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Muon Identification With the Event Filter of the ATLAS Experiment at CERN LHC

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***Abstract*—The Large Hadron Collider at CERN offers unprecedented challenges to the design and construction of detectors and trigger/data acquisition systems. For ATLAS, a three level trigger system has been developed to extract interesting physics signatures with a 10^6 rate reduction. To accomplish this, components of physics analysis traditionally deferred to off-line physics analysis must be embedded within the on-line trigger system.**

For the Muon trigger, the specific off-line algorithms MOORE (Muon Object Oriented REconstruction) and MuId (Muon Identification) have been adopted so far for the on-line use, imposing an operation in a Bayesian-like environment where only specific hypotheses must be validated.

After a short review of the ATLAS trigger, the paper shows the general strategy of the Muon Identification and Selection accessing the full event data, or being seeded from results derived at a previous stage of the trigger chain.

***Index Terms*—Algorithms, ATLAS, event filter, mesons, particle tracking, pattern recognition, trigger.**

I. INTRODUCTION

ATLAS (A Toroidal LHC ApparatuS detector [1]) is a high energy physics (HEP) experiment designed to exploit the full physics potential provided by the Large Hadron Collider (LHC), under construction at CERN. Its inner elements are a trajectory tracker enclosed in a superconducting solenoidal magnet (with a field of an average value of 2 T), which is surrounded by the calorimetry system. The global detector dimensions (diameter 22 m, length 42 m) are defined by a large air-core muon spectrometer, whose toroidal field shape motivates the detector name. The physics program [2] is widely diversified; it ranges from discovery physics to precision measurements of the Standard Model parameters. LHC will provide proton–proton collisions at a center-of-mass energy of 14 TeV and an optimal luminosity of 10^{34} $\text{cm}^{-2}\text{s}^{-1}$. The corresponding 40 MHz bunch crossing rate (with an average of $\sim$23 superimposed events) and the large number of detector channels ($\sim 10^8$) outline the challenge of the ATLAS Trigger and Data Acquisition (Trigger DAQ) system.

II. ATLAS TRIGGER DAQ

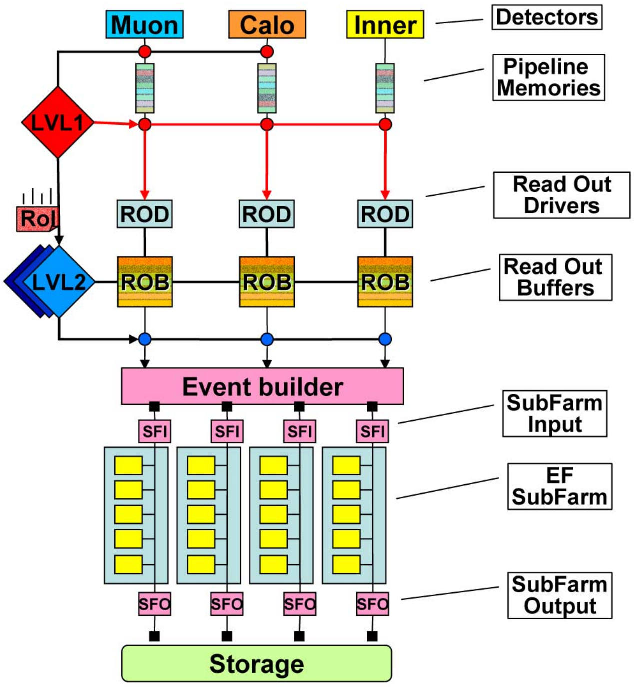

Fig. 1. Block diagram of the ATLAS Trigger DAQ system.

The ATLAS Trigger DAQ system must be able to reduce the initial 40 MHz bunch crossing rate to about 200 Hz of maximum data storage rate, in order to achieve the foreseen storage capability and meet the physics requirements of the experiment. The required data reduction factor, equivalent to a rejection factor of about 5 orders of magnitude, is achieved on-line via a trigger system organized in three different levels (Fig. 1).

The Level-1 trigger (LVL1) [3], implemented in hardware by custom electronics, will perform the first level of event selection, reducing the initial data rate from the 40 MHz collision rate to 75 kHz, with a fixed latency of 2.5 μs. For accepted events the LVL1 identifies the detector regions, defined in rapidity and azimuthal angle, where the signal exceeds programmable thresholds. These regions of interest (RoIs) are used to guide the Level-2 (LVL2) selection process that can access full granularity event data from all detectors. The Level-2 and Level-3, called Event Filter (EF), are software based systems and are collectively referred to as the High Level Trigger (HLT). The HLT must provide a further reduction factor of about 10^3. The goal is to achieve an average decision time of 10 ms and 1 s for LVL2 and EF respectively, although the system could easily scale to accommodate larger execution times, if needed. The LVL1 trigger system is directly connected to the detector front-end electronics of the calorimeter and muon detectors. Data of accepted events are stored in pipeline memories, connected to the read-out drivers (RODs) and made available to the HLT through read-out buffers (ROBs). Several ROBs are logically grouped in Read Out System (ROS) elements. If an

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event is accepted by LVL2, the Event Builder (EB) collects all the event data fragments from the ROBs. The complete event is then made available to the Event Filter (EF) for the final stage of triggering. The primary function of the EF is the reduction of the data flow and rate to a value acceptable by the mass storage system and by the subsequent off-line data reconstruction and analysis steps. The EF can also provide initial event sorting into streams for off-line production and global physics and detector monitoring, essential to ensure the quality of recorded data. The running environment for the trigger algorithms is the HLT Event Selection Software framework (ESS) [4], which is based on the ATLAS off-line reconstruction and analysis environment ATHENA (ATlas realization of a High Energy and Nuclear physics data analysis Architecture[5]). A common framework for developing and running both the on-line and off-line software allows the re-use of existing off-line algorithms, facilitates the development procedures and guarantees the consistency of trigger performance evaluation and trigger selection validation. The HLT algorithms either reconstruct new event quantities or check trigger hypotheses with previously computed event features. The Event Filter has to work at the LVL2 accept rate with an average event treatment time of about 1 s. Compared to LVL2, more sophisticated reconstruction algorithms, tools adapted from those of the off-line, and more complete calibration and alignments information are used here in making the selection. The EF receives fully built events which are then available locally for analysis. Also the EF processing can profit from the results of the earlier trigger stages, for example, using the results of LVL2 for seeding the EF processing.

III. MUON IDENTIFICATION

In ATLAS, the Muon Spectrometer [6] provides a standalone muon identification and measurement from typically three stations (multilayers) in the toroids (fitted with tracking detectors using four different technologies). The high-precision tracking system is based on Monitored Drift Tube (MDT), covering most of the acceptance and Cathode Strip Chambers (CSC) in the small angle-regions (η greater then 2). The Level-1 trigger is provided by Resistive Plate Chambers (RPC) in the barrel and Thin Gap Chambers (TGC) in the end-cap. The RPCs will also measure the track coordinates in the magnetic field direction to complement the precision tracking provided by the MDT which only measure the track coordinates in the bending plane (r,z) of the magnetic field. The global efficiency is typically 95%, due to holes for detector support and services and drops at very high p_T (above 500 GeV/c) due to catastrophic energy loss in the calorimeters, for which electromagnetic showering disturbs the pattern recognition. Below 6 GeV/c, the muon energy loss in the calorimeter is of the order of its initial energy so that it is no longer possible to follow the muon in the inhomogeneous magnetic field.

The reconstructed muon can be backtracked to the interaction region through the calorimeter, corrected for its estimated energy loss, and combined with its inner detector track in order to improve the momentum resolution for p_T up to 20 GeV/c. The off-line packages *Muon Object Oriented REconstruction* (MOORE)[7] and *MuonIdentification* (MuId) [8] have been developed in the ATHENA framework for the purposes of muon reconstruction and identification in ATLAS. They are two complementary reconstruction packages.

A. MOORE

MOORE (Muon Object Oriented REconstruction) reconstructs tracks inside the Muon Spectrometer, starting with a search for regions of activity within the detector, and subsequently performing pattern recognition and track fitting. The final reconstructed objects are tracks whose parameters are expressed at the first measured point inside the Muon Spectrometer.

The bending power of the toroidal magnetic field in the (x,y) plane is negligible almost everywhere in the detector, so a track can be approximated to a straight line in the plane transverse to the beam line (r,ϕ) plane, allowing the construction of segments, that are essentially vectors of digits measuring the ϕ coordinate.

The tracks crossing the ATLAS Muon Spectrometer bend in the (r,z) plane. Nevertheless in this plane a crude pattern recognition can be applied locally (in every station) assuming the tracks to be straight lines and approximating the precision measurements, e.g., for a Monitored Drift Tube (MDT) module the tube center is used to approximate the hit position. These approximations make it possible to construct track segments in (r,z) using the same procedure that is used to construct segments in the (r,ϕ) view. The (r,z) segments are subsequently refined by later phases of the pattern recognition. The refinement is restricted only to segments that have a corresponding segment in the (r,ϕ) plane in order to optimize the time latency of the algorithm. For each precision hit a drift circle is defined, with radius equal to the drift distance. For each pair of precision hits (one in each multilayer), the four tangential lines are found. Then, a track segment is built adding one by one all the hits having a residual distance from the line smaller than a given cut. The selected precision hits are fitted linearly and the segment is kept if it is successfully fitted, if it has a number of hits above a cut and if points to the interaction vertex. This track segment is referred as a road.

The use of hit information coming from the trigger chambers in order to guide the reconstruction in the precision chambers allows the restriction of the number of track segment candidates in the high background environment of the precision chambers.

The tracks produced by MOORE have the parameters expressed at their first measured point in terms of perigee parameters. In the final step of the fitting procedure, a looping procedure over all the roads, allows to assign to each road the hits from layers without trigger chambers. After having assigned hits from all the muon layers on a track, the track fit takes into account energy loss and Coulomb scattering effects. Finally, a cleaning procedure is performed to remove hits with high residuals.

B. MuId

The MuId (Muon Identification) package associates tracks reconstructed by MOORE in the Muon Spectrometer with the corresponding Inner Detector tracks found using the reconstruction program iPatRec [9] as well as with calorimeter information. The final objects are identified muons whose track parameters are given at the interaction region. The purpose of MuId is to identify muons among the Inner Detector tracks, to obtain improved parameter resolutions at moderate momenta from 20 GeV/c up to 100 GeV/c, and to clip the tails of badly measured high momentum muons (such as those resulting from catastrophic bremsstrahlung and the pattern recognition errors caused by showering in the Muon Spectrometer).

The first step (MuId standalone) is to re-fit the Muon Spectrometer tracks to express their parameters at the production vertex. The traversed calorimeters are represented by five additional parameters with measurements, namely two scatterers and an energy loss parameter. Two scatterers are sufficient to give deflected position and direction distributions (plus correlations) at the Muon Spectrometer entrance consistent with the simulation. The energy loss measurement (with error) is obtained either from the observed calorimeter energy deposition or from a parametrization.

In the next step (MuId combined), tracks are matched by forming a χ^2 with five degrees of freedom from the difference between the five track parameters of the track and their summed covariance matrix. The Inner Detector and standalone fits are used for this. To obtain the optimum track parameters, combined fits are performed to all matches with χ^2 probability above 10^{-4}. A combined fit is a refit to all the measurements and scatterers from the Inner Detector, calorimeter, and Muon Spectrometer systems. When no matches satisfy the above criterion, a combined fit is attempted for the best match within a road around the standalone track.

Finally, all matches to the Inner Detector giving a satisfactory combined fit are retained as identified muons.

The MOORE/MuId procedure provides the optimal track-parameter measurement expressed at the interaction region as well as the probability representing the compatibility of the track combination with a muon hypothesis. Ambiguities and low-probability matches are retained such that harder cuts can be applied as appropriate during physics analysis.

IV. MOORE AND MUID IN HLT

The requirements and the conceptual design of the HLT core software are discussed in [4], [10] and [11]. At the heart of the philosophy of the High Level Trigger design is the concept of seeding. Algorithms functioning as Event Filter should not operate only in a general purpose or exclusive mode, but they must retain the possibility of working in seeded mode, processing the trigger hypotheses formed at a previous stage in the triggering process. The HLT algorithms working in seeded mode typically need to access the event data that pertains to a region in ($\Delta\eta$,$\Delta\phi$), preliminarily set to (0.2,0.2), around the center of a RoI. For this need the algorithm must use the RegionSelector tool [12] that allow to select the Region to be accessed by the data. To implement the algorithm in an online environment, the basic requirement to the algorithms is to inherit from the `HLTAlgo` Base Class that augments the ATHENA Algorithm Base Class with same function usefull to the trigger environment. To avoid an explicit dependency from the Trigger in the off-line package and to be able to use the software components of the trigger framework, we have implemented the software for the Event Filter in the package TrigMOORE [13], that depends from the offline packages: MOORE and MuId.

Two main strategies have been developed:

- *Full scan strategy*—In this strategy TrigMOORE accesses directly the pointers of the off-line version of the algorithms allowing it to execute those algorithms as they are in the off-line package.
- *Seeded strategy*—In this strategy TrigMOORE accesses ad hoc algorithms that perform a *seeded* search only inside the Region of Interest. The main difference of these algorithms with respect to the off-line algorithm is the fact that by using the RegionSelector the algorithm accesses only the chambers that pertains to a certain geometrical region. After the search in the RoI and the construction of intermediate reconstruction objects, the typical off-line processing chain is executed.

The seeding in TrigMOORE can be provided either from LVL1 or LVL2. In particular, the full chain LVL1 simulation → LVL2 → Event Filter, also called *muon vertical slice*, has been integrated and tested within the HLT steering. The HLT processing flow is disaggregated into steps, and the decision to go further in the process is taken at every new step [4]. In the sequence of the HLT, TrigMOORE is called with a trigger element produced by the previous level as input parameter. From the trigger element it is possible to retrieve information about the Region of Interest. The RoI contains, among other information, its position in η and ϕ. The algorithms use the RegionSelector to know the chambers that pertain to a certain region ($\Delta\eta$, $\Delta\phi$) around the center of the RoI. The RegionSelector returns the list of detector elements that are contained within the region. Only these elements will be accessed from the seeded algorithms.

V. VALIDATION WITH SINGLE MUON SAMPLES

The physics performance of MOORE/MuId have been estimated with Monte Carlo simulation studies. Single muon events in a range of transverse momentum (p_T from 3 GeV/c to 1000 GeV/c) have been simulated and reconstructed to determine the optimum performance of the detector and software. In Fig. 2, the global efficiencies and the $1/p_T$ resolution of the off-line muon reconstruction algorithms are shown at different transverse momenta: in addition to MOORE and MuId (both StandAlone and Combined versions), also the reconstruction performance of the Inner Detector with iPatRec [9] are reported.

It is seen that the final reconstruction muon efficiency is greater than 90% for p_T above 7 GeV/c, but falls off rapidly with decrease of p_T, to approximately 25% at 3 GeV/c. The decrease results from absorption of the muons in the calorimeter material. For the $1/p_T$ resolution, it is seen that the global resolution is dominated by the Muon Spectrometer at low values, while at high p_T the Inner Detector prevails. The results show a rather good agreement with the expected performance [2].

VI. BACKGROUND REJECTION

At low transverse momenta the dominant source of muons at LHC and thus of rate in the LVL1 Muon System comes from in-flight decays of charged pions and kaons. The aim of the HLT muon trigger is the rejection of such soft muons selecting at the same time with high efficiency the prompt muons. This can be achieved using also the information coming from the Inner Detector and comparing the tracks reconstructed in such system

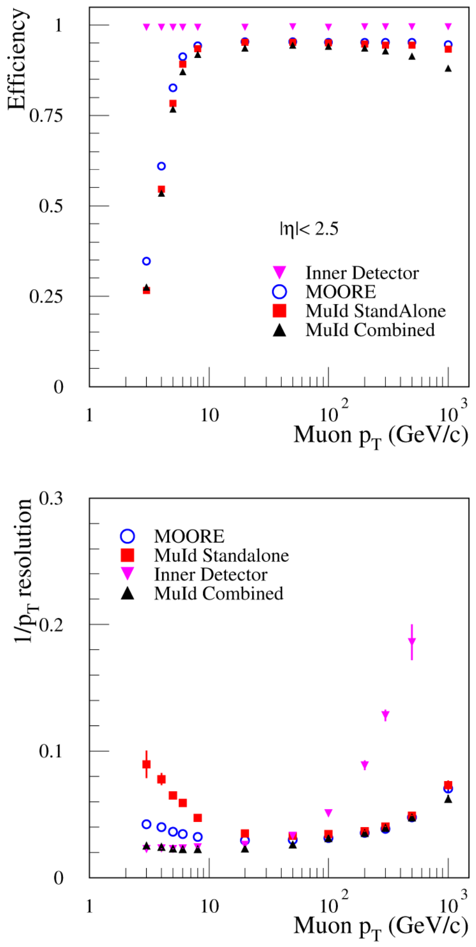

Fig. 2. Efficiency (upper figure) and $1/p_T$ resolution (lower figure) of single muon reconstruction as a function of p_T for MOORE, MuId Standalone, Inner-Detector(iPatRec) and MuId Combined.

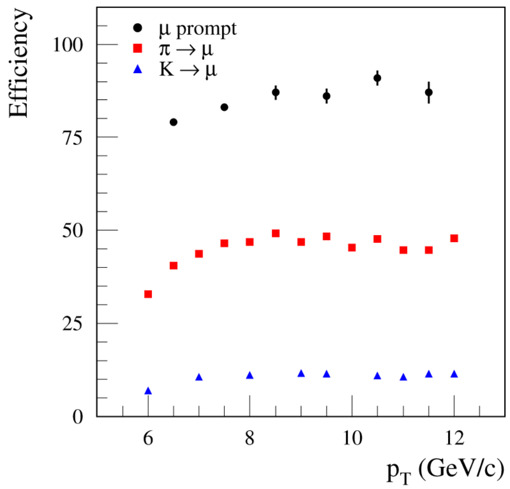

Fig. 3. Reconstruction efficiency for μ prompt and for muons coming from pions/kaons as a function of the p_T of the initial particle.

with those obtained in the Muon Spectrometer. In order to investigate the rejection of the Muon Event Filter a sample of simulated inclusive muons from $b\bar{b} \rightarrow \mu X$ events and muons from K or π in-flight decays in the p_T range (6–12) GeV/c has been simulated and studied (no Level-1 and Level-2 selection have been made here). In Fig. 3 the corresponding reconstruction efficiency curves, after the rejection cuts, are represented as functions of the transverse momentum of the prompt muons and of the starting mesons. Only the 5%-10% of muon from K decays and the 30%-50% of muons from π decays are misidentified as prompt muons. The efficiency for prompt muons goes from about 80% to about 90%. Another source of background in the Muon Spectrometer is represented by the background that will be present in the ATLAS experimental area (cavern background). This noise is fundamentally due to particles produced in the interaction of primary hadrons from p–p collisions with the materials of the detector and of the LHC elements. These particles (mainly neutrons) interact with matter and produce secondaries, behaving like a gas of time-uncorrelated neutral and charged particles diffusing through the apparatus. The reconstruction with MOORE has been tested on single prompt events embeded with minimum bias events and cavern background superimposition. For a conservative analysis, besides a "predicted" $\times 1$ factor [14], [15], corresponding to the expected amount of background for ATLAS, the "safety" factors $\times 2$, $\times 5$, and $\times 10$ (obtained by boosting the predicted background) have been considered. In Fig. 4 the reconstruction efficiency for TrigMOORE seeded by LVL1 is shown as a function of the p_T in case of single muons. The upper figure refers to the reconstruction inside the Muon Spectrometer (MOORE) while the lower figure refers to the efficiency after the extrapolation to the interaction region (MuId standalone). The efficiency lower while raising the background safety factor, this is related to the high population of the precision chambers that make the pattern recognition harder.

VII. EXECUTION TIME PERFORMANCE

The target mean execution time for an algorithm operating as Event Filter is $\sim$1 s. The timing performance of the MOORE algorithm both for seeded and full scan mode have been evaluated using a Intel XEON(TM) CPU 2.40 GHz processor, 1 GHz RAM. The time measurements include the data access, and are referred to the reconstruction including the extrapolation to the vertex. Average execution times per event are shown in Table I for both the seeded and the full scan version at different p_T values and also with predicted background $\times 1$ and a safety factor $\times 2$ of background superimposed. While the seeded reconstruction allows the study of a restricted portion of detector, it introduces in the data preparation an overhead since the presence of a certain detector in the data sample is verified by a search over the data collection. The small time overhead is evident in Table I. In fact when the portion of data accessed in the two execution mode are comparable (single muon samples without background), the average execution time for the seeded mode can be slightly higher than in full scan mode. The difference in timing between samples without/with background is related to the highly populated precision chambers, that make the pattern recognition, and raise the number of combinatorial used during the construction of the roads.

To compute the values in Table I, a 95% fraction of events has been retained, rejecting the events with the longest processing

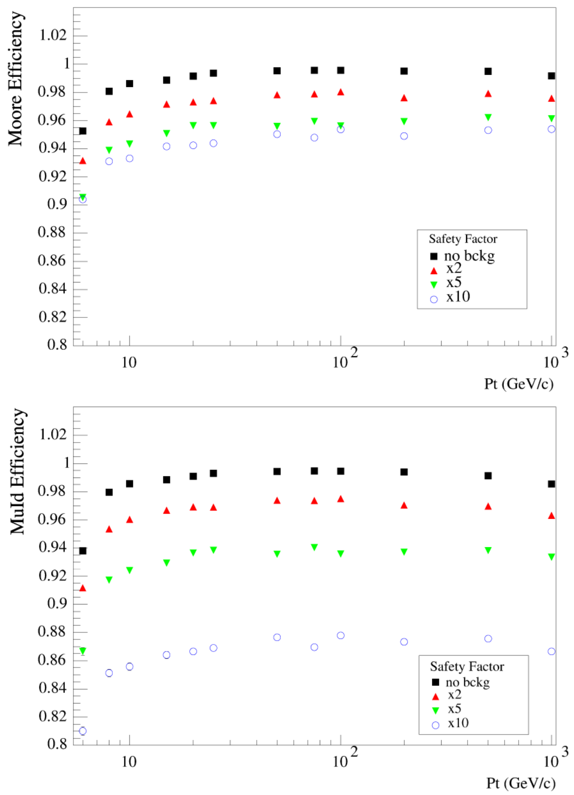

Fig. 4. Reconstruction efficiencies obtained with MOORE and MuId stand-alone seeded by LVL1 as a function of p_T for single muons. For a conservative analysis, different safety factors for cavern background have been added.

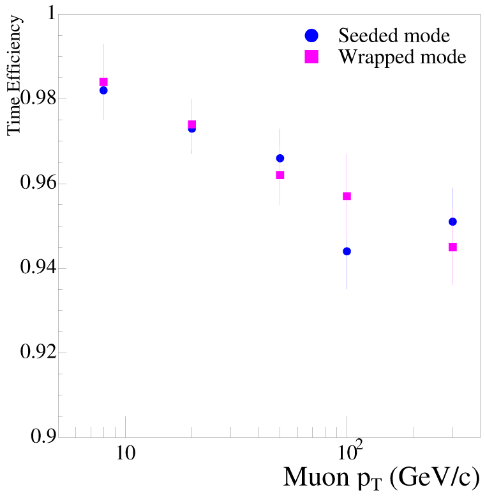

Fig. 5. Time efficiency for seeded and full scan mode for different p_T values.

TABLE I
TIMING TESTS WITH SEEDED AND FULL SCAN STRATEGY

Sample (GeV/c)	Time (ms) seeded mode average (rms)	Time (ms) full scan mode average (rms)
8	73 (30)	68 (30)
20	59 (15)	58 (21)
50	61 (21)	58 (25)
100	61 (19)	64 (26)
300	75 (23)	64 (32)
100 ×1	763 (37)	2680 (450)
100 ×2	1218 (50)	5900 (1100)

times. In order to show the impact of events with longer execution times a time efficiency as the ratio between the number of reconstructed tracks in one second and the total number of tracks has been defined. The resulting plot is shown in Fig. 5 for both seeded and full scan mode. It is not yet decided how much the system will allow the accomodation of the longer tail of the distribution. The main idea is to accept only track within a certain time limit, that is not yet been defined.

An optimization of the algorithm time consuming has not been performed so far, and those timing studies are considered only as a starting point. Several improvements in data access, preparation and algorithm time consuming are under study. The timing evaluation has been used as a monitor for the main changes in the off-line core software (e.g., Geometrical Representation and Identification of Detector Elements).

VIII. CONCLUSION

This paper describes a specialized implementation of the off-line version of the ATLAS muon reconstruction programs MOORE and MuId designated to work as Event Filter algorithm in the HLT environment. Two different strategies have been foreseen. The first is referred as the full scan strategy and permits to run the off-line package from the HLT framework, allowing for a full event reconstruction. The second is the so-called seeded strategy, that performs a seeded reconstruction, starting from the Regions of Interest from the previous trigger level. The reconstruction performance of the packages MOORE and MuId have been discussed, in terms of momentum resolution, efficiency, and rejection power. In addition, the execution time performance have been evaluated and testing also the effect of the muon cavern background. The overall results demonstrate that there is a well-defined possibility for the use of MOORE and MuId in the on-line environment as Event Filter.

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