



Master Thesis

Development of a Concept for the Muon Trigger of the ATLAS Detector at the HL-LHC

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Abstract

Highly selective first level triggers are essential to exploit the full physics potential of the ATLAS experiment at the High Luminosity-Large Hadron Collider, where the instantaneous luminosity will exceed the LHC Run 1 instantaneous luminosity by almost an order of magnitude. The ATLAS experiment plans to increase the rate of the first trigger level to 1 MHz at 6 μ s latency. The momentum resolution of the existing first level muon trigger is limited by the moderate position resolution of the trigger chambers. Including the data of the precision Monitored Drift Tube (MDT) chambers in the first level muon trigger decision will increase the selectivity of the first level muon trigger substantially.

Run 1 LHC data with a centre-of-mass energy of $\sqrt{s} = 8$ TeV and a bunch spacing of 25 ns was used to study the achievable selectivity of a muon trigger making use of the MDT data. It could be shown that it is not necessary to fully reconstruct the muon trajectory. The position and direction information of the straight track segments reconstructed in the MDT chambers is sufficient to measure the momentum with a precision that allows for a rate reduction compared to the expected Phase-I trigger rate of over 70 % for the whole ATLAS muon spectrometer.

Fast algorithms employed in the trigger electronics are required for the reconstruction of the track segments within the trigger latency. For the end-cap ($1.05 < |\eta| < 2.4$) the ATLAS collaboration considered a 1-dimensional Hough transform algorithm, which is seeded by the trigger chamber data. The algorithm is not applicable in the barrel region ($0 < |\eta| < 1.05$) because of the lower spatial resolution of the trigger chambers in the barrel region than in the end-cap region. Extending the algorithm to a Binned 2D-Hough Transform, which improves the track segment reconstruction quality sufficiently for all regions apart from the outer barrel MDT chambers. In this thesis, a new track segment finding algorithm, that makes use of tangents to drift radii, was developed and shown to be applicable to the entire muon spectrometer ($|\eta| < 2.4$).

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1

Introduction

New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained.

— Freeman Dyson

Particle physics, claiming a long tradition back to the roots of ancient Greek philosophers, searches for the building blocks of matter and the interactions between its most fundamental constituents. In a first order approximation, matter is composed from atoms. The forces acting between atoms are mostly attributed to the electromagnetic interaction.

By construing the scattering of alpha particles from gold atoms, Ernest Rutherford was able to infer the substructure of the atom from the angular distribution of the alpha particles in 1911 [1]. An atom consists of a massive and dense nucleus in the centre and electrons distributed around the nucleus. While the electron is, to this day, truly considered to be an elementary particle, the nucleus is composed of protons and neutrons, the nucleons, which are subject to the strong interaction. This fundamental force is responsible for the binding of the nuclear constituents. Another scattering experiment at the **S**tanford **L**inear **A**ccelerator **C**enter (SLAC) in the 1970s [2], this time with a momentum transfer high enough to probe the structure of the nucleons, proved that the nucleons also exhibit a substructure of three point-like particles, the quarks.

The fundamental constituents of matter are two groups of spin- $1/2$ fermions: quarks and leptons. The integer charged leptons are subject to the electromagnetic and weak interactions, two appearances of the unifying electroweak interaction [3]. The weak force is responsible for particle decays. The electromagnetic, strong, and weak interactions are formulated as gauge invariant quantum field theories and are imbedded in a theoretical model founded on symmetry principles. This is highly successful in reproducing the values measured by experiment and is simply called the **S**tandard **M**odel (SM). Quarks come with electric charge divided by three and are, in addition to the interactions shared with leptons, strongly interacting. There are six quarks and

six leptons, which can be grouped in three generations, sharing most properties but increasing in mass with each generation. In the framework of quantum field theory, interactions are mediated by spin-1 gauge bosons and take place between particles with a charge belonging to the type of interaction. The existence of an additional scalar Higgs boson is a consequence of the mechanism of spontaneous electroweak symmetry breaking, which allows massive electroweak gauge bosons and massive elementary fermions preserving the gauge invariance of the theory [4–7].

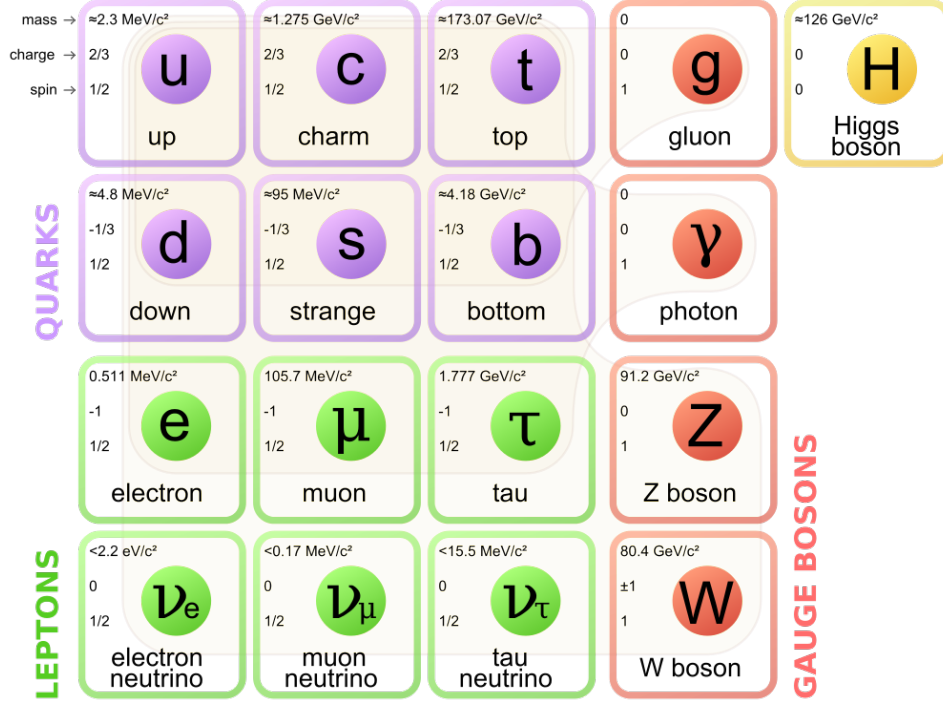


Figure 1.1: Particle content of the Standard Model [8].

Of special interest in this thesis are the muons, particles similar to the electron but with much greater mass $m_\mu = 105.7 \text{ MeV}$ and an eponymous mean life $\tau = 2.2 \mu\text{s}$ [9], which are well detectable indicators for many interesting electroweak processes.

Continuing the fruitful tradition of scattering experiments, the **L**arge **H**adron **C**ollider (LHC) is the most advanced particle collider, located at the European Centre for Particle Physics CERN. The largest of the four LHC experiments is the ATLAS detector. The discovery of the Higgs boson in 2012 [10] by the ATLAS and CMS collaborations at CERN constitutes a remarkable corroboration of the SM.

To let the the prospects of discovery thrive even further, the LHC and its experiments will be subject to an upgrade increasing the luminosity about an order of magnitude.

In the context of the **H**igh-**L**uminosity **L**HC (HL-LHC), this thesis focuses on the technology employed in the outermost part of the detector, responsible for the precise detection of muons: **M**onitored **D**rift-**T**ube (MDT) chambers. Two questions are addressed in the course of discussion:

How much does the inclusion of the MDT chambers in the first level trigger decision improve the selectivity of the trigger and hence allow for the reduction of the muon trigger rate without compromising the physics programme?

In this first part of the thesis it will become apparent that the much higher momentum resolution of the MDT precision detectors compared to the trigger chambers will prove as indispensable for the predicted rates at the HL-LHC. This motivates the second question, which is of more practical nature:

What is the most effective strategy to reconstruct muon track segments in MDT chambers?

The limiting constraint is the time window allocated for pattern finding and track segment reconstruction, which sets the need for a fast track reconstruction algorithm on trigger level. The segment reconstruction has to match the precision required for the improvement in trigger selectivity.

2

The ATLAS experiment at the Large Hadron Collider

2.1 The Large Hadron Collider

The LHC [11] is the world's largest synchrotron particle accelerator, designed to collide proton beams at a centre-of-mass energy of $\sqrt{s} = 14$ TeV with an instantaneous luminosity of $\mathcal{L} = 1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and heavy ion ($^{208}_{82}\text{Pb}$) beams at a centre-of-mass energy of $\sqrt{s} = 2.76$ TeV per nucleon with an instantaneous luminosity of $\mathcal{L} = 1 \times 10^{27} \text{ cm}^{-2} \text{ s}^{-1}$. It is operated at the European Centre for Particle Physics CERN near Geneva and is located in the tunnel formerly host of the Large Electron Positron Collider (LEP) with a circumference of 26.7 km in a depth of 50 m to 175 m. The pre-accelerator chain of its predecessor shown in Figure 2.1 is being reused, listed in order of increasing centre-of-mass energy consisting of the LINAC2, the BOOSTER, the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS).

The LHC beam is held on track by 1232 superconducting dipole magnets operated at a temperature of 1.9 K with magnetic field strengths of up to 8.3 T and powered by radio frequency cavities with an electric field strength of up to 5.5 MV/m. The proton beams are not continuous but structured in 2808 bunches of about 10^{11} protons each which collide every 25 ns at one of the four interaction points, where the experiments are located.

The LHC hosts complementary experiments to pursue a rich physics programme. The multi-purpose experiments ATLAS [13] and CMS [14], which are situated at opposite sides of the ring, perform high-precision tests of the SM of strong and electroweak interactions and searches for physics beyond the SM. In 2012 both experiments announced the discovery of a Higgs boson [10, 15]. To this day, measurements of the Higgs boson's properties show no significant deviations from the SM expectations [16–21].

The physics programme of these experiments is complemented by the LHCb exper-

CERN's Accelerator Complex

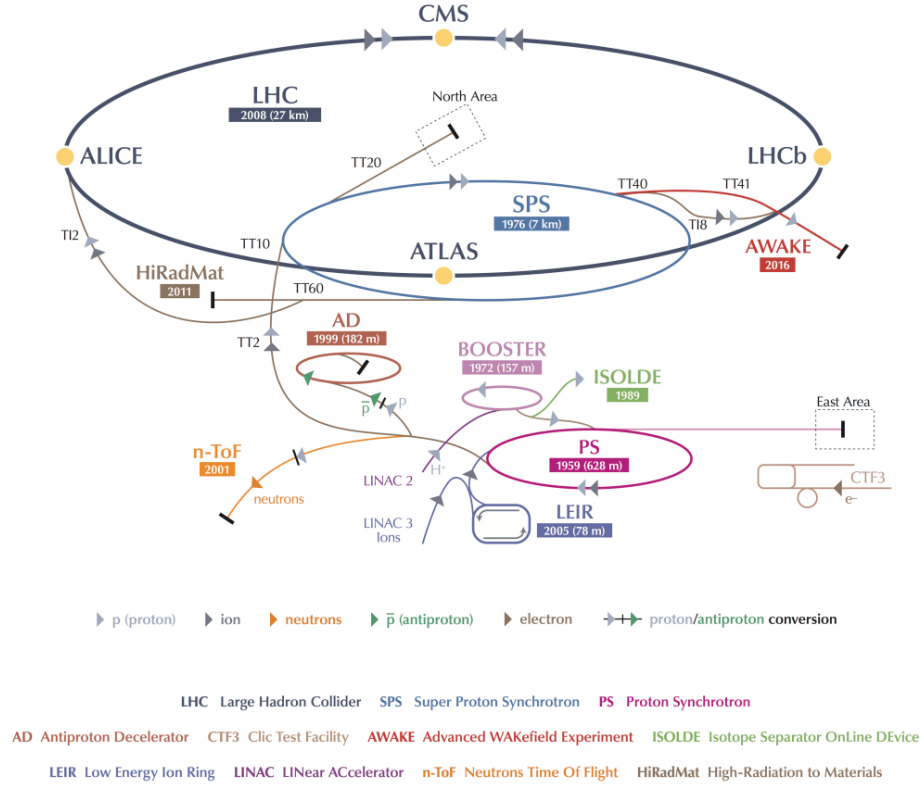


Figure 2.1: The CERN accelerator complex showing the succession of machines that accelerate the proton bunches to the final energy at the LHC [12].

iment [22], which studies CP violation and the physics of heavy flavour hadrons, including rare B meson decays searches for new hadrons. The ALICE experiment [23] studies the quark-gluon plasma in heavy ion collisions.

To achieve the physics goals, two quantities of equal importance have to be considered: a high centre-of-mass energy and a high event rate. A high centre-of-mass energy is desired to produce yet undiscovered phenomena which usually have tiny cross sections σ , while a high event rate, corresponding to a high luminosity $\mathcal{L} = \frac{1}{\sigma} \dot{N}$, is required to become sensitive to them.

The centre-of-mass energy is limited by the circumference of the accelerator and

the bending-power of the dipole magnets. The integrated luminosity increases with operation time of the LHC, while the instantaneous luminosity of the LHC can be increased with upgrades, resulting in a faster accumulation of data.

2.1.1 Upgrades to the High-Luminosity LHC

Several luminosity upgrades are envisaged in the course of upgrading the LHC to the **High Luminosity LHC** (HL-LHC). The planned upgrade schedule is outlined in Figure 2.2. In the current Run 2 the LHC is operated slightly below its design energy delivering pp collisions at 13 TeV centre-of-mass energy.

The Phase-I upgrade of the LHC injectors during the so-called Long Shutdown 2 is scheduled from 2019 to 2020 with aim of reaching the 14 TeV centre-of-mass energy and increasing the instantaneous luminosity by a factor of three.

The Phase-II upgrade, taking place between 2024 and 2026, will eventually complete the increase in luminosity leading to the HL-LHC with a peak luminosity of $\mathcal{L} = 7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and an integrated luminosity of 250 fb^{-1} per year made possible by installation of new elements including new focussing magnets and crab cavities. This final luminosity corresponds to an expected mean number of 200 interactions per bunch crossing [24].

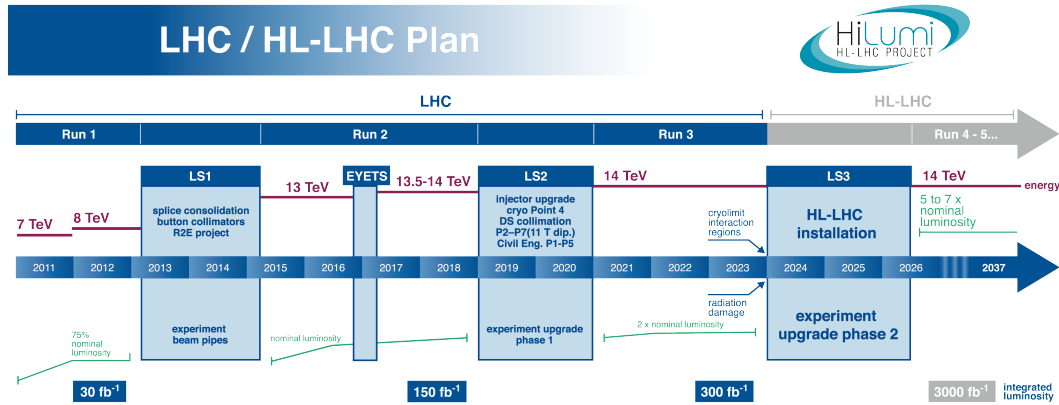


Figure 2.2: Upgrade schedule for the LHC/HL-LHC showing shutdown- and data-taking-periods with intended instantaneous luminosity and centre-of-mass energy [25].

2.2 The ATLAS experiment

Together with the LHC, its detectors will be subject to several upgrades to prepare them for higher rates. In this section the ATLAS experiment [13] in its original design will be introduced. Then, the planned upgrades of the Muon Spectrometer will be discussed.

The ATLAS detector is a multi-purpose particle physics apparatus with forward-backward symmetrical cylindrical geometry with a length of 44 m and a diameter of 25 m. It achieves almost 4π coverage in solid angle. The structure of the detector is shown in Figure 2.3.

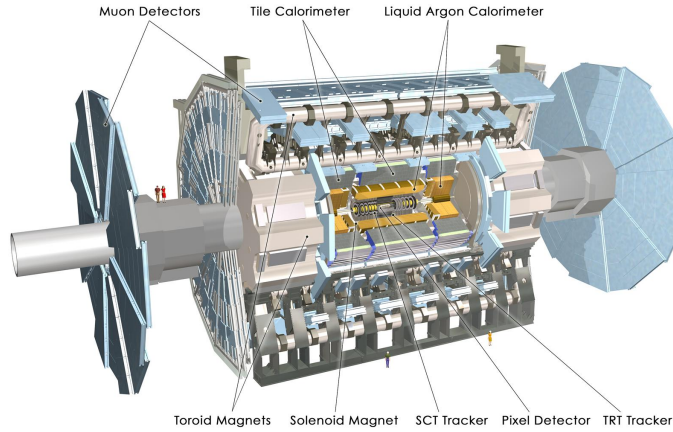


Figure 2.3: Schematic view of the ATLAS detector and its subsystems [26].

ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector. The z -axis points along the beam pipe, the x -axis points from the IP to the centre of the LHC ring, and the y -axis points upward. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ as $\eta = -\ln \tan(\theta/2)$. Angular distances are defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Energies and momenta are specified in natural units, $\hbar = c = 1$.

The detector consists of four main sub-systems, starting with the innermost component: **I**nnner **D**etector (ID), **E**lectromagnetic **C**ALorimeter (ECAL), **H**adronic **C**ALorimeter (HCAL) and **M**uon **S**pectrometer (MS). They are introduced briefly in the following. A detailed description of the ATLAS detector can be found in Ref. [13].

2.2.1 The Inner Detector

The ID, shown in Figure 2.4, provides high precision tracking of charged particles and vertexing to their origin to the experiment. The innermost 12 cm radial distance from the beam line are covered by the silicon pixel detector, where three layers of silicon pixel modules make up 8×10^7 readout channels. At larger radii up to 52 cm, less fine resolution is needed, enabling the use of four layers of silicon strip detectors in the silicon micro-strip tracker with 6.3×10^6 read-out channels. These two detectors can measure tracks up to $|\eta| = 2.5$ in the solenoidal magnetic field of 2 T. Surrounding the semiconductor detectors, the transition radiation straw tube tracker covering $|\eta| < 2.0$ constitutes the outermost part of the ID operating with 3.4×10^5 read-out channels. For a region with minimal material budget in $0.25 < |\eta| < 0.50$, the resolution of the transverse impact parameter is $\sigma_{d_0} = 10 \mu\text{m}(1 \oplus 14 \text{ GeV}/p_T)$ and the resolution of the longitudinal impact parameter is $\sigma_{z_0 \times \sin \theta} = 91 \mu\text{m}(1 \oplus 2.3 \text{ GeV}/p_T)$ for pions [13]. The vertex resolution of the ID for 20 tracks is $25 \mu\text{m}$ in $R - \phi$ plane and $50 \mu\text{m}$ in z direction [27].

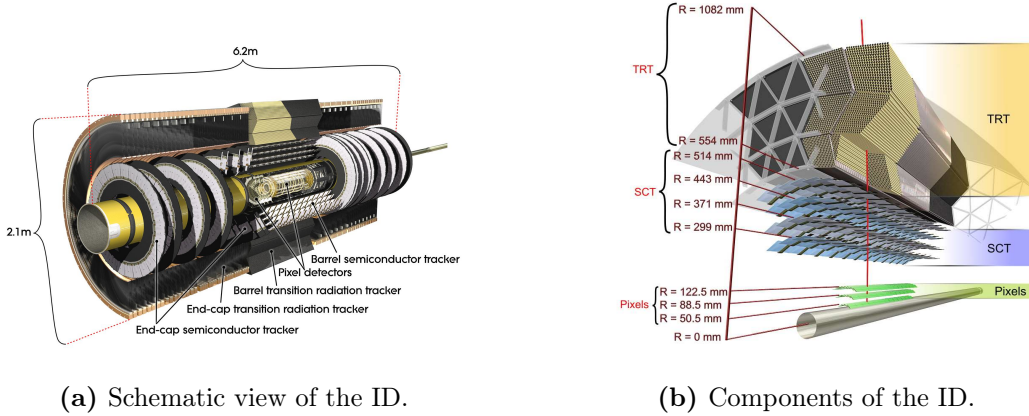


Figure 2.4: Illustrations of the ATLAS ID [28].

2.2.2 The Calorimeter System

The calorimeter system, as shown in Figure 2.5, encloses the ID and covers the pseudorapidity range $|\eta| < 4.9$. The high-granularity liquid-argon (LAr) sampling ECAL is divided into one barrel ($|\eta| < 1.475$) and two end-cap components ($1.375 < |\eta| < 3.2$) with an energy resolution of $\frac{\sigma_E}{E} = \frac{10\%}{\sqrt{E}}$. The HCAL, a steel/scintillator-tile calorimeter, follows in radial direction and provides hadronic coverage in the range $|\eta| < 1.7$ with an energy resolution of $\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}}$. The end-cap and forward regions,

spanning $1.5 < |\eta| < 4.9$, are instrumented with liquid-argon calorimeters with an energy resolution of $\frac{\sigma_E}{E} = \frac{100\%}{\sqrt{E}}$.

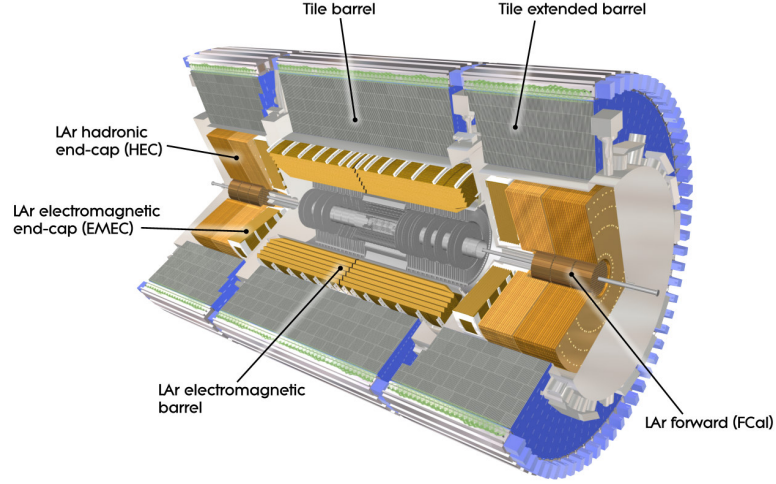


Figure 2.5: Schematic view of the Calorimeter System [29].

2.2.3 The Muon Spectrometer

The calorimeters are surrounded by the muon system. The MS is based on three large air-core super-conducting toroidal magnets, one in the barrel region (with bending-power of $1.5 \text{ T m} < \int B dl < 5.5 \text{ T m}$) and two in the end-caps (with bending-power of $1.0 \text{ T m} < \int B dl < 7.5 \text{ T m}$), providing a magnetic field orthogonal to the direction of the muon tracks. In the central region, the detector comprises a barrel ($|\eta| < 1.05$) that is arranged in three concentric cylindrical shells of muon chambers around the beam axis. In the end-cap region ($1.05 < |\eta| < 2.7$), muon chambers form three wheels perpendicular to the z-axis, called Small Wheel, Big Wheel and Outer Wheel. The detector elements are grouped in large and small chambers, each arranged in eight-fold symmetry around the beam axis. Several detector technologies, as shown in Figure 2.6, are utilised to provide both precision tracking and triggering.

The Level-1 muon trigger makes use of three layers of **R**esistive **P**late **C**hambers (RPCs) in the barrel region ($|\eta| < 1.05$), and three layers of **T**hin **G**ap **C**hambers (TGCs) in the end-cap regions ($1.05 < |\eta| < 2.4$). The trigger chambers provide trigger signals and coarse tracking for **R**egions of **I**nterest (RoI) defined in η and ϕ . They complement the precision position measurement of the radial and η coordinate with the ϕ coordinate. The precision position measurement of the muon trajectories

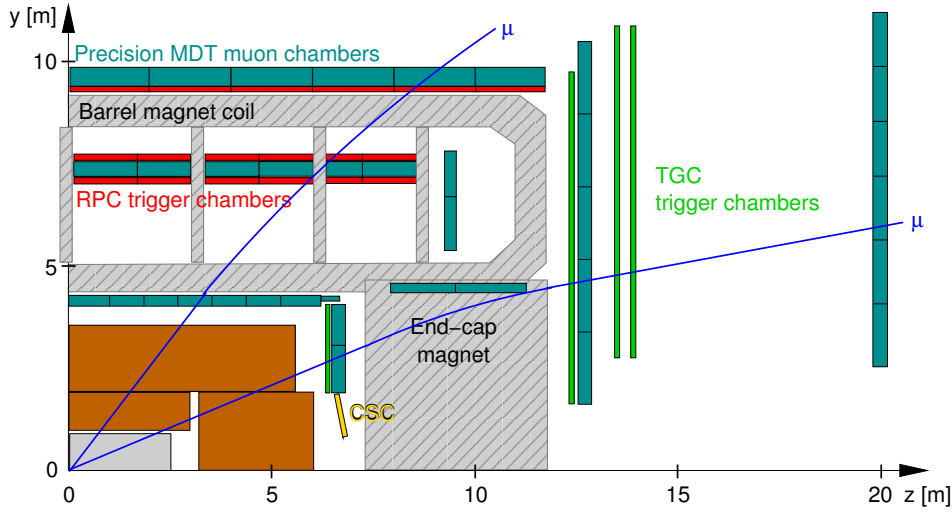


Figure 2.6: Profile schematic view of a quadrant of the MS [30].

(tracks), which are deflected in the magnetic field, is performed using hits in three layers of precision MDT chambers for $|\eta| < 2$. In the region $2.0 < |\eta| < 2.7$, Cathode Strip Chambers (CSCs) are used.

The MS provides a stand-alone muon momentum resolution of $\sigma_{p_T}/p_T < 10^{-4} \frac{p}{\text{GeV}}$ for muon transverse momenta of $p_T > 300 \text{ GeV}$, $\sigma_{p_T}/p_T < 3\%$ for $p_T < 300 \text{ GeV}$ and $\sigma_{p_T}/p_T = 10\%$ for $p_T < 1 \text{ TeV}$. The resolution in the lower momentum range is limited by energy loss fluctuations in the calorimeter and by multiple scattering. A detailed account of the contributions to the momentum resolution in the MS is given in Section 4.1.

The Monitored Drift-Tube Chambers

The centrepiece of the precision muon measurement in the ATLAS detector are the over 1200 MDT chambers, each different in shape and length depending on the position in the detector. The mechanical structure of a chamber and a cross-section of a single tube are shown in Figure 2.8. Each chamber is equipped with a RASNIK optical alignment system, which monitors mechanical deformations of the chambers and movements of the chambers with respect to each other.

An MDT chamber consists of two multi-layers with three or four layers of drift tubes per multilayer. The drift tubes are made of aluminium with a tungsten-rhenium anode wire in the centre. The main specifications of the ATLAS MDT detectors [31] are listed in Table 2.1.

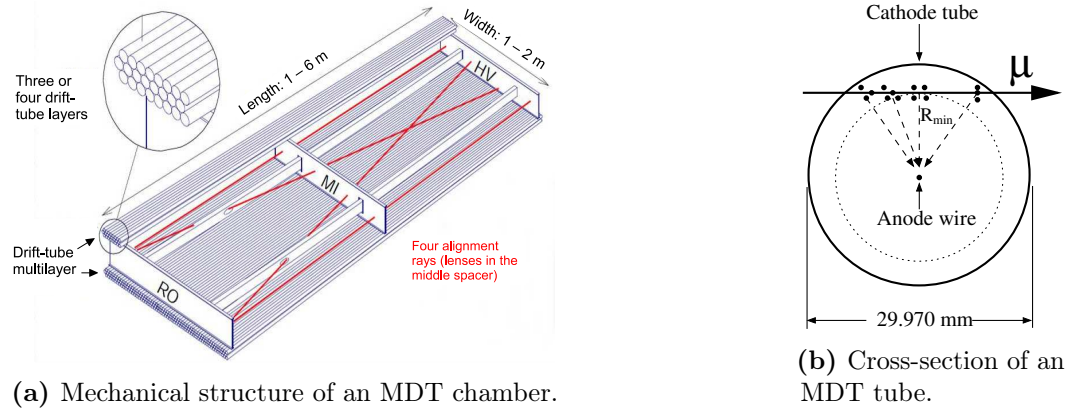


Figure 2.7: Illustrations of the ATLAS MDT chambers [13].

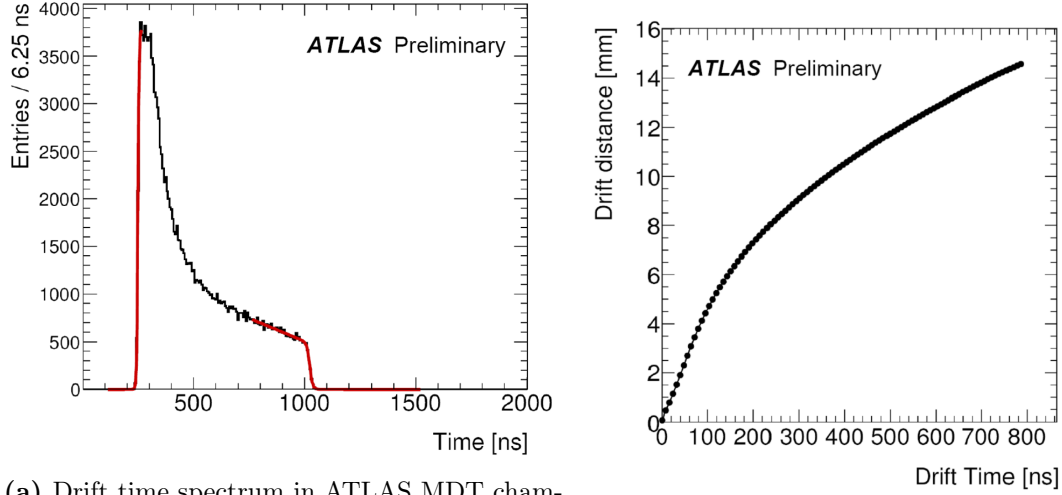
Table 2.1: MDT parameters

Parameter	Value
Tube diameter	29.97 mm
Tube wall thickness	0.4 mm
Gas mixture	Ar:CO ₂ (93% : 7%)
Gas pressure	3 bar (absolute)
Wire potential	3080 V
Maximum drift time	700 ns

The principle of operation is illustrated in Figure 2.7b. A muon traverses the drift tube and ionises argon atoms along its track. A muon with $p_T = 100$ GeV creates on average about 100 clusters per cm containing typically three ionisation electrons [32].

The electric field inside the tubes pulls the ionisation electrons to the central wire, which is the anode, while the ions drift to the tube wall. The electric field is proportional to $1/r$, such that the field in the vicinity of the anode wire is large enough to trigger an avalanche of secondary electrons leading to the amplification of the primary ionisation charge. The amount of the amplification, the so-called gas gain, is 2×10^4 for the MDT tubes used in ATLAS. The ions of the avalanche drifting to the tube walls induce a measurable signal. The time between primary ionisation and the arrival of the primary ionising particles is called the drift time. A typical drift-time spectrum is shown in Figure 2.8a. With a calibrated space-to-drift-time ($r-t$) relation, as shown in Figure 2.8b, the drift time can be converted into the drift radius which is a measure of the distance of the muon track from the anode wire. The muon can also knock out an electron from an atom in the tube wall, which is then called δ -electron.

A δ -electron can pass the tube at a shorter distance to the wire than the muon and mask the muon hit.



(a) Drift time spectrum in ATLAS MDT chambers [33]. The red lines show fits to the leading and falling edges of the drift time spectrum. (b) Space time relationship of the ATLAS MDT chambers [33].

Figure 2.8: Drift time spectrum and r - t -relation

Each MDT chamber is uniquely identified by six parameters $[B][I][L][X][A][Y]$.

1. $B \in \{B, E\}$ denotes whether the chamber belongs to the barrel or the end-cap.
2. $I \in \{I, M, O, E\}$ denotes the position of the chamber, which can belong to the **I**nner, **M**iddle, **O**uter or **E**xtended shell of the MS.
3. $L \in \{S, L, F, G, R, M\}$ denotes the type of the chamber, which can be **S**mall, **L**arge, or a special type as shown in Figures 2.9 and 2.10.
4. $X \in \{1, 2, 3, 4, 5, 6, 7, 8\}$ denotes to which η station the chamber belongs.
5. $A \in \{A, B, C\}$ denotes the detector side, where in the ATLAS coordinate system A stands for $z > 0$, B stands for $z = 0$ and C stands for $z < 0$.
6. $Y \in \{1, 2, \dots, 16\}$ denotes the sector, where sector 1 corresponds to the positive x-axis.

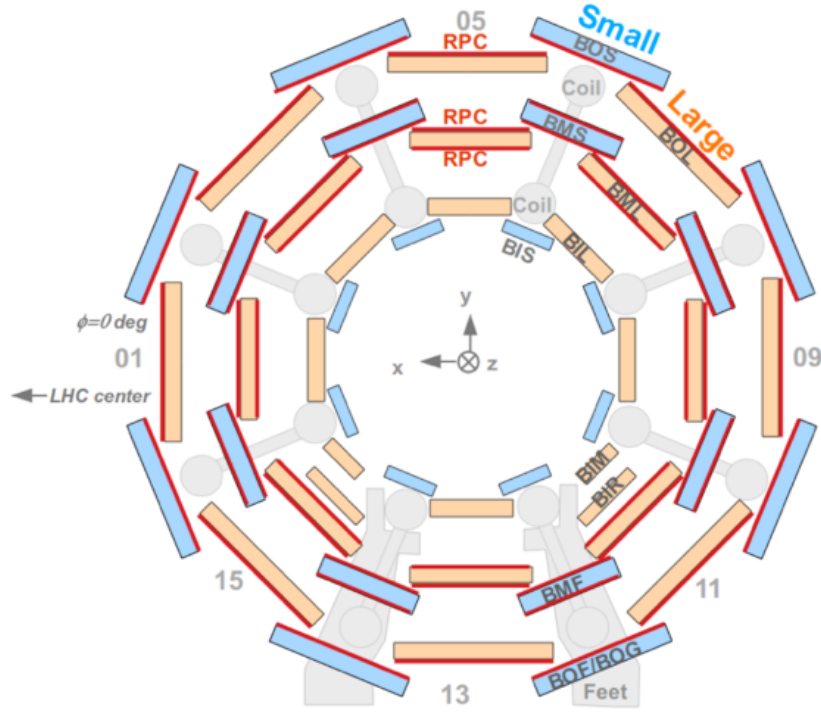


Figure 2.9: Cross-sectional view of the barrel muon spectrometer perpendicular to the beam axis [34]. The MDT chambers in large (small) sectors are shown in orange (light blue), the RPC chambers are shown in red. The eight coils are also visible.

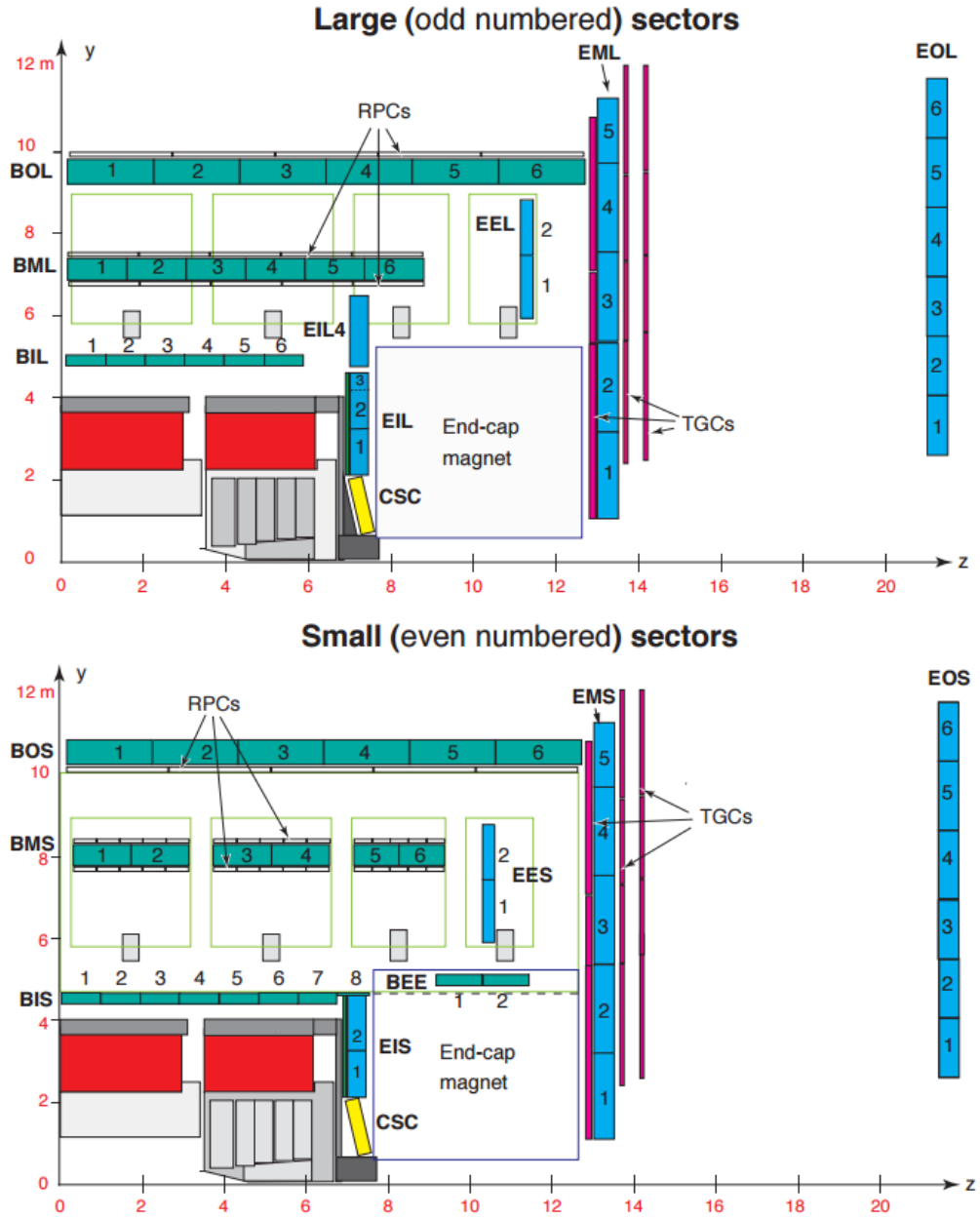


Figure 2.10: Schematic side view of the ATLAS muon spectrometer depicting the naming and numbering scheme [31].

2.3 ATLAS upgrades for high luminosities

To maintain its capabilities and profit from increased centre-of-mass energy and high rates provided by the HL-LHC, a major detector upgrade of the ATLAS experiment is planned, proceeding in three phases.

The first step of the upgrade, known as Phase-0, has already taken place during **Long Shutdown 1 (LS1)**. An additional pixel layer was inserted at a radius of 3.2 cm from the beam line together with a smaller beam pipe of 2.4 cm of inner radius, which will help to improve identification of short-living particles like jets with b-hadrons or tau leptons. New small diameter **MDT** (sMDT) chambers with half the tube diameter (15 mm) of the standard MDT chambers were installed to improve detection efficiency at $1.0 < |\eta| < 1.3$.

In Phase-I of the upgrade, which will take place during LS2, the installation of the **New Small Wheel (NSW)** will replace the current Small Wheel in the forward region of the detector [35]. The NSW will employ small strip TGC high-resolution trigger chambers to reject fake muon triggers and improve the momentum resolution at trigger level, which is shown in Figure 2.11.

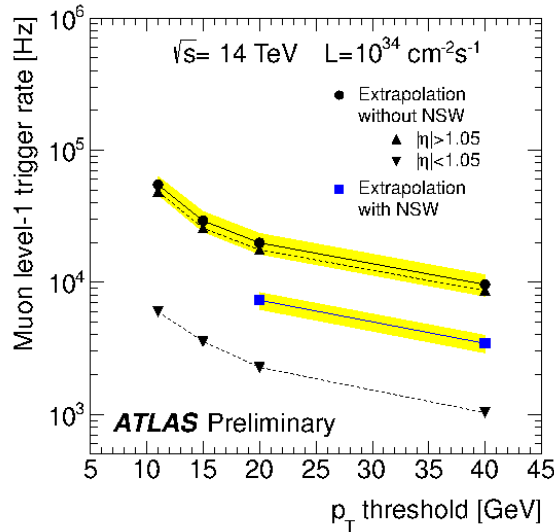


Figure 2.11: Estimated reduction of the Level-1 trigger rate by the NSW [36].

MicroMega gaseous micro-pattern detectors will be used for triggering and precision tracking. A dedicated hardware-based track finder, which will make use of the full pixel detector information will be implemented to improve the Level-2 trigger. Upgrades of the calorimetry system will improve the segmentation in the front and middle ECAL

sampling layers providing a better discrimination of electrons and jets. Inside the barrel toroid coils at the boundary between barrel and end-caps 16 new muon stations will be installed. These are integrated sMDT-RPC chambers, which will improve the muon trigger selectivity and to increase the high-rate capability.

The final step of the upgrade process, Phase-II, will take place during LS3. The increased luminosity and accumulated radiation damage will render the current ID no longer suitable for operation. Already for $\mathcal{L} = 5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ the straw tube TRT will be fully occupied by background. The ID will be replaced by a new all-silicon tracker, based on a new layout featuring high granularity, improved material budget, and increased radiation hardness. The design consists of four pixel layers and six strip layers in the barrel part and six pixel and seven strip double-sided disks in each of the two end-caps to provide pattern recognition and precise position measurements close to the vertex. A new read-out scheme will allow the implementation of a track trigger improving the ATLAS triggering capabilities. The calorimeters will receive new front- and back-end electronics, as these are subject to significant radiation exposure and have to meet the increased radiation tolerance requirement for higher background.

The upgrades concerning the MS [30] are discussed in more detail given their relevance for this thesis. They are summarised in the schematic drawing in Figure 2.12.

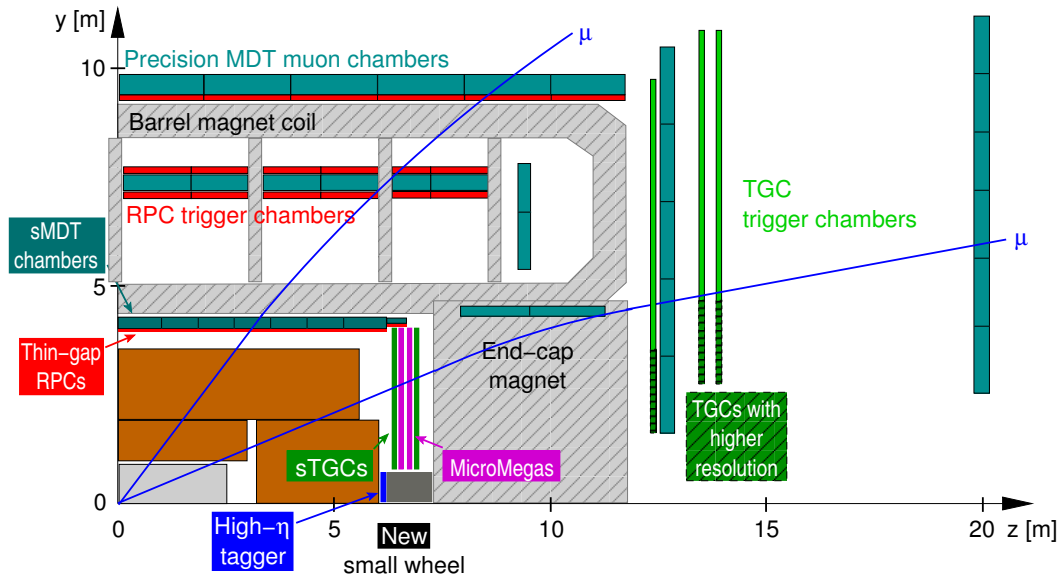


Figure 2.12: Schematic drawing of a quadrant of the ATLAS muon spectrometer illustrating the planned upgrades of the MS [30].

In the outer and middle layers of the barrel the replacement of MDT and RPC electronics compatible with the expected rates is envisaged. For safe operation ensuring

the longevity of the RPC chambers, their operating voltage has to be reduced, which leads to inefficiencies in the trigger. To recuperate the reduced muon trigger efficiency and to close acceptance gaps in the detector layout, additional thin-gap RPCs with over four times better high-rate capability than the present RPC chambers will be installed in the inner barrel layer. This requires the replacement of the MDT chambers with sMDT chambers, which have a 10 times better high-rate capability than the present MDT chambers, to free space for the RPCs. The replacement of MDT electronics in the inner layer is challenging because of the proximity to the toroid magnet coils, but necessary to make full use of the trigger scheme presented in this thesis.

The installation of a high- η tagger in the immediate vicinity of the NSW is planned to identify muons up to $|\eta| = 4.0$. The Big Wheel will be equipped with small strip TGCs, providing higher resolution in the region close to the beam pipe at $|\eta| \sim 2.7$ to cope with background. The MDT electronics needs to be replaced to include the MDT data in the trigger decision.

2.4 Expected background rates in the Muon Spectrometer at the HL-LHC

The majority of hits in the MDT chambers are caused by background radiation. The background sources in the MS can be classified in two categories [37]:

1. Correlated background: consists of primary collision products penetrating into the muon spectrometer through the calorimeters, which are correlated in time with the p-p interaction. At small $p_T < 10$ GeV the background is dominated by semileptonic decays of pions and kaons, while at moderate $p_T > 10$ GeV heavy flavours and gauge boson decays also contribute. Other correlated background sources are shower muons and hadronic punch-through.
2. Uncorrelated background: consists mostly of neutrons and photons in the 1 MeV range originating from secondary interactions of proton collision products.

The uncorrelated background is the main source of background for the MDT chambers. Expected background rates for the HL-LHC luminosity of $\mathcal{L} = 7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ in the ATLAS MS [38] are shown in Figure 2.13. They are also listed in Table 3 and Table 4 in the Appendix.

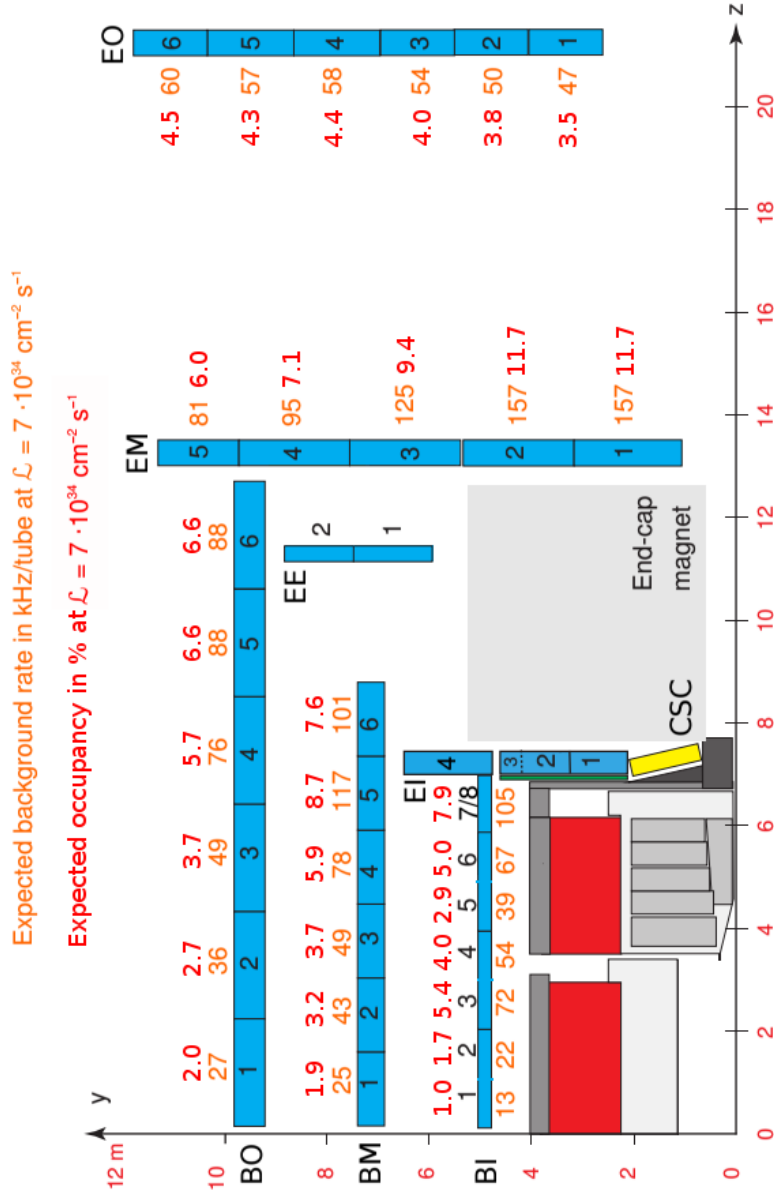


Figure 2.13: Expected background rates per tube and occupancy for $t_{\text{Drift}} = 750 \text{ ns}$ in the ATLAS muon chambers per drift tube at $\sqrt{s} = 8 \text{ TeV}$, adapted from Ref. [39]. The rates are extrapolated from 2012 data to the expected HL-LHC luminosity of $\mathcal{L} = 7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [38]. The uncertainty on the background rates is approximately 10%.

3

A new Level-0 Muon Trigger for the HL-LHC

3.1 Design of the ATLAS Level-1 trigger in Run-1

With a bunch spacing of 25 ns, individual proton collisions take place in the LHC with a frequency of 1×10^9 Hz [13], while the assumed production rate of rare events, such as Higgs production, is of the order of 1×10^{-2} Hz to 1×10^{-5} Hz, which is shown in Figure 3.1.

Since the data storage rate is limited to 300 kHz, a highly selective trigger system is needed to select rare events out of an extremely high background, which is realised as a staged trigger system in ATLAS.

Before introducing the concept for a new Level-0 Muon Trigger for the High-Luminosity Large Hadron Collider, the trigger scheme adapted in Run-1 [13] is discussed, which is shown in Figure 3.2.

The ATLAS trigger consists of **Level-1** (L1) trigger, **Level-2** (L2) trigger and the **Event Filter** (EF). L1 is a hardware-based trigger level, which uses FPGAs¹ and ASICs² to identify Regions of Interest for further processing with the larger granularity of the muon system and calorimeter information synchronous to the LHC bunch structure. It is based on hit coincidences of the RPC and TGC detector layers within defined geometrical regions, which define the muon transverse momentum as one of six different trigger thresholds. Figure 3.3 shows a block diagram of the ATLAS **Level-1** (L1) trigger in the present status. The overall L1 accept decision is made by the central trigger processor, which takes input from the calorimeter and muon triggers. With a latency of 2.2 μ s the rate is reduced from 1 GHz to 75 kHz.

L2 is seeded by the L1 candidates to find physics objects such as electrons, muons,

¹Field Programmable Gate Array

²Application-Specific-Integrated-Circuit

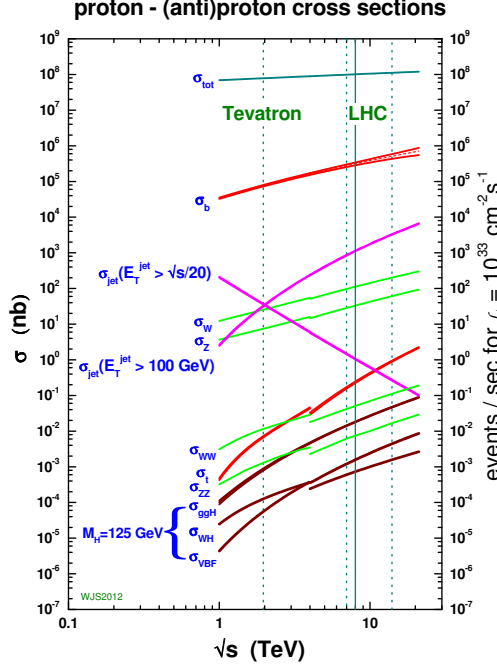


Figure 3.1: Standard Model cross sections as a function of collider energy [40].

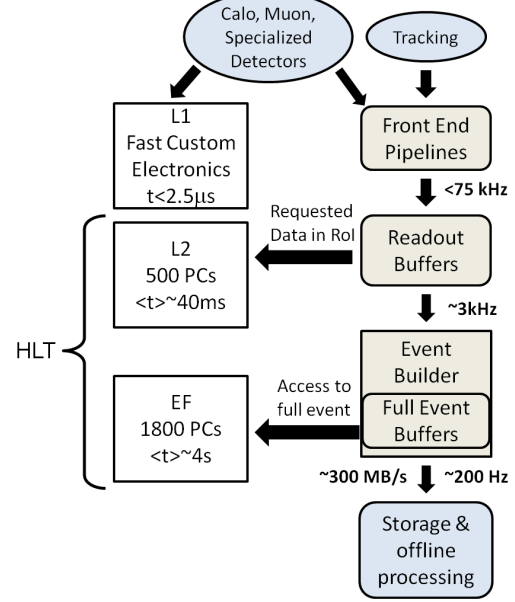


Figure 3.2: Schematic diagram of the ATLAS trigger system [41].

photons, taus, jets or missing energy with reduced event information within the RoIs defined by the L1 trigger information. Only the combined detector data within the RoI is processed, allowing for fast reconstruction with a latency of 40 ms. L2 further reduces the rate to ~ 2 kHz.

EF has access to the full event information with full granularity of all detectors and performs a fast data analysis based on the information passed by L2. The average execution time is 4 s. The accepted events are written to mass storage with a rate of 300 kHz.

The first trigger stage is ATLAS' bulwark against the multitude of events. When increasing the event rate in the LHC, clearly the first trigger stage has to be fortified by improving its selectivity to maintain an accept rate usable by the higher trigger stages. The improvement of the muon trigger can contribute to this goal. The selectivity is quantified by the trigger efficiency, which is defined as the fraction of muons with a certain transverse momentum, which are accepted by the trigger. Ideally, the functional form of the trigger efficiency in dependence of the muon momentum, the so-called turn-on curve, has the form of a Heaviside step function centred on the

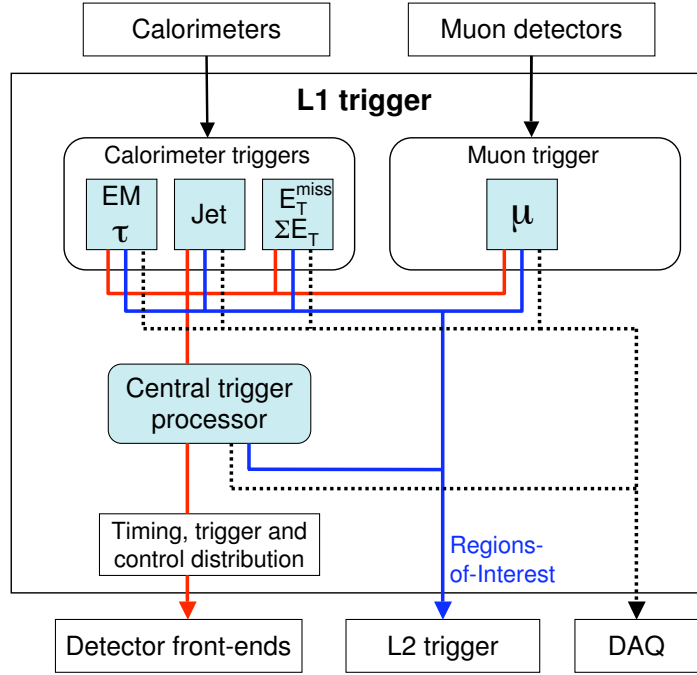


Figure 3.3: Block diagram of the L1 trigger. The paths to the detector front-ends, Level-2 trigger, and the data acquisition system are shown from left to right in red, blue, and black respectively [13].

trigger threshold. Because of the finite momentum resolution of L1 it is widened in shape similar to a Fermi function for temperatures above absolute zero.

Figure 3.4 shows the (barrel) L1 trigger efficiency in dependence of p_T , ϕ and η . The trigger threshold indicated by the label MU20, whose turn-on curve saturates at $p_T = 20$ GeV is a strong candidate for operation at the HL-LHC. The lower trigger efficiency for the high- p_T thresholds is due to reduced RPC coverage in the outer detector layers, which are used for the three high- p_T thresholds.

The inefficiencies of the barrel trigger in ϕ and η are due to lower detector coverage. Most striking is the region $-2 < \phi < -1$, where the reduced efficiency is caused by the mechanical support of the ATLAS detector. The efficiency of small sectors is smaller because of the toroid mechanical structure affecting the detector coverage.

Also in Figure 3.4d, the reduced RPC detector coverage in η regions, where the barrel toroid mechanical structures and the ATLAS feet support are located, is well apparent.

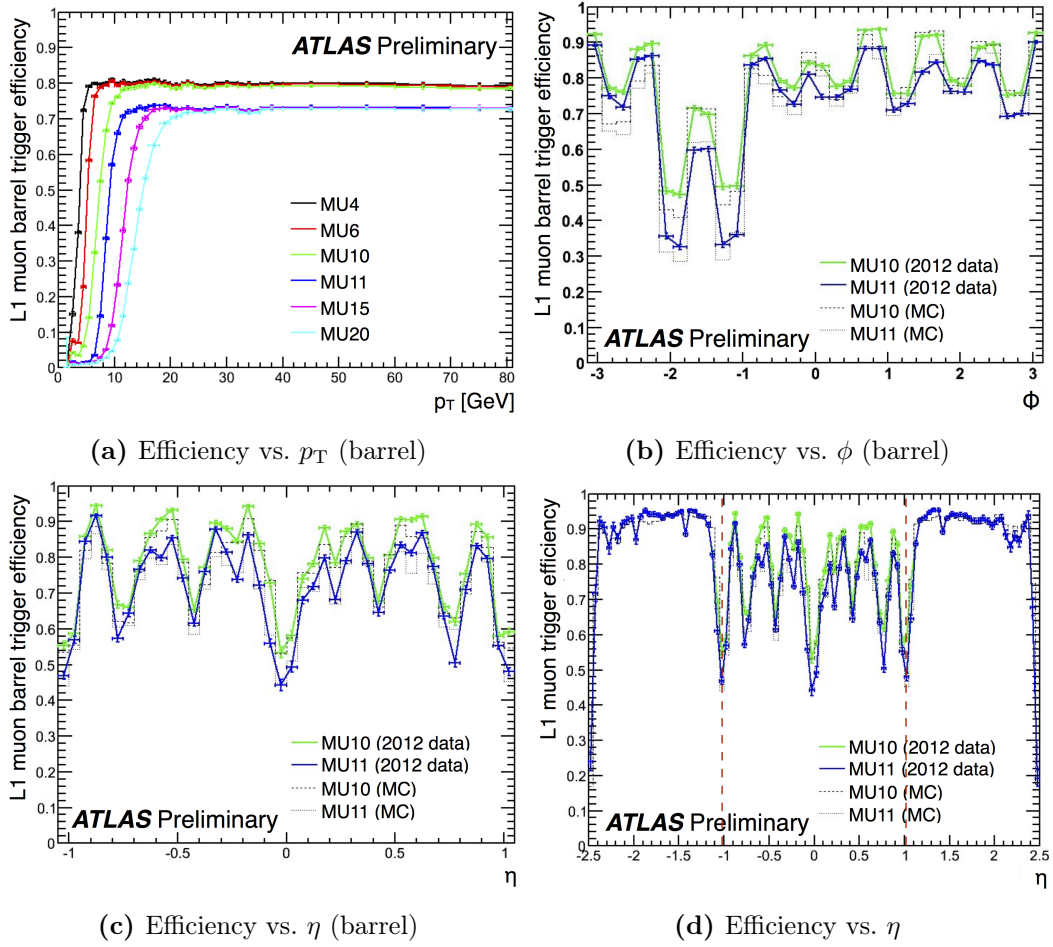


Figure 3.4: L1 muon trigger efficiency for different thresholds [42].

The upgrade towards higher luminosities, which was discussed in Section 2.3, includes the installation of additional detectors to increase the covered area. However, it remains vitally important to refine the trigger selectivity to exploit the high rate environment at the HL-LHC for high prospects of discovery.

3.2 Requirements of the muon trigger for the HL-LHC

The HL-LHC upgrade will allow for precision measurements of standard model processes and it will highly increase the sensitivity of searches for rare processes. To give two examples, searches for complex supersymmetry cascade decays and measurements of the Higgs couplings will be significantly improved by a large data sample. The availability of additional rare channels, such as $H \rightarrow \mu\mu$, the vector boson fusion production of $H \rightarrow \gamma\gamma$ and $H \rightarrow \tau\tau$, the associated production with a top pair $t\bar{t}H$ with $H \rightarrow \gamma\gamma$ will improve limits on new physics that can be inferred from loops and increase measurement precision of fermion couplings [43].

In both cases triggering and reconstruction of low p_T leptons is indispensable. The relatively low mass of the Higgs boson discovered in 2012 makes it necessary to maintain p_T thresholds at around 20 GeV for single lepton triggers to preserve the acceptance of key signatures such as W and Z bosons and $t\bar{t}$ pairs. The acceptance for muons from $t\bar{t}$, WH and supersymmetry processes would also suffer a reduction between 1.3 and 1.8 when increasing the trigger threshold from 20 GeV to 30 GeV [43]. Thus the physics goals suggest maintaining trigger thresholds at around 20 GeV to ensure sufficient flexibility to adapt to emerging physics scenarios.

The anticipated L1 trigger rates for Phase-II at HL-LHC luminosities are stated in Table 3.1, which are based on the Phase-I hardware system and are partially extrapolated from the trigger budget in 2012.

Table 3.1: Estimates for the anticipated L1 trigger rates at $\mathcal{L} = 7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, based on the Phase-I hardware system. The tau trigger rate is the exclusive rate. The estimated rates for the JET and MET triggers are based on an extrapolation of the fraction of the trigger budget used for these triggers in 2012 [43].

Trigger	Estimated L1 Rate
EM_20 GeV	200 kHz
Mu_20 GeV	>40 kHz
Tau_50 GeV	50 kHz
di-lepton	100 kHz
JET + MET	~ 100 kHz
Total	500 kHz

The total trigger rate of 500 kHz for the trigger items listed in Table 3.1 is the minimum required trigger rate for the physics programme at the HL-LHC. In order to be able to loosen trigger conditions to widen the acceptance for rare processes the first level trigger of the ATLAS experiment is designed to operate at a trigger rate up to 1 MHz at a latency of 6 μs [43].

3.3 Composition of the trigger rate

Before addressing the new muon trigger concept, the composition of the trigger rate is reviewed to identify ways of improvement. Figure 3.5a shows the distribution of first-level muon triggers for a 10 GeV transverse momentum threshold as a function of η in LHC Run 1 data. The trigger rate is dominated by triggers in the end-cap regions ($|\eta| > 1.05$). A large fraction of these triggers are caused by charged particles, mainly protons emerging from the radiation shielding and the materials of the end-cap toroid into the muon system where they leave traces in the TGCs behind the toroid magnet which look like high- p_T muons from the interaction point (cf. Figure 3.5b).

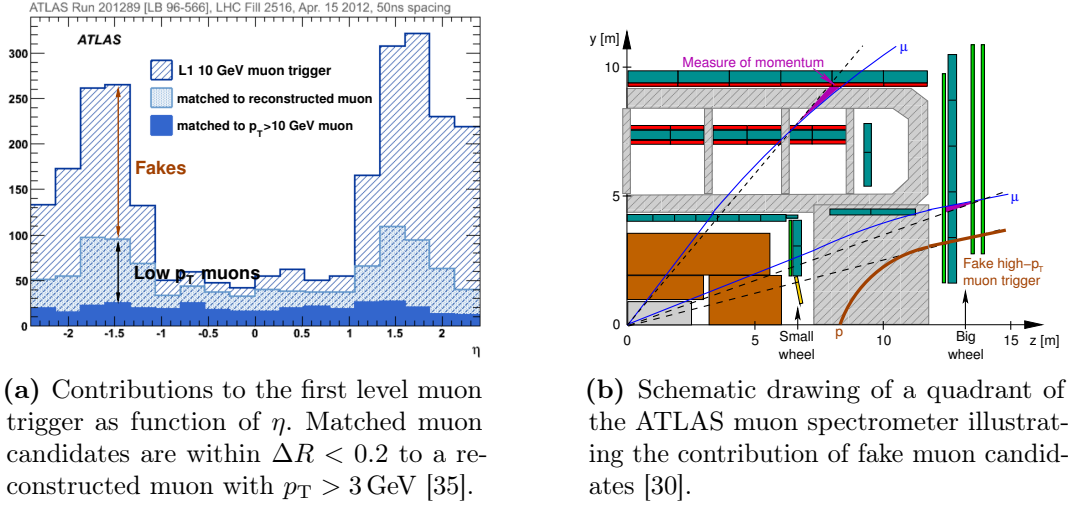


Figure 3.5: Contributions to the muon trigger rate.

The second contribution to the trigger rate are muons with $p_T < 10$ GeV, which are selected due to the poor momentum resolution at L1 caused by the moderate spatial resolution of the trigger chambers. The importance of a high momentum resolution for the reduction of the first level single muon trigger rate is a consequence of the p_T dependence of the inclusive muon cross section plotted in Figure 3.6. Below $p_T \sim 30$ GeV the main source for muons are decays of hadrons, which lead to the steeply falling cross section with increasing p_T . This means in turn that a high momentum resolution at the trigger threshold p_T^{thresh} is crucial to minimise the trigger rate.

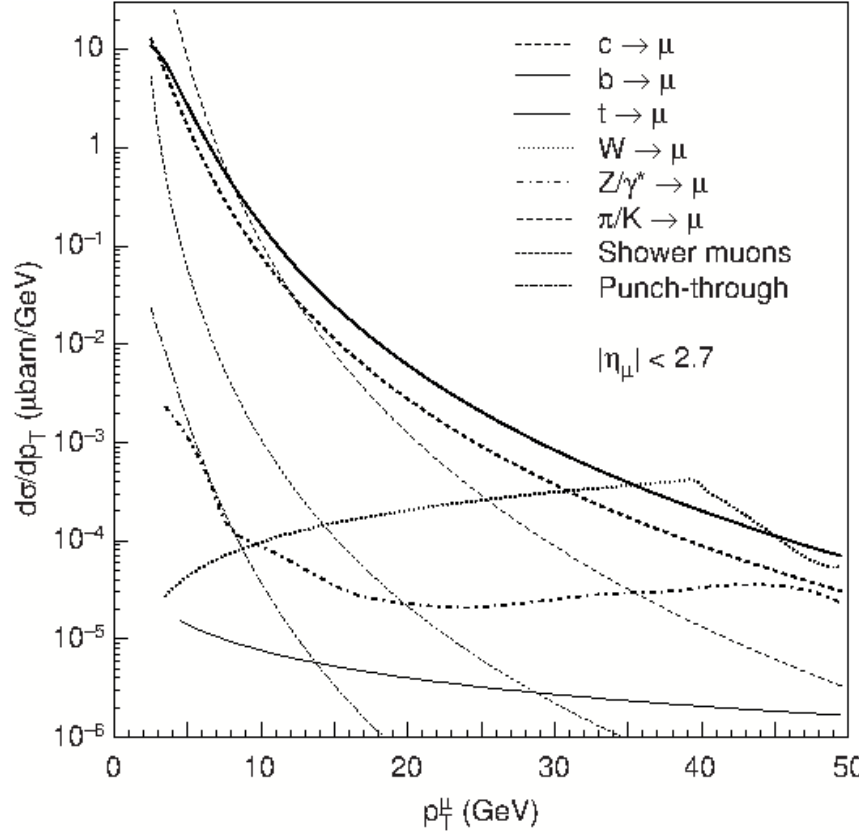


Figure 3.6: Differential inclusive cross-sections $d\sigma/dp_T$ for the dominant muon production processes, shower muons and hadronic punch-through as function of the muon transverse momentum [44].

3.4 The concept of an MDT based Level-0 muon trigger

The present ATLAS trigger scheme will be modified for operation at the HL-LHC. A two stage trigger system is envisaged. The first stage **Level-0** (L0) is a hardware trigger with a rate of up to 1 MHz and a latency of 6 μ s. The second stage is the **High Level Trigger** (HLT) and it will feature a reconstruction quality comparable to the full off-line reconstruction.

In the Phase-I upgrade, the inclusion of the NSW in the first level muon trigger decision will eliminate contributions from tracks which do not pass through the NSW and do not originate from the interaction point [35].

In the Phase-II upgrade, the L0 trigger will be based on the calorimeter and muon triggers and their combination in topological processors. The RPCs belonging to the barrel trigger will receive new electronics enabling data bandwidth reduction by zero suppression and improvement of the track position measurement by employing a charge driven centroid method. By installing a third layer of RPCs in the inner layer of the barrel, coverage and trigger efficiency will be improved. The end-cap trigger will be based on hits in the TGC Big Wheel and the NSW.

As the origin of the high rate due to low- p_T muons is the poor momentum resolution of the trigger chambers even at transverse momenta as low as 20 GeV, the inclusion of the MDT precision chambers in the trigger decision, made possible by the increased latency of the first level trigger to 6 μ s at the HL-LHC, enhances the trigger selectivity. The resulting high momentum resolution makes it possible to suppress the low- p_T muon background.

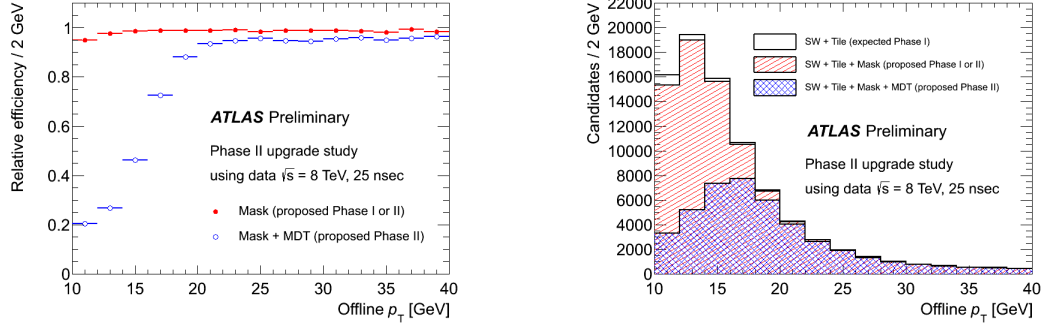
The momentum reconstructed with the MDT measurement is used to validate loose RPC and TGC triggers. In order to take the trigger decision within the latency requirements, the momentum has to be measured using the position information delivered by fast track segment reconstruction algorithms, which are seeded by the trigger RoIs. All calculations have to be performed via hardware. The concrete implementation has yet to be decided. Currently three options for the hardware implementation are considered: the implementation on an FPGA, the use of a CPU in combination with an FPGA, and the use of associate memory chip in combination with an FPGA [45].

3.5 Estimation of the performance of an MDT-based first level trigger at the ATLAS experiment using a deflection angle measurement

A first study was performed to assess the potential of a minimal MDT trigger in refining the first level muon trigger decision [46]. The study was carried out with Run 1 data by selecting muon candidates matched with the tracks reconstructed by a full off-line analysis and requiring the L1 muon trigger with transverse momentum threshold of 20 GeV. The deflection angle $|\beta|$, which is the difference of the straight muon track segment polar-angle between outer and middle layer for the barrel and between the Small Wheel and the Big Wheel in the end-caps, was used as a measure of the muon transverse momentum.

The requirement based on the MDT chambers combined with a spot mask for the transition region of the barrel and end-cap toroidal magnets sharpens the turn-on curve of the trigger without much loss in the plateau region, as shown in Figure 3.7a. The values for the efficiency are relative to the expected trigger rate for the Phase-I upgrade, based on requirements on the precision tracking chambers in the inner station of the end-cap and the extended-barrel tile calorimeter. The impact of the spot mask and the MDT requirement on the reduction of the number of candidate events is shown in Figure 3.7b. Muons with $p_T < 20$ GeV that would have passed the trigger solely based on TGC and RPC chambers are filtered by the MDT requirement.

In Figure 3.8 the reduction over the whole η -range is shown. The trigger rate relative to the expected rate after Phase-I upgrades can be reduced by 50% by the minimal integration of the MDT data. It will be shown in the following chapter, how one can achieve a significantly larger rate reduction by the maximum use of the MDT chamber data.



(a) Efficiency for a spot mask in the transition region of the barrel and end-cap toroidal magnets (red dots with error bars) and for a deflection angle requirement based on the MDT chambers (blue open circles with error bars) depending on the off-line transverse momentum p_T . [46].

(b) Distribution of the muon candidate's transverse momentum p_T for applying the requirements expected for the Phase-I upgrade (white), by further applying a spot mask (red) and further applying a deflection angle requirement based on the MDT chambers (blue) [46].

Figure 3.7: Reduction of the number of trigger candidates by an MDT deflection angle condition.

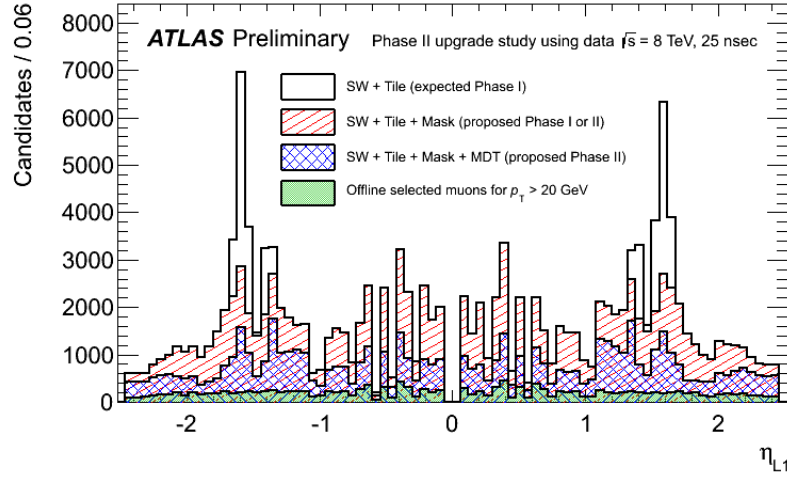


Figure 3.8: Distribution of the Run 1 L1 muon candidate's pseudorapidity η for applying the requirements expected for the Phase-I upgrade (white), by further applying a spot mask (red) and further applying a deflection angle requirement based on the MDT chambers (blue). The green (shaded) distribution is obtained by further requiring the transverse momentum p_T reconstructed in a full off-line analysis to satisfy $p_T > 20$ GeV [46].

4

Rate Study for the MDT Level-0 Muon Trigger

The Phase-II upgrade requires a highly selective first trigger stage to maintain reasonable trigger rates. In this chapter a novel concept for integrating the MDT precision information in the L0 muon trigger is presented. It makes use of the excellent position resolution of the MDT chambers of $40\,\mu\text{m}$ [44] for a measurement of the muon momentum, with a precision comparable to the present Level-2 trigger, to refine the trigger selectivity of the first level trigger. The optimal way to integrate the MDT chambers in L0 is to determine the muon transverse momentum from the hits in all three layers of the MS (BI, BM BO, or NSW, EM, EO).

In the beginning of this chapter, the sagitta as a measure of the transverse momentum is introduced, and contributions to the momentum resolution of a sagitta measurement are discussed. The inhomogeneity of the ATLAS magnetic field requires a finely partitioned parametrisation of the transverse momentum as a function of the sagitta with local corrections for the magnetic field variations, which is obtained by an iterative fitting procedure.

The MDT muon trigger concept employing a sagitta measurement is tested with ATLAS data taken in 2012 at a centre-of-mass energy of $\sqrt{s} = 8\,\text{TeV}$ and 25 ns bunch-spacing to investigate the applicability and the potential in sharpening the first level muon trigger. The data sample used for the rate study was restricted to trigger candidates for which a sagitta computation was possible, i.e. candidates with at least one reconstructed track segment in each of the three muon system layers. A trigger decision based on the momentum determined by the stand-alone off-line reconstruction characterises the ideal MDT muon trigger. The trigger efficiency and trigger rate reduction obtained by this method are used as a benchmark to put the efficiency of the MDT muon trigger in perspective. Finally, the momentum resolution, and thereby sharpened trigger selectivity and possible rate reduction, are presented with an extrapolation of the trigger rate of the L0 trigger.

4.1 Description of the MDT trigger concept using a sagitta measurement

The momentum of a particle with charge q is determined by measuring the track curvature $\kappa = 1/R$ in a homogeneous magnetic field $\mathbf{B}$ with magnitude $B = |\mathbf{B}|$. The transverse momentum is related to the curvature radius R by

$$p_T = qBR.$$

The sagitta s is a measure of the track curvature. It is defined as the trajectory's largest orthogonal distance from a straight line connecting the entrance and exit points in the magnetic field [47]. Figure 4.1 illustrates the geometry for three position measurements.

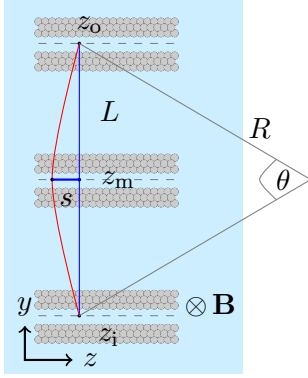


Figure 4.1: Illustration of the sagitta determined by three position measurements.

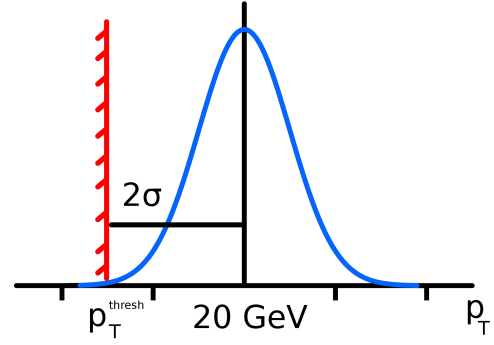


Figure 4.2: Sketch of the adequate choice of a trigger threshold (red) based on the momentum resolution (blue).

To derive the relation of transverse momentum and sagitta, the simplified case valid for small incidence angles $\theta/2 \approx \frac{L/2}{R}$ is considered. With the truncated series expansion of the cosine and the relation between curvature radius R and transverse momentum, one gets

$$\begin{aligned} s &= R \left(1 - \cos \frac{\theta}{2} \right) \approx R \left(1 - \left(1 - \frac{1}{2} \cdot \frac{\theta^2}{4} \right) \right) \\ &= R \left(\frac{\theta^2}{8} \right) = R \left(\frac{L^2}{8R^2} \right) = \frac{0.3}{8} \frac{L^2 B}{p_T}. \end{aligned}$$

The adequate choice of a trigger threshold p_T^{thresh} is illustrated in Figure 4.2. In order to select muons with a transverse momentum above 20 GeV one would naively reject

all muons with a transverse momentum greater than $p_T^{\text{thresh}} = 20 \text{ GeV}$. To account for the finite momentum resolution, however, it is necessary to include a safety margin to prevent the accidental rejection of muons with transverse momentum above the trigger threshold. For normally distributed errors, the choice of $p_T^{\text{thresh}} = 20 \text{ GeV} \cdot (1 - 2 \cdot \frac{\sigma_{p_T}}{p_T})$ ensures that 95% of all muons with $p_T > p_T^{\text{thresh}}$ will pass the trigger.

For the adequate choice of p_T^{thresh} , the relation between momentum resolution σ_{p_T}/p_T , sagitta uncertainty σ_s , and the uncertainty in position measurement σ_z , needs to be understood.

For the configuration shown in Figure 4.1, the sagitta can be obtained by $s = z_m - (z_i + z_o)/2$. Since the uncertainties of the three measurements are uncorrelated, the sagitta uncertainty can be calculated with Gaussian error propagation as $\sigma_s^2 = \sigma_z^2 + 2 \cdot \frac{\sigma_z^2}{4} = \frac{3}{2} \sigma_z^2$. Because of the linear dependence of sagitta and curvature $s = \frac{L^2}{8} \kappa$ and the inverse proportionality of curvature and momentum $p_T = qB/\kappa$, one gets

$$\sigma_{p_T} = \frac{p_T^2}{|q|B} \sigma_\kappa = \frac{8p_T^2}{|q|BL^2} \sigma_s = \sqrt{\frac{3}{2}} \frac{8p_T^2}{|q|BL^2} \sigma_z.$$

Two facts can be learned from this relation. The uncertainty in measuring the momentum is proportional to the uncertainty of the position measurement. This is why the excellent position resolution of the MDT chambers strongly improves the trigger selectivity. Additionally, the uncertainty in measuring the momentum is proportional to p_T^2 . Thus the contribution of the sagitta measurement to the fractional momentum resolution, which is

$$\frac{\sigma_{p_T}}{p_T} = \frac{8p_T}{|q|BL^2} \sigma_s,$$

is proportional to p_T .

There is, however, a second contribution to the momentum resolution due to multiple scattering [47]. The average maximum offset $\langle s_{\text{MS}} \rangle = \frac{1}{4\sqrt{3}} \frac{13.6 \text{ MeV}}{p\beta} z \sqrt{\frac{x}{X_0}}$ of the trajectory of a muon with speed β and momentum p traversing a material of thickness x with radiation length X_0 and atomic number z makes the sagitta appear to be larger. The contribution to the momentum resolution due to multiple scattering is

$$\left(\frac{\sigma_{p_T}}{p_T} \right)_{\text{MS}} = \frac{0.0136 \sin \theta}{0.3\beta LB} \sqrt{\frac{L/\sin \theta}{X_0}}.$$

For relativistic particles, this contribution is independent of p_T and therefore a lower bound of the momentum resolution.

Particularly relevant for the momentum measurement in the muon system, which surrounds the calorimeters, energy loss fluctuations give rise to another contribution

Figure 4.4 shows the combined transverse momentum resolution of the MDT chambers for $|\eta| < 1.5$ together with its individual contributions. For $|\eta| > 1.5$, the contribution of energy loss fluctuations to the momentum resolution is smaller, since for the same value of p_T the muon momentum $p = p_T \cdot \cosh \eta$ in the end-cap is larger compared to the barrel region.

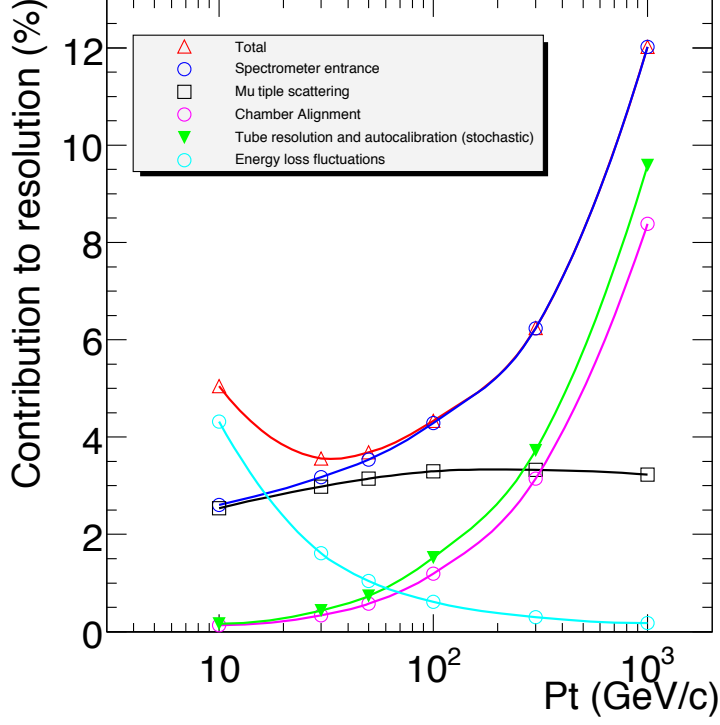


Figure 4.4: Contributions to the momentum resolution for muons reconstructed in the Muon Spectrometer as a function of p_T for $|\eta| < 1.5$. The alignment curve is for an uncertainty of $30 \mu\text{m}$ in the chamber positions.

Once the sagitta is measured, the transverse momentum can be obtained by the relationship

$$p_T = \frac{0.3}{8} \frac{L^2 B}{s}.$$

The MDT chambers provide position measurements in inner, middle, and outer station (z_i, r_i), $i \in \{i, m, o\}$, where the radial coordinate r_i is the projection of the track position vector in the $r - z$ precision plane. In the general case, the sagitta can be

calculated with help of the slope of the interconnecting line between inner and outer measurement points

$$m = \frac{z_o - z_i}{r_o - r_i}.$$

For the general case of three position measurements shown in Figure 4.5, the sagitta s is given by

$$s = \frac{m \cdot (r_m - r_i) + z_i - z_m}{\sqrt{1 + m^2}}.$$

4.1.1 Sagitta measurement in the ATLAS Muon Spectrometer

The detector geometry of the ATLAS Muon System requires the sagitta measurement to be performed in a specific way for different regions of the detector, as illustrated in Figure 4.5.

In the barrel region ($|\eta| < 1.05$) the sagitta measurement is performed with position measurements in the inner, middle and outer barrel layers. High-momentum tracks with $|\eta| > 1.05$ do not pass all three barrel layers, which requires the use of an additional layer of **E**xtra **E**nd-cap (EE) chambers in the transition region between barrel and end-cap ($1.05 < |\eta| < 1.3$). The sagitta measurement is performed with position measurements in the NSW, the EE chambers, and the Big Wheel.

In the end-cap region ($|\eta| > 1.3$) the vanishing magnetic field between the Big Wheel and the Outer Wheel makes a sagitta measurement as described above impossible.

Therefore a substitute 'pseudo-sagitta' is introduced, which is defined as the deviation of the extrapolated line connecting the Outer Wheel and the Big Wheel from the position measurement in the NSW. This quantity, as a measure of the track curvature in the magnetic field generated by the end-cap magnet, can be used similarly to the sagitta to parametrise the transverse momentum.

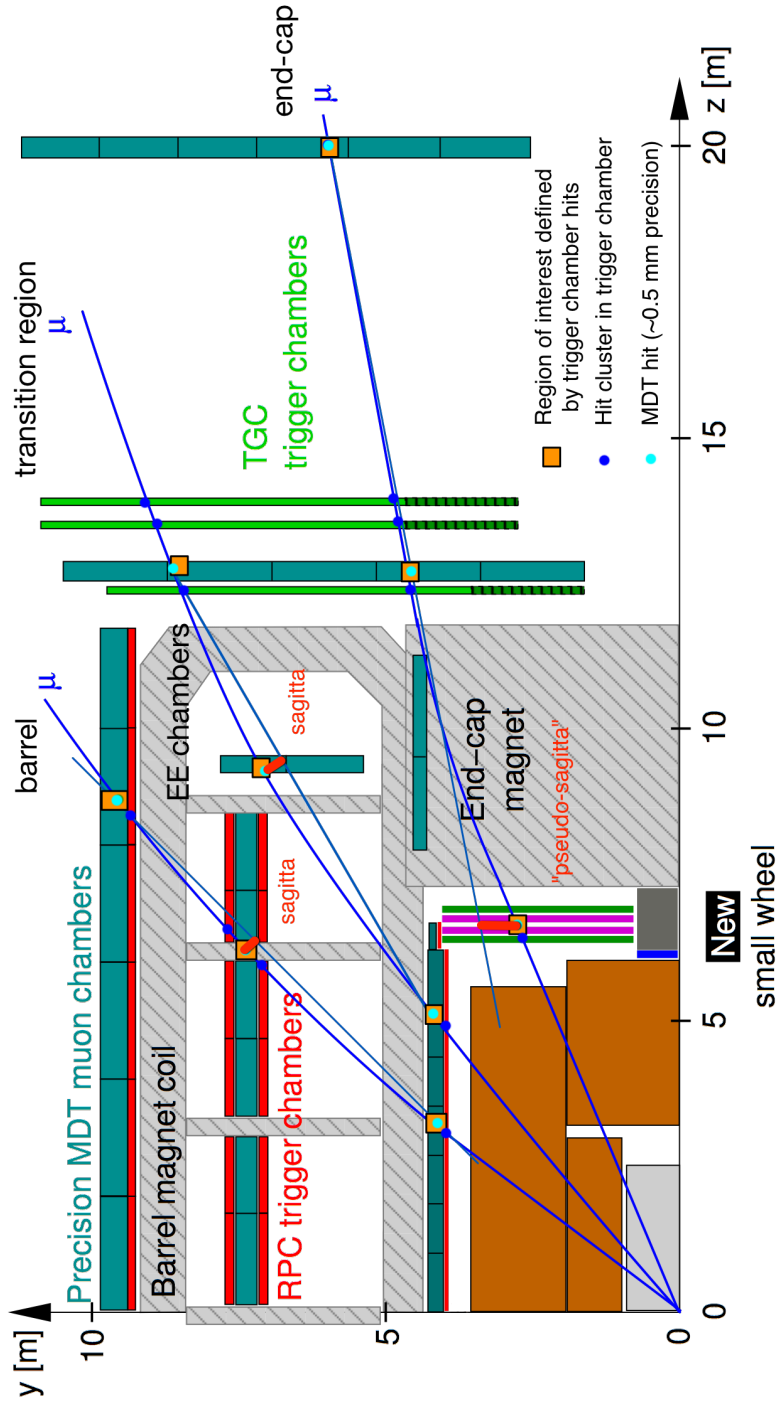


Figure 4.5: Illustration of the sagitta and 'pseudo-sagitta' definitions in MDT trigger concept. It is possible to calculate the sagitta in the barrel ($|\eta| < 1.05$) with BI, BM and BO chambers and in the transition region ($1.05 < |\eta| < 1.3$) with BI, EE, and EM chambers respectively. Since there is no magnetic field in the end-cap ($|\eta| > 1.3$) between the Big Wheel and the Outer wheel, a different measure of the track curvature is used in the end-cap region, which is defined as the deviation of the position measurement in the NSW from the extrapolated line connecting the Outer Wheel and the Big Wheel.

4.2 From sagitta measurement to transverse momentum estimation

Until now the case of a homogeneous magnetic field has been discussed, but this is not the case in the ATLAS muon system. Because of the inhomogeneous field, which is illustrated via the field integral $\int \mathbf{B} d\mathbf{l}$ along a muon trajectory in Figure 4.6, corrections have to be applied to account for the non-uniformity of the magnetic field in ϕ and η .

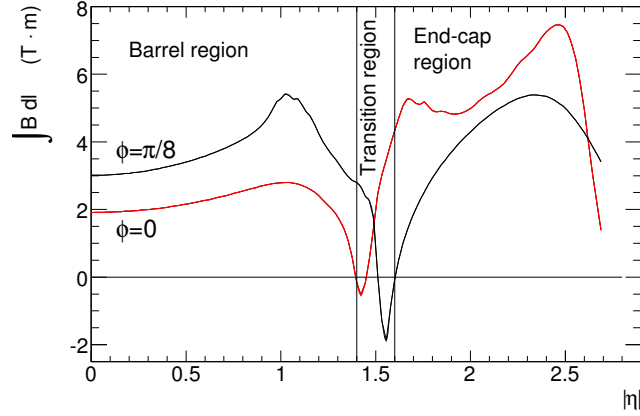


Figure 4.6: Magnetic field integral for $\phi = 0$ and $\phi = \pi/8$ in dependence of $|\eta|$ with the transition region of the toroid magnet indicated [13].

Because of the strong variation of the field integral $\int B dL$, it is necessary to divide the detector volume in many small regions in which the series expansion of $B(\phi, \eta)$ to the second order about the local minimum provides sufficient accuracy for the p_T determination, to obtain

$$p_T = \frac{qL^2 B(\phi, \eta)}{8s} \approx S_1(s) + P_2(\phi) + E_2(\eta)$$

with

- $S_1 = (1/s - a_0)/a_1$
- $P_2(\phi) = \sum_{i=0}^2 p_i \cdot \phi^i$
- $E_2(\eta) = \sum_{i=0}^2 e_i \cdot \eta^i$.

In this way, a locally valid parametrisation $p_T^{\text{on}}(s, \phi, \eta)$ is obtained for each region. The parameters a_i , e_i , p_i can be determined numerically with experimental data.

The way of dividing the detector volume into small regions, in which the sagitta can

be sufficiently well parametrised, is guided by the detector architecture. Each sagitta measurement uses track segments from a specific combination of three MDT chambers, such as 'BIL1C01-BML1C01-BOL1C01'. The set of common combinations of three MDT chambers partitions the detector volume in over 440 small regions, which each define a locally valid parametrisation. This set of parametrisations $p_T^{\text{on}}(s, \phi, \eta)$ is called the *precision parametrisation*.

To account for trigger candidates in between the regions defined by chamber combinations, an additional set of parametrisations $p_T^{\text{on}2}(s, \phi, \eta)$ based on coarse detector regions defined in η and ϕ was determined using the same iterative fit procedure. The definition of the region boundaries used for the second parametrisation is given in Table 2 in the Appendix. The additional set is called the *supplementary parametrisation*.

Because of the hundreds of possible combinations, a large amount of data was necessary to obtain a parametrisation with minimal statistical uncertainty on the data. A selection of 37 206 232 events from the beginning of the ATLAS data-taking in 2012 with $\sqrt{s} = 7$ TeV and a bunch-crossing interval of 50 ns with at least one positive muon trigger decision was used. The event selection was guided by strict demands on the muon track reconstruction quality. Only events containing a single muon with $p_T < 100$ GeV with exactly one segment in each inner, middle, and outer layer with six or more hits were used in the iterated fit procedure to obtain the calibration. Since the NSW has not been installed yet, the position information from the MDT and CSC chambers in the present Small Wheel is used.

The ATLAS off-line reconstruction uses two different muon reconstruction algorithms. The combined algorithm makes use of the combined information from the inner tracking detectors and the muon spectrometer. It has the best transverse momentum resolution and hence is considered as reference algorithm for the parametrisation. The stand-alone algorithm reconstructs the muon transverse momentum with information from the muon spectrometer only. It will be used as the benchmark for the trigger algorithm. Quantities measured with the combined and stand-alone algorithm are indicated by the superscripts ^{CB} and ^{SA}, respectively.

The process of obtaining the parametrisation is illustrated in Figure 4.7 using the example of a combination of three chambers in large barrel sectors closest to the interaction point.

First the inverse of the sagitta $1/s$ is plotted against the transverse momentum of the off-line muon provided by the combined reconstruction p_T^{CB} . The dependence is fitted with a straight line $1/s = a_1 p_T^{\text{CB}} + a_0$ and used to obtain

$$p_T^{\text{on}}(s) = \frac{1/s - a_0}{a_1}.$$

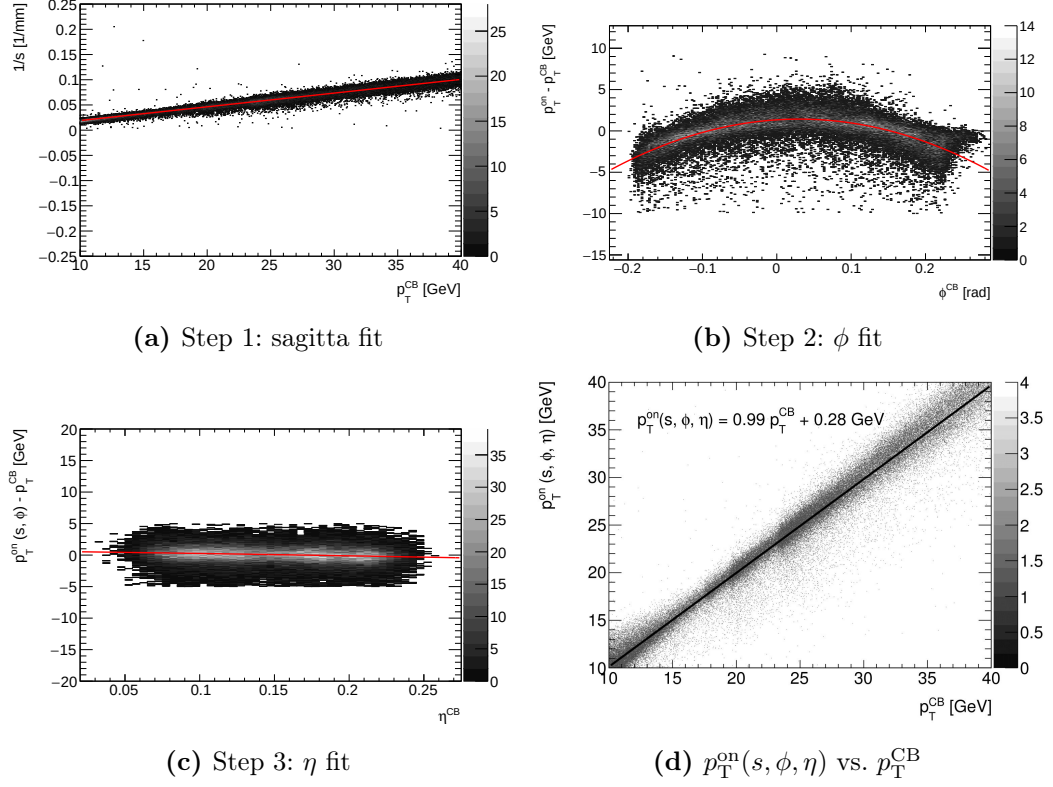


Figure 4.7: Illustration of the iterative fitting procedure using the example of the combination 'BIL1A01-BML1A01-BOL1A01'.

Then the deviation of $p_T^{\text{on}}(s)$ from p_T^{CB} is plotted against ϕ^{CB} . Since this combination used in this example only contains segments from large sectors, the ϕ -dependence, shown in Figure 4.7b, reflects the ϕ dependence of the magnetic field integral $\int \mathbf{B} d\mathbf{l}$. It has a minimum at $\phi = 0$ in between two toroid magnet coils and increases towards the coils. The ϕ -dependence is fitted with a parabola $P_2(\phi) = \sum_{i=0}^2 p_i \cdot \phi^i$ to obtain

$$p_T^{\text{on}}(s, \phi) = \frac{1/s - a_0}{a_1} + \sum_{i=0}^2 p_i \cdot \phi^i.$$

The last step of the iterated fitting procedure accounts for the dependence in η . The deviation of $p_T^{\text{on}}(s, \phi)$ from p_T^{CB} is plotted against η^{CB} , and fitted with a parabola $E_2(\eta) = \sum_{i=0}^2 e_i \cdot \eta^i$ to obtain the final parametrisation

$$p_T^{\text{on}}(s, \phi, \eta) = \frac{1/s - a_0}{a_1} + \sum_{i=0}^2 p_i \cdot \phi^i + \sum_{i=0}^2 e_i \cdot \eta^i.$$

The resulting parametrisation $p_T^{\text{on}}(s, \phi, \eta)$ is plotted against p_T^{CB} in Figure 4.7d. The parametrisation slightly overestimates the transverse momentum because the fitting procedure does not account for the tails of the energy loss distribution to large values of the energy loss.

4.3 Description of the data sample used for the rate study

The estimation of the performance of the MDT muon trigger is based on a special data sample of proton-proton collisions accumulated by the ATLAS detector in the end of 2012 with a bunch-crossing interval of 25 ns and a centre-of-mass energy of $\sqrt{s} = 8$ TeV. The maximum number of multiple interactions per bunch crossing is 12 [46].

The sample consists of the events of the LHC runs 216399, 216416 and 216432 in the data taking period M. In these runs a special trigger configuration was used, which accepts events passing the main L1 physics triggers without any further High Level Trigger selection.

Events were selected by requiring the L1MU20 trigger and additional Phase-I trigger requirements. The additional Phase-I trigger requirements are

- coincidence in the NSW EI and the TGC Forward Inner (FI) station with $\Delta\eta < 0.2$ and $\Delta\phi < 0.2$,
- a minimum deposited energy of $\Delta E > 500$ MeV in two calorimeter cells in $1.0 < |\eta| < 1.3$ corresponding to the TGC sector delivering the trigger signal
- an emulated NSW coincidence requirement for $\Delta\eta$ and $\Delta\phi$ between NSW and Big Wheel and a threshold definition for the polar angle deviation from an infinite-momentum track measured in the NSW. Both threshold definition and coincidence requirement are η -dependent. The threshold definitions are given in Table 1 in the Appendix.

After these requirements expected to be included in the Phase-I upgrade, an additional requirement, called the RoI mask is imposed. Events which provide L1 trigger candidates in 18 RoIs in each end-cap octant are rejected. These RoIs belong to the transition region between the barrel and end-caps toroid system at $|\eta| \sim 1.5$, where the field integral becomes 0 and no stand-alone muon momentum is possible. This requirement reduces the trigger rate to 87% while keeping the efficiency for $p_T^{\text{CB}} > 20$ GeV over 99% [46].

In total 122 701 events are accepted after the Phase-I trigger requirements.

Only triggers which could be matched to a muon reconstructed by the combined algorithm were used in the study. These were selected by requiring the muon to be contained in the trigger's Region of Interest $|\eta^{\text{CB}} - \eta^{\text{RoI}}| < 0.1$ and $|\phi^{\text{CB}} - \phi^{\text{RoI}}| < 0.1$. The muon with smallest distance to the Region of Interest's center $dR = \sqrt{(\eta^{\text{CB}} - \eta^{\text{RoI}})^2 + (\phi^{\text{CB}} - \phi^{\text{RoI}})^2}$ is chosen, if more than one muon is contained within the RoI.

After applying the requirements listed in Table 4.1, the selected data sample for the study consists of 102 292 events.

Table 4.1: Event selection

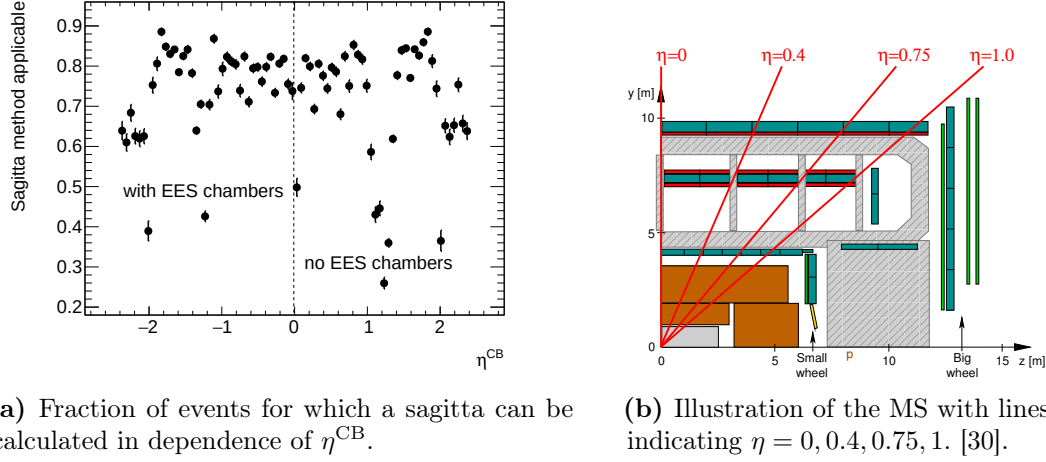
Step in event selection	Number of events
Expected Phase-I trigger events	122 701
Matched to off-line muon	109 950
$p_{\text{T}}^{\text{CB}} < 100$ and $p_{\text{T}}^{\text{SA}} < 100$	102 292
Sagitta method applicable	76 270

For 76270 events, which is 75% of the selected data sample and 60% of all expected Phase-I trigger events, the sagitta can be determined. This requires track segments in each of the three precision chamber layers (BI, BM, BO or BI, EE, EO or EI, EM, EO) for a trigger candidate. The track segments used for the sagitta calculation were chosen from within a Region of Interest around the muon of $dR = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.1$. The majority of events contains exactly three segments, in which case the sagitta is uniquely defined. If there is more than one segment in a chamber, the segment with the highest number of hits is selected for the sagitta measurement.

Figure 4.8 shows the fraction of events, for which the sagitta is defined, in dependence of η^{CB} .

In most regions for $\sim 80\%$ of all trigger candidates a sagitta measurement is possible, except for the regions $|\eta| > 2$ and $|\eta| \sim 1.5$. The inefficiency at $|\eta| = 2.0$ in the distribution is an artefact of the instrumentation during data taking. It is caused by the lower segment efficiency in the CSC chambers that are used for $|\eta| > 2.0$. This will go away after the installation of the NSW. The asymmetry of the distribution in η is explained by the fact that during the data taking only the region $\eta < 0$ was instrumented with EES chambers.

The inefficiency at $\eta = -1.2$ in the transition region is due to segments which neither pass the Outer Wheel nor the EE chambers. It is likely to increase the fraction of events in the transition region for which a sagitta can be defined by an elaborate η -dependent scheme for finding the optimal combinations of available measurements in EI, EE, BE, EM and EO. For events, for which no sagitta can be calculated,



(a) Fraction of events for which a sagitta can be calculated in dependence of η^{CB} . (b) Illustration of the MS with lines indicating $\eta = 0, 0.4, 0.75, 1$. [30].

Figure 4.8: Fraction of events for which a sagitta can be calculated for different regions in η .

the requirement imposed on the deflection angle [46], which was introduced in the previous chapter, can be used as a fall-back solution.

Before restricting the study to the data sample of events for which a sagitta is defined, the distributions containing all 102 292 events are presented, with the events for which no sagitta is calculated overlayed in red. Figure 4.9 shows the distribution of number of segments per event and the distributions of p_{T}^{CB} , η^{CB} and ϕ^{CB} .

The shape of the p_{T}^{CB} distribution is due to the dominant production of muons with a small transverse momentum. The fraction of events, where the sagitta method is not applicable, consists mostly of muons below the trigger threshold.

The high number of events in $1.05 < |\eta| < 1.3$ comes from hadronic punch-through out of the calorimeter, which is misidentified as a high- p_{T} muon and from the inhomogeneous magnetic field impeding the momentum measurement.

The structure of the ϕ^{CB} -distribution is due to the alternating structure of large and small sectors. The two dips at $\phi = -1.1$ and $\phi = -2.0$ originate from the inferior instrumentation in the feet region of the ATLAS detector and thus lower segment efficiency.

A fraction of 15.6% events was not covered by the set of combinations of three MDT chambers contained in the precision parametrisation. The trigger candidates in these events are either detected far from the centre of a sector ($\Delta\phi = \pm 0.22$) or belong to the region $-1.3 < \eta < -1.05$.

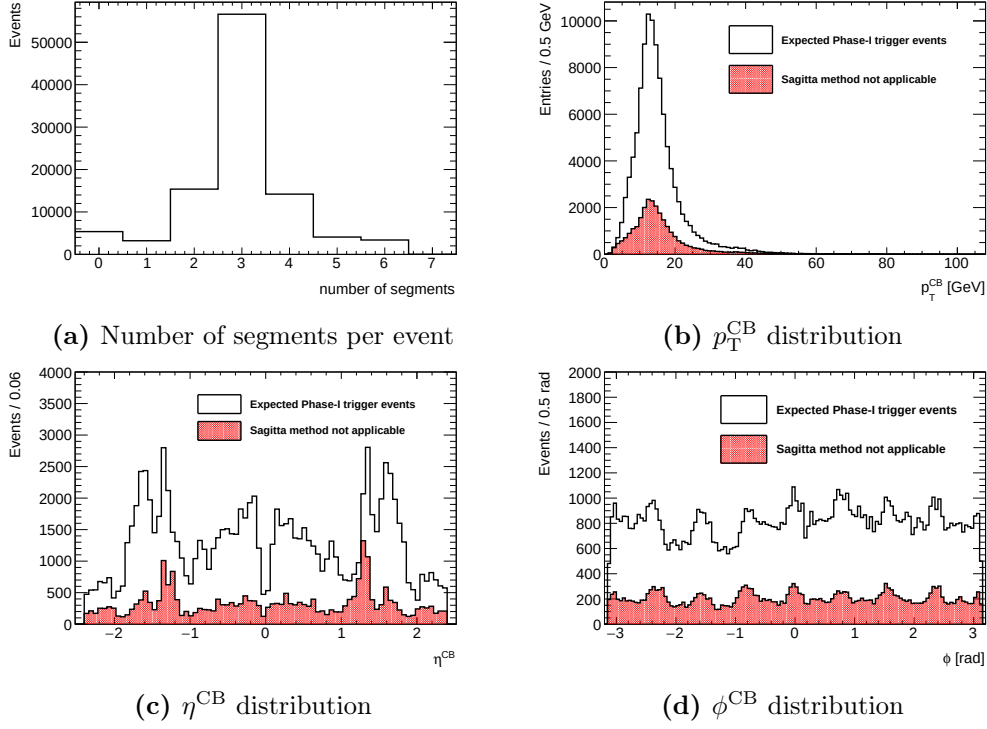


Figure 4.9: Distribution of the number of segments per event and distributions of p_T^{CB} , η^{CB} and ϕ^{CB} with events, for which the sagitta could not be calculated, overlaid in red.

The reason why the precision parametrisation could not be used for the trigger candidates in the region $-1.3 < \eta < -1.05$ is because the additional EES chambers were installed after the data used for obtaining the parametrisation was taken. This required to base the supplementary parametrisation on the data sample used for the rate study itself. Self-correlation effects from using the very same sample for obtaining the supplementary parametrisation and for evaluating the MDT trigger concept are negligible, which was checked in $|\eta| < 1.05$ and $|\eta| > 1.3$ with a supplementary parametrisation based on different data recorded in 2012.

Because of the supplementary parametrisation the fraction of 15.6% events which would otherwise have passed the muon trigger could be reduced by 55%.

4.4 Rate study for the MDT Level-0 muon trigger

In this section the trigger efficiency and resulting rate reduction achievable with the sagitta method are presented. A trigger decision based on the stand-alone algorithm used in the off-line analysis will be used as a benchmark in the discussion of the method employing the sagitta measurement. As the off-line stand-alone algorithm utilises a full track fit taking into account the magnetic field map and material distribution, it sets an upper limit on the achievable momentum resolution at the trigger threshold, which in turn determines the highest possible trigger threshold p_T^{thresh} to maintain 95% efficiency for muons with $p_T > p_T^{\text{thresh}}$. As the selectivity of the trigger is related to the momentum resolution at trigger level, the achievable momentum resolution will be discussed first.

The momentum resolution was determined by comparing the momentum measured with the MDT chambers with the momentum reconstructed by the combined algorithm as reference. Because the combined algorithm measures the transverse momentum at the interaction point, whereas the stand-alone algorithm measures the transverse momentum in the muon spectrometer, a correction for the mean energy loss in the calorimeter $\langle \Delta E \rangle$ is applied before comparison.

Figure 4.10 shows the momentum resolution of the sagitta method based on the precision parametrisation and the momentum resolution obtained with the stand-alone algorithm. The distribution of the relative deviations of the transverse momentum obtained with the precision parametrisation from the reference is almost normally distributed. The tail to the left is attributed to fluctuations in energy loss of the muon. Because of the long tail in the distribution, the Gaussian core of the distribution was fitted to obtain a measure of the momentum resolution.

The momentum resolution of the precision parametrisation is $\sigma_{p_T^{\text{on}}} = 4.9 \pm 0.1\%$, while the supplementary parametrisations' resolution is $\sigma_{p_T^{\text{on2}}} = 6.0 \pm 0.2\%$. The superior resolution of the precision parametrisation is due to the over four times finer granularity of regions in which the local parametrisations are defined.

Compared to the best possible transverse momentum resolution obtained with the stand-alone algorithm, which is $\sigma_{p_T^{\text{SA}}} = 3.5 \pm 0.1\%$, the momentum resolution obtained with the sagitta measurement is only 1.5% away from the limit set by the off-line momentum resolution.

The momentum resolution in the barrel region obtained with the precision parametrisation is $\sigma_{p_T^{\text{on}}} = 4.5 \pm 0.1\%$ compared to the resolution achieved by the stand-alone algorithm $\sigma_{p_T^{\text{SA}}} = 3.3 \pm 0.1\%$. The even smaller difference to the limit set up by the

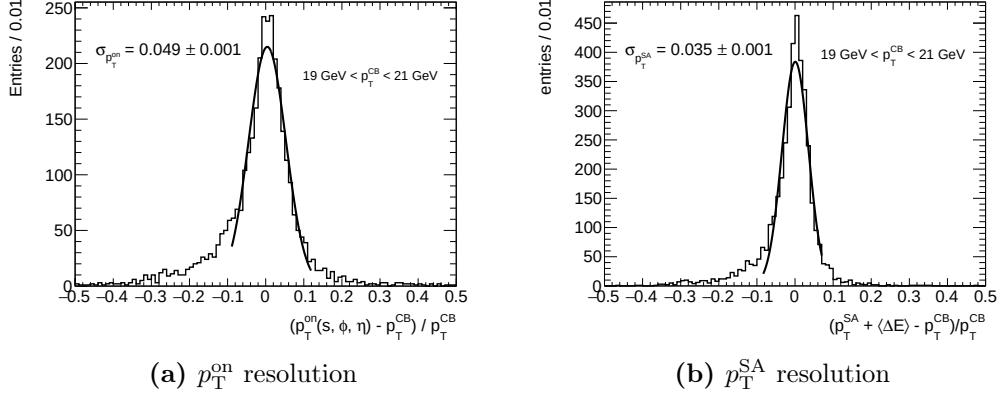


Figure 4.10: Momentum resolution of the precision parametrisations p_T^{on} and of the stand-alone algorithm p_T^{SA} .

stand-alone algorithm of 1.2% promises particularly good performance of the MDT trigger in the barrel region.

Despite the smaller contribution due to energy-loss fluctuations in the end-cap, the momentum resolution obtained with the precision parametrisation for $|\eta| > 1.05$ is only $\sigma_{p_T^{\text{on}}} = 4.8 \pm 0.02\%$. The end-cap regions with small values of the field integral deteriorate the momentum resolution. When the region $1.4 < |\eta| < 1.8$ is excluded, the end-cap momentum resolution is $3.7 \pm 0.2\%$, which is similar to the resolution obtained with the stand-alone algorithm.

If the relative deviation of the stand-alone momentum from p_T^{CB} followed a normal distribution, the threshold could be defined by $p_T^{\text{thresh}} = 20 \text{ GeV} \cdot (1 - 2\sigma_{p_T}/p_T)$ to ensure that 95% of all muons with $p_T > p_T^{\text{thresh}}$ will pass the trigger. Because of the tails due to energy loss fluctuations this approach does not work. The adequate thresholds ensuring that the trigger efficiency¹ is over 95% for muons with $p_T^{\text{CB}} > 20 \text{ GeV}$ must be determined by scanning threshold values.

To account for the variation of the momentum resolution different regions of the muon system, an individual threshold was defined for each of the over 440 regions in the precision parametrisation. For the coarse supplementary parametrisation 26 different thresholds were defined. The thresholds for the requirement based on the momentum obtained from the stand-alone algorithm were defined for 288 different detector regions.

¹The definition of 95% efficiency requires the fraction of candidates accepted by the trigger in the interval $20 \text{ GeV} < p_T^{\text{CB}} < 40 \text{ GeV}$ to the number of all events in the interval $20 \text{ GeV} < p_T^{\text{CB}} < 40 \text{ GeV}$ to be equal or greater than 95%.

With these thresholds the distributions of accepted trigger candidates were determined and consequently the trigger efficiency. In Figure 4.11 the efficiency of the MDT muon trigger is shown together with the scaled L1 trigger for Run 1 and with the efficiency curve obtained from the stand-alone requirement.

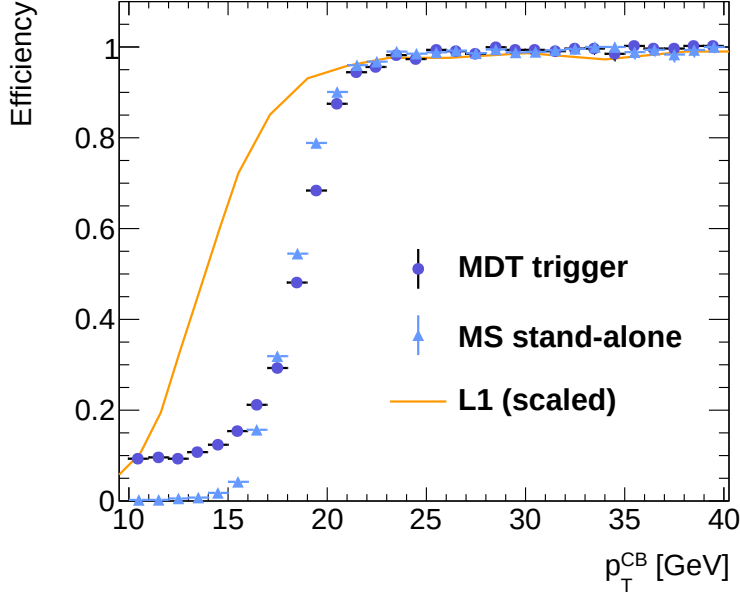


Figure 4.11: Turn-on curve of MDT trigger.

The turn-on curve obtained using the sagitta measurement is much steeper than for L1. Up to $p_T = 15$ GeV only one out of ten trigger candidates is inadvertently accepted by the first-level trigger. For higher transverse momenta the turn-on curve obtained using the sagitta measurement follows the course of the MS stand-alone turn-on curve very closely. Both curves saturate at 99% above $p_T \geq 25$ GeV. The pedestal of the MDT trigger turn-on curve for low momenta is caused by the poor momentum resolution of the sagitta measurement in regions of small field integral, which is discussed later. The threshold definition ensures high efficiency for muons with $p_T \geq p_T^{\text{thresh}}$ but at the cost of letting some muons below the trigger threshold pass. The choice of a reasonable trigger threshold has to be a compromise between high efficiency for muons above the trigger threshold and good rejection of muons below the trigger threshold.

The expected reduction of trigger candidates from Phase-I trigger candidates by the MDT trigger is shown in Figure 4.12, overlaid with the candidates passing the stand-alone momentum requirement and the candidates with $p_T^{\text{CB}} > 20$ GeV. Over

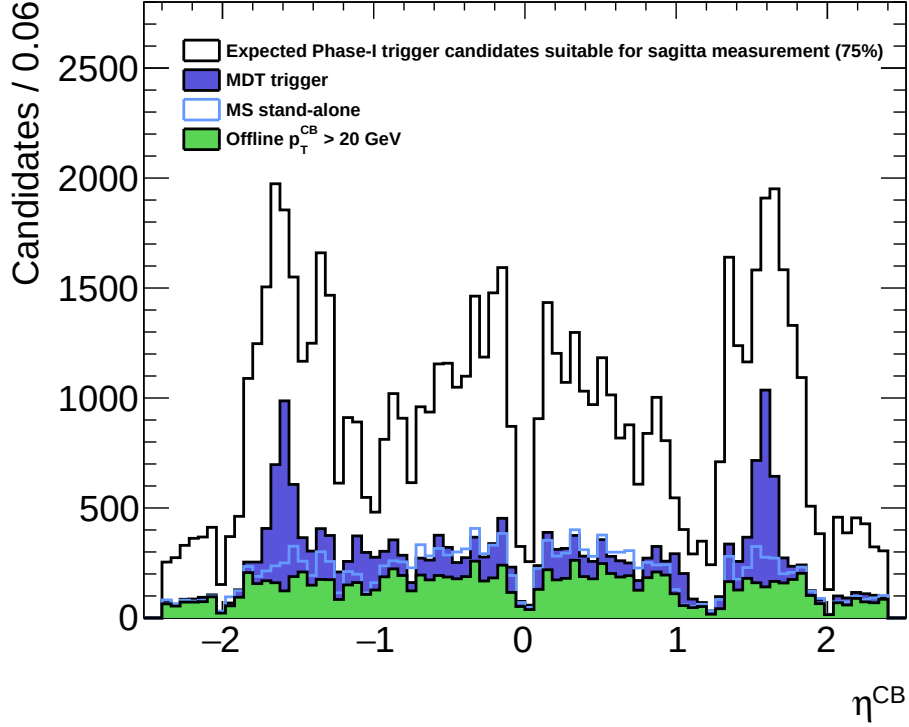


Figure 4.12: Expected trigger candidates overlayed with candidates passing the MDT trigger, candidates passing the stand-alone requirement and candidates with $p_T^{\text{CB}} > 20 \text{ GeV}$, in dependence of η^{CB} .

the whole MS the MDT trigger using a sagitta measurement can reduce the Phase-I accept rate of trigger candidates eligible for the sagitta method by 70%.

The reduced momentum resolution due to the inhomogeneous magnetic field causes the inefficiencies at $|\eta| \sim 1.5$. In some parts of the barrel, the sagitta method achieves a better performance than the requirement based on the stand-alone momentum, which is caused by the finer granularity of the thresholds definitions for the latter method. Apart from the two regions with inhomogeneous magnetic field and thus poor momentum resolution the MDT trigger performs very well in the whole η region. In relation to the achievable trigger rate reduction using the stand-alone algorithm of 76%, the trigger rate reduction achieved by the sagitta method is remarkably close to the optimal value.

Since the momentum resolution varies for different detector regions, the individual

efficiency and trigger rate reduction are discussed for barrel region, transition region and end-cap region (cf. Figure 4.5) in the following paragraph.

In the barrel region ($|\eta| < 1.05$) the reduction of Phase-I trigger candidates eligible for the sagitta method is 71.5%. The p_T^{CB} distribution and the turn-on curve for the barrel region are shown in Figure 4.14. The efficiency obtained with the sagitta method for $p_T^{\text{CB}} < 15$ GeV is smaller than 10% and then rises almost as steep as the one defined by the stand-alone requirement, resulting in the strong suppression of trigger candidates with small transverse momentum.

In the transition region between barrel and end-cap ($1.05 < |\eta| < 1.3$) the reduction of the Phase-I trigger candidates eligible for the sagitta method is 69.9%. Figure 4.15 shows the p_T^{CB} distribution and the turn-on curve for the transition region. The results are very similar to the barrel region, since both regions share the same method of determining the track curvature. The large error bars of the turn-on curve for $p_T^{\text{CB}} > 25$ GeV are due to the low statistics in this region.

In the end-cap region ($1.3 < |\eta|$) the overall reduction of Phase-I trigger candidates eligible for the sagitta method is 70.8%. Figure 4.16 shows the p_T^{CB} distribution and the turn-on curve for the end-cap region. Although the turn-on-curve close to the threshold is similarly steep as the turn-on curves of the other two regions, the p_T^{CB} distribution has a large pedestal towards transverse momenta $p_T^{\text{CB}} < 15$ GeV. The pedestal originates from trigger candidates in the two regions around $|\eta| = 1.5$ with small field integral and poor momentum resolution, resulting in many fake triggers. The sign change of the magnetic field causes an s-shaped muon trajectory in this region, deteriorating the sagitta measurement. The deflection angle criterion introduced in Section 3.5 achieves a better momentum resolution for this region if only the part of the muon trajectory with approximately constant curvature is used. A statistical combination of sagitta measurement and deflection angle criterion is likely to achieve a better momentum resolution.

The excellent momentum resolution provided by the CSCs in the high- η region $|\eta| > 2$ is able to partly compensate the high rate due to the fake triggers. The combination of the overall better momentum resolution in the end-cap and the high rate in $|\eta| \sim 1.5$ causes the flat shape of the p_T^{CB} distribution compared to the barrel region.

In conclusion, the MDT trigger using a sagitta method is able to reduce the trigger rate of eligible trigger candidates by over two thirds over almost the whole η region. The performance is close to the limit set by the off-line algorithm.

4.4.1 Rate estimation for the Phase-II first-level single muon trigger

Based on a simple extrapolation of the predicted rates for the Phase-I single muon trigger operating at a centre-of-mass energy of $\sqrt{s} = 14$ TeV and a luminosity $\mathcal{L} = 1 \times 10^{34} \text{ m}^{-2} \text{ s}^{-1}$, which were shown in Figure 2.11, the trigger rates achievable with the MDT single muon trigger at the HL-LHC are estimated. For the 20 GeV trigger threshold a first-level muon trigger rate without MDTs of 50 kHz is estimated for the final HL-LHC luminosity. The first-level muon trigger rates for other trigger thresholds are shown in Figure 4.13.

For 122701 expected Phase-I triggers the sagitta could be calculated for a fraction of 60%. With a correction for the improved segment efficiency in $|\eta| > 2.0$ provided by the NSW, this fraction is 70%. The MDT trigger based on a sagitta measurement reduces the trigger rate for these trigger candidates to 30%. 10% of the expected Phase-I triggers could not be matched to a reconstructed muon. It is assumed that these will pass the MDT trigger in order not to comprise the efficiency. Assuming the remainder 20% of the triggers can be reduced by 50% using the deflection angle requirement, the expected trigger rate using an MDT trigger is reduced to $0.7 \cdot 30\% + 0.2 \cdot 50\% + 0.1 \cdot 100\% \sim 40\%$. The estimated first-level MDT single muon trigger rate is 20 kHz. This is half the expected single muon trigger rate for operation at HL-LHC of 40 kHz stated in Ref [24] and demonstrates the potential of the inclusion of the MDT chambers in the trigger decision, providing high quality momentum resolution based on a sagitta measurement.

This already promising result presents a pessimistic estimate of the rate. There are indications that the deflection angle based requirement is more precise in regions with inhomogeneous magnetic field. In addition, the concept described in Section 3.5 only takes into account one out of three possible combinations of the polar angles for calculating the deflection angle. The combination of the sagitta method and an adaptive deflection angle requirement optimised for detector regions is likely to improve the rate reduction further. Finally, studies investigating the influence of rejecting the 10% of the expected Phase-I triggers which could not be matched to a reconstructed muon on the efficiency will show if the rate can be even further decreased without comprising the efficiency, by setting a requirement on the minimum number of track segments.

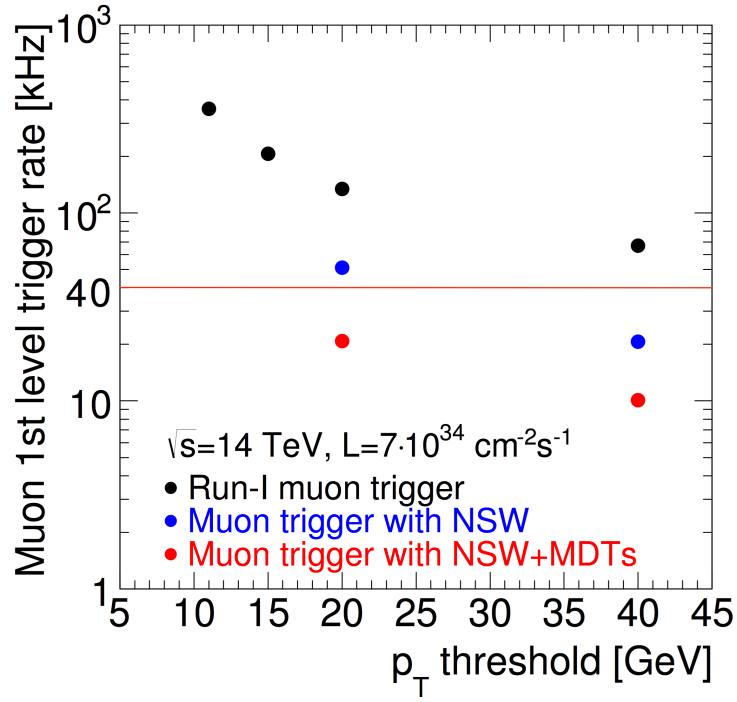


Figure 4.13: Expected first level accept rates in dependence of p_T^{CB} . The red line indicates the expected single muon trigger rate of 40 kHz stated in Ref [24].

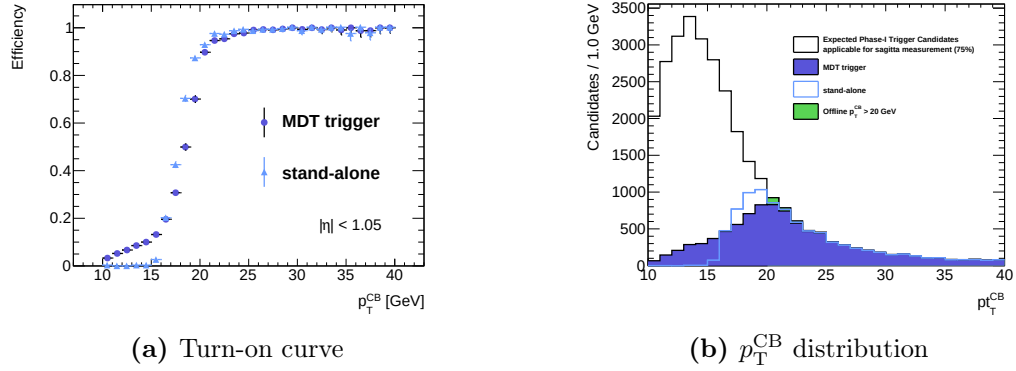


Figure 4.14: Efficiency and p_T^{CB} distribution for $|\eta| < 1.05$.

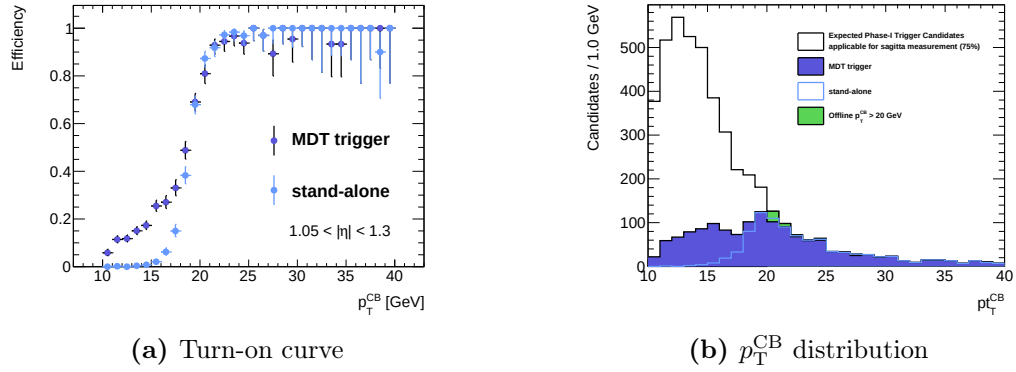


Figure 4.15: Efficiency and p_T^{CB} distribution for $1.05 < |\eta| < 1.3$.

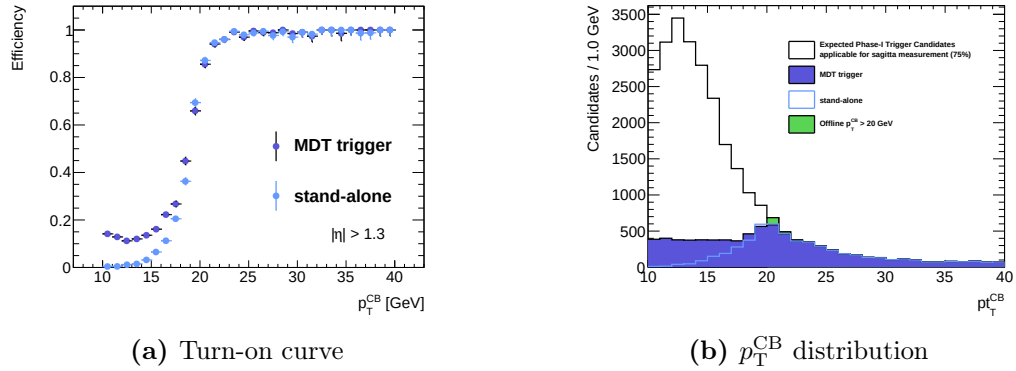


Figure 4.16: Efficiency and p_T^{CB} distribution for $|\eta| > 1.3$.

5

Fast Track Reconstruction Algorithms for the MDT Muon Trigger

In the previous chapter, the improvements in trigger selectivity by including the MDT precision data in the first level trigger decision have been estimated. In order to obtain the momentum resolution required for the estimated trigger selectivity, and to maintain full efficiency for $p_T \geq 40$ GeV muons, a sagitta resolution of at least $\sigma_s = 0.8$ mm needs to be achieved, which translates to a resolution of $\sigma_z = 0.65$ mm for the segment position in a chamber.

To be able to use the direction angle method as a fall-back solution when the sagitta method is either not applicable or limited in precision by the detector geometry, the angle measurement must perform with a resolution of 1 mrad.

To meet these two requirements within the trigger latency, the trigger electronics must employ fast track reconstruction algorithms. The latency for the Level-0 muon trigger is 6 μ s, half of which is needed for the event detection by the trigger chambers, and the data transfer, leaving the algorithm less than 3 μ s to recognise a track segment out of a hit pattern. Clearly this requirement puts a strong constraint on the choice of an adequate trigger algorithm. Fortunately, it is not necessary to reconstruct the full muon trajectory. It is sufficient to reconstruct three straight track segments, and to compute the muon momentum from segment positions and angles as shown in Chapter 4.

This stipulates the criteria by which a fast track segment reconstruction algorithms is evaluated, which are introduced first in this chapter together with the description of the simulation framework used to test the algorithms. After a general introduction of track reconstruction algorithms for drift tube detectors, three algorithms are introduced. The applicability of the first algorithm was already demonstrated in the end-cap region ($1.05 < |\eta| < 2.4$) in Ref. [50], but the algorithm does not meet the requirements in the barrel region ($0 < |\eta| < 1.05$). A variant of the first algorithm relies on running multiple instances of the algorithm in parallel, with each slightly

different parameters, to compensate for the reduced precision in the barrel region. It meets the requirements in the barrel region well, but requires hardware support for parallel computing. This fact motivates the development of a novel algorithm, which makes use of tangents to drift radii. All algorithms tested in a simulation framework to determine the optimal set of parameters and to quantitatively prove their usefulness in terms of precision and stability in presence of background events.

5.1 Evaluation of performance

In this section the criteria, which are used to assess the algorithms, are defined. In general, one is interested in the efficiency of the algorithm, which is defined as the ratio of the number of accepted tracks divided by the total number of tracks. An accepted track is called a well reconstructed muon track if the deviation of its slope from the true slope of the muon trajectory $m_{\text{rec}} - m_{\text{true}}$ is within the 3σ -interval defined by the MDT slope resolution needed for the expected trigger selectivity $3\sigma_{\text{MDT}} = 3(\sigma_{\theta} \cdot \frac{dm}{d\theta}) = 3(1 \text{ mrad} \cdot (1 + \tan^2 \theta))$, which is the product of the MDT chamber's angular resolution σ_{θ} and a correction factor for the polar angle.

	$n_{\text{hits}} \geq n_{\text{threshold}}$	$n_{\text{hits}} < n_{\text{threshold}}$
$ m_{\text{rec}} - m_{\text{true}} < 3\sigma_{\text{MDT}}$	well reconstructed track	track rejected
$ m_{\text{rec}} - m_{\text{true}} > 3\sigma_{\text{MDT}}$	poorly reconstructed track	track rejected

Table 5.1: Classification of reconstructed track segments

As shown in Table 5.1, a track is accepted if the number of accumulated hits on the reconstructed track segment n_{hits} is equal to or greater than a specified threshold $n_{\text{threshold}}$. The two categories of accepted tracks suggest the following two quantities to assess the quality of an algorithm:

1. The accepted track might satisfy the condition for a well reconstructed muon track. The fraction of **accepted well reconstructed tracks** is referred to as 3σ -efficiency and is defined as

$$\varepsilon = \frac{\text{nb. of tracks with } |m_{\text{rec}} - m_{\text{true}}| < 3\sigma_{\text{MDT}} \text{ and } n_{\text{hits}} \geq n_{\text{threshold}}}{\text{number of tracks}}.$$

The 3σ -efficiency characterises the amount of the tails in a residual distribution. A low 3σ -efficiency is caused by inefficiencies due to δ -electrons and by the occupancy of the drift tube.

2. The accepted track might not satisfy the condition for a well reconstructed muon track. The fraction of **accepted poorly reconstructed tracks** is defined as

$$n_{\text{poor}} = \frac{\text{nb. of tracks with } |m_{\text{rec}} - m_{\text{true}}| > 3\sigma_{\text{MDT}} \text{ and } n_{\text{hits}} \geq n_{\text{threshold}}}{\text{number of tracks}}.$$

In this study the 3σ -efficiency ε , which should be maximal, and the fraction of accepted poorly reconstructed tracks n_{poor} , which should be minimal, will be quoted as a measure of the algorithm performance. The efficiency is the sum of the two quantities.

5.2 Track reconstruction for drift tube detectors

The position information delivered by drift tube detectors consists of a circle centred on the spatial position of the anode wire, which is tangential to the muon trajectory. The circle's radius is determined from the drift time of the primary ionisation electron by the space-to-drift time relation of the gas, hence it is referred to as the drift circle. Figure 5.1 shows a typical event with both drift circles originating from the muon and drift circles due to background. The task of a pattern finding algorithm is to select the drift circles originating from the muon and to resolve the ambiguity which point on the drift circle belongs to the muon trajectory. The point, which is tangential to the muon trajectory, will be called the muon hit from now on. In order to cope with the expected high background at the HL-LHC, non-iterative algorithms are preferred to ensure the pattern recognition in the given time window.

5.3 Monte-Carlo study

5.3.1 The simulation framework

The algorithm performance was studied with simulated data generated with a simulation program originally written by Oliver Kortner and modified by the author. The simulation framework constructs a chamber geometry specified by the parameters

- drift tube radius R ,
- thickness of the wall of a drift tube d_{wall} ,
- number of multilayers n_{ML} ,
- number of layers per multilayer n_{LY} ,

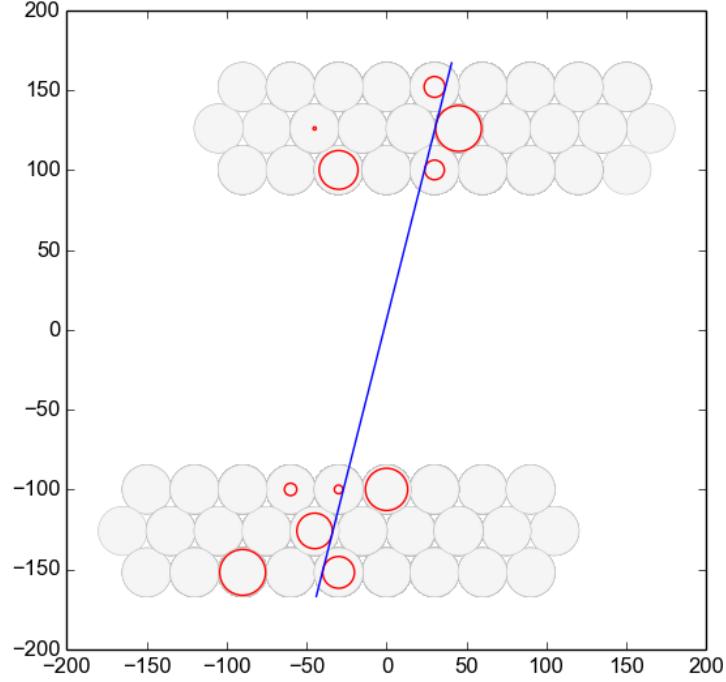


Figure 5.1: Typical event of a muon (blue) passing through a MDT chamber and drift radii (red).

- number of tubes per layer n_{TB} ,
- spacer thickness d .

A straight muon track segment is generated with parameters taken from uniform distributions, whose boundaries are determined from the positions of the different chamber types in the muon system. Hits in the drift tubes are generated in a road of ± 60 mm (± 120 mm for EO) around the muon track. The number of background hits that are generated depends on the occupancy of the chamber. The occupancy of a drift chamber is defined as the product of the maximum drift time and the background hit rate

$$\text{occupancy} = n_{\text{background}} \cdot t_{\text{drift, max}}.$$

The simulation framework also takes delta electron hits into account.

5.3.2 Parameters for track generation

Each set of chambers of the muon spectrometer was investigated for this study. Depending on chamber geometry and position in the muon spectrometer the parameters for the simulation framework differ and had to be obtained from ATLAS data, documentation and publications.

The spacer thickness and other mechanical parameters were taken from Ref. [31]. The predicted background hit rates $n_{\text{background}}$ for a luminosity of $7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, which are discussed in Section 2.4, were taken from Ref. [38] by taking the average of the rate predictions for the detector hemispheres. The occupancy was calculated with a maximum drift time of $t_{\text{drift, max}} = 750 \text{ ns}$ ¹.

The minimum and maximum expected slopes of track segments were determined with ATLAS data from Run 1. Track segments, which could be matched to muons with $p_T > 10 \text{ GeV}$, whose trajectories were reconstructed from hits in the inner detector and the muon system with a χ^2 per degree of freedom < 3 , were used to determine the interval containing 99% of all slopes for each set of chambers. Examples of two track segment slope distributions are shown in Figure 5.2. The maximum and minimum expected track segment intercepts were assumed to be $\pm 60 \text{ mm}$, corresponding to a region of interest covering around four drift tubes.

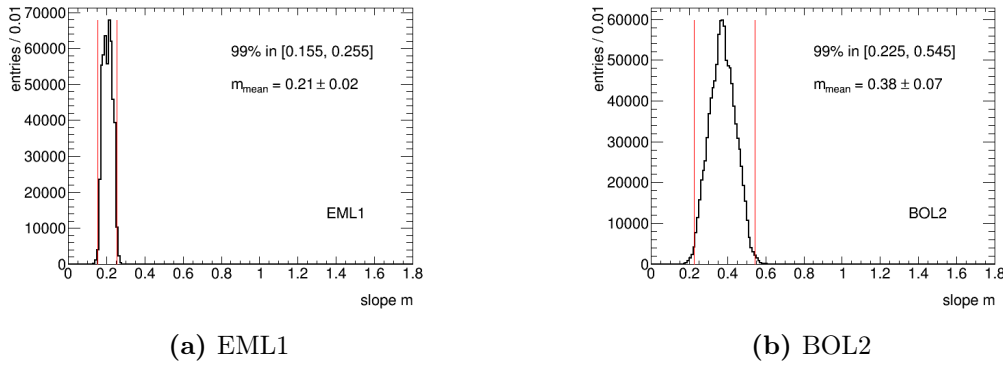


Figure 5.2: Illustrative distributions of track segment slope distributions. The interval indicated by the red bars contains 99% of all slopes.

For all chambers a TDC resolution of 12.5 ns is used.

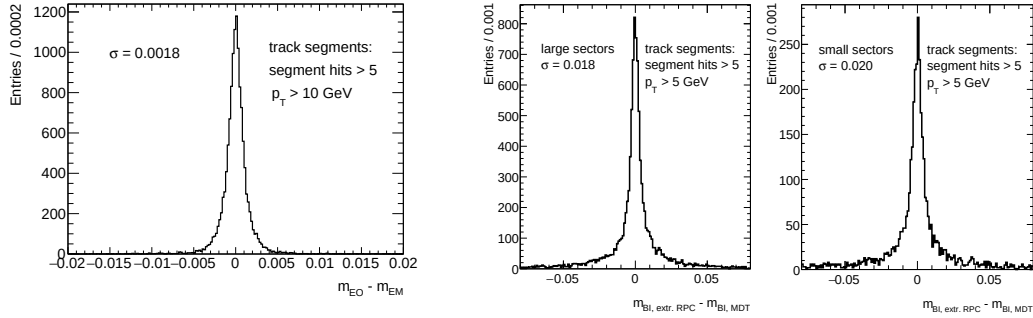
The algorithms presented in this thesis use the track information provided by trigger chambers. The precision with which the MDT segment slopes and intercepts can be predicted from the measurements of the trigger chambers depends on the location of

¹The small admixture of water to the Ar-CO₂ gas mixture increases the drift time from 700 ns to 750 ns .

an MDT chamber. The different configurations and how to treat them are discussed in the following paragraphs. The TGC track segment resolutions for muons with transverse momenta of 10 GeV for EM chambers were studied in Ref. [51], which served as a reference for the EM seed track's angular resolution $\sigma_{EO} \sim 5$ mrad.

In EO there are no TGC trigger chambers. Due to the low magnetic field between EM and EO it is possible to extrapolate linearly the track segment direction in EM to EO. The distribution of differences between MDT track segment slopes in EO and EM is shown in Figure 5.3a. The assumed EO seed track angular resolution is the quadratic sum of the width of the distribution shown in Figure 5.3a and the TGC resolution used for extrapolation is $\sigma_{EO} = \sqrt{\sigma_{TGC}(\eta)^2 + \sigma_{EO-EM}^2} \sim 5$ mrad.

The RPC track segment slope resolution in BM is $\sigma_{BM} = 0.015$. The RPC track segment slope resolution in BI was determined by calculating the segment slope $m_{BI, \text{extr. RPC}}$ from the line defined by the interaction vertex and a MDT position measurement in BI, which was smeared by the position resolution of the RPC chamber and the MDT segment slope $m_{BI, \text{MDT}}$ as a measure of the true value. The width of the residual distribution, which is shown in Figure 5.3b, was used to determine the seed track slope resolution in BI for large and small chambers, which is $\sigma_{BIL} = 0.018$ and $\sigma_{BIS} = 0.020$ respectively.



(a) Distribution of slope differences in EO and EM.

(b) Slope resolution of BI chambers.

Figure 5.3: Distributions for determining the trigger chamber seed track resolution. The distributions were created using MDT track segments with associated muon transverse momentum of $p_T > 10$ GeV and six or more accumulated hits on each segment.

A similar method was used to determine the RPC track segment slope resolution in BO. The seed track slope resolutions for large sectors in BO were determined by comparing the slope of a parabola at BOL through the MDT position measurements in BI, BM, and BO smeared by the RPC resolution with the MDT track segment slope in BOL. More than five accumulated hits, an associated muon with $p_T > 10$ GeV

and χ^2 per degree of freedom < 3 were required. The seed track slope resolution in BOL is $\sigma_{BOL} = 0.075$.

For small sectors in BO an extrapolation using a straight line through BOS and BMS has proven to be sufficient. The trigger chamber seed track slope resolution in BOS is $\sigma_{BOS} = 0.085$. These values should be treated as indicators for the order of magnitude of the BO seed track slope resolution. The residual distributions for the BO seed track slopes are shown in Figure 5.4.

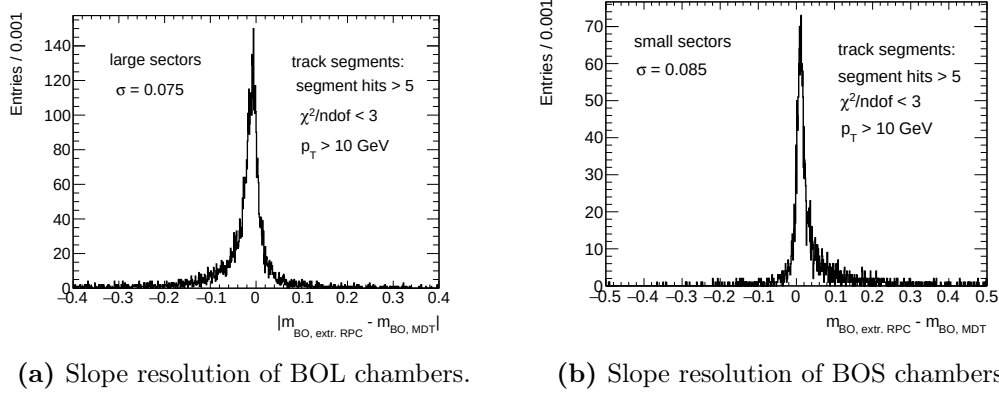


Figure 5.4: Distributions for determining the seed track resolution. The distributions were created using track segments with associated muon transverse momentum of $p_T > 10$ GeV, χ^2 per degree of freedom < 3 and 6 or more accumulated hits.

In summary, the track segment slope resolution of the trigger chambers in the end-cap region is $\sigma_{EM,EO} \sim 0.005$, whereas in the barrel region it is at least thrice this value. In the barrel inner layer, the track segment slope resolution of the trigger chambers is $\sigma_{BI} \sim 0.020$, in the barrel middle layer it is $\sigma_{BM} \sim 0.015$, and in the barrel outer layer it is $\sigma_{BO} \sim 0.080$.

In Table 3 in the appendix the parameters for the simulation of each chamber in the end-cap are shown, respectively Table 4 for the barrel region.

5.4 Histogram-based Pattern Recognition Algorithm

The Histogram-based Pattern Recognition (HbPR) algorithm [50] makes use of the information provided by the trigger chambers. For each trigger candidate, the ATLAS trigger level architecture provides a TGC or RPC track segment with the resolution mentioned before. The track segment reconstructed by the trigger chambers can serve as a seed for the fast MDT segment reconstruction. If the seed track had perfect

resolution, meaning it would be identical to the muon trajectory, the projection of the hits originating from the muon on the axis orthogonal to the muon trajectory would all be identical within the spatial resolution of the tubes. However, since the seed track has a finite resolution, the distribution of projected hits is widened.

The algorithm is split in a pattern-recognition step and a track reconstruction part. The description of the pattern recognition part is illustrated by the steps shown in Figure 5.5.

1. The information given to the algorithm consists of the drift tube's wire positions (x_i, y_i) , **drift circles originating from a muon**/**drift radii originating from uncorrelated background** with drift radius $r_{\text{drift},i}$ and the slope $m = \tan \alpha$ of the **seed track** in the chamber coordinate frame. The uncertainty in the slope is indicated by a region of lighter colour around the muon trajectory in Figure 5.5a.
2. The chamber coordinate frame is rotated by α around the x -axis such that the z' -axis of the new frame is collinear with the axis defined by the seed track.
3. The problem of finding the hit position on the drift circle is reduced to a left-right ambiguity. The projection of the muon hits on the y' -axis is

$$d_i^{\pm} = x_i \cos \alpha + y_i \sin \alpha \pm r_{\text{drift},i}$$

4. A histogram is filled with the two possible projections for each drift circle. The hits contained in the bin with the maximum number of entries are subsequently used for track reconstruction.

The track reconstruction part consists of fitting a straight line to the hits obtained by the pattern recognition using the method of least squares. The straight track $y(z) = \alpha_0 + \alpha_1 \cdot z$ determined by the track points $(z_i, y_i), i = 1, \dots, n$ is reconstructed by minimising

$$\chi^2 = \sum_{i=1}^n \frac{1}{\sigma_i^2} (y_i - \alpha_0 - \alpha_1 \cdot z)^2,$$

where $\sigma_i = \sqrt{\sigma_{\text{single tube}}^2 + \sigma_{\text{TDC}}^2}$ is the spatial resolution of each hit, determined by the single tube resolution and the influence of the limited precision of the TDC. The detailed treatment of the straight track reconstruction can be found in the appendix. If multiple track candidates are found by the algorithm, the one with lowest χ^2 value is retained.

There are two parameters in the algorithm for which optimal values have to be determined, depending on the seed resolution and occupancy:

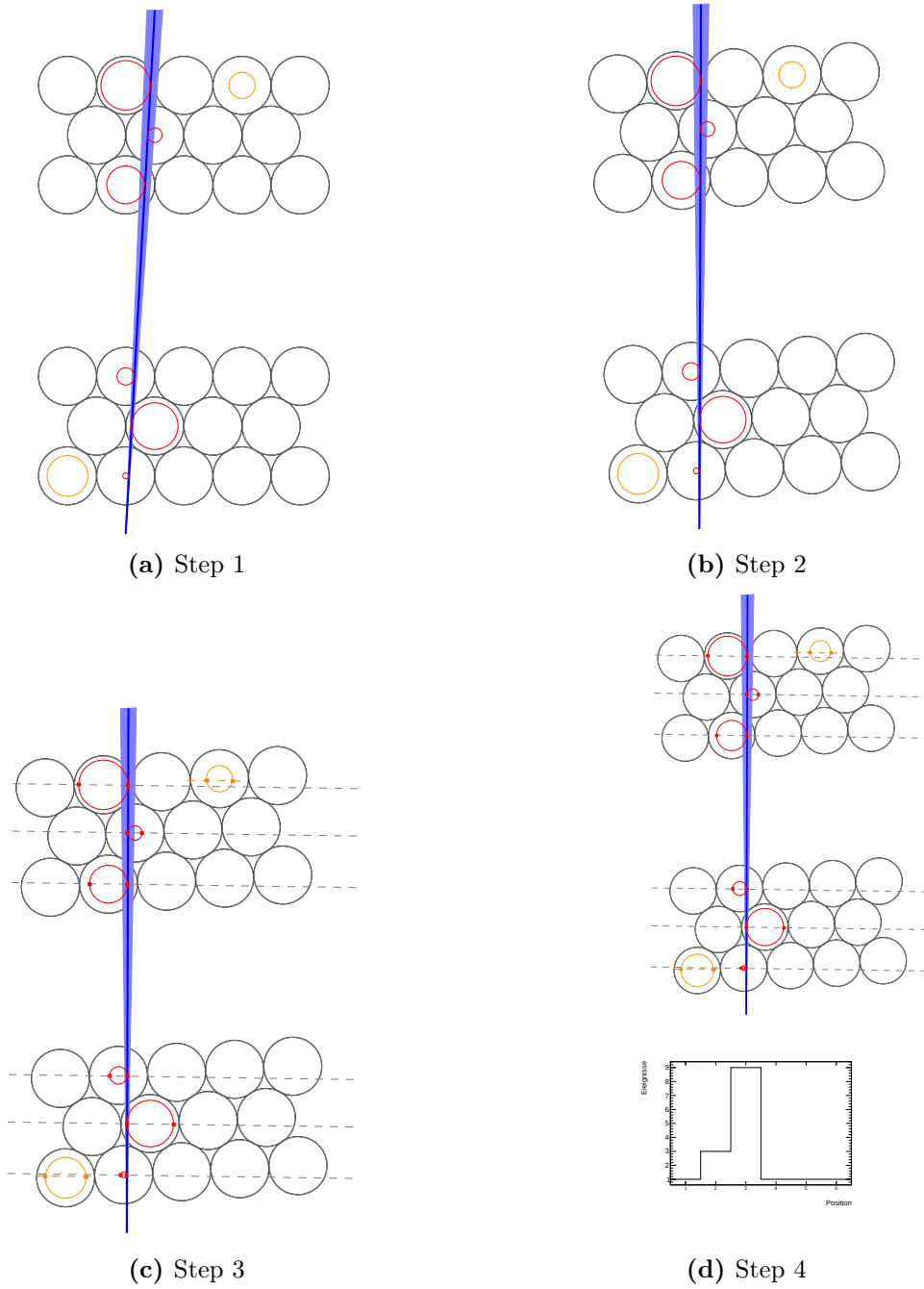


Figure 5.5: Schematic illustration of the Histogram-based Pattern Recognition algorithm.

- bin width of the histogram,
- minimum number of hits in a peak, called the threshold $n_{\text{threshold}}$ in the following.

This algorithm relies on a rather precise seed. Therefore it seems to be promising for the end-cap region of the muon system, where the TGC chambers already provide a good angular resolution, making the track segments reconstructed by the TGCs useful seeds for the algorithm.

A detailed description of the algorithm's performance will be given only for one of the most critical chamber among the chambers with the highest uncorrelated background, which is EML1. The results for the other chambers are summarised later.

In Figure 5.6 the track reconstruction efficiency for bin widths from 1.0 mm to 4.5 mm is shown for different thresholds. The smallest threshold, which is still sufficient to calculate the χ^2 of the fit and to resolve the left-right ambiguity is $n_{\text{threshold}} = 3$ hits. The efficiency increases for a larger bin width and for a lower threshold. For low thresholds effectively all tracks are accepted, resulting in a high efficiency. Similarly, a larger bin width leads to more hit points in the track reconstruction step, also leading to a higher efficiency.

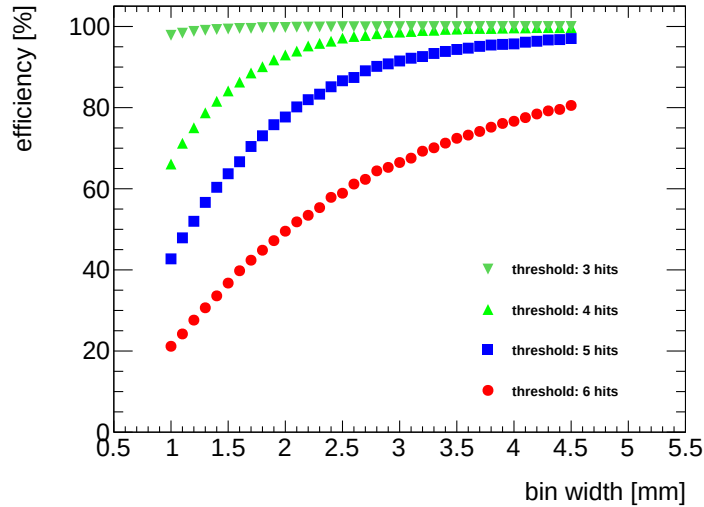


Figure 5.6: Track reconstruction efficiency of HbPR algorithm for EML1 chamber.

Since the efficiency, solely measuring the quantity of reconstructed tracks, makes no statement about the quality of the reconstructed segment, the residuals of the reconstructed track segment slopes are used as a quality measure.

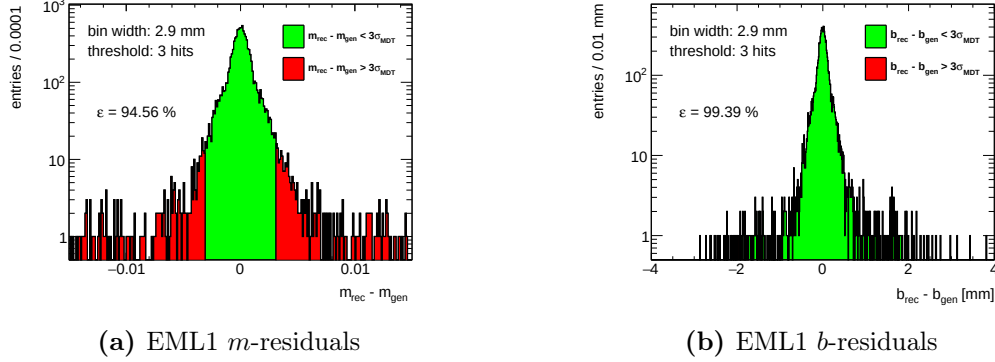


Figure 5.7: Distributions of track segment slope and intercept residuals in EML1 reconstructed with HbPR algorithm with bin width 2.9 mm and threshold 3 hits. The fraction of the histogram in green contributes to the respective ε , the fraction in red to n_{poor} .

In Figure 5.7 the track segment slope residuals $m_{\text{rec}} - m_{\text{gen}}$ (5.7a) and intercept residuals $b_{\text{rec}} - b_{\text{gen}}$ (5.7b) for a reconstruction with a bin width of 2.9 mm and a threshold of 3 hits are shown. The 3σ -intervals defined by the MDT slope resolution of 0.001, respectively the required intercept resolution of 2 mm for precise sagitta measurements of 40 GeV muons, are used to distinguish between well and poorly reconstructed muon track segments. The algorithm is able to reconstruct $\varepsilon = 94.56\%$ of the slopes well and over 99.39% of the intercepts. It is therefore sufficient to focus on the reconstruction quality of the segment slopes from now on.

In Figure 5.8 ε and n_{poor} are shown for different thresholds with varying bin width. The highest 3σ -efficiency is achieved for a threshold of 3 hits and forms a plateau for bin widths from 2.5 mm to 3.2 mm. The smallest corresponding fraction of poorly reconstructed tracks $n_{\text{poor}} = 5.44\%$ is achieved with a bin width of 2.9 mm. The maximum 3σ -efficiency is 94.56% for EML1.

The optimal values of ε , n_{poor} and the corresponding parameters for the other chambers are listed in Table 5.3. For all chambers in the end-cap region the value of ε varies from $\sim 95\%$ for the chambers closest to the beam-pipe to $\sim 90\%$ for the outer chambers. The value of n_{poor} varies accordingly from $\sim 5\%$ to $\sim 10\%$. This is due to the algorithm's dependence of the TGC seed track resolution, which is less precise for the outer chambers.

An implementation of the HbPR algorithm on a ZC706 evaluation board featuring the XC7Z045 FFG900 -2 AP System on a Chip was realised by Sebastian Nowak [50]. In Figure 5.9 the results of processing the simulated data for EML1 with a perfect seed track resolution are shown. The 3σ -efficiency of 98.58% is achieved within the order of magnitude of the first level trigger latency. Exploiting the full potential of a

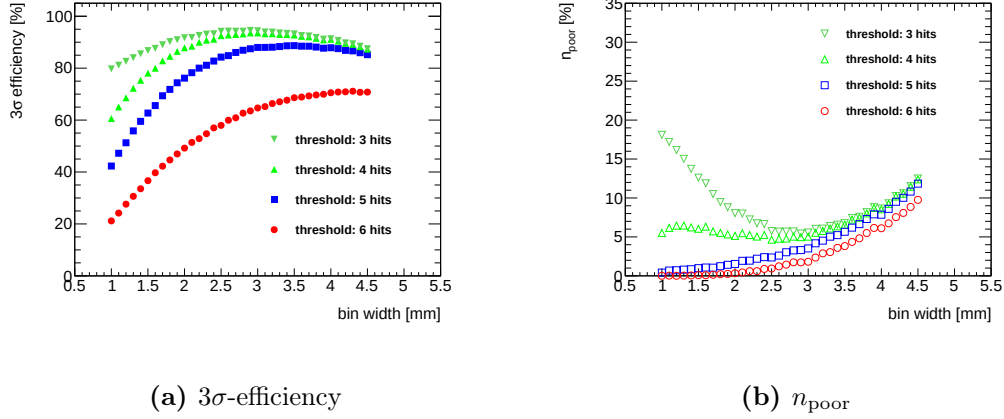


Figure 5.8: 3σ -efficiency and n_{poor} of HbPR algorithm for EML1.

combination of look-up tables provided by an FPGA² and a fast microprocessor is expected to enable the algorithm to meet the demands by the trigger latency.

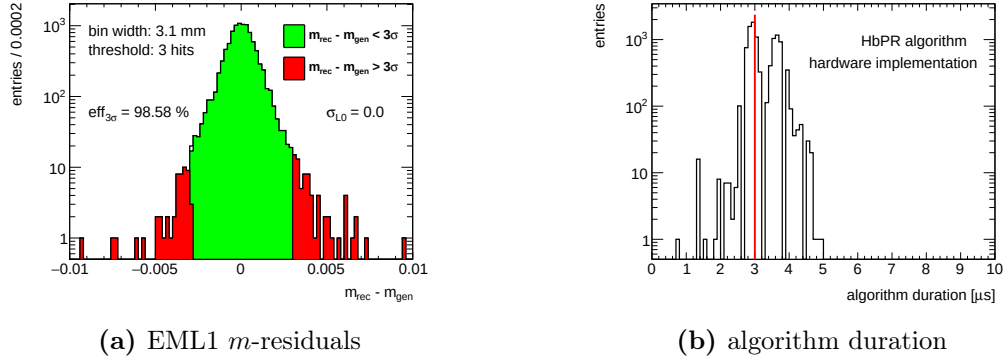


Figure 5.9: Distributions of track segment slope residuals in EML1 reconstructed with the hardware implementation of the HbPR algorithm with bin width 3.1 mm and threshold 3 hits for perfect seed tracks and distribution of reconstruction time. The red line indicates the expected time budget for the track segment reconstruction algorithm.

In the barrel region there is hardly a chamber, for which the algorithm surpasses a maximum 3σ -efficiency of 60%, because the quality of the seed track provided by the RPCs is substantially worse than in the end-cap. The effect of the reduced resolution on the residual distribution is shown in Figure 5.10. For outer barrel chambers ε even only reaches values of 10% to 22%. This makes the HbPR algorithm only a viable choice in the end-cap.

²Field Programmable Gate Array

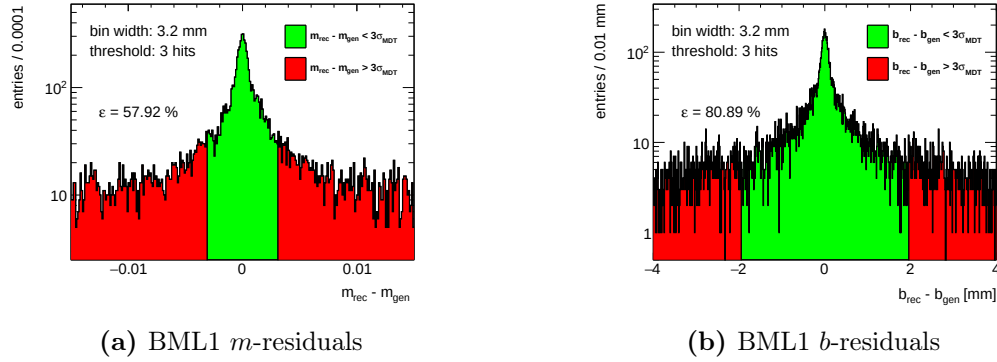

 Figure 5.10: BML1 b -residuals

Table 5.2: Optimal parameters for HbPR in MDT chambers of the end-cap of the ATLAS muon system.

chamber	ε [%]	n_{poor} [%]	bin width [mm]	threshold [hits]
EML1	94.56	5.44	2.9	3
EML2	95.20	4.79	2.8	3
EML3	96.34	3.64	3.0	3
EML4	93.84	6.15	3.0	3
EML5	90.87	9.13	3.4	3
EMS1	94.71	5.27	3.0	3
EMS2	95.28	4.68	2.7	3
EMS3	96.27	3.73	2.8	3
EMS4	90.54	9.46	3.2	3
EMS5	91.20	8.80	3.6	3
EOL1	95.21	4.75	2.9	3
EOL2	92.94	7.02	3.0	3
EOL3	95.74	4.25	3.0	3
EOL4	95.87	4.12	2.9	3
EOL5	94.34	5.66	3.6	3
EOL6	90.99	9.0	3.1	3
EOS1	95.47	4.51	3.0	3
EOS2	92.75	7.23	3.2	3
EOS3	95.96	4.02	2.8	3
EOS4	96.22	3.77	3.0	3
EOS5	94.17	5.82	2.8	3
EOS6	90.49	9.45	3.2	3

Table 5.3: Optimal parameters for HbPR in MDT chambers of the barrel region of the ATLAS muon system.

chamber	ε [%]	n_{poor} [%]	bin width [mm]	threshold [hits]
BIL1	58.61	41.35	3.2	3
BIL2	53.96	46.04	4.4	3
BIL3	49.69	50.31	4.3	3
BIL4	45.64	54.36	3.2	3
BIL5	46.10	53.88	3.9	5
BIL6	48.25	51.74	4.1	5
BIS1	67.79	32.21	3.5	3
BIS2	63.36	36.64	3.2	3
BIS3	49.45	50.49	2.7	3
BIS4	41.60	58.05	2.6	4
BIS5	41.38	57.26	2.5	5
BIS6	42.64	53.21	2.4	6
BML1	53.84	46.07	4.4	3
BML2	54.67	45.26	4.4	3
BML3	51.78	48.21	4.3	3
BML4	50.22	49.78	4.3	3
BML5	51.96	48.04	4.4	3
BML6	55.19	44.79	4.5	4
BMS1	63.66	36.14	3.8	3
BMS2	63.08	36.87	4.5	3
BMS3	58.76	41.23	3.6	3
BMS4	54.59	45.38	3.2	3
BMS5	52.83	47.15	3.2	3
BMS6	55.99	44.01	2.9	3
BOL1	21.64	62.08	4.5	3
BOL2	17.37	72.09	4.5	3
BOL3	14.25	78.51	4.0	3
BOL4	12.14	85.78	4.3	3
BOL5	11.27	87.83	4.1	3
BOL6	12.70	82.81	4.2	4
BOS1	19.60	56.87	4.2	3
BOS2	16.06	67.10	4.3	3
BOS3	12.54	79.34	4.3	3
BOS4	10.54	83.44	3.9	3
BOS5	10.10	76.34	4.5	4
BOS6	11.15	81.29	4.5	4

Binned 2D-Hough Transform

A possible way to overcome the dependency of the seed track precision could be the extension of the HbPR to a binned 2D-Hough Transform [50]. A Hough Transform [52] is a pattern recognition algorithm which identifies patterns by finding maxima in a parameter space. The algorithm described in the previous section is a special case, where only one slice of the two dimensional parameter space defined by the seed track is considered. This constitutes the elementary algorithm of the Binned 2D-Hough Transform. Running several elementary algorithms with seed tracks shifted in slope in parallel corresponds to performing a two-dimensional Hough Transform with discrete bins. For finding a straight lines with the Hough Transform [53] the line's normal parametrisation specified by the angle α of its normal and its algebraic distance to the origin

$$d = x \cdot \cos \alpha + y \cdot \sin \alpha$$

is used, which is unique for $0 \leq \alpha < \pi$. In this case there is an isomorphic map of the points (x_i, y_i) , $i = 1, \dots, n$ to sinusoidal curves in the d - α -plane. Since curves corresponding to points of the same co-linear figure intersect in one point in the d - α -plane, searching for the point belonging to the most intersections will result in finding the corresponding straight line in position space.

The case of running $1 + n_{\text{add. alg.}}$ elementary algorithms with seed tracks shifted in slope $m = \tan \alpha$ in parallel and retaining the candidate with most accumulated hits in the maximum bin of a histogram filled with

$$d_i = x_i \cdot \cos \alpha_j + y_i \cdot \sin \alpha_j \pm r_{\text{drift}, i}.$$

corresponds to the 2D-Hough Transform described before, with the bin width of the histogram defined as in Section 5.4 and equidistant bins of the angular coordinate $\alpha_j = \alpha + j \cdot n\sigma_\alpha$ with $j = -\frac{n_{\text{add. alg.}}}{2}, -\frac{n_{\text{add. alg.}}}{2} + 1, \dots, \frac{n_{\text{add. alg.}}}{2}$. The left-right ambiguity is resolved by both adding and subtracting the drift radius $r_{\text{drift}, i}$ for each space point (x_i, y_i) defined by the position of the hit wire.

The correspondence between space points and sinusoidal curves in parameter space is shown in Figure 5.11.

There are four parameters in the algorithm, for which optimal values have to be determined:

- bin width of the histogram,
- minimum number of hits in a peak called the threshold as above,
- number of elementary algorithms $1 + n_{\text{add. alg.}}$,

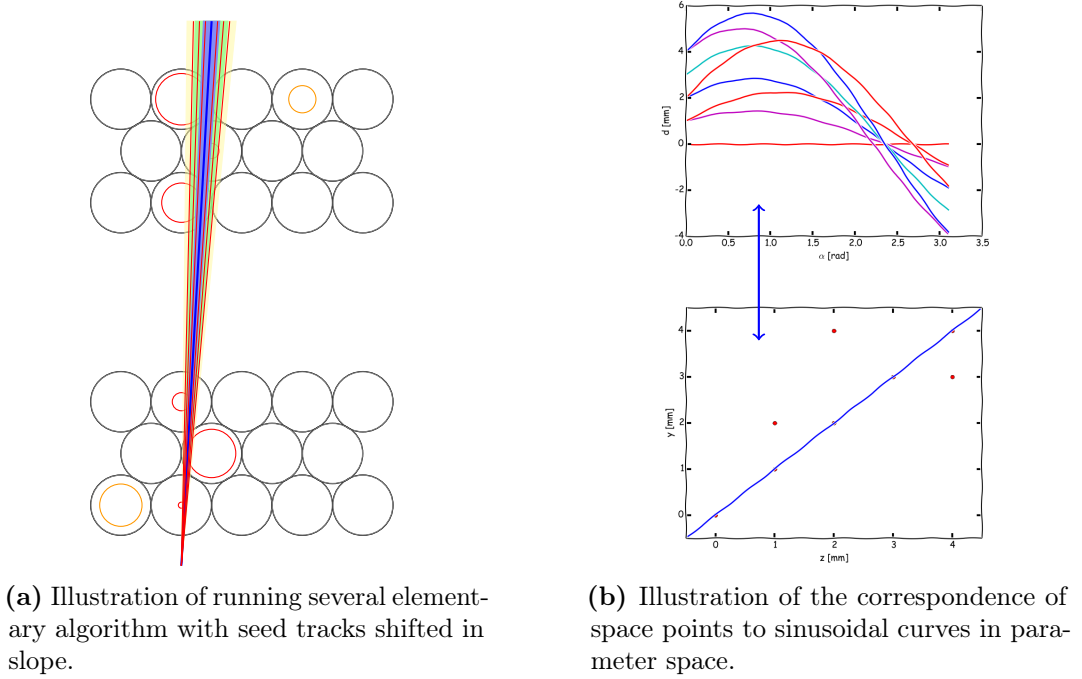


Figure 5.11: Schematic illustration of the Binned 2D-Hough Transform algorithm.

- the width of the angular coordinate interval covered in parameter space, which is parametrised in integer multiples n of the seed track slope resolution $\sigma_{m_{\text{seed}}}$: $[m_{\text{seed}} - n \cdot \sigma_{m_{\text{seed}}}, m_{\text{seed}} + n \cdot \sigma_{m_{\text{seed}}}]$.

As before, the bin width was varied from 1.0 mm to 4.5 mm. The 2D-Hough Transform was studied with $n_{\text{add. alg.}} = 2, 6$ and 10 additional algorithms, covering an interval in slope parameter space defined by an integer multiple $n = 1, 2$ and 3 of the seed track slope resolution $\sigma_{m_{\text{seed}}}$.

The number of elementary algorithms, corresponding to the granularity of the binning in the angular coordinate, is essential for the efficiency and reconstruction quality of the algorithm.

In Figure 5.12 the track reconstruction efficiency for bin widths from 1.0 mm to 4.5 mm is shown for a low and a high threshold of respectively 3 and 5 hits and for 3, 7 and 11 elementary algorithms running in parallel. For the low threshold a full track reconstruction efficiency is achieved for all combinations of bin widths and number of elementary algorithms under study. For the high threshold and running more than 3 elementary algorithms, the efficiency is above 90%, whereas the case of running 3

elementary algorithms is very similar to the results for the HbPR algorithm, which is the reason why included in the ensuing discussion.

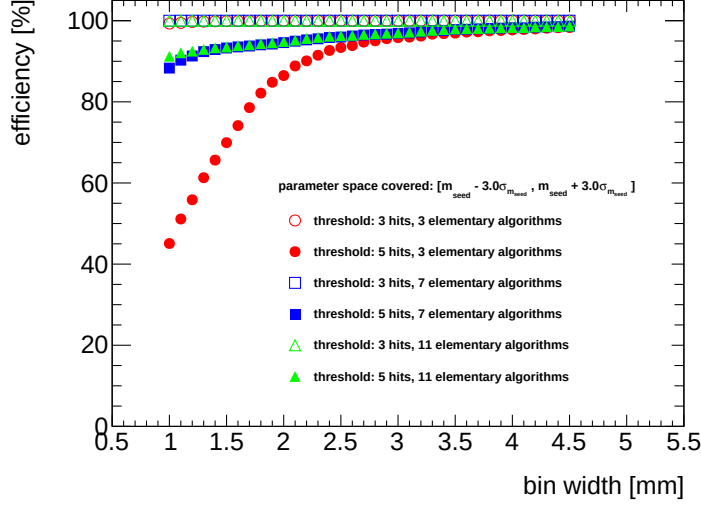


Figure 5.12: Track reconstruction efficiency of Binned 2D-Hough Transform algorithm for EML1 chamber.

The track reconstruction quality of the already good performance of the HbPR algorithm is improved by employing the Binned 2D-Hough Transform algorithm. In Figure 5.13 ε and n_{poor} are shown for the same parameter configurations as in Figure 5.12. While for a fine granularity of the binning in the angular coordinate small bin widths are preferred, for lower angular granularities, with the HbPR algorithm as the limiting case of only one angular bin, larger bin widths result in a better reconstruction quality.

As expected the highest 3σ -efficiency $\varepsilon = 98.75\%$ is achieved for the finest granularity with 11 elementary algorithms spread over an interval in parameter space spanned by $3\sigma_{m_{\text{seed}}}$ with a threshold of 3 hits and a bin width of 1.2 mm. However, the difference to the reconstruction quality with only 7 elementary algorithms is small and noticeable only for high thresholds. The smallest corresponding fraction of poorly reconstructed tracks is $n_{\text{poor}} = 1.25\%$.

The optimal values of ε , n_{poor} and the corresponding parameters for the other chambers in the end-cap region are listed in Table 5.4. The value of ε is above 98% for all chambers for all chambers in the end-cap region, with a corresponding value of n_{poor} of well below 2%. The already good reconstruction quality of the HbPR algorithm in the end-cap region can be improved by using the Binned 2D-Hough Transform algorithm. In particular n_{poor} is significantly reduced. It needs to be evaluated against the ne-

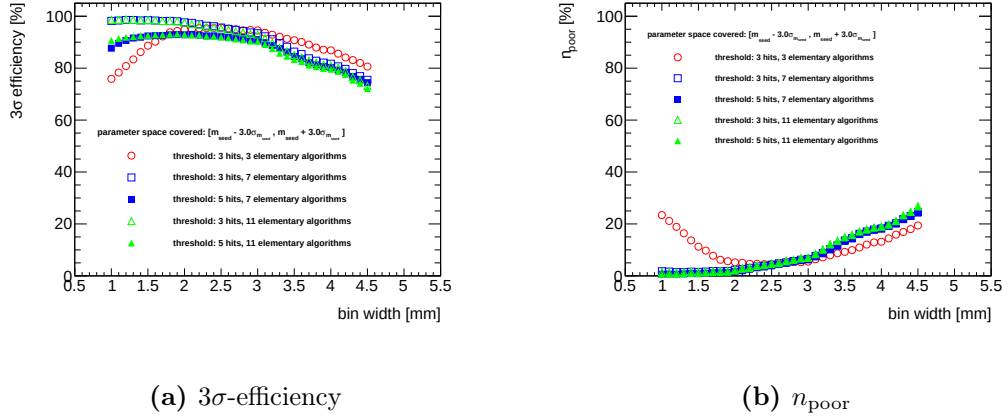


Figure 5.13: 3σ -efficiency and n_{poor} of Binned 2D-Hough Transform algorithm for EML1.

cessary computational effort. In the barrel region on the other hand, the improved efficiency of the Binned 2D-Hough Transform algorithm is urgently needed.

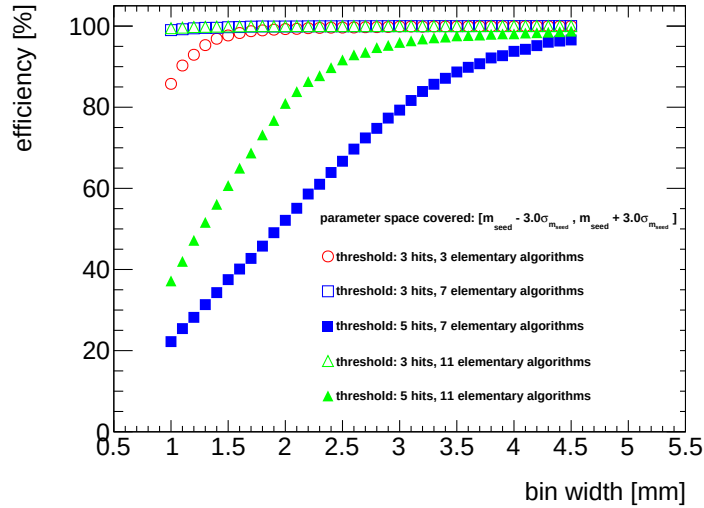


Figure 5.14: Track reconstruction efficiency of Binned 2D-Hough Transform algorithm for BML1 chamber.

In Figure 5.14 the track reconstruction efficiency is shown for bin widths from 1.0 mm to 4.5 mm for the same parameter configurations as in Figure 5.12 with the omission of the combination of running 3 elementary algorithms with a threshold of 5 hits, for which less than half the efficiency of the combination of running 7 elementary algorithms with a threshold of 5 hits is achieved. As it was the case for EML1, a full

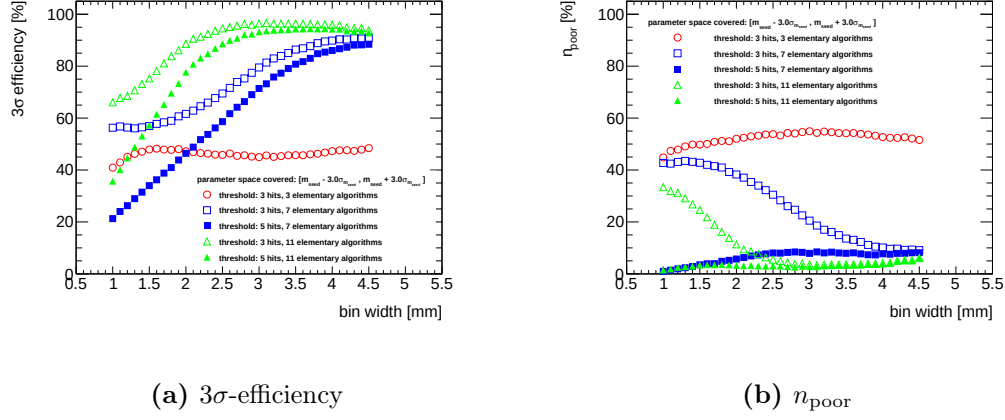


Figure 5.15: 3σ -efficiency and n_{poor} of Binned 2D-Hough Transform algorithm for BML1.

track reconstruction efficiency is achieved with the low threshold of $n_{\text{hits}} \geq 3$ hits for all combinations of bin widths and number of elementary algorithms under study. For the high threshold of $n_{\text{hits}} \geq 5$ hits larger bin widths are preferred.

A higher number of elementary algorithms corresponds to a higher efficiency as a dense grid of bins in position coordinate and angular coordinate is more likely to find the correct track, even if the starting position supplied by the seed track segment slope is imprecise.

It is required to cover angular coordinate interval spanned by at least $3\sigma_{m_{\text{seed}}}$ centred at m_{seed} to ensure that 99% of all track segments can be found by the algorithm. For an interval spanned by $1\sigma_{m_{\text{seed}}}$ the 3σ -efficiency is bounded above by 80%. For larger intervals spanned by $5\sigma_{m_{\text{seed}}}$, a higher number of elementary algorithms than 11 is needed to maintain the required granularity for a good track reconstruction quality. A lower number of elementary algorithms can be partially compensated by increasing the bin width of the elementary algorithm's histogram.

The optimal 3σ -efficiency of $\varepsilon = 96.67\%$ with $n_{\text{poor}} = 3.33\%$ is achieved with running 11 elementary algorithms in parallel covering the interval $[m_{\text{seed}} - 3\sigma_{m_{\text{seed}}}, m_{\text{seed}} + 3\sigma_{m_{\text{seed}}}]$ in parameter space, each with a bin width of 3.1 mm and a threshold of at least 3 hits.

The optimal values of ε , n_{poor} and the corresponding parameters for the other chambers in the barrel region are listed in Table 5.5. With the Binned 2D-Hough Transform algorithm it is possible to achieve values of ε well above 96% in the inner and middle barrel layers. The values of n_{poor} for these chambers are below 4%. Because of the poor seed track resolution $\sigma_{m_{\text{seed}}} \sim 0.080$ of the outer chambers, an even finer binning in the angular coordinate is required for a good reconstruction quality. When running

11 elementary algorithms in parallel, the Binned 2D-Hough Transform can achieve $\varepsilon \sim 70\%$ and $n_{\text{poor}} \sim 30\%$. Both a large interval in the angular parameter space and a fine granularity are needed: when running 25 elementary algorithms in the interval $[m_{\text{seed}} - 3\sigma_{m_{\text{seed}}}, m_{\text{seed}} + 3\sigma_{m_{\text{seed}}}]$, the 3σ -efficiency can be increased to $\varepsilon \sim 85\%$, with $n_{\text{poor}} \sim 15\%$.

With the emergence of multiprocessor system-on-chip (MPSoC) architecture featuring new high-end GPUs, strongly relying on parallel processing, which is suggested naturally by the Binned 2D-Hough Transform's concept of elementary algorithms, is a promising option to meet the latency requirements. The overall excellent reconstruction quality with $\varepsilon > 96\%$ for most chambers of the muon system gives reason for investigating the hardware realisation of the algorithm. However, given the computational effort associated with the Binned 2D-Hough Transform and the performance for the outer barrel chambers, it seems worthwhile to search for an alternative algorithm.

Table 5.4: Optimal parameters for Binned 2D-Hough Transform in MDT chambers of the end-cap of the ATLAS muon system.

chamber	ε [%]	n_{poor} [%]	bin width [mm]	$1 + n_{\text{add. alg.}}$	n	threshold [hits]
EML1	98.75	1.25	1.2	11	3	3
EML2	98.6	1.38	1.4	11	3	3
EML3	99.09	0.91	1.0	11	3	3
EML4	98.26	1.74	1.3	11	3	3
EML5	99.34	0.66	1.3	11	3	3
EMS1	98.52	1.43	1.1	11	3	3
EMS2	98.77	1.22	1.0	11	3	3
EMS3	98.82	1.17	1.3	11	3	3
EMS4	98.03	1.97	1.1	11	3	3
EMS5	98.81	1.19	1.4	11	3	3
EOL1	98.95	1.05	1.6	11	3	3
EOL2	99.19	0.8	1.3	11	3	3
EOL3	99.23	0.77	1.2	11	3	3
EOL4	99.19	0.81	1.1	11	3	3
EOL5	99.2	0.8	1.1	11	3	3
EOL6	98.56	1.44	1.0	11	3	3
EOS1	99.14	0.86	1.3	11	3	3
EOS2	99.27	0.72	1.3	11	3	3
EOS3	99.24	0.76	1.4	11	3	3
EOS4	99.34	0.65	1.0	11	3	3
EOS5	99.32	0.68	1.4	11	3	3
EOS6	98.4	1.6	1.4	11	3	3

Table 5.5: Optimal parameters for Binned 2D-Hough Transform in MDT chambers of the barrel region of the ATLAS muon system.

chamber	ε [%]	n_{poor} [%]	bin width [mm]	$1 + n_{\text{add. alg.}}$	n	threshold [hits]
BIL1	98.62	1.38	2.6	11	3	4
BIL2	98.71	1.29	2.6	11	3	4
BIL3	97.89	2.11	2.1	11	3	4
BIL4	99.59	0.41	1.9	11	3	5
BIL5	99.89	0.11	1.9	11	3	5
BIL6	99.94	0.06	1.8	11	3	6
BIS1	96.8	3.19	1.5	11	3	4
BIS2	96.96	3.04	1.4	11	3	4
BIS3	96.34	3.66	1.6	11	3	4
BIS4	97.16	2.83	1.2	11	3	5
BIS5	98.94	1.06	1.0	11	3	5
BIS6	99.43	0.55	1.0	11	3	6
BML1	96.67	3.33	3.1	11	3	3
BML2	96.86	3.11	3.0	11	3	4
BML3	96.46	3.51	2.7	11	3	4
BML4	99.02	0.98	2.7	11	3	4
BML5	99.39	0.61	2.6	11	3	4
BML6	99.44	0.56	2.6	11	3	4
BMS1	97.41	2.58	2.0	11	3	3
BMS2	97.68	2.32	1.9	11	3	3
BMS3	97.56	2.44	1.9	11	3	3
BMS4	98.52	1.48	1.7	11	3	3
BMS5	99.42	0.58	1.8	11	3	3
BMS6	99.77	0.22	1.8	11	3	4
BOL1	69.6	28.75	4.2	11	1	3
BOL2	68.83	30.36	4.3	11	1	3
BOL3	68.15	31.63	4.3	11	1	3
BOL4	69.99	29.93	3.6	11	1	3
BOL5	72.14	26.48	3.3	11	1	4
BOL6	73.34	23.37	3.3	11	1	5
BOS1	65.46	32.73	4.5	11	1	3
BOS2	66.34	32.74	4.5	11	1	3
BOS3	64.26	35.39	4.2	11	1	3
BOS4	65.48	34.31	4.1	11	1	3
BOS5	69.34	28.8	3.7	11	1	4
BOS6	71.08	27.6	3.5	11	1	4

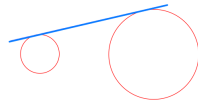
5.5 Fast Track Finder

The *Fast Track Finder* algorithm was developed in scope of this thesis. It employs a different method for pattern recognition. It makes use of the fact that the muon trajectory is tangential to all drift circles originating from the muon. The task of the pattern finding algorithm is to determine a straight line which is the tangent to a combination of drift circles. It is possible with elementary geometric methods to compute the tangent to two circles analytically. For a set of two drift circles there are four different ways to construct a tangent to both circles.

Only combinations of two drift circles in different layers of the same multilayer are taken into account for calculating the tangents. This way either the slope and intercept of the calculated tangent are close to the true parameters or they are way off. This allows for using the seed track to select the correct one out of the four possible tangents even if its slope is not precisely known. An interval is defined in which the tangent's deviations from the track slope m must lie to be further considered in the algorithm. Similarly an interval for the deviations in track intercept b can be defined. By then taking the average over all tangents compatible with the seed track, a line is constructed from the averaged tangent parameters. This line is used to resolve the ambiguity where on a drift circle the muon's position is located. For each drift circle the muon hit position is defined as the point of closest approach to this line. All muon hits within a certain distance from this line are taken into account for the track reconstruction, which follows the method outlined in Section 5.4. The Fast Track Finder algorithm is described below, structured in steps, which are illustrated by Figure 5.16.

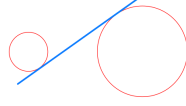
1. For each combination of two drift circles in different layers of the same multilayer with drift radii r_1 and r_2 , a special coordinate frame is constructed, in which the origin is at position of the first drift wire and which axis are rotated such that the connecting line between centres of the circles is collinear to the z' -axis.
2. In the special coordinate frame, in which the z' -axis coincides with the straight line through the position of the wires of the two tubes, the parameters of the tangents can be calculated analytically and are given by

a)



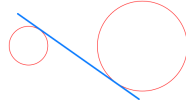
$$m' = \frac{r_2 - r_1}{\sqrt{L^2 - (r_1 - r_2)^2}} \quad b' = r_1 \cdot \sqrt{1 + m'^2}$$

b)



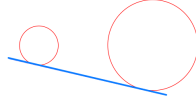
$$m' = \frac{r_1 - r_2}{\sqrt{L^2 - (r_1 - r_2)^2}} \quad b' = -r_1 \cdot \sqrt{1 + m'^2}$$

c)



$$m' = -\frac{r_1 + r_2}{\sqrt{L^2 - (r_1 + r_2)^2}} \quad b' = r_1 \cdot \sqrt{1 + m'^2}$$

d)



$$m' = \frac{r_1 + r_2}{\sqrt{L^2 - (r_1 + r_2)^2}} \quad b' = -r_1 \cdot \sqrt{1 + m'^2}$$

3. The parameters are transformed back to the chamber coordinate frame. Transforming from a special coordinate frame rotated by the angle α with respect to the chamber coordinate frame and translated by (y_0, z_0) back to the chamber coordinate frame, the tangent's parameters are given by

$$m = \tan(\alpha + \arctan(m')) \quad b = y_0 + \cos \alpha \cdot b' + m \cdot (\sin \alpha \cdot b' - z_0)$$

The arithmetic mean is calculated from those tangents which parameters are in a certain region around the seed track.

4. The **straight line** with the parameters obtained from averaging over the tangents is used to select the muon hits by taking the points with the smallest distance to the line. Only points within a certain range are then used in the track reconstruction step.

There are four parameters in the algorithm for which optimal values have to be determined, depending on seed resolution and occupancy:

- width of b interval for selecting the tangents to be included in the average,
- width of m interval for selecting the tangents to be included in the average,
- search road width around the averaged tangent in which hits are collected for the track fit,

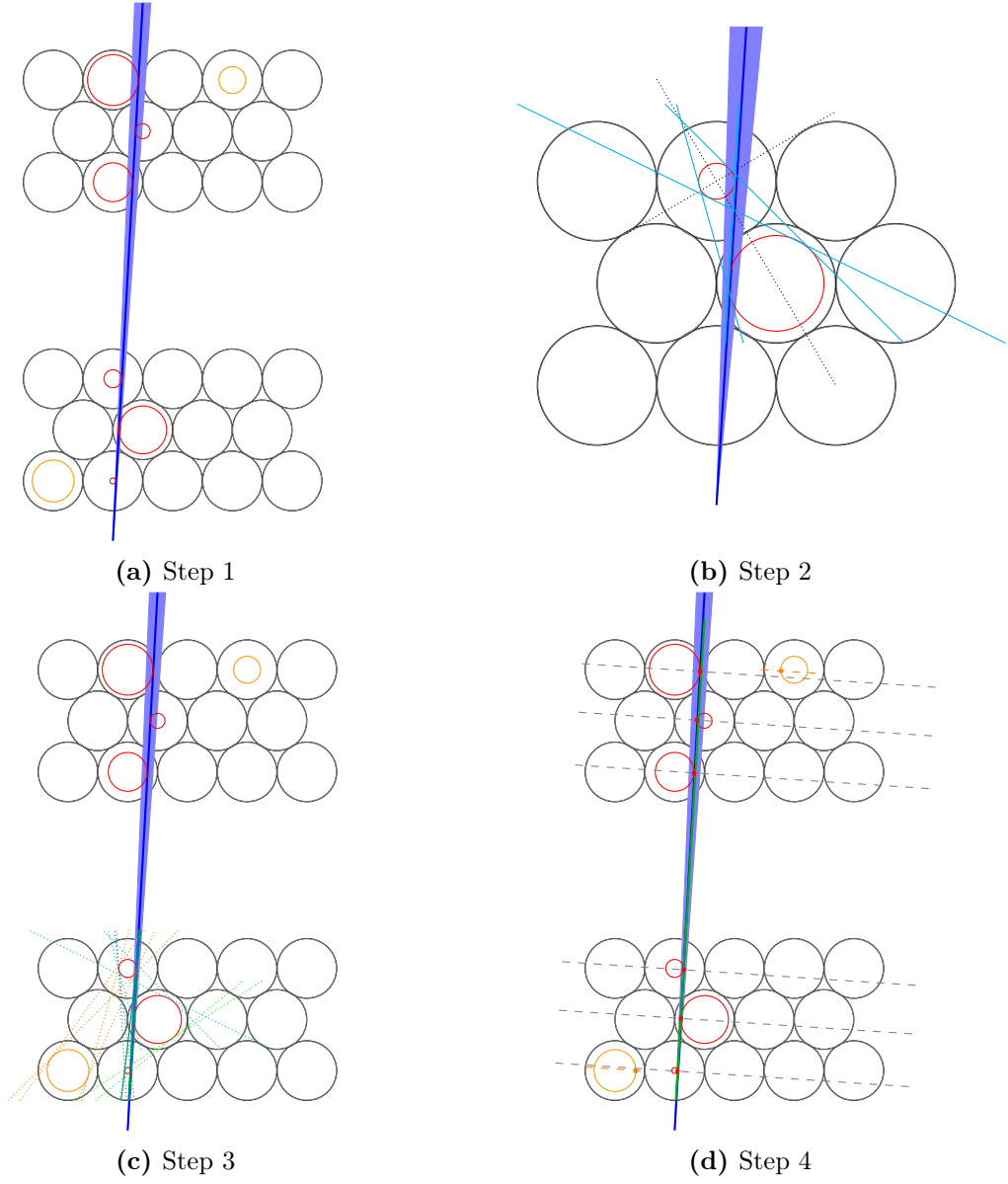


Figure 5.16: Schematic illustration of the Fast Track Finder algorithm.

- minimum number of hits found by the pattern recognition step called the threshold as before.

The effect of the intercept cut parameter b on ϵ is well below the order of percent, where high values of it are favoured. Therefore no cut on track segment intercepts for

averaging the tangent parameters is performed. The effect of the slope cut parameter m on ε is not strong either, however can be studied more systematically and is varied from 0.001 to 0.005 in 0.001 steps and from 0.006 to 0.024 in 0.002 steps for the chambers in the end-cap. In the barrel region, the parameter range was extended with the additional variation of the slope cut parameter from 0.020 to 0.200 in 0.020 steps, from 0.200 to 0.800 in 0.050 steps and from 0.800 to 1.500 in 0.100 steps. The parameter for the search road width around the averaged tangent is varied in steps of 0.3 mm from 0.3 mm to 5.1 mm.

In case of EML1, for search road width around the averaged tangent in which hits are collected above 1 mm, a low m width is favourable, because then only tangents very close to the seed track are used for creating the average. The optimal value of the m cut parameter for EML1 is 0.002. However, as long the m cut parameter is suitably well adapted to the seed track resolution, the effect on ε is negligible. As a rule of thumb, the m cut parameter value should be chosen in the same order of magnitude of the seed track resolution. For chambers with lower seed track resolution, as it is the case in the barrel region, larger values of the slope cut parameter are preferred.

The slope and intercept residuals of reconstructed straight track segments are shown in Figure 5.17.

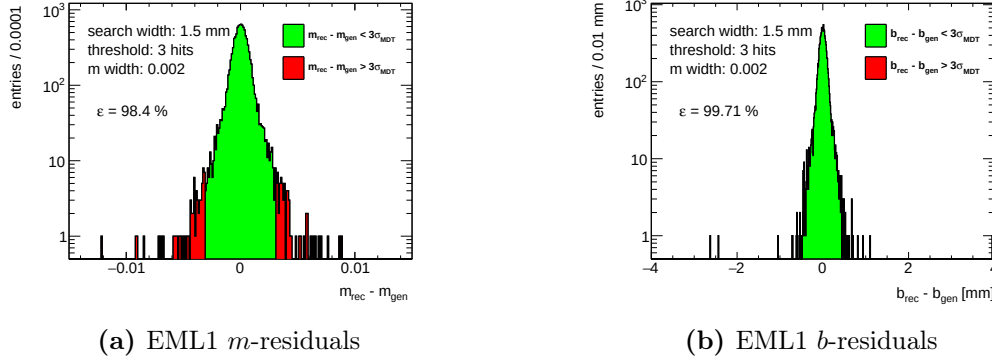
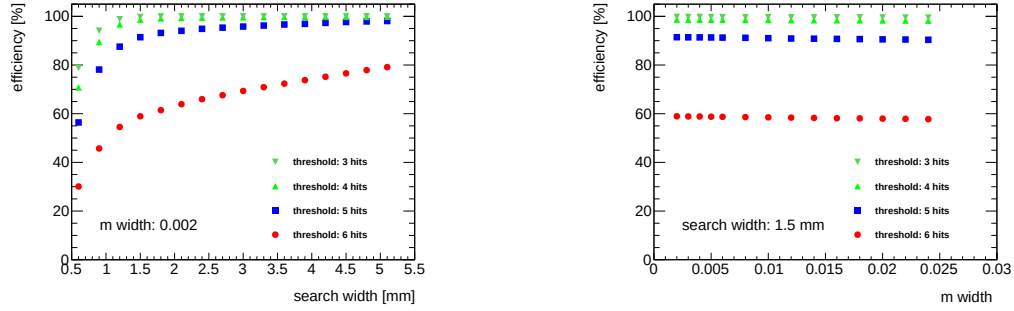


Figure 5.17: Distributions of track segment slope and intercept residuals in EML1 reconstructed with Fast Track Finder algorithm with search width 1.5 mm, threshold 3 hits and m interval width of 0.002. The fraction of the histogram in green contributes to the respective ε , the fraction in red to n_{poor} .

The efficiency for different thresholds in dependence of the search width with a fixed m interval width of 0.002 and in dependence of the m interval width with a fixed search width of 1.5 mm for EML1 is shown in Figure 5.18. Overall, the efficiency is better than for the HbPR algorithm and the efficiency curve enters saturation already for small search widths. The variation of the m interval width has almost no effect on the efficiency.



(a) Efficiency in dependence of search road width

(b) Efficiency in dependence of m interval width

Figure 5.18: Track reconstruction efficiency of Fast Track Finder algorithm for EML1 chamber.

As it is the case for the HbPR algorithm, it is sufficient to focus on the reconstruction quality of the segment slopes.

In Figure 5.19 ε and n_{poor} are shown for different search widths and thresholds for the fixed m interval width of 0.002. The maximum value of ε is achieved with a search width of 1.5 mm for a threshold of 3 hits. For low thresholds small values of the search width parameter result in a higher muon acceptance rate, while for higher thresholds larger search widths are favoured, in order to accumulate the necessary amount of hits specified by the threshold. The effect of the m width parameter on ε is negligible in the investigated parameter range, similar to the dependence depicted in Figure 5.18b. With increasing search width the fraction of poorly reconstructed tracks increases as proportionally more wrong hit positions are considered in the fit, as both hit positions on a drift circle enter. Considering the drift-time spectrum and the r - t -relation of the drift tubes, the increase in n_{poor} starting from a search width of 1.5 mm seems plausible.

Compared to the HbPR algorithm, the fraction of poorly reconstructed tracks is over four times lower and increases slowly for large search widths. The optimal values for track reconstruction with the Fast Track Finder in EML1 are achieved for a search width of 1.5 mm, a threshold of 3 hits and an m width of 0.002. The optimal values are $\varepsilon = 98.40\%$ and $n_{\text{poor}} = 1.34\%$.

The optimal values of ε , n_{poor} and the corresponding parameters for the other chambers are listed in Table 5.6 for the end-cap.

Having demonstrated a reconstruction quality surpassing the HbPR algorithm in the

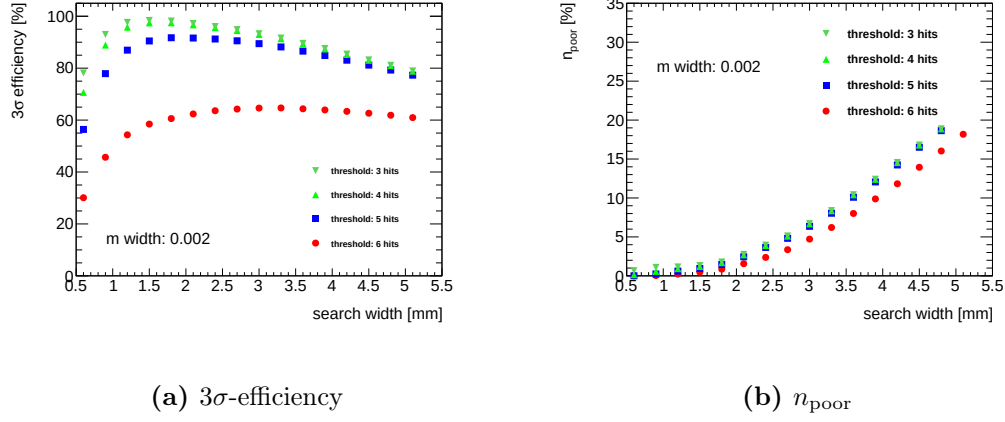


Figure 5.19: 3σ -efficiency and n_{poor} of the Fast Track Finder algorithm for EML1.

end-cap, in the following the performance of the Fast Track Finder algorithm in the barrel region is presented.

The efficiencies for different thresholds for BML1 are shown in Figure 5.20. Similar to the performance of the algorithm in the end-cap region, the efficiency is over 90% even for restrictive demands on the accumulated hits on reconstructed track segments, proving the effectiveness of the tangent-driven pattern recognition. In contrast to the end-cap region the dependence of the m width parameter is not constant but suggests that large values are favoured in order to compensate the seed track resolution in the barrel region.

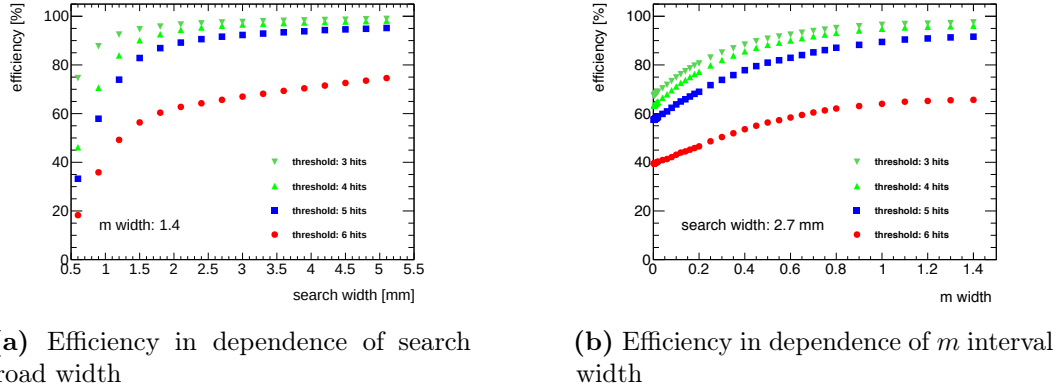


Figure 5.20: Track reconstruction efficiency of Fast Track Finder algorithm for BML1 chamber.

In Figure 5.21 ε and n_{poor} are shown for different thresholds and search widths. The

Table 5.6: Optimal parameters for Fast Track Finder in MDT chambers of the end-cap of the ATLAS muon system.

chamber	ε [%]	n_{poor} [%]	search width [mm]	m width	threshold [hits]
EML1	98.40	1.34	1.5	0.002	3
EML2	98.67	1.12	1.5	0.002	3
EML3	99.26	0.69	1.5	0.002	3
EML4	98.61	1.27	1.8	0.002	3
EML5	98.77	1.07	1.8	0.004	3
EMS1	98.49	1.17	1.5	0.002	3
EMS2	98.8	1.04	1.5	0.004	3
EMS3	99.25	0.65	1.5	0.002	3
EMS4	97.66	1.9	1.8	0.002	3
EMS5	98.37	1.27	1.8	0.008	3
EOL1	98.69	1.02	1.5	0.002	3
EOL2	97.93	1.84	1.8	0.008	3
EOL3	98.87	0.88	1.5	0.016	3
EOL4	99.19	0.63	1.5	0.003	3
EOL5	98.45	1.44	1.8	0.002	3
EOL6	97.4	2.47	2.1	0.003	3
EOS1	98.65	1.22	1.5	0.002	3
EOS2	97.73	1.98	1.8	0.006	3
EOS3	98.86	0.96	1.5	0.004	3
EOS4	99.1	0.77	1.5	0.010	3
EOS5	98.53	1.3	1.8	0.002	3
EOS6	97.14	2.75	2.1	0.003	3

maximum value of $\varepsilon = 95.16\%$ is achieved with a search width of 2.7 mm, a cut on the maximal deviations of accepted tangent slopes from the seed slope of 1.4 and a threshold of 3 hits. Up to search widths of 2.7 mm the ε is almost identical to the efficiency for higher thresholds above five hits and very similar in form for lower thresholds. For search widths above 2 mm the ε enters a high plateau up to values above 4 mm, for which the inclusion of hits not belonging to the muon trajectory slightly deteriorates ε to values of 90%.

The optimal values of the 3σ -efficiency, n_{poor} and the corresponding parameters for the other chambers in the barrel region are stated in Table 5.7.

The Fast Track Finder achieves a 3σ -efficiency in the end-cap of well over 95% for all chambers, which exceeds the HbPR. In the barrel region for most chambers a 3σ -efficiency of over 95% is achieved for most chambers.

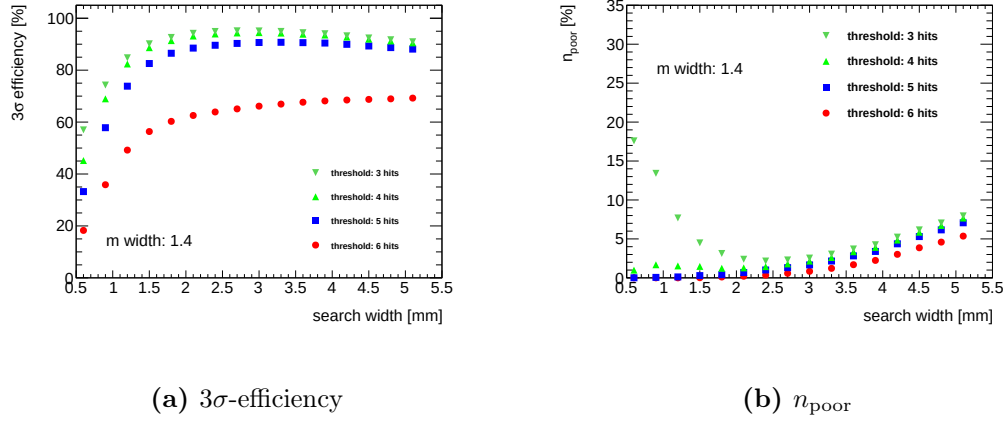


Figure 5.21: 3σ -efficiency and n_{poor} of the Fast Track Finder algorithm for BML1.

The Fast Track Finder surpasses the track reconstruction quality of the HbPR algorithm for all chambers. In the barrel region the difference is most pronounced because of the robustness of the Fast Track Finder for imprecise seed tracks.

The performance of the Fast Track Finder is comparable to the Binned 2D-Hough Transform in the end-cap region and for inner and middle barrel chambers. While the 3σ -efficiency achieved by the Binned 2D-Hough Transform surpasses the Fast Track Finder by a few percent, this comes at the cost of running 11 elementary algorithms in parallel. The Fast Track Finder achieves the same reconstruction quality while being less computationally involved. For the outer barrel chambers it is clearly superior because of the weak dependence of the seed track quality. This makes the Fast Track Finder algorithm the algorithm of choice for the barrel region. A first test implementation in hardware was able to reproduce the 3σ -efficiencies stated in Table 5.6 and Table 5.7.

5.5.1 Fast Track Finder without track fit

The execution time of the Fast Track Finder can be shortened by specifying the reconstructed track segment as the arithmetic average of all tangent's slopes and intercepts within certain limits. Skipping the track fit step reduces the execution time.

There are two parameters in this algorithm for which optimal values have to be determined:

- width of b interval for selecting the tangents to be included in the average,

- width of m interval for selecting the tangents to be included in the average,
- minimum number of tangents included in the average.

The idea to directly process the average tangent slope and intercept from selected tangents proves not to be successful in the end-cap, where no case is observed, in which the algorithm exceeds $\varepsilon = 69\%$. The speed gained by using the average tangent slope, which is faster computed than a fit of compatible position measurements, does not outweigh the reduced precision. In the barrel region this algorithm is still less efficient than the Fast Track Finder, but performs far better than in the end-cap because of the lower occupancy in the barrel-region. For BIL (BIS) chambers values of $\varepsilon = 88\%$ (over 70%) were observed, while for BM and BO chambers values of ε around 80% were observed. The optimal values of the 3σ -efficiency, n_{poor} and the corresponding parameters for all chambers are stated in Table 5.8.

If the hardware implementation of the Fast Track Finder algorithm with a track fit proves to be too time-consuming to be used in the MDT trigger scheme, further studies are necessary to optimise the Fast Track Finder without Track Fit to be useful as a fall-back solution.

5.6 Study of higher background rates

In order to study the stability of the algorithms for very high back background rates, the simulation of EML1 was performed assuming twice the predicted occupancy. In this case the results were similar to the ones discussed before. For the HbPR algorithm a slightly smaller bin width of 2.7 mm for a threshold of 3 hits is more favourable, resulting in $\varepsilon = 92.59\%$ and $n_{\text{poor}} = 7.29\%$. The Binned 2D-Hough Transform algorithm can reconstruct track segments in presence of twice the occupancy with $\varepsilon = 97.54\%$ and $n_{\text{poor}} = 2.42\%$ with the same set of parameters that produced the optimal result presented before. The Fast Track Finder reconstructs track segments with $\varepsilon = 98.67\%$ and $n_{\text{poor}} = 1.12\%$ for a m width interval of 0.002 and a search width for collecting hits around the averaged tangent of 1.5 mm. Out of the three algorithms it achieves the best performance in presence of twice the occupancy, proving its robustness against higher background.

5.7 Summary

In this chapter three algorithms for fast track reconstruction of straight track segment candidates required for the MDT first level trigger were discussed. The Histogram-based Pattern Recognition algorithm is well applicable with $\varepsilon \sim 93\%$ in the end-cap

region but due to its dependence on the seed track information it does not perform well in the barrel region. The natural extension of this algorithm, the Binned 2D-Hough Transform, performs well with $\varepsilon \sim 97\%$ in both end-cap and barrel region with exception of the outer barrel chambers but requires parallel computing to meet the latency requirement. The novel Fast Track Finder makes use of drift-radii and is far less dependent on the seed track information. It performs well with $\varepsilon \sim 95\%$ for all chambers of the muon system.

Table 5.7: Optimal parameters for Fast Track Finder in MDT chambers of the barrel region of the ATLAS muon system.

chamber	ε [%]	n_{poor} [%]	search width [mm]	m width	threshold [hits]
BIL1	97.03	0.97	2.4	0.5	3
BIL2	97.26	1.18	2.7	0.6	3
BIL3	92.37	5.05	3.3	0.55	3
BIL4	98.14	1.72	3.3	1.3	4
BIL5	99.18	0.78	3.3	1.4	3
BIL6	98.97	0.95	3.3	1.4	3
BIS1	94.01	3.07	1.2	0.25	3
BIS2	94.7	2.13	1.2	0.2	3
BIS3	92.09	4.69	1.5	0.2	3
BIS4	93.53	3.1	1.2	0.1	3
BIS5	95.76	2.33	1.5	0.12	3
BIS6	96.23	2.14	1.5	0.1	3
BML1	95.16	2.3	2.7	1.4	3
BML2	94.99	1.82	3.0	1.3	3
BML3	93.45	3.29	3.9	1.3	3
BML4	97.46	1.55	3.6	1.4	3
BML5	96.77	2.1	3.9	1.4	3
BML6	97.24	1.89	4.2	1.2	3
BMS1	94.05	2.65	2.1	1.0	3
BMS2	95.57	1.5	1.8	0.8	3
BMS3	91.49	3.52	2.4	0.5	3
BMS4	93.75	2.49	2.4	0.55	3
BMS5	95.7	1.38	2.4	0.45	3
BMS6	95.99	1.49	2.7	0.6	3
BOL1	94.38	2.22	3.0	1.4	3
BOL2	94.58	1.77	3.0	1.4	3
BOL3	93.28	2.99	3.6	1.4	3
BOL4	95.21	2.19	3.6	1.4	3
BOL5	97.29	1.23	3.6	1.4	3
BOL6	97.74	1.25	4.5	1.4	4
BOS1	93.84	2.68	3.0	1.4	3
BOS2	95.86	1.71	2.7	1.4	3
BOS3	92.46	3.56	3.6	1.4	3
BOS4	94.76	2.54	3.6	1.4	3
BOS5	96.68	1.82	3.9	1.4	3
BOS6	97.26	1.68	4.2	1.4	3

Table 5.8: Optimal parameters for Fast Track Finder without track fit in MDT chambers of the barrel region of the ATLAS muon system.

chamber	ε [%]	n_{poor} [%]	search width [mm]	m width	threshold [hits]
BIL1	89.8	10.2	0.5	0	
BIL2	94.3	5.7	0.45	0	
BIL3	87.52	12.48	0.35	0	
BIL4	94.13	5.87	0.4	0	
BIL5	94.38	5.62	0.3	0	
BIL6	93.66	6.34	0.25	0	
BIS1	76.34	23.66	0.18	0	
BIS2	80.63	19.37	0.2	0	
BIS3	83.26	16.74	0.2	0	
BIS4	85.49	14.51	0.2	0	
BIS5	87.36	12.64	0.18	0	
BIS6	87.86	12.14	0.18	0	
BML1	73.17	26.83	0.9	0	
BML2	84.79	15.21	0.8	0	
BML3	86.16	13.84	0.9	0	
BML4	92.83	7.17	1.0	0	
BML5	91.34	8.66	1.0	0	
BML6	91.63	8.37	1.0	0	
BMS1	67.28	32.72	0.65	0	
BMS2	80.7	19.3	0.6	0	
BMS3	84.44	15.56	0.5	0	
BMS4	87.02	12.98	0.6	0	
BMS5	89.56	10.44	0.65	0	
BMS6	90.83	9.17	0.6	0	
BOL1	72.9	27.1	1.0	0	
BOL2	83.19	16.81	0.8	0	
BOL3	86.14	13.86	0.9	0	
BOL4	90.43	9.57	1.1	0	
BOL5	91.64	8.36	1.1	0	
BOL6	92.42	7.58	1.0	0	
BOS1	71.39	28.61	1.2	0	
BOS2	82.04	17.96	1.0	0	
BOS3	85.04	14.96	1.0	0	
BOS4	88.66	11.34	1.0	0	
BOS5	91.66	8.34	1.1	0	
BOS6	92.7	7.3	1.1	0	

6

Summary

The High Luminosity upgrade of the Large Hadron Collider is expected to begin operations in 2026 as a discovery machine at the high energy frontier with the goal of achieving the ultimate instantaneous luminosity $\mathcal{L} = 7 \times 10^{34} \text{ m}^{-2}\text{s}^{-1}$ and collecting a total integrated luminosity 3000 fb^{-1} . This large dataset will allow to pursue a rich physics programme, which includes searches for new phenomena both in higher mass scales and in rare processes, as well as precision measurements of the electroweak symmetry breaking sector including the Higgs boson.

The corresponding upgrade of ATLAS detector to fully exploit the intended physics programme will allow operation in the high-rate environment expected at the HL-LHC. Single muon and electron triggers maintaining the low trigger thresholds at the electroweak scale are essential for successful operation of the ATLAS detector. The selectivity of these triggers has to be highly improved to keep their rates at an acceptable level.

The topic of this thesis is the optimisation of the single muon trigger. The selectivity of the present first level muon trigger is limited by the poor momentum resolution caused by the moderate spatial resolution of the trigger chambers. The inclusion of the MDT precision measurements with an excellent spatial resolution of $40 \mu\text{m}$ in the first-level muon trigger decision would contribute a substantial improvement of the momentum resolution resulting in a much steeper turn-on curve around the trigger threshold and a thereby significantly reduced trigger rate compared to the poor momentum resolution provided by the current trigger chambers.

This work estimates the performance of a first-level MDT muon trigger operating at a trigger threshold of 20 GeV . The optimal fast method to determine the transverse momentum for the trigger decision measures the sagitta s of a trigger candidate. To resolve the inhomogeneity of the ATLAS toroidal magnetic field in η and ϕ sufficiently well, a set of local parametrisations of the transverse momentum $p_{\text{T}}^{\text{on}}(s, \phi, \eta)$ is determined numerically by an iterative fitting procedure. With this method a momentum resolution of $\sigma_{p_{\text{T}}^{\text{on}}} = 4.9 \pm 0.1\%$ is achieved for muons at the trigger

threshold of 20 GeV, which is close to the maximum achievable momentum resolution of $\sigma_{p_T^{\text{SA}}} = 3.5\%$.

Due to the very good momentum resolution the turn-on curve of the first-level muon trigger is sharpened, while maintaining efficiency $\geq 95\%$ for muons above the trigger threshold. The number of trigger candidates provided by the trigger chamber system which are eligible for a sagitta measurement is reduced by 70% for almost the whole ATLAS muon spectrometer. To account for trigger candidates, which are not eligible for a sagitta measurement, a requirement based on the deflection angle in the magnetic field can be imposed. The rate reduction of an MDT trigger that uses a combination of sagitta and deflection angle requirements is estimated to be $\gtrsim 70\%$. Based on an extrapolation of the Phase-I trigger rate the estimated first-level MDT single muon trigger rate at the HL-LHC is 20 kHz.

Fast track segment algorithms employed in the trigger electronics are required to make the trigger decision within the latency of 6 μs . Three algorithms for fast MDT track segment reconstruction are presented in this work and tested with simulated data describing the anticipated background in the high-rate environment.

For the end-cap ($1.05 < |\eta| < 2.4$) the ATLAS collaboration considered a Histogram-based Pattern Recognition algorithm, which is seeded by the trigger chamber data. It performs well in the end-cap region ($|\eta| < 1.05$) and can reconstruct $\varepsilon = 95\%$ of all segments with sufficient precision for the required MDT trigger momentum resolution. The algorithm is not applicable in the barrel region ($0 < |\eta| < 1.05$) because of the lower spatial resolution of the RPC chambers installed in the barrel region.

Extending the algorithm to a Binned 2D-Hough Transform by running multiple instances ($\mathcal{O}(10)$) in different regions of the parameter space improves the track segment reconstruction quality significantly ($\varepsilon \geq 97\%$) for all regions apart from the outer barrel MDT chambers. The algorithm requires parallel computing to meet the latency requirement.

A new track segment finding algorithm, that makes use of tangents to drift radii, was developed in the thesis and shown to be applicable to the entire muon spectrometer ($|\eta| < 2.4$) with very good track reconstruction quality ($\varepsilon = 97\%$).

The inclusion of the MDT chambers substantially reduces the trigger rate and allows for realisation of the uncompromised physics programme at the HL-LHC. While this thesis demonstrated the prospects of a first-level trigger including the MDT precision information and evaluated algorithms for the concrete implementation, the actual demonstration of the trigger concept will mark the next step towards the high-luminosity era of the ATLAS experiment at the HL-LHC.

Appendix

1 Threshold definition for the New Small Wheel coincidence and polar angle deviation

Table 1: Threshold definition for different η -regions for the NSW Phase-I requirement

$ \eta $	$d\theta$	$\Delta\eta$	$\Delta\phi$
1.3 - 1.5	0.015	0.05	0.06
1.5 - 1.7	0.015	0.05	0.06
1.7 - 1.9	0.010	0.05	0.06
1.9 - 2.1	0.025	0.05	0.06
2.1 - 2.3	0.07	0.07	0.06
2.3 - 2.4	0.07	0.07	0.06

2 Definition of fit regions for the supplementary parametrisation

Table 2: Definition of fit regions for supplementary parametrisation $p_T^{\text{on2}}(s, \phi, \eta)$

Detector part	Regions in $ \eta $	Subdivision
Barrel	(0.00, 0.40), (0.40, 0.80), (0.80, 1.05)	BIL/BIM/BIR/BIS, $s > 0$ or $s < 0$
Transition region	(1.05, 1.10), (1.10, 1.15), (1.15, 1.20), (1.20, 1.25), (1.25, 1.30), (1.30, 1.35)	large/small sector, $s > 0$ or $s < 0$
End-cap	(1.30, 1.40), (1.40, 1.50), (1.50, 1.60), (1.60, 1.70), (1.70, 1.80), (1.80, 1.90), (1.90, 2.00), (2.00, 2.10), (2.10, 2.20), (2.20, 2.30), (2.30, 2.40)	large/small sector, $s > 0$ or $s < 0$

3 Reconstruction of Straight Tracks

This section follows closely the work presented in Ref. [54]. To reconstruct a straight track $y = \alpha_1 \cdot z + \alpha_0$ through the points (z_i, y_i) , $i = 1, \dots, n$, the χ^2 function

$$\chi^2 = \sum_{i=1}^n w_i (y_i - (\alpha_1 \cdot z_i + \alpha_0))^2,$$

where w_i is the weight for a given track point, is minimised.

To minimise the function the extremal parameters $\tilde{\alpha}_0$ and $\tilde{\alpha}_1$ are determined by requiring $\frac{\partial \chi^2}{\partial \alpha_1}|_{\tilde{\alpha}_1} = 0$ and $\frac{\partial \chi^2}{\partial \alpha_0}|_{\tilde{\alpha}_0} = 0$. From these requirements follows

$$\begin{aligned} \sum_{i=1}^n w_i (y_i - \alpha_1 \cdot z_i - \alpha_0) &= 0 \\ \sum_{i=1}^n w_i z_i (y_i - \alpha_1 \cdot z_i - \alpha_0) &= 0 \end{aligned}$$

For compact notation the parameters g_1, g_2 and $\Lambda_{11}, \Lambda_{12}, \Lambda_{22}$ are defined as

$$\begin{aligned} (g_1, g_2) &= \sum_{i=1}^n w_i y_i (1, z_i), \\ (\Lambda_{11}, \Lambda_{12}, \Lambda_{22}) &= \sum_{i=1}^n w_i (1, z_i, z_i^2) \end{aligned}$$

With definition of these parameters, the requirements for an extremum become a linear system of equations

$$\begin{aligned} \Lambda_{11} \alpha_0 + \Lambda_{12} \alpha_1 &= g_1 \\ \Lambda_{12} \alpha_0 + \Lambda_{22} \alpha_1 &= g_2 \end{aligned}$$

By solving this system of equations one obtains the parameters of the fitted track $y = \alpha_1 \cdot z + \alpha_0$

$$\alpha_0 = \frac{1}{\Lambda_{11} \Lambda_{22} - \Lambda_{12}^2} (g_1 - \Lambda_{22} - g_2 \Lambda_{12})$$

and

$$\alpha_1 = \frac{1}{\Lambda_{11} \Lambda_{22} - \Lambda_{12}^2} (-g_1 - \Lambda_{12} - g_2 \Lambda_{11}).$$

4 Parameters of ATLAS MDT Chambers for the Monte Carlo Study

Table 3: Parameters of end-cap chambers for simulation framework

chamber	spacer width	L0 seed track $\sigma_{m_{\text{TGC}}}$	occupancy	m_{min}	m_{max}
EML1	170 mm	0.004	0.1174	0.15	0.26
EML2	170 mm	0.004	0.1178	0.23	0.41
EML3	170 mm	0.004	0.0938	0.36	0.54
EML4	170 mm	0.005	0.0714	0.49	0.59
EML5	170 mm	0.006	0.0604	0.61	0.85
EMS1	170 mm	0.004	0.1174	0.16	0.29
EMS2	170 mm	0.004	0.1178	0.27	0.43
EMS3	170 mm	0.004	0.0938	0.40	0.57
EMS4	170 mm	0.006	0.0714	0.49	0.59
EMS5	170 mm	0.006	0.0605	0.45	0.82
EOL1	170 mm	0.004	0.0353	0.15	0.22
EOL2	170 mm	0.005	0.0378	0.20	0.31
EOL3	170 mm	0.004	0.0402	0.28	0.39
EOL4	170 mm	0.004	0.0439	0.35	0.46
EOL5	170 mm	0.005	0.0431	0.41	0.51
EOL6	170 mm	0.006	0.0450	0.48	0.58
EOS1	170 mm	0.004	0.0353	0.15	0.22
EOS2	170 mm	0.005	0.0378	0.19	0.29
EOS3	170 mm	0.004	0.0402	0.27	0.37
EOS4	170 mm	0.004	0.0439	0.35	0.43
EOS5	170 mm	0.005	0.0431	0.42	0.51
EOS6	170 mm	0.006	0.0450	0.48	0.59

Table 4: Parameters of barrel chambers for simulation framework

chamber	spacer width	L0 seed track $\sigma_{m_{\text{RPC}}}$	occupancy	m_{min}	m_{max}
BIL1	170 mm	0.018	0.0099	0.06	0.27
BIL2	170 mm	0.018	0.0165	0.26	0.51
BIL3	170 mm	0.018	0.0536	0.48	0.71
BIL4	170 mm	0.018	0.0403	0.69	0.97
BIL5	170 mm	0.018	0.0294	0.92	1.15
BIL6	170 mm	0.018	0.0497	1.08	1.24
BIS1	6.5 mm	0.020	0.0099	0.00	0.26
BIS2	6.5 mm	0.020	0.0165	0.23	0.41
BIS3	6.5 mm	0.020	0.0536	0.46	0.67
BIS4	6.5 mm	0.020	0.0403	0.65	0.93
BIS5	6.5 mm	0.020	0.0294	0.87	1.13
BIS6	6.5 mm	0.020	0.0497	1.04	1.22
BIS7	6.5 mm	0.020	0.0788	1.23	1.61
BIS8	6.5 mm	0.020	0.0468	1.40	1.67
BML1	317 mm	0.015	0.0190	0.00	0.30
BML2	317 mm	0.015	0.0320	0.25	0.55
BML3	317 mm	0.015	0.0367	0.48	0.81
BML4	317 mm	0.015	0.0588	0.71	1.12
BML5	317 mm	0.015	0.0874	0.88	1.24
BML6	317 mm	0.015	0.0760	1.03	1.30
BMS1	170 mm	0.015	0.0190	0.00	0.27
BMS2	170 mm	0.015	0.0320	0.19	0.46
BMS3	170 mm	0.015	0.0367	0.42	0.74
BMS4	170 mm	0.015	0.0587	0.58	0.89
BMS5	170 mm	0.015	0.0874	0.79	1.12
BMS6	170 mm	0.015	0.0759	0.91	1.26
BOL1	317 mm	0.075	0.0201	0.00	0.31
BOL2	317 mm	0.075	0.0272	0.22	0.55
BOL3	317 mm	0.075	0.0365	0.39	0.74
BOL4	317 mm	0.075	0.0567	0.61	0.99
BOL5	317 mm	0.075	0.0664	0.83	1.25
BOL6	317 mm	0.075	0.0661	1.03	1.39
BOS1	317 mm	0.085	0.0201	0.00	0.27
BOS2	317 mm	0.085	0.0272	0.16	0.50
BOS3	317 mm	0.085	0.0365	0.39	0.75
BOS4	317 mm	0.085	0.0567	0.55	0.96
BOS5	317 mm	0.085	0.0664	0.75	1.21
BOS6	317 mm	0.085	0.0661	0.91	1.37

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