Strong supersymmetry: A search for squarks and gluinos in hadronic channels using the ATLAS detector
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The LHC and the ATLAS detector

To study the direct production of new massive particles, an experimental set-up is needed where particles collide with high centre-of-mass energy, and where the final state particles are detected with high precision. To this end, collisions provided by the LHC accelerator are studied by the ATLAS experiment. This chapter describes the configuration and performance of the accelerator in the first section, and that of the ATLAS detector in the succeeding sections.

2.1 The LHC accelerator

The Large Hadron Collider \[\text{[104]}\] is a circular proton-proton accelerator and collider situated at the CERN laboratory, near the city of Geneva at the border of France and Switzerland. It is placed in the 26.7 km long tunnel constructed in the 1980s for the Large Electron Positron (\text{LEP \[\text{[105]}\]} collider, which was shut down in the year 2000. The circular tunnel sits approximately 100 m below the surface, at 170 m below the surface at the Jura-side of the ring and 45 m below the surface at the side of Lake Geneva (Lac Léman). The LHC is designed to conduct proton-proton collisions which reach a centre-of-mass energy of 14 GeV with a luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. Yet due to an accident at the initial start-up in September 2008 it has been decided to run with a lower centre-of-mass energy of $\sqrt{s} = 7$ TeV in 2010-2011, which was increased to $\sqrt{s} = 8$ TeV in 2012. The accelerator will be upgraded to the full design energy only in 2015. This still means that the LHC is the world’s highest energy collider: the Tevatron collider, situated at Fermilab near Chicago, ran up to September 2011 at $\sqrt{s} = 1.96$ TeV, while the Super Proton-antiproton Synchrotron (\text{SPS}) situated at CERN in the 1980s collided protons and anti-protons at $\sqrt{s} = 540$ GeV, which was upgraded to 630 GeV. Finally, the previously mentioned LEP accelerator collided electrons and positrons with centre-of-mass energies up to 209 GeV. Apart from protons the LHC also has a program to accelerate and collide lead nuclei, as well as protons with lead nuclei. These are outside the scope of this thesis.

The protons are produced by stripping off electrons from hydrogen atoms, thus ionising these atoms. Before arriving at the LHC accelerator ring these protons traverse...
Chapter 2 The LHC and the ATLAS detector

Figure 2.1: The CERN accelerator complex: the chain of LHC pre-accelerators, starting with the LINAC, ending up in the LHC. The four main LHC experiments are shown in the large ring. Taken from [106].

A series of pre-accelerators to prepare them for the LHC injection energy of 450 GeV. The first step is acceleration to 50 MeV in the Linear Accelerator (LINAC). From here the protons are accelerated in a series of three circular pre-accelerators: to 1.14 GeV in the Proton Synchrotron Booster (PSB); to 26 GeV in the Proton Synchrotron (PS); and finally the Super Proton Synchrotron (SPS) accelerates the protons to an energy of 450 GeV, with protons travelling with nearly the speed of light. During this sequence the protons are arranged into small packets – the design for these proton bunches is to contain \( \sim 10^{11} \) protons each, with a separation of 25 ns between them. The SPS finally injects these bunches into the LHC in both the clockwise and the anti-clockwise direction. A schematic view of the CERN accelerator complex is shown in figure 2.1.

To keep the proton beams in their circular path in the LHC, 1232 superconducting dipole magnets are used, providing a magnetic field strength of 8.33 T. To achieve this they are cooled with liquid helium to 1.9 K. As the existing tunnel is 3.7 m in diameter, there is no room for a separate clockwise and anti-clockwise ring. Both beams thus need to travel through two separate vacuum beam-pipes, and are bent by separate dipole systems, all within one single iron yoke and using one cryostat.

To accelerate the protons, Radio Frequency (RF) cavities are placed at one point in the ring. These accelerate the protons each revolution by use of an oscillating electric field of 2 MV with a frequency of 400 MHz. Accelerating the proton beams from their injection energy of 450 GeV to the final 4 TeV took approximately 15 minutes at the end of 2012.

At certain points in the LHC ring the two proton beams cross each other, enabling proton-proton collisions. Around these points particle detectors are built: there are four large and two smaller detectors to conduct experiments with the LHC data. The two largest are ATLAS [107] and CMS [108], situated at opposite sides of the LHC.
2.1 The LHC accelerator

Table 2.1: The LHC performance during its three years of data taking. The various rows give the centre-of-mass energy $\sqrt{s}$, the total integrated luminosity per year, both the amount delivered by the LHC to ATLAS and that which was actually recorded, the maximum number of colliding bunches that year, the bunch spacing used, and the maximum instantaneous luminosity. The last two rows give the average number of interactions per bunch crossing $\langle \mu \rangle$ and the maximum number of interactions per bunch crossing (peak $\mu$). The values represented by a dash were not available. The design values are taken from [113].

<table>
<thead>
<tr>
<th></th>
<th>2010</th>
<th>2011</th>
<th>2012</th>
<th>design</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sqrt{s}$</td>
<td>7 TeV</td>
<td>7 TeV</td>
<td>8 TeV</td>
<td>14 TeV</td>
</tr>
<tr>
<td>Delivered integrated luminosity [fb$^{-1}$/year]</td>
<td>0.049</td>
<td>5.62</td>
<td>23.25</td>
<td>80-120</td>
</tr>
<tr>
<td>ATLAS recorded integrated luminosity [fb$^{-1}$]</td>
<td>0.045</td>
<td>5.25</td>
<td>21.74</td>
<td>–</td>
</tr>
<tr>
<td>Max. number of colliding bunches</td>
<td>348</td>
<td>1854</td>
<td>1380</td>
<td>2808</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>75</td>
<td>75/50</td>
<td>50</td>
<td>25</td>
</tr>
<tr>
<td>Peak instantaneous luminosity [cm$^{-2}$s$^{-1}$]</td>
<td>$2.07 \times 10^{32}$</td>
<td>$3.65 \times 10^{33}$</td>
<td>$7.73 \times 10^{33}$</td>
<td>$10^{34}$</td>
</tr>
<tr>
<td>$\langle \mu \rangle$</td>
<td>–</td>
<td>9.1</td>
<td>20.7</td>
<td>19.2</td>
</tr>
<tr>
<td>Peak $\langle \mu \rangle$</td>
<td>3.78</td>
<td>32.21</td>
<td>69.49</td>
<td>–</td>
</tr>
</tbody>
</table>

ring. Both ATLAS and CMS are so-called 4$\pi$ general purpose detectors. They are designed to detect the full-range of possibilities from proton-proton collisions, including precision measurements of known SM processes, searches for the SM Higgs boson as well as searches for phenomena which cannot be explained by the Standard Model. On either side between them are two detectors built to study specific phenomena: the ALICE [109] and LHCb [110] detectors. The former is dedicated to the heavy-ion collisions, studying the properties of high energy density nucleus-nucleus interactions. Its goal is to form and observe a new matter phase, the quark-gluon plasma. The LHCb experiment is devoted to B-hadron physics, studying CP-violation and rare decays of the B-hadrons.

The two smallest detectors are TOTEM [111] and LHCf [112]. The former studies the total proton-proton cross section, which measurement is used by all other experiments, while the latter performs measurements of neutral particles emitted in the very forward region of the collisions, i.e. very close to the direction of the beams.

2.1.1 Short description of LHC operations

In 2010 and 2011, the first two full years of operation, the LHC accelerated the proton beams to 3.5 TeV each. This was increased in 2012 to 4 TeV which was decided to be the maximum energy the accelerator could reach while remaining relatively safe from magnet quenches. This will be increased to near its design energy of 7 TeV per beam after a shut-down in the years 2013 and 2014. The instantaneous luminosity,
proportional to the number of protons per beam and inversely proportional to the area of interaction, has increased dramatically over the three years from $2.07 \times 10^{32}$ cm$^{-2}$s$^{-1}$ at the end of 2010 to $7.73 \times 10^{33}$ cm$^{-2}$s$^{-1}$ at the end of 2012. This was mainly due to increasing the number of protons per bunch, increasing the number of bunches in the machine and decreasing the bunch diameter. Although the goal of a 25 ns bunch spacing has not yet been reached, during 2010 and the first months of 2011 the LHC operated with a bunch spacing of 75 ns, while from the second half of 2011 the LHC has operated with a 50 ns bunch spacing. The number of bunches which crossed each other at the ATLAS interaction point increased from 113 at the end of 2010 to 1377 at the height of 2012 data taking.

As the bunch intensity drops during a run due to proton-gas and proton-proton collisions, the LHC runs for $\sim 10 - 20$ hours with one fill, after which it needs to be refilled. Furthermore, time is needed for maintenance. This has a result that the LHC delivers collisions about $\sim 30\%$ of the time. The total delivered integrated luminosity in this time was $49$ pb$^{-1}$ in 2010, $5.6$ fb$^{-1}$ in 2011, both at $\sqrt{s} = 7$ TeV, and $23.3$ fb$^{-1}$ in 2012 at $\sqrt{s} = 8$ TeV. This performance of the LHC in the first three years of operation is summarised in table 2.1 and the accumulation of data during these years is shown in figure 2.2 with the integrated luminosity delivered to ATLAS as a function of time in green, and recorded by ATLAS in yellow. The left figure shows the 2011 values, and the right figure those of 2012.

2.2 Overview of ATLAS

The ATLAS (A Toroidal LHC ApparatuS) detector [107] is a colossal construction, measuring 44 m in length and 25 m in height, and weighing 7000 tonnes. The size is mostly due to the toroid magnet used for the momentum measurement by the muon.
Figure 2.3: Cutaway view on the ATLAS detector. The various detector elements are denoted by different colours and their description. Note the pair of people drawn to scale on the left. Taken from [107].

The ATLAS detector consists of several sub-detectors, which are placed around the interaction point, as seen from the illustration in figure 2.3. These are organised in a barrel region, which consists of concentric cylindrical layers, and two end-cap regions where the detector-elements are constructed in wheels which close off the barrel cylinders. The detector can be categorised in three main layers, which all have a specific purpose, and each consist of multiple sub-detectors. The inner detector (ID) sits closest to the interaction point, and has as its main purpose the tracking of charged particles and the measurement of their momentum, through their deflection in the magnetic field of a solenoid magnet. The ID is discussed further in section 2.4. The electromagnetic and hadronic calorimeters absorb hadrons, photons and electrons, and measure their energy. This is discussed in section 2.5. The remaining particles (apart from the weakly interacting neutrino) to fly through the calorimeters are mostly muons, which are tracked by ATLAS’s outermost sub-detector, the muon spectrometer (MS). It tracks the trajectory of the muons through the magnetic field generated by the toroid magnet and thus measures their momentum. The muon spectrometer is discussed further in section 2.6. The magnet system providing the necessary bending power is described in section 2.3.

As mentioned in the previous section, the ATLAS detector is a general purpose detector, with multiple physics goals:

- The search for and discovery of the Higgs boson. The Higgs boson has several decay channels, of which the best detectable channels are the decay to two
photons \((H \rightarrow \gamma\gamma)\) for a light Higgs boson, while for a heavier Higgs boson the decay into two Z bosons or two W bosons is preferred, with their corresponding leptonic decay:

\[ H \rightarrow ZZ \rightarrow l^+l^-l^+l^- \quad \text{and} \quad H \rightarrow W^+W^- \rightarrow l^+\nu l^-\bar{\nu}. \]

On the 4th of July 2012 it was announced that a Higgs-like scalar boson with a mass of \(\sim 125\) GeV was found in both ATLAS \[20\] and CMS \[21\], which has since then been proven to be a Higgs boson \[114\].

- The search for direct evidence of physics beyond the standard model. Apart from searches for supersymmetry, this includes more exotic scenarios such as extra dimensions \[115\], micro black holes \[116\] or new heavy gauge bosons \[117\].

- Precision measurements of known SM particles, such as the top quark \[118\] and the W boson \[119\], and high precision tests of QCD \[120\].

- Studying the properties of a quark-gluon plasma from lead ion collisions \[121\].

- Flavour physics, studying CP-violation through the decay of B-hadrons \[122\].

**Requirements**

Each of these physics goals can be translated into requirements on the detectors. The detection of particles originating from Higgs decay for instance requires a good photon and lepton identification and energy (momentum) reconstruction, together with a good reconstruction of the missing transverse energy. A pair of produced supersymmetric particles would decay in cascades of particles, leading to high momentum jets, possible leptons and missing transverse energy, which would all need to be identified and reconstructed to a high precision. Thus a set of requirements has been formulated which the detector should meet:

- The high particle flux coming from the interaction point requires radiation hard detector elements with fine granularity, while the high collision rate requires fast electronics.

- A near hermetic coverage is needed to ensure no high momentum particles are missed. This is important for both the lepton and jet identification, and the reconstruction of both the transverse energy and missing transverse energy of an event.

- Good momentum resolution of charged particles is needed in the inner tracker system. The vertex reconstruction performed should be able to identify secondary vertices coming from \(\tau\) or B-hadron decays.

- Good muon momentum resolution is needed for a wide range of muon momenta.

- Due to computing and storage limitations, a highly efficient trigger mechanism is needed on interesting events, with a high background rejection.
## 2.2 Overview of ATLAS

The resolution is parameterised as an energy (or momentum) dependent term and a constant term. For calorimeters this can be interpreted as follows: the first term is the stochastic fluctuations of the response, while the second constant term reflects local non-uniformities of the response, for instance due to leakage [107].

A quantitative summary of these requirements is shown in table 2.2, where requirements on the momentum and energy resolution of the various sub-detectors are given together with their spatial coverage, given as a range in the pseudorapidity $\eta$ described in the following section. On top of this, a requirement on the resolution of the reconstruction of impact parameters and vertex positions exists. For high momentum particles in the central region of the detector, the design requires a transverse impact parameter resolution of $10 \, \mu m$ [123]. Here the impact parameter is defined as the closest perpendicular distance between a track and the primary vertex. In view of the lifetimes of $(c \tau)_\tau \sim 90 \, \mu m$ and $(c \tau)_b \sim 500 \, \mu m$ for $\tau$ leptons and $B$ hadrons respectively [124], together with the corresponding Lorentz boost $\gamma$, the design requirement on the resolution of the main (primary) vertex is less than 1 mm in the $z$-direction [125].

In sections 2.3–2.7 each of the elements of the ATLAS detector is described in more detail, together with their operational performance. The reconstruction of objects is discussed in chapter 4, where also its performance is described, such as the momentum and energy resolutions.

### Coordinate system

It is useful for the remainder of the thesis to specify the coordinate system used in the ATLAS detector. The nominal interaction point, right in the centre of the detector, is chosen as the origin. From here the $x$-axis points to the centre of the LHC ring, the $y$-axis points upwards and the $z$-axis lies along the beam-pipe. To obtain a right-handed coordinate system the $z$-axis points in anti-clockwise direction along the ring. The positive $z$-side of the detector is called side-A, whereas the opposite side is called side-C of the detector. The $x$-$y$ plane is perpendicular to the beam direction and thus is referred to as the transverse plane. This plane is used often throughout this thesis, for instance for variables declared in this plane such as the transverse momentum.

<table>
<thead>
<tr>
<th>Detector component</th>
<th>Required resolution</th>
<th>$\eta$ coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tracking</td>
<td>$\sigma(p_T)/p_T = 0.05%$ $p_T \oplus 1%$</td>
<td>$</td>
</tr>
<tr>
<td>EM calorimetry</td>
<td>$\sigma(E)/E = 10%/\sqrt{E} \oplus 0.7%$</td>
<td>$</td>
</tr>
<tr>
<td>Hadronic calorimetry (jets)</td>
<td>$\sigma(E)/E = 50%/\sqrt{E} \oplus 3%$</td>
<td>$</td>
</tr>
<tr>
<td></td>
<td>$\sigma(E)/E = 100%/\sqrt{E} \oplus 10%$</td>
<td>$3.1 &lt;</td>
</tr>
<tr>
<td>Muon spectrometer</td>
<td>$\sigma(p_T)/p_T = 10%$ at $p_T = 1$ TeV</td>
<td>$</td>
</tr>
</tbody>
</table>

Table 2.2: A summary of the performance requirements of the ATLAS detector.
\[ p_T = \sqrt{p_x^2 + p_y^2}. \]

The cylindrical symmetry of the detector allows for the definition of several angles: the azimuthal angle \( \phi \in [-\pi, \pi] \) is taken around the beam axis, and the polar angle \( \theta \in [0, \pi] \) measures the angle with the beam axis. From this polar angle the more convenient pseudorapidity \( \eta \) is defined: \( \eta = -\ln \tan(\theta/2) \) which is preferred above \( \theta \) because the particle flux coming from the interaction is approximately constant as a function of \( \eta \). Furthermore, differences in \( \eta \) are invariant under Lorentz boosts. Finally the separation \( \Delta R \) between objects in \((\phi, \eta)\) space can be defined as \( \Delta R = \sqrt{\Delta \phi^2 + \Delta \eta^2} \).

### 2.3 Magnet system

The size and design of the ATLAS detector is mostly due to the choice of the magnet system. Magnetic fields are imperative for the measurement of the momentum of charged particles, as these will deflect in the presence of such a field. The momentum of a particle determines the curvature of the track, hence measuring the curvature, when knowing the magnetic field, equals measuring its momentum. Particles travelling through the inner detector and the muon spectrometer, should therefore travel through a magnetic field in each sub-detector. These fields are produced by two magnet systems: a central superconducting solenoid magnet, providing a magnetic field inside the inner detector, and a superconducting toroid magnet system providing the field in the muon spectrometer. A schematic view of the magnet system is shown in figure 2.4.

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1 To be precise, the particle flux is approximately constant as a function of the rapidity \( y \), defined by \( y = 1/2 \ln((E + p_z)/(E - p_z)) \). For massless objects the pseudorapidity is very close to the rapidity. For massive objects, such as jets, this is not the case.

2 As becomes obvious after close inspection of the name of the detector.
2.4 The Inner Detector

Solenoid magnet system

The cylindrical superconducting solenoid magnet is 5.8 m long, has a diameter of approximately 2.5 m and is embedded inside the electromagnetic calorimeter. The nominal current of 7730 A running through the bore provides a homogeneous 2 T magnetic field parallel to the beam axis inside the inner detector, which has a stored energy of 40 MJ. The design is optimised to keep the amount of material in front of the electromagnetic calorimeter as low as possible, adding up to only \( \sim 0.66 \) radiation lengths \((X_0)\) on top of 1-2.5 \(X_0\) of material in the inner detector. This is in part done by sharing its cryostat with the electromagnetic calorimeter.

Toroid magnet system

The toroid magnet system consists of a barrel toroid and two end-cap toroids, one on either side. All consist of eight superconducting rectangular coils placed in a cylindrical configuration – those of the barrel 25.3 m in length, with an inner diameter of 9.4 m and outer diameter of 20.1 m, while the end-cap coils are 5.0 m long and have an inner and outer radius of 1.65 m and 10.7 m, respectively. They thus define the size of the ATLAS detector. Operating at only 4.6 K, the average barrel field strength in the muon spectrometer is 0.5 T at a nominal current of 21 kA, storing an energy of 1.1 GJ. The end-cap toroids provide a local magnetic field in between the first two wheels of the muon spectrometer end-caps, with an average field strength of 1.0 T and a stored energy of \(2 \times 0.25\) GJ.

2.4 The Inner Detector

2.4.1 General layout

The innermost subsystem, going by the appropriate name of ‘inner detector’, is a tracking system, designed to track the particles in their outward trajectory, measure their momentum and perform a vertex identification. To do this with high precision for the large number of particles traversing the detector at every collision, it consists of three complementary sub-detectors, from inside to outside: a silicon pixel detector, a silicon strip detector and a straw tube detector. These are arranged in three concentric cylinders around the beam axis, called the barrels, and on either side of each sub-detector a set of end-cap disks perpendicular to the beam axis. Figure 2.5 on the next page shows in the top figure a schematic view of one opened half of the ID and a schematic view of the barrel configuration in the middle figure. A more detailed blueprint of one quarter of the inner detector is shown in the bottom figure. As mentioned before, the requirements of the inner detector are to have a good momentum resolution for the pseudorapidity range of \(|\eta| < 2.5\). The reconstruction of the high number of particles is accommodated by the fine granularity of the sub-detectors, while the momentum measurement is performed using the 2 T magnetic field provided by the solenoid magnet, which has been discussed in the previous section.
Figure 2.5: The ATLAS inner detector (ID). The top figure shows a cutaway view on the total inner detector, while the middle gives a better view on the dimensions and construction of the barrel. Taken from [107]. The bottom shows a schematic view of one quarter of the ATLAS inner detector, showing the configuration of the various barrel and end-cap layers of the three sub-detectors. Adapted from [107].
2.4.2 Pixel detector

The **pixel detector** is the innermost detector, and therefore subject to the highest particle flux. It should be therefore radiation hard, and have a fine enough granularity to separate the large number of tracks. It consists of three layers in the barrel with a radius of 50.5 mm, 88.5 mm and 122.5 mm, and three disks in each end-cap. This hermetic configuration assures that each particle typically crosses three pixel layers in its trajectory through the detector. The barrel and end-caps consist of a total of 1744 silicon modules, made of a 250 $\mu$m thick silicon wafer, implemented with readout pixels with a size of $50 \times 400 \mu m^2$, resulting in a total of 80.4 million readout channels. Particles traversing the pixel detector will ionise the charge depleted silicon layer, resulting in a local charge deposition in a cluster of pixels. This charge deposition is read out by the dedicated electronics which is bump-bonded to the pixel sensor. The centre of the cluster is taken as the hit position, leading to a discrete space-point measurement. The spatial resolution of the detector is $10 \mu m \times 115 \mu m$ in $R-\phi \times z$ for the barrel, and the same in $R-\phi \times R$ in the end-caps. The difference between $R-\phi \times z$ and $R-\phi \times R$ comes from the configuration of barrel and end-caps respectively: in the barrel, modules are placed along the z-direction in a circular pattern around the beam pipe, while in the end-cap, modules are placed perpendicular to the beam pipe, along the $R$-direction. To protect the detector from radiation damage, the silicon sensors need to be cooled to approximately $-5$ to $-10^\circ C$ [127]. More details on the detection principle of silicon detectors is given in section 2.4.3, where the SCT is discussed in detail.

The barrel layer closest to the beam-pipe is essential for primary and secondary vertex reconstruction, and consequently the tagging of $b$-jets, and has the appropriate name B-layer. The proximity to the interaction point results in a high radiation environment. The original design required a replacement of the B-layer after three years of operation under nominal luminosity. This design has been revisited: in the two years of the first LHC shut-down (2013-2014) an extra pixel layer will be inserted, on the inside of the inner layer. This **insertable B-layer** [128,129] will improve the vertexing and tagging precision.

2.4.3 Semiconductor Tracker

The second high precision tracker is a silicon strip detector, called the **semiconductor tracker**, or SCT, adding four possible space-point measurements further from the interaction point to the track. Because of the larger distance from the interaction point, the SCT becomes increasingly important for the momentum determination when tracking particles with higher momenta.

Like the majority of ATLAS sub-detectors, the SCT is made up of a barrel and two end-caps – the former consisting of four concentric cylindrical layers, while of the latter each is made of 9 disks perpendicular to the beam axis at either side of the barrel. The barrel extends to $|\eta| < 1.4$, while the end-cap disks are placed such that

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*The ionisation in the pixel detector is based on the same principle as that in the SCT, which is described in more detail in section 2.4.3.*
the SCT provides four additional space-points for the total pseudorapidity range up to $|\eta| < 2.5$ as can be seen in figure 2.5(c).

Each of the barrel and end-cap layers consists of smaller modules made up of two layers of 285 $\mu$m thick silicon wafers, each containing 768 strips. In total the SCT consists of 4088 of such modules, with in total 63 m$^2$ of silicon, resulting in more than 6 million readout channels. In each barrel cylinder, one layer lies with the strips along the beam-axis, measuring the $R-\phi$ direction, as silicon strips do not give information in their longitudinal direction. The second layer has a small angular offset of 40 mrad with respect to the first, thus enabling a measurement of the $z$ direction for particles traversing both layers; likewise for the end-caps. The detection principle, explained in more detail below, is similar to that of the pixel detector. The choice for strips instead of pixels is due to the lower particle flux further away from the interaction point. The lower expected multiplicity requires less readout channels, reducing the cost of the detector. As is the case with the pixel detector, the silicon in the SCT needs to be cooled between approximately $-5$ to $-10$ $^\circ$C. Two module performance requirements are a detection efficiency higher than 99% and low noise occupancy, defined as the fraction of hits not related to a crossing particle, of less than $5 \times 10^{-4}$.

Each of the 2112 barrel modules (figure 2.6(a)) has the same design: two 6.4 cm long sensors are linked together by wire bonds, creating 12.8 cm long wafers placed alongside one another. This results in a rectangular module with a width of 6.36 cm. Each side of the module has 768 readout strips with a high bias voltage applied, plus two inactive strips at either side defining the edge. These are tiled on top of each other, forming a hermetic coverage in the full $\phi$ range. The silicon strips in the barrel have a pitch (the distance between the middle of two neighbouring strips) of 80 $\mu$m.

The end-cap design is somewhat different, with disks made of three rings of trapezium shaped modules. The inner, middle and outer rings are made of different types of modules, with a different geometrical design to achieve the best hermetic acceptance. Due to these geometrical reasons, disk 9 (the furthest from the interaction point) has
2.4 The Inner Detector

only outer modules, while disks 1, 7 and 8 have no inner modules. Furthermore, the inner modules have only one set of sensors, making them half as long – the same is true for the middle modules of disk 8, which are thus called ‘short middle’ modules. This configuration can be seen in figure 2.5. Due to the trapezium shape, the pitch of the strips vary in the end-cap, from 56.9 $\mu$m to 94.2 $\mu$m.

The two layers of the module, with the small angular offset, are glued on top of a thin base-board made of thermal pyrolytic graphite, providing the structure and thermal conductivity path between sensors and coolant. Each of the sensors is read out by a Application Specific Integrated Circuits (ASIC) chip, with 6 chips per module side. Each chip thus operates 128 readout channels. These chips are mounted on a hybrid, placed in the middle of the barrel modules and at the end of the end-cap modules, as seen in figure 2.6.

Detection principle of the SCT

Semiconductor devices build upon the principle of doping, contaminating the silicon with impurities such that the conductivity is changed. Doping silicon can lead to p-type material, with an excess of holes, or n-type material with an excess of electrons. A ‘hole’ in this sense is nothing else than the absence of an electron in the lattice of silicon atoms, which can travel through the lattice as if it were a positively charged particle. Bringing n-type and p-type doped silicon in contact with each other, electrons move from the n- to the p-type, and inversely for the holes, creating a so called p-n junction. Near the contact layer of the two materials, a depletion zone is created, with an absence of free charge carriers. Yet the electrons diffusing to the p-type material

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**Figure 2.7:** Diagram of a p-n junction at zero bias voltage. The top shows the p-type silicon on the left and n-type on the right. The three diagrams below show the charge density (a), the electric field (b) and the potential (c) in the depletion region. Taken from [132].
leave positively charged ions in the n-type region, and vice versa for the holes. Thus two oppositely charged layers are created near the p-n interface, creating an electric field. As this electric field is in the opposite direction to the diffusion current, it stops the flow of the current, arriving at a static situation. This is illustrated in figure 2.7. When an external reverse bias potential is applied to the silicon, with the p-type silicon attached to the negative terminal, the already built up potential is increased, increasing the depletion zone. In a detecting device, this depletion zone is ideally the full thickness of the sensor.

When a charged particle travels through semiconducting material, electron-hole pairs are produced—a minimum ionising particle travelling through a 285 \( \mu \text{m} \) thick layer of silicon will create approximately 25000 electron-hole pairs, generating a charge deposition of \( \sim 4 \text{ fC} \) in the silicon \[133\]. If this happens in a depletion zone, the holes will drift to the p-side, while electrons drift to the n-side of the material. Here the charge is collected on metal readout strips, with a signal strength proportional to the induced current. The SCT uses for the silicon wafers an n-type bulk, with p-type strips implanted. On top of these implants, resting on an insulator, metal readout strips are placed with a nominal bias voltage of 150 V \[127\].

The strip pitch defines the tracking resolution: for a finer resolution, a lower strip pitch should be achieved. The intrinsic resolution of SCT modules is 17 \( \mu \text{m} \) in the \( R-\phi \) direction and 580 \( \mu \text{m} \) in the \( z \) or \( R \) direction, for barrel or end-cap modules respectively.

**SCT readout**

Approximately 10 ns after a particle traverses the silicon, the charge is collected by the readout strips \[127\]. The current is amplified by two amplifiers on the corresponding chip. A discriminator then compares the amplitude of the signal against a pre-defined threshold. This threshold is taken nominally at 1 fC, which allows the detector to reach its performance goals with respect to the noise occupancy and efficiency \[127\]. The output of the discriminator is either a ‘1’, when the signal is above threshold, or a ‘0’ when it is not. For each of the 128 channels of a chip this results in a binary ‘hit or no hit’ decision, stored as a single bit in a 132-bit pipeline. This simple binary decision allows for a simple chip, reducing the size and power consumption and thus the cost.

When the readout buffer receives the level-1 trigger of a certain bunch crossing (see section 2.7), the corresponding data is passed to the data compression logic, together with that of the previous and following bunch crossing. The compression logic only transfers the data of an event on to the readout logic if the channel obeys the required hit pattern. Four of these hit patterns are available, shown in table 2.3. The Any hit pattern requires at least a hit in one of the three available bunch crossings, without requirement on hits in the other bunch crossings. This pattern is used for detector studies. Level sensing and edge sensing are the two patterns used in data taking.

The former requires at least a hit in the bunch crossing corresponding to the L1 trigger, and is used for regular data taking. The latter, edge sensing, requires no hit in the previous bunch crossing, a hit in the correct bunch crossing and anything in the...
2.4 The Inner Detector

<table>
<thead>
<tr>
<th>Selection criteria</th>
<th>Hit pattern</th>
<th>Usage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test</td>
<td>XXX</td>
<td>Test mode</td>
</tr>
<tr>
<td>Any hit</td>
<td>1XX, X1X or XX1</td>
<td>Detector alignment</td>
</tr>
<tr>
<td>Level sensing</td>
<td>X1X</td>
<td>Data taking</td>
</tr>
<tr>
<td>Edge sensing</td>
<td>01X</td>
<td>Data taking</td>
</tr>
</tbody>
</table>

Table 2.3: The available hit patterns for the compression logic. The middle column represents the three time-bins read out: from left to right the previous, the current and the following bunch crossing. A 1 represents a hit in the corresponding time-bin, a 0 no hit, and an X means no requirement. Adapted from [127].

following crossing. It is designed for data taking with 25 ns LHC bunch spacing. The pattern can be explained as follows: one would not expect a hit in the strip before the bunch crossing itself, yet as the length of the signal might be longer than 25 ns, leading to a signal over the threshold for two bunch crossings, there might a hit in the following time-bin. The readout logic finally reads the data, and transmits it from the chip via two optical links to off-detector electronics. The chips are chained, creating redundancy such that malfunctioning chips can be bypassed.

2.4.4 Transition Radiation Tracker

The third ID sub-detector, furthest from the beam-pipe, is a straw tube detector called the transition radiation tracker (TRT). Its design provides the tracking algorithm with many space-points, while also identifying electrons through transition radiation. The tracking is done with 73 layers of straw tubes in the barrel, and 160 layers in the end-caps.

The straw tubes, with a diameter of 4 mm and a length up to 144 cm, are filled with a xenon-based gas mixture, with a gold plated tungsten anode wire running through the middle of the tube. The potential difference between tube and wire cause free electrons created by passing charged particles ionising the gas to drift towards the wire. The drift time is proportional to the distance of the traversing particle to the wire.

These straws are embedded in polypropylene fibres and foil in the barrel and end-caps respectively, with varying refractive indices. Relativistic charged particles traversing transitions in the dielectric constant will emit X-ray photons with an intensity that is directly proportional to their Lorentz factor $\gamma$. The photons are absorbed by the xenon in the straw tubes, where, as the electron mass is 273 times smaller than the charged pion mass, electrons will produce a higher signal than pions for the same momentum. Applying two thresholds, one optimised to detect ionisation and one optimised to detect transition radiation from electrons, the TRT provides a method to distinguish electrons from pions.
2.5 Calorimeters

The second set of sub-detectors a particle produced at a collision encounters are the calorimeters. These measure the energy of both charged and neutral particles, and are the only detector element able to identify the latter. The ATLAS calorimeter system consists of two types of calorimeters: closest to the interaction point is the electromagnetic calorimeter, designed to measure the energy of electrons and photons through their electromagnetic interactions; further from the interaction point lies the hadronic calorimeter, designed to detect showers from hadrons and hadronically decaying taus, and measure their energy through both their electromagnetic and strong interactions. In the barrel the calorimeter system is cylindrical and extends radially from approximately 1.4 m to 4.2 m from the interaction point. It consists of a barrel and two end-cap regions, which together cover the pseudorapidity range up to $|\eta| < 3.2$, plus an additional forward detector on either side providing coverage for the range $3.1 < |\eta| < 4.9$. A view on the calorimeter system is shown in figure 2.8 where a part is cut out for a better view of the inside.

ATLAS uses sampling calorimeters, which consist of multiple layers of alternating an absorbing material and an active medium. A particle interacting with the dense absorbing material loses some of its energy in the production of particle showers. Electromagnetic (EM) showers produced by electrons and photons are the result of Bremsstrahlung and $e^+e^-$ pair production from the interaction with the absorbing material. Hadronic showers on the other hand are caused by interactions with nuclei of the hadron with the absorber, resulting in a shower of low energy hadrons (e.g.
2.5 Calorimeters

The subsequent layer containing the active medium measures the energy deposited by charged particles in these showers. After several of these sequences the incoming particles will have lost all their energy. The number of produced shower particles will be proportional to the energy of the initial particle, thus by measuring the total shower the energy of the incoming particle can be calculated (after careful calibration).

Charged particles moving through a medium lose energy by ionisation and photon emission (bremsstrahlung). The energy-loss via ionisation depends via the Bethe formula \[ \text{[19]} \] on the properties of the active medium, but also on the particles speed and mass – a lighter particle loses more energy. The higher mass of a muon with respect to an electron requires a much larger stopping length for the muon to lose all its energy, which means muons with a momentum above \( \sim 3 \text{ GeV} \) will not be stopped in the calorimeter and will reach the muon spectrometer (see section 2.6). On the other hand, ultrarelativistic charged particles lose more energy via bremsstrahlung with increasing \( \beta = v/c \). The high velocity of high-momentum electrons ensures that these lose all of their energy in the calorimeter. The weakly interacting neutrino has an energy dependent cross section for nuclear interactions of only \( \sim 10^{-38} \text{ cm}^2 \) \[ \text{[134]} \]. It typically does not interact with the calorimeter (or any other detector system) and thus is not measured. However, some information can be found from the missing transverse energy or \( E_T \), which is described in detail in section 4.5.

Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL) consists of a barrel section, constructed as a cylinder around the interaction point extending to \( |\eta| < 1.475 \), and an end-cap wheel at either side spanning the pseudorapidity range \( 1.375 < |\eta| < 3.2 \). These both use the same design, using lead plates as absorbing material and liquid argon (LAr) as the active material. The lead plates have an accordion shape, giving a gap-less \( \phi \) coverage. The choice for LAr in between these plates is supported by its linear response and its radiation hardness. The signal, in the form of a current from free charges in the LAr, is read out by electrodes between the absorbers.

The design of the ECAL is optimised to stop all electromagnetic (EM) showers, with maximum possible transparency for hadronic objects such as jets. This is achieved with an ECAL thickness corresponding to between 22 and 33 radiation lengths \( (X_0) \) for the barrel and between 24 and 38 in the end-cap, while the material amounts to only \( \sim 1.5 \) nuclear interaction lengths \( \lambda \). Here \( X_0 \) is the characteristic interaction length in the material, defined by the distance it takes an electron to lose all but a factor \( 1/e \) of its energy by Bremsstrahlung, while \( \lambda \) is the mean distance travelled by a hadron before interacting with a nucleus.

The barrel calorimeter is constructed in three layers: the innermost layer, which is the smallest with a depth of \( 4.3 \times X_0 \), has the finest segmentation in \( \eta \) with a granularity of \( \Delta\eta \times \Delta\phi = 0.003 \times 0.1 \), allows for a better separation of photons and \( \pi^0 \) versus electrons. The second layer has a coarser \( \eta \) granularity at \( \Delta\eta \times \Delta\phi = 0.025 \times 0.025 \) and makes up for the largest part of the calorimeter with a depth of \( 16 \times X_0 \). The last layer,
of only 2 $X_0$ in depth, has again a coarser granularity. Its purpose is to distinguish EM showers from hadronic showers, which have most of their energy deposit at a larger distance. This configuration can be seen in figure 2.9 (a). For the largest part, the end-cap wheels have the same specifics, with a slightly deeper detector. The innermost part, with $2.5 < |\eta| < 3.2$, only has two coarser grained layers.

The space between the electrodes and absorbers is 2.1 mm, corresponding to a drift time of 450 ns. This is significantly longer than the bunch spacing of the LHC, and thus incorporates information of previous collisions, leading to out-of-time pile-up. This is countered by using a bipolar signal shaper, which quickly produces a short signal pulse proportional to the peak current [135].

The ‘crack’-region between the barrel and end-caps at $1.37 < |\eta| < 1.52$ has a degraded energy resolution, and is thus not used for precision measurements.

**Hadronic Calorimeter**

Just like the ECAL it surrounds, the hadronic calorimeter (HCAL) is constructed as a cylindrical barrel and two end-cap wheels. Its barrel system consists of a central barrel spanning $|\eta| < 1.0$, and an extension on either side covering the region $0.8 < |\eta| < 1.7$. The gap between these is used for services for the inner detector, EM calorimeter and

---

**Figure 2.9:** Schematic view of an electromagnetic calorimeter module (a) and tile calorimeter module (b). The three layers with varying granularity in the ECAL module are indicated, just as the accordion shaped lead absorber. The schematic view of the HCAL module shows the varying layers of steel absorber and scintillator, as well as the photomultiplier configuration. Taken from [107].
solenoid magnet.\footnote{The given pseudorapidity ranges causes one to think there is not a gap, but an overlap between the central barrel and the extension. Note that this is a caused by the definition of the pseudorapidity, which is an angle. Figure 2.8 shows the gap between the central barrel and its extension.} Both barrel and end-caps have an inner radius of 2.3 m and an outer radius of 4.3 m. This sampling calorimeter uses steel as absorber, and scintillating plastic tiles as active material – the hadronic barrel calorimeter therefore is also known as the tile calorimeter. Particle showers entering the tile calorimeter produce light in the scintillating tiles, which is collected and transported to photomultiplier tubes which amplify and read out the signal. As hadronic showers are wider than EM showers, the granularity of the tile calorimeter can be coarser than that of the ECAL, at $0.1 \times 0.1$ in $\Delta \eta \times \Delta \phi$. A schematic view of a HCAL module can be seen in figure 2.9 (b). The detector response time of the tile calorimeter is approximately 75 ns.

The hadronic end-cap calorimeters, HECs, are again liquid argon calorimeters, consisting of two wheels on each side which are both made of parallel copper plates with LAr as active material between them. The wheels cover a range of $1.5 < |\eta| < 3.2$, and are built of 32 wedge shaped modules. The inner wheel’s copper plates are 25 mm thick, while those of the outer wheel are twice that. Its detection principle is the same as for the EM calorimeter discussed before.

The depth of the hadronic calorimeter is approximately $7.5 \lambda$ for the barrel, with $\lambda$ the nuclear interaction length, and $10 \lambda$ for the end-cap. This is enough to contain most energetic showers, with low probability of a punch-through to the muon system. In such an event the hadronic shower is not stopped completely by the calorimeter and spills over into the muon spectrometer.

**Forward Calorimeter**

For the determination of the missing transverse energy, it is important to have a good hermetic coverage. Therefore, a separate calorimeter is constructed which can withstand the high particle fluxes in the very forward region, $3.1 < |\eta| < 4.9$, which comes down to a radius of only $\sim 8$ cm around the beam. This forward calorimeter (FCAL) consists of three wheels on either side, which are all liquid argon-based. The innermost is optimised for electromagnetic showers and has copper absorbers, while the outer two measure the hadronic showers and have tungsten as the absorbing material. The high particle flux requires a large depth of the calorimeter: the wheels have a depth of $27.6 \ X_0$, $91.3 \ X_0$ and $89.2 \ X_0$ from inner to outer wheel respectively.

## 2.6 The Muon Spectrometer

The muon spectrometer is the outermost system of ATLAS. Of all possible SM particles produced by the collision or in subsequent decays (except neutrinos), the muons will travel the furthest, due to their long lifetime and low energy emission in the form of Bremsstrahlung, and are not easily stopped by the calorimeters. The muon system identifies muons, and measures their position and momentum. The muon momentum can be measured by the muon spectrometer alone for muons with
Chapter 2  The LHC and the ATLAS detector

Figure 2.10: Cross section of the muon spectrometer: (a) in the $x$-$y$ plane, with the interaction point in the middle, and (b) of one quarter of the $y$-$z$ plane. In the left figure the overlap in the placing of the various MDT stations is clearly visible. In (b), the stations denoted with a number are all MDTs. The dashed lines denote the trajectories muons with infinite momentum would follow, crossing three muon stations each. Taken from [107].

a momentum between about 3 GeV and 3 TeV, although the momentum resolution for low momentum muons is driven by the inner detector. It is designed to have a momentum resolution of 10% for muons with a $p_T$ of 1 TeV.

Precision tracking

The momentum measurement is performed by precisely measuring the track of a particle in a strong magnetic field. From the curvature of the track, and knowing the magnetic field strength, the momentum can be deduced. High momentum tracks will have smaller curvature, therefore both a strong magnetic field and a large distance between the position measurements is needed for an accurate momentum measurement. This drives the construction of the muon spectrometer, shown in figure 2.10.

The precision tracking is performed by two detection systems. Monitored drift tubes (MDTs) are placed in three layers in the barrel region, $|\eta| < 2.0$, at approximately 5 m, 7.5 m and 10 m from the interaction point. The layers consist of 16 MDT chambers overlapping slightly, as seen in figure 2.10 (a). There is a hole in this configuration at $\eta = 0$, to provide for services to the underlying detectors and solenoid magnet. This gap, which spans an angular range of $|\eta| \leq 0.08$ at its largest, leads to a resolution degradation, discussed in section 4.3.1. The forward region, $2.0 < |\eta| < 2.7$, is built up of three wheels, of which the outermost two are made up of solely MDTs, while closest to the beam-pipe the inner wheel has a layer of cathode-strip chambers (CSCs), which are better adapted to the high particle flux in this region. An additional gap in the coverage is caused by the ‘feet’ of the detector support structure, in sectors 12 and 14 (see figure 2.10 (a)).

The MDTs are configurations of 30 mm wide aluminium tubes, between 1 and 6 m
2.6 The Muon Spectrometer

Figure 2.11: Schematic view of an MDT station, with three of four drift tube layers stacked on top of each other (a) and cross section of a drift tube (b), with the detection principle shown.

in length, filled with Ar/CO$_2$ gas at 3 bar, with a tungsten-rhenium anode wire in the centre on which a potential of 3080 V is applied. A traversing charged particle will ionise the gas – the freed electrons will free new electrons, creating an avalanche of electrons – see figure 2.11. This causes an electrical signal in the wire, which can be read out. Each MDT chamber consists of three to eight layers of drift tubes. As the tubes are placed along the $\phi$ direction, the MDTs only provide a high precision in the $R$–$z$ plane. Unlike the MDTs, the CSCs have two cathode strips per plane, placed perpendicular to each other, and multiple anode wires, making them multi-wire proportional chambers. There are four of these planes in each CSC chamber, which are trapezium shaped, measuring $\sim$ 1.1 m in length and $\sim$ 0.5 − 1 m in width [136].

The charges induced on the cathode strips are read out instead of the wire.

The bending of the muons is achieved by the large toroid magnet for pseudorapidities below 1.4, while it is achieved for $|\eta| > 1.6$ by two smaller end-cap magnets on either side. For the transition region between these, $1.4 < |\eta| < 1.6$, a combination of the barrel and end-cap fields is used. This configuration gives approximately an orthogonal field to trajectories of muons from the interaction point, as discussed in section 2.3.

Trigger chambers

The triggering on muons is done by resistive plate chambers (RPCs) in the barrel region ($|\eta| < 1.05$) and thin gap chambers (TGCs) in the end-cap wheels, where $1.05 < |\eta| < 2.4$. To be able to trigger on muons, these systems should provide fast information on the tracks inside the detector, with information on both azimuthal and radial components. Aside from the trigger function of both trigger systems, the information on the azimuthal coordinate complements the MDT measurement, which can only be done in the $R$–$z$ direction. The aforementioned gaps in the MDT coverage due to the services and support structure occur in the trigger chambers as well, leading to a degradation of the triggering efficiency at these coordinates.

The conditions differ between the barrel and end-cap regions, with higher radiation
levels in the end-cap region, while the $|\eta|$ dependence of the muon $p_T$ requires a finer granularity in the end-cap to match the $p_T$ resolution in the barrel. These requirements lead to trigger chambers with different designs between the barrel and end-cap.

Two RPC stations are placed below and above the middle MDT layer, while a third is placed on the outer side of the outer MDT layer. Each station consists of two RPC layers, corresponding to a total of six measuring points of $\eta$ and $\phi$. This redundancy improves the efficiency and helps to reject fake tracks, coming for instance from detector noise. The large distance between the outer and inner chambers allows for triggering on high momentum tracks, with a lower thresholds from 9 to 35 GeV, while the small distance between the two innermost chambers extends this to low $p_T$ ($6 - 9$ GeV) \cite{137}. The RPCs are gaseous detectors, which unlike the previously described chambers are wireless. An RPC consists of two parallel resistive plates placed 2 mm apart, with an electric field of 9.8 kV between them. Charged tracks traversing the detector ionise the gas, and the liberated electrons will accelerate through the electric field, causing avalanches of charged particles to move towards the anode. This is detected by readout strips mounted on the anode. The RPCs are designed to have a spatial resolution of 5-10 mm, and a time resolution of $\sim 1$ ns \cite{137}.

In the end-cap, the triggering is performed by TGC stations, one of which is placed on the inner layer of the end-cap wheels, while three surround the middle MDT wheel. They are based on the same multi-wire principle applied in the CSCs, yet unlike these the TGCs have a smaller distance between the wires (1.4 mm) than between wire and anode (1.8 mm). This guarantees drift times shorter than 25 ns, the time between two consecutive bunch crossings. The radial readout strips provide a measurement on the $\phi$ coordinate, while the $\eta$ coordinate is measured using the anode wires. Again each station consists of two TGC layers except the outermost station, which only has one. The lack of TGCs at the outer MDT wheel is no problem: as there is no magnetic field between the outermost wheels, the extrapolation towards the outer layer can be done accurately.

### 2.7 Trigger system

After every collision, the particles coming from the interaction point are detected by one or more ATLAS sub-detectors. The electrical signals coming from their respective readout modules are subsequently stored. As discussed at the beginning of the chapter, there is a collision every 25 ns under nominal LHC operations, leading to a collision rate of 40 MHz. However, not all these events can be stored: at an the average event size of 1.6 MB, the high collision rate would result in storing 60 TB every second, which is unfeasible in terms of both computing power for event reconstruction and data storage requirements. At the same time, the majority of the collisions are uninteresting ‘soft collisions’, where the centre-of-mass energy of the interacting partons is not enough to produce particles corresponding to the physics goals of ATLAS.

To solve this problem, ATLAS possesses a highly selective trigger system which pre-selects interesting events as they happen, bringing down the event rate by a factor of $10^5$ to a value of $\sim 400$ Hz. This final rate is mostly limited by the available storage...
2.7 Trigger system

2.7.1 Three trigger levels

The trigger system consists of three consecutive levels, which select events based on certain criteria: level 1 (L1), level 2 (L2) and event filter (EF). Each following level has a refined set of criteria, bringing the trigger accept rate down.

Level 1 trigger

The L1 trigger performs a hardware-based selection, using reduced-granularity information from the calorimeters and muon trigger chambers (RPC and TGC), in less than 2.5 $\mu$s. The L1 calorimeter trigger (L1Calo) identifies large energy deposits in the calorimeters, coming from electrons, jets or photons, as well as events with large $E_T$. Furthermore, isolation requirements can be imposed on electrons and photons, setting a limit on the total deposited energy in a ring around the region of interest (RoI), giving the coordinates in $(\eta, \phi)$ where interesting features are seen. Likewise a threshold is placed on the hadronic energy behind an EM cluster. Several energy thresholds can be programmed for each object type, above which the L1Calo fires.

The muon L1 trigger searches for signals from both the RPC and TGC, corresponding to a track coming from the interaction point. Events with hit patterns consistent with a high $p_T$ muon are used, if the muon is above one of six programmable muon $p_T$ thresholds.

The final decision is made by combining the information of both the L1Calo and L1 muon trigger, and comparing to 256 items in the trigger menu. If an event contains any signature in the menu, the event is passed on to L2, together with RoIs. The L1 trigger reduces the event rate from 40 MHz to below $\sim 75$ kHz. With increasing instantaneous luminosity the triggers using low $p_T$ thresholds need to be prescaled to keep the rate at the required value. This also holds for the next two levels of the trigger.

Level 2 trigger

The regions of interest defined by the L1 trigger are further scrutinised by the L2 trigger. This software-based trigger uses information from the full detector only within the RoIs to do a fast reconstruction with finer detector granularity, while refining the selection criteria. Because of the reconstruction it takes longer than the L1 trigger, at 40 ms per event. This trigger reduces the event rate to $\sim 6$ kHz, which depends on the available computing power.

Event filter

The last in the series is the event filter (EF), which looks into the full reconstructed events passing L2. This stage takes approximately 4 s per event, requiring a computing farm with approximately 1500 computers to reduce the rate to 400 Hz. Events passing the EF are moved to permanent event storage.
2.7.2 Trigger menu and streams

The total sequence of algorithms an event passes is called the trigger chain, and is used to select events in offline analyses. The naming of these trigger chains tells one about the triggers the event has passed – for instance, an event passing $\text{EF}_{\mu\text{24i}_{-}\text{tight}}$ has one isolated muon which breaches the momentum threshold of 24 GeV, and passes a 'tight' muon criterion. ATLAS runs with many of these trigger chains simultaneously in a trigger menu (up to 1000 in 2012). These need to be updated with increasing instantaneous luminosity to be able to still fulfil the requirement on the event rate.

The trigger system selects events for various purposes, the most apparent being physics analysis, but also other purposes such as calibration and monitoring. The EF not only performs the last event selection, but also categorises the event. For further physics analysis the events are categorised in three physics streams, according to their significant objects: the Muons, Egamma and JetTauEtmiss stream. For instance, an event containing an electron and two high $p_T$ jets will be added to both the Egamma and JetTauEtmiss stream. In this thesis, focussing on the search for supersymmetric in fully hadronic events, we will use the JetTauEtmiss stream most often. A fourth physics stream, MinBias, contains a random sample of events. These minimum bias events allow for a search in events where no interesting features were expected. Furthermore, the stream can be treated as a background sample, for instance for detector performance studies.

2.8 Operational performance of the ATLAS detector

The performance of the ATLAS detector has been outstanding. During the three years of operation, ATLAS has recorded data with an average efficiency of 93.2%, while each of the sub-detectors has recording data $> 99\%$ of the time in stable beams. The operational status of the ATLAS detector in the middle of October 2012 is shown in table 2.4. It should be noted that this is a snapshot, and the precise operational fraction can change from run to run. This section discusses the operational performance of the various sub-detectors. As mentioned before, the performance of the reconstructed objects can be found in chapter 4. First the hit efficiency of the SCT sub-detector will be discussed, after which the operational status of the other sub-detectors is addressed.

2.8.1 Operational status and hit efficiency of the SCT

To ensure high quality tracking, a high efficiency of all tracking sub-detectors is imperative. In the SCT, this efficiency consists of three components: the operational status, describing the relative number of operational SCT silicon components during a run; the data-taking efficiency, representing the relative time the detector elements are turned on and can send back information; and an intrinsic hit efficiency, giving how well the silicon sensors which are operational are performing.
2.8 Operational performance of the ATLAS detector

<table>
<thead>
<tr>
<th>Sub-detector</th>
<th>Number of channels</th>
<th>Approximate operational fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>$80 \times 10^6$</td>
<td>95.0%</td>
</tr>
<tr>
<td>SCT Silicon Strips</td>
<td>$6.3 \times 10^6$</td>
<td>99.3%</td>
</tr>
<tr>
<td>TRT Transition Radiation Tracker</td>
<td>$3.5 \times 10^5$</td>
<td>97.5%</td>
</tr>
<tr>
<td>LAr EM Calorimeter</td>
<td>$1.7 \times 10^5$</td>
<td>99.9%</td>
</tr>
<tr>
<td>Tile calorimeter</td>
<td>$9.8 \times 10^3$</td>
<td>98.3%</td>
</tr>
<tr>
<td>Hadronic end-cap LAr calorimeter</td>
<td>5600</td>
<td>99.6%</td>
</tr>
<tr>
<td>Forward LAr calorimeter</td>
<td>3500</td>
<td>99.8%</td>
</tr>
<tr>
<td>LVL1 Calo trigger</td>
<td>7160</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Muon RPC trigger</td>
<td>$3.7 \times 10^5$</td>
<td>100%</td>
</tr>
<tr>
<td>LVL1 Muon TGC trigger</td>
<td>$3.2 \times 10^5$</td>
<td>100%</td>
</tr>
<tr>
<td>MDT Muon Drift Tubes</td>
<td>$3.5 \times 10^5$</td>
<td>99.7%</td>
</tr>
<tr>
<td>CSC Cathode Strip Chambers</td>
<td>$3.1 \times 10^4$</td>
<td>96.0%</td>
</tr>
<tr>
<td>RPC Barrel Muon Chambers</td>
<td>$3.7 \times 10^5$</td>
<td>97.1%</td>
</tr>
<tr>
<td>TGC End-cap Muon Chambers</td>
<td>$3.2 \times 10^5$</td>
<td>98.2%</td>
</tr>
</tbody>
</table>

Table 2.4: The operational status of the ATLAS detector on the 19th of October 2012.

<table>
<thead>
<tr>
<th>SCT component</th>
<th>Barrel</th>
<th>End-cap A</th>
<th>End-cap C</th>
<th>Total SCT</th>
<th>Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modules</td>
<td>10</td>
<td>4</td>
<td>14</td>
<td>28</td>
<td>0.68%</td>
</tr>
<tr>
<td>Chips</td>
<td>35</td>
<td>6</td>
<td>5</td>
<td>46</td>
<td>0.09%</td>
</tr>
<tr>
<td>Strips</td>
<td>3859</td>
<td>3501</td>
<td>3787</td>
<td>11147</td>
<td>0.18%</td>
</tr>
</tbody>
</table>

Table 2.5: Number and fraction of disabled modules, chips and strips in the SCT on May 20th 2012. Note that the total number of modules in the barrel and each of the end-caps is 2112 and 998, respectively, with each 12 chips and 1536 strips. The number of chips (strips) exclude those which are automatically disabled on disabled modules (modules and chips).

Operational status and data-taking efficiency

During the first run of the LHC (Run 1), spanning three years from 2010 to the end of 2012, the SCT has been operating very stably. In every data taking run at least 99% of all SCT modules were operational, while in general less than 0.1% individual chips were disabled, and less than 0.2% individual silicon strips. Table 2.5 lists the number of disabled detector components in May 2012. Note that, although these numbers are typical for Run 1, they represent just a snapshot, with the precise numbers varying slightly over time. Half of the disabled modules are due to a leak in the cooling device.
for one quadrant of the outermost disk of end-cap C. All modules cooled by this cooling loop had to be disabled. The remaining half of the disabled modules are predominantly due to malfunctioning connections on the detector side. Disabled strips are mainly due to constant high noise. Finally, disabled chips are mostly due to failing optical read out links: when an optical link fails, the link on a neighbouring module can take over. This rerouting method does however lead to the information loss of one chip. The number of optical links using this redundancy was around 1% at the end of Run 1.

The SCT has been fully operational during the data taking periods in Run 1. It recorded 99.9%, 99.6% and 99.1% of the proton-proton data delivered by the LHC in 2010, 2011 and 2012, respectively. The small losses are predominantly due to errors in the read-out driver boards (RODs), which perform the control and data handling of up to 48 modules each. When a ROD gave such an error, a signal (‘busy’) was sent to the data acquisition system inhibiting data taking by the modules of that ROD. Apart from this error, a potential source of data loss comes from the time it takes between the declaration of stable beam conditions by the LHC operators and increasing the bias voltage from 50 V at standby to the nominal bias voltage for of 150 V on all SCT modules. However, as the turning on of the SCT typically takes 60 seconds, less than several other sub-detectors, the data lost due to this effect is negligible.

SCT hit efficiency definition

With the highest luminosity ever achieved, the effect of radiation damage and the so-called ageing of the detector is very important to keep in check. One of the main properties of the SCT which is influenced by this effect is the intrinsic hit efficiency.

The hit efficiency of the SCT is computed using a ‘holes on track’ method, where for each well-reconstructed track the extrapolated trajectory through the detector is scrutinised. For every possible encounter of the track with an SCT module the number of clusters or hits are counted, as well as the number of ‘holes’. A hole is defined as a lack of a hit where one is expected. Here the inactive material around each module is taken into account: if the intersection of the track with the SCT is outside the sensitive area of the module or within 3 standard deviations from the edge of the active material, it is not counted as a hole. This procedure ensures we measure the efficiency of the active material. Likewise, inactive modules and chips are excluded from the calculation; however, isolated inactive strips are not excluded, and thus contribute to the inefficiency. The hit efficiency $\epsilon_{\text{hit}}$ thus tells us how often a hit is detected when there should have been one, and is defined as:

$$\epsilon_{\text{hit}} = \frac{N_{\text{hit}}}{N_{\text{hit}} + N_{\text{hole}}},$$

with $N_{\text{hit}}$ the number of found hits and $N_{\text{hole}}$ the number of holes on the track.

Misalignments of the SCT might lead to a bias in the track fitting procedure, affecting the calculated efficiency. To reduce this bias, hits are added to a track if they are within 200 $\mu$m of a track intersection. Only 4.4% of these hits are due
2.8 Operational performance of the ATLAS detector

<table>
<thead>
<tr>
<th>Track collection</th>
<th>COMBINEDINDET Tracks</th>
<th>SCTSTANDALONE Tracks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of other hits</td>
<td>≥ 6</td>
<td>≥ 7</td>
</tr>
<tr>
<td>(\chi^2) cut</td>
<td>&lt; 3</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>(</td>
<td>d_0</td>
<td>) cut</td>
</tr>
<tr>
<td>(p_T) cut</td>
<td>&gt; 1 GeV</td>
<td>&gt; 1 GeV</td>
</tr>
<tr>
<td>Number of tracks</td>
<td>&lt; 250</td>
<td>&lt; 250</td>
</tr>
</tbody>
</table>

Table 2.6: Track selection for COMBINEDINDET tracks and SCTSTANDALONE tracks used in the SCT hit efficiency calculation.

...to noise or incorrect track associations, while the remainder indeed originates from track reconstruction inefficiencies [138], where the tracking algorithm has wrongly not included the hit in the reconstructed track.

**Track selection**

To have a clean sample of tracks for the efficiency calculation, we ask for a very pure sample of tracks, as summarised in table 2.6. Two sets of tracks are used: tracks reconstructed with combined information from the whole inner detectors (COMBINEDINDET tracks) and those from SCT measurements alone (SCTSTANDALONE tracks). Tracks in both sets are required to come from the interaction point via a cut on the impact parameter \(d_0\), defining the transverse distance to the primary vertex. Tracks must be fitted well by the pattern recognition algorithm via a cut on the \(\chi^2\) of the track, and are required to have \(p_T > 1\) GeV. Also, an ‘X1X’ hit pattern, or level sensing, is required, meaning that only channels with a hit in the time-bin of the bunch crossing are read out. Finally, there should be at least 6 (7) other hits on the COMBINEDINDET (SCTSTANDALONE) track excluding the hit or hole under consideration. This last requirement builds confidence that the track indeed leaves a hit at (nearly) all intersections with the modules.

When comparing the evolution of the hit efficiency throughout the run of data taking period with a high number of interactions per bunch crossing with that of a run with low \(\langle \mu \rangle\) (figure 2.12 (a)), an interesting observation is made. As a function of the respective luminosity block, which is a certain portion of data taking \(^5\) the hit efficiency is observed to increase during a run in data taking periods with high \(\langle \mu \rangle\). These high \(\langle \mu \rangle\) runs have a high number of tracks per event. This is illustrated in figure 2.12 (b), where the track multiplicity is shown for events from a run with \(\langle \mu \rangle \sim 25\), and for a run with \(\langle \mu \rangle < 1\). Events with many tracks leave a large number of hits in the SCT detector, or a high occupancy. This occupancy ranges between 1 and 2% per SCT layer in 2012 data taking. The tracking algorithm, described in section 4.1, may lead to a bias in these events: hits might be ascribed to tracks incorrectly, leading to ‘fake’ inefficiencies. Figure 2.12 (c) shows the measured SCT hit efficiency as a function

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\(^5\) In 2012 one luminosity block corresponded to 1 minute worth of data
Figure 2.12: (a) Evolution of the SCT barrel hit efficiency throughout a run, as a function of the luminosity block (relative to the first with stable beams), measured in two runs: in red with a high mean number of interactions per collision $\langle \mu \rangle \sim 25$, taken from 2012 data at $\sqrt{s} = 8$ TeV; in black with $\langle \mu \rangle < 1$, measured in 2010 at $\sqrt{s} = 7$ TeV. (b) Measured number of tracks per event for the same data. (c) SCT hit efficiency as a function of the number of tracks per event, for barrel (circles), end-cap A (triangles) and end-cap C modules (squares), measured in a run with $\langle \mu \rangle < 1$. (d) SCT hit efficiency of the barrel as a function of the high voltage, measured in data taken from cosmic muons. Error bars show statistical uncertainties.

of the number of tracks. The efficiency decreases with increasing number of tracks, confirming the above assumption. For this reason, only events with less than 250 tracks are used for the hit efficiency calculation. During the run, the instantaneous luminosity decreases due to both proton-proton and proton-gas collisions, leading to a lower number of $pp$ collisions per bunch crossing and thus less tracks, explaining the
Figure 2.13: The SCT hit efficiency of (a) end-cap A and (b) the barrel in 2010 run '165591' at $\sqrt{s} = 7$ TeV, for CombinedInDet tracks and SCT-StandAlone tracks. The efficiencies are shown for each individual layer. Error bars, showing statistical uncertainties, are smaller than the markers. The given mean efficiency excludes the fully efficient layers. Although not shown, the efficiency for end-cap C is very similar to that of end-cap A.

increase of hit efficiency seen in figure 2.12 (a). To study the effect of the value of the bias voltage on the efficiency of the SCT, data from cosmic muons gathered in 2009 is used. During several of these cosmic data taking runs, the third layer of the barrel had a non-standard bias voltage applied. To be able to select cosmic muons travelling through the detector, the $d_0$ requirement is disregarded. Figure 2.12 (d) shows the hit efficiency of the barrel layer as a function of the bias voltage. A clear turn-on is observed: from 60 V onwards the efficiency is above 99%, while it seems to be on a plateau from 100 V, validating the decision to reject data taken during the warm start of the detector, where the bias voltage is still increasing but not yet at the standard 150 V.

During the run the instantaneous luminosity decreases due to both proton-proton and proton-gas collisions, leading to a lower number of $pp$ collisions per bunch crossing and thus less tracks.

Hit efficiency during Run 1

The calculated intrinsic efficiency of the SCT changes slightly between runs, mainly due to changes in the configuration of the detector such as differences in disabled strips. Figure 2.13 shows the hit efficiency for a typical run in 2010 with $\sqrt{s} = 7$ TeV data for the barrel and both end-caps, comparing the efficiency with CombinedInDet tracks to SCT-StandAlone tracks. The mean efficiency is above 99.7% for all components, while the SCT-StandAlone tracks have a somewhat higher efficiency due to the tighter cut on the number of hits. Looking closely, layers at the end and
beginning of tracks are fully efficient: for combined indet tracks these are just the outer end-cap layers, while for sct standalone tracks the inner and outer layers of both barrel and end-cap can be the beginning or end of a track. These layers artificially obtain a 100% efficiency due to the fact that the efficiency calculation interprets the first (last) hit on track to be the (beginning) end of the track itself; any hole before or after the track is not counted as a hole, while a hit is counted in the calculation. For this reason, the mean efficiency given in the figures excludes these layers.

To investigate the stability of the SCT during the first two years of LHC operation, and thus get more than a snapshot of the SCT performance, the trend in the efficiency is plotted in figure 2.14. This trend is obtained by calculating the average efficiency of the barrel (shown in red), end-cap A (black) and end-cap C (blue) for many runs.
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under the same conditions. For each data taking sub-period, two runs with the largest number of events are selected. The intrinsic efficiency is seen to be stable over the two first years of running for each of the components. A small dip can be seen at the start of the 2011 data taking, coming from a combination of the fact that the SCT was recording data in ‘XXX’ mode, using data with hits outside the bunch-crossing time-bin, and a higher number of disabled strips. In May the SCT was reconfigured to ‘X1X’ level sensing. Alignment improvements introduced July 2011 lead to the increase in efficiency seen in the last few months.

Finally, the SCT hit efficiency in 2012 has not deteriorated. The intrinsic efficiency for each SCT layer is shown in figure 2.15 for a typical run in 2012. The mean value, represented by the dashed line, is 99.74 ± 0.04%, where the error is a systematic uncertainty derived from varying the distance cut for non-associated hits and track selection criteria. Again, the efficiency for barrel modules is about 0.2% higher than for end-cap modules. This is explained by studying the fraction of inactive strips, shown in the blue histogram. Modules in both end-caps have a higher number of isolated disabled strips than modules in the barrel, and even a anti-correlation between efficiency and number of inactive strips is seen. Thus differences in efficiency between layers seem to predominantly be due to relative differences in the number of inactive strips.

2.8.2 Operational status of the other sub-detectors

The various sub-detectors have mostly been performing well. Figure 2.16 (a) shows the hit efficiency of each of the layers of the pixel detector for data taken in 2010, with √s = 7 TeV. This gives the probability of finding a hit in a pixel layer after a track has crossed it. It can be seen that all layers except the two outer end-caps have an efficiency around 99%. The outer layers are affected by some dead or inefficient regions on some modules, but are still above 97% efficient. The full efficiency of the inner B-layer is due to the track selection, and thus is 100% by construction. The detector noise is under control, as can be seen by the noise occupancy shown in figure 2.16 (b). The noise occupancy gives the probability of detecting a random hit not associated with a track. It is obtained by measuring the detector occupancy in empty bunch crossings. After reconstruction there are less than 10⁻⁹ noise hits per pixel per bunch crossing, or less than 0.04 hits per event.

The hit efficiency of the barrel of the TRT is shown in figure 2.16 (c) as a function of the track’s distance of closest approach to the wire. The hit efficiency is defined as the number of straws traversed by the track with a hit, divided by the total number of straws traversed by the track. Here the known disabled straws are excluded from the calculation. The mean of the efficiency is above 94% in the plateau region – only for tracks far away from any straw centre the efficiency drops. On the right,
Figure 2.16: (a) Measured hit efficiency of the pixel detector. The non-functioning pixels are excluded from the efficiency calculations. (b) Measured noise occupancy of the pixel detector. After reconstruction the noise occupancy is $< 10^{-9}$ hits per pixel per bunch crossing. (c) Hit efficiency of the TRT barrel as a function of the distance of the track to the straw centre, with a mean of 94.4% in the plateau region. Data taken in 2010 is compared to Monte Carlo simulations. The non-functioning straws are excluded in the efficiency calculation. (d) Probability for a transition radiation hit producing a signal over the threshold in the TRT barrel as a function of their momentum and $\gamma$ factor. Tracks from pions are shown left (triangles), electrons coming from $Z$ boson decays (black) and photon conversions (blue) are shown right. Data is compared to Monte Carlo simulations (open markers). All data taken in 2010 at $\sqrt{s} = 7$ TeV. Figures taken from [139].

in figure 2.16 (d), the probability for a track creating transition radiation to produce a signal above the high-threshold is shown, for both pion tracks (left) and electron tracks (right). It is given as a function of track momentum, or alternatively $\gamma$ factor. The data used was taken with $\sqrt{s} = 7$ TeV data in 2010, and is compared to a minimum bias Monte Carlo simulation. Electrons have up to 25% chance of giving a high-threshold hit in a given straw tube, of which they traverse up to 34 per track,
enabling the discrimination of electrons and pions.

The liquid argon calorimeters, ECAL, HEC and FCal, all have more than 99.5% of the channels operational. The main source of loss of data in these calorimeters is due to high voltage trips. This is shown in figure 2.17 as a function of the gathered integrated luminosity in 2012. Apart from the very first period, which only consisted of a small fraction of the total gathered data, none of the data taking periods suffered a loss of more than 1% of data due to these trips, with an average of 0.46% over the whole year. The total loss of data, including other sources, was 0.88%. In May and June of 2011, 6 front-end boards (FEBs) were non-operational due to an electronics failure. This affected the second and third layer of the ECAL in the region $0 < \eta < 1.4$ and $-0.8 < \phi < -0.6$, where no energy could be measured. From July onwards, 4 out of the 6 FEBs were recovered, recovering the full second layer. As shown in table 2.4 on average about 98% of the number of cells has been operational in the Tile calorimeter. Yet in between shut-downs, without access to the detector, the low voltage power supply failed for several units containing front-end electronics, leading to a loss of operational cells of up to 5% of total at the end of 2011.

Without counting the so-called EE chambers (see figure 2.10) which are not yet installed, the fraction of operational channels in the muon spectrometer is above 96%. The uncertainty on the momentum resolution from the MS alignment is somewhat higher than the design level given in table 2.2 at $\sigma(p_T)/p_T = 13\%$ TeV$^{-1}$ for the barrel, $\sigma(p_T)/p_T = 17\%$ TeV$^{-1}$ for the MDT end-caps and $\sigma(p_T)/p_T = 14\%$ TeV$^{-1}$ for the CSC end-caps [140].

### 2.8.3 Pile-up and vertexing in ATLAS

As mentioned in section 2.1.1, the conditions for the ATLAS detector have changed during the three years of data taking. Arguably the most important change has been the evolution of the average number of collisions per bunch crossing, which has in-
increased dramatically from around one in 2010 to more than 20 at the end of 2012. Figure 2.18 shows the amount of recorded integrated luminosity as a function of the mean number of interactions per bunch crossing $\langle \mu \rangle$, for both 2011 and 2012. The rise is clearly visible, with an average $\langle \mu \rangle = 20.7$ over 2012. Here $\mu$ is calculated in data as

$$\mu = \frac{L \times \sigma_{\text{inel}}}{n_{\text{bunch}} f_r},$$

with $L$ the integrated luminosity, $\sigma_{\text{inel}}$ the total inelastic cross section, $n_{\text{bunch}}$ the number of colliding bunches and $f_r$ the revolution frequency of the protons. The inelastic cross section is taken as 71.5 mb from PYTHIA \([142]\), with a 3% uncertainty due to the differences between this value and the measured value of $73.5 \pm 1.9$ mb by TOTEM \([143]\) and $69.1 \pm 2.4 \pm 6.9$ mb by ATLAS \([144]\). The uncertainties on the ATLAS measurement are the experimental and extrapolation uncertainties, respectively.

The high mean number of collisions per bunch crossing has several implications for physics analyses. As a positive effect, and the main reason for this configuration, a higher collision rate means a higher number of interesting events. Yet this comes at a price. First of all, the trigger encounters more interesting events, and due to the restrictions on the output rate more stringent thresholds need to be set. More interactions also lead to more charged tracks in the inner detector, which need to be reconstructed, and more energy deposits in the calorimeters. By reconstructing the primary vertex (the vertex of interest) with high precision, and tracking the particles on their path to the calorimeters, the separate events can be disentangled. The pile-up causes jets to have extra energy, while the $E_T$ resolution decreases. The effects of this in-time pile-up on the jet reconstruction are discussed further in section 4.2.