A LEVEL-2 TRIGGER ALGORITHM FOR THE IDENTIFICATION OF MUONS IN THE ATLAS MUON SPECTROMETER

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Abstract

The ATLAS Level-2 trigger provides a software-based event selection after the initial Level-1 hardware trigger. For the muon events, the selection is decomposed in a number of broad steps: first, the Muon Spectrometer data are processed to give physics quantities associated to the muon track (standalone feature extraction) then, other detector data are used to refine the extracted features. The "μFast" algorithm performs the standalone feature extraction, providing a first reduction of the muon event rate from Level-1. It confirms muon track candidates with a precise measurement of the muon momentum. The algorithm is designed to be both conceptually simple and fast so as to be readily implemented in the demanding online environment in which the Level-2 selection code will run. Nevertheless its physics performance approaches, in some cases, that of the offline reconstruction algorithms. This paper describes the implemented algorithm together with the software techniques employed to increase its timing performances.

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INTRODUCTION

The ATLAS experiment [1] will search new particles at the Large Hadron Collider (LHC), the CERN p-p ring designed to provide 14 TeV centre of mass energy and 10^{34}cm^{-2}s^{-1} maximum luminosity. These values of energy and luminosity will allow to probe the High Energy Physics frontier up the the scale of ~ 1 TeV but will also set an harsh experimental environment where the QCD background particles have a production rate several orders of magnitude greater than the physics signals.

Moreover, the high particle flux and the short bunch crossing separation, 25 ns, impose to use fast time response detectors with a fine read-out granularity, especially for the central tracker. This implies a large number of electronics channels that produce a very large amount of data ($O(10^8$ MByte/s)).

Therefore triggering at LHC will be more difficult than in current experiments: the huge event rate, O(1GHz), must be reduced to a manageable level (10-100 events/s) for the storage system and the offline computing. The trigger must provide an event rejection of 10^7 and, in order to cope with the high QCD background, it must be able to identify physics objects with performances similar to the offline selection.

Among the several trigger subsystems the one based on muon identification and reconstruction is particularly important because it allows the selection of the cleanest channel for the Higgs discovery ($H\rightarrow ZZ\rightarrow 4\mu$) and of events for precision physics (CP violation, M_W).

THE ATLAS MUON SYSTEM

The ATLAS Muon System [2] is designed to provide muon identification and to perform a standalone high precision measurement of the muon momentum up to $\eta \approx 3$. It exploits three air core toroidal magnets providing a field of 0.5 Tesla. Inside the magnetic field are housed

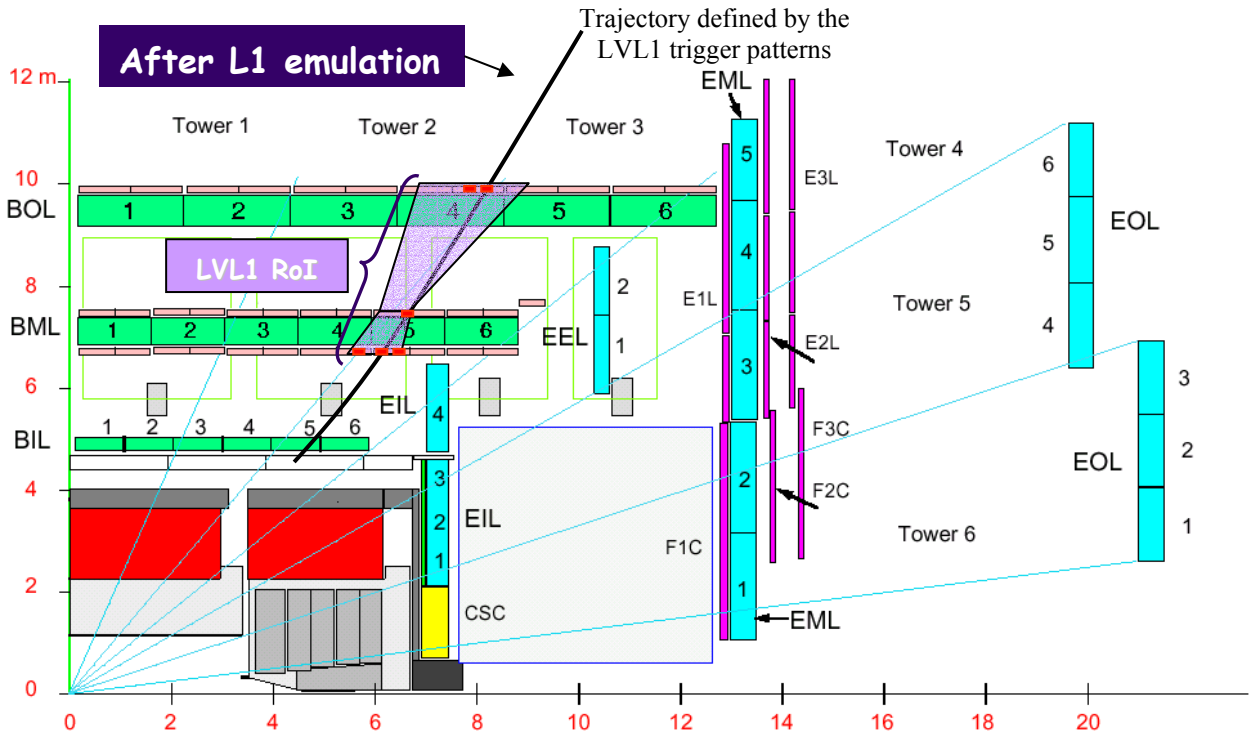

Figure 1: Longitudinal view of the ATLAS Muon Spectrometer showing the measurement stations for the barrel (BIL, BML, BOL) and for the endcap (EIL, EML, EOL). The Level-1 RoI for a muon tack is also shown together with the hits left on trigger chamber (red dots) and the approximated trajectory reconstructed from RPC data.

planes of tracking chambers, arranged in three measurement stations (figure 1), which measure the coordinate in the bending projection with an intrinsic precision of 80 μm. Monitored Drift Tubes (MDT) [2] technology is used in most of the Spectrometer. In the very forward region ($2 \leq \eta \leq 3$) Cathode Strip Chambers (CSC) [2] are employed because they support an higher particle flux. The tracking system is complemented with an independent and fast trigger system that provides also the measurement of the second coordinate. The trigger system employs Resistive Plate Chambers (RPC) [3] in the barrel and Thin Gap Chambers (TGC) [4] in the endcaps.

THE ATLAS TRIGGER

The ATLAS trigger performs the event selection in three sequential steps of increasing complexity: Level-1, Level-2 and Event Filter. The Level-1 trigger [5] receives the data at the bunch crossing frequency (40 MHz). The latency time is about 2 μs and the maximum output rate is 75 KHz. The trigger is made of hardwired processors which analyze coarse granularity data and apply simple algorithms to find physics activities above threshold. In the Muon System only data from trigger chambers are used to take a trigger decision.

The other two trigger levels [6] are based on software algorithms which run in processor farms. Level-2 uses the full granularity data but processes only the detector regions flagged by Level-1 as containing activity, the so called Regions of Interest (RoIs). This technique reduces the data throughput down to 2% of the full event. The Level-2 analysis is performed in two steps: first fast algorithms reconstruct physic objects (e, γ, μ, jets ...) within the RoIs, then the event is selected combining the physics objects according to a trigger menu. Altogether the Level-2 reduces the event rate by a factor of about 100 with a men latency time of 10 ms.

The Event Filter is the last stage of the online selection and access the full event data. At this stage the latency time is ~2 s and allows to use offline-like algorithms that provide a refined reconstruction of the physics objects. The Event Filter performs the final classification of the events reducing the event rate by a further factor of 10.

LEVEL-2 MUON RECONSTRUCTION

Muon reconstruction at Level-2 is performed to confirm the Level-1 muon RoI and to build "muon" objects for the trigger menu. It proceeds through the "μFast" algorithm that, using only the Muon Spectrometer data, provides an accurate muon track reconstruction within an RoI and a precise estimation of the muon p_T at the interaction vertex. These parameters are subsequently refined using other detector data (Inner Detector to refine the p_T estimation, Calorimeters to provide isolation checks) by different algorithms.

μFast gathers together RoI data and processes them in three sequential steps:

- "Global Pattern Recognition" which involves trigger chambers data and positions of MDT tubes;

- "Track Fit" using the drift time measurements, performed on each MDT chamber;
- "Fast p_T Estimate" using a Look Up Table to avoid a time consuming fit method.

The result of the algorithm is the η, ϕ position and the direction of flight of the muon track, plus the muon p_T at vertex.

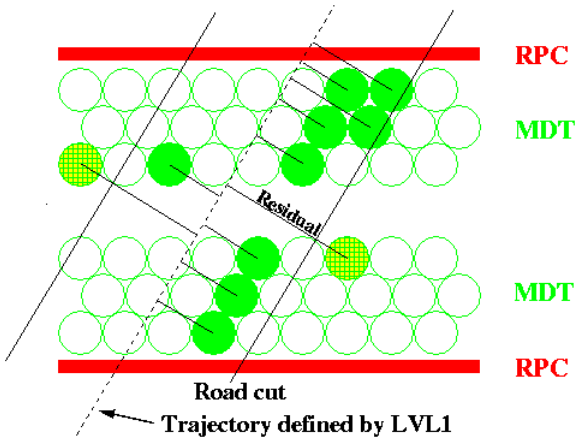

Figure 2: example of the MDT pattern recognition in a barrel middle station (BML). Residuals are the distance of the centre of hit tube from the Level-1 trajectory.

The global pattern recognition selects MDT muon hits for the track fit, and is seeded by the trigger chambers data. Trigger hits plus the interaction vertex position are used to define the initiator of the muon trajectory (figure 1), then a road is opened around this trajectory to collect MDT hit tubes within it (figure 2). A contiguity algorithm is finally applied on the selected hits to further remove the background. Notwithstanding the road dimension are very tight (~ 20 cm) this method selects muon hits with 96% of efficiency.

In order to save CPU time, the muon track is fitted locally on each MDT station through straight segments, using only 1 hit per MDT layer. The intersection of the fitted lines with the middle of the chamber determines precision points used to compute the track sagitta. For the fit, an approximated R-t relation is used (no Lorentz effects are taken into account) and the time-of-flight and propagation time along the wire are subtracted from the raw drift time. The approximations (use of straight segments instead of a curve and no use of the calibrated R-t relations) are negligible with respect to the muon sagitta for p_T equal to the trigger thresholds: ~5 cm (20 GeV) and ~25 cm (6 GeV).

Finally the muon transverse momentum is estimated using a linear relationship between the measured sagitta (s_m) and p_T

$$\frac{1}{s_m} = A_0 \cdot p_T + A_1 ,$$

which is stored in Look Up Tables for diferrent η, ϕ regions. To take into account the non-uniformity of the magnetic field, the energy loss of the muon when it crosses the calorimeters and the multiple scattering at the calorimeters exit, tables with an η, ϕ granularity of 30×60 are used for each detector octant. The total data volume of the LUTs is about 130 Kbytes.

μFast performances

The aim of μFast is to reject fake muons accepted by the Level-1 trigger, to perform a measurement of the transverse momentum of muon candidates, and to exclude those muon tracks with a momentum below threshold. The physics performance indicators are thus the track finding efficiency relative to the Level-1 output, and the resolution of the reconstructed muon p_T.

The track finding efficiency is determined by the hit selection efficiency of the muon roads and by the geometrical coverage of the MDT chambers. While the former is tunable, the latter contributes approximately to (1÷3)% of the total inefficiency depending on the muon momentum. The net track finding efficiency of μFast is about 97%.

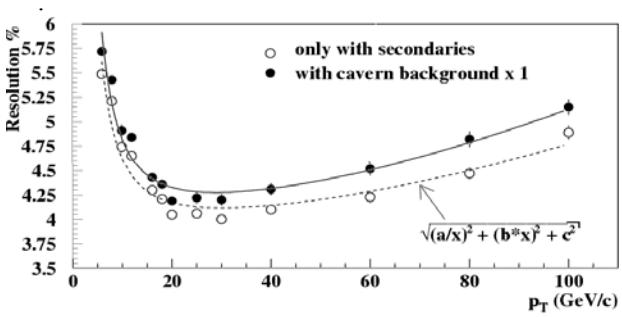

Figure 3: The p_T resolution of μFast as a function of the muon p_T in the region $|\eta| \leq 1$. The Cavern Background is simulated at the maximum luminosity.

The p_T resolution of the algorithm has been measured with and without Cavern Background[†] (figure 3). The resolution is not significantly degraded by the presence of background and is about 6% for the 6 GeV threshold and 4% for the 20 GeV threshold. These values are only a factor of two worse than those obtained by the offline reconstruction program.

The algorithm is optimized to yield a trigger efficiency for prompt muons of 90% at threshold. The good resolution on transverse momentum allows to apply a p_T cut much sharper than the one applied by the Level-1, thus reducing the event rate of the non prompt muons coming from the π/k decays. This reduction is more effective at the low-p_T threshold (6 GeV) where the π/k decays cross section dominates the inclusive muon production and is exponentially increasing towards p_T=0.

A summary of the muon event rates at Level-1 and at Level-2 using μFast is shown in Table 1. μFast reduces the total muon event rate by a factor of 2 at low-p_T threshold and by a factor of 10 at high-p_T threshold.

[†] Cavern Background is constituted by low energy neutrons and photons which originates from the collisions at the vertex. Hits from these particles are the dominant contribution to the difficulties of performing the pattern recognition.

Table 1: total output rates of the Level-1 and Level-2 muon trigger for the barrel region ($|\eta| \leq 1$).

Processes	6 GeV (10^{33} cm^{-2} s^{-1})		20 GeV (10^{34} cm^{-2} s^{-1})	
	Level-1 KHz	μFast KHz	Level-1 KHz	μFast KHz
Beauty	1.40	0.75	0.50	0.06
Charm	0.80	0.40	0.21	0.02
$W \rightarrow \nu\mu$	0.003	0.003	0.03	0.02
π/k decays	7.10	2.70	0.68	0.04
Fakes	1.0	~0	~0	~0
Total	10.3	3.9	1.42	0.15

CODE OPTIMIZATION

The μFast code runs in the Level-2 processing unit (L2PU), the trigger component that steers the algorithms to classify the event and manages the RoI data requests. The target Level-2 mean event processing time is 10 ms, thus the fraction of processing time left to μFast reconstruction is O(1 ms)[‡].

To meet this strict constraint, the design of μFast doesn't employ techniques that increase the CPU load, like memory allocation on demand or data organization through STL containers. The reconstruction tasks described in the previous section are implemented by procedures that operate on data organized in appropriate structures. This reduces at minimum the latency due to the exchange of complex classes modelling the data, and at the same time allows a fast access to the processed data.

Further optimization is achieved tuning the definition of the trajectory reconstructed from RPC data using the position of the interaction vertex. As a result the muon road size is reduced, becoming much smaller than the MDT chamber dimension, while the muon hit selection efficiency is left untouched. This simplifies the task of the pattern recognition yielding a reduction of the overall processing time. A small road size increases the algorithm robustness against background: it removes most of the MDT hits present in a chamber, that arise from background in the ATLAS cavern.

The optimization work has also concerned with the procedure for requesting the event data. Inside the L2PU, μFast receives RoI data through an infrastructure which is implemented using offline software components. Such components access raw data from detector elements inside the RoI region and automatically convert them into data classes suitable for the reconstruction. Those components are not optimized for speed. Thus the data request competes with the algorithm processing in terms of CPU usage and dominates the overall processing time if it is not tuned for the muon case.

[‡] μFast is not the only algorithm to run on muon events; the reconstruction of muon tracks is also performed in the Inner Detector and in the Calorimeters to refine the muon object properties.

In particular, accessing the MDT chambers data through the muon RoI region is not efficient: typically seven MDT chambers belong to a muon RoI, while the muon track data are inside three of them. On the contrary the muon road selects a thin slice of the Spectrometer around the muon track. So it is the best candidate for issuing the MDT data request because it eliminates the time overhead due to the conversion of useless data.

Though it is not allowed to modify the infrastructure that converts the raw data, optimization is still possible by choosing a data model structure that eases the decoding task and thus saves processing time. Further optimization in this area is obtained performing the "data preparation" (i.e. associate space points to detector hits, calibrate the data, …) only on the data entering the fit. This implies to perform this task inside the algorithm employing an ad hoc code that provides fast access to the detector geometry.

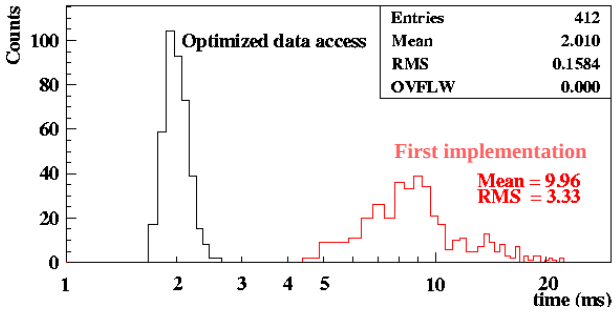

Figure 4: Execution time of the Level-2 muon reconstruction on a XEON CPU clocked at 2.4 GHz.

The result of this optimization work is shown in figure 4, where the execution time of an old μFast implementation is matched with the optimized one. The optimized version is fully compliant with the Level-2 latency.

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