1 The Muon Spectrometer

The muon spectrometer [1, 2] of the ATLAS experiment is equipped with three layers of muon detectors in a toroidal magnetic field of $3-6$ Tm bending power generated by a superconducting air-core magnet system. The spectrometer is designed to provide muon momentum resolution of better than 10% for transverse momenta up to 1 TeV/c over a pseudo-rapidity range of $|\eta| \leqslant 2.7$. This requires a very accurate track sagitta measurement with three layers of muon detectors which have to be aligned relative to each other with an accuracy of up to $30\,\mu$m in the bending direction in the magnetic field. Drift chambers with very high spatial resolution of $40\,\mu$m, the Monitored Drift Tube (MDT) chambers, have been developed to cover the active area of the spectrometer of $5500\,\mathrm{m}^2$ with only 5% gaps mainly in the region of the detector feet.

The cylindrical central part of the spectrometer (barrel) contains eight race-track shaped magnet coils of 25 m length and 5 m radial width. The layout of the muon chambers follows the eightfold symmetry of the magnet around the proton beam axis in eight small and eight large azimuthal sectors (see Figure 1). The barrel part of the spectrometer is complemented by two endcaps each consisting of eight superconducting coils housed in a common cryostat fitting into the inner bore of the barrel toroid magnet and three wheel-shaped layers of muon detectors.

The MDT chambers built in Munich consist of two triple layers of 30 mm diameter aluminium drift tubes of 3.8 m length equipped with a central gold-plated tungsten-rhenium sense wire which are separated by an aluminium space frame. The drift tubes are operated with Ar:CO_2 (93:7) gas mixture at a pressure of 3 bar and a gas amplification of 20,000 (corresponding to a operating voltage between tube wall and wire of 3080 V) and provide a position resolution of about $80\,\mu$m . The sense wires are positioned within a chamber with an accuracy of better than $20\,\mu$m in order to achieve the required spatial resolution of the chambers [3].

In the years 2001 to 2006, 88 MDT chambers were constructed at the MPP [4] containing about 36000 drift tubes. They cover about 15% of the active area of the spectrometer.

1.1 Installation and Commissioning of the ATLAS Monitored Drift Tube Chambers

The 88 Monitored Drift Tube chambers built at the Max-Planck-Institut für Physik were installed in the ATLAS experiment from February to June 2006, after being integrated with their respective trigger chambers and tested at CERN in 2005 [5–8]. The chambers were the first to be mounted on the rail system in the barrel part of the spectrometer and were positioned with an accuracy of about 1 mm [7], well within the specifications. The barrel part and the middle wheels of endcaps of the muon spectrometer were installed in 2006, the missing inner and outer endcap wheels followed in 2008, completing the muon spectrometer. 10 of 62 additional chambers improving the acceptance in the barrel-endcap transition region have been installed in 2009, the rest will follow in 2012.

The Max-Planck-Institut für Physik has taken a leading role in the commissioning of the ATLAS muon spectrometer and, via a representative in the ATLAS Muon Steering Group, is responsible for the overall coordination of the operation and maintenance of all MDT chambers since beginning of 2008. In addition, our MDT group provides on-call gas system and detector experts, as well as the data quality expert, who is responsible for the final sign-off of the MDT data. The MPP team is also involved in providing training and documentation for the shifters operating the detector in the ATLAS control room.

The commissioning of the MDT chambers should have followed their installation closely, but it was delayed due to the late installation of the final services in the experiment—the routing of the low and high voltage cables, readout fibers, and gas pipes and valves—and the availability of the commercially manufactured power supply boards. Thus, the commissioning phase of the muon spectrometer spanned from the end of 2006—with only 13 MDT chambers operational on temporary services—to September 2008, when the first beam was circulated in the Large Hadron Collider (LHC), and 98.8% of the 350000 channels of the 1088 MDT chambers of the muon spectrometer were operational.

A notable exception to the general commissioning strategy were the MPP MDT chambers: immediately after their installation and in regular intervals afterwards their gas tightness, HV stability and the stability of the chamber geometry has been tested [7]. As

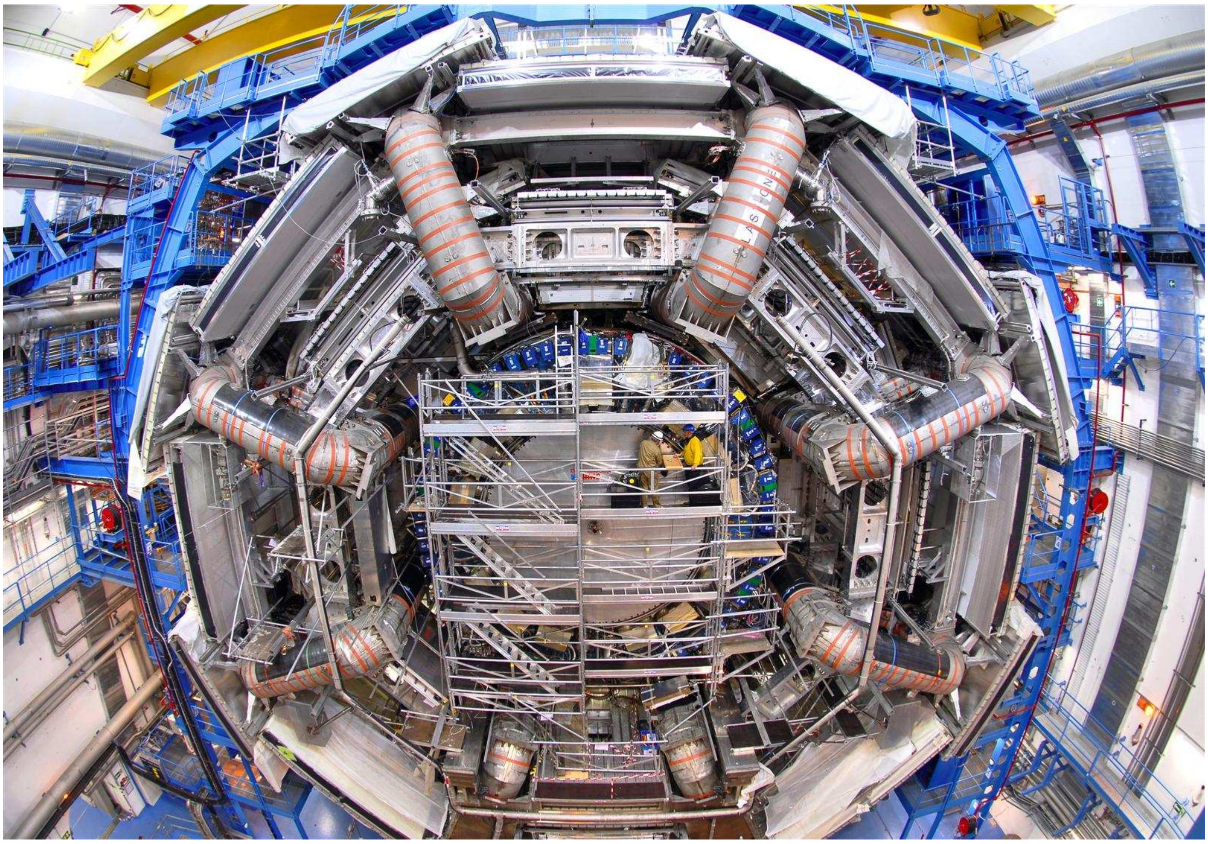

Figure 1: The barrel part of the ATLAS muon spectrometer viewed from the LHC tunnel after completion of the muon chamber installation in November 2006. The MDT chambers built in Munich are mounted on rails on the outside of the eight superconducting magnet coils.

a result, these chambers exhibited less problems than other types when finally put into operation. The chambers were connected to the ATLAS gas system in 2007 and to the power supplies and read-out chain in 2008 by a team of 3 technicians and 4 physicists from MPP. Due to their exposed position at the outside of the ATLAS detector and the hostile environment with cooling and cryogenic stations and electronics racks on the surrounding structures nearby, the MPP chambers showed an increased noise pickup compared to the inner chambers. The situation was remedied by designing additional low-pass filters for the high voltage lines which were mounted on all MPP chambers in 2008 [9]. These filters are now also used on other chambers in the muon spectrometer which suffer from high noise rates.

The commissioning of the ATLAS muon spectrometer encompasses the connection of services to the chambers and the electronic racks in the experimental cavern. The MPP team supported this global work with 1–2 technicians and 2–4 physicists during 2007 and 2008. About 50% of all barrel MDT chambers were connected by the team and subsequently integrated in the read-out and debugged. Faulty front-end electronics cards were exchanged and high voltage failures due to a few broken anode wires in the drift tubes or dirt in the Faraday cages—caused by the ongoing installation of other subdetectors—were fixed. The channel mapping of the optical fibers for the read-out and the high and low voltage cabling of the whole spectrometer was verified and corrected. After the chambers had been integrated in the read-out of the experiment, data taken with cosmic ray muons is used to verify their proper operation and test their performance [10, 11]. Figure 1.1 shows an overview of the number of MDT chambers read-out as a function of time, denoted by periods of either combined muon system cosmic data taking (P-weeks) or combined cosmic data taking of all ATLAS subdetectors (milestones, M-weeks). An event display of one of the first recorded cosmic muons traversing the entire muon spectrometer during the P4 period is shown in Figure 1.1.

A major part of the commissioning phase consisted of taking into operation the recirculating MDT gas system—-the largest gas system of any LHC experiment. This effort was coordinated and to a large part executed by the MPP team. The system consists of 15 distribution racks serving 226 individual gas manifolds, each connected to 4 to 32 MDT chambers. The total gas volume of 2.2×10^6 bar L is exchanged once every 24 hours, and about 10% of the gas is replaced. In addi-

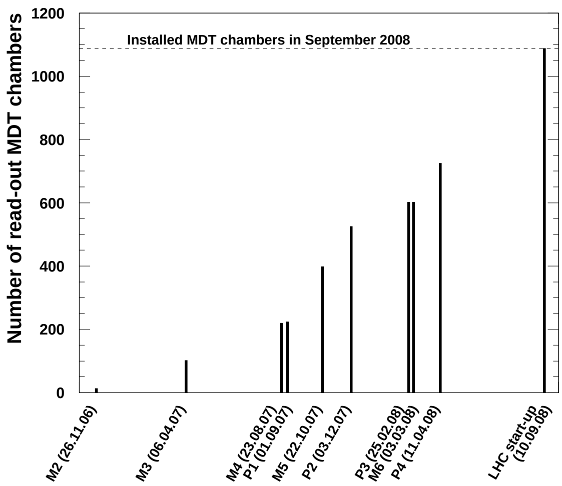

Figure 2: Number of MDT chambers read-out as a function of time from Nov. 2006 to the LHC start-up in Sep. 2008. Pi denotes the ith combined muon data taking, Mi denotes the ith milestone of combined data taking of the ATLAS detector components.

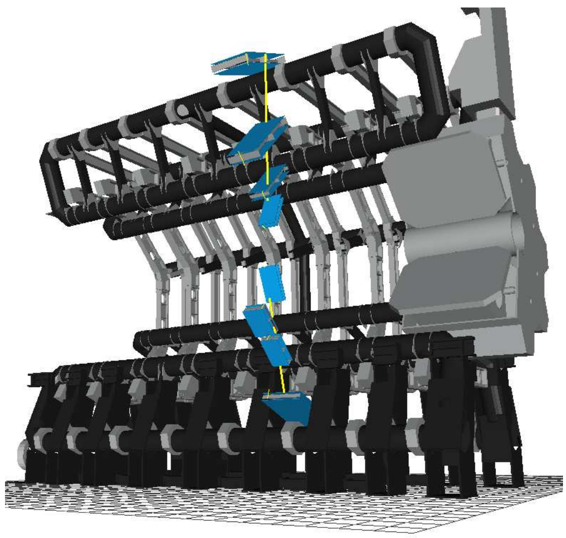

Figure 3: A cosmic muon traversing the ATLAS muon spectrometer, recorded during the P4 period in 2008. Only the MDT chambers with hits close to the reconstructed track and part of the toroid magnet system is shown. The topmost MDT chamber was built at MPP.

tion to the 2.8 million O-ring seals of the on-chamber gas distributions, the systems has about 4500 manual valves and 18000 connections. Stringent requirements exist for the allowed leak rate which should not exceed $2 \cdot 10^{-7}$ bar L/s per drift tube to avoid back diffusion of air into the system which would change the space to drift relation and degrade the drift tube efficiency. The vast majority of all chambers and connections fulfills the tightness requirements after several hundreds of leaks were repaired. At the moment, the total leak rate of the system is about 30% higher than the allowed limit, caused by several larger leaks which will be repaired during the next LHC shutdown when access is possible. No adverse effect of the larger leaks has been observed so far. The purging of all MDT chambers, the leak search and repair, and the adjustment of the distribution system took an estimated manpower of 1.5 man years during 2007 and 2008. Periodic leak tests are still performed to spot new leaks in the system.

As all other subdetectors of the ATLAS experiment, the MDT system has entered routine operation in 2009 and 2010. Annual failure rates of the active and passive front-end electronics on the chambers, the high voltage distribution, and the detector control system are all well below 1%, but the more than 50000 different components nevertheless requires a continuous maintenance of the system to which the Max-Planck-Institut für Physik contributes a major share of manpower and expertise. The MDT system has been operational with 99.7% of all channels taking high quality data for the past two years.

1.2 Muon Detector Commissioning with Cosmic Rays

The MPP group is contributing to all aspects of the software development for the analysis of the ATLAS muon detector data, including the calibration of the space drift-time relationship of the MDT chambers [12–18], the alignment of the muon spectrometer with muon tracks [7, 9, 20–24], the evaluation and monitoring of the data quality of the muon detector [25, 26], optimisation of the muon reconstruction for the high background rates expected at the LHC [22, 27], and the Monte Carlo simulation programs for the muon spectrometer [28, 29]. The first two projects which are of central importance for the operation and performance of the ATLAS muon spectrometer and in which the MPP group plays a leading role are discussed in more detail in the following.

Drift Tube Calibration

The prassurised drift-tube technology has been chosen for the ATLAS muon tracking chambers because of the high spatial resolution of better than $80\,\mu$m which can be achieved for individual drift tubes by measuring the drift time of the ionisation electrons to the sense wires. In order to reach the required spatial resolution of the chambers of $40\,\mu$m not only the the sense wires have to be positioned in a chamber with an accuracy of $20\,\mu$m but also the space drift-time relationship of the approximately 400,000 drift tubes in ATLAS has to be known with the same precision. The drift properties of the electrons depend on the temperature and pressure of the drift gas as well as on the magnetic field and the rate of background hits from neutrons and photons which can be very high at the Large Hadron Collider (LHC). For the regular calibration of the space drift-time relationship, correlations between the positions measurements of the drift tubes hit by a traversing muon can be used.

We have developed fast and efficient algorithms for the determination of the space drift-time relationship [6,12] and of the spatial resolution [13] of the MDT chambers which are now part of the ATLAS data reconstruction software. The algorithms have been extensively tested with simulated data, cosmic ray commissioning data [11,12], in a muon beam at CERN [14,15] and under LHC operating conditions, in magnetic fields and at high background rates, using test beam data taken by our group at the Gamma Irradiation Facility at CERN [16]. A model for magnetic field corrections to the space drift-time relationship has been derived from the measurements [17].

The large sample of cosmic ray muons recorded by the ATLAS detector in 2008 and 2009 allowed detailed studies of the robustness of the calibration algorithms. The r-t calibration algorithm showed robust operation for all the chambers apart from the chambers with muons at 30° incidence angles where all drift radii are equal. The r-t calibration method originally applied to straight track segments in triplelayers of the muon chambers had to be extended to curved track segments in the muon chambers to achieve the same level of robustness for all muon chambers [30]. Figure 1.2 shows the accuracy of the space drift-time relationship provided by the improved calibration algorithm as a function of the number of collected muon track segments in a chamber for simulation and cosmic ray data. The

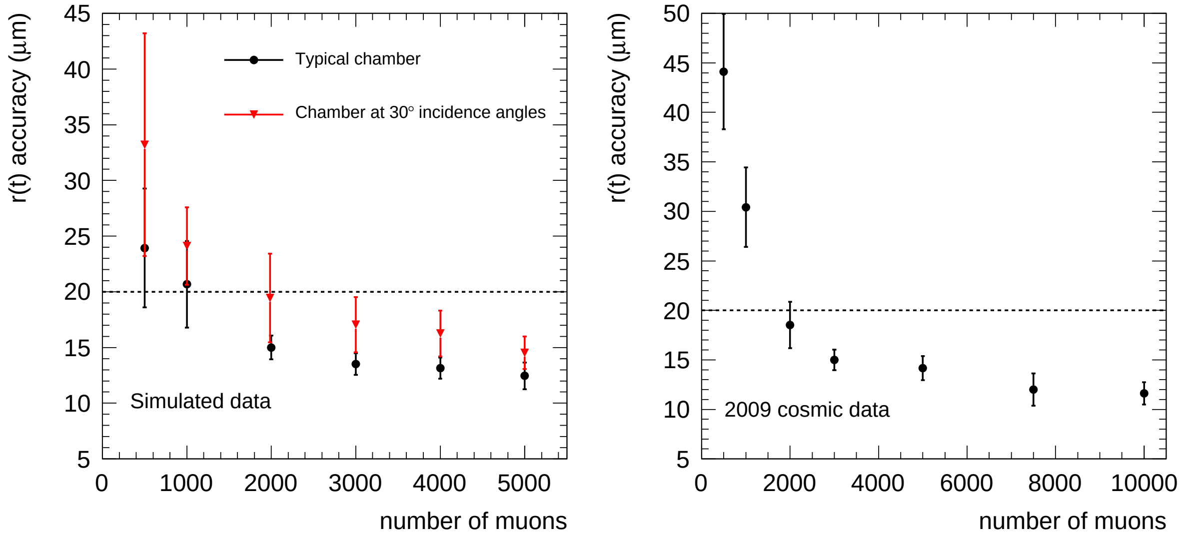

Figure 4: Accuracy of the calibration of the space drift-time relationship of the drift tubes of the ATLAS MDT chambers as a function of the number of cosmic muon tracks used per chamber. Left: Simulated data. Right: Cosmic ray data confirming the predicted r-t accuracies.

required accuracy of 20 μm is reliably achieved with 3000 muons per chamber for all chambers of the muon spectrometer. The predicted accuracy is confirmed by the studies with muons from cosmic rays.

The dependence of the drift time on the magnetic field strength measured with cosmic rays in the ATLAS detector agrees well with the model based on the test beam measurements (see Figure 1.2).

The MPP group is operating one of the three computing centres dedicated to the calibration and the alignment of the ATLAS muon spectrometer [18] using a special data stream of muon tracks reconstructed by the ATLAS second level trigger algorithms. The commitment of the MPP group to calibrate roughly one third of the MDT chambers and to align the muon detectors with muon trajectories includes the development of fully automated calibration and alignment procedures and monitoring tools [31].

Muon Chamber Alignment with Tracks

To achieve the required momentum resolution of the ATLAS muon spectrometer up to the highest muon energies, the relative positions of the chambers have to be continuously monitored and misalignment corrections have to be applied to the measured track sagitta with an accuracy of 30 μm. The MPP group contributed significantly to the development and test of the high-precision optical alignment monitoring system for the muon spectrometer [1]. The group also developed algorithms for the alignment of the ATLAS muon spectrometer with muon tracks [20–24].

In the barrel part of the spectrometer, only the large chamber sectors mounted in between the magnet coils can be fully aligned with optical sensor measurements. The small chamber sectors mounted on the coils (see Figure 1) have to be aligned with respect to the large sectors with muon tracks passing through the overlap regions between the the small and large sectors. The MPP group is providing these alignment corrections using the muon calibration data at the Munich calibration and alignment computing centre [18, 20].

Straight muon tracks measured while the toroid magnets are turned off are needed for the precise determination the initial chamber positions after installation as a starting point for the monitoring of further chamber movements by the optical sensors mounted on the chambers. An efficient algorithm has been developed and successfully applied to cosmic ray commissioning data [21]. Figure 1.2 shows the mean value of the ap-

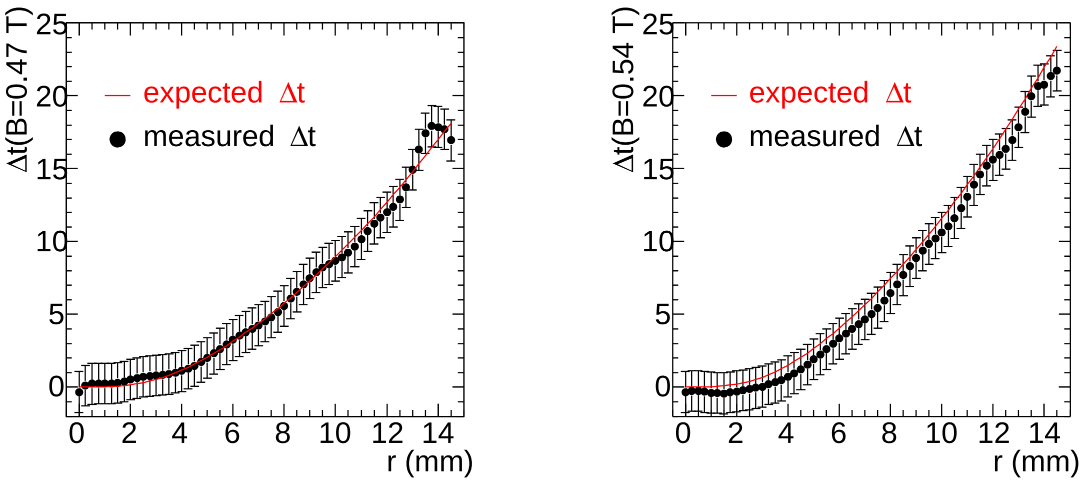

Figure 5: Magnetic field corrections to the drift time t in different regions of magnetic-field strength (0.47 T on the left, 0.54 T on the right) in MDT chambers in the middle layer of the large sectors of the barrel muon spectrometer as a function of the drift distance r. The measured difference in the drift times with and without magnetic field B agrees well with the model expectation in red derived from test beam measurements. The error bars of data points correspond to the estimated r-t accuracy of 20 μm. The drift time correction increases with the distance to the wire because of the deflection of the drifting electrons in the magnetic field oriented in the direction of the tube axis.

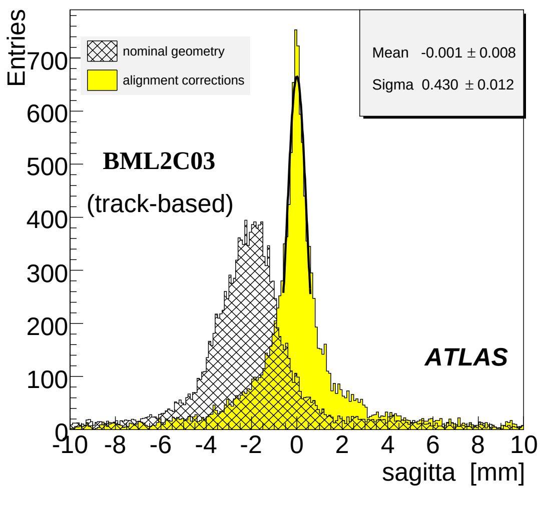

Figure 6: Sagitta distributions of straight cosmic ray muon tracks before and after the alignment with tracks. The mean value is on the order of a mm before the alignment procedure consistently with the mechanical installation accuracy. The mean value of the distribution is shifted towards 0 and its width is reduced by the track alignment procedure.

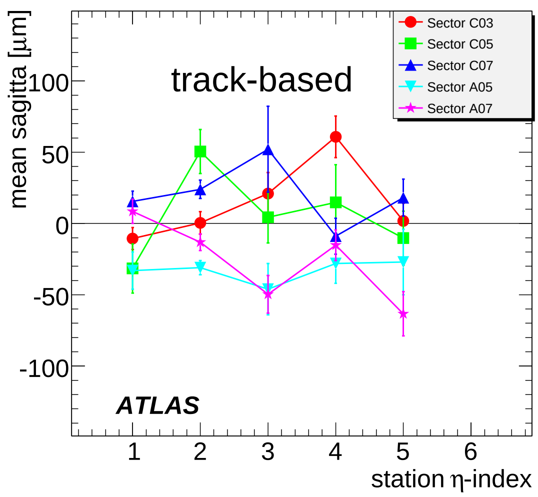

Figure 7: Mean value of the apparent track sagitta distributions obtained using a track-based alignment (large sectors). The station index describes the position of the MDT chamber along the z-direction (parallel to the beam pipe). The achieved accuracy of the alignment is independent of the sector and station index.

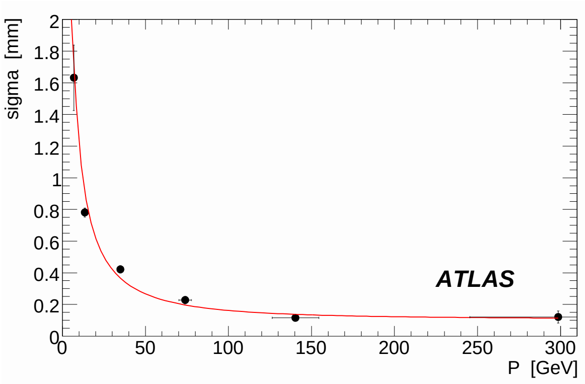

Figure 8: Resolution of the sagitta measurement as a function of the muon momentum as measured in ATLAS cosmic ray data. The red line illustrated the fitted resolution which is the quadratic sum of a term proportional to the inverse momentum taking into account multiple scattering and a constant term (of 100 μm) reflecting the limitation of the resolution by the spatial resolution and the alignment of the muon chambers.

parent sagitta of straight cosmic muon tracks after the initial alignment with straight cosmic muon tracks. In Figure 1.2 the mean value of the apparent sagitta distributions of the large sectors are shown as a function of the position of the MDT chamber along the z-direction (parallel to the beam pipe). The accuracy of the initial alignment is of the order of 50 μm or better and close to the desired ultimate accuracy of 30 μm. Improvements of the alignment accuracy are expected when chamber deformations will be taken into account in the track reconstruction. The measurement of the sagitta resolution of straight tracks in the muon spectrometer as a function of the muon momentum measured by the inner detector is presented in Figure 1.2. It improves with increasing momentum as multiple scattering decreases with increasing momentum ans reaches a plateau value of about 100 μm at high momenta reflecting the limited spatial resolution and the residual misalignment of the muon chambers. The achieved resolution is about a factor 2 larger than the target value of 50 μm because the chambers are only aligned with 50 μm instead of 30 μm precision.

The method is being extended to the alignment of the muon chambers with curved muon tracks in the magnetic field during normal operation of the experiment in order to verify the optical alignment corrections. This requires an independent measurement of the muon momentum which is insensitive to misalignment of the MDT chambers along the muon track. The MDT chambers with their two triple or quadruple layers of precisely positioned drift tubes measure not only track coordinates with high accuracy but also the local track direction. This feature can be utilised for independent momentum determination from measurement of the track deflection angles between the inner and the outer chamber layer and between the two multilayers of the chambers in the middle layer located inside the magnetic field. Studies with simulated data showed that the required alignment accuracy can be achieved within two days of data taking at the nominal LHC luminosity of $10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [22, 24].

1.3 Performance of the Muon Identification in ATLAS

The huge sample of cosmic ray muons made it possible to study the performance of the muon identification in great detail up to muon momenta of 300 GeV/c [32, 33]. Figure 1.3 shows the track reconstruction efficiency in the ATLAS muon spectrometer for cosmic ray muons reconstructed in the inner detector. The efficiency is close to 100% in the instrumented regions of the muon spectrometer. The drop of the efficiency at $|\eta| = 0$ is caused by the acceptance gap of the muon spectrometer which is needed for the services of the inner detector and the calorimeters.

The momentum of cosmic ray muons traversing the entire ATLAS detector are measured twice, first in the top part of the muon spectrometer, then in the bottom part of the muon spectrometer. The comparison of the two momentum measurements allowed us to measure the fractional momentum resolution of the muon spectrometer up to muon with $p_T = 300$ GeV/c (see Figure 1.3). The measured momentum resolution is in agreement with the expected momentum resolution for $p_T \lesssim 100$ GeV/c, but is a factor 2-3 worse than expected above 300 GeV/c due to the residual misalignment of the muon spectrometer.

The muon reconstruction efficiency and the momentum scale and resolution will be measured for low p_T with $J/\Psi \to \mu^+\mu^-$ decays and for high p_T with $Z \to \mu^+\mu^-$ decays in pp collision data at the LHC [34, 35]. First $J/\Psi \to \mu^+\mu^-$ events have been observed by the ATLAS experiment. The invariant mass distribution of the $J/\Psi \to \mu^+\mu^-$ events is shown in Figure 1.3

The position of the Z resonance peak is a measure

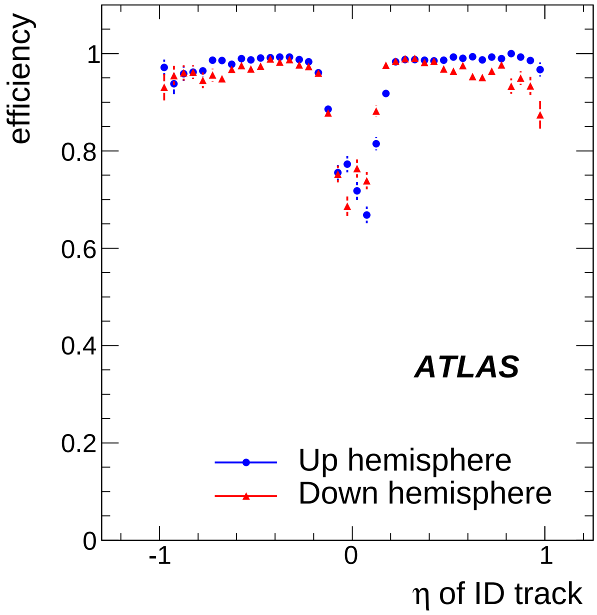

Figure 9: Track reconstruction efficiency in the muon spectrometer as a function of the pseudorapidity of the cosmic ray muon reconstructed by the inner detector. The muon momentum in the inner detector was requested to be greater than 5 GeV for the top part and greater than 9 GeV for the bottom part. The loss of efficiency in the region near $|\eta| = 0$ is due to acceptance holes of the muon spectrometer needed for services of the inner detector and the calorimeters.

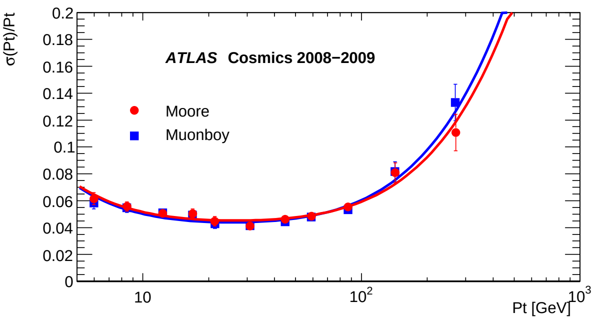

Figure 10: Transverse momentum resolution of the muon spectrometer evaluated by comparing the momentum of cosmic ray muons measured in the top part of the spectrometer with the momentum in the bottom part of the spectrometer in the barrel region of the muon spectrometer. The results of two complementary track reconstruction algorithms show similar performance.

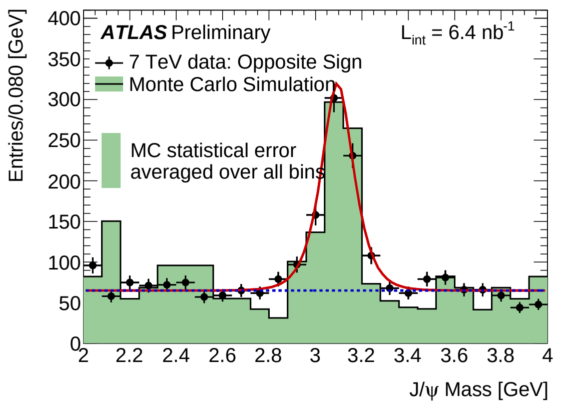

Figure 11: Invariant mass distribution of reconstructed $J/\Psi \rightarrow \mu^+\mu^-$ candidates. The points with error bars are data. The solid line is the result of maximum likelihood unbinned fit to all di-muon pairs in the mass window 24 GeV and the dashed line is the result for the background of the same fit. MC from both prompt J/Ψ and minimum bias simulation are superimposed.

for the momentum scale, its width a measure for the momentum resolution. The muon reconstruction efficiency will be measured by the so-called "tag-and-probe method". In the tag-and-probe method events with an isolated muon and an inner detector track giving an invariant mass compatible with the Z boson mass are selected. The fact that one of the two tracks is identified as muon ensure that the second track is also a muon and one can count how often the second track is reconstructed as a muon. The method has been studied on Monte-Carlo data and is able to reproduce the muon reconstruction efficiency with a systematic uncertainty of 0.2%.

First $Z \rightarrow \mu^+\mu^-$ candidate events have been observed in the ATLAS detector. One such event is shown in Figure 1.3. In the early phase of the LHC operation the rate of dimuon decays of Z bosons is too low for the tag-and-probe method and alternative methods have to be used to get a handle on the muon spectrometer reconstruction efficiency. The efficiency of the standard muon reconstruction is measured with respect to an alternative muon identification approach. In the alternative approach an inner detector track which deposits only little energy in the calorimeters and which can be matched with a track segment in the muon spectrometer is identified as muon. The relative efficiency

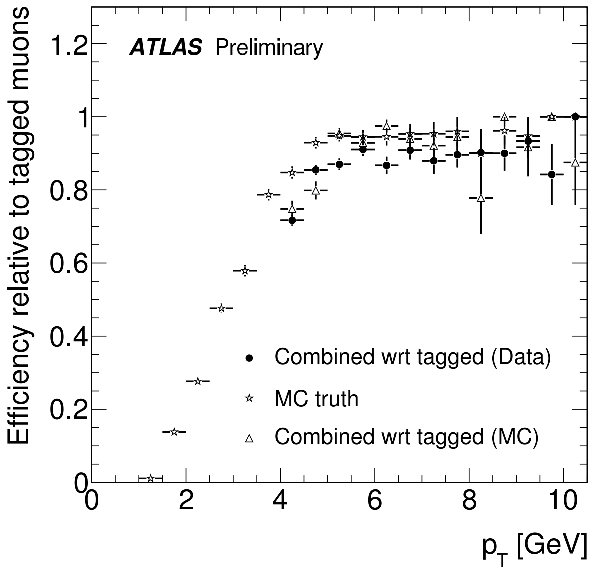

Figure 12: Comparison of the relative efficiency of the standard muon reconstruction algorithm with respect to reference muons as defined in the text with the Monte-Carlo prediction for $p_T > 4$ GeV/c. The star-shaped symbols labelled as MC truth show the standard muon reconstruction efficiency for muons identified as true muons in the simulation.

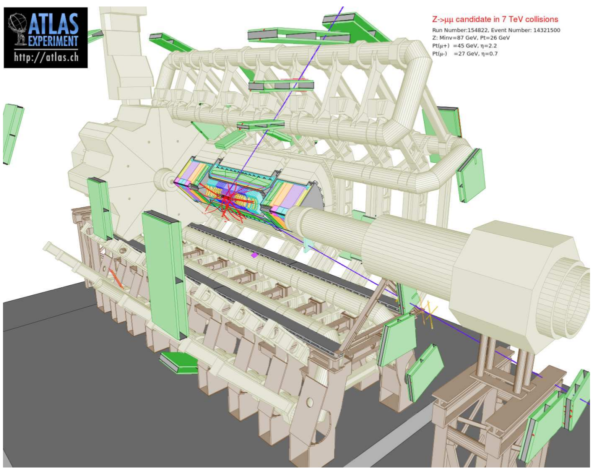

Figure 13: Event display of a $Z \rightarrow \mu^+\mu^-$ candidate event recorded at a centre-of-mass energy of $\sqrt{s}$ = 7 TeV

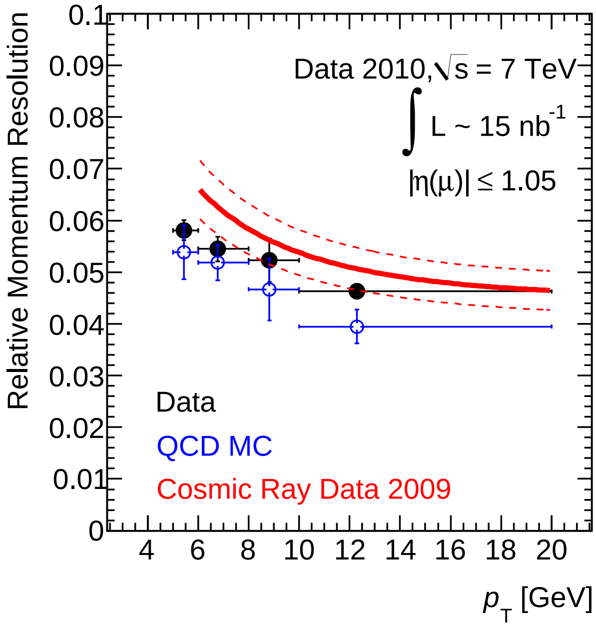

Figure 14: Comparison of the momentum resolution in the barrel part of the muon spectrometer measured with muons from pp collisions in comparison with the expected resolution from Monte-Carlo data and the analysis of cosmic ray data. The measured resolution agrees with the prediction within the measurement uncertainties.

of the standard muon reconstruction with respect to the alternative selection is shown as a function of the transverse muon momentum in Figure 1.3 [36]. The relative efficiency agrees with the Monte-Carlo prediction within errors. It is lower than the true efficiency as the alternative muon selection has a lower rejection power against muons from pion and kaon decays in flight than the standard reconstruction.

At transverse momenta below 20 GeV/c the momentum resolution in the momentum resolution is significantly larger than in the inner detector and can be measured by comparing the momentum measured in the muon spectrometer with the momentum measured in the inner detector. The resolution measured this way is in agreement with the Monte-Carlo prediction and the measurement with cosmic ray muons within the measurement uncertainties (see Figure 1.3) [37].

The analysis of cosmic ray data and the first results of the analysis of pp collision data confirm the expected performance of the muon spectrometer.

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