Chapter 3

LHC AND THE ATLAS DETECTOR

Among the principal instruments of modern experimental particle physicists are accelerators and detectors. This chapter begins with a general introduction to two basic collider parameters, the centre-of-mass energy and luminosity. Then, CERN is introduced and the Large Hadron Collider (LHC) is presented. Finally, the ATLAS detector, including its trigger system, is discussed.

3.1 BASIC COLLIDER PARAMETERS

Modern collider experiments make use of accelerators and detectors, where particles are accelerated to some energy before being made to collide. The higher is the energy, the higher is the mass scale which an experiment can reach. Accordingly, an important collider parameter is the centre-of-mass energy.

3.1.1 Centre-of-Mass Energy

To begin, consider two particles with four-momenta p_1 and p_2. The total momentum squared, which is a Lorentz invariant quantity, is

$$s = (p_1 + p_2)^2 = (E_1 + E_2)^2 - (\mathbf{p}_1 + \mathbf{p}_2)^2.$$

In the centre-of-mass frame, the three-momenta are opposite, and $\mathbf{p}_1 + \mathbf{p}_2 = 0$. As a result, assuming the particles have the same energy E, we may write

$$\sqrt{s} = 2E. \tag{3.1}$$

This quantity, $\sqrt{s}$, is referred to as the centre-of-mass energy. The higher are the energies of the participating particles, the higher is the centre-of-mass energy. Modern colliders are therefore designed to be able to accelerate the colliding particles to a very high energy.

A discussion of the LHC accelerator at CERN will be given in later sections.

3.1.2 Luminosity

In addition to the centre-of-mass energy, luminosity is also an important basic collider parameter. The higher is the luminosity, the better is the chance a clean signal may be extracted out of the undesired backgrounds. Indeed, given a physics cross section σ, the number of events N that is produced is given by

$$N = L\sigma$$

where the quantity L is referred to as the luminosity. The number of events is thus directly proportional to the luminosity.

We often speak of the number of events produced per unit time. Then, the relevant quantity is the instantaneous luminosity L_I, and

$$L = \int L_I dt$$

Colliders are built to achieve high luminosity. Consider two colliding beams with N_1 and N_2 number of particles. A general formula for the instantaneous luminosity, assuming Gaussian profiles of the beams, is

$$L_I = f\frac{N_1 N_2}{4\pi\sigma_x\sigma_y}$$

where

- f is the frequency at which the beams collide
- σ_x and σ_y are the root-mean-square horizontal and vertical beam sizes.

On the other hand, we need to deal with so-called pileup events that come from high luminosity. They are undesired events on top of the hard scattering, and may occur in two scenarios. Either many interactions occur in each collision, in which case we have in-time pileup, or interactions that belong to different collisions are (incorrectly) recorded together, in which case we have out-of-time pileup.

3.2 CERN AND THE LARGE HADRON COLLIDER

Broadly speaking, the development of physics rests upon two sources, the first, the availability of a set of physical phenomena and the second, active theoretical investigations. At the turn of the 20th century, atomic phenomena confirmed the discrete nature of physical quantities previously thought to be continuous and motivated the development of quantum mechanics. Subsequently, the quest to unify quantum mechanics and special relativity, in parallel with probes into sub-atomic phenomena, led to the development of quantum field theory and eventually gave birth to the Standard Model of particle physics. At present, more than ever before, both technological advances and active theoretical investigations are being pushed to the limit to scrutinize the Standard Model and go beyond it. In this respect, the Large Hadron Collider based at CERN has been playing a leading role, being the most powerful collider at the moment.

3.2.1 CERN

CERN [27], also known as European Organization for Nuclear Research, was established in the post-war era, the 1940s, to foster physics development and scientific collaboration in Europe.

CERN's core mission is fundamental physics, to uncover what the universe is made of and how it works. It relies on the participation and funding of a number of parties, which are classified into

- Member states: These are countries that provide financial and managerial assistance and responsibility to CERN.
- Non-member states: These are countries that contribute to the financing, construction, and operation of the experiments on which they collaborate.
- Observers: These are countries that have made significant contributions to the CERN infrastructure, and organizations which maintain close links with CERN.

In addition, CERN has scientific contact with a number of countries not belonging to the above groups.

3.2.2 The Large Hadron Collider

The Large Hadron Collider [28] was designed to explore physics beyond the Standard Model. It reuses the Large Electron Position (LEP) tunnel, 26.7 km in circumference, that was built in the period 1984-1989 at CERN. The tunnel lies between 45 m and 170 m underground.

The LHC has two rings with counter-rotating proton beams. The beams are accelerated by a high-frequency standing wave, and by design take the form of bunches of particles. The beam particles are kept along a circular trajectory and focused near the collision points using dipole and quadrupole magnets. Notable at the LHC is the use of superconducting magnets that operate at 2K and lower.

The LHC is part of a system that consists of one accelerator and four detectors. The designed centre of mass energy is 14 TeV. At this energy, Higgs physics and some beyond the Standard Model physics become accessible.

Figure 3.1 shows the CERN's accelerator complex. The four detectors are ATLAS, CMS, ALICE, and LHCb, all located at different collision points. Among them, the high luminosity experiments are ATLAS and CMS, where the target instantaneous luminosity is around $L_I = 2 \times 10^{34}\text{cm}^{-12}\text{s}^{-1}$.

In this thesis we will focus exclusively on the ATLAS detector.

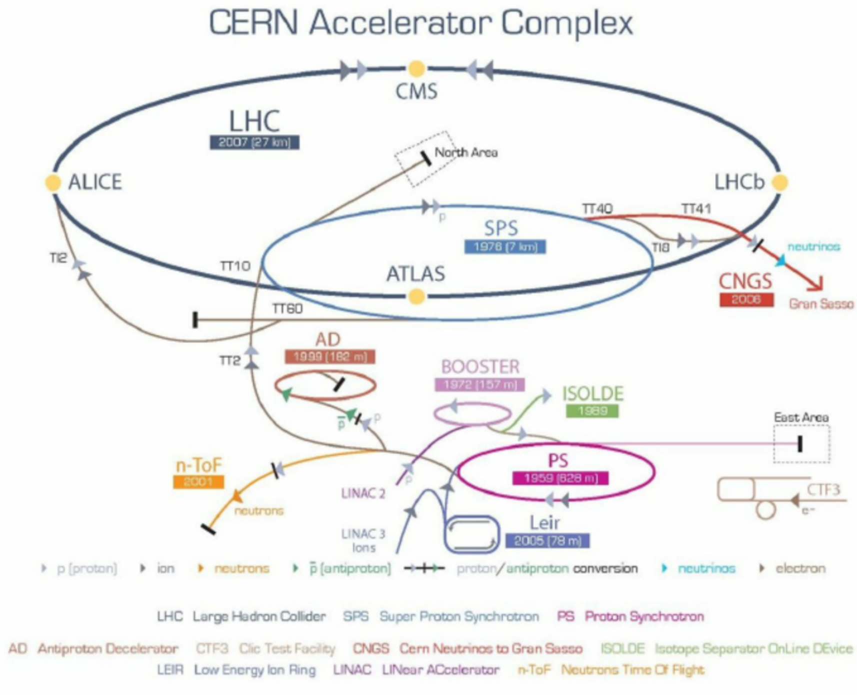

Figure 3.1: CERN's Accelerator Complex
[30]

3.3 THE ATLAS DETECTOR

ATLAS [29] is a general-purpose detector located at one among several collision points at the LHC. The LHC, at 14 TeV designed centre-of-mass energy, is capable of probing not only Higgs physics but also some beyond Standard Model physics. Since the new hypothetical particles are typically expected to decay to energetic Standard Model particles, ATLAS is designed to be able to identify and measure important physics objects such as photons, electrons, muons, taus, hadronic jets, and neutrinos and other weakly interacting particles in the form of missing transverse energy. In addition, with regard to jets, it needs to be able to distinguish between heavy flavour jets (b and c quarks) and other light jets.

An overview of the ATLAS detector is shown in Figure 3.2. It is 25 m in diameter and 44 m in length, and weights approximately 7000 tons.

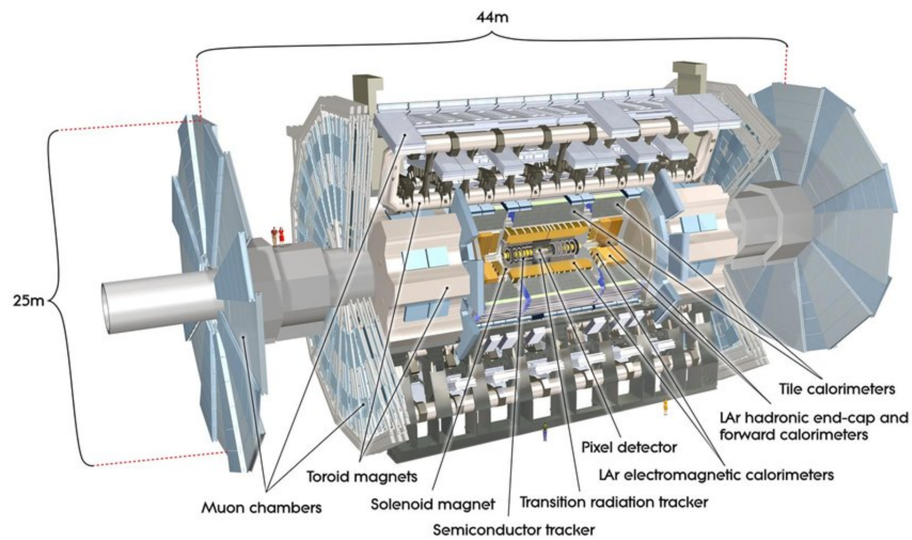

Figure 3.2: The ATLAS Detector
[31]

In conformity with modern detector design, ATLAS is made up of a number of subsystems that surround one another in layers. Innermost is the inner detector, or the tracker. Next, in order, are the electromagnetic calorimeter, the hadronic calorimeter, and the muon chamber. These subsystems work in combination to provide detection capability in many possible physics scenarios. They are built out of components that are fast, precise, and that can stand against high radiation. Moreover, they are supplemented by an efficient trigger system.

The entire detector is nominally forward-backward symmetric with respect to the interaction point. The magnet configuration, which determines the overall design of the detector, consists of

- A thin superconducting solenoid that surrounds the inner-detector cavity,
- Three large superconducting toroids around the calorimeters, arranged with an eight-fold azimuthal symmetry.

3.3.1 The ATLAS Coordinate System

Each nominal interaction is given a coordinate system [29], where

- The origin is taken to be the interaction point;
- The z-axis is defined by the beam direction

Thus the $x - y$ plane is transverse to the beam direction. The positive x-axis points from the interaction point to the centre of the LHC ring. The positive y-axis points upwards.

The following quantities are used to reconstruct the kinematic Lorentz vectors of the final state particles; some of them are illustrated in Figure 3.3, which also illustrates the ATLAS coordinate system.

- The azimuthal angle ϕ,
- The polar angle θ,
- The rapidity

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

- The pseudorapidity

$$\eta = - \ln \left(\tan \frac{\theta}{2} \right),$$

The pseudorapidity is thus zero on the axis perpendicular to the beam axis, and is infinite along the beam axis. At ATLAS, pseudorapidity is reachable up to 4.9.

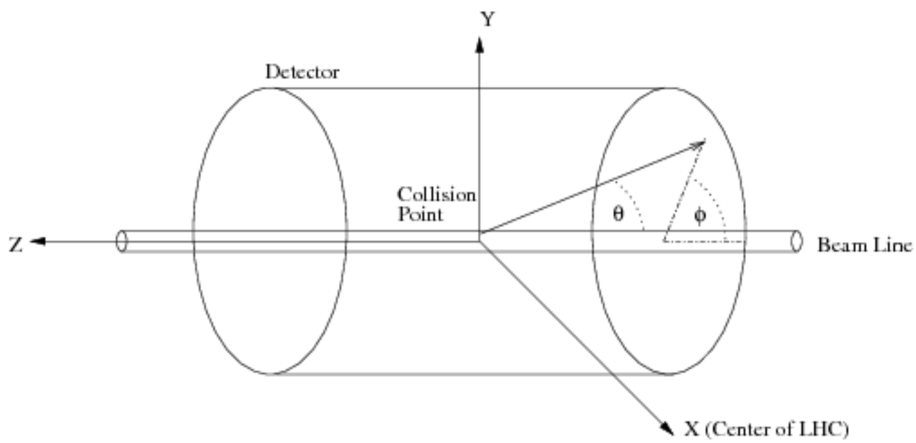

Figure 3.3: The ATLAS Coordinate System []

The transverse plan plays an important role and there the transverse momenta and the transverse energy are defined according to the formulas

$$p_T = p \sin \theta, \qquad E_{\mathrm{T}} = E \sin \theta$$

Distances in the $\eta - \phi$-plane are measured using a quantity called the angular separation

$$\Delta R = (\Delta\eta^2 + \Delta\phi^2)^{1/2} \tag{3.2}$$

3.3.2 The ATLAS Detector Components

3.3.2.1 The Inner Detector

The Inner Detector (ID) [29], also called the tracker, is built to reconstruct trajectories of charged particles from which momenta can be computed. It is capable, at high precision and high resolution, of momentum and primary vertex measurements. Moreover, it is also able to measure impact parameters and secondary vertices, and thus is capable of identifying heavy flavour jets.

Figure 3.4 illustrates the ID. The ID is 2.1 m in diameter and 6.2 m in length.

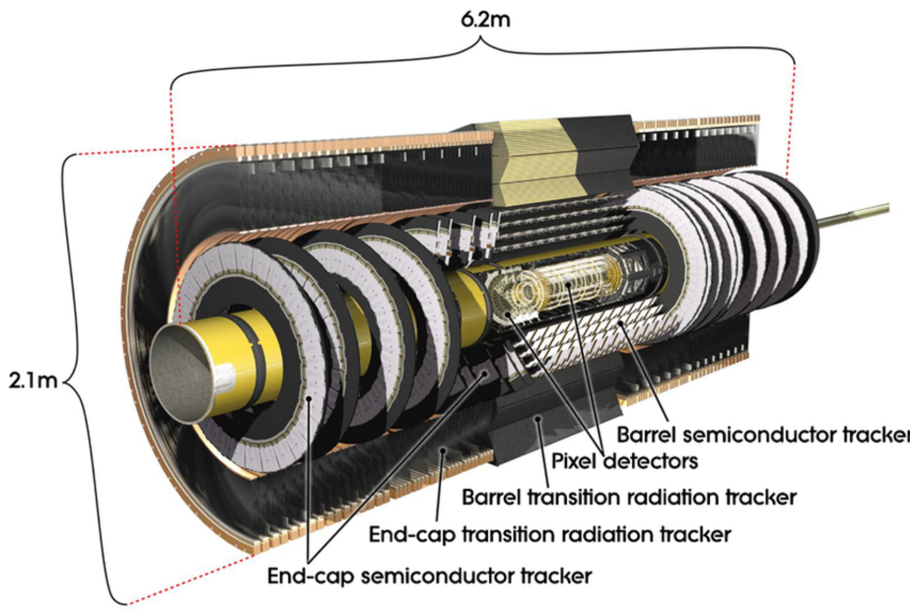

Figure 3.4: The ATLAS Inner Detector

The ID is surrounded by a 2T magnetic field parallel to the beam axis. It is this field that deflects the paths of charged particles. The tracks are bent, and their curvatures are then used to compute momenta of charged particles.

To achieve the desired performance, the ID is built up of semiconductor pixel and strip detectors in the inner part and straw-tube tracking detectors in the outer part. The pixel and the strip detectors are silicon detectors.

The ID is divided into three main components. Thus, the Pixel Detector and the semiconductor tracker (SCT) are to work in combination with the transition radiation tracker (TRT).

The Pixel Detector and the SCT work with each other to provide precision tracking near the interaction point. They cover the region $|\eta| < 2.5$. In terms of arrangement:

- In the barrel region, they lie on concentric cylinders around the beam axis.
- In the end-cap regions, they lie on disks perpendicular to the beam axis.

The Pixel Detector The Pixel Detector surrounds the beam pipe. Made up of silicon pixel detectors, it is able to cope with very high track density that is expected. It is constructed in the form of segmented layers of identical sensors in the $R-\phi$ plane and along the z-axis, where the sensors are of size $500\times400\,\mu\mathrm{m}^2$. Typically, a track is expected to cross three such layers. The achieved accuracies in the barrel are approximately 10 µm in the $R-\phi$ plane and 115 µm in the z direction. The Pixel Detector has approximately 80.4 millions readout channels.

In May 2014, an additional pixel layer was installed between the pixels and the beam spot, at a distance of 3.3 cm from the beam pipe. It is called the insertable B-layer (the IBL [34]) and provides an additional 8 millions pixels. The results are improvements in track reconstruction, vertex measurement, and b-jet identification.

SCT A track is typically expected to cross eight strip layers of the SCT. In the barrel region, the $R-\phi$ coordinates are measured by small-angle stereo strips that lie along the beam direction, and which are distributed one set per layer. In the end-cap regions there are two sets of strips, one running radially and one at a small angle. The accuracies achieved in the barrel are 17 µm in the $R-\phi$ plane and 580 µm in the z direction, while those in the disks are 17 µm in the $R-\phi$ plane and 580 µm in the R direction. The SCT has approximately 6.3 millions readout channels in total.

The Pixel Detector and the SCT function at small radii.

TRT The TRT is only in the $R-\phi$ plane and covers the region $|\eta| < 2.0$. It consists of straw tubes, 4mm in diameter, that typically register 36 hits per track. Each straw tube achieves an accuracy of 130 µm.

In terms of arrangement:

- In the barrel region, the straw tubes are manufactured at length 144 cm and lie parallel to the beam axis.
- In the end-cap regions, they are manufactured at length 37 cm and lie radically, in wheels.

The TRT is installed at a larger radius, and has approximately 351000 readout channels. High precision momentum measurement is achieved with a large number of measurements and longer track length.

The ID system supplements the calorimeters and the muon detector, to be discussed below.

3.3.2.2 The Calorimeters

Calorimeters are built to measure energies of particles. As particles traverse the calorimeters, they interact with the materials in the calorimeters, losing their energies and exhibiting characteristics that enable themselves to be identified.

The ATLAS calorimeters [29, 35] consist of two systems, the Electromagnetic Calorimeter and the Hadronic Calorimeter. Electromagnetic particles develop shower shapes in the former, whereas hadronic particles penetrate the latter and also develop shower shapes.

An outline of the calorimeter system is shown in Figure 3.5. The required resolutions are

- The Electromagnetic Calorimeter: $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$

- The Hadronic Calorimeter: $\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$ (barrel and end-cap regions)

Each resolution is a quadratic combination of two separation terms, one coming from the statistical nature of the shower shape, and one constant term reflecting other uncertainties such as calibration etc.

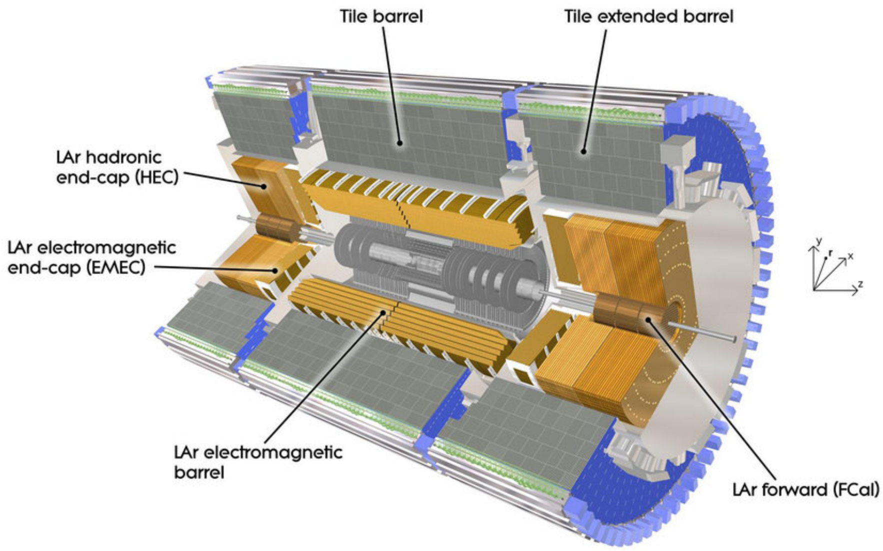

Figure 3.5: The ATLAS Calorimeter System
[31]

The Electromagnetic Calorimeter The Electromagnetic Calorimeter provides electron and photon identification and measurements. These particles lose their energies mainly through bremsstrahlung, pair production, and ionization, where the first two dominate for high-energy particles, leading to the development of shower shapes in the calorimeter.

By design, the Electromagnetic Calorimeter is a lead-LAr (Liquid Argon) detector. The lead, in the form of lead plates, functions as an absorber, and the liquid argon is used in the active layers.

There are:

- The barrel part, covering $|\eta| < 1.475$, which is > 22 radiation lengths in thickness.

- Two end-cap components, covering $1.375 < |\eta| < 3.2$, where each is > 24 radiation lengths in thickness.

The barrel is made up of two identical half-barrels, with a gap of 4 mm in between at $z = 0$. On the other hand, each end-cap is made up of an outer wheel that covers the region $1.375 < |\eta| < 2.5$ and an inner wheel that covers the remaining region.

There is a presampler detector, which is an active LAr layer of 1.1 cm in thickness in the barrel and 0.5 cm in thickness in each end-cap, covering the region $|\eta| < 1.8$.

It is used to correct the energy lost by electrons and photons in the materials they traverse before they reach the calorimeter, such as those in the inner detector.

The Electromagnetic Calorimeter is complemented by the Hadronic Calorimeter, discussed in more detail below. Together, they contain electromagnetic and hadronic showers and limit penetration into the muon system.

The Hadronic Calorimeter The Hadronic Calorimeter surrounds the Electromagnetic Calorimeter. It is built to measure energy of hadronic particles, which also show up in the form of showers in the calorimeter.

In terms of thickness, the Hadronic Calorimeter is approximately 10 interaction lengths in the barrel region as well as in the end-cap regions. This not only provides a good containment but also helps with measurement of missing transverse energy.

The Hadronic Calorimeter is divided into three parts:

- Tile calorimeter: A sampling calorimeter, where steel is used as the absorber and scintillating tiles as the active material. It is placed directly outside the EM calorimeter envelope. It has a barrel that covers the region $|\eta| < 1.0$ and two extended barrels which cover the region $0.8 < |\eta| < 1.7$. The barrel as well as the extend barrels have three layers, designed with sufficient interaction lengths.

- LAr hadronic end-cap calorimeter: The Hadronic End-cap Calorimeter is also a sampling calorimeter, where copper in the form of plates functions as the absorber and LAr gaps as the active medium. It has two independent wheels per end-cap. The wheels are put directly behind the end-cap electromagnetic calorimeters. Those closest to the interaction points use 25 mm parallel copper plates, and the rest uses 50 mm copper plates. The copper plates extend a radius from approximately 0.4 m to approximately 2 m, and in between are gaps of LAr materials.

- LAr forward calorimeter: The Forward Calorimeter is approximately 10 interaction lengths in depth. It has three modules in each end-cap, with one (copper) optimized for electromagnetic measurements and the remaining two (tungsten) hadronic measurements. Each module is a metal matrix of longitudinal channels, where the channels are filled with electrode structure which are in turns made up of concentric rods and tubes parallel to the beam axis, with LAr between them.

3.3.2.3 The Muon Spectrometer

The Muon Spectrometer [29] provides muon identification as well as muon momentum and charge measurement. It surrounds the hadronic calorimeter and defines the overall dimensions of the ATLAS detector.

The Muon Spectrometer is illustrated in Figure 3.6. It is made up of three layers of precision tracking chambers plus trigger chambers.

Deflection of the muon tracks is effected by the built-in superconducting magnets, which is a system of three large air-core toroids. In detail,

- The barrel toroid provides deflection over the range $|\eta| < 1.4$
- The end-cap magnets at both ends of the barrel toroid, over the range $1.6 < |\eta| < 2.7$
- A combination of barrel and end-cap magnets, over the range $1.4 < |\eta| < 1.6$ (also called the transition region)

The magnetic field created by this configuration is approximately orthogonal to the muon trajectories. At the same time, this setting minimizes the effect of multiple scattering on momentum resolution.

Muon tracks are measured in the tracking chambers. They are the Monitored Drift Tubes over most of the $|\eta|$-range, and Cathode Strip Chambers at large $|\eta|$-range. The chambers are arranged in the following manner:

- Around the beam axis, in the form of three cylindrical layers
- In the transition ($1.4 < |\eta| < 1.6$) and end-cap regions, in three planes perpendicular to the beam

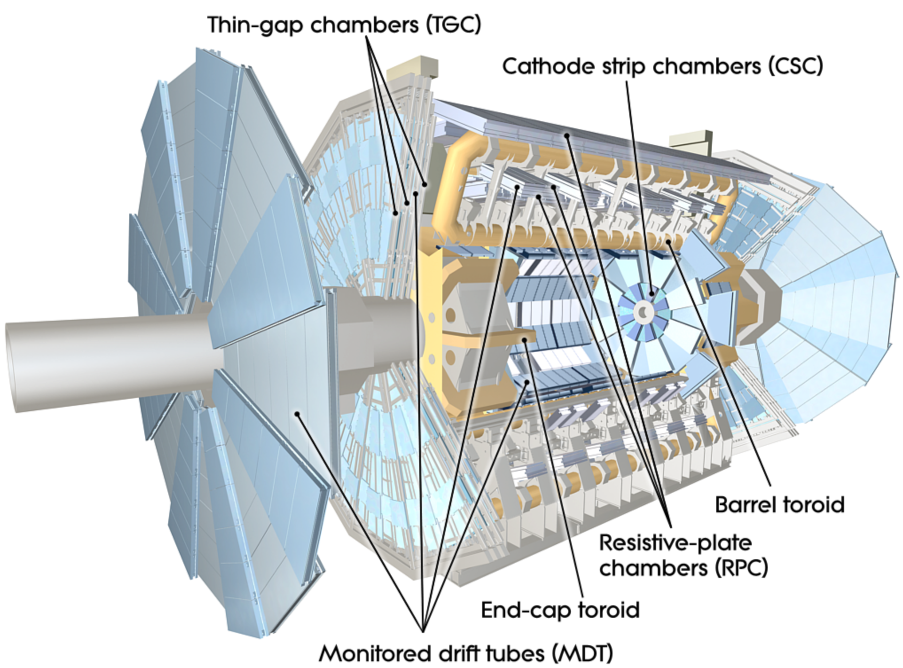

Figure 3.6: The ATLAS Muon Spectrometer

The trigger system works in the range $|\eta| < 2.4$. The trigger chambers, which are Resistive Plate Chambers in the barrel and Thin Gap Chambers in the end-cap regions, provide the following functionalities:

- Bunch-crossing identification
- Well-defined transverse momentum thresholds
- Measurements muon coordinate in the direction orthogonal to that determined by the precision-tracking chambers.

3.3.3 The ATLAS Trigger System

Due to the high luminosity of the LHC, ATLAS, with limited storage capacity and technology, is only able to record potentially interesting physics events. An event is classified as potentially interesting or not by a trigger system that is made up of three distinct levels, L1, L2, and the event filter. L1 is a hardware level trigger, while L2 and the event filter make up the high-level software trigger (HTL) at ATLAS.

The trigger system helps reducing the event rate from approximately 1 GHz at the designed luminosity of $10^{34}\mathrm{cm}^2\mathrm{s}^{-1}$ to approximately 200 Hz.

3.3.3.1 The Hardware L1 Trigger

At L1, a decision is made in less than 2.5 µs. L1 helps reducing the rate to about 75 kHz.

L1 identifies high transverse-momentum muons, electrons, photons, jets, and taus that decay into hadrons. It also searches for events with large missing and total transverse energy. To achieve its purpose, L1 is implemented using custom-made electronics, and uses low-resolution information from the calorimeters and the muon spectrometer.

An event passing L1 is forwarded to the subsequent triggers. In addition, the event is also defined one or more regions of interests — for examples the η and ϕ coordinates where something potentially useful has been seen — which will subsequently be checked by the high level trigger.

3.3.3.2 The L2 and Event Filters

The events that pass the L1 trigger are sent to the L2 trigger. L2 reduces the event rate to approximately 3.5 kHz and takes, on average, about 40 ms to process an event. It looks at the regions of interests defined by L1 where it uses the best possible information available from the calorimeters and the muon spectrometer for its selections.

Those events that pass L2 are sent to the event filter, which further reduces the event rate to about 200 Hz. Here events are processed using offline analysis procedures, and on average each event takes approximately four seconds.