Track based software package for measurement of the energy deposited by muons in the calorimeters of the ATLAS detector

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Abstract. The measurement of the muon energy deposition in the calorimeters is an integral part of muon identification, track isolation and correction for catastrophic muon energy losses, which are the prerequisites to the ultimate goal of refitting the muon track using calorimeter information as well. To this end, an accurate energy loss measurement method in the calorimeters is developed which uses only Event Data Model tools and is used by the muon isolation tool in the official ATLAS software, in order to provide isolation related variables at the Event Summary Data level. The strategy of the energy deposition measurement by the track in the calorimeters is described. Inner Detector, or Muon Spectrometer tracks are extrapolated to each calorimeter compartment using existing tools, which take into account multiple scattering and bending due to the magnetic field. The energy deposited in each compartment is measured by summing-up cells, corrected for noise, inside a cone of desired size around the track. The results of the measured energy loss in the calorimeters with this method are validated with Monte Carlo single muon samples.

1. Introduction
A precise method for the measurement of the muon energy deposition in the ATLAS detector calorimeters [1] is based on the ‘track update’ principle where a track is followed through its trajectory inside the calorimeter volume, starting either from the Inner Detector(ID) [2] or the Muon Spectrometer(MS) [3]. This is achieved by using existing Event Data Model (EDM) [4] tools of the official ATLAS software, for track extrapolation to varying depth in the calorimeters and for obtaining the energy sum of the cells within a cone around the muon track. This concept is realized in the TrackInCaloTools software package. This paper describes the principle of TrackInCaloTools and presents results from validation with Monte Carlo single muon samples.

2. The ATLAS Detector
ATLAS [5, 6] is one of the four experiments of the LHC currently being built at CERN. A schematic layout of the ATLAS detector is shown in Figure 1. It is a huge 4π general purpose detector which consists of three main sub-detector elements:

- the Inner Detector sitting inside a 2T solenoidal magnetic field used for tracking and momentum measurement
Figure 1. The ATLAS detector.

- the Calorimeter System which consists of a high granularity Liquid Argon Electromagnetic (LArEM) calorimeter in $|\eta| < 3.2$ and a hadronic calorimeter in $|\eta| < 4.9$. The LArEM and hadronic calorimeters are longitudinally segmented into 3 layers of cells.
- the Muon Spectrometer inside an air-core toroid magnet system with an average field of $\sim 0.5$ T, allowing for muon related measurements.

3. TrackInCaloTools

TrackInCaloTools is a software package which acts as a tool in the official ATLAS Software Framework, ATHENA [7]. It is controlled by the Tool Service of ATHENA in the sense that any component of the framework (reconstruction algorithms and other tools) can call TrackInCaloTools during reconstruction. In Figure 2 a schematic diagram of the ATHENA framework is given where the basic components of the framework are illustrated.

TrackInCaloTools is used by MuonIsolationTool to provide the muon energy deposition measurements needed by the latter to create isolation related variables to the final reconstruction data output formats, the Event Summary Data (ESD) and Analysis Object Data (AOD) [8]. It is also providing the calorimeter cells related to the measurement of the energy deposition by the crossing muon track, which are thereafter used by MuonIsolationTool to produce a muon calorimeter cluster. Inputs are:
- Any tracks reconstructed in the ID or the MS that are of the class type Trk::Track or track parameters of the class type Trk::TrackParameters [4].
- The cone size around the track where the energy will be measured.

Outputs are:
- The energy deposition inside a cone around the muon track
- The calorimeter cell cluster related to the energy measurement

4. Method

TrackInCaloTools exploits the principle of the 'track update' method. The general concept of the 'track update' method is to provide measurements of the energy deposited by muons in the
calorimeters by summing the energy of the calorimeter cells which lie inside a cone of radius 
\[ dR = \sqrt{\Delta \eta^2 + \Delta \phi^2} \] around the muon track in each of the calorimeter compartments. This 
requires a precise determination of the position in \( \eta \) and \( \phi \) of the muon track while traversing 
the calorimeter volume which is achieved by extrapolating the track to the entrance of each 
compartment. Figure 4 illustrates this concept.

**Figure 3.** TrackInCaloTools method flow chart.

**Figure 4.** Track update principle. The orange points represent the centers of the opened cones.

Examples of extrapolations used in TrackInCaloTools are shown in Figures 5 and 6, where 
\( \Delta \eta \) and \( \Delta \phi \) are the differences in \( \eta \) and \( \phi \) of the track at the start and end points of the 
extrapolation. In Figure 5 \( \Delta \eta \) is given for the case of extrapolating an ID track from the perigee 
to the entrance of the middle compartment of the electromagnetic LAr calorimeter, while in 
Figure 6 \( \Delta \phi \) is plotted as a function of the track momentum for the same distance. It should be 
noticed the small, momentum independent, change in \( \eta \) (5) and the large, momentum dependent, 
change in \( \phi \) which is expected because multiple scattering and bending in the solenoidal field
affect only the transverse direction.

![Image](image.png)

**Figure 5.** Differences in $\eta$ of the track at the start and end points of the extrapolation.

![Image](image.png)

**Figure 6.** Differences in $\phi$ of the track at the start and end points of the extrapolation.

The procedure of the measurement method is represented by the flow diagram of Figure 3 and can be summarized in the following steps:

- Tracks from the ID or the MS are extrapolated to each calorimeter compartment using the ATLAS extrapolation tools. They take into account multiple scattering and bending in the magnetic field.
- On the basis of the $\eta$ of the track, a dedicated method decides whether the track resides in the barrel or endcap region and assigns the corresponding calorimeter compartment as the end point of the extrapolation.
- The new $\eta$ and $\phi$ of the track on the calorimeter, is used to open a cone around it.
- The energy of each cell in the cone is compared to the noise rms and if found to be greater than a user defined threshold is added to the total energy deposition. The rms of the noise is retrieved from CaloNoiseTool [9] and accounts for both electronic noise and pile-up. By default this threshold is set to $3.4 \times RMS_{\text{noise}}$ and is the value used in the following results.
- Calorimeter cells are calibrated to electrons thus an energy scale factor is applied to account for the muon energy scale.
- The above steps are repeated for each calorimeter compartment and the total energy is obtained.

5. Results

In Figures 7, 9 and 11 the measured energy loss for single muons of transverse momentum 10, 100 and 300 GeV is shown as a function of $\eta$ averaged in bins of $\eta$. In the same $\eta$ bins the average ‘true’ energy, obtained from GEANT parametrization, lost between the interaction point and the entrance of the MS, is shown.

The underestimation of the energy loss in the region $|\eta| < 1.5$ is mainly attributed to the dead material of the detector while the discrepancy in $|\eta| > 1.5$ is enhanced by the high noise level of the LAr Hadronic Endcap calorimeter.

In Figures 8, 10 and 12 the difference between the ‘true’ and the measured $E_t$ loss is shown for muons of momentum 10, 100 and 300 GeV respectively. The average difference is varying between 300 and 400 MeV.
6. Summary

TrackInCaloTools is a software package which can be called by reconstruction algorithms in the ATHENA software framework of the ATLAS experiment and is used by dedicated packages to provide the muon energy deposition measurements needed to create the isolation related
variables and the calorimeter cells related to the measurement of the energy deposited around the muon track. The energy lost by muons in the calorimeters, has been proven that it is well estimated by the measurement method performed in TrackInCaloTools, in the limit that corrections for the energy loss in the inert material have not been taken into account.

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