The Cosmic Muon Integrated Intensity in the ATLAS Detector at the Large Hadron Collider

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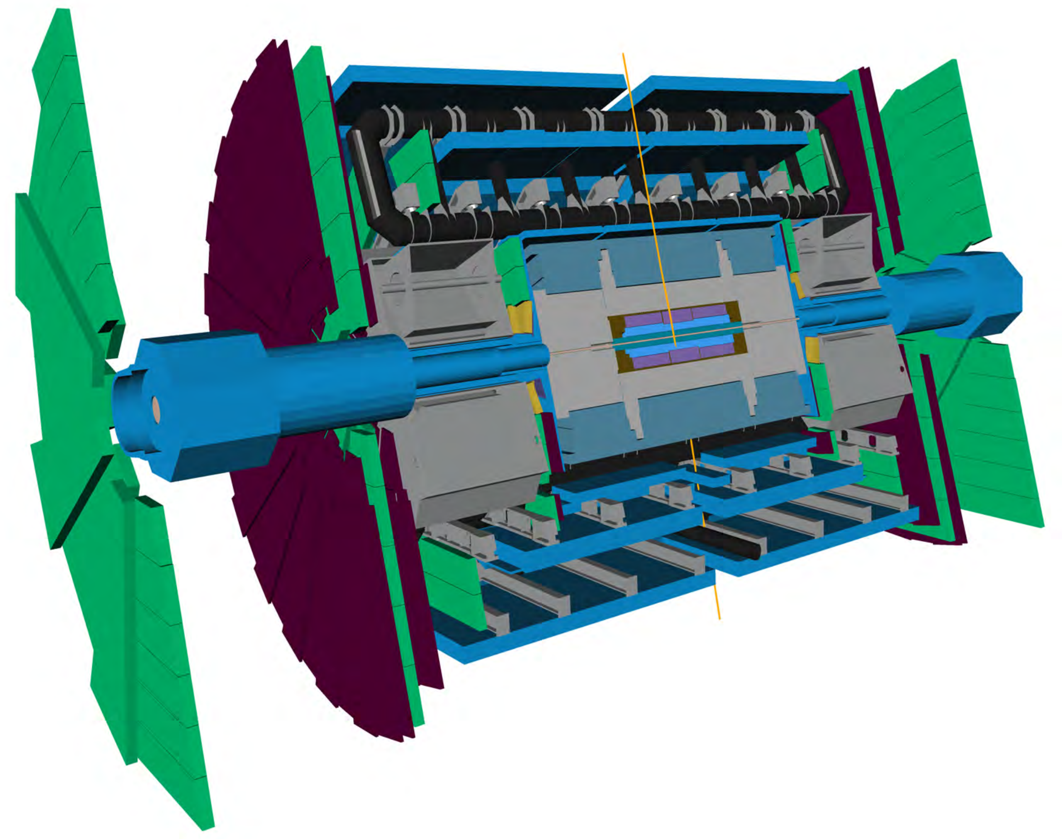
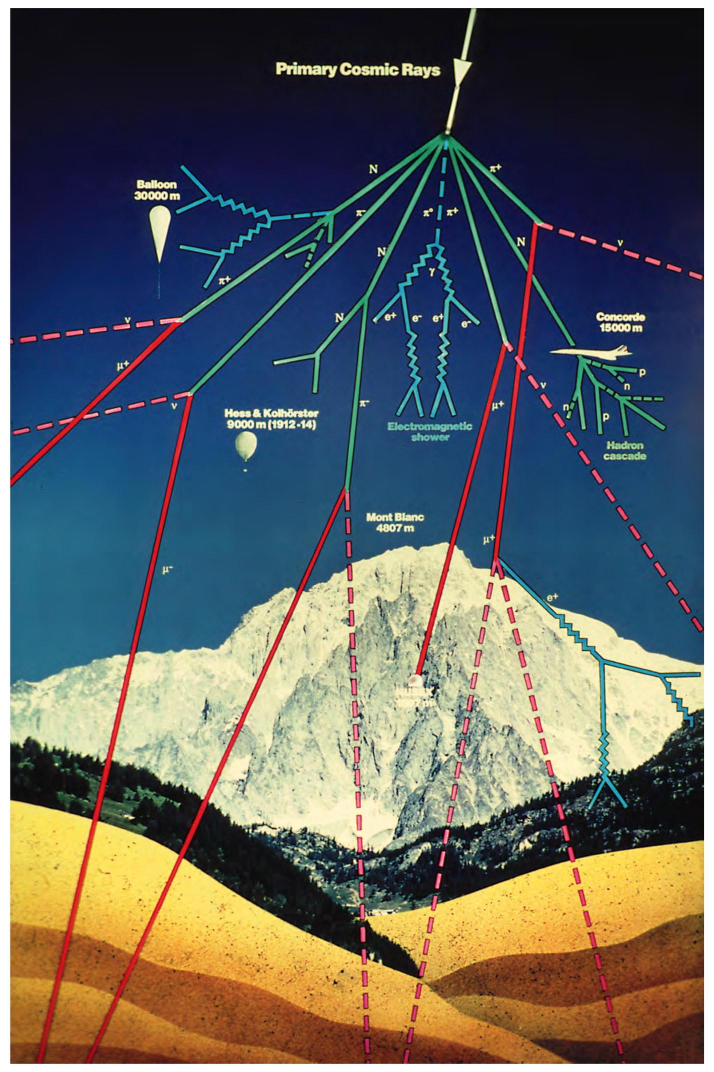
1 - Introduction

ATLAS is a multi-purpose particle physics detector at CERN's LHC. Many different ATLAS analyses study events with muons in them including those analyses aiming to detect top quarks and those searching for the elusive Higgs boson and new physics. However, cosmic rays that hit the Earth's atmosphere can also produce muons that can enter the detector and occasionally mimic the trajectory of a muon from a beam collision. Cosmic events where this happens would be a background to other physics studies that look for events with high-momentum muons. Measuring the cosmic muon integrated intensity in ATLAS is a first step in quantifying the importance of the cosmic muon backgrounds to these analyses.



2 - Cosmic Radiation and ATLAS



Cosmic muons produced in the atmosphere are one of the most abundant charged particles at sea level, where their integrated intensity is approximately constant. Cosmic muons are of interest to particle collider experiments because they form a background to muons from collisions. The ATLAS detector is shielded from most of the lower-energy cosmic radiation because it is almost 100m underground; however, the two main access shafts to the ATLAS cavern allow for a higher integrated intensity of muons to reach the detector than the areas where there is only solid rock above it.

Example of studied particle decay chains that include muons:

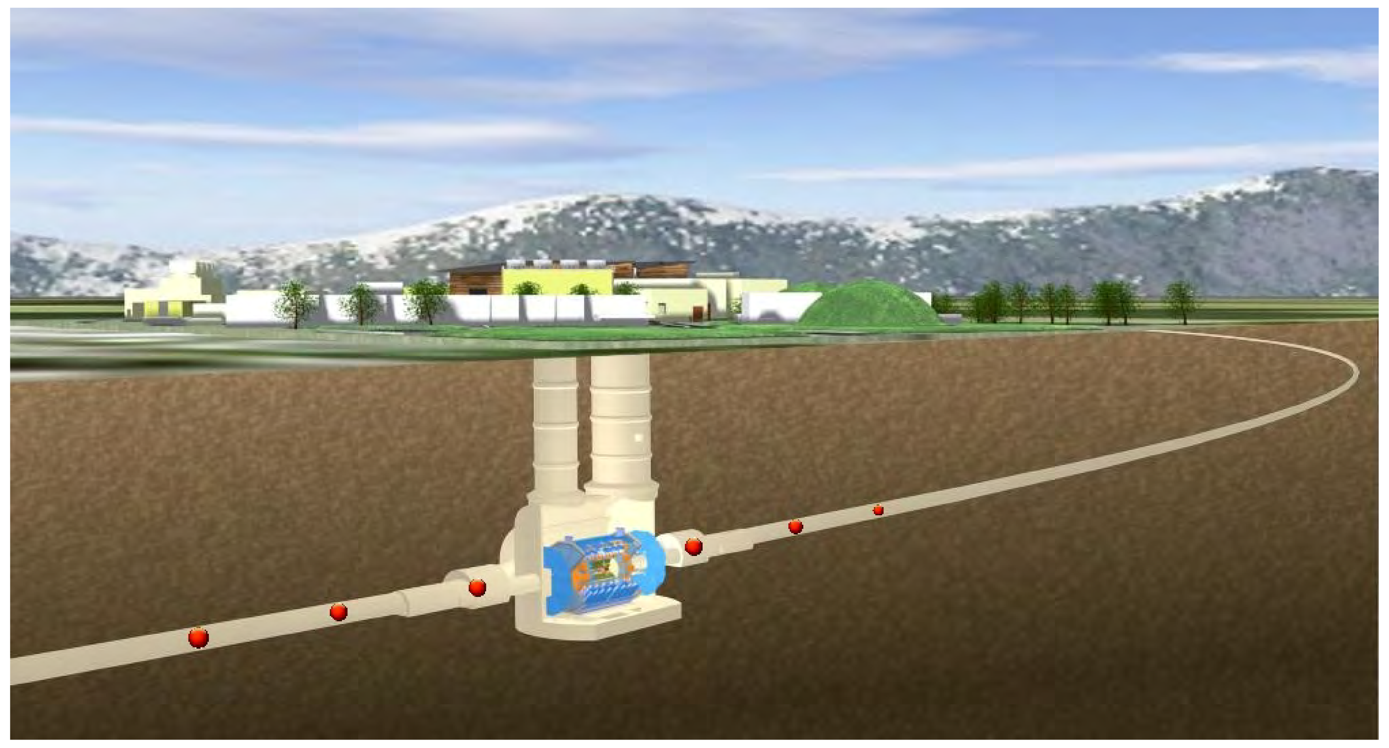
$t \to Wb,\ W \to \mu\nu$
$H \to W^+W^- \to \mu\nu\mu\nu, \mu\nu qq$
$H \to ZZ^{(*)} \to \mu\mu\mu\mu$
$Z' \to \mu\mu$

Example of cosmic interactions and particle decay chains that include muons:

$$NN \to \begin{cases} \pi^\pm + X, \pi^\pm \to \mu\nu \\ K^\pm + X, K^\pm \to \mu\nu \end{cases}$$

Cosmic radiation (originating mostly from the sun) hitting the atmosphere is also the cause for the Aurora Borealis and Aurora Australis!

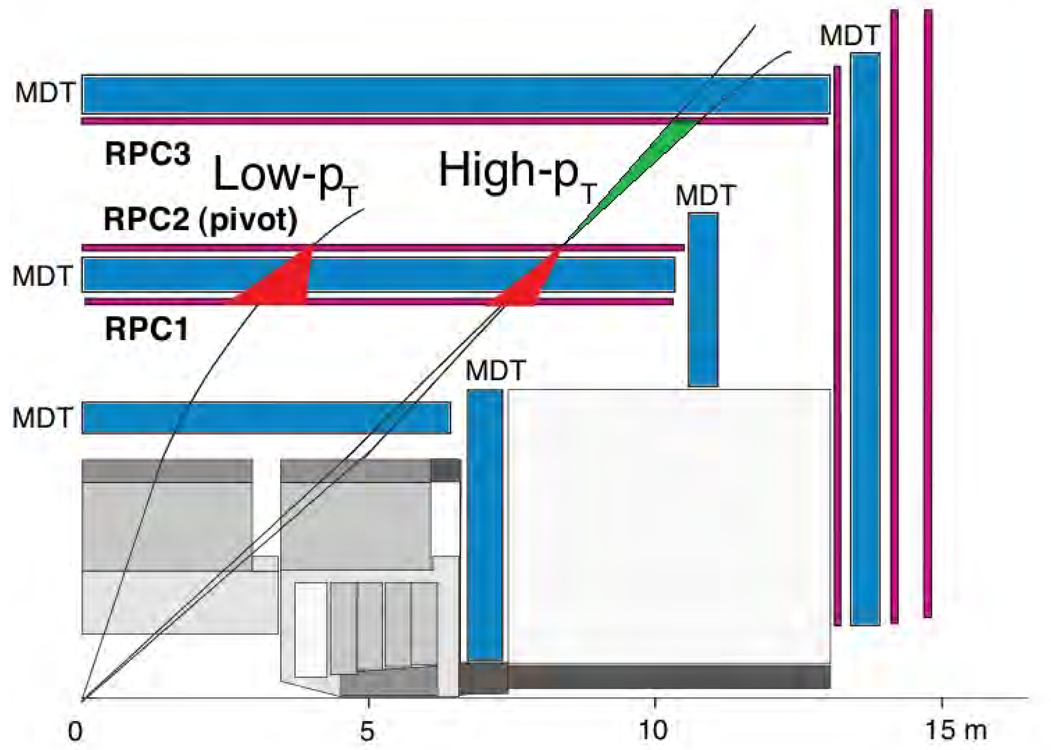
3 - The LHC Beam and Triggering



The nominal spacing of proton bunches in the LHC is 25 ns (roughly 7.5 m) but not all of these Radio Frequency (RF) buckets are filled. There are 3564 RF buckets for containing proton bunches but only 2808 can ever be used in the nominal filling scheme. The empty buckets are present for safety reasons, and used for cosmic studies and detector tests. At the nominal bunch spacing the event rate is approximately 40 MHz. A three-leveled triggering system is used to intelligently filter the different types of events to save to disk. Each level further reduces the rate of accepted events:

- Level-1 (L1): 40 MHz $\to 75$ kHz
- Level-2 (L2): 75 kHz $\to 3.5$ kHz
- Event Filter: 3.5 kHz $\to 200$ Hz

4 - Level-1 Muon Trigger and Timing



It is important to understand how the L1 trigger works for muons from collisions *and* muons from cosmic radiation. The L1 muon trigger (all analog electronics) searches for hit patterns that are indicative of muons originating from the interaction region. The muon trigger is set up with three low-p_T (transverse momentum) and three high-p_T threshold triggers. In the barrel the low-p_T muon triggers look for coincident hits in the two innermost RPC doublets within a road. The high-p_T trigger also requires coincident hits in the outermost RPC doublet. The width of the road determines the p_T threshold.

The hits along a track are made to be coincident by internally delaying the signals in 3 ns intervals to arrive at the same time at the the trigger algorithm chip. Cosmic muons are special as they travel "backwards in time" in the upper half of ATLAS compared to the direction of muons from LHC collisions. In the upper half of ATLAS:

- low-p_T threshold trigger:
  - muon time of flight < 3 ns
  - trigger has a higher probability of firing
- high-p_T threshold trigger:
  - muon time of flight > 3 ns
  - trigger has a much lower probability of firing.

5 - Cosmic Muon Integrated Intensity Calculation

$$\Phi_\mu = \frac{1}{A}\frac{\text{The actual number of muons traversing the detector}}{\text{The time interval during which the data were taken}} \quad (1)$$

$$= \frac{1}{A}\frac{\frac{1}{\epsilon_{\text{trig}}}\frac{1}{\epsilon_{\text{rec}}}\sum_{i\in G} k_i^{\text{PS}} N_i^{\mu_{\text{meas}}}}{\sum_{j\in G} k_j^{\text{trig}}\left(1-k_j^{\text{DT}}\right)\Delta t_j} \quad (2)$$

A	Cross-sectional area through which the particles pass.
ϵ_{trig}	Trigger efficiency.
ϵ_{rec}	Reconstruction efficiency.
G	The set of all good luminosity blocks (a short time interval of known duration) used for the analysis.
k_i^{PS}	Trigger prescale in luminosity block i.
$N_i^{\mu_{\text{meas}}}$	Number of muons in luminosity block i that were recorded and passed the selection cuts.
k_j^{trig}	Fraction of time that the detector is capable of triggering on data per beam rotation in lumiblock j. This is a function of the bunch crossing setup scheme as well as the trigger livetime window per RF bucket crossing.
k_j^{DT}	Deadtime fraction for luminosity block j.
Δt_i	Duration of luminosity block i.

6 - High Level Data Selection

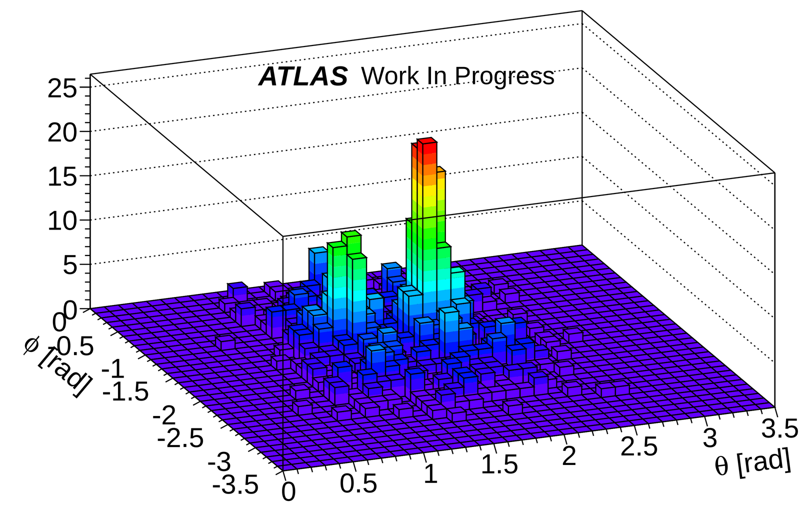
Overall data requirements:

- Dedicated cosmic run
- Detector settings set as they would be for collisions (nominal magnetic fields etc.)
- Level-1 single muon trigger (low-p_T roads only)
- Trigger prescale of roughly 10
- Deadtime fractions are relatively small, constant, and have no random spikes or troughs
- Use only the empty RF buckets that are also not used for testing
- Data quality flags set as being good for the relevant sub-detectors

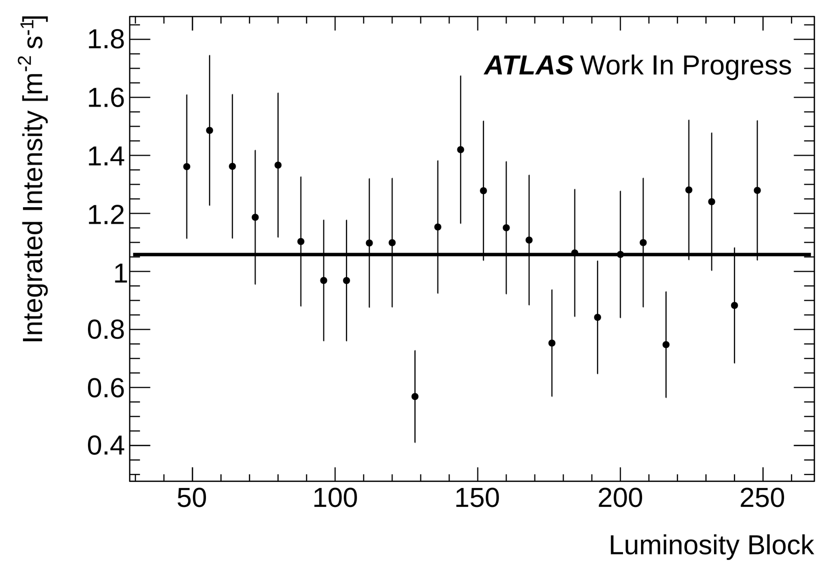
Data used: Run 152344 from April 2 2010

- Luminosity blocks 45-255
- Luminosity block duration ~ 2 minutes
- L1_MU6_EMPTY trigger with: Prescale $= 14$, Deadtime $\sim 9\%$

7 - Results and Conclusions



The two-dimensional histogram shows the number of muon candidates as a function of their directions in θ and ϕ. The distribution of the directions shows regions of higher integrated intensities (higher densities) where the two main access shafts are located and lower integrated intensities (lower densities) at shallower angles where there is more rock above to traverse.



The cosmic muon integrated intensity for muons with transverse momenta above 20 GeV is measured almost 100 m underground to be constant at $1.10 \pm 0.05\,(\text{stat.})\ \text{s}^{-1}\ \text{m}^{-2}$. This value is of the same order of magnitude as the approximated integrated intensity of cosmic muons with energies above 20 GeV at sea level of $6.0\ \text{s}^{-1}\ \text{m}^{-2}$ in the range $\theta < 75°$.