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The Muon Trigger in ATLAS

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The trigger system of the ATLAS experiment at LHC must reduce the interaction rate of ∼1GHz to the ∼200 Hz of the event acquisition rate. The system is organized in three hierarchical levels. The first trigger level (LVL1) is hardware based, while Level-2 (LVL2) and Event Filter (EF) compose the High Level Trigger (HLT), software based, which will run on the on-line trigger farms. In this paper we describe the implementation of the muon trigger system and its performance, evaluated on Monte Carlo simulations, in terms of signal efficiency and resolutions.

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1. The ATLAS experiment at LHC and the trigger requirements

ATLAS (A Toroidal LHC ApparatuS) is a general-purpose experiment at LHC (Large Hadron Collider), the new accelerator facility under costruction at CERN, the European Laboratory for Particle Physics in Geneva, Switzerland. LHC is an hadron collider, consisting of two accelerating rings crossing each other in the interaction points where the experiments are located. It will allow to reach in the p-p collisions the center of mass energy of 14 TeV, never accessed before.
At the design istantaneous luminosity, L=10^{34} cm^{-2} s^{-1}, in average 23 inelastic proton-proton collisions per bunch crossing will take place. Since the bunch crossing frequency is 40 MHz, the expected event rate is $\sim$1 GHz. On the other hand, the acquisition rate is limited by the maximum affordable data throughput rate, that is 300 MByte/s. In ATLAS, the mean event size is $\sim$1.5 MByte, entailing a maximum allowed acquisition rate of $\sim$200 Hz. Moreover, the cross sections of the interesting processes at LHC are very rare compared to the total inelastic p-p cross section (fig. 1). As an example, the leptonic W decay (an interesting process for precise Electro-Weak

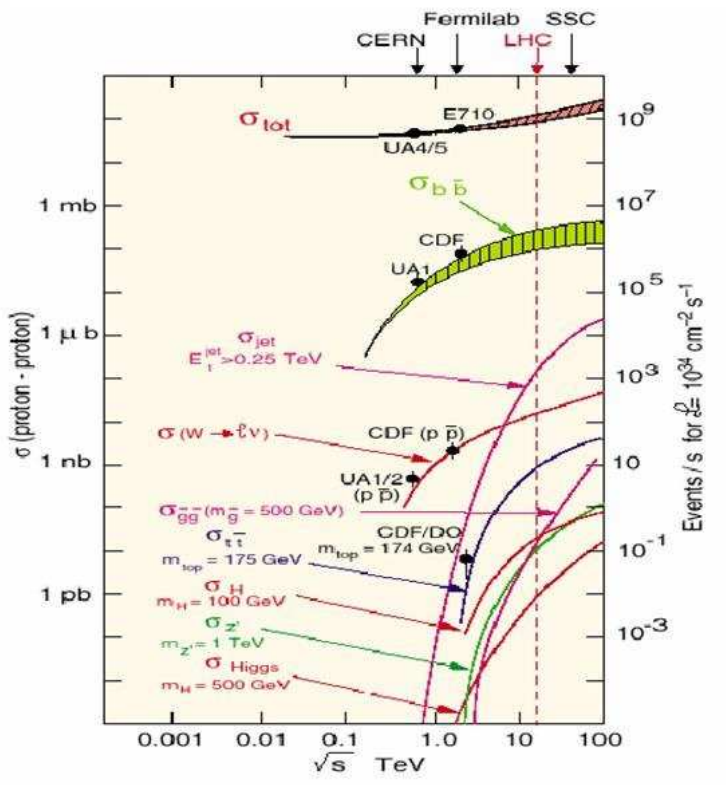

Figure 1: Production cross section as a function of center of mass energy

measurements and for detector calibrations) is $\sim 10^{-6}$ w.r.t. σ_{tot}, and the Higgs Boson production (for $m_H = 100$GeV) is expected to be $\sim 10^{-9}$. Such environment requires a *trigger system with high selection efficiency*.
The ATLAS detector is designed to observe a wide range of physics processes, involving the Physics of the Standard Model and beyond. In particular, the detector is optimized for the Higgs

search, the Super Symmetry discovery and to observe signals from any exotic scenario of new Physics at the TeV scale (Extra Dimensions, new heavy bosons, etc.). The detector is currently under commissioning and will be ready to observe the first LHC collisions expected for the next year (2008). It consists of different subsystems and technologies (fig. 2):

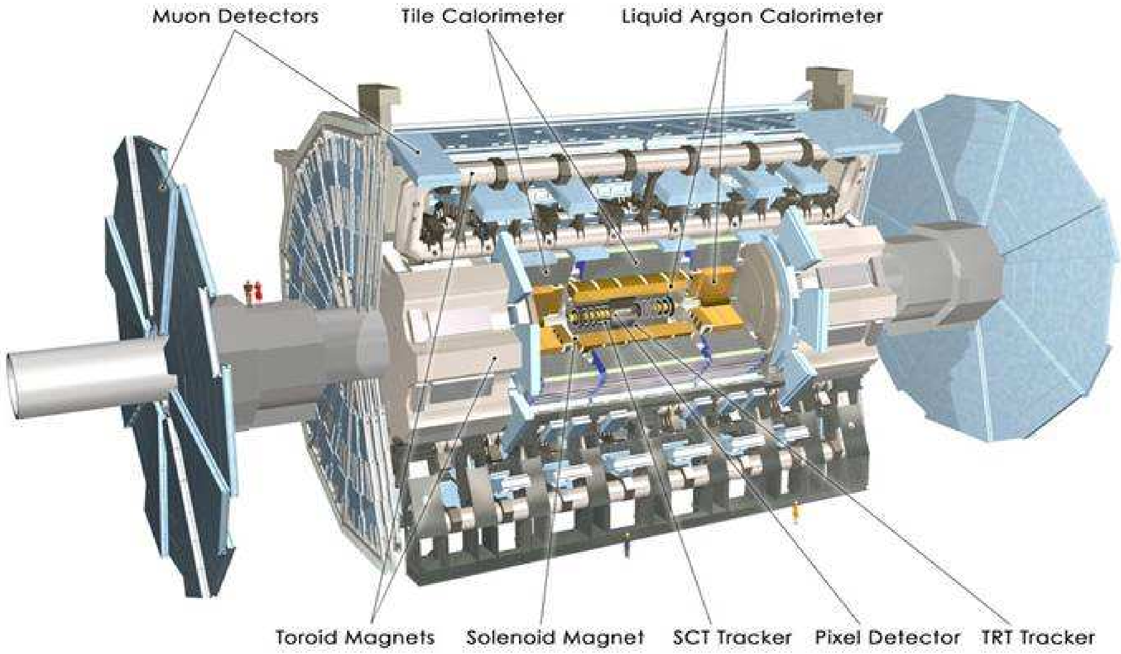

Figure 2: The ATLAS experiment

- the *Inner Detector* (ID), that measures the tracks of charged particle and performs particle identification and is composed by Silicon detectors (3 layers of pixels in the barrel and 4 endcap wheels up to $|\eta| < 3$, 4 layers of microstrips in the barrel and 9 disks in the endcaps up to $|\eta| < 2.7$), and a Transition Radiation Tracker up to $|\eta| < 2.7$. A thin solenoidal superconducting magnet provides high bending power ($2T$) and low amount of matter in front of the calorimeters;
- the *Electromagnetic Calorimeter* ($|\eta| < 4.9$), a sampling calorimeter made of Pb-liquid Argon (at the temperature of 80 K), which provides an Energy resolution of $\sim 10\%/\sqrt{E}$;
- the *Hadronic Calorimeter* ($|\eta| < 4.9$), consisting of scintillation tiles interleaved to copper slabs in the barrel (up to $|\eta| < 1.7$) and using the copper-liquid Ar technology in the forward region;
- the *Muon Spectrometer* (MS), composed by trigger chambers (Resistive Plate Counters, Thin Gap Chambers), precision chambers (Monitored Drift Tubes and Cathode Strip Chambers) with high resolution on the sagitta measurement ($\sim$50 μm) and a toroidal magnetic field in air that bends charged particles in the $R-z$ plane.
  The MS and ID performance is crucial for the Muon Trigger System.

2. The ATLAS Trigger

The ATLAS Trigger System is structured in three levels (fig. 3): each level refines the hypothesis formed at the previous one. The Level-1 (LVL1) is implemented in custom programmable

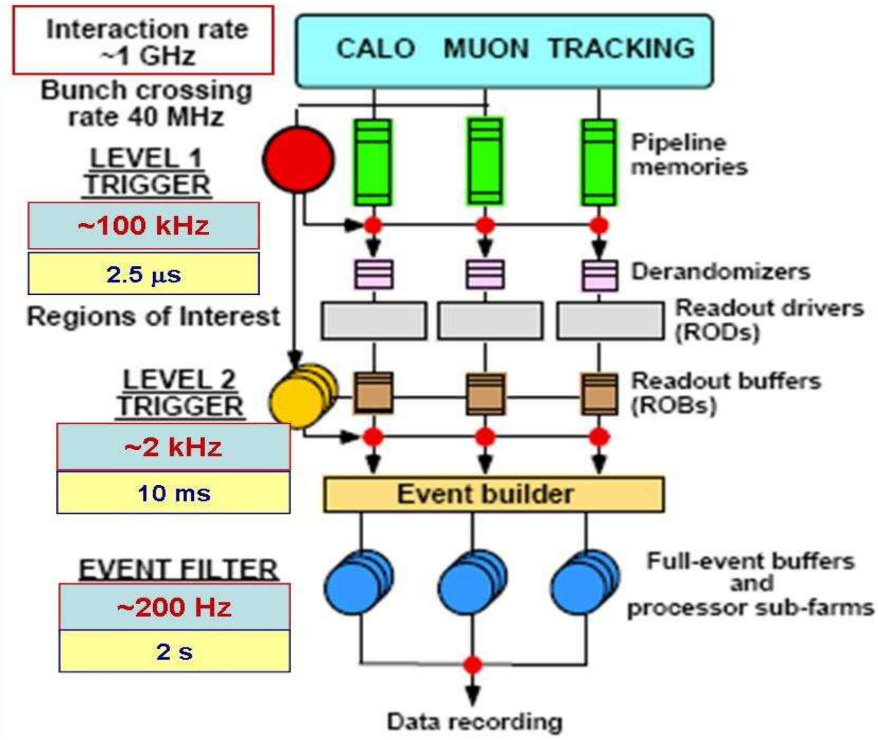

Figure 3: The ATLAS Trigger architecture

electronics, directly connected to the front-end of calorimeters and muon detectors. It uses coarse granularity data from trigger chambers and has to reduce the event rate from 1 GHz to 100 kHz (which corresponds to the input bandwidth of the LVL2 system) within a latency of 2.5 μs. At this stage Regions Of Interest (ROIs) are defined, i.e. regions of the detector where significant activity is present. Only data fragments from the ROIs are passed to the Level-2 (LVL2), thus reducing drastically the processing time.

The second (LVL2) and third (EF) trigger levels are implemented via sequences of algorithms running on dedicated computing farms. They are usually referred as High Level Trigger. At LVL2 full granularity data, inside the ROI identified at the previous level, are available. The LVL2 selection reduces the event rate from 100 kHz to 2 kHz, with a latency time of 10 ms. The last Trigger Level is the *Event Filter* (EF),accessing the entire detector data. The total latency of the EF is $\sim$2s and sofisticated algorithms are executed in order to refine the selection and reduce the data throughput to 200 Hz. The EF algorithms can be seeded by LVL2 (or LVL1 ROIs) or they can run over all event data.

3. The Muon Trigger

High p_T muons are important signatures of many processes predicted in various new physics scenarios. Moreover they allow to select SM processes which are usually exploited for calibration and commissioning of the esperiment for physics: W and Z bosons production, but also J/ψ resonances. Therefore, the muon trigger performance has a strong impact on the physics reach of the experiment. For muon identification and reconstruction ATLAS uses a toroidal magnetic field in air. As a consequence, the MS standalone reconstruction benefits of the low multiple scattering thus reaching an high resolution on the track parameters ($\sim$10 % for muons of p_T = 1 TeV in a large η interval) and the possibility to trigger muons of transverse momentum as low as 6 GeV/c.
Currently the Muon Spectrometer is under commissioning with cosmic rays. The LVL1 muon trigger is succesfully running in a special configuration in order to allow the selection of muon tracks non pointing to the detector center. In addition, several technical runs have been performed by running the full HLT chain on the final online processors with the aim of commissioning the HLT selection algorithms on the real online platforms.
The results reported in this work summarize the muon trigger performance as estimated by the software emulation of the LVL1 and HLT algorithms with simulated data in offline-like computing environments. The Muon Trigger architecture is sketched in fig. 4.
The LVL1 emulation was essential in order to define the coincidence windows and to optimize

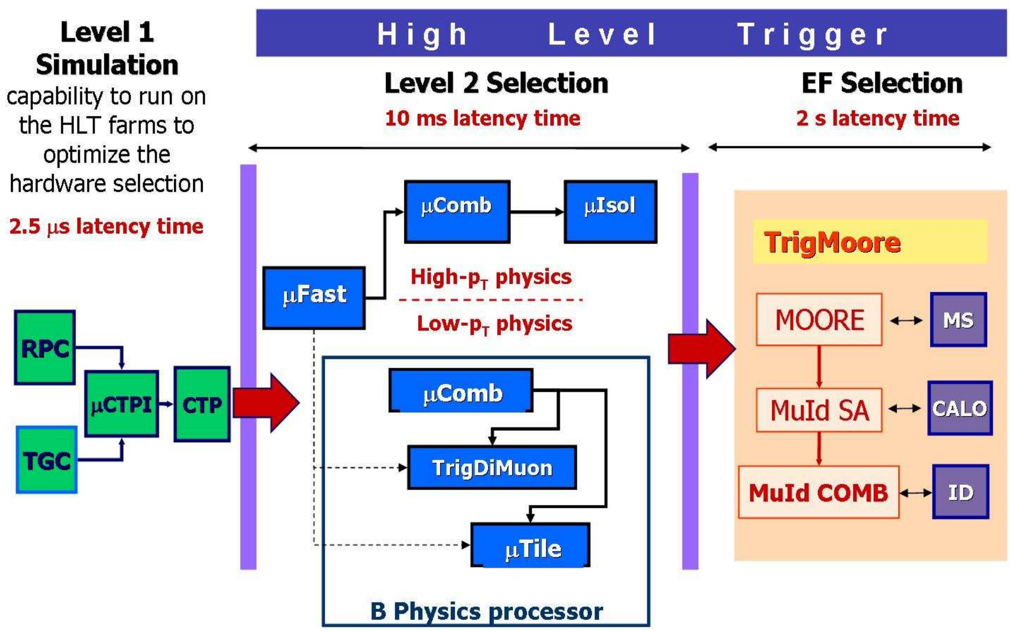

Figure 4: The ATLAS Muon Trigger architecture

the logic to be implemented in the LVL1 electronics. Nowadays it is used to assess the expected trigger efficiencies and resolution and to study non-standard trigger configurations (like cosmics or very low-p_T thresholds). The LVL2 has two different operating modes: “high p_T physics” and “B-

physics triggers". The LVL2 algorithms uses data from the Muon Spectrometer, the Inner Detector and the Calorimeters.
The Event Filter performs its selection starting from the muon recontructed in the MS, then the Calorimeters measurement is used to correct for the energy loss and propagate back to the Impact Point (IP), where a matching with a reconstructed ID track is required.
The Muon Trigger will be analized in more detail in next sections.

3.1 Level 1

The LVL1 selection is based on the definition of allowed geometrical roads, the *Coincidence Windows* (CW, see fig. 5. Given a track that hits the middle trigger station (*pivot* plane), the algorithm searches for time-correlated hits in the *confirm* plane, inside a geometrical region around the ϕ and η of the hit on the pivot plane: the size of the (η,ϕ) intervals defines the CW. There are two confirm planes: one for low p_T triggers in the inner trigger plan (at a distance of about 70 cm from the pivot plane), and another located in the outer MS station, where hits are required, in addition to a low-p_T trigger, for high p_T muons.
A track of infinite momentum originating at the IP with direction given by η and ϕ, defines the center of the CW. For each direction the window size determins a specific p_T threshold. To calculate the appropriate window size, single muons of the same p_T of the nominal threshold are simulated. Starting from the center, the window opening in η is increased until a 90% fraction of the muons is collected. Tracks of higher transverse momentum will be more straight and consequently will fall into the CW.
The LVL1 electronics is designed to hold three different thresholds for the low-p_T configuration and three for the high-p_T, for a total of six thresholds. The standard thresholds are 6, 8, 10 GeV/c and 11, 20, 40 GeV/c. They are implemented on FPGA and can be reconfigured to optimize the trigger selection for different running conditions.
Figure 6 shows the LVL1 acceptance in the barrel and endcap regions: the barrel geometrical acceptance is limited (83% for low-p_T thresholds and 79% for high-p_T thresholds) by the absence of trigger chambers in the feet and elevator regions.
The LVL1 efficiency curves are reported in figure 7: the efficiency at the plateau is determined by the acceptance and the sharpness of the curve rising is a function of the algorithm p_T resolution.
The trigger rates at LVL1 can be estimated (fig. 9) from a convolution of the inclusive differential muon cross sections ($d\sigma/dp_T$) expected at the LHC with the trigger efficiency (fig. 8). In the contest of the activities for the definition of trigger menus at the LHC startup, when luminosity as low as $10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is expected, CW for a threshold of 5 GeV/c have been studied togheter with a "very low-p_T trigger ", obtained by allowing the CW to remain "fully" open. In the latter case the algorithm acceptance is limited by the cabling of the trigger chambers and by the residual pointing requirement, which determine an effective threshold of approximately 3 GeV/c on the transverse momentum. It can be used to trigger on cosmics or in very low luminosity run conditions.

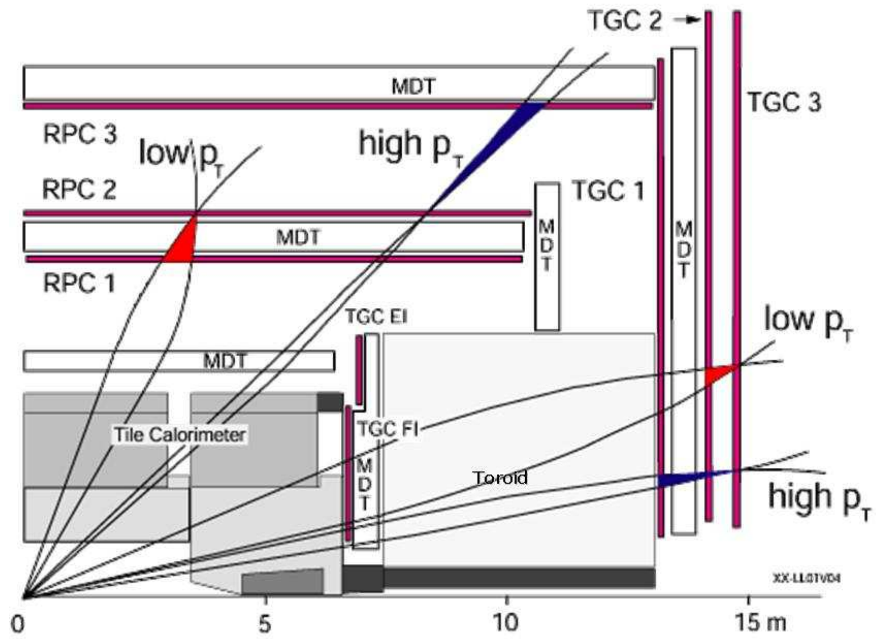

Figure 5: The "Coincidence window", the LVL1 selection logic

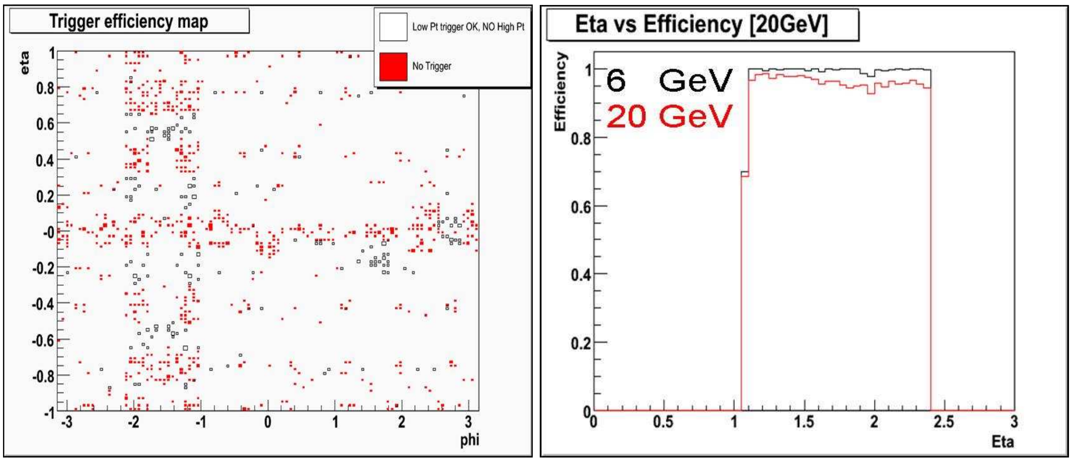

Figure 6: Left: LVL1 *barrel* acceptance, as a function of η and ϕ, obtained using simulated single muons of p_T = 100 GeV/c. The barrel geometrical acceptance is limitated by the absence of trigger chambers in the apparatus feet ($\phi = -2$ and -1.2) and elevator ($\eta = 0$). Right: LVL1 *end-cap* acceptance for the 6 GeV/c and 20 GeV/c thresholds.

3.2 High Level Trigger

The High Level Trigger (HLT) must reduce the LVL1 output up to the final expected rate for physics. Both LVL2 and EF are composed by several Feature Extraction Algorithms (FEX), that

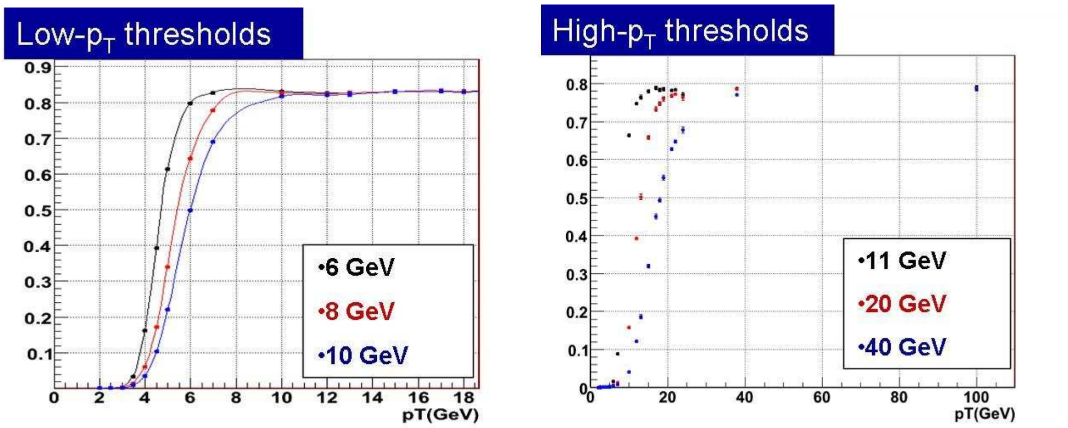

Figure 7: LVL1 turn-on curves for low and high p_T thresholds values in the barrel

calculate the physical quantities, and by Hypothesis Algorithms (HYPO) that apply cuts on these quantities. The flow of data and algorithms is managed by the HLT steering, a software component that drives the trigger decision according to sequences configured to validate the trigger items listed in the trigger menus.

3.3 Level 2

The first LVL2 algorithm, *muFast*, performs a "global pattern recognition", a "local segment reconstruction" and a "fast p_T estimate" via Look-Up-Table (LUT). The global pattern recognition in the Barrel region extrapolates the candidate tracks to the innermost MDT station, that is not instrumented with trigger chambers, and selects the MDTs in a "road" around the RPC hits. In the selected MDT stations a local linear fit is performed using MDT precision drift measurements. The track segments are then used to evaluate the radius of the muon track. The transverse muon momentum is estimated using a "Look Up Table" (LUT), whose entries are the track radius, ϕ and η at the entrance of the MS. For muons in the Endcap region the pattern recognition starts from the TGC detectors in the middle muon station. The momentum evaluation via LUT, in the Endcap, uses various reconstructed quantities to take into account the magnetic field inhomogenities.
At LVL2 it is possible to combine the MS reconstructed tracks with the informations coming from other detectors. The *muComb* algorithm combines the MS candidate with the ID tracks, using a fast procedure that doesn't involve time consuming fit. The combination increases the sharpness of the threshold at low-p_T and helps to reject muons from decays in-flight of light mesons (π, K).
The calorimetric information is used by the μ*Isol* algorithm in order to tag isolated muons and increase the robustness of the standard muon triggers. μ*Tile* is another algorithm that allows to gain some trigger efficiency for very low-p_T muons, in particular for muons that are not triggered by RPC or TGC, but produce a track segment in the innermost MS station, which can be validated by the pattern of energy depositions in the three layers of the tile calorimeter.
The LVL2 resolutions as a function of p_T for muFast and muCombare reported in fig. 10 and 11.

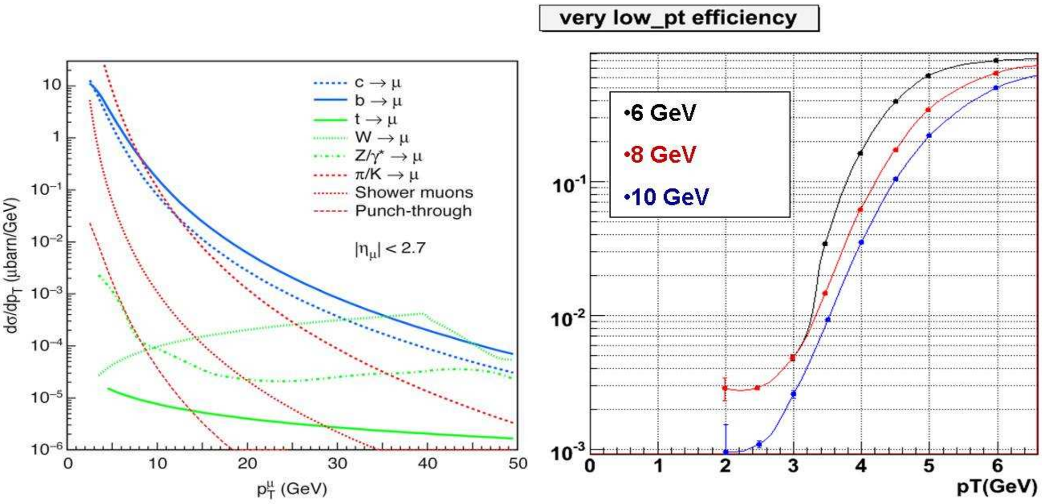

Figure 8: Left: differential cross sections for muon production at LHC; right: LVL1 turn on curves for very low p_T thresholds (barrel)

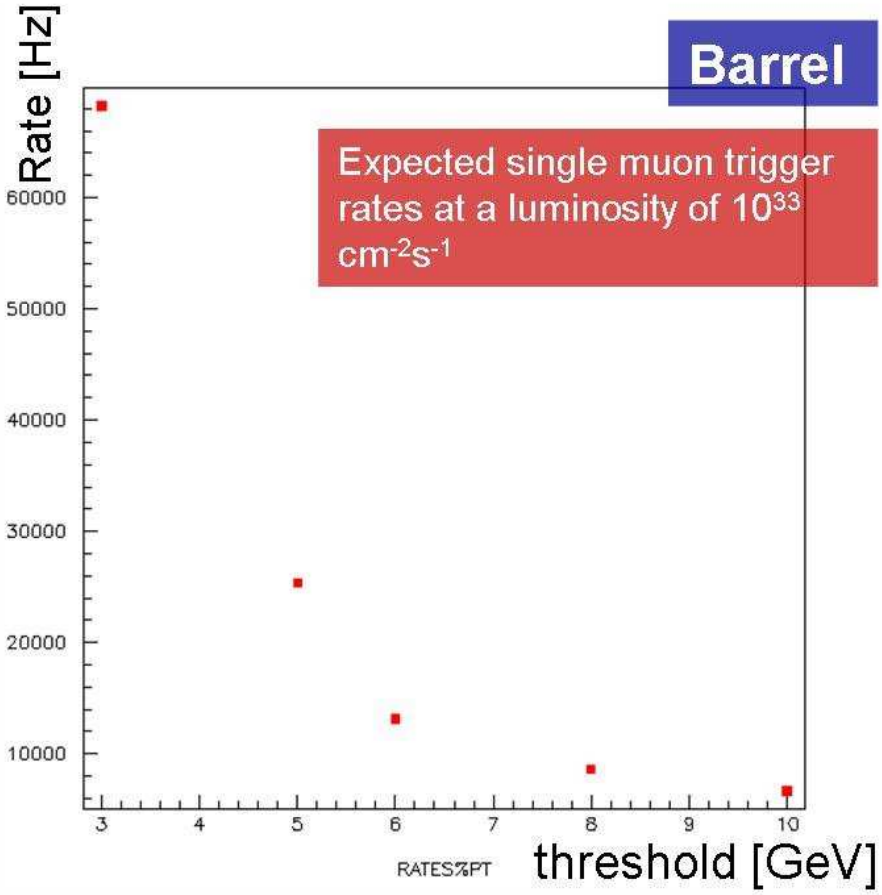

Figure 9: LVL1 rates as a function of the p_T threshold. The point at 3 GeV/c corresponds to the fully open Coincidence Window in LVL1 configuration

3.4 Event Filter

The muon Event Filter, implemented in the *TrigMoore* algorithm, uses the same algorithms of the Offline package for muon reconstruction (*Moore*/*Muid*). The trigger decision operates via the insertion, in any point of the trigger chain, of the Hypothesis Algorithms. As mentioned before, the EF is seeded by the LVL2 result, in the standard configuration, in order to reduce the time spent in data access and therefore the trigger latency. The algorithm flexibility allows other seeding configurations by LVL1 or running accessing the entire event ("unseeded"). TrigMoore uses three main FEX:

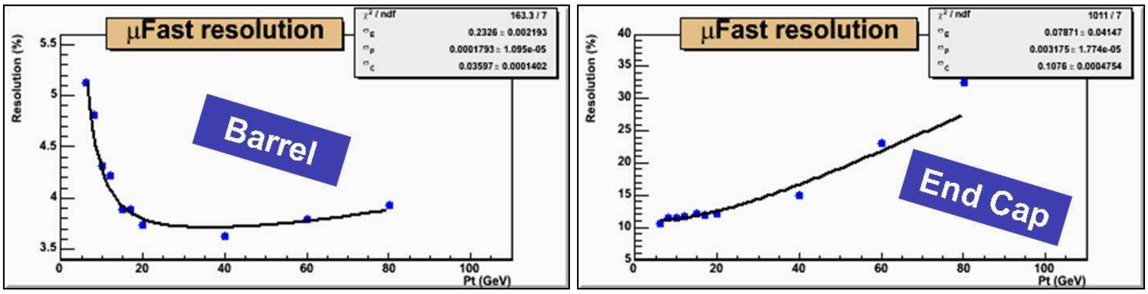

Figure 10: muFast p_T resolution in the Barrel (left) and in the Endcap (right)

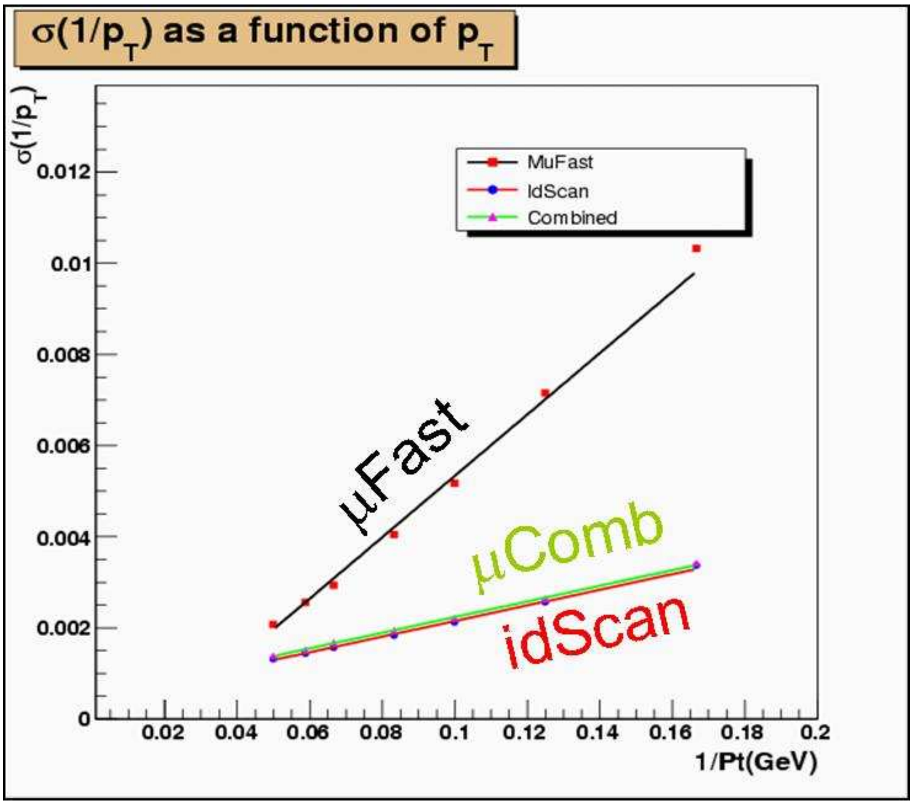

Figure 11: μComb resolution compared to the LVL2 ID (idScan) and MS (μFast) resolutions.

- *Moore*, that performs track reconstruction in the Muon Spectrometer;
- *Muid Standalone*, that propagates the reconstructed tracks in the magnetic field up to the Interaction Point;
- *Muid Combined*, that combines the MS muon track candidate with a matching track in the Inner Detector.

The transverse momentum resolution of the muon EF is reported in figure 12. In the p_T range from

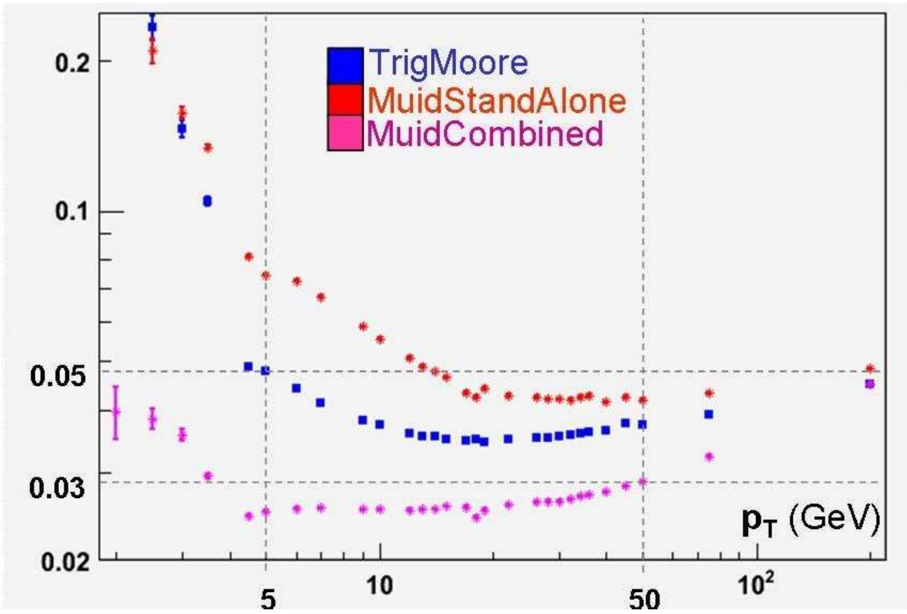

Figure 12: p_T resolution in the Barrel for TrigMoore algorithms

5 GeV/c up to 50 GeV/c, the precise measurement in the Inner Detector allows to reach a relative resolution lower than 3%; at higher transverse momentum the resolution is dominated by the MS and remains below 10% up to 1 TeV, thanks to the big lever arm in the toroidal field. In particular, figure 13 shows the relative importance of the error sources in the MS p_T measurement. The dominant contributions at high-p_T are the chamber alignment and the tube resolution, the multiple scattering contribution to the relative p_T error is quite costant over p_T and the energy loss fluctuations are more important at low-p_T. In figure 14 the relative transverse momentum resolution is reported as a function of η: in the barrel-endcap transition region the resolution is spoiled by the magnetic field in-homogeneity. Once the hypothesis algorithms are applied we can estimate the EF efficiency as a function of the muon p_T for the different p_T thresholds with respect to events accepted by LVL2. These can be used, together with the LVL1 and LVL2 efficiencies, in order to estimate the trigger rates, starting from the cross sections of the various relevant processes. The rates estimated for the standard trigger chain (LVL1, muFast, muComb, TrigMoore) are reported in table 16 for two low-p_T and two high p_T thresholds along with the contributions of the main muon production channels. The contribution to the rates from muons coming from jets is overestimated in this analysis which doesn't take into account any discriminating power of kinematic and

fit quality parameters. The optimization of the muon selection requires dedicated studies, currently being updated with recent simulations, for the reduction of this major sources of rate at low p_T.

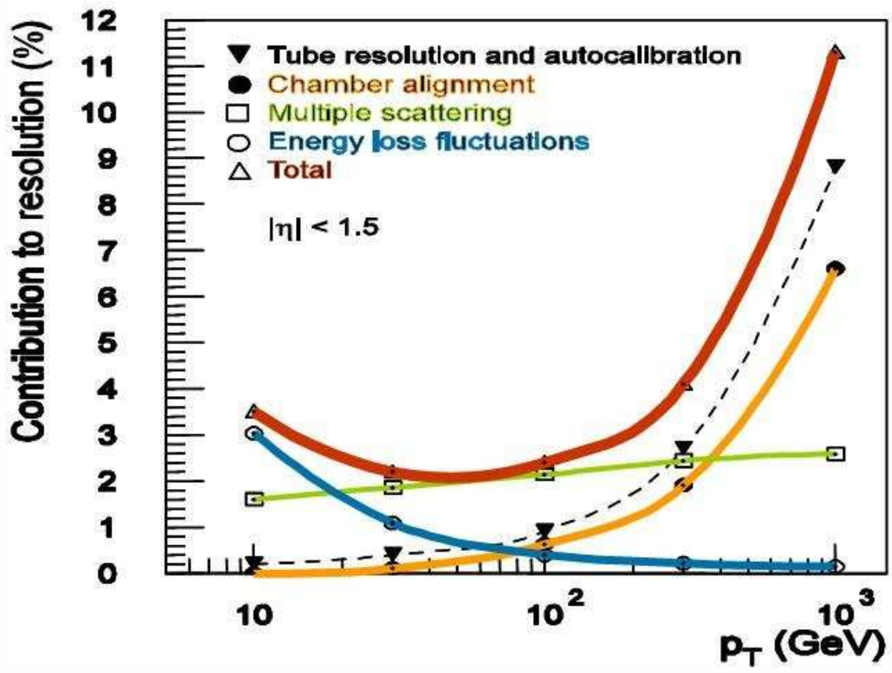

Figure 13: The different contributions to the muon p_T resolution of the MS

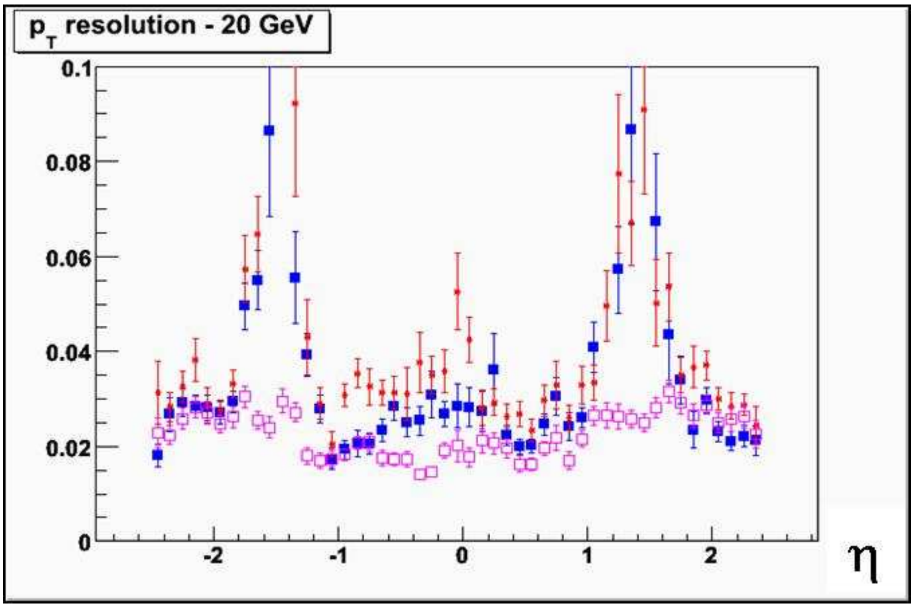

Figure 14: p_T resolution vs η for TrigMoore algorithms: Moore(blue), MuidStandalone (red), MuidCombined (magenta)

Another important source of LVL1 trigger, not included in table 16 and which deserves further studies, is the accidental coincidence of uncorrelated hits from cavern background in the muon chambers at high luminosity. As a matter of fact, the diffuse background of thermal neutrons and low energy photons, induced by the high rate of hadronic activity, produces a sizable occupancy of the muon chambers potentially leading to fake triggers.
The entire ATLAS software, including the muon trigger emulation, has been recently used to simulate and reconstruct (in the offline environment) all the data required for the Computing System Commissioning. $20 \cdot 10^6$ simulated physics events were dedicated to the optimization of the future physics analysis, with emphasys to the trigger menus definitions. In addition $15 \cdot 10^6$ calibration events have been simulated to the purpose of algorithm optimization. This effort has demonstrated the algorithm robustness. On the other hand, the LVL1 selection and the HLT software have been used to trigger cosmic rays, demonstrating the functionality of the trigger in this configuration.

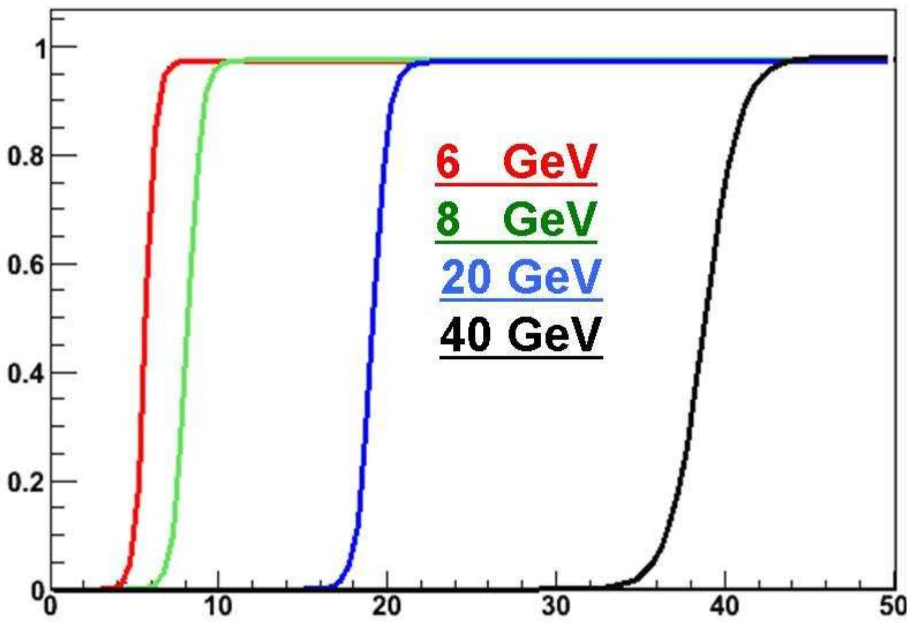

Figure 15: EF efficiency curves vs different p_T thresholds

6 GeV 10^{33}cm^{-2}s^{-1}	Barrel (Hz)	Endcap (Hz)
π/K	1918	1462
beauty	641	845
charm	327	426
top	negligible	negligible
W	3	4.0
TOTAL	**2889**	**2737**

8 GeV 10^{33}cm^{-2}s^{-1}	Barrel (Hz)	Endcap (Hz)
π/K	281	313
beauty	172	291
charm	77	134
top	negligible	negligible
W	2.8	3.9
TOTAL	**533**	**742**

20 GeV 10^{34}cm^{-2}s^{-1}	Barrel (Hz)	Endcap (Hz)
π/K	50	48
beauty	73	118
charm	28	46
top	negligible	negligible
W	22.3	32.6
TOTAL	**173**	**244**

40 GeV 10^{34}cm^{-2}s^{-1}	Barrel (Hz)	Endcap (Hz)
π/K	0.2	0.3
beauty	2.5	4.5
charm	0.87	1.6
top	negligible	negligible
W	3.9	7.1
TOTAL	**7.5**	**13.6**

Figure 16: TrigMoore output rates for different p_T thresholds

4. Conclusions

Next year we will have first collisions at LHC and we will start the detector commissioning with proton beams. At that point a fully functional trigger will be fundamental. At the moment the trigger has collected first cosmic runs and the HLT system is extensively tested on simulations. All studies indicate that the major requirements for the ATLAS Muon Trigger are satisfied and the first LHC low luminosity runs will help for the system optimization.

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