ATLAS jet and missing energy reconstruction, calibration and performance in LHC Run-2

A. Hrynevich on behalf of the ATLAS collaboration

Institute for Nuclear Problems of Belarusian State University,
Bobrujskaya Str., Bdg. 11, Minsk 220030, Belarus

E-mail: aliaksei.hrynevich@cern.ch

Abstract: The performance of the reconstruction and calibration of the jet energy scale and missing transverse energy scale with the ATLAS detector at the LHC is a key component to realize the ATLAS full physics potential, both in the searches for new physics and in precision measurements. New algorithms used for the reconstruction and calibration of jets and missing energy with the ATLAS detector during LHC Run-2 are presented. Measurements of the performance and uncertainties are derived from data. The results from the 2016 pp collision data set at $\sqrt{s} = 13$ TeV are reported.

Keywords: Analysis and statistical methods, Missing Transverse Energy studies
1 Introduction

Jets, collimated sprays of hadrons, are the dominant physics objects arising in proton-proton collisions at the LHC. Jets play a key role in a variety of Standard Model physics analyses and searches for new phenomena in the ATLAS experiment. The precision of the jet energy measurement directly affects the performance of the missing transverse energy reconstruction. Missing transverse energy is a measure of the transverse momentum imbalance created by detected and well measured objects in an event. A good performance of missing transverse energy reconstruction is crucial for many SUSY and dark matter searches.

The algorithms for the jet and missing transverse energy reconstructions, as well as for the jet energy scale (JES) calibration were developed and validated in ATLAS during the LHC Run-1. The proton-proton collisions at the centre-of-mass energy of $\sqrt{s} = 13$ TeV at the LHC Run-2 force the evolution of these algorithms in presence of multi-TeV final states towards the highest precision.

The main algorithms for the jets and missing transverse energy reconstructions are presented and their performances at Run-2 ATLAS data and Monte Carlo simulation are reported.

2 Jet reconstruction and calibration

The main jet identification algorithm used by the ATLAS collaboration is the anti-$k_t$ algorithm [2] with a distance parameter $R = 0.4$. Various objects can be used as inputs to this algorithm: calorimeter energy deposits, inner detector tracks [3] or a combination of both [4]. Stable particles with a lifetime longer than 10 ps, excluding muons and neutrinos, are used for the jet identification in the Monte Carlo simulation. Jets reconstructed from tracks, also referred to as the track jets, have low dependence on the pile-up activity since only tracks originating from the primary vertex are used for the jet finding. However, the reconstruction of track jets is limited by the ATLAS tracker acceptance to $|\eta| < 2.5$. Therefore, the majority of ATLAS analyses uses a jet reconstruction based on calorimeter deposits, calorimeter jets.

The inputs for calorimeter jets reconstruction are the topologically clustered calorimeter cells, so-called topo-clusters [5]. The topological clustering algorithm groups cells with the significant
energy deposits aiming for effective noise suppression. The total noise in calorimeter cells, \( \sigma \), is calculated as the quadratic sum of the measured electronics and pile-up noise. The clustering algorithm starts from the seed cells with the energy deposits above 4\( \sigma \). All neighbor cells are iteratively added to the topo-cluster if their energy is above 2\( \sigma \). This is followed by the addition of all adjacent cells. As the final step, the cluster splitting algorithm separates produced topo-clusters based on local energy maxima to avoid overlap. Topo-clusters are considered to be massless and only those with positive energy are used for jet reconstruction.

The energy of the calorimeter cells is measured at electromagnetic (EM) scale, established using electrons at test beams. The local cell weighting (LCW) calibration [6] can be applied to topo-clusters classified as hadronic to account for the difference in the detector response to electromagnetic and hadronic particles. In addition, it improves the jet energy resolution. The LCW calibration is derived using Monte Carlo simulation of single pion events.

The jet energy scale calibration [7] restores the energy scale of reconstructed jets to that of simulated truth jets. Different sets of correction factors are developed for jets reconstructed using the EM and LCW topo-clusters. The JES calibration includes origin correction, pile-up correction, absolute correction of the detector response based on Monte Carlo simulation, global sequential correction and residual in situ calibration.

The origin correction forces the four-momentum of the jet to point to the hard-scatter primary vertex rather than to the center of the detector while keeping the jet energy constant.

The centre-of-mass energy in proton-proton collisions of \( \sqrt{s} = 13 \) TeV and the reduced bunch spacing intervals (25 ns) at Run-2 increased the pile-up, biasing the measured jet transverse momentum. A two step procedure is used to subtract the pile-up contribution. First, it removes the effect of pile-up exploiting the average energy density and the area of the jet. Second, a residual correction removes the remaining dependence of the jet on the number of reconstructed primary vertices (\( N_{PV} \)) and the expected average number of interactions per bunch crossing (\( \langle \mu \rangle \)). The performance of the pile-up correction is shown in Figure 1 (a).

The jet energy scale and \( \eta \) calibration correct the reconstructed jet to the particle-level energy scale to account for the difference of the calorimeter energy response using Monte Carlo simulation. In addition, it corrects any bias of the reconstructed jet \( \eta \) caused by the transition between different calorimeter regions and the difference in calorimeter granularity. The energy response as a function of detector \( \eta \) for jets of different simulated truth energy is shown in Figure 1 (b).

The global sequential correction (GSC) [8] is designed to reduce the jet response dependence on the flavour of the initiated-jet parton. The correction uses global properties of the jets such as the portion of the jet energy measured in the first layer of the hadronic calorimeter, the portion of the jet energy measured in the third layer of the electromagnetic calorimeter, the average \( p_T \)-weighted transverse distance in the \( \eta \)-\( \phi \) space between the jet axis and all tracks associated to the jets, the number of tracks associated to the jet and the number of muon track segments associated to the jet, accounting for punch-through correction. The correction removes the jet response dependence on the listed observables.

The in situ JES calibration is applied to jets measured in data. The correction is calculated as the jet response difference between data and Monte Carlo simulation using the transverse momentum balance of a jet and a well-measured reference object.
Figure 1. (a) The dependence of EM scale jet transverse momentum on $N_{PV}$ as a function of $|\eta|$ before pile-up corrections (blue), after the area-based correction (violet), and after the residual correction (red). (b) The average jet energy response as a function of the detector pseudorapidity for different truth energies [9].

Jets from the central detector region ($|\eta_{\text{det}}| < 0.8$) are used to derive a residual calibration for jets in the forward region (0.8 < $|\eta_{\text{det}}| < 4.5$) exploiting dijet events ($\eta$-intercalibration). Figure 2 (a) shows the relative jet response measured using Run-2 ATLAS data with the integrated luminosity $\int L = 3.6 \, \text{fb}^{-1}$ and in Monte Carlo simulation as a function of detector pseudorapidity in a single jet $p_T$ bin. The lower panel depicts the $\eta$-intercalibration correction.

Two methods to calibrate jets with $p_T$ up to 950 GeV using Z+jet and $\gamma$+jet events are employed. The Direct Balance method relies on perfect transverse-momentum balance of a jet and a reference Z-boson or $\gamma$ in the $2 \rightarrow 2$ process at leading order. However, the measurement can be affected by additional parton radiation contributing to the recoil of a boson and appear as subleading jets, or due to energy loss outside of the considered jet cone. The Missing Projection Fraction method utilizes the full hadronic recoil of the event rather than a single reconstructed jet, and thus less sensitive to the jet definition and out-of-cone radiation. However, it does not directly reflect the energy within the reconstructed jet cone. These two methods are complementary and both are pursued to check the compatibility of the measured response.

Topologies with three or more jets are used to calibrate high-$p_T$ jets (up to 2 TeV) using a recoil system composed of several lower-$p_T$ jets (Multijet Balance).

The combined in situ corrections are shown in Figure 2 (b) as a function of the jet $p_T$ measured using Z+jet, $\gamma$+jet and multijet events. The listed calibrations are derived and applied sequentially and the systematic uncertainties are propagated through the calibration scheme.

3 Jet energy scale uncertainty

The jet energy is measured with the precision of up to 1% using Run-2 ATLAS data with the integrated luminosity $\int L = 3.6 \, \text{fb}^{-1}$. The measurement is described by a set of 80 independent sources of systematic uncertainties. The total systematic uncertainty is shown in Figure 3 as a function of jet transverse momentum at $\eta = 0$. The total uncertainty at low jet $p_T$ reaching up to 6% is driven by the in situ methods uncertainties and the difference of the jet flavour composition...
between Monte Carlo generators. The in situ methods uncertainties of about 1% solely dominate at high jet transverse momentum $p_T > 200$ GeV.

Jets with transverse momenta above 2 TeV are not covered by Multijet Balance calibration and a larger uncertainty is taken from the single particle response measurement. Each uncertainty is independent from the others and fully correlated across $p_T$ and $\eta$. A reduced set of systematic uncertainties is available for physics analyses while minimising the loss of correlations.

Figure 3. Relative jet energy scale uncertainty as a function of jet transverse momentum at $\eta = 0$ [10].

4 Missing transverse energy performance

The missing transverse momentum ($E_T^{\text{miss}}$) is reconstructed as the negative vector sum of transverse momenta ($\vec{p}_T$) of reconstructed physics objects. The magnitude of the missing transverse energy is denoted by $E_T^{\text{miss}}$. The physics objects considered in the $E_T^{\text{miss}}$ calculation are electrons, photons, muons, $\tau$-leptons and jets (hard terms). The reconstructed momentum not associated to any of the hard terms is referred as the soft term and is also considered in the $E_T^{\text{miss}}$ calculation. Several algorithms can be used to reconstruct the $E_T^{\text{miss}}$ soft term using calorimeter energy deposits or tracks [11]. The main algorithm for the soft term reconstruction used by ATLAS at Run-2 fully relies on tracks, the so-called Track Soft Term (TST). The algorithm is very robust against varying pile-up condition, but it misses the contribution from neutral particles.
The removal of pile-up jets is essential for $E_T^{\text{miss}}$ resolution. This is done with the jet-vertex-tagger (JVT) technique which extracts the pile-up jets using track-to-vertex association method [12]. In addition, a novel forward pileup tagging technique (fJVT) that exploits the correlation between central and forward jets originating from pileup interactions is developed [13]. The fJVT improves the $E_T^{\text{miss}}$ resolution in high pile-up conditions as shown in Figure 4.

![Image](image_url)

**Figure 4.** The Track Soft Term $E_T^{\text{miss}}$ resolution as a function of $N_{PV}$ measured in Monte Carlo simulated $Z \rightarrow \mu\mu$ events using different strategies for pile-up suppression [14].

The performance of TST $E_T^{\text{miss}}$ is validated using events with small $E_T^{\text{miss}}$ such as $Z \rightarrow ll$, $W \rightarrow l\nu$ and $t\bar{t}$ events. Good agreement of TST $E_T^{\text{miss}}$ measured using 8.5 fb$^{-1}$ Run-2 ATLAS data and Monte Carlo simulation is observed as shown in Figure 5 (a) with $Z \rightarrow ee$ events.

The TST systematic uncertainties are evaluated exploiting the differences between data and Monte Carlo using the balance of a soft term and a calibrated physics objects. The systematic uncertainties of each hard term are propagated to the $E_T^{\text{miss}}$. The mean of the TST distribution as a function of the hard term $p_T$ measured using 36.5 fb$^{-1}$ Run-2 ATLAS data agrees with Monte Carlo simulation within the systematic uncertainty as shown in Figure 5 (b).

![Image](image_url)

**Figure 5.** (a) TST $E_T^{\text{miss}}$ distribution for a selection of $Z$ boson decays to a pair of electrons at Run-2 ATLAS data. The expectation is superimposed by Powheg+Pythia8 Monte Carlo simulated events for the relevant signal physics processes including some background processes while diboson backgrounds use Sherpa. The shaded band represents the statistical uncertainty of Monte Carlo simulations [15]. (b) The mean of the TST distribution projected in the direction longitudinal to the hard term $p_T$ for $Z \rightarrow ee$ events measured using Run-2 ATLAS data and Monte Carlo simulation. The shaded band represent the systematic uncertainty [14].
5 Conclusions

The LHC opens new frontiers in particle physics using proton-proton collisions at the centre-of-mass energy of $\sqrt{s} = 13$ TeV at Run-2. The multi step jet energy scale calibration brings reconstructed jet energies to that of particle level reaching about 1% precision over a wide jet $p_T$ range. The reconstructed missing transverse energy is validated using Run-2 ATLAS data showing a good agreement with Monte Carlo simulation.

References