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Muon identification procedure for the ATLAS detector at the LHC using Muonboy reconstruction package and tests of its performance using cosmic rays and single beam data

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Abstract.

ATLAS is one of the four experiments at the Large Hadron Collider (LHC) at CERN. This experiment has been designed to study a large range of physics including searches for previously unobserved phenomena such as the Higgs Boson and super-symmetry. The ATLAS Muon Spectrometer (MS) is optimized to measure final state muons in a large momentum range, from a few GeV up to TeV. Its momentum resolution varies from (2-3%) at 10-100 GeV/c to 11% at 1 TeV, taking into account the high level background environment, the inhomogeneous magnetic field, and the large size of the apparatus (24 m diameter by 44 m length). A robust muon identification and high momentum measurement accuracy is crucial to fully exploit the physics potential of the LHC.

The basic principles of the muon reconstruction packages *Muonboy*, *STACO*, *MuTag* are discussed in this paper. Details of the modifications done in order to adapt the pattern recognition to the cosmic-ray configuration as well as its performance with the recent cosmic-rays and single beam data are presented.

1. Introduction

The ATLAS detector ([1, 2]) is designed to fully exploit the discovery potential of the LHC at CERN. Its Muon Spectrometer[3] designed to detect tracks over a large region of pseudo-rapidity $|\eta| < 2.7$, is made of a large toroidal magnet (with an average magnetic field of 0.5 Tesla) and consists of four detectors, each using a different technology. It has one Barrel Region (BR) and two End-cap Regions (ER). Monitored Drift Tube chambers (MDT) in both the BR and ER sections and Cathode Strip Chambers (CSC) are used as precision chambers, whereas Resistive Plate Chambers (RPC) in the Barrel Region and Thin Gap Chambers (TGC) in the End-cap Regions are used as trigger chambers. In the Barrel region the chambers are assembled in 'stations'. For instance to form a typical barrel station, MDT tubes are first grouped in 6 to 8 layers separated into two multi-layers. These multi-ayers, sandwiched by RPC chambers, form a station. In the transition and End-cap Regions the chambers are arranged also in three 'stations', therefore particles traverse most of the time at least three stations with a lever arm of several meters.

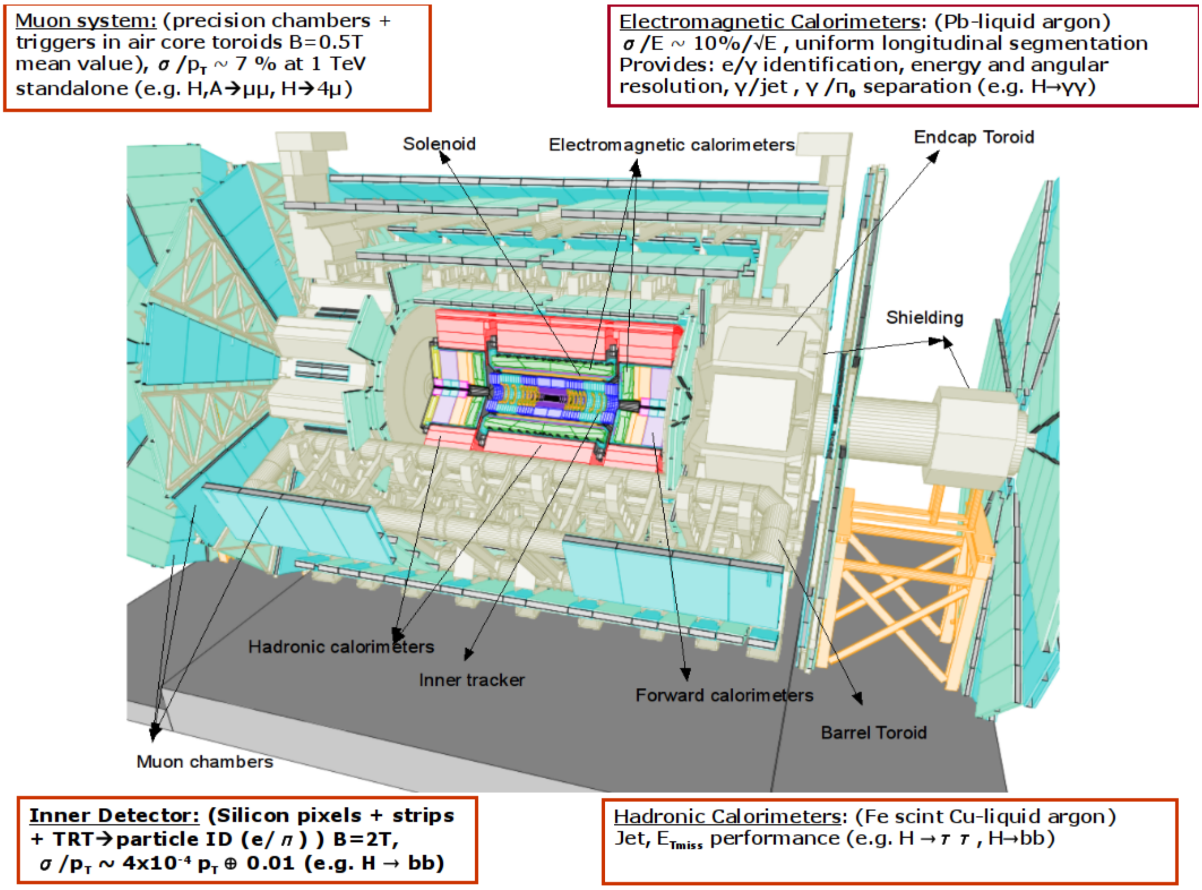

Figure 1. Illustration of the ATLAS detector.

2. Muon Reconstruction Principles

The passage of a muon in each station allows to measure locally its position and direction, i.e. to reconstruct a segment of its trajectory. These measurements are then used to adjust globally a track, i.e a reconstruction of the full muon trajectory. Various methods have been implemented for the identification and reconstruction of muon tracks.

- Standalone reconstruction: Muon tracks are reconstructed in the Muon Spectrometer only and the tracks are extrapolated to the beam line. The software package for this purpose described in the following sections is called *Muonboy*([3, 4]).
- Combined reconstruction: Muon tracks reconstructed in the Muon Spectrometer by *Muonboy* are combined with the tracks reconstructed in the Inner Detector (ID) using a statistical method. The software package for this purpose described in the following sections is called *STACO*[4].
- Tagged muons: Tracks reconstructed in the Inner Detector are extrapolated to the Muon Spectrometer looking for nearby hits. The software package for this purpose described in the following sections is called *MuTag*[4].

2.1. Reconstruction of Muons in the Muon Spectrometer

The ATLAS Muon system is designed to obtain high-momentum resolution over a large fraction of the (η, phi) space covered by the detector, up to muons with P_T of the order of a few TeV.

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Muonboy has been designed to match the high quality of the Muon Spectrometer. In particular the pattern recognition program copes with the following basic points:

- high background level present in the ATLAS experimental hall which yields high single tube occupancy, may spoil or mask muon hits and create fake tracks from combinatorial hit associations;
- the high inhomogeneity of the magnetic field which forbids any assumption on simple analytical shapes for the muon tracks;
- the variety of the muon chambers used and the complexity of the layout of these chambers;
- the large distances between measuring stations which induce significant extrapolation uncertainties;
- the physical separation between precision and second-coordinate chambers which precludes the use of truly three-dimensional information.

The strategy of the pattern recognition algorithm, described below, can be summarized in four main points:

(i) identification of regions of activity in the muon system, through the RPC/TGC systems;
(ii) reconstruction of local segments in each muon station in these regions of activity;
(iii) combination of segments of different muon stations to form muon track candidates using three-dimensional tracking in the magnetic field;
(iv) global track fit of the muon track candidates through the full system using individual hit information.

2.1.1. Region of activity: In the first step, regions of activity (ROA) that may comprise several chambers in the (η, ϕ) space are identified using information from the trigger chambers. The size of these regions is roughly $\mathrm{d}\eta \times \mathrm{d}\phi = 0.4 \times 0.4$ and they are centered where there exists at least one RPC/TGC hit in both coordinates. Then, all muon chambers intersecting with these ROAs are selected for the muon track reconstruction.

2.1.2. Segment reconstruction: Next, straight track segments are formed by trying to combine each MDT hit of a multilayer with, in turn, every MDT hit in the other multilayer of the same or adjacent station. At this stage the hits are close enough in space for the straight line approximation to be valid locally. Magnetic field deflections will be taken into account at track fitting stage. The pair of hits in the two multi-layers is required to point loosely to the interaction vertex, in order to suppress background tracks and random hit combinations. This pair of hits gives two circles to which candidate segments should be tangent. There is thus four such candidate segments. All four possible segment candidates associated with a pair of hits are extrapolated to the remaining tubes in the MDT chamber and matched with hits recorded there, to possibly validate the trial and resolve the four-fold ambiguity. A track segment is declared valid if its quality factor (combination of standard χ^2 for found hit tubes and penalty for missing ones) is sufficiently small. The following effects are taken into account in computing this factor, resulting in a probability distribution that deviates from that of a purely statistical χ^2:

- the possible masking of a genuine muon hit by a particle such as a δ-ray crossing the tube closer to the wire than the muon does. Tube hits with a drift time shorter (by an amount that does not exceed the dead time) than that expected from track extrapolation to this tube, have a lower contribution than hits with a drift time longer than the expected value;

- detection efficiency of individual MDT tubes. The higher the tube efficiency assumed, the larger the contribution of tubes which are crossed by the extrapolated candidate track segment, but which do not contain a valid hit.

In a first pass, track segments are required to be associated with at least one second-coordinate hit. This so-called "strict search" is therefore performed only for the outer and middle stations in the barrel, and the inner and middle stations in the end-cap, i.e. where second-coordinate trigger chambers are available.

A second, "loose" track segment search follows the strict search, based on less stringent cuts and without requiring matching with second-coordinate hits. As for the "strict" search, all available hits compatible with a ROA are used. When no second-coordinate measurement is available in the station under consideration, several second-coordinate positions are tried, because the azimuthal track position influences the measured drift time through signal propagation delay along the wire and Lorentz-angle effects.

These searches are each complemented by a second class of straight track segments, those crossing only one of the two multi-layers in a station: the principle is the same as for segments extending on two multi-layers, except that the loop is here done on all pairs of hits in a same multilayer. Here, in order to reduce the large number of possible combinations, only those hits left unassociated with track segments found in previous searches, are considered, and only candidate segments which do not cross the other multi-layer (either because on the edge or because of dead channels) are kept.

2.1.3. Track fit

(i) Tracks are first seeded from the "strict" segments, with a first rough estimate of the momentum deduced from the position and direction of the segment. Each of these segments is then extrapolated to the other (i.e. to inner or outer if starting from a middle one) stations using tracking in the magnetic field; several trials are performed for different values of the momentum around the first rough estimate ("momentum scan"). If some matching exists, in position and direction, of the extrapolated tracks with one (or several) "loose" segment(s) in this next station, the one with the best matching is included in the candidate track and a fit is performed leading to a second and more accurate estimate of the momentum. In this fit (and the following ones) full tracking is performed at each step of the minimization procedure.

(ii) A second and finer "momentum scan" around the improved momentum estimate is then performed with extrapolations to all other potentially crossed stations. In the fitting procedure, only one segment is kept per crossed station. Any matching loose segment in these stations is included in the candidate track. After this stage, a candidate track is kept only if it contains at least two segments. Using all the segments belonging to the candidate track, a new fit is performed to fine tune its position, direction, and momentum;

(iii) Then, a global fit is performed, starting from the best result of the previous fits, but using this time directly the raw information available (i.e. the TDC values and hit strips instead of the pre-reconstructed straight track segments). The purpose of this last stage is to get a global and more realistic estimate of the likelihood of the candidate track and, for example, to make it possible to select, among all the hits a priori belonging to the track, the "good" ones from the "bad" ones (those spoiled by δ-rays or gamma or neutron background) which are too far away from the reconstructed path of the muon.

(iv) Finally, a final fit including matter is performed. In contrast to Kalmman filter method for example, this is done by adding to the track parameters additional fit parameters. The inert material traversed by the muon is discretized into a finite number of scattering centers. At these centers energy is lost and the track direction can change discontinuously to take into account multiple scattering effects. The corresponding scattering angles are free parameters in the fit with their Gaussian distribution (small angle approximation) added as a constraint in the χ^2. In order to keep the number of free parameters at an acceptable level, an optimized procedure merges close-by neighboring scattering centers into single ones. The energy loss is also taken into account at this stage using parametrization of the most probable energy loss as a function of the momentum and the amount of matter crossed and is applied at these scattering points. Eventually, the selection of reconstructed muons is made according to the value of the χ^2 of this final fit.

2.1.4. Adaptation of muon reconstruction algorithm for cosmic rays When running on cosmics, some changes have been necessary in order to cope with the different running conditions compared to collisions: the timing is more complicated, and the tracks are not pointing.

The topology of cosmics is addressed by relaxing the ROA requirement (segments and tracks are looked for in the whole region of the Muon Spectrometer) and the pointing criteria when looping on hit pairs while making segments or when matching segments while fitting tracks. Also, as the detector is still in commissioning phase, and not fully working, all segments (and not only the strict ones) may seed a track.

The problem of timing is more complex: the "end of drift" time on each wire is measured, but the starting time (of each station) is not known with sufficient accuracy and must be added as a free parameter in the segment fit procedure. As the pattern of tubes compatible with a segment may change when varying this starting time (T0), the procedure used was to scan different values of T0, doing a full segment reconstruction on each one. The value of the T0 giving the best reconstruction (quality factor as explained before) is kept, and a parabolic fit is performed (using this best value, the preceding one and the following one) in order to improve the resolution on this T0.

2.2. Combined muon Reconstruction

Muon tracks are reconstructed in the two tracking devices of the ATLAS detector, the Inner Detector and the Muon Spectrometer.

The *STACO* algorithm performs a statistical combination of these two independent measurements using the parameters of the reconstructed tracks and their covariance matrices. This combination improves the momentum resolution over a wide range of transverse momentum $6<P_T<200$ GeV/c and allows for the rejection of muons from secondary interactions as well as the ones from π/K decays in flight. In general the Inner Detector dominates in the range of P_T up to ≈ 30 GeV/c and the Muon Spectrometer in the region above ≈ 200 GeV/c.

The *MuTag* algorithm has been developed initially to tag low P_T muons. In this case, Inner Detector tracks with sufficient momentum are propagated up to the first stations of Muon Spectrometer trying to match with nearby segments reconstructed in these stations which are not yet associated to a combined *STACO* track. Moreover in particular regions of the Muon Spectrometer in which a track traverses only one station (for example in the region of $|\eta| \approx 1.2$) the Inner Detector tracks are propagated also up to the medium stations in order to increase the efficiency of the tagging. The Inner Detector track is used to evaluate the muon kinematics in this case. The *MuTag* algorithm serves as a supplement to *STACO* but improves the efficiency of muon reconstruction over the full range of muon momenta.

3. Results

3.1. Performance of muon identification algorithms using simulation samples

The performance of the muon reconstruction and tagging algorithms described in the previous section is evaluated using various simulated samples. In figure 2 the efficiency of the standalone and combined reconstruction algorithms *Muonboy*, *STACO*, *MuTag* as a function of pseudo-rapidity η is shown in a simulation sample of single muon tracks of P_T=100 GeV/c. We observe that the *STACO* efficiency is $\approx$ 96% on the single muon samples and is dropping in regions where the Muon Spectrometer coverage is thin. The combined muon efficiency is supplemented with the standalone *Muonboy* efficiency to extend the η coverage up to 2.7. The *MuTag* algorithm provides a supplement to *STACO* especially in the region of $|\eta| \approx 1.2$ with the succesfull extrapolation of the Inner Detector track up to the medium stations.

Figure 3 shows the P_T resolution of *Muonboy* algorithm obtained on muon tracks coming from the leptonic decays of a W boson produced in a $t\bar{t}$ sample. A resolution of $\approx$ 4% is obtained over a large region of P_T.

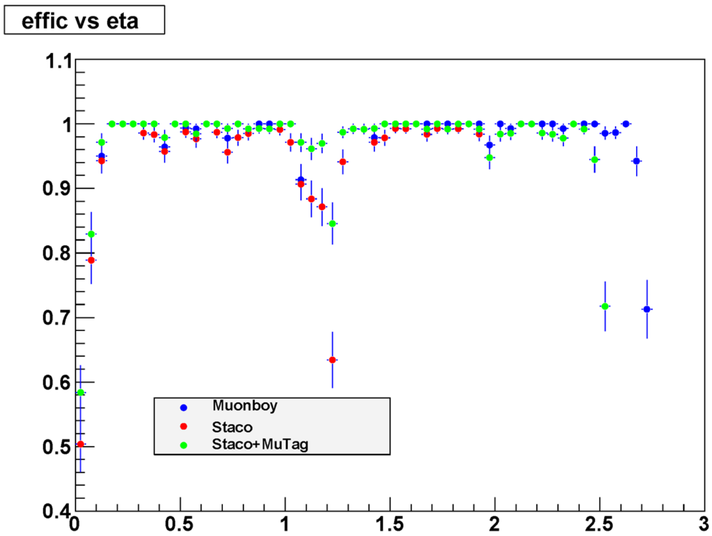

Figure 2. Efficiency as a function of pseudo-rapidity $|\eta|$ from standalone and combined μ reconstruction algorithms, obtained on a single muon simulated sample of P_T=100 GeV/c

3.2. Performance of muon identification algorithms using cosmic events and the first LHC single beam data

The commissioning phase of the ATLAS detector started two years ago. During that time, cosmic-ray runs were recorded with various configurations in terms of the ATLAS sub-detectors involved, which allowed for a detailed monitoring of the performance of the detector as well as various tests of the full software chain from the data acquisition up to the reconstruction of these events. Two examples of some measurements performed in the Muon Spectrometer with one cosmic run recorded in the absence of the toroidal magnetic field of ATLAS, are shown in figures 4(a) and 4(b). These figures show the residual distribution of the reconstructed tracks calculated as the signed track distance from each of the MDT or TGC hits forming this track. The MDT chambers give precise and redundant measurement in the η coordinate while the trigger chambers give a rough measurement in the η and ϕ coordinate.

The distribution of the MDT residual 4(a) allows to check for the quality of the reconstruction, whereas the TGC-η residual distribution 4(b) allows to check the relative alignment of TGC chambers with respect to the MDTs. The TGC wheels in this period of data taking were shifted by 25 mm compared to their nominal position. This shift was recovered as we observe on

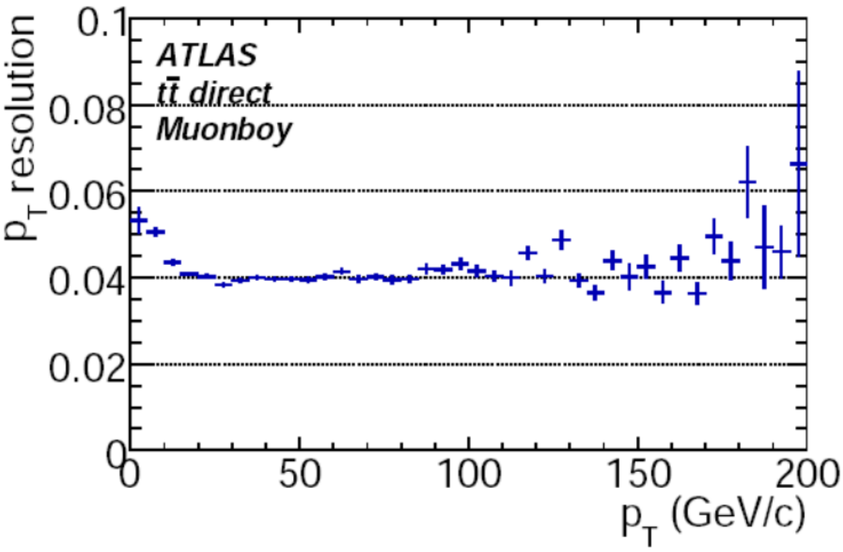

Figure 3. P_T resolution as a function of P_T of *Muonboy* obtained from muons in a $t\bar{t}$ simulated sample

the figure 4(b) where the nominal position is represented in blue and the TGC residuals after alignment corrections in hatched red.

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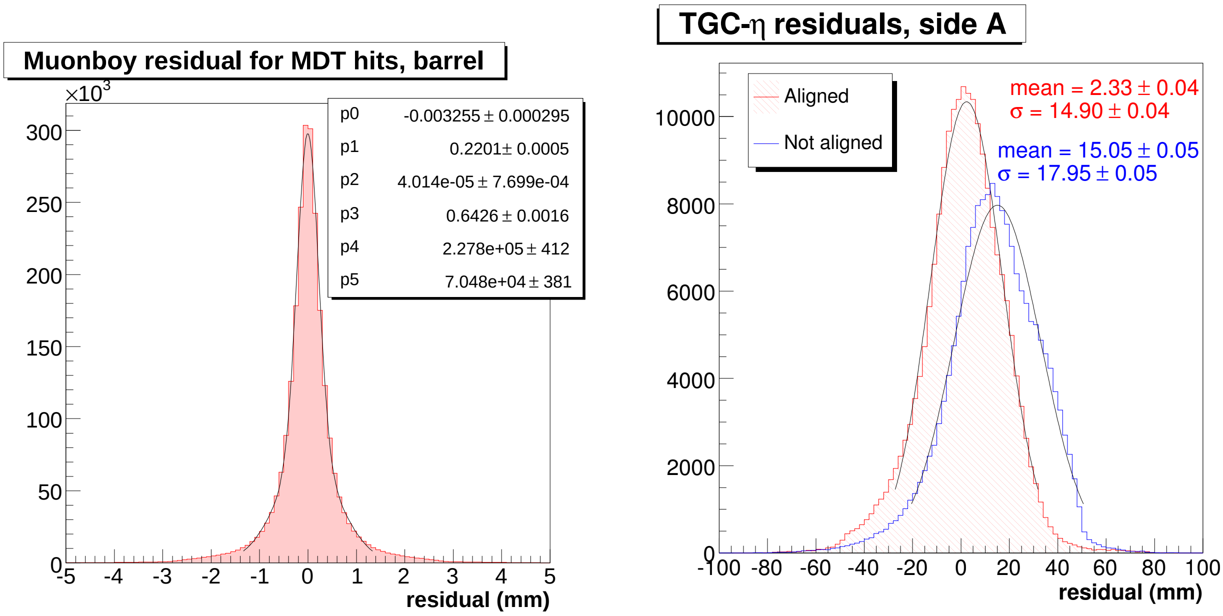

(a) (b)

Figure 4. (a)MDT track residuals for chambers in the barrel section of the Muon Spectrometer, as obtained from one cosmic-ray run in the absence of toroidal magnetic field. (b)TGC track residuals with (red hatched) and without alignment corrections, as obtained from one cosmic-ray run in the absence of toroidal magnetic field.