Performance of missing transverse momentum reconstruction in ATLAS studied in proton-proton collisions in 2012 at 8 TeV

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Abstract. The missing transverse energy plays a really important role in reconstructing events produced at hadron colliders. Undetectable particles, such as neutrinos, pass through the matter with a negligible probability of interaction. Hence, no direct evidence of them can be measured in a general purpose detector, as ATLAS. However, the total momenta in the transverse plane to the beam axis has to be conserved and computed. In particular, it is used in searches for the Standard Model Higgs boson channels, such as: \( H \rightarrow WW \), \( H \rightarrow ZZ \) and \( H \rightarrow \tau \tau \). The benefit of using this conservation law is that an energy imbalance may signal the presence of such undetectable particles. Therefore, it becomes also a powerful tool for new physics searches at the Large Hadron Collider, such as Supersymmetry and Extra Dimensions. The performance of the missing transverse momentum reconstruction in the ATLAS detector is evaluated using data collected in 2012 in proton-proton collisions at a centre-of-mass energy of 8 TeV. An optimised reconstruction of missing transverse momentum is used and the effects arising from additional proton-proton interactions superimposed on the hard physics process are suppressed with various methods. Results are shown for a data sample corresponding to an integrated luminosity of about 20 \( fb^{-1} \) and for events with different topologies with or without a genuine missing transverse momentum due to undetected particles.

1. Introduction

In a hadron collider event the missing transverse momentum is defined as the momentum imbalance in the plane transverse to the beam axis, where momentum conservation is relevant. Such an imbalance may signal the presence of undetectable particles, such as neutrinos or new 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, \( E_T^{\text{miss}} \).

An optimised reconstruction and calibration of \( E_T^{\text{miss}} \) [1] was developed by the ATLAS Collaboration. 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 methods were developed to suppress such contributions [2]. This article describes the performance, in terms of resolution, response and tails, of the reconstructed \( E_T^{\text{miss}} \) after pile-up suppression.

The event samples used to assess the quality of the \( E_T^{\text{miss}} \) reconstruction are events with leptonically decaying \( W \) and \( Z \) bosons. These test the detector capability in the reconstruction...
of different physics objects and the methods of pile-up suppression. The $E_{T}^{\text{miss}}$ performance is studied in both data and Monte Carlo simulation and comparisons are made. In simulated events, the $E_{T}^{\text{miss}}$ is calculated from all non-interacting particles in the event, including neutrinos from heavy flavour decay, and is referred to as true $E_{T}^{\text{miss}}$ ($E_{T}^{\text{miss,True}}$) in the following.

This article is organised as follows. Section 2 shows the data samples and event selection used for this performance study, followed by Section 3, where the Monte Carlo simulation samples are also shown. In Section 4, the $E_{T}^{\text{miss}}$ reconstruction is described and, Section 5 lists the different methods for pile-up suppression. Section 6 shows the results for the $E_{T}^{\text{miss}}$ performance studies and finally, in Section 7, the conclusions are summarized.

2. Data samples and event selection

During 2012, proton-proton (pp) collisions at a centre-of-mass energy of 8 TeV were recorded with stable proton beams and nominal ATLAS magnetic field conditions. Only data with a fully functioning calorimeter, inner detector and muon spectrometer are analysed.

The data sets used correspond to a total integrated luminosity of approximately 20 fb$^{-1}$, collected in 2012 with a bunch crossing interval (bunch spacing) of 50 ns. The mean number of interactions per bunch crossing was about 20.7, reaching values up to 35 at the beginning of a fill during the 2012 LHC running period.

Selection criteria applied for the study of events with leptonically decaying W and Z bosons are described in these references [1, 2, 3].

3. Monte Carlo simulation samples

Monte Carlo (MC) samples of $Z \rightarrow ll$ and $W \rightarrow l\nu$ production are generated with the next-to-leading (NLO) order POWHEG [4] model, with the final state partons showered by the PYTHIA8 [5, 6] program and the ATLAS AU2 tune [7].

Additional inelastic pp interactions, known as pile-up interactions, are generated using the PYTHIA8 program with the ATLAS MC12 A2M tune [7] and the MSTW08 leading order PDF [8].

The GEANT4 software toolkit [9] within the ATLAS simulation framework simulates the propagation of the generated particles through the ATLAS detector and their interactions with the detector material.

The same trigger and event selection criteria used for $Z \rightarrow ll$ and $W \rightarrow l\nu$ data are also applied to the simulated events.

4. $E_{T}^{\text{miss}}$ reconstruction

The $E_{T}^{\text{miss}}$ reconstruction [1] uses 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.

The $E_{T}^{\text{miss}}$ calculation uses reconstructed and calibrated physics objects. Calorimeter energy deposits 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. The $E_{T}^{\text{miss}}$ is calculated as follows:

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss,e}} + E_{x(y)}^{\text{miss,\gamma}} + E_{x(y)}^{\text{miss,\tau}} + E_{x(y)}^{\text{miss,jets}} + E_{x(y)}^{\text{miss,SoftTerm}} + E_{x(y)}^{\text{miss,\mu}}$$ (1)

where each term is calculated as the negative sum of the calibrated reconstructed objects, projected onto the x and y directions. Only jets with calibrated $p_T$ greater than 20 GeV are used to calculate the jet term in Equation 1. The soft term is calculated from topoclusters and tracks not associated to high-$p_T$ objects (i.e. from unassociated topoclusters and tracks).
The total transverse energy in the calorimeters, $\sum E_T$, which includes also the unassociated low-$p_T$ tracks used in the soft term, is an important quantity to parameterise and understand the $E_T^{\text{miss}}$ performance. It is defined as the scalar sum:

$$\sum E_T = \sum E_T^e + \sum E_T^\gamma + \sum E_T^\tau + \sum E_T^{\text{jets}} + \sum E_T^{\text{SoftTerm}}$$

which is the scalar sum of the transverse energy of reconstructed and calibrated objects and of the soft term according to the scheme described above for $E_T^{\text{miss}}$. The total transverse energy in the event is obtained by summing the $p_T$ of muons and the $\sum E_T$ in the calorimeters:

$$\sum E_T(\text{event}) = \sum E_T + \sum p_T^\mu$$

(2)

5. Methods for pile-up suppression in $E_T^{\text{miss}}$

In Reference [2], it was shown that a clear deterioration of the performance is observed when the average number of pile-up interactions per event increases. Methods to suppress pile-up are therefore needed, which can restore the $E_T^{\text{miss}}$ resolution to values more similar to the ones observed in the absence of pile-up.

All $E_T^{\text{miss}}$ terms in Equations 1 and 2 are affected by pile-up, but the terms which are most affected are the jets and soft term, because the pile-up largely produces hadronic energy and they are reconstructed from larger regions in the calorimeters. Methods for the suppression of pile-up in these terms are summarized in this section.

5.1. Pile-up suppression in the $E_T^{\text{miss}}$ jet term based on tracks

Pile-up not only distorts the energy reconstructed in jets but can also create additional jets. To further suppress the jets originating from pile-up, a cut is applied based on the Jet Vertex Fraction (JVF) [10], i.e. the fraction of momenta of tracks matched to the jet which are associated with the hard scattering vertex. JVF is defined as:

$$JVF = \frac{\sum_{\text{tracks matched to jet}} p_T}{\sum_{\text{tracks associated with PV}} p_T}$$

where the sums are taken over the tracks matched to the jet and PV denotes the tracks associated to the Primary Vertex (PV). Only tracks with $p_T > 400$ MeV and passing further quality criteria relating to impact parameters and number of hits in different tracking sub-detectors are used to make primary vertices.

5.2. Pile-up suppression in the $E_T^{\text{miss}}$ soft term based on tracks

The pile-up largely affects the soft term. Since the $E_T^{\text{miss,SoftTerm}}$ can have an important contribution to the momentum balance in the event, completely neglecting its contribution in the $E_T^{\text{miss}}$ reconstruction gives a poorer performance [2]. Two different methods for suppressing the pile-up in the soft term are described in the following, one based on the use of tracks and the other one based on the jet area method.

Tracks provide an excellent method for pile-up suppression, since they can be associated with the primary vertex from the hard scattering collision. It is calculated, in a similar way as JVF, as:

$$STVF = \frac{\sum_{\text{tracks unmatched to physics objects}} p_T}{\sum_{\text{tracks associated with PV}} p_T}$$

where the sums are taken over the tracks unmatched to physics objects and PV denotes the tracks associated to the primary vertex. The $E_T^{\text{miss,SoftTerm}}$ is multiplied by the STVF factor and the $E_T^{\text{miss}}$ calculated, with this corrected soft term, is named STVF.
5.3. Pile-up suppression in the $E_{T}^{\text{miss}}$ soft term using the jet area method

The event transverse momentum density ($\rho$) is used to determine the contribution due to pile-up in the jet area, which is subtracted from each jet: $p_{T}^{\text{jet,corr}} = p_{T}^{\text{jet}} - \rho A^{\text{jet}}$. Two different $E_{T}^{\text{miss,SoftTerm}}$ calculations are considered here and the $E_{T}^{\text{miss}}$ is then recalculated using each of them. The two methods differ only in their calculation of the $\rho$. One is named Extrapolated Jet Area Method and the other named Jet Area Filtered.

6. Study of $E_{T}^{\text{miss}}$ performance in different event topologies

6.1. Characterization of samples used for the study of $E_{T}^{\text{miss}}$ performance

The $E_{T}^{\text{miss}}$ performance depends on the event topology: presence of leptons, jet activity, etc. The values of quantities relevant for $E_{T}^{\text{miss}}$ studies in the MC samples used in this note are shown in Figure 1. In Figure 1 the reconstructed $\sum E_{T}$ before and after pile-up suppression is compared with the true values. As can be seen, the $\sum E_{T}$ is strongly suppressed by all the pile-up suppression methods and it is closer to the true value. Figure 1 (right) shows the importance of the soft term, in the different samples. The average value of $E_{T}^{\text{miss,SoftTerm}}$ is not much different in the various samples but its contribution is dominant in $Z$ samples and important in $W$ events, while it becomes less important in events with higher jet multiplicity, where the $E_{T}^{\text{miss,jets}}$ is dominant, as can be seen from the distribution of the ratio of $\sum E_{T}^{\text{SoftTerm}} / \sum E_{T}$.

6.2. Comparison of $E_{T}^{\text{miss}}$ distributions in $Z \rightarrow \mu\mu$: Data and MC simulation

The distributions of $E_{T}^{\text{miss}}$ for data are shown in Figure 2 for $Z \rightarrow \mu\mu$ events. The MC simulation expectations, from $Z \rightarrow \mu\mu$ events and from the dominant backgrounds, are superimposed. Each MC sample is weighted with its corresponding cross-section and then the total MC expectation is normalized to the number of events in data. A good agreement between data and MC simulation is observed in the $E_{T}^{\text{miss}}$ distribution, both before and after pile-up suppression.

6.3. Study of $E_{T}^{\text{miss}}$ resolution

A first study of the $E_{T}^{\text{miss}}$ resolution is performed using the ratio:

$$R = \frac{\text{RMS}(E_{T}^{\text{miss}}/E_{T}^{\text{miss, True}})}{<E_{T}^{\text{miss}}/E_{T}^{\text{miss, True}}>}$$

Figure 3 shows the ratio R for two samples. Before pile-up suppression, R decreases with increasing $E_{T}^{\text{miss, True}}$ and is of the order of 0.1 for larger $E_{T}^{\text{miss, True}}$ values in both samples. After
Figure 2. Distribution of $E_T^{\text{miss}}$ measured in data samples $Z \rightarrow \mu\mu$ events before (left) and after pile-up suppression with the STVF method (right). The lower part shows the ratio data/MC. Plots obtained from this reference [3].

pile-up suppression, in $W \rightarrow l\nu$ events, there is a reduction of R in the region of $E_T^{\text{miss},\text{True}} < 40$ GeV, while the improvement of R is smaller for larger $E_T^{\text{miss},\text{True}}$ values. In the low $E_T^{\text{miss},\text{True}}$ region there are some concurrent effects: the region is mostly populated by events without jets, so the reduction of R indicates that the pile-up suppression methods in the soft term improve the $E_T^{\text{miss},\text{True}}$ resolution.

Figure 3. Resolution (R) as function of $E_T^{\text{miss},\text{True}}$ in MC $W \rightarrow e\nu$ (left) and $W \rightarrow \mu\nu$ (right). Plots obtained from this reference [3].

6.4. Study of $E_T^{\text{miss}}$ linearity
The $E_T^{\text{miss}}$ linearity is defined as the mean value of the ratio: $(E_T^{\text{miss}} - E_T^{\text{miss},\text{True}}) / E_T^{\text{miss},\text{True}}$. The mean value of this ratio is expected to be zero if $E_T^{\text{miss}}$ is reconstructed at the correct scale. The linearity for the different MC samples considered is shown in Figure 4.

For both $W \rightarrow l\nu$ samples a positive bias is observed for low $E_T^{\text{miss},\text{True}}$ values which is due to the finite resolution of the $E_T^{\text{miss}}$ measurement. For larger $E_T^{\text{miss},\text{True}}$ values, the bias is within 5%. Differences in the linearity before and after pile-up suppression are visible. In particular, a larger non-linearity is observed for STVF, because of the strong pile-up suppression mainly in events without jets.
Figure 4. $E_T^{\text{miss}}$ linearity in $W \rightarrow e\nu$ (left) and $W \rightarrow \mu\nu$ (right) MC events vs $E_T^{\text{miss, True}}$. Plots obtained from this reference [3].

7. Conclusions
The missing transverse momentum $E_T^{\text{miss}}$ performance has been studied in events with different topologies in proton-proton collisions at a centre-of-mass energy of 8 TeV recorded with the ATLAS detector in 2012.

The value of $E_T^{\text{miss}}$ is calculated from calibrated reconstructed objects and from the unmatched topological clusters and tracks ($E_T^{\text{miss,SoftTerm}}$). Several methods for pile-up suppression in the soft term are described, based on the use of tracks (STVF method) or on the jet area method.

The Monte Carlo simulation describes the data in general rather well. Some discrepancy in data-MC comparison is observed after pile-up suppression in the $E_T^{\text{miss,SoftTerm}}$ and in the contribution from jets, due to corrections applied for pile-up suppression.

The $E_T^{\text{miss}}$ resolution improves after pile-up suppression in events where the contribution of the soft term is important and it becomes closer to that observed in the absence of pile-up, mainly the STVF.

The linearity of the $E_T^{\text{miss}}$ measurement is studied in MC simulation as a function of the true $E_T^{\text{miss}}$. Except for the bias observed at small true $E_T^{\text{miss}}$ values (visible up to 40 GeV), due to the finite $E_T^{\text{miss}}$ resolution, the linearity is better than 5%.

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