Performance of Missing Transverse Momentum Reconstruction in ATLAS with Proton-Proton Collisions at $\sqrt{s} = 7$ TeV

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Abstract. The performance of the missing transverse momentum reconstruction in the ATLAS detector is evaluated using data collected in proton-proton collisions at a centre-of-mass energy of 7 TeV in 2010. Evaluation of the systematic uncertainty on the missing transverse momentum scale is presented. A method to mitigate the effects arising from additional proton-proton interactions superimposed on the hard physics process is also discussed for the 2011 beam conditions.

1. Introduction
In a hadron collider event the missing transverse momentum is defined as the event momentum imbalance in the plane transverse to the beam axis, where momentum conservation is expected. Such an imbalance may signal the presence of undetectable particles, such as neutrinos or new stable, weakly-interacting particles. The vector momentum imbalance in the transverse plane is obtained from the negative vector sum of the momenta of all particles detected in a proton-proton ($pp$) collision and is denoted as missing transverse momentum, $E_T^{\text{miss}}$. The symbol $E_T^{\text{miss}}$ is used for its magnitude.

An important requirement on the measurement of $E_T^{\text{miss}}$ is the minimization of the impact of limited detector coverage, finite detector resolution, the presence of dead regions and different sources of noise, as well as cosmic-ray and beam-halo muons crossing the detector, that can produce fake $E_T^{\text{miss}}$. The ATLAS calorimeter [1] coverage extends to large pseudorapidities\(^\dagger\) to minimize the impact of high energy particles escaping in the very forward direction.

The $E_T^{\text{miss}}$ measurement is significantly affected by the contributions of additional $pp$ collisions superimposed on the hard physics process, referred to as pile-up in the following, so it is important to develop methods to suppress such contributions. Such a method is described in the last section of this note. The performance, in terms of resolution, scale and tails, of an optimised reconstruction and calibration of $E_T^{\text{miss}}$ [2] developed by the ATLAS Collaboration is described.

The event samples used to assess the quality of the $E_T^{\text{miss}}$ reconstruction are minimum bias and

\(^\dagger\) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis coinciding with the axis of the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$ axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. 
QCD di-jet events and events with leptonically decaying $W$ and $Z$ bosons. The performance in both data and Monte Carlo simulation as well as their comparison is studied. The data sample corresponds to an integrated luminosity of $36 \text{ pb}^{-1}$ from 2010 and $4.2 \text{ fb}^{-1}$ from 2011. The latter is used for the study of the performance in pile-up conditions, where the average number of extra interactions ranges from 6 to 15.

2. Calibration and Reconstruction
The $E_T^{\text{miss}}$ reconstruction includes contributions from energy deposits in the calorimeters and muons reconstructed in the muon spectrometer. Tracks are added to recover the contribution from low-$p_T$ particles which are missed in the calorimeters. Muons reconstructed from the inner detector are used to recover muons in regions not covered by the muon spectrometer. The $E_T^{\text{miss}}$ reconstruction uses calorimeter cells calibrated according to the reconstructed physics object to which they are associated. Calorimeter cells are associated with a reconstructed and identified high-$p_T$ parent object in a specific order: electrons, photons, hadronically decaying $\tau$-leptons, jets and finally muons. Cells not associated with any such objects (referred to as “CellOut” below) are also taken into account in the $E_T^{\text{miss}}$ calculation [2].

Once the cells in the calorimeters are associated with objects as described above, the $E_T^{\text{miss}}$ is calculated as follows:

\[
E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss},e} + E_{x(y)}^{\text{miss},\gamma} + E_{x(y)}^{\text{miss},\tau} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,softjets}} + (E_{x(y)}^{\text{miss,calo,}\mu}) + E_{x(y)}^{\text{miss,CellOut}} + E_{x(y)}^{\text{miss,}\mu},
\]

where each term is calculated from the negative sum of calibrated cell energies, projected onto the $x$ and $y$ direction, inside the corresponding objects (within $|\eta| < 4.9$) and the $E_{x(y)}^{\text{miss,}\mu}$ is calculated from the negative sum of the momenta of muon tracks reconstructed with $|\eta| < 2.7$. Note that the $E_{x(y)}^{\text{miss,calo,}\mu}$ term, the energy loss by a muon in the calorimeter, is only taken into account for muons isolated with respect to jets at the calorimeter. Because of the high granularity of the calorimeter, it is important to suppress noise contributions. Therefore, cells used in the $E_T^{\text{miss}}$ sum belong to three-dimensional topological clusters, referred to as topoclusters hereafter, with the exception of electrons and photons for which a different clustering algorithm is used.

The calibration scheme used is the one yielding the best performance in data, as described in detail in Ref. [2]. Electrons are calibrated with the default electron calibration, photons with the electromagnetic scale (EM) [2] and $\tau$-jets with the local hadronic calibration (LCW). The LCW scheme calibrates clusters according to their classification as hadron-originated or not, and corrects for energy losses in the dead material. The jets are reconstructed with the anti-$k_t$ algorithm [3] with distance parameter $R = 0.4$. They are calibrated with the LCW scheme if $10 < p_T < 20 \text{ GeV}$ (soft jets) and with the LCW+JES scheme, where JES is the jet energy scale (from calorimeter to particle level) if $p_T > 20 \text{ GeV}$ [4]. The contribution from topoclusters not associated to high-$p_T$ objects (CellOut) is calculated with LCW calibration combined with tracking information. The value of $E_T^{\text{miss}}$ is calculated as:

\[
E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}.
\]

The total transverse energy in the calorimeters, $\sum E_T$, is defined as the scalar sum of transverse energy of cells associated to the different objects where cells are calibrated according to the scheme described above for $E_T^{\text{miss}}$.

2 The EM scale is the basic calorimeter signal scale for the ATLAS calorimeters. It provides the correct scale for energy deposited by electromagnetic showers. It does not correct for the lower energy hadron shower response nor for energy losses in the dead material.
3. Performance and resolution
The distributions of $E_T^{\text{miss}}$ in minimum bias, di-jet, $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ events from data are compared with the expected distributions from the MC samples. In the minimum bias, di-jet events and $Z \rightarrow \ell\ell$ events, apart from a small contribution from the semi-leptonic decay of heavy-flavour hadrons in jets, no genuine $E_T^{\text{miss}}$ is expected. Thus most of the $E_T^{\text{miss}}$ reconstructed in these events is a direct result of imperfections in the reconstruction process or in the detector response. The comparisons show very good agreement and control of tails. Figure 1 shows the very good description of the data by the MC for $W \rightarrow e\nu$ events, where the $E_T^{\text{miss}}$ is non-zero due to the neutrino.

The $E_T^{\text{miss}}$ resolution is estimated from the width of the combined distribution of $E_{x}^{\text{miss}}$ and $E_{y}^{\text{miss}}$ in bins of $\sum E_T$, expressed by the fitted $\sigma$ of a Gaussian distribution over twice the expected resolution, as obtained from earlier studies. Figure 2 shows the resolution from data at $\sqrt{s} = 7$ TeV for $Z \rightarrow \ell\ell$ events, minimum bias and di-jet events as a function of the total transverse energy in the event, obtained by summing the $p_T$ of muons and the $\sum E_T$ in calorimeters. The resolution of the two $E_T^{\text{miss}}$ components is fitted with a function $\sigma = k \cdot \sqrt{\sum E_T}$ and the parameter $k$ quantifies the $E_T^{\text{miss}}$ resolution. There is reasonable agreement in the $E_T^{\text{miss}}$ resolution in the different physics channels, as can be seen from the fit parameters $k$ reported in the figure. They range from 0.42 GeV$^{1/2}$ for $Z \rightarrow \ell\ell$ events to 0.51 GeV$^{1/2}$ for di-jet events and agree with the $k$ values obtained in simulated events. For all data samples the uncertainty on the fitted $k$ value is small. The $E_T^{\text{miss}}$ resolution is better in $Z \rightarrow \ell\ell$ events because the lepton momenta are measured with better precision than jets.

![Figure 1. $E_T^{\text{miss}}$ distribution in $W \rightarrow e\nu$ events compared to Monte Carlo simulation [2].](image1)

![Figure 2. $E_T^{\text{miss}}$ and $E_y^{\text{miss}}$ resolution as a function of the total transverse energy in the event. The fitted values of $k$, in GeV$^{1/2}$, (see text) are reported [2].](image2)

4. Response and Scale
The in situ evaluation of the scale bias in events with no $E_T^{\text{miss}}$ and the validation of the scale in events with $W \rightarrow e\nu$ decays is presented here.

In $Z \rightarrow \ell\ell$ events one can define an axis in the transverse plane such that the component of $E_T^{\text{miss}}$ along this axis is sensitive to detector resolution and biases. This axis, $A_Z$, is defined by the reconstructed momenta of the leptons as $A_Z = (p_T^{\ell^+} + p_T^{\ell^-})/\sqrt{\sum p_T^{\ell^+} + \sum p_T^{\ell^-}}$, where $p_T^{\ell}$ are the vector transverse momenta of the lepton and anti-lepton and represents the direction of motion of the $Z$ boson.
The mean value of the projection of $E_T^{\text{miss}}$ onto the longitudinal axis, $\langle E_T^{\text{miss}} \cdot A_Z \rangle$, is a measure of the $E_T^{\text{miss}}$ scale, as this axis is sensitive to the balance between the leptons and the hadronic recoil. These mean values are used as a diagnostic to validate the $E_T^{\text{miss}}$ reconstruction algorithms. If the leptons perfectly balanced the hadronic recoil $E_T^{\text{miss}} \cdot A_Z$ would be zero. Instead, $\langle E_T^{\text{miss}} \cdot A_Z \rangle$ displays a small bias, as shown in Figure 3 as a function of $p_T^Z$ separately for events with $Z \rightarrow \ell \ell$ produced in association with jets or not. The figure shows a negative bias in $\langle E_T^{\text{miss}} \cdot A_Z \rangle$ for events with no jets, dominated by the $E_T^{\text{miss}}$, $\text{CellOut}$ term, which increases with $p_T^Z$ up to 6% and confirms that the bias is due to mis-calibration of the soft hadronic recoil.

It is very important to validate in situ the $E_T^{\text{miss}}$ scale in events with genuine $W \rightarrow \ell \nu$ events. Two complementary methods to determine the absolute scale of $E_T^{\text{miss}}$ using $W \rightarrow \ell \nu$ events are exploited. The $E_T^{\text{miss}}$ range discussed here starts at $\approx 25$ GeV.

The first method uses a fit to the distribution of the transverse mass, $m_T$, of the lepton-$E_T^{\text{miss}}$ system, and is sensitive both to the scale and the resolution of $E_T^{\text{miss}}$.

The lepton transverse momentum, $p_T^\ell$, and the $E_T^{\text{miss}}$ are used to calculate $m_T = \sqrt{2 p_T^\ell E_T^{\text{miss}} (1 - \cos \phi)}$, where $\phi$ is the azimuthal angle between the lepton and $E_T^{\text{miss}}$ directions. Template histograms of the $m_T$ distributions are generated by convolving the true transverse mass distribution with a Gaussian function $E_T^{\text{miss,smeared}}(z) = \alpha E_T^{\text{miss, True}}(z) \ast \text{Gauss}(0, k \cdot \sqrt{\Sigma E_T^z})$, with parameters $\alpha$ and $k$ being the $E_T^{\text{miss}}$ scale and resolution respectively.

These parameters are determined through a fit of the $m_T$ distribution to data using a linear combination of signal and background $m_T$ distributions obtained from simulation. The results are shown in Table 1, with the values of $\alpha$ representing the bias. The results for the $\alpha$ and $k$ using the $m_T$ distribution of the simulated signal are also shown in Table 1, and they are in good agreement with the results from data. The results obtained with this method are compatible, at the few percent level, with the ones from simulated W events on scale linearity and resolution (see figure 2). The uncertainty due to background subtraction is already included in the uncertainty reported in Table 1. The $E_T^{\text{miss}}$ scale uncertainty after checking the dependence of $\alpha - 1$ when varying selections and generator, is about 1.5% and 2% for the $W \rightarrow e \nu$ and $W \rightarrow \mu \nu$ decay channels, respectively, while the bias is less than 5%.

The second method uses the interdependence of the neutrino and lepton momenta in the $W \rightarrow e \nu$ channel, and the $E_T^{\text{miss}}$ scale is determined as a function of the reconstructed electron transverse momentum to determine the scale in $W \rightarrow e \nu$ events. The average bias is calculated to be $2.0 \pm 0.1 \pm 2.0\%$ in data, while the calculation on signal MC events alone results in $2.9 \pm 0.1\%$.

### Table 1. Results of $m_T$ fit in $W \rightarrow \ell \nu$ events. The second and third columns show the scale and resolution parameters. The uncertainties take into account background subtraction uncertainties and correlations [2].

| Channel           | $\alpha - 1$ (%) | $k$         | $\chi^2$/ndof |
|-------------------|------------------|-------------|---------------|
| $W \rightarrow \mu \nu$ data | $5.1 \pm 0.8$ | $0.52 \pm 0.01$ | $68/87$         |
| $W \rightarrow \mu \nu$ MC | $5.5 \pm 0.8$ | $0.50 \pm 0.01$ | $70/78$         |
| $W \rightarrow e \nu$ data | $-0.8 \pm 1.6$ | $0.49 \pm 0.01$ | $54/75$         |
| $W \rightarrow e \nu$ MC | $1.8 \pm 1.7$ | $0.50 \pm 0.01$ | $38/54$         |

5. **Systematic uncertainties**

The $E_T^{\text{miss}}$ uncertainty is evaluated from the individual uncertainties of the reconstructed objects used to build it. The overall systematic uncertainty on the $E_T^{\text{miss}}$ scale is then calculated by
combining the uncertainties associated with each term. The relative impact of the uncertainty of the constituent terms on $E_{T}^{\text{miss}}$ depends on the final state being studied.

The uncertainty on the scale of the $E_{T}^{\text{miss,CellOut}}$ term, which is built from topoclusters with a correction based on tracks, can be calculated from the topocluster energy scale uncertainties. These uncertainties can be estimated from comparisons between data and MC simulation using the $E/p$ response from single tracks, measured by summing the energies of all calorimeter clusters around a single isolated track. The effects of these uncertainties on the $E_{T}^{\text{miss,CellOut}}$ term can be evaluated by varying the energy scale of topoclusters that contribute to the $E_{T}^{\text{miss,CellOut}}$ term in $W \to e\nu$ MC samples where it is dominant.

The shift in the topocluster energy scale is applied by multiplying the topocluster energy by the function $1 \pm a \times (1+b/p_T)$, with $a = 3(10\%)$ for $|\eta| < (>) 3.2$, $b = 1.2$ GeV. The $a$ parameter addresses the uncertainty on the cluster energy scale, obtained by comparing the ratio of the cluster energy and the measured track momentum, $E/p$, in data and MC simulation while the $b$ parameter addresses the possible change in the clustering efficiency and scale in a non-isolated environment.

The value of the fractional $E_{T}^{\text{miss,CellOut}}$ uncertainty evaluated by shifting the energy of the topoclusters, is found to be approximately 13%, decreasing slightly with increasing $\Sigma E_{T}^{\text{CellOut}}$. This uncertainty is very conservative and much larger than the alternative estimation based on detector or reconstruction effects, shower modeling and generator uncertainties. Similarly, the uncertainty of the $E_{T}^{\text{miss,softjets}}$ term is evaluated to be about 10%.

Using as inputs the systematic uncertainties on the different reconstructed objects and on $E_{T}^{\text{miss,CellOut}}$ and $E_{T}^{\text{miss,softjets}}$, the overall $E_{T}^{\text{miss}}$ systematic uncertainty in $W \to e\nu$ and $W \to \mu\nu$ events is estimated.

Figure 4 shows the overall fractional $E_{T}^{\text{miss}}$ uncertainty together with the contributions of the individual terms uncertainties, as a function of the event $\Sigma E_{T}$ in $W \to e\nu$ events. The uncertainties on $E_{T}^{\text{miss,softjets}}$ and $E_{T}^{\text{miss,CellOut}}$ are considered to be fully correlated. The average overall uncertainty on the $E_{T}^{\text{miss}}$ scale is estimated to be about 2.6% both for $W \to e\nu$ and $W \to \mu\nu$ events. The $E_{T}^{\text{miss}}$ scale uncertainty depends strongly on the event topology.

6. Performance in pile-up conditions

A large deterioration of the resolution is observed in 2011 data and MC simulation with respect to that in 2010 due to the increased average number of pile-up interactions per event, as can be seen in Figure 5 which shows the $(E_{x}^{\text{miss}}, E_{y}^{\text{miss}})$ resolution as a function of the number of
primary vertices in the event. The $E_{T}^{\text{miss,SoftTerm}}$ term, the combination of $E_{T}^{\text{miss,CellOut}}$ and $E_{T}^{\text{miss,softjets}}$, is significantly affected by pile-up. This term cannot be omitted since it has an important contribution to the momentum balance in the event.

The method used here scales the $E_{T}^{\text{miss,SoftTerm}}$ with the soft term vertex fraction (STVF), i.e. the fraction of tracks matched to the $E_{T}^{\text{miss,SoftTerm}}$ which are associated with the hard scattering vertex and is calculated as: STVF $= \sum_{\text{track,PV}} p_T / \sum_{\text{tracks}} p_T$, where the sums are taken over the tracks unmatched to physics objects and PV denotes the tracks associated to the main primary vertex. Figure 5 shows that, after the correction of the $E_{T}^{\text{miss,SoftTerm}}$ with STVF, the dependence of the $E_{T}^{\text{miss}}$ resolution on $N_{\text{pv}}$ is significantly reduced in MC $Z \rightarrow \mu\mu$ events with no jets with $p_T > 20$ GeV. The dependence of the $E_{T}^{\text{miss}}$ resolution on $N_{\text{pv}}$ in inclusive $Z \rightarrow \mu\mu$ events is further reduced if each jet is scaled using the value of the jet vertex fraction, JVF, which is calculated in the same way as STVF using the tracks matched to the jet and has been used as an estimator of the probability of a jet to originate from pile-up. The pile-up suppression using STVF does not create additional tails in the $E_{T}^{\text{miss}}$ distribution; very few tails (< 1 per mil) are created by the pile-up suppression in jets using JVF. Figure 6 shows that the pile-up suppression in $E_{T}^{\text{miss}}$ restores the resolution to the level of events with average number of interactions per bunch crossing $\langle \mu \rangle = 0$.

![Figure 5](image1.png)  
**Figure 5.** $E_{T}^{\text{miss}}$ and $E_{T}^{\text{miss}}$ resolution vs $N_{\text{pv}}$ in $Z \rightarrow \mu\mu$ events without jets of $p_T > 20$ GeV. The pile-up suppressed $E_{T}^{\text{miss,SoftTerm}}$ is shown for MC [5].

![Figure 6](image2.png)  
**Figure 6.** $E_{x}^{\text{miss}}$ and $E_{y}^{\text{miss}}$ resolution vs the event $\sum E_{T}$ in $Z \rightarrow \mu\mu$ MC events for different values of $\mu$ [5].

7. **References**

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3 The main primary vertex is the primary vertex with the largest track $\sum p_T^2$ associated with it.