The $\phi(1020)$-meson production cross section measured with the ATLAS detector at $\sqrt{s}=7$ TeV

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Chapter 3

ATLAS Inner Detector

The inner detector [80] consists of three separate detectors: the pixel detector, a semiconductor tracker (SCT) and the Transition Radiation Tracker (TRT). The design of the detector is such that a particle originating from the interaction point crosses three pixel layers, eight SCT strip layers and around 36 TRT straws, giving on average 43 position measurements on a track. A layout of the inner detector is schematically shown for four tracks with different pseudorapidities in figure 3.1. The inner pixel layer is at 5.05 cm from the beam and the TRT extends to a radius 1.05 m from the beam line. In this chapter the inner detector is discussed from the inside out and the last section is devoted to the monitoring of the data quality of the SCT in 2010 and 2011.

The inner detector provides track and vertex reconstruction, with an efficiency for reconstructing an isolated track with \( p_T = 5 \) GeV of \( \geq 95\% \) [67]. The achieved resolution is measured with cosmic rays and is \((4.83 \pm 0.16) \cdot 10^{-4} \text{ GeV}^{-1}\) for the measurement of the ratio of the charge over the momentum and \(22.1 \pm 0.9 \mu m\) for the transverse impact parameter [81]. Its acceptance covers the full azimuthal angle in the region \(|\eta| \leq 2.5\) for precision measurements. The inner detector is housed in a superconducting solenoid magnet that generates a homogeneous magnetic field in the positive \( z \)-direction along the beam line with a field strength of about \( 2 \) T at \( z = 0 \). In this magnetic field, particles are deflected in the \( x-y \) plane, so the inner detector is built to have the highest precision in the transverse direction. The detector can measure charged particles with momenta \( p_T \gtrsim 100 \text{ MeV} \).

3.1 Pixel detector

The pixel detector [82] is the sub-detector closest to the beam line. When running at high luminosity every cm\(^2\) of the pixel detector is hit by millions of particles per second. This close to the interaction point, the design is constrained by the occupancy and radiation damage. Reducing the size of the active elements brings occupancy to a manageable level and it tempers some effects of radiation damage of the sensors. The fine granularity allows the reconstruction of the individual tracks of charged particles with a high efficiency and it enables the identification of primary and secondary vertices.

The pixel detector consists of 1744 modules grouped in three cylindrical layers in the bar-
Figure 3.1: A drawing showing the sensors and structure of the inner detector, being traversed by four charged tracks with $p_T = 10$ GeV with $\eta = 1.0, 1.35, 2.0$ and $2.5$. [67]

The inner detector consists of 80M sensors and three disks in each forward region. It has 256 $\mu$m thick n+ bulk silicon with n+ implants on the read-out side and each module is 62.4 mm long and 21.4 mm wide. The size of an individual pixel is $50 \times 400 \mu$m$^2$ in the local x and y direction. As the collected charge is assigned to the center of a pixel, the hit resolution of a single pixel is expected to be $(\text{pixelsize})/\sqrt{12} = 14 \times 173 \mu$m$^2$ and as illustrated in figure 3.2(a) the resolution is $\sim 20 \mu$m if measured using 7 TeV collision data as the RMS of the residuals in the local x-direction [83].

There are 16 front-end chips in each pixel module that are read out by one module control chip. Each module is then connected to the off-detector Read-out Drivers (RODs) through optical-fiber links. One optical-fiber link is used to transmit clock, trigger, commands and configuration data from the RODs to the chips, while one or two links are used for event readout. The conversion of the electronic to optical signal needed for the communication between the modules and the RODs is done with laser diodes (VCSELs [84, 85]). The same VCSEL design has been used for the diodes located close to the modules (on-detector) and in the data acquisition racks (off-detector). From May 2010, the VCSELs started failing, resulting in parts of the pixel detector not being readout until replacement of the diode. This was a common problem to the pixel and SCT detectors and will be discussed further in the next section.

In the pixel readout cells, the signal is amplified and compared to a discriminator threshold. When the signal is above threshold, the pixel address, a hit time stamp and the recorded time over thresholds are transferred to the module control chip. The time over threshold information is proportional to the collected charge and used for energy loss measurements as detailed in chapter 4. The time over threshold recording also allows for a better hit resolution compared to a binary readout, because the center of gravity of each cluster of hits can be used.

The hit efficiency, the noise occupancy and the resolution are important measures of detector

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$^1$VCSEL = Vertical Cavity Surface Emitting Laser
3.1. PIXEL DETECTOR

Figure 3.2: a) The RMS of residuals along the precise pixel direction for collision data, as a function of the track incident angle, corrected for the Lorentz angle. b) Hit to track association efficiency per pixel barrel layer or end-cap disk. Dead modules are excluded from the association efficiency computation, but otherwise dead regions contribute to the inefficiency. Both from [83].

The hit efficiency is shown in figure 3.2b) and is defined as the probability for a track to have a hit associated to it when crossing a pixel detector layer. When the efficiency is corrected for known dead modules, it is approximately 99% for all layers, except the outer disks, where the efficiency is slightly lower. The occupancy was measured in randomly triggered events with empty bunches in April and May 2010. The noise rate is dominated by few pixels (300-1500 out of 80M) which are detected for each data-taking period of a few hours by offline prompt calibration and masked during processing before data are made available for physics. The remaining noise occupancy is \(< 10^{-7} \text{hit/pixel/(bunch crossing)}\) as shown in figure 3.3a).

The expected total fluence the pixel detector is designed to withstand is approximately \(1 \cdot 10^{15} \text{ neutron equivalent cm}^{-2}\) [86]. Aside from the increase in leakage current, radiation damage will invert the sensor bulk and then the depletion voltage gradually increases. As shown in figure 3.3b), the evolution of the leakage current is proportional to the total integrated luminosity and all measurements of the current are in good agreement with each other and with the model predictions [87]. The current decreases at a time scale of weeks due to beneficial annealing (see section 3.2.4) and this annealing is more effective when the detector is not actively cooled. This is seen as the drop of the current in Winter 2011-2012 in figure 3.3b). Type-inversion of the n-bulk has occurred in the two innermost layers in the last quarter of 2012 [88]. Oxygen impurities have been introduced in the bulk to increase the tolerance of the silicon against bulk damage caused by charged hadrons [89]. To further mitigate the effects of radiation damage, the detector is kept at \(-7^\circ \text{C}\).
By the time of writing this thesis, the pixel detector has been operated for more than four years in the ATLAS cavern taking data from cosmic rays, from \textit{pp} collisions and from the lead lead collisions. In the years 2010, 2011 and 2012 the detector was operated with a focus on stable detector operation. During data taking, approximately 95.0\% of the 80M channels were operational \cite{90}. During \textit{pp} collisions in 2012, there were on average 88 (5\%) disabled modules and an average failure rate of 12 modules per year has been observed. The failures were found to be highly correlated with the temporarily stops of the cooling of the detector and therefore the operations team tried to reduce thermal cycling to the minimum. Most common failures are in the optical communication boards (failures in the cold soldering, broken wire bonds and VCSELs), less common were module failures. In general, the pixel detector has been operated reliably in 2010, 2011 and 2012.

### 3.2 Semiconductor Tracker

The SCT is a silicon strip detector and it consists of four layers in the central barrel and has nine end-cap disks on each side. The SCT inner barrel layer is located at a radius of 30 cm from the beam line. Here the charged particle density is low enough to use silicon strips instead of pixels, which reduces the number of readout-channels. The design ensures that particles pass through at least eight silicon detectors (making four space points) in the acceptance region. The SCT is the most crucial part of the inner detector for track finding in the plane perpendicular to the beam. In this section the SCT lay-out and operational performance are explained in detail.
3.2. SEMICONDUCTOR TRACKER

The SCT comprises 61 m$^2$ of silicon sensors with in total 6.3M readout channels. The modules are mounted in four cylindrical barrel layers at radii 30–51 cm and $|\eta| < 1.1–1.4$ and nine end-cap disks on each side that cover $1.1 < |\eta| < 2.5$ and radii extending to 56 cm. The SCT silicon sensors consist of a 285 $\mu$m thick n-type bulk material with 786 p-type strips each. The 8448 barrel sensors have sizes of 64.0 $\times$ 63.6 mm$^2$ and 80 $\mu$m strip pitch. The 6944 sensors used in the end-caps are wedge-shaped, with the strip pitch ranging from 54 $\mu$m up to 90 $\mu$m. An SCT barrel module consists of two pairs of sensors, wire-bonded together in the middle and glued back-to-back under a small stereo angle of 40 mrad to provide a measurement along the strip length, now in total 12 cm. See figure 3.4 for a photo of the barrel and end-cap modules.

Figure 3.5 shows a schematic cross section of a p-in-n sensor. The p$^+$-type is implanted in strips on an n-type substrate. To achieve the reverse bias, the backplane is put at a positive voltage with respect to the strips. The strips are surrounded by a guard ring structure at the edges that is connected to the same potential as the backplane. This avoids a potential difference along the edges of the sensor, which could lead to high leakage currents. An n$^+$-type layer is implanted on the backside, because the metal-semiconductor contact forms a Schottky barrier, a charge barrier similar to a pn-junction. Adding a highly-doped region of silicon to make the contact, reduces the width of the potential barrier, making the characteristic resistance of the formed junction very small.

A charged particle passing a silicon sensor will transfer energy, eventually creating electron-hole pairs in the material. The electrons can move in the conduction band, while the corresponding vacant spots in the valence band can be occupied by other electrons, causing the holes to also “move”. Under the influence of the reverse bias, the electrons are drawn to the n-side and the holes to the p$^+$-side, but they have differently velocity. The time required for a charge carrier to cross the detector volume is called the collection time and is up to ten ns for a sensor of
∼ 300 µm thick, if fully depleted. To speed up the charge collection to about 8 ns for electrons and three times that for holes, the SCT is operated with a reverse bias of 150 V, while it is already fully depleted at ∼ 70 V.

Each side of a module is readout by six ABCD chips [92]. The chips have a binary readout with a programmable threshold, nominally set to 1.0 fC. A minimum ionizing particle causes a charge deposit of about 3 fC in 285 µm silicon. The output of the comparison of the signal to the threshold is stored on the chip every 25 ns, awaiting the ATLAS trigger. If a trigger signal is received, the contents of the storage of three clock cycles are collected. This is referred to as *three time bins* readout. The timing of the readout is optimized at a module-by-module basis, such that a hit from a collision track results in a 01X occupancy pattern in the sampled time bins (no hit in first bin, hit in second bin, no requirement for the third bin). The readout can be tuned for optimal efficiency during different types of data-taking, the different selection modes are listed in table 3.1.

Communication between modules and the off-detector electronics occurs via optical links...
3.2. SEMICONDUCTOR TRACKER

An overview of the SCT optical link architecture is given in figure 3.6. The usage of optical fibers minimizes the material and the signals in the fibers do not suffer from nor give electro-magnetic interference. For each module two data receiving (RX) links and one Timing, Trigger and Control (TX) link are in place. VCSEL arrays are used as light sources, and silicon $p$-$i$-$n$ diodes for the detection of light signals.

Redundancy options for the optical links are available in case a fiber breaks, a VCSEL is lost or $p$-$i$-$n$ diode problems. If a module loses its Timing, Trigger and Control (TTC) signal for some reason, the neighboring module can share its signal, without impact on data taking. For the data receiving links, one side of the module can be configured to use the link of the other side. Using the redundancy option to receive data results in reduced readout bandwidth, but no data have to be lost. The use of this redundancy has been relatively stable at about 2.5% of the links. Most of these links broke even before the installation of the SCT. The use of redundancy of the TTC links to send commands to the modules has varied due to losses of the VCSELs in the readout creates, as discussed in more detail in section 3.2.2.

The SCT is operated in a near zero humidity nitrogen environment and is cooled by a bi-phase evaporate cooling system which runs with $C_3F_8$ fluid at -25°C. The target temperature for the SCT silicon sensors after irradiation was -7°C to suppress the effects of radiation damage as discussed in more detail in section 3.2.4.

3.2.2 Operations

More than 99% of the SCT strips were functional and available for data-taking at all times during 2010 and 2011. The SCT delivered tracking data for 99.9% and 99.6% of the delivered $pp$ luminosity in these years. The evaporative cooling for the SCT kept the modules of the inner three barrel layers at a temperature of approximately 2°C, while the modules of the outermost barrel layer and the end-caps were maintained at about 7°C. The mean temperatures
of each layer or disk were stable within about one degree during running.

Although individual strips can be masked, the largest contribution to missing strips for data-taking is due to (temporarily) disabled modules. The fraction of disabled modules as a function of time is shown as a function of time in figure 3.7. About 15 modules are permanently out of configuration due to low-voltage, high-voltage and readout problems, and 13 modules are disabled for data taking due to one cooling loop that is closed as a result of an inaccessible leak in that loop. Although the sensors could be operated at a higher temperature, the ABCD chips would become too hot if not cooled. This might not only damage the chips, but may also affect the glue holding the module together.

Shortly after the start of data-taking, the VCSELs of the TX transmitters started failing, at a typical rate of three or four deaths per day, explaining the rises in the fraction of disabled modules in figure 3.7, for example in the end of July 2010. These VCSELs are located in one of the counting rooms (~100 m from the detector) and can be exchanged during access. Operationally, the impact of TX deaths was minimized by using redundancy until no longer possible. During short shutdowns between data taking periods, dead VCSELs were replaced and the fraction of disabled modules drops. After thorough investigation, the cause of the VCSEL failure was traced back to exposure to humidity in the off-detector areas where the TXs are installed. The on-detector VCSELs can not be re-placed, but as the detector is operated in a very dry environment, this did not cause extra VCSEL losses.

Before merging the SCT data with the data from other detectors to do physics data analysis the quality of the SCT data is carefully checked. For example errors in the DAQ system may compromise the integrity of a data set. DAQ unavailability happened on very rare occasions, mostly due to two reasons. Firstly, chips may become disfunctional after a Single Event Upset (SEU). During such an SEU one of the thresholds of a chip may be changed, resulting in non-reliable data. The occurrence of SEUs became apparent in 2011 (see section 3.4) and it was resolved by implementing an automatic re-configuration of all chips every half hour during collision runs. Secondly, a Readout Driver Board (ROD), which reads out and controls up to 48 modules, may exert a BUSY signal, obstructing the total ATLAS data flow until resolved. The RODs went BUSY more often than expected in the first half of 2011 due to the TX problems, because a death results in time-out errors until the transmitter is configured to use redundancy or is replaced. At the higher trigger rates, a ROD will go busy if more than eight links throw

Figure 3.7: The number of SCT modules switched OFF as function of time.
3.2. SEMICONDUCTOR TRACKER

Figure 3.8: If the strips of the two sides of an SCT module would be under a 90° angle, two traversing charged particles would create four possible hits a), when the strips are under a smaller angle (10° for illustration in b), the two particles leave two hits.

time-out errors. This may happen if during running a VCSEL that already supplies redundant TX signal for a neighbor fails, increasing the number of timed-out links with four after one TX death. The short-term solution was to make sure a BUSY ROD was recovered without having to stop ATLAS running within a few minutes, and in the longer term the RODs were reprogrammed to handle time-out errors differently.

3.2.3 Tracking performance

The SCT was designed to operate with a noise occupancy of less than $5 \cdot 10^{-4}$ at a hit efficiency of 99% [80]. Several parameters, like the noise occupancy, hit efficiency and cluster widths, are monitored online and offline to ensure the detector is in the expected condition and is efficiently operated.

The position resolution is determined in the first place by the strip “pitch” $p$ and is expected to be 16 $\mu$m in the $R-\phi$ plane. The SCT strip length is 12 cm, limited by the electronic noise and the expected hit rate per strip. To acquire a position measurement along the strip length, two sets of strips with a mutual angle are used. The mutual stereo angle between the sensors of the SCT is 40 mrad, resulting in an expected hit resolution of 5.8 mm in the direction of the strips. The most accurate two dimensional position resolution is obtained when the strips are mutually perpendicular, but this leads to a higher rate of ghost hits, as illustrated in figure 3.8, which would impede the pattern recognition.

The SCT alignment can be measured using the hit residuals, that are defined as the measured hit position minus the expected position from the track extrapolation in the local $x$-and $y$-direction [97]. Figure 3.9 shows the unbiased residual distribution in local $x$, the direction
perpendicular to the strips, for all hits-on-tracks in the SCT barrel layers for simulated data with design geometry and after the autumn 2010 alignment with collision data (run 153565) taken in April 2010. Tracks are selected to have \( p_T > 2 \text{ GeV} \) and \( > 5 \) silicon hits. The residual is defined as \( \sigma = \text{FWHM}/2.35 = 36 \text{ \( \mu \)m} \), which approaches the simulated value of \( 34 \text{ \( \mu \)m} \), that is achieved with perfect alignment [98]. The mechanical stability of the SCT is continuously monitored to ensure stable residuals [99].

The noise occupancy can be measured by counting the fraction of triggers which result in a hit when there is no particle activity in the detector. Figure 3.10 a) shows the noise occupancy, which is significantly below \( 5 \cdot 10^{-4} \) [81].

The SCT hit efficiency is shown in figure 3.10 b) and is measured as the probability to record a hit at the passage of a charged particle. Particles are required to have \( p_T > 1 \text{ GeV} \) and at least seven SCT hits, excluding the hit under test. The track is again reconstructed without the hit in the detector under test, unless the hit under test is at the extremes of the track. If the track is still reconstructed without this hit, it is checked if there indeed was a hit in the SCT layer that the track traversed. The efficiencies in the innermost and outermost layer (‘0 inner’ and ‘3 outer’ for the barrel) are undefined by definition for the SCT stand-alone tracks as they are on the extremes of the track. The measured efficiencies are well above the required design efficiency of 99% [98].

The drift of charge carriers through the silicon bulk material under the influence of an electric field \( \mathbf{E} \) may be deflected in the presence of a magnetic field \( \mathbf{B} \). In the SCT barrel modules, \( \mathbf{E} \) and \( \mathbf{B} \) are mutually perpendicular. The charge carriers drift along the Lorentz angle \( \theta_L \) with respect to the normal of the sensor plane. If \( \mathbf{E} \) and \( \mathbf{B} \) are mutually perpendicular, the Lorentz angle is given by:

\[
\tan \theta_L = \mu_H B = \gamma_H \mu_d B, \tag{3.1}
\]

where \( \mu_H \) is the Hall mobility, the product of the charge carrier mobility \( \mu_d \) and the Hall factor \( \gamma_H \), which is of the order of unity. The charge carrier mobility depends on the bias voltage and the sensor temperature [100]. For fully-depleted modules, the average expected shift of the collected charge is approximately 10 \( \mu \)m.
3.2. SEMICONDUCTOR TRACKER

Figure 3.10: a) The SCT noise occupancy for each chip averaged for the different parts of the detector is measured at 150V and is found to be below the TDR specification of $5 \cdot 10^{-4}$ (dashed line). b) The intrinsic module efficiency for tracks measured in the SCT barrel. This hit efficiency is the number of hits per crossing of a charged particle, where dead modules and chips are excluded from the measurement. [98]

Figure 3.11: a) Cluster width size in strips as a function of track incident angle for the SCT barrel layers. b) Measured Lorentz angle for each barrel layer from a 2011 collision run with Monte Carlo predictions overlaid. [98]
The Lorentz angle is measured from the dependence of the cluster size on the incident angle of the charged particle. When the incident angle equals the Lorentz angle, all charge carriers drift along the particle direction and are collected on the same point (apart from diffusion) on the sensor surface, giving a minimum cluster size. The value of the Lorentz angle depends on the magnetic and electric fields within the silicon, the temperature and the amount of accumulated radiation damage, so analysis of the Lorentz angle and its development with time is used to understand the detector. Figure 3.11a) shows the cluster widths for the barrel sensors facing the beam line, indicating the Lorentz angle, panel b) shows the measured Lorentz angles for each barrel layer compared with model predictions. As seen in figure 3.11b) the Lorentz angle in barrel layer 3 is lower than in the other layers, because this layer is operated at a higher temperature [98]. The TRT that is closest to this outermost layer can not be operated at 2°C and the heater pads that were installed to ensure running with the SCT colder than the TRT are not functioning.

3.2.4 Radiation damage

The SCT was designed to withstand a particle fluence of $2 \times 10^{14}$ 1 MeV neutron equivalent cm$^{-2}$ and a $1 \times 10^5$ Gy ionizing dose. This corresponds to the fluence after an integrated luminosity of 700 fb$^{-1}$. Until December 2012 an integrated luminosity of $\sim 29$ fb$^{-1}$ has been delivered to the ATLAS experiment and as a result of radiation damage an increase of the leakage current has been observed. Radiation damage to silicon detectors occurs in two ways: bulk damage and surface damage. In this section the possible radiation effects and the impact of radiation damage on the SCT performance are discussed.

Bulk damage is caused by the non-ionizing energy loss interactions of an incident particle with sufficient energy ($\sim 25$ MeV) with the silicon atoms that can displace the silicon atom from its position in the lattice. The atom is then called a primary knock-on atom (PKA). The recoil energy of the PKAs can be up to 130 keV and therefore they can remove other atoms from the crystal lattice, giving rise to a PKA cascade. Most of the displacements repair and only 2% of all generated defects form electrically active states. Such disordered regions are referred to as defect clusters. Defect clusters have high local defect density and can be tens of nanometers wide. At temperatures above 150 K these primary defects diffuse within the silicon bulk. These defects can generate higher leakage currents and change the effective doping concentration which leads to a modification of the depletion voltage.

The increase of depletion voltage is due to an increase in the effective doping concentration $N_{eff}$, the difference between the number of ionized donor and acceptors in the depletion region of the sensors. The depletion voltage is given by:

$$V_{dep} \approx \frac{q_0}{2\varepsilon_0\varepsilon_r} |N_{eff}| d^2,$$

where $q_0$ is the electron charge, $d$ the detector thickness and $\varepsilon_0\varepsilon_r$ the permittivity of silicon. Unirradiated, the SCT bulk material is n-doped. Defects in the silicon become charged by capturing charge carriers and the silicon bulk changes from being effectively n-doped to p-doped, which is referred to as type inversion and this has already occurred in the two innermost pixel barrel layers. After three years of running, the depletion voltage in the SCT is still well below the initial operational setting of 150 V.
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The increase in leakage current is a measure for the amount of damage due to non-ionizing radiation to the bulk material. It correlates strongly with the luminosity delivered by the LHC and the temperature of the sensors. The leakage current is monitored over time and compared to simulation with the FLUKA transport code [101, 102]. As illustrated in figure 3.12, the leakage current has increased from $\sim 4 \cdot 10^{-3} \mu$A in July 2010 to $\sim 4 \mu$A in August 2011, which is in excellent agreement with expectations from simulation [98]. The limit for a module to trip was set to $5 \mu$A in 2010 and increased to $50 \mu$A to be well above the initial and evolved leakage current.

Dislocated atoms thermally move back into the lattice, which is referred to as beneficial annealing. This results in a decrease in leakage current. Beneficial annealing happens at relatively short time scales of weeks and does not occur if the detector is cold. In figure 3.12, the reductions of the leakage current due to beneficial annealing during the winter stops when the cooling plant of the inner detector was shut down is clearly visible.

Reverse annealing on the other hand increases the leakage current at a longer time scale ($\approx 500$ days), such that simultaneously an initial improvement due to the beneficial annealing is observed, while the leakage current increases again after more than a few weeks. It is possibly due to the diffusion of dislocations. To mitigate the effect of reversed annealing, the SCT was designed to be kept at $-7^\circ$C after irradiation and eventually operated at $2^\circ$C.

The charge collection efficiency and the amount of collected charge are also lowered, since the electrons and holes, created by the traversing particle, may become temporarily trapped by a defect. Both electrons and holes can be trapped for a short period of time, resulting in a
reduced number of carriers \( N_{e,h} \) measured. There is an exponential decrease in the number of \( e, h \), described by:

\[
N_{e,h}(t_c) = N_{e,h}(0)e^{-\frac{t_c}{\tau_{\text{eff}}}},
\]

where \( N_{e,h}(0) \) is the initial number of charge carriers, \( t_c \) the charge collection time and \( \frac{1}{\tau_{\text{eff}}} \) the effective trapping probability. This effect is small after three years of running.

Surface damage is determined mostly by the design of the detector and is caused by trapped charges in the oxide layers. The incident particle traversing the surface can create \( eh \)-pairs in the \( \text{SiO}_2 \) layer. The pairs do not recombine and represent an additional contribution to the total oxide charge to which electrons are attracted that form an accumulating layer. This leads to an increase of the capacitive coupling between pixels or strips. Direct consequences are the larger charge sharing between strips and an increased noise due to the rise of the capacitive load seen by the electronic readout.

### 3.3 Transition Radiation Tracker

The TRT, the outermost component of the inner detector, is a transition radiation tracking detector. Drift tubes (straws), each four millimeters in diameter and up to 144 cm long in the barrel and 37 cm in the end-caps, are used to detect charged particles. All straws are filled with a gas mixture\(^2\) and contain a 30 \( \mu \text{m} \) thick anode wire. When a charged particle passes through, some of the gaseous atoms become ionized and the free electrons in the gas are multiplied after they drift closer to the wire. The positive ions drift to the tube wall and the resulting current is measured. The TRT barrel is divided into three layers of 32 sectors each and has a maximal number of 73 straw layers covering \( |\eta| < 1 \). In each end-cap the straws are oriented perpendicular to the beam axis and extend up to \( |\eta| < 2 \).

The TRT measures at least 30 hits per track to improve the pattern recognition and to enhance the separation between electrons and charged pions. To achieve the best hit resolution the distance from the straw at which the charged particle traversed is determined from the drift time of the electrons. Figure 3.13 a) shows the track-to-wire distance as a function of the measured drift time fitted with a third order polynomial. The intrinsic accuracy per hit expected from the drift-time measurement is 108 \( \mu \text{m} \) in the barrel and 135 \( \mu \text{m} \) in the end-caps. To measure the hit resolution, the width of the distribution of the distance from the predicted track position to the measured hit position in the module is used. The TRT position resolution is 142 \( \mu \text{m} \) in the barrel, see figure 3.13 b), and 161 \( \mu \text{m} \) in the end-caps. The intrinsic hit resolution and the track parameter errors contribute to the width of this hit residuals distribution, which is therefore larger than the intrinsic hit accuracy only.

Electron/pion separation is achieved with layers of materials with different dielectric constants between the straws. When a high energetic particle crosses the boundaries between the layers transition radiation photons with energies between 5 keV and 10 keV are produced. The amount of transition radiation depends on the Lorentz factor \( \gamma = E/m \) of the incoming particle. Pions are more than 250 times heavier than electrons, so over the entire energy range, electrons produce much more transition radiation photons since they are ultra-relativistic. These photons

\(^2\) The TRT is filled with a gas mixture of 70% Xe, 27% \( \text{CO}_2 \) and 3% \( \text{O}_2 \).
3.4. DATA QUALITY MONITORING

Figure 3.13: a) The distance as a function of drift-time for the TRT barrel. The points show the peak position of the fit to the track-to-wire distance distribution in slices of measured drift time. The line shows the third order polynomial that is used to determine drift distance based on the measured drift time [103]. b) Comparison of TRT hit residuals for the barrel modules [97].

are absorbed by the xenon gas mixture and thus produce extra electrons in the gas. To detect this extra signal, the TRT is readout with a high and low threshold. The high threshold probability as a function of the $\gamma$ factor is shown in figure 3.14(a). The pion misidentification probability is of the order of 10% for high threshold hits that give 90% electron efficiency, see figure 3.14(b).

The TRT hit efficiency calculated as the ratio of the number of hits associated to track and the number of straws crossed by the charged particle is about 95% [104]. The efficiencies measured in data agree very well with simulation. The hit efficiency in the TRT is lower than in the silicon detectors, but with $\sim$ 36 TRT hits on track, compared to three and eight hits in the pixel and SCT detectors, this is not a problem. The TRT has been reliably operated since 2008. During the years 2010 and 2011 97.3% of the 350k read out channels were operational [90] and data quality is constant.

3.4 Data Quality Monitoring

Each of the sub-detectors of ATLAS have dedicated services like power, cooling and gas supply. A Detector Safety System (DSS) has been built to detect possible operational problems and abnormal and potentially dangerous situations at an early stage and, if needed, to bring the relevant part of ATLAS automatically into a safe state [106]. To ensure the data taken are of good enough quality for physics analysis and to provide fast feedback to the operating teams, a fraction of the events that passed the Event Filter are written to the express stream. Events from the express steam are processed at the CERN computing center and histograms are produced for Data Quality Monitoring (DQM). The DQM histogram production is done by dedicated modules in the ATLAS software framework ATHENA [107]. The DQM differs from the DSS as notifications by the DQM do not always require immediate follow-up. If the detector becomes too warm, measures will need to be taken before something breaks down, but data that do not
fulfill all the data quality requirements may still be useful for all physics analysis.

The DQM is for example used to detect possible small detector movements, resulting in detector misalignment. Misalignment of the detector results in a bias of the hit residuals and thus an increase of the average $\chi^2$ of reconstructed tracks. To detect detector movements early on, the $\chi^2$ of all tracks is monitored. To enable DQM, automated checks are run and the outcome of these checks is considered online by a shifter on duty in the control room and made available offline on the web after a full run is processed. The online DQM is mainly focused on efficient running and focuses on noise, hit efficiency and detector status. The offline DQM checks are performed before the data are re-processed for physics and provide the opportunity to mask dead detector parts or exclude parts of the data run if for example the detector was not fully functional.

The data quality depends both on the status of the sub-systems and on the performance of the tracking and trigger. The data are flagged as “good” if they pass all checks and may be flagged differently otherwise. The flagging procedure changed in 2011, when specific “defects” were introduced that can be assigned to (parts of) a data run. The defect “more than forty noisy modules” sometimes used by the SCT operations team was considered “tolerable”, while a number of 120 noisy modules is considered “intolerable”.

Each sub-system may have different requirements for variables to be checked and specific monitoring may even use a specific trigger. For example empty events are triggered for noise monitoring. The operating team need feedback on the state of the detector before the actual physics data taking has started, which is achieved by monitoring the noise and for example the number of dead modules directly from randomly picked (empty) L2 accepted events at all times during ATLAS running. Tracks from events passing the High Level Trigger are reconstructed
and used for the data quality assessment. The monitoring is run in separate tasks, or jobs, and specific trigger selection can only be applied per job. The final variables shown in the control room to the shifter are selected from these different jobs.

Online, the shifter will receive a visual warning if one of the DQM checks is not passed and he or she will need to decide if action is needed. The data are available to the shifter in the control room via two presentation tools:

- The Data Quality Monitoring Display (DQMD) \[108\], that graphically presents the different detector regions. The regions are colored and the color indicated if the histograms in that region passed the DQ checks implemented.

- The Online Histogram Presenter (OHP) \[109\], a simple GUI that directly shows the histograms, meant to serve as backup for the DQMD, but in practice used as the main tool by most shifters because of its easy usage.

If the online DQM software reports that the data taken are useless, the problem can hopefully be resolved before the LHC stops a run. Reoccurring problems are “taken offline” and preventive measures can be taken. In 2010 and 2011 85% of all delivered luminosity by the LHC was good for physics analyses \[110\].

The following two examples of operational problems with the SCT were first noticed with the online DQM. Firstly, in June 2011 the shifter reported the occurrence of SCT modules that were extremely noisy; having three orders of magnitude more hits than the surrounding modules. These so-called “hot modules” started appearing every run, so further investigation was needed. A correlation between the appearance of clusters (groups of adjacent strips hit) with a width of 128 strips and the hot modules was spotted shortly after. As one chip reads out 128 strips, it was suggested that the hot modules are caused by a single event upset (SEU) \[111\], where the threshold of a chip is changed due to passage of a charged particle. Whether or not the hot modules were really caused by SEUs, a re-configuration of the SCT was installed to happen every half hour and the hot modules were not seen anymore after. A verification of the SEU hypothesis is provided by studying the correlation between SEU rate and module fluence. The average number of SEUs / module / number L1 triggers depends linearly on the cluster occupancy / mm\(^2\), which supports the SEU hypothesis \[112\].

Secondly, when time between bunches in the LHC was for the first time lowered from 100 ns to 50 ns in April 2011, the SCT hit efficiency appeared to have dropped from > 99% to ∼ 98%. This was a feature of the combination of the three time bin readout and the hits accepted by the tracking. As mentioned above, the SCT is readout three times 25 ns at trigger. When the bunch spacing in the LHC was reduced to 50 ns, tracks from a previous bunch crossing can contribute to the current event if the SCT is readout long enough. If a track is found, but there is no hit in a module anymore, the reconstructed hit efficiency is artificially low. The problem was solved by changing the readout to record only ‘X1X’ hits.