Summary

No one can comprehend what goes on under the sun.
Despite all his efforts to search it out, man cannot discover its meaning.
Even if a wise man claims he knows, he cannot really comprehend it.
Ecclesiastes 8:17

The ‘Standard Model’ of elementary particles has been a very successful theory for the last few decades and has met every experimental test. It incorporates the Glashow-Weinberg-Salam theory of electro-weak interactions and the quantum chromodynamics theory of the strong interactions, and thereby includes all known forces between elementary particles except gravity. The Standard Model includes the ‘Higgs’ mechanism to endow the particles with mass. This mechanism, however, requires the existence of the ‘Higgs boson’. This is the only particle of the Standard Model that has escaped experimental observation, despite many efforts of the last four decades. Current indirect measurements from the experiments at the LEP accelerator at CERN indicate that the mass of the Standard Model Higgs particle falls in the range 114 - 196 GeV / c² with a probability of 90%.

The LEP accelerator and its detectors are currently being dismantled to be replaced by the more powerful LHC accelerator and its four new experiments (called ATLAS, CMS, ALICE and LH-Cb). This new accelerator will be a proton-proton collider with a center-of-mass energy of 14 TeV, and will become operational in 2007. One of the key elements of the LHC physics program is the search for the Standard Model Higgs particle, since it is one of the corner stones of the model. Numerous Higgs particles will be produced at the LHC, if it exists at all, and its discovery should be possible after a few years of data taking.

This thesis is devoted to ATLAS, one of the two general-purpose detectors at the LHC. It focuses on that sub-detector, which will play a crucial role in the analysis of the Higgs decay channel $H \rightarrow Z^0Z^0 \rightarrow \mu^+\mu^-\mu^+\mu^-$: the muon spectrometer. This specific Higgs decay is an important discovery channel, because of the clear signature that the decay products leave in the detector. This thesis covers the main contributions to the precision with which the momentum of the muons can be measured. The scope is limited to the barrel part of the muon spectrometer.

The momentum of a muon is determined by measuring the deflection of the particle in a magnetic field. This is done by measuring three segments along the particle track. The particle momentum is directly related to the ‘sagitta’, which is defined as the distance from the middle segment to the straight line connecting the two outer segments. The more precise the sagitta is measured, the more precise the muon momentum is determined. For muons with high momentum (1 TeV/c), the precision of the momentum measurement is limited by this sagitta measurement. For muons with lower momentum (< 100 GeV), however, the precision of the measurement is limited by multiple scattering of the muon in the detector material and by fluctuations of its energy loss in the calorim-
Precision of the ATLAS muon spectrometer

eters (two of the other ATLAS sub-detectors). This thesis presents results on the two main contributions to the precision of the sagitta measurement: the precision of the individual segments measured along the track (i.e. local) and the precision of the relative alignment of the detector elements measuring the segments (i.e. global).

The target precision of the momentum measurement is 10% for a muon with a momentum of 1 TeV/c. This translates into the target precision of the sagitta measurement of 50 μm. This precision is composed of the target precision of 40 μm for the contribution of the segment measurements, and the target precision of 30 μm for the contribution of the alignment.

The coordinates of the individual segments in the bending direction of the muon are measured by Monitored Drift Tube (MDT) chambers. An MDT is an aluminium tube with a diameter of 30 mm. It holds a wire at its centre with a precision of 7 μm. The MDTs are precisely assembled to form chambers of various sizes. The largest barrel chamber type (‘BOL’, constructed at NIKHEF), for example, consists of 432 tubes arranged in two times three layers of 72 tubes, which are 5 m long.

A dedicated measurement apparatus, the X-ray tomograph, was developed at CERN to measure the precision of the wire positions of a complete MDT chamber. The tomograph measures the wire positions with a precision of a few μm over the full working space of 2.2 x 0.6 m². The few BOL chambers that have been X-rayed have a precision of 15 μm on the wire positions, which is a remarkable achievement for such a large object (2.2 x 0.5 x 5 m³). A comparison between the results of the X-ray tomograph and the quality control monitoring data taken during chamber assembly reveals a correspondence of better than 7 μm. This justifies that only a limited number of the produced chambers (one in eight) is being measured in the X-ray tomograph.

After construction of a BOL chamber, it is tested by operating it in a dedicated set-up at NIKHEF using cosmic muons. With this set-up dead and noisy channels can be found, the detection efficiency can be measured, and the uniformity is checked. Eventually the wire positions will also be determined using the cosmic muons. This set-up is also used to measure the resolution of the drift tubes and the precision of the reconstructed muon track segment in a single BOL chamber. The space-time relation of the drift tube is determined in an auto-calibration procedure, with an average left-over systematic deviation of less than 3 μm. The larger systematic deviations near the wire (up to 70 μm) need some more attention, although they are still significantly smaller than the local resolution. The average measured single tube resolution is 82 μm after correction for multiple scattering. This includes errors from the calibration procedure and errors due to the limited precision of the wire positions and is therefore the relevant resolution. The achieved resolution is close to the target resolution of 80 μm. The method that is used to determine the resolution uses only the data of the MDTs themselves. It results in a flat probability distribution, which gives confidence in the method. The average measured precision on the track position is 36 μm after correction for multiple scattering. This is close to the target precision of 32 μm. The detection efficiency of the tubes is excellent (99.98%). The hit-on-track inefficiency (5%) is dominated by δ-electrons ejected by the muons, which mask the real muon hit. Significant systematic tube-to-tube variations in the operation point have been observed, which are related to the (partly serial) gas distribution system, and need further investigation.

The ‘twin-tube’ concept, where two drift tubes are interconnected at the high-voltage end to provide an effective read-out on both sides of the tubes, is shown to provide an adequate second coor-
dinate measurement. It thereby transforms the two-dimensional drift tube chambers into a real three-dimensional tracker system. The twin-tube concept is not the ATLAS baseline, but it may actually be implemented in the outer stations of the muon spectrometer.

The precision of the global alignment of the MDT chambers has been tested in an experimental set-up called DATCHA, which was assembled at CERN. It consists of one full-size ‘tower’ of the ATLAS muon spectrometer using prototype detectors, and is equipped with Rasnik alignment systems. The detectors are operational and cosmic muons are used as a reference to compare the Rasniks to. For several controlled displacements of one MDT chamber, the average measured sagitta of the muon tracks is compared to the average sagitta of the Rasnik measurements. It has been demonstrated that the alignment systems are capable of monitoring changes in the geometry with a precision of 11 μm on the muon track sagitta. This achievement has one caveat: it is a relative test, because the Rasniks were not calibrated. It is yet to be demonstrated that the alignment system can provide the absolute corrections using pre-calibrated Rasnik systems, which is what is needed for ATLAS.

From the point of view of the search for the Standard Model Higgs boson in the decay channel \( H \rightarrow Z^0Z^0 \rightarrow \mu^+\mu^-\mu^+\mu^- \) (assuming a Higgs mass < 200 GeV), the requirement on the alignment precision could easily be relaxed to 100 μm without any significant loss in the resolution of the muon momentum measurement.