

Summer Student Report

Testing the ATLAS Phase-II MDT Trigger Processor with
Cosmic-Ray Muons

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1 Introduction

The first-level trigger of the ATLAS experiment processes up to 40 million events per second in real time using fast, dedicated hardware. It collects data from various detector components, including calorimeters and muon detectors such as Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs).

With the upgrade of the LHC to the High-Luminosity phase (HL-LHC), the number of simultaneous collisions (pile-up) per bunch crossing is expected to increase from around 65 to 200. To cope with these demanding conditions, the entire ATLAS detector and its trigger system will undergo a major upgrade as part of the so-called Phase-II upgrade. This term refers to the comprehensive improvements of the ATLAS detector and data acquisition system scheduled to be operational when the HL-LHC starts.

In particular, precise spatial information from the Monitored Drift Tubes (MDTs) will be incorporated into the first-level trigger to enhance muon identification and reduce the rate of misidentified muons. This is made possible through the MDT Trigger Processor (MDT-TP), which is a key component of the Level-0 muon trigger. The MDT-TP receives hit information from the MDT chambers in real time, reconstructs track segments with high precision, and forwards the results to the global trigger system. The MDT-TP relies on on-detector electronics, namely the Time-to-Digital Converters (TDCs) and Chamber Service Modules (CSMs).

Within this broader context, this project focuses on a test setup composed of three MDT chambers, along with two scintillators and the associated Phase-II on-detector electronics. The goal is to match scintillator coincidences with MDT hits and reconstruct the trajectories of cosmic ray muons using the Legendre transform, in line with the developments for the MDT-TP.

2 Project context

2.1 The ATLAS experiment

The ATLAS experiment is one of the four main experiments at the Large Hadron Collider (LHC), alongside CMS, ALICE, and LHCb.

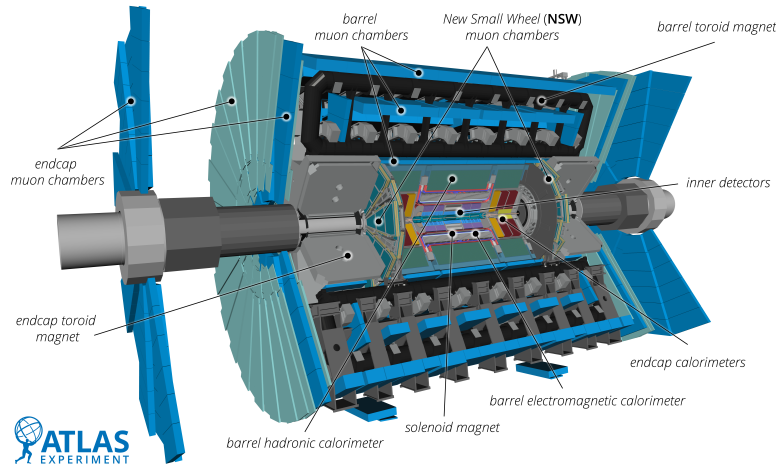


Figure 2.1: Schematic view of the ATLAS detector and its subsystems [1]

As shown in Fig. 2.1, the ATLAS detector is a large, multi-layered system at the LHC, designed to detect and measure particles produced in collisions with nearly full 4π coverage. Its four main layers are the Inner Detector, the Electromagnetic Calorimeter, the Hadronic Calorimeter, and the Muon Spectrometer. To cope with higher collision rates at the HL-LHC, several upgrades are planned, especially for the muon spectrometer and muon trigger system.[1]

2.2 The ATLAS Muon Spectrometer and Muon Trigger System

The ATLAS Muon Spectrometer (MS) surrounds the calorimeters and is designed to measure the momentum of muons with high precision. The MS uses a system of three large air-core toroidal magnets—one in the central barrel and two in the end-caps. Precise muon tracking is performed using Monitored Drift Tube (MDT) chambers in most regions and Cathode Strip Chambers (CSCs) in the forward region. Since Run 3 (2022), the inner “small wheel” has been replaced by the New Small Wheel, equipped with Micromegas and Small-strip TGCs (sTGCs), which provide fast signals for the Level-1 muon trigger.

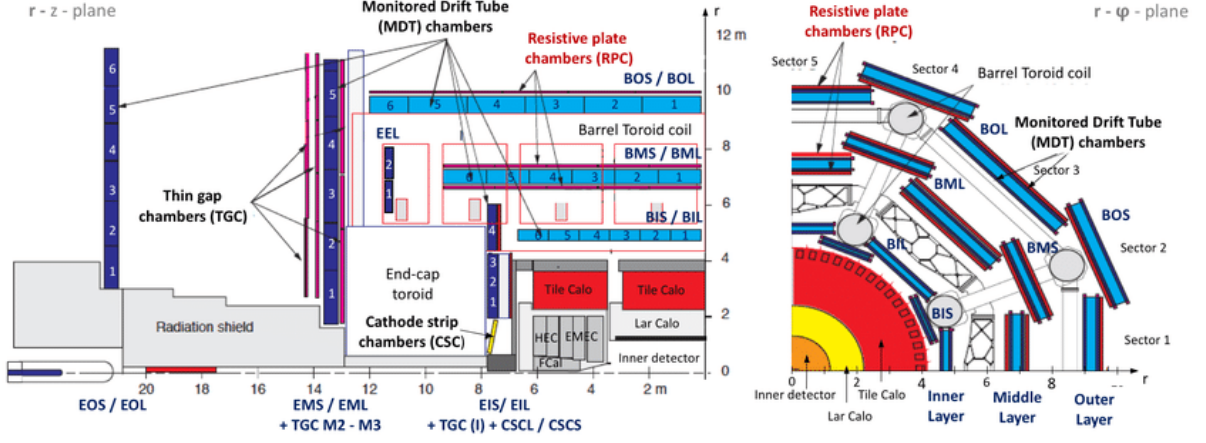


Figure 2.2: Schematic views of a quadrant of the MS [1]

In the current detector configuration, MDTs are used primarily for offline analysis and not for triggering. However, for the High-Luminosity LHC (HL-LHC) Phase-II upgrade, MDT data will be incorporated into the Level-0 muon trigger system to improve muon identification under high-rate conditions.

2.3 The Monitored Drift-Tube (MDT)

The core of precision muon tracking in ATLAS consists of over 1200 Monitored Drift Tube (MDT) chambers, each adapted in size and shape to its position in the detector. Each chamber contains multiple layers of aluminium drift tubes filled with an Ar:CO₂ gas mixture and is equipped with an optical alignment system to monitor deformations and displacements. As represented in Fig 2.3, when a muon passes through a tube, it ionises the gas; the resulting electrons drift toward a central wire where they are amplified, and the measured drift time is converted into the distance of the track from the wire using the function from Fig. 2.4. The maximum drift radius is the radius of the tube and the corresponding maximum drift time is 750 ns (30 BC).

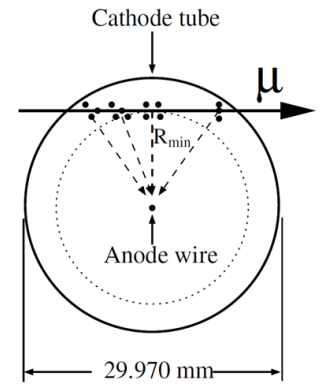


Figure 2.3: Cross-section of an MDT tube. [1]

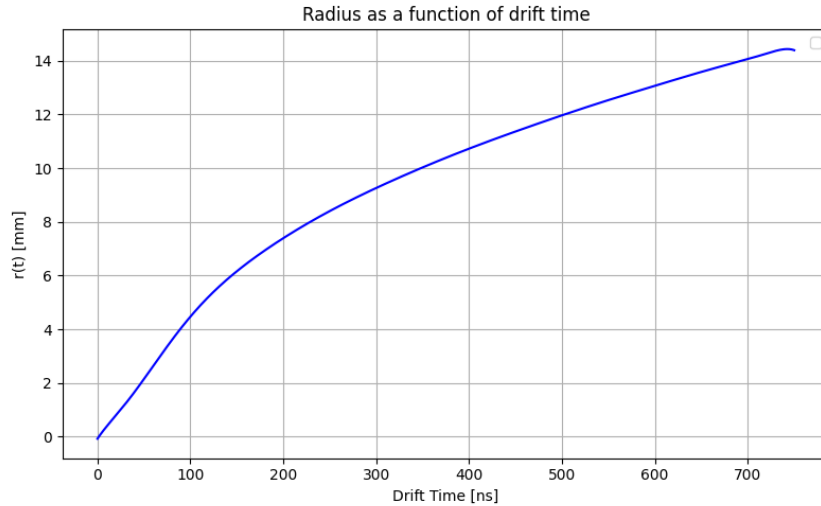


Figure 2.4: Drift radius as a function of drift time.

2.4 MDT - Trigger Processor

The Monitored Drift Tubes Trigger Processor (MDT-TP) is a crucial component of the ATLAS Level-0 Muon trigger upgrade, designed to meet HL-LHC requirements. It uses the high-resolution MDT hits for hardware-based muon tracking, improving trigger performance. A total of 64 MDT-TP boards are planned, each interfacing with several detectors through the Chamber Service Module (CSM) to collect timing data, configure the front-end electronics, and manage trigger and control (TTC) signals. The MDT-TP also serves as the DAQ interface to the FELIX system.[2]

3 MDT system overview

3.1 Detectors and on-detector electronics

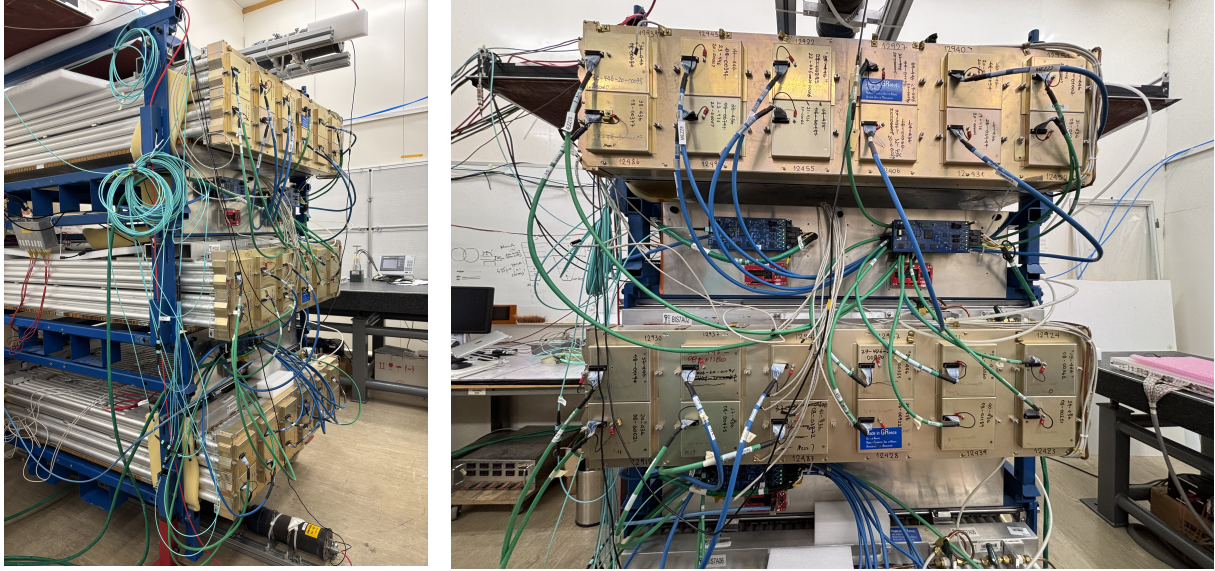


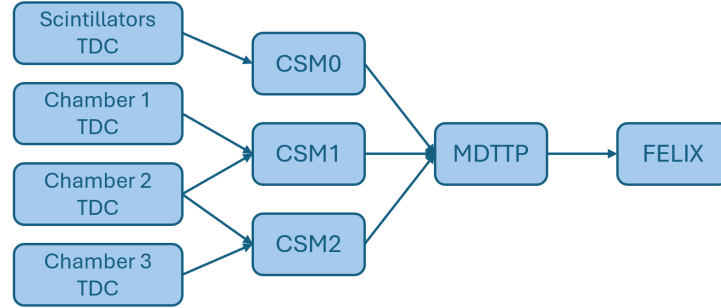
Figure 3.1: Views of the MDT system.

The setup shown in Fig 3.1 consists of three Monitored Drift Tube (MDT) chambers that were originally installed in the ATLAS detector. These chambers are responsible for detecting muons by measuring their trajectories with high precision. The system also includes two scintillators, which serve as trigger detectors. They provide fast timing signals to indicate the passage of a particle through the setup, allowing synchronization of the data acquisition.

To control and read out the MDT chambers, three Chamber Service Modules (CSM) are used. Each CSM manages the electronics and services required by the MDT chambers, such as powering the tubes and handling data flow. For precise time measurements, 36 Time-to-Digital Converters (TDC) are employed. Each TDC digitizes the timing signals from the drift tubes, converting the analog drift times into digital values for analysis. Each TDC is connected to 24 drift tubes, allowing it to measure the drift times of ionization electrons inside those tubes, which is crucial for reconstructing the muon tracks accurately. The CSMs and TDCs used in this setup are prototypes of the electronics that will be employed in ATLAS during the Phase-II upgrade.

3.2 Data processing

In this project, all hits are directly recorded via the **Front-End Link eXchange (FELIX)** system using pass-through firmware on MDT-TP - without applying any trigger logic. The Chamber Service Modules (CSMs) are connected to the **MDT Trigger Processor (MDTTP)**, which is responsible for configuring the CSM and TDC boards, collecting and forwarding the data to FELIX.



3.3 Coincidence system

The coincidence system presented in Fig. 3.2 operates as follows: the signals generated by the MDT tubes are first amplified to increase their strength. These amplified signals are then sent to discriminators, which produce digital pulses only if the signal exceeds a set threshold, helping to remove noise.

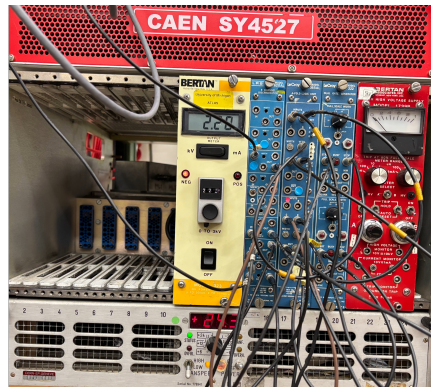


Figure 3.2: Coincidence system

4 Data Acquisition Analysis

4.1 Hit Data Format

Each recorded TDC hit is described by a 42-bit word including several fields that capture both timing and hardware-related information. Their meanings are detailed below:

- **Pulse width - 8 bits:** The duration of the detected signal pulse, typically measured in time bins. It provides an estimate of the deposited charge or the signal strength.
- **Fine time - 5 bits:** Provides a precise measurement of the signal's arrival within the local TDC clock cycle.
- **Coarse time - 12 bits:** Represents a coarse timestamp of the signal, expressed in units of bunch crossings (BC) corresponding to the TDC clock cycle (25 ns). It is encoded on 12 bits and therefore rolls over every 4096 BC. This periodic reset must be taken into account when comparing time values across events.
- **TDC edge mode - 2 bits:** Indicates whether the time measurement corresponds to the rising edge, the falling edge, or both.
- **Channel ID - 5 bits:** The identifier of the input channel that detected the hit, local to a given TDC. It ranges from 0 to 23.
- **CSM ID - 2 bits:** Specifies which *Chamber Service Module* (CSM) board the TDC belongs to. It ranges from 0 to 2.
- **TDC ID - 5 bits:** Identifies which *Time-to-Digital Converter* (TDC) chip, within a CSM, registered the signal. Each TDC manages a subset of the channels. The TDC ID ranges from 0 to 17.

4.2 Coordinate Mapping

The hardware configuration is such that **CSM0** corresponds to the output of the scintillator, while the modules **CSM1** and **CSM2** correspond respectively to the two halves of the MDT (Monitored Drift Tube) readout system, as shown in Fig. 4.1. The channel numbers follow a repeated pattern, as illustrated for Mz 10 and Mz 11.

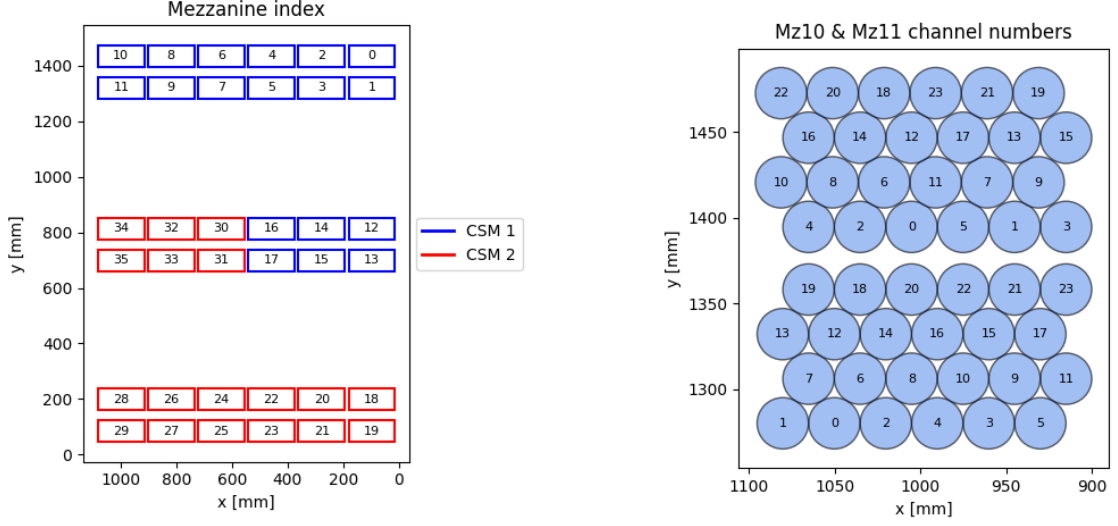


Figure 4.1: Mezzanine and channel mapping.

To associate a hit with its corresponding physical position in space, a separate coordinate file is used. This file includes the following mapping information:

- **Mz**: mezzanine index, ranging from 0 to 35
- **MezzCh**: mezzanine channel identifier (the value modulo 100 gives the actual channel index within the mezzanine)
- **locY, locX**: the spatial coordinates (Y, X) associated with each channel

In order to map a hit characterized by a specific **channel**, **CSM**, and **TDC** to its corresponding spatial coordinates, the following transformation is applied:

$$\text{mz} = \text{tdc} + (\text{csm} - 1) \times 18 \quad (4.1)$$

This index **mz** is then matched against the entries in the coordinate file according to the condition:

$$\text{MZ}[j] == \text{mz} \quad \text{and} \quad \text{MezzCh}[j] \% 100 == \text{ch} \quad (4.2)$$

where j is the index running over the entries (rows) of the coordinate file. If the condition is satisfied, the corresponding (X, Y) position is retrieved and associated with the hit.

4.3 Hit map distribution

The hit map shown in Fig. 4.2 illustrates the spatial distribution of all signals recorded in the MDT chambers, originating from both cosmic muons and electronic noise. This visualization serves as an important diagnostic tool: unusually high rates can indicate

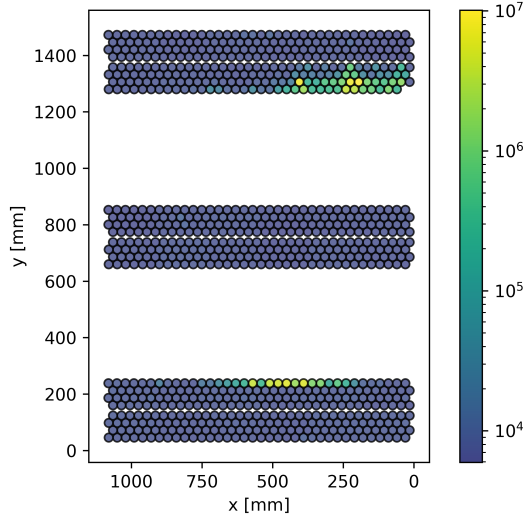


Figure 4.2: Hit distribution

excessive noise in specific channels, while regions with very low or no hits may reveal dead or inefficient tubes. Potential inefficiencies may also arise from incorrect gas composition or pressure within the MDT tubes. By analysing the occupancy patterns, one can assess the overall performance, coverage, and operational health of the chamber system.

4.4 Pulse width distribution

Fig. 4.3 show the ADC pulse width distributions for TDC0 to TDC5.

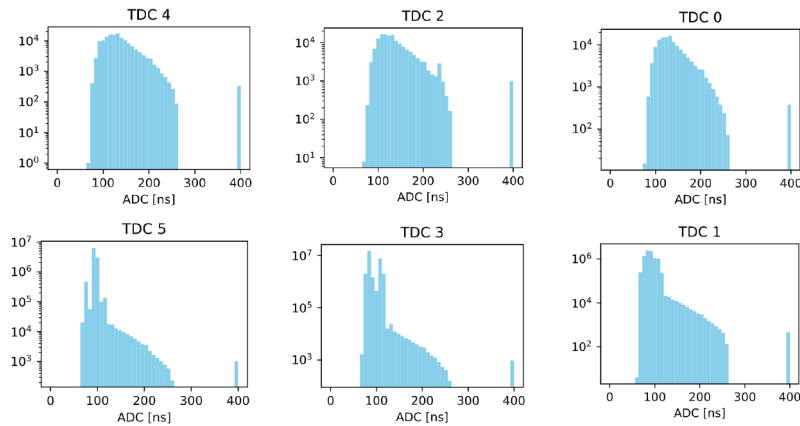
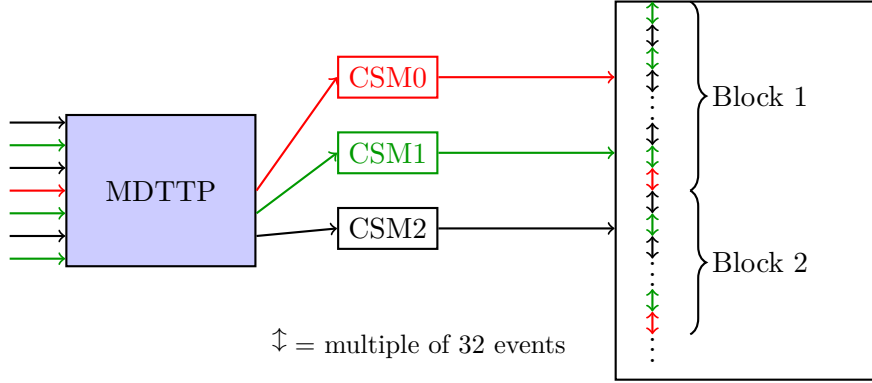


Figure 4.3: Histograms of ADC for TDC0 to TDC5

The plots from TDC1, TDC3, and TDC5, corresponding to the noisy TDCs in the hit map (Fig. 4.2), show a peak for ADC values below 120 ns, indicating that hits shorter than this are likely noise. In contrast, TDC0, TDC2, and TDC4 do not exhibit such a peak and do not correspond to noisy TDCs. Therefore, only hits exceeding the 120 ns threshold will be retained in the following analysis.

5 Coincidence matching

5.1 Data file structure



Hits are temporarily stored in buffers corresponding to each CSM. Each buffer can hold up to 32 events. When a buffer becomes full, its contents are flushed to the output file. This approach introduces a challenge, as the aggregated data are consequently not maintained in strict chronological order. Furthermore, the time counter is stored using 12 bits, which means it resets every 4096 counts. This complicates the reliable matching of hits with their corresponding coincidences because we don't have a way to track how many times the coarse time resets.

To enable reliable matching between hits and coincidences, we modified the MDTTP firmware to append a 42-bit counter to each recorded TDC hit (timestamp from the 40 MHz clock of the MDT-TP). This counter increments at the same rate as the coarse time and, since it is implemented in the MDT-TP, it is synchronous for all hits recorded in the buffer at a given moment.

5.2 Coincidence algorithm

The Fig. 5.1 is an histogram of the pulse width from the scintillator, we can clearly see two peaks, the first one (around 100 ns) correspond to the noise and the second one (above 200 ns) correspond to the coincidences. The coincidence algorithm identifies pulses from the scintillators with a width greater than 200 ns, which are considered candidate muon events.

For each coincidence, the algorithm searches for MDT hits whose the counter time ct_{hit} satisfies the condition:

$$t_0 = ct_{\text{CSM0}} - \text{time offset}$$

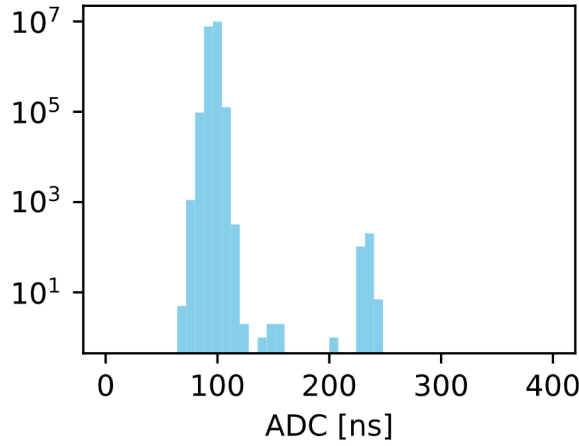


Figure 5.1: CSM0 pulse width

$$t_0 < ct_{\text{hit}} < t_0 + \text{window time}.$$

Here, the time offset accounts for delays introduced by optical fibers and electronics, while the time window corresponds to the maximum electron drift time within the MDT tube. The time window is well known and has a value of 30 bc (750 ns), whereas the time offset must be determined.

5.3 Time offset optimization

In order to determine the time offset, we scan a range of time offset values and, for each configuration, record the corresponding number of hits. We repeat the process over several coincidences and sum the number of hits for each time offset.

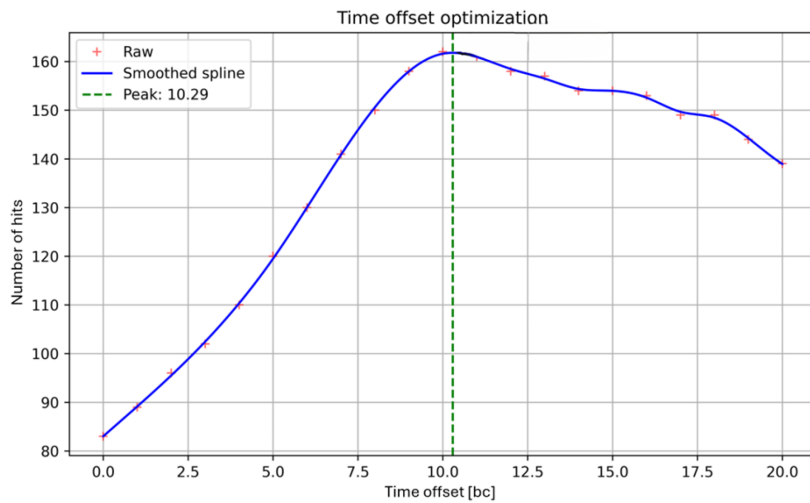


Figure 5.2: Time offset optimization for 5 coincidences - smoothed spline

The time offset optimization for five coincidences is illustrated in Fig. 5.2. The

maximum number of hits is reached when the time offset is about 10.29 BC. To obtain a more accurate estimate of this value, we search for the optimal time offset in a more restricted window and for even more coincidences.

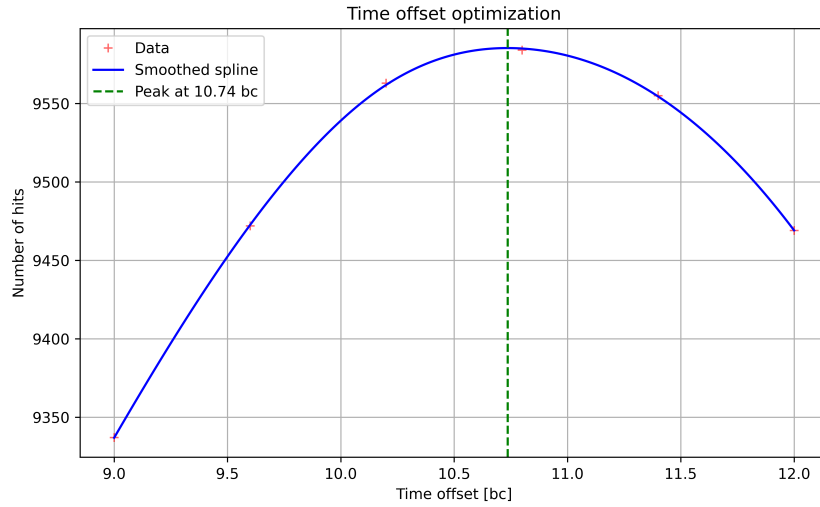


Figure 5.3: Time offset optimization for 315 coincidences - smoothed spline

The time offset optimization for 315 coincidences is illustrated in Fig. 5.3. The maximum number of hits is reached when the time offset is about 10.74 bc.

Finally, using a time offset of 10.7 BC (268 ns) and a time window of 30 BC (750 ns), we can reconstruct the muon paths corresponding to the coincidences shown in Fig. 5.4.

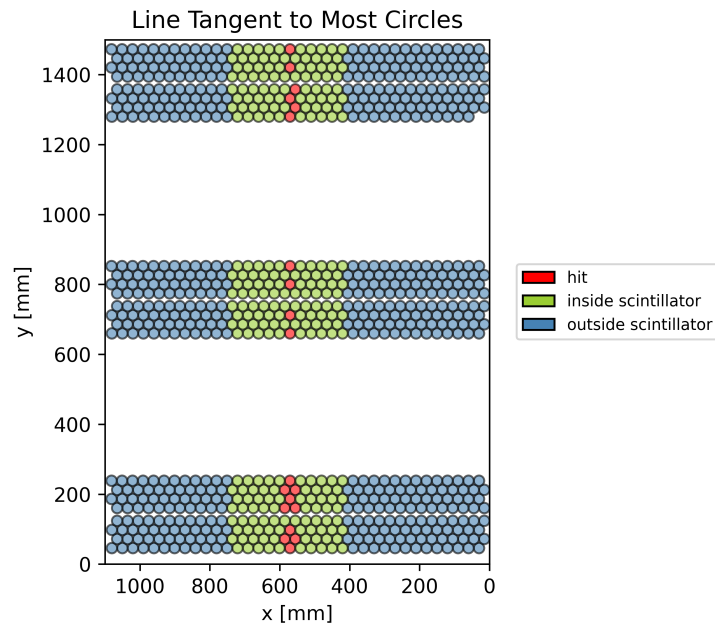


Figure 5.4: Path of one muon

6 Segment Finding Algorithm

6.1 Legendre algorithm

The **Legendre Transform (LT)** is a mathematical tool particularly suited for segment finding in MDT chambers.

As illustrated in Fig. 6.1, each drift circle, defined by its wire position and drift radius, is transformed into a point cloud in *Legendre space*, a polar coordinate space. In this space, each drift circle corresponds to two lines (one for the convex, one for the concave edge). A point (r, θ) in Legendre space represents a line tangent to a drift circle in real space.

Applying the LT to all hits in a chamber results in a density map in Legendre space. The bin with the highest occupancy corresponds to the tangent line that best matches the majority of drift circles, and thus to a potential muon segment.

This method is robust against noise: hits that do not align with a common tangent do not contribute significantly to the most populated bin, and therefore have little effect on segment reconstruction.

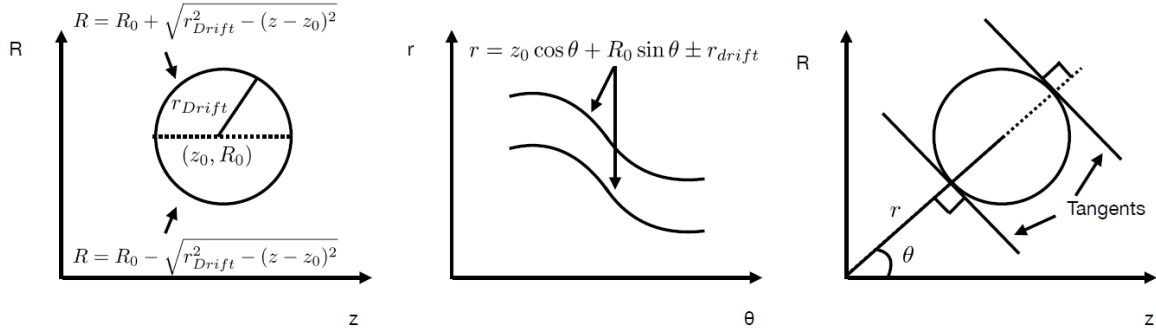


Figure 6.1: Basic principle and mathematical properties of the LT.

6.2 Mathematical Principle of the Legendre Transform Algorithm

The algorithm finds the line tangent to the most circles, each defined by center (x_i, y_i) and radius r_i . A line with slope m and intercept b is tangent to a circle if the distance from the center to the line equals the radius:

$$\frac{|mx_i - y_i + b|}{\sqrt{m^2 + 1}} = r_i.$$

This gives two possible intercepts for each m :

$$b = y_i - mx_i \pm r_i \sqrt{1 + m^2}.$$

By scanning over a range of m and b , the algorithm counts how many circles each line is tangent to. The parameters $(m_{\text{best}}, b_{\text{best}})$ with the highest count define the best fitting line.

6.3 Legendre algorithm implementation

The algorithm searches for a line in a coordinate system where the usual x and y axes are inverted. This approach simplifies the reconstruction of vertical muon tracks, which are predominantly detected when coincidences occur in the scintillators.

The track reconstruction obtained with the Legendre transform with the corresponding dual space histogram is illustrated in Fig.6.2.

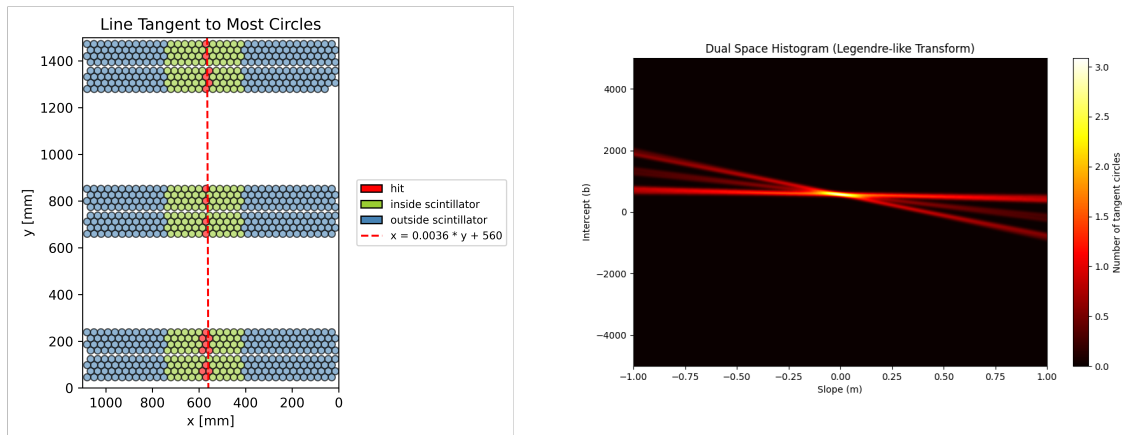
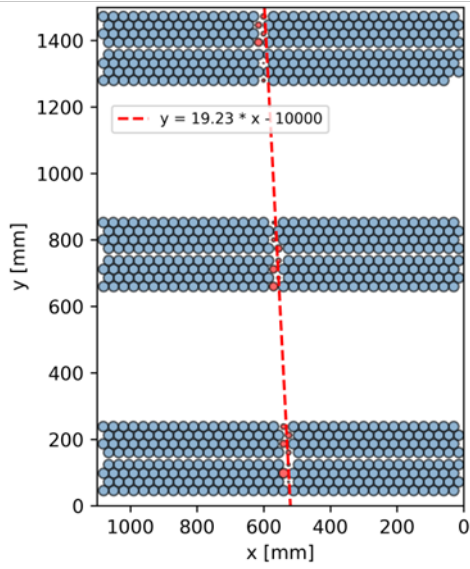


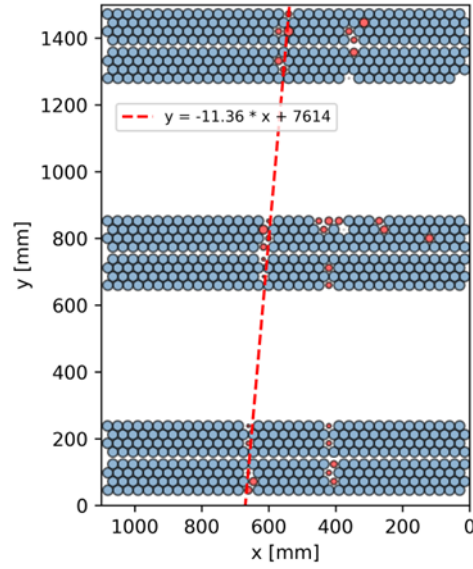
Figure 6.2: Track reconstruction and histogram

6.4 Track reconstruction of cosmic muons

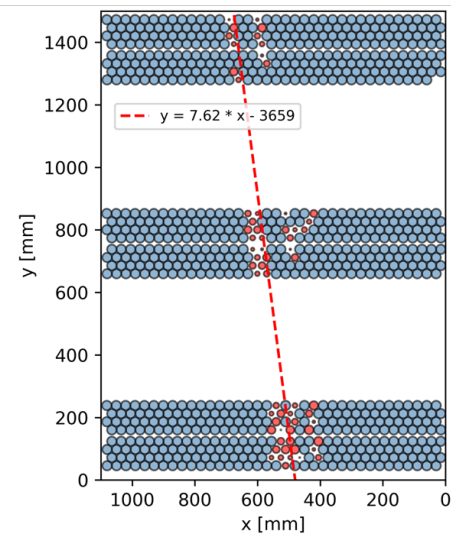
We are now able to reconstruct the trajectory of a muon for all 315 coincidences. However, not all coincidences correspond to the passage of a single muon: some events record significantly more hits. Within a single coincidence window, multiple muons may be detected, or the data may be dominated by noise. Examples are shown in the figures 6.3a, 6.3b, 6.3c, 6.3d.



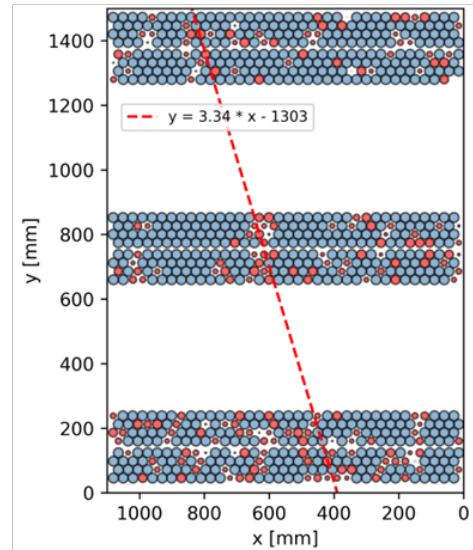
(a) Detection of one muon (20 hits)



(b) Detection of two muons (36 hits)



(c) Detection of three muons (63 hits)



(d) Detection of many hits (212 hits)

The histogram representing the number of hits per coincidence is shown in Fig. 6.4.

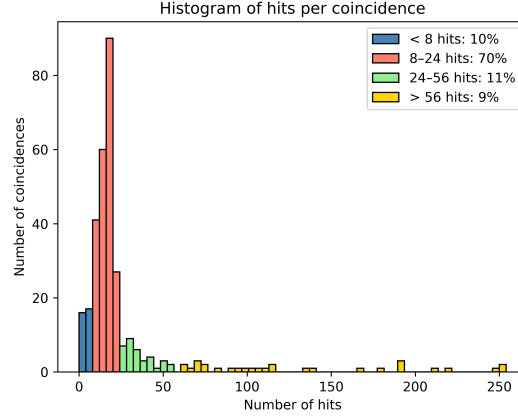


Figure 6.4: Histogram of the number of hits per coincidence

Out of the 315 recorded coincidences, the vast majority (70%) contain between 8 and 24 hits, consistent with the detection of a single muon, while 10% have fewer than 8 hits, 11% fall in the range of 24–56 hits, and 9% involve more than 56 hits.

We now focus on coincidences with 8 to 24 hits, which are expected to correspond to single-muon events. The target is to determine whether the reconstructed tracks lie within the scintillator range. As shown in Fig. 6.5, 90% of these tracks are contained within the scintillator boundaries.

A cosmic muon track is considered *inside* the scintillator if its trajectory, described by $y(x) = mx + c$, passes through the scintillator bounds at both the first and last MDT layers. Specifically, the track is inside if $a < c < b$ and $a < m \cdot L + c < b$, otherwise it is considered *outside*. Here, $a = 410$ mm, $b = 750$ mm, and $L = 1500$ mm is the distance between the first and last MDT layers.

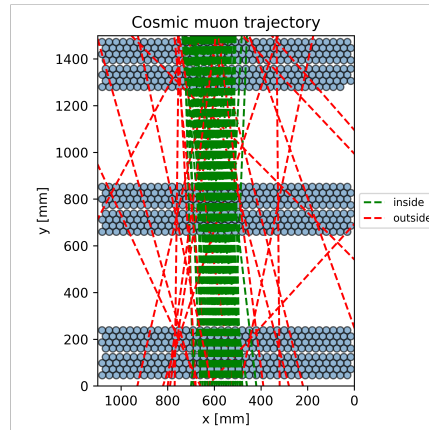


Figure 6.5: Cosmic muon trajectory inside or outside the scintillator range.

7 Conclusion

In this study, we tested the ATLAS Phase-II MDT Trigger Processor using cosmic-ray muons. By mapping hit distributions, we were able to identify detector inefficiencies and determine an appropriate ADC cut to filter out electronic noise. Time offsets were then optimized to correctly align MDT signals with scintillator triggers, allowing us to match coincidences and select the relevant events. The Legendre algorithm was implemented to reconstruct cosmic muon tracks, and the fraction of reconstructed tracks corresponding to the targeted muons was estimated. Together, these steps provide a comprehensive framework for evaluating MDT chamber performance and reconstructing cosmic muon trajectories.

8 Acknowledgments

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