Implementation and performance of the third level muon trigger of the ATLAS experiment at LHC

S. Armstrong, K. A. Assamagan, J. T. M. Baines, C. P. Bee, M. Bellomo, M. Biglietti, J. A. Bogaerts, V. Boisvert, M. Bosman, G. Carlino, et al.

Implementation and Performance of the Third Level Muon Trigger of the ATLAS Experiment at LHC

S. Armstrong, K. A. Assamagan, J. T. M. Baines, C. P. Bee, M. Bellomo, M. Biglietti, J. A. Bogaerts, V. Boisvert, M. Bosman, G. Carlino, B. Caron, P. Casado, G. Cataldi, D. Cavalli, M. Cervetto, G. Comune, P. Conde Muino, F. Conventi, A. De Santo, J. M. de Seixas, M. Diaz Gomez, A. Di Mattia, A. dos Anjos, M. Dosil, N. Ellis, D. Emeliyanov, B. Epp, S. Falciano, A. Farilla, S. George, V. Ghete, S. González, M. Grothe, S. Kabana, A. Khomich, G. Kilvington, N. Konstantinidis, A. Kootz, A. Lowe, L. Luminari, T. Maeno, J. Masik, C. Meessen, A. G. Mello, G. Merino, R. Moore, P. Morettini, A. Negri, N. Nikitin, A. Nisati, C. Padilla, N. Panikashvili, F. Parodi, V. Perez-Reale, J. L. Pinfold, P. Pinto, M. Primavera, Z. Qian, S. Resconi, S. Rosati, C. Sanchez, C. Santamarina, D. A. Scannicchio, C. Schiavi, E. Segura, S. Sivoklokov, R. Soluk, E. Stefanidis, S. Sushkov, M. Sutton, S. Tapprogge, E. Thomas, F. Touchard, B. Venda Pinto, A. Ventura, V. Vercesi, P. Werner, S. Wheeler, F. J. Wickens, W. Wiedenmann, M. Wielers, and H. Zobernig

***Abstract*—The trigger system of the ATLAS experiment at the LHC aims at a high selectivity in order to keep the full physics potential while reducing the 40 MHz initial event rate imposed by the LHC bunch crossing down to $\sim$100 Hz, as required by the data acquisition system. Algorithms working in the final stage of the trigger environment (Event Filter) are implemented to run both in a "wrapped" mode (reconstructing tracks in the entire Muon Spectrometer) and in a "seeded" mode (according to a dedicated strategy that performs pattern recognition only in regions of the detector where trigger hypotheses have been produced at earlier stages). The working principles of the offline muon reconstruction and identification algorithms (MOORE and MuId) implemented and used in the framework of the Event Filter are discussed in this paper. The reconstruction performance of these algorithms is presented for both modes in terms of efficiency, momentum resolution, rejection power and execution times on several samples of simulated single muon events, also taking into account the high background environment expected for ATLAS.**

***Index Terms*—ATLAS, event filter, HLT, Muons.**

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 2×10^{33} cm^{-2}s^{-1} is expected to be delivered before the 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 read-out 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 an unprecedented performance for the ATLAS Trigger and Data Acquisition (TDAQ) systems.

The main challenge of the ATLAS TDAQ is to exploit the full physics potential of the experiment while reducing the huge volume of data produced by the detector itself. Since the average raw data event size is $\sim$1.6 MByte and the TDAQ system is designed to handle a data flow of few hundreds MB/s, the final required event rate can be of the order of 100 Hz.

In the Level-1 (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 of about 2 μs, which is the time needed to form and distribute the LVL1 trigger decision.

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.

In this paper, we present the implementation of the offline packages for muon reconstruction/identification MOORE and MuId in the HLT framework of the experiment. Adapting these packages to act as algorithms within the EF environment has been made possible by means of an efficient and fast access to event data, limited to dynamically defined regions of the apparatus where relevant physics activity has been detected by the previous stages of the triggering process.

Manuscript received November 15, 2004; revised February 4, 2006.

Please see the Acknowledgment section of this paper for the author affiliations.

Digital Object Identifier 10.1109/TNS.2006.871504

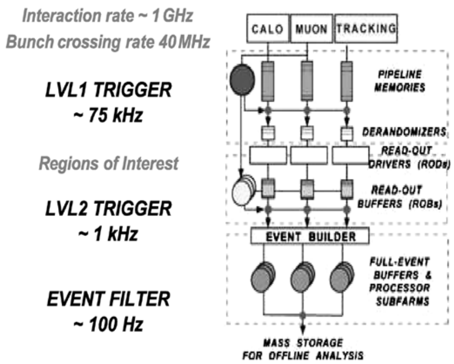

Fig. 1. Schematic representation of the three-level ATLAS TDAQ system. The Event Filter plays a fundamental role in its architecture, reducing the data flow for mass storage operations and allowing offline reconstruction and analysis.

II. ATLAS High Level Trigger

Similarly to LVL1, the event selection in the 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 the 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 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 $\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 of the physics potential at LHC: events with muons in the final state can provide evidence of new physics or relevant signatures for b-physics. A muon moving through the ATLAS detector leaves hits in the Inner Detector [4] 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 arranged in three *layers* at different radii in the barrel and at different z coordinates in the endcaps. The magnetic field is mostly orthogonal to the muon trajectories, and the degradation of resolution due to multiple scattering is reduced to a minimum. Other particles than prompt muons that are not stopped in the calorimeters can give rise to charged background. The absorptive thickness of all the materials in front of the muon system is more than 10 absorption lengths [6].

The Muon Spectrometer has the stand-alone capability to measure muon momenta with a $1/p_T$ resolution not exceding 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. This reduces the tails in the p_T resolution distribution of the Muon Spectrometer and improves charge determination for high energy muons (thanks to the longer lever arm). This allows to better discriminate muons from secondaries and to reject muons from the decay of charged kaons or pions by asking for tracks originated from the primary vertex. Moreover, track fragments in the inner chambers of the Muon Spectrometer can be combined with track segments in the Inner Detector, thus providing a higher efficiency when reconstructing low-energy muons not reaching middle/outer Muon Spectrometer chambers.

The offline packages "Muon Object Oriented REconstruction" (MOORE) and "MuonIdentification" (MuId) have been projected and 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 the following, 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 $(\mathrm{barrel} + \mathrm{endcaps})$ of the Muon Spectrometer. The description given in this work is limited to the barrel.

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: first in the ϕ trigger hits from the Resistive Plate Chambers (RPCs) and subsequently in the r–z view considering the precision hits of the Monitored Drift Tubes (MDTs). More information on each sub-detector can be found in [1]. Provided information on hits and clusters in the Muon Spectrometer volume includes spatial position, drift time and corresponding errors.

Drift distances from the wires inside MDTs are computed starting from drift times, measured with respect to the trigger provided by RPC planes coincidences, by applying time-to-distance relations, taking into account the effects of the muon time of flight, the propagation time along the wire and the Lorentz angle. These effects are evaluated thanks to the knowledge of the ϕ coordinate provided by the RPC detectors. Within each layer in the Muon Spectrometer, the pattern recognition procedure selects all hits having a residual distance from a track segment[1] smaller than a given cut. Then, each set of selected hits belonging to a track segment is fitted to a straight line, which is kept for further processing if its number of hits is above a cut and if it points to the interaction vertex. Individual segments (in the same or in different layers) are combined if their directions satisfy suitable proximity criteria. Segment combinations obtained so far, together with the information on the ϕ coordinate from contiguous RPC hits, provide track candidates that, if successfully fitted (i.e., having χ^2 below a given cut) and if involving at least two layers, are finally kept.

The track fit procedure is based on the iPatRec [4], [5] 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 hits 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

In order to perform physics studies, tracks are extrapolated to their production point by means of another offline package, MuId [5], which has been designed to efficiently identify muons by combining tracks in the Muon Spectrometer with the corresponding track found by iPatRec in the Inner Detector. Combined information from these two detectors allows to select prompt muons with a high precision vertexing, as well as to find and reject tracks with a kink (e.g., muons from pion or kaon decays).

In a first step, to get kinematic information that is comparable with what reconstructed in the Inner Detector, MuId propagates back through the magnetic field all MOORE tracks, thus obtaining the needed parameters at the nominal beam intersection. This is done with the Runge–Kutta method by also taking into account multiple scattering and energy loss in the calorimeters. Up to this stage, MOORE and MuId can be executed in sequence as a standalone package for the muon reconstruction (MuId *StandAlone mode*).

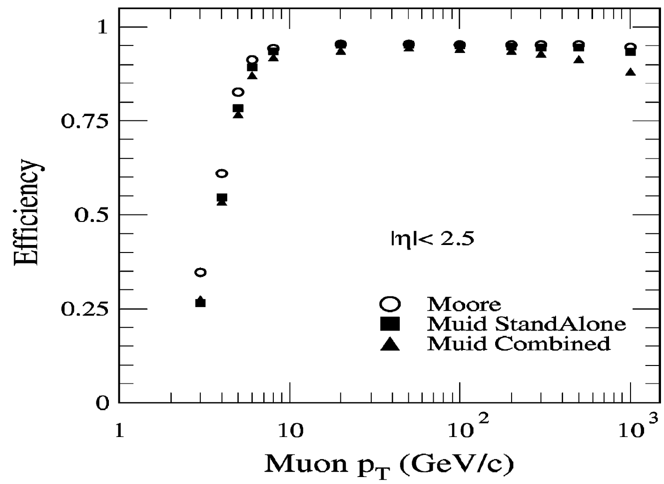

Fig. 2. Efficiency of single muon reconstruction as a function of p_T. The different marks correspond to the reconstruction algorithms described in the text.

Subsequently, Inner Detector and Muon Spectrometer tracks are matched together (MuId *Combined mode*), and a five d.o.f. χ^2 is built with the track parameter differences and summed covariances. A combined fit is then performed for all matches above a given χ^2 probability. In case of a satisfactory combined fit, these matches are finally kept as identified muons, with track parameters expressed at the interaction vertex.

VI. Reconstruction Performance

The reconstruction performance of the packages MOORE and MuId have been evaluated on Monte Carlo samples containing single muons of fixed transverse momentum, in the range from 3 GeV/c to 1 TeV/c.

In Fig. 2 the efficiencies of the offline muon reconstruction algorithms are shown at different transverse momenta for MOORE and MuId (both StandAlone and Combined versions). All algorithms show efficiencies higher than 90% for $p_T > 8$ GeV/c. A small drop at higher transverse momenta can be observed in the case of MuId Combined, due to the increasing probability of electromagnetic showers along the muon track when crossing dense materials (mainly in the calorimeters), that can produce additional hits in the Muon Spectrometer, with consequent failures in the combining procedure. The $1/p_T$ resolution[2] 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. The combined version of MuId takes advantage of

[1]A track segment is obtained from the best combination of the tangential lines built for each pair of MDT hits.

[2]In the case of MOORE, the $1/p_T$ resolution is computed with respect to the simulated value at the entrance of the Muon Spectrometer.

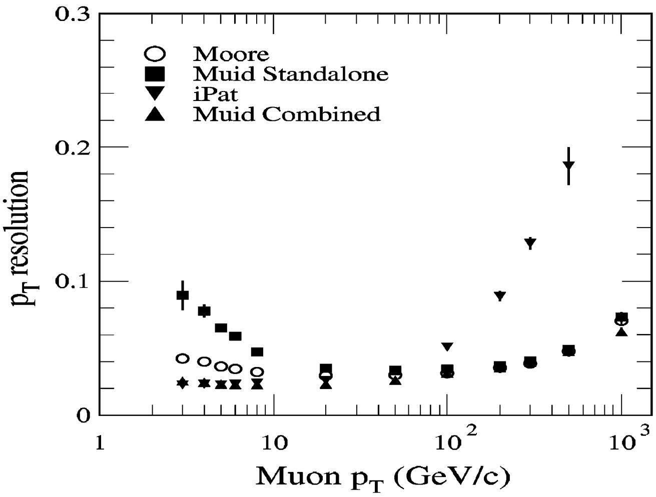

Fig. 3. Momentum resolution for single muons as a function of p_T.

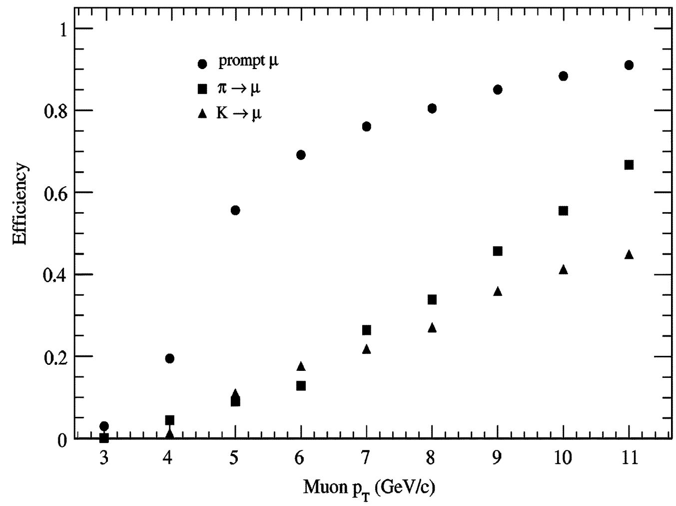

Fig. 4. Reconstruction efficiency expected for prompt μ and for muons coming from pions/kaons as a function of the muon p_T.

both detectors and provides the best p_T resolution over the full momentum range.

At low transverse momenta the main contribution to the 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 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 in-flight decays of charged π and K has been simulated and studied.

Good performance in the rejection of a muon from a K/π decay is possible by requiring the extrapolated track (by MuId StandAlone) to have a small impact parameter and asking for a good matching (by MuId Combined) between the track in Inner Detector and the one in the Muon Spectrometer. In Fig. 4 the corresponding reconstruction efficiencies are shown as functions of the transverse momentum of the muon in the low p_T region. Differential muon trigger rates computed for the processes discussed above [6] in the region $p_T > 6$ GeV/c show that the sum of contributions from π and K in-flight decays is reduced to a fraction $\sim 1/4$ of the total rate.

VII. TrigMOORE as Event Filter Algorithm

In order to avoid explicit dependencies on the Trigger in the Offline environment, the MOORE software has been adapted 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, following the approach described in Section II.

In the seeded strategy, differently from what happens in the wrapped one, all HLT algorithms start accessing only the event data that refer to a spatial region centered around a given RoI and defined in terms of position (i.e., by means of fixed pseudo-rapidity and azimuthal angle intervals $\Delta\eta, \Delta\phi$).

To get information from the geometrical areas of the sub-detectors involved in a specific Region of Interest, as any other HLT algorithm, TrigMOORE has to ask the *Region Selector* tool for a list of collection identifiers, that unambiguously identify the detector elements included within the region itself, using only a very small fraction of the available latency at Event Filter. Starting from this list of identifiers, TrigMOORE can then retrieve and sort all the data connected to the RoI, which are contained in collections within the Transient Data Store (TDS) according to a suitable format.

Typically RoIs are defined by the Region Selector as simple cones spanning various sub-detectors, but they can also be more complex volumes, which take into account the uncertainty in the z position of the primary vertex, due to the beam spread. The granularity chosen in defining the RoIs is the result of a compromise between a minimization of the data requests and a convenient usability by the trigger algorithms, but all the data from the sub-detectors with full granularity can be available, if necessary.

After the definition of the detector elements included in the RoI, as provided by the Region Selector, the reconstruction procedure goes on (only for the corresponding data) according to the usual offline processing chain. In the case of TrigMOORE, the "seeding" procedure can be provided from either LVL1 or LVL2. It has been integrated and tested within the *full muon slice* (LVL1 simulation, LVL2 and Event Filter).

The wrapped and seeded strategies have been applied on samples of single muons with different p_T. In Fig. 5 the $1/p_T$ resolution has been plotted as a function of transverse momentum both in the case of wrapped strategy and of seeded strategy driven by muon reconstructed RoIs coming from the LVL1: no relevant differences are observed in the two cases within errors.

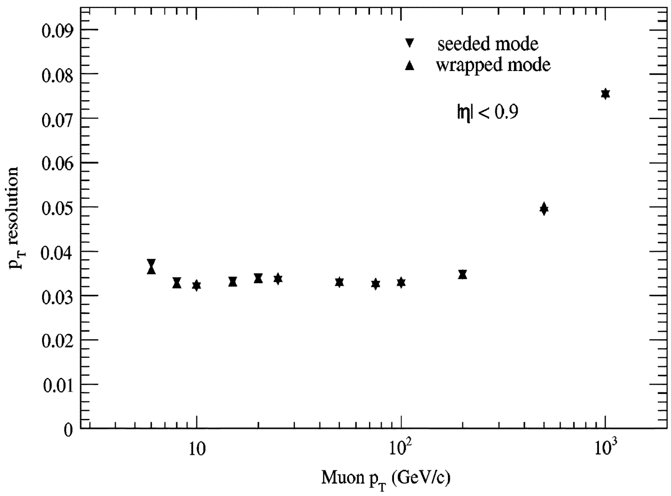

Fig. 5. Transverse momentum resolution obtained with MOORE in seeded and in wrapped mode.

A. Studies With 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 performance has to consider minimum bias (at the design luminosity $\sim$23 inelastic interactions will be produced at every beam crossing) and cavern background. This noise 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. The contribution of punch-through has been also simulated, while the effects of intrinsic noise in the muon chambers have been evaluated to be negligible. Besides the "nominal" background intensity (as predicted by FLUKA [9] and GCALOR [10]), scenarios obtained with background levels higher than the nominal one by factors 2 and 5 have been also considered. In these cases, the shape of the muon reconstruction efficiency as a function of p_T is similar to the one of Fig. 2, but with lower values in average. For single muons with $p_T = 100$ GeV/c, the reconstruction efficiencies of TrigMOORE seeded by LVL1 have been measured to be $0.954 \pm 0.010, 0.930 \pm 0.012$, and 0.891 ± 0.014 for no-background, factor $\times$ 1 and factor $\times$ 5 scenarios, respectively.

B. Timing Performance

Specific timing tests have been performed with TrigMOORE on an Intel XEON(TM) 2.4 GHz processor, with 1 GB RAM.

TABLE I
TIMING TESTS WITH SEEDED AND WRAPPED VERSIONS OF TRIGMOORE ON SINGLE MUON EVENTS

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)

Average execution times per event are shown in Table 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 safety factors). In particular, for events with background, the seeded mode algorithm allows to achieve lower processing times, compatibly to what required by the trigger environment. Times include the whole reconstruction procedure and the track extrapolation to the vertex (MuId). For a more conservative estimate, also the time for accessing data is included. To compute these values a 95% fraction of events has been retained, rejecting the events with the longest processing times. This requirement actually drives to negligible effects on the efficiency (around 1%), since single muon events in which the reconstruction procedure fails mainly are also those requiring the highest processing times. All results are to be compared with the 1 s latency time requested for an algorithm working as Event Filter.

VIII. CONCLUSION

An overall $\sim 10^6$ reduction factor is required by 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 performance 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.

ACKNOWLEDGMENT

S. Armstrong and K. A. Assamagan are with Brookhaven National Laboratory (BNL), Upton, NY 11973 USA.

J. T. M. Baines, D. Emeliyanov, and F. J. Wickens are with Rutherford Appleton Laboratory, Chilton, Didcot, U.K.

C. P. Bee, C. Meessen, Z. Qian, and F. Touchard are with the Centre de Physique des Particules de Marseille, IN2P3-CNRS-Université d'Aix-Marseille 2, France.

M. Bellomo, A. Negri, D. A. Scannicchio, and V. Vercesi are with Istituto Nazionale di Fisica Nucleare (INFN) and University of Pavia, Pavia, Italy.

M. Biglietti is with University of Michigan, Ann Arbor, MI 48109 USA.

J. A. Bogaerts, V. Boisvert, P. Conde Muino, N. Ellis, M. Grothe, T. Maeno, C. Padilla, P. Pinto, S. Rosati, C. Santamarina, and P. Werner are with the European Organization for Nuclear Research (CERN), Geneva, Switzerland.

M. Bosman, P. Casado, M. Dosil, G. Merino, C. Sanchez, E. Segura, and S. Sushkov are with Institut de Física d'Altes Energies (IFAE) and University of Barcelona, Barcelona, Spain.

G. Carlino and F. Conventi are with INFN and University of Naples Federico II, Naples, Italy.

B. Caron, R. Moore, J. L. Pinfold, and R. Soluk are with University of Alberta, Edmonton, AB T6G 2 H1 Canada.

G. Cataldi, M. Primavera, and A. Ventura are with INFN of Lecce, Lecce, Italy (e-mail: andrea.ventura@le.infn.it).

D. Cavalli and S. Resconi are with INFN and University of Milan, Milan, Italy.

M. Cervetto, P. Morettini, F. Parodi, and C. Schiavi are with INFN and University of Genoa, Genoa, Italy.

G. Comune, S. Kabana, V. Perez-Reale, and E. Thomas are with Laboratory for High Energy Physics, University of Bern, Bern, Switzerland.

A. De Santo, S. George, G. Kilvington, and A. Lowe are with Royal Holloway, University of London, Egham, U.K.

J. M. de Seixas, A. dos Anjos, and A. G. Mello are with Federal University of Rio de Janeiro, Rio de Janeiro, Brazil.

M. Diaz Gomez is with Section de Physique, Université de Genéve, Geneva, Switzerland.

A. Di Mattia, S. Falciano, L. Luminari, and A. Nisati are with INFN and University of Rome La Sapienza, Rome, Italy.

B. Epp and V. Ghete are with Institut für Experimentalphysik der Leopald-Franzens Universität, Innsbruck, Austria.

A. Farilla is with INFN and University of Rome "Roma Tre," Rome, Italy.

S. González, W. Wiedenmann, and H. Zobernig are with Department of Physics, University of Wisconsin, Madison, WI 53706 USA.

A. Khomich is with Lehrstuhl für Informatik V, Universität Mannheim, Mannheim, Germany.

N. Konstantinidis, E. Stefanidis, and M. Sutton are with Department of Physics and Astronomy, University College London, London, U.K.

A. Kootz is with Fachbereich Physik, Bergische Universität Wuppertal, Germany.

J. Masik is with Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic.

N. Nikitin and S. Sivoklokov are with Institute of Nuclear Physics, State University of Moscow, Moscow, Russia.

N. Panikashvili is with Department of Physics, Technion, Haifa, Israel.

S. Tapprogge is with Institut für Physik, Universität Mainz, Germany.

B. Venda Pinto is with Universidade de Lisboa, Faculdade de Ciências (CFNUL), Lisbon, Portugal.

S. Wheeler is with University of Alberta, Edmonton, AB T6G 2 H1 Canada, and also with the University of California at Irvine, Irvine, CA 92697 USA.

M. Wielers is with University of Victoria, Victoria, BC V8W 3P4 Canada.

Digital Object Identifier 10.1109/TNS.2006.871504

REFERENCES

[1] ATLAS Detector and Physics Performance Tech. Design Rep., ATLAS Collab., CERN-LHCC 99-14 and 99-15, 1999.

[2] ATLAS Level-1 Trigger: Tech. Design Rep., ATLAS Collab., CERN-LHCC-98-014, ATLAS-TDR-12, Jun. 1998.

[3] ATLAS High-Level Triggers, DAQ and DCS Tech. Proposal, ATLAS Collab., CERN/LHCC 2000-17, Mar. 2000.

[4] ATLAS Inner Detector Tech. Design Rep., ATLAS Collab., CERN/LHCC 97-16, Apr. 1997.

[5] Th. Lagouri *et al.*, "A muon identification and combined reconstruction procedure for the ATLAS detector at the LHC at CERN," *IEEE Trans. Nucl. Sci.*, vol. 51, no. 6, p. 3030, Dec. 2004.

[6] ATLAS Muon Spectrometer Tech. Design Rep., ATLAS Muon Collab., CERN/LHCC 97-22, May 1997.

[7] Athena Developer Guide [Online]. Available: http://atlas.web.cern.ch/Atlas/GROUPS/SOFTWARE/OO/architecture/

[8] D. Adams *et al.*, "Track Reconstruction in the ATLAS Muon Spectrometer with MOORE," ATLAS Note, ATL-SOFT-2003-007.

[9] A. Fassó, A. Ferrari, P. R. Sala, and J. Ranft, "FLUKA: Status and prospects for hadronic applications," in *Monte Carlo Conf.*, Lisbon, Portugal, Oct. 23–26, 2000.

[10] C. Zeitnitz and T. A. Gabriel, "The GEANT-CALOR interface and benchmark calculations for zeus calorimeters," *Nucl. Instrum. Meth. Phys. Res. A*, vol. 349, pp. 106–111, 1994.