

Particle Physics Research Centre  
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## **Measurements of $H \rightarrow b\bar{b}$ decays and $VH$ production**

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# Chapter 1

## The ATLAS Detector at the Large Hadron Collider

### 1.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [1] is a large circular machine located 100 m underground straddling the Swiss-French border at the European Organisation for Nuclear Research (CERN). The machine is primarily a proton collider <sup>1</sup> and is circular in design so that protons may be accelerated over many revolutions to high energies before being allowed to collide. The diameter of the LHC is 27 km, the tunnel in which the machine resides was originally excavated for the LEP [2] experiment and at the time was the largest civil engineering project in Europe. There are many experiments at CERN all with the goal of improving our understanding of a particular area of physics some of which are marked in figure 1.1. In particular there are seven experiments that record data from the collisions at the LHC: ATLAS [3], CMS [4], LHCb [5], ALICE [6], MoEDAL [7], TOTEM [8] and LHCf [9].

The LHC receives protons that have already been accelerated somewhat by the Super Proton Synchrotron (SPS), another of the accelerators at the CERN accelerator complex shown in figure 1.1. The circular design of both the LHC and SPS allows

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<sup>1</sup>The LHC also collides other charged particles such as ions of lead or xenon.

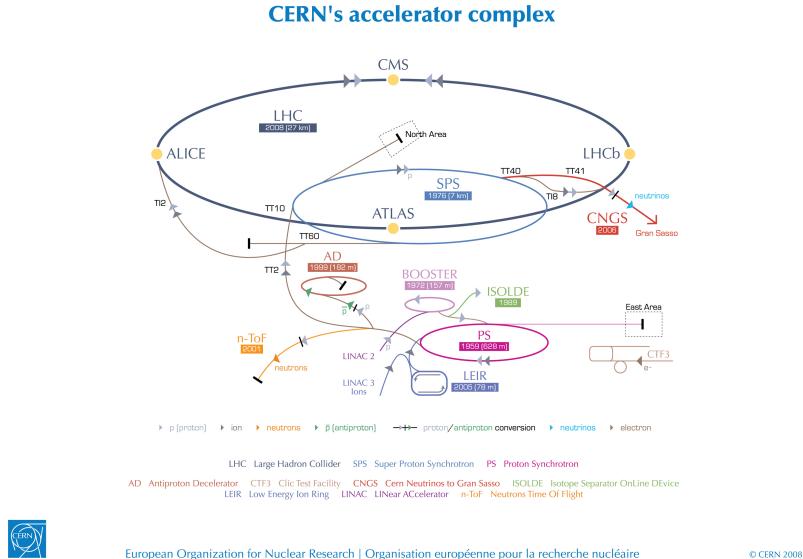


Figure 1.1: The CERN accelerator complex [10].

protons to be accelerated many times around their respective rings until their velocity is fast enough for a high energy collision. The highest energy collisions achieved at the time of writing take place at a centre of mass energy of  $\sqrt{s} = 13$  TeV, although the design energy of the LHC is  $\sqrt{s} = 14$  TeV. Despite having not yet reached its design energy the LHC collides particles with the highest energy of any particle collider in history and is currently alone at the energy frontier of modern physics. At the time of writing the LHC is in its second long shutdown during which maintenance and upgrades to the LHC and the particle detectors located around its ring take place. The LHC has completed two main runs of collisions Run 1 took place between 2009 and 2013, followed by a long shutdown period and then Run 2 between 2015 and 2018. Many analyses from Run 1 have been published including most notably the discovery of the Higgs boson [11, 12]. Some Run 2 analyses have also published results notably LHCb's discovery of charge parity violation in charm decays [13]. Despite these impactful results there are many more results expected from the LHC experiments as data continues to be analysed.

The statistical nature of particle physics analyses means that larger datasets (more recorded collisions) increase the sensitivity of searches and measurements. Constraints on the number of years the LHC is able to run mean that the best way to record more collisions is to collide more particles per second. A quantity

known as the luminosity is often used to describe how much data is available for an analysis, it is written as

$$L = \frac{1}{\sigma} \frac{dN}{dt}, \quad (1.1)$$

where  $\sigma$  is the interaction cross-section, a volume within which particles must pass by one another in order to interact, and  $N$  is the number of events recorded in a period of time  $t$ . For luminosity at the LHC  $N$  can be expressed as

$$N = n_{bp} n_1 n_2 \nu_r, \quad (1.2)$$

where  $n_{bp}$  is the number of colliding bunch pairs,  $n_1$  and  $n_2$  are the number of protons in each beam and  $\nu_r$  is the frequency with which the beams rotate around the LHC's circumference. It is clear that to increase luminosity any one of these parameters can be increased. The LHC has already exceeded its design luminosity providing physicists with more data to analyse than expected and plans are well underway for the upgrade to a High-Luminosity LHC (HL-LHC) [14].

## 1.2 The ATLAS Detector

The ATLAS detector [15] resides at a location on the LHC ring called Point 1, its full name is A Toroidal LHC ApparatuS. A diagram of the detector is shown in figure 1.2. ATLAS is considered to be a general purpose particle detector and has a wide physics program including: Higgs boson physics, top quark physics, searches for Supersymmetry and exotic states, probes of CP violation in b-quarks and light states and heavy ion physics. The work in this report is concerned with the measurement of products from proton-proton collisions. The detector itself is very large in size, spanning a width of 25 m and a length of 44 m and weighs 7000 tonnes which is comparable to the weight of the wrought iron content of the Eiffel tower [16].

Due to the composite nature of the proton, the decay products of collisions are extremely numerous. Additionally when two bunches of protons cross there is the

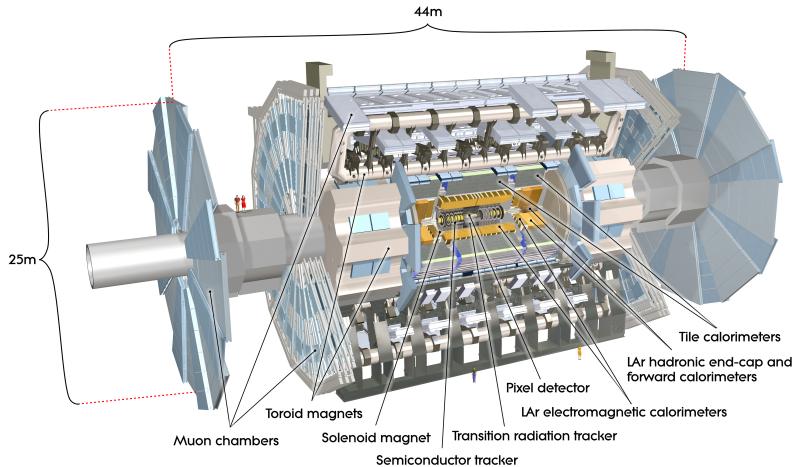


Figure 1.2: Computer generated image of the whole ATLAS detector with the major sub detectors labeled [17].

chance that more than one hard scattering event occurs and softer glancing collisions are also a possibility. The number of hard scattering events in a given bunch crossing is known as the pile-up of the collision and is often denoted with the symbol  $\mu$ . As can be seen by inspecting equation 1.2 increasing the luminosity will often cause a higher pile-up environment in the detector. High pile-up, along with the numerous decay products of each collision necessitate the use of specialised sub-detectors in order to accurately measure the output of collisions. For certain types of decay product there are different dedicated sub-systems in ATLAS with the purpose of measuring properties of particles of that type. At this stage it is sufficient to say that the treatment of electrically charged particles must be different to those that are electrically neutral but this concept will be expanded upon in more detail in the further sections. It is interesting to note that despite the many charges that are associated with the forces of nature discussed in chapter ?? the only one that we can directly measure is electric charge<sup>2</sup>.

The ATLAS sub-systems are located in either the barrel of the detector or one of the end-caps. These two areas have a different geometry and so the design of a sub-system in the barrel will differ from the same sub-system in the end-cap. What follows is a description of the ATLAS sub-systems and their individual components,

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<sup>2</sup>This is true for current human technology, it is not known if future or alien technology can access other charges.

for each component more detail will be given about which properties of which types of particles it is used to measure. These details are based on the ATLAS technical design report volumes [18, 19] unless another citation is present. Before detailing individual components it is important to detail certain properties of the detector relevant to all sub-systems. The coordinate system used to describe the ATLAS detector is known as right-handed. Three orthogonal axes ( $x, y, z$ ) are used to describe the 3D space of the detector. The x-axis points towards the centre of the LHC ring, the y-axis points upwards and the z-axis points along the LHC beam pipe y-axis. The three axes meet at the interaction point which is the nominal position where bunches cross, located in the centre of the detector. Cylindrical coordinates  $(r, \phi)$  are also often used to describe the physical features of the detector and phenomena caused by interactions in the detector that shall be referred to as analysis objects. Their definitions are that  $\phi$  is the azimuthal angle in the x-y plane (transverse) around the beam pipe and  $r$  is the distance from the interaction point. A final quantity used due to its compatibility with description relativistic objects in the detector is pseudo-rapidity  $\eta = -\ln(\tan(\theta/2))$  where  $\theta$  is the zenith angle measured from the z-axis.

The grouping of particles into electrically charged or neutral is largely due to the fact charged particles experience the Lorentz force

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}), \quad (1.3)$$

whereas neutral particles have  $q = 0$ , and so they do not. The magnetic field  $\vec{B}$  has the effect of changing the direction of the particles trajectory only. This is due to the fact that any force  $\vec{F}$  resulting from the cross product of two vectors, in this case the field vector and the velocity  $\vec{v}$ , must act in a perpendicular to the two crossed vectors and thus perpendicular to the direction of the motion (the direction of velocity). Similarly the electric field term  $\vec{E}$  has the effect that the particle is accelerated in the direction (or opposite in the case of a negative particle) of the field lines. The consequence of this is that in a known magnetic field the velocity of a particle can be

calculated by measuring the radius of curvature of its trajectory. It also means that magnetic fields can be used to alter a particles path through a detection medium so that it passes through a greater amount of material than in the situation where its path was straight. In order to exploit these properties of charged particles a large portion of the ATLAS detector is immersed in magnetic fields created by the magnet systems. There are four magnet systems in ATLAS the solenoid, the barrel toroid, and two end-cap toroids. The solenoid surrounds the inner detector whilst the toroid systems surround the muon chambers. Figure 1.3 shows a heat map of the magnetic field strengths within ATLAS, the image is from an article detailing the superconducting magnet system [20]. The magnet systems store a total energy of 1.6 GJ and produce fields of a combined volume of approximately  $12 \times 10^4 \text{ m}^3$ .

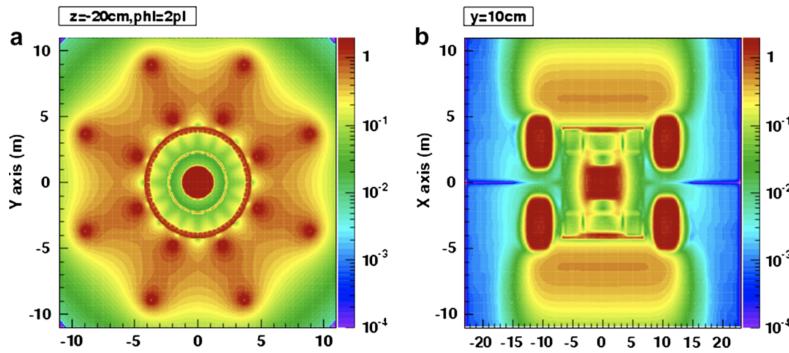


Figure 1.3: ATLAS magnetic field profile, showing a transverse cross-section in the centre of the detector (a), and a longitudinal section (b) [20].

## Inner Detector

The Inner Detector (ID) is comprised of pixel detectors, the semiconductor tracker (SCT) and a transition radiation tracker (TRT) as seen in figure 1.4. It covers a volume corresponding with the total  $\phi$  angle. In relation to  $\eta$  the pixel detectors and SCT cover the range  $|\eta| < 2.5$  and the TRT covers  $|\eta| < 2.0$ . Being the innermost sub-detector of ATLAS the primary goals of the ID are to reconstruct the locations of the origin of interactions (known as the interaction vertex), and to track the propagation of charged particles through the detector. This is achieved by measuring a sequence of hits for each charged particle that propagates through

its material, upon which reconstruction algorithms can be applied known as track finding algorithms. From this sequence of hits interaction vertices can also be reconstructed, the vertex which comes from the highest energy collision in a given event is known as the primary vertex. By using the combined information the vertices and tracks decay products in more outer regions of the detector can be matched with their vertices. Each reconstructed track will have a momentum assigned to it, which is calculated using equation 1.3. The magnetic field that the ID is immersed in is produced by the solenoid magnet system. The system is made of a single layer coil with an inner diameter of 2.46 m and produces 2 T field in the axial direction with respect to the beam-pipe.

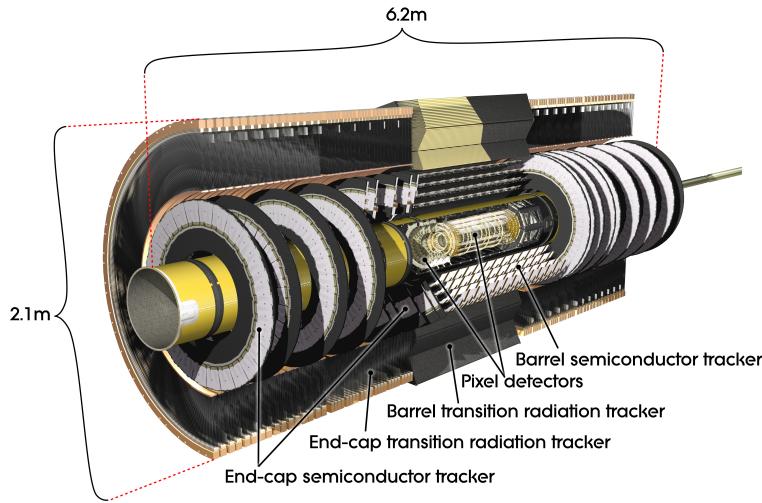


Figure 1.4: Computer generated image of the ATLAS inner detector [21].

## Pixel Detectors

There are four layers of pixel detectors that are the closest components of the ID to the beam-pipe. The design originally had three layers, each  $250\ \mu\text{m}$  thick with  $50\ \mu\text{m}$  by  $250\ \mu\text{m}$  pixels, of oxygen doped n-type silicon crystals. During the first long shutdown a fourth layer, closest to the beam-pipe (which was also replaced for a smaller radius version) was added. This layer is known as the insertable B-layer (IBL) [22], the motivation for its addition was to maintain the existing performance of the ID despite irreversible damage to the original three pixel layers due to heavy

radiation exposure. As well as the inclusion of the IBL performance degradation will be mitigated by increasing the bias voltage across the pixels from 100 V (their starting voltage) to up to 600 V. There are no pixel detectors in the end-caps.

### Semiconductor Tracker

Next closest to the beam-pipe are the semiconductor trackers. Similarly to the pixel detectors the semiconductor trackers are also made of silicon. In contrast the n-type silicon of the pixels, the semiconductor trackers use p-in-n type technology. The semiconductor modules are comprised of two back to back silicon wafers that are offset by a small angle in order to improve coverage. Each wafer has a series of strips of p-in-type material covered in a metalised layer, the strips are separated by a distance of 80  $\mu\text{m}$ . The strips have a bias voltage applied and on the wafers the necessary electronics are mounted for readout as seen in figure 1.5. In order

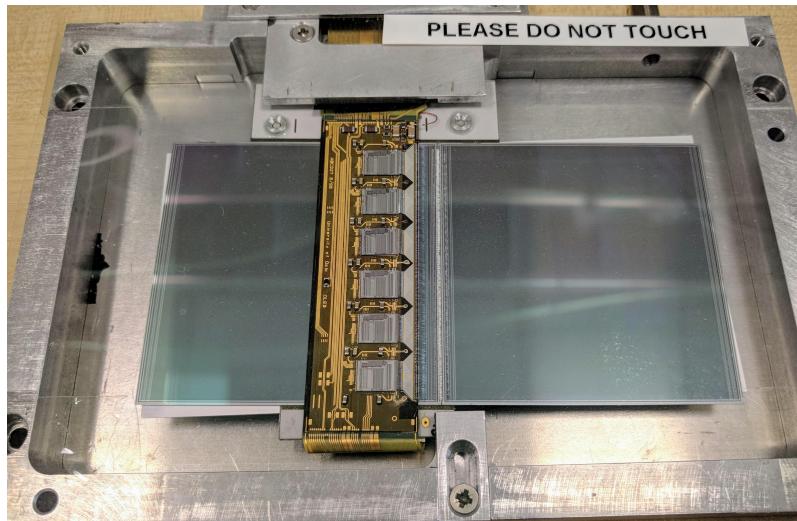


Figure 1.5: An image of an SCT long strip module mounted in a rig for testing at Queen Mary University of London.

to calibrate the response of the strips a  $100 \text{ M}\Omega$  poly-silicon resistor is located at the end of each strip. Figure 1.6 shows an image of the snake-like structure of a poly-silicon resistor from the end of an SCT module. The modules come in two different designs, short strips and long strips with the short strips forming the layer closest to the pixel detectors and the long strips on the outside.

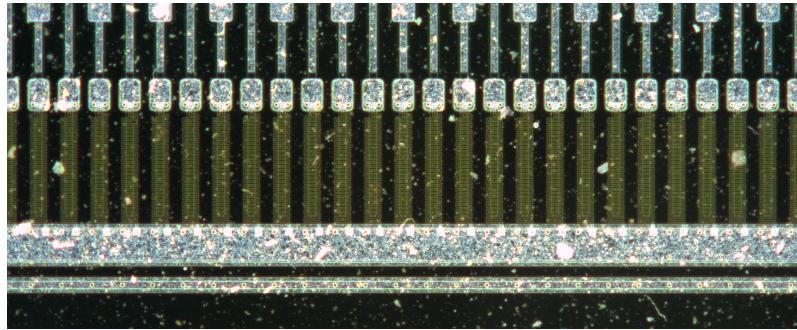


Figure 1.6: A close up image of the end of an SCT sensor in which the snake-like poly-silicon resistors are visible as a yellowish coloured structure at the end of each strip. This image was taken with a high resolution automatic area scanner commissioned by the author [23] in order to take full scans of strip sensors during the production of the ATLAS Inner Detector upgrade known as the Inner Tracker (ITk) [24, 25].

The original operating bias voltage was 150 V but again due to radiation exposure this will raise to up to 350 V over time as necessary. There are four layers of semiconductor trackers in the barrel arranged so that sensors have a tilt with respect to a perfect coaxial cylinders of approximately  $11^\circ$ . This tilt increases the amount of material that particles will travel through and is optimized to the geometry of the detector. Similarly the end-cap modules are arranged in petal like structures, with a number of different geometric designed based on the position within the end-cap.

### Transition Radiation Tracker

The final layer of the ID is the TRT, the primary role of the TRT is to aid electron identification by measurement of transition radiation. The TRT is mostly made up of polyimide drift tubes with a diameter of 4 mm. The drift tubes are filled with a gas mixture whose majority constituent is xenon. These tubes operate with a voltage of -1530 V and are contained within a carbon fibre support structure. The geometric layout of the tubes is optimized for both the barrel and end-caps.

### Calorimeters

The purpose of the calorimeters is two-fold, firstly the measure the energy of particles that pass all the way through the ID, and secondly to act as a barrier to stop charged

particles passing through to the muon spectrometers (apart from muons). There are two calorimeter systems in ATLAS the electromagnetic calorimeter (ECAL) and the hadronic calorimeter (HCAL), they will be explained in the following sections. The calorimeters are not immersed in a significant magnetic field compared to the rest of the ATLAS as seen in the heat map of figure 1.3. This is because measuring the energy of particles and acting as a barrier to them does not require curved trajectories. The geometric layout of the calorimeter systems, as well as the location of specific components can be seen in figure 1.7, in which the ID can also be seen (greyed out). Information from the two calorimeters is used in conjunction for any particles whose decay products propagate through both volumes. Both calorimeters are split up into cells of material that are used to determine the position of decay products in the detector.

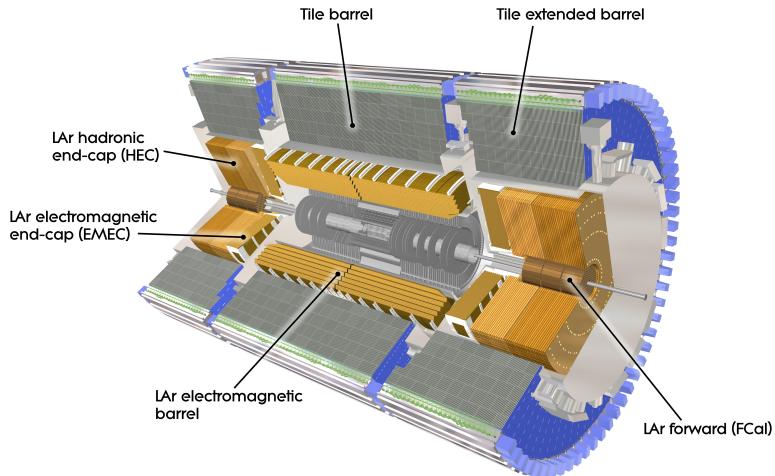


Figure 1.7: Computer Generated image of the ATLAS calorimeter [26].

### Electromagnetic Calorimeter

The ECAL is primarily concerned with measuring the energy and stopping the trajectory of electrons and photons. It has liquid argon (LAr) as it's active material. Particles initiate an electromagnetic shower of decay products in the active material which ionizes it. An applied electric field causes these ions to drift in such a way that the current induced is proportional to the energy deposited by the incident particle.

## Hadronic Calorimeter

The HCAL also has a LAr component which works in a similar way to that of the ECAL but with different optimizations for the HCAL's specialised design. The HCAL is specifically tasked with measuring the energy and stopping the trajectory of hadrons. The HCAL also contains a tile calorimeter which uses scintillation light produced in the tiles as a means to measure the deposited energy of hadrons.

## Muon Spectrometers

Surrounding the calorimeters are the muon spectrometers, which form the most outer layer of the detector. Though muons are charged leptons just like electrons, their specific properties mean that dedicated muon spectrometers are required to detect them. Muons deposit far less energy per distance traveled than other particles meaning that they punch through most materials with ease. As can be seen in figure 1.8 the components of the muon spectrometers are the thin-gap chambers, cathode strip chambers, resistive plate chambers and monitor drift tubes. The barrel and end-cap toroid magnets immerse the muon spectrometers in a magnetic field which at its peak (visible in figure 1.3) has a strength of 4 T. Despite a stronger peaking magnetic field than in the solenoid observed muon tracks are often far less curved than that of their lighter cousins the electrons. This is due to the increased mass of the muon. Muons do leave tracks in the ID and also deposit small amount of energy in the calorimeters. Tracks in the muon spectrometers are matched up to tracks in the ID with the aid of the location of energy deposits in the calorimeters if possible. The full tracking information for muons can be used in algorithms such as overlap removal, which is used to remove muons from jets that they have been erroneously associated with by matching the muon with its ID track.

## Trigger Systems

The trigger systems in ATLAS allows data to be recorded only when an event meets certain criteria. Without triggering there would be no way to decide which events

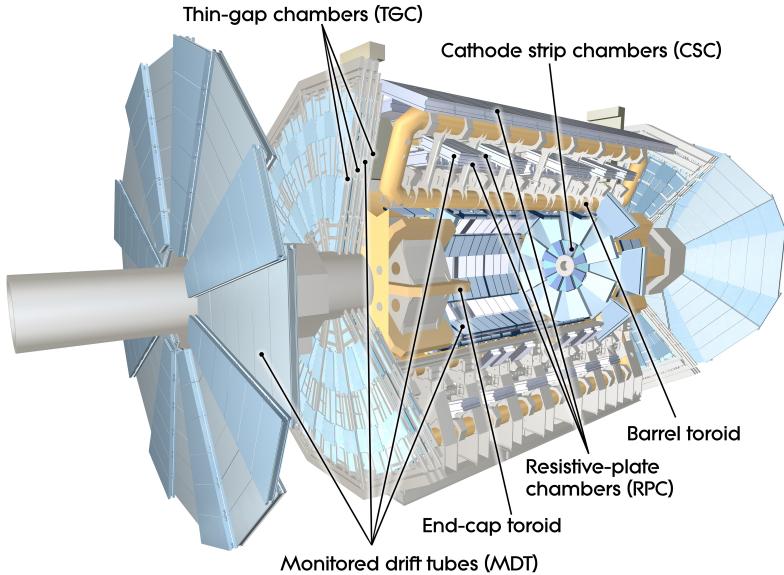


Figure 1.8: Computer generated image of the ATLAS Muons subsystem [27].

to readout and which to ignore. It would be impossible to readout every interaction that occurs in the detector. The reason for this is that the geometric constraints of the detector mean that there is only a small space available for readout wires, as detection medium needs to be prioritized for sensitivity and technology limits the data rate that one can achieve through a cable of fixed area. The trigger system comes in two parts, hardware component referred to as level one (L1) and software component referred to as the high level trigger (HLT). The L1 system is comprised of the L1 calorimeter (L1Calo) trigger which operates by searching for clusters of energy in the calorimeters and the L1 muon (L1Muon) system which coincidences in the muon systems. A third system L1 topological (L1Topo) uses regions of interest built from the L1Calo and L1Muon data which are passed to central trigger processors for selection. The various limitations of the hardware mean that these selections must be passed up to the next level of triggering, the HLT in a time window of  $2.5 \mu\text{s}$ . The HLT takes information from the L1 systems and uses faster versions of an offline style analysis in order to select or reject events for readout. Events must pass fully the trigger of one of the algorithms defined by an extensive trigger menu. More information about the triggers used in the  $VH(bb)$  analysis will be given in a later chapter.

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