

The Muon High Level Trigger of the ATLAS experiment

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Abstract. The ATLAS experiment at CERN's Large Hadron Collider (LHC) has been designed and built for new discoveries in High Energy Physics as well as for precision measurements of Standard Model parameters. To satisfy the limited data acquisition and recording capability, at the LHC project luminosity, the ATLAS trigger system must select a very small rate of physically interesting events (~ 200 Hz) among about 40 million events per second. In the case of events containing muons, as described in this work, the first hardware-based level (Level-1) starts from coincidence of hits in the Muon Spectrometer trigger chambers to select Regions of Interest (RoI) where muons produce significant activity. Such RoIs are used as seeds for the two subsequent trigger levels (Level-2 and Event Filter), running on dedicated online farms, which constitute the High Level Trigger (HLT). This seeding strategy is crucial to drastically reduce the total processing time. Within the Muon HLT, few algorithms are implemented in different steps according to predefined sequences of Feature Extraction (FEX) and Hypothesis (HYPO) algorithms, whose goal is to validate the previously selected muon objects. The ATLAS muon trigger system, thanks to its particular design and to the peculiar structure of the Muon Spectrometer, is able to provide muon stand-alone event trigger decisions, that can be furtherly refined by exploiting the muon information coming from the other ATLAS subdetectors. Muon HLT algorithms are described here in terms of working functionality and performance both on simulated and real data, including non-standard trigger configurations (like cosmic data and LHC start-up scenarios).

1. Introduction

ATLAS (A Toroidal LHC ApparatuS) is a general purpose high-energy physics detector [1] designed to detect proton-proton collisions at CERN's Large Hadron Collider. Its primary goals are to explore the mechanism for electroweak symmetry breaking and to search for new physics beyond the Standard Model (for example Supersymmetry or Extra-Dimensions).

Proton-proton collisions will be provided at a center of mass energy of 14 TeV, with a design luminosity of $10^{34} \text{cm}^{-2} \text{s}^{-1}$ and a bunch-crossing rate of 40 MHz. Since for every bunch intersection about 25 inelastic proton-proton interactions will be expected, a final rate of $\sim 10^9$ interactions per second will have to be handled. The limits on the capability of the ATLAS Trigger-Data Acquisition (TDAQ) system to store data and the expected event size impose an upper limit of 200 Hz to the final trigger output. A rejection power of $\sim 10^6$ is therefore required to the TDAQ system, together with a high efficiency for the interesting events. In order to accomplish this, the ATLAS trigger is structured in three subsequent levels of increasing precision, designed with the goal of progressively reducing rates.



The first level, Level-1 [2], uses custom built electronics and has to bring the initial rate down to ~ 75 kHz with a maximum latency time of $2.5 \mu\text{s}$. The so-called High Level Trigger (HLT) [3] is made up of two software-based levels, the second level (Level-2) and the third level (Event Filter), whose aim is to reduce the total event rate to ~ 3 kHz first and then to ~ 200 Hz, with average processing times of ~ 40 ms and ~ 4 s, respectively. HLT algorithms will be running on dedicated farms of about 500 quad-core CPUs for the Level-2 and of 1800 dual quad-core CPUs for the Event Filter. Figure 1 describes the flow of the algorithms belonging to the muon trigger, including the corresponding rate reduction and the processing time required at each step.

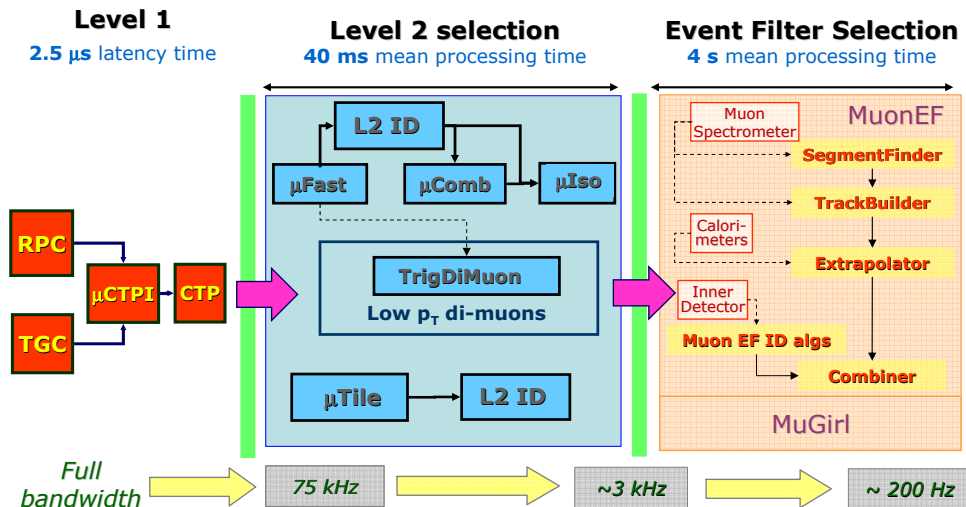


Figure 1. Algorithmic flow of the ATLAS muon trigger.

In this work the implementation of the algorithms belonging to the Muon High Level Trigger will be presented. Their performance on simulated physics events will also be described and, finally, some preliminary results obtained during 2008 cosmics data taking will be shown.

2. The ATLAS Muon Trigger

The ATLAS Level-1 muon trigger selects events with high transverse momentum (p_T) muons and allows for the correct association to the bunch-crossing of interest. It is composed of a barrel section in the region with pseudorapidity $|\eta| < 1.05$ (instrumented with Resistive Plate Chambers, or RPC), two endcap sections in $1.05 < |\eta| < 2.4$ (instrumented with Thin Gap Chambers, or TGC) and the MuCTPI (Muon to Central Trigger Processor Interface). By using the RPC and TGC detectors, located in the external layers of the Muon Spectrometer (MS), it is able to select muons with p_T above six programmable thresholds and to give a rough estimate of their positions in terms of *Regions of Interest* (RoI), with coordinates pseudorapidity η and azimuthal angle φ . For the single beam run in September 2008, a special Level-1 configuration

with the largest possible coincidence windows was set in order to increase the acceptance, allowing for tracks not pointing to the interaction region as for standard running,

The muon Level-2 trigger can access to the full detector granularity data inside a RoI passed by Level-1, improving the estimate of muon's position and transverse momentum by means of optimized algorithms, specifically written to perform a fast selection of prompt muons and an efficient rejection of background. Data analyzed by Level-2 are 1-2% of the full event size.

Also the muon Event Filter (EF) has access to full detector granularity, with seed provided by Level-2 FEX's, and in addition it can potentially use the full event reconstruction. Algorithms used at the EF are more sophisticated than at Level-2, and they are the same implemented in the offline reconstruction, adapted in the online framework. Moreover, the latest calibration and alignment information are available for the EF selection.

3. Muon Level-2 Trigger

The first Level-2 algorithm, *muFast*, aims at confirming or discarding muon candidates provided by Level-1. It selects hits from Monitored Drift Tubes (MDT) of the Muon Spectrometer stations within a road where the Level-1 trigger detectors were fired. In each station a local linear fit is performed to obtain the intersection of the muon trajectory with the station itself and its slope: in the barrel, starting from the track radius corresponding to these points and the (η, φ) coordinates at the entrance of the MS, the muon transverse momentum is computed by means of a Look Up Table (LUT), which allows to avoid lengthy calculations and a heavy access to external services, thus reducing algorithm execution time to few ms. In the endcap regions suitable reconstructed quantities are used as input for the LUT, in order to take into account the magnetic field inhomogeneities.

The performance of *muFast*, as well as of the other algorithms described in the following, has been tested on various Monte Carlo samples, with the goal of measuring trigger efficiencies, p_T and spatial resolution, trigger and fake rates. In Figure 2 the transverse momentum resolution is shown as a function of the generated p_T in single muon simulated samples. The various points in the plot correspond to different η regions.

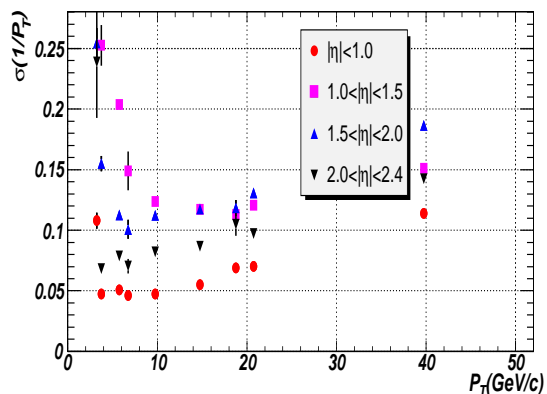


Figure 2. Transverse momentum resolution of *muFast* in different pseudorapidity regions.

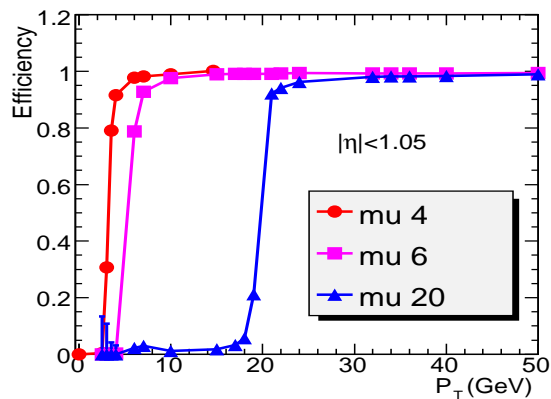


Figure 3. Efficiency of *muComb* with respect to *muFast* in the barrel region as a function of the muon transverse momentum.

At Level-2 muon tracks in the MS can be combined with information coming from other detectors, such as the Inner Detector (ID) [4]. This is done by the *muComb* algorithm, that

matches MS and ID trajectories by means of spatial windows determined analytically with a very fast procedure based on optimized LUTs. Transverse momentum is calculated as resolution-weighted average of ID and muFast transverse momenta. The efficiency of muComb with respect to muFast in $|\eta| < 1.05$ as a function of generated muon p_T is reported in Figure 3 for three different p_T thresholds: 4, 6 and 20 GeV. The main goal of muComb is to reduce rates from in-flight decays of pions or kaons, which are expected to be dominant in the low- p_T range. This is possible thanks to a p_T resolution improved by a factor of ~ 2.5 with respect to muFast, that allows to reject muons from light meson in-flight decays with a reduction of 26% (estimated on simulated single π/K samples) against a signal loss of the order of % [7].

Another relevant source of background to isolated muons in the middle-low p_T region is given by muons reconstructed in jets, originated by charm and beauty semileptonic decays. The Level-2 algorithm *muIso* selects high momentum isolated muons found by muFast or muComb and by using information from the ID and from the Liquid Argon [5] and the Tile [6] calorimetric systems of the ATLAS apparatus. Access to calorimetric information is done in a $\Delta\eta, \Delta\varphi$ portion of the detector according to the direction of the muon RoI candidate provided by the seeding algorithm: few quantities are then evaluated inside an inner and an outer cone around the muon direction of suitably defined radii, such as the total energy released and the number of cells hit inside such cones. A threshold energy is used in order to reduce the impact of pile-up and of electronic noise. A similar approach is followed for muon isolation based on the Inner Detector: in this case the most relevant variables are the charged track multiplicity in a given cone around the muon direction, and the ratio between the p_T of the muon and the sum of the transverse momenta of all the tracks reconstructed inside the cone itself. In Figure 4 the performance of

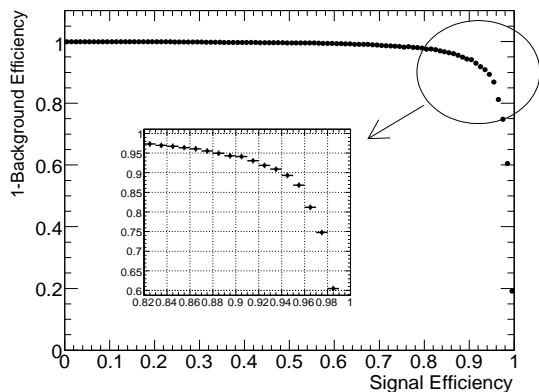


Figure 4. Background rejection versus efficiency for muIso estimated on simulated events with non-isolated and isolated muons, respectively.

muIso is shown: the rejection of non-isolated muons (obtained on simulated $b\bar{b}\mu X$ events with muons having $p_T > 15$ GeV) is reported in ordinate versus the algorithm efficiency on isolated muons (evaluated on a simulated $Z \rightarrow \mu\mu$ sample) in abscissa. As can be observed in the plot, muIso is able to maintain a high efficiency (at least 95%) whilst background rejection is kept close to $\sim 90\%$.

Another Level-2 algorithm designed for gaining efficiency on very low- p_T muons is *muTile*: this is particularly helpful for enhancing trigger in B-physics events, where muons are triggered by RPC or TGC detectors with relatively poor probability, since their transverse momentum is so low that track segments are produced only in the innermost layer of the Muon Spectrometer. The identification procedure starts by searching for muon candidates in all the outer layer cells of the Tile Calorimeter, checking that the energy deposited in each cell is compatible with a muon (energy thresholds are defined using simulated single muon events). Subsequently the search is extended in the central and innermost layer cells according to projective patterns in η toward the interaction point (IP), evaluating at each step the compatibility of the cell

energy with the energy expected to be deposited by a muon. Finally, η and φ coordinates are estimated as averages of the crossed cells in the three layers. The search for muon candidates can be performed following two possible strategies: a full scan in the calorimeter (which has the advantage of being independent of the MS trigger and reconstruction results but takes longer processing times), or a RoI-based method (which concentrates on specific regions pointed out by the muon Level-1 and provides faster results though with few % of event loss). In the full scan strategy, the efficiency of muTile in the region $|\eta| < 1.4$ is found to be, in average, about 60% down to $p_T = 2$ GeV.

4. Muon Event Filter

Two software packages are implemented in the Muon Event Filter: *TrigMuonEF* and *TrigMuGirl*. They both are *wrappers* of muon offline reconstruction tools, and have the task to confirm or discard muon candidates validated at Level-2 (for debug purposes, the seed can come also directly from Level-1 RoIs). The main difference between these two packages is in the strategy used to reconstruct muons: while the former starts from the MS and extrapolates back to the IP, the latter begins from the ID and carries on muon identification outwards.

TrigMuonEF consists of a chain of four sequential FEX algorithms, and corresponding HYPO algorithms allowing or not to produce the final trigger decision: *SegmentFinder*, *TrackBuilder*, *Extrapolator* and *Combiner*. Segments are made first, starting from MDT precision hits, then track are built from segments inside the Muon Spectrometer, adding information from the other muon detectors. In the following steps, the reconstructed tracks are extrapolated back to the IP taking into account the magnetic field, the energy loss in the calorimeters and the effect of the multiple scattering through all the crossed materials. In the last step, extrapolated tracks are combined with spatially matching tracks (if present) in the Inner Detector, by means of a global refit of all the hits actually used in both MS and ID systems. In Figure 5 the efficiency with respect to Level-2 (muComb) is presented as a function of the generated muon p_T for the *TrackBuilder*, *Extrapolator* and *Combiner* algorithms in a simulated sample of $t\bar{t}$ events. No p_T thresholds have been applied in this case. Pseudorapidity resolution as a function of transverse momentum is shown in Figure 6 for EF algorithms *Extrapolator* and *Combiner*, compared to Level-2 muFast and muComb and to Level-1. It can be observed that the spatial resolution is improved at each trigger level and, most of all, passing from MS-only tracks to MS+ID combined tracks.

TrigMuGirl implements muon reconstruction and tagging at Event Filter starting from candidates provided by EF Inner Detector algorithms, inside the muon Level-2 RoI. Tracks are subsequently extrapolated toward MS chambers, looking for hits around the ID track direction, making segments from hits and improving extrapolation using segments. Hit and segment information is collected to identify muon-like candidates, which are finally reconstructed by performing a global fit using the initial ID track together with the hits found. Together with a good timing performance, *TrigMuGirl* is characterized by efficiency and resolution results which are comparable with those by *TrigMuonEF*. Moreover, when segment reconstruction is imperfect, *TrigMuGirl* can be run in a dedicated mode in order to select and trigger possible events containing slow particles (for instance low- β R-hadrons [7]) by properly estimating β from MDT and RPC and then correcting MDT hit/segment finding by taking into account this β to reconstruct the mass of the particle.

5. Results on 2008 cosmics data

Before the start-up phase of the LHC, in which the running strategy will mainly focus on the commissioning of the trigger and of the detector based on the expected physics processes, the muon trigger has been tested and validated during the 2008 cosmic running period with the HLT running online. Results shown in the following refer to few different runs with data taken in

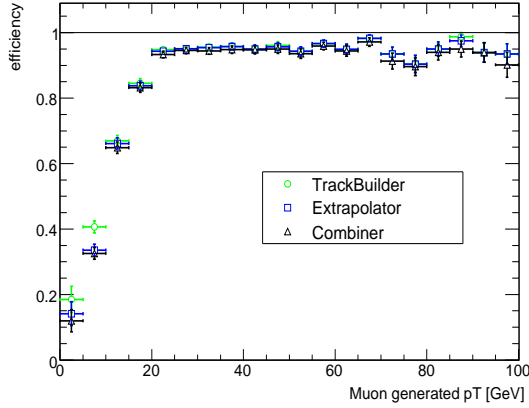


Figure 5. Efficiency as a function of p_T with respect to muComb of the three reconstruction steps of the TrigMuonEF package.

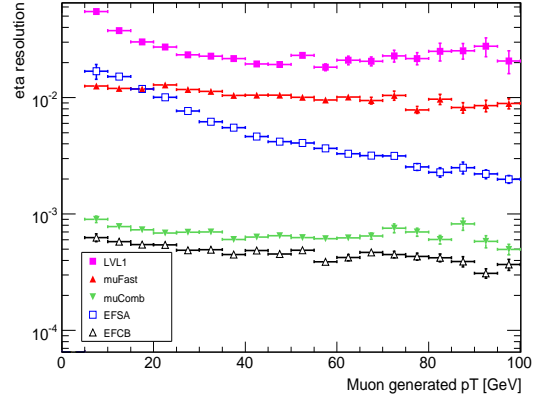


Figure 6. Pseudorapidity resolution evaluated at the interaction point as a function of p_T for Level-1 and for several Level-2 and Event Filter algorithms.

various running conditions, and are intended to give general examples of the Muon HLT working functionality on real data.

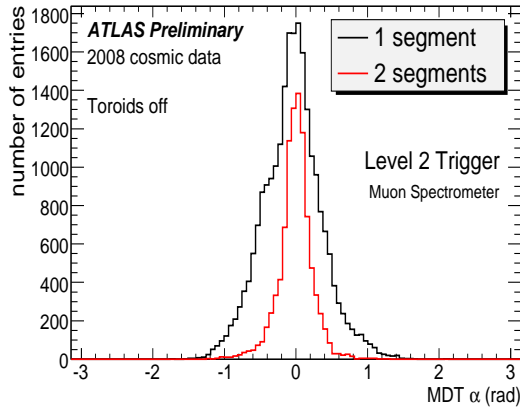


Figure 7. α angle (see the text) with respect to the pointing direction for *muFast* tracks with 2 MDT segments out of 3.

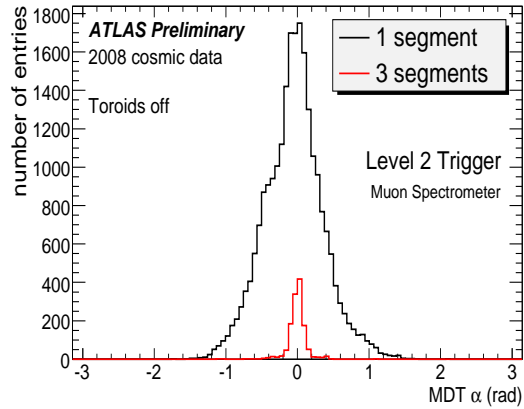


Figure 8. α angle (see the text) with respect to the pointing direction for *muFast* tracks with 3 MDT segments out of 3.

Figure 7 shows the distribution of the polar angle α in the r - z plane of the MDT track fit slope with respect to the direction pointing to the IP for *muFast* tracks reconstructed using 2 MDT segments out of 3 in pattern recognition (red curve), superimposed to the *muFast* reconstruction obtained with only 1 MDT segment in the middle station (black curve). These data were taken with solenoidal field on and toroidal field off, thus straight tracks were detected in the Muon Spectrometer. In Figure 8 the same angle distribution is shown in the case of 3 MDT fit segments: with this tighter request, the performance of the pattern recognition is significantly improved as α is measured to be much closer to 0, although the number of reconstructed tracks is strongly reduced, since *muFast* is an algorithm designed to reconstruct muons originating at the IP while the results shown here are obtained on non-pointing cosmic rays. By measuring the

track sagitta on straight tracks (with resolution of 5.6 mm and approximately gaussian tails), one can obtain a limit to the intrinsic resolution achievable by muFast in the evaluation of p_T , which is presently dominated by the limited knowledge of misalignments in the MDT stations, to be improved when alignment corrections will be used in Level-2 muon trigger. Further details on this analysis are available in [8].

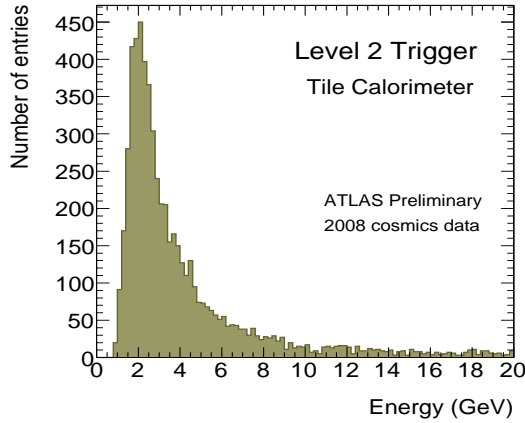


Figure 9. Deposited energy in the Tile Calorimeter measured with muTile.

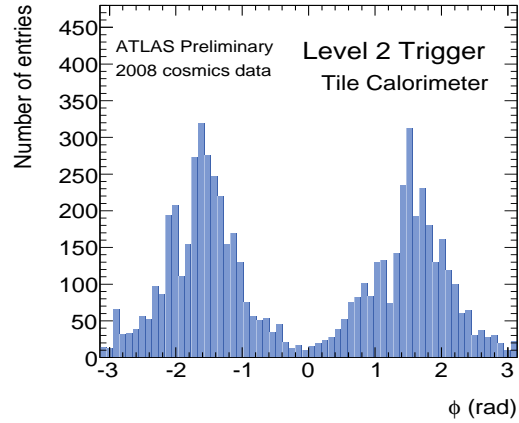


Figure 10. φ angle distribution in the Tile Calorimeter obtained with muTile.

In Figure 9, the distribution of the energy deposited by cosmic muons in the Tile Calorimeter is represented, as obtained with the Level-2 algorithm muTile run in full scan mode on a set of data taken with the magnetic field switched off. The request of energy per cell $E > 300$ MeV was applied in order to take into account and reduce the effects of the electronic noise. Consistently to what can be observed on Monte Carlo simulations for the deposited energy of muons crossing the ATLAS Tile Calorimeter, a peak is found around 2.5 GeV. For the same run, the azimuthal angle φ distribution obtained with muTile is shown in Figure 10. A typical up-down distribution can be observed in this case, as expected for cosmic muons passing through the calorimetric system.

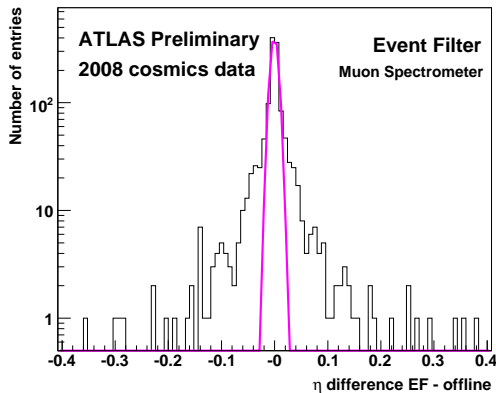


Figure 11. Pseudorapidity resolution for *TrigMuonEF* tracks with respect to corresponding offline muon tracks.

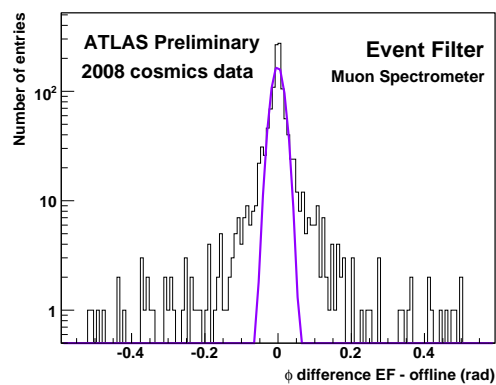


Figure 12. Azimuthal angle resolution for *TrigMuonEF* tracks with respect to corresponding offline muon tracks.

In Figures 11 and 12 the performance of TrigMuonEF reconstruction is tested by comparing the spatial position of the EF tracks with respect to the position of the corresponding tracks obtained by the offline MS reconstruction tool, in terms of pseudorapidity η and of azimuthal angle φ , respectively. The resolution obtained from the fit to a Gauss function of the differences of the considered variables is about 0.007 for η and 17 mrad for φ . In the data considered here, both solenoidal and toroidal fields were on. Although muon EF algorithms are nothing but wrappers of the muon offline reconstruction tools, some non-gaussian tails in the resolution can be observed: they can be attributed to residual differences between the (η, φ) estimates in the two frameworks, such as the use of different calibration constants and other minor effects coming from the RoI-based seeding strategy of the muon EF instead of the standard full-scan reconstruction used in the muon offline environment.

6. Conclusion

The Muon High Level Trigger has been designed and implemented to cope with the demanding requirements of the ATLAS Trigger system in the high luminosity environment of the LHC. The stability of the performance of all algorithms is constantly under control and continuously validated on suitable simulated samples. The Muon Trigger commissioning on cosmics data and on single beam data is ongoing, with the goal of getting ready for the restart of the LHC.

7. Acknowledgments

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