# Muon Event Filter Software for the ATLAS Experiment at LHC

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*Abstract*

At LHC the 40 MHz bunch crossing rate dictates a high selectivity of the ATLAS Trigger system, which has to keep the full physics potential of the experiment in spite of a limited storage capability. The level-1 trigger, implemented in a custom hardware, will reduce the initial rate to 75 kHz and is followed by the software based level-2 and Event Filter, usually referred as High Level Triggers (HLT), which further reduce the rate to about 100 Hz. In this paper an overview of the implementation of the offline muon recostruction algortihms MOORE (Muon Object Oriented REconstruction) and MuId (Muon Identification) as Event Filter in the ATLAS online framework is given. The MOORE algorithm performs the reconstruction inside the Muon Spectrometer providing a precise measurement of the muon track parameters outside the calorimeters; MuId combines the measurements of all ATLAS sub-detectors in order to identify muons and provides the best estimate of their momentum at the production vertex. In the HLT implementation the muon reconstruction can be executed in ”full scan mode”, performing pattern recognition in the whole muon spectrometer, or in the ”seeded mode”, taking advantage of the results of the earlier trigger levels. An estimate of the execution time will be presented along with the performances in terms of efficiency, momentum resolution and rejection power for muons coming from hadron decays and for fake muon tracks, due to accidental hit correlations in the high background environment of the experiment.

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## THE ATLAS HIGH LEVEL TRIGGER

The LHC bunch crossing frequency will be 40 MHz and will have to be reduced to the order of 100 Hz by the ATLAS Trigger and Data Acquisition (TDAQ) systems in order to achieve the foreseen storage capability and meet the physics requirements of the experiments. The level-1 trigger (LVL1) [1], implemented in a custom hardware, will make the first level of event selection, reducing the initial event rate to less than about 75 kHz in less then 2.5 $\mu$s. Operation at up to about 100 kHz is possible with somewhat increased dead time. The result of LVL1 contains informations about the type of trigger and the position of possible particle candidates that cause the event to be accepted. The second (LVL2) and third level, also called Event Filter (EF), are software based systems and are referred togheter as High Level Triggers (HLT). The HLT must reduce the event rate further to O(100) Hz. Each selected event will have a total size of 1.5 Mbyte giving a required storage capability of a few hundred Mbyte/s. The LVL2 and the Event Filter differ in several important respects. The LVL2 is composed of a combination of high rejection power with fast, limited precision algorithms using modest computing power; the Event Filter instead has a modest rejection power with slower, high precision algorithms using more extensive computing power. The LVL2 trigger must work at the LVL1 accept rate with an average latency of about 10 ms. 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 offine, and the latest calibration and alignement information are used here in making the selection. The EF receives fully built events, so the entirety of the data is 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. Although the algorithms used at LVL2 and at EF stages are different, it has been decided to use the ATLAS common software architecture ATHENA [2] for the event selection code across LVL2, EF and online studies. This facilitates the use of common infrastructure (such as detector calibration and alignment data) and simplifies online studies and development of the HLT algorithms.

## MUON EVENT FILTER ALGORITHMS

The offline packages “Muon Object Oriented REconstruction” (MOORE) and “MuonIdentification” (MuId) [3] have been developed in the ATHENA framework for the purposes of muon reconstruction and identification in ATLAS. The former performs track reconstruction in the Muon Spectrometer while the latter extrapolates the track to the interation point (MuId Standalone) and combines the muon and Inner Detector track segments (MuId combined). The implementation of MOORE and MuId in the ATLAS High Level Trigger framework at the Event Filter stage is presented in this paper. The requirements and the conceptual design of the HLT core software are discussed in [4], [5], [6]. 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 seeding mode typically need to access the event data that pertains to a region in ($\Delta\eta$, $\Delta\phi$) around the center of a Region of Interest. For this need the algorithm must use the RegionSelector tool [6]. The basic requirement to the algorithms is to inherit from the `HLTAlgo` Base Class that augments the ATHENA Algorithm Base Class with some HLT Navigation helper functions. To avoid an explicit dependency from the Trigger in the Offline package and to be able to use the software components of the trigger framework we have isolated the software for the Event Filter in the package TrigMOORE. A sketch of the dependencies is shown in Figure 1. 1.

There are two main strategies developed:

- *Full scan strategy* - In this strategy TrigMOORE accesses directly the pointers of the offline version of the algorithms allowing to execute those algorithms as in the offline package.
- *Seeded strategy* - In this strategy TrigMOORE accesses algorithms that perform a *seeded* search of the Region of Activity and substitute the first steps of the offline version of the algorithms. The main difference with respect to the offline 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 Region of Interest and the construction of intermedials reconstruction objects, the typical offline 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. The trigger hypothesys are represented by an object called TriggerElement [4]. In the sequence of the HLT, TrigMOORE is called with a trigger element produced by the previous level as input parameter. This trigger Element has a navigable link to a Region of Interest (RoI). The RoI contains, among other information, its position in $\eta$ and $\phi$. The Algorithms call the RegionSelector to know the chambers located in a a certain region ($\Delta\eta$, $\Delta\phi$) around the center of the RoI. The RegionSelector returns a list of identifiers of detector elements that are contained within the region. Only these elements will be accessed from the seeded algorithms.

## VALIDATION WITH SINGLE MUON SAMPLES

In order to verify the performances of the offline muon reconstruction program, we have analized single muon samples in a range of transverse momentum from $3\ GeV/c$ to $1000\ GeV/c$. In Fig. 2, the efficiencies and the $1/p_T$ resolution of the offline muon reconstruction algorithms are shown at different transverse momenta: in addition to MOORE and MuId (both StandAlone and Combined versions), also the reconstruction performances of the Inner Detector with iPatRec [7] are reported. Global resolution on $1/p_T$ is dominated by the Inner Detector at low values, at high $p_T$ the Muon Spectrometer prevails. The results show a rather good agreement with the expected performances [8].

## BACKGROUND REJECTION

At low transverse momenta the main source of muon rate at LHC comes from in-flight decays of pions and kaons. The aim of the HLT muon triggers is the rejection of such fake muons selecting in 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 with those obtained in the Muon Spectrometer. To investigate the rejec-

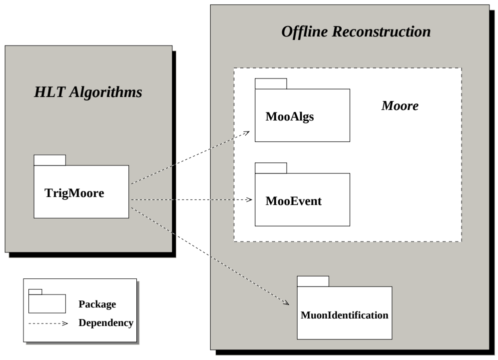


Figure 1: The MOORE/MuId packages in offline and online environment. The arrows show the dependencies between the packages.

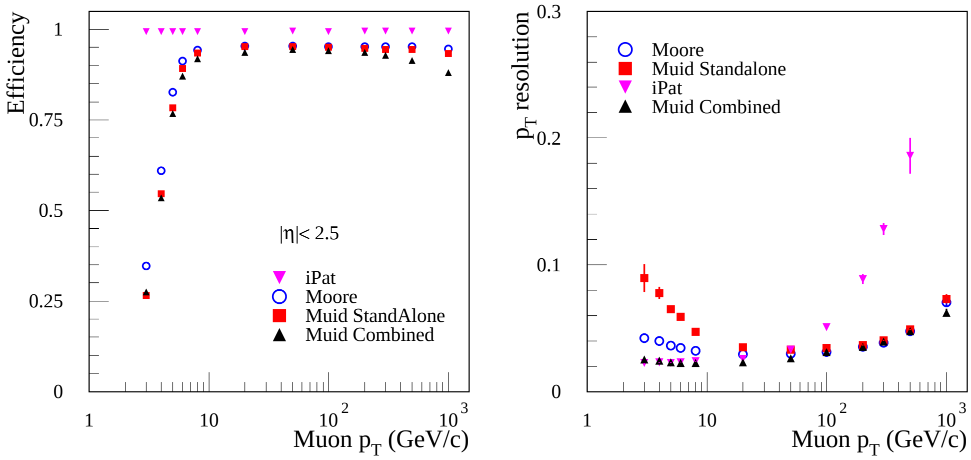


Figure 2: Efficiency and momentum resolution of single muon reconstruction as a function of $p_T$.

tion of the Muon Event Filter a sample of simulated inclusive muons from $b\bar{b} \rightarrow \mu X$ events and muons from $K$ or $\pi$ in-flight decays has been simulated and studied. 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 $\pi$ decays are misidentified as prompt muons. The efficiency for prompt muons goes from about 80% to about 90%.

An other source of background in the Muon Spectrometer is represented by the uncorrelated background that will be present in the ATLAS experimental area. 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 collider. 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 muon events with pileup superimposition. Besides a "nominal" $\times 1$ factor, corresponding to the expected amount of background for ATLAS, the "safety" factors $\times 2$, $\times 5$ and $\times 10$ (obtained by boosting the nominal $\times 1$) have been considered. In Fig. 4 the efficiency of TrigMOORE seeded by LVL1 is shown as a function of the cut on the number of $\sigma$'s of the $p_T$ resolution, in case of single muons with $p_T = 100\ GeV/c$, both in case of no-pileup and in case of pileup occurring with factors $\times 1$ and $\times 5$.

## EXECUTION TIME PERFORMANCES

The requested latency time for an algorithm operating as Event Filter is 1 sec. This time should include only the algorithmic part and not the time spent in accessing the data. The timing performance of the Moore algorithm both for seeded and full scan mode have been evaluated using a Intel XEON(TM) CPU 2.40GHz processor, 1GHz ram. The time measurements include the accesses to the event, and are referred to the reconstruction including the extrapolation to the vertex. Average execution times per event are shown in Tab. 1 for both the seeded and the full scan version at different $p_T$ values and also with $\times 1$ and $\times 2$ safety factors background added. The execution times include the data access and track extrapolation to the vertex. To compute these values a 95% fraction of events has been

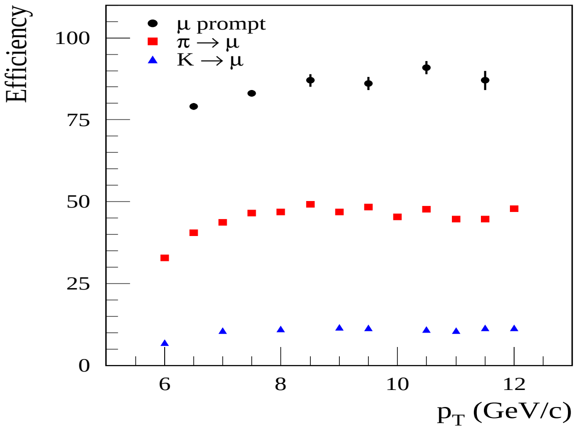


Figure 3: Reconstruction efficiency for $\mu$ prompt and for muons coming from pions/kaons as a function of the $p_T$ of the initial particle.

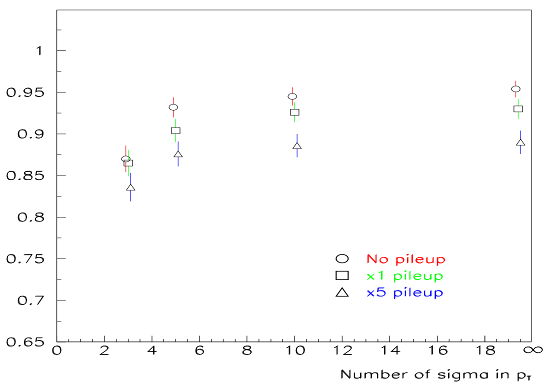


Figure 4: Reconstruction efficiencies obtained with MOORE seeded by LVL1 on 100 $GeV/c$ $p_T$ single muons without and with pileup addition.

retained, rejecting the events with the longest processing times.

## CONCLUSIONS

This paper describes a specializated implementation of the offline 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 offline 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 performances of the packages MOORE and MuId have been discussed, in terms of momentum resolution, efficiency, rejection power. In addition, the execution time performances have been evaluated and testing also the effect of the muon cavern background. The overall results demonstrate that there is a well definite possiblility for the use of MOORE and MuId in the online environment as Event Filter.

Table 1: 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 $\times 1$ | 763 (37) | 2680 (450) |
| 100 $\times 2$ | 1218 (50) | 5900 (1100) |

## REFERENCES


[1] ATLAS collab., *ATLAS Level-1 Trigger: Technical Design Report*, CERN-LHCC-98-014, ATLAS-TDR-12, June 1998.

[2] http://atlas.web.cern.ch/Atlas/GROUPS/SOFTWARE/OO/architecture/

[3] D. Adams et al., *Track Reconstruction in the ATLAS Muon Spectrometer with MOORE*, ATL-COM-MUON-2003-012, ATL-COM-SOFT-2003-007.

[4] G. Comune et al., *The Algorithm Steering and Trigger Decision mechanism of the ATLAS High Level Trigger*, hep-ex/0306009

[5] M. Elsing et al., *Configuration of the ATLAS Trigger System*, ATLAS Note ATL-DAQ-2003-038

[6] V. Boisvert et al., *A New Implementation of the Region-of-Interest Strategy for the ATLAS Second Level Trigger*, ATLAS Note ATL-DAQ-2003-034

[7] R.Clifft, A.Poppleton, *IPATREC: inner detector pattern-recognition and track-fitting*, ATL-SOFT-94-009; ATO-PN-9.- 14 Jun 1994

[8] TDR, *Atlas Detector and Physics Performance Technical Design Report*, CERN/LHCC 99-14, 25 May 1999