Implementation and Performance of the Event Filter Muon Selection for the ATLAS experiment at LHC

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***Abstract*— The ATLAS Trigger system is composed of three levels: an initial hardware trigger level (LVL1) followed by two software-based stages (LVL2 trigger and Event Filter) included in the High Level Trigger (HLT) and implemented on processor farms. The LVL2 trigger starts from LVL1 information concerning pointers to restricted so-called Regions of Interest (ROI) and performs event selection by means of optimized algorithms. If the LVL2 is passed, the full event is built and sent to the Event Filter (EF) algorithms for further selection and classification. After that, events are finally collected and put into mass storage for subsequent physics analysis. Even if many differences arise in the requirements and in the interfaces between the two HLT stages, they have a coherent approach to event selection. Therefore, the design of a common core software framework has been implemented in order to allow the HLT architecture to be flexible to changes (background conditions, luminosity, description of the detector, etc.).**

Algorithms working in the Event Filter are designed to work not only in a general purpose or exclusive mode, but they have been implemented in such a way to process given trigger hypotheses produced at a previous stage in the HLT dataflow. This is done by acting in separate steps, so that decisions to go further in the process are taken at every new step. An overview of the HLT processing steps is given and the working principles of the EF offline algorithms for muon reconstruction and identification (MOORE and MuId) are discussed in deeper detail. The reconstruction performances of these algorithms in terms of efficiency, momentum resolution, rejection power and execution times on several samples of simulated single muon events are presented, also taking into account the high background environment that is expected for ATLAS.

***Index Terms*— ATLAS, HLT, Muons, Event Filter.**

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I. INTRODUCTION

ATLAS is a general-purpose high-energy physics experiment to investigate proton-proton collisions at a center-of-mass energy of $14\ TeV$, currently under construction at the Large Hadron Collider (LHC) facility of the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. The ATLAS detector [1] has been designed to study the wide number of physics processes at the LHC, including searches for unobserved phenomena like the Higgs boson and new particles predicted by super-symmetric models.

In the LHC program an initial luminosity of $2 \times 10^{33}\ cm^{-2}s^{-1}$ will be delivered to ATLAS and then a full design luminosity of $10^{34}\ cm^{-2}s^{-1}$ will be reached, with an average of 23 collisions per bunch crossing. Owing to the high number of final state particles at a proton-proton collider, ATLAS has required highly granular and large scale detector systems, involving a total number of electronic channels of the order of 10^8.

The extremely high bunch crossing rate at LHC ($40\ MHz$) and the very high radiation environment in which all the detectors and their electronics have to work, demand unprecedented performances for the ATLAS Trigger and Data Acquisition (TDAQ) systems.

The main challenge of the ATLAS Trigger is to exploit the full physics potential of the experiment in spite of a limited storage capability. In particular, the task of the TDAQ system

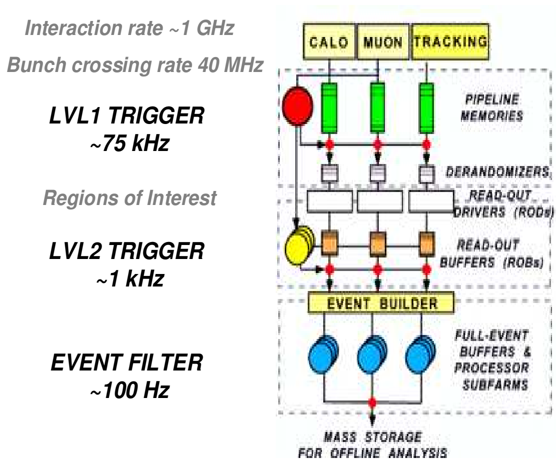

Fig. 1
A SCHEMATIC REPRESENTATION OF THE TRIGGER AND DATA ACQUISITION SYSTEM IN ATLAS.

is to reduce the huge volume of data produced by the ATLAS detector itself (corresponding to an average event size of about 1.6 MByte) down to a manageable amount.

In the LVL1 stage [2], implemented in a custom hardware, the trigger will reduce the initial event rate to $75\ kHz$. At this level, coarse-granularity information from the calorimeter and muon spectrometer systems based on high p_T signals has to be very quickly treated in order to achieve selection/rejection of events with a latency time not exceeding $2\ \mu s$.

Two software-based triggers follow: the Level-2 (LVL2) and the Event Filter (EF), that comprise the so-called ATLAS High Level Trigger (HLT) system [3]. Their task is to bring the input event rate given by the LVL1 to the data acquisition rate of $\sim 100\ Hz$. They are implemented on commodity processor nodes running a commercially available operating system. A diagram illustrating the three levels of the ATLAS trigger is shown in Fig. 1.

II. THE ATLAS HIGH LEVEL TRIGGER

Similarly to LVL1, the event selection in HLT is based on inclusive high-p_T signals, with the aim not to introduce biases and to be open to possible signatures of new physics. Both stages of HLT use the same trigger selection framework and differ essentially in the amount of data they have to access for each event. Not strictly defined bounds between LVL2 and EF allow the HLT to have the best possible adaptability for working in different running conditions.

The Level-2 [4] works on a farm of processor nodes running software algorithms which have been specifically developed to take a decision on each event with an average latency of $10\ ms$. Geometrical information provided by the first level trigger can guide the access to the event data in terms of Regions of Interest (RoIs), *i.e.* parts of the detector where the interesting physics signals have been already found at the previous stage of the trigger chain. A quicker access to data can be achieved by circumscribing the reconstruction only to the RoIs: even if this *seeding* strategy is quite complex to achieve, the effective networking and computing power are drastically brought down to few per-cent of what would be needed for the full event reconstruction. From the incoming $75\ kHz$, the LVL2 can reduce the event rate to $\sim 1\ kHz$.

After an event passes the second level trigger, it is sent to the Event Filter, that refines the selection according to the LVL2 classification and performs a complete reconstruction of the full event with more detailed alignment and calibration data, based on the use of sophisticated offline algorithms. The rate is finally reduced to a rate of $\sim 100\ Hz$ with a $\sim 1\ s$ latency time. At the end of the selection, events are written to mass storage.

Besides operating in a general purpose mode, all algorithms in the Event Filter must be able to work in seeded mode, guided by hypotheses elaborated in the earlier trigger levels. Moreover, algorithms have to be organized with suitable modularity, in order to work properly as Event Filter in the HLT environment both for the final standard data acquisition and for test beam data.

III. MUON RECONSTRUCTION AND IDENTIFICATION

Reconstructing and identifying muons with high accuracy represents an essential task to take full advantage from the physics potential at LHC: events with muons in the final state can provide evidence of new physics or relevant signature for b-physics. A muon moving through the ATLAS detector leaves hits in the Inner Detector [5] and in the Muon Spectrometer [6], as well as in the electromagnetic and hadronic calorimeters. Momenta are measured via magnetic deflection of muon tracks in a system of three large superconducting air-core toroid magnets, instrumented with trigger and high precision tracking chambers. The magnet field is mostly orthogonal to the muon trajectories, and the degradation of resolution due to multiple scattering is reduced to minimum. The Muon Spectrometer has the stand-alone capability to measure muon momenta with a resolution $\Delta p_T/p_T < 10\%$ up to $1\ TeV/c$.

The best possible measurement of the muon momentum can be obtained by combining information from the Muon Spectrometer and the Inner Detector. The tails in the p_T resolution distribution of the Muon Spectrometer are reduced and the charge determination for high energy muons is improved (thanks to the longer lever arm). The discrimination of muons from secondaries can be furthermore improved and muons from kaons or pions can be rejected by asking for tracks originated in the primary vertex. A better discrimination of muons in jets is possible, thus improving the efficiency of inner tracker pattern recognition, which is lower than for isolated muons. Track fragments in the inner chambers of the Muon Spectrometer can be associated with track segments in the Inner Detector: a higher efficiency can be therefore obtained in reconstructing low-energy muons not reaching middle/outer Muon Spectrometer chambers.

The offline packages "Muon Object Oriented REconstruction" (MOORE) and "MuonIdentification" (MuId) have been developed in the ATHENA [7] framework for the purposes of muon reconstruction and identification in the ATLAS Muon Spectrometer. The former performs track reconstruction in the Muon Spectrometer while the latter extrapolates the track to the vertex and combines Muon Spectrometer tracks with Inner Detector track segment. Their working principles are discussed in this paper, and their implementation in the ATLAS High Level Trigger framework at the Event Filter stage (TrigMOORE) is then presented.

IV. MOORE

MOORE [8] is an offline package for track reconstruction in the full η range (barrel+endcaps) of the Muon Spectrometer. The description given here is limited to the barrel, since at present the trigger chain considers only this region. In the ATLAS offline environment, MOORE starts from collections of digits or clusters in the Muon Spectrometer volume to build fitted reconstructed tracks with parameters measured at the entrance of the Muon Spectrometer.

All the reconstruction proceeds in successive stages, each one performed by an algorithm module that creates partially or finally reconstructed objects by using objects produced by the previous algorithms. After being built, objects are temporarily stored and kept available for other modules. A rigorous separation is made between data and algorithms: algorithms have to know how data objects are structured before accessing to or creating them, but objects must be independent of algorithms. The stepped sequence used in the reconstruction allows to define which algorithm will produce an object at run-time.

MOORE begins its overall reconstruction process by looking for activity regions in two different projections of the Muon Spectrometer: firstly in the ϕ trigger hits from RPCs and subsequently in the r-z view considering the precision hits of MDTs.

Drift distances inside MDTs are computed starting from drift times by applying time-to-distance relations, taking into account the time of flight, the second coordinate, the Lorentz effect and the propagation along the wire. To reconstruct a track segment, the best tangential line to the drift circles is taken among the possible four. All MDT segments of the outer and middle stations are then combined by the pattern recognition procedure. After that, MDT hits in the segments are considered together with the ϕ information coming from RPCs, and track candidates are consequently obtained.

If successfully fitted, outer track candidates are kept for further processing and used to associate inner station MDT hits. When a collection of RPC hits and MDT hits provides a successful fit from at least two layers, a track is definitively built. The track fit procedure is based on the iPatRec [9] package, developed for the Inner Detector. Final refinements allocate scattering centers along each track, so allowing the track fit to take into account effects due to energy loss and Coulomb scattering. Hits with residuals above a given threshold are discarded: this can occur either because of faults in assigning digits to tracks during pattern recognition, or because of a poor local spatial resolution in case of badly measured drift distances. Once the fit procedure completes, the resulting track is accepted and its parameters are expressed at the first measured point inside the Muon Spectrometer.

V. MuId

To be properly used for physics studies, a track has to be extrapolated to its production point. This crucial task is achieved by means of another offline package, MuId [10], which has been designed to efficiently identify muon tracks by combining tracks in the Muon Spectrometer with the corresponding track found by iPatRec in the Inner Detector.

At a first step, MOORE tracks are extrapolated back to the vertex region, so that the kinematic parameters can be compared to those reconstructed in the Inner Detector. MuId accesses the previously reconstructed track and propagates it back through the magnetic field to obtain the track parameters and their associated covariance matrix corresponding to the point of closest approach to the beam intersection. Effects due to multiple scattering in the calorimeters are taken into account by a parametrization with a set of scattering planes. Moreover, muon energy loss is estimated both from the calorimeter measurements and from a function parametrized with muon's η and p_T. Up to this stage, MOORE and MuId can be executed in sequence as a standalone package for the Muon reconstruction (MuId *StandAlone mode*).

Subsequently, Inner Detector and Muon Spectrometer tracks are matched together, and a five d.o.f. χ^2 is built with the parameter differences and summed covariances. A combined fit is performed at the vertex for all combinations above a given χ^2 probability. Hits found in the two subdetectors with separate standalone algorithms are then used to combine tracks (MuId *Combined mode*). In case of a satisfactory combined fit, all matches to the Inner Detector are finally kept as identified muons.

VI. Reconstruction performances

The reconstruction performances of the packages MOORE and MuId have been evaluated using single muons samples with fixed transverse momentum, in the range from 3 GeV/c to 1 TeV/c, produced for the Data Challenge 1 (DC1).

In Fig. 2 the efficiencies of the offline muon reconstruction algorithms are shown at different transverse momenta: beside MOORE and MuId (both StandAlone and Combined versions), the reconstruction performance in the Inner Detector with iPatRec is reported. Global resolution on $1/p_T$ is presented in Fig. 3 as a function of p_T. Transverse momentum is better measured by the Inner Detector at low values and by the Muon Spectrometer at high values.

At low transverse momenta the main source of trigger rate in the LVL1 muon system comes from in-flight decays of pions and kaons. The goal of the HLT muon trigger is to reject such muons while having high selection efficiency on prompt muons. It is therefore crucial to combine reconstructed tracks

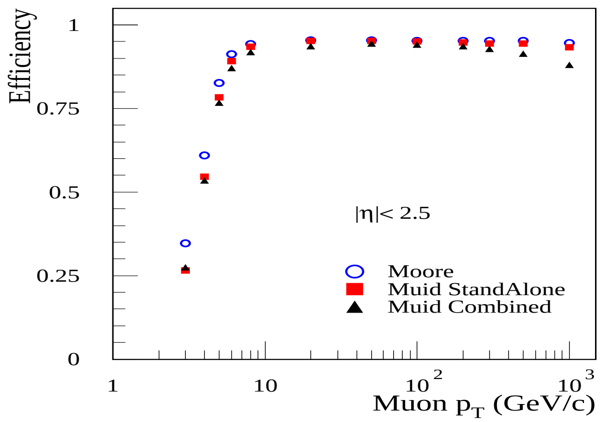

Fig. 2

EFFICIENCY OF SINGLE MUON RECONSTRUCTION AS A FUNCTION OF p_T. THE DIFFERENT MARKS CORRESPOND TO THE RECONSTRUCTION ALGORITHMS DESCRIBED IN THE TEXT.

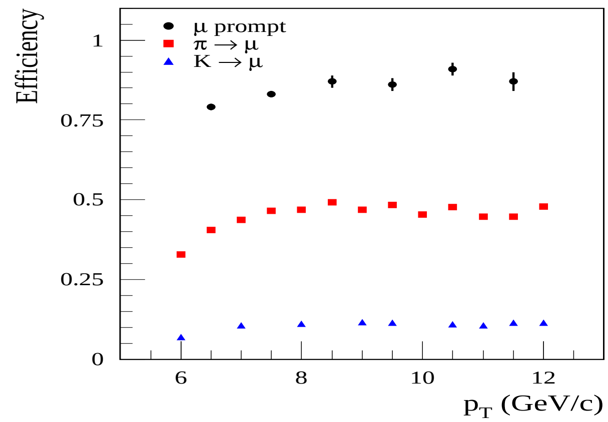

Fig. 4

RECONSTRUCTION EFFICIENCY FOR μ PROMPT AND FOR MUONS COMING FROM PIONS/KAONS AS A FUNCTION OF THE p_T OF THE INITIAL PARTICLE.

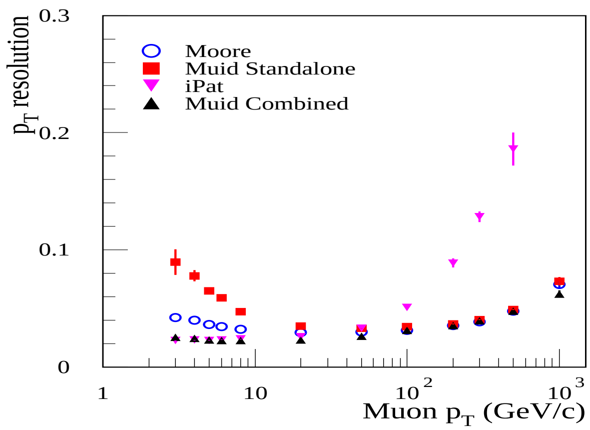

Fig. 3

MOMENTUM RESOLUTION FOR SINGLE MUONS AS A FUNCTION OF p_T.

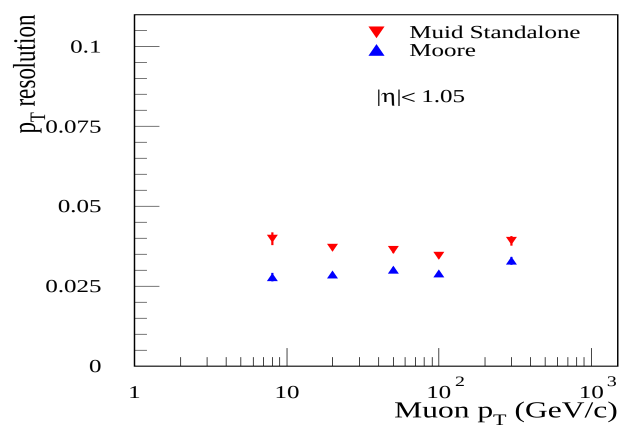

Fig. 5

TRANSVERSE MOMENTUM RESOLUTION IN GeV/c OBTAINED WITH MOORE AND MUID ALGORITHMS (SEEDED MODE).

information from the Inner Detector and the Muon Spectrometer. 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 has been simulated and studied. In Fig. 4 the corresponding reconstruction efficiencies are represented as functions of the transverse momentum of the prompt muons and of the parent mesons.

VII. TRIGMOORE AS EVENT FILTER ALGORITHM

In order to avoid explicit dependencies on the Trigger in the Offline environment, the MOORE software has been isolated for the Event Filter in the TrigMOORE package. This C++/Object-Oriented package can be run in two different main strategies:

- wrapped strategy – In this mode algorithms access to the full event, and are executed exactly as those in the offline version.
- seeded strategy – In this mode the reconstruction is performed with a seeded search of the regions of relevant activity in the detector. In this strategy, differently from what happens in the wrapped one, the algorithms access only those chambers belonging to the geometrical areas of the detector identified by the HLT Region Selector [11], according to hypotheses found in the previous trigger levels (either LVL1 or LVL2).

The seeded strategy has been integrated and tested within the *full muon slice* (LVL1 simulation, LVL2 and Event Filter). The two strategies have been applied on samples of single muons with different p_T.

In Fig. 5 the p_T resolution has been plotted as a function of transverse momentum in the case of a seeded strategy driven by muon reconstructed RoIs coming from the LVL1 [12].

A. Studies with cavern background

The Muon Spectrometer is very sensitive to the low energy physics background that will be present in the ATLAS experimental hall. A realistic study of reconstruction performances

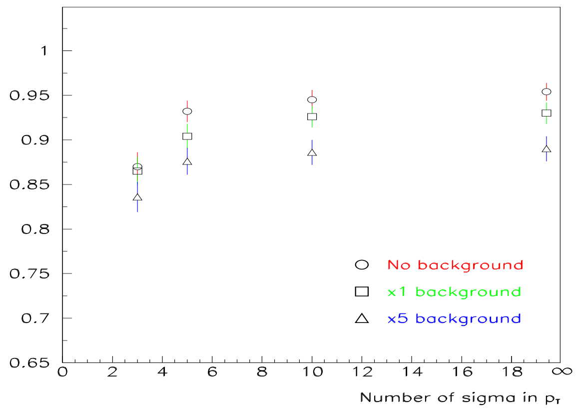

Fig. 6

RECONSTRUCTION EFFICIENCIES WITH TRIGMOORE SEEDED BY LVL1 ON 100 GeV/c p_T SINGLE MUONS WITHOUT AND WITH BACKGROUND ADDITION. $\times 1$ CORRESPONDS TO THE NOMINAL BACKGROUND INTENSITY.

has to consider minimum bias (at the design luminosity ~ 23 inelastic interactions will be produced at every beam crossing) and cavern background. This background is fundamentally due to particles produced in the interaction of primary hadrons from proton-proton 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 and throughout the cavern.

For a conservative analysis of such background, besides the simulated samples containing just muons, the reconstruction with TrigMOORE has been tested on single muon events with background superimposition. Besides the "nominal" background intensity (as predicted by FLUKA [13] and GCALOR [14], see also [15]), scenarios obtained by boosting by a factor 2, 5, and 10 the nominal background levels have been considered.

In Fig. 6 the efficiency of TrigMOORE seeded by LVL1 is shown as a function of the cut on the number of σ's of $p_T^{rec} - p_T^{gen}$, in case of single muons with $p_T = 100\ GeV/c$, both in case of no-background and in case of background occurring with factors $\times 1$ and $\times 5$.

B. Timing performances

Specific timing tests have been performed with an optimized-code version of TrigMOORE on an Intel XEON(TM) 2.4 GHz processor, with 1 GB RAM. To estimate the time needed by TrigMOORE to process a single event, only the algorithmic contribution should be considered (and not the dead time in accessing the event). Average execution times per event are shown in Tab. I for the seeded and the wrapped versions of TrigMOORE at different p_T values and also with background added ($\times 1$ and $\times 2$ factors). The reconstruction procedure involves track extrapolation to the vertex (MuId). Also the time for accessing data is included. To compute these values a 95% fraction of events has been retained, rejecting the events with

TABLE I

TIMING TESTS WITH SEEDED AND WRAPPED TRIGMOORE.

Muon sample (GeV/c)	Time (ms) seeded mode average (rms)	Time (ms) wrapped 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)

the longest processing times. These results (discussed in [8], [12] in more detail) are to be compared with the 1 s latency time requested for an algorithm working as Event Filter.

VIII. CONCLUSIONS

An overall $\sim 10^6$ reduction factor is requested to the ATLAS trigger system in order to bring the huge initial event rate at LHC down to reasonable rates for interesting physics events to be acquired and subsequently studied. This requires that offline algorithms optimized for physics analysis have to be inserted within the High Level Trigger environment. In order to accomplish this, a specialized version of the offline package MOORE has been implemented to work in the HLT system, taking into account the need of facing particular data access requirements and reduced latency times.

The reconstruction performances of the packages MOORE and MuId have been discussed, in terms of momentum resolution, efficiency, rejection power and execution times. Different single muons samples of fixed transverse momentum have been used, also investigating the effects induced by cavern background. The results described in this work demonstrate that MOORE and MuId are capable of functioning as Event Filter within the ATLAS trigger system.

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