Muons in early ATLAS data: from first collisions to W+ W- production
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Citation for published version (APA):

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The ATLAS Detector at the Large Hadron Collider

2.1 CERN

After the end of the second world war the world tried to prevent future devastating wars by creating various international organizations to increase and strengthen international relationships and survey. Particularly the demonstrated massive destruction power of nuclear weapons was a major concern threatening reinvigorating european civilizations. On 29th of September 1954, Le Centre pour la Recherche Nucléaire, abbreviated to CERN was founded by the first member states: Belgium, Denmark, France, the Federal Republic of Germany, Greece, Italy, the Netherlands, Norway, Sweden, Switzerland, the United Kingdom and Yugoslavia. This organization should insure that the european nations work together on nuclear research of a pure scientific and fundamental character [65]. The tasks of CERN were defined to

- **Research**: Seek and find answers to the origin and nature of our universe.
- **Technology**: Advance the frontiers of technology.
- **Collaboration**: Bring nations together through science.
- **Education**: Train the next generation scientists.

In the following decades, CERN proved to be one of the most successful international cooperations of history, counting to date 608 contributing universities and institutes in 113 countries around the world. Developments and research at CERN led to the discovery of many new particles and phenomena of nature, yielding a new and more profound understanding of the building blocks of matter and our universe and was rewarded with 5 Nobel Prizes up to now.
The ATLAS Detector at the Large Hadron Collider

Just two years after the establishment of CERN in Geneva the first accelerator, a synchrocyclotron with a center of mass energy of 600 MeV became operational. In 1959 the Proton Synchrotron, PS started up as the highest energy particle collider in the world, supplying experiments with beam energies of 28 GeV. Also the world’s first proton-proton collider ISR (Intersection Storage Ring) was designed and built at CERN with a circumference of about 940 meters. 1976 marks the next milestone in CERN history, with the SPS (Super Proton Synchrotron) becoming operational. This seven kilometer circumference accelerator was originally designed to collide protons. However, at a later stage it ran as a proton-antiproton collider which would provide the data to discover the $W^\pm$- and $Z$-bosons, awarding a Nobel prize to Carlo Rubbia and Simon van der Meer in 1984.

LEP, the Large Electron Positron collider was commissioned in 1989 and heralded yet a new era at CERN. Excavating the 26.7 km long tunnel between 45 and 170 meters under the earth’s surface, that accommodated the highest energy lepton collider ever built also marked Europe’s largest civil-engineering project at the time. In the end of the year 2000 the very successful LEP collider and its dedicated experiments were closed to make way for the next generation accelerator.

2.2 The LHC

The Large Hadron Collider (LHC) is located in the former LEP tunnel. Being a proton-proton collider, two rings are needed to accelerate the particles, as opposed to particle-antiparticle colliders, such as LEP, where a single ring design is sufficient. To fit the LHC in the former LEP tunnel, twin bore magnets were used that consist of two sets of coils and beam pipes within the same mechanical structure and cryostat [21]. The first design studies of this new proton-proton collider at CERN reach back to the early 80’s of the last century. The LHC consists of 1232 superconducting dipole magnets designed to create a magnetic field of up to 8.33 Tesla. The magnets are cooled down to 1.9 Kelvin using superfluid helium. The technology for this ultra cold superconductors was originally developed for the French Tokamak Tore Supra fusion reactor and for the first time adopted to particle colliders. With this magnetic field strength a center of mass energy of 14 TeV is reached, a factor seven larger than the energy of the Tevatron proton-antiproton collider at Fermilab in the United States [26]. To accelerate proton beams up to 7 TeV the particles need to be injected in the LHC with an energy of 450 GeV. Protons with this injection energy are highly cost-efficiently provided by the previous generation CERN hadron accelerators. A linear accelerator, or linac takes ionized hydrogen atoms and pre-accelerates them to 50 MeV before they are boosted to 1.4 GeV by the PS booster. In the PS itself, the bunches of protons are then accelerated to 25 GeV before they enter the SPS where the bunches are collected and accelerated up to the LHC injection energy. With a bunch spacing of 25 ns the LHC can hold 2808 bunches of $10^{11}$ protons each, for each beam. The resulting design luminosity $\mathcal{L} = 10^{34}$ cm$^{-2}$s$^{-1}$ is an important key figure of the machine. The high center of mass energy together with the high luminosity will provide the dedicated experiments with the means to spot and measure rare processes of nature being the key to understand the fundamentals of our world.
In addition to protons, the LHC and its accelerator chain were conceptualized such, that they can accelerate and collide heavy ions as well. The current LHC schedule foresees 6 to 8 weeks of heavy ion runs each year. During these periods, atomic lead nuclei are collided in the bunch crossing points of the LHC. The focus of LHC operation lies however on colliding proton bunches. The beams are collided in four bunch crossing points along the LHC. Four experiments are situated at these bunch-crossing points, see Figure 2.1. A brief summary of the four experiments is given here in alphabetic order:

- **ALICE** is an experiment designed for heavy ions collisions to study the characteristics of an extremely early state of matter in our universe [23].

- **ATLAS** and **CMS** are multi purpose detectors designed to explore the full spectrum of proton-proton physics. However, they have been shown to also substantially contribute to heavy ion studies. A detailed description of ATLAS follows in the subsequent section while for further information on CMS, the reader is referred to [24].

- **LHCb** is a single arm spectrometer dedicated to the study of rare B meson decays [25].

![Figure 2.1: A schematic view on the LHC accelerator chain with the location of the four major experiments is shown.](image)

Only 9 days after the first circulating beams in September 2008, a faulty electrical connection between 2 dipole magnets sparked which led to a sudden vaporization of the cooling helium causing severe damage to the machine. It took over a year to replace and repair 53 damaged dipole magnets and install additional safety systems to prevent
similar incidents in the future. After all connections between the magnets were thoroughly checked it was decided to run the machine in 2010 and 2011 only up to beam energies of 3.5 TeV. In the scheduled longer technical shutdown of the LHC that will follow a first data taking period, all dubious connection will be replaced which will allow the machine to reach its design beam energy of 7 TeV after the shutdown. However, the performance of the LHC since its restart in March 2010 is remarkable and exceeded the most optimistic predictions. The aim of providing the large LHC experiments with an integrated luminosity of 1 fb$^{-1}$ of collision data by the end of 2011 was already reached in spring 2011 as shown in Figure 2.2(b). Since then, the luminosity of the machine could be increased even more and over 5 fb$^{-1}$ were recorded before October 2011.

Figure 2.2: The delivered integrated luminosity of the LHC as well as the fraction recorded by ATLAS is shown by days since the restart of the machine in March 2010 up to October 2011.
2.3 The ATLAS Detector

ATLAS (A Toroidal LHC ApparatuS) is a detector designed to fully exploit the potential of the LHC. Its goals are diverse and reach from improved measurements of the Standard Model and the properties of its known particles to new physics that might unveil at these energies. As a central benchmark to establish the performance of ATLAS the search for the Standard Model Higgs particle was chosen. Together with the very high interaction rates of the LHC resulting in high particle multiplicities and radiation doses, this led to the following requirements for the ATLAS detector [22]:

- the detector elements and electronics need to be fast and radiation-hard.
- a highly efficient trigger, providing sufficient background rejection is indispensable to cope with the high luminosities delivered by the LHC.
- high detector granularity is required to handle the particle fluxes and overlapping events.
- a large acceptance with full azimuthal angle coverage is needed for all major sub-systems.
- a good charged-particle momentum resolution is required next to a high reconstruction efficiency.
- good electromagnetic calorimetry for electron and photon identification is needed in addition to hadronic calorimetry for precise jet and transverse energy measurements.
- a highly efficient muon identification is essential.

The last point is one of the key aspects of this thesis and will be discussed in detail in Chapter 4 and 5.

To meet these requirements, ATLAS consists of multiple sub-detector systems illustrated in Figure 2.3. The individual subsystems are arranged in cylindrical layers around the beam pipe which form the detector barrel. On each side of the barrel the subsystems are completed by wheels perpendicular to the beam pipe, the end-caps. The individual subsystems can be grouped into three sub-detectors. Closest to the beam pipe, track measurements are performed by the Inner Detector (ID). The calorimeters surround the ID and measure the particle energies. The Muon Spectrometer is the outermost system, a tracking device to measure the tracks of traversing muons. It also defines the dimensions of ATLAS, which is with its 44 times 25 meters the largest of the LHC experiments.

The design resolution and coverage of the individual systems are summarized in Table 2.1. After the coordinate system of ATLAS is introduced, all detector systems will be discussed in the given order.

As shown in Figure 2.2, ATLAS had a remarkable start of collision data taking, with over 93% of the provided luminosity being recorded in the first year. The individual detector systems proofed to work reliably. Table 2.2 shows the time fraction the sub-detectors were operational [69]. All systems show an uptime of > 96%.
**Figure 2.3:** A cut-away view of the ATLAS detector. Sub-detector systems are labeled.
### 2.3 The ATLAS Detector

<table>
<thead>
<tr>
<th>detector component</th>
<th>$\eta$ coverage</th>
<th>design resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Detector</td>
<td>±2.5</td>
<td>$\sigma_{p_T}/p_T = 0.05% \times p_T \oplus 1%$</td>
</tr>
<tr>
<td>Pixel</td>
<td>±2.5</td>
<td></td>
</tr>
<tr>
<td>SCT</td>
<td>±2.5</td>
<td></td>
</tr>
<tr>
<td>TRT</td>
<td>±2.0</td>
<td></td>
</tr>
<tr>
<td>EM calorimeter</td>
<td>±3.2</td>
<td>$\sigma_E/E = 10%/\sqrt{E} \oplus 0.7%$</td>
</tr>
<tr>
<td>Hadronic calorimeter</td>
<td>±3.2</td>
<td>$\sigma_E/E = 50%/\sqrt{E} \oplus 3%$</td>
</tr>
<tr>
<td>barrel + end-cap</td>
<td>3.1 &lt; $</td>
<td>\eta</td>
</tr>
<tr>
<td>forward</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Muon Spectrometer</td>
<td>±2.7</td>
<td>$\sigma_{p_T}/p_T = 10%$ at $p_T = 1$ TeV</td>
</tr>
<tr>
<td>MDT</td>
<td>±2.7</td>
<td></td>
</tr>
<tr>
<td>RPC</td>
<td>±1.05</td>
<td></td>
</tr>
<tr>
<td>TGC</td>
<td>1.05 &lt; $</td>
<td>\eta</td>
</tr>
<tr>
<td>CSC</td>
<td>2.0 &lt; $</td>
<td>\eta</td>
</tr>
</tbody>
</table>

**Table 2.1:** The requirements on coverage and resolution are listed for the individual subsystems of ATLAS.

<table>
<thead>
<tr>
<th>detector component</th>
<th>readout channels</th>
<th>operational</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner Detector</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pixel</td>
<td>≈ 80.4 million</td>
<td>≈ 96.8 %</td>
</tr>
<tr>
<td>SCT</td>
<td>≈ 6.3 million</td>
<td>≈ 99.1 %</td>
</tr>
<tr>
<td>TRT</td>
<td>≈ 351000</td>
<td>≈ 97.5 %</td>
</tr>
<tr>
<td>EM calorimeter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>barrel + end-cap</td>
<td>173312 (^1)</td>
<td>≈ 99.8 %</td>
</tr>
<tr>
<td>forward</td>
<td>15484</td>
<td>≈ 97.5 % + 99.8 %</td>
</tr>
<tr>
<td>Hadronic calorimeter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>forward</td>
<td>3524</td>
<td>≈ 99.8 %</td>
</tr>
<tr>
<td>Muon Spectrometer</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MDT</td>
<td>354000 (^2)</td>
<td>≈ 99.7 %</td>
</tr>
<tr>
<td>RPC</td>
<td>373000</td>
<td>≈ 97.0 %</td>
</tr>
<tr>
<td>TGC</td>
<td>318000</td>
<td>≈ 98.1 %</td>
</tr>
<tr>
<td>CSC</td>
<td>30700</td>
<td>≈ 97.7 %</td>
</tr>
</tbody>
</table>

**Table 2.2:** The number of readout channels is listed together with the approximate fraction of time the individual detector system was operational during data-taking.

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\(^1\)This number includes the 9344 channels of the presampler.

\(^2\)The quoted numbers are the design values for the fully operational MS. There are about 50 chambers that have not been installed yet and are foreseen to be integrated in the MS in the coming technical shutdown the end of 2011 and 2012 \[^{[83]}\]. These chambers are situated in the transition region between barrel and endcap stations.
2.3.1 Coordinate System

The nominal interaction point (IP) defines the origin of the right-handed ATLAS coordinate system. The positive $x$-axis is pointing towards the center of the LHC ring, while the positive $y$-axis is pointing upwards towards the ground surface. The $x$-$y$ plane is hence perpendicular to the beam pipe and is referred to as the transverse plane. The positive $z$-axis is defined to point along the beam pipe towards the west, thus in the counterclockwise direction.

In view of the ATLAS geometry, a cylindrical coordinate system is often used with azimuthal ($\phi$) and a polar angle ($\theta$) in addition to a radius $R$. These coordinates are defined as:

\begin{align}
R &= \sqrt{x^2 + y^2} \\
\phi &= \arctan\left(\frac{y}{x}\right) \\
\theta &= \arccos\left(\frac{z}{R}\right)
\end{align}

(2.1)

where $\phi \in [-\pi, \pi]$ and $\theta \in [0, \pi]$. Instead of $\theta$ the pseudorapidity $\eta$ is commonly used, that is defined as

\[ \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right) \]

(2.2)

i.e. $\eta \in ]-\infty, \infty[$. A convenient property of the pseudorapidity is that the production of charged particles is approximately flat in $\eta$. Also the difference in $\eta$ of two massless particles is Lorentz invariant.

2.3.2 Inner Detector

The ATLAS Inner Detector is a tracking device designed to precisely measure traversing charged particles with a high spatial and momentum resolution. It is further capable in reconstructing primary and secondary vertices. Its first cylindrical detector layer is as close as 5 cm to the beam pipe to insure a high vertex resolution. The inner most subsystem is a silicon pixel detector, which is surrounded by a silicon strip detector (SemiConductor Tracker, SCT). The third, outermost subsystem is a transition radiation detector (Transition Radiation Tracker, TRT). The three detector systems are embedded in a solenoidal magnetic field with a field strength of 2 T parallel to the beam axis. A cut-away view of the ID is shown in Figure 2.4.

Pixel Detector

The ATLAS Pixel Detector is the inner most system with the first of its three layers, the so-called B-Layer reaching about 5 cm to the interaction point, as illustrated in Figure 2.4. The three barrel layers are completed with corresponding end-caps on each side, which leads to an expected number of three hits for charged collision products. Being so close to the interaction point implicates a high granularity to match the requirements on vertex and track momentum resolution. A total of over 80 million readout channels
2.3 The ATLAS Detector

Figure 2.4: A sketched cutaway of the ATLAS Inner Detector showing the setup of the three subsystems in the barrel. The tube at $R = 0$ is the beam pipe.

is deployed. The barrel layers and disks are equipped with $50 \times 400 \, \mu m^2$, respectively $50 \times 600 \, \mu m^2$ semiconducting silicon pixels providing a design hit resolution of $10 \, \mu m$ in $R - \phi$ and $115 \, \mu m$ in $z$. Traversing charged particles ionize the charge depleted zone of the sensors, creating electron-hole-pairs in the silicon, which are separated by the applied potential. The induced signal is measured as time-over-threshold by a discriminator in the readout electronics after the signal was amplified.

The efficiencies of the individual barrel layers and end-cap disks measured on early data in 2010 are shown in Figure 2.5(a). “Dead modules are excluded from the association efficiency computation, but otherwise dead regions contribute to the inefficiency. The full efficiency of B-Layer is due to the track selection, the lower efficiency for the most external disks is mainly due to inefficient regions on some modules. Error bars are smaller then marker sizes.”

The noise occupancy is shown in Figure 2.5(b) as a function of time, using randomly triggered events with empty bunches between April and May 2010. The noise rate is dominated by few pixels which are detected on a run-by-run basis by offline prompt calibration and masked during the bulk processing. For the bulk processing, the

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3 The quoted text is literal text from the ATLAS web side.
4 typically 300 - 1500 out of 80 million,
remaining noise occupancy is less than 10 hits per pixel per bunch crossing, corresponding to less than 0.2 noise hits per event when reading out 5 bunch crossings [70].

Figure 2.5: The efficiency for a track to have a hit associated when crossing a Pixel Detector layer is shown in (a). The noise rate for the Pixel detector measured on empty bunches is shown in (b). The plots are taken from [70].

Semiconductor Tracker

The SCT, surrounding the Pixel Detector provides typically four space point measurements (8 hits) of traversing charged particles. To insure a good momentum resolution, extending the Pixel Detector measurements is particularly important for high momentum particles, where the curvature of the track in the magnetic field is small. The SCT barrel consists of 4 cylindrical detection layers while each end-cap is made of nine detection disks. As for the Pixel Detector, silicon is used as detection material, however the SCT is segmented in strips. This design limits the number of readout channels and is hence cost efficient. The SCT detector modules consist of two silicon sensors glued back-to-back with an angle of 40 mrad providing a 2 dimensional measurement. In the barrel the strips on one side of the modules are aligned parallel to the beam axis, while the strips on one side of the disk modules run radially. Each sensor is made of 768 strips with a strip pitch of 80 µm. The design resolution is 17 µm in R − φ and 580 µm in z.

The intrinsic SCT module efficiency has been measured on data to be on average larger than 99.7 %. The performance is detailed at [71] and shown in Figure 2.6. The “hit efficiency is the number of hits per possible hit, where dead modules and chips are taken into account. […] The efficiency is shown for two different types of tracks: SCT stand-alone and Inner Detector combined tracks, both with the requirement of a transverse momentum of above 1 GeV. For stand-alone tracks we demand at least 7 SCT hits (not including the hit under test for efficiency) while for combined tracks at least 6 SCT Hits are required. The efficiencies in layer 0 inner and 3 outer are biased for the SCT stand-alone tracks as holes beyond the last measurement are not counted.” [71]
2.3 The ATLAS Detector

Figure 2.6: The hit efficiencies of the SCT barrel (a) and end-cap C modules (b) are shown. Since the performance differences of the two end-caps are negligible, the efficiencies of only one end-cap is shown. The plots are taken from [71].

Transition Radiation Tracker

The outermost ID subsystem uses two independent detection principles. It contributes to the ID track measurement up to $|\eta| = 2$ using wire chambers while also allowing for the identification of particles by the emitted transition radiation.

The TRT barrel consists of 73 layers of 144 cm long straws parallel to the beam axis, while each end-cap contains 18 disks of 37 cm long straws which are radially aligned. The straws are gas filled tubes with a 4 mm diameter which are kept as cathodes on $-1530$ V. The gold plated, 31 $\mu$m tungsten wire in the center of each tube, supported at the straw ends, is kept on ground potential. In the barrel, the wires are divided into two halves at $\eta = 0$ to deal with the high occupancies. Traversing charged particles ionize the Xe:CO$_2$:O$_2$ (70:27:3 %) gas mixture and the free charges drift towards the wire under the applied potential. The resulting induced current is measured. The TRT provides only a $R - \phi$ measurement. The design resolution is 130 $\mu$m.

The TRT straws are coated by materials with different dielectrical constants, causing a charged particle to emit X-ray photons when traversing the boundaries between these material layers. These photons are referred to as transition radiation. The amount of emitted transition radiation depends on the particles Lorentz factor $\gamma = E/m$. A charged pion, carrying 273 times the mass of an electron produces hence a significantly smaller amount of transition radiation, which is absorbed by the Xenon in the gas mixture of the tubes and yield much larger signal amplitudes than traversing ionizing particles. Thus, tracking signal and transition radiation are distinguished by two separate thresholds in readout electronics of the TRT.
2.3.3 Calorimeter

As shown in Table 2.1, the ATLAS calorimeters cover the wide range up to $|\eta| = 4.9$. They are designed to measure the energy of all incoming particles by absorbing them. Muons and neutrinos are the only known particles that are not absorbed and can traverse the calorimeter. In addition, their total minimal thickness of 11 nuclear interaction lengths ($\lambda$) limits punch-through into the muon system. Combining the ID and calorimeter measurements provides an identification of electrons, photons and gives probabilities for a jet to result from a $b$ or $\tau$ decay.

Different techniques depending on the radiation environment are used to meet the physics requirements, leading to 6 calorimeters that can be grouped into electromagnetic (EM) and hadronic calorimeters and are displayed in Figure 2.7. ATLAS uses sampling calorimeters, which consist of alternating layers of absorbers, dense materials used to degrade the energy of the incident particle and active materials that are used to measure the deposited energy.

![Figure 2.7: A cut-away view of the ATLAS calorimeters, with the Inner Detector in the center.](image)

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5 Traversing the calorimeter requires the muons to have an energy of at least 3 GeV.
6 The thickness is a function of $\eta$ and increases to more than 18 $\lambda$ for the forward regions. The nuclear interaction length $\lambda$ is defined as the mean path length in which the number of relativistic charged particles is reduced by a factor $1/e$. 

26
Electromagnetic Calorimeter

The ATLAS EM calorimeter is attached to the solenoid enclosing the ID. Direction and energy of electromagnetic showers caused by Bremsstrahlung and pair production of incident electrons and photons are precisely measured using lead as absorber and liquid argon (LAr) as the active material. An accordion shape geometry was chosen for the alternating layers providing complete $\phi$ symmetry without azimuthal cracks. The first of its three layers in barrel and end-caps has a finer granularity to allow for electron, photon and pion identification. The thickness corresponds to more than 22 radiation lengths ($X_0$) in the barrel and more than 24 $X_0$ in the end-caps. The covered pseudorapidity range and expected energy resolution is listed in Table 2.1. For $|\eta| < 1.8$ a presampler detector in front of the first EM calorimeter layer corrects for the energy electrons and photons lost upstream of the calorimeters.

A cell occupancy map of the EM calorimeter, measured on collision data in April 2010 is shown in Figure 2.8 and published at [72].

![Figure 2.8: The cell occupancy in the EM calorimeter is shown. The plot is taken from [72].](image)

Hadronic Calorimeter

Strong interacting particles deposit only a small fraction of their energy in the EM calorimeter. The hadronic calorimeter is used to measure energy and direction of hadrons through their strong and electromagnetic interactions. Since hadronic showers are wider and longer than their electromagnetic counterparts, the hadronic calorimeters allow for a coarser granularity but are significantly more massive. The barrel, which is called Tile

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7 The radiation length $X_0$ is defined as the mean path length in which the energy of a high energetic electron is reduced by a factor $1/e$. 

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Calorimeter extends from an inner radius of 2.28 m to an outer radius of 4.25 m, covering the pseudorapidity range of $|\eta| < 1.0$. It is extended by two additional barrels in the range $0.8 < |\eta| < 1.7$ as shown in Figure 2.7. Steel is used as the absorber while scintillating tiles measure the signal, which is read out by wavelength shifting fibres into photomultiplier tubes. The corresponding end-caps, one on each side, use copper as absorber and LAr as the active medium, sharing some infrastructure with the EM calorimeter end-caps. They are hence referred to as the LAr hadronic end-cap calorimeters (HEC). Figure 2.9 shows the “mean value of the $E/p$ variable as a function of $\eta$, integrated over all $p$ ranges for 2010 Data and Monte Carlo simulation. $E$ refers to the energy deposited in the Tile Calorimeter ($|\eta| < 1.7$) by the isolated charged particles with momentum $p$ and pseudorapidity $\eta$ (excluding the energy deposited in the scintillators). Charged particles have been selected applying a MIP-like signal requirement for the energy deposition in the LAr calorimeter.” [73] The $E/p$ distribution in $\phi$ is to a good approximation flat and not shown here.

The pseudorapidity coverage of the ATLAS hadronic calorimeter is extended by the Forward Calorimeter (FCal) up to $|\eta| = 4.9$ to improve the measurement of the missing transverse energy which is caused by collision products that stay undetected, like neutrinos. The FCal consists of two end-caps using LAr as the active medium while copper is the absorber in the first layer, being optimized for EM measurements, while the other two layers use tungsten, measuring the energy lost in hadronic interactions.

![Figure 2.9: The mean value of $E/p$ is shown as a function of momentum (a) and pseudorapidity (b) for the ATLAS Tile Calorimeter. The bottom plots show the data-Monte Carlo ratio of the mean value of the $E/p$ variable, fitted with a constant function. The errors are statistical. The plots are taken from [73].](image)

### 2.3.4 Muon Spectrometer

The Muon Spectrometer (MS) is another tracking device. This outermost subsystem of ATLAS was designed to provide a muon trigger as well as a precise muon track re-
2.3 The ATLAS Detector

<table>
<thead>
<tr>
<th>Type</th>
<th>Function</th>
<th>Chamber resolution (RMS) in</th>
<th>Measurements/track</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$z/R$ [mm]</td>
<td>$\phi$ [mm]</td>
</tr>
<tr>
<td>MDT</td>
<td>tracking</td>
<td>$35 \times 10^{-3}$</td>
<td>–</td>
</tr>
<tr>
<td>CSC</td>
<td>tracking</td>
<td>$40 \times 10^{-3}$</td>
<td>5</td>
</tr>
<tr>
<td>RPC</td>
<td>trigger</td>
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<tr>
<td>TGC</td>
<td>trigger</td>
<td>2 - 6</td>
<td>3 - 7</td>
</tr>
</tbody>
</table>

Table 2.3: The parameters of the four sub-systems of the ATLAS Muon Spectrometer are shown. The intrinsic time resolution of the individual chambers is quoted. No contributions from signal-propagation or electronics are included.

construction based on measurements in typically 3 stations. Its three cylindrical layers, forming the barrel of the MS are positioned at radii of 5, 7.5 and 10 meters from the beam-axis. They are referred to as the inner, middle and outer station. The corresponding MS end-caps are positioned at $z$ equals ±7.4, ±14 and ±21.5 meters. The spatial MS coverage as shown in Table 2.3 has a few acceptance holes due to support structures. At $|\eta| \lesssim 0.1$ a shaft to provide ID, solenoid and calorimeter services makes the installation of muon chambers impossible. Also in the feet regions of ATLAS at $\phi \approx -1.0$ rad and $\phi \approx -2.0$ rad the support structures of the large toroid and the detector barrel limit the acceptance.

To allow for a precise momentum measurement, a magnetic field is provided by the superconducting air-core ATLAS toroid. Up to $|\eta| < 1.4$ the large barrel toroid provides a field mostly orthogonal to the traversing muon directions. For $1.6 < |\eta| < 2.7$ muon tracks are bent by two smaller end-cap magnets. The pseudorapidity range $1.4 < |\eta| < 1.6$ is commonly referred to as the transition region, where the two magnetic fields of barrel and end-cap toroids are overlapping.

The MS is equipped with high precision tracking chambers and separate trigger chambers. Their $\eta$ coverage and number of readout channels is summarized in Table 2.1, while the individual chamber resolutions and corresponding measurements per track are listed in Table 2.3. The trigger chambers are required to provide fast and coarse tracking information including a transverse muon momentum estimate as well as bunch-crossing identification. The transverse $x$-$y$-view of the barrel detector in Figure 2.10 and the side view of the upper ATLAS quadrant in Figure 2.11 illustrate the location of all individual MS chamber types which are described in detail in the following.

**Monitored Drift Tube Chambers**

The Monitor Drift Tubes (MDT’s) provide precision measurements in the ATLAS MS. Figure 2.12 shows a cut-away view of a typical middle or outer station MDT barrel chamber consisting of two multilayers with three layers of MDTs each. The layer dimensions and sizes of the MDT chambers increase in proportion to their distance from the interaction point. However, a considerable number of specially shaped chambers have been built to minimize acceptance losses in the regions around magnets and support structures. The general layout alternates small and large chambers in $\phi$. The naming of the chambers is
Figure 2.10: The cross section of the ATLAS detector barrel is shown perpendicular to the beam-axis, illustrating the muon system.

Figure 2.11: The cross section of an upper quadrant of the ATLAS detector is shown parallel to the beam-axis, illustrating the muon system.
based on their location (‘B’arrel, ‘E’ndcap), their assignment to inner, middle, or outer stations (‘I’, ‘M’, ‘O’) and their size (‘S’mall, ‘L’arge). A BOL chamber refers thus to a large chamber in the outer station of the barrel. To improve the pattern recognition, the inner station MDT chambers are equipped with four multilayers.

The basic elements of the MDT chambers are the individual aluminum tubes with a 30 mm diameter, pressurized by an Ar:CO$_2$ (93:7 %) gas mixture at 3 bar. Their individual lengths varies between 1685 and 2820 mm in the barrel inner stations up to 4202 to 6503 mm in the outer end-cap stations. The tungsten-rhenium wire is gold plated and kept at a potential of 3080 V in the center of each tube, while the tubes are on ground potential. Free charges, created by the traversing ionizing muons in the gas, drift through the applied potential and induce a measured current in the central wire. When a predefined threshold in the readout electronics is reached the signal and corresponding time is recorded. The measured time is the drift time of the free charges which is converted into a drift radius, the minimal distance of the traversing muon to the wire. Figure 2.13(a) shows the relation of drift time and drift radius measured in 2010, while the measured drift time spectrum is shown in Figure 2.13(b) [41]. The measurement of the drift circle gives a precise position in one plane with an average tube resolution of 80 $\mu$m. The resolution quoted in Table 2.3 shows the average resolution per chamber. The position along the tube is not measured by the MDT’s.

Figure 2.12: A cut-away view of the typical MDT layout. The shown configuration with 2 multilayers of 3 tube layers is used in the barrel middle and outer stations.

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Exceptions are the two MDT twin-tube chambers installed for testing in the outer barrel stations. MDT’s are paired in these chambers to reconstruct the second coordinate from the two correlated measured times of the individual MDT’s, see [64] for details on the MDT twin-tubes.
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Figure 2.13: The drift time - drift radius relation is shown in (a) while (b) shows the drift time spectrum. Note that (b) shows an arbitrary time scale where the drift time starts at around 350 ns. The plots are taken from [41].

**Cathode Strip Chambers**

The particle fluxes and track density are highest in the forward regions of the detector ($|\eta| > 2.0$). At LHC design luminosity, the counting rates will be too high for the MDT’s to provide an efficient measurement in the inner stations in this region. The fast Cathode Strip Chambers (CSC’s) replace the MDT inner stations in the region $2.0 < |\eta| < 2.7$. They combine high spatial, time and track resolution (see Table 2.3) with high counting rate capability and low neutron sensitivity. The CSC system consists of 2 disks mounted about 7 m from the interaction point, one on each side of the detector. Each disk consists of 8 small and 8 large chambers alternating in $\phi$, resembling the MDT layout. The CSC’s are multi-wire proportional chambers with 30 $\mu$m diameter anode wires oriented in the radial direction. Both cathodes are segmented, one in strips parallel and one perpendicular to the wires, providing a two dimensional position measurement. The chambers are filled with an Ar:CO$_2$ (80:20 %) gas mixture that is ionized by traversing charged particles. The operating voltage is 1900 V. Unlike the MDT’s, the wires are not read out. Instead, the induced current in neighboring cathodes provides the signal. Each CSC chamber consists of 4 identical CSC planes providing 4 independent position measurements in $\eta$ and $\phi$ for every charged particle traversing a CSC.

**Resistive Plate Chambers**

The Resistive Plate Chambers (RPC’s) are an important complement to the MDT’s in the detector barrel, providing a $\phi$ measurement and a trigger for muons. Two RPC’s are mounted on the middle station MDT chambers and one on the outer station MDT chambers, see Figure 2.11. Thus, the three muon trigger stations are formed. The RPC’s
are gaseous parallel electrode-plate detectors. Two plastic plates are installed with a distance of 2 mm. The chambers are filled with a low cost and nonflammable gas mixture of C\(_2\)H\(_2\)F\(_4\):Iso-C\(_4\)H\(_{10}\):SF\(_6\) (94.7:5:0.3 \%). The strong electric field of 4.9 kV/mm between the plates allows electron avalanches to form along the path of a traversing charged particle. The signal at the anode is read out via capacitive coupling to metallic strips mounted on the outer faces of the plastic plates.

**Thin Gap Chambers**

In the end-caps, the muon trigger is provided by the Thin Gap Chambers (TGC’s). Four disks in each end-cap provide on average nine measurements per traversing particle. The MDT end-cap inner station has two layers, while the EM stations have 7 layers of TGC’s. TGC’s are like CSC’s multi-wire proportional chambers. The anode wires operated at 2900 V are thin gold wires while the cathodes are made of graphite which are read out using copper strips. Both, cathodes and wires are read out, providing an \(\eta\) and a \(\phi\) measurement. The chambers are operated with a gas mixture of CO\(_2\):n-C\(_5\)H\(_{12}\) (55:45 \%).

### 2.3.5 Magnets

The ATLAS magnet system provides the magnetic fields in the Inner Detector and the Muon Spectrometer to allow for a momentum measurement of charged particles. It consists of 4 large superconducting magnets, shown in Figure 2.14, with an energy of 1.6 GJ stored. The entire system is 22 m in diameter and 26 m in length, providing a magnetic field over the volume of 12000 m\(^3\). Figure 2.3 indicates where the magnets are located in the detector with respect to the individual sub-detector systems.

**Solenoid**

The ID is embedded in a 2 T strong axial magnetic field of the ATLAS solenoid, which is operated at 7730 A. The windings of the solenoid lie inside the tile calorimeter volume. It has a total length of 5.8 m with an inner diameter of 2.46 m and an outer diameter of 2.56 m.

**Torroids**

For the MS a system of three large air-core toroids was designed to provide a magnetic field of approximately 0.5 T in the barrel and 1 T in the end-cap region. A nominal current of 20500 A is needed to reach this field strength. A total mass of 650 tonnes need to be cooled down to 4.6 K, the operational temperature of the superconducting magnets. The barrel toroid is 25.3 m in length and its inner and outer diameters are 9.4 m and 20.1 m, respectively.
Figure 2.14: A cut-away view on the ATLAS magnet system. The eight toroid coils are shown for barrel and both end-cap toroids. The tile calorimeter is shown in the center, hosting the solenoid.

B-field monitoring

In order to achieve the design momentum resolution of 10% for a muon with transverse momentum of 1 TeV, stated in Table 2.1, the magnetic field needs to be known to a relative precision of approximately $4 \times 10^{-4}$ [27]. The magnetic field is modeled with the contribution of all magnet windings and material effects, particularly from the calorimeters. However, the high self-weight of the toroids as well as the inwards directed net Lorentz force of approximately 1400 tonnes per coil lead to a deflection of the toroids. In addition, perturbations of the magnetic field induced by metallic materials e.g. used in the calorimeters, and the transition region $1.4 < |\eta| < 1.6$ where barrel and end-cap toroid fields overlap introduce further uncertainties on the magnetic field map. To counter all these effects, about 1800 Hall probes have been distributed over the entire MS volume, measuring continuously the toroidal field. Figure 2.15 shows the distribution of the sensors in space. The toroid coils and general structure of the ATLAS MS are visible. All sensors have been calibrated to provide exact values of the measured magnetic field strength. Their measurements are compared to the computed magnetic field map and corrections can be applied to the model, that is used to reconstruct muon tracks in the MS.

Measurements of the magnet currents supplement the measurements of the B-field sensors which are analyzed on a daily bases. Figure 2.16 shows the solenoid and toroid currents as a function of time, starting at the day where the first data used in this thesis was
recorded, the 23rd of April 2010. Each entry corresponds to one day and shows the average current. The values in between 0 and the nominal current correspond to days, where the magnet currents were either ramped up or ramped down. During the technical stop at the end of the year 2010 until the mid February 2011 the magnets were off. Missing entries correspond to failures in the daily B-field sensor monitoring, as for example at the end of June 2010 where the software was updated.

A worry were possible aging effects that could change the calibration of the Hall probes over time. The measured values would thus not be reliable any longer. Figure 2.15(b) shows the average $|B|/I$ values of each day between April 2010 and July 2011 on which the toroid current was all day nominal and B-field monitoring data is available. Each entry is the average of all B-field sensor measurements on the corresponding day. Ideally, the value should not change over time since the toroid current is constant. The displayed distribution is indeed extremely narrow with a RMS of $1.5 \times 10^{-4}$ and we hence conclude, that the B-field sensors work as expected and perform reliably without any visible aging effects.

**Figure 2.15:** The position of the B-field monitoring sensors in the MS are shown in (a). The projection of the average measured $|B|/I$ as function of time is shown for measurements between April 2010 and July 2011.

### 2.3.6 Summary

ATLAS had an extraordinary start in the collision data taking phase in 2010. In the past two years, 2010 and 2011 the most optimistic expectations were far exceeded in both, the amount and the quality of the recorded data. After almost 30 years of research, development, construction and commissioning, the ATLAS detector is fully operational.

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9 This day marks the start of the first run in 2010’s data period B.

10 The B-field monitoring system was updated to a new operating system leading to major compatibility issues that took multiple weeks to be sorted out.
and up for the tasks it was designed for. The ATLAS performance measurements are widely based on collision data and do not rely on Monte Carlo simulations anymore. We discussed in this section the technical aspects and design of the individual subsystems of ATLAS enriched with a selection of performance plots on collision data to illustrate the excellent shape of the detector.

Figure 2.16: Solenoid and toroid current are shown for the first data taking periods, i.e. end of April 2010 until end of July 2011.