

The RPC Level-1 Muon Trigger of the ATLAS Experiment at the LHC

A. Aloisio, G. Carlino, F. Conventi, V. Izzo, A. Migliaccio
University of Naples Federico II and I.N.F.N. Naples, Italy

V. Bocci, A. Di Mattia, L. Luminari, A. Nisati, F. Pastore, E. Petrolo, R. Vari, S. Veneziano
I.N.F.N. Rome, Italy

A. Salamon
University of Rome Tor Vergata and I.N.F.N. Rome2, Italy

Abstract—The initial interactions rate foreseen at LHC at the designed luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ is 1 GHz. Such an extremely large rate must be reduced by the trigger system to 200 Hz in order to allow permanent data storage preserving the much less probable physics signals against a large background.

The ATLAS Level-1 muon trigger will be crucial for the online selection of events with high transverse momentum muons and for its correct association to the bunch-crossing of interest. The overall rejection factor is 10^4 .

The muon trigger in the barrel region is provided by three layers of Resistive Plate Chambers (RPC). The logic is based on the search of patterns of hits in the RPC stations consistent with a muon track originated from the interaction vertex. Two p_T regimes with different programmable thresholds have been implemented: 3 low- p_T trigger thresholds and 3 high- p_T one. The associated trigger electronics is based on a custom chip, the Coincidence Matrix (CM), that performs space coincidences and time gates providing also the readout of the RPCs. A package with very detailed simulation of the algorithm and the logic of the hardware components has been developed in order to optimize the performances of the system. Trigger performances and rates calculation has been evaluated for muons over a wide range of p_T and will be presented along with studies on the impact of accidental triggers due to low energy background particles in the experimental area.

I. INTRODUCTION

ATLAS is one of the four apparatus presently under construction at the Cern Large Hadron Collider (LHC). LHC is a $\sqrt{s}=14$ TeV proton-proton collider with a designed luminosity that, starting from an initial value of $\sim 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ during the year 2007, will reach the value of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in 2010. Protons beams will collide every 25 ns and 23 interactions per crossing are expected at the designed luminosity.

The detector design is optimized to fulfill the wide LHC physics program (discovery of the Higgs boson(s), new physics and precision measurements). Starting from the interaction vertex towards the outside the main subdetector blocks are the central inner tracker, the Liquid Argon electromagnetic calorimeter, the hadronic calorimeter and the Muon Spectrometer. The magnet system is based on an inner thin superconducting solenoid surrounding the inner detector cavity and a large superconducting air-core toroids outside the calorimeters.

The ATLAS [1] trigger system is based on three levels of online physics selection aiming at reducing the foreseen initial

interaction rate from 1 GHz to 200 Hz in order to allow permanent data storage. The overall rejection factor of 10^7 must be obtained retaining very high efficiency for the rare physics processes of interest, such as Higgs boson decays.

The whole trigger system is splitted in two subsystems: the Level-1 trigger [2], a hardware system based on dedicated electronics accessing only a subset of data coming from the calorimeters and muon detectors, and the High-Level Trigger (Level-2 trigger and Event Filter) [3], a software system accessing data coming from all the ATLAS subdetectors. The large number of detector channels leads to a mean event size of ~ 1.5 MB thus providing a very challenging networking task for the Trigger/DAQ system.

II. THE LEVEL-1 TRIGGER

The Level-1 trigger selects events with experimental signature compatible with the presence of interesting physical objects like either high p_T muons identified by the muon trigger chambers or high p_T electrons and photons identified by the calorimeter trigger. Information coming from muon and calorimeter trigger processors are sent to the Central Trigger Processor (CTP) that makes the final Level-1 Accept decision (L1A) on the basis of lists of selection criteria, implemented as a trigger menu.

The level-1 trigger uniquely identifies the bunch crossing of interest and also provides information on the position and p_T range of candidate objects (Region of Interest mechanism). These data are sent to the Level-2 trigger which accesses only to the data in the Region of Interest (RoI) (usually a few per cent of the whole event data). After the Level-1 the 1 GHz initial rate must be reduced to 75 KHz with a maximum latency time of 2.5 μs . A schematic overview of the ATLAS Level-1 trigger is shown in fig. 1.

III. THE LEVEL-1 MUON TRIGGER IN THE CENTRAL REGION OF ATLAS

The Level-1 muon trigger in the barrel region of the ATLAS Muon Spectrometer is based on the use of Resistive Plate Chambers as trigger detectors.

RPC are gaseous detector with time resolution of ~ 1.5 ns and high efficiency ($\sim 98\%$). An ATLAS RPC chamber

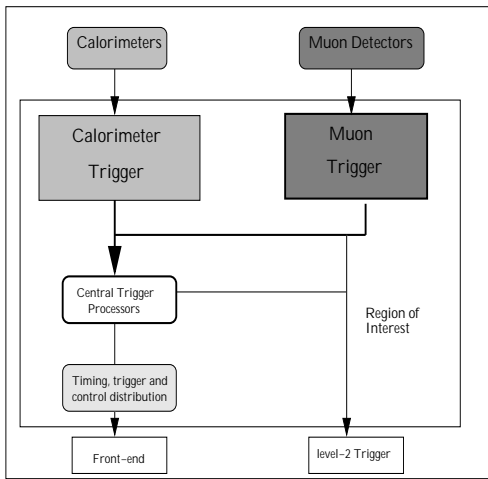


Fig. 1. Overview of the ATLAS level-1 trigger.

is composed of units with two gas volume each one defined by two bakelite plates ($\rho \sim 10^{10} \Omega \text{ cm}$) which are separated by a grid of 2 mm thickness polycarbonate spacers. The gas mixture is composed of $\text{C}_2\text{H}_2\text{F}_4$ (94.7%), iso- C_4H_{10} (5%) and SF_6 (0.3%) used as streamer suppressor. The rate capability foreseen is 100 Hz/cm^2 . The internal surface of the resistive plates are varnished with linseed oil and the external surfaces are coated with a thin layer of graphite paint connected to the high voltage system. Each gas volume is equipped with two orthogonal layers of readout strips allowing the measurement of the coordinate in the bending plane (η strips) and in the azimuthal plane (ϕ strips), the latter case being required also for the offline pattern recognition since the precision chambers (Monitored Drift Tube) only provide measurements in the bending plane. This way each RPC unit allow two η and two ϕ coordinate measurements.

The total area covered by the RPC trigger system is 3650 m^2 . The produced chambers undergo strict quality control tests and are finally checked in cosmic ray stands. The cosmic ray tests ensure the uniformity of the detection efficiencies and the timing characteristics of each detector [5]. The LHC detectors have to survive for at least 10 years in the very high-radiation background environment of the experimental hall. As part of the production QA process each RPC detector is irradiated at the X5 Irradiation Facility at CERN [6].

The barrel region of the muon spectrometer is composed of two independent subsystem (half barrel). The first located in the region $z < 0$ and the second in the region $z > 0$. Tracks are measured in chambers arranged in three cylindrical stations around the beam axis (fig. 2). Precision measurement of the track coordinates in the principal bending direction of the magnetic field is provided by Monitored Drift Tubes (MDTs).

The RPC chambers arranged in projective towers form three cylinders concentric ('layers') with the beam axis. Two RPC layers (RPC1 and RPC2) are located in the second stations of the muon spectrometer while the third RPC layer (RPC3) is located in the outer station.

RPC layers have a 16-fold segmentation in the azimuthal plane that follows the eightfold symmetry of the magnetic structure (fig. 2). This layout symmetry is partially broken by the presence of detector services. In particular magnetic support structure (magnet feet) and ribs cause a loss of coverage in some regions of the central muon spectrometer. Each RPC station is formed by six or seven RPC chambers, depending from the station type.

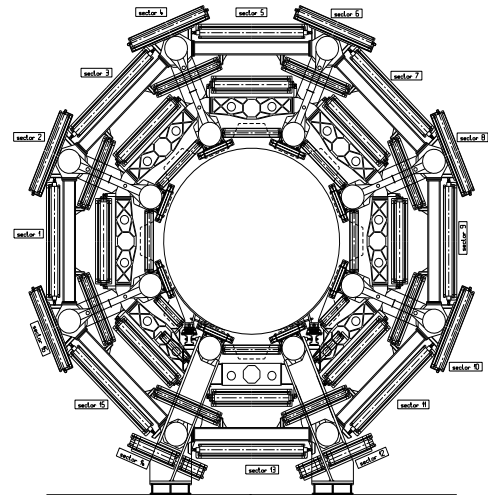


Fig. 2. ATLAS barrel muon spectrometer view in the azimuthal plane. Three concentric RPC stations are located in the middle and in the outer stations of the Muon Spectrometer.

A. Trigger algorithm

The basic principle of the level-1 algorithm is the selection of events with muons having a large p_T coming from the interaction vertex. The algorithm works in the following way: If a hit is found on the second RPC layer (RPC2, pivot plane) a search for hits is made on the other layers (RPC1 and/or RPC3) within a geometrical road (Coincidence windows) whose centre is defined by the line of conjunction of the hit in the RPC2 and the interaction vertex (see fig. 3). Muon tracks are deflected under the action of the toroidal magnetic field thus the track distance from the centre of the Coincidence windows is mainly a function of the p_T . The higher is the p_T the smaller is the distance. This way the algorithm selects only muons with a p_T greater than a certain value.

The ATLAS physics benchmark [4] has suggested two threshold regimes for muon triggers:

- Low- p_T trigger: it analyzes data coming only from the first two RPC stations (RPC1 and RPC2). In particular this regime maximizes the B-physics trigger capabilities in the context of a possibly reduced initial Trigger and Data Acquisition (DAQ) system [7].
- High- p_T trigger: it operates only in presence of a low- p_T trigger requiring the spatial coincidence with the RPC3 station. This regime is specialized for heavy objects searches.

Although the algorithm is more selective in the bending plane the same selection scheme is also applied in the azimuthal

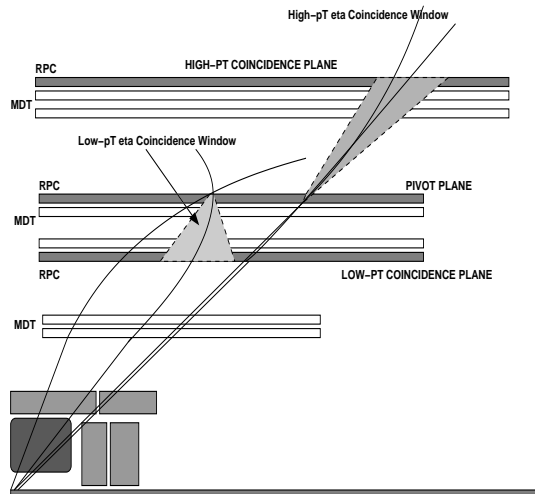


Fig. 3. Schematic view of the trigger algorithm in the bending plane.

plane to reduce accidental coincidences. Moreover to cope with background from low-energy particles in the experimental hall [8], a 3/4 or 4/4 majority coincidence of the four possible hits in the first two RPC doublets has to be required (low- p_T trigger) and 1/2 or 2/2 of the hits in the outer RPC station (high- p_T trigger). Only when trigger conditions are satisfied for both views, a valid trigger signal is generated.

IV. SYSTEM DESCRIPTION

A. On-detector electronics

RPC signals are amplified, discriminated and digitally shaped by the Front-End electronics [9], before being processed by the real core of the trigger system: the Coincidence Matrix ASIC (CMA) chips [10].

Almost all the relevant trigger functionalities (coincidence and majority operations, as well as thresholds cuts, pipelined delays, clusterizing of hits, derandomizing buffering) and RPC readout are altogether performed inside this chip.

The ASIC operates with the LHC machine 40 MHz clock, and its internal logic works at 320 MHz. Inputs from the RPC stations are called I0 and I1, 32 strips each, coming from the RPC2 pivot plane for the low- p_T trigger or from the low- p_T trigger pattern output for the high p_T trigger, and J0 and J1, 64 strip each, coming from RPC1 or RPC3.

The system is designed so that three p_T thresholds in each projection can be performed in parallel. The coincidence matrix contains thus $3 \times 32 \times 64$ cells. The trigger output of the coincidence blocks is a hit pattern containing hits which generated the valid trigger, the highest threshold value, two bits indicating overlap conditions (to reduce the fake double-muon trigger rate due to a single track crossing two overlapping trigger chambers) and the three lower bits of the Bunch Crossing counter. The trigger pattern is sent to the latency memory for readout and to the trigger output to the rest of the trigger pipeline logic.

Information from two adjacent CMAs in the η projection and two in the ϕ projection are combined inside the same

box called PAD. Up to 8 PAD boxes are foreseen in a trigger sector. In particular inside the PAD box the Region of Interest (RoI) logic is performed. The associated RoI is defined as the overlap of the η and ϕ activated CMAs and has a 0.1×0.1 width in the $\eta - \phi$ plane.

A low- p_T PAD processor, containing a low- p_T PAD motherboard and four low- p_T CMAs, is mounted on top of the central RPC station (RPC2) and transmits its outputs to the corresponding high- p_T PAD, mounted on top of the outer station (RPC3), which collects both low and high p_T trigger results and sends them to the off-detector system (see fig. 4). The configuration of the coincidence windows requires that signals coming from confirmation stations (RPC1 and RPC3) could be sent to different CMAs. Dedicated Splitter boxes are then used to fan out these signals. Splitter boxes contain power distributions, devices for temperature and voltage monitoring. In ATLAS 832 PAD boxes and an equal number of Splitter boxes will be installed.

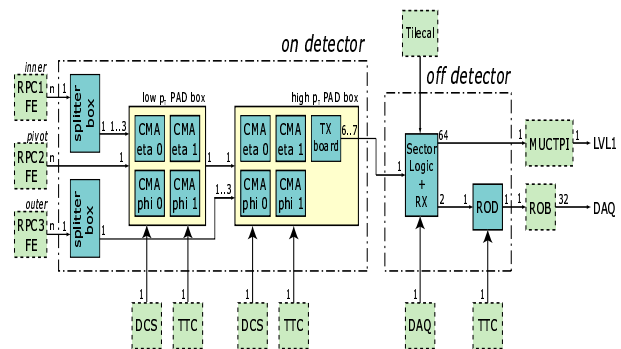


Fig. 4. Trigger slice layout, showing different on- and off-detector devices

B. Off-detector electronics

Trigger and readout information are sent to the off-detector electronics via optical links transmitter, synchronously at 40 MHz.

Data coming from up to eight high- p_T PAD belonging to the same ATLAS trigger sector are collected by a Sector Logic board located in the USA15 counting room. 64 Sector Logic boards are foreseen in the level-1 barrel muon trigger. Each Sector Logic board selects two candidate muons those with the highest thresholds and associates a Region of Interest and a unique bunch crossing number to each one. Moreover Sector Logic boards perform other various functions (timing, check for energy deposit in calorimeter, overlap flag) all fully programmable [11].

The output of the Sector Logic board is sent to the Muon to Central Trigger Processor Interface (MUCTPI). The MUCTPI elaborates the data from the Sector Logic boards (solve ambiguity in the azimuthal plane, selects up to 7 muon candidates/event) and sends its output to the Central Trigger Processor (CTP). The ATLAS Level-1 Central Trigger Processor (CTP) [12] combines information from the Level-1 calorimeter and muon trigger processors, as well as from

other sources such as calibration triggers, and makes the final Level-1 Accept decision. The algorithm used by the CTP to combine the different inputs allows events to be selected on the basis of trigger menus.

C. Trigger performances at Test Beams

During the year 2004 two one-week periods with a 25 ns bunch structured muon beam at the CERN H8 test area have been used to test the whole trigger chain (from the front-end to the CTP).

The experimental setup reproduces a piece of a standard ATLAS trigger sector with two RPC chambers, containing inner and middle low- p_T units, and other two RPC chambers, containing the outer high- p_T layer. This way trigger performances and synchronizations could be studied. The Region of Interest information was correctly transmitted along the slice, and checked at the CTP output. The Muon Barrel system showed a 99.5 % efficiency in identifying the correct Bunch Crossing (BC). This ensured that the BC identification capability is not significantly degraded along the trigger data path.

The key parameter of the level-1 trigger system is the trigger latency, the time delay imposed to the front-end electronics before sending the readout data. It's fixed by the required trigger processing time plus the time propagation along the cabling system. The maximum acceptable value in ATLAS is 2 μ s. Test beam data have been used to extrapolate ATLAS trigger latency for the Barrel Muon system at the input of the MUCTPI. Level-1 latency results in ~ 1024 ns with an uncertainty of 15 ns, equal to ~ 41 BCs.

V. SIMULATION

In order to optimize the Level-1 trigger logic design and to understand his performances a C++ package has been developed. Moreover the simulation package is essential to:

- Define the connectivity of the RPC detectors to the trigger processors;
- Define the best trigger processor configuration for the cosmics run and the initial data taking phase;
- Provide the trigger detector data decoding;
- Provide the software for the detector and trigger processor timing calibration;

The widths of the Coincidence Windows inside each Coincidence Matrix have been defined using an automatic procedure [14] (~ 10000 foreseen Coincidence Matrix). For each trigger threshold, the width is defined as the one for which at least 90% of muons of both charges having p_T equal to the threshold are within the geometrical road.

A large sample (10^6) of single muon over a wide p_T range ($3 \div 50$ GeV) has been tracked in the simulated ATLAS detector, processed using the Level-1 simulation code and applying the predefined Coincidence Windows.

The barrel regions not covered by RPC detectors (magnet ribs and support structure, elevator hole and central crack)

restrict the system geometrical acceptance. The overall acceptance is 82% for low- p_T trigger and 78% for high- p_T trigger.

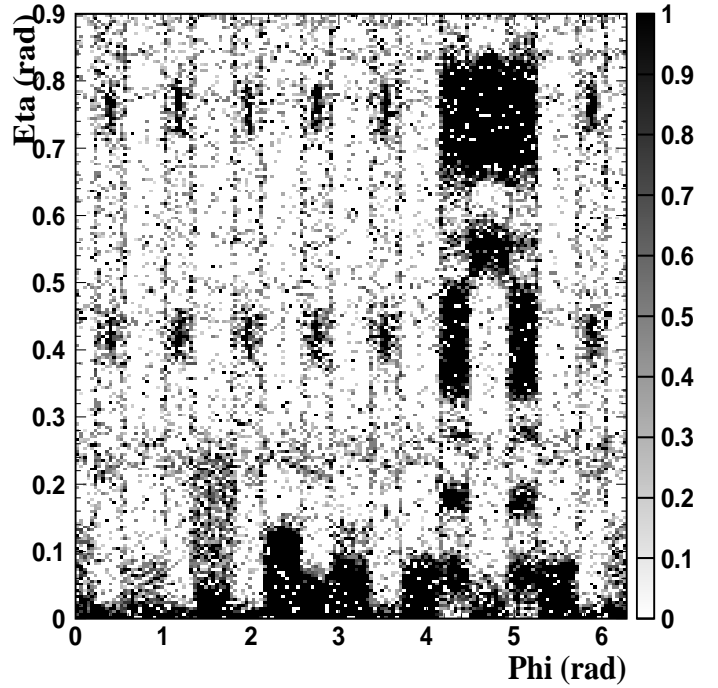


Fig. 5. Level-1 geometrical acceptance in the η vs ϕ plane (low- p_T).

Detailed map of inefficiency regions is shown in fig 5.

The two biggest inefficiency regions correspond to magnet support structure (feet sectors) and muon spectrometer central crack ($\eta \sim 0$). The contribution to the geometrical acceptance due to the presence of the *feet sectors* is $\sim 5\%$. Moreover smaller inefficiency patterns are clearly visible and are due to magnet ribs in small trigger sectors.

The efficiency curves as a function of the muons p_T have been determined both for the low- p_T and the high- p_T system for the standard configuration (Low- p_T threshold=6, 8, 10 GeV/c; High- p_T threshold=20, 40 GeV/c; 3/4 majority logic) and are shown in fig. 6 and fig. 7. The plateau value corresponds to the system geometrical acceptance. A fit to the efficiency curves has been applied using the function:

$$Eff = \frac{A}{1 + e^{\beta(p_T - p_T^0)}} \quad (1)$$

Fit results have been used to calculate threshold sharpness (Δp_T from 10 to 90% of efficiency). For standard thresholds (6 and 20 GeV/c) we obtained 1.4 GeV/c and 5.4 GeV/c respectively.

Trigger rates have been calculated by the convolution of the inclusive muon cross sections for the main decay mode that give rise to muons in the detector with the trigger efficiency curves. The inclusive muon cross-sections at LHC for the decays of b and c hadrons, top quark and W/Z boson decays have been calculated using the MonteCarlo program Pythia

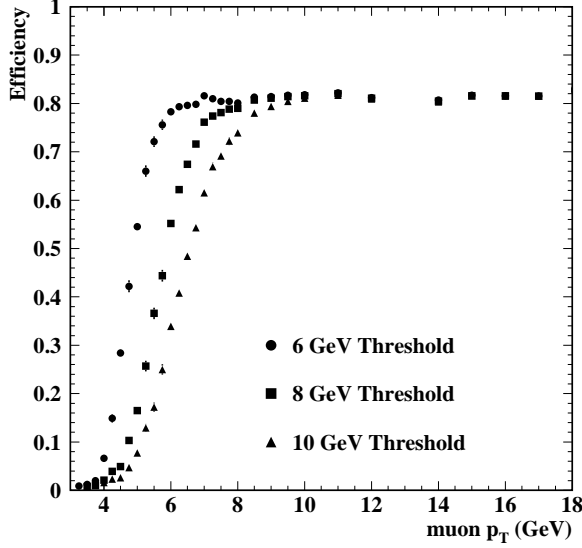


Fig. 6. Level-1 Muon Trigger Efficiency curves for low- p_T system.

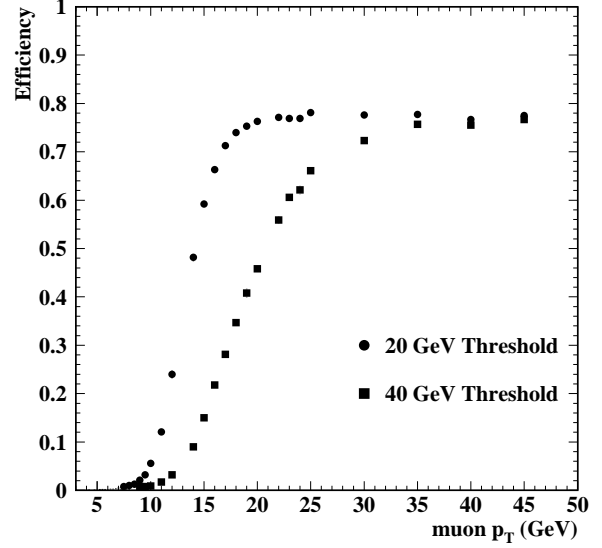


Fig. 7. Level-1 Muon Trigger Efficiency curves for high- p_T system.

5.7 [15] while the in-flight decays of π/K mesons have been calculated using the DPMJET MonteCarlo program [16].

The inclusive muons production cross sections, integrated in the kinematic region ($|\eta| < 2.7$, $p_T > 3$ GeV), as a function of p_T are shown in fig. 8.

μ sources	Low- p_T (Hz)	High- p_T (Hz)
π/K	7100	680
b	1400	500
c	800	210
W	3	26
t	~ 0	~ 0
Total	~ 9300	~ 1400

TABLE I

TRIGGER RATES FOR DIFFERENT MUON SOURCES AT LHC

At lower p_T (3-6 GeV/c) the π/K decays are the dominant source of muons with a production cross section that grows exponentially when p_T approaches to zero. Therefore, although low- p_T trigger efficiencies are very small in this p_T range the overall effect is to produce a very large increase of the trigger rates. A dedicated study has shown that the effect of the π/k decay kink is negligible with respect to other experimental effects, as the multiple scattering, therefore the selection efficiency for muons coming from π/K decay is quite the same of the one for prompt muons.

For $p_T > 10$ GeV the cross sections are dominated by the semileptonic decays of b and c hadrons which represent major sources for the high- p_T trigger rates. The estimated rates are shown in table I for the standard low- p_T (6 GeV/c, $\mathcal{L}=10^{33}$ cm $^{-2}$ s $^{-1}$) and high- p_T (20 GeV/c, $\mathcal{L}=10^{34}$ cm $^{-2}$ s $^{-1}$) thresholds. Uncertainties on trigger rates arise from several sources. The most important are significant uncertainties in

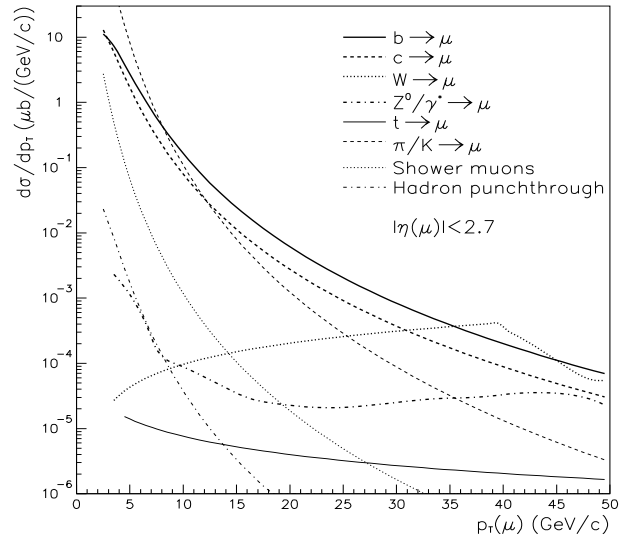


Fig. 8. Inclusive muon cross section as a function of p_T .

the prompt-muon cross sections estimated by Pythia mainly in the lower p_T range ($p_T < 6$ GeV) and uncertainties in the modelled muon rate from π/K decays. Other minor sources such as statistical uncertainties on the trigger efficiency curves and convolution numerical method are well understood and the effect on the final trigger rate is low.

The high background level expected in the ATLAS experimental hall can contribute to the muon trigger rate by accidental coincidences of hits produced by background particles in the trigger chambers. This background originates from the interaction of hadrons produced in primary collisions with very forward ATLAS detectors and machine element. The result are mainly neutrons that diffuse throughout the

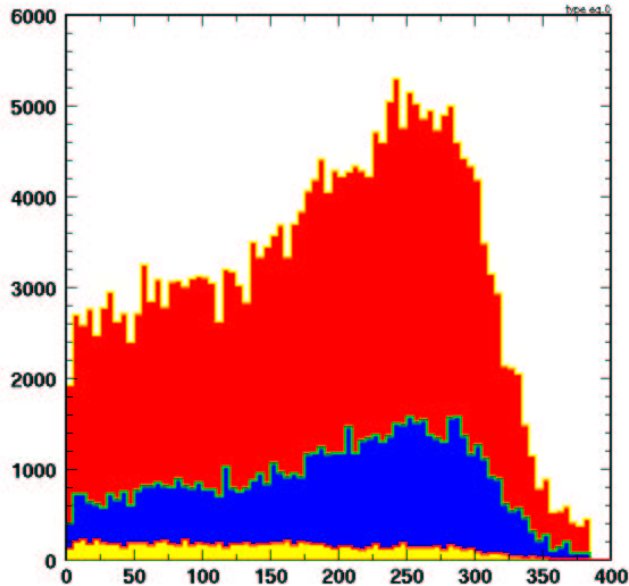


Fig. 9. RPC activity with respect to the η coordinate for different background levels (no background, nominal and boosted by a factor 5).

the experimental hall producing secondary particles when interacting with matter. This background behaves as a particle gas with no time correlation with the bunch crossing.

In order to evaluate the impact of the fake muon trigger rate on the level-1 trigger performances a sample of simulated single muons with a p_T in the range between 3 and 50 GeV/c merged with RPC hits coming from background activity has been used. The background particles induces high trigger detectors counting rates as shown in fig. 9.

Level-1 efficiency curves have been calculated for standard configuration (3/4 majority logic) both for low- p_T and high- p_T system assuming the nominal background level boosted by a factor 2. Results are shown in fig. 10. The muon trigger system appears robust against the accidental coincidences even for a background level higher than that is expected from detailed MonteCarlo simulation programs.

VI. CONCLUSIONS

Resistive Plate Chambers will be used in the ATLAS detector as dedicated trigger detectors in the central region of the ATLAS Muon Spectrometer. Level-1 muon trigger system is designed to perform a coarse tracking and a fast selection of the candidates muon events using RPC data. Moreover the system identifies the corresponding bunch crossing of interest and provides information on the geometrical position of candidate muon objects (Region of Interest mechanism) to Level-2 Trigger. Trigger logic is performed by a set of dedicated programmable electronics. A brief description of the whole Level-1 RPC muon trigger slice with preliminary test beam results on the functionality of the full trigger chain

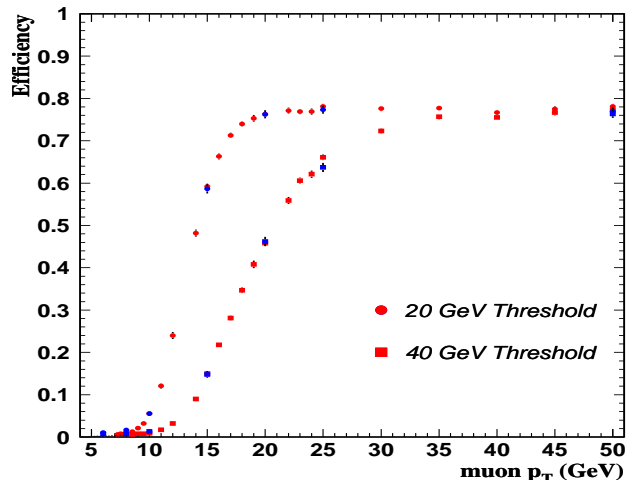


Fig. 10. Level-1 Muon Trigger Efficiency curves for high- p_T threshold for simulated single muon events (red) and events merged with background hits (blue).

has been given. Detailed simulation studies are required both to understand system performances and to define the best trigger processor configuration. Results on trigger simulation concerning system performances (Efficiency curves, trigger rates and cavern background effects) are also given.

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