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The ATLAS Muon Trigger "Slice"

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***Abstract*—The ATLAS experiment at the LHC will face the challenge of selecting interesting candidate events in proton-proton collisions at 14 TeV center of mass energy, while rejecting the enormous number of background events. The trigger system architecture is organized in three levels. From a bunch crossing rate of 40 MHz the First Level trigger, hardware implemented, will reduce this rate to around ∼75 kHz. Then the software based High Level Trigger (HLT), composed by the Second Level Trigger and the Event Filter reduces the rate to ∼ 200 Hz. HLT is implemented on commercial CPUs using a framework built on the common ATLAS object oriented software architecture. Inclusive trigger selections are used to collect events for the ATLAS physics program; final states with muons are crucial for Electroweak precision measurements as well as Higgs and SUSY searches. In this paper we will present the implementation of the muon slice, signal efficiencies, background rejection rates and system performances (execution time,...) for online muon selection based on MonteCarlo simulations and results obtained on real events collected during cosmic data taking runs.**

I. Introduction

ATLAS is one of the LHC (Large Hadron Collider) experiments at CERN. ATLAS is a general purpose experiment analyzing proton-proton collisions at $\sqrt{s} = 14$ TeV. The ATLAS detector will face several technological challenges. The data acquisition system has to cope an extremely high interaction rate of collisions and reduce the 40 MHz bunch-crossing frequency, corresponding to an interaction rate of 1 GHz at the design instantaneous luminosity ($\mathcal{L} = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$), to about $\sim$ 200 Hz allowed by the permanent storage system.

Final states with muons represent a key signature for many physics measurements and discoveries: B-physics, Top physics, W and Z bosons final states (Electroweak physics, Higgs boson,...), Physics Beyond Standard Model (SUSY, Extra Dimensions,...).

The capability to select events with muons at an early stage of the trigger system is therefore crucial to cope with the expected rates and to perform the various physics measurements of the ATLAS physics program.

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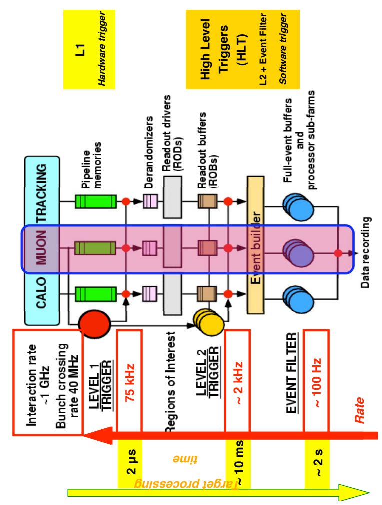

Fig. 1. Architecture of the ATLAS Trigger System [1]

The ATLAS *Trigger Muon Slice* is the full integrated chain of DAQ/Trigger running from the muon spectrometer data and is composed by three trigger levels: an hardware implemented Level-1 (LVL1) and a software implemented High Level Trigger (HLT) composed by Level-2(LVL2) and Event Filter (EF). The architecture of the ATLAS trigger system is sketched in Fig.1.

In the following, the first section describes the LVL1 muon trigger, while the second one is devoted to the HLT. Each section describes the algorithms and their performances. A third section presents the results of the commissioning cosmic runs.

II. Level-1

Muon trigger LVL-1 is an asynchronous process with a fixed latency of 2.5 ms. Using the full granularity of the Thin Gap Chambers (TGC) and Resistive Plate Chambers (RPC),

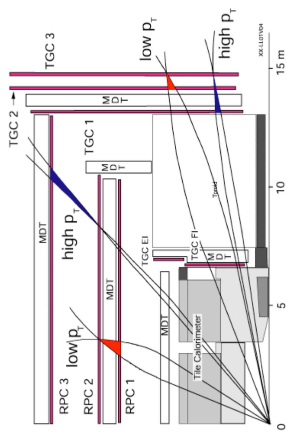

Fig. 2. Layout of the ATLAS Muon Spectrometer.

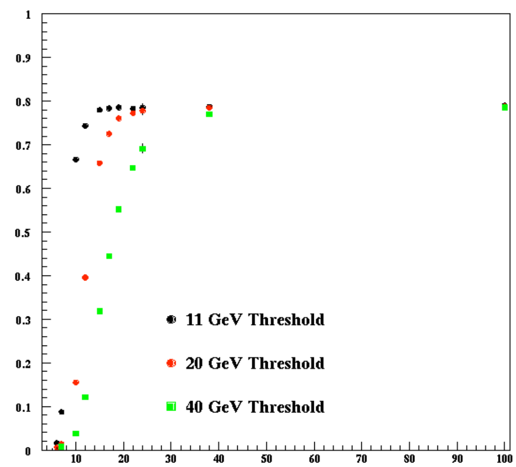

Fig. 3. Level-1 trigger efficiencies as a function of muon momentum (Barrel).

respectively, for the endcap ($1.0 < |\eta| < 2.4$) and barrel regions ($|\eta| < 1$) of the Muon Spectrometer (MS), it selects muons with transverse momentum above six programmable thresholds with a coarse evaluation of the pseudorapidity and azimuthal angle coordinates (respectively, η and ϕ) and associates the trigger candidate with the correct LHC bunch crossing. A schema of the MS layout is shown in Fig.2.

The algorithm looks for hit coincidences within different RPC or TGC detector layers inside the programmed geometrical roads which define the transverse momentum cut. A coincidence is required on both eta and phi projections. For the barrel region the thresholds are divided in "low-Pt" thresholds that uses only the two innermost RPC stations and "high-Pt" ones where all the RPC stations are used. For the Endcap region, only the middle TGC station is used for the coincidence. A tight time coincidence of the trigger detector hits is required as well. Regions where the muon track is found are called Region of Interest (RoI) corresponding to a $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$ in the barrel and a finer segmentation in the end-cap region. The combination of hits is made using a Coincidence Matrix ASICs [2], [3]. The trigger efficiency as a function of the muon transverse momentum are shown in Fig.3 and Fig.4 respectively for the barrel and endcap regions. The total[1] Level-1 output rate has to be less than ~ 75 kHz[2].

The trigger efficiency curves convoluted with the differential cross sections with respect to muon momentum give the expected Level-1 output rates shown in Tab.I as a function of the thresholds[3]. The *cosmic threshold* indicates the LVL1 configuration used for the cosmic runs *i.e.* with coincidence windows fully open. This configuration will be used for the cosmic data taking and the first LHC runs at low luminosity.

The LVL1 event-decision part is implemented by the Central

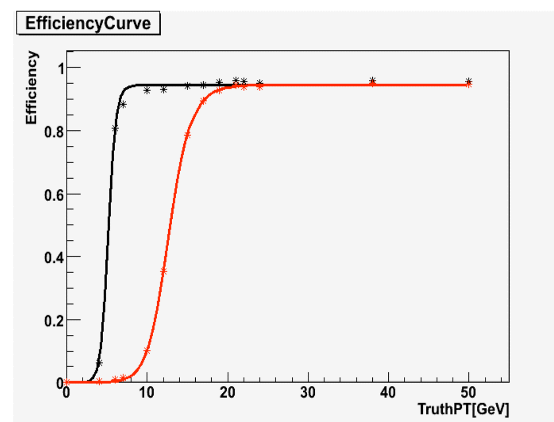

Fig. 4. Level-1 trigger efficiencies as a function of muon momentum (EndCap).

Trigger Processor (CTP) that also resolves double counting of muons that traverse more than one detector region. This is crucial to avoid high rates from low-momentum di-muon triggers due to single muon final states[4]. The logic implemented in the CTP reduces the expected double counting fake rate from ~ 850 Hz to ~ 150 Hz for an instantanous luminosity of $\mathcal{L} = 10^{33}\mathrm{cm}^{-2}\mathrm{s} - 1$.

[1] including with muons candidates also electromagnetic and hadronic ones.
[2] Level-1 output rate can handle up to ~ 100 kHz with some deadtime.
[3] The $\sim$ 90$ efficiency above momentum threshold is caused by the geometrical acceptance of the Muon Spectrometer trigger chambers.

[4] The expected cross section of genuine dimuon final states for $P_T = 6$ GeV is $\sim 10^2$ nb that is $\sim 10^2$ time less than single muon rate.

TABLE I
LEVEL-1 OUTPUT EXPECTED TRIGGER RATES FOR THE BARREL REGION(IN KHZ) AND THE INDICATED INSTANTANEOUS LUMINOSITY FOR DIFFERENT THRESHOLDS.

Muon Sources	"Cosmic"	6 GeV	8 GeV	11 GeV	20 GeV
	$\mathcal{L} = 10^{33}\text{cm}^{-2}\text{s}^{-1}$			$\mathcal{L} = 10^{34}\text{cm}^{-2}\text{s}^{-1}$	
π/K	62.5	10.5	8.8	7.4	3.5
b-decays	3.4	1.7	1.2	2.3	0.8
c-decays	2.4	1.0	0.7	1.1	0.3
W and top	-	-	-	-	-
Total	68.3	13.2	10.7	10.8	4.6

III. HIGH LEVEL TRIGGER

The High Level Triggers (HLT) decrease the first trigger level output rate to the final DAQ rates [4]. The HLT system uses farms of commercial processors where reconstruction algorithms with increasing complexity can be executed. Only data in the RoI selected by Level-1 are analyzed at Level-2. Event building occurs at Level-2 output, before the final trigger selection, the Event Filter (EF). Whith this architecture, a smaller bandwidth is required since the event building occurs only for events passing the Level-2 selection. In both Level-2 and EF, different algorithms run in sequence, rejecting as early as possible events that do not pass the required selections. The steering mechanism is responsible to run in the correct order and with the correct input data the trigger algorithms [5]. The ATLAS HLT use selections implemented in software where some *offline* reconstruction code has been reused. However *online* software trigger algorithms have different requirements than *offline* ones. For example, the execution times must be within the HLT specified processing times ($\sim$10 ms for Level-2 and $\sim$ 2s for EF), they have to be more robust and should be able to run on the specific *online* environment (*e.g.* multithread environment,...). Depending on some stringent requirements, specific trigger algorithms have to be implemented. The total Level-2 and Event Filter output rates has to be respectively within $\sim$ 1kHz and $\sim$ 200 Hz.

A. Level-2

The first algorithm to run in the muon selection sequence at Level-2 is a MS *standalone* reconstruction algorithm. It runs on full granularity data within the RoI defined by Level-1. In the barrel region, a Level-1 emulation is used to reconstruct the RPC hit pattern that fired the Level-1 trigger. The nominal interaction vertex is used for defining the trajectory of "low-pT" and "high-pT" candidates and to perform the extrapolation to the innermost MDT station where RPC hits are not available. A road to select MDT is build around the RPC reconstructed tracks. In each MDT station a local linear fit is performed using MDT precision drift time measurements. The left-right ambiguity with respect to the sensitive wire is solved by fitting all the possible segments through the drift circles and choosing the one with the best χ^2. From the reconstructed segments and their intersection with the detector planes, the radius of the muon trajectory is measured. The transverse muon momentum is determined as an output of a Look Up Table (LUT) whose entries are radius, ϕ and η at the entrance of the MS. The expected resolutions as a function of muon momentum in the barrel region are shown in Fig.5 [6]. For muons in the Endcap region, the pattern recognition starts from the TGC detectors in the middle muon station. A momentum dependent road for selecting MDT hits[5] is computed. As in the Barrel, a MDT segment finding procedure and a muon momentum measurement is performed. LUT for momentum eveluation use different reconstrcted quantities for the Endcap region taking in account the non-homogeneity of the toroidal magnetic.

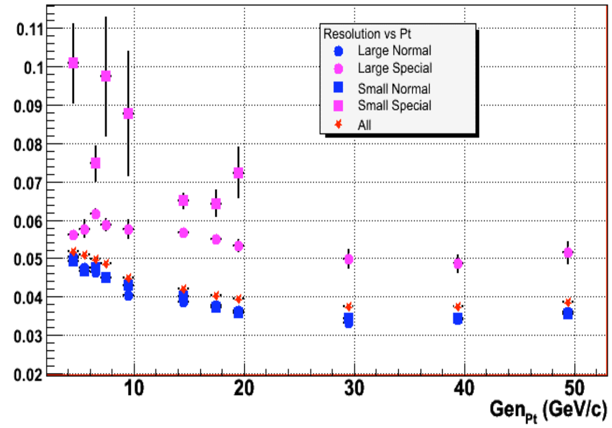

Fig. 5. Level-2 trigger MS standalone muon momentum resolution. Red stars show the resolution integrated over all the MS (Only barrel region $|\eta| < 1$.)

At Level-2 it is possible to combine the information provided by other subdetectors, for example the Inner Detector (ID) and the Calorimeters. For candidates passing the MS standalone selection, InnerDetector (ID) tracks are combined to the MS candidate by a fast (*e.g.* without using complicated and lengthy fit procedure) combination algorithm to further reduce the rates of muons coming from π/K inflight decays and improving the momentum resolution for low and intermediate muon momentum ranges ($P_T \lesssim 100$GeV).

To cope with the high rates for low momentum muons while still having a good selection efficiency, a Level 2 Dimuon Trigger is implemented to select dimuon events coming from J/Ψ (*e.g.* $B \to J/\Psi X$). Starting from a single low momentum Level-1 muon candidate, an additional ID reconstructed track compatible with a low momentum muon is searched. A final selection around the J/Ψ invariant mass is performed.

An additional LVL2 trigger algorithm combines the electromagnetic and hadronic energy deposition measurements

[5]Cathode Strip Chambers are used to increase acceptance up in the region $2.0 < |\eta| < 2.5$.

(respectively in the Liquid Argon and Tile calorimeters) in a cone around the muon. This algorithm discriminates between isolated muons coming from W and Z decays and non-isolated ones coming from *beauty* and *charm* semileptonic ones.

B. Event Filter

The final EF accesses the full event with its full granularity after the Event Building occurred [7] [8], it uses *offline* reconstruction algorithms in the Trigger and DAQ framework. It combines measurements from other ATLAS sub-detectors. The reconstruction algorithms performs: a stand-alone reconstruction in the MS *TrigMoore*, an extrapolation of the muon momentum to the primary vertex of the interaction taking into account the energy loss in the calorimeters *TrigMuID* and a combined reconstruction using ID hits *TrigmuComb*. The Event Filter reconstruction can follow two different strategies: *full scan* where the whole event is accessed and *seeded* where the EF algorithm performs a search seeded by Level-2 candidates. The algorithm reconstruct tracks inside the MS, starting with a search of regions of activity in the detector performing pattern recognition and track fitting. Since the bending power of the toroidal magnetic field is negligible in the transverse plane, a track is approximated to a straight line in the (R, ϕ) projection. A crude pattern recognition in the bending plane (R, z) is performed using the MDT wire positions and fitting locally the hits to a straight track. A refinement is performed using the MDT drift time precision measurement and fitting the MDT hits of a single multilayer station to a straight track. 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 final track fit takes into account energy loss and Coulomb scattering effects, a cleaning procedure is performed to remove hits with high residuals.

The combination with ID tracks allows a better momentum resolution and minimize the tails of the resolution distributions caused by catastrophic brehmstrahlung and energy losses in the calorimeters.

The expected resolutions of muon momentum as a function of pseudorapidty for muon with $P_T = 20$ GeV are shown in Fig.6.

The expected rates EF rates for different momentum thresholds are shown in Fig.7 and Fig.8.

The muon Level-1 Trigger rate is dominated by K and π in-flight decays. One of the goals of the HLT selection is to keep muons from beauty and charm semileptonic decays (for b-physics measurements at low luminosity) and the ones from W and Z bosons (for high-Pt physics measurements at higher luminosity) rejecting non-prompt muons from K and π. This can be achieved combining the Muon Spectrometer StandAlone track with the one reconstructed within the Inner Detector both at Level-2 and at Event Filter.

Another source of noise in the spectrometer is the uncorrelated cavern background that will be present in the ATLAS experimental area, essentially due to particles (mostly neutrons) produced in the interaction of primary hadrons from p-p collisions with the detector/collider materials, and then interact

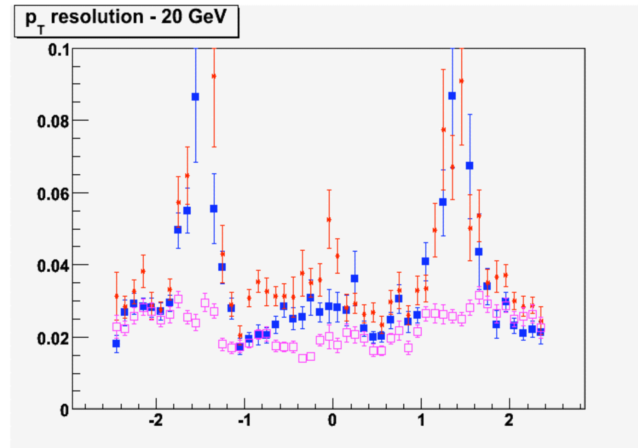

Fig. 6. Expected muon momentum resolution as a function of η for the different reconstruction algorithms (Muon fixed $P_T = 20$ GeV).

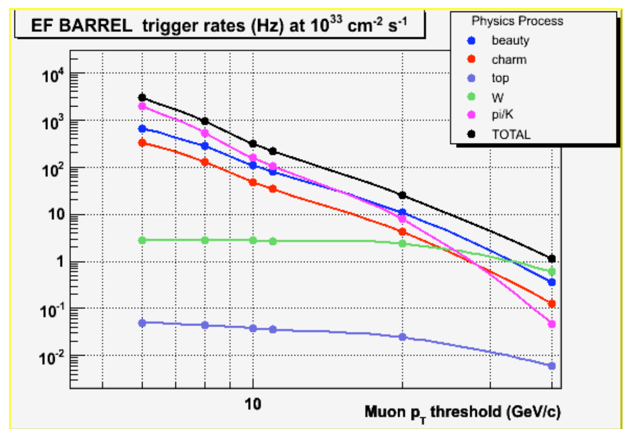

Fig. 7. Expected final output trigger rates with different momentum thresholds. (Barrel region only).

with matter producing neutral and charged secondaries, that diffuse like a gas through the apparatus and the cavern. Such background has been simulated and extensively studied with the HLT algorithms with simulated datasample with the nominal expected background intensity and including some additional saffety factors ($\times 2, \times 5, \times 10$).

IV. Commissioning

During the last year, following the installation and integration of the ATLAS detector, the commissioning of the ATLAS Muon Trigger slice started during cosmic data taking. These events will provide a real signal of a minimum ionizing particle (MIP) and a clear track which can be used for checking the

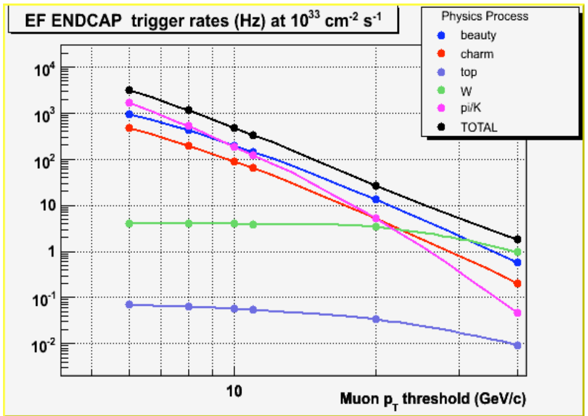

Fig. 8. Expected final output trigger rates with different momentum thresholds. (Endcap region only).

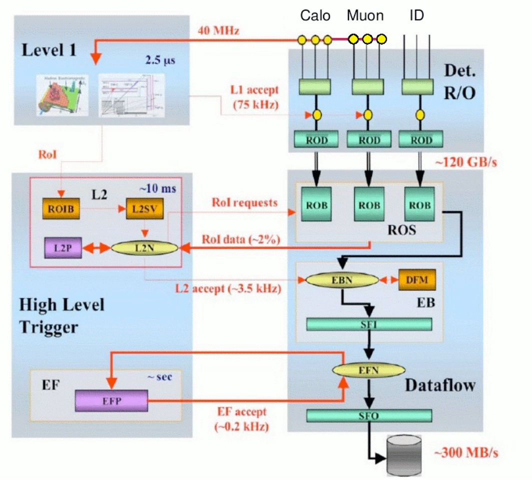

Fig. 10. ATLAS trigger implementation showing the different components.

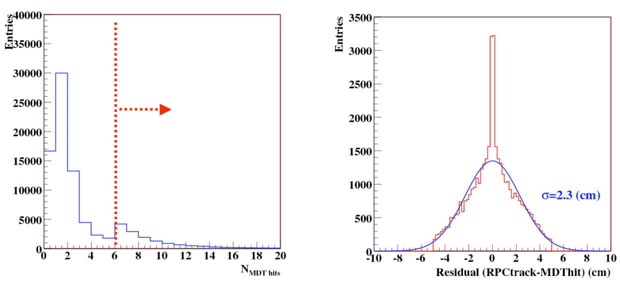

Fig. 9. MC Simulated cosmic events. Left: MDT multiplicities *per* track. Red line separated the fake tracks from "good" ones. Right: Residual RPCtrack-MDTtrack compatible with RPC spatial resolution.

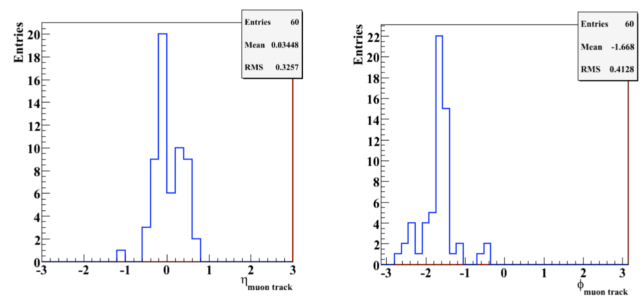

Fig. 11. Real cosmic events. Pseudorapidity (left) and azimuthal (right) position of Level-2 reconstructed candidates.

whole trigger chain. Only events from a portion of the MS, the one closest to the bottom[6], have been collected and analyzed.

The trigger algorithms in the muon slice are mostly designed to work for proton-proton collision events while having poor efficiencies for comics data.

Installation and commissioning of various detectors will be performed also with cosmic muon data analysis. Therefore, the LVL1 and HLT must provide a way to trigger cosmic events with various detector configurations. The Level-1 configuration chosen is the one with the coincidence windows fully opened (the *cosmics* configuration). A specific Level-2 MS *standalone* algorithm has been designed to be efficient on tracks not pointing to the nominal interaction vertex. RPC hits are selected and reconstructed to form RPC tracks. The algorithm runs from Level-1 RoI candidated or performing a full RPC scan. MDT hits are selected from roads build around RPC tracks, and reconstructed in segments. MDT segments are then combined in MDT tracks. Combination with ID tracks is envisaged.

Events from cosmic runs have been simulated and used to test the performances of the *cosmic* configurations. The multiplicity of MDT hits per track and the residuals between the RPC track and MDT track are shown in Fig.9.

Although the whole HLT farms have not been installed yet a working sub-system has been implemented for some recent integrated cosmic runs (February 2007)[7] including the Level-2 Supsersivor (L2SV), some Level-2 processing units (L2PU)

[6] *a.k.a.* Sector 13.

[7] For this *cosmic* run, MDT were not integrated.

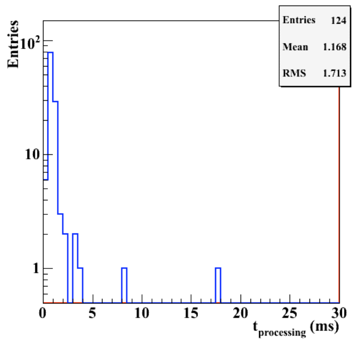

Fig. 12. Real cosmic events. Level-2 processing time per event (in ms).

and a common event builder in the SubFarm Input (SFI). These elements are shown in Fig.10.

The azimuthal and pseudorapidity distribution of the Level-2 reconstructed candidates are shown in Fig.11.

Level-2 processing times for the *online* cosmic integration runs are shown in Fig.12 showing a latency time well below the allowed latency time of 10 ms.

V. Conclusions

The ATLAS muon trigger slice seems to match the stringent requirements from LHC collisions in terms of efficiencies, background rejection and processing time. We are deploying and commissioning our systems and are developing the strategies for the LHC start-up.

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