

Chapter 2

The ATLAS Experiment at the Large Hadron Collider

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator, designed to collide protons at a center of mass energy of 14 TeV. It was built by the European Organization for Nuclear Research (CERN) between 1998 and 2008, and is the latest addition to CERN's accelerator complex. There are four main experiments at the LHC, all run by international collaborations. There are over 10,000 scientists and engineers from more than 100 countries, as well as hundreds of universities and laboratories working at CERN's experiments. The two largest and multi-purpose experiments, ATLAS and CMS, are built to analyze the myriad of particles produced by the LHC. They have been conceived to pursue an ambitious physics program, where at the head of the list was the discovery of the Higgs boson, achieved in 2012. Having two independently designed detectors is vital for cross-confirmation of any new discoveries made.

This chapter introduces CERN's accelerator complex (Sect. 2.1) and describes the ATLAS detector (Sect. 2.2), used to perform the physics analysis described in this dissertation.

2.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [1] is a two-ring, superconducting, hadron collider located at the European Organization for Nuclear Research ("*Conseil Européen pour la Recherche Nucléaire*", CERN) facility near Geneva, Switzerland. The LHC is installed approximately 175 m underground in a 27 Km circumference tunnel. It is designed to collide protons at a center of mass energy of up to $\sqrt{s} = 14$ TeV. The accelerator rings consist of superconducting magnets and accelerating cavities. The magnets bend and focus the proton beams into a circular trajectory while radio-frequency cavities boost their energy.

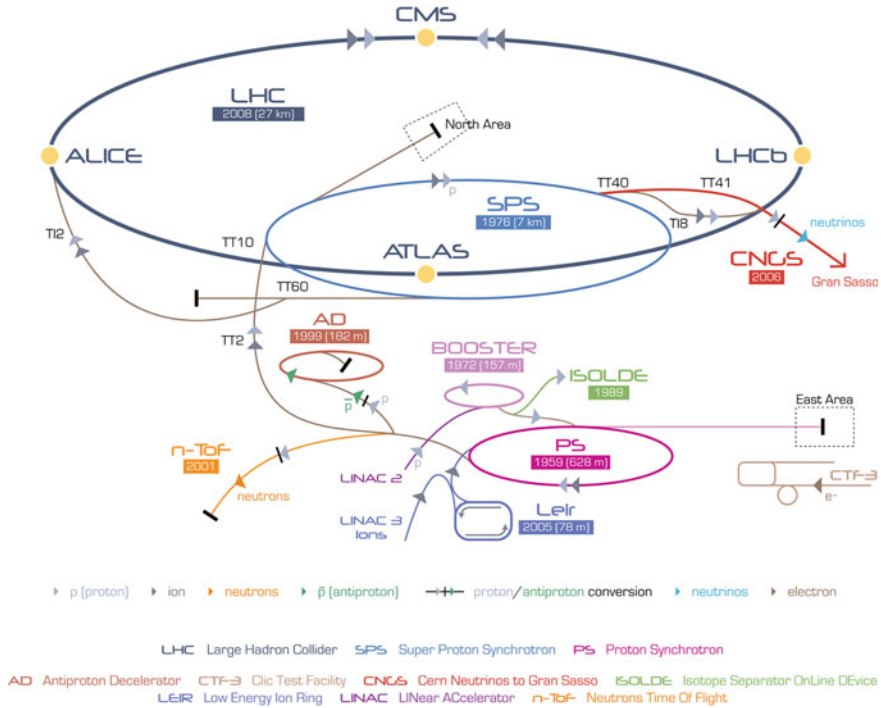


Fig. 2.1 Schematic view of the CERN particle accelerator complex. The four main LHC experiments are shown at the interaction points. Figure taken from reference [6]

The proton beams undergo several acceleration steps before reaching the desired energy. A schematic view of the acceleration chain is shown in Fig. 2.1. First, protons are obtained by ionization of hydrogen gas and accelerated up to 50 MeV in the linear accelerator LINAC2. Then they are transferred into the Proton Synchrotron Booster (PSB), where the energy is increased up to 1.4 GeV. Then the Proton Synchrotron (PS) accelerates the protons up to 25 GeV and injects them into the Super Proton Synchrotron (SPS), which brings the energy of protons to 450 GeV. Finally the protons enter the two LHC beam pipes where the energies are boosted up to 7 TeV.

To record and study the collisions delivered by the LHC four main-experiment detectors have been built around four different interaction points, as shown in Fig. 2.1:

- **ALICE.** A Large Ion Collider Experiment [2], designed to study heavy-ion collisions;
- **ATLAS and CMS.** A Toroidal LHC ApparatuS [3] and Compact Muon Solenoid [4], the multipurpose experiments designed to study a broad range of physics processes;
- **LHCb.** LHC-beauty [5], experiment specialized in the study of heavy particles containing a b -quark;

One of the main parameters of the accelerator is the *instantaneous luminosity* $\mathcal{L}$, defined as:

$$\mathcal{L} \equiv f_r \times \frac{n_b \times n_1 \times n_2}{A}, \quad (2.1)$$

where f_r is the collider revolution frequency, n_b is the number of bunches, n_1 and n_2 are the number of particles in each of the two bunches, and A is the beam cross-section. The event rate of a certain process, R can be obtained as the product of the process cross section and the instantaneous luminosity:

$$R \equiv \frac{dN}{dt} = \mathcal{L} \times \sigma. \quad (2.2)$$

Integrating the instantaneous luminosity over a certain accelerator active time one can obtain the *integrated luminosity*, L , which is used to describe the amount of collision data delivered by the accelerator over that period:

$$L \equiv \int \mathcal{L} dt = \frac{n_{\text{tot}}}{\sigma}, \quad (2.3)$$

where n_{tot} is the total number of produced events and σ is the process cross-section.

The first collisions at the LHC were observed on November 30, 2009. During 2010 and 2011 the LHC delivered proton collisions at a center-of-mass energy $\sqrt{s} = 7$ TeV, while in 2012 the collisions were at a center-of-mass energy $\sqrt{s} = 8$ TeV. The total integrated luminosity recorded by the ATLAS and CMS experiments in 2010 was about 45 pb^{-1} (47 pb^{-1} delivered) with a final uncertainty of $\pm 2.8\%$. In 2011 and 2012 the total integrated luminosity reached about 5.1 fb^{-1} (5.5 fb^{-1} delivered) with a final uncertainty of $\pm 1.8\%$ and 21.3 fb^{-1} (22.8 fb^{-1} delivered) with a final uncertainty of $\pm 2.8\%$ accordingly. By the time the first proton physics run (Run 1) ended in February 2013, the total integrated luminosity delivered to ATLAS and CMS had reached nearly 30 fb^{-1} and enabled the discovery of a Higgs boson.

The peak instantaneous luminosity delivered to ATLAS per day versus time during the 2012 year is shown in Fig. 2.2a. In Fig. 2.2b the delivered luminosity by the LHC to ATLAS and the luminosity recorded by ATLAS during stable beam conditions are shown. The difference in luminosity delivered to and recorded by the ATLAS experiment is due to different Data Acquisition (DAQ) inefficiencies. Of the recorded luminosity, only a part is usable for analysis, which is referred to as “good data”, i.e. the data that satisfy Data Quality (DQ) requirements assessed after reprocessing (see Sect. 2.2.8).

Due to the high frequency of collisions and the high density of the bunches necessary to achieve such a high luminosity, there is a non-zero probability that several events, originating from different pp collisions, may occur simultaneously. These events are referred to as “pile-up” and are categorized as *in-time* or *out-of-time* pile-up. The first one are caused by multiple inelastic interactions of protons in the same bunch collision, while the second one occurs when the detector records events

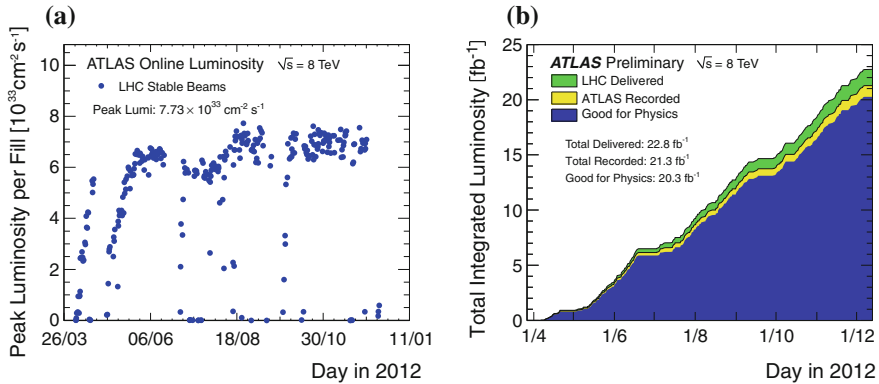


Fig. 2.2 (a) The peak instantaneous luminosity delivered to the ATLAS experiment per day versus time during the pp runs in 2012. (b) Total integrated luminosity versus time delivered by the LHC to ATLAS (in green), recorded by the experiment (in yellow) and selected as good data for analysis (in blue) for pp collisions at $\sqrt{s} = 8 \text{ TeV}$ in 2012. Figures taken from reference [7]

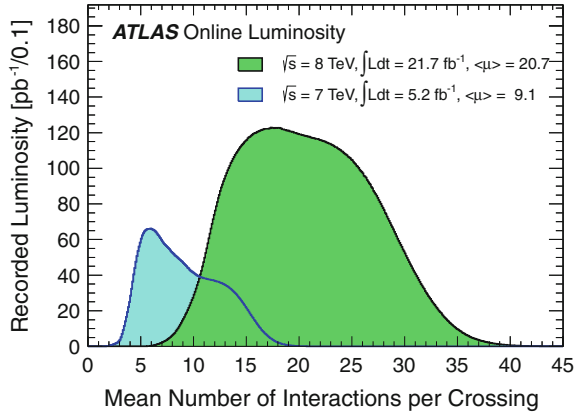


Fig. 2.3 Mean number of interactions per beam crossing during the 2011 (green) and 2012 (blue) LHC runs. Figure taken from reference [7]

originated in different bunch-crossings. The mean number of interactions per bunch crossing $\langle \mu \rangle$, which is taken as measure of the pile-up activity, is defined as:

$$\langle \mu \rangle = \frac{A \cdot \Delta \mathcal{L}}{f \cdot n_b}, \quad (2.4)$$

where $\Delta \mathcal{L}$ is the average instantaneous luminosity over a time period $\Delta t \gg 600 \text{ ns}$. The number of mean interactions per bunch crossing in 2011 and 2012 is summarized in Fig. 2.3. It amounts to $\langle \mu \rangle = 9$ and $\langle \mu \rangle = 21$ in 2011 and 2012 respectively, while in 2010 $\langle \mu \rangle$ was smaller than 3.

Table 2.1 Overview of the parameters for the LHC performance comparing the design values with their time evolution during the Run 1 operation in 2010–2013

Parameters	Design value	2010	2011	2012
Beam energy (TeV/c)	7	3.5	3.5	4
Beta function β^* (m)	0.55	2.0/3.5	1.5/1.0	0.6
Bunch spacing (ns)	25	150	75/50	50
Max. # bunches/beam	2808	368	1380	1380
Max. # protons/bunch	1.15×10^{11}	1.2×10^{11}	1.45×10^{11}	1.7×10^{11}
Peak luminosity ($\text{cm}^{-2}\text{s}^{-1}$)	1.00×10^{34}	2.1×10^{32}	3.70×10^{33}	7.7×10^{33}
Emittance ϵ_n (μrad)	3.75	2.0	2.4	2.5
Max. $\langle\mu\rangle$	19	4	17	37

In Table 2.1 the relevant parameters for the LHC performance is summarized for the Run 1 operation in 2010–2013. On 13 February 2013 the LHC’s Run 1 officially ended, and it was shut down for planned upgrades. “Test” collisions restarted in the upgraded collider on 5 April 2015, reaching 6.5 TeV per beam on 20 May 2015. The LHC’s Run 2 commenced on schedule on 3 June 2015 and by the end of 2015 it had delivered an integrated luminosity of 4.2 fb^{-1} to the ATLAS and CMS experiments.

2.2 The ATLAS Experiment

ATLAS (A Toroidal LHC ApparatuS) [3] is one of two general-purpose experiments at the LHC, aimed at exploring a vast range of physics scenarios and designed to measure the particles at unprecedented energies and instantaneous luminosity. It is the biggest detector of its kind ever built: about 46 m long, 25 m wide and weighs 7000 t. The ATLAS detector is characterized by a full coverage of the space around the pp interaction point and complete containment of the particles produced in the collision.

When a collision which may be of interest occurs, this usually means that some heavy and therefore short-lived particle or resonance has been created. In general these short lived particles quickly decay into two or more new particles, which in turn continue into the detector. These new particles carry information from the original event which produced them, and the purpose of the ATLAS detector is to record as much information as possible about the outgoing particles. This is accomplished

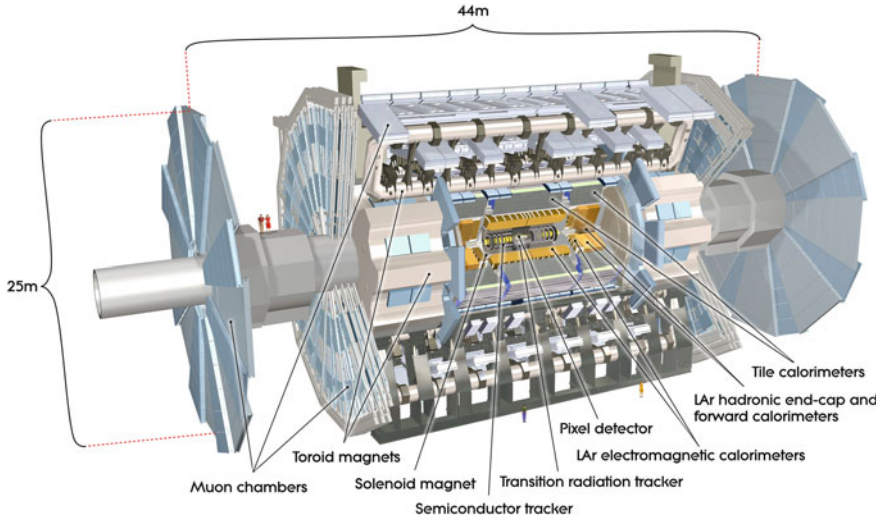


Fig. 2.4 Drawing of the ATLAS detector showing the different subdetectors and the magnet systems. Figure taken from reference [3]

through different detecting subsystems, that identify the particles and measure their momentum and energy (see Fig. 2.4):

- **Magnets.** The magnet system, which curves the charged particles so their momenta can be measured.
- **Inner Detector.** Immersed in a solenoidal magnetic field, it is used to identify and measure the momenta of charged particles and to identify the interaction vertices and the displaced vertices.
- **Calorimeters.** Consists of electromagnetic and hadronic calorimeters, used to identify and measure the energy of neutral and charged particles. They are designed to stop most types of particles, except muons and neutrinos.
- **Muon Spectrometer.** A muon detection system used to detect and measure the properties of muons. Because muons minimally interact with the other parts of the detector and have long lifetimes, they are identified and measured in the outermost detector layer.

The reason that detectors are divided into many components is that each component measures a specific set of particle properties. In Fig. 2.5 the interactions of various particles with the different components of the detector are shown. Each particle type has its own “signature” in the detector. For example:

- Charged particles, like electrons and protons, are detected both in the tracking system and the calorimeters.
- Neutral particles, like neutrons and photons, are not detectable in the tracking system. Photons are detected by the electromagnetic calorimeter, while neutrons are evidenced by the energy they deposit in the hadronic calorimeter.

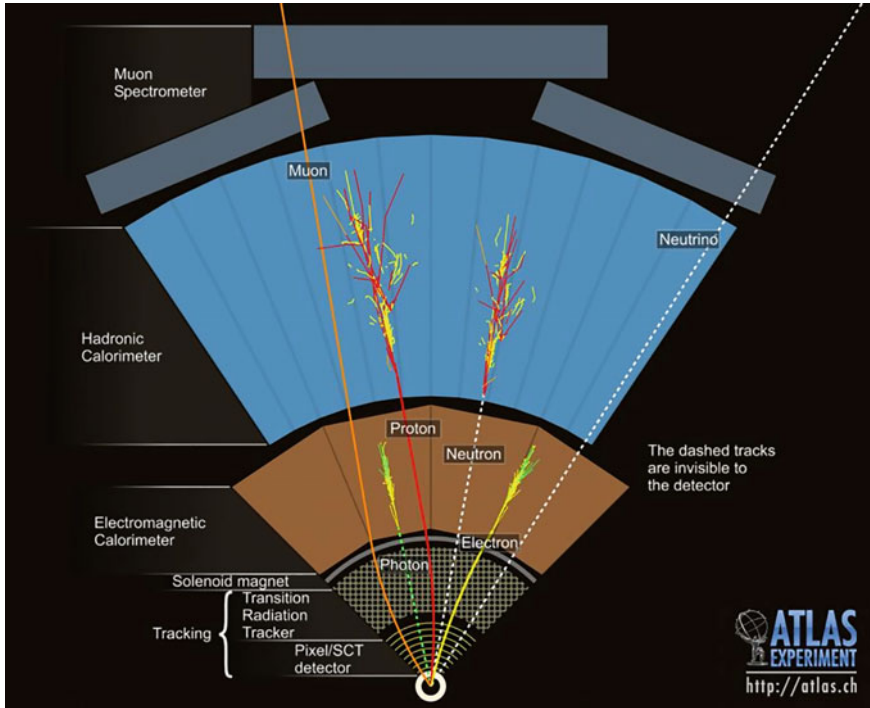


Fig. 2.5 Drawing of the detection of particles going from the interaction point through the whole detector. Figure taken from reference [8]

- Muons are hard to stop and generally exit the detector completely. Similar to the tracking system, the muon detection employs a series of tracking chambers to measure the trajectories of muons, which are bent by a toroidal magnet field.
- Neutrinos do not produce a signal in any of the detectors because they rarely interact with matter. Their presence is inferred as missing transverse momentum.

2.2.1 Coordinate System

In Fig. 2.6 the coordinate system used in the ATLAS detector is shown. The origin of three dimensional XYZ right-handed coordinate system is taken at the nominal Interaction Point (IP) in the center of the detector. The X-axis points toward the center of the LHC ring, the Y-axis points upward, and the Z-axis is along the beam direction. The detector half at positive Z-values is referred to as the “A-side”, the other half the “C-side”. The transverse plane is often described in terms of $R - \phi$ coordinates, with the azimuthal angle ϕ measured around the beam axis, ranging

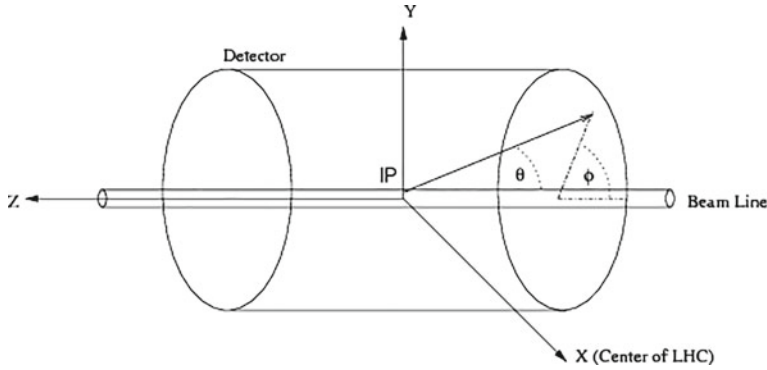


Fig. 2.6 The ATLAS coordinate system. Figure taken from reference [9]

between $-\pi$ and $+\pi$ with respect to the X-axis. The polar angle θ is measured from the positive Z-axis and varies from 0 to π .

Since the momentum and initial energy of the colliding partons along the Z-axis is unknown, it is useful to define the transverse component of variables of interest, like the energy and the momentum, as their projection on the XY plane, which are boost-invariant along the Z-axis:

$$E_T = E \sin \theta, \quad p_T = p \sin \theta. \quad (2.5)$$

Another common variable used at hadron colliders to describe the polar distribution and preferred to the simple polar angle θ is the rapidity:

$$y \equiv \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (2.6)$$

which, for vanishing particle mass, is equal to the pseudorapidity η :

$$\eta \equiv -\ln \left(\tan \frac{\theta}{2} \right). \quad (2.7)$$

The advantage of pseudorapidity over θ is that pseudorapidity difference $\Delta\eta$ is boost-invariant along the Z-axis. For visualization the correspondence between the polar angle and the pseudorapidity for some values are reported in Table 2.2.

The distance between two particles in $\eta - \phi$ space is then defined as:

Table 2.2 Pseudorapidity versus polar angle values

θ	0°	5°	10°	20°	30°	45°	60°	80°	90°
η	∞	3.13	2.44	1.74	1.31	0.88	0.55	0.18	0

$$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}. \quad (2.8)$$

ATLAS covers the pseudorapidity region up to $|\eta| < 4.9$, while physics analyses typically consider objects restricted to $|\eta| < 2.5$.

2.2.2 Magnet System

A magnetic field is used in the ATLAS detector to measure the momenta of charged particles. When a charged particle moves in a magnetic field, it bends in a circular motion in the plane perpendicular to the magnetic field. High momentum particles bend very little while low momentum particles bend more. The deflection can be measured, and thus the particle momentum can be determined. In addition, the direction in which the deflection occurs determines the charge of the particles.

The magnet system in the ATLAS detector is composed of four large superconducting magnets: one central solenoid and three “open-air” toroids, as shown in Fig. 2.7.

The central solenoid magnet provides a 2 T axial magnetic field which bends charged particles in the ϕ -direction and gives rise to its curvature in the Inner Detector. Placed between the Inner Detector and the Electromagnetic CALorimeter (ECAL), it is only 5.8 m long, has an inner diameter of 2.46 m and is 45 mm thick. The cooling of the magnets is done with liquid Helium, sharing the cryostat with the ECAL.

The toroidal magnet system produces the magnetic field needed by the muon spectrometer to bend muons in the η direction. It consists of the eight air-core superconducting barrel loops and two end-cap air toroidal magnets. The barrel toroid generates a magnetic field of 3.9 T, has a length of 25 m, an inner radius of 4.7 m and an outer radius of 10.05 m. The end-cap magnet produces a magnetic field of 4.1 T and is rotated by 22.5° with respect to the barrel toroid to give a radial overlap and to optimize the bending power in the transition region between the two. Each coil of

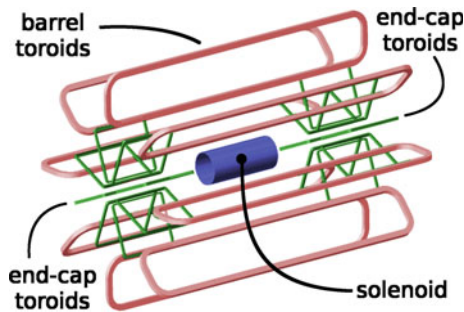


Fig. 2.7 Schematic view of the magnet system of the ATLAS detector. Figure taken from reference [10]

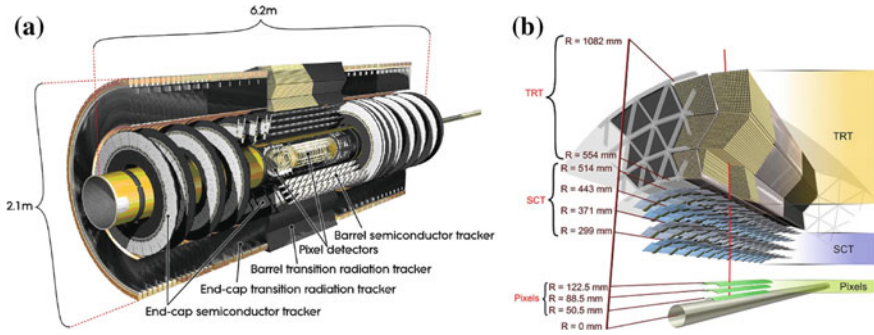


Fig. 2.8 (a) Cut-away view of the ATLAS Inner Detector. (b) Detailed schematic of the barrel section of the ID showing the three subsystems and reporting the distance to the center of the beam pipe. Figures taken from reference [3]

the barrel toroid has an individual vacuum vessel, while the end-caps toroid systems have a single integrated cooling system each. The choice of the “open air” toroid configuration was made to improve the muon reconstruction performance without relying on the Inner Detector. Such configuration allows to efficiently generate the magnetic field over a large volume with a reduced amount of material. This minimizes the amount of multiple scattering,¹ which represents one of the factors limiting the muon momentum resolution.

2.2.3 Inner Detector

The Inner Detector (ID) is the subsystem closest to the IP, tracking the charged particles arising from collisions and allowing the measurement of their momentum and the reconstruction of vertices with excellent position resolution. It combines the Pixel Detector as the innermost component followed by microstrip detectors of the SemiConductor Tracker (SCT) with tracking straw tubes in the outer Transition Radiation Tracker (TRT). Typically, for each track about 36 measurement points are provided by the ID, to which the SCT contributes four space points and the pixel detector three points. The ID system provides coverage for tracks with $|\eta| < 2.5$.

The outer radius of the ID is 1.15 m, and the total length is about 7 m. In the barrel region the high-precision detectors are arranged in concentric cylinders around the beam axis, while the end-cap detectors are mounted on disks perpendicular to the beam axis. A schematic view of the ID is shown in Fig. 2.8a.

¹Multiple scattering is defined as the electromagnetic interaction of a charged particle with the atomic structure of the medium. The result of the interaction with the very large number of nuclei and electrons results into a random smearing of the momentum of the incoming particle.

2.2.3.1 Pixel Detector

The pixel detector is the innermost part of the ID. It faces the highest amount of particle flux due to its closeness to the beam pipe, corresponding to the largest radiation damage and hit occupancy in ATLAS. The silicon detectors are chosen to fit this requirement. Due to the fine granularity of the detector segments, they also provide a high precision set of measurements close to the IP. Each pixel of silicon detector has a size of $50 \times 400 \mu\text{m}^2$, resulting in total ~ 80.4 million readout channels, achieving a very fine granularity. The pixel detector is subdivided into three barrel layers in its center, at radii of 50.5, 88.5 and 122.5 mm respectively, and three disks on either side for the forward detection, at a distance of 49.5, 58 and 65 cm respectively in the ϕ -direction from the center of the detector, as shown in Fig. 2.8b. With the total length of approximately 1.4 m, it typically detects three hits per traversing particles with $|\eta| < 2.5$, with the transition between barrel and disk structures being at $|\eta| \approx 1.9$. The position resolution achieved is $10 \mu\text{m}$ in $R - \phi$, and $115 \mu\text{m}$ in Z (R) in the barrel (end-cap) region. The very first layer is called B-layer and, thanks to its position really close to the IP (50.5 mm), it allows for the reconstruction of secondary vertices associated with the production of long-lived particles such as b -hadrons. This information is very useful to identify jets originating from the fragmentation of b -quarks.

2.2.3.2 Semiconductor Tracker

The SCT forms the middle subdetector of the ID. It consists of four nested cylindrical barrels in the center and nine disks in each of two end-caps, as shown in Fig. 2.8a. The barrels cover a region from 30 to 52 cm in the ϕ -direction and have an active length of 153 cm, centered around the IP. The respective barrel layers are fully covered by 32, 40, 48 and 56 rows of twelve identical modules, overlapping in a tile structure in order to ensure full coverage, making a total 2112 modules. The end-caps consist of nine disks each placed between $Z = 83.5$ to $Z = 278.8$ cm and ϕ -direction ranging from 25.9 to 56 cm. The discs are placed in three rings overlapping azimuthally, two on one side, one on the other side, in order to achieve full coverage.

The SCT barrel modules are made of four sensors, glued in pairs on either side of a thermally highly conductive baseboard. The sensors are approximately $6 \times 6 \text{ cm}^2$ p -in- n silicon wafers of $300 \mu\text{m}$ thickness. Each sensor has 768 strips with $80 \mu\text{m}$ pitch.

The end-cap modules are made of two or four wedge-shaped sensors of varying size depending on their position on the end-cap rings. The strip pitch varies from $57 \mu\text{m}$ on the inner edge of the innermost sensors to $94 \mu\text{m}$ on the outer edge of the outermost sensors. The sensor pairs are mounted on a thermally highly conductive carbon base board that provides cooling. The SCT sensors are operated at -7°C to prevent reverse annealing radiation damage. The spatial resolution achieved is $17 \mu\text{m}$ in $R - \phi$ and $580 \mu\text{m}$ in Z (R) in the barrel (end-cap) region.

2.2.3.3 Transition Radiation Tracker

The TRT is the outermost part of the ID. It provides charged particle tracking based on the use of straw detectors with 420,000 readout channels, as well as electron identification through transition radiation measurements. The TRT consists of 144 cm long cylindrical barrel layers ranging from 56 to 108 cm in the ϕ -direction and two end-caps ranging from 84 to 271 cm in Z and 64 to 103 cm in the ϕ -direction. Both barrel and end-cap parts contain similar carbon-polyimide straw tubes of 4 mm in diameter which are equipped with a 30 μm diameter gold-plated W-Re wire. The straws are filled with a nonflammable gas mixture of 70% Xe, 27% CO₂ and 3% O₂, the first component being the main gas in which ionization occurs and the latter had to be added to avoid etching problems with the glass joints that hold the wires. The straws are operated in proportional mode with the electrodes being on approximately 1530 V bias. The 52544 straws in the barrel form two modules embedded in polypropylene radiator foils in which transition radiation is produced. The modules are then formed into three rings to compose the entire barrel such that the straws are parallel to the z-axis. The end-caps are composed of 160 planes of 122880 radially arranged straws of 37 cm length. The TRT is only segmented in $R - \phi$, and it provides a resolution of 130 μm per straw. The covered pseudorapidity region is $|\eta| < 2.0$. A schematic view of the TRT is presented in Fig. 2.8b.

2.2.3.4 Inner Detector Combined Performance

The three ID subsystems give very precise $R - \phi$ and Z measurements, as well as good track pattern recognition. Using the combined information from the three subdetectors the transverse momentum resolution, measured with cosmic muons calibration runs [11], is:

$$\frac{\sigma_{p_T}}{p_T} = P_1 \oplus P_2 \times p_T, \quad (2.9)$$

where $P_1 = 1.6 \pm 0.1\%$ and $P_2 = (53 \pm 2) \times 10^{-5} \text{ GeV}^{-1}$. This gives a resolution of $\sim 1.6\%$ for tracks with $p_T \sim 1 \text{ GeV}$ and $\sim 50\%$ for tracks with $p_T \sim 1 \text{ TeV}$.

2.2.4 Calorimeters

The calorimeter system is located directly outside the magnetic solenoid and consists of two parts: the Electromagnetic CALorimeter (ECAL), made of liquid argon and forming the innermost layer, and the hadronic calorimeter, which is made up of the Tile Calorimeter (TileCal) and the Liquid Argon (LAr) calorimeters, forming the outer layer. The ECAL absorbs the energy from particles that interact electromagnetically while the hadronic calorimeter absorbs the energy of particles that interact via the strong force. A schematic view of the calorimeter system is presented in Fig. 2.9.

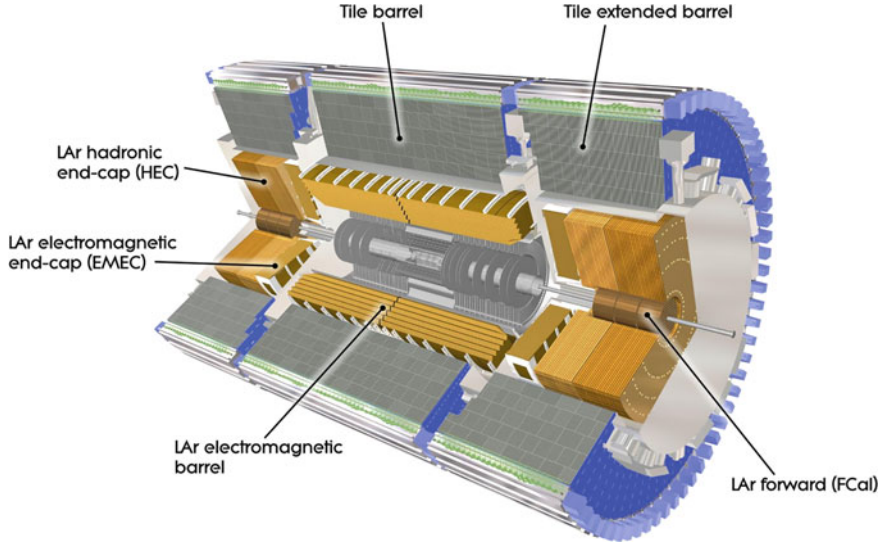


Fig. 2.9 Schematic view of the calorimeter system of the ATLAS detector. Figure taken from reference [3]

Besides particles energy measurement, the calorimeters provide particle identification information, discriminating electrons, photons and jets, and the determination of the missing transverse energy. The coverage area of the full system is up to $|\eta| < 5$ and an almost full coverage in the ϕ -direction. The relative energy resolution of the calorimeter is usually parameterized by:

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (2.10)$$

where a is the *stochastic* term, related to how the shower develops in the sampling calorimeter; b is the *noise* term, which includes the contribution from electronic noise and pile-up energy fluctuation; c is the *constant* term, that depends on calibration, shower containment, inactive material and on the linearity of the response. The experimental values for these terms are respectively $a \simeq 10\%$, $b \simeq 17\%$ (without pile-up) and $c = 0.7\%$ for the ECAL [12], while for the hadron calorimeter the values are $a \simeq 50\%$ and $c = 5\%$ [13].

Electromagnetic Calorimeter

The ECAL [12] is designed to measure electrons and photons energies in the range from 50 MeV to 3 TeV and cover a range of $|\eta| < 3.2$. It uses liquid argon detector with accordion-shape electrodes as active material and lead plates as absorber. The liquid argon solution was adopted for its intrinsic linear behavior, high ionization yield, stability and resistance to radiation. To collect the ionization electrons from the interaction a high voltage is applied between absorber plates, which also amplifies

the signal strength. In the barrel region the ECAL is referred to as ElectroMagnetic Barrel (EMB), which is divided into two identical semi-barrels EMBA and EMBC, and covers the pseudorapidity region $|\eta| < 1.457$. Two end-cap detectors, referred to as ElectroMagnetic End-Cap (EMEC), are divided into two coaxial wheels and cover the pseudorapidity region $1.375 < |\eta| < 3.2$.

The EMB is segmented into layers with very different depths and cell structure in the $\eta - \phi$ plane, as shown in Fig. 2.10. The first layer has a thickness of $4.3 X_0$ and is segmented in η with thin readout strips of $\Delta\eta \times \Delta\phi = 0.0031 \times 0.098$, providing precise measurement of the direction in pseudorapidity of the particles. The second layer has a thickness of $16 X_0$ and represents most of the thickness of the calorimeter ($\sim 70\%$). It is divided in towers of size of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ and provides the position measurement of the cluster. Most of the shower energy ($\sim 95\%$) is deposited in a matrix of 3×7 towers in $\Delta\eta \times \Delta\phi$. The third layer, only $2 X_0$ thick, is used to estimate the amount of energy lost beyond the ECAL. Towers in this section have a dimension of $\Delta\eta \times \Delta\phi = 0.05 \times 0.0245$.

A design similar to the EMB has been used for the EMEC, which is divided into two wheels covering the ranges $1.375 < |\eta| < 2.5$ and $2.5 < |\eta| < 3.2$. The inner wheel has a coarser granularity in $\eta - \phi$, limiting the region devoted to precision physics to $|\eta| < 2.5$. In the central region an additional pre-sampler layer is placed in front of the EMB and the EMEC at $|\eta| < 1.8$ to correct for energy lost in front of the calorimeter.

Hadronic Calorimeter

Hadronic calorimeters are designed to completely absorb high-energy hadrons, which will deposit only part of their energy in the electromagnetic calorimeter. It is divided in three components: the Tile Calorimeter (TileCal) in the central barrel and the two extended barrels, the LAr Hadronic End-Cap (HEC) calorimeter, and the LAr Forward CALorimeter (FCAL). Each component has its own particular technology and choice of material.

The TileCal [14] is placed just after the ECAL and measures the energy and position of jets and isolated hadrons. It is divided into one long barrel with $|\eta| < 1.0$ and two extended barrels with $0.8 < |\eta| < 1.7$. Both type of barrels are segmented into 64 modules in ϕ , each of $\Delta\phi \sim 0.1$. Each module is further segmented radially into three layers, with the thickness of approximately 1.5, 4.1, 1.8 hadronic interaction lengths (λ) in the long barrel and 1.5, 2.6, 3.3 λ in the extended barrels. The $\Delta\eta \times \Delta\phi$ segmentation of each module is 0.1×0.1 in the first two radial layers and 0.2×0.1 in the third one.

The TileCal in the barrel region is made of steel tiles as absorber with plastic scintillator tiles as active material. Wavelength-shifting fibers coupled to the scintillator tiles on either ϕ edge of the cells collect the light produced and are read out by two photo-multiplier tubes (PMT), each linked to one readout channel. The readout channels are grouped into cells forming a pseudo-projective geometry in η . A schematic view of TileCal is shown in Fig. 2.11.

The HEC collects the energy from particles that are not completely contained in the EMEC and in particular is used to reconstruct jets and the missing transverse

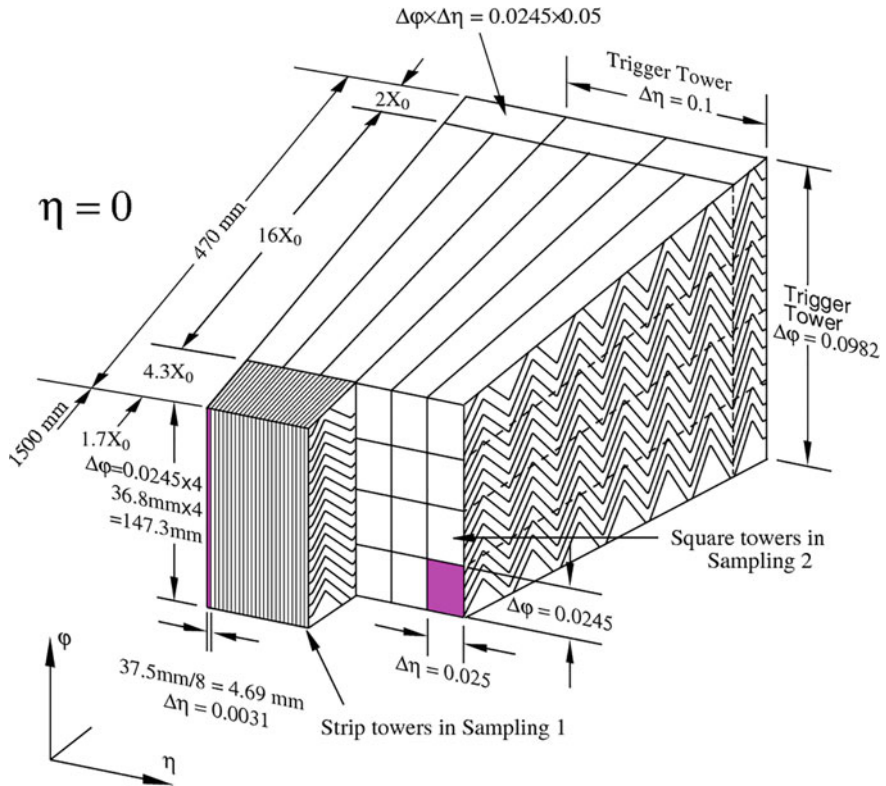


Fig. 2.10 Schematic view of the Electromagnetic barrel calorimeter. Figure taken from reference [12]

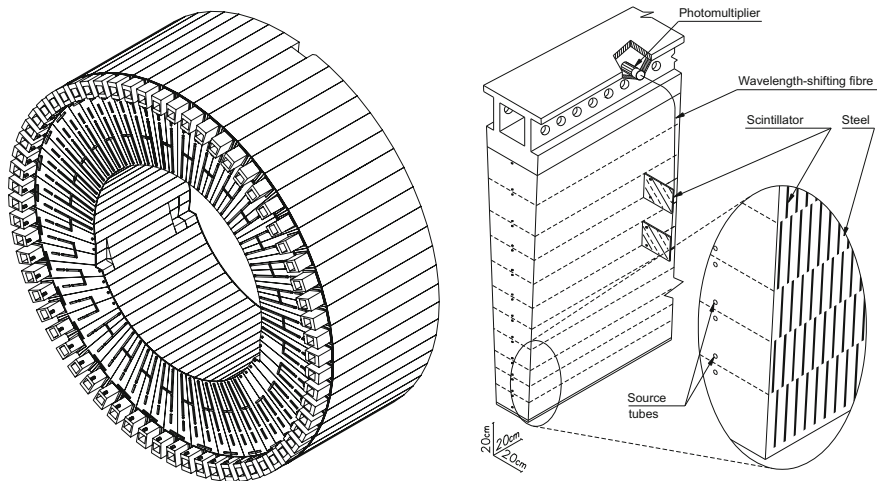


Fig. 2.11 Schematic view of the Hadronic barrel calorimeter. Figure taken from reference [12]

energy. It is made of copper as passive material and LAr as active material, chosen for its radiation hardness in a region exposed to a significant amount of particle flux. Each HEC is composed of two independent wheels with different segmentation, varying with η . In the region $1.5 < |\eta| < 2.5$, the $\Delta\eta \times \Delta\phi$ segmentation is 0.1×0.1 in the first two longitudinal layers, and 0.2×0.1 in the last one. In the region $2.5 < |\eta| < 3.2$, the $\Delta\eta \times \Delta\phi$ segmentation is 0.2×0.2 in all three samples.

The FCAL covers the very forward region of pseudorapidity $3.1 < |\eta| < 4.9$, making the calorimeter system achieve its good hermeticity and minimize the energy losses. It has an electromagnetic part that uses copper as absorber and two hadronic compartments with tungsten as passive material. The liquid argon is used as active material.

2.2.5 Muon Spectrometer

The last subsystem of ATLAS detector is the muon spectrometer [15]. It is designed to detect charged particles exiting the barrel and end-cap calorimeters. Due to the total large value of λ of the previous systems, muons are the only charged particles expected to reach this detector. The muon spectrometer consists of four subdetectors: Monitored Drift-Tube (MDT) chambers, Cathode Strips Chambers (CSC), Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC), as shown in Fig. 2.12.

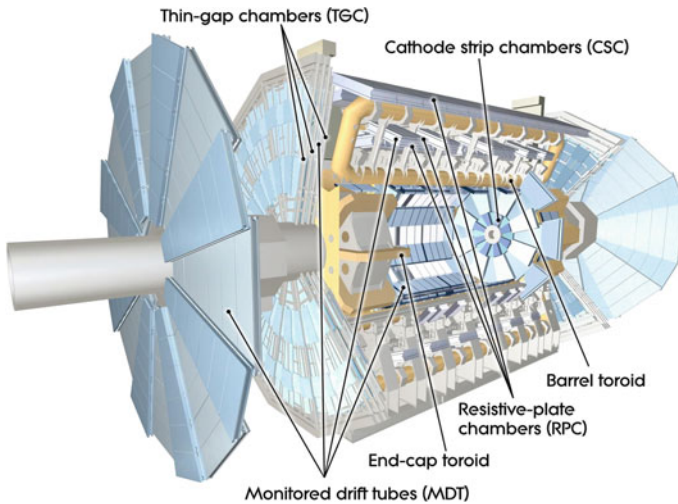


Fig. 2.12 Schematic view of the muon spectrometer of the ATLAS detector. Figure taken from reference [3]

MDTs and CSCs chambers have precise position and momentum measurement for track detection. These chambers, with a combination of toroidal superconducting magnets, provides a measurement of the momentum of muons for $|\eta| < 2.7$.

RPCs and TGCs chambers are for the triggering and time measurements. These chambers provide p_T thresholds, the possibility to identify the bunch-crossing thanks to their time resolution, and the measurement of the track coordinate in the ϕ plane with a precision ranging between 2 and 10 mm.

In standalone measurements the muon spectrometer has 10% resolution for a 1 TeV muon track, and muon tracks can be measured with good precision in the p_T range from 3 GeV to 3 TeV.

Monitored Drift-Tube Chambers

MDTs are proportional chambers used in the barrel region with pseudorapidity coverage of $|\eta| < 2.0$. It is based on pressurized drift tubes made of aluminum with a diameter of 30 mm and length varying from 0.9 m to 6.2 m. Tubes are filled with a 93% argon and 7% carbon dioxide mixture and the anode is a 50 μm tungsten-rhenium wire producing a radial electric field. Each chamber is composed by a group of six or eight tubes placed transverse to the beam axis. This number of tubes allows for a very good track reconstruction and high reduction of fake tracks from random associations of background hits, providing a resolution on position of 80 μm for an individual tube, 40 μm for a chamber and 30 μm for the three layers of MDTs.

Cathode Strip Chambers

CSCs are multi-wire proportional chambers used in end-cap regions and cover the pseudorapidity region of $2.0 < |\eta| < 2.7$. They are arranged in a system of two end-caps with eight chambers each. Each chamber contains four multi-wire proportional chambers with wires oriented in the radial direction, spaced by 2.5 mm and filled with the same gas mixture of argon and carbon dioxide as for the MDT chambers. The cathode strips are oriented either perpendicularly to the anode wires, giving the precision coordinate, or parallel to the wires, giving the transverse coordinate. The resolution provided by the interpolation between the charges induced in neighboring cathode strips ranges between 50 and 70 μm .

Resistive Plate Chambers

For the trigger system RPCs are used in the barrel region and cover the pseudorapidity region of $|\eta| < 1.05$. They are filled with a gas mixture of $\text{C}_2\text{H}_2\text{F}_4$ (94.7%), $\text{Iso-C}_4\text{H}_{10}$ (5%) and SF_6 (0.3%) between two resistive Bakelite plates, spaced by 2 mm. RPCs measure six points per coordinate for each particle, quickly collecting the avalanches with two orthogonal sets of pick-up strips that provides a position resolution of 1 cm in each plane and 1 ns time resolution, allowing for individual bunch crossing discrimination. RPCs also provide the ϕ coordinate for the tracks, since MDT chambers only give the η coordinate.

Thin Gap Chambers

TGCs are multi-wire proportional chambers, similar to the CSCs. They are used in the end-cap regions and cover the pseudorapidity region of $|\eta| < 2.4$. For a

fast collecting time, they have 1.8 mm wire-to-wire separation and 1.4 mm wire-to-cathode separation. Each chamber is filled with a highly quenching gas mixture of 55% CO₂ and 45% n-C₅H₁₂, and provide a spatial resolution of about 1 mm and a time resolution of 5 ns.

2.2.6 Forward Subdetectors and Luminosity Measurement

To reach the ultimate precision in measurement of processes of interest a good determination of the integrated luminosity is needed. The instantaneous luminosity, $\mathcal{L}$, defined in Eq. 2.1, can be rewritten as:

$$\mathcal{L} = \frac{\mu_{vis} \times n_b \times f_r}{\sigma_{vis}}, \quad (2.11)$$

where f_r is the collider revolution frequency, n_b the number of bunches and σ_{vis} the visible inelastic cross section (total inelastic cross section times the detector acceptance and efficiency). The visible interaction rate per bunch crossing is denoted as μ_{vis} . It is extracted mainly from the signals coming from specific luminosity detectors. The simplest algorithm consists in “simple counting” of bunch crossings where detectors reported a signal, but more refined algorithms are used [16], in particular when the pile-up contamination is no longer negligible. In order to use the measured μ_{vis} for luminosity determination, each detector and algorithm must be calibrated by determining its visible cross section σ_{vis} . The calibration technique exploits the *van der Meer* scans [17]. These are special low-intensity LHC runs where the beam separation in the transverse planes is varied (scanned) in order to determine the beams overlap profile. Through the determination of the beam lateral profile the absolute luminosity of the particular run can be inferred using Eq. 2.1, and σ_{vis} can be determined for each subdetector.

ATLAS is equipped with subdetectors in the forward regions used for monitoring tasks. The Minimum Bias Trigger Scintillators (MBTS), embedded in the structure of TileCal extended barrel modules, consist of 32 scintillator paddles assembled in two disks covering the pseudorapidity region $2.09 < |\eta| < 3.84$ and are used to detect minimum bias activity and to indirectly measure the luminosity. The main detectors for luminosity measurement are listed below:

LUCID (Luminosity Measurements Using Cherenkov Integrating Detector)

LUCID is a Cherenkov detector specifically designed for luminosity measurement. It consists of 16 aluminum tubes surrounding the beam pipe at 17 m from the interaction point. Each tube is filled with C₄F₁₀ and is coupled to a photo-multiplier in the back-end.

BCM (Beam Conditions Monitor)

BCM consists of 1 cm^2 diamond detectors located at $Z = \pm 184\text{ cm}$ around the beam pipe. Their fast readout and good time resolution (0.7 ps) allow them to provide luminosity information for each bunch crossing. At the same time, they are also employed to trigger on beam losses and induce the dump of the beam, thus protecting the silicon detectors from damage that might result from an uncontrolled beam.

ALFA (Absolute Luminosity For ATLAS)

ALFA is a subdetector that is only activated during special runs. It consists of eight scintillating fibers detectors placed at 240 m from the interaction point inside roman pots, above and below the beam pipe.

In addition, cross-checks of the luminosity measurement have been performed using information from other standard subdetectors: counting of primary vertices reconstructed by the ID and integrated signals from the Tile and forward calorimeter. The precision achieved is of a few % depending on the data-taking year.

2.2.7 Trigger and Data Acquisition System

Due to technical limitations (space, bandwidth), not every LHC collision can be recorded by the ATLAS detector. At nominal operation conditions, bunches of 10^{11} protons will cross each other at 40 MHz , resulting in ~ 25 proton-proton interactions per bunch crossing. Nevertheless, only a small fraction of this $\sim 1\text{ GHz}$ event rate results in interesting physics processes. The Trigger and Data Acquisition (TDAQ) system of the ATLAS detector was designed to select a manageable rate of such events for permanent storage and further analysis, reducing the event rate from about $\sim 1\text{ GHz}$ to $\sim 200\text{ Hz}$. The ATLAS trigger system [19] has a three-layer structure with increasingly detailed levels of information used in the reconstruction: the first level trigger (LVL1), the second level trigger (LVL2) and the Event Filter (EF) system. A schematic view of TDAQ systems of the ATLAS detector is shown in Fig. 2.13.

Level 1 Trigger

The LVL1 is completely based on the hardware of the detector, using coarse information from calorimeters, muon spectrometer trigger systems and from the MBTS. At this level the event rate is reduced from 40 MHz to 75 kHz by choosing events with high transverse momentum or high missing transverse energy. The LVL1 takes decisions within $2.5\text{ }\mu\text{s}$, while the front-end electronics of the several subdetectors keep the complete data in the pipeline memories. The data is then moved to the Readout Buffers (ROB) via the Readout Drivers (ROD).

Level 2 Trigger

The LVL2 receives a list with Regions of Interest (RoI), which contains the positions of the objects selected by the LVL1. Starting from the RoI, the LVL2 reduces the

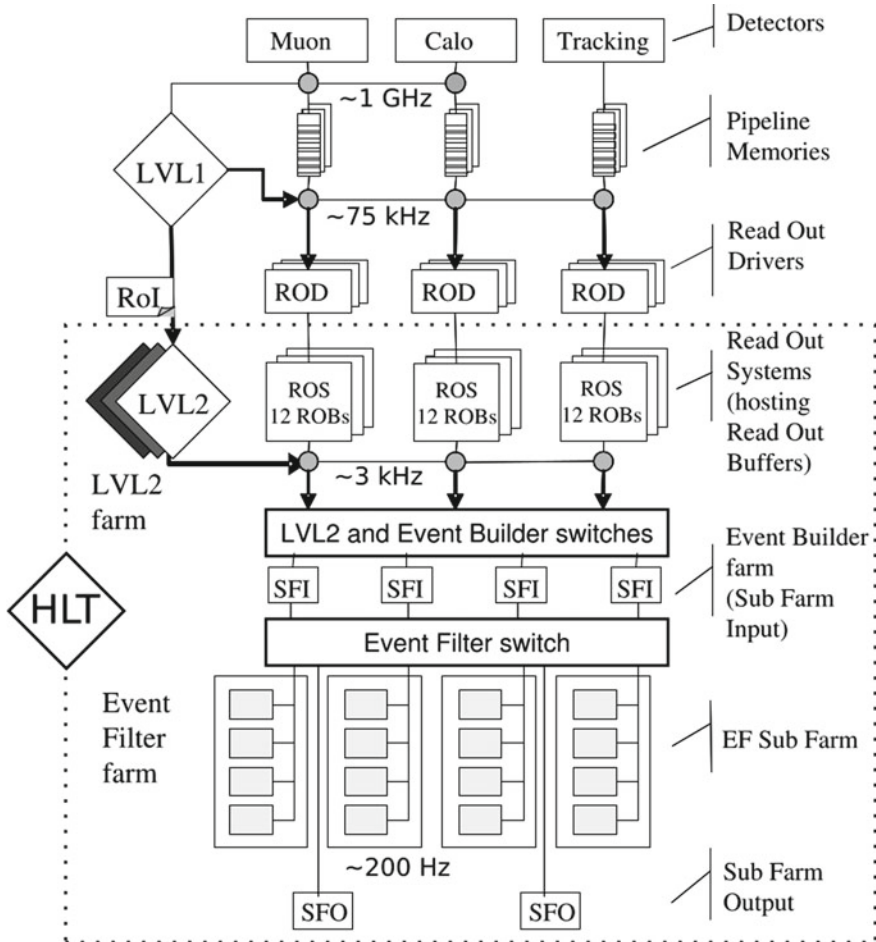


Fig. 2.13 Schematic view of the trigger and data acquisition systems of the ATLAS detector. Figure taken from reference [18]

rate from 75 kHz to 3.5 kHz with an average decision time of 40 ms. At this stage the information from the trackers is incorporated to the RoI to build candidate object (electrons, photons, muons) and better obtain its position and energy with simplified algorithms quick enough to respect the limit on the decision time. The event information is then passed to the Sub-Farm Input (SFI), which provides the full data to the EF.

Event Filter

The final trigger level is the EF, which together with LVL2, is referred to as High Level Trigger (HLT). At this point the physics objects are built using the same algorithms as used in the offline reconstruction. With an execution time amounting to 4 s, the EF

reduces the event rate to the goal value of 200 Hz. Events passing the EF are assigned to streams defined to separate the events into different datasets for different analysis interests, e.g. electron streams, muon streams, jet streams etc. The selected events are then moved into the Sub-Farm Output (SFO) and stored to be analyzed later.

Trigger Menu

The trigger system is configured via a trigger *menu* which defines trigger *chains*. Each chain is defined by a sequence of steps at each trigger level. Thresholds are increasingly tightened at each level in order to maximize selection efficiencies. For each HLT level, a sequence of read-out, reconstruction and selection steps is specified. A trigger is defined as the combination of the LVL1 seeding item and the two HLT (LVL2 and EF) chains. Triggers are categorized based on the object reconstructed (jets, muons, etc.), and the selection requirements, such as energy thresholds, multiplicity or isolation. This categorization, together with other distinctions, depending on the reconstruction algorithm and its configuration, are encoded in the trigger name. The naming convention is as follow:

$$[\text{LEVEL}][\text{N}][\text{TYPE(S)}][\text{THRESHOLD}][\text{ISOLATION}][\text{QUALITY}], \quad (2.12)$$

where the components, from left to right, are: the trigger level used, the multiplicity of the type, the object candidate, the threshold applied to the transverse momentum or energy of the object candidate, the object isolation, and additional requirements related to the type of algorithm used.

Defining the data taking period time unit as Luminosity Block (LB), typically one minute of data taking, information on beam conditions, detector performance and events passing any of the trigger chains of the trigger menu are stored to be then used in the analyses. All the LBs occurring between the start and the end of a stable beam collision period compose a “run”. Runs are finally grouped in “Data Periods”, labeled with capital letters (“Period A”, “Period B”, etc.), when they pertain to the same general detector condition, machine configuration and trigger menu.

2.2.8 Data Quality

The totality of pp collisions recorded by ATLAS, which differs from the amount delivered by the LHC because of data-taking inefficiencies, is still not 100% usable by physics analyses. Indeed, every subdetector needs to perform some routine checks on the quality of the data they recorded in order to certify that its performance was conform to the expectations. Therefore, so-called “Good Runs Lists” (GRL) are compiled recording for each LB which subdetectors satisfied the requirements. The single analyses will then decide which GRL to use, based on their specific needs of the individual subsystems. The fraction of data considered as “good” is $\sim 95\%$, giving a total integrated luminosity of 20.3 fb^{-1} satisfying data quality that is used for this analysis.

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