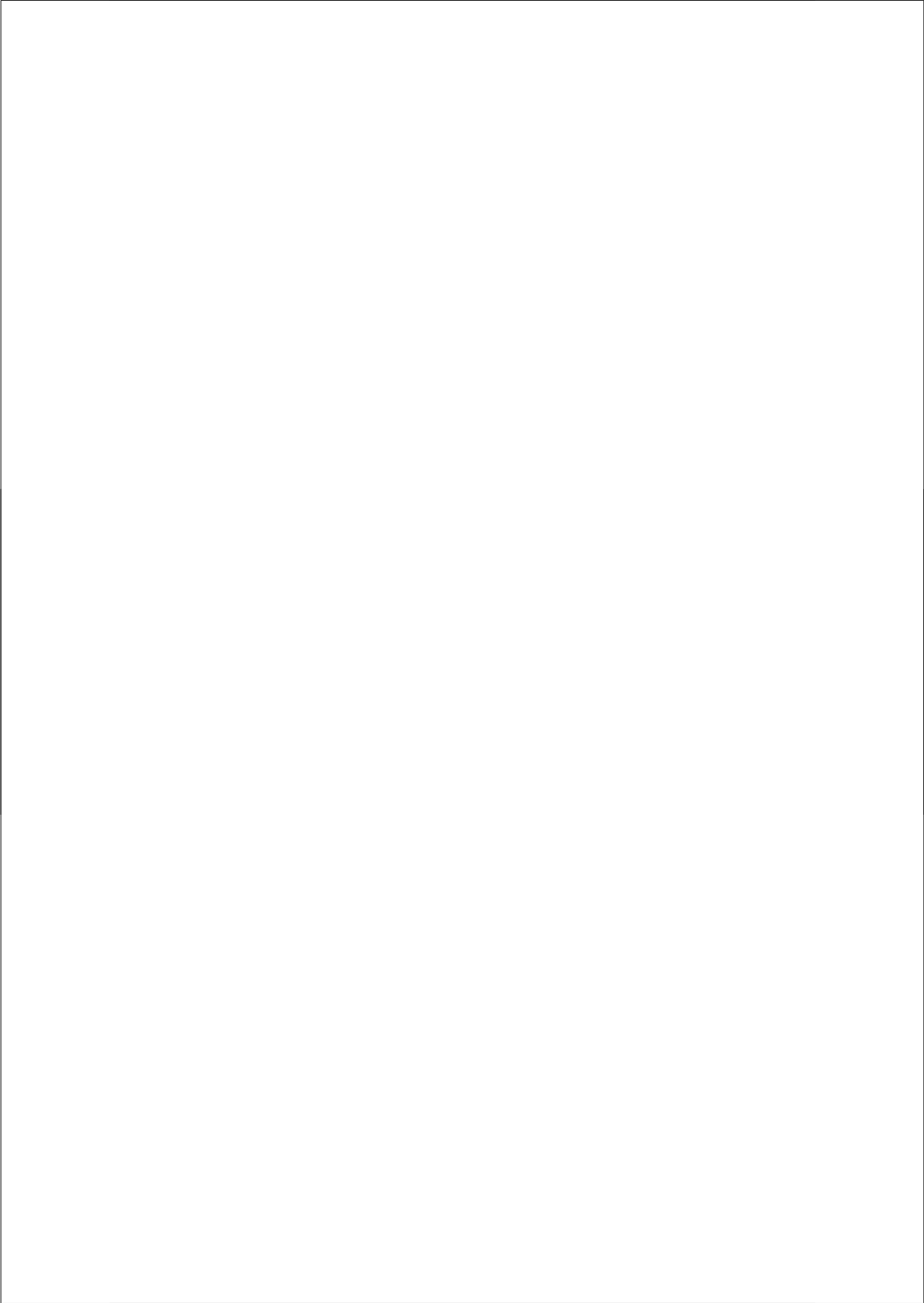


Identification of muons in ATLAS

Zdenko van Kesteren



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AAN DE UNIVERSITEIT VAN AMSTERDAM
OP GEZAG VAN DE RECTOR MAGNIFICUS
PROF. DR. D. C. VAN DEN BOOM
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Contents

Introduction

Particle physics

Experimental *particle physics* studies matter at the sub-atomic scale. The world at these distance scales has its own laws of Nature. Whereas classical mechanics explains the paths and interactions between macroscopic billiard balls on the table, processes at the sub-atomic scale are described by relativistic quantum field theory. Over the past decades, an elegant relativistic quantum field theory known as the Standard Model has been developed, describing the building blocks of matter and their interactions at the most fundamental level [1].

The Standard Model

All chemical elements consists of atoms, that build up molecules. An atom consists of a tiny nucleus, surrounded by one or more electrons. In turn, the nucleus consists of protons and neutrons. These protons and neutrons consist of even smaller particles called *quarks*: a number of up-type quarks and a number of down-type quarks.

The building blocks for ordinary matter around us are: *up*-quarks (u), *down*-quarks (d) and *electrons* (e). In addition, the electron has a partner, the *electron neutrino* (ν_e). These four particles build up the *first generation* of matter particles of the Standard Model, see Figure 1.

The second and third generation contain the heavier versions of the first generation particles, which have the same properties (quantum numbers) except for their mass. The second generation partner of the electron is the *muon* (μ), which is approximately 200 times heavier than the electron. The muon is, as all the heavy particles from the higher generations, unstable and decays into lighter particles, in this case the electron. The third generation partner of the electron is the *tau* lepton (τ), which in turn is heavier than the muon. The muon neutrino (ν_μ) and the tau neutrino (ν_τ) are the second and third generation neutrino partners of the leptons respectively. The second generation of quarks consist of the *charm* (c) quark and the *strange* (s) quark. The third generation consist of the *top* (t) quark and the *bottom* (b) quark. The top quark is by far the heaviest particle of the Standard Model, approximately $3.5 \cdot 10^5$ times as heavy as the electron.

All these particles obey the Pauli exclusion principle as they have spin $1/2 \hbar$ and are called *fermions*. Where as all daily matter around us consist of the stable fermions

Three Generations of Matter (Fermions)				
	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name→	u	c	t	γ
	up	charm	top	photon
Quarks	4.8 MeV	104 MeV	4.2 GeV	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	d	s	b	g
	down	strange	bottom	gluon
Leptons	<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
	0	0	0	0
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	ν_e	ν_μ	ν_τ	Z^0
	electron neutrino	muon neutrino	tau neutrino	weak force
Bosons (Forces)	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
	-1	-1	-1	± 1
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
	e	μ	τ	$W^\pm$
	electron	muon	tau	weak force

Figure 1: The Standard Model of elementary particles.

from the first generation, heavier particles are produced in high-energetic processes of the cosmos, or are produced in particle physics laboratories.

The Standard Model not only describes the fermions, it describes the interactions between these particles as well. The interaction between the fermions, occurs via the exchange of gauge bosons that have spin 1. The Standard Model incorporates three fundamental forces:

- The *Electromagnetic force* is mediated by photons (γ).
- The *Weak force* is mediated by the massive gauge bosons W^+ , W^- and Z^0 .
- The *Strong force* is mediated by gluons (g)

Gravity is not incorporated in the Standard Model. However, its strength it is many orders of magnitude smaller than the other fundamental forces at the sub-atomic scale and can therefore safely be neglected at particle accelerators.

All fermions interact via the weak force, i.e. they feel the presence of W and Z^0 bosons. All the charged fermions, hence all matter particles except the neutrinos, interact in addition via the electromagnetic force. On top of that, the quarks carry color charge and hence interact also via the strong force. It turns out that quarks do not

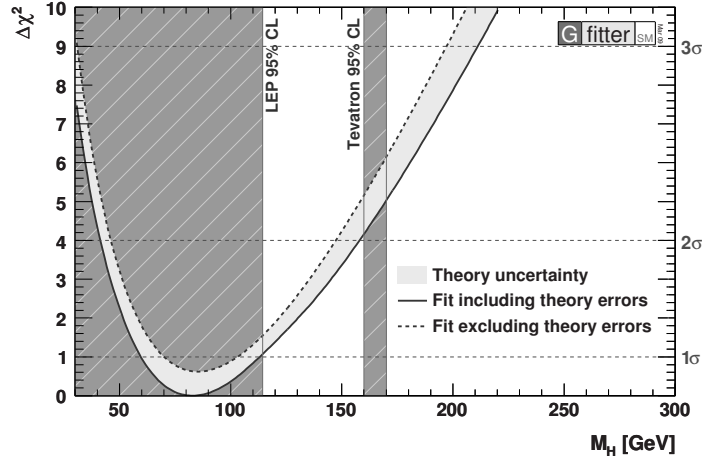


Figure 2: Electroweak global fit to the Higgs mass.

occur freely in nature but are confined to bound states that are color neutral. Such states consist of either three quarks, called *baryons* (from which the proton and neutrons are examples), or a combination of a quark and an anti-quark, called *mesons*. With these rules, many combinations of quarks can be built, and have been identified experimentally. For example the J/ψ is a bound state of a charm and an anticharm quark.

In over twenty years of experimenting, the predictions of the Standard Model have been extensively tested and shown to accurately match the experimental observations, often to astounding precision. However, successful as the Standard Model is, it is not complete and a number of questions remain unanswered. Apart from the fact that gravity is not included, the model is unable to predict the mass of particles in a direct manner.

The Higgs boson

Particle masses are introduced into the Standard Model by the mechanism of spontaneous symmetry breaking. This mechanism was proposed in 1964 by Higgs, Englert and Brout [2] [3]. In the simplest form, a new field with non-zero expectation value is introduced. This field is assumed to interact with all particles of the Standard Model. The masses of the particles appear as a consequence of their interactions with the ground state of this so called *Higgs field*. The quantum mechanical excitation of the Higgs field corresponds to a massive scalar particle called the *Higgs boson*. The mass of this particle turns out to be a free parameter of the model.

Therefore the discovery of the Higgs boson and determination of its properties will justify this picture and provides deep insight in the origin of particle masses in the Standard Model.

Earlier experiments at particle accelerators searched for the Higgs boson. The Large

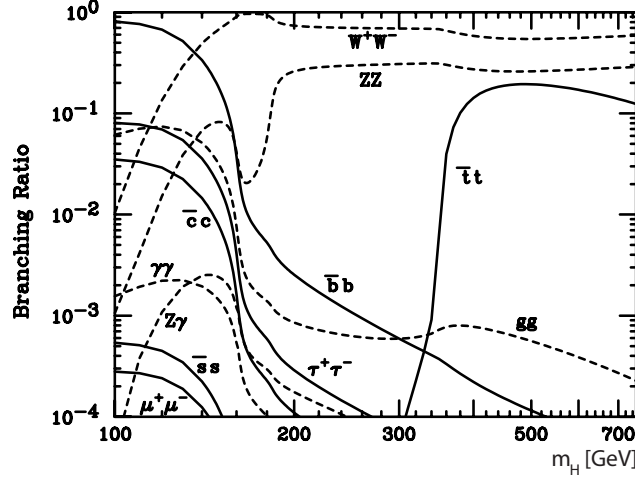


Figure 3: Branching ratios of the Standard Model Higgs boson.

Electron Positron collider (LEP) at CERN has established a lower limit for the Higgs boson mass of 114 GeV¹ at a 95% confidence level [4]. The combined data of CDF and DØ at the Tevatron in Fermilab have excluded a Higgs boson mass between 160 GeV and 170 GeV at 95% confidence level [5] [6]. Indirectly, high precision electroweak data constrain the mass of the Higgs boson via their sensitivity to loop corrections. Figure 2 shows the χ^2 curve of a global fit to precision electroweak data as function of the Higgs boson mass [7]. In this figure the excluded masses from LEP and Tevatron are shown as the darkly shaded areas. The associated bands in the plots represents the estimate of the theoretical uncertainty. Clearly, a mass of the Higgs boson between 114 GeV and 160 GeV is favored in this picture.

Figure 3 shows the branching ratios of the possible decay channels of the Higgs boson as function of the Higgs boson mass. For low masses, the $H^0 \rightarrow b\bar{b}$ decay channel is most abundant. Experimentally, this channel proves challenging to detect due to large backgrounds in proton-proton collisions. The $H^0 \rightarrow \gamma\gamma$ decay channel has a lower branching ratio, but a more controlled background and gives good prospects for a detectable signal at the LHC.

For higher mass Higgs bosons, the $H^0 \rightarrow W^+W^-$ and $H^0 \rightarrow Z^0Z^0$ channels dominate the decay modes. The escaping neutrinos from the W boson decays will make the precision of the mass peak measurement more difficult than the Z^0 boson decay. The decay of Z^0 bosons into leptons provides a clean signal with low background. The *golden channel* $H^0 \rightarrow Z^0Z^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$ gives an especially clean experimental signature.

¹In this thesis, *natural units* are used. In these units, $c = 1$ and particle masses are expressed in units of GeV.

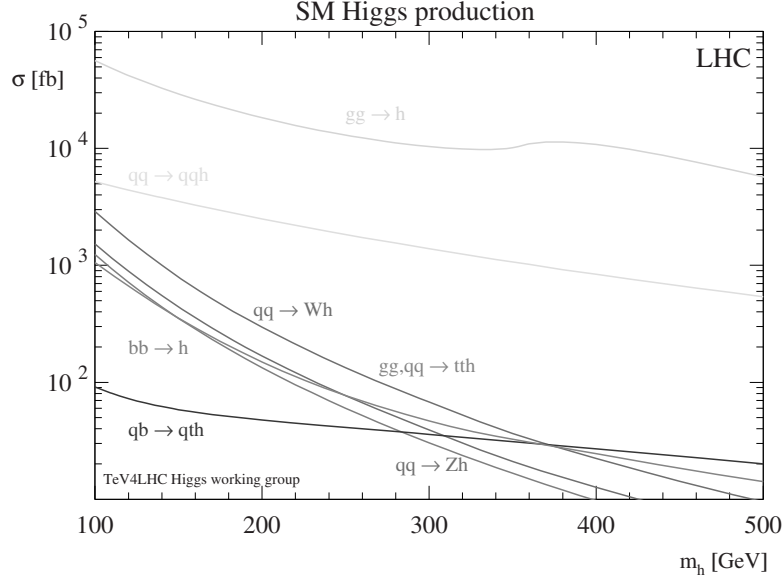


Figure 4: Higgs boson production cross sections versus the Higgs boson mass.

Proton collisions

To produce and discover the Higgs boson, particle collisions with a very high center of mass energy are needed. In addition, Higgs boson production cross sections are very small, thus large number of collisions are needed. The *Large Hadron Collider* (LHC) at CERN provides proton-proton (pp) collisions at an unprecedented center of mass energy of 14 TeV and an exceptional high luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. With this rate and energy, rare physics processes with small cross sections will be studied. Figure 4 shows the Higgs boson production cross section as function of the Higgs boson mass at 14 TeV center of mass energy [8]. At this energy, Higgs bosons will be predominantly produced by gluon-gluon fusion.

Figure 5 shows the (pp) cross sections for several processes as a function of the center of mass energy. On the right hand side of the figure, the event rate is shown given an instantaneous luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The dotted line indicates the center of mass energy at which the LHC will operate. The production rate of Higgs bosons at this energy is around nine orders of magnitude smaller than the total pp collision rate. Identifying these rare Higgs events in the vast amount of collisions is one of the main experimental challenges to be faced at the LHC.

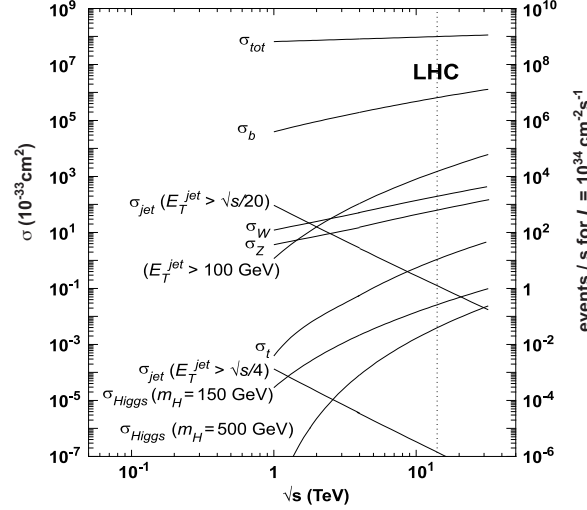


Figure 5: Cross sections of proton-proton collisions.

The muon roadmap to the Higgs boson

As mentioned, a Higgs boson decaying into four muons is a promising signal for its discovery. From an experimental point of view, muons give a clear signature in the detector. These leptons are capable of traversing the calorimeters and create hits in the outer layers of the detector where the Muon Spectrometer is placed. One needs an excellent muon reconstruction performance in order to detect Higgs bosons this way.

Thus one needs to understand the detector and optimize muon reconstruction in order successfully detect the Higgs boson, if it exists. In practice this is done by first studying other, known muon processes in the detector.

Before LHC operation starts, muons from cosmic rays provide an excellent mean to commission the detector. Detecting these muons is the first step in understanding the detector and to test the muon reconstruction.

When LHC will produce its first collisions, standard physics processes provide means to further understand the detector performance and validate the muon reconstruction. During the start of the experiment, the detector performance is far from optimal. Several components need to be calibrated and aligned and detector channels may be non functional. Furthermore, the detector energy and momentum scales are not yet fully understood in the beginning.

Standard physics processes with muon final states will give deep insight into the detector performance. The J/ψ mesons that decay into two muons is such a physics process. Due to its large cross section, these particles will be produced copiously at the LHC. This process represents one of the first physics processes that will be studied when the LHC has first collisions. Measuring these particles when the data quality is

not optimal will contribute to the reconstruction efficiency measurements for all future measurements at the LHC.

A heavier known particle with a di-muon end state is the Z^0 boson. As the properties of this particle are well known, measuring its mass, its width and decay modes can be exploited to measure the detector momentum scale, its resolution and lepton identification efficiency.

An important physics channel during the early days of data taking at the LHC is the production of top quarks. At start-up, it is expected that the top quark signal can be separated from the background, even with an imperfectly calibrated detector. The first measurement of the top quark mass will provide feedback on the detector performance such that they can be used to understand and calibrate the detector. Furthermore, top quark events are background processes to other physics processes and therefore a good understanding of top quark physics is essential.

Outline of the thesis

In this thesis, a new muon reconstruction algorithm is introduced, called **MuTagIMO**. This algorithm provides robust and efficient muon reconstruction. The reader is introduced to the ATLAS experiment, the ATLAS software framework and then to the ATLAS reconstruction software. Furthermore, the performance of the new muon tagging algorithm is compared to existing muon reconstruction packages on both cosmic ray muons and simulated physics processes.

The outline of this thesis is as follows. In Chapter 1 the ATLAS experiment is discussed. Chapter 2 covers the software framework deployed by the ATLAS experiment and explains the generation of simulated events used in the studies throughout this thesis. The reconstruction of tracks is explained in Chapter 3, where the reader is introduced to the notion of a track, tools for tracking and the sets of muon reconstruction algorithms available in the ATLAS software. Chapter 4 introduces the new muon tagging algorithm **MuTagIMO** and discusses the algorithm in detail. Chapter 5 focuses on the hardware commissioning and performance of part of the ATLAS Muon Spectrometer, the muon stations constructed at the Nikhef institute in Amsterdam. In Chapter 6, the muon tagging performance of the **MuTagIMO** algorithm on cosmic ray muons is discussed, whereas in Chapter 7, the performance on simulated physics events is presented.

Introduction

Chapter 1

The LHC and the ATLAS detector

1.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [9] is a proton-proton collider that will operate at the highest center of mass energies ever achieved, 14 TeV.

The LHC accelerator is located at the CERN laboratory near Geneva at the Swiss-French border. Protons are pre-accelerated using a linac to an energy of 50 MeV before being injected in the Proton Synchrotron booster in which they are accelerated to an energy of 1.4 GeV, see Figure 1.1. The next acceleration step is the Proton Synchrotron (PS) giving the protons an energy of 26 GeV. The Super Proton Synchrotron (SPS) increases the beam energy to 450 GeV which is the energy of the protons when injected in the LHC where an ultimate beam energy of 7 TeV is reached. The LHC is built in the tunnel of the former accelerator, the Large Electron Proton accelerator (LEP). The main parameters of the LHC accelerator are given in table 1.1.

The LHC consists of two counter rotating proton beams crossing at four different points along the ring. More than 1200 superconducting dipole magnets with magnetic fields up to 9 T are used to steer the proton beams, consisting of 2808 bunches of protons with 10^{11} protons per bunch. The bunches are inter spaced with a 25 ns time interval, giving rise to 40 million bunch crossings per second at each crossing point.

The LHC started up on the 10th of September 2008, successfully sending the proton

Parameter	Value	Unit
Circumference	26659	m
Beam energy	7	TeV
Injection energy	0.45	TeV
Luminosity	10^{34}	$\text{cm}^{-2}\text{s}^{-1}$
Luminosity lifetime	10	hours
Bunch spacing	25	ns
Particles per bunch	10^{11}	
Bunches per beam	2808	

Table 1.1: *The main LHC parameters*

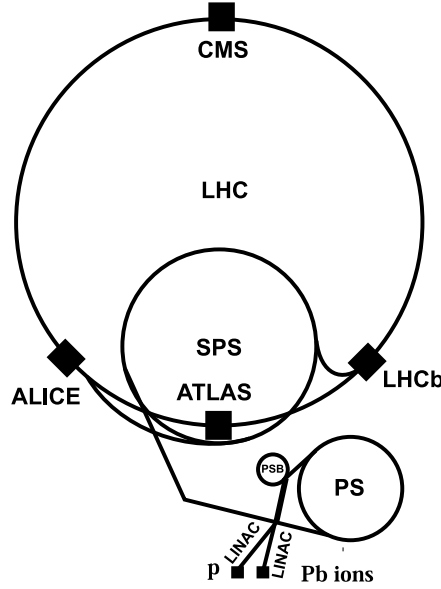


Figure 1.1: An overview of the accelerator complex at CERN.

beams around in the accelerator. A malfunction caused by a faulty electrical connection resulted in mechanical damage on the 19th of September that year [10]. A total of 53 of the superconducting dipole magnets had to be removed from the tunnel for cleaning and repairs. The schedule at the time of writing this thesis foresees that the LHC will restart late 2009.

The design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ will be reached after a period of operating at a lower luminosity of $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. At restart, it is expected that the LHC will run at a lower center of mass energy of 10 TeV.

Six detectors are designed and constructed to measure the physics events at the LHC. Two general-purpose detectors, ATLAS [11] and CMS [12] are designed to cover a wide range of physics. The LHCb [13] experiment is dedicated to study B physics and CP violation. ALICE [14] is designed to study physics of the quark-gluon plasma by studying collisions of heavy ions, Pb-Pb collisions at the LHC. TOTEM [15] will measure the total proton-proton cross-section and elastic scattering. LHCf [16] studies the energy distributions of particles very close to the beam line.

1.2 The ATLAS detector

The ATLAS experiment is one of the two general-purpose detectors at the LHC. The high interaction rates, radiation doses, particle energies and multiplicities as well as the requirement of high precision measurements has set high standards for the design of the

apparatus.

The search for the Standard Model Higgs boson has been used as benchmark to establish the performance of the subsystems of ATLAS. This imposes the following requirements on the detector design:

- *Fast and radiation hard* electronics and detector elements are needed in the high luminosity environment.
- *Large acceptance* over the full polar and azimuthal angle, ensuring a hermetic detection volume in which no high momentum particle is undetected.
- *Efficient tracking* for charged particles with high transverse momentum, together with electron and photon identification. In addition, secondary vertex reconstruction is required for τ -lepton, charm and bottom identification.
- *Muon reconstruction* and identification for muons over a large momentum range and the ability to determine the charge of high transverse momentum muons.
- *Excellent calorimetry* with electromagnetic calorimeters for electron and photon identification and energy measurements, complemented by full-coverage hadronic calorimetry for accurate jet and missing transverse energy measurements.
- *Highly efficient triggering* on low transverse momentum objects with sufficient background rejection is a prerequisite to obtain an acceptable trigger rate for most physics processes of interest.

To meet these requirements, ATLAS consists of three subsystems, as indicated in Figure 1.2. Closest to the interaction point, a high precision Inner Detector tracker is deployed in a solenoidal field to track charged particles. The energies of the particles and jets are measured in the calorimeters, which are built around the inner tracker. The Muon Spectrometer is built around the calorimetry detectors, to achieve high precision muon momentum measurements.

The ATLAS coordinate system

The ATLAS detector has an approximate cylindrical design. The detector is organized in a central barrel part and two end caps. The interaction point defines the origin of the global coordinate system used to describe the detector. The positive x axis points from the interaction point to the center of the LHC ring. The z axis lies along the beam line. The (positive) y -axis is perpendicular to the x and z axis and points upwards. The direction of the positive z -axis is such that the coordinate system describes a right-handed system. The positive z -side of the detector is referred to as the A side of the detector, the part on the negative z -axis as the C side. The radial distance R is defined as $R = \sqrt{x^2 + y^2}$. The azimuthal angle ϕ is defined in the xy -plane. It is zero at the positive x -axis and increases clockwise when looking down the positive z -direction. The polar angle θ is the angle from the positive z -axis in the Rz -plane. The pseudo-rapidity (η) is often used and defined as $\eta = -\ln(\tan(\theta/2))$. The transverse momentum is defined in the xy -plane.

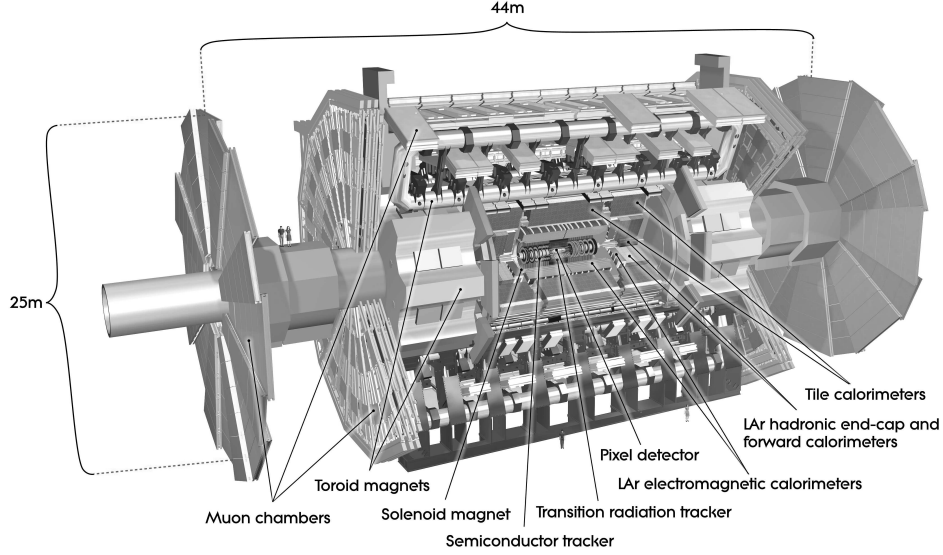


Figure 1.2: Cut-away view of the ATLAS detector.

1.2.1 Inner Detector

The Inner Detector tracker (ID) is situated closest to the interaction point. It is designed to track charged particles produced in the proton collisions. At design luminosity, the number of charged particles produced in the tracker is of the order 1000 per collision. For each track, the momentum, direction and impact parameter are measured, as well as the charge of the particle. The primary vertex and possibly secondary vertices are also reconstructed. The ID is embedded in a 2 T solenoidal magnetic field.

High granularity and fast detectors are required for this task. Silicon pixel and strip trackers, used in conjunction with straw tubes transition radiation trackers offer these features. Figure 1.3 shows the Inner Detector tracker consisting of three technologies which are discussed below. Some parts have been removed to show the inner structure of the detector.

Closest to the interaction point, high granularity semiconducting silicon pixel (Pixel) detectors provides 3-dimensional measurements used for pattern recognition and vertex finding. Around the pixel detector, the Semiconductor Tracker (SCT) provides four layers of space measurements for improved pattern recognition. Finally, a transition radiation straw tube tracker (TRT) provides measurements in the bending plane ($R\phi$ -plane) and electron identification.

The silicon detectors have an $|\eta|$ coverage up until 2.5, the TRT has a coverage up to $|\eta| < 2$. The Inner Detector will give a typical momentum resolution of $\Delta p_T/p_T = 0.04\% \times p_T \oplus 2\%$ with p_T in GeV and an impact parameter resolution of $15 \mu\text{m}$ in the transverse plane.

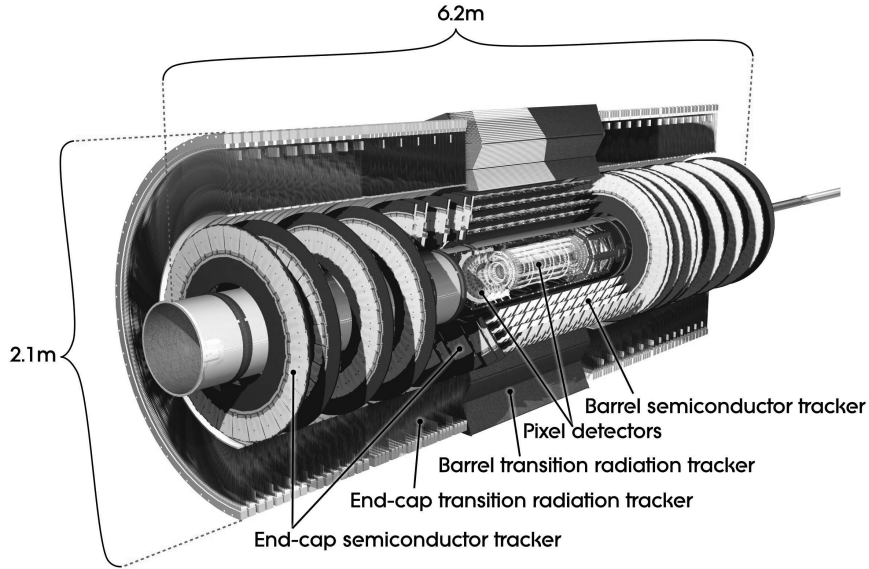


Figure 1.3: Cut-away view of the ATLAS Inner Detector. The three subsystems, Pixel, SCT and TRT are indicated.

The pixel detector

The pixel detector consists of three concentric layers in the barrel and three discs per end cap in the forward regions. The distances of the three barrel layers to the beamline are 5.05, 8.85 and 12.25 cm respectively. A traversing charged particle liberates charge in the silicon sensor and a discriminator in the readout electronics determines if the signal is above threshold. The time over threshold is written out and makes it possible to reconstruct the amount of charge that was deposited.

The pixels have an $R\phi - z$ size of $50 \times 400 \mu\text{m}^2$. The spatial resolution is approximately $12 \mu\text{m}$ in the $R\phi$ -coordinate and $110 \mu\text{m}$ in the z -coordinate. The detector contains approximately 80.4 million readout channels. Being closest to the interaction point, the pixel detector dominates the impact parameter resolution. Because of its high granularity, the pixel detector plays an important role for pattern recognition as well.

The SCT detector

The silicon strip detector is built in four concentric layers of SCT modules in the barrel region, with the strips arranged axially along the beam line. The strip pitch is around $80 \mu\text{m}$ and gives a 1-dimensional measurement. Two strip modules are glued back-to-back with a small stereo angle of 40 mrad, making it possible to measure the second coordinate. The spatial resolution of the first coordinate is $23 \mu\text{m}$ and of the second coordinate $800 \mu\text{m}$.

The end cap region of the SCT is constructed with 9 discs per end cap with SCT modules mounted in concentric circles. The strips are arranged to point radially to the beam line. Unlike the Pixel detector, the SCT readout is binary.

The total number of channels in the SCT detector is more than 6 million. The detector contributes to the resolution of the impact parameter, momentum and z -position of the tracks. Due to the high granularity, the SCT is important for pattern recognition.

The TRT detector

The transition radiation detector consists of 4 mm diameter straws with a gold-plated tungsten wire in the middle. The straws are filled with a drift gas mixture of $Xe : CO_2 : O_2 = 70 : 27 : 3$. When a charged particle traverses the straw, it ionizes the drift gas, causing the ionization clusters to drift towards the central wire due to a large potential difference between the walls of the straw and the wire. From the time it takes to reach the wire, the distance of the track to the wire is measured with an accuracy of $130 \mu\text{m}$.

In addition, the Xenon in the drift gas mixture is sensitive to transition radiation photons generated in the radiator material between the straws. Electrons produce more transition radiation photons than other particles, making the TRT suitable for electron identification.

The straws in the barrel are oriented axially in 73 concentric layers, giving measurements in the bending plane $R - \phi$. The active length of the straw is 71.2 cm, covering half a barrel. In the end cap, the straws are aligned radially in 18 discs per end cap. The total number of channels for the TRT detector is over 350,000. The detector improves the momentum resolution significantly and provides electron identification.

1.2.2 Calorimetry

The ATLAS calorimeters measure energies of jets over a region up to $|\eta| < 4.9$. Particle identification is possible, photons are distinguished from electrons and from charged pions by using tracks from the Inner Detector.

ATLAS has both electromagnetic and hadronic calorimetry. Both calorimeters use sampling techniques in which layers of passive material and active material are arranged alternately. The passive material (absorbers) make charged particles shower and the active layers detect the resulting particles. In the ATLAS calorimeter, liquid Argon (LAr) and scintillating plastic tiles are used as active material. Several absorber materials (lead, copper, steel and tungsten) are deployed in various regions of the calorimeter.

The calorimetry system is divided in four different subsystems. Figure 1.4 shows an overview of the ATLAS calorimetry system with the different technologies. Parts of the detector are removed to show the inner structure of the detector.

Electron/pion separation ($e^\pm/\pi^\pm$) and photon/pion separation (γ/π^0) is done with a sampling layer in the electromagnetic calorimeter with fine granularity. Coarser granularity over the rest of the calorimeters is sufficient for the physics requirements for energy measurements, jet reconstruction and missing energy measurements.

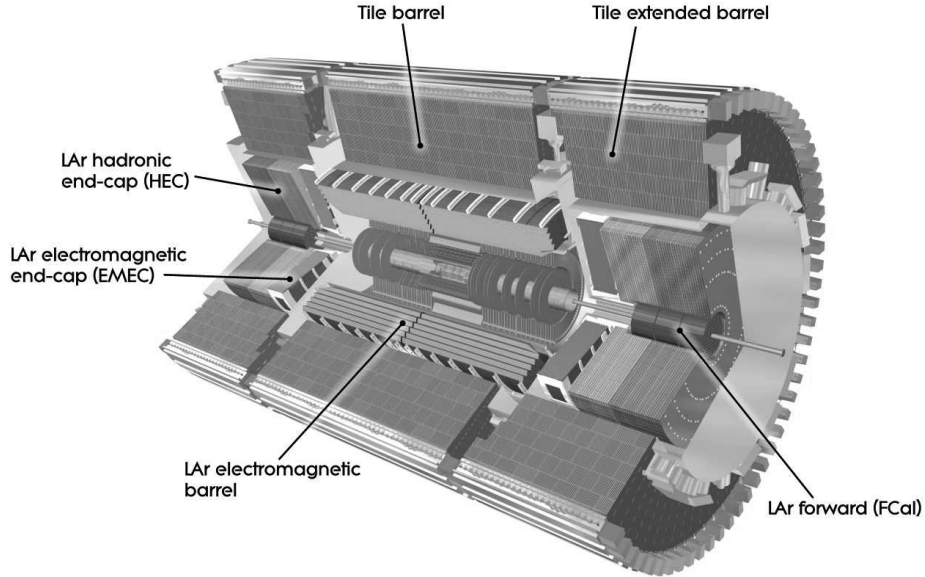


Figure 1.4: Cut-away view of the ATLAS calorimetry detectors.

The electromagnetic calorimeter

The electromagnetic calorimeter measures the energy of electrons and photons. It is divided in a barrel part ($|\eta| < 1.475$) and two end caps ($1.375 < |\eta| < 3.2$). Lead is used as absorber with liquid Argon as active medium to measure the signal. The lead is folded in a typical accordion shape, see Figure 1.5, ensuring that no cracks in the $R\phi$ plane are present. The finer granularity of first of the three sampling layers provide particle identification for photons, electrons and pions.

The depth of the electromagnetic calorimeter is more than 24 radiation lengths¹, ensuring that no electromagnetic showers go undetected. Test beam results have shown that an energy resolution of $\sigma_E/E = 11.5\%/\sqrt{E} \oplus 0.5\%$ (E in GeV) is obtained.

In the region of $|\eta| < 1.8$, a presampler consisting of a layer of liquid Argon is used to correct for the energy lost by electrons and photons upstream of the calorimeter.

The hadronic calorimeter

The task of the hadronic calorimeter is to measure the energy and direction of particle jets from hadronized quarks and gluons and hadronically decaying particles. Hadronic showers are longer and wider than their electromagnetic counterparts, with a broader

¹One radiation length is the typical length over which an electrons energy is reduced with a factor e (2.71).

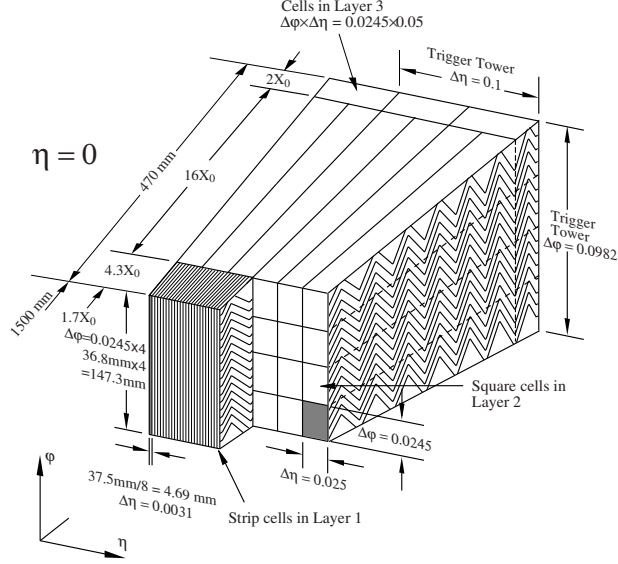


Figure 1.5: A barrel module of the electromagnetic calorimeter. The granularity of the three different sampling layers is shown.

variance. The minimum depth of the hadronic calorimeters is around 10 interaction lengths². This depth is sufficient to reduce punch-through, i.e. unstopped hadronic particles, well below the irreducible level of prompt muons or muons from decays.

In the barrel region, hadronic calorimetry uses iron absorbers and scintillating plastic tiles. The iron in the hadronic calorimeter functions as return yoke for the solenoidal magnetic field of the Inner Detector. Two sides of the scintillating tiles are read out by wavelength shifting fibers into two photomultiplier tubes. The readout cells are pseudo projective towards the interaction region in η . The central barrel covers $|\eta| < 1.0$, two extended TILE barrels have a coverage of $0.8 < |\eta| < 1.7$.

In the end cap region, $1.5 < |\eta| < 3.2$, liquid Argon is used as active medium with copper plates as absorber. High radiation levels dictate this choice of materials. The energy resolution of the hadronic calorimeters is demonstrated to be $\sigma_E/E = 56\%/\sqrt{E} \oplus 5.5\%$ (E in GeV) [11].

The forward calorimeter

A forward calorimeter (FCal) is installed close to the beam line to extend calorimetry coverage to $3.1 < |\eta| < 4.9$. The FCal reduces radiation background levels in the Muon Spectrometer. In order to reduce cavern background rates in the Inner Detector, the front face of the FCal is placed 1.2 m in front of the EMCAL end cap front face. To

²An interaction length is the mean free path of a high-energy hadron.

ensure sufficient interaction length depth of the FCal, a high density design is deployed.

The forward calorimeter is split longitudinally in three segments. The first segment has a copper absorber for electromagnetic measurements. The other two segments use tungsten absorbers for hadronic measurements. The segments have a grid of holes for positioning electrodes and contains liquid Argon as active medium. The energy resolution of the FCal is demonstrated to be $\sigma_E/E = 70\%/\sqrt{E} \oplus 3\%$ for pions and $\sigma_E/E = 28.5\%/\sqrt{E} \oplus 3.5\%$ for electrons [11].

1.2.3 Muon Spectrometer

The Muon Spectrometer forms the outermost layer of the ATLAS detector and is designed to measure high transverse momentum muons with high precision, independent of the Inner Detector. The spectrometer is embedded in a toroidal magnetic field (discussed in section 1.2.4) and provides at least 3 station measurements for a muon in most of the acceptance. From the curvature of the muon track, its momentum is derived. The muon system is designed to achieve a momentum resolution of 10% for 1 TeV muons, which corresponds to muon measurements with a precision of 50 μm or better. Furthermore, trigger detectors in the muon system provide an independent muon trigger.

The Muon Spectrometer is arranged in a barrel and two end caps, each with three layers of detector stations. Figure 1.6 shows the cross-section of the Muon Spectrometer barrel in the non-bending plane, perpendicular to the beam axis. The cylinders are positioned at radii of 5, 7.5 and 10 m and referred to as the inner, middle and outer layer. Sixteen sections in the xy -plane are identified, 8 with large and 8 with small detector stations positioned in an overlapping structure to ensure total azimuthal coverage. Figure 1.7 shows the cross-section of a quadrant of the spectrometer in the bending Rz -plane, at an azimuthal angle such that the large muon stations are shown. Each end cap consists of three wheels at a distance z from the interaction point of approximately 7.4 m for the inner wheel, 14 m for the middle wheel and 21.5 m for the outer wheel. Extra stations in the barrel-end cap transition region are positioned in a wheel at $z = 10.4$ m, called the extended stations. The installation of parts of these stations is staged.

The Muon Spectrometer deploys *Monitored Drift Tube* (MDT) chambers to make precision measurements in the region of $|\eta| < 2.4$. Very close to the beam line at the inner layer of the end cap, where very high particle rates are present, *Cathode Strip Chambers* (CSC) are positioned because of their fine granularity and fast operation. *Resistive Plate Chambers* (RPCs) serve as trigger detectors in the barrel region where as *Thin Gap Chambers* (TGCs) provide trigger measurements in the end cap.

A naming scheme is adopted for the MDT stations, according to the position of the stations in the spectrometer. The first letter of the three-letter name states if the station is in the *barrel* (B) or in the *end cap* (E). The second letter refers to the layer of the station which can be *inner* (I), *middle* (M) or *outer* (O). The last letter is defined by the size of the station, *large* (L) or *small* (S). Thus a BOL station is a large muon station in the barrel outer layer. Some special stations that do not follow this naming scheme are placed in regions with low coverage, for instance in the regions between the feet of the barrel toroid.

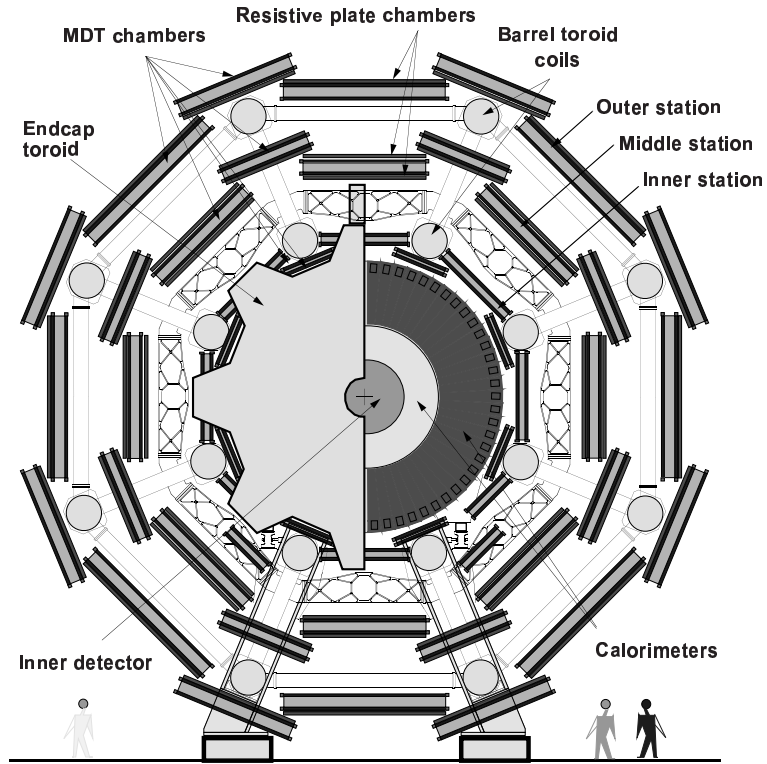


Figure 1.6: Cross-section of the barrel Muon Spectrometer perpendicular to the beam axis.

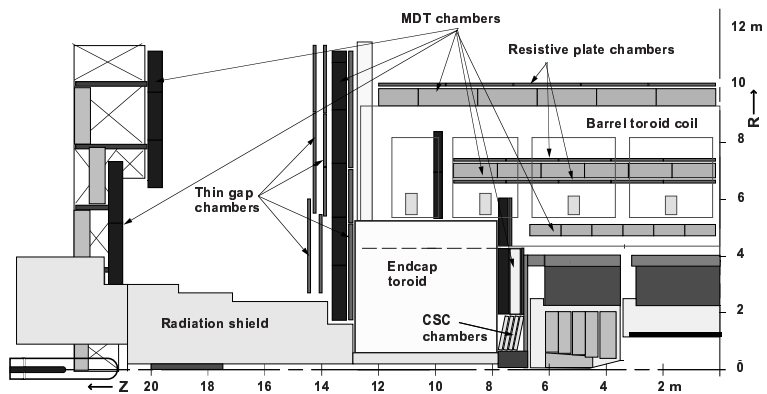


Figure 1.7: Cross-section of a quadrant of the Muon Spectrometer parallel to the beam axis.

Monitored drift tube chambers

MDT chambers (or stations) provide most of the precision measurements in the Muon Spectrometer. Figure 1.8 shows a cut-out for a typical middle or outer MDT barrel station with two multi-layers consisting of three layers of MDTs. The inner stations are equipped with four layers per multilayer to improve the local pattern recognition. An MDT consists of an aluminium tube with a radius of 30 mm filled with a drift gas mixture of $Ar : CO_2 = 93 : 7$. The gold plated tungsten anode wire has a diameter of $50\ \mu\text{m}$. The tube operates at a pressure of 3 bar and a voltage of 3040 V. When a charged particle traverses the tube, ionization clusters are produced in the drift gas, which will drift to the wire, creating a signal. The distance between the particle and the wire is determined by measuring the arrival time of the first cluster that reaches the wire causing the signal to pass a threshold, as is shown in Figures 1.9-a and b [17]. The measured drift time is converted to a drift radius of the measurement via an *rt-relation*. This relation is not linear (see Figure 1.9-d) and is sensitive to various external conditions such as temperature, gas-mixture and magnetic field. These local conditions are monitored with magnetic field sensors and temperature sensors installed on the MDT stations.

Note that the measurement of the drift circle gives a precise position in one plane, with a typical resolution of $80\ \mu\text{m}$ per tube ($35\ \mu\text{m}$ per chamber). The position of the particle along the tube is not measured by the MDT chambers, except for some special chambers that are equipped with so called twin-tubes [18]. Measurements from the RPCs or extrapolation from the Inner Detector system provides the second coordinate of the measurement. The MDT stations are positioned such that the precision plane is in the bending plane of the toroid magnetic field.

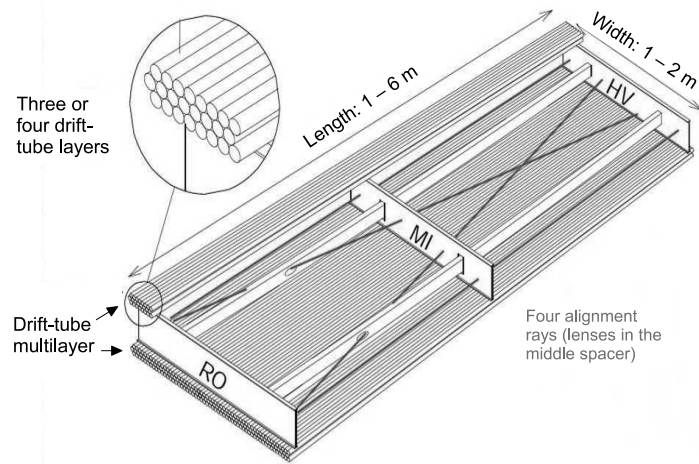


Figure 1.8: Schematic overview of a barrel MDT station. Part of the top multi-layer is removed to show the interior of the station.

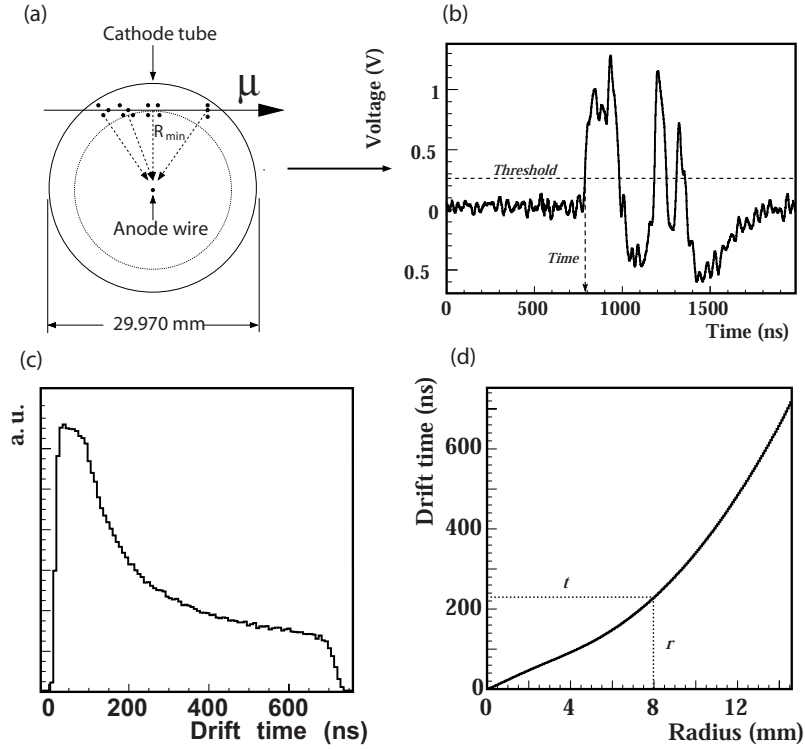


Figure 1.9: The operational principle of MDTs. a) A muon traversing the tube creates charged clusters which drift towards the anode wire. b) The measured pulse crosses the threshold. c) Typical drift time spectrum. d) rt -relation.

Figure 1.10 shows the transverse momentum resolution of the MDT chambers for the barrel ($|\eta| < 1.5$) and end cap ($|\eta| > 1.5$). For muons with a transverse momentum of less than 20 GeV, energy loss fluctuations in the calorimeters form the dominant contribution to the momentum resolution. For muons with transverse momenta between 20 GeV and 200 GeV, multiple scattering dominates the resolution. For very high transverse momentum muons, over 200 GeV, the resolution is dominated by the intrinsic MDT tube resolution and chamber alignment.

Cathode strip chambers

In the region of $2 < |\eta| < 2.7$ in the inner wheel of the end caps, CSC are installed for precision measurements. The expected particle rate of over 150 kHz/cm² gives a too high occupancy for MDT chambers. The CSCs can handle this high rate and achieve a typical resolution of 40 μ m in the precision plane and 5 mm in the second coordinate. Eight small and eight large stations are installed in sectors like the MDT chambers.

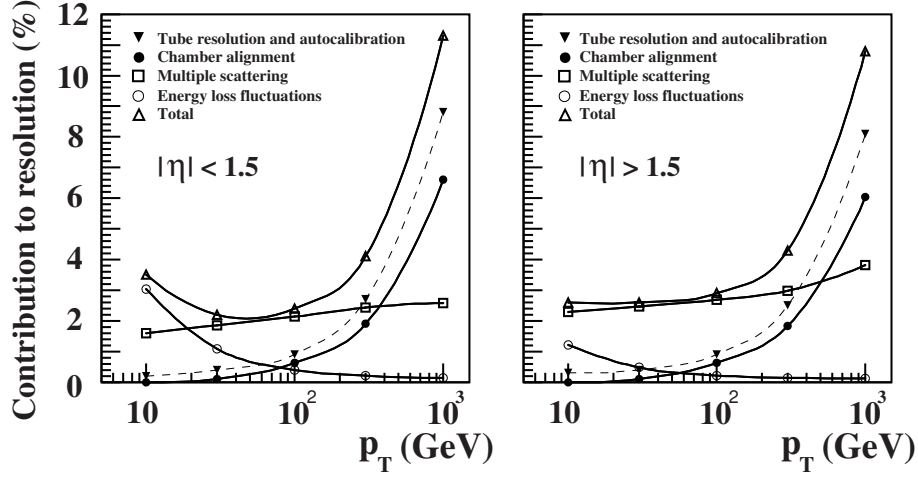


Figure 1.10: Contributions to the transverse momentum resolution, averaged over $|\eta| < 1.5$ (left plot) and $|\eta| > 1.5$ (right plot) .

CSCs are multi-wire proportional chambers with anode wires oriented radially and cathode strips oriented perpendicular to them, segmented in either η or ϕ . Interpolation of the charge picked up by the strips provides a position measurement. Each crossing muon will give four measurements in both η and ϕ planes, making it possible to resolve multiple particles per station. The small gas volume and gas mixture ($Ar : CO_2 = 80 : 20$) provide small drift times resulting in a time resolution of 7 ns.

Resistive plate chambers

The RPCs provide a trigger for muons in the barrel region. Two RPC stations are mounted on the middle barrel MDT chambers and the outer barrel MDT chambers are equipped with one RPC station, see Figure 1.7. Each RPC station provides two measurements in η and ϕ , giving a total of six measurements per muon traversing the barrel spectrometer. The ϕ measurements provide the second coordinate for the MDT precision measurements. The typical resolution of the RPC measurements is 10 mm in both the bending and the non-bending plane.

The RPC is a gaseous parallel electrode-plate detector. Two resistive plates made of phenolic-melamine plastic are kept parallel at a distance of 2 mm. As drift gas, a mixture of $C_2H_2 : ISO - C_4H_{10} : SF_6 = 94.7 : 5 : 0.3$ is used. This gas-mixture allows operation at a voltage of 9.8 kV and gives a signal width of 5 ns. Per gas gap, the signal is read out via metallic strips in η and ϕ . Each RPC station consists of two gas gaps.

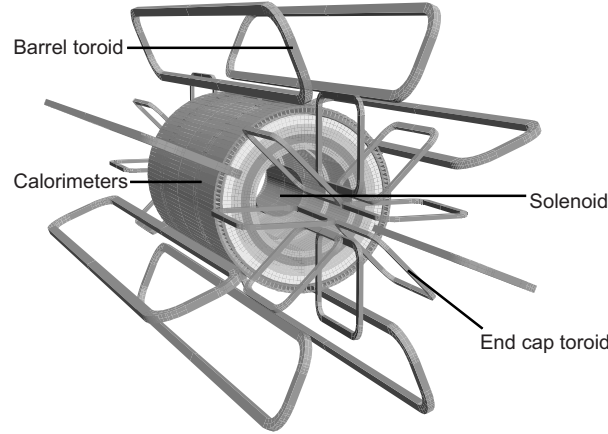


Figure 1.11: *Geometry of the ATLAS magnet system and the iron in the hadronic calorimeters.*

Thin gap chambers

Trigger measurements in the end caps of the spectrometer are provided by TGCs. TGCs are multi-wire proportional detectors operating with a gas mixture of $CO_2 : n-C_5H_{12} = 55 : 45$, operated at 2.9 kV. The radial coordinate is measured with gold-coated tungsten anode wires, the azimuthal position is measured by pick-up strips. A TGC unit consists of two gas gaps (doublet) or three gas gaps (triplet).

The units are installed in four wheels per end cap, see Figure 1.7. A doublet unit is positioned before the inner MDT wheel, a triplet before the middle MDT wheel. Two doublet units after the middle MDT wheel give a total of 9 measurements per particle traversing the end cap spectrometer. The typical resolution of the TGC chambers is 2-6 mm in the bending plane and 3-7 mm in the non-bending plane.

1.2.4 Magnet system

ATLAS has four large superconducting magnets to provide the magnetic field to bend charged particle trajectories. The superconducting magnet system is cooled down to 4.6 K and consists of the following components (see Figure 1.11):

- A *central solenoid* providing a 2 T axial magnetic field for the Inner Detector system. It consists of a single-layer wound coil with a Al-stabilized NbTi conductor. The inner diameter of the superconducting coil is 2.46 m, the outer diameter 2.56 m and its axial length 5.8 m. The flux is returned via the steel in the hadronic calorimeters.
- A *barrel toroid* providing a 0.5 T toroidal magnetic field in the Muon Spectrometer barrel volume. Eight Al-stabilized NbTi/Cu conductor coils in their personal

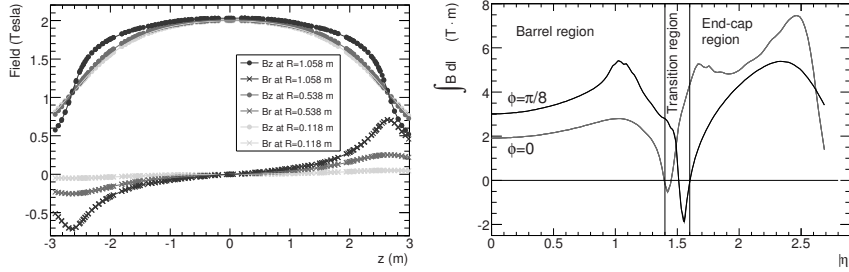


Figure 1.12: left plot: R - and z -dependence of the radial and axial component of the Inner Detector cavity. right plot: Predicted field integral as function of $|\eta|$ from the innermost to outermost MDT layer in one toroid octant.

vacuum vessels provide this field. The inner diameter of the coil is 9.4 m, the outer diameter 20.1 m with a length of 25.3 m.

- Two *end cap toroids* providing a 1.0 T toroidal magnetic field in the Muon Spectrometer end cap volume. Each end cap consists of a single cold mass constructed from eight square coil units. The superconducting coils are from the same material as the barrel toroid.

The solenoid magnet is shorter than the Inner Detector length, causing the magnetic field to drop from 2 T from the center of the Inner Detector to around 1 T in the forward regions. The left plot in Figure 1.12 shows the axial and the radial components of the solenoidal magnetic field at a fixed azimuthal angle. Due to the inhomogeneity of the magnetic field, the use of a magnetic field map is needed for tracking and reconstruction.

The right plot in Figure 1.12 shows the bending power in the form of a field integral $\int B dl$ in the toroid magnet system as function of $|\eta|$. Two values of the azimuthal angle are shown, one traversing a toroid coil ($\phi = \pi/8$) and one between two toroid coils. The field integral drops significantly around $|\eta| = 1.5$, called the transition region between the barrel and end cap toroids. Although an iron core would enhance the magnetic field strength, an air-core toroid was chosen to minimize multiple scattering in the Muon Spectrometer.

1.2.5 Trigger system

The LHC has a bunch crossing rate of 40 MHz and the average size of an event is approximately 1.3 Mb. It is not possible to store the complete data for offline on tape. Moreover, not all bunch crossing events contain hard collisions. ATLAS deploys a three-level trigger scheme to select potentially interesting physics events and reduce the amount of data to be stored. Figure 1.13 shows the three distinct levels of the trigger system: a level-1 (LV1) trigger, a level-2 (LV2) trigger and the event filter (EF) as a

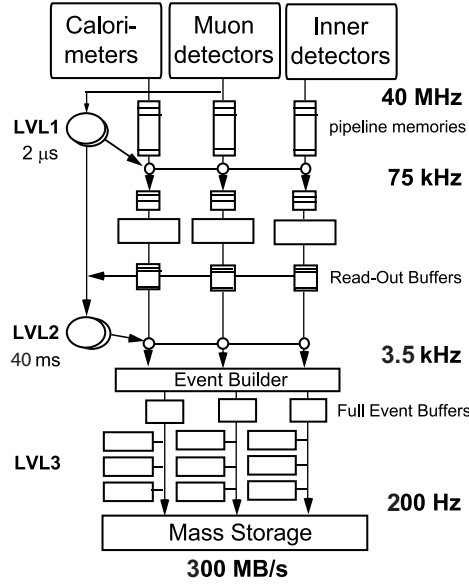


Figure 1.13: Schematic overview of the ATLAS trigger system.

third level trigger. The level-2 and event filter combined are called the high level trigger (HLT).

Level-1 trigger

The LV1 trigger is a hardware-based trigger with the task to select high transverse momentum leptons, photons and jets, as well as large missing transverse energy (E_T^{miss}) events. The events are selected by using reduced granularity information from the calorimeters and the trigger chambers of the Muon Spectrometer. The LV1 trigger defines regions of interest (RoIs), which are regions in η and ϕ in which interesting features are defined. This level consists of a pipeline memory system such that multiple crossings can be analyzed simultaneously. The decision reduces the event rate to 100 kHz within a decision time of less than $2.5 \mu\text{s}$.

Level-2 trigger

The LV2 trigger is a software-based trigger and is seeded by the RoIs defined by the LV1 trigger. At the second level, the full granularity and precision of the measurements within the RoIs are used to select interesting events. This accounts to 2% of the total amount of data. The LV2 uses dedicated software to reconstruct and identify physics objects (e.g. electrons, muons and jets) in the RoIs. This reduces the event rate to below 3.5 kHz with a latency of around 40 ms per event.

Event filter

The EF uses offline analysis procedures on the full event information to select events, reducing the event rate further to approximately 200 Hz, with an average processing time of 4 s. The EF reconstruction runs on a dedicated computer cluster near the ATLAS site. Events passing the EF are written to mass storage and made available for further offline processing.

The operation of the trigger is configured using *trigger menus*, that define a set of trigger conditions. A trigger condition contains a physics object and a defined threshold or cut value (such as $p_T > 20$ GeV). The trigger menus are designed such that the interesting events are accepted.

Events that pass the selection criteria are tagged based on the decision of the EF and sorted accordingly in *data streams*. Example physics streams are the *electron stream*, the *muons stream* and the *missing transverse energy stream*. Besides physics streams, a *calibration stream* is available for data used to calibrate the detectors. Finally an *express stream* is used to monitor the data quality. Further analysis will be based on these streams.

Chapter 2

ATLAS software and simulation

2.1 Introduction

This chapter gives an overview of the ATLAS software framework used to simulate, reconstruct and analyze events. Here we use the notion of *event* for both proton-proton collisions and cosmic ray activity in the detector.

In ATLAS, a flexible modular software framework called ATHENA is developed. Due to the modular design, the reconstruction can be implemented with common tracking software and the muon identification can use these software modules.

ATHENA can handle both real data and simulated events and is discussed in section 2.2. The simulated events are used to study the performance of the detector and validate the reconstruction algorithms. Section 2.3 explains the process of data simulation and presents the various data samples used to validate the muon identification software.

2.2 ATHENA

Due to the complexity of the ATLAS experiment, a modular software framework is needed. The framework implemented for ATLAS is required to fulfill the following tasks:

- The software is able to handle different tasks such as event generation, simulation, reconstruction and analysis.
- The software is extendable and flexible such that it can adapt to the need of the users and allow for software development.
- The software is robust and maintainable by a large community.

For these reasons, the ATLAS software framework is realized as a component model-based framework. This framework makes a clear distinction between algorithmic classes performing dedicated tasks and data classes for communication between the different algorithmic modules. By defining common interfaces of the algorithms and using a well

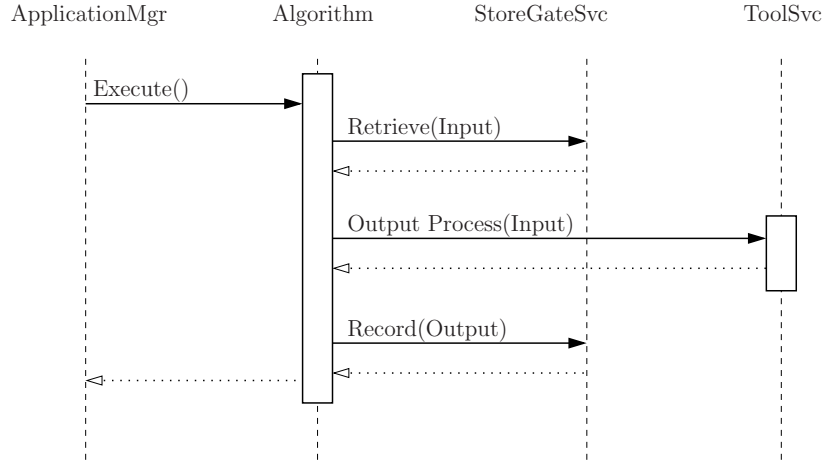


Figure 2.1: A simplified diagram of the data flow and sequence steering of an ATHENA job.

defined Event Data Model (EDM) for the data classes, ATHENA ensures commonality between lower level sub-detector specific algorithms and for higher level combinations between various systems used by the physics groups. The high modularity of the software framework ensures flexibility and maintainability of the software packages.

Blackboard architecture

ATHENA uses a blackboard architecture style of data processing [19] [20], which is characterized by the concept of having a common repository (the *blackboard*) from which software modules can retrieve information from and write out information to. A controller, the `applicationManager`, steers the software job by collecting the modules which are to be executed and organizing the order of execution. The communication between the separate modules is done via the common repository, called `StoreGate` within ATHENA, via which the data classes are retrieved and stored. Data classes contain the event information and define the interface of the software modules.

Figure 2.1 shows a job in which the `applicationManager` has a sequence of one `Algorithm`. An `Algorithm` performs a dedicated task and is called once per event. The module accesses the `StoreGateSvc` to retrieve the input data classes and is responsible for recording the output objects to the repository. An example `Algorithm` is `MuTagIMO`, taking inner detector and muon spectrometer information as input and providing tagged muons as output.

An `Algorithm` may delegate the processing to `Tools` (Figure 2.1 shows one `Tool`). The `Tool` may be called many times per event by the `Algorithm`. An example tool is the `MuTagMatchingTool`, which is called by the `MuTagIMO` algorithm every time inner detector and muon spectrometer information is matched.

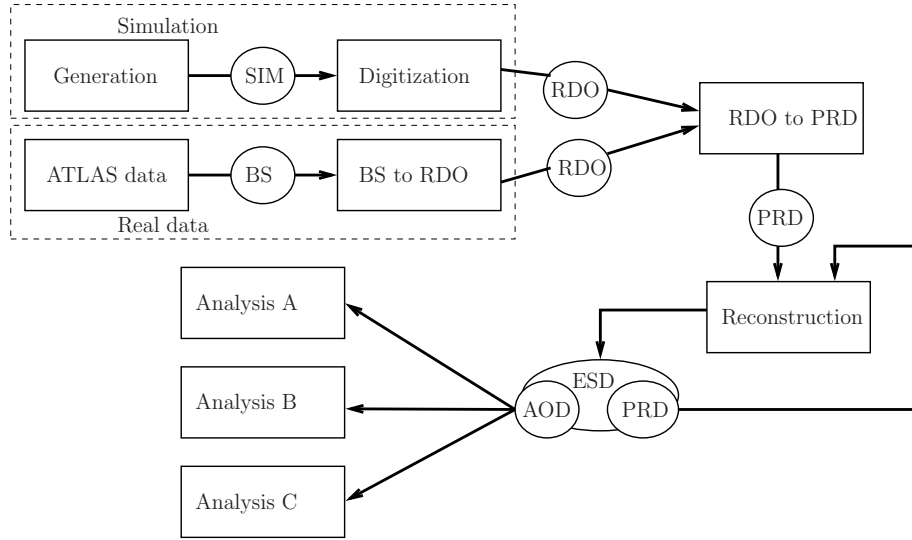


Figure 2.2: The modularity of an ATHENA job is ensured by using data classes. Any input data can be handled by the reconstruction as long as its format is PRD (Prepared Raw Data). The output of the reconstruction is of the format ESD (Event Summary Data), from which an AOD (Analysis Object Data) is extracted.

A **Service** is a class designed to provide functionality during the entire program execution. Figure 2.1 shows the **ToolService** as an example **Service**, providing the **Tool** class used by the algorithm.

Data classes

The concept of data classes is the second ingredient to a modular software design, besides the algorithm modules. By defining the format of input/output data objects to be processed by the algorithm, interchangeability of modules is ensured. Figure 2.2 shows a flow diagram of a full job in ATLAS, starting from either simulation or real ATLAS data to physics analysis. Simulation in ATLAS is discussed in the next section.

Data from ATLAS is realized as a *byte-stream* (BS) which is translated to *Raw Data Objects* (RDOs), C++ classes representing raw hits. The RDO illustrates the concept of modular design and the use of an EDM explicitly. Simulated data are translated to RDO objects as well. The module responsible for translating the RDO to *Prepared Raw Data* (PRD) objects takes any RDO as input. It does not need to know the source of the RDO enabling the same reconstruction flow for both real and simulated data in ATHENA.

Similarly, the reconstruction takes any PRD as input, producing *Event Summary Data* (ESD) objects and *Analysis Object Data* (AOD) objects [21]. These objects can be analyzed by several user analysis modules. The ESD is the output of the reconstruction

job and contains the full event information. Its content is suitable for re-reconstruction and calibration as well. For analysis purposes the ESD is too large and a slimmed object, the AOD, is extracted from the ESD. The AOD contains containers of physics objects such as four-momenta of the particles (muons, electrons, jets) in the event. The AOD can be analyzed by several analysis modules.

2.3 Simulation

Simulated data is important for developing and validating the reconstruction software, in the absence of real physics data, or, when data becomes available, to compare the data with expectations.

The simulation starts with generating the physics process using an event generator. Example event generators are Pythia [22] and Herwig [23], modeling the hard process of the collision, initial and final state radiation, hadronization and decays¹. The particles are then propagated through the detector taking into account the interactions with the material of the detector. This is done by G4ATLAS, an algorithm based on the Geant4 toolkit [25], customized to the ATLAS geometry. G4ATLAS propagates particles with small steps through the detector geometry, evaluating the physics effects of the interaction with matter per step. ATLAS uses the geometry description *GeoModel* [26], which forms the interface to the geometry description used by G4ATLAS.

The last step in the simulation process is to take the detector response into account. This step is called digitization. The position of the hits in the detector are translated to signals, e.g. electrical pulses, charges, as they would be recorded in the detector. The simulated hits (SIM) are translated to raw hits, *Raw Data Objects* (RDO). RDOs are converted to PRD data objects that serve as input for reconstruction.

First, the event generation of hadron collisions is discussed. Then, event generation of cosmic ray muons is explained. The data samples used in this thesis are discussed in the last section.

2.3.1 Proton-proton collision simulation

The collision of protons at high energy are in fact collision between the partons inside the proton. The partons carry a fraction of the total proton momentum, and this fraction is described by the *Parton Distribution Functions* (PDFs). The hard parton-parton scattering cross section can be calculated within the framework of perturbative QCD.

The simulation of a hadronic collision is decomposable into several independent subprocesses. An event simulation of a proton-proton collision in ATLAS consists of a *hard scattering* (HI), *initial and final state radiation* (ISR and FSR), *hadronization and decay* and *underlying event* (UE). These different subprocesses are shown in Figure 2.3, showing an illustration of a hard scattering where $t\bar{t}H^0$ production takes place [27].

¹Dedicated packages exist that can be interfaced to Herwig or Pythia to simulate specific processes. For example, the MC@NLO [24] package models the hard collision between partons at the NLO QCD level for a number of processes.

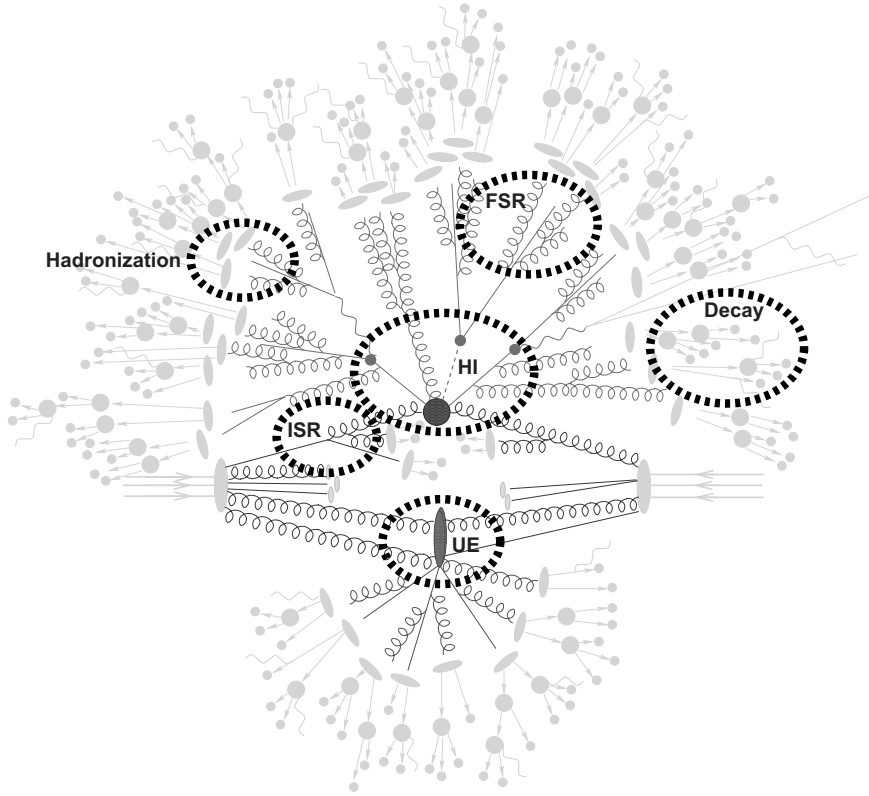


Figure 2.3: Pictorial representation of a $t\bar{t}H^0$ event as produced by an event generator. The various sub-processes are indicated in the figure. The depiction of the Underlying Event (UE) is for completion of the picture, no transverse momentum balance is implied. The Figure is taken from [28].

The hard scattering describes how the incoming partons interact with each other and produce new particles. The parton-parton interaction can be calculated perturbatively using Feynman diagrams.

The incoming and outgoing partons of the hard scattering are colored objects and hence radiate gluons. These gluons in turn can split up into gluons and quark-antiquark pairs. This process is called parton showering and is generic in a sense that it is independent of the hard scattering process. The showering of incoming partons to the hard interaction is referred to as initial state radiation, showering of outgoing partons final state radiation.

The parton showering is cut off at an energy scale and the color connected partons are grouped into color singlet hadrons. This process is called hadronization. The unstable hadrons in turn have to decay into stable particles which can finally be detected. Two

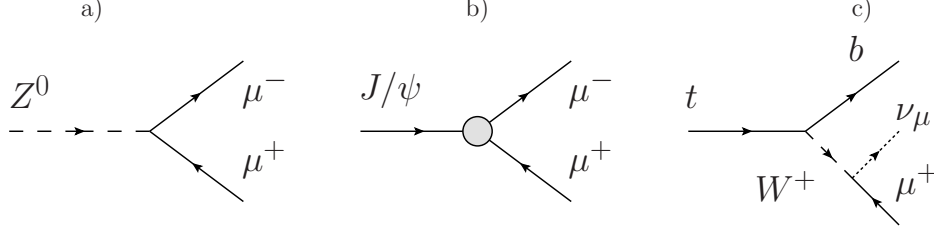


Figure 2.4: Leading order decay modes of a) Z^0 bosons, b) J/ψ particles and c) top quark into muons.

models of hadronization are available: cluster hadronization implemented in Herwig and string hadronization in Pythia.

Besides the partons involved in the hard scattering, other partons in the proton remnants also interact. Collectively, these interactions are referred to as the underlying event.

Throughout the following chapters of this thesis, a set of various simulated *benchmark* physics processes with muon final states are used for validation studies and to evaluate the muon reconstruction performance. We choose these benchmark processes by the fact that they will definitely be produced in ATLAS and that they have very different characteristics. These processes are the decay of Z^0 bosons and J/ψ mesons in to two muons, and top-antitop ($t\bar{t}$) production with a leptonic decay mode. As discussed in the introduction of this thesis, these benchmark physics processes will play an important role for understanding the detector and validating the reconstruction when analyzing the first data of the LHC.

Figure 2.4 a) shows the lowest order Feynman diagrams of the Z^0 boson. The mass of the Z^0 boson is 91.1876 ± 0.0021 GeV and the branching ratio to muons is 3.4% [29]. The J/ψ decays to two muons as shown in Figure 2.4 b). The mass of the J/ψ is 3096.916 ± 0.011 MeV and the branching ratio to muons is 5.9%. Finally, in Figure 2.4 c), the decay of a top quark is shown. The top quark has a mass of 172.4 ± 0.7 GeV [30]. The specific decay shown in the figure, with the W boson leptonically decaying into a muon, has a branching ratio of 9.4 %. The bottom quark hadronizes and muons may be also produced by the decay of the resulting B-meson.

The transverse momentum spectrum of the muons from the aforementioned processes is shown in Figure 2.5. The muons from the Z^0 boson are shown by the black line, muons from the J/ψ decays are shown by the dotted line. In grey, the muons from top quark decays are shown. The distributions are normalized to unity. At generator level, a requirement is made on the transverse momentum of the muons from the Z^0 decays to be above 5 GeV. For the muons from the J/ψ sample, one muon has a minimum transverse momentum of 6 GeV and the second muon of 4 GeV, which gives the double peak structure in the picture. The muons from the Z^0 decay are notably harder than the muons from the lighter J/ψ meson. The muons from the top quark decay cover a

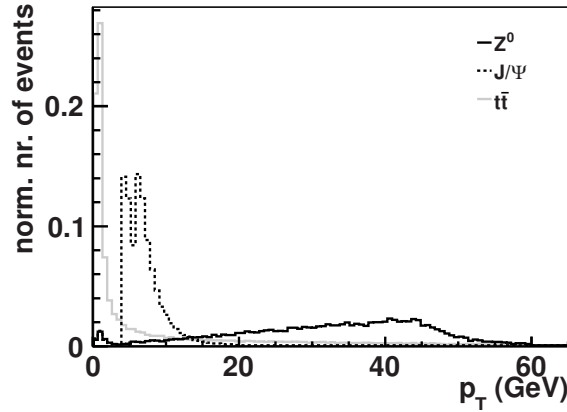


Figure 2.5: Transverse momentum of the muons from Z^0 boson decays, J/ψ decays and top quark decays.

wide range in transverse momentum. Decaying W bosons generate muons with a high transverse momentum, and in addition relatively softer muons from b-meson decays.

2.3.2 Cosmic simulation

For the period of December 2006 until September 2008, muons from cosmic rays [29] were used to commission the detector and the reconstruction software. To cross-check the commissioning data sets, samples of simulated cosmic muon events are available.

The momentum spectrum of cosmic muons at sea level is shown in Figure 2.6. An overall slope of the spectrum of $p_\mu^{-1.7}$ is taken out of the distribution for clarity. For the cosmic samples at ATLAS, muons are generated according to the distribution shown in Figure 2.6, with momenta between 10 GeV to 2 TeV in a surface of $600 \times 600 \text{ m}^2$. For practical reasons, a fiducial volume is defined, a sphere around the interaction point with a radius of 17 m [32] to which the surface cosmic muons must point in order to be propagated to the detector. The G4ATLAS package takes into account the rock, the service shafts and the ATLAS detector in simulating the path of the cosmic muons through the material. Figure 2.7 shows the ATLAS detector in the cavern, together with the access shafts and a part of the tunnel.

2.3.3 Cavern background

A part in the simulation of physics processes is the treatment of cavern background. Since this background affects the reconstruction and identification of muons, the origin of this type of background radiation is discussed here.

Cavern background radiation results from the calorimeter material becoming radioactive from the large particle flux at the high luminosity runs. Neutral particles such

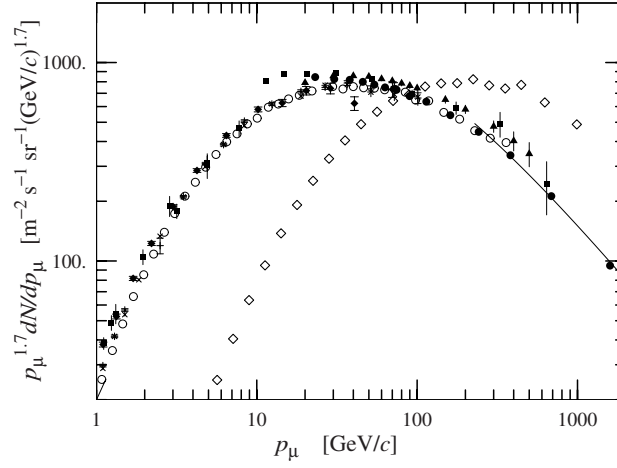


Figure 2.6: The momentum spectrum of cosmic muons at sea level, measured by various experiments [31]. The distribution is with respect to an overall slope of $p_\mu^{-1.7}$. The left distribution are muons with incident angle $\theta = 0^\circ$, the right distribution describes muons with incident angle $\theta = 70^\circ$.

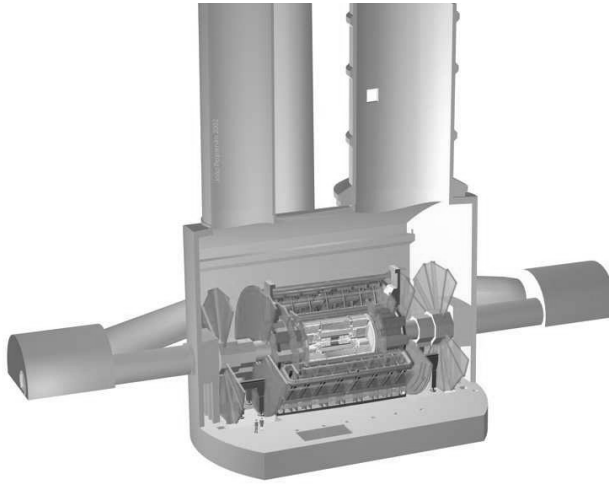


Figure 2.7: The ATLAS detector in the ATLAS cavern as used in the cosmic simulation.

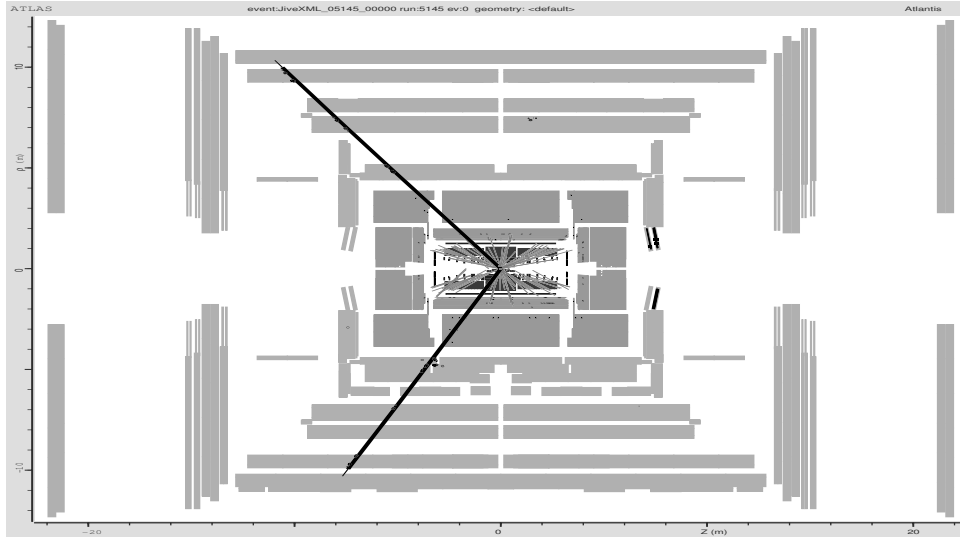


Figure 2.8: Event display of a $Z^0 \rightarrow \mu^+ \mu^-$ event.

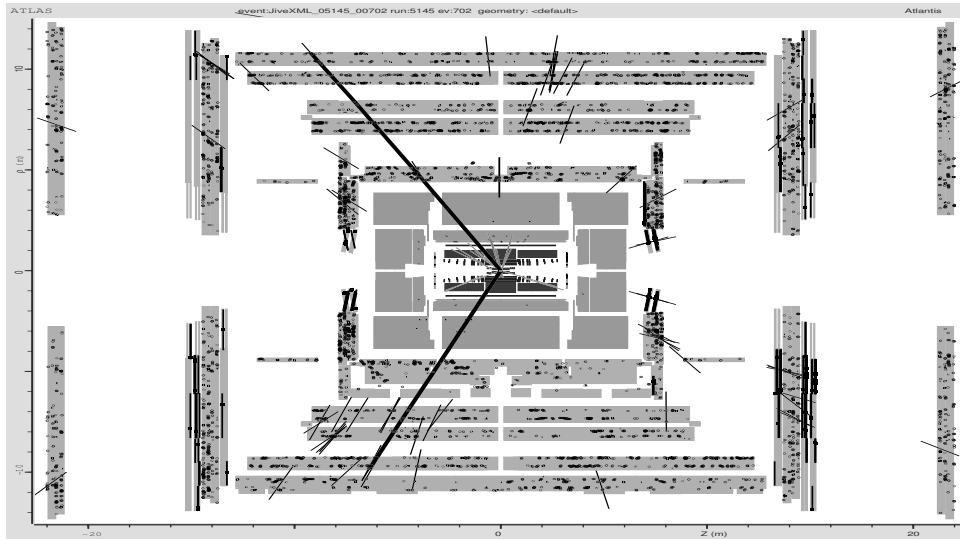


Figure 2.9: Event display of a $Z^0 \rightarrow \mu^+ \mu^-$ event with cavern background SF5 added.

as neutrons and photons are emitted by the calorimeters. In the material of the muon spectrometer, they give rise to charged particles due to conversions.

The cavern background events are normalized to a 25 ns window for pp collisions at a luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The rate of cavern background is given by a *safety factor* (SF). SF1 stands for cavern background rates at $10^{34} \text{ cm}^{-2}\text{s}^{-1}$, SF5 for rates at a luminosity of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. In order to perform tests on the performance of the reconstruction software samples with large safety factors are generated.

Figure 2.8 shows an event display of an $Z^0 \rightarrow \mu^+\mu^-$ event in ATLAS. A projection in the Rz -plane is shown. The detector elements are shown in gray scales, hits in the muon spectrometer are shown in black circles and strips. Two muon tracks are shown as (thick) black lines. Figure 2.9 shows an event display of an other $Z^0 \rightarrow \mu^+\mu^-$ event with added cavern background (safety factor 5). Such events are much busier with large number of hits in the muon spectrometer. The thin line segments are reconstructed segments. Muon track reconstruction in such busy events is challenging and these background samples are used to test and validate the muon reconstruction software.

2.3.4 Data samples

Table 2.1 summarizes the samples used in validation studies described in this thesis. Besides the benchmark physics processes, a cosmic ray muon sample is used to study muon reconstruction of cosmic ray muons. To provide a stress-test of the muon reconstruction, a sample of Z^0 boson decays with added cavern background is used. This collection of samples provide means for various studies throughout this thesis.

sample	sample specifics	events
<i>cosmic muons</i>	muons generated according to section 2.3.2	20,000
$J/\psi \rightarrow \mu^+\mu^-$	J/ψ forced to decay to two muons, one with $p_T > 4 \text{ GeV}$ and one with $p_T > 6\text{GeV}$, both within $ \eta < 2.5$	16,000
$Z^0 \rightarrow \mu^+\mu^-$	Z^0 forced to decay to two muons, each within $ \eta < 2.8$ and with $p_T > 5 \text{ GeV}$	10,000
$t\bar{t} \rightarrow b\bar{b}W^+W^-$	with at least one W decaying leptonically	30,000
$Z^0 \rightarrow \mu^+\mu^- + bkg$ SF5	the $Z^0 \rightarrow \mu^+\mu^-$ sample overlain with five times the expected cavern background rate as for design luminosity	1,000

Table 2.1: A summary of the data samples used for studies throughout this thesis.

Chapter 3

Pattern recognition, tracking and combined muon reconstruction

3.1 Introduction

The ATLAS detector is designed to be efficient in the detection of muons over a large momentum and rapidity range. With its two tracking systems, the Inner Detector and the Muon Spectrometer, precise measurements of the properties such as momentum, charge and direction of muons are possible. Software has been developed to reconstruct these muons, e.g. identifying the tracks and providing a measure for their position, direction and momentum.

In this chapter, the track reconstruction software for muons is discussed. In the first section, reconstruction of charged particles in the Inner Detector is presented. In the next section, track reconstruction in the Muon Spectrometer is covered. Both systems make use of the *common tracking software*, which is explained in the subsequent sections. Combined reconstruction and muon tagging rely heavily on these common tracking tools and benefit greatly from the modular structure of the reconstruction software. The last section covers the combined muon reconstruction and discusses the set of reconstruction algorithms available within the ATLAS software framework.

3.2 Tracking in the Inner Detector

The Inner Detector track reconstruction makes no clear distinction between pattern recognition and track fitting. Pattern recognition is selecting hits together that belong to the same trajectory, providing a first estimate of the parameters of the trajectory. The parameters are the position, direction and momentum of the particle at one point along the trajectory. Track fitting gives the best estimate of the parameters of the trajectory given the set of hits from the pattern recognition step. Section 3.4 will cover the concept of a track and its parameters in more detail.

Tracking in the Inner Detector is done in two main sequences: the *inside-out* reconstruction followed by the *outside-in* reconstruction. The outside-in reconstruction

recovers inelastic material interactions and decays of neutral particles in flight. For muon reconstruction, the inside-out sequence is the most important one.

3.2.1 Inside-out tracking

The reconstruction starts with the formation of 3 dimensional representations of hits in the silicon detectors called **SpacePoints**. The pixel modules provide 3 dimensional hit information that consists of a two dimensional measurement associated to a detector element surface. For the SCT modules, a **SpacePoint** is constructed using the measurements from the two sensors glued back to back under a stereo angle on a single module, as mentioned in section 1.2.1.

SpacePoints from the pixel detector serve as seeds for track candidates, optionally using a z vertex constraint. Track candidates are made by performing a Kalman fit [33] to the pixel seeds, following the trajectory and including successive silicon hits in the fit.

The seeded track finding results in a high number of track candidates from which many may share hits or are incomplete. Shared hits are called *ambiguities* and need to be resolved, e.g. each hit needs to be associated to one track. Ambiguities are resolved by refitting the track and evaluating a χ^2 over number of degrees of freedom. Also, a track scoring strategy is deployed. Track scoring favors fully reconstructed tracks by weighting different types of measurements with different scores (e.g. precision measurements from pixels have a higher weight than non-precision measurements). The χ^2 -probability, the number of measurements and the number of holes¹ are integrated in the scoring function.

Hits that are shared between tracks are assigned to the track with the higher score and the track without the formerly shared hit is refitted and again scored. The refitted track is once more evaluated for shared hits with other track candidates. Tracks that fall beyond a certain scoring and χ^2 cut are rejected.

Silicon track candidates are used as seeds to define narrow roads in the TRT detector, from which hits are added to the track. A fit is performed, combining the TRT and silicon hits, together with track scoring. Two techniques are available for combined fitting: a Kalman fitter-smoother procedure or a global χ^2 fit [34]. The combined fit procedures use a detailed geometry description in order to treat material effects properly. This will be discussed later, in the common tracking software section.

If the TRT extension improves the silicon track, the TRT measurements are associated to the track. This collection of tracks defines the *inside-out* track collection.

3.2.2 Pattern recognition using Hough transforms

A second strategy for Inner Detector tracking follows the opposite direction as mentioned above. It uses the TRT detector as a seed for finding tracks in the silicon detector. TRT segments are reconstructed by using Hough transforms [35] and histogramming techniques. The concept of a Hough transform is explained using a two dimensional

¹ *Holes* are sensors passed by the track which do not provide a measurement.

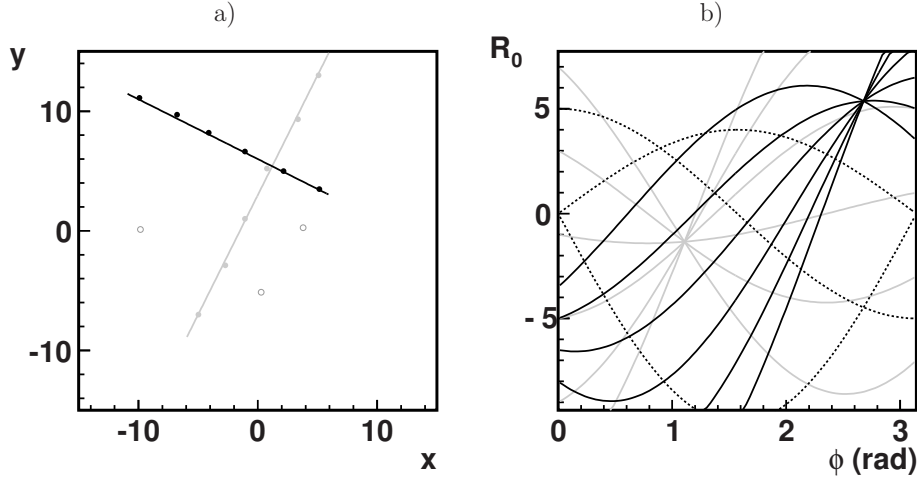


Figure 3.1: a) A set of points in space and b) their representation in Hough space. Intersecting lines in Hough space denote a common representation of the points. The two tracks a) correspond to the two points in Hough space b) with the most intersections.

example. A two dimensional line track can be parametrized by:

$$x \sin(\phi) - y \cos(\phi) = R_0 \quad (3.1)$$

where R_0 is the perigee (point of closest approach) of the line and ϕ the angle between the line and the x -axis. Every point in the (x, y) -space is described by a curve in (ϕ, R_0) -space, called *Hough space*. Since an infinite number of lines may be drawn through a point, infinite combinations of (ϕ, R_0) parameterizations exist per point, creating a curve in Hough space.

Figure 3.1 shows two sets of points in (x, y) -space (left) and their corresponding curves in Hough space (right). The intersect of the Hough curves denotes a common (ϕ, R_0) parameterization for a set of points in (x, y) -space. These points belong to the same line. The figure shows the set of lines and Hough curves belonging to the same line in gray and black. Hough curves from points not belonging to the same track do not intersect in the same point. These are shown by the dotted line.

The intersect of the curves in Hough space is found by binning the Hough space. Intersecting curves give rise to *peaks* in the binned Hough space as is shown in Figure 3.2. The more lines intersect, thus the more hits share the same track, the higher the peak in the binned Hough space becomes. The procedure of finding the peaks in Hough space is discussed in [36].

Depending on the Hough transform used, this technique can be used to find curved tracks as well as the straight line track in the example.

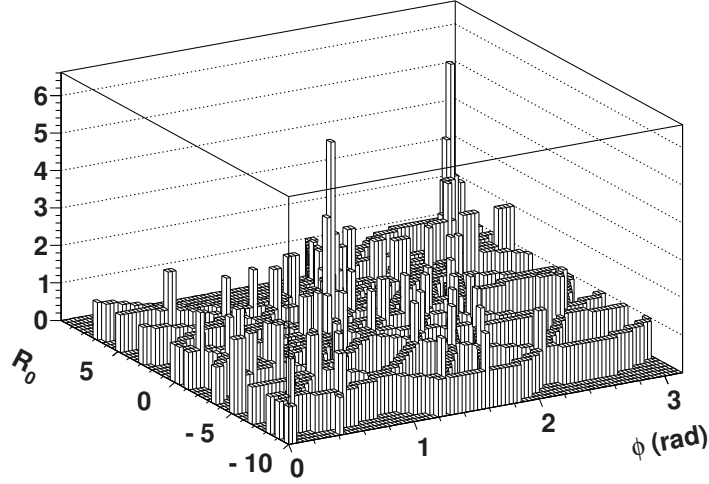


Figure 3.2: Representation of points in a Hough histogram.

3.2.3 Outside-in tracking

Straight line patterns in the TRT detector found by the Hough transform are fitted with a Kalman fitter-smoother procedure giving rise to a set of segments.

Outside-in tracking starts from TRT segments, extrapolates to the silicon detectors and collects **SpacePoints**. A Kalman fit is performed, adding successive silicon measurements producing a global track. After resolving the ambiguities as described in the *inside-out* tracking section, the *outside-in* track collection is built using a full track fit with either a Kalman filter technique or a global χ^2 fit. These techniques are explained in section 3.4.5.

This method recovers tracks from particle decays in the Inner Detector such as V_0 decays ($K^0 \rightarrow \pi^+\pi^-$ or $\Lambda^0 \rightarrow p^+\pi^-$), conversion electrons ($\gamma \rightarrow e^+e^-$) and bremsstrahlung electrons. These tracks have too few hits in the silicon tracker to have an efficient inside-out tracking performance.

3.2.4 Merging the Inner Detector track collections

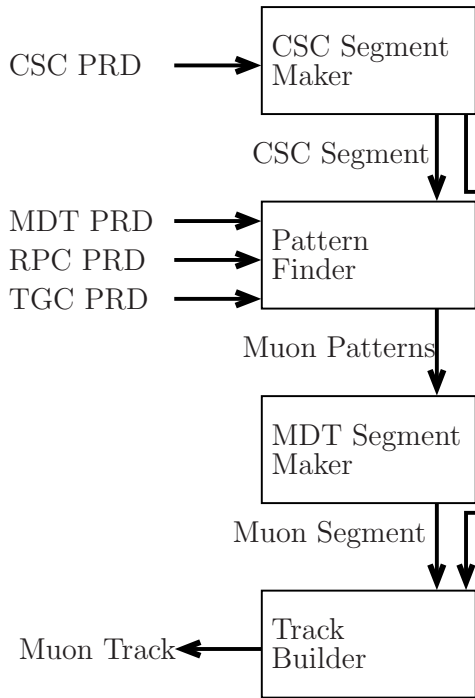
TRT segments not combined with silicon tracks are converted to *TRT-only* tracks. Finally, this track collection is merged with the inside-out and outside-in track collection. The TRT-only tracks have measurements in the $R\phi$ -plane in the barrel region and in the Rz -plane for the end-cap region. Tracks containing silicon hits as well have precise measurements in both planes. The TRT-only tracks are important for V_0 reconstruction and electron identification but are challenging to use for muon identification.

3.3 Tracking in the Muon Spectrometer

Two main muon reconstruction software packages exist in ATHENA, Muonboy [37] and MOORE [38]. MOORE is designed conform to the modular philosophy of ATHENA software, using common tracking tools and will be discussed in this section. For a discussion on the Muonboy package, the reader is referred to [37].

MOORE track reconstruction makes a clear distinction between pattern recognition, segment finding and track reconstruction. A schematic overview of the reconstruction flow is shown in Figure 3.3. Patterns found in the pattern recognition step are used as seeds for segment reconstruction. From these segments the tracks in the Muon Spectrometer are reconstructed.

3.3.1 CSC segment reconstruction



Segments are reconstructed in the CSC detector. Clusters are formed by fitting charge depositions on ϕ and η strips. A straight line is fitted through the clusters of one type giving rise to ϕ and η segments. The ϕ and η segments are then combined into one segment containing 3-dimensional position and direction information.

3.3.2 Muon pattern finding

Global pattern recognition in the full Muon Spectrometer is done with Hough transforms and histogramming techniques [36]. The measurements from the CSC segments besides the PRDs from the other sub-detector systems (MDT, RPC and TGC) are used as input for this module. The search for patterns is done in two orthogonal planes, the xy -plane searching for patterns which we denote as ϕ patterns and in the Rz -plane for searching for the so-called η patterns. The Muon Spectrometer uses different track models and Hough transforms for different regions in the spectrometer. Since there are regions without magnetic field in the end cap and

Figure 3.3: Flow diagram of the MOORE muon reconstruction package.

the magnetic bending is in the Rz -plane, the transformations are divided in three regions, see Figure 3.4:

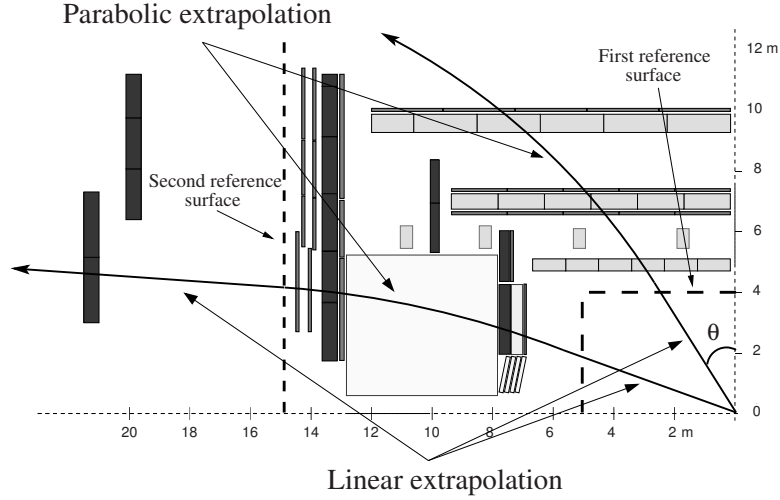


Figure 3.4: The various regions of the Muon Spectrometer in the Rz -plane, which have different Hough transformations.

- a *straight line* $R\phi$ transformation is used for finding patterns in the xy -plane;
- a *curved* $R\theta$ transformation is used for finding patterns in the Rz -plane barrel spectrometer and the inner part of the end-cap spectrometer;
- a *straight line* $R\theta$ transformation is used for finding patterns in the Rz -plane for the outer part of the end cap, where no magnetic field is present in the Rz -plane;

The ϕ and η -patterns are combined by associating hits from a ϕ -pattern to an η -pattern and vice versa. The combined patterns provide an estimate of the position and the direction of the track candidate, with a typical precision on the direction of the pattern is 100 mrad. The patterns serve as a seed for the segment finding algorithm [17].

3.3.3 MDT segment reconstruction

The MDT hits from the patterns are used as input for the segment making algorithm. A segment is a straight line track at station level. In each of the stations, the two outer MDT hits are taken. Of the pair of hits, four possible tangent lines are made (Figure 3.5). If the line is within 0.2 rad of the pattern direction estimate and sufficient hits are found within 1.5 mm of the line, a straight line fit is performed to the measured drift circles. The minimum number of hits on a segment is 3.

When the χ^2 over degrees of freedom ($\chi^2/ndof$) of the fit is larger than 10, the MDT hit with the largest contribution is dropped and the segment is refitted. This procedure is repeated until the $\chi^2/ndof$ is smaller than 10. When the number of MDT hits is less

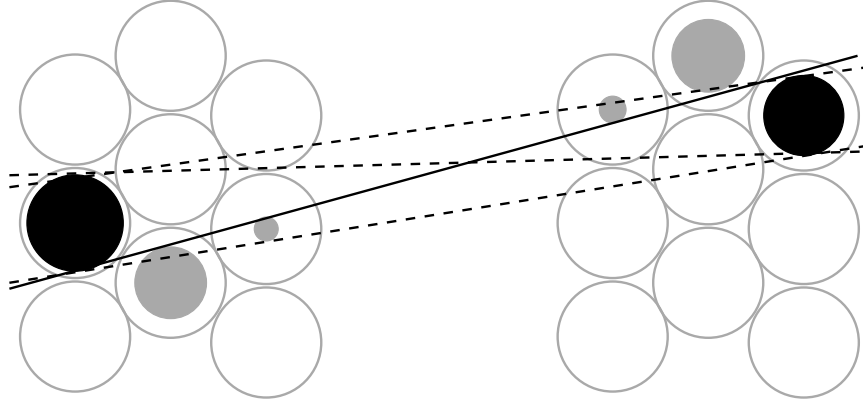


Figure 3.5: Drift circle seeds (black) with possible tangent lines (dotted). The best candidate line (solid) fits most drift circle hits.

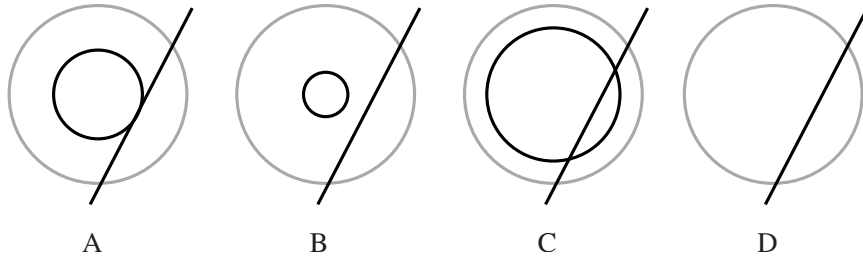


Figure 3.6: Different type of MDT hits are: A) Hit on track, B) δ -electron hit, C) hit out-of-time, D) a 'hole' is a missed hit.

than 3, the segment is discarded. After the segment is found, trigger hits associated to the pattern from the RPC and TGC detectors are associated to the segment.

The resulting segments may still contain ambiguities. Segments are ambiguity solved by ranking them according to the following priority list: most hits on track, smallest sum $N_{\delta} + N_{out} + N_{hole}$, most trigger hits, smallest $\chi^2/ndof$. N_{δ} stands for the number of δ -electron² hits (hits with a too small drift radius), N_{out} is the number of out-of-time hits (hits with a too large radius) and N_{hole} is the number of missed hits (crossing the tube without hit), see Figure 3.6. The δ -electron type of hits have a smaller drift radius than the segment expects due to the δ -electron passing the anode wire closer than the muon. Out-of-time hits correspond to an unphysical situation.

Segments sharing hits with higher ranked segments are dropped.

² δ -electrons are electrons knocked out of their atom by the passing muon.

3.3.4 Muon tracking

The MDT and CSC segments are combined and track candidates are built. A track candidate is a set of segments from one pattern, where the segments are compatible with a (curved) track. Compatibility is defined by extrapolating a segment to another station and matching segments according to their position and direction.

From each track candidate, segments from the outermost station are used for seeding a track fit. Segments from the next station layer closer to the interaction point, the middle stations, are fitted to the track seed. This is repeated for all the segments in the middle station. If the fit succeeds, the two-segment tracks are extrapolated to the innermost station where this procedure is repeated. In this way, multiple tracks can be fitted from one track seed.

The set of tracks are sorted by quality according to the number of hits and the smallest $\chi^2/ndof$. Then pairs of tracks are ambiguity solved, i.e. shared hits are assigned to the track with the highest ranking. From the track with the lowest score, the shared hits are dropped. The track is refitted with a detailed geometry description, for correct treatment of the material effects. When the refit fails, the track is dropped.

Finally, the tracks are extrapolated to the beam line to evaluate the track parameters at the perigee. The perigee is the point of closest approach to the interaction point.

3.4 Common tracking

A *common* track model and software is used both in the Inner Detector and Muon Spectrometer, i.e. the mathematics of track parameter propagation, extrapolation and fitting are the same. Concrete implementations depends on the sub-detector geometry and magnetic field configuration.

The common tracking software has a modular design, in which common reconstruction tasks are identified for both tracking systems and delegated to specific software modules. Abstract interfaces between these modules ensure the interchangeability of modules with similar functionality but with (sub-detector dependent) concrete implementations. The modules communicate through a common *Tracking Event Data Model* (EDM) [39] [40], a set of data classes describing the objects with tracking information.

First, part of the Tracking EDM used throughout this thesis is explained. Section 3.4.2 covers the extrapolation of track parameters through the detector. Material effects implemented in the extrapolation are explained in section 3.4.4.

3.4.1 Tracking event model

Modular software requires a well defined format of data objects which are passed between the software modules. An Event Data Model (EDM) ensures the commonality between the modules. Within the Tracking EDM [39] [40] data objects are split into three categories:

- *Raw data* is represented in `PrepRawData`(PRD) objects, describing the transient

form of raw data. Besides the raw data it contains a link to the detector geometry and a crude calibration of the measurement.

- *Calibrated data* is represented in **Reconstructed Object on Track**(ROT). These objects represent calibrated detector data after the pattern recognition and give access to information available on the PRDs.
- *Reconstructed objects* such as **Tracks**, **Segments** and **TrackParticles**.

For combined track reconstruction and muon identification, the last category is of most importance and will be discussed in more detail in the following sections.

Track object

A particle crosses many geometrical layers propagating through the ATLAS detector, referred to as *surfaces*. These surfaces can be detector elements and provide measurements to the track, or material layers causing the particle to interact giving rise to energy losses and multiple scattering.

In the common tracking software framework [41] the **Track** object plays a crucial role in the Tracking EDM. It holds the full information of a particle traversing the detector, i.e. the states of the track described at surfaces along the trajectory.

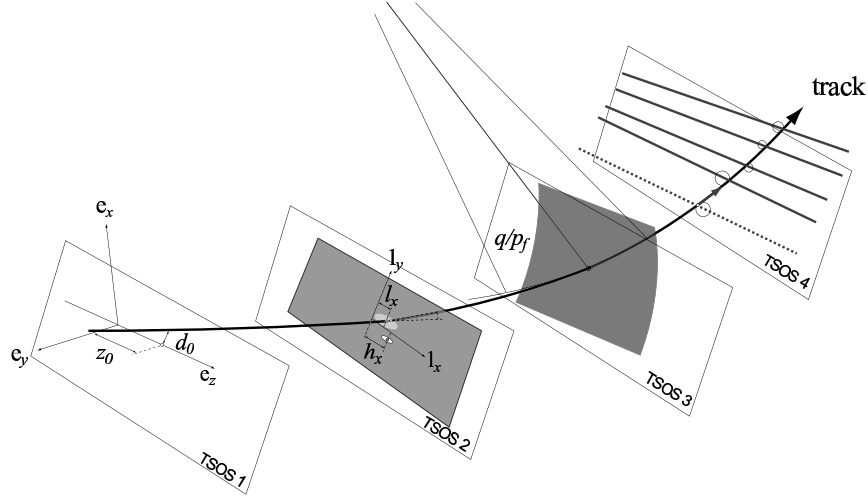


Figure 3.7: Track containing multiple *TrackStateOnSurfaces* (TSOS). TSOS 1 contains the track representation to the nominal beam line. TSOS 2 holds both a measurement through a hit and the fitted track parameters on the measurement surface. TSOS 3 represents an interaction with material. TSOS 4 integrates several fitted measurements through a single segment representation.

The **Track** object is represented by a container of **TrackStateOnSurface** (TSOS) objects, describing the state of the track with respect to a given surface. A **TrackStateOnSurface** may contain the following:

- The *track parameter* vector and optionally their covariance matrix together with the geometrical surface the parameters are expressed at.
- The *measurement* found on that surface. The different types of measurements are:
 - a *cluster* or *drift circle* after calibration corrections have been applied.
 - a *group* of measurements on the same detector surface.
 - a **Segment**, i.e. a part of a track within a detector station.
 - a **SpacePoint** describing the three dimensional spatial information of a measurement in global coordinates.
- An interaction with the *material*, i.e. a change in direction or curvature of the track caused by scattering, or bremsstrahlung.
- The *fit quality* of the measurement, i.e. the χ^2 of the fit and number of degrees of freedom.

Figure 3.7 [40] shows a track with a set of **TrackStateOnSurface** objects. TSOS1 contains the track representation with respect to the nominal beam line (perigee parametrization). TSOS2 contains a measurement, hit information on a surface, together with the fitted track parameters at the measurement surface. TSOS3 holds a material interaction, illustrated by the change in direction and momentum (curvature) of the track. TSOS4 represents a set of measurements fitted to a single **Segment**, assigned to the track.

A **TrackParticle** is a representation of the **Track** on AOD level. It is a smaller version of the **Track** but still provides sufficient information for physics analysis. The Lorentz-vector representation of the **TrackParticle** is given by the parameters at the perigee, closest to the production vertex.

Segment object

A **Segment** is a straight line track reconstructed locally in a detector element such as a muon station. It contains a set of measurements and a segment quality. The segment holds a fit quality to describe the quality of the local fit. Other quality parameters such as the number of delta electrons and holes are stored on the **Segment** as well.

Parameters on the TrackStateOnSurface object

Global parameters can be assigned to a track at any point in the detector. They are characterized by a set of variables $(\vec{x}, \vec{p}, q)$: position, momentum and charge. However, track finding and fitting operate in local coordinates which are dependent on the type of

local parameters	@ cylinder	@ disc	@ plane	@ line	@ perigee
$loc1$	$locR\phi$	$locR$	$locX$	$locR$	d_0
$loc2$	$locZ$	$loc\phi$	$locY$	$locZ$	z_0

Table 3.1: Local parameters defined at different types of surfaces.

surface on which the parameters are defined. The track parameter vector $\mathbf{T}$ is defined as:

$$\mathbf{T}^T = (loc1, loc2, \phi, \theta, q/p) \quad (3.2)$$

Table 3.1 summarizes the different types of local parameters ($loc1, loc2$) for a given surface type. For example, the local position coordinates of a **TrackStateOnSurface** described at a plane surface is given by x and y , called $locX$ and $locY$ in the common tracking software. The representation of momentum $(\phi, \theta, q/p)$ is expressed in global coordinates since it gives better computing performance for material corrections in the tracking algorithms.

TrackStateOnSurfaces usually contain the covariances on the track parameters as well, stored in a covariance matrix:

$$C = \begin{pmatrix} var(loc1) & cov(loc1, loc2) & cov(loc1, \phi) & cov(loc1, \theta) & cov(loc1, q/p) \\ cov(loc2, loc1) & var(loc2) & cov(loc2, \phi) & cov(loc2, \theta) & cov(loc2, q/p) \\ cov(\phi, loc1) & cov(\phi, loc2) & var(\phi) & cov(\phi, \theta) & cov(\phi, q/p) \\ cov(\theta, loc1) & cov(\theta, loc2) & cov(\theta, \phi) & var(\theta) & cov(\theta, q/p) \\ cov(q/p, loc1) & cov(q/p, loc2) & cov(q/p, \phi) & cov(q/p, \theta) & var(q/p) \end{pmatrix} \quad (3.3)$$

At surfaces where the parameters are defined without a measurement, the errors are defined by propagating the errors of the track to that surface. For measurements, another covariance matrix is stored. It is formed by a sub-matrix of C containing only those coordinates which are actually measured. For a **Segment**, the covariances come from the intrinsic track fit.

3.4.2 Track extrapolation

Extrapolation is the transport of track parameters and their associated covariances to a destination surface. Following the track through the detector, interactions of the particle with the detector material have to be taken into account.

Track reconstruction heavily uses extrapolation techniques for local pattern recognition, track fitting and for track matching. The common tracking framework deploys a dedicated extrapolation package [42] for this task.

Parameter propagation

In the absence of a magnetic field a particle follows a straight line, in a homogeneous magnetic field a helix curve. For these examples, a track model (straight line, helix) can be formulated and the extrapolation can be solved analytically. In ATLAS, the

magnetic field is highly inhomogeneous, see Figure 1.12. Therefore, extrapolation needs to be done numerically.

A fourth order Runge-Kutta-Nyström integration formalism with adaptive step estimation is used to evaluate the equations of motion of a particle through a magnetic field. The numerical *propagation* of the track parameters through the detector is implemented in two ways in the tracking framework:

- Energy loss is applied at scattering points, thin layers of material. This is implemented in the `RungeKuttaPropagator`. The equation of motion has the form

$$\frac{d^2\mathbf{r}}{ds^2} = \frac{q}{p} \left[\frac{d\mathbf{r}}{ds} \times \mathbf{B}(\mathbf{r}) \right] \quad (3.4)$$

Where $\mathbf{r}$ is the position of the particle along path s , $\mathbf{B}$ the magnetic field.

- Energy loss can also be applied per integration step. In that case thick layers of dense material are traversed. The implementation of this method is by the `STEP_Propagator`. The equation of motion as in expression 3.4 is extended with an energy loss function:

$$\frac{d^2\mathbf{r}}{ds^2} = \frac{q}{p} \left[\frac{d\mathbf{r}}{ds} \times \mathbf{B}(\mathbf{r}) \right] \quad (3.5)$$

$$\frac{d(q/p)}{ds} = -\frac{qE}{p^3} \left(\frac{dE}{ds} \right) \quad (3.6)$$

where $\frac{dE}{ds}$ is the total mean energy loss per unit distance.

Both propagation methods stop the numerical iteration when the distance to the destination surface drops below a certain cut value. Material effects such as energy loss and multiple scattering enlarge the errors on the track parameters. A more detailed discussion of these effects will be covered in section 3.4.4.

The direction of the extrapolation is usually in the direction of the momentum of the particle. Extrapolation in the opposite direction is possible as well. Material effects are reversed: energy losses are added to the track parameters and covariances will become more precise. Extrapolating tracks in opposite direction with respect to the momentum is used for instance for back-extrapolation from the Muon Spectrometer to the vertex (section 3.5) and cosmic muon reconstruction (section 6.3).

3.4.3 Tracking geometry

Track extrapolation requires a detailed description of the detector geometry. The location of the detector surfaces in space is needed for the detailed propagation. The material distribution in the detector should be described in detail as well.

ATLAS uses the detector description `GeoModel` [26], built from a common geometry database. `GeoModel` forms the interface for the geometry used by full simulation

(G4Atlas, see section 2.3.2) and reconstruction. Using the full ATLAS detector description for track reconstruction is not feasible due to CPU and memory consumption. For track reconstruction, we are forced to use a simplified version of the geometry. The level of simplification is optimized to provide a fast and light geometry description while ensuring accurate tracking.

In the common tracking framework, the lightweight geometry is called the **TrackingGeometry** [43], a set of volumes and surfaces describing the ATLAS detector. It is a direct translation from **GeoModel**, guaranteeing the correct treatment of material and alignment corrections with a geometry database. Figure 3.8 shows parts of the Muon Spectrometer described in the **TrackingGeometry**. The barrel muon stations are left out to show the inactive material of the barrel toroid magnet and its support system.

The volumes (**TrackingVolumes**) contain, besides the geometrical structure, magnetic field information and material properties. The material properties may be accessed by layers for point-like material updates, used by the **RungeKuttaPropagator**, or treated as a homogeneous material volume, used by the **STEP_Propagator**. Material properties describe the material in terms of traversed material thickness and the radiation length X_0 .

3.4.4 Material effects

Particles traversing material lose energy and their direction is changed. Within the common tracking framework, the two processes are treated independently. This assumption

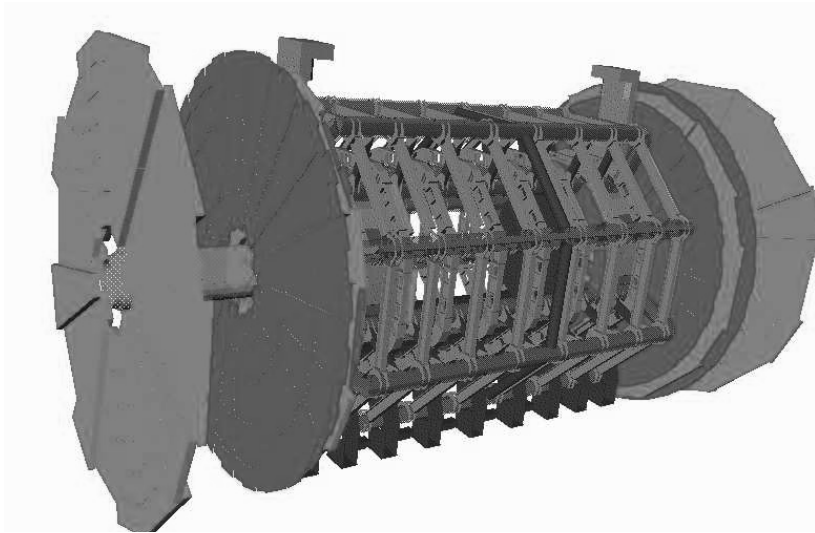


Figure 3.8: Part of the Muon Spectrometer as described by the Tracking Geometry. The barrel muon stations are left out in this picture.

is valid since the energy loss is in general small compared with the momentum of the particle.

Energy loss

Estimating the energy loss of muons traversing through the calorimeters is an important aspect of (combined) muon reconstruction. Tracks reconstructed in the Muon Spectrometer are extrapolated through the calorimeters back the beam line and a correct treatment of energy loss is needed to provide a correct estimate of the track perigee. Combined reconstruction algorithms use the energy loss estimation in their track fits.

For the energy loss estimation of a muons traversing material, ionization is the dominant process. Bremsstrahlung and pair production become dominant at high muon energies. The total mean energy loss per unit length s is described by the three processes:

$$\left(\frac{dE}{ds}\right)_{\text{total}} = \left(\frac{dE}{ds}\right)_{\text{ionization}} + \left(\frac{dE}{ds}\right)_{\text{bremsstrahlung}} + \left(\frac{dE}{ds}\right)_{\text{pair production}} \quad (3.7)$$

The mean energy loss from ionization is given by the Bethe-Bloch equation [44]:

$$\left(\frac{dE}{ds}\right)_{\text{ionization}} = -Kz^2 \frac{Z\rho}{A\beta^2} \left(\frac{1}{2} \ln \frac{2m_e\beta^2\gamma^2 E_{\text{max}}}{I^2} - \beta^2 - \ln \frac{28.816\sqrt{\rho Z/A}}{I} + \ln \beta\gamma - \frac{1}{2} \right) \quad (3.8)$$

with K a constant, z the charge of the incident particle, $\beta = p/E$, $\gamma = E/m$, m_e the mass of the electron and E_{max} the maximum kinetic energy which can be transferred to the electrons of the medium. ρ is the density and I the mean excitation energy of the medium. Z and A stand for the atomic number and weight of the traversed material.

The mean energy loss from bremsstrahlung is given by the Bethe-Heitler equation [45]

$$\left(\frac{dE}{ds}\right)_{\text{bremsstrahlung}} = -\frac{E}{X_0} \left(\frac{m_e}{m}\right)^2 \quad (3.9)$$

with m the mass of the incident particle.

The mean energy loss from pair production (and photo-nuclear interactions of muons with the medium) is parametrized [46] [47] in two energy ranges:

$$\left(\frac{dE}{ds}\right)_{\text{pair production}}^{8\text{GeV} < E < 1\text{TeV}} = 0.5345 \frac{1}{X_0} - 6.803 \cdot 10^{-5} \frac{E}{X_0} - 2.278 \cdot 10^{-11} \frac{E^2}{X_0} + 9.899 \cdot 10^{-18} \frac{E^3}{X_0} \quad (3.10)$$

$$\left(\frac{dE}{ds}\right)_{\text{pair production}}^{E > 1\text{TeV}} = 2.986 \frac{1}{X_0} - 9.253 \cdot 10^{-5} \frac{E}{X_0} \quad (3.11)$$

with E the energy of the traversing particle in MeV.

Figure 3.9 [46] shows the contributions of ionization (equation 3.8), bremsstrahlung (equation 3.9), pair production and photo-nuclear interactions (equation 3.11) to the

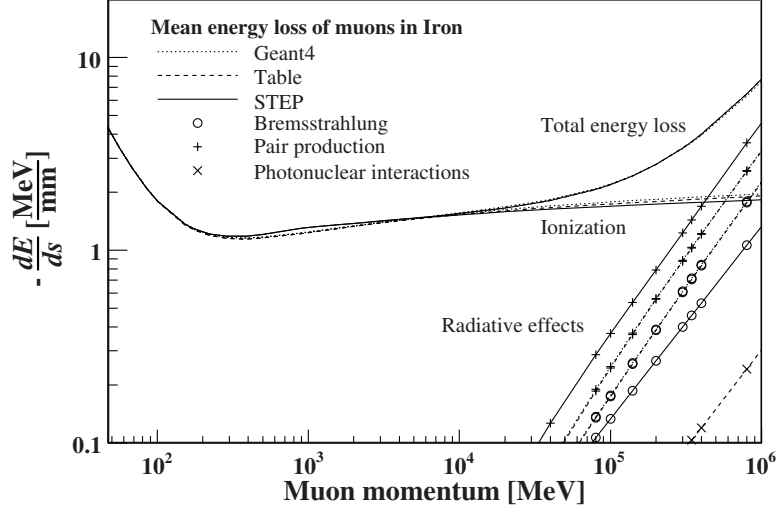


Figure 3.9: Mean energy loss of muons in iron. The contributions of ionization, bremsstrahlung, pair production and photo-nuclear interactions is shown.

total mean energy loss of muons in iron. Up to 20 GeV the dominant contribution to the total energy loss is from ionization. For muons with energies above 200 GeV, pair production and bremsstrahlung become the dominant process. Both the energy loss included in the Geant4 simulation and the estimation from the STEP_Propagator is shown.

The total mean energy loss per unit length shown in equation 3.7, enters the equation of motion 3.6 implemented in the STEP_Propagator. The material effects implemented for the RungeKuttaPropagator project the material effects onto layers. The Landau distribution for the energy loss is parametrized by the most probable value, E^{mpv} , and a width parameter E^σ [48]. Both are described by the function

$$E^{mpv/\sigma}(p_\mu, x) = a_0(p_\mu) + a_1(p_\mu)x \ln(x/X_0) \quad (3.12)$$

with

$$a_i(p_\mu) = b_{i,0} + b_{i,1} \ln(Bp_\mu) + b_{i,2}p_\mu \quad (3.13)$$

Where a_i and b_{in} are fitted parameters. Besides the continuous and the parameterized treatment of energy loss in material, measured energy depositions in the calorimeter cells can be used as well to reconstruct the energy loss of muons in the calorimeter.

Figure 3.10 shows the most probable value of the energy loss versus $|\eta|$ of muons with different momenta going through the ATLAS calorimeters: 10 GeV (top left plot), 100 GeV (top right plot) and 1 TeV (bottom plot). The circles denote the energy loss as calculated by the STEP_Propagator algorithm, the line represents the energy loss values

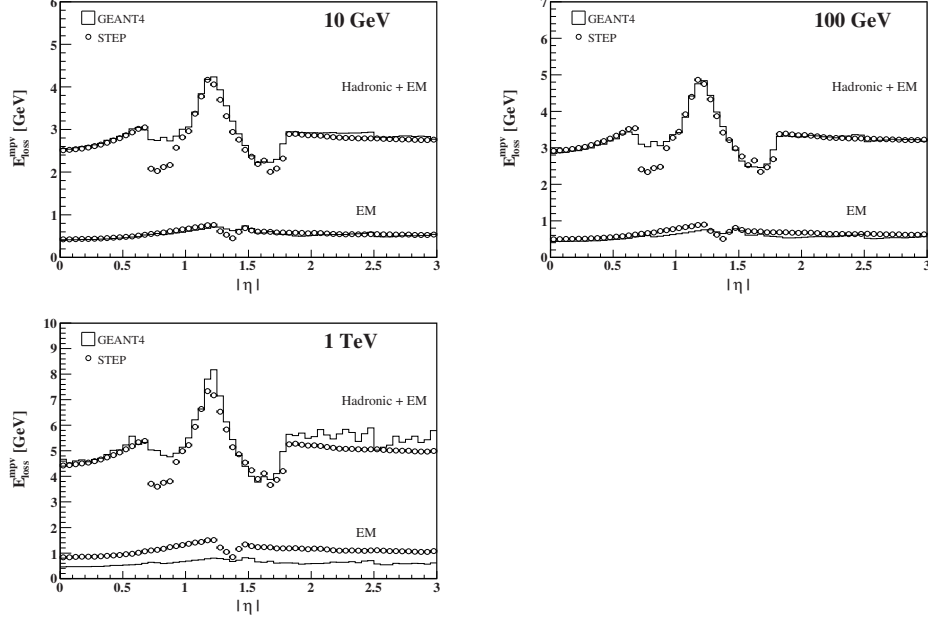


Figure 3.10: The most probable value of the energy loss distributions of muons in the ATLAS calorimeters for muons with momentum of 10 GeV (top left plot), 100 GeV (top right plot), 1 TeV (bottom plot). The circles show values estimated values from the track extrapolation, the line shows simulated values by the Geant4 toolkit.

simulated by Geant4. The energy losses in the electromagnetic calorimeter and the losses from both hadronic and electromagnetic calorimeters are shown separately. The plots are averaged over ϕ . The deviations between the simulated values and the values estimated by the tracking at $|\eta|$ around 0.8 are probably caused by the underestimation of the inactive material in the tracking geometry. Most of the muons with an energy of 2 GeV are stopped in the calorimeters.

Multiple scattering

A particle traversing material undergoes successive small angle deflections caused by multiple Coulomb scatterings. This is a stochastic process, giving rise to a Gaussian distribution for the angle deflections with a mean value of zero. The width of the distribution affects the errors of the directional parameters of the track, $\text{var}(\phi)$ and $\text{var}(\theta)$.

The calculation of the scattering angle width σ_{MS} of a (heavy) particle with momentum p (in MeV) through a material of thickness s (in fractions of radiation length X_0)

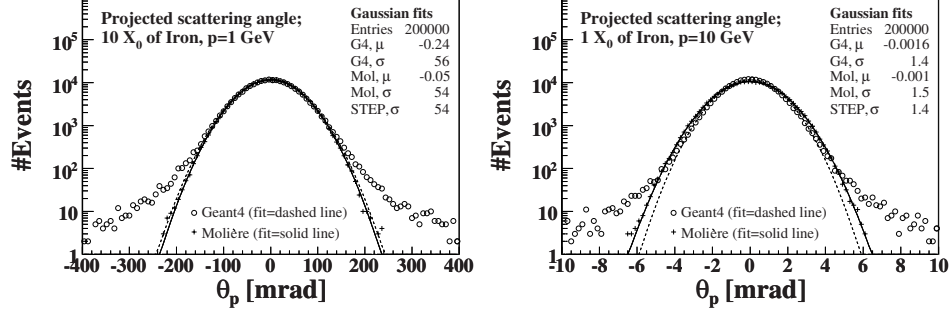


Figure 3.11: The multiple scattering of muons in iron.

is given by the Highland scattering formula [49]:

$$\sigma_{MS} = \frac{13.6}{\beta c p} \sqrt{\frac{s}{X_0}} \left[1 + 0.038 \ln \left(\frac{s}{\beta^2 X_0} \right) \right] \quad (3.14)$$

Where $\beta = \frac{v}{c}$. This width applies for scattering in the polar angle θ of the particle and can be applied directly to the covariance term for $var(\theta)$. For the error on the azimuthal angle ϕ , a projection correction of $\frac{1}{\sin(\theta)}$ has to be applied.

Figure 3.11 shows the distribution of the multiple scattering angle for muons traversing iron. Muons with a momentum of 1(10) GeV passing through 10 X_0 (1 X_0) of iron are shown in the left(right) plot. The open circles show the distribution as given by Geant4 simulation. An alternative scattering model (Molière model [50]) is shown in the plots as well. The legends of the plots show the fitted values of the mean and the width of the Gaussian fits, together with the width extracted from the STEP_Propagator module used in the track extrapolation. The two Gaussian fits describe the simulated data for the core of the distributions. The tails present in Geant4 are not described by a single Gaussian assumption.

Formula 3.14 is based on the assumption that the magnitude of the momentum of the scattered particle does not change. For muons this is the case, though not for electrons. The treatment of electrons is outside the scope of this thesis but is covered in detail in references [42] and [46].

3.4.5 Track fitting

Track fitting is an important component of tracking. A track fit is the estimation of the best set of parameters describing a track trajectory for a collection of hits. Several track fitting algorithms are available in the common tracking framework, all relying on the extrapolation techniques and the material description as discussed in the previous sections.

The common tracking software deploys two main types of track fitters, the **Kalman-Fitter** and the **GlobalChi2Fitter**.

The `KalmanFitter` implements forward filtering, backward smoothing and outlier rejection in the track fit [33]. It relies on the extrapolation engine to calculate filter step predictions. Material effects are included progressively during the filtering as process noise.

The `GlobalChi2Fitter` [34] is based on the minimization of a global χ^2 value built from the hit residuals at every measurement surface to get the best estimator of the track trajectory. Material effects enter the χ^2 function as additional fitting parameters (scattering angles).

Both fitting algorithms give identical results [34]. The `KalmanFitter` algorithm is on average twice as fast as the global method since the latter calculates the fit by solving linear equations through CPU intensive matrix inversion. The `GlobalChi2Fitter` however is more robust since it needs no initial estimate of the covariance matrix of the track parameters which is a delicate point in the progressive method. Moreover, the global χ^2 fit yields the scattering angles on the track which can e.g. be used in alignment procedures.

3.5 Combined muon reconstruction

The previous sections covered the stand alone reconstruction strategies in the two ATLAS tracking sub-detectors. This section focuses on the combination of the two systems in combined muon reconstruction.

Section 3.3 described the modular reconstruction program `MOORE`. Another Muon Spectrometer based muon reconstruction package exist, called `Muonboy` [37]. Both packages reconstruct muons standalone in the Muon Spectrometer. A set of algorithms are present in the ATLAS offline software framework to combine Muon Spectrometer tracks with the Inner Detector tracks. The algorithms can be divided into two *families*, the *Muid* and *STACO* families.

Three main strategies are used to reconstruct different *types* of muons:

- *Standalone* muons are identified using only the Muon Spectrometer to reconstruct tracks. The tracks are extrapolated to the beam region to give the track parameters at the perigee of the track. The parameters at the vertex are important for physics analysis.
- *Combined* muons are formed by matching Inner Detector tracks with Muon Spectrometer tracks.
- *Tagged* muons are Inner Detector tracks that are identified by using either the energy depositions in the calorimeters or hits and segments in the muon spectrometer.

The different algorithms are shown in Table 3.2. Muons identified by the `MOORE`, `Muid`, `MuGirl` and `MuTagIMO` algorithms are stored in a track collection called *Muid* muons. The *STACO* muon collection consists of muons identified by the `Muonboy`, `STACO` and `MuTag` algorithms. A third collection of muons consists of muons tagged by the `CaloMuonTag`

Muon type	Muid family	STACO family	Calo family
Standalone	MOORE	Muonboy	
Combined	Muid	STACO	
Tagged	MuGirl, MuTagIMO	MuTag	CaloMuonTag

Table 3.2: A summary of the muon reconstruction families Muid and STACO.

algorithm. Figure 3.12 shows the various muon types schematically. A standalone muon is reconstructed in the Muon Spectrometer only. A combined muon consists of a Muon Spectrometer and Inner Detector track combined. The tagged muons consist of an Inner Detector track with additional information from either the calorimeters or the Muon Spectrometer.

The algorithms for combined reconstruction are summarized in section 3.5.1, the muon tagging algorithms in section 3.5.2.

3.5.1 Combined muon tracking algorithms

Both standalone muon reconstruction algorithms MOORE and Muonboy extrapolate the spectrometer track back through the calorimeters to the Inner Detector region to evaluate the track parameters close to the beam line. This back extrapolation introduces uncertainties on the track parameters since the particles suffer from material effects in the calorimeters. The quality of the muon track and the precision of the track parameters improve by combining Inner Detector tracks with muon standalone tracks.

The combined algorithms Muid and STACO perform a matching between pairs of Inner Detector tracks and Muon Spectrometer tracks and a match chi squared χ^2_{match} is calculated:

$$\chi^2_{match} = (\mathbf{T}_{MS} - \mathbf{T}_{ID})^T (\mathbf{C}_{MS} + \mathbf{C}_{ID})^{-1} (\mathbf{T}_{MS} - \mathbf{T}_{ID}) \quad (3.15)$$

where $\mathbf{T}$ is the vector of the five track parameters (expression 3.2) for either the Muon

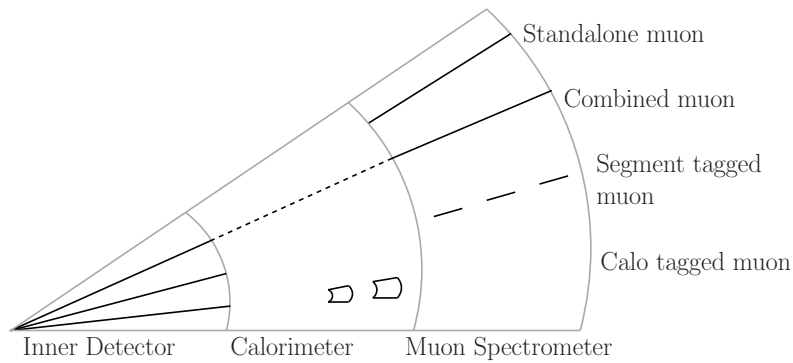


Figure 3.12: Different types of identified muons: standalone, combined, segment tagged and calorimeter tagged muons.

Spectrometer track (MS) or the Inner Detector track (ID), and $\mathbf{C}$ the covariance matrix (see expression 3.3) of the track parameters.

The χ^2_{match} is used to decide whether the match is successful and the Inner Detector track is identified as a muon. To obtain the track parameters of the combined track the two algorithms have a different approach.

STACO does a statistical combination of the inner and muon track parameters to calculate the combined track parameters:

$$\mathbf{T} = (\mathbf{C}_{ID}^{-1} + \mathbf{C}_{MS}^{-1})^{-1}(\mathbf{C}_{ID}^{-1}\mathbf{T}_{ID} + \mathbf{C}_{MS}^{-1}\mathbf{T}_{MS}) \quad (3.16)$$

Muid performs besides the χ^2 match an additional comparison between Inner Detector tracks and Muon Spectrometer tracks. Inner Detector tracks are extrapolated to the first measurement on the Muon Spectrometer track. A position match and a momentum balance check decides whether the Inner Detector track matches with the Muon Spectrometer track. To obtain the combined track parameters, Muid performs a refit of the Inner Detector and Muon Spectrometer measurements³. The extrapolation tools from the tracking framework are used for this refit.

3.5.2 Muon tagging

Muon tagging identifies Inner Detector tracks as corresponding to a muon by using energy depositions from the calorimeters or hits and segments in the Muon Spectrometer. In contrast to the combined muon identification algorithms, muon tagging does not require a fully reconstructed Muon Spectrometer track to identify a muon.

Tagged muons complement the combined muons in regions of the detector where Muon Spectrometer tracking is difficult. This is the case in the region around $\eta = 0$ and the overlap region between the spectrometer barrel and end cap at $|\eta| = 1.2$. At $\eta = 0$ the Muon Spectrometer has a gap for the services for the Inner Detector and calorimeters to enter the ATLAS detector, see section 1.2.3. In the overlap region, the missing MDT stations give rise to fewer measurements.

Besides recovering muons in these regions, muon tagging increases the muon identification efficiency for low momentum muons. These muons may be stopped in the calorimeters, or when they do reach the Muon Spectrometer, only hit few stations due to their large curvature. In the last case, Muon Spectrometer tracks are not reconstructed, but spectrometer measurements and segments are available.

Several muon tagging algorithms are available in ATLAS:

- The CaloMuonTag [51] algorithm starts by extrapolating an Inner Detector track through the calorimeters, collecting the energy measurements in the cells closest to the extrapolated track of each traversed sampling layer. Especially energy depositions in the last sampling and in the one and two previous sampling layers give the most reliable muon signals. Since the calorimeters do have coverage at $|\eta| \sim 0$, this method is recovering muon identification efficiency in this region, as

³Before the 15.0.0 software release the refit started from the Inner Detector track parameters fitting the Muon Spectrometer measurements.

well as muons with low transverse momenta. **CaloMuonTag** muons are stored in a separate muon collection, the *CaloMuon* collection.

- The **MuGirl** algorithm extrapolates Inner Detector tracks to the inner and middle layer of the muon system and performs matching at hit level. An artificial neural network is used to define a matching discriminant. Muon segments are produced from the matching Muon Spectrometer hits. Finally, a refit of the Inner Detector track with the matched muon hits is performed. **MuGirl** muons are added to the *Muid* muon collection.
- The **MuTag** algorithm starts from an Inner Detector track and extrapolates it to the inner stations of the Muon Spectrometer. A χ^2 based match is performed to a subset of **Muonboy** segments. Only the segments which do not share hits with muons identified by **STACO** are used for matching. In the region around $|\eta| \sim 1.2$ the extrapolation is done to the middle station layer of the Muon Spectrometer. Low momentum muons are recovered by this algorithm, as well as muons in regions where Muon Spectrometer tracking performance is low. **MuTag** muons are added to the *STACO* muon collection.
- The **MuTagIMO** algorithm extrapolates Inner Detector tracks to all station layers in the Muon Spectrometer, performing a χ^2 based match to segments. By default, (**MOORE**) segments are used. Multiple segments may be associated to the Inner Detector track and enter the discriminant for defining a match. This algorithm is explained in detail in the following chapter. Both low momentum muons and muons in the difficult regions of the Muon Spectrometer are recovered by this algorithm. **MuTagIMO** muons are added to the *Muid* muon collection.

3.5.3 The Muon collections

Muon reconstruction in ATLAS produces collections of various types of muons (stand-alone, combined and tagged). The various muons are collected per family (*Muid*, *STACO* or *CaloMuon*) and the collections produced by the different algorithms of the same family are *merged*. These merged muon collections are stored on the ESD.

The muon object is part of the ATLAS EDM and is referred to as an **Analysis::Muon**. The muon objects consists of the following objects:

- *A TrackParticle*. The muon object holds several types of **TrackParticles**, depending on the algorithm which reconstructed the muon. A combined muon holds the Inner Detector track, the Muon Spectrometer track and a refitted combined track. A standalone muon stores a Muon Spectrometer track only. A tagged muon holds the Inner Detector track identified as muon track. A muon tagged by the **MuGirl** algorithm may contain an Inner Detector track and a refitted **MuGirl** track.
- *Tagging information*. Depending on which algorithm was used to tag the track as muon, additional information is stored on the **Analysis::Muon**. For the segment

tagging algorithms, the associated segments are stored. For the calorimeter-based tagging algorithms, the energy deposits are stored. Muons tagged both by **MuGirl** and **MuTagIMO** store the **MuTagIMO** associated segments in the case that the job is run over commissioning data. When running over simulated data, **MuGirl** segments are stored.

- *Authors*. A list of the algorithms which reconstructed the muon is stored on the muon object.

After the merging of the collections, the muons are checked for *overlaps* and muon collections are created in which overlapping muons are stored only once. A hierarchy in muon type is deployed, favoring combined muons over standalone muons, and standalone muons over tagged muons. Combined, standalone and tagged muons overlap when they share an Inner Detector or Muon Spectrometer track. A standalone muon overlaps with a tagged muon when they share more than 2 Muon Spectrometer hits. Muons reconstructed by several algorithms are considered of the type highest in the hierarchy. That algorithm is the *main author* of the muon object. A muon may be identified by different algorithms or authors.

After overlap removal the muons are stored on the AOD.

3.6 Summary

In this chapter, muon track reconstruction has been presented. The concept of pattern recognition, track fitting and ambiguity resolving has been presented, as well as the implementation of these concepts for track reconstruction in the Inner Detector and the Muon Spectrometer. The underlying common tracking framework and its components such as the tracking EDM, the tracking geometry and track extrapolation has been discussed.

The landscape of combined muon reconstruction was covered in the last part of this chapter, giving an overview of the types of muons available on the AOD and the various identification algorithms providing these muons.

Chapter 4

Muon segment tagging

4.1 Introduction

Muon segment tagging is the process of identifying Inner Detector tracks as muons by matching the track with Muon Spectrometer segments. As a complement to the combined and standalone muon reconstruction, the muon tagging procedure improves the total muon reconstruction performance in several ways. First of all, the tagging algorithm recovers muons in the region where the Muon Spectrometer has limited coverage. Secondly, muon tagging is efficient for identifying muons with low transverse momentum. Finally, muon tagging provides a robust alternative to the combined and standalone algorithms since it applies a looser matching technique.

In this Chapter, the principles of muon tagging are explained. Furthermore, the implementation of a specific muon tagging algorithm, **MuTagIMO**, is explained in detail. The performance of the muon tagging is discussed in Chapter 6 for cosmic ray muon events and in Chapter 7 for simulated physics events.

Section 4.2 explains the principle of muon segment tagging. The subsequent sections 4.3-4.7 discuss the implementation of the muon tagging algorithm. The final section, 4.8, discusses the technical implementation of **MuTagIMO** in ATHENA.

4.2 Muon segment tagging principle

The procedure of tagging muons using reconstructed segments in the Muon Spectrometer can be divided in several steps:

1. As a starting point, Inner Detector tracks are taken. *Track filtering* is performed to remove low momentum tracks. Other filter criteria may be applied as well.
2. Not all segments are used in the tagging procedure and a *segment filter* is applied to the segments. Segments of low quality, for instance with too few hits, are omitted at this stage.
3. The Inner Detector tracks are *extrapolated* through the calorimeters to the Muon Spectrometer. The common tracking tools are used to perform the extrapolation.

The extrapolation results in a prediction of where the Inner Detector track would end up in the Muon Spectrometer under the hypothesis that the track originates from a muon.

4. The extrapolated track parameters are *matched* with the parameters of segments in the muon stations. Matching variables are constructed that serve as a measure of the quality of the match. Tracks and associated segments that pass the matching criteria are labeled as muon candidates.
5. After the track-segment matching step, the muon candidates are collected. In an *ambiguity solving* procedure, multiple associated segments in one muon station are solved by associating the segment with the best match and removing the association of the remaining segments. Multiple tracks sharing the same segment are solved by associating the segment to the track with the best match.
6. From the resulting muon candidates, muons are built.

The **MuTagIMO** tagging algorithm will be explained in more detail in the following sections.

4.3 Track and segment filtering

The Inner Detector tracker reconstructs of the order of a hundred tracks per event. It is therefore sensible to filter out tracks which will most probably not be identified as muons. This lowers the fake rate and makes the tagging algorithm faster.

Muons lose more than 3 GeV energy in the calorimeters, as shown in Figure 3.10. For this reason, tracks with momentum lower than 3 GeV are not extrapolated to the muon system. Tracks with low transverse momenta, smaller than 2 GeV, are not extrapolated either.

A fraction of the Inner Detector tracks contain only hits from the TRT sub-detector. These tracks have a high probability to originate from V_0 particles and bremsstrahlung electrons rather than from muons, as discussed in section 3.2. Therefore these tracks are not used for muon tagging. This is brought about by requiring at least 4 hits from the pixel and SCT detectors on a track.

A dedicated tool is available to perform track selection with: **TrackParticleFilterTool**. The track selection cuts are summarized in table 4.1.

The Muon Spectrometer segments are filtered to suppress mis-identified tracks. Segments reconstructed in MDT stations are required to have at least two hits per multilayer and at most three holes on a segment. A hole is a hit expected but not found, see the detailed explanation section 3.3.3. Some MDT stations (chamber type BEE) have only one multilayer. To segments from these stations only the hole criterion is applied. Segments reconstructed in CSC chambers are passed without further requirements to the tagging algorithm.

The selection of segments is performed by the **SegmentsFilterTool**. The setting of the **SegmentsFilterTool** is summarized in table 4.2.

property	value
minimum momentum p	3 GeV
minimum transverse momentum p_T	2 GeV
min nr pixel+SCT hits	4
$\eta_{\min}$	disabled
$\eta_{\max}$	disabled

Table 4.1: The properties of the *TrackParticleFilterTool*, shown with the default setting for *MuTagIMO*.

property	value
max nr of holes per segment	3
min nr hits per multilayer	2
station list	all MDT stations
$\eta_{\min}$	disabled
$\eta_{\max}$	disabled

Table 4.2: The properties of the *SegmentsFilterTool*, shown with the default setting for *MuTagIMO*.

4.4 Segment preselection

After the filtering of Inner Detector tracks and spectrometer segments, the tracks are extrapolated to the Muon Spectrometer volume. Extrapolation is a CPU intensive procedure. Extrapolating each track to *each segment* would potentially cause the tagging algorithm to become slow. A preselection of segments is made by selecting segments in the region of the Muon Spectrometer where the extrapolated track traverses the spectrometer. This way, the number of segments to extrapolate to will be reduced.

The estimation is done by extrapolating the track to a set of *abstract surfaces*, 3 cylinders and 2 times 4 discs, following the design of the ATLAS spectrometer station layers. The abstract surfaces are defined with such dimensions (see table 4.3) that hermicity is ensured, the cylinders describing the barrel spectrometer overlap with the discs describing the end caps. A loose, global match is made between the extrapolated track and segments to preselect segments candidates.

Note that the extrapolation of the track is done with the hypothesis that the track is coming from a muon. The extrapolated track is the *prediction* of where the muon track would traverse the Muon Spectrometer.

The preselection is done in 3 steps. First, a requirement on matching station layer level is done to select the segments reconstructed in the same station layer as the abstract surface. Secondly, a match is performed using the distance of the extrapolated track to the segment.

- *Station layer requirement:* A selection is done on the station in which the segment is reconstructed and the abstract surface to which the track is extrapolated. In this way, no segments in the inner barrel stations will be assigned as a candidate

CylinderSurface	R (mm)	h (mm)
BI	5000	7000
BM	7000	10000
BO	9500	13000

DiscSurface	z (mm) positive for A side negative for C side	$R_{\min}$ (mm)	$R_{\max}$ (mm)
EI(A/C)	7500	1700	6200
EM(A/C)	13200	1500	12000
EO(A/C)	20000	2200	12000
EE(A/C)	9700	5000	8500

Table 4.3: Abstract surfaces describing the Muon Spectrometer station layers.

match of a track extrapolated to an outer end-cap disc surface.

- *Global ϕ cut:* The next requirement is on the position in the non-precision plane of the Muon Spectrometer, the global xy -plane. With this requirement one selects segments in the right sector of the spectrometer. The value of the distance requirement in this coordinate depends on the presence of ϕ measurements on the segment, hits in the xy -plane. Segments reconstructed by MDT hits alone do not have a measurement of the second coordinate and therefore a looser cut is applied. The resolution of a segment without ϕ hits on the second coordinate is approximately the tube length.

The global angle ϕ^{pos} in the xy -plane calculated from the global position is:

$$\phi^{\text{pos}} = \text{acos}(y_g, x_g) \quad (4.1)$$

Where y_g and x_g are the global coordinates of the measurement. The difference of the positions $\Delta\phi^{\text{pos}}$ between the extrapolated track and the segment is given by:

$$\Delta\phi^{\text{pos}} = \phi_{\text{exTrk}}^{\text{pos}} - \phi_{\text{seg}}^{\text{pos}} \quad (4.2)$$

Where $\phi_{\text{exTrk}}^{\text{pos}}$ is the position of the extrapolated track, $\phi_{\text{seg}}^{\text{pos}}$ the position of the segment, see Figure 4.1 a). The criterion of passing the requirement is given by

$$|\Delta\phi^{\text{pos}}| < \sqrt{c_\phi^2 + \sigma_\phi^2}, \quad c_\phi = \begin{cases} 0.5 \text{ rad} & \text{for segments without } \phi \text{ hits} \\ 0.25 \text{ rad} & \text{for segment with } \phi \text{ hits} \end{cases} \quad (4.3)$$

where σ_ϕ is the extrapolation error in ϕ . The value of c_ϕ , the cut-off distance, can be set in the `MuTagMatchingTool` and is per default set to 0.5 rad, corresponding to roughly one sector.

The preselection in the precision plane of the Muon Spectrometer is done in the Rz -plane. For the barrel and end cap regions two variables are defined:

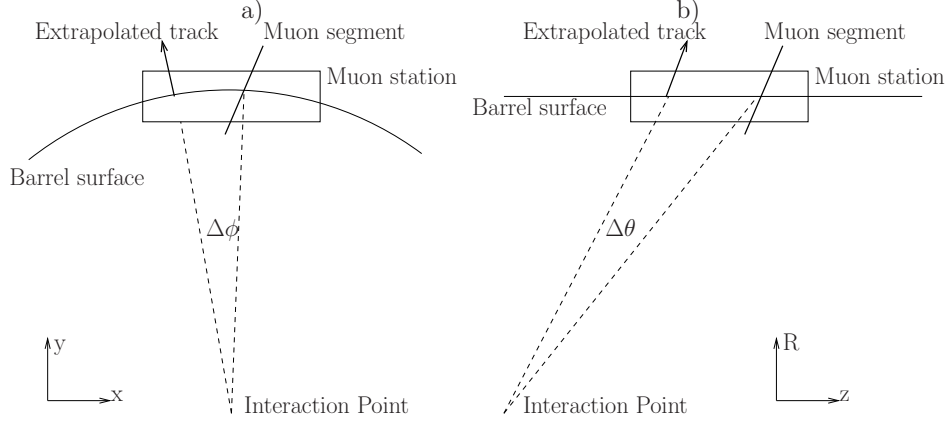


Figure 4.1: Graphical representation of the segment preselection variables in the Muon Spectrometer barrel: a) $\Delta\phi$ and b) $\Delta\theta$.

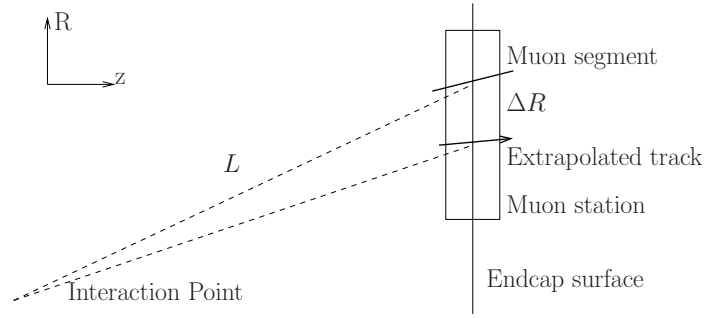


Figure 4.2: Graphical representation of the segment preselection variable in the Muon Spectrometer endcap: ΔR .

- *Global θ cut:* For segments reconstructed in the Muon Spectrometer barrel, a requirement is set on the precision coordinate of the Muon Spectrometer, θ^{pos} . The variable θ^{pos} is the global angle in the Rz -plane calculated from the position of the track and segment:

$$\theta^{\text{pos}} = \text{atan}(R, z_g), \quad R = \sqrt{x_g^2 + y_g^2} \quad (4.4)$$

The difference in position in the global Rz -plane in the barrel $\Delta\theta^{\text{pos}}$ is given by:

$$\Delta\theta^{\text{pos}} = \theta_{\text{exTrk}}^{\text{pos}} - \theta_{\text{seg}}^{\text{pos}} \quad (4.5)$$

Where $\theta_{\text{exTrk}}^{\text{pos}}$ is the position of the extrapolated track, $\theta_{\text{seg}}^{\text{pos}}$ the position of the

segment, see Figure 4.1 b). The criterion of passing the requirement is given by:

$$|\Delta\theta^{\text{pos}}| < c_\theta \quad (4.6)$$

Where c_θ is set on a value of 0.1 rad.

- *Global R cut:* For end cap stations in the forward region of the Muon Spectrometer, the precision coordinate in the global Rz -plane is the transverse distance R .

$$\Delta R = R_{\text{exTrk}} - R_{\text{seg}} \quad (4.7)$$

When a segment from an end cap station passes the requirement on ϕ^{pos} , a requirement on the ratio $\Delta R/L$ is set, where L stands for the 3 dimensional distance $\sqrt{x_g^2 + y_g^2 + z_g^2}$:

$$\frac{|\Delta R|}{L} < c_R \quad (4.8)$$

Where c_R is the cut-off value set in the `MuTagMatchingTool` to a default value of $\frac{2}{15}$, such that a ΔR of 1000 mm for segments at a 3D distance $L = 7500$ mm gets accepted. Figure 4.2 shows ΔR graphically.

Segments meeting these requirements are preselected.

4.5 Segment matching

After the segment preselection, precise matching is performed between the track and segment candidates. The Inner Detector track is extrapolated to the surface on which the segment is defined. Matching is done in the *local coordinate system* of the segment station, on both the position and the direction in the precision plane. For low momentum tracks, more stringent requirements are placed.

The extrapolated track parameters are expressed with respect to a *plane surface* on which the segment is defined, as described in section 3.4.1. Figure 4.3 shows the local coordinate system of a plane surface associated to an MDT segment. The origin of the plane surface is taken as the position of the reconstructed segment. The x -axis is in the direction of the wire, making the local position parameter $locX$ the non-precision coordinate of the segment. In this reference frame, $locY$ is the precision coordinate of the segment in this plane (see table 3.1 for the definitions of the local parameters).

The direction in the local coordinate system of the plane surface is given by the parameters α_{xz} and α_{yz} . The angle α_{xz} is the angle of the projection of the segment in the local xz -plane, angle α_{yz} the angle in the local yz -plane. With these definitions, α_{yz} represents the direction in the precision plane and α_{xz} the direction in the non-precision plane.

Muon candidates are tracks that meet the following requirements:

- *Local position pull cut:* the *pull* is the distance between the extrapolated track and segment position divided by the errors in the precision plane:

$$|\mathcal{P}_{\text{locY}}| < c_{\text{locY}}, \quad \mathcal{P}_{\text{locY}} = \frac{\Delta_{\text{locY}}}{\sqrt{\sigma_{\text{exTrk,locY}}^2 + \sigma_{\text{seg,locY}}^2 + \sigma_{0,\text{locY}}^2}} \quad (4.9)$$

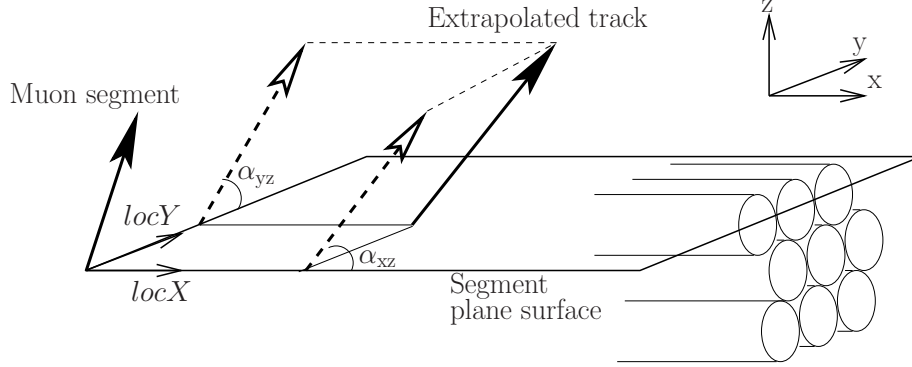


Figure 4.3: Local coordinate system of a plane surface.

Where Δ_{locY} is the difference of the locY -position between segment and extrapolated track, $\sigma_{\text{exTrk,locY}}$ the error of the locY -parameter given by the extrapolation, $\sigma_{\text{seg,locY}}$ the error of the locY -parameter as given by the segment fit. An extra safety-factor is introduced here, $\sigma_{0,\text{locY}}$, which protect the pull of becoming too large for very high momentum tracks, when the errors on the track may become very small. The value can be set by properties of the `MuTagMatchingTool`, a default value of 10 mm is applied. The value of c_{locY} is set to 5. Thus matches with a pull of less than 5σ are accepted.

- *Local direction pull cut:* where the pull is based on the angular difference divided by the error in the precision plane:

$$|\mathcal{P}_{\alpha_{yz}}| < c_{\alpha_{yz}} , \quad \mathcal{P}_{\alpha_{yz}} = \frac{\Delta_{\alpha_{yz}}}{\sqrt{\sigma_{\text{exTrk},\alpha_{yz}}^2 + \sigma_{\text{seg},\alpha_{yz}}^2 + \sigma_{0,\alpha_{yz}}^2}} \quad (4.10)$$

Where $\Delta_{\alpha_{yz}}$ is the difference in the precision angle of the segment and extrapolated track, $\sigma_{\text{exTrk},\alpha_{yz}}$ the error of the α_{yz} direction parameter as given by the extrapolation. To obtain the error on α_{yz} , a transformation between the global and local coordinates should be made since the extrapolation provides errors with respect to the global coordinate system. This transformation involves a Jacobian which is explained in appendix A. $\sigma_{\text{seg},\alpha_{yz}}$ stands for the error of the local direction parameter, provided by the segment fit. As in the position matching, a safety-factor is implemented to prevent very large pulls in the precision direction. The value of the safety-factor is set to 0.5 mrad. The value of $c_{\alpha_{yz}}$ is set to 5.

Throughout this chapter, performances are shown for various simulated samples. The performances are shown for *muon candidates*: Inner Detector tracks with one or more Muon Spectrometer segments associated to it. The Inner Detector tracks are truth-matched with simulated particles and classified as either *muon* or *non-muon*. A track is truth-matched to a simulated particle when more than 80% of its hits originate from the

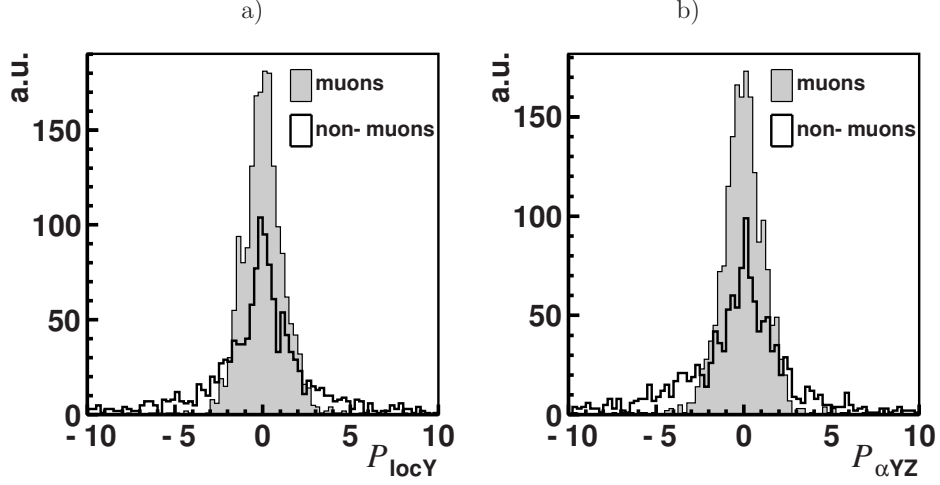


Figure 4.4: The pull distributions of the two precision matching variables; a) $\mathcal{P}_{locY}$ and b) $\mathcal{P}_{\alpha YZ}$.

particle. *Muon tracks* are tracks which are truth-matched to a simulated muon. *Non-muon tracks* are tracks which are not truth-matched or truth-matched to a particle that is not a muon. Figure 4.4-a) shows the pull distribution of the matching variable $\mathcal{P}_{locY}$ and Figure 4.4-b) shows the distribution of $\mathcal{P}_{\alpha YZ}$ for a $t\bar{t}$ sample. The gray distributions show the matching variables for muons, the black lines show the distributions for non-muon tracks. The width of the pull distribution is wider for non-muons than for muons. Non-muon track parameters that are extrapolated to the segment surface have a poorer match to the segment parameters than extrapolated muon track parameters. Requiring that the pull of the matching variable is less than 5 selects muons and rejects some non-muons. Additional requirements have to be imposed to reduce the non-muon background which fall within the 5 sigma peak.

The width of the pull distribution of the muon track matches is around 1.1 for both $\mathcal{P}_{locY}$ and $\mathcal{P}_{\alpha YZ}$. The errors of the matching variables are thus under estimated. The dominant contribution to the errors are from the extrapolation of the Inner Detector track parameters.

Figure 4.5 shows the distribution of transverse momentum of tagged tracks for the $t\bar{t}$ -sample, both for muon tracks (gray) and for non-muon tracks (black). Most of the non-muon tracks have low transverse momenta. To reduce the mis-identification rate a more stringent requirement, dependent on the track momentum, is imposed.

- *Transverse momentum dependent pull cut:* To suppress low transverse momentum

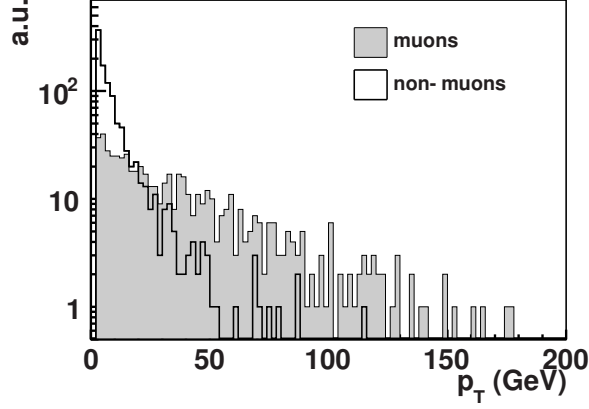


Figure 4.5: The transverse momentum distributions of muon candidates.

non-muon background, a p_T dependent cut is introduced:

$$c_{\text{pull}} = \frac{1}{4} \left(\frac{1}{2} p_T - 1 \right)^2 + 2 \text{ for } 2 < p_T < 9 \text{ GeV} \quad (4.11)$$

Where p_T stands for the transverse momentum of the Inner Detector track in GeV. For very low momentum tracks, a tighter cut on the pull variables is applied. The requirement on the pull starts at a value of 2 for tracks with a p_T of 2 GeV, the minimum value of the track p_T used by the track filter. The requirement relaxes to a value of 5, the default value used in the segment matching, for tracks with a p_T of around 9 GeV. The parabolic shape of c_{pull} is an empiric interpolation such that the variable pull requirement works well for both $t\bar{t}$ events and $Z^0 \rightarrow \mu^+\mu^-$ events with added cavern background safety factor 5.

The p_T -dependent cut is applied on the following matching variables:

$$|\mathcal{P}_{\text{locY}}| < c_{\text{pull}} \quad (4.12)$$

$$|\mathcal{P}_{\alpha_{yz}}| < c_{\text{pull}} \quad (4.13)$$

$$|\mathcal{P}_{\text{locX}}| < 2 \cdot c_{\text{pull}} \quad (4.14)$$

The requirement is looser for the second position coordinate pull, $\mathcal{P}_{\text{locX}}$, since this coordinate is measured with less precision in the Muon Spectrometer. The $\mathcal{P}_{\text{locX}}$ matching variable is defined in the same way as $\mathcal{P}_{\text{locY}}$ (Eq. (4.9)).

Eq. (4.11) is shown in Figures 4.6 and 4.7 (black curve) together with the distributions of the locY matching variable for two samples, $t\bar{t}$ events (Figure 4.6) and $Z^0 \rightarrow \mu^+\mu^-$ events with cavern background safety factor 5 (Figure 4.7). Plot a) shows muon tracks, plot b) shows non-muon tracks. The figures demonstrate the effectiveness of the requirement. The p_T -dependent pull cut works well for high-multiplicity samples, such as the $Z^0 \rightarrow \mu^+\mu^-$ sample with cavern background safety factor 5, as is demonstrated in Figure 4.7.

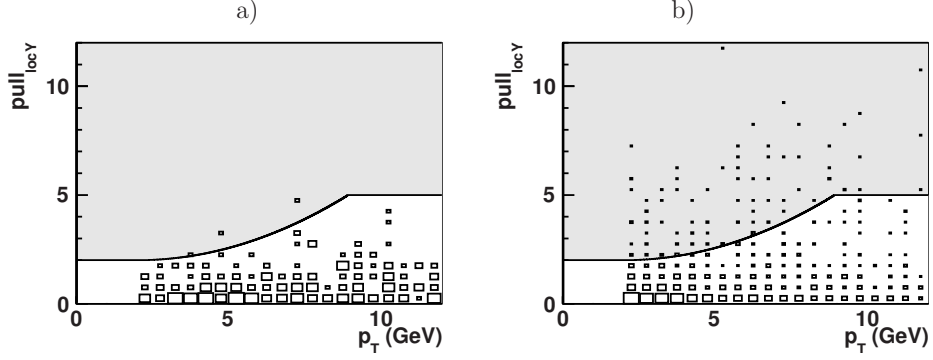


Figure 4.6: The distribution of $\mathcal{P}_{locY}$ as function of transverse momentum p_T for a $t\bar{t}$ sample, shown together with the added c_{pull} value (shaded area). The distribution for a) muon tracks, b) non-muon tracks.

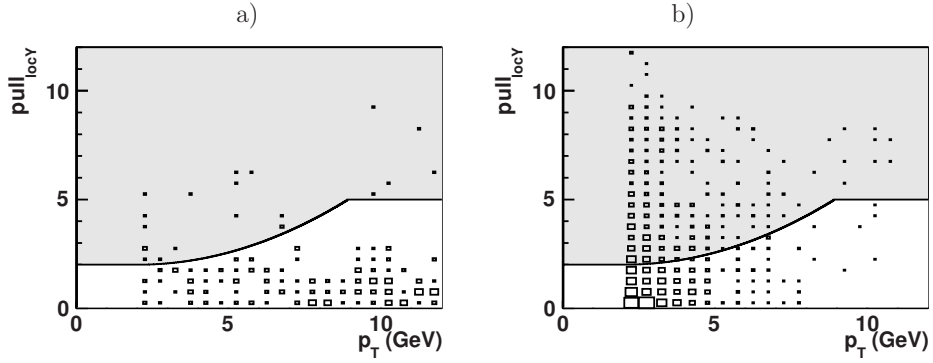


Figure 4.7: The distribution of $\mathcal{P}_{locY}$ as function of transverse momentum p_T for a $Z^0 \rightarrow \mu^+\mu^-$ sample with cavern background safety factor 5, shown together with the added c_{pull} value (shaded area). The distribution for a) muon tracks, b) non-muon tracks.

- *Residual cut:* the segment and extrapolated track should not be displaced too much, even though the pull matching variables are small. A maximum value for the residuals in local position Δ_{locY} and local direction $\Delta_{\alpha_{yz}}$ is applied to reject matches with very low momentum tracks.

$$|\Delta_{locY}| < c_{\Delta_{locY}}, \quad |\Delta_{\alpha_{yz}}| < c_{\Delta_{\alpha_{yz}}} \quad (4.15)$$

The cut-off values are $c_{\Delta_{locY}} = 500$ mm and $c_{\Delta_{\alpha_{yz}}} = 300$ mrad. Figure 4.8 shows the distribution for a) Δ_{locY} and b) $\Delta_{\alpha_{yz}}$ for both muons (gray) and non-muons (black) of a $t\bar{t}$ sample. Non-muon matches have in general, a large residual. Fig-

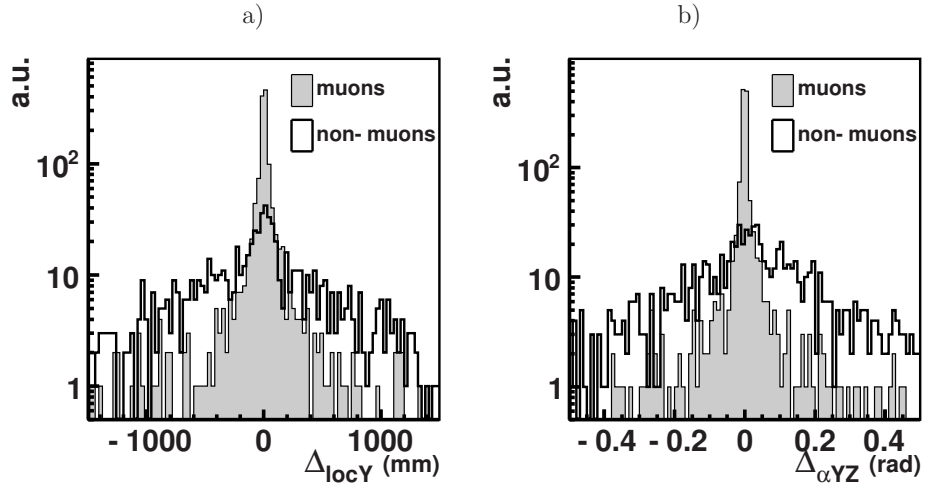


Figure 4.8: The residuals a) Δ_{locY} and b) $\Delta_{\alpha_{\text{YZ}}}$ for a $t\bar{t}$ sample. The gray distribution shows values for muons, the black line for non-muons.

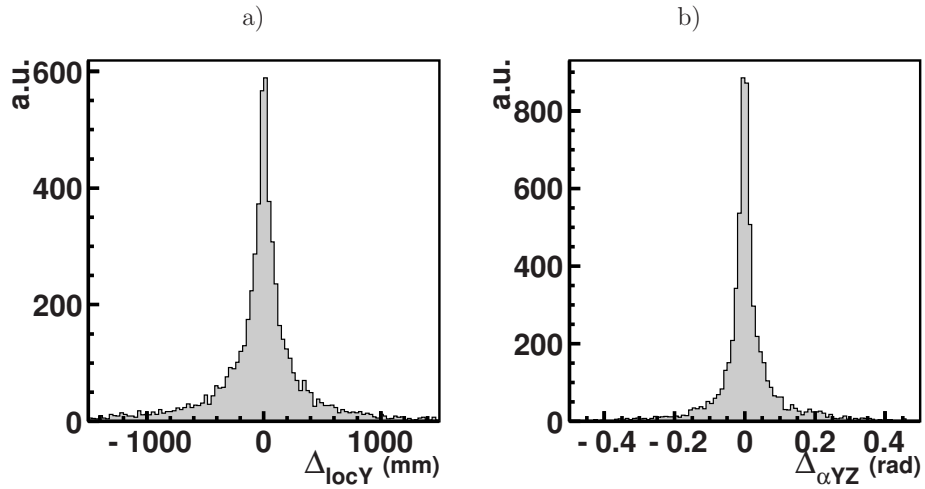


Figure 4.9: The residuals a) Δ_{locY} and b) $\Delta_{\alpha_{\text{YZ}}}$ for muons from a J/ψ sample.

Figure 4.9 shows the residuals for muons from a J/ψ sample. The requirements on the maximum residual reduces the non-muon background in the $t\bar{t}$ sample whilst retaining most of the muons in J/ψ events.

Segments matching with the extrapolated track are associated to that track. Tracks

variable	value	description
c_ϕ	0.5 rad	segment preselection xy -plane
c_θ	0.1 rad	segment preselection Rz -plane barrel
c_R	2/15	segment preselection Rz -plane end cap
$c_{\text{loc}Y}$	5	position matching in Rz -plane
$c_{\alpha_{yz}}$	5	direction matching in Rz -plane
$c_{\text{loc}X}$	5	position matching in xy -plane
$c_{\alpha_{xz}}$	5	direction matching in Rz -plane
$c_{\Delta_{\text{loc}Y}}$	500 mm	position matching in Rz -plane
$c_{\Delta_{\alpha_{yz}}}$	0.3 rad	direction matching in Rz -plane
$\sigma_{0,\text{loc}Y}$	10 mm	safety-factor position
$\sigma_{0,\alpha_{yz}}$	0.5 mrad	safety-factor direction

Table 4.4: The properties of the *MuTagMatchingTool*, shown with the default setting for *MuTagIMO*.

with associated segments are referred to as muon candidates.

4.5.1 Matching configuration

The extrapolation of tracks and the matching with segments is done with a dedicated tool, the *MuTagMatchingTool*. The requirements on the various matching parameters, the global matching variables used to preselect segments and the local matching variables used in the segment association, can be set in this tool as well. The safety-factors appearing in the calculations of the pull matching variables in expressions 4.9 and 4.10 can be configured as well. Table 4.4 summarizes the properties and cuts of the *MuTagMatchingTool* for running on simulated data. For tagging commissioning data such as cosmics, a looser matching is preferable and the *MuTagMatchingTool* is configured accordingly. Chapter 6 will discuss cosmic muon tagging in detail.

4.6 Ambiguity solving

Muon candidates may contain ambiguities such as multiple segments associated to the same track in the same muon station, or tracks associated to the same segment. The set of muon candidates are cleaned up in three steps: *Segment cleaning* and *track cleaning* followed by *final track and segment cuts*.

4.6.1 Segment cleaning

Multiple segments from the same muon station may be associated to the muon candidate. Only one segment per station is expected. The segment with the smallest distance in the precision plane is associated to the muon candidate; the other segments are dropped.

4.6.2 Track cleaning

Multiple Inner Detector tracks may have the same segment(s) associated. This occurs especially in events with collinear tracks, or events with high Inner Detector activity. In order to decide which track belongs to the segment, a *rejection factor* f_R is calculated. The rejection factor is a measure of how likely the track is coming from a muon, given a set of matching variables. When muon candidates share associated segments, the candidate with the highest rejection factor is most likely to be a muon. The other candidates lose association to the shared segment.

The following variables are used to construct the rejection factor:

- *number of MDT segments, ($nSeg$)*. A muon is more likely to reach multiple MDT chambers than other particles. Favoring tracks traversing a larger part of the Muon Spectrometer suppresses the low momentum background.
- *position residual, (Δ_{locY})*. The track with the smallest precision position distance is more likely to be the correct track.
- *direction residual, ($\Delta_{\alpha_{yz}}$)*. The track with the smallest angular difference is more likely to be the correct track.

For each of the matching variables, a *rejection factor* is calculated by dividing the distributions of the variable for muon over non-muon tracks. The discriminating variable f_R is defined as the product of the rejection factors of the three matching variables:

$$f_R(nSeg, locY, \alpha_{yz}) = f_{R_{nSeg}}(nSeg) \cdot f_{R_{locY}}(locY) \cdot f_{R_{\alpha_{yz}}}(\alpha_{yz}) \quad (4.16)$$

with $f_{R_{nSeg}}$ the rejection factor of the number of segments, $f_{R_{locY}}$ and $f_{R_{\alpha_{yz}}}$ the rejection factor of the position and direction residual respectively.

In order to treat the large tails in the distribution of the position and direction residuals properly, the residuals are transformed in the following way:

$$L_{locY} = \ln \left(1 + \frac{\Delta_{locY}}{w_{locY}} \right), \quad L_{\alpha_{yz}} = \ln \left(1 + \frac{\Delta_{\alpha_{yz}}}{w_{\alpha_{yz}}} \right) \quad (4.17)$$

Where w_{locY} and $w_{\alpha_{yz}}$ are constants which one can chose arbitrarily. The values are set to $w_{locY} = 20$ mm and $w_{\alpha_{yz}} = 4$ mrad. This operation transforms large values of the residuals in the tails closer to the core of the distribution.

Figure 4.10 shows the distributions of the number of segments, and the residuals for both muon tracks (gray) and non-muon tracks (black) for the $t\bar{t}$ sample. Figure 4.11 shows the rejection factors versus the matching variables (black dots) together with a parametrized function (gray line) fitted to the shape of the rejection factor. The rejection factor of the number of segments is fitted by a Fermi function in the range $0 < nSeg < 3$:

$$f_{R_{nSeg}}(nSeg) = \frac{\alpha}{1 + \exp(\beta - \frac{nSeg}{\gamma})} + \delta, \quad \begin{cases} \alpha = 3.62 \\ \beta = 20.45 \\ \gamma = 0.13 \\ \delta = 0.10 \end{cases} \quad (4.18)$$

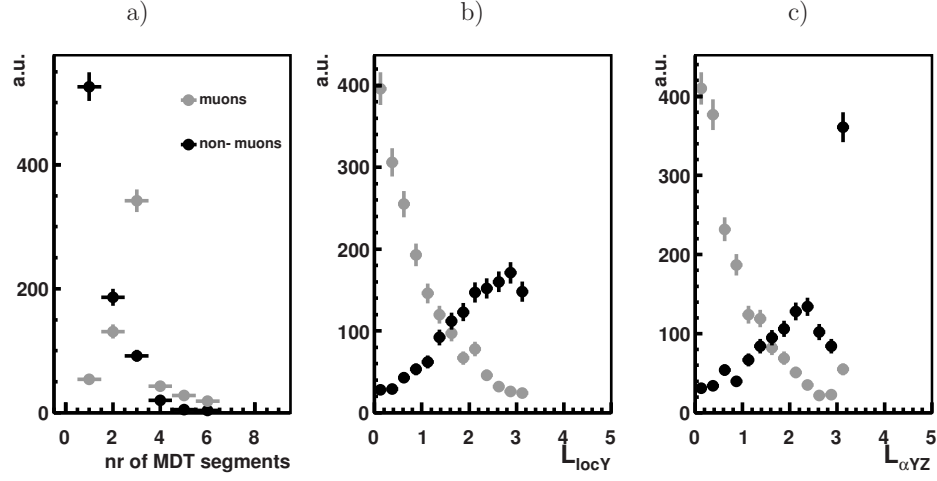


Figure 4.10: Distributions of a) the number of MDT segments, b) L_{locY} and c) $L_{\alpha YZ}$ for muon candidates sharing association to the same segment. Muon tracks are shown in gray, non-muon tracks in black.

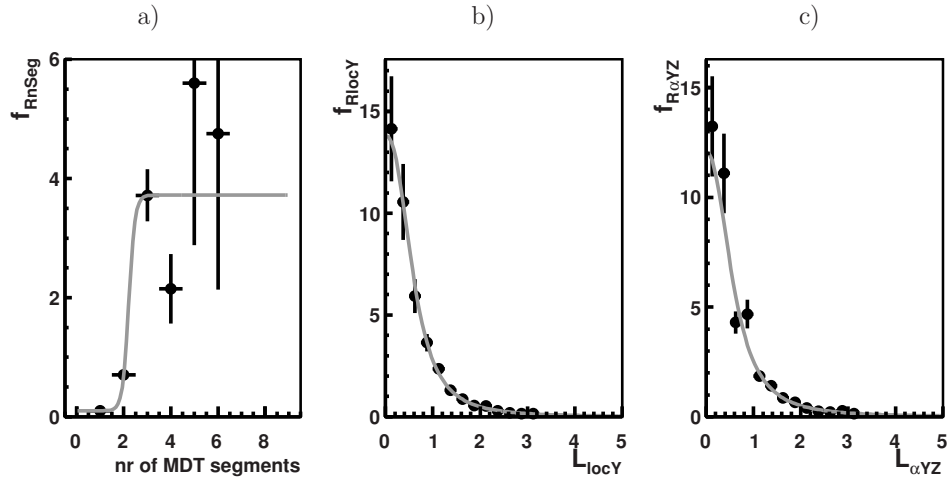


Figure 4.11: Rejection factors as function of a) the number of MDT segments, b) L_{locY} and c) $L_{\alpha YZ}$.

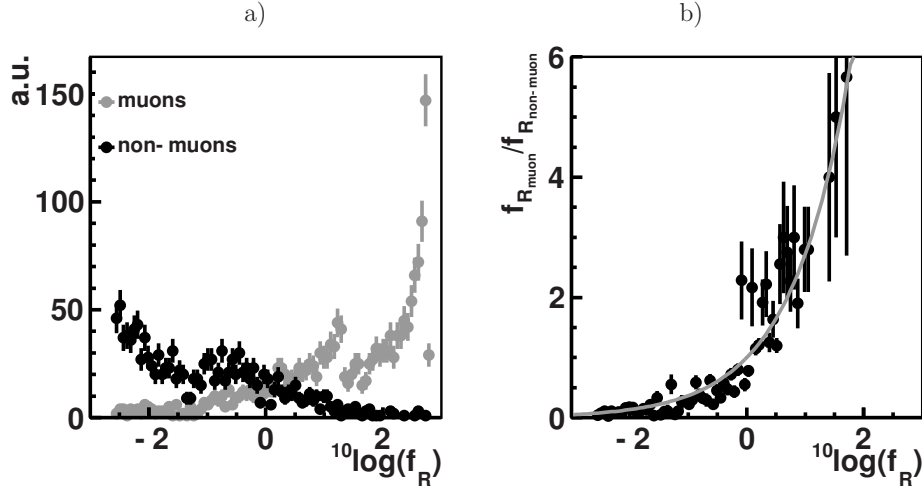


Figure 4.12: The rejection factor f_R of muons (gray) and non-muons (black) is shown in plot a). Plot b) shows the ratio $f_{R_{\text{muon}}} / f_{R_{\text{non-muon}}}$ versus $\log(f_R)$ (black) shown with the function $e^{\log(f_R)}$ (gray).

The rejection factor for the residuals is fitted by the following empirical functions:

$$f_{R_{\text{locY}}}(L_{\text{locY}}) = \frac{\alpha}{1 + \beta L_{\text{locY}}^2 + \gamma L_{\text{locY}}^3}, \begin{cases} \alpha = 13.83 \\ \beta = 1.24 \\ \gamma = 2.73 \end{cases} \quad (4.19)$$

$$f_{R_{\alpha_{yz}}}(L_{\alpha_{yz}}) = \frac{\alpha}{1 + \beta L_{\alpha_{yz}}^2 + \gamma L_{\alpha_{yz}}^3}, \begin{cases} \alpha = 12.07 \\ \beta = 1.88 \\ \gamma = 1.89 \end{cases} \quad (4.20)$$

For each set of muon candidates sharing a associated segment, the rejection factor $R(n\text{Seg}, \text{locY}, \alpha_{yz})$ is calculated using the parameterized rejection functions. Plot a) in Figure 4.12 shows the rejection factor distribution for both muons (gray) and non-muons (black). The muon candidate with the highest f_R factor keeps the association to the segment. The muon candidates with the lower f_R value loses the association to the shared segment. The muon candidate is dropped when it has no more associated segments left.

In Eq. (4.16), the *total* rejection factor $R(n\text{Seg}, \text{locY}, \alpha_{yz})$ is defined as the product of the rejection factors per variable. If the variables are independent and the rejection functions per variable are properly parametrized, the factorized rejection is the optimal value one can obtain. In other words, the total rejection factor has the highest discriminating power. In that case, the *ratio* of the distribution of the rejection factor for muons over non-muons will have a value of 1 for a rejection of 1 and will have a linear behavior

with respect to f_R . This is explained in more detail in appendix B.

Figure 4.12-b) shows the ratio of the rejection factor of muons over non-muons plotted versus the (logarithm of) the rejection as black dots. The gray line is the function $e^{\log(f_R)}$ and illustrates the behavior of the distribution. The distribution has a value of 1 for a rejection of 1 and follows the exponential, indicating that the variables are independent and the rejection functions are properly parametrized.

4.6.3 Final track and segment cuts

The non-muon background can be further reduced by looking at the full event topology and tightening the requirements on the segment quality and track momentum in complicated events.

Figure 4.13 shows the number of MDT segments used to tag an Inner Detector track as muon, for the $t\bar{t}$ sample. The gray histogram shows the muon tracks (tracks truth matched to simulated muons), the black line the non-muon tracks (tracks truth matched to other simulated particles, or tracks which are not truth matched at all). Most of the non-muon background come from tracks tagged with a single-MDT segment. Figure 4.5 shows the transverse momentum distribution for muon tracks (gray) and non-muon tracks (black line). Most of the non-muon background comes from low momentum tracks.

Reducing the mis-identification rate by just removing low momentum tracks is not an option, since that will reduce tagging efficiency for low momentum muons from J/ψ decays. Simple rejection of tracks tagged with only one MDT segment will reduce the fake rate too at the cost of muon tracks, especially those which will not be identified by combined muon algorithms in regions with limited coverage of muon stations.

More intelligent cuts are needed to reduce the non-muon background without losing

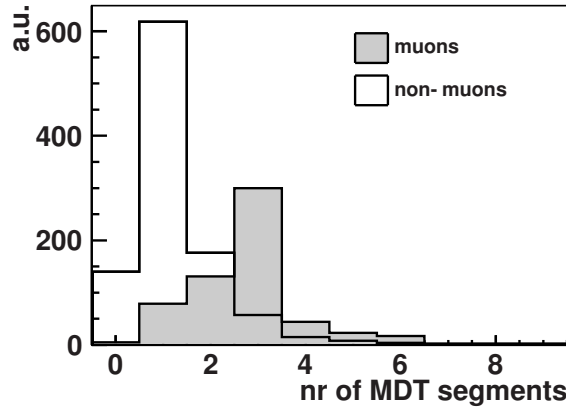


Figure 4.13: Number of segments associated to the muon candidate. Muons are shown in gray, non-muons in black.

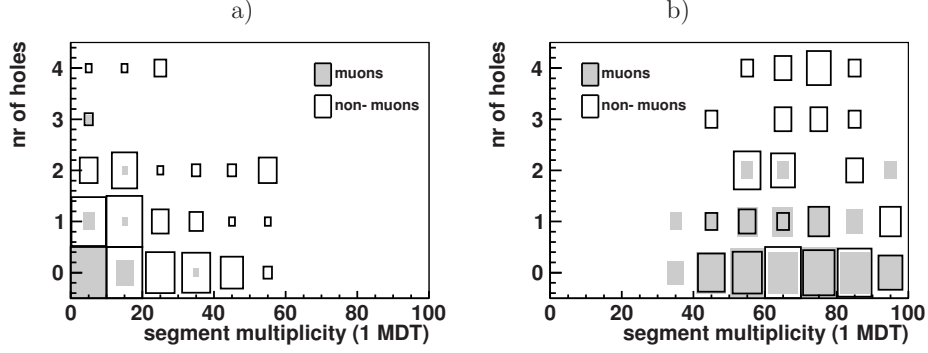


Figure 4.14: Number of holes on the associated segment versus the segment multiplicity of the event, for muon candidates with 1 MDT segment associated. a) $t\bar{t}$ sample, b) $Z^0 \rightarrow \mu^+\mu^-$ sample with cavern background safety factor 5.

muon tracks. Muon track candidates are selected applying the following stringent cuts:

- *At least one MDT segment associated:* Figure 4.13 shows the number of associated MDT segments for a $t\bar{t}$ sample. It is clear that muon candidates without MDT segments associated, i.e. only CSC segments are used to tag the track, are non-muon tracks. Requiring the muon candidate to have at least one MDT segment associated reduces the non-muon background.

Since most of the non-muon background comes from muon candidates with only one MDT segment associated, the following cuts are added to muon candidates with one MDT segment association:

- *Segment holes cut:* In busy events, where the number of segments is high, a stricter cut on the number of holes ($holes_{seg}$) on the reconstructed segments is applied to enforce that high quality segments are used in a tag:

$$holes_{seg} < c_{holes}, \quad c_{holes} = \begin{cases} 4 & n_{seg} < 30 \\ 3 & 30 < n_{seg} < 50 \\ 2 & 50 < n_{seg} \end{cases} \quad (4.21)$$

Figure 4.14-a) shows the distribution of the number of holes on the MDT segment associated to the muon candidate versus the segment multiplicity of the event, for a $t\bar{t}$ sample. Figure 4.14-b) shows the same for a $Z^0 \rightarrow \mu^+\mu^-$ with added cavern background (safety factor 5) sample. Muon tracks are shown by gray boxes, non-muon tracks by open boxes. The background is lowered by rejecting muon candidates that do not pass the segment holes cut.

- *Track p_T cut:* Since most of the non-muon background comes from low transverse momentum muon candidates, a stricter cut on the track p_T is applied for events with a high number of muon segments:

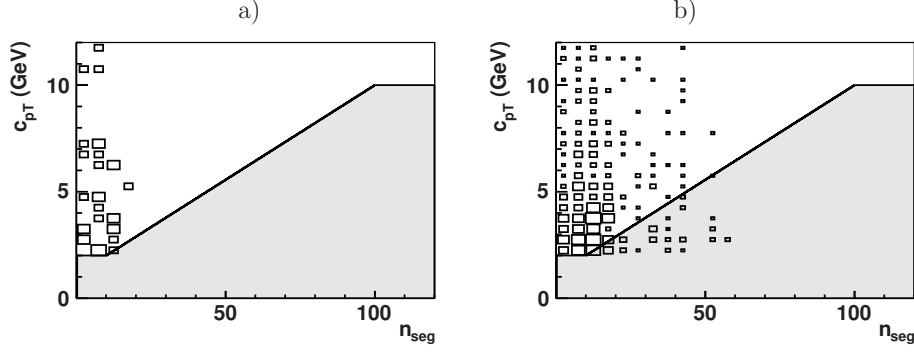


Figure 4.15: Muon candidate transverse momentum versus segment multiplicity for $t\bar{t}$ events. The muon tracks are shown in plot a), non-muon tracks in plot b). The shaded area shows the added p_T -cut imposed on single MDT muon candidates.

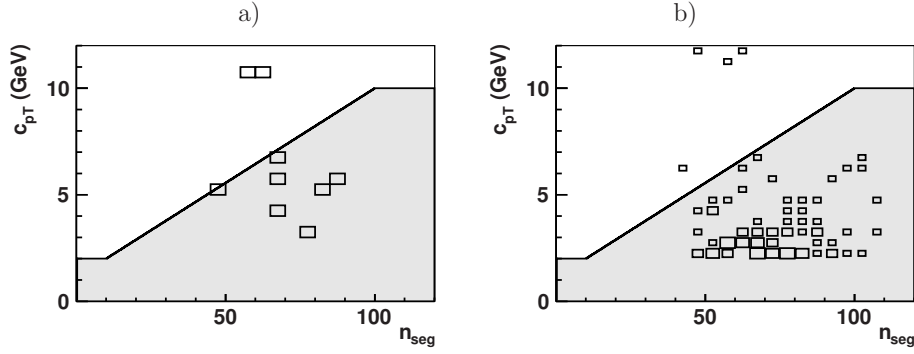


Figure 4.16: Muon candidate transverse momentum versus segment multiplicity for $Z^0 \rightarrow \mu^+\mu^-$ events with cavern background SF5. The muon tracks are shown in plot a), non-muon tracks in plot b). The shaded area shows the added p_T -cut imposed on single MDT muon candidates.

$$p_T < c_{p_T}, \quad c_{p_T} = \begin{cases} 2 \text{ GeV} & n_{\text{seg}} < 10 \\ \frac{8 \cdot n_{\text{seg}}}{90} + \frac{10}{9} \text{ GeV} & 10 < n_{\text{seg}} < 100 \\ 10 \text{ GeV} & 100 < n_{\text{seg}} \end{cases} \quad (4.22)$$

Where n_{seg} is the segment multiplicity of the event and p_T the transverse momentum of the Inner Detector track. The lower limit of 2 GeV tracks coincides with the momentum cut at the track filtering step. The upper limit of 10 GeV is only applied on tracks in very busy events.

Figure 4.15 shows the transverse momentum for muon candidates versus the segment multiplicity of the event for the $t\bar{t}$ sample. Muon tracks are shown in plot

a), non-muon tracks in plot b). The added transverse momentum cut is shown by the line; track candidates with a transverse momentum under the c_{p_T} value are dropped, as is shown by the shaded area. $t\bar{t}$ events are moderately busy and imposing a tighter momentum cut removes only a fraction of the mis-identified particles. Busier events such as $Z^0 \rightarrow \mu^+\mu^-$ with added cavern background (safety factor 5) benefit significantly from the added transverse momentum cut as is shown in Figure 4.16.

Muon candidates passing the final track and segment cuts are passed to the muon builder.

4.7 Muon building

After the ambiguity solving step, the Inner Detector tracks with their associated muon spectrometer segments are identified as muon and a *muon object* (see section 3.5.3) is made.

The track and its associated segments are grouped as an object called `MuTagObject`. This object contains the Inner Detector track, the associated segments grouped with the extrapolated track parameters evaluated at the segment surface. The constructed matching variables are stored as well. The `MuTagObject` is part of the MuTag EDM described in appendix C. The `MuTagObject` is converted to the ATLAS EDM `Analysis::Muon` object, as discussed in section 3.5.3, with tools available in the MuTag framework.

First, a track is extracted from the `MuTagObject` describing the Inner Detector track and its hits. Secondly, a so called `Rec::TrackParticle` is created from the track by associating a vertex to the track. For this, an extra input collection `VxCandidates` is needed to provide the vertices. Finally, a muon object is created in the form of an `Analysis::muon` and the segments used to tag the track, are added to the muon object.

These muon building steps are performed by dedicated converter tools described in appendix C.

4.8 MuTagIMO algorithm structure

This section describes the software package `MuonSegmentTaggers`, developed to perform muon segment tagging as described in the previous sections. Each step in the tagging procedure described in section 4.2 corresponds to a set of dedicated tools in the `MuonSegmentTaggers` package. The package itself is an extension to the MuTag framework described in appendix C.

Figure 4.17 shows a schematic overview of the `MuonSegmentTaggers` packages. The `MuTagIMO` algorithm collects the tracks and segments according to the tracking EDM classes `Rec::TrackParticleCollection` and `Trk::SegmentCollection`. The input class of vertex locations, `VxContainer`, is required in the final muon building step.

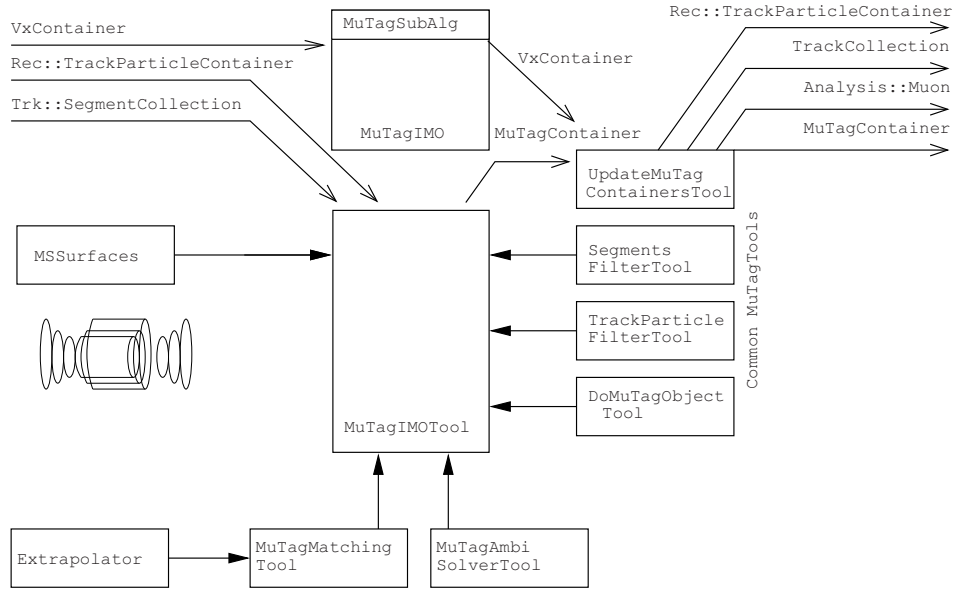


Figure 4.17: A schematic overview of the *MuonSegmentTaggers* package.

The **MuTagIMO** algorithm delegates the full tagging procedure to the **MuTagIMOTool**. This tool calls the filtering tools **TrackParticleFilterTool** and **SegmentsFilterTool** to prepare the input collections. The set of abstract muon station layer surfaces according to table 4.3 is provided by the **MSSurfaces** class. The extrapolation of tracks and matching with segments is performed by the **MuTagMatchingTool** that uses the ATLAS extrapolator (see section 3.4.2) configured. The resulting tag candidates are further processed by the **MuTagAmbiSolverTool** performing the ambiguity solving.

The grouping of the muon candidates tracks with their associated segments into a **MuTagObject** is done by the **DoMuTagObjectTool**. From the **MuTagObject**, a set of converters in the **UpdateMuTagContainersTool** construct the output collections **Trk::TrackCollection**, **Rec::TrackParticleContainer** and **Analysis::MuonContainer**.

4.9 Summary

In this chapter, the concepts of muon segment tagging is presented. This includes the implementation of muon segment tagging as done by the **MuTagIMO** algorithm. The filtering of the tracks and segments, the preselection of segments and the matching of the segments to the track is discussed in detail. The ambiguity solving step with several techniques to suppress the non-muon background has been presented, as well as the building of muons from muon candidates. The technical implementation of the **MuTagIMO** algorithm has been summarized in the last section.

Chapter 5

ATLAS BOL commissioning

5.1 Introduction

In this chapter we present the performance of the 96 BOL muon stations, assembled and tested at Nikhef in Amsterdam. After construction at Nikhef, the MDT chambers were shipped to CERN and assembled with RPCs before being installed in the ATLAS Muon Spectrometer. During the construction and assembly, the performance of the stations was tested and commissioned on various aspects to ensure that the design specifications were met. The domain of these tests range from pure hardware issues all the way to testing the processing of large amounts of data with dedicated offline reconstruction software.

In section 5.2 the hardware components of the MDT chamber are presented, and the journey of a BOL station from construction to its final installation is followed. Section 5.3 discusses the commissioning of the MDT chambers in detail. Section 5.4 focuses on the cosmic ray data, used to commission the Muon Spectrometer and ATLAS. In Section 5.5 the hardware performance of the BOL chambers as on October 2008 is presented.

5.2 MDT electronics and services

Figure 5.1 shows a schematic overview of the MDT electronics used to read out the signal from an MDT chamber, as well as the electronics used to monitor the temperature and magnetic field. On one side of the drift tube, on the right side of the figure, the monitored drift tubes are connected to high voltage (HV). The HV is distributed over the tubes via so-called HV hedgehog cards which are mounted on the tubes.

The signal is read out at the other end of the tubes, the read-out (RO) side of the chamber. The raw tube signals are Amplified, Shaped and Discriminated, eight tubes served by one ASD chip. The ASD chip measures the deposited charge with an Analogue-to-Digital Converter (ADC) in Wilkinson ADC counts. The ADC value is used for timing corrections and monitoring of the gas-gain. The differential signal outputs of the ASDs are routed to the Time-to-Digital Converter (TDC), where arrival

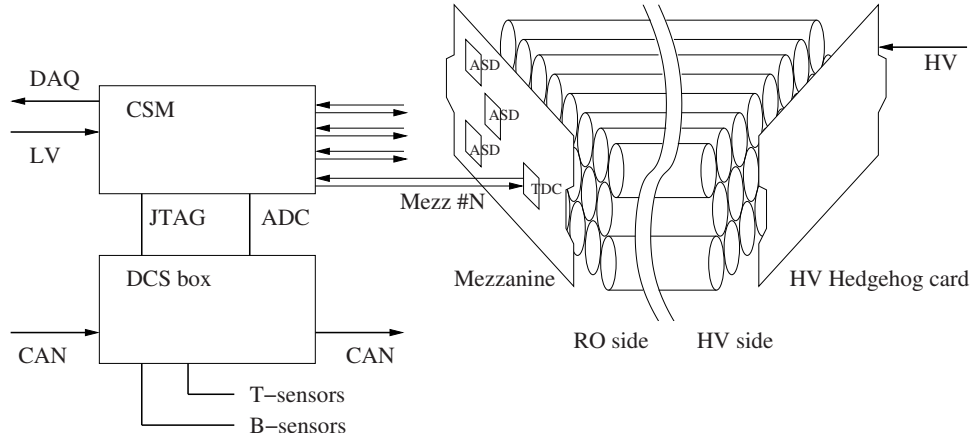


Figure 5.1: Schematic overview of the MDT electronics.

times of the leading and trailing edges of the signal are stored in a buffer. Three ASD chips route the signals to one TDC chip, which in turn serves 24 MDTs. The ASDs and TDC are implemented on a printed circuit-board called a Mezzanine. BOL chambers are produced in different types of different sizes with different number of tubes, consisting of up to 18 Mezzanine elements.

The Mezzanines are controlled by a local processor, the Chamber Service Module (CSM). The CSM collects the hits from the TDC and sends them via an optical link to the Data Acquisition (DAQ) system. The CSM and the read-out electronics are powered by a low voltage (LV) power supply.

An other element in the MDT electronics scheme is the Detector Control System (DCS), which sets the chamber up for data taking by controlling the read out electronics and monitoring its condition. It monitors up to 30 temperature sensors (T-sensors) and up to four magnetic field sensors (B-sensors), mounted on each MDT chamber. These parameters are relevant for the calibration of the r - t relation which relates the time measurement to the radial distance of the hit to the wire, since the drift properties of the gas is dependent on both temperature and magnetic field. The initialization and configuration of the Mezzanines is done via the Joint Task Action Group (JTAG) protocol. This protocol programs all parameters of the ASD and TDC chips, e.g. the setting of discriminator thresholds and dead times. The DCS monitors the voltages and the temperatures of the Mezzanines as well.

The various MDT chambers are connected via the DCS box on a (CAN) field-bus for distributed control and monitoring.

An optical alignment system is deployed in the Muon Spectrometer to monitor the relative positions of the MDT stations with respect to each other, the Rasnik system [52]. The Rasnik alignment system is a set of optical paths, consisting of three elements. A led (RasLed) projects a coded mask via a lens onto a CCD camera (RasCam). The



Figure 5.2: *The cosmic ray test stand at Nikhef.*

system monitors the relative displacements of the three elements. Relative movements of each of the elements are measured by changes in the image of the mask on the camera. Analysis of the images results in a very precise ($30\ \mu\text{m}$ [53]) measurement of the positions and deformations of the muon stations.

The optical paths *within* an MDT station, connecting the high-voltage side of the station with the read-out side is called the In-plane system and measures chamber deformations. For the In-plane system, the three Rasnik elements are within the same station. Other optical paths such as the Axial system monitors the relative positions of MDT stations in the same station layer and the Projective system measures the relative positions of stations in different station layers. For these systems, one station has the RasLed mounted whereas the other station has the RasCam.

5.2.1 BOL MDT testing and installation - a time line

After production at Nikhef, the BOL MDT chambers underwent a series of tests in order to ensure the best possible detector quality. The MDT electronics were checked for internal consistency and cosmic ray muon signals were used to assure the quality of the data. In further parts of this chapter we will look into the tests in more detail. During the commissioning at Nikhef, not all the elements of the electronics were mounted on the BOL chambers and part of the tests were performed with prototype electronics. Nevertheless as significant number of checks were performed at Nikhef and after successful completion of the tests, the chambers were transported to CERN.

At CERN, for practical reasons, the BOL chambers were first stored until the chambers were further transported to the BB5 assembly hall where they were *reception tested* to check for damage during transport. The installation of electronics was completed and the chambers were mounted with RPC detectors. The combined RPC station and BOL chamber are called *stations*. In the next step, the stations were tested in a cosmic ray setup to validate the data quality. At this point, malfunctioning electronics and broken wires could still be replaced. Again for practical reasons, the stations were stored until installation.

Before installation in the ATLAS cavern, the BOL stations were once more subject to a round of tests to verify readiness for installation (the *Ready For Installation* or RFI-tests). This was done at the surface above the ATLAS cavern, in the SX1 hall. Malfunctions could still be addressed at this point, which are very complicated after installation of the chambers where the services and electronics are difficult to reach. No new problems were found and all BOL chambers were ready for installation. After installation, the MDT chambers were regularly subjected to cosmic ray tests, as is described in section 5.4, to commission the Muon system and to integrate the other sub-systems such as the Inner Detector and Calorimeters as well. At the time of writing of this thesis, continuous commissioning efforts are still performed.

5.3 Commissioning

To ensure that the performance of the MDT chambers stated in the design report [54] were met, the chambers were extensively commissioned. Commissioning can be described in various ways, such as chronologically. Though, in this chapter, the description of the commissioning is categorized in *type* of commissioning, e.g. in the following three parts:

- *Hardware:* All the hardware components of the MDT chambers were tested, such as the gas system, the detector control system, alignment system and the high voltage supply for the chamber. This part also includes the read out of signals and the MDT electronics also.
- *Online software:* Besides the pure hardware aspects of the MDT chambers, the DAQ system and the overall quality of the data was tested. These tests were performed using cosmic muons mostly.
- *Offline software:* The final aspect of commissioning is the muon reconstruction software chain, which was commissioned with large data runs of cosmic ray muons. This entails the large scale data processing and the deployment of databases as well.

The following sections describe the commissioning of the MDT hardware, the online and the offline software in more detail.

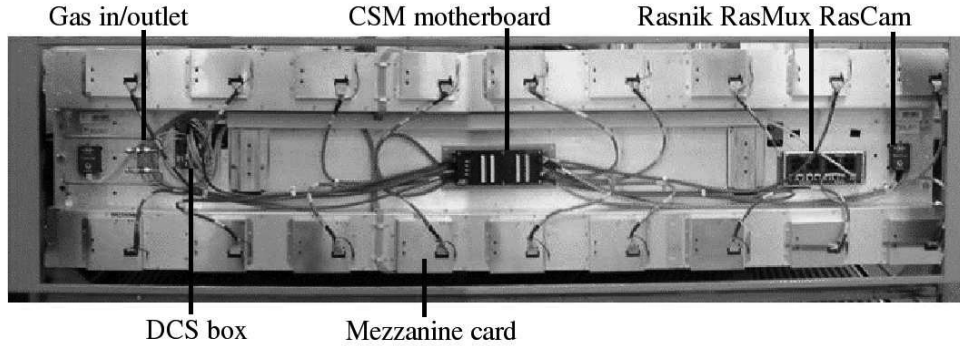


Figure 5.3: Read-out side of the BOL MDT chamber.

5.3.1 MDT hardware commissioning

Figure 5.3 shows the read out side of a BOL MDT chamber. See Figure 1.8 for the layout of an MDT chamber. The various components discussed in the previous section such as the CSM and DCS box are indicated. In this picture, 18 Mezzanines are connected to the CSM. Besides the read out electronics and the temperature and magnetic field monitoring, the alignment system Rasnik is indicated as well. Rasnik has various components which are connected to a multiplexer, the RasMux. The in- and outlet of the gas system are shown in the left of the picture. These various components were tested during the hardware commissioning as follows:

- A visual test was performed to verify that the chambers had no visible damage.
- The chambers were tested on gas-tightness. The drift properties of the gas mixture depend on the gas pressure. To ensure stability in the drift processes the pressure drop of the BOL chambers should not exceed 1 mbar/day. The gas-tightness is tested by measuring the pressure in the tubes for a certain amount of time. The environment temperature has a large impact on the gas pressure and is corrected for in these measurements. Practically, the pressure tests were done in two modes. First, the pressure was monitored for a couple of hours and small pressure drops were interpreted in pressure stability.
Secondly, the pressure was measured after storing the stations under pressure for a long period, typically of a few months. These tests were interpreted in leak tightness. Pressure drops detected at this point were due to not properly closed valves.
- The HV supply at the HV end of the muon chambers is checked to make sure that all the tubes are properly provided of HV. The chambers were tested for current leaks by applying a voltage of 3.08 kV, which corresponds to the normal

operation point, and measuring the current through the multi layers. For the BOL chambers, a leak current of $2\ \mu\text{A}$ is expected due to small discharges at the hedgehog cards. High leak currents could have various causes. The HV hedgehog cards, turned out often to be the culprit in the system and replacing the card solved the problem. Sometimes, a single tube is leaking current. These problems are localized by disconnecting tube layers and jumpers until the leaking zone of 8 tubes is identified. For one BOL station, dirty paths between the HV and ground on the end-plugs gave rise to current leaks and was cleaned.

- The read out side of the tube is tested by measuring the noise distribution of the drift tubes. Data is taken with a random trigger without and with high voltage applied to the wire. The average noise level per chamber should stay below an average rate of 5 kHz per tube when the HV is applied. Single tube noise degrades track reconstruction and rates should be kept much lower than the expected physical background in ATLAS. Therefore, a single tube should not exceed a noise rate of 40 kHz.

The HV hedgehog cards or Mezzanine cards turned out to be sources of noise and were replaced. In cases where this action did not help, the channel was disabled in the software by masking the tube.

- The magnetic field sensors (B-sensors) and temperature sensors (T-sensors) were read out and their data was checked on consistency. The B sensors were already tested and calibrated at CERN [55], for the BOL hardware commissioning the functionality is tested by reading out the sensors via the DCS system. Two measurements are taken, one with and one without holding a magnet above the B sensor. Sometimes the measurement hinted at a malfunctioning sensor. This was always due to a broken cable or connector, which was then replaced.
- The Rasnik alignment system [52] elements mounted on the MDT chamber were read out and all the optical paths were tested for functionality.

Before installation, the In-plane systems are checked by analyzing the images. For the Axial and Projective optical paths this is not possible since the optical path is not yet connected. For these elements, the RasCams are tested by illuminating them with a flashlight, the RasLeds are tested by collecting the light with a portable RasCam. Malfunctioning elements were replaced, in practice most common malfunctions were broken cables or connectors.

After installation of the MDT chamber in ATLAS, the optical paths between the MDT stations were installed and checked regularly. The problems arising were mostly blocked optical paths by services, support or scaffolding. In few cases (2 optical paths) the path was given up. Since the alignment system has some redundancy, this has no significant effect on the Muon Spectrometer performance.

Summary reports of the RFI-tests were archived in a database [56]. *Dead tubes*, i.e. tubes with broken wires, or tubes which were disconnected, and *noisy tubes*, i.e. tubes

with rates higher than 40 kHz, were flagged in this database. This information was made available to the offline reconstruction software. Tubes with broken wires were repaired at this stage.

5.3.2 Online software commissioning

The online software commissioning entails the testing of the read out performance of the MDTs and the quality of the data. Data from cosmic ray muons provide an excellent mean for online software commissioning since it provides ‘real data’ for the detector and the read out systems.

Cosmic ray setups were present at the MDT construction sites where the chambers were tested before shipping to CERN. These setups typically deployed a scintillator hodoscope as a trigger. At the BB5 assembly hall, the BOL stations were installed in a cosmic ray set-up, where the stations used the RPC detectors as trigger. After installation in ATLAS, the cosmic ray test were performed on an increasingly more large scale as more and more detectors were ready and included in the read out chain of the Muon Spectrometer. The organization of these cosmic ray tests will be discussed in section 5.4.

Typical MDT performances which were checked during the online software commissioning are the following:

- The charge distribution of the signal was monitored to check for possible read-out malfunctioning. Figure 5.4-a) shows a typical Wilkinson ADC distribution of an MDT tube in black. The large peak at 40 ADC counts corresponds to noise hits. These hits are ignored in the reconstruction where a requirement is imposed for hits having at least 50 ADC counts. The broader peak consists of hits caused by traversing charged particles. The gray distribution shows the ADC values for hits on segments. The noise hits were rejected ‘a priori’ in the reconstruction of segments.

The MDT stations are designed to operate in an magnetic field. Figure 5.4 shows the ADC and TDC distributions of the same MDT station shown in Figure 5.4, in an magnetic field. The electronics appear to work properly in the magnetic field.

- The drift time spectrum of the tube was monitored. The TDC value recorded is a measure for the arrival time of the first electron cluster, as discussed in section 1.2.3. Figure 5.4-b) shows a typical TDC spectrum, black for all the hits (noise hits included) and in gray for hits on segment. Hits used on segments in general have a cleaner drift time spectrum than noise hits. The leading edge of the spectrum is called the t_0 of the spectrum, the trailing edge of the spectrum the t_{max} .

Particularly sensitive to the gas flow in the tube is the value for the drift time, $t_{max} - t_0$. The fluctuation per tube of the drift time is of the order of 20 ns. Typically time differences of 50 ns were found for stations with obstructed gas flow [57].

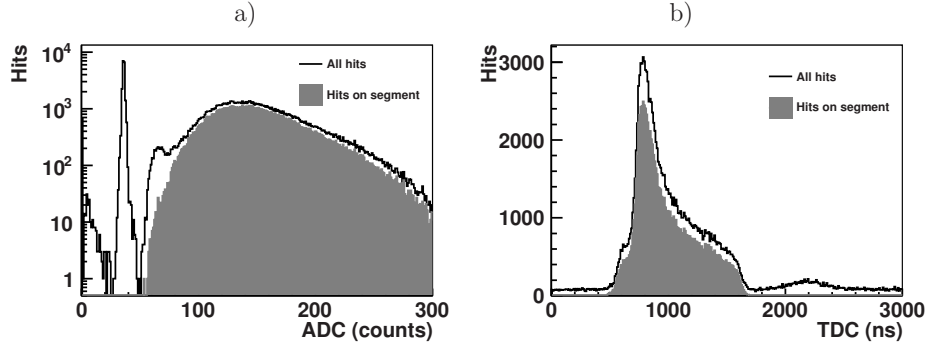


Figure 5.4: Data taken from the MDTs without magnetic field: a) the Wilkinson ADC spectrum and b) the TDC spectrum.

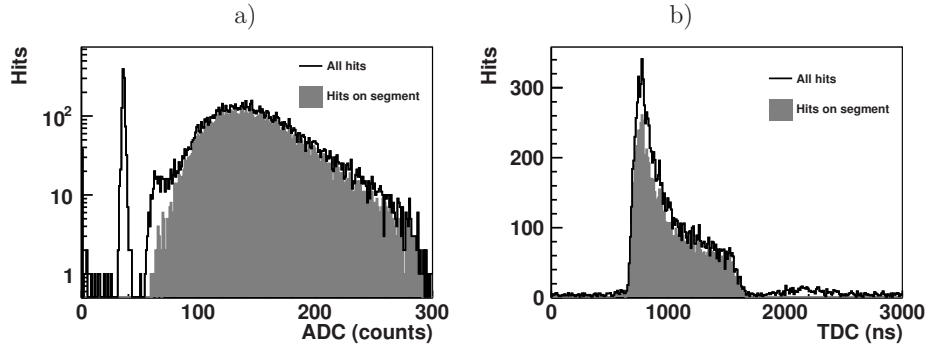


Figure 5.5: Data taken from the MDTs with magnetic field: a) the Wilkinson ADC spectrum and b) the TDC spectrum.

- Hit maps were made for each tube layer. The number of hits per tube is plotted versus the tube number resulting in a map of the tube occupancy. Inefficient tubes were found as well as dead tubes. In the case of low occupancy, the gas system, HV hedgehog cards and Mezzanines were checked and if needed replaced. Dead tubes which were identified as broken wires were repaired. A more detailed analysis on BOL hit maps is presented in section 5.5.

After installation, online monitoring software GNAM [58] was taking over the task of monitoring the data quality of the MDTs and the other Muon Spectrometer technologies. GNAM is a framework which is independent of detector subsystem, e.g Inner Detector, Calorimeters and Muon Spectrometer, interfaced to the DAQ. Detector dependent plugins decode the raw data from the detectors and provide monitoring histograms [59].

5.3.3 Offline software commissioning

Reconstruction of cosmic muons provided the most realistic test-case for the offline software system. Large amounts of cosmic data, in the order of millions of events, were processed. Various aspects from the offline software were validated:

- *Computing model.* The handling and distribution of the ATLAS data, the so-called ‘computing model’ [21] was heavily tested. Large amounts of data, several million of events, were processed by the offline reconstruction software at computer facilities at CERN, the so-called Tier-0 facility.
- *Offline reconstruction chain.* A dedicated cosmic reconstruction configuration was implemented and used to validate offline reconstruction of muons. The full software chain, as described in section 2.2, was tested. For instance, data preparation from **Byte Stream** to **Prepared Raw Data** objects were checked for internal consistency. Several problems in the hardware which were not found earlier in the hardware commissioning or online software commissioning were found and addressed at this stage. For instance, the reconstruction of cosmic muon tracks had revealed mismatches between the cabling of the detector and the software description of the cabling.
- *Software robustness.* The processing of large amounts of real data was used to validate the software robustness. For instance, the software should be able to handle incomplete data fragments from the DAQ system. Various protections in the code had to be implemented to prevent the large scale processing to crash when handling corrupted data. For example, an incomplete data fragment from the MDT read-out should be properly handled in the **Bytestream** conversion and not cause the reconstruction job to fail. Furthermore, rare non-standard event topologies revealed weak points in the software robustness which could be then be addressed. For example, infinite loops caused the code to hang at certain events. The very large amount of data processed at the Tier0 facility, in the order of millions of events, revealed points ready for improvement in the software. The failure rate of the processing jobs decreased from around 10 % at the first cosmic runs to less than 1 ‰ in later cosmic runs. Much effort is put into maintaining this low failure rate during the running period of ATLAS.
- *Software optimization.* The large scale processing revealed parts of the code which were running slow or took too much memory. The CPU-consumption of the various algorithms in the offline software was addressed to optimize the code. It appeared that much CPU was consumed by only few events, such as cosmic shower events with complicated topologies which were not modeled in simulated data.

5.4 Muon commissioning in the ATLAS cavern

Commissioning with cosmic muons after installation of the detectors is organized in ATLAS in the so-called *Milestone runs* or M-runs. For the M-runs, the focus was

on integration of the different sub-detectors (Inner Detector, Calorimeters and Muon Spectrometer), data acquisition and trigger. Dedicated data-taking periods for Muon Spectrometer commissioning are referred to as P-runs. After summer 2008, cosmic data was taken continuously until the LHC start-up. The commissioning of ATLAS is still ongoing at the time of writing of this thesis.

5.4.1 October 2008 cosmic muon run

The results shown in this chapter are from the data taken in October 2008. During this period, 2 million events from the run 91060 were analyzed. For this run, the full ATLAS Muon Spectrometer was read out, except for the EE stations (see section 1.2.3), which were only installed during spring 2009. For the analysis, data from the RPC trigger stream was used. Due to the poor trigger timing synchronization, only the RPCs from the middle stations were used for LVL-1 triggering. The muon trigger was set with the largest possible coincidence window and the HLT trigger passed all the events [60]. Due to several problems in the RPC trigger, the trigger and read out coverage was reduced to approximately 60 %. Synchronization problems caused 11 of 64 sector logic boards to be masked. Due to broken optical links and initialization problems, some trigger towers were not operated. Finally, an entire layer of a sector was switched off due to a broken gas line¹.

During this period the timing of the trigger was not yet optimized, resulting in an average trigger efficiency of around 70 % [61].

5.5 Hardware performance BOL

To monitor the MDT station hardware performance, hit maps of the 96 BOL MDT stations are made. These hit maps are presented in Appendix D. The results of the hardware performance, based on these hit maps are summarized in this section.

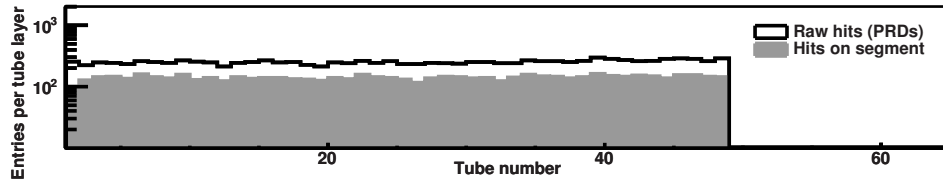


Figure 5.6: Hit map of one tube layer. Raw hits are shown by open histograms, hits on segments in gray.

Figure 5.6 shows a typical hit map of one tube layer. All the hit maps in Appendix D use this convention. Raw hits are the `PrepRawData` objects used as input of the reconstruction and are displayed as the open histogram. To suppress noise, only raw MDT

¹During the winter shutdown, most of these problems were addressed.

chamber	ML	L	problems identified [62]
BOL4A09	2	1,2,3	high voltage supply problem
BOL4A11	1	1,2,3	gas leak, 3 tubes need to be disconnected
BOL6A11	2	1	broken wire, needs to be disconnected
BOL1C13	1	1,2,3	draws current, probably a broken wire
BOL2C13	2	1,2,3	draws current, probably a broken wire
BOL4C13	2	1,2,3	high voltage supply problem
BOL5C13	2	3	high voltage connector broken
BOL6A13	1	1	broken wire, needs to be disconnected
BOL5A15	1	1,2,3	gas leak
BOL5A15	2	1,2,3	gas supply blocked

Table 5.1: *MDT station problems identified with run 91060.*

hits with an ADC value of larger than 50 are taken into account for these hit maps. This cut is applied in the segment reconstruction as well. Hits on segments reconstructed by the **Moore** program (described in section 3.3.3) are shown in gray. The x -axis shows the tube number, running from 1 to 64, corresponding to the maximum number of tubes in one tube layer for the BOL stations. The y -axis has a logarithmic scale with a minimum value fixed at 10 and a maximum value fixed at 2×10^3 .

The hit maps show clearly that some of the multilayers and tube layers were not functional during run 91060, as these (multi)layers have only a few raw hits. Table 5.1 summarizes the BOL stations with problems. Dead tubes are visible in the hit maps as well, summarized in table 5.2-a). In total, 7 multilayers, 3 tube layers and 20 single tubes were not operational during this run. This corresponds initially to a total of 1492 tubes out of the 33,696 BOL monitored drift tubes, thus 4.4 %. In the following we describe how this number can be reduced by ‘in-situ’ repair of various problems.

The 7 multilayers and 3 tube layers were disconnected from high voltage (HV) during this run because of various reasons. Some tube layers have a tube with a broken wire, causing large *leak currents*. That (multi)layer was therefore disconnected from HV. The tube layer may be reconnected when the single tube is disconnected. An other reason to disconnect a multilayer from HV was when large *gas leaks* were present. Falling objects in the ATLAS cavern had caused gas leaks in two BOL stations. In order to reconnect the multilayer, the leaking tube needed to be disconnected from HV. The gas supply is arranged such that three tubes are sharing one gas inlet. In practice this means that one tube leaking gas results in three tubes disconnected from the gas system, and thus from HV. Finally, in three MDT stations malfunctioning HV supplies had been identified, which will be replaced. At the time of writing of this thesis, this repair work is still in progress.

Dead tubes were recognized by empty channels in the hit maps, or channels with a lower occupancy (less than 10 %) than the neighboring channels. The stations with dead tubes are summarized in table 5.2-a). After repairing the problems summarized in table 5.1, 10 more dead channels are to be expected, adding up to a total of 30

dead channels out of the total of 33,696 channels for the MDT BOL stations. This corresponds to a dead tube rate of 0.9 ‰ which is comparable to the full ATLAS MDT dead tube rate of 1.1 ‰ [63].

Table 5.2-b) presents a list of noisy channels. In this analysis a tube was named noisy when it had more than 3 times the amount of hits compared to the median of the other tubes in the muon station. Noisy channels were flagged in the conditions database and made available for offline reconstruction.

In sectors 1 and 9 one can observe that the tube occupancy is somewhat lower than for the other sectors. This is because of the RPC trigger which has a smaller geometrical acceptance for these sectors. The orientation of the stations in these sector with respect to the average direction of the cosmic muons give a smaller trigger rate for events passing the two sectors.

For sector 1 and 9, the segment reconstruction efficiency is lower than for the other sectors as well. This is observable by the lower fraction of hits on segment compared with the raw hits in the stations from this sector. This effect is largest for stations with a high η value (at the sides of the spectrometer). The segment reconstruction, which is optimized for collision events, has a harder time reconstructing segments from muons traversing the station under large angles.

The segment reconstruction is constant over the whole MDT station, e.g. no tube-dependent or Mezzanine-dependent efficiency changes are observed. Such inefficiencies would have been due to mismatches between the cabling of the electronics and the mapping in the software. The BOL MDT stations appear to be properly cabled.

5.6 Conclusion and outlook

After an intensive period of Muon Spectrometer commissioning, the hardware performance of the MDT stations has been evaluated. For run 91060, 4.4 ‰ of the BOL MDT channels were not operational. In the following chapters, the impact of dead channels on muon reconstruction will be discussed. Muon tagging algorithms are expected to provide robust muon identification that can cope with inefficiencies in the hardware. The hardware problems will be repaired where possible and ultimately, in the best case, only about 1 ‰ of the 33,696 channels will be disconnected.

a)				b)			
station	ML	L	tube number	station	ML	L	tube number
BOL1A01	1	1	32	BOL1A07	1	1	32
BOL1A01	1	3	43	BOL1A07	1	2	32
BOL2A01	1	2	9	BOL1A07	1	3	33
BOL5A01	1	3	60	BOL1A07	2	1	36
BOL4C01	2	1	25, 26	BOL1A07	2	2	36
BOL4C01	2	1	20, 21	BOL1A07	2	3	37
BOL6A03	1	1	19	BOL3A07	1	1	1
BOL2A05	2	3	29	BOL1C11	1	1	36
BOL1C09	1	1	52	BOL1C11	1	2	36
BOL6A11	1	3	35, 36, 37, 38	BOL1C11	1	3	37
BOL1A13	1	1	1, 2	BOL1C11	2	1	40
BOL3A13	1	1	31, 41	BOL1C11	2	2	40
BOL3C15	2	2	11	BOL1C11	2	3	41
				BOL6C15	1	1	1
				BOL6C15	1	2	1
				BOL6C15	1	3	1
				BOL6C15	2	1	1
				BOL6C15	2	2	1
				BOL6C15	2	3	1

Table 5.2: List of MDT channels with problems: a) Dead tubes; MDT channels with less than 10 % of entries compared to the median value of the other tubes in the same MDT station. b) Noisy tubes; MDT channels with a rate higher than 40kHz.

Chapter 6

Muon tagging performance on cosmic muons

6.1 Introduction

This chapter presents the performance of muon tagging with the **MuTagIMO** algorithm on cosmic muons. The algorithm itself is described in Chapter 4. In this chapter we study both simulated and real data. In order to efficiently tag cosmic muon events, we have to adapt the reconstruction software, which is optimized for collision events. In section 6.2, these adaptations are discussed. Section 6.3 describes the configuration of the **MuTagIMO** algorithm optimized for cosmic muons. Section 6.4 discusses the data samples used for the performance studies. Section 6.5 presents the **MuTagIMO** tagging performance on cosmic muons.

6.2 Cosmic muon reconstruction

Reconstruction of cosmic muons differs in many ways from reconstruction of muons that originate from proton collisions in the beam pipe, and therefore adaptations to the pattern recognition and track reconstruction algorithms are needed. The ATLAS detector is designed to observe particles that originate from the Interaction Point (IP). It is constructed such that particles traverse the Inner Detector, the calorimeters and three layers of the Muon Spectrometer respectively. In contrast, cosmic muons do not point towards the interaction point as they arrive from all directions. The following issues have to be considered:

- *Detector module orientation.* For tracks that originate from the IP, the measurement planes are close to orthogonal to the track direction. In cosmic events this is no longer true, as the angle between the measurement plane and track may become small as well.
- *Time of flight corrections.* Since cosmic muons do not come from the IP, the sequence with which the cosmic muon traverses the various detector parts is different

from particles that originate from the IP. The time of flight of a particle from the IP is the time it takes, traveling with the speed of light, to reach the measurement plane. The reconstruction takes this time into account. For cosmic muons, the time of flight should be accounted for in an other way than for muons from the IP.

- *Trigger time uncertainty* Events from proton collisions are well timed with the LHC clock. Cosmic muons are not synchronized with the LHC clock. This causes a random displacement with the LHC clock of between 0 and 25 ns, the time between two bunch-crossings.

To address these issues, several modifications are made to the reconstruction software for tracks in the Inner Detector and Muon Spectrometer. We then present the configuration of the MuTagIM0 muon tagging algorithm.

6.2.1 Reconstruction of cosmic tracks in the Inner Detector

Track reconstruction in the Inner Detector starts by creating `SpacePoints` from the raw hits, then using the Pixel measurements and the IP constraint to create seeds for track building, as described in section 3.2. For track reconstruction in cosmic events, all interaction point constraints are removed. Furthermore, the following modifications were made to the software [64]:

- *Data preparation:* The TRT measures the drift time of the signal at the anode wire. For collision events, the drift radius is calculated via the rt -relation obtained from calibration. For cosmic ray events, which are not synchronized to the LHC clock, the drift time is corrected by a component called the phase time t_p . The phase time lies within 0 and 25 ns, i.e. it is a flat distribution within one bunch crossing. TRT `SpacePoints` are made by running track reconstruction in two steps. First TRT tracks from hits with zero drift radius with an error of $4/\sqrt{12}$ mm are made. The phase time is then calculated by comparing the fitted track radius to the measured drift radii [65].
- *Track finding:* Two different track reconstruction algorithms are used. A special version of NewTracking [41] with an adjusted pattern recognition is implemented. The second algorithm is the dedicated Cosmic and Test-beam Tracking [66]. Both algorithms are run in parallel.
- *Merging of tracks:* Hits from the upper and lower part of the detector are merged to a large, single track traversing both upper and lower part of the Inner Detector. By convention, the direction of the track points *downwards*, in the direction of the muon.
- *Adjusted post-processing:* In contrast to normal track reconstruction, no attempt is made to reconstruct primary vertices or detect converted photons in the post-processing step.

The modifications result in a stable and efficient reconstruction of downward pointing cosmic muon tracks in the Inner Detector. Studies with simulated cosmic events show that a reconstruction efficiency of 98 % [67] within the Inner Detector acceptance is achieved.

6.2.2 Reconstruction of cosmic tracks in the Muon Spectrometer

In order to tag muons we do not need to reconstruct the full track in the Muon Spectrometer. An efficient reconstruction of segments inside the MDT stations, which is part of the track reconstruction as well, is sufficient. In order to optimize the segment reconstruction, a number of modifications are made to the reconstruction software:

- *Cosmic pattern recognition:* The pattern recognition in the Muon Spectrometer is based on a Hough transform of the hits in the spectrometer, as described in section 3.3. For events with tracks coming from the IP, a transform is used which takes the curvature of the track into account. For cosmic muon reconstruction however, the Hough transform is restricted to a straight line in the $R\theta$ -plane.
- *Cosmic segment reconstruction:* For segment reconstruction in proton collision events, the direction of the pattern is used as a constraint for the segment reconstruction, as discussed in section 3.3.3. For reconstructing cosmic segments, this is only used as a loose constraint.
- *Non-perfect detector:* At this stage, the detector systems are not fully aligned and uncertainties in the MDT calibration are present. These effects are taken into account by enlarging the errors on the MDT driftcircles to a value of 2 mm. When the detector is aligned and calibrated, the errors calculated from the rt -relation will be used.
- *Time reference t_0 :* As the cosmic muons are not synchronized with the LHC clock and the time of flight cannot be deduced, the reference time t_0 is left as a free parameter in the segment fit. Hence each segment acquires an independent t_0 time.
- *Track splitting:* Tracks traversing the ATLAS detector from the top to the bottom, crossing the calorimeter volume, are split and are treated as two separate muon tracks. Cosmic muons crossing the Muon Spectrometer end-cap in general do not cross the calorimeter volume and are not split.

The segment reconstruction efficiency for cosmic muons can be obtained from cosmic data by selecting events with reconstructed tracks in the spectrometer which cross three station layers. These tracks are required to have hits in at least two out of the three station layers. The track is then extrapolated to each of the station layers and the presence of a reconstructed segment is checked. The segment efficiency is obtained by the fraction of segments found in the stations over the number of crossed stations. On average, the segment reconstruction efficiency is measured to be 99.5 % [68].

6.3 Muon tagging optimization

To optimize the identification of cosmic muons, the `MuTagIMO` algorithm is configured in a special way. Most salient is the relaxed treatment of matching requirements. These were implemented to reduce non-muon background in very busy events, i.e. events with a high track multiplicity and for cosmic muons this is not needed.

- *Track filter:* The requirements on the track filter step, as discussed in section 4.3 are relaxed. First, only the momentum requirement of at least 2 GeV is imposed on the Inner Detector tracks, no requirements on the transverse momentum is set. Secondly, the requirement of having at least four hits in the silicon detectors of the Inner Detector, i.e. Pixel and SCT hits, is dropped. The reason that this requirement can safely be dropped is that the reconstruction of photon-conversion tracks is not a source of non-muon background for cosmic muons. By dropping this constraint, muons crossing the Inner Detector without traversing the SCT volume are passed to the tagging algorithm.
- *Segment selection:* The requirements on the filtering of segments, discussed in section 4.3 is relaxed. No requirement on the number of MDT multi layers is imposed, and no requirement on the maximum number of holes per segment is applied. Segments from cosmic muons may have large angles with respect to the muon stations and may traverse only one multilayer.

- *Relaxed segment preselection and matching:* The matching of the ID track to segments is done in two steps. First, the segments are preselected by performing a rough search on segments in the vicinity of the station layers the ID track is crossing as discussed in section 4.4. For cosmic events, the preselection of segments that are considered to be matched to an ID track is relaxed from 0.1 rad to 0.5 rad in the Rz -coordinate and from 0.5 rad to 1 rad in the xy -coordinate.

Secondly, the ID track is extrapolated to the measurement surface of the preselected segment, as discussed in section 4.5. Matching of the segments to the ID track is relaxed to accomodate for the misalignment of the Muon Spectrometer with respect to the Inner Detector and the enlarged uncertainty of the Muon Spectrometer segments. Hence, the matching variables c_{locY} and $c_{\alpha_{YZ}}$ are required to be within 30σ as opposed to 5σ for tagging tracks pointing to the IP. Furthermore, as the cosmic tracks are rather isolated we can relax the requirements that were developed to decrease the mis-identification rate. The p_T dependent pull requirement described by Eq. 4.11 is dropped for cosmic muon tagging, as well as the requirements on the matching distance defined in Eq. 4.15.

- *Bidirectional extrapolation:* Most cosmic muons traversing the Inner Detector volume pass the Muon Spectrometer volume twice, in the upper and the lower hemisphere. In order to scan both hemispheres for segments, the ID track is extrapolated in *two directions*. The track extrapolator algorithm is called with the direction argument `alongMomentum` and `oppositeMomentum` to extrapolate to the

variable	default value	cosmic value	description
c_ϕ	0.5 rad	1.0 rad	segment preselection xy -plane
c_θ	0.1 rad	0.5 rad	segment preselection Rz -plane barrel
c_R	2/15	2/15	segment preselection Rz -plane endcap
$c_{\text{loc}Y}$	5	30	position matching in Rz -plane
$c_{\alpha_{yz}}$	5	30	direction matching in Rz -plane
$c_{\text{loc}X}$	5	30	position matching in xy -plane
$c_{\alpha_{xz}}$	5	30	direction matching in Rz -plane
$c_{\Delta_{\text{loc}Y}}$	500 mm	-	position matching in Rz -plane
$c_{\Delta_{\alpha_{yz}}}$	0.3 rad	-	direction matching in Rz -plane

Table 6.1: The properties of the *MuTagMatchingTool*, shown with the optimized settings for tagging cosmic muons with the *MuTagIMO* algorithm.

lower and upper hemisphere respectively. This feature of the ATLAS extrapolator is described in section 3.4.2.

- *ID tracks without silicon hits:* The majority of the tracks traversing the Inner Detector volume do not traverse the SCT detector volume. These tracks are built from TRT hits only and will not have precision measurements in the Rz -plane. With the above mentioned modifications, these tracks do now actually pass the track filter and will only be matched in the xy -plane.

The configuration of the *MuTagIMO* matching tool for cosmic muon tagging is summarized in Table 6.1. The performance of *MuTagIMO* muon tagging on cosmic muons will be discussed in the following sections.

6.4 Cosmic data samples

To study the *MuTagIMO* tagging performance on cosmic muons both simulated events and real data from the October 2008 cosmic run were used.

In the previous chapter we studied run 91060 for the hardware commissioning. This run was taken without magnetic field on. Now, for the performance of the tagger, run 91890 with the solenoid and toroid magnets on is selected. From the curvature of the track, the momentum of the muon can be measured. The full ATLAS detector was operational, except for the staged muon stations in the barrel-endcap transition region which were installed in spring 2009. The RPC chambers from the middle muon stations were used for the LVL-1 trigger of the event, like with run 91060 used in section 5.4.1. The same RPC trigger issues as discussed in section 5.4 were present during this run. In order to study only events with activity in the Inner Detector, we used the *IDCosmic* data stream. Besides 'real' cosmic data, we studied Monte Carlo simulated cosmic data, as described in section 2.3.2. Simulated cosmic event samples are available for various geometrical acceptances: muons traversing the Muon Spectrometer volume, the calorimeter volume and the Inner Detector volume. For our muon tagging studies, the

last one is of most interest. Samples simulating the 91890 data run conditions were used¹. The magnetic fields were switched on in the simulation as well. However, at the time of writing of this thesis, the trigger was not simulated for this sample.

We applied a selection requirement to ensure the simulation sample coincides with the 91890 detector sample:

- At least three RPC ϕ hits in the Muon Spectrometer [69] are required to model the RPC trigger conditions of the 91890 sample. This requirement was not imposed on the run 91890 events.
- Cosmic ray *shower* events are removed from the 91890 data events, since these are not simulated by the Monte Carlo. Moreover, cosmic showers events have multiple Inner Detector tracks and have a high muon segment multiplicity. These kind of events are not used in the muon identification performance studies. Events with more than 20 segments are rejected.

6.4.1 Inner Detector tracks

To evaluate the muon tagging performance, a selection of events is made to identify well reconstructed Inner Detector tracks. Inner Detector tracks that pass the following requirements are referred to as *good ID tracks*:

- At least 8 hits are from the silicon detectors are present (both the SCT and the Pixel detectors).
- At least 20 hits from the TRT detector are present.
- The transverse impact parameter d_0 of the Inner Detector track should be smaller than 250 mm.
- The Inner Detector track momentum is at least 2 GeV.

From the 91890 data events, around 10 % of the events have a *good ID track*. From the simulated events this rate is 3 %. These selection efficiencies are very different in data and simulation because the conditions in data and simulation were different. We believe however, that after these requirements, the samples describe the same phase space and can be mapped on each other.

Figure 6.1-a) shows the polar angle θ distribution of the reconstructed cosmic tracks. The polar angle is defined with respect to the z-axis of the track, without requirement that the track passes the origin. A polar angle of $\theta = \pi/2$ corresponds to a straight downward going track. The distributions shows two peaks at $\theta = 1.2$ rad and $\theta = 1.9$ rad, they correspond to the access shafts of the ATLAS pit. Most cosmic muons are absorbed by the rock above the cavern and the muons reaching the detector have a

¹The samples of the set `valid2.108867.CosSimIDVolSolOnTorOn.digit.RD0.s540_d167_-tid065777`. Both simulated and real data samples are reconstruction with software release 15.2.0.11. The distributions shown in this chapter consist of 30,000 events per sample.

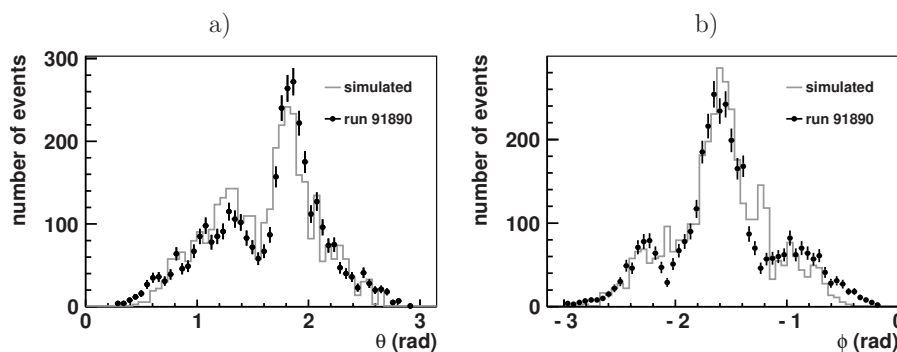


Figure 6.1: The a) polar direction θ and b) azimuthal ϕ direction of the track. Both 91890 data (black markers) and simulated cosmoics (gray line) are shown. The simulated data is normalized to the 91890 data.

higher probability to have passed through the shafts. The access shaft at the positive z-axis side of ATLAS is larger than the shaft at the negative z-axis. Therefore the peak at $\theta = 1.9$ rad is higher than the peak at $\theta = 1.2$ rad.

The discrepancies between the simulated events (gray) and 91890 data events (black) come from non-read out sectors in the data [69] and the inhomogeneous RPC trigger efficiency [70]. The different timing of the RPC trigger towers causes a (θ, ϕ) -dependent Inner Detector track reconstruction efficiency. Figure 6.1-b) shows the azimuthal angle distribution of the reconstructed cosmic track. As described in section 6.2, the Inner Detector tracks is merged from an upper and lower hemisphere of the detector. The *good ID tracks* have a negative ϕ -angle which means that the muons are pointing downwards as is expected from cosmic ray events.

In Figure 6.2 the reconstructed track momentum of the cosmic muons from simulated events (gray) and 91890 data (black) is shown. The figure shows that the momentum of cosmic muons may reach a hundred GeV and distributions are compatible with each other.

6.4.2 Muon Spectrometer segments

We now investigate the reconstructed Muon Spectrometer segments in the data and simulation. Figure 6.3-a) shows the number of segments in the Muon Spectrometer per event. For both simulation (gray) and 91890 data (black), the events have a large segment multiplicity. Note that we require that events have less than 20 segments in order to remove cosmic shower events. A muon traversing through the full ATLAS detector typically traverses six stations. More than six stations can be traversed if the track is inclined and large and additional small muon chambers are crossed. Combinatorics of segment building from MDT hits may cause multiple segments in a station to be reconstructed.

Good ID tracks are tagged as *muon tracks* by associating segments to the track.

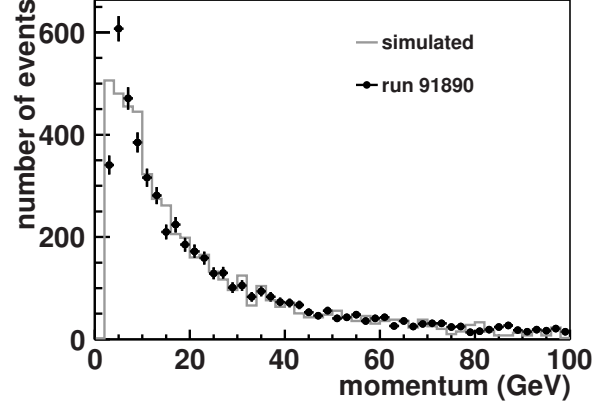


Figure 6.2: The momentum of the track in GeV. Both 91890 data (black markers) and simulated cosmoics (gray line) are shown. The simulated data is normalized to the 91890 data.

Figure 6.3-b) shows the distribution of associated segments per *good ID track*. Most of the tracks are tagged by associating six segments to the track. Overlaps in stations give rise to more associated segments to the track. Only one segment per station is associated to the track. When multiple segments per station are reconstructed due to combinatorics, the best matching segment is associated. Hence the peak at six segments consists of *good ID tracks* tagged by associating three segments in the upper hemisphere and three segments in the lower hemisphere.

6.5 MuTagIMO tagging performance

When a cosmic muon traverses the Inner Detector of the ATLAS detector, it has crossed the upper part of the Muon Spectrometer. When the muon has an energy of more than approximately 6 GeV, it will cross the lower part of the spectrometer as well since it then has enough energy to cross the calorimeters. We make use of these energetic muons to evaluate the performance of the MuTagIMO tagging algorithm.

The Muon Spectrometer segments are divided in two categories, *upper* hemisphere segments and *lower* hemisphere segments. The segments are separated according to their position relative to the perigee of the *good ID track*:

$$r_{\text{seg}} = (x_{0,\text{trk}} - x_{\text{seg}}) \cos(\phi_{\text{trk}}) + (y_{0,\text{trk}} - y_{\text{seg}}) \sin(\phi_{\text{trk}}), \quad (6.1)$$

$$\begin{cases} r_{\text{seg}} > 0 & \text{upper hemisphere segment} \\ r_{\text{seg}} < 0 & \text{lower hemisphere segment} \end{cases} \quad (6.2)$$

Where $x_{0,\text{trk}}, y_{0,\text{trk}}$ is the point of closest approach of the track to the IP in the transverse plane, ϕ_{trk} the polar angle of the track and $x_{\text{seg}}, y_{\text{seg}}$ the x and y coordinate of the

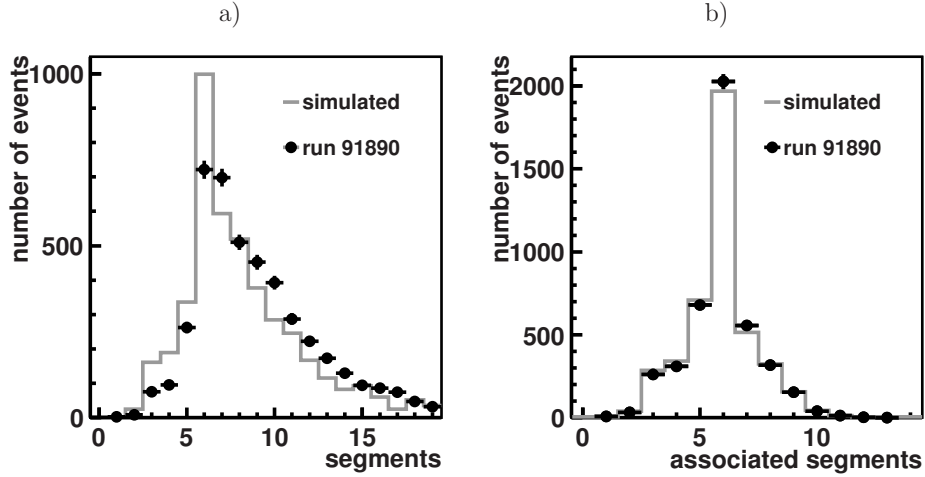


Figure 6.3: a) Number of segments per event and b) number of segments associated to a good track. Both 91890 data (black markers) and simulated cosmoics (gray line) are shown. The simulated data is normalized to the 91890 data.

segment.

Figure 6.4 shows the distribution of the number of segments associated to the track versus the momentum of the track, for the 91890 data sample. The black open boxes show the upper hemisphere segments, the gray boxes the lower hemisphere segments. Tracks have typically three segments associated in the upper hemisphere. This is expected from the geometry of the ATLAS Muon Spectrometer. Low momentum cosmic muons are likely to be stopped in the calorimeters, which is visible by the smaller number of associated segments in the lower hemisphere for tracks below 6 GeV. Cosmic muons with sufficient energy to penetrate the calorimeters have associated segments in the lower hemisphere of the spectrometer. For such tracks, the distribution of associated segments in the lower and upper hemisphere become similar.

In order to cross-check the MuTagIMO efficiency in the upper and lower hemisphere, cosmic muons with a momentum of at least 6 GeV were selected. For these tracks, the upper and lower hemisphere act as two separate tagging systems. Figure 6.5 shows the number of associated segments to the track in the upper and lower hemisphere. No correlations were observed and in both hemispheres three segments were typically associated to the track.

The MuTagIMO *tagging efficiency* is defined here as the number of *good ID tracks* tagged by the MuTagIMO algorithm divided by the number of *good ID tracks*. Equivalently, the tagging efficiency of the upper (lower) hemisphere is defined as the number of *good ID tracks* tagged by associating one or more segments from the upper (lower) hemisphere divided by the number of *good ID tracks*. Note, that *no conditions* are im-

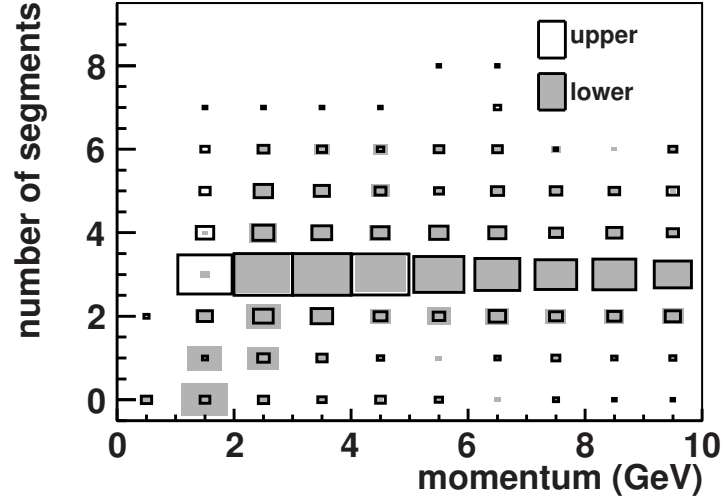


Figure 6.4: The number of associated segments versus the Inner Detector track momentum. The segments from the upper and lower hemisphere are shown in black and gray respectively. Tracks with a momentum of more than 6 GeV traverse both hemispheres and hit three stations on average.

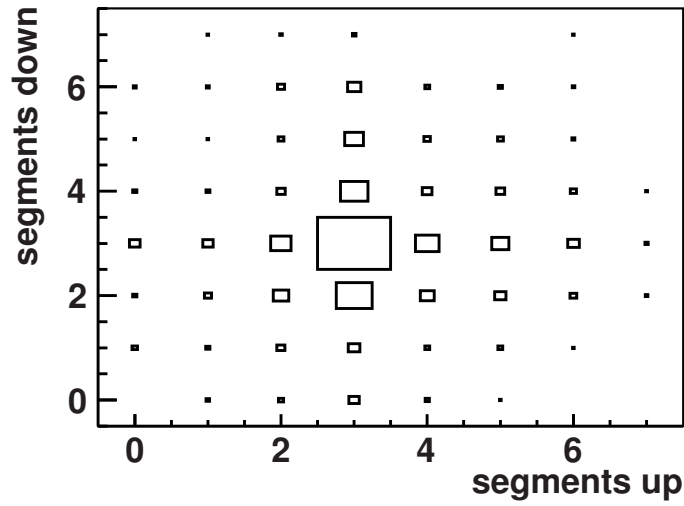


Figure 6.5: The number of associated segments of both hemispheres, demonstrating that the Muon Spectrometer acts as two separate systems. Segments associated to tracks with a momentum higher than 6 GeV are shown.

6.5 MuTagIMO tagging performance

	data		simulation	
	good ID track > 2 GeV	good ID track > 6 GeV	good ID track > 2 GeV	good ID track > 6 GeV
Upper and lower hemispheres combined				
events	4416	3666	1605	1336
tagged	4395	3656	1601	1336
efficiency (%)	99.5 ± 0.1	99.7 ± 0.1	99.8 ± 0.1	100 ± 0.1
Upper hemisphere				
tagged	4331	3604	1571	1308
efficiency (%)	98.1 ± 0.2	98.3 ± 0.2	97.9 ± 0.4	97.9 ± 0.4
Lower hemisphere				
tagged	4178	3606	1506	1309
efficiency (%)	94.6 ± 0.3	98.4 ± 0.2	93.8 ± 0.6	98.0 ± 0.4

Table 6.2: *MuTagIMO* performance on 91890 data and simulated cosmic events.

posed on the presence of an upper hemisphere tag when evaluating the tagging efficiency in the lower hemisphere. The presence of a *good ID track* in the cosmic runs appears to be a strong enough tag to probe the hemispheres separately and independently. One expects that for cosmic ray muons with a momentum higher than 6 GeV the efficiencies of upper and lower hemisphere are similar.

Table 6.2 shows the tagging efficiency of the *MuTagIMO* algorithm for the 91890 cosmic data set. The first column shows the performance of the tagging of *good ID tracks* with a momentum of 2 GeV and higher. The second column shows the results for tracks with a momentum of more than 6 GeV. From the *good ID tracks*, 99.8 ± 0.1 % were identified as muon tracks by the tagging algorithm. The identification is done by segments from either one of both hemispheres. For *good ID tracks*, with a minimum momentum of 2 GeV, the *MuTagIMO* efficiency is higher for the upper hemisphere than for the lower hemisphere, 98.4 ± 0.2 % versus 94.7 ± 0.4 % respectively. This difference can be explained by the absorption of the low momentum muons in the calorimeters.

From the 2840 *good ID tracks*, 2363 have a momentum larger than 6 GeV. The *MuTagIMO* efficiency for this sub-sample of tracks is 99.8 ± 0.1 % using segments from both hemispheres. For these high momentum tracks, the tagging efficiency per hemisphere is 98.3 ± 0.2 % for the upper hemisphere and 98.2 ± 0.2 % for the lower part of the spectrometer. These values are of interest since for collision events, muon tagging is done with one hemisphere.

In about 1.6 % of the cases, a *good ID track* with momentum above 6 GeV was not tagged in one of the hemispheres. These “lost tracks” are studied in more detail. In three quarters of these cases, not a single segment was reconstructed in that particular hemisphere. This is due to the fact that the Muon Spectrometer has a hole around $\eta = 0$, corresponding to $\theta = \pi/2$, as described in section 1.2.3. Figure 6.6-a) shows the *MuTagIMO* efficiency versus the polar angle θ of the upper hemisphere, Figure 6.6-b) of the lower hemisphere. The gray distribution shows the efficiency of the simulated sample, the black distribution for data. For both hemispheres, the polar angle of the

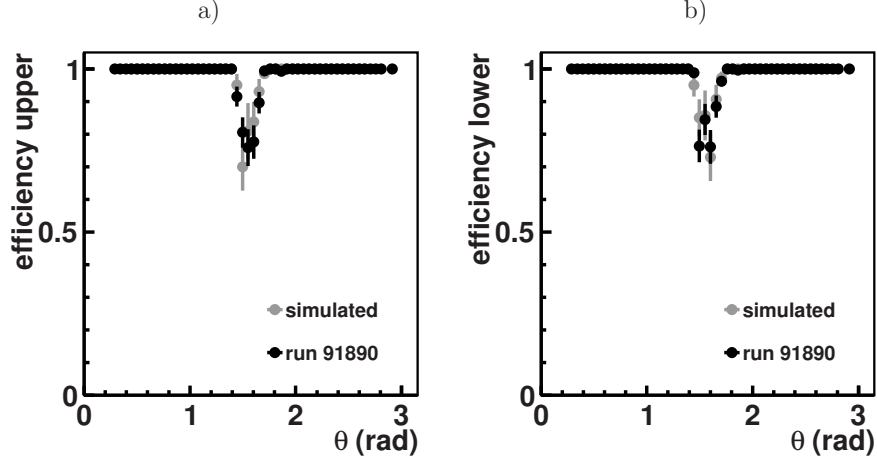


Figure 6.6: Polar distribution of the MuTagIMO tagging efficiency for tracks tagged with segments from a) the upper hemisphere of the Muon Spectrometer and b) the lower hemisphere. Results from the simulated data sample is shown in gray, the run 91890 data sample is shown in black.

“lost” track is centered around $\theta = \pi/2$. These tracks are pointing in the direction of the Muon Spectrometer where the Muon Spectrometer has a hole.

Figure 6.7-a) and b) shows the MuTagIMO tagging efficiency versus the azimuthal angle ϕ of the upper and lower hemispheres respectively. For these plots, *good ID tracks* around the gap around $\theta = \pi/2$ are rejected in order to detect structures in the efficiency profile of the azimuthal angle without convoluting the (very localized) inefficiencies around the Muon Spectrometer hole. No significant azimuthal dependence of the tagging efficiency is observed.

Table 6.2 summarizes the MuTagIMO performance for *simulated* events as well. The tagging efficiency of good tracks is 99.9 ± 0.1 % when using segments from both hemispheres. The reduced tagging efficiency for low momentum good tracks with segments from the lower hemisphere is observed in the simulated sample as well. The tagging of *good ID tracks* with a momentum higher than 6 GeV show efficiencies which are compatible within the statistical errors with the results of the data². The inefficiency of the tagging algorithm appears in the same θ region for both simulation and data indicating that the performance of the muon identification is understood to be limited by the ATLAS Muon Spectrometer geometry.

²When comparing results for the simulated and real data samples, one should correct for the absence of the η and ϕ dependent trigger in the simulated data. When taking the η distribution into account, the corrected MuTagIMO tagging efficiency for simulated data for the upper and lower hemisphere becomes 98.0 ± 0.6 % and 98.2 ± 0.5 % respectively.

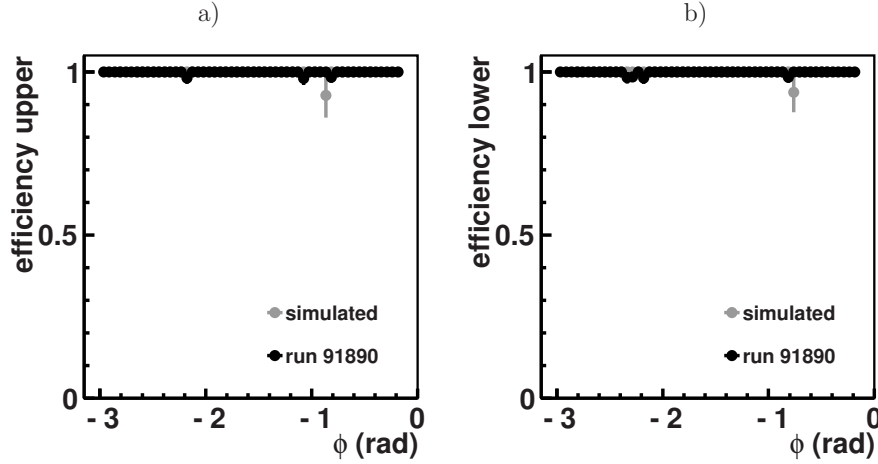


Figure 6.7: Azimuthal distribution of the MuTagIMO tagging efficiency for tracks tagged with segments from a) the upper hemisphere of the Muon Spectrometer and b) the lower hemisphere. Results from the simulated data sample is shown in gray, the run 91890 data sample is shown in black. Tracks with a polar angle θ between 1.4 and 1.7 are excluded from this plot.

6.6 Conclusion on cosmic muon tagging

In this chapter the reconstruction of cosmic ray muons for the Inner Detector and the Muon Spectrometer has been described. The adjustments to the MuTagIMO algorithm were discussed in detail. The several modifications to the reconstruction software resulted in an efficient cosmic muon identification performance.

Cosmic muon events, both simulated and real data have been studied. For good tracks, the distributions of simulated and real data are compatible, giving confidence in our level of understanding the detector, the data and reconstruction.

For the data, as defined by run 91890, the MuTagIMO tagging efficiency for *good ID tracks* with a momentum above 6 GeV is demonstrated to be $99.8 \pm 0.1 \%$ when associating segments from both the upper and lower hemisphere of the spectrometer. For muon tagging using only one of the spectrometer hemispheres, as will be the case for muon tagging in collision events, the MuTagIMO tagging efficiency is $98.3 \pm 0.2 \%$. The loss of $1.7 \pm 0.2 \%$ is due to the absence of muon stations in the region around $\theta = \pi/2$. Efficiencies obtained from the simulated sample are compatible with the data sample, within the statistical errors.

Chapter 7

Muon tagging performance on physics events

7.1 Introduction

The previous chapter discussed the performance of the muon tagging on cosmic muon data. As no collision data is available at the moment of writing of this thesis, we study the performance of the muon tagging algorithm on collision events with simulated physics events. This chapter will discuss the tagging efficiency and mis-identification rates of the various muon reconstruction algorithms, focusing on the **MuTagIMO** muon tagging algorithm. Throughout this chapter, we refer to the **MuTagIMO** algorithm as the *tagging algorithm*.

As discussed in section 3.5, the ATLAS muon reconstruction software consists of a set of algorithms reconstructing different types of muons, *Standalone*, *combined* and *tagged* muons. Combined muons, built from tracks from both the Inner Detector and the Muon Spectrometer are of high quality since it uses information from the different detector subsystems to reconstruct the muon. The geometry of the Inner Detector, limits the reconstruction acceptance of the combined algorithms going to $|\eta| < 2.5$.

Standalone muons are reconstructed in the Muon Spectrometer up to $|\eta| < 2.7$. Muons reconstructed in the Muon Spectrometer are extrapolated to the beam-line where the track parameters are evaluated. Furthermore, the Muon Spectrometer has no coverage at $|\eta| = 0$ and limited coverage between $|\eta| \sim 1.1$ and $|\eta| \sim 1.4$, as is discussed in section 1.2.3. This causes losses of muons in these regions. An implicit requirement on standalone muon reconstruction is that at least two muon stations should be traversed by the muon to build a muon track, as discussed in section 3.3.4. Muons that have very low momentum, less than 5 GeV, traverse less stations and are less efficiently reconstructed by the standalone algorithms.

The limited coverage of the Muon Spectrometer in the region of $|\eta| = 0$ was clearly visible in the muon tagging efficiency on cosmic ray muon data. For the evaluation of muon tagging on simulated physics events, the default (collision) configuration of the tagging algorithm is used. This is in contrast to the previous chapter where a setting was used which was optimized for cosmic muon tagging.

Combined and standalone muon reconstruction algorithms rely on an optimal understanding of the ATLAS detector. In other words, the hardware inefficiencies, as discussed in chapter 5 should be fully understood as well as the detector alignment and calibration and taken into account in the offline reconstruction. At LHC startup, it is foreseen that this level of understanding is not yet achieved and the muon reconstruction is expected to be less performing¹. An algorithm that is very robust and reliable can therefore provide an alternative to the combined and standalone muon reconstruction.

In this chapter, we will show that the tagging algorithm proves to be a valuable addition to the combined and standalone reconstruction algorithms. Summarizing, the tagging algorithm improves muon reconstruction in the following ways:

- The tagging algorithm recovers muons in the regions where the Muon Spectrometer has weak coverage, e.g. $\eta = 0$ and $1.1 < |\eta| < 1.4$, hereafter referred to as $|\eta| \sim 1.2$.
- The tagging algorithm recovers muons at *very low transverse momenta*, e.g. $2 < p_T < 5$ GeV.
- The tagging algorithm provides a *robust* alternative for the combined and standalone reconstruction algorithms.

First, the definitions of performance used in this chapter will be defined in section 7.2. Section 7.3 will show the results of how the tagging algorithm improves the efficiency of muon reconstruction. Section 7.4 discusses the mis-identification rate of the muon reconstruction. Section 7.5 presents the results from a study of the robustness of the muon reconstruction. Section 7.6 summarizes the performance results of the tagging algorithm and discusses the need of the tagging algorithm when reconstructing first data at the LHC.

7.2 Performance definitions

The muon identification efficiency ϵ is defined as the number of reconstructed muons which are truth-matched to a generated muon, divided by the number of generated muons:

$$\epsilon = \frac{N_{\text{reconstructed}}^{\mu}}{N_{\text{generated}}^{\mu}} \quad (7.1)$$

A reconstructed muon is truth-matched to a generated muon when angular difference $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ is smaller than 0.07, where $\Delta\eta$ is the difference in pseudorapidity between the reconstructed muon and generated muon, $\Delta\phi$ the difference in azimuthal angle. All stable final-state muons which are generated in the range of $|\eta| < 2.5$ and with a transverse momentum above 2 GeV are considered in the truth-matching. This means that the muon in the physics samples may have various origins. For example, in events with $t\bar{t}$ quark production in the semi- and di-lepton decay mode, the muon

¹Typically, track fitting techniques require a detailed understanding of the detector. Rejecting muons on χ^2 requirements will cause losses of muons when the detector is not properly modeled.

may originate from the hard decay of the W -boson as well as from the somewhat softer decay of the B-mesons in jets.

Note, that this definition of the efficiency gives the *physics performance* of the muon reconstruction, i.e. how many of the generated muons will be reconstructed and available for physics studies. An other definition of efficiency, requiring in addition that simulated hits are present in the Muon Spectrometer, gives the *algorithmic performance* of the muon reconstruction, i.e. how well the algorithms are performing. Throughout this thesis, the physics performance definition of efficiency is used, since it is of most interest for physics analysis. To evaluate the performance of the reconstruction however, the algorithmic performance takes into account the Muon Spectrometer acceptance and gives a measure for how well the algorithms perform.

The mis-identification rate, or *fake rate* R_{fake} , is defined as the number of reconstructed muons which are *not* truth-matched to a generated muon per event:

$$R_{\text{fake}} = \frac{N_{\text{reconstructed}}^{\text{non-}\mu}}{N_{\text{events}}} \quad (7.2)$$

The combination of efficiency and mis-identification rate tells the user if an algorithm is performing properly or not. A highest possible efficiency and a lowest possible fake rate is of course pursued, but in practice not feasible. Moreover, the performance of the algorithms are dependent on the transverse momentum of the reconstructed muon. It therefore depends on the physics analysis whether an efficiency is sufficient or a fake rate is acceptable. In the following sections the algorithm is assumed to be performant when the efficiency is close to the geometrical acceptance of the Muon Spectrometer and when the fake rate of the tagging algorithm is of the same order as the fake rate of the combined and standalone algorithms together.

7.3 Muon reconstruction efficiency

In order to evaluate the muon identification efficiency, we chose physics samples with muon final states with various topologies. A $Z^0 \rightarrow \mu^+\mu^-$ sample provides high energy muons in a relative quiet environment and serves as a benchmark for the muon identification performance studies, as discussed in section 2.3.4. A $J/\psi \rightarrow \mu^+\mu^-$ sample provides muons with low transverse momentum and serves to investigate the muon tagging performance for very low momentum muons. A $t\bar{t}$ sample provides muons from a wide range of transverse momenta. These events have many tracks from charged particles, making muon tagging challenging. Figure 7.1 shows the track multiplicities for the three samples. It is clear that the $Z^0 \rightarrow \mu^+\mu^-$ and the $J/\psi \rightarrow \mu^+\mu^-$ samples have less reconstructed tracks than the busy $t\bar{t}$ events.

In this section we show the impact on the efficiency and mis-identification rate of adding *tagged* muons to the collection of *combined* and *standalone* muons.

The muons reconstructed are written to the AOD, as discussed in 2.2. The muon can be reconstructed by various algorithms, as discussed in section 3.5. For example, a muon from the *Muid* collection can be reconstructed by both the standalone algorithm

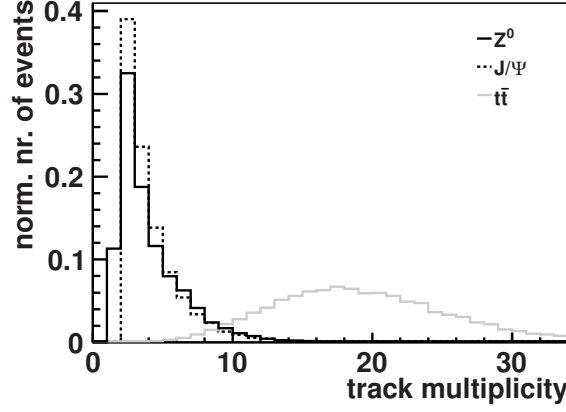


Figure 7.1: The number of reconstructed tracks, or track multiplicity, for three types of events.

(MOORE) and tagging algorithm (MuTagIMO). Muons stored on the AOD are removed from such *overlaps* and thus stored only once. The set of algorithms which reconstructed the muon are stored in an author list. The muon is assigned a *main author*, favoring the combined algorithm over the standalone algorithm and the standalone algorithm over the tagging algorithm.

The study is done on the *Muid* muon collection, see section 3.5. As discussed in section 3.5.1, the standalone muons are extrapolated to the beam line in order to evaluate the track parameters close to the IP. In the rest of this chapter, these muons are referred to as *standalone* (SA) muons. The refitted *combined* (CB) muons and the standalone muons together are compared to the set of standalone, combined and tagged muons, in order to evaluate the added value of the muon tagging algorithm.

Figure 7.2 shows the muon identification efficiency of the two sets of algorithms. The gray markers show the performance of the combined and standalone algorithms, the black markers add the tagged muons to the collection. Three different samples are studied: the top row shows results from the $Z^0 \rightarrow \mu^+ \mu^-$ sample, the middle row of the $J/\psi \rightarrow \mu^+ \mu^-$ sample and the $t\bar{t}$ sample in the lower row. The column a) presents the efficiency versus pseudorapidity η and column b) versus transverse momentum p_T . A minimal transverse momentum requirement of 2 GeV is imposed for these plots.

The efficiency for the $Z^0 \rightarrow \mu^+ \mu^-$ sample is shown in the upper left plot of Figure 7.2. The efficiency for the combined and standalone muons is close to 95 % over the full pseudorapidity range. The distinguished dips in the distribution at $\eta = 0$ and around $|\eta| \sim 1.2$ are inefficiencies due to the gaps in the coverage of the Muon Spectrometer. Adding tagged muons to the collection recovers the muons in the $|\eta| \sim 1.2$ region, since the algorithm does not require a muon track to be reconstructed in the Muon Spectrometer, but muon segments. In this region with partial coverage, the muon is likely to traverse only one muon station layer while at least two segments are required

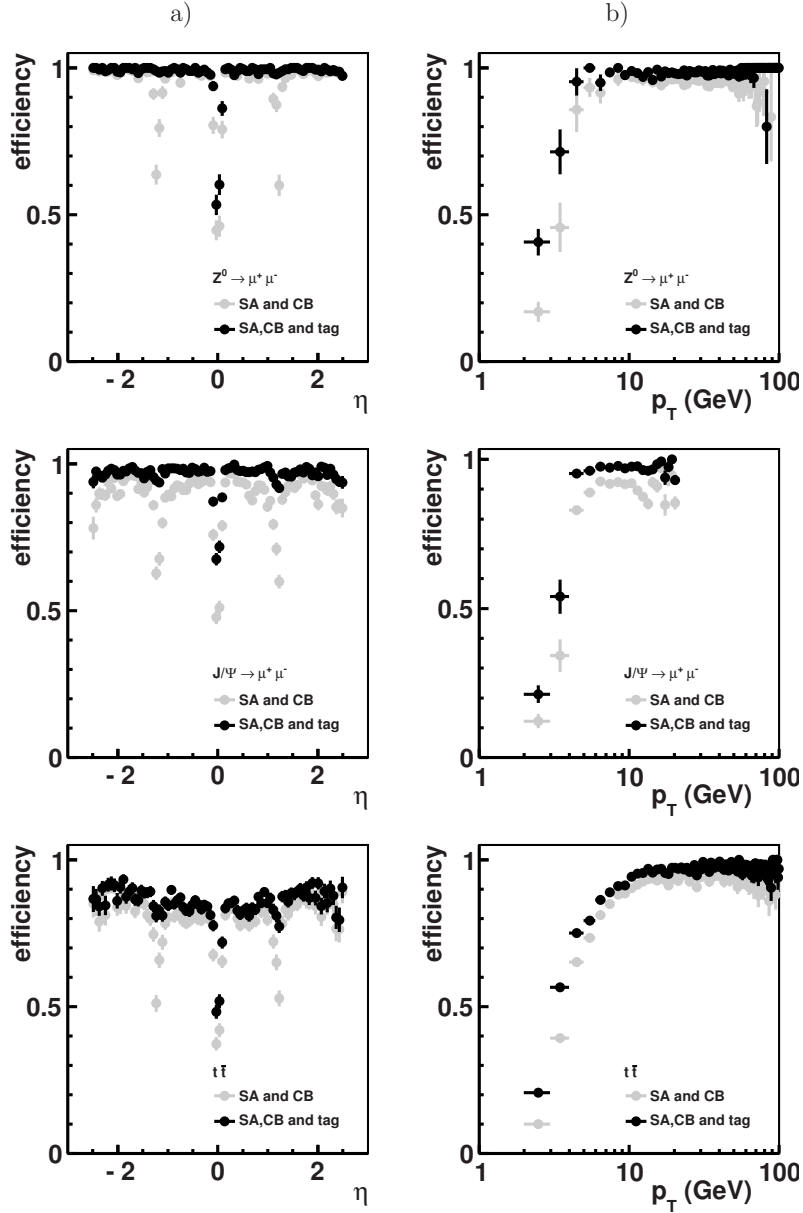


Figure 7.2: Efficiencies versus a) η and b) transverse momentum of the Inner Detector track. The upper figures show the results of the $Z^0 \rightarrow \mu^+ \mu^-$ sample, the middle figures show the J/ψ sample and the lower figures the top sample.

$Z^0 \rightarrow \mu^+\mu^-$	$p_T > 2 \text{ GeV}$	$p_T > 5 \text{ GeV}$	$p_T > 20 \text{ GeV}$
CB and SA muons	$95.1 \pm 0.2\%$	$95.8 \pm 0.2 \%$	$95.8 \pm 0.2\%$
tagged muons	$97.6 \pm 0.1\%$	$98.2 \pm 0.1 \%$	$98.2 \pm 0.1\%$
CB, SA and tagged muons	$97.9 \pm 0.1\%$	$98.4 \pm 0.1 \%$	$98.5 \pm 0.1\%$
$J/\psi \rightarrow \mu^+\mu^-$			
CB and SA muons	$88.7 \pm 0.2\%$	$91.3 \pm 0.2 \%$	
tagged muons	$94.9 \pm 0.1\%$	$97.1 \pm 0.1 \%$	
CB, SA and tagged muons	$96.1 \pm 0.1\%$	$97.1 \pm 0.1 \%$	
$t\bar{t}$			
CB and SA muons	$78.6 \pm 0.3\%$	$91.5 \pm 0.2 \%$	$94.2 \pm 0.2\%$
tagged muons	$81.6 \pm 0.3\%$	$92.8 \pm 0.1 \%$	$96.0 \pm 0.2\%$
CB, SA and tagged muons	$83.9 \pm 0.3\%$	$94.8 \pm 0.2 \%$	$97.2 \pm 0.2\%$

Table 7.1: Combined, standalone and tagged muon identification efficiencies on various simulated samples, for different p_T requirements.

to build a track. Some muons are recovered in the $\eta = 0$ region, where muons traverse e.g. one station close to the gap in the Muon Spectrometer. Muon segments from these stations are used to tag tracks in the $\eta = 0$ region which would otherwise be lost.

In the $J/\psi \rightarrow \mu^+\mu^-$ sample, shown in the middle plot of Figure 7.2-b), the tagging algorithm recovers as expected muons in the same η regions as the $Z^0 \rightarrow \mu^+\mu^-$ sample. Besides that, an increase over the full pseudorapidity range is observed when adding tagged muons to the collection. Muons from J/ψ decays have relatively low transverse momentum, as is shown in Figure 2.5. These muons may not traverse the three station layers of the Muon Spectrometer, resulting in a lower efficiency for the combined and standalone algorithms. Segments, however, are reconstructed and used by the muon tagging algorithm to identify muon tracks. Thus tagged muons are recovered in the low transverse momentum region.

The lower row of Figure 7.2-a) shows the recovery of muons in the η regions as discussed above for the $t\bar{t}$ sample. Muons from B-meson decays cause low momentum muons which are subject to the same reconstruction inefficiencies as low momentum muons from J/ψ decays. In the lower plot of Figure 7.2-b), the increase in efficiency by adding tagged muons to the collection is most apparent for low transverse momentum muons.

Table 7.1 summarizes the integrated efficiencies for the two sets of muons and for tagged muons only, for the three benchmark physics samples. Furthermore, results for three p_T cuts are presented in the table. The 2 GeV requirement represents the minimal transverse momentum a muon needs to have in order to traverse the Calorimeters. This requirement is set in the configuration of the muon tagging algorithm, as shown in Table 4.1. The 5 GeV requirement is a standard requirement used in the muon reconstruction community to evaluate performances. Most high- p_T physics analyses such as $t\bar{t}$, Z^0 and W [71] impose a 20 GeV cut on muon transverse momentum.

The muon tagging efficiency without considering combined and standalone algorithms is above $98.2 \pm 0.1 \%$ for muons from Z^0 boson decays with a transverse mo-

momentum higher than 5 GeV. For muons from J/ψ decays above 2 GeV the efficiency is 94.0 ± 0.1 %. For muons coming from top quark decays, the muon tagging efficiency is 96.0 ± 0.2 % for muons above 20 GeV. In general, the tagging efficiency is higher than the efficiency of the combined and standalone reconstruction combined. In the ATLAS muon reconstruction, tagged muons are added to the collection of combined and standalone muons. It is more sensible to look at the results of what the tagging algorithm adds to the combined and standalone algorithms.

Tagged muons adds around 2.7 % efficiency for all three momentum cuts for the $Z^0 \rightarrow \mu^+\mu^-$ sample. Since the gains are due to recovery of muons in the pseudorapidity range where the Muon Spectrometer has lower coverage, the gains are not momentum dependent. For the $J/\psi \rightarrow \mu^+\mu^-$ sample however, the muon tagging algorithm improves the muon reconstruction efficiency with 7.4 % for muons above 2 GeV and 5.8 % for muons above 5 GeV transverse momentum. For the $t\bar{t}$ sample, gains in efficiency of around 5.3 % are shown for muons above 2 GeV, going to a value of 3.0 % for muons with transverse momentum above 20 GeV.

As can be observed in Table 7.1, some muons are reconstructed by the combined and standalone algorithms and *not* tagged. Two types of processes cause this behaviour. For standalone muons, which are built from a Muon Spectrometer track which is extrapolated to the beam line, no Inner Detector track is available. This results in a track which is not picked up by the combined or tagged algorithm. Secondly, some tracks reconstructed by the combined algorithm are not tagged. The tagging algorithm has assigned the wrong track to the Muon Spectrometer segments in the ambiguity solving step.

7.4 Mis-identification rate

It is clear that adding the muon tagging algorithm to the set of muon reconstruction algorithms improves the efficiency significantly. The muon tagging algorithm performs matching, as described in section 4.5, and applies loose requirements to the matching criteria. It is therefore expected that adding tagged muons will increase the mis-identification rate. In chapter 4 we presented techniques applied by the **MuTagIMO** tagging algorithm to reduce the mis-identification rate whilst still being efficient. The algorithm is tuned to balance the gain in muon reconstruction and keeping the fake rate at an acceptable level.

Figure 7.3 shows the number of fake muons per event, e.g. tracks which were tagged as a muon but which were not truth matched to a muon. Column a) shows the distribution of fake muons per event versus pseudorapidity η , column b) versus transverse momentum p_T . The upper row shows results from the $Z^0 \rightarrow \mu^+\mu^-$ sample, the middle row from the $J/\psi \rightarrow \mu^+\mu^-$ sample and the lower row of a $t\bar{t}$ sample. Two sets of reconstructed muons are presented, combined and standalone muons in gray and combined, standalone and tagged muons in black. The minimal transverse momentum of the tracks in these figures was required to be 5 GeV.

For the $Z^0 \rightarrow \mu^+\mu^-$ and $J/\psi \rightarrow \mu^+\mu^-$ sample, the fake rate increases when adding

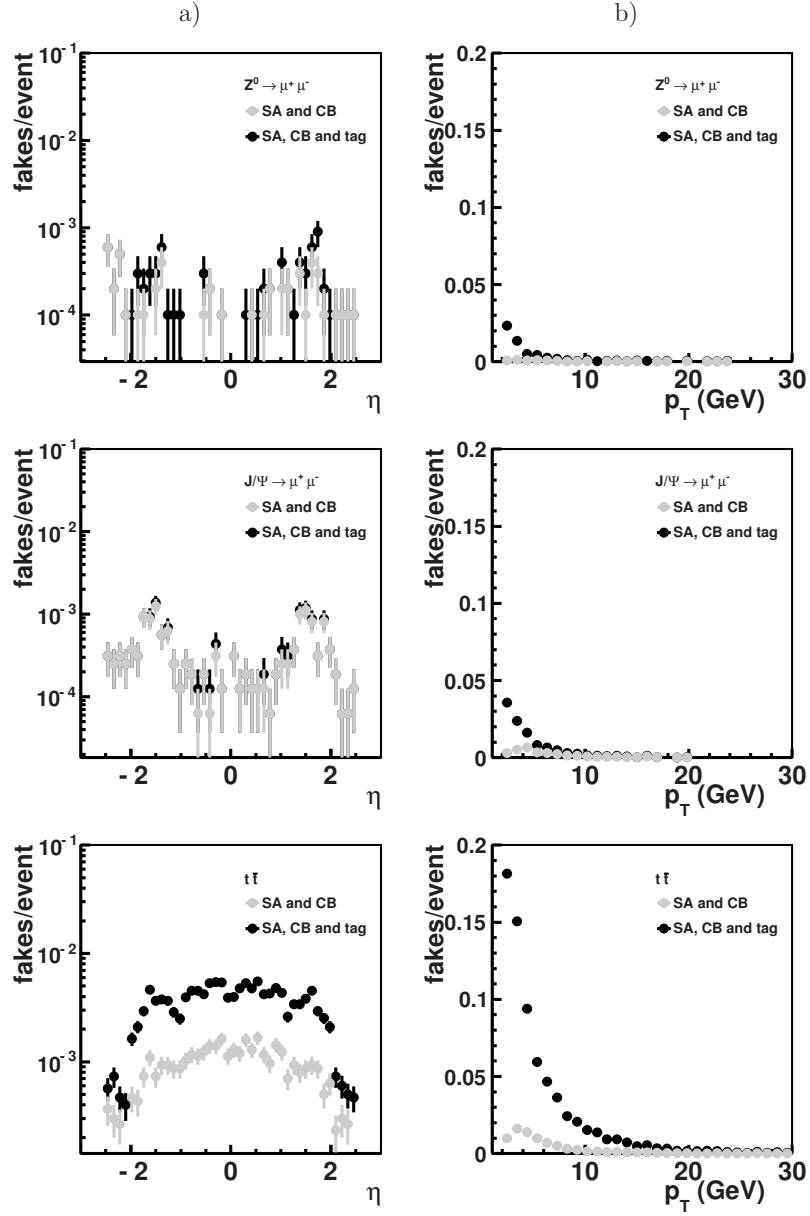


Figure 7.3: Fake muons versus a) η and b) transverse momentum of the Inner Detector track. The upper figures show the results of the $Z^0 \rightarrow \mu^+ \mu^-$ sample, the middle figures show the J/ψ sample and the lower figures the top sample.

$Z^0 \rightarrow \mu^+\mu^-$	$p_T > 2 \text{ GeV}$	$p_T > 5 \text{ GeV}$	$p_T > 20 \text{ GeV}$
CB and SA muons	$1.2 \pm 0.1\%$	$0.5 \pm 0.1 \%$	$0.14 \pm 0.04\%$
tagged muons	$2.7 \pm 0.2\%$	$0.7 \pm 0.1 \%$	$0.12 \pm 0.03\%$
CB, SA and tagged muons	$3.4 \pm 0.2\%$	$0.8 \pm 0.1 \%$	$0.16 \pm 0.04\%$
$J/\psi \rightarrow \mu^+\mu^-$			
CB and SA muons	$3.4 \pm 0.1\%$	$1.5 \pm 0.1 \%$	
tagged muons	$4.9 \pm 0.2\%$	$1.3 \pm 0.1 \%$	
CB, SA and tagged muons	$5.8 \pm 0.2\%$	$1.6 \pm 0.1 \%$	
$t\bar{t}$			
CB and SA muons	$17.0 \pm 0.2\%$	$3.7 \pm 0.1 \%$	$0.4 \pm 0.1\%$
tagged muons	$33.3 \pm 0.3\%$	$12.9 \pm 0.2 \%$	$1.0 \pm 0.1\%$
CB, SA and tagged muons	$44.5 \pm 0.4\%$	$13.7 \pm 0.2 \%$	$1.1 \pm 0.1\%$

Table 7.2: Combined, standalone and tagging fake rates on various simulated samples, for different p_T requirements.

tagged muons to the collection. Most of the mis-identified tracks come from low transverse momentum tracks, as is observed in column b). For these tracks, material effects such as multiple scattering and energy loss, as described in section 3.4.4, worsen the muon tagging algorithms matching performance. In busy events with high track multiplicities, as is the case for $t\bar{t}$ events in the lower plots of Figure 7.3, the fake rate increases significantly when adding tagged muons to the collection.

Table 7.2 summarizes the fake rates for the three samples, integrated over the full pseudorapidity range, for the two sets of reconstruction algorithms. The results for three different cuts on the transverse momentum are presented. As expected, the mis-identification rate can be significantly reduced by applying a transverse momentum cut. For selecting a $Z^0 \rightarrow \mu^+\mu^-$ sample a transverse momentum requirement of 20 GeV is applied and the fake rate of $0.16 \pm 0.04 \%$ is achieved for the combined, standalone and tagged muon collection. For selecting a $t\bar{t}$ sample a 20 GeV cut on the transverse momentum is applied, in this case a fake rate is $1.1 \pm 0.1 \%$ when MuTagIMO muons are added to the collection. For selecting $J/\psi \rightarrow \mu^+\mu^-$ a lower transverse momentum cut is applied. The mis-identification rate is $5.8 \pm 0.2 \%$ when selecting muons above 2 GeV and $1.6 \pm 0.1 \%$ when selecting muons above 5 GeV. For reference, the mis-identification rate for the tagging algorithm alone is shown in the table as well.

Figure 7.4 shows the efficiency and fake rates of the tagging algorithm versus the number of reconstructed tracks in the Inner Detector, e.g. track multiplicity. For these plots, the transverse momentum is required to be above 5 GeV. The grey markers show the $J/\psi \rightarrow \mu^+\mu^-$ sample, the black dots the $Z^0 \rightarrow \mu^+\mu^-$ sample and the $t\bar{t}$ sample is shown by black triangles. Figure 7.4-a) shows that the tagging efficiency decreases for events with increasing track multiplicity. Figure 7.4-b) shows that the mis-identification rate increases significantly for busier events. The numerous Inner Detector tracks make it more likely that a wrong track is matched to a Muon Spectrometer segment. This results in an increase of the mis-identification rate and a decrease in tagging efficiency.

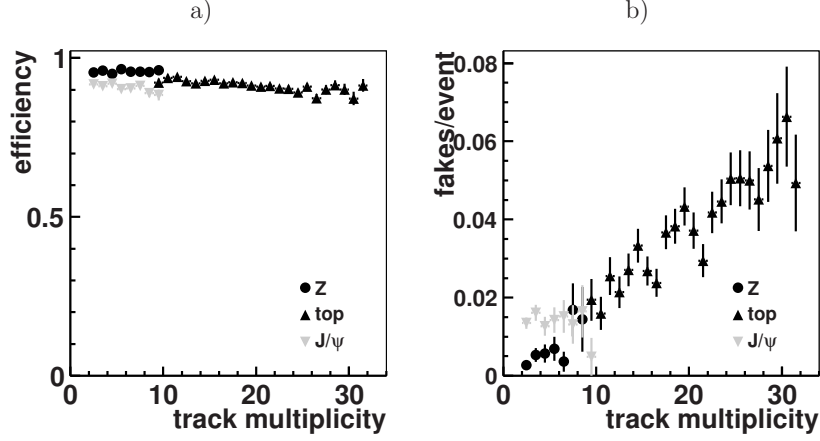


Figure 7.4: a) Efficiencies and b) the number of fake muons per event, plotted versus the number of reconstructed tracks per event.

7.5 Robustness

The muon tagging algorithm is designed to be a robust alternative for the standalone and combined algorithms. A study has been performed [72] to estimate the reconstruction efficiency robustness for the various algorithms when severe detector failure occurs. This section summarizes the results for two sets of muons, one with the combined and standalone muons, the other with the MuTagIM0 tagged muons added to the collection.

Detector failure is simulated by removing raw hits (PrepRawData hits, see section 2.2) from MDT and CSC chambers before running the muon reconstruction. As a worst-case scenario test, entire station layers (inner and middle station layers) are disabled in the reconstruction. This situation is very severe and unlikely. More realistic are failures at the level of chambers or multi layers as is discussed in section 5.5.

Events from a $Z^0 \rightarrow \mu^+\mu^-$ sample `valid1.005145.PythiaZmumu.digit.RD0.e322_s405` were used. This sample was simulated and digitized with software release 13.0.40. Reconstruction is done in software release 14.5.0. The truth-matching between reconstructed tracks and simulated particles is done at hit-level. A muon track is associated to a generated particle when simulated hits match hits associated to the track. The efficiencies quoted below are *physics efficiencies*, as discussed in section 7.2, in which no presence of generated hits in the Muon Spectrometer is required. An *algorithmic efficiency* is calculated by requiring at least one truth hit in the Muon Spectrometer. For the quoted efficiencies, a transverse momentum of more than 5 GeV was required.

Figure 7.5 shows the reconstruction efficiency of the two sets of algorithms versus pseudorapidity η for three cases of detector failure. The upper plot shows the nominal reconstruction efficiency, where no chambers were removed from reconstruction. For the middle plot, the Inner (I) station layer is removed and for the lower plot, the Middle

Physics efficiency	nominal	Inner stations removed	Middle stations removed
CB and SA muons	$95.1 \pm 0.2\%$	$78.8 \pm 0.5 \%$	$81.9 \pm 0.4\%$
CB, SA and tagged muons	$97.4 \pm 0.1\%$	$94.4 \pm 0.2 \%$	$95.0 \pm 0.2\%$
Algorithmic efficiency			
CB and SA muons	$95.9 \pm 0.2\%$	$79.3 \pm 0.5 \%$	$82.8 \pm 0.4\%$
CB, SA and tagged muons	$98.3 \pm 0.1\%$	$95.2 \pm 0.2 \%$	$96.8 \pm 0.2\%$

Table 7.3: Muon reconstruction efficiency evaluating a $Z^0 \rightarrow \mu^+\mu^-$ sample. Results are shown for the nominal detector geometry and when removing the Inner station layer and the Middle station layer respectively.

(M) station layer is removed². The gray markers show the efficiency for the combined and standalone muons, the black markers adds tagged muons to the collection.

The *nominal* efficiency distribution shows an efficiency close to 100 % over the full pseudorapidity range for the combined and standalone muons, with the familiar gaps at $\eta = 0$ and around $|\eta| \sim 1.2$ due to the Muon Spectrometer coverage. The muon tagging algorithm recovers muons in these regions.

When *Inner stations* are removed from the reconstruction, the efficiency of the combined and standalone reconstruction decreases. Periodic losses in the barrel region are observed due to gaps in the middle station layer where the toroid ribs intersects the station layer. Losses are severe in the barrel-endcap transition region where muons only traverse the Inner and Middle station layers from which one is now removed. Adding tagged muons to the collection recovers most of the muon losses over the full pseudorapidity range.

Removing the *Middle station* layer results in similar losses for the combined and stand alone muons, as is shown in the lower plot in Figure 7.5. The recovery in the barrel-endcap region is not as complete as in the case that inner stations were removed. At a pseudorapidity $|\eta| = 1.2$ the muon traverses the only the Middle station layer in the endcap and removing this layer causes muons to be lost.

Table 7.3 summarizes the η -integrated *physics* efficiencies for the two sets of reconstruction algorithms for no station layer removed, Inner station layer removed and Middle station layer removed. The efficiency for the combined and standalone algorithms drops from $96.2 \pm 0.2 \%$ to $84.1 \pm 0.4 \%$ ($79.8 \pm 0.5 \%$) when the Inner (Middle) station layer is removed. When the muon tagging algorithm is added to the set of muon reconstruction algorithms, the efficiency losses are less. The efficiency drops from $98.6 \pm 0.1 \%$ to $97.5 \pm 0.2 \%$ ($95.7 \pm 0.2 \%$) when the Inner (Middle) station layer is removed. The *algorithmic* efficiencies are presented in the lower two columns of Table 7.3. Overall, the efficiencies are around a percent higher compared to the physics efficiency. In column b) of Figure 7.5 it can be seen that for the nominal geometry, the difference in physics and algorithmic efficiency is almost exclusively due to the gap in the Muon Spectrometer at $\eta = 0$.

²For this analysis, the BEE stations are considered Inner stations.

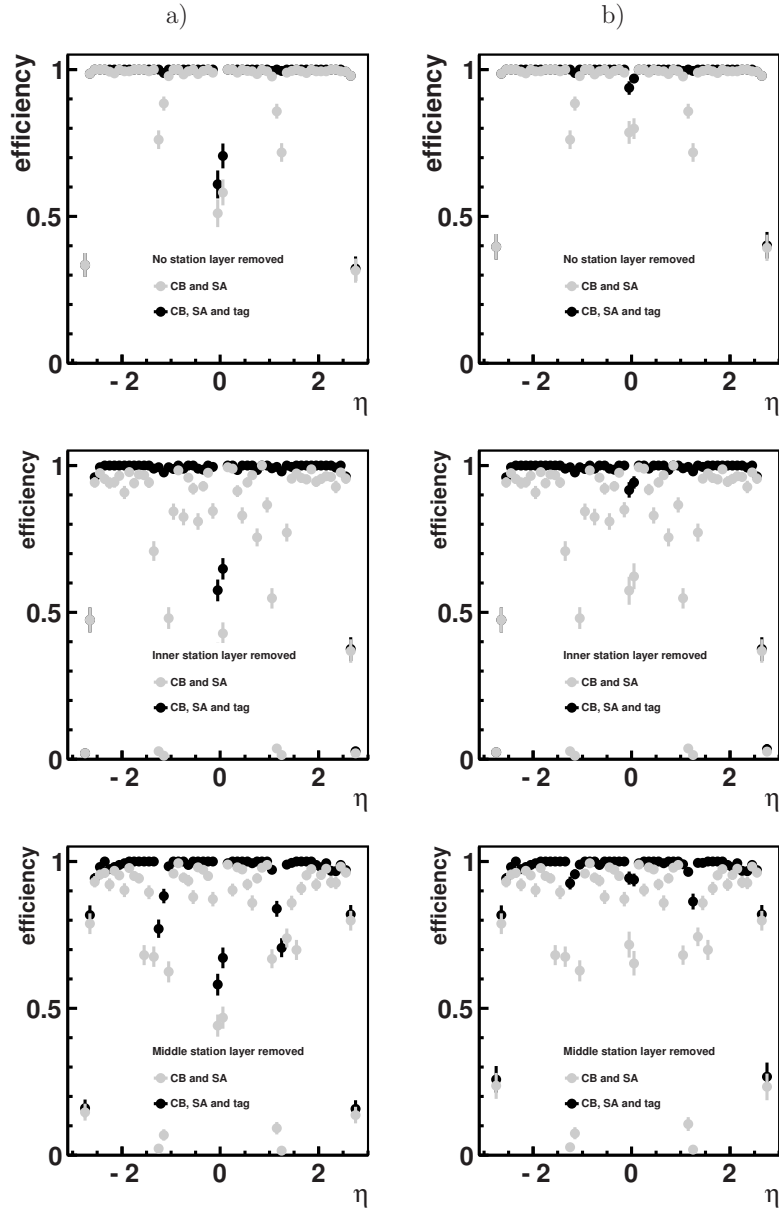


Figure 7.5: Muon reconstruction efficiency versus pseudorapidity η for $Z^0 \rightarrow \mu^+\mu^-$ events when parts of the ATLAS Muon Spectrometer are switched off. For the upper plot, no stations were switched off. For the middle plot, the Inner station layer was switched off. For the lower plot, the Middle station layer was switched off. Both a) Physics efficiency and b) Algorithmic efficiency are shown.

7.6 Prospects and conclusion

The MuTagIMO tagging algorithm will prove invaluable for analysis with the first collision data of the LHC, when the detector is not yet fully understood. In the beginning, the ATLAS detector is not fully calibrated nor aligned, and the momentum and energy scales need to be measured. In this chapter we have presented performances of the muon reconstruction based on simulated physics data, though at LHC startup these quantities need to be measured from real data. The benchmark muon final state processes used in this chapter will be used for these measurements when LHC will have first collisions.

The measurement of J/ψ and Z^0 events will be one of the first physics processes to be analyzed at ATLAS. Figure 7.6 shows the invariant mass of the di-muon events of the J/ψ sample, Figure 7.7 of the Z^0 sample. Events reconstructed from combined and standalone muons are shown in grey, events from muons which were either combined, standalone or tagged are shown in black. In both plots, muons with a transverse momentum above 2 GeV are used to reconstruct the invariant mass with. Using tagged muons in the analysis in addition to the combined and standalone muons adds $15.3 \pm 0.3\%$ entries to the plot for the J/ψ sample and $5.8 \pm 0.3\%$ entries for the Z^0 sample. The increase is most pronounced for the J/ψ sample since low momentum muons are used to reconstruct the invariant mass. As discussed in section 7.3, the tagging algorithm adds predominantly low momentum muons.

The relative increase in entries of the invariant mass plots of the two samples are directly related to the increase of the muon reconstruction efficiency when adding tagged muons to the combined and standalone muons. For the muons from Z^0 boson decays the muon reconstruction efficiency increases from 95.1 % to 97.9 % when adding tagged muons. As expected, the difference of the squared efficiencies is 5.4 % and compatible with the value observed in the invariant mass plot. For the muons coming from J/ψ decays the reconstruction efficiency increases from 88.7 % to 96.1 % when adding tagged muons. This in turn corresponds to a squared efficiency difference of 13.7 %, also compatible with the value observed in the invariant mass plot.

Figure 7.8 shows the invariant mass of four muons from a Higgs boson decaying to four leptons. The generated Higgs mass is 130 GeV. First combinations of two muons are made. One combination is required to lie within 20 GeV from the Z^0 boson mass. From the dimuon combinations of the other muons, the combination with the highest invariant mass is chosen. Both muons combinations are then combined to one state from which the invariant mass is shown in the figure. Again, two sets of muon reconstruction algorithms are shown: combined and standalone muons in gray, and combined, standalone and tagged muons in black. Adding tagged muons to this analysis adds $2.1 \pm 0.3\%$ to the number of entries in the plot.

We have shown that the tagging algorithm provides a very efficient addition to the combined and standalone muon reconstruction algorithms. The efficiency gain is due to the recovery of muons in regions where the Muon Spectrometer has poor coverage, namely the hole at $\eta = 0$ and in the barrel-endcap transition region at $1.1 < |\eta| < 1.4$. Moreover, gains in efficiency are observed for muons down to 2 GeV transverse momentum. The increase of efficiency comes with an increase of the mis-identification

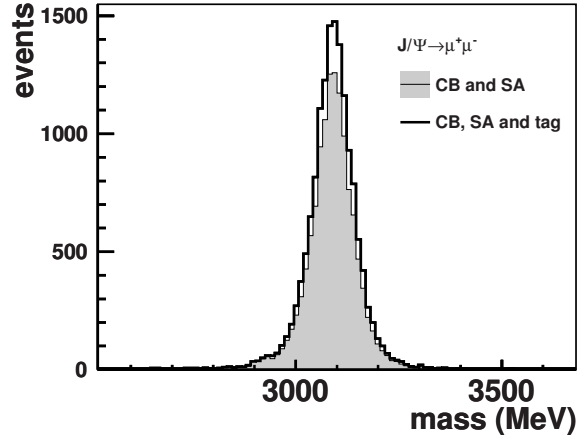


Figure 7.6: Invariant mass of the two reconstructed muons in the $J/\psi \rightarrow \mu^+\mu^-$ sample.

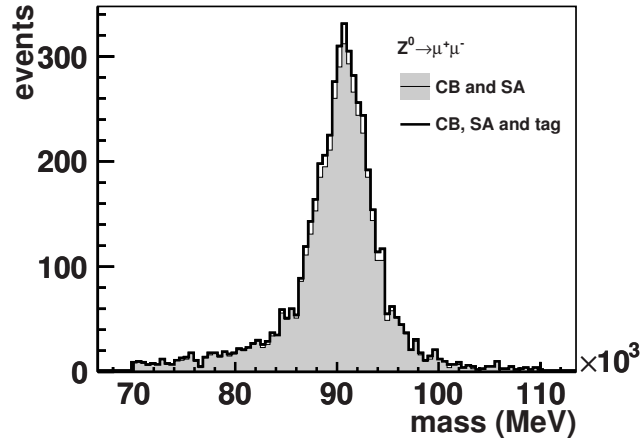


Figure 7.7: Invariant mass of the two reconstructed muons in the $Z^0 \rightarrow \mu^+\mu^-$ sample.

	$Z^0 \rightarrow \mu^+\mu^-$	$J/\psi \rightarrow \mu^+\mu^-$	$H^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$
CB and SA muons	4660	12762	3044
CB, SA and tagged muons	4948	15071	3109
increase (%)	5.8 ± 0.3	15.3 ± 0.3	2.1 ± 0.3

Table 7.4: The number of entries in the invariant mass plots of the various physics processes.

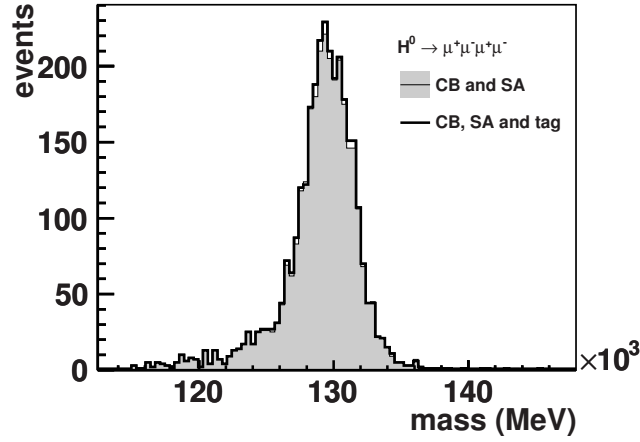


Figure 7.8: Invariant mass of four reconstructed muons in the $H^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$ sample.

rate. This origin of this increase is well understood and application of cuts at transverse momentum keeps the fake rate at an acceptable level. The tagging algorithm has proven to be very robust as well, keeping an excellent efficiency in severe scenarios where parts of the Muon Spectrometer are not operational.

The muon identification efficiency for the decay of the Z^0 boson into two muons with a transverse momentum above 5 GeV is demonstrated to be $98.4 \pm 0.1 \%$, for muons which are combined, standalone or tagged. This value is compatible with the muon identification efficiency measured in real data from cosmic ray muons, which is $98.3 \pm 0.2 \%$. The muon tagging efficiency in both cases is close to the geometrical acceptance of the Muon Spectrometer.

Appendix A

Transformation from global to local angles

The MuTagIMO tagging algorithm matches Inner Detector tracks to Muon Spectrometer segments. Matching is performed on a set of variables, from which one is the direction difference between the track and segment. The representation of the track direction is in *global coordinates* ϕ and θ , which is a useful representation when dealing with multiple scattering processes during the track parameter extrapolation. The segment however, represents the direction in the *local coordinates* of the MDT station α_{XZ} and α_{YZ} , which are the natural coordinates when fitting the segment to driftcircles. Figure 4.3 shows the local MDT station coordinate system. Each station has its own orientation in the global ATLAS coordinate system, represented by a (3×3) rotation matrix R , expressed in cartesian coordinates.

When matching extrapolated track parameters to a segment, the representation of the covariances of the directional coordinates of the track cov_{global} is transformed to the segments *local coordinate system* cov_{local} . This transformation is given by

$$cov_{\text{local}}^{-1} = J_{\text{global} \rightarrow \text{local}}^T \cdot cov_{\text{global}}^{-1} \cdot J_{\text{global} \rightarrow \text{local}} \quad (\text{A.1})$$

Where $J_{\text{global} \rightarrow \text{local}}$ is a Jacobian matrix describing the transformation between the global to the local coordinate systems.

An intermediate representation in cartesian coordinates is required to calculate the Jacobian $J_{\text{global} \rightarrow \text{local}}$ using rotation R . The Jacobian $J_{\text{global} \rightarrow \text{local}}$ is constructed from two separate Jacobians, one transforming from the global angles ϕ and θ into the cartesian coordinate system x, y, z in which R is expressed. The second part transforms from cartesian coordinates to the local angle representation α_{XZ} and α_{YZ} :

$$J_{\text{global} \rightarrow \text{local}} = J_{\text{cartesian} \rightarrow \text{local}} \cdot R \cdot J_{\text{global} \rightarrow \text{cartesian}} \quad (\text{A.2})$$

Given the expression of the cartesian coordinates in the global angles:

$$x = \sin \theta \cos \phi \quad (\text{A.3})$$

$$y = \sin \theta \sin \phi \quad (\text{A.4})$$

$$z = \cos \theta \quad (\text{A.5})$$

The Jacobian $J_{\text{global} \rightarrow \text{cartesian}}$ is as follows:

$$J_{\text{global} \rightarrow \text{cartesian}} = \begin{pmatrix} \frac{\partial x}{\partial \phi} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial \phi} & \frac{\partial y}{\partial \theta} \\ \frac{\partial z}{\partial \phi} & \frac{\partial z}{\partial \theta} \end{pmatrix} = \begin{pmatrix} -\sin \theta \sin \phi & \cos \theta \cos \phi \\ \sin \theta \cos \phi & \cos \theta \sin \phi \\ 0 & -\sin \theta \end{pmatrix} \quad (\text{A.6})$$

The second part of the Jacobian uses the expression of the local angles in cartesian coordinates:

$$\alpha_{XZ} = \text{atan}(z/x) \quad (\text{A.7})$$

$$\alpha_{YZ} = \text{atan}(z/y) \quad (\text{A.8})$$

Such that the Jacobian can be calculated to be:

$$J_{\text{cartesian} \rightarrow \text{local}} = \begin{pmatrix} \frac{\partial \alpha_{XZ}}{\partial x} & \frac{\partial \alpha_{XZ}}{\partial y} & \frac{\partial \alpha_{XZ}}{\partial z} \\ \frac{\partial \alpha_{YZ}}{\partial x} & \frac{\partial \alpha_{YZ}}{\partial y} & \frac{\partial \alpha_{YZ}}{\partial z} \end{pmatrix} = N \begin{pmatrix} \frac{-\sin \alpha_{XZ}}{\sin \alpha_{YZ}} & 0 & \frac{\cos \alpha_{XZ}}{\sin \alpha_{YZ}} \\ 0 & \frac{-\sin \alpha_{YZ}}{\sin \alpha_{XZ}} & \frac{\cos \alpha_{YZ}}{\sin \alpha_{XZ}} \end{pmatrix} \quad (\text{A.9})$$

Where N is a normalization factor given by:

$$N = \sqrt{(\cos \alpha_{XZ} \sin \alpha_{YZ})^2 + (\sin \alpha_{XZ} \cos \alpha_{YZ})^2 + (\sin \alpha_{XZ} \sin \alpha_{YZ})^2} \quad (\text{A.10})$$

The segment surface provides the rotation matrix R of the transformation of global to local coordinates. From rotation R and the global angles ϕ and θ , the Jacobian in expression A.2 is calculated. With the $J_{\text{global} \rightarrow \text{local}}$ Jacobian, the covariances of the extrapolated track (expressed in global coordinates) are transformed to local covariances.

Appendix B

Hypothesis distribution

B.1 Introduction

The MuTagIMO tagging algorithm deploys several techniques to optimize muon tagging efficiency and reduce the misidentification rate. One of the sources of misidentification is the association of segments to the *wrong* track when multiple tracks match the same segments. A track selection method is presented in section 4.6.2, based on a discriminating variable, the *rejection factor* f_R , built from three matching variables: $f_R(nSeg, locY, \alpha_{yz})$. The claim was made that given that:

- the rejection factor is *factorizable* in its three matching variables
- and that the separate rejection factors $f_R(nSeg)$, $f_R(locY)$ and $f_R(\alpha_{yz})$ are properly parametrized

that the discriminating variable will be optimal when the matching variables are *uncorrelated*.

Furthermore, to verify whether the two conditions are met the distribution of the parametrized variables should be linear versus its parametrization, as will be shown in the following section. We will start with proving that this holds for a parametrization of a distribution of one variable.

B.2 Testing the hypothesis of a distribution

For a given distribution $D(x)$ we write down a parametrization $t(x)$ of that distribution: $D(x) \equiv t(x)$. A distribution which can be parametrized by a bijective function is taken, i.e. a transformation in which one $t(x)$ value exists for each value of x . For such a function, its inverse exist.

We test a measured distribution $\tilde{D}(x)$ to be compatible with the hypothesis of the parametrized distribution by evaluating the distribution $\tilde{D}(t)$. For each value of x from distribution $\tilde{D}(x)$ we calculate t and we look at the distribution of t .

Since a bijective transformation is taken, one can write down the distribution of t in terms of x ,

$$\tilde{D}(t) = \tilde{D}(x(t)) \quad (\text{B.1})$$

And since a bijective transformation has an inverse, this is the same as

$$\tilde{D}(t) = \tilde{D}(D^{-1}(t)) \quad (\text{B.2})$$

Given that the bijective transformation was indeed a proper parametrization of the distribution, e.g. $\tilde{D}(x) \sim D(x)$ we can write

$$\tilde{D}(t) = D(D^{-1}(t)) = t \quad (\text{B.3})$$

This works too for the parametrization of ratios of distributions, as is the case for the rejection factor defined in section 4.6.2. In that case one can test the correctness of the parametrization of the rejection factor by verifying that the following holds:

$$\frac{P_\mu(t)}{P_{\text{fake}}(t)} = t = f_R(x) \quad (\text{B.4})$$

B.3 Factorization of the rejection factors

We built the total rejection factor $f_R(nSeg, locY, \alpha_{yz})$ out of the product of the individual rejection factors as is done in Eq. 4.16. The claim that this factorized total rejection factor is the *optimal* rejection, however, is only true when the different variables $nSeg$, $locY$ and α_{yz} are *uncorrelated*.

For uncorrelated variables, the ratio of the distributions may be factorized as follows:

$$\frac{P_\mu(nSeg, locY, \alpha_{yz})}{P_{\text{fake}}(f_R(nSeg, locY, \alpha_{yz}))} = \frac{P_\mu(nSeg)}{P_{\text{fake}}(nSeg)} \cdot \frac{P_\mu(locY)}{P_{\text{fake}}(locY)} \cdot \frac{P_\mu(\alpha_{yz})}{P_{\text{fake}}(\alpha_{yz})} \quad (\text{B.5})$$

$$f_R(nSeg, locY, \alpha_{yz}) = f_R(nSeg) \cdot f_R(locY) \cdot f_R(\alpha_{yz}) \quad (\text{B.6})$$

Each rejection factor per variable obeys, when properly parametrized, Equation B.4. In that case, the ratio of the distributions of the rejection factors

$$\frac{\tilde{P}_\mu(f_R(nSeg, locY, \alpha_{yz}))}{\tilde{P}_{\text{fake}}(f_R(nSeg, locY, \alpha_{yz}))} = \frac{\tilde{P}_\mu(f_R(nSeg))}{\tilde{P}_{\text{fake}}(f_R(nSeg))} \cdot \frac{\tilde{P}_\mu(f_R(locY))}{\tilde{P}_{\text{fake}}(f_R(locY))} \cdot \frac{\tilde{P}_\mu(f_R(\alpha_{yz}))}{\tilde{P}_{\text{fake}}(f_R(\alpha_{yz}))} \quad (\text{B.7})$$

is the same as

$$f_R(nSeg) \cdot f_R(locY) \cdot f_R(\alpha_{yz}) = f_R(nSeg, locY, \alpha_{yz}) \quad (\text{B.8})$$

Figure 4.12-b shows exactly this relation, although on a logarithmic representation, proving that the variables are *uncorrelated* and that the distributions were properly parametrized.

Appendix C

The MuTag framework

The **MuTagIMO** tagging algorithm is implemented as a package within the existing **MuTag** framework¹. Additional tools were developed to implement the techniques described in chapter 4 such as the **MuTagMatchingTool** and the **MuTagAmbiSolverTool**. In this way, no code was duplicated and the advantages of using a well developed framework were exploited.

The **MuTag** framework consists of an internal event data model (EDM), suitable to elegantly handle the data objects containing the information needed for muon tagging. Furthermore, the **MuTag** framework is designed in such a way that one *steering class* organizes the tagging procedure, data object conversion and configuration of Tools. Several tagging algorithms can be configured by configuring multiple instances of the steering class. This model allows, for example, the implementation of a muon tagger optimized for tagging cosmic muons. It also allows ‘permutations’ of software modules such as **MuTagIMO** tagging with **Muonboy** segments, or vice versa, **MuTag** tagging with **MOORE** segments.

In this section, the **MuTag** framework will be discussed. First, the **MuTag** EDM will be discussed. Secondly, the structure of the framework will be explained. Finally, a set of common tools provided by the framework is presented.

C.1 MuTag data objects

A *muon candidate*, i.e. an Inner Detector track with associated Muon Spectrometer segments can be fully described by the class **MuTagObject** (see figure C.1). The **MuTagObject** contains an element link to the Inner Detector **Rec::TrackParticle** and a pointer to the matched **Trk::Segment**. This segment is stored in a **MuTaggedSegment**, described below. The **MuTagObject** owns a **MuTagAuthor**, telling the object by which **MuTag** tagging algorithm it has been tagged.

The **MuTaggedSegment** describes the association of the segment to the muon candidate track. The object holds an element link to the Muon Spectrometer **Trk::Segment** which was associated to the Inner Detector track. In order to access the matching of the

¹developed by the Saclay group

segment to the track, the parameters of the track evaluated at the segments surface are written to the object as well as a `Trk::MeasuredAtaPlane` object. The set of matching variables (`matchTheta`, `matchPhi`, `matchThetaAngle`, `matchPhiAngle`) are stored as well. For the `MuTagIM0` algorithm, these matching variables correspond with

- `matchTheta`: The precision position matching variable $pull_{locY}$, as defined in Equation 4.9.
- `matchPhi`: The second position matching variable $pull_{locX}$ defined in the same way as $pull_{locY}$.
- `matchThetaAngle`: The precision direction matching variable $pull_{\alpha_{YZ}}$ as defined in Equation 4.10.
- `matchPhiAngle`: The second direction matching variable $pull_{\alpha_{XZ}}$, defined similar as $pull_{\alpha_{YZ}}$. This variable is cut on according expression 4.14.

The `MuTagContainer` is a `DataVector` of `MuTagObjects`, able to be stored on `StoreGate` when desired.

The `MuTag` EDM is only used in `MuTag` internally. For Athena to handle the muon candidates, dedicated converter Tools are implemented to convert a `MuTagObject` to the general EDM classes such as `Rec::TrackParticle`, `Trk::Track` and `Analysis::Muon`.

C.2 MuTag structure

The class organizing the different components of the `MuTag` framework is the `MuTagMain` class. This class defines the input collections and retrieves them from the transient data store, i.e. `StoreGate` as discussed in section 2.2. The collections are passed to a set of algorithm classe which are called `MuTagSubAlgs`, for processing. The main package also defines the output collections and writes them out to `StoreGate`.

The `MuTagSubAlg` is an abstract Algorithm defining common functionalities of the tagging algorithms such as the creation of `MuTagObjects` and the conversion of the internal `MuTag` EDM to the general EDM classes. Concrete implementations of `MuTagSubAlgs` are listed in table C.2, as well as the functionality of the algorithms.

MuTagContainer	MuTaggedSegment
DataVector<MuTagObject>	ElementLink<Rec::TrackParticleContainer> Trk::MeasuredAtaPlane
MuTagObject	Chi2, NDoF Eloss, has2ndCoordinate MatchTheta, MatchPhi MatchThetaAngle, MatchPhiAngle ThetaMS, ThetaID, PhiMS, PhiID ThetaAngleID, PhiAngleID ThetaAngleMS, PhiAngleMS
ElementLink<Rec::TrackParticleContainer> std::vector<const MuTaggedSegment*> MuTag::MuTagAuthor Chi2, NDoF Par[0...4], Cov[0...4][0...4]	

Figure C.1: An UML diagram of the `MuTag` EDM classes.

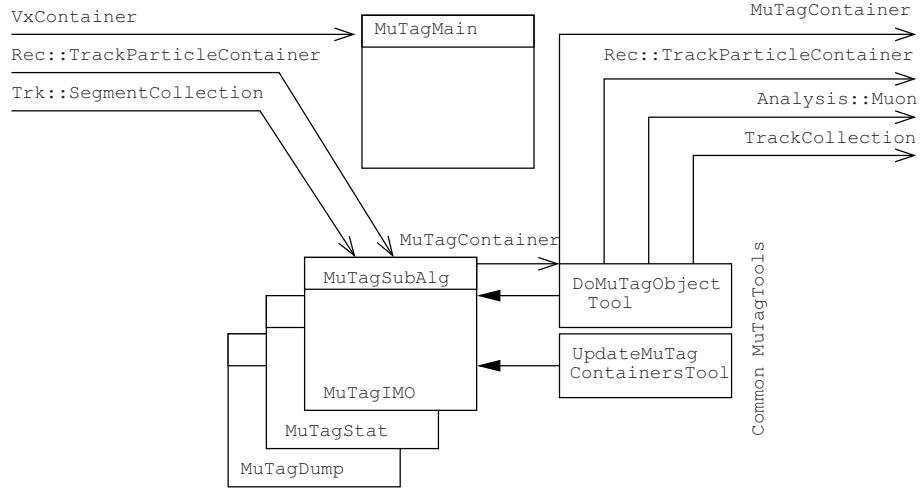


Figure C.2: A schematic overview of the MuTag Framework.

Algorithm name	Function
MuTagDump	Dumps content of the various output containers into logfiles
MuTagStat	Keeps track of the number of MuTagObjects created during the job
MuTagInner	Muon tagging using Inner Muon Spectrometer stations
MuTagMedium	Muon tagging using Middle Muon Spectrometer stations
MuTagCosmicsInner	Cosmic muon tagging using Inner Muon Spectrometer stations
MuTagCosmicsMedium	Cosmic muon tagging using Middle Muon Spectrometer stations
MuTagIMO	(Cosmic) muon tagging using the full Muon Spectrometer

Table C.1: The list of the various MuTagSubAlgs with a brief description of its functionality.

C.3 MuTag common tools

A set of common tools are available in the MuTag framework, designed to perform tasks common for the several concrete **MuTagSubAlg** implementations. The tools can be configured in such a way that within one **MuTagMain** application, different configurations of the same **MuTagTool** can be used. An example is the **SegmentFilterTool**, selecting a different set of Muon Spectrometer segments for the **MuTagSubAlgs** **MuTagInner** and **MuTagMedium**. The most important tools are listed below:

- **MuTagEDMHelperTool**, a tool providing several helper functions.
- **DoMuTagObjectTool** creates a **MuTagObject** object from the track and segment.
- **UpdateMuTagContainersTool** is called by the taggers at the end of each event, filling the output containers as defined by **MuTagMain** by converting the **MuTagObject**

to the appropriate Tracking EDM objects with help of the following converters:

- `MuTagToTrackTool` converts the Inner Detector `Rec::TrackParticles` from the `MuTagObject` to a `Trk::Track`. Only the Inner Detector track is converted. The hits of the associated Muon Spectrometer segments are not stored on the resulting track.
- `MuTagToCombinedMuonTool` converts the `MuTagObject` to an `Analysis::Muon`, which holds besides the Inner Detector `Rec::TrackParticle`, the set of associated Muon Spectrometer segments as well.
- `MuTagToParticleTool` stores the Inner Detector `Rec::TrackParticles` from the `MuTagObject`.
- `SegmentsFilterTool` performs a preselection on the input Muon Spectrometer segment collection before passing them to the tagging algorithm. Typical selection criteria e.g. the segment station (for `MuTagInner` and `MuTagMedium`) and segment quality variables.
- `TrackParticleFilterTool` performs a preselection on the input Inner Detector `Rec::TrackParticles` before passing them to the tagging algorithm. Typical selection criteria are the track momentum, transverse momentum and the number of SCT and Pixel hits on the track.

Appendix D

BOL hit maps

This section presents the hit maps of the BOL MDT chambers on which the discussion on the hardware performance in section 5.5 is based.

The hit maps listed in figures D.1 - D.8 show the number of hits per tube. Figure 1.8 shows an MDT barrel chamber with three layers per multi-layer. Per MDT chamber, the tube hits in the six layers are shown. The two multilayers are numbered 1 and 2, the tube layers are numbered 1, 2 and 3. The hit maps present the (multi)layers in the following way:

multilayer 1	layer 1
	layer 2
	layer 3
multilayer 2	layer 1
	layer 2
	layer 3

In the following pages, hit maps from twelve stations are shown, from 3 η values of 4 sectors. The BOL station names are given as $BOL/\eta/side/\phi$, where η runs from 1 to 6 and denotes the position of the chamber along z . The letter at position *side* can be either an *A* or a *C*. Stations at the *A* side have a positive z position, *C* side chambers have a negative z position. The last two digits denote the sector or ϕ value of the muon chamber, which runs from 1 to 16. For the 'Large' chambers, ϕ takes only odd values.

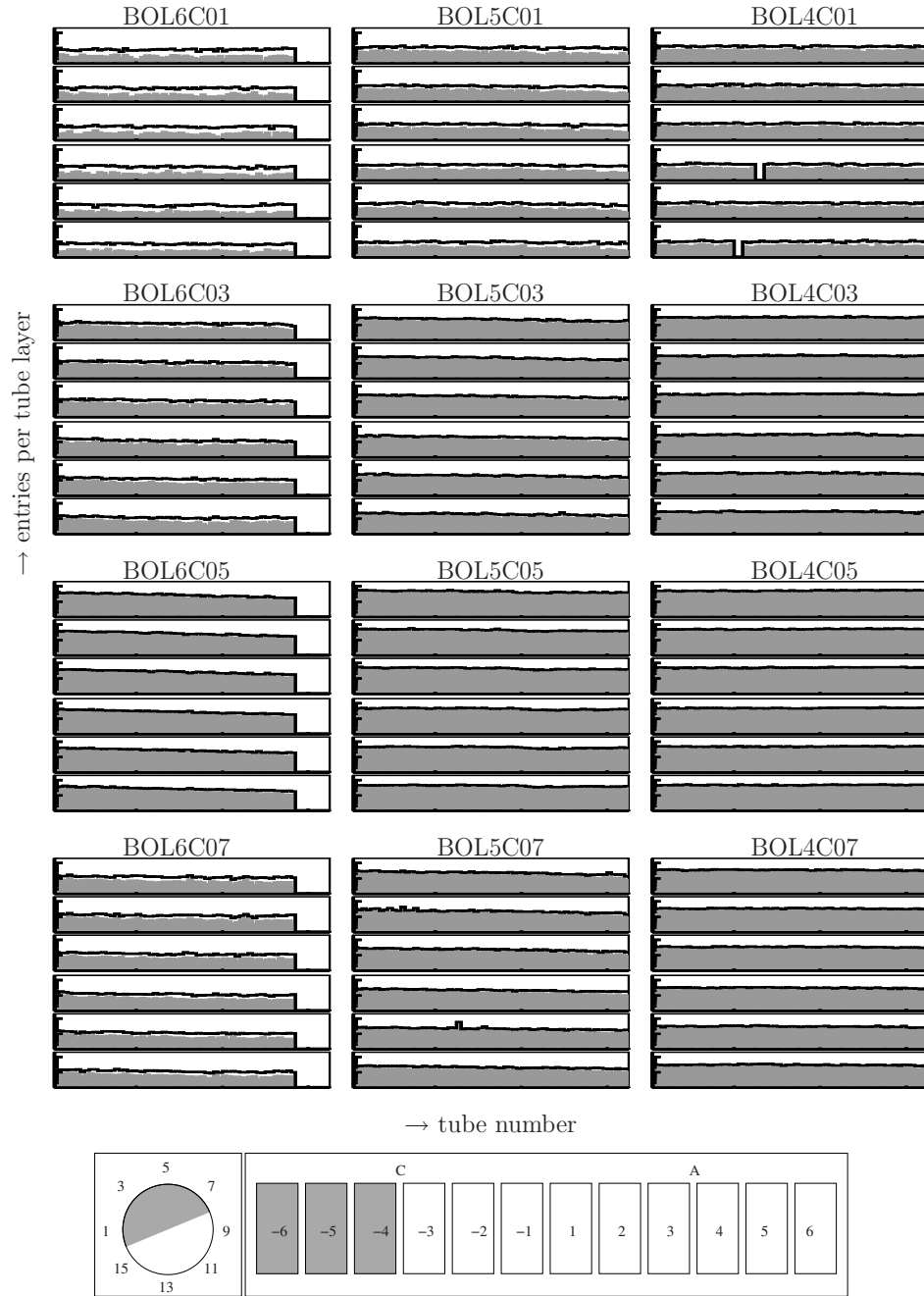


Figure D.1: Hit maps of BOL chambers.

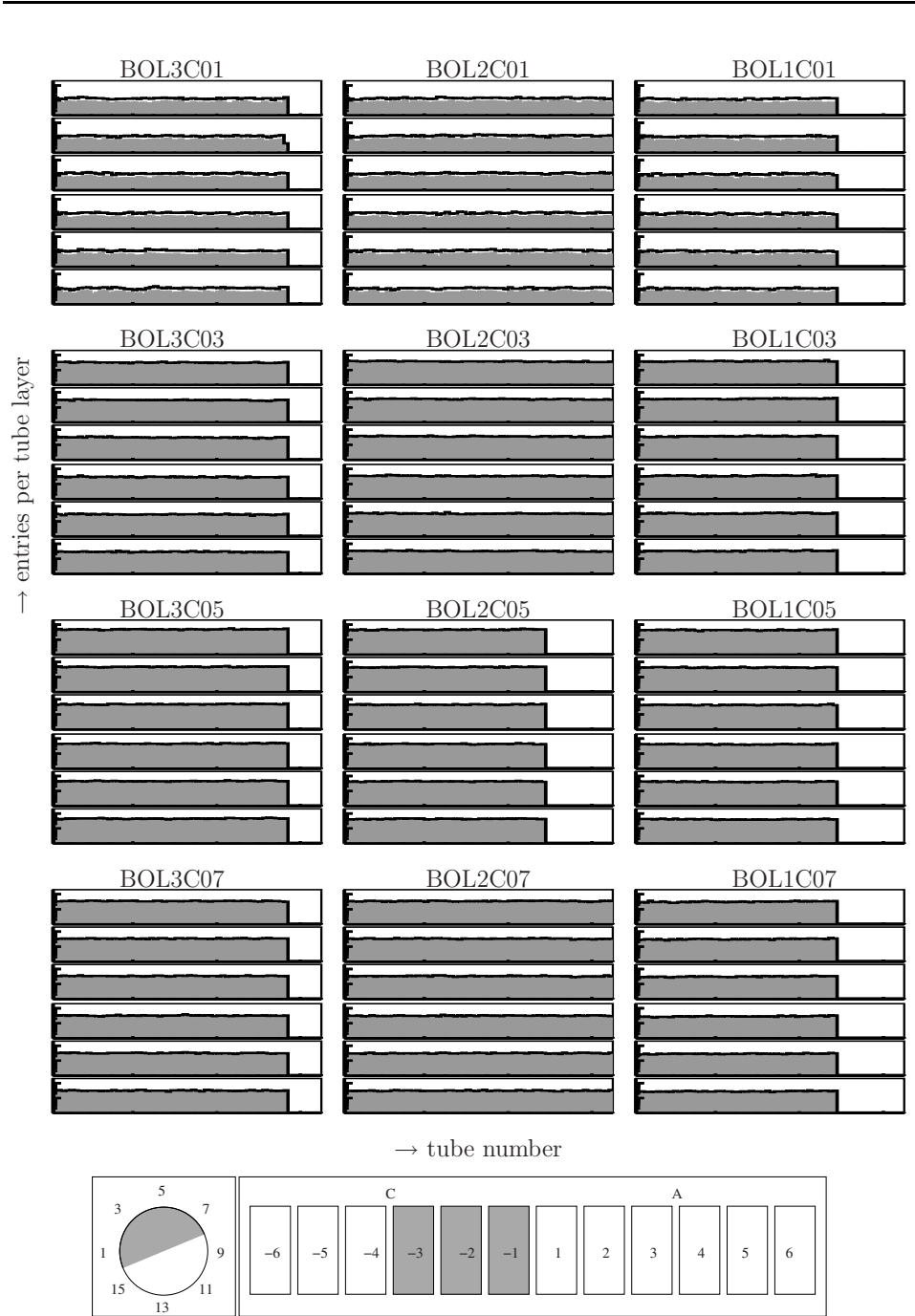


Figure D.2: Hit maps of BOL chambers.

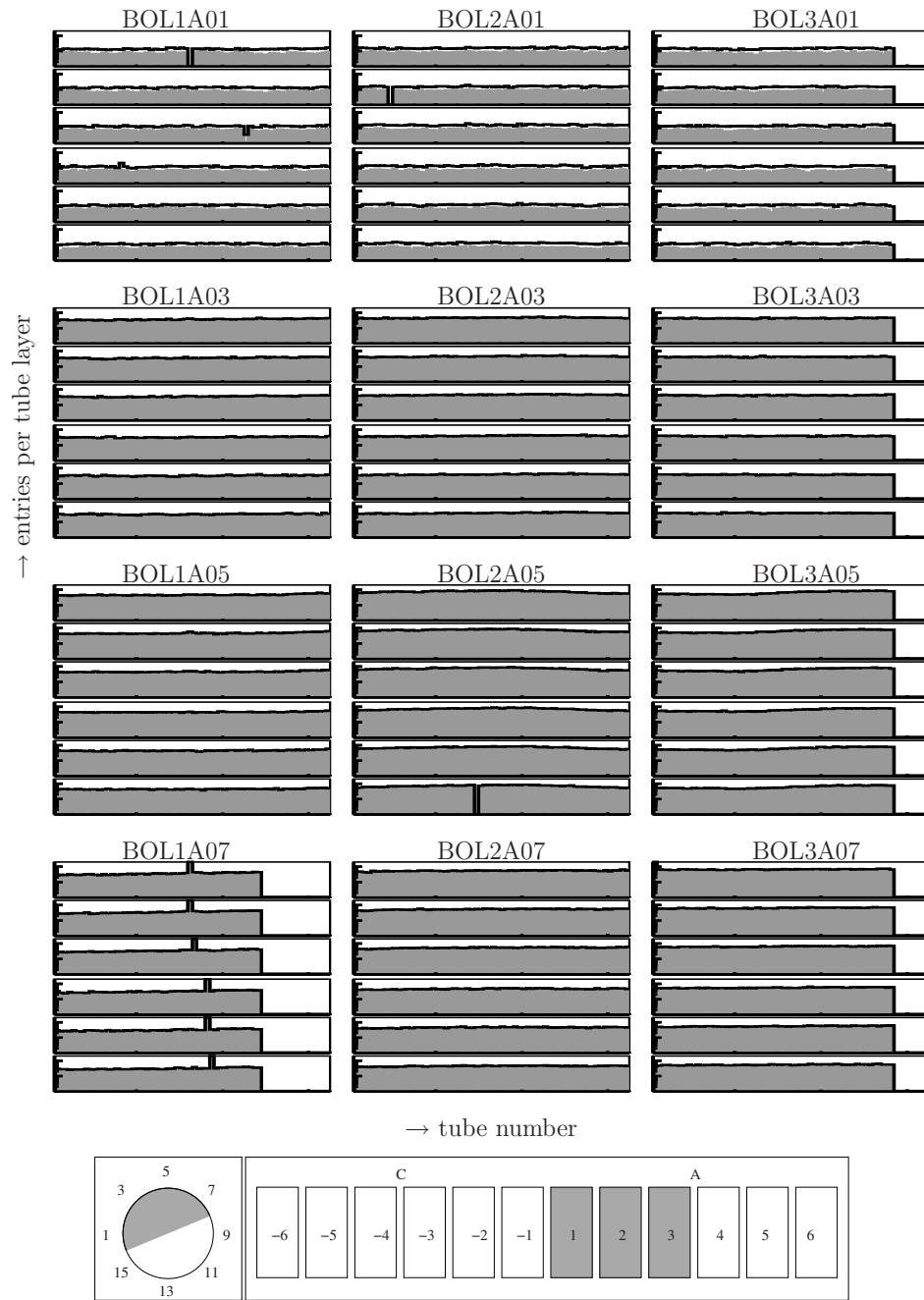


Figure D.3: Hit maps of BOL chambers.

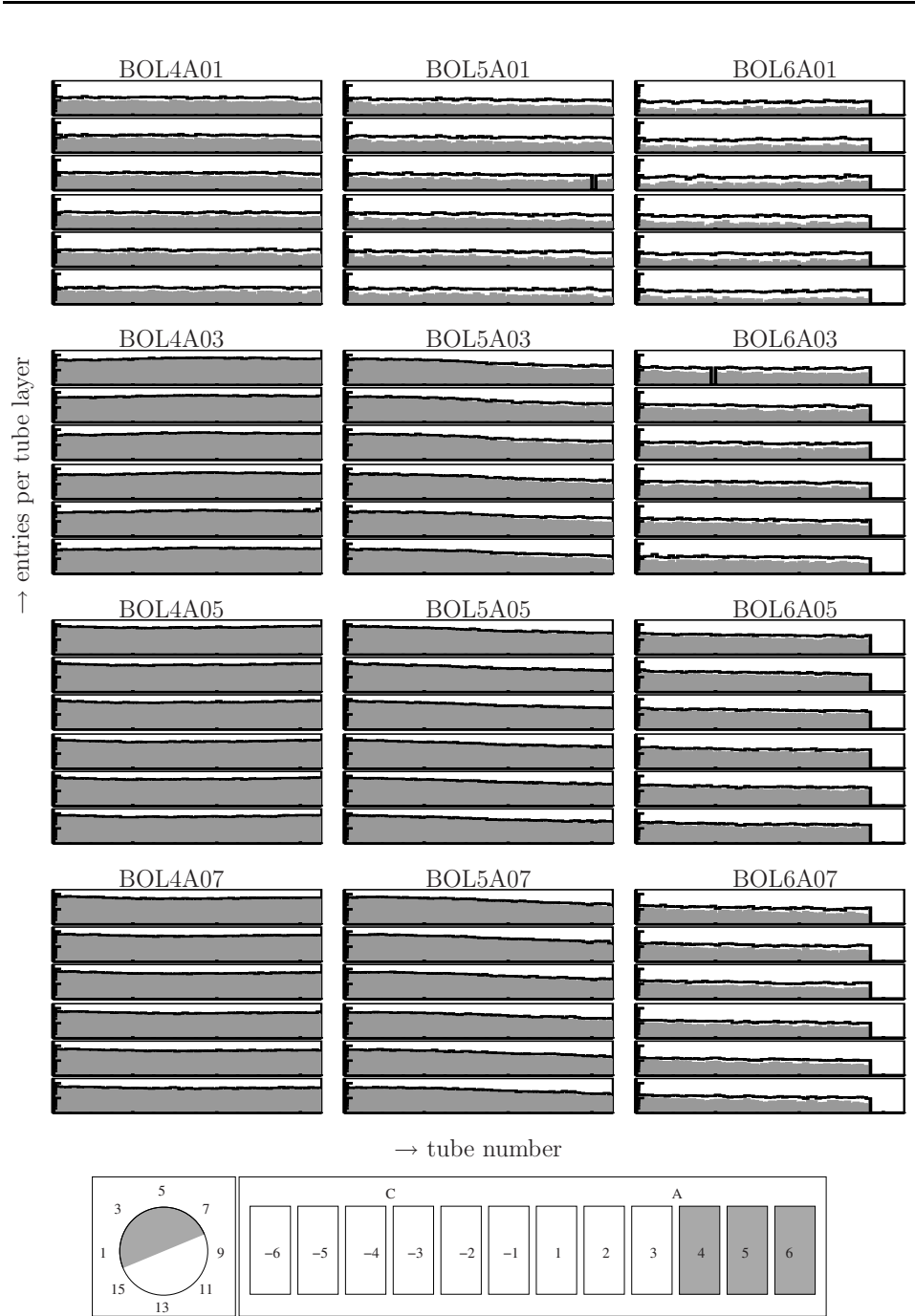


Figure D.4: Hit maps of BOL chambers.

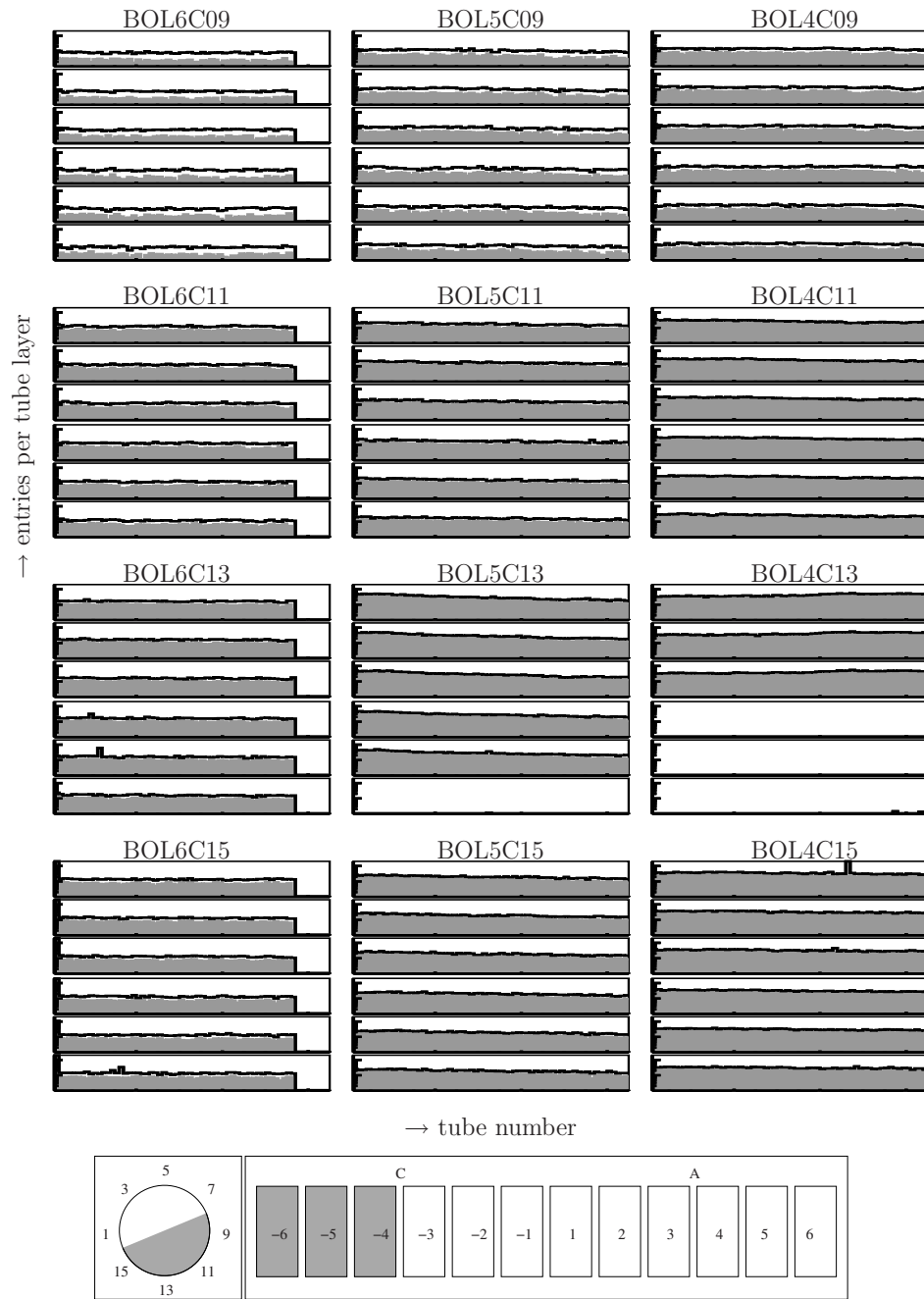


Figure D.5: Hit maps of BOL chambers.

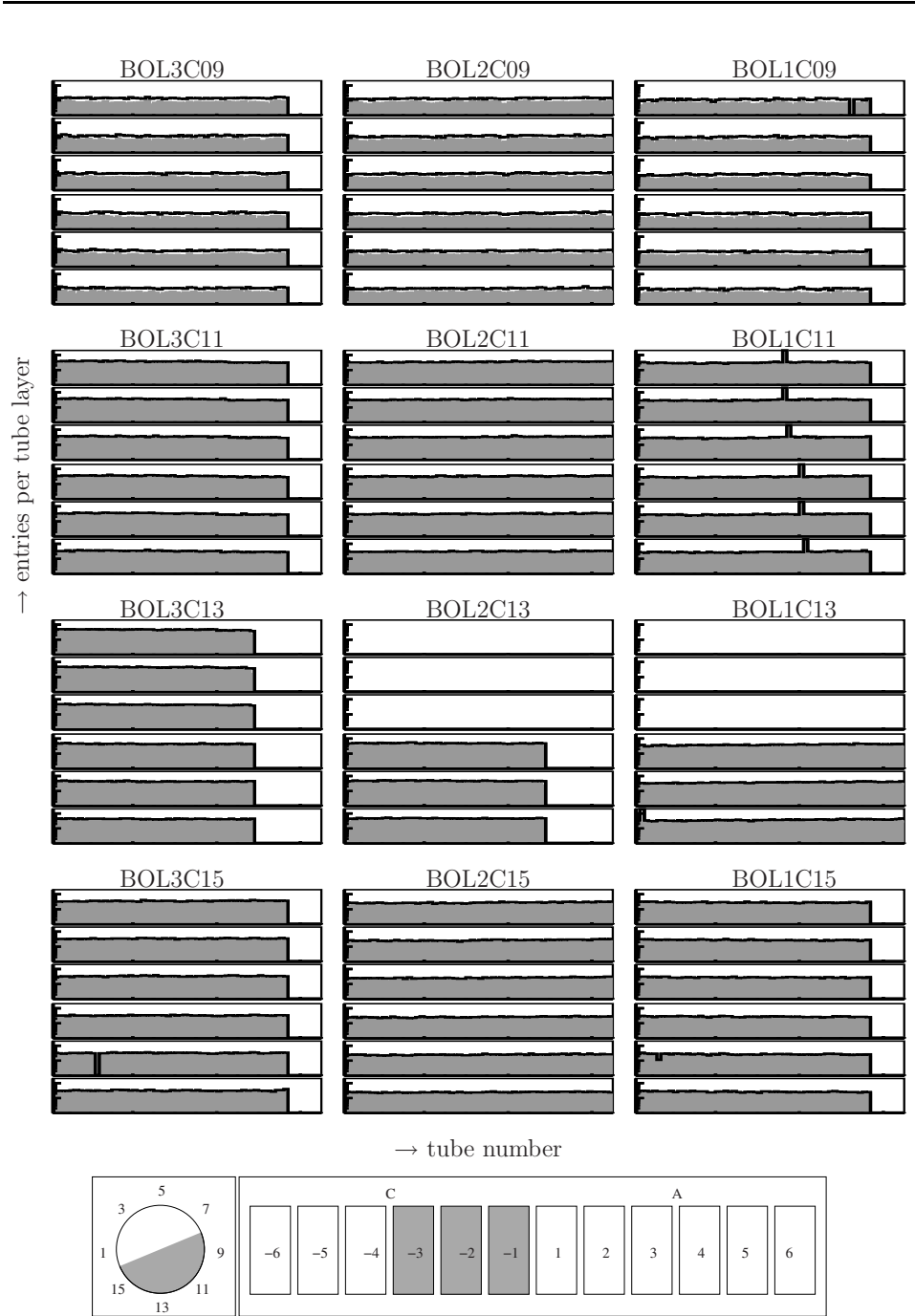


Figure D.6: Hit maps of BOL chambers.

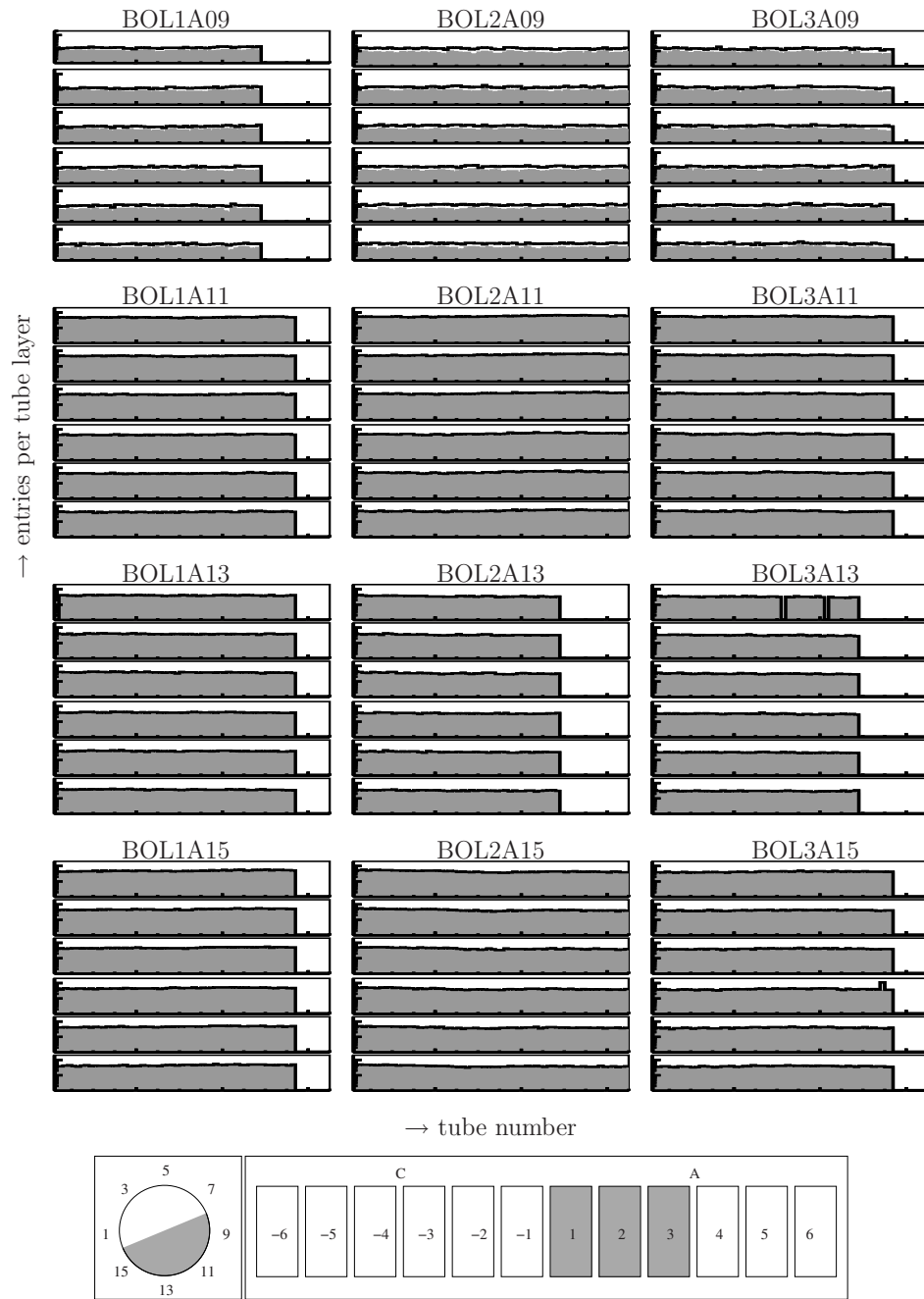


Figure D.7: Hit maps of BOL chambers.

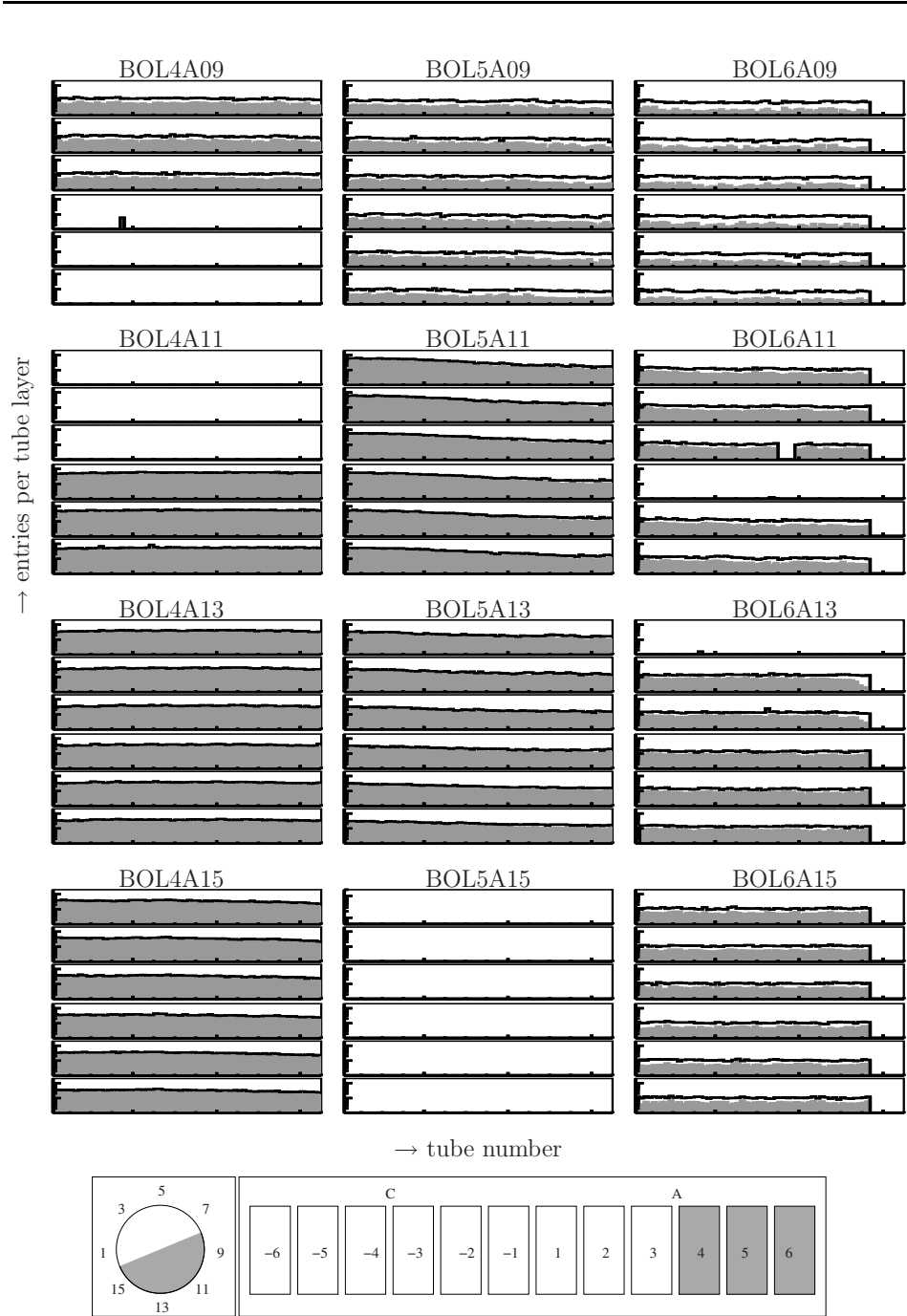


Figure D.8: Hit maps of BOL chambers.

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Bibliography

Summary

The Standard Model of Elementary Particles is an elegant theory which describes the fundamental building blocks of matter: particles and their interactions. In over twenty years of experimenting, the predictions of the Standard Model have been extensively tested and shown to accurately match the experimental observations, often to astounding precision. The only particle predicted by the Standard Model that has not been observed yet is the Higgs boson.

To produce the (heavy) Higgs boson, particle collisions at a high center of mass energy are needed. The Large Hadron Collider (LHC) at the CERN laboratory in Geneva, Switzerland, provides proton-proton collisions at an unprecedented center of mass energy of 14 TeV and will produce the Higgs boson, if it exists. If the Higgs boson is not found at the LHC, particle masses in the Standard Model cannot be explained.

The Higgs boson is unstable and will decay into lighter particles. By measuring these decay products one can reconstruct the Higgs boson from these particles. One of the cleanest decay modes of the Higgs boson is its decay into four muons.

The ATLAS detector, one of the LHC general purpose detectors, is designed to discover the Higgs boson. It consists of an Inner Detector tracker, mounted close around the interaction point to measure particle tracks. Around the Inner Detector, massive detectors are placed which are designed to measure particle energies: the Calorimeters. Finally, ATLAS is equipped with a Muon Spectrometer for measuring with high precision muon tracks.

The focus of this thesis is the identification of muons in the ATLAS detector. Before one can accurately identify muons, both the detector parts as well as the reconstruction software should be commissioned. A chapter in this thesis is devoted to the hardware commissioning of a part of the Muon Spectrometer: the monitored drift tube (MDT) chambers, constructed at the Nikhef institute in Amsterdam, The Netherlands.

Muons are reconstructed in a series of steps. First, the electrical signals from the muon detectors are used to make hits in space. A pattern recognition algorithm groups these hits into patterns. These patterns are used as seeds for the reconstruction of track segments, which in turn are combined into a Muon Spectrometer track. These muon tracks can be combined with tracks in the Inner Detector to reconstruct a muon track with an even better precision.

This thesis focuses on the development and performance of a particular muon identification algorithm, **MuTagIMO**. This algorithm identifies Inner Detector tracks as muons, using track segments reconstructed in the Muon Spectrometer. This method has several advantages. First of all, muons are identified efficiently, also the muons with very

low transverse momenta. Secondly, the algorithm is capable of tagging Inner Detector tracks even in regions where the Muon Spectrometer registers only a few hits. Finally, this method is proven to be robust. It has a high efficiency even when parts of the Muon Spectrometer are not operational. A disadvantage of this method is the increased rate of mis-identified tracks: some Inner Detector tracks which did not come from a muon are wrongly identified as muons.

In order to successfully identify muons, the detector systems should be well calibrated and aligned. The magnetic field and the amount of material traversed by the muons should be known to high precision. During the start up of the LHC and ATLAS, these requirements will not be met. This makes muon tagging a valuable addition to the muon identification programme.

At the time of writing of this thesis, LHC collision data was not yet available. The performance of the identification algorithm is therefore evaluated using cosmic ray muons. The results of cosmic ray muon data are compared with simulated cosmic ray events. The results are consistent and show a 98.6 % identification efficiency. The inefficiency is due to the lack coverage in certain regions of the Muon Spectrometer. This effect is observed in both data and simulation, giving confidence that the ATLAS detector is properly modeled.

Cosmic muon events have a different topology than collision events. The performance of the algorithm is evaluated with muons from simulated collision events as well. The algorithm is shown to be very efficient, also for muons with low momenta. The algorithm has a high efficiency, even in the regions where the Muon Spectrometer has lower coverage. The algorithm is robust against exclusion of part of the MDT chambers from the detector. The mis-identification rate is shown to be understood and well under control.

The **MuTagIMO** algorithm will be extremely useful for identification of muons during the start-up phase of the LHC.

Samenvatting

Het Standaard Model van de Elementaire Deeltjes is een van de grootste successen van de moderne Natuurkunde. Dit model geeft een elegante beschrijving van de fundamentele bouwstenen van de natuur en de krachten tussen deeltjes. Het Standaard Model heeft het bestaan van verscheidene deeltjes voorspeld die later door experimenten daadwerkelijk zijn gemeten. Het enige deeltje dat door het Standaard Model wordt voorspeld en nog niet gemeten is, is het Higgs boson.

Metingen aan het Standaard Model worden gedaan door deeltjes te versnellen tot hoge energieën met behulp van een deeltjesversneller, en deze vervolgens op elkaar te laten botsen. Hierbij ontstaan zwaardere, instabiele deeltjes die in zeer korte tijd vervallen in stabiele, lichtere deeltjes die we kunnen waarnemen met speciale detectoren. Hoe hoger de energie is waarmee de deeltjes op elkaar botsen, hoe zwaarder de deeltjes kunnen zijn die bij de botsingen ontstaan.

Om het zware Higgs boson te kunnen produceren, is een sterke deeltjesversneller nodig. Om de deeltjes te kunnen meten bij het verval van het Higgs boson gemaakt worden zijn zeer nauwkeurige detectoren nodig. De Large Hadron Collider (LHC) op het CERN deeltjes laboratorium te Genève, Zwitserland, is de grootste deeltjes versneller ter wereld. De LHC botst protonen op protonen met een zwaartepunts energie van 14 TeV. Deze energie is hoog genoeg om het Higgs boson te produceren. Als het Higgs boson niet gevonden wordt bij de LHC versneller, kan het Standaard Model zoals we deze nu kennen niet kloppen.

De ATLAS detector is één van de LHC detectoren. Bij het ontwerpen van de ATLAS detector is speciaal aandacht besteed aan het meten van de vervalproducten van het Higgs boson. Het Higgs boson kan op verscheidene manieren vervallen in verschillende deeltjes. De kans op het ontdekken van het Higgs boson is (onder andere) afhankelijk van hoe goed we de vervalproducten kunnen meten. Een van de meest veelbelovende manieren om het Higgs boson te meten is het reconstrueren van het verval van het Higgs boson in vier muonen. De ATLAS detector is uitgerust met een sporen detector, de Inner Detector. Deze staat rondom het punt waar de botsingen plaats vinden. Rondom de Inner Detector staan Calorimeters, detectoren die de energie van deeltjes kunnen meten. Tenslotte is ATLAS uitgerust met een Muon Spectrometer, speciaal ontworpen om efficiënt en met hoge precisie muonen te detecteren. Het Nikhef instituut in Amsterdam heeft meegewerkt aan het ontwerpen, produceren en het installeren van de grote muonen kamers, een van de onderdelen van de Muon Spectrometer. Ook is dit instituut actief in het ontwikkelen van software algorithmes die de elektronische signalen van de ATLAS detector omzetten naar gemeten sporen van de muonen.

Het onderwerp van dit proefschrift is de identificatie van muonen in ATLAS. Om muonen te meten in de ATLAS detector, moeten zowel de detector onderdelen van de Muon Spectrometer als de software algorithmes zorgvuldig worden getest. Deze tests worden uitgevoerd met muonen afkomstig van botsingen die in de atmosfeer plaats vinden. Deze muonen worden cosmische muonen genoemd. Met deze deeltjes worden de detector onderdelen en de software algorithmes getest. Een hoofdstuk in dit proefschrift is gewijd aan de ingebruikneming van de muonen kamers en het testen van deze detectoren met behulp van cosmische muonen.

Het reconstrueren van muonen gaat in een aantal stappen. De signalen uit de detectoren worden gelocaliseerd in de ruimte. Deze hits worden door een patroonherkenning algoritme gegroepeerd tot patronen. Deze patronen worden als uitgangspunt genomen voor het reconstrueren van segmenten. De segmenten worden op hun beurt weer gecombineerd tot een spoor in de Muon Spectrometer. Sporen in de Muon Spectrometer kunnen worden gecombineerd met sporen in de Inner Detector om muonen met een hogere precisie te reconstrueren.

In dit proefschrift ligt het zwaartepunt op de ontwikkeling en prestaties van een nieuw muon identificatie algoritme: **MuTagIMO**. Dit algoritme is ontwikkeld om Inner Detector sporen te identificeren als muonen, gebruik makende van spoorsegmenten gemeten in de Muon Spectrometer. **MuTagIMO** heeft als voordeel dat zeer efficiënt muonen geïdentificeert kunnen worden, zelfs muonen met een lage impuls. Ook is dit algoritme in staat om in de regionen waar de Muon Spectrometer weinig hits registreert, muonen efficiënt te identificeren. Tenslotte is de methode robuust en blijft de efficiëntie hoog in het geval dat delen van de Muon Spectrometer zouden uitvallen. Tegenover deze voordelen, heeft het algoritme als nadeel dat het de Inner Detectoren sporen die niet van muonen komen, soms fout als muon identificeert.

Het succesvol identificeren van muonen in ATLAS is afhankelijk van vele factoren. Zo moeten de muonen kamers goed gecalibreerd zijn, en zowel het materiaal in de ATLAS detector als het magneetveld waardoor de geladen deeltjes heen gaan nauwkeurig bepaald zijn. In het begin tijdperk wanneer de LHC aan zal gaan, zal nog niet aan al deze voorwaarden voldaan zijn. Het algoritme is bij uitstek geschikt voor het identificeren van muonen in de begindagen van de LHC en ATLAS.

Ten tijden van het schrijven van dit proefschrift, waren nog geen botsingen in de LHC beschikbaar. Voor de evaluatie van de identificatie efficiëntie van het algoritme is gebruik gemaakt van cosmische muonen. Deze gemeten cosmische muonen zijn vergeleken met gesimuleerde cosmische muonen. Een efficiëntie van 98.3 ± 0.2 % is gemeten met cosmische data en simulatie. Het verlies van 1.7 % efficiëntie wordt veroorzaakt door het ontbreken van detectoren in bepaalde gebieden van de Muon Spectrometer. Dit effect is waargenomen in de cosmische data en simulatie. Dit geeft vertrouwen dat de modellen die we hanteren om deeltjes in ATLAS te simuleren, een nauwkeurige weergave van de werkelijkheid zijn.

Deze cosmische muon metingen zijn echter maar tot op een zekere hoogte te vergelijken met de muon metingen van botsingen in de LHC. Zo komen cosmische muonen vanuit de atmosfeer en niet vanuit het hart van ATLAS waar de LHC botsingen plaats vinden. De prestaties van het identificatie algoritme zijn ook geëvalueerd op muonen

van gesimuleerde LHC botsingen. Ook hier is het algoritme zeer efficiënt, ook voor muonen met een lage impuls en muonen in regionen waar de Muon Spectrometer maar weinig hits registreert. Het algoritme blijft efficiënt muonen identificeren als detector onderdelen van de Muon Spectrometer uitgeschakeld zijn. Tenslotte is aangetoond dat de mate waarin het algoritme de Inner Detector sporen fout als muon identificeert, goed begrepen en onder controle is.

Met het **MuTagIMO** algoritme zijn we goed voorbereid op het identificeren van muonen bij toekomstige botsingen in het ATLAS experiment.

Samenvatting

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