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Muon Identification with the Event Filter of the ATLAS Experiment at CERN LHC's

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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 offline physics analysis must be embedded within the online trigger system.

For the Muon trigger, the specific off-line algorithms MOORE (Muon Object Oriented REconstruction) and MuId (Muon Identi-

fication) 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.

I. INTRODUCTION

The 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 trajectory tracker enclosed in superconducting solenoidal 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 geometry 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 pp collisions at a centre-of-mass energy of 14 TeV and a design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The corresponding 40 MHz bunch crossing rate (with an average of ~ 23 superimposed events) and the huge amount of detector channel ($\sim 10^8$) outline the challenge of the ATLAS Trigger and Data Acquisition (TDAQ) system.

II. ATLAS TRIGGER DAQ

The ATLAS TDAQ system must be able to select and store each second, out of millions of events (1 GHz interaction rate corresponding to about 60 TB/s), the most interesting ones, compatibly with a tolerable storage data flux of some hundred MB/s. Given an average event size of $\sim 1.5 \text{ MB}$, the storage rate is then about 200 Hz. The required data reduction factor, equivalent to a rejection factor of about 6 orders of magnitude, is achieved on-line via a data acquisition system organized in three different trigger levels (Figure 1).

The Level-1 trigger (LVL1) [4], implemented in hardware by a custom electronics, will perform the first level of event selection, reducing the initial data rate from the 40MHz collision rate to about 75 kHz. For accepted events the LVL1 identifies the detector regions, defined in rapidity and azimuthal angle, where the signal exceeds programmable thresholds. These Region of Interests (RoIs) are used to guide the LVL2 selection process that can access full granularity event data from all detectors.

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Fig. 1. Block diagram of the ATLAS TDAQ system.

The Level-2 (LVL2) and Level-3, called Event Filter (EF), are software based systems and are referred together as High Level Triggers (HLT). The HLT must provide a further reduction factor of about 10^3 .

The LVL1 trigger 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 ROS (Read Out System) elements. If an 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 trigger.

The primary function of the EF is certainly the reduction of data flow and rate to a value acceptable by the mass storage operations 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. Indeed, whereas the upstream trigger levels are latency and bandwidth limited, the EF is highly processing time dominated.

The running environment for the trigger algorithms is the HLT event selection software framework (ESS [3]), which is based on the ATLAS off-line reconstruction and analysis environment ATHENA [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 offline, and the latest calibration and alignment 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.

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) and Cathode Strip Chambers (CSC) in the small angle-regions. 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 direction of the magnetic field. The 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 order of its initial energy so that it is not possible anymore 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 offline 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 Phi-view, allowing the construction of segments, that are essentially vectors of digits measuring the Phi coordinate.

The tracks crossing the ATLAS Muon Spectrometer bend in the RZ-plane. Nevertheless in this plane a crude pattern recognition can be applied locally (in every detector module) assuming the tracks to be straight lines and approximating the measurements, e.g. for a Monitored Drift Tube (MDT) module the tube center is used to approximate the hit position. Also in this view is then possible to build segments. These 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 phi view in order to optimize the time latency of the algorithm. In the refinement phase, 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, it has a number of hits above a cut and 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 to restrict the number of track segment candidates in the high background environment of the precision chambers and take into account that the large drift times of the precision chambers relative to the bunch spacing of LHC would forbid an efficient reconstruction in presence of pileup.

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 of hits having high residuals is performed.

B. MuID

MuID (Muon IDentification) associates tracks found in the Muon Spectrometer with the corresponding Inner Detector tracks as well as with calorimeter information. The final objects are identified muons whose track parameters are given at the interaction region. The MuID Muon Identification package combines Muon Spectrometer tracks reconstructed by MOORE with Inner Detector tracks found using iPatRec [9]. The purpose of MuID is to identify Inner Detector tracks as muons at all momenta, to obtain improved parameter resolutions at intermediate momenta, 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 and their summed covariance from the Inner Detector and standalone fits. To obtain the

Fig. 2. The MOORE/MuID packages in offline and online environment. The arrows show the dependencies between the packages.

optimum track parameters, combined fits are performed to all matches with χ^2 probability above 0.001. When no matches satisfy this criterion, a combined fit is attempted for the best match within a road about the standalone track. A combined fit is a refit to all the measurements and scatterers from the Inner Detector, calorimeter, and Muon Spectrometer systems.

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 [3], [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 $(\Delta\eta, \Delta\phi)$, preliminary set to $(0.2, 0.2)$, around the center of a Region of Interest. For this need the algorithm must use the RegionSelector tool [12]. 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 [13]. A sketch of the dependencies is shown in Figure 2. 2.

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.

Fig. 3. Efficiency (left figure) and $1/p_T$ resolution (right figure) of single muon reconstruction as a function of p_T for MOORE, MuID standalone, iPatRec and MuID combined.

- *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 pertain to a certain geometrical region. After the search in the Region of Interest and the construction of intermediate 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 $\rightarrow$ LVL2 $\rightarrow$ 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 hypothesis are represented by an object called TriggerElement [3]. 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 η and ϕ . The Algorithms call the RegionSelector to know the chambers located in 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.

V. VALIDATION WITH SINGLE MUON SAMPLES

The physics performances of MOORE/MuIS 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. 3, the global 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 [9] are reported.

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.

It is seen that the final reconstruction muon efficiency is greater than 90% 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 and not from algorithmic shortcomings. For the $1/p_T$ resolution, Global resolution on p_T it is seen that the global resolution 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 [2].

VI. 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 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 (no Level-1 and Level-2 selection have been made here). In Fig. 4 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 uncorrelated 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 collider. These particles (mainly neutrons)

Fig. 5. Reconstruction efficiencies obtained with MOORE and MuId standalone seeded by LVL1 on 100 GeV/c p_T single muons without and with pileup addition.

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 minimum bias events and cavern background superimposition. For a conservative analysis, 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 uncorrelated background $\times 1$) have been considered. In Fig. 5 the reconstruction efficiency for TrigMOORE seeded by LVL1 is shown as a function of the p_T in case of single muons with $p_T = 100$ GeV/c. The left figure shows the efficiency is referring to the reconstruction inside the Muon Spectrometer (MOORE) while the right figure refers to the efficiency after extrapolating to the vertex (MuId standalone).

VII. 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. I 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 retained, rejecting the events with the longest processing times.

VIII. CONCLUSION

This paper describes a specialized 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

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

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 possibility for the use of MOORE and MuId in the online environment as Event Filter.

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