A Thesis Title

Author Name

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I, Author Name, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the work.

Abstract

My research is about stuff.

It begins with a study of some stuff, and then some other stuff and things.

There is a 300-word limit on your abstract.

Acknowledgements

Acknowledge all the things!

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Chapter 1

Introductory Material

Some stuff about things.[?] Some more things.

Inline citation:

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Chapter 2

The ATLAS Detector

2.1 ATLAS and the LHC

High-energy particle colliders have a rich history of discovery of new particles, including the discovery of the Z and W bosons using the Super Proton Synchotron at CERN in 1983 [1, 2, 3, 4] and the discovery of the top-quark at Tevatron in 1995 [5, 6]. The Large Hadron Collider (LHC) is the highest-energy collider ever built, hosted by the *Conseil Européen pour la Recherche Nucléaire (CERN)*. Lying in a tunnel 100m beneath the Swiss/French border near Geneva, the LHC is a 27km circumference ring of superconducting magnets and accelerating structures, which in 2015 and 2016, accelerated bunches protons to a maximum energy of 6.5 TeV. These protons are collided in four different locations on the LHC ring, creating 13 TeV proton-proton collisions, the highest energy particle collisions every achieved by a particle accelerator. Around each collision point a different detector is constructed to observe these collisions, and at one of these collision points is the ATLAS detector.

2.2 ATLAS Detector Description

The ATLAS (**A** **T**oroidal **L**arge Hadron Collider **A**pparatu**S**) detector design, construction and performance has been described in detail previously [7, 8, 9], so what follows in this chapter is a general description of the detector with a focus on the needs of the analysis that is being presented. The ATLAS detector is effectively a large closed-cylindrical detector, made up of four key components which sit in concentric rings around the interaction point, where the proton bunches collide. These parts are the Inner Detector, Calorimeters, Muon Spectrometer and the Magnets; each of which are described in further detail below. An outline of the detector is shown in Figure 2.1

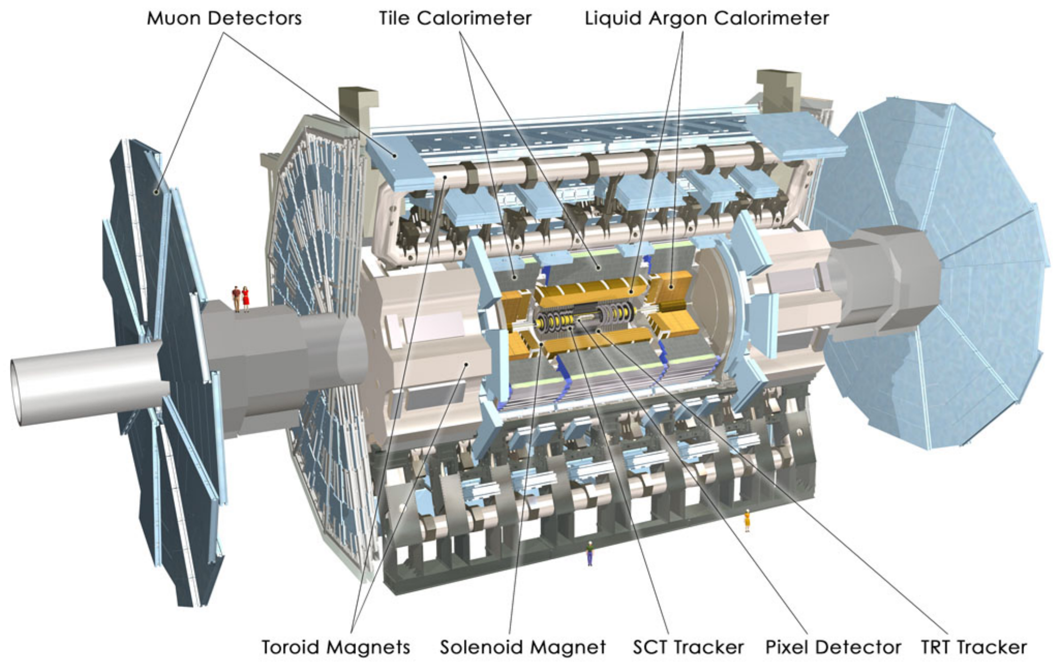

Figure 2.1: A cut-away schematic of the ATLAS detector.

2.2.1 ATLAS Co-ordinate System

Firstly, to describe the detail of the ATLAS detector there must be a description of the co-ordinate system that is used. ATLAS uses a right-handed coordinate system, in which the origin lies at the interaction point. The x-axis points to the centre of the LHC ring parallel to the surface of the earth, the y-axis points towards the surface of the earth and the z-axis runs along the beam-pipe, pointing anti-clockwise along the LHC. The azimuthal angle, ϕ, is defined right-handedly around the z-axis starting at the x-axis.

The polar angle, θ, is defined as the angle measured from the z-axis, such that along the z-axis corresponds to $\theta = 0$ and anti-aligned with the z-axis corresponds to $\theta = \pi$. However, this is not typically used, instead the ATLAS co-ordinate system uses pseudo-rapidity, η, which is defined as a function of θ,

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right] \tag{2.1}$$

Hence, $\eta = 0$ corresponds to a particle travelling perpendicular to the beam-pipe, where a positive value of η corresponds to a particle travelling with a tilt towards the z-axis. The quantity is called pseudo-rapidity as in the massless limit ($\lim_{E\to|\vec{p}|}$) it can be shown that η converges to rapidity, y, where rapidity is defined as,

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \tag{2.2}$$

A key property of rapidity is that the differences in rapidity are invariant against Lorentz boosts along the z-axis. Hence, due to the relation of η with both θ and y and the above mentioned property of y mean that η is the final variable used in the ATLAS co-ordinate system. One final quantity commonly used with in ATLAS is the variable ΔR, which is defined as

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \tag{2.3}$$

ΔR represents an angular separation between two vectors within the ATLAS co-ordinate system.

Now that we have discussed the ATLAS co-ordinate system, we can provide a description of the components of the ATLAS detector.

2.2.2 Inner Detector

The Inner Detector (ID), the innermost sub-detector on ATLAS, measures the trajectory, momentum and charge of charged particles passing through the detector. The ID is constructed form many concentric layers of detector, and as the particle passes through the detector each of the layers provides a position measurement, known as a hit. Then using the hits from the many layers, the trajectory of each of the charged particles can be determined; the measured trajectory is known as a track. The ID is immersed in a 2 T magnetic field which bends the particle's trajectories; from the sign and magnitude of the track's curvature the charge and momentum of the particle can be inferred. The ID is made of three main component parts; the pixel detector, the Semi-Conductor Tracker (SCT) and the Transition Radiation Tracker (TRT), as visualised in Figure 2.2. The ID is made up of both barrel, which lies perpendicular to the beam-pipe and covers low absolute values of η, and the end-caps, which lie perpendicular to beam-pipe and cover large values of absolute η: here the description focuses on the barrel as this covers the η range considered by the analysis.

The innermost component of the ID is the silicon pixel detector; in the barrel this de-

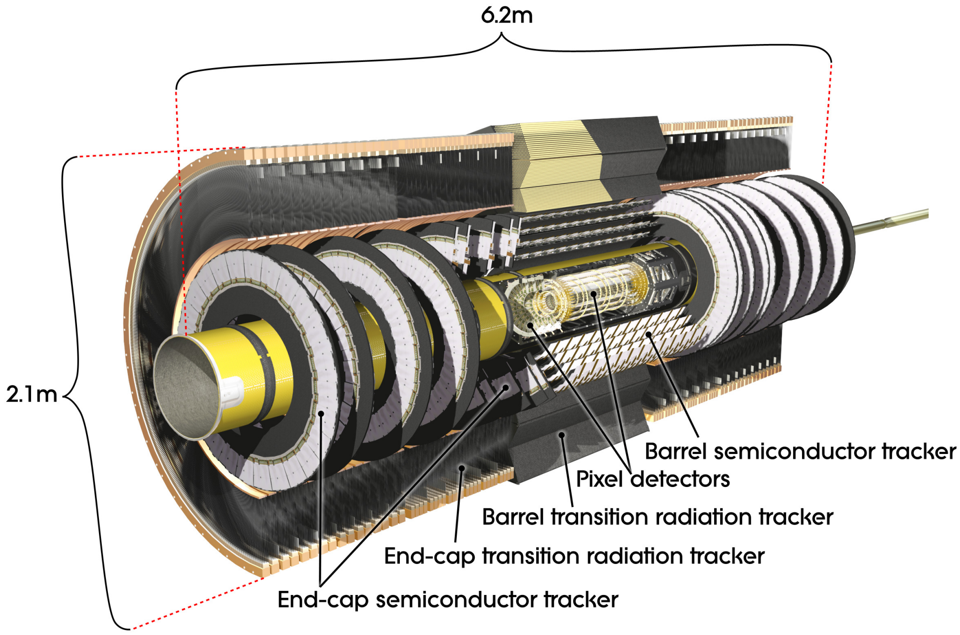

Figure 2.2: A cut-away schematic of the ATLAS Inner Detector (ID).

tector consists of 4 high-granularity layers of silicon based pixel modules surrounding the beam pipe, covering a range of $-2.5 < \eta < 2.5$ and a radial distance of 33 mm to 122.5 mm. The high-granularity of the pixel layers, allows for high precision measurements, with an intrinsic resolution of approximately resolution of $\sim 10\,\mu$m in $R-\phi$ plane and $\sim 115\,\mu$m in the z-direction [10, 11]. These precision tracking measurements close to the beam-pipe are vital for identification of vertices, which in turn are used for the identification of long-lived B and C hadrons.

Moving radial outwards the next component of the ID is the Semi-Conductor Tracker; which, in the barrel, comprises of 4 cylindrical layers of silicon microstrips covering a range of $-2.5 < \eta < 2.5$ and a radial distance of 299 mm to 514 mm. The SCT has an intrinsic resolution of $\sim$17 μm in $R-\phi$ plane and $\sim$580 μm in the z-direction.

The outermost component of the ID is the Transition Radiation Tracker (TRT), which, in the barrel, comprises of many 4mm radius tubes filled with xenon. As a charged particle passes through the gas, it will ionise allowing a measurement of its position using drift-time. Each tube provides a measurement in the $R-\phi$ plane with an intrinsic resolution of 130 μm and the TRT will typically provide 36 hits per track. In addition to a position measurement, due to the choice of the material between the tubes, a particle passing through the detector will radiate photons at an intensity inversely correlated to the mass of that particle, providing additional information for particle identification.

2.2.3 Calorimeters

The ATLAS calorimeter is the next sub-detector after the ID, located on the outside of the magnet solenoid. The ATLAS calorimeter is designed to provide an energy measurement of the traversing particles, which is essential for reconstructing the mass from two decay products of a mediator particle. The calorimeter at ATLAS is made up of two different systems that are built in concentric rings; the inner-most is the Electromagnetic Calorimeter system (ECAL), which is used to measure electromagnetic objects such as photons and electrons. Outside of that is the Hadronic Calorimeter system (HCAL), designed to provide an energy measurement of hadronic material. The HCAL is built from the Tile and Hadronic Endcap calorimeters. Both the ECAL and HCAL have barrel and end-cap components to make energy measurements at a large range of η values. Figure 2.3 shows a cut-away of the ATLAS calorimeter.

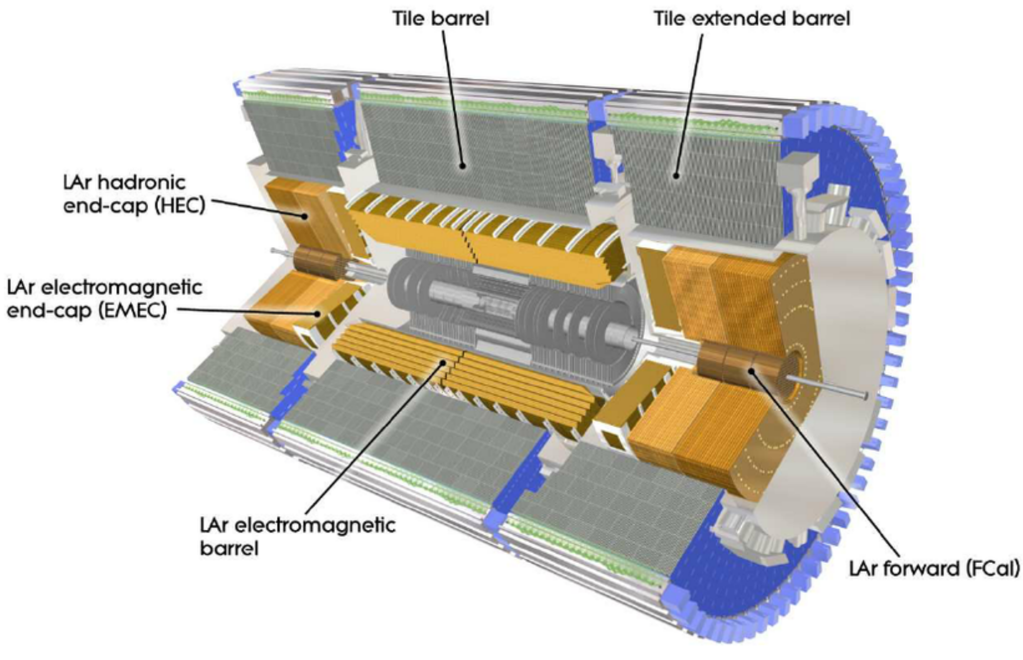

Figure 2.3: A cut-away schematic of the ATLAS calorimeter system.

Below I provide a more detailed description of the calorimeter components; however, the principle behind each detector is common so is described first. The calorimeters at ATLAS are sampling calorimeters, which means they consist of alternating layers of absorber and active material. The role of the of the absorber layer is to force the particle, whose energy we want to measure, to emit secondary particles. These secondary particles will again emit further particles and so on meaning a “particle cascade” is formed. The role of the active material layer is to measure the energy of the resulting many particles from the cascade. The ATLAS detector is built such that the initial particle will cascade within the volume of the calorimeter system and then, from a measurement of the energy of all the cascade particles, the energy of the initial particle can be inferred.

2.2.3.1 Electromagnetic Calorimeter (ECAL)

For the electromagnetic interaction, at high-energy ($\sim\geq 1$ GeV) the particle cascade process is mainly caused by two processes; bremsstrahlung, ($e^{+/-} \rightarrow e^{+/-} + \gamma$) and pair production ($\gamma \rightarrow e^{+} + e^{-}$). The electromagnetic calorimeter at ATLAS is known as the Liquid Argon (LAr) calorimeter. The absorber material used in the LAr calorimeter is lead, due to its large density of atoms which increases the rate of the cascade processes. The active material is liquid argon; when a cascade particle passes through the liquid argon it causes ionisation, and the released electrons are captured using an electric field. The number of released electrons is proportional to the energy of the cascade particle, meaning that the energy of the cascade particle can be measured.

As discussed above the LAr is split up into two sections; the barrel section covers a region of $|\eta| < 1.475$ and two end-cap components cover $1.375 < |\eta| < 3.2$. The depth of an electromagnetic calorimeter is often expressed in terms of the radiation length, X_0, which is the distance that an electron’s energy reduces by a factor of e^{-1} through bremsstrahlung, or 7/9 of the mean free path for a photon to pair produce electrons. The LAr calorimeter has a depth of $> 22\ X_0$ in the barrel and $> 24\ X_0$ in the end-caps, meaning that almost all of the particle shower from a high-energy photon or an electron can be contained within electromagnetic calorimeter.

2.2.3.2 Hadronic Calorimeter (HCAL)

If a particle can also interact through strong interactions, such as the components of a hadronic jet, then the particle cascade is a more complicated process. In addition to the electromagnetic processes, there is a contribution to the cascade from strong interaction processes such as ionisation **isn't this an EM process**, nuclear spallation and neutron generation [12]. During these strong interaction processes many π_0 mesons are made, which can decay to a pair of photons and thus form electromagnetic cascade as described above.

For hadronic interactions, the size of detector is measured by the interaction length, λ, defined as the distance required to reduce the number of relativistic hadrons by e^{-1}. Due to the nature of hadronic interactions, the interaction length is larger by an order of magnitude than the radiation length **Do I need more justification of this sentence**. This means that by the end of the LAr calorimeter there is 2.3 λ of active material **check logic with AK** in the barrel, so the full hadronic shower cannot be captured by the LAr calorimeter alone. For a full measurement of the hadronic energy, the Hadronic Calorimeter system (HCAL) is required.

The Tile Calorimeter is constructed from absorber layers of steel and active material layers of scintillating tiles, and has a depth of 7.4 λ, meaning the majority of the hadronic shower can be captured by either the LAr calorimeter or the Tile calorimeter. The Tile Calorimeter is split up into the barrel and the extended barrel components; the barrel covers the region $|\eta| < 1.0$ and the extended barrel covers the region $0.8 < |\eta| < 1.7$.

To cover the more forward regions there are two more calorimeter detectors. The Hadronic Endcap Calorimeter (HEC) is housed in two large wheels at either end of the ATLAS detector and covers a region of $1.5 < \eta < 3.2$. The HEC is a sampling calorimeter built using copper as the absorber layers and liquid argon as the active material. In addition the Forward Calorimeter (FCAL) covers the region $3.1 < \eta < 4.9$, which is outside the range used in this analysis.

2.2.4 Muon Spectrometer

The only standard model particle visible to ATLAS which can pass through the calorimeter is the muon; hence to identify and obtain the momentum of muons an additional detector, the Muon Spectrometer (MS), is used. The MS is a detector which surrounds the the hadronic calorimeter, measuring the momentum of muons by observing the curvature of the trajectories of muons in magnetic fields, analogous to what is done in the ID. In the barrel region ($|\eta| < 1.4$) the large barrel toroid provides the magnetic field, in the end-cap region $1.6 < |\eta| < 2.7$ the two smaller end-cap magnets provide the magnetic field. and finally in the transition region, ($1.4 < |\eta| < 1.6$) both sets of magnets contribute to the magnetic field. Muon chambers are the detector tasked with measuring the muon trajectories. In the barrel region, muon chambers are arranged in three concentric cylindrical layers of chambers formed around the beam-pipe, whilst in the transition and end-cap regions there are three layers of chambers either side of the barrel lying in disks perpendicular to the beam-pipe. In the region $|\eta| < 2.0$, the muon chambers are made from Monitored Drift Tubes (MDTs), whilst at large pseudo-rapidities ($2.0 < |\eta| < 2.7$), Cathode Strip Chambers (CSCs) are used.

2.2.5 Magnets

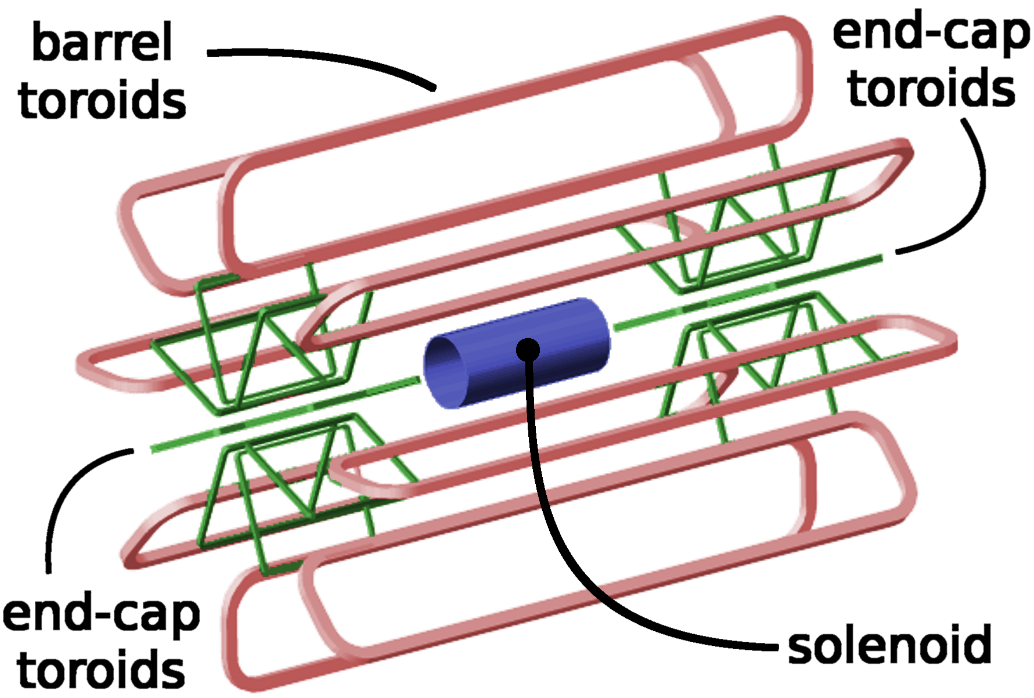

Figure 2.4: The layout of the ATLAS magnets.

In ATLAS magnetic fields are important for obtaining the momentum and charge of particles from their observed trajectories in the ID and Muon Spectrometer. ATLAS is made up of four large superconducting magnets; the inner solenoid which surrounds the inner detector and provides a 2 T magnetic field within the ID, the barrel toroid magnet which provides the a magnetic field of up to 2.5 T in the central regions of the muon spectrometer, and the two end-cap toroid magnets which produce a magnetic field of up to 3.5 T in the forward regions of the MS. Figure 2.4 shows the layout of the magnets in ATLAS [13].

2.3 Data Acquisition and Trigger

Chapter 3

General Conclusions

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Appendix A

An Appendix About Stuff

(stuff)

Appendix B

Another Appendix About Things

(things)

Appendix C

Colophon

This is a description of the tools you used to make your thesis. It helps people make future documents, reminds you, and looks good.

(example) This document was set in the Times Roman typeface using LaTeX and BibTeX, composed with a text editor.

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