Abstract

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Missing $E_T$ Reconstruction with the CMS Detector

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1. Introduction

In the CMS experiment, missing $E_T$ (MET) in proton-proton collisions is reconstructed and used in a wide range of physics analyses. MET is the imbalance in the transverse momentum of all visible particles, particles which interact with the electromagnetic or strong forces, in the final state of proton-proton collisions. Because momentum is conserved in each direction, MET is the transverse momentum that must have been carried by something invisible. Neutrinos, for example, are invisible particles; therefore, MET is an estimate of transverse momentum of neutrinos. We use MET in measurements of W bosons, top quarks, and tau leptons as these particles can decay into neutrinos. Further, many models of physics beyond the Standard Model predict the existence of particles or something else which are invisible and can carry momentum; e.g., Dark Matter models, supersymmetric models, unparticle models, and models with large extra dimensions. For this reason, we use MET to test such models.

Accurate reconstruction of MET is demanding because it entails reconstruction of all visible particles in an event with precision. This requires a hermetic detector which can detect all particles which electromagnetically or strongly interact with matter. The CMS detector, located at one of two high luminosity interaction points of the Large Hadron Collider (LHC), meets this requirement. The subsystems of the CMS detector include highly granular electromagnetic calorimeters, hermetic hadronic calorimeters, redundant muon systems, and all silicon trackers in a strong magnetic field. A thorough description of the CMS detector can be found in Ref. [1].

Based on 36 pb$^{-1}$ of data collected at the center-of-mass energy $\sqrt{s} = 7$ TeV in 2010, the CMS collaboration published the results of comprehensive studies of the MET reconstruction performance [2]. In 2011, the CMS detector collected a considerably larger amount of data. These proceedings summarize preliminary results of the MET reconstruction performance study based on the data collected in 2011 [3, 4].
With the increase in the LHC luminosity, the number of multiple proton-proton interactions in the same bunch crossing (in-time pile-up) and overlapping detector signal from previous or following bunch crossings (out-of-time pile-up) significantly increased. The pile-up events worsen the performance of the MET reconstruction. We have developed several techniques to mitigate the effect of pile-up events.

2. The 7 TeV proton-proton collision run in 2011

These proceedings use 4.6 fb$^{-1}$ of proton-proton collision data collected with the CMS detector at the center-of-mass energy $\sqrt{s} = 7$ TeV in 2011. We divided the data collection period into two eras: Run 2011A and Run 2011B. For proton-proton collisions, Run 2011A started in March 2011 and ended in August 2011; Run 2011B started in September 2011 and ended in October 2011. Of the 4.6 fb$^{-1}$ of data, 2.0 fb$^{-1}$ was collected in Run 2011A and 2.6 fb$^{-1}$ was collected in Run 2011B. Since the LHC luminosity rapidly increased over the year, Run 2011B was shorter than Run 2011A but more data were collected. In addition, the number of pile-up events also increased. The average number of the reconstructed vertices in a single bunch crossing, which indicates the average number of in-time pile-up events, increased from 5.5 in Run 2011A to 9.2 in Run 2011B. The distributions of the number of the reconstructed vertices in a single bunch crossing are shown in Figure 1.

![Figure 1](image.png)

Figure 1. The distributions of the number of reconstructed vertices in a single bunch crossing in Run 2011A (left) and Run 2011B (right). The events contained Z bosons decaying into dimuons. The detail of the reconstruction and selection of events can be found in Ref. [4].

3. MET reconstruction algorithms and corrections

MET used in these proceedings is based on a particle-flow algorithm and includes the Type-I MET correction, a propagation of jet energy corrections. This MET, both with and without the correction, is called particle-flow MET (pfMET) in Ref. [2]. Ref. [2] contains more detailed description of pfMET and the Type-I MET correction as well as other definitions of MET and corrections to MET.

First, raw MET was defined as the imbalance in the transverse energy$^1$ of all particles in the event reconstructed by a particle-flow algorithm. The detail of the particle-flow algorithm at CMS can be found in Ref. [5]. In short, the particle-flow algorithm uses information from all CMS detector subsystems, i.e., trackers, calorimeters, and muon systems; then, it reconstructs

$^1$ We will use the transverse momentum instead of the transverse energy in the near future.
four momenta of all visible particles, each of which is identified as one of five particle types, i.e., electrons, photons, muons, charged hadrons, and neutral hadrons.

The raw MET is systematically different from true MET, i.e., the transverse momentum carried by invisible particles, for many reasons including the non-compensating nature of the calorimeters. To make MET a better estimate of true MET, the Type-I MET correction was applied. The Type-I MET correction replaces the transverse energy of particles which can be clustered as jets with the transverse momentum of the jets to which jet energy corrections are applied. The detail of jet energy corrections at CMS can be found in Ref. [6].

4. False MET and event cleaning

Large MET is caused not only by interesting physics processes in proton-proton collisions such as production of invisible particles. In fact, large MET has more often uninteresting causes such as detector noise, cosmic rays, and beam-halo particles. MET with uninteresting causes is called false MET or anomalous MET. For an accurate reconstruction of MET, it is, therefore, not sufficient to reconstruct all visible particles produced in proton-proton collisions.

We developed several algorithms to identify false MET. These algorithms, for example, use timing, pulse shape, and topology of signal. After the identified false MET was removed, the agreement of the MET spectrum with simulation, in which causes of false MET were not explicitly simulated, significantly improved (Figure 2).

![Figure 2](https://example.com/figure2)

**Figure 2.** MET spectrum in dijet events collected in early 2011 before and after the cleaning. The highest bin includes the overflow. The simulation includes QCD events, top pair production events, W + jets production events, and Z + jets production events. The simulation does not explicitly include sources of false MET such as cosmic rays or beam-halo particles. The detail of the event selection and cleaning can be found in Ref. [3].

5. Performance of MET reconstruction

MET response and resolution are measures of MET reconstruction performance. We evaluated them by artificially inducing MET in events very likely to have only little or no true MET. We used events with vector bosons, either Z bosons decaying into dimuons or photons. These vector bosons are predominantly produced in interactions with no true MET, such as $qg \rightarrow q\gamma$, $qq \rightarrow Z$, $qg \rightarrow qZ$, $qg \rightarrow gZ$. Therefore, an event is primarily composed of a vector boson and
its hadronic recoil. The dimuons and photons were measured with precision by, respectively, the trackers and muon systems, and the electromagnetic calorimeters. To induce MET for the performance evaluation, we excluded the dimuons or photons from the MET reconstruction; the dimuons or photons played the role of invisible particles. Then, the MET performance can be indicated by how close reconstructed MET is to the transverse momentum of the excluded dimuons or photons.

The transverse momentum of the vector boson is $\vec{q}_T$. The vector sum of the transverse energy of all reconstructed particles except the vector boson, i.e. the hadronic recoil, is $\vec{u}_T$. Thus, the induced MET is $\vec{E}_T = -\vec{u}_T$. The projection of $\vec{u}_T$ on $\vec{q}_T$ is $u_||$, which is typically negative. The component of $\vec{u}_T$ perpendicular to $\vec{q}_T$ is $u_\perp$. These kinematic variables are illustrated in Figure 3.

MET response is defined as $-u_||/|\vec{q}_T|$, the ratio of the MET component parallel to the transverse momentum of the vector boson and the magnitude of the transverse momentum of the vector boson. Figure 4 shows the MET response in events with Z bosons decaying into dimuons. The response is close to unity at above certain $|\vec{q}_T|$ and has little dependence on the number of pile-up events.

MET resolutions are defined as the RMS of $u_\parallel$ and $u_\perp$ about their mean values, denoted, respectively, as RMS($u_\parallel$) and RMS($u_\perp$). Figure 5 shows the MET resolutions in Z events as a function of the number of reconstructed vertices for data collected in Run2011A and Run2011B. Figure 6 shows the MET resolutions as functions of $|\vec{q}_T|$ in photon events for four different numbers of vertices.
The resolutions degrade as the number of reconstructed vertices (in-time pile-up events) increases. The resolutions are worse in events for Run2011B than events with the same number of in-time pile-up events for Run2011A because the out-of-time pile-up increased.

![Figure 5](image5.png)

**Figure 5.** MET resolutions RMS($u_T$) (left) and RMS($u_\perp$) (right) as functions of the number of reconstructed vertices ($N_{vtx}$) in events with Z bosons decaying into dimuons. MET resolutions are separately shown for data collected in Run2011A and Run2011B and for MC simulation for each era. The detail of the reconstruction and selection of events can be found in Ref. [4].

![Figure 6](image6.png)

**Figure 6.** MET resolutions RMS($u_T$) (left) and RMS($u_\perp$) (right) as functions of the photon $|q_T|$ in events with photons for data collected in early Run2011A, shown separately for events with four different numbers of reconstructed vertices. A curve which fit data for events with one vertex collected in 2010 is also shown. The detail of the reconstruction and selection of events can be found in Ref. [3].
6. Mitigation of MET degradation in high pile-up events
This section briefly introduces one of the techniques that CMS used to mitigate the degradation of the MET performance caused by the pile-up events.

As shown in the previous section, the MET performance becomes worse as the number of pile-up events increases. Then, when MET is used in event selections in physics analyses, the efficiency of selecting signal events decreases. In order to prevent the efficiency from decreasing, an analysis of the search for the Higgs boson decaying into a pair of W bosons [7] defined another kinematic variable similar to MET, which is called TrackMET in Ref. [4]. TrackMET is the imbalance in the transverse momentum of charged particles originating from the primary vertex of the high-\(p_T\) event. By its construction, it depends little on the number of pile-up events. It was shown that using a combination of TrackMET and MET improved the signal efficiency in this analysis [7].

7. Summary
MET is an estimate of the transverse momentum of neutrinos and other invisible particles or some stuff with momentum. In the CMS experiment, MET plays a central role in both precision measurements of Standard Model physics and searches for physics beyond the Standard Model.

Using 4.6 fb\(^{-1}\) of proton-proton collision data at the center-of-mass energy \(\sqrt{s} = 7\) TeV collected with the CMS detector in 2011, we evaluated the performance of the reconstruction of MET, which was based on a particle-flow algorithm, and in particular how it was affected by pile-up events. After false MET was removed, the MET spectrum was well described by MC simulation. While the MET response exhibited little dependence on the number of pile-up events, the MET resolutions became worse as the number of pile-up events increased. We have developed several techniques to mitigate the effect of the pile-up events. As the LHC luminosity is expected to keep rapidly increasing, it will be important to continue to develop and refine techniques to handle a large number of pile-up events.

In 2012, the CMS detector is collecting proton-proton collision data at the center-of-mass energy \(\sqrt{s} = 8\) TeV at the increasing luminosity. MET will remain an important object to be reconstructed for a variety of physics analyses at the CMS experiment.

References