

TrackInCaloTools: a package for measuring muon energy loss and calorimetric isolation in ATLAS

B. Lenzi, R. Nicolaidou and S. Hassani

¹ CEA / Irfu / SPP, Centre de Saclay, F-91191 Gif-sur-Yvette, FRANCE

E-mail: Bruno.Lenzi@cern.ch

Abstract.

Muons in the ATLAS detector are reconstructed by combining the information from the two tracking devices: the Inner Detector and the Muon Spectrometer (MS), located in the outermost part of the experiment. Until they reach the MS, muons traverse typically 100 radiation lengths (X_0) of material, most part instrumented by the electromagnetic and hadronic calorimeters. The proper account for multiple scattering and energy loss effects is essential for the reconstruction and the use of the calorimeter measurement can improve the transverse momentum resolution, specially in case of high energy deposits. On the other hand, the calorimeter activity around a muon, or conversely its isolation, is one of the most powerful features to distinguish W and Z decays from semi-leptonic decays of heavy flavour mesons (containing b and c quarks). The principle of the software package that performs these tasks, called *TrackInCaloTools* is presented together with the expected performance in physics analyses.

1. Introduction

As one of the general purpose experiments in the Large Hadron Collider (LHC), ATLAS was designed to measure charged particles and photons that will emerge from p+p collisions at $\sqrt{s} = 10 - 14$ TeV, expected to start this year.

In the search for the Higgs boson and evidences of new physics beyond the Standard Model, the main objectives of the collider, muons play a special role as clear signatures in several physical processes, and special attention was dedicated to their identification in the concept of the experiment.

The main source of muons are decays in-flight of light mesons or semi-leptonic decays of heavy flavour mesons. The identification of leptonic decays of vector bosons (W and Z) relies greatly on the ability to define calorimetric and tracking activity around the particle.

The calorimeters can be used not only to measure the activity around the muon, but also the energy it loses on its way to the Muon Spectrometer. The use of this information in the reconstruction might improve the momentum resolution. This proceeding describes the software used for calorimetric isolation and energy loss measurements - *TrackInCaloTools*, illustrating the application of these quantities in physics analyses with the expected performance for first data, obtained from Monte Carlo simulations.

2. Muons in the ATLAS detector

To explore all aspects of the collisions at TeV energies, ATLAS can measure muons, electrons, photons, taus and hadrons over a wide range of momenta. An illustration of the detector and

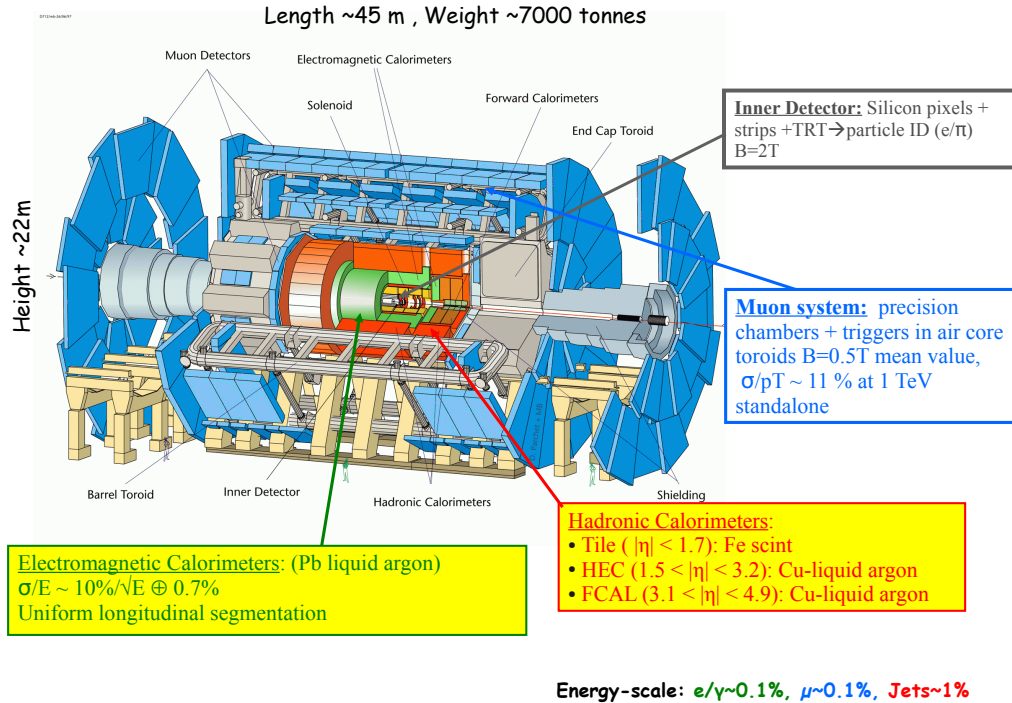


Figure 1. Illustration of the ATLAS detector.

some features are presented in Fig. 1. Detailed information can be found at [1, 2].

The outermost part of the detector is the Muon Spectrometer (MS), composed by precision and trigger chambers in air core toroids that provide an average magnetic field of 0.5 T. The system offers standalone triggering and precision tracking capabilities, with momentum resolutions of the order of 11% for muons up to 1 TeV.

Ultimate resolution and very low fake rates are obtained by combining the information from the Inner Detectors (ID) and the Muon Spectrometer. Muons measured at the MS are back-tracked to the perigee with respect to the interaction point, and their momenta is corrected using a parametrization of the material traversed.

Between the interaction point and the spectrometer, a particle sees typically 100 radiation lengths (X_0), most part instrumented by the electromagnetic and hadronic calorimeters, as shown in Fig. 2. Energy loss fluctuations are considerable, specially for high- p_T muons (Fig. 3(a) and Fig. 3(b)), and they can limit the spectrometer resolution and even the efficiency for the combination with the ID. A Bayesian method takes advantage of the knowledge of the energy loss distribution given by the parametrization to reduce the fluctuations on the calorimeter measurement. This leads to an improved transverse momentum resolution with respect to each quantity alone, as described in details in ref. [3] and illustrated in Fig. 4.

The software package that retrieves the measurement in the calorimeter is called *TrackInCaloTools*, originally designed for this purpose[4] and adapted to deal with isolation. Its working principle is the subject of the next section.

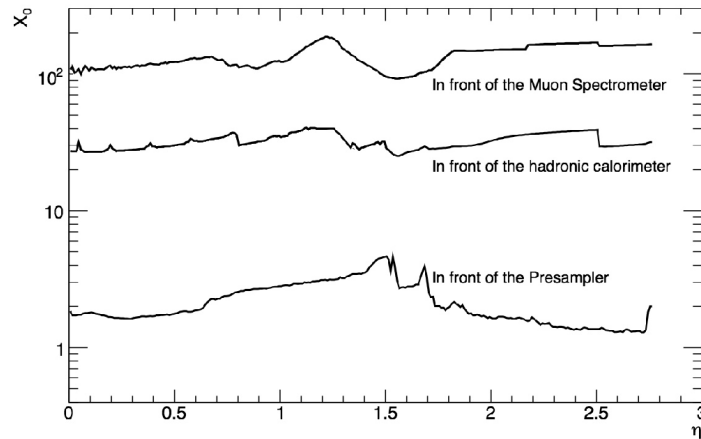


Figure 2. Material distribution in the ATLAS detector as a function of pseudo-rapidity (η) [2].

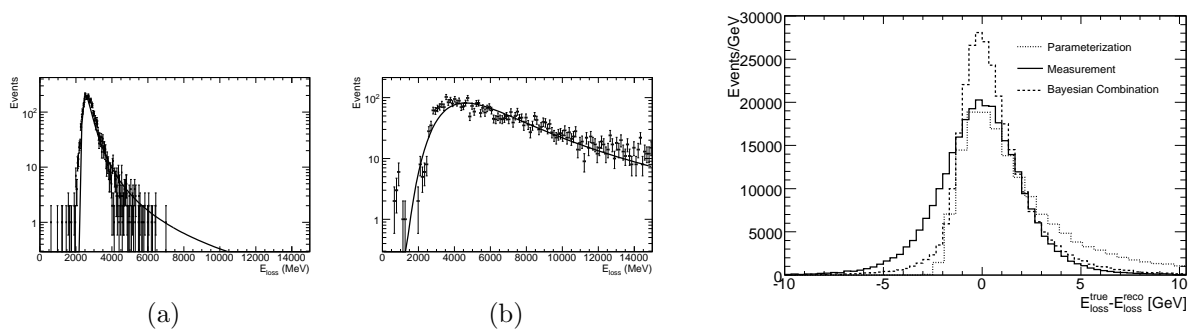


Figure 3. Energy loss distributions in the calorimeters for (a) 10 GeV and (b) 1 TeV muons for $|\eta| < 0.15$, fitted with a Landau function [2].

Figure 4. Difference between the true energy loss and the one used in reconstruction for the parametrization, the measurement and their combination using a Toy Model [2].

3. Muon isolation using calorimeter information

The activity around a muon is a powerful information to identify its origin. In practice, one can use the tracks that accompany it, recorded in the Inner Detector, or the energy deposits in the calorimeter. The latter is discussed in this section.

As the particle flux is approximately constant in $\eta - \phi$, the quantity typically used in several physics analyses, as shown in section 3.2, is the sum of the transverse energy E_T collected around a cone in these directions. The calorimeter is sensitive also to the energy loss of the muon, defined here as core energy or E_T^{core} . This implies that the latter quantity has to be subtracted to define the isolation. A cone of 0.05 is currently used for this matter, chosen as a compromise between the granularity of the calorimeter layers and the rejection power of the isolation variables. Other possibilities are under study, in particular using a given number of cells in $\eta - \phi$ per layer, to account more precisely for the variations in the cell geometry.

In summary, for a cone of size y , the isolation variable $etcone_y$ is defined as:

$$etcone_y = \sum E_T^{dR=y} - \sum E_T^{core}, \text{ with} \quad (1)$$

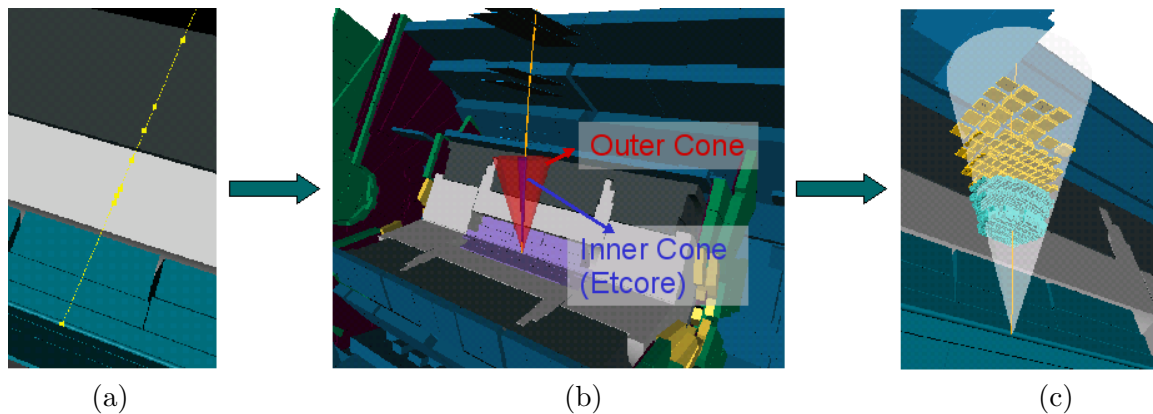


Figure 5. Illustration of the working principle of *TrackInCaloTools*: (a) the track is extrapolated to each calorimeter layer, (b) an internal cone is used to define the muon energy loss E_T^{core} and its energy is subtracted from the energy inside an outer cone, defined by (c) the cells collected on each compartment, above a noise threshold.

$$dR = \sqrt{\Delta\eta^2 + \Delta\phi^2} \quad (2)$$

calculated from track position on each compartment to the center of each calorimeter cell. The track position is given by the Atlas Extrapolator[5], which starts from the measurement at the perigee, and takes into account magnetic field and material effects to propagate the track through the detector, updating the track parameters on each material layer defined by the ATLAS Tracking Geometry [6].

Only the cells closer than the given dR with respect to the extrapolation point, and above a noise threshold defined by the user are collected for the sum. Fig. 5 illustrates this process.

3.1. Framework

The package that provides isolation and energy loss measurements - *TrackInCaloTools* - is integrated in the ATLAS software framework ATHENA [7], as part of standard event reconstruction. It provides the isolation variables (*etcare*) for cone sizes of 0.1, 0.2, 0.3 and 0.4 and a list of cells around each muon track, that can be used for future reprocessing. Both quantities are present in the standard inputs of the ATLAS Event Data Model: Event Summary Data (ESD) and Analysis Object Data (AOD).

Although the default usage is related to muons, the tools are suitable to handle any kind of particle with an associated track object. More than providing the standard isolation variables, the package is configurable and flexible to handle isolation and energy loss measurements as the needs of each analysis may differ when dealing with those quantities.

The package comprises two tools:

- *TrackExtrapolatorToCalo* relies on the Atlas Extrapolator to provide the extrapolation positions on each calorimeter layer, the associated track parameters, the path length of the track and the parametrized energy loss.
- *TrackInCaloTools* uses the extrapolation points to collect the cells around the track and yield the energy measured on each compartment for a given cone size (transverse or total). It can also return the cells crossed by the track and the core energy, corresponding to the muon energy loss. The definition of this core energy can be chosen between a cone size

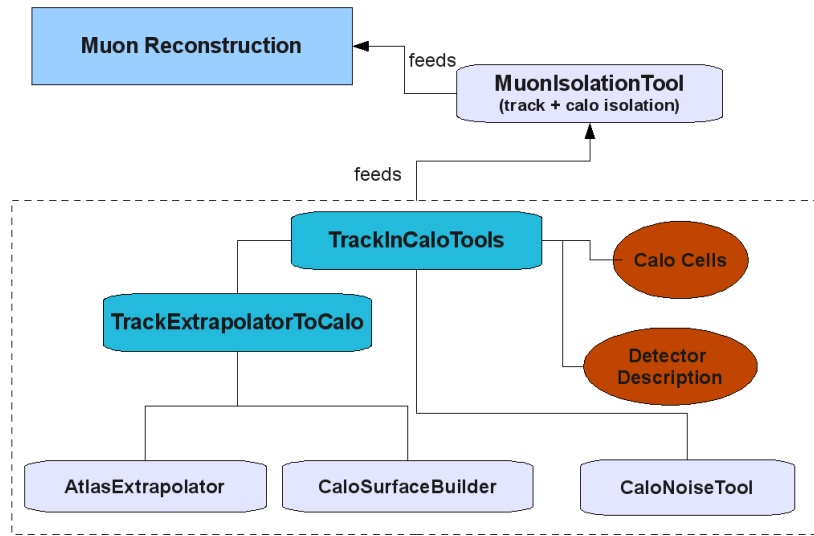


Figure 6. Illustration of the integration of *TrackInCaloTools* in the ATHENA framework.

(0.05 by default) or $n \times m$ cells in $\eta - \phi$. Since the calorimeter is calibrated to the electron energy, a scale factor can be applied to yield the correct muon energy losses.

An illustration of how the package is inserted in ATHENA is shown in Fig. 6. The functionalities provided by *TrackInCaloTools* can be summarized in the following list:

- Input:
 - Track parameters at the perigee with respect to the interaction point
- Outputs from *TrackExtrapolatorToCalo*:
 - Parameters and positions of the track extrapolation on each calorimeter layer
 - Path length traversed by the track on each layer
 - Parametrized energy loss
- Outputs from *TrackInCaloTools*:
 - Energy measured per layer for a given cone
 - Cells around the track for a given cone
 - Cells crossed by the track
 - Measured energy loss (core energy)
- Configurables:
 - Noise threshold used to collect cells, defined as the minimum ratio of the energy of the cell to the RMS noise.
 - Whether to use or not cells with negative energies¹.
 - Whether to use the extrapolation to follow the track bending in the magnetic field, or a straight track approximation.
 - Definition of the core energy on each layer. The user can choose between a cone, the cells crossed by the track, a given number of cells in $\eta \times \phi$ and the parametrized energy loss.

¹ Negative energy values are caused by noise fluctuations and are kept to avoid biases in the energy measurement.

3.2. Calorimetric isolation in physics analyses

The isolation variables provided by *TrackInCaloTools* are used as one of the main discriminants to identify muons from W and Z decays. As the dominant background is composed from muons inside jets, the calorimeter activity around those particles is expected to be significantly different, as shown in Fig. 7(a).

An example of the application of calorimetric isolation is the Higgs search using the 4-muon decay channel. The most important reducible backgrounds in this analysis are the processes $t\bar{t} \rightarrow 4\mu$ and $Zb\bar{b} \rightarrow 4\mu$, where the muons from the b-decays are expected to be non-isolated. Fig. 7(b) shows the rejection power of the *etcone* variables against $Zb\bar{b}$ background.

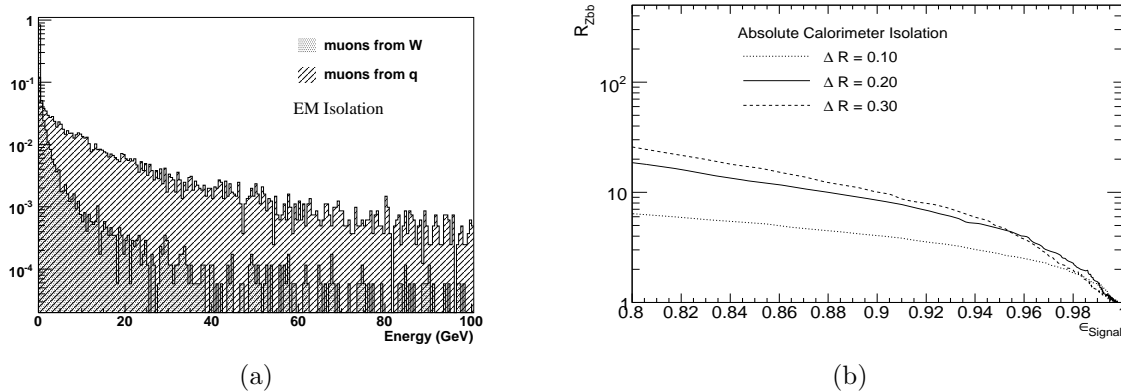


Figure 7. (a) Isolation energy in the electromagnetic calorimeter of muons from a $t\bar{t}$ sample. (b) $Zb\bar{b}$ rejection (R_{Zbb}) versus $H \rightarrow 4\mu$ efficiency for various calorimetric isolation cone sizes [2].

4. Summary

The software package that handles energy loss measurements and calorimeter-based isolation for muons in ATLAS - *TrackInCaloTools* - was presented. It can be used, combined with a parametrization of the energy loss, to improve the muon momentum resolution, especially for large energy deposits.

The tools are fully integrated in the ATLAS software framework, providing isolation-related variables in the standard muon reconstruction, which are widely used in physics analyses. Examples were given for Standard Model analysis and Higgs searches. Moreover, the package offers flexibility to meet specific needs of each analysis when dealing with those quantities through a set of configurable parameters.

Acknowledgments

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