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Measurements of $H \rightarrow b\bar{b}$ decays and VH production

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Abstract

Proton-proton collision data recorded by the ATLAS detector at CERN’s Large Hadron Collider, in which protons collide at a centre of mass energy of 13 TeV, is used study the process called VH(bb). The VH(bb) resolved analysis aims to measure events in which a Higgs boson is produced in association with a vector boson and also in which that Higgs boson decays to a pair of b-quarks. The resolved version of the analysis is concerned with events in which jets initiated by the b-quarks can be resolved from one another in the detector. Both the VH production mechanism and the Hbb decay channel were discovered in 2018 at ATLAS and CMS. Subsequent measurements of the VH(bb) process aim to further our understanding of the Higgs by providing more precise measurements of the VH signal strength as well as using methods to obtain the WH and ZH signal strengths. The Standard Model can be tested by comparing these values with its predictions. Many improvements have been made to the analysis since the previous publication including a method that uses machine learning to compare multi-dimensional distributions in order to evaluate modelling uncertainties. The analysis strategy will be outlined highlighting a number of the aforementioned improvements along the way. The expected results of the upcoming publication using the full run 2 dataset (140 fb^{-1} recorded between 2012 - 2018) will be shown.

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Chapter 1

Introduction

In 2012 the Higgs boson was discovered by the ATLAS and CMS collaborations at the Large Hadron Collider [1, 2]. It was said to form the last piece of the Standard Model of Particle Physics, a framework that describes three of the four fundamental forces of nature, described in more detail in Chapter 2. Despite apparent completeness after the Higgs discovery, it is known that the theory does not describe gravity, the fourth of the known fundamental forces of nature. The theory also has other shortcomings, it cannot explain the presence of dark matter [3–13] or a number of other observed phenomena [14–18]. So far the model has stood up to all experimental tests [19, 20] concerning its own predictions but there are still parameters of the model that have not been measured. Given the theory’s understood shortcomings, it is hoped that continued scrutiny of the models predictions will yield unexpected results, perhaps hinting at a new way forwards in terms of a theory that describes everything or simply exposing further gaps in our knowledge of the universe. For this reason it is more important than ever to study in detail the most recently discovered piece of the model, the Higgs boson.

This work focuses on studying a specific production mechanism and decay mode of the Higgs boson, specifically a vector boson associated Higgs boson decaying to two bottom quarks, denoted $VH(bb)$. This decay mode is of importance as it is currently the only decay mode of the Higgs decaying to quarks that has been observed [21]. A summary of the full spectrum of production mechanisms and decay modes of the

Higgs will be given in Chapter 2.

The study of this decay mode was carried out with the ATLAS detector, and made possible by the hard work of all members of the ATLAS collaboration. In Chapter 3 the detector is described in full.

Chapter 2

Physics Theory

The following chapter outlines the physics theory that informs and guides the experimental process of searching for new particles or making measurements at a particle collider. Not only are the physics theories described here useful in that context but they also provide an almost complete picture of the universe at certain scales. This chapter was written with the aid of notes taken at the annual STFC High Energy Physics Summer School, and with the aid of several books [22, 23], in which a more detailed description of the theories can be found.

The Standard Model of particle physics is a theoretical framework that describes all elementary particles and three of the fundamental forces of nature. Notably the only force that is not described by the theory is gravity. Particles described by the model are listed in table 2.1 with a white gap separating the matter particles (fermions) from the force carrying particles (bosons). Fermions, which make up solid matter obey Fermi-Dirac statistics [24, 25] whereas bosons obey Bose-Einstein statistics [26]. The Higgs boson is special in that as far as we know it does not carry a force in the conventional sense, instead it is responsible for giving fundamental particles mass, discussed in more detail in section 2.5. In the table of particles quarks (blue) and leptons (red) are ordered in columns by increasing mass, apart from the neutrinos, which are massless in the theory.

As mentioned the model describes forces as being mediated by certain particles, the photon (γ) mediates the electromagnetic force, particles experiencing electro-

<i>u</i> <i>up quark</i>	<i>c</i> <i>charm quark</i>	<i>t</i> <i>top quark</i>	<i>g</i> <i>gluon</i>	<i>H</i>
<i>d</i> <i>down quark</i>	<i>s</i> <i>strange quark</i>	<i>b</i> <i>bottom quark</i>	γ <i>photon</i>	<i>Higgs</i>
e^- <i>electron</i>	μ^- <i>muon</i>	τ^- <i>tau</i>	Z^0 <i>Z boson</i>	
ν_e <i>electron neutrino</i>	ν_μ <i>muon neutrino</i>	ν_τ <i>tau neutrino</i>	W^\pm <i>W boson</i>	

Table 2.1: The particles of the standard model with fermions displayed on the left and bosons on the right. Quarks are in blue, leptons in red, vector bosons in yellow and scalar bosons in green.

magnetic repulsion or attraction are described as exchanging photons. The strength and direction of the force experienced is proportional to the electromagnetic charge of particles involved. The Standard Model is a theory of quantum fields in which the strength of interactions between fields, or particles which are described as excitations in the fields, is parametrised by something known as a coupling constant. It is natural to assume that the strength of the interaction between photons and charged particles is related to the electromagnetic charge of the particles involved. Indeed this is the case consider the Coulomb force between two protons,

$$F = \frac{e^2}{4\pi\epsilon_0 r}, \quad (2.1)$$

where e is the elementary charge, ϵ_0 is the electric constant and r is the distance between the two protons in question and also the energy of a photon given by

$$E = \frac{hc}{\lambda}, \quad (2.2)$$

where h is Planck's constant, c is the speed of light and λ is the wavelength of the photon. The value of the ratio of these two quantities

$$\alpha = \frac{e^2\lambda}{4\pi\epsilon_0 rhc}, \quad (2.3)$$

known as the fine structure constant, is the coupling constant that describes the strength of the interactions between the photon field and fields of particles with

electromagnetic charge. So as is now clear this coupling constant does indeed depend on the electromagnetic charge of the objects involved and so it is not really constant.

As well as the electromagnetic force the Standard Model describes the strong nuclear force and the weak nuclear force, shortened to just the strong and weak forces respectively. Like the electromagnetic force they too are mediated by the exchange of particles, the gluons (g) carry the strong force and the W^\pm and Z^0 bosons carry the weak force.

The charge associated with the strong force is known as colour which can take values that are mapped onto colours in the visible spectrum (red, green, blue) for ease of description. For each of these colours an anti-colour is also allowed (anti-red, anti-green, anti-blue). Unlike with the electromagnetic charge, particles with colour charge are not found freely in nature. Instead we find particles known as hadrons which are bound states of quarks and anti-quarks (e.g. the proton). The phenomenon of coloured particles being bound in such a manner is known as colour confinement, and the bound states are described by the quantum numbers isospin (I) and hypercharge (Y_c). It is commonly assumed that all free particles in nature are colour singlets e.g. for a hadron the state could be written as

$$\frac{(r\bar{r} + b\bar{b} + g\bar{g})}{\sqrt{3}}, \quad (2.4)$$

where r , b and g represent red, blue and green charges respectively. This phenomenon is known as quark confinement. Gluons carry colour and anti-colour indicating that there should be nine possible quantum mechanical states for the gluon given the available number of colour/anti-colour combinations, however when one considers that the strong force is exclusively short range, and therefore that there should be no free gluons (disallowing colour singlet gluons) the number of possible states is reduced to eight. The state of a particle, as far as its description with respect to the strong force is concerned, is given by a vector which lives in a vector space, in which elements of the Lie group $SU(3)_C$ act as unitary operators, where the C denotes that the group is associated with the colour charge. The $SU(3)$ group

is the group of 3×3 unitary matrices whose determinant is one. These correspond to the eight generators of $SU(3)$ where in general for a group $SU(N)$ the number of generators is given by $N^2 - 1$.

Describing the weak force requires introducing further quantum numbers weak isospin T and weak hypercharge Y_W . The state of a particle with regards to the weak force is given by a vector which lives in a vector space in which elements of $SU(2)_L \times U(1)_{Y_W}$ act as unitary operators where the L denotes that only particles in left-handed chiral states interact with the weak force¹. Left-handed fermions are represented as doublets in the theory with weak isospin $T = 1/2$ whilst right-handed fermions are singlets with weak isospin $T = 0$.

Along the way we have described particle states with respect to particular forces as vectors living in some vector space where the action of the element of a group has been as a unitary operator. If we are to describe a particle state taking into account the full model, the group whose elements should act as unitary operators on the particle state (the gauge group) is $SU(3)_C \times SU(2)_L \times U(1)_{Y_W}$. For each of the groups in the direct product we have established a (gauge) symmetry and therefore due to Noether's theorem [27] there should be an associated conserved quantity. The conserved quantities in this case are the electric charge, the weak hypercharge and isospin and the colour charge.

2.1 Historical Aside

This section provides some historical context surrounding the Dirac equation which will later be used as the starting point in the discussion of quantum electrodynamics, which is the sector of the Standard Model that describes electromagnetic interactions.

In 1905 Albert Einstein first proposed the idea of special relativity [28]. The aim of the idea was to unify the then inconsistent theories of Maxwell's electromagnetism

¹More specifically only left-handed chiral particles participate in weak charged current interactions.

and Newtonian mechanics. The result of Einstein's work was a theory of motion which agreed with the predictions of Newtonian mechanics at velocities much smaller than the speed of light but whose predictions were accurate also at much higher velocities (for which Newtonian predictions fail). Arguably, the most far reaching consequence of special relativity is that it demands that any equation of motion must be invariant under Lorentz transformations, at least in terms of the formulation of new theories is concerned. Many physical phenomena predicted by special relativity could be considered of higher consequence in general, for example the phenomena of length contraction, time dilation, energy-mass equivalence and the universal speed limit (equal to the speed of light in vacuum), all of which are extensively scrutinised experimentally [29–35]. It is the Lorentz transformation however that should be kept in mind for the following discussion, the transformation may be written as

$$\begin{aligned} t' &= \gamma(t - vx/c^2) \\ x' &= \gamma(x - vt) \\ \text{with } \gamma &= \frac{1}{\sqrt{1 - v^2/c^2}}, \end{aligned} \tag{2.5}$$

in a single dimension of space x and one of time t where v represents the velocity of the system described by the primed coordinates relative to the unprimed coordinates and c is the speed of light in vacuum.

Twenty years after Einstein introduced the ideas of special relativity Erwin Schrödinger postulated new ideas regarding the motion of quantum mechanical systems [36]. Though he knew his new equation was not invariant under Lorentz transformations, and therefore incomplete, Schrödinger's formulation of quantum mechanics changed the way physicists thought about the universe for ever. His famous equation

$$i\hbar \frac{\partial}{\partial t} \Psi(\vec{x}, t) = \left(\frac{-\hbar^2}{2m} \nabla^2 + V(\vec{x}, t) \right) \Psi(\vec{x}, t), \tag{2.6}$$

describes the states of particles as wave-functions Ψ which can only be interpreted in a probabilistic manner and contains Planck's constant the quantum of action. This

work had many consequences including the quantisation of the values of measured observables (meaning they can only take discrete values) and the descriptions of particles as waves.

It was the aim of Paul Dirac to make the Schrödinger equation Lorentz invariant and thus provide a more complete description of quantum systems. Along the way he came to the realisation that in order for his equation to satisfy his needs the wavefunction had to be replaced with a four component spinor (ψ) and the introduction of matrices known now as the Dirac matrices (labeled γ^μ with $\mu = 0, 1, 2, 4$) was required. Though not the form he originally wrote down Dirac's Lagrangian density takes the form

$$\mathcal{L}_{Dirac} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi, \quad (2.7)$$

where the repeated up and down indices are implicitly summed over (∂_μ represents the partial derivative taken with respect to a spatial coordinate $\mu = 1, 2, 3$ or time $\mu = 0$).

2.2 Quantum Electrodynamics

In order to take Dirac's Lagrangian (eq. 2.7) and turn it into something that appropriately describes quantum electrodynamics (QED), we should consider a $U(1)$ gauge transformation of the Dirac spinor and it's adjoint

$$\begin{aligned} \psi \rightarrow \psi' &= e^{i\alpha(x)}\psi, \\ \bar{\psi} \rightarrow \bar{\psi}' &= e^{-i\alpha(x)}\bar{\psi}, \end{aligned} \quad (2.8)$$

with $\bar{\psi} \equiv \psi^\dagger \gamma^0$ and where $\alpha(x)$ is a local phase. Under this transformation the Lagrangian transforms as

$$\mathcal{L}_{Dirac} \rightarrow \mathcal{L}'_{Dirac} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi - \bar{\psi}\gamma^\mu \alpha(x)\psi \quad (2.9)$$

which is not equivalent to the original due to the factor resulting from the derivative of the transformed spinor. Instead let us change the derivative to the gauge covariant derivative

$$D_\mu = \partial_\mu + ieA_\mu \quad (2.10)$$

where we interpret A_μ as the photon field, with coupling constant e , parametrising the interaction strength. The field is also referred to as the electromagnetic gauge field since it arrives during the process of making the Lagrangian invariant under the $U(1)$ group, the gauge group of electromagnetism. Note that here what we have labeled e is nothing more than the fine structure constant previously denoted α in eq. 2.3. The transformation of the new field under the action of the gauge is defined as

$$A_\mu \rightarrow A'_\mu \equiv A_\mu - \frac{1}{e}\partial_\mu\alpha(x). \quad (2.11)$$

This means that the action of the gauge covariant derivative on the spinor transforms as

$$D_\mu\psi \rightarrow D'_\mu\psi' = e^{i\alpha(x)}D_\mu\psi \quad (2.12)$$

which means that the new Lagrangian

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi \quad (2.13)$$

is invariant under the action of the gauge as desired. What remains in order to write a description of QED is to write down a kinetic term for the photon field. An appropriately gauge and Lorentz invariant term is

$$-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (2.14)$$

where the electromagnetic tensor is defined as

$$F_{\mu\nu} \equiv \partial_\mu A_\nu - \partial_\nu A_\mu. \quad (2.15)$$

Putting everything together we can define the Lagrangian for QED as

$$\mathcal{L}_{QED} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \quad (2.16)$$

2.3 Quantum Chromodynamics

Quantum Chromodynamics (QCD) is the theory of the strong force. It's mathematical formulation is similar to that of QED. Except the gauge group for QCD is $SU(3)_C$ where the C denotes that the force is associated with colour charge. As previously discussed the eight generators of the group are associated with the eight gluons of the Standard Model. The generators are present in the form of the transformation of a fermion field under an element of $SU(3)$

$$\psi \rightarrow \psi' = \exp\left(i\alpha_a(x) \cdot \frac{\lambda_a}{2}\right)\psi, \quad (2.17)$$

where the λ_a are the Gell-Mann matrices, generators of $SU(3)$. A key difference between the strong force and the other forces described by the Standard Model is that it increases in strength with range. This property leads to a phenomena known as quark confinement which has been discussed previously. Quark confinement is the reason for many of the complications that arise when trying to detect certain particles in a particle detector such as ATLAS. Specifically, quarks that are produced in collisions undergo a process called hadronisation whereby they transition from their coloured states to colour singlets. Excess energy present in this process results in the creation of lots of different states, some which decay to leptons, with the overall process producing a conical shower of particles known as a jet.

2.4 Electroweak theory

The Glashow-Salam-Weinberg model of electroweak interactions [37–39] describes the weak force and electromagnetism as a quantum field theory, which is gauge

invariant under transformations that are elements of $SU(2)_L \times U(1)_{Y_W}$. As previously mentioned the L and Y_W subscripts denote that the gauge groups in the direct product that are associated with left-handed chiral particles and weak hypercharge respectively. The association with weak hypercharge distinguishes this $U(1)$ group with the $U(1)$ group from QED. The transformation of the fermion fields under $SU(2)$ is given by

$$\psi \rightarrow \psi' = \exp\left(i\vec{\alpha}(x) \cdot \frac{\vec{\sigma}}{2}\right)\psi, \quad (2.18)$$

where $\vec{\sigma}$ is a vector of the Pauli matrices σ_i with $i = 1, 2, 3$, a familiar representation of $SU(2)$ generators. Constructing a gauge covariant derivative for the full transformation under $SU(2) \times U(1)$ requires the addition of new fields analogous to the photon field from QED, the new derivative takes the form

$$D_\mu = \partial_\mu - i\frac{g_1}{2}Y_W B_\mu - i\frac{g_2}{2}\sigma_i W_\mu^i, \quad (2.19)$$

where coupling constants g_1 and g_2 parametrise the strength of interactions with each field. The index i runs over the three Pauli matrices and three new fields W_μ^i with $i = 1, 2, 3$ which are associated with the $SU(2)$ gauge. The B_μ field is associated with the $U(1)_{Y_W}$ gauge and is obtained in the same way as the photon field in QED but is given a new symbol as it is *not* the photon field.

In fact none of the fields added here are the physical fields that we have access to in nature associated with the electromagnetic force or the weak currents. In order to obtain the physical fields for the weak charged current one can simply take the linear superposition

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2). \quad (2.20)$$

In order to recover the photon field and reveal the field for the weak neutral current the idea of weak mixing must be introduced. Weak mixing was introduced to theory after the discovery of parity violation [40]. Parity is equivalent to chirality for massless particles, however for particles with mass a Lorentz boost can always appear to flip the chirality of the particles state whereas parity is a fundamental property

of a particle. A fermion field with left or right handed chirality can be obtained by multiplication with one of two corresponding projection operators defined as

$$\begin{aligned} P_L &= (1 - \gamma^5)^2 / 2, \\ P_R &= (1 + \gamma^5)^2 / 2, \end{aligned} \quad (2.21)$$

with $\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$, where γ^μ are the Dirac matrices, like so

$$\begin{aligned} \psi_L &= P_L \psi, \\ \psi_R &= P_R \psi. \end{aligned} \quad (2.22)$$

It is known that the weak neutral current and indeed the electromagnetic force both interact with particles of left and right handed chirality. Spontaneous symmetry breaking, theorised to have occurred due to an electroweak phase transition in the early universe, has the effect of rotating the plane defined by the B_μ and W_μ^3 fields into the physical fields we see in nature today. The mixing of the fields due to this rotation takes the form

$$\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix}, \quad (2.23)$$

where θ_W the Weinberg angle parametrises the amount of mixing. This picture shows that unification of QED and a description of the weak force has been achieved. Although it at first seems like the $U(1)_{EM}$ gauge group is not present in $SU(2)_L \times U(1)_{Y_W}$ gauge group of electroweak theory it has been shown that the QED gauge symmetry is recovered by spontaneous symmetry breaking. Also the Y_W subscript in the gauge group represents weak hypercharge which is related to electric charge Q by the following relationship

$$Y_W = 2(Q - T^3), \quad (2.24)$$

where T^3 is the third component of isospin, the component that is conserved.

The particles associated with the weak neutral and charged currents are observed to have masses in nature [41–44] therefore one would naively like to write mass terms of the form

$$\mathcal{L}_{mass} \propto M_B^2 B^\mu B_\mu \quad (2.25)$$

$$+ M_W^2 W_a^\mu W_\mu^a. \quad (2.26)$$

The above mass terms are however not gauge invariant therefore another solution is required, one which will be discussed in the next section.

2.5 The Brout-Englert-Higgs Mechanism

The Brout-Englert-Higgs mechanism was made complete almost simultaneously by R. Brout and F. Englert [45], P. Higgs [46] and, G. Guralnik, C. R. Hagen and T. Kibble [47]. The underlying mechanism was proposed prior to this work by P. Anderson [48], though this initial theory was not relativistic invariant. It was initially proposed as a means to give the vector bosons mass terms that were gauge invariant. The theory predicts a complex scalar field (the Higgs field) that undergoes spontaneous symmetry breaking. Interactions with this field are predicted to be mediated by a massive spin-1 scalar particle that is now known to be the Higgs boson. This particle also gives mass to the fermions via a different mechanism. In general spontaneous symmetry breaking is a process by which a symmetry breaks once conditions meet some threshold. An example of this is a hot sphere of ferromagnetic material whose spins are isotropically oriented. As the sphere cools the ferromagnetic property of the material will align the spins. In the hot scenario the sphere had symmetry in all spatial directions, by this it is meant that the changes to the sphere's orientation were indistinguishable. Once the spins have aligned however this is no longer the case, the fact that the spins point in a specific direction means that direction is special and so some of the symmetry was spontaneously broken. It can be noted though that a preserved symmetry still exists as rotations about the

axis defined by the direction of the spins would leave the sphere invariant. In the Standard Model the symmetry that breaks is that of the complex scalar Higgs field. Consider a Lagrangian involving the field ϕ of the form

$$\mathcal{L} = T - V(\phi) = \partial_\mu \phi^\dagger \partial^\mu \phi - \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad (2.27)$$

$$\text{with } \phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2). \quad (2.28)$$

Invariance under global phase transformations of the form $\phi \rightarrow e^{i\theta}\phi$ depends on the parameters of the potential μ and λ . Figure 2.1 shows two sketches of the potential for the scenarios where $\mu^2 > 0$, $\lambda < 0$ (left) and $\mu^2 < 0$, $\lambda < 0$ (right). To suggest

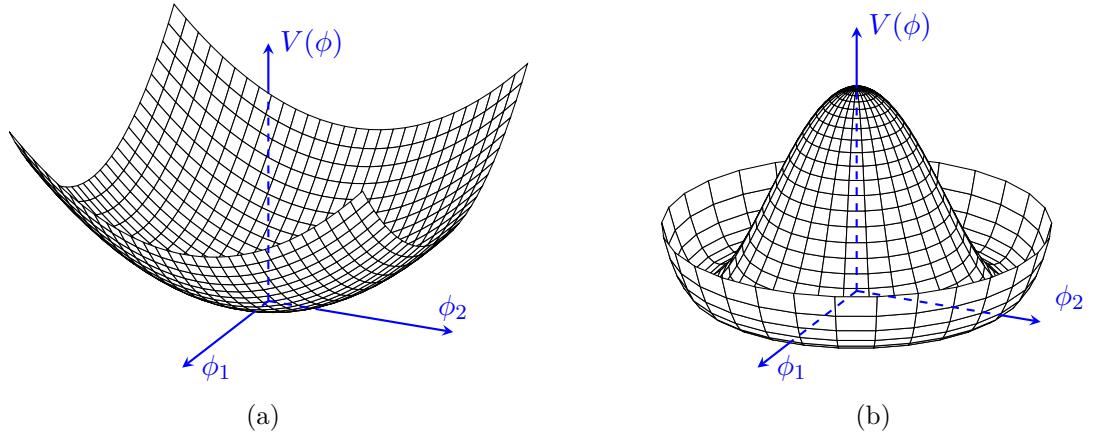


Figure 2.1: The Higgs potential in its fully and broken symmetric forms.

that in our universe this symmetry is spontaneously broken is to suggest that the values of these parameters evolved over time from the full to the broken state. This ends up leading to masses for the vector bosons that are dependent on μ^2 .

2.6 Higgs bosons at the LHC

Higgs bosons are produced at the LHC in a number of different ways, the four most common of which are shown in figure 2.2. The prevalence of these processes with respect to the centre of mass energy of the proton-proton collision is shown in figure 2.3 (a). It can be seen the gluon-gluon fusion (fig 2.2 a) is by far the dominate contributor occurring over an order of magnitude more than the next

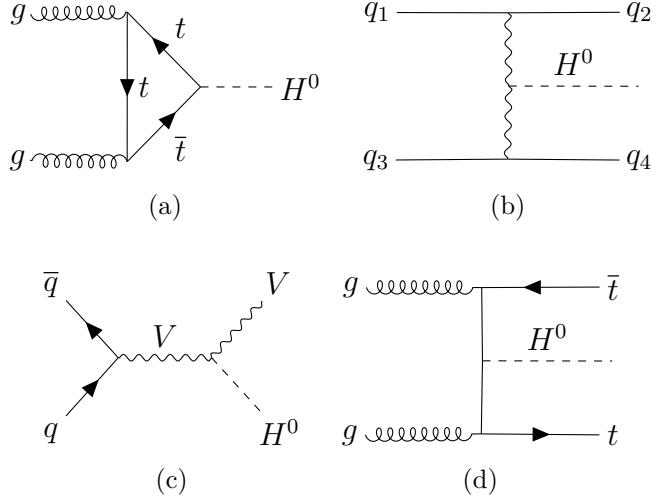


Figure 2.2: The four most common Higgs boson production methods from proton-proton collisions at the LHC.

highest process which is quark associated production (fig 2.2 b). The next highest production channel with respect to cross section is vector boson associated (fig 2.2 c) which will be the focus of the rest of this report. Finally top quark associated production (fig 2.2 d) has the smallest cross section of these processes. The Higgs boson is predicted by the Standard Model to decay in a number of different ways depending on its mass, a free parameter of the model. In figure 2.3 (b) the branching ratios of the Higgs can be seen, plotted with respect to Higgs mass. The decay that will be focused on for the rest of this report is $H \rightarrow b\bar{b}$. Given that the focus here

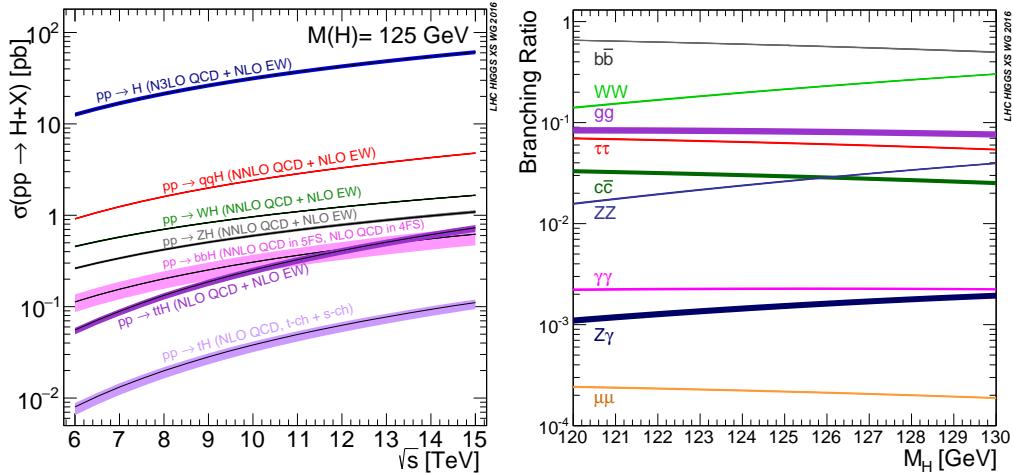


Figure 2.3: Higgs production cross-sections (left), and branching ratios (right) for a range of centre of mass energies and Higgs boson masses respectively [49].

is on vector boson associated production of a Higgs boson it is also important to

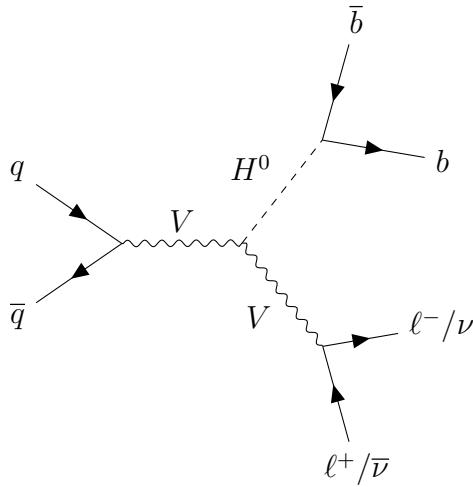


Figure 2.4: A diagram showing a Higgs boson (decaying to a pair of b quarks) produced in association with a vector boson (decaying to 0, 1, or 2 charged leptons denoted $\ell^{+/-}$).

consider the decay of the vector boson. Three possible scenarios are represented in figure 2.4, namely the situations where the vector boson decays to 1, 2 or 3 charged leptons and the appropriate number of neutrinos. It is in fact these leptonic decay modes that motivate the reason for studying this production mechanism as opposed to one of the more common ones. The issue with looking at the other production modes is that very large QCD generated backgrounds are present due to initial state radiation. Whilst these backgrounds are also present when looking at the vector associated channel they can be partially suppressed by triggering on a lepton.

Chapter 3

The ATLAS Detector at the Large Hadron Collider

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [50] 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 ¹ 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 [51] 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. 3.1. In particular there are seven experiments that record data from the collisions at the LHC: ATLAS [52], CMS [53], LHCb [54], ALICE [55], MoEDAL [56], TOTEM [57] and LHCf [58].

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 3.1. The circular design of both the LHC and SPS allows

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

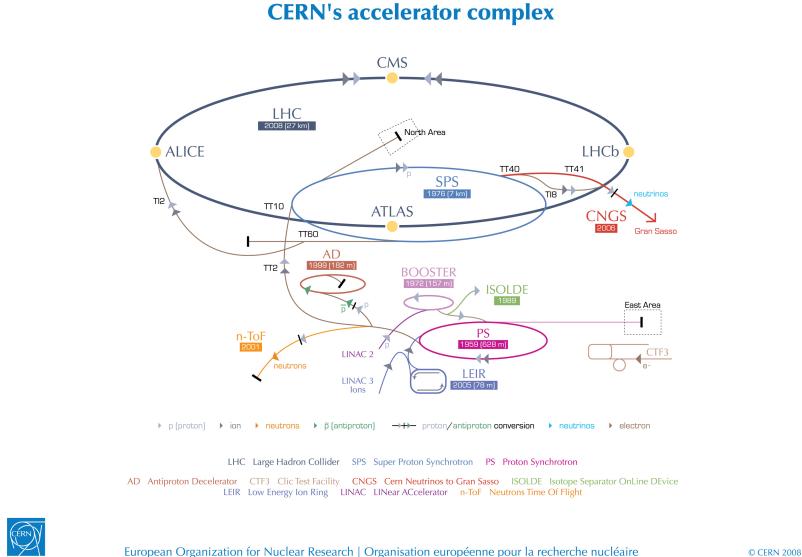


Figure 3.1: The CERN accelerator complex [59].

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 [1, 2]. Some Run 2 analyses have also published results notably LHCb's discovery of charge parity violation in charm decays [60]. 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

$$L = \frac{1}{\sigma} \frac{dN}{dt}, \quad (3.1)$$

where σ 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

$$N = n_{bp} n_1 n_2 \nu_r, \quad (3.2)$$

where n_{bp} is the number of colliding bunch pairs, n_1 and n_2 are the number of protons in each beam and ν_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) [61].

3.2 The ATLAS Detector

The ATLAS detector [62] 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 3.2. 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 [63].

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

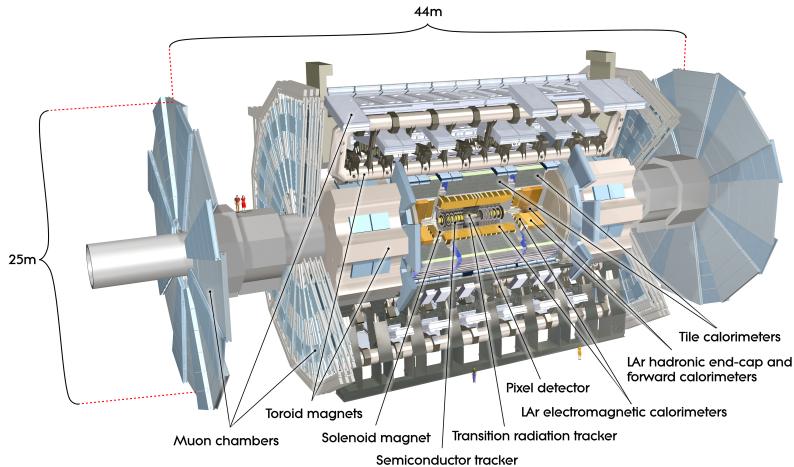


Figure 3.2: Computer generated image of the whole ATLAS detector with the major sub detectors labeled [64].

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 μ . As can be seen by inspecting equation 3.2 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 2 the only one that we can directly measure is electric charge².

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,

²This 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 [65, 66] 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, ϕ) 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 ϕ 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 θ 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

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}), \quad (3.3)$$

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 3.3 shows a heat map of the magnetic field strengths within ATLAS, the image is from an article detailing the superconducting magnet system [67]. The magnet systems store a total energy of 1.6 GJ and produce fields of a combined volume of approximately $12 \times 10^4 \text{ m}^3$.

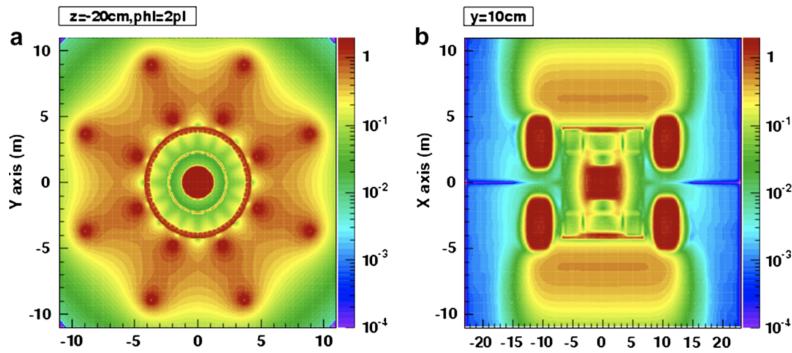


Figure 3.3: ATLAS magnetic field profile, showing a transverse cross-section in the centre of the detector (a), and a longitudinal section (b) [67].

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 3.4. It covers a volume corresponding with the total ϕ angle. In relation to η 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 3.3. 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.

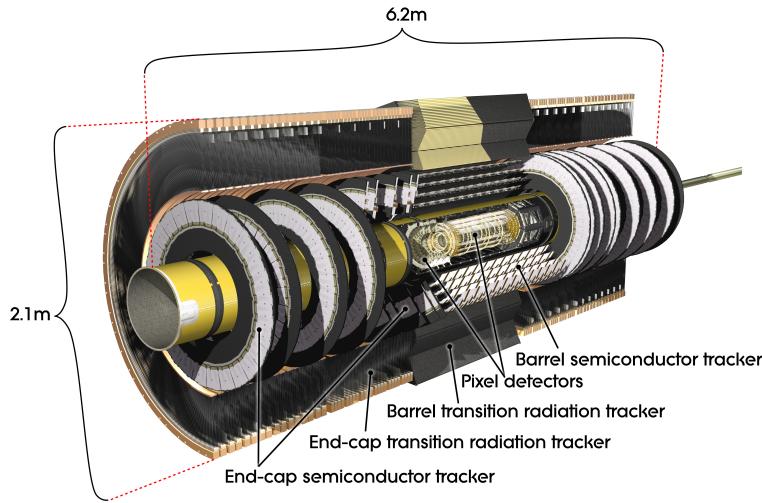


Figure 3.4: Computer generated image of the ATLAS inner detector [68].

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 $250\text{ }\mu\text{m}$ thick with $50\text{ }\mu\text{m}$ by $250\text{ }\mu\text{m}$ 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) [69], 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 μm . The strips have a bias voltage applied and on the wafers the necessary electronics are mounted for readout as seen in figure 3.5. In order

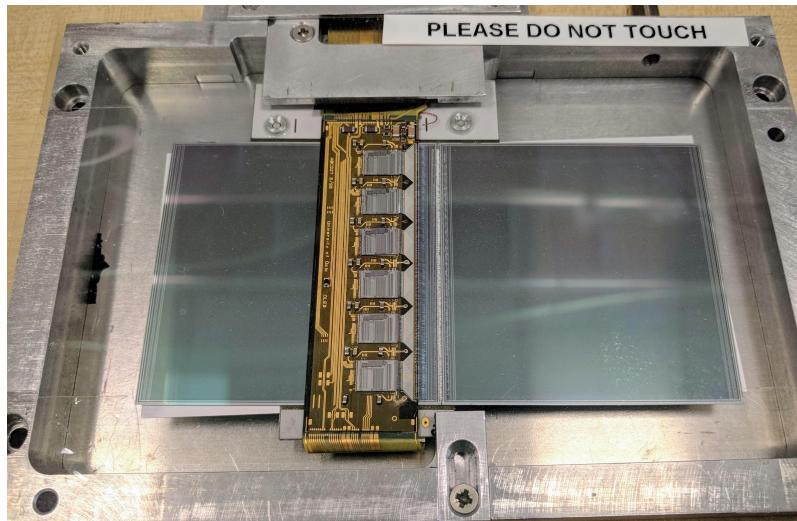


Figure 3.5: An image of an SCT long strip module mounted in a rig for testing at Queen Mary University of London.

to calibrate the response of the strips a $100 \text{ M}\Omega$ poly-silicon resistor is located at the end of each strip. Figure 3.6 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.

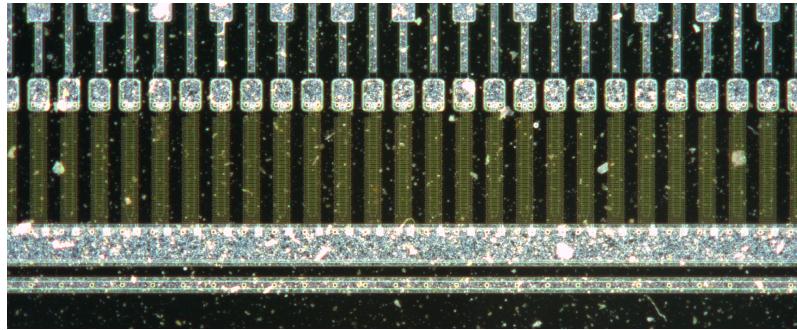


Figure 3.6: A close up image of the end of an SCT sensor in which the snake-like poly-silicon resistors are visible as a yellowish coloured structure at the end of each strip. This image was taken with a high resolution automatic area scanner commissioned by the author [70] in order to take full scans of strip sensors during the production of the ATLAS Inner Detector upgrade known as the Inner Tracker (ITk) [71, 72].

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 °. 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 3.3. 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 3.7, 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.

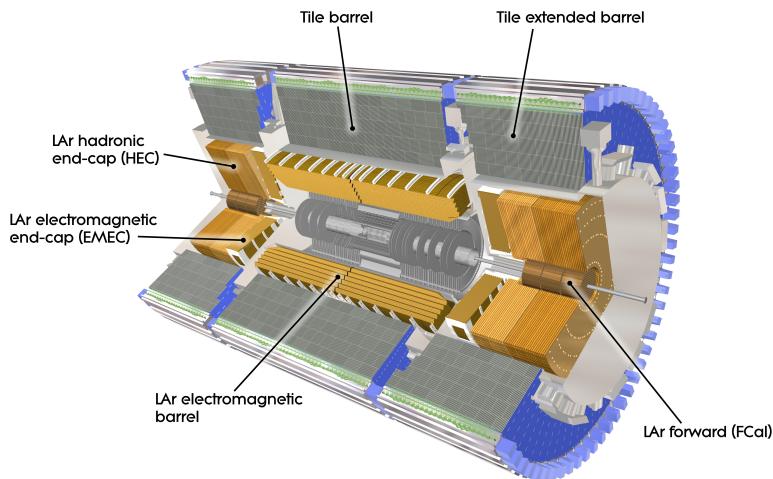


Figure 3.7: Computer Generated image of the ATLAS calorimeter [73].

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 3.8 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 3.3) 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

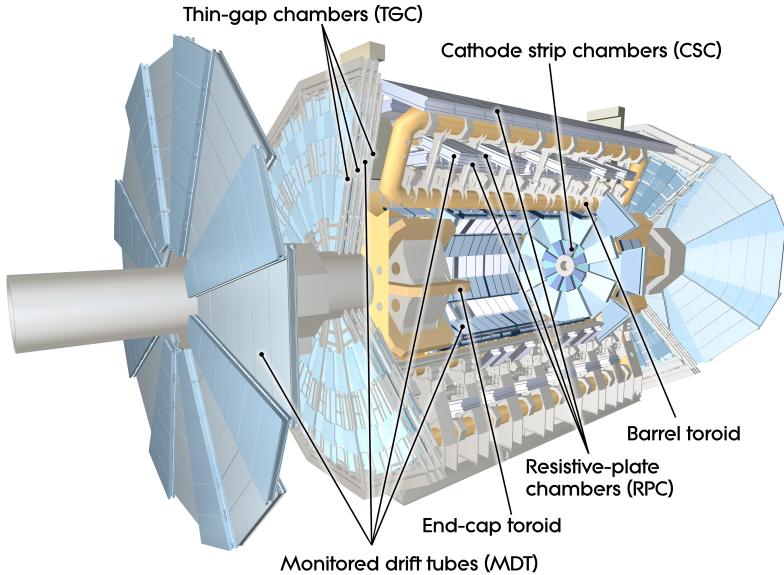


Figure 3.8: Computer generated image of the ATLAS Muons subsystem [74].

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.

Chapter 4

Machine Learning Theory

4.1 Boosted Decision Trees

4.2 Neural Networks

4.3 Parametrised Neural Networks

Chapter 5

Analysis Methodology

5.1 Channel Definitions and Selections

Top $e\mu$ control region

$\Delta R(b, b)$ Control Regions

5.2 Profile Likelihood Fits

5.3 Fit Models

5.4 VH(b,b) multi-variate discriminant fit

5.5 Di-jet mass fit

5.6 VZ Cross-check fit

Chapter 6

Background Modelling

6.1 Novel Modelling Techniques

Multi-dimensional re-weighting

Inferring missing information with parametrised neural networks

6.2 2 lepton channel Z + jets modelling

Extrapolation to 0 lepton channel

6.3 Modelling of other backgrounds

Chapter 7

Results

**7.1 VH(b,b) multi-variate discriminant fit
results**

7.2 Di-jet mass fit results

7.3 VZ Cross-check results

Chapter 8

Conclusion

8.1 Future studies

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