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Reconstructing Jets and Missing Transverse Energy using the CMS Detector

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Abstract

In 2007, the Large Hadron Collider (LHC) will circulate and collide proton-proton beams for the first time. The Compact Muon Solenoid (CMS) is one of four experiments at the LHC and is entering the final phases of construction and initial phases of commissioning. This report discusses the expected performance of reconstructing jets and missing transverse energy using the CMS Detector. In addition, strategies for calibrating the energy scale using real data are presented.

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1 Introduction

The Compact Muon Solenoid (CMS) is a multi-purpose, nearly 4π-solid-angle-coverage detector, which is being constructed at the future Large Hadron Collider (LHC) located at CERN near Geneva, Switzerland. A brief introduction to the CMS calorimeter system is provided here. More details of the CMS detector and its expected performance may be found in [1] and [2].

The barrel part of the CMS Electromagnetic Calorimeter (ECAL) covers the pseudorapidity range $|\eta| < 1.479$ with a total of 61 200 lead-tungstate crystals. The crystal cross-section corresponds to $\Delta\eta \times \Delta\phi = 0.0174 \times 0.0174$ and the length corresponds to 25.8 X_0. The two endcaps cover the rapidity range $1.479 < |\eta| < 3.0$ and are comprised of 7 324 crystals each.

The central barrel and endcap CMS Hadronic Calorimeter (HCAL) subdetectors completely surround the ECAL and are fully immersed within the 4T magnetic field of the solenoid. The barrel and endcap are joined hermetically with the barrel extending out to $|\eta| = 1.4$ and the endcap covering the overlapping range $1.3 < |\eta| < 3.0$.

The forward calorimeters extend the pseudorapidity coverage from $|\eta| = 2.9$ to $|\eta| = 5$ and are specifically designed to measure energetic forward jets and to increase the hermeticity of the missing transverse energy measurement. Central shower containment in the region $|\eta| < 1.26$ is improved with an array of scintillators located outside the solenoid in the outer barrel HCAL.

Readout cells in HCAL are arranged in a tower pattern in η, ϕ space, pointing towards the nominal interaction point. The cells in the barrel region have a segmentation of $\Delta\eta \times \Delta\phi = 0.087 \times 0.087$, becoming progressively larger in the endcap and forward regions. Since the ECAL granularity is much finer than HCAL, combined "calorimeter towers" are formed by adding the ECAL "plus" HCAL signals within η, ϕ bins corresponding to individual HCAL cells. In total there are 4 176 such projective calorimeter towers.

The results presented in this brief report are obtained with the full CMS detector simulation and reconstruction software, including pile-up effects corresponding to an instantaneous luminosity of $2 \times 10^{33} \text{cm}^{-2}\text{s}^{-1}$.

2 Jet Reconstruction

Calorimeter towers are used as input to several well known jet clustering algorithms (iterative cone, midpoint cone and inclusive k_T jet algorithm) and are treated as massless particles, with the energy given by the total tower energy, and the direction defined by the interaction point and the center of the tower.

The reconstructed jet energy resolution, using the iterative cone $R = 0.5$ algorithm and requiring $|\eta| < 1.4$, is determined from a sample of simulated QCD dijet events, generated roughly flat in the parton transverse momenta ($\hat{p}_\text{T}$) within the range 0–4000 GeV, and is well described by the following [1]:

$$\frac{\sigma(E_\text{T})}{E_\text{T}} = \frac{1.25}{\sqrt{E_\text{T}}} \oplus \frac{5.6}{E_\text{T}} \oplus 0.033 \tag{1}$$

The first term is due to the stochastic response of the calorimeter measurements. The second term comes from fixed energy fluctuations in the jet cone from electronic noise, pile-up and underlying event energy. And, the last term is a constant resulting from residual non-uniformities and non-linearities in the detector response.

2.1 Jet Energy Scale Calibrations

Calibrations to the jet energy scale are based on two possible schemes: corrections to the "particle-level" (accounting for detector effects only), or corrections to the "parton-level" (including effects due to theoretical modeling) [1].

Monte Carlo simulation based methods are used to correct the reconstructed jet energy to the energy of the particles resulting from the fragmented primary quark or gluon, independently clustered by the same algorithm and matched to the reconstructed jet; this is known as "particle-level" calibration.

An average offset correction is applied resulting from multiple interactions in the event's bunch crossing, pile-up from interactions from neighboring bunch crossings, the underlying event, and any residual electronic noise after calorimeter thresholds. This is followed by a response correction (at a given p_T and η) to the average equivalent particle-level jet, resulting from nonlinear response of the calorimeter to hadrons, differences in response among

the calorimeter regions in η, lower response of cracks between calorimeters, and from the different particles contributing to the independently clustered particle-level and reconstructed jets due to magnetic field and shower spreading effects.

While Monte Carlo methods provide a starting point for understanding the initial jet energy calibration, data driven methods will be used to facilitate the overall calibration procedure to the "parton-level."

Apart from higher-order initial-state effects, the direct photon produced from Compton ($qg \to q + \gamma$) and annihilation ($q\bar{q} \to g + \gamma$) processes have a transverse momentum that is balanced by the jet. The high resolution ($\sim 1\%$) of the ECAL provides an accurate measurement of the photon and thus forms the basis for calibrating hadronic jets. CMS expects to be able to use this technique to calibrate jet energy scales to within $\sim 5\%$.

Transverse momentum balance may also be used in QCD dijet events to measure relative jet response and resolution from data. Events are selected having one of the two leading jets in the region $|\eta| < 1$ (the "barrel" jet), while the other leading jet (the "probe" jet) may be at any value of η. Because of the high QCD cross-section at the LHC, a single day's worth of data taking is expected to be enough to calibrate the relative response of the detector to jets with a statistical error of 0.5% in the barrel and 2% in the endcap.

Finally, via the well-measured W boson mass, one can determine the absolute energy scale of reconstructed jets from the decay $W \to q\bar{q}$ in a selected sample of $t\bar{t} \to bW\bar{b}W \to bq\bar{q}\bar{b}\mu\nu_\mu$ events. The current estimate for the precision of the absolute jet energy scale using this technique is about 3%, which is systematically limited by the estimated effects due to pile-up.

3 Missing Energy Reconstruction

The missing transverse energy vector is calculated by summing the x, y components of individual calorimeter towers having energy E_n, polar angle θ_n and azimuthal angle ϕ_n:

$$
\begin{aligned}
\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}} &= \Sigma(E_n \sin\theta_n \cos\phi_n \hat{\mathbf{i}} + E_n \sin\theta_n \sin\phi_n \hat{\mathbf{j}}) \\
&= E_x^{\mathrm{miss}}\hat{\mathbf{i}} + E_y^{\mathrm{miss}}\hat{\mathbf{j}}.
\end{aligned}
\tag{2}
$$

In addition, the scalar ΣE_{T} is calculated by taking the simple scalar energy, E_n, and summing over all individual calorimeter towers.

Reconstructing $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$ at the LHC is complicated by pile-up and the underlying event. Further, the non-compensating nature of the CMS calorimeter towers' response to electrons and pions significantly affects the resolution of $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$. On the other hand, the excellent cell segmentation, hermeticity, and good forward coverage of CMS assist in the measurement of $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$. Considering all effects, including the sweeping away of low-p_T tracks in the 4 T magnetic field, the $\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$ resolution in CMS is still expected to be dominated by calorimeter resolution.

In QCD dijet events, where no $E_{\mathrm{T}}^{\mathrm{miss}}$ is expected, the observed $E_{\mathrm{T}}^{\mathrm{miss}}$ balance is directly related to the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution. A fit to the ratio of the reconstructed missing transverse energy to the scalar summed E_{T} (ΣE_{T}) is well described by:

$$
\frac{< E_{\mathrm{T}}^{\mathrm{miss}} >}{\Sigma E_{\mathrm{T}}} = \frac{1.23}{\sqrt{\Sigma E_{\mathrm{T}}}} \oplus \frac{5.4}{\Sigma E_{\mathrm{T}}} \oplus 0.019
\tag{3}
$$

and is consistent with the jet transverse energy resolution [1].

3.1 Cosmic and Beam Halo Cleaning

The quality of the $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction depends strongly on the ability to reject accelerator- and detector-related backgrounds (such as beam halo background or electronic noise), as well as cosmic ray events. Studies of the CMS response to a beam halo background simulation at LHC Point 5 show that by requiring at least one primary vertex in the event together with a requirement on the event electromagnetic fraction, $F_{em} < 0.1$ (ratio of the electromagnetic fraction of clustered energy to the total clustered energy) and the event charged fraction, $F_{ch} < 0.175$ (ratio of the total charged track p_T associated to clustered energy over the total clustered energy) can be used to help distinguish between real and fake jet and missing energy events [2].

3.2 Calibration Strategies

The response of the CMS detector to real missing energy can be calibrated using leptonic decays of the Z boson, $Z \to ll +$ jets (where ll is either dielectrons or dimuons) with $P_{\mathrm{T}}^Z > 200$ GeV/c. The advantage of the muon

channel is the efficient CMS muon detection due to the tracking and muon systems; the advantage of the electron channel is the excellent energy resolution of the ECAL. Simulations show that the "Z-mass" tag requirement is approximately 90% efficient and, considering both the electron and muon decays of the Z boson, a statistically adequate ($\sim$5% precision) sample which is needed to normalize the $Z \to \nu\nu$ + jets predictions for $E_T^{\mathrm{miss}} > 200$ GeV is expected to be obtained after $\sim$1.5 fb^{-1} of data has been collected [2].

4 Recent Testbeam Results

Data taken during a combined ECAL and HCAL Testbeam run in the Autumn of 2006, with particle energies ranging from 2 GeV to 300 GeV and very clean particle (pion, electron, muon) identification [3], demonstrate that the non-compensating nature of the calorimeter towers' response to electrons (E) versus pions (H) can be effectively corrected. Such a correction improves the calorimeter tower energy resolution from $\sim 120\%/\sqrt{E} \oplus 5\%$ (uncorrected for E/H) to $\sim 80\%/\sqrt{E} \oplus 8\%$ (corrected for E/H) and indicates that significant improvements in the resolution for jets and missing energy may still be possible.

5 Summary and Outlook

The results presented in this brief report are obtained with the full CMS detector simulation and reconstruction software, including pile-up effects corresponding to an instantaneous luminosity of 2×10^{33}cm^{-2}s^{-1}. Under such conditions, the performance of reconstructing jets and missing transverse energy using the CMS Detector is expected to be, $125\%/\sqrt{E_T}$ (stochastic term) in the case of jets and, $123\%/\sqrt{\Sigma E_T}$ (stochastic term) in the case of E_T^{miss}. Encouraging results from the recent testbeam in 2006 indicate that improvements in the resolution for jets and missing energy may still be possible.

References

[1] CMS Collaboration, **CERN/LHCC 2006-001** (2006).

[2] CMS Collaboration, **CERN/LHCC 2006-021** (2006).

[3] L. Berntzon, "Test beam results, CMS combined ECAL, HCAL testbeam," Contribution to these proceedings, IPRD06, Siena (2006)