, missing transverse energy ($E_T$) indicates a non-uniform detector response or the presence of particles that have escaped detection. For example, an event with low $E_T$ may signal SM particles decaying into neutrinos, while a high $E_T$ may be the most striking piece of evidence for new physics with escaping weakly interacting particles such as the neutralinos in SUSY. It is, however, hard to measure $E_T$ given the experimental challenges to achieve good resolution and understand the tail of the distribution [1].

This proceedings describe how jets and $E_T$ are defined and reconstructed in CMS, as well as how the CMS detector performs in measuring these physics objects. Performance results are derived from the CMS simulation application [2], based on Geant4, and also from noise and cosmic commissioning data taken before the first collision event was recorded by CMS in November 2009.

## 2. The CMS Detector

The CMS detector is described elsewhere [3]. It is a hermetic apparatus which covers almost the full solid angle. A silicon tracker measures 10 GeV tracks with a $p_T$ resolution better than 1 %, while a tungstate electromagnetic calorimeter (ECAL) measures electron and photon energy with a resolution better than 0.5 % above 120 GeV. The hadron calorimeters (HCAL) that cover the central pseudorapidity regions, HB ($|\eta| <$1.3) and HE (1.3$< |\eta| <$3), are made of brass and scintillator while the forward hadron calorimeters, HF ($|\eta| >$3), are made of steel and quartz fibers. Since the calorimeter system is non-compensating, it yields a non-linear response to hadrons and a limited energy resolution (S=110% and C=8.5%), which is greatly improved by reconstruction techniques that combine information from all sub-detectors to benefit from the high ECAL granularity and excellent tracking.

## 3. Jet Types and Algorithms

Jets are the experimental signature of quarks and gluons. We may reconstruct *parton jets* from partons immediately after the hard  scattering, or *particle jets* from final state colorless particles after hadronization, or *detector jets* from detector read out information. In CMS, detector jets are reconstructed from either tracks only, calorimeter towers only, which may or may not be corrected a posteriori with the track measured momenta, or from individually reconstructed particles using the particle-flow (pflow) technique. A clustering algorithm is executed at the end of the jet reconstruction process to define a jet of any type, at any level.

### 3.1 Detector Jets

The most simple detector jet type is the *CaloJet*, defined by a clustering algorithm run on calorimeter towers with energy depositions above a given energy threshold to minimize noise. The size of a calorimeter tower is 0.087 by 0.087 in $\eta - \phi$ space and, longitudinally, composed in most cases of only two segments: a 5x5 crystal matrix and an HCAL channel. CMS physicists have the choice to use the basic CaloJets or to apply on them the *Jet Plus Tracks* (JPT) corrections [4] to reduce, according to detector simulations, the jet energy response correction from a factor of 2.5 at 20 GeV to only a few percent at the same $p_T$. JPT corrections add to a CaloJet the momentum of selected charged tracks and subtract the mean calorimeter response to the charged hadron associated to the track. The track momentum and the single particle response will be measured from collider data.

The ultimate way to reconstruct jets is to run a clustering algorithm on pflow particles to form *Particle-Flow Jets* [5]. The pflow algorithm reconstructs and identifies all particle types using a combination of all the CMS sub-detectors. In very simple terms, a track associated with an ECAL cluster is an electron; if there was also activity in the HCAL, the particle would be a charged hadron.

There is also the option to reconstruct detector jets from track information only, *Track Jets*, as described in reference [6].

### 3.2 Jet Clustering Algorithms

There are two main classes of jet clustering algorithms which are described elsewhere [7]: the fixed cone type and the sequential clustering type. In order to run them at different levels and detector input types, these algorithms should be collinear and infrared safe, easy to calibrate, as well as robust against the contributions of pileup and underlying event. The CMS reconstruction sequence includes most of the jet clustering algorithms in the market but assigns first priority to the Anti-$k_T$ algorithm in what regards to calibration, because it fulfills the above requirements best.

In a nutshell, the $k_T$ algorithm favors the merging of low $p_T$ elements into a high $p_T$ core, while Anti-$k_T$ favors the clustering of high $p_T$ elements. The result is an object of irregular shape in $\eta - \phi$ space in the case of $k_T$, and a cone-like shape in the case of Anti-$k_T$. Anti-$k_T$ is therefore CMS's "cone" algorithm of choice. Although the iterative cone algorithm has been extensively used in CMS, including all the results contained in these proceedings (R=0.5 unless noted otherwise), its use in the analyzes based on the upcoming 2010 collider run is highly discouraged because it is not infrared and collinear safe. The seedless infrared safe cone algorithm (SISCone) addresses the safety issue by considering all stable cones as proto-jets, without seeds involved in the reconstruction process. Simulations, however, predict that time performance deteriorates significantly for SISCone as instantaneous luminosity increases or for a heavy ion environment.

## 4. Jet Performance

### 4.1 Jet Energy Scale

The observed energy of detector jets need to be corrected for electronic noise, pileup, detector inhomogeneity and non-linearity, as well as physics effects. CMS has developed a data driven

factorized approach to measure Jet Energy Corrections (JEC) [8]. The offset, relative, and absolute corrections are required while the electromagnetic, flavor, underlying event, and parton corrections may be applied or not depending on the analysis. The offset correction removes from each jet, on average, the energy due to noise and pile-up [9]. It will be measured from a non-zero suppressed trigger running continuously at a low rate. Monte Carlo (MC) studies predict a noise contribution of 0.15 GeV at $\eta$=0 while the additional contribution per pileup event is estimated to be 0.25 GeV. The data driven relative correction removes the $\eta$ dependence of the jet energy response using the dijet balance technique on a dijet trigger sample [10]. Figure 1 shows the $\eta$ dependence of the jet energy response before and after the correction. The absolute correction [11], also shown in Fig. 1, removes the $p_T$ dependence of the jet response which is very large for low $p_T$ CaloJets due to the non-linear behavior of the Ecal/Hcal system. The absolute correction is measured from data using $p_T$ balance on $\gamma$ and $Z$+jets samples. Since this technique balances the jet against a photon or a $Z$ boson, it returns a correction to the parton level, which is by default mapped to the particle level for the flavor mix in the inclusive dijet sample. Detailed simulation studies focused on the first 10 pb$^{-1}$ to be collected predict a total systematic uncertainty in the central $\eta$ region for CaloJets of less than 10%. The ultimate 1-2 % uncertainty may be obtained in the longer term from MC after it has been tuned to collider data with high accuracy. The jet response for JPT and pflow jets is much higher and flatter versus $p_T$ than for CaloJets [4, 5]. While CaloJets need to be corrected by a factor of $\approx$ 2.5 at 20 GeV, the residual correction for JPT and pflow jets is only a few percent. In addition, the energy and position resolutions are significantly improved, and the flavor dependence is reduced to a negligible effect.

### 4.2 Jet Energy and Position Resolutions

CMS has demonstrated and is planning to use the dijet asymmetry method developed at the Tevatron to measure jet energy resolutions [12]. The use of measured tracks by the JPT and the pflow algorithms promises a large improvement in jet energy resolutions at low $p_T$ with respect to the performance of CaloJets (Figure 2) [4, 5]. The same holds true for the $p_T$ dependence of the jet matching efficiency, as well as for the jet $\phi$ ($\eta$) resolution, which improves from 0.1 (0.06) to 0.03 (0.025) for $p_T$=30 GeV jets [5].

## 5. Missing $E_T$ Types and Performance

Calorimeter $E_T$ or *CaloMET* [13] is calculated from the vector sum of the $x$ and $y$ components of the energy of individual calorimeter towers. Jet energy corrections are subsequently applied by vectorially adding to CaloMET the reconstructed raw $p_T$ of all jets in the event, and subtracting the corrected values. Corrections for $\mu$'s, $\tau$'s, and unclustered energy are also applied. After corrections, the difference between measured and generated $E_T$ is greatly reduced. The experimental challenge to improve $E_T$ resolution and reduce the detector induced high $E_T$ tails is addressed by using information from other parts of the detector.

Track corrected CaloMET objects, or *tcMET* [14] are derived by first correcting Calo MET for the missing muon $\vec{p}_T$. The second step involves the vector addition of the expected average transverse energy deposited by charged hadron tracks and the subtraction of the associated tracks $\vec{p}_T$ measured at vertex. This method relies on the accurate measurement of the pion response

function versus $p_T$ and $\eta$, and promises to reduce the number of $Z(ll)$ events with $E_T > 30$ (50) GeV by a factor of 3.4 (6.8). An improvement of 20% in $E_T$ resolution is also predicted for $t\bar{t}$ events. (See Fig. 3.)

Missing $E_T$ is also reconstructed from particle flow objects into a *pfMET* [5]. Simulation studies predict that the $E_T$ resolution would be improved by a factor of $\approx 2$ with respect to CaloMET in $t\bar{t}$ events. (See Fig. 3.)

## 6. Jet and $E_T$ Commissioning at Startup

The results based on detector simulation presented here are very encouraging, but measuring $E_T$ in real collider data is not an easy task. Fake $E_T$ appears naturally in multi-jet events due to detector malfunctioning and noise, hot cells, cosmic rays, beam halo contamination, particles falling in the cracks, and large hadron shower fluctuations. Using cosmic ray runs and MC samples, CMS has developed a combined set of noise filters and jet quality cuts to remove spurious energy clusters and measure clean samples of events with jets and $E_T$ [15, 16]. At the end of the collider data commissioning period, CMS should be delivering jet energy corrections with uncertainties of the order of 5%, as well as a first pass to data driven energy resolutions and efficiencies. There are several good reasons why the startup period should be reasonably short. The first one is that CMS has run for many years in test beam and cosmic ray modes. The detector has been thoroughly debugged and the simulation carefully tuned including material budget, physics, and noise. Second, the working groups have benefited from the accumulated experience at previous hadron collider experiments. There is evidence for an excellent performance of the CMS detectors and accuracy of the simulation tools. As examples, the muon track position resolution measured in cosmic rays agrees with the MC prediction within a few percent [17], and the simulated single pion response agrees with test beam measurements within 2% above 2 GeV.

## 7. Summary and Outlook

The CMS jet and $E_T$ reconstruction, cleaning, and calibration tools are well developed and validated with MC, test beam, and cosmic data. A jet and $E_T$ startup plan is in place which includes a data quality monitoring and prompt analysis task force to identify and fix problems as they arise. A close working relationship with the detector groups should ensure the necessary synchronization to adjust quickly to eventual changes in run and detector conditions.

## References

[1] CMS Collab., *TDR Vol.II: Physics Performance*, J. Phys. G: Nucl. Part. Phys. 34 995-1579, 2007.

[2] CMS Collab., *TDR Vol.I: Detector Performance and Software*, CERN/LHCC 2006-001, 2006.

[3] CMS Collab., *The CMS experiment at the CERN LHC*, JINST 3:S08004, 2008.

[4] CMS Collab., *The Jet Plus Tracks Algorithm for Calorimeter Jet Energy Corrections in CMS*, CMS-PAS-JME-09-002.

[5] CMS Collab., *Particle-Flow Event Reconstruction in CMS and Performance for Jets, Taus, and MET*, CMS-PAS-PFT-09-001.

[6] CMS Collab., *Performance of Jet Reconstruction with Charged Tracks only*, CMS-PAS-JME-08-001.

[7] JHEP, 0705:086, (2007). JHEP, 9708:001, (1997). JHEP, 0804:063, (2008).

[8] CMS Collab., *Plans for Jet Energy Corrections at CMS*, CMS-PAS-JME-07-002.

[9] CMS Collab., *Offset Energy Correction for Cone Jets*, CMS-PAS-JME-09-003.

[10] CMS Collab., *Determination of the Relative Jet Energy Scale at CMS from Dijet Balance*, CMS-PAS-JME-08-003.

[11] CMS Collab., *Jet energy calibration with γ+jet events*, CMS-PAS-JME-09-004.
CMS Collab., *Determination of the jet energy scale using $Z(e^+e^-)$+jet $p_T$ balance and a procedure for combining data driven corrections*, CMS-PAS-JME-09-005.
CMS Collab., *Calibration of the absolute jet energy scale with $Z(\mu\mu)$+jet events at CMS*, CMS-PAS-JME-09-009.

[12] CMS Collab., *Determination of the Jet Energy Resolutions and Jet Reconstruction Efficiency at CMS*, CMS-PAS-JME-09-007.

[13] CMS Collab., *Missing ET Performance*, CMS-PAS-JME-07-001.

[14] CMS Collab., *Performance of Track-Corrected Missing Transverse Energy in CMS*, CMS-PAS-JME-09-010.

[15] CMS-DP-2009-009.

[16] CMS Collab., *Calorimeter Jet Quality Criteria for the First CMS Collision Data*, CMS-PAS-JME-09-008.

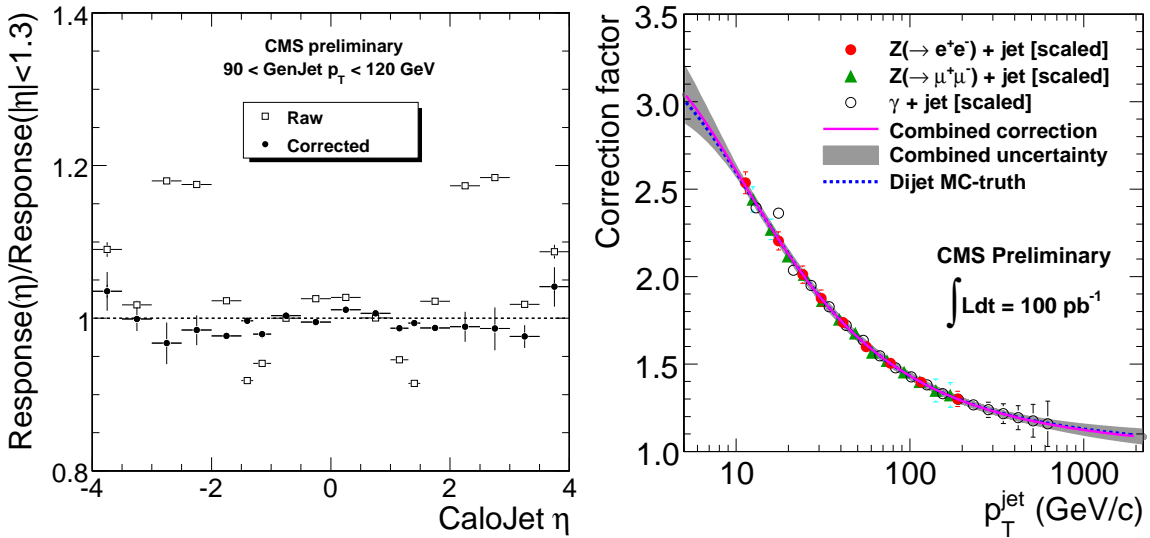[17] CMS Collab., *Alignment of the CMS Silicon Tracker during Commissioning with Cosmic Rays*, arXiv:0910.2505v1.

**Figure 1:** η dependence of the jet energy response before and after the correction (left). Absolute energy response correction correction versus $p_T$ (right).
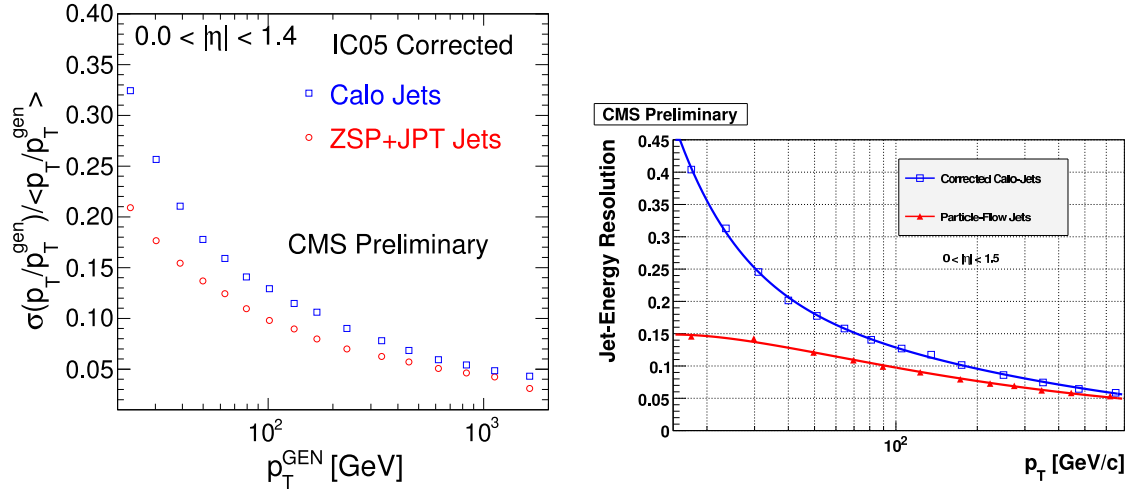
**Figure 2:** Jet fractional $p_T$ resolution for CaloJets and JPT jets (left). Jet fractional $p_T$ resolution for CaloJets and pflow jets (right).
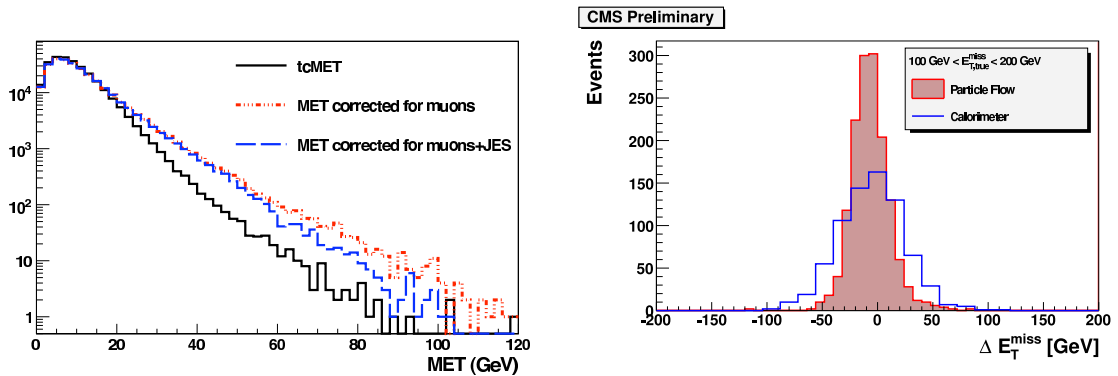


**Figure 3:** High $E_T$ tail reduction in $Z(ll)$ with tcMET (left). $E_T$ resolution improvement in $t\bar{t}$ with pflow $E_T$ (right).