UNIVERSITY OF CALIFORNIA

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AN INCLUSIVE SEARCH FOR THE DECAY OF A BOOSTED HIGGS BOSON IN THE $H \to b\bar{b}$ CHANNEL WITH THE ATLAS DETECTOR

A dissertation submitted in partial satisfaction of the

requirements for the degree of

DOCTOR OF PHILOSOPHY

in

PARTICLE PHYSICS

by

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Acknowledgments

Chapter 1

Introduction

Every dissertation should have an introduction. You might not realize it, but the introduction should introduce the concepts, backgrouand, and goals of the dissertation.

Part I

Theoretical Motivations and the Standard Model

Chapter 2

The Standard Model and Beyond

The Standard Model (SM) of Particle Physics is humanities best "guess" at the force laws that describe the observed behavior of all particles in our universe. Its formulation is a collection of Quantum Field Theories (QFT) that describe the following interactions of elementary matter in Nature: the electromagnetic force, the weak nuclear force and the strong nuclear force. Gravity is noticeably absent as currently there is no viable quantum theory for observed gravitational effects. The Glashow-Salam-Weinberg (GSW) theory of Quantum Electrodynamics (QED) describes the electromagnetic and weak forces, while Quantum Chromodyanmics (QCD) describes the strong force. These theories form the following symmetry group of the Standard Model.

$$\underbrace{\mathrm{SU_C}(3)}_{\mathrm{QCD}} \otimes \underbrace{\mathrm{SU_L}(2) \otimes \mathrm{U_Y}(1)}_{\mathrm{GSW}}. \tag{2.1}$$

The gauge principle states that the SM Lagrangian and its predictions must be invariant under local transformations using an operator from any of these constituent groups. Thus, any theory must only include transformations and terms that maintain the local invariance of the complete Lagrangian. In particular, this requirement was violated by any attempt to include an explicit mass term for the Gauge Bososns of QED and for all fermions. Around 1960 a possible solution to this lack of mass was proposed in the form of the spontaneous breaking of the ElectroWeak symmetry, now known as the Higgs mechanism. In the following sections I will go into more detail about the Lagrangian formalism of the Standard Model, QCD, QED and this recently verified Higgs Mechanism.

2.1 The Standard Model

At the turn of the 20th century our understaning of the constituent matter of the universe was limited to what we could see with microscopes and imply from the observations of light and elctricity, giving us evidence for both the photon and the electron. In the first half of the century we discovered the field of subatomic physics with Rutherfords 1911 gold foil scattering experiment, and Dirac successfully demonstrated the quantization of the electromagnetic field, the first step towards a fully Gauge Invariant Quantum Field Theory. In the second half we literally delved deeper, discovering that the nucleus contained structure and extended our theories to include the the complex mechanics of quarks and gluons. With the discovery of the Higgs in 2013 the Standard Model has become an irrefutable framework as can be seen in the high level of agreement betwee theory experiment in figure 2.1.

The QCD and QED theories predict two classes of particles: fermions and bosons shown in figure 2.2. These particles represent the quanta of the quantum fields of the Standard Model and the mediators of the fundamental forces of Nature.

2.1.1 Bosons

These spin-1 particles are known as the vector gauge bosons and are the force carriers of the SM. The most commonly known is the electromagnetic force's un-charged and massless photon (γ) which interacts with all charged particles and is often refered to as "light". The weak nuclear force is involved in nuclear interactions such as beta decays and is carried by 3 bosons all of which have mass and couple to all fermions; the $W^{\pm}$ bosons, which mediate the charged weak nuclear interaction and allow for flavor changing currents; and the Z boson which mediates the neutral weak nuclear interaction. Finally we have 8 massless gluons which mediate the strong nuclear force and only interact with fermions with a "color" charge such as the quarks contained inside the nucleus. The only spin-0 boson, the Higgs Boson (h) is the key to generating mass terms in the SM Lagrangian for the massive Gauge Bosons and for fermions. This is done through the so called Higgs Mechanism and is discussed in more detail in section 2.4.

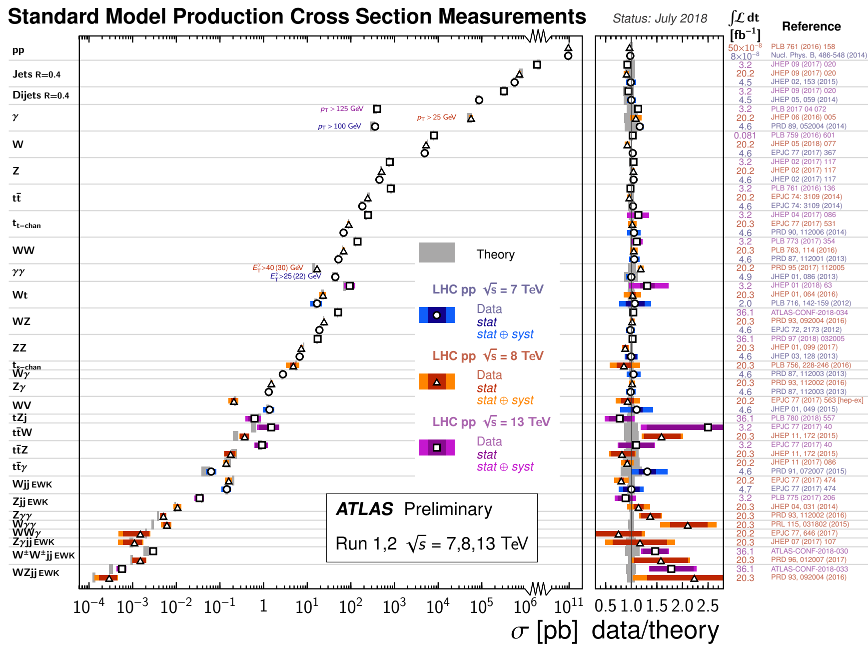


Figure 2.1: Summary of several Standard Model total and fiducial production cross section measurements, corrected for leptonic branching fractions, compared to the corresponding theoretical expectations. All theoretical expectations were calculated at NLO or higher. The dark-color error bar represents the statistical uncertainty. The lighter-color error bar represents the full uncertainty, including systematics and luminosity uncertainties. The data/theory ratio, luminosity used and reference for each measurement are also shown. Uncertainties for the theoretical predictions are quoted from the original ATLAS papers. They were not always evaluated using the same prescriptions for PDFs and scales. The Wgamma and Zgamma theoretical cross-sections have non-perturbative corrections applied to the NNLO fixed order calculations (PRD 87, 112003 (2013)). Not all measurements are statistically significant yet.

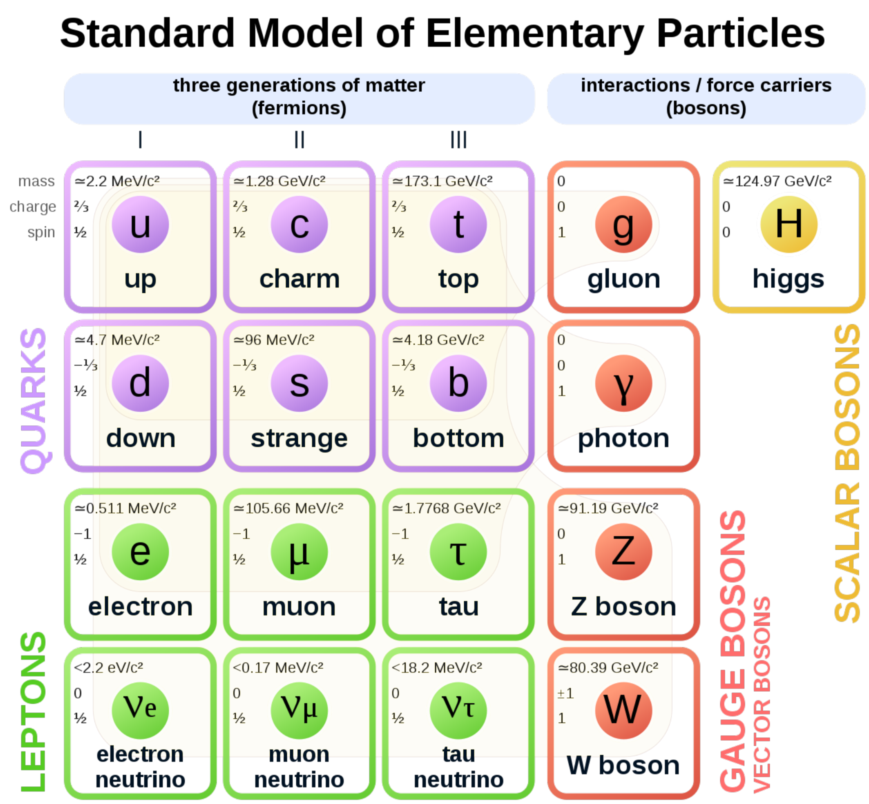


Figure 2.2: Table of all observed fundamental particles of the current Standard Model.

2.1.2 Fermions

These spin-1/2 particles can be further broken up into two distinct familes of particles, the leptons and the quarks, both of which contain three ”generations” each with an ”up” and ”down” type particle. The leptons ”up” type members are the electrically charged electron (e), muon (μ) and tau (τ) while the ”down” type are their electrically neutral counterparts ν_e, ν_μ, ν_τ. The quarks ”up” type members are the up (u), charm (c), and top (t) each with a $+2/3$ elementary charge, while the ”down” type members are the down (d), strange (s), and bottom (b) all of which have a $-1/3$ elementary charge. Each quark carrys a ”color” charge thus allowing them to participate in strong force interactions. Due to the observed color confinement of the strong force these quarks are only observed in colorless bound states known as ”mesons” (1 quark and 1 anti-quark) and ”baryons” (an odd number of quarks and anti-quarks). All of the above fermions have an anti-particle partner which has the opposite electrical charge but is otherwise identical.

2.2 Quantum Electrodynamics

In the SM the Electromagnetic and Weak nuclear forces are unified into the Electroweak interaction which is represented by the $SU(2)_L \times U(1)_Y$ gauge group. The L represents the physical observable that the Weak interaction, and thus the $SU(2)$ transformation, only acts on left handed particle states. The Y states that this is the $U(1)$ symmetry for the weak hypercharge Y instead of the electromagnetic charge. The particle states for these interactions are solutions to the Dirac equation and are represented as Dirac spinor doublets ($\boldsymbol{\Psi_L}$) for the left handed states, and as Dirac spinor singlets (Φ_R) for the right handed states. Thus when a general transformation from the Electroweak gague group is applied to the left handed spinor doublet you get equation 2.2

$$\boldsymbol{\Psi_L} \rightarrow \boldsymbol{\Psi_L'} = exp\left(\underbrace{ig^{'}\frac{Y_L}{2}\zeta(x)}_{U(1)_Y} + \underbrace{ig_W\boldsymbol{\alpha}(x)\cdot\mathbf{T}}_{SU(2)_L}\right)\boldsymbol{\Psi_L}. \tag{2.2}$$

For the right handed spinor singlet the $SU(2)_L$ doesn't contribute and you get equation 2.3

$$\Phi_R \rightarrow \Phi_R^{'} = exp\left(\underbrace{ig^{'}\frac{Y_R}{2}\zeta(x)}_{U(1)_Y}\right)\Phi_R. \tag{2.3}$$

We can see that these local gauge transformations have introduced space-time dependant terms $\boldsymbol{\alpha(x)}$ and $\zeta(x)$ into our electroweak Lagrangian. Due to the derivatives contained within the kinetic term of this lagrangian, this new configuration would introduce additional terms, thus violating our required local gauge invariance. Luckily, we can remove these additional terms by replacing the standard derivative (∂_μ) with th covariant derivative (D_μ) as seen in equation 2.4 for the left handed states and 2.5 for the right handed states.

$$D_\mu = \partial_\mu - \underbrace{\frac{1}{2} i g^{'} B_\mu Y_L}_{U(1)_Y} - \underbrace{\frac{1}{2} i g_W \mathbf{W}_\mu \cdot \boldsymbol{\tau}}_{SU(2)_L} \tag{2.4}$$

$$D_\mu = \partial_\mu - \underbrace{\frac{1}{2} i g^{'} B_\mu Y_R}_{U(1)_Y} \tag{2.5}$$

Here we see two new gauge fields; B_μ the weak hypercharge field and $\boldsymbol{W_\mu}$ the charged weak field. The form of these fields is chosen such that the final Lagrangian is invariant under $SU(2)_L \times U(1)_Y$ transformations, and thus we have restored gauge invariance for the kinetic term of our electroweak Lagrangian! Inserting these new definitions into the Lagrangian for the spinor field Ψ which satisfies the free-particle Dirac equation we get

$$\mathcal{L} = i \bar{\boldsymbol{\Psi}}_{\boldsymbol{L}} \gamma^\mu \left(\partial_\mu - \frac{1}{2} i g^{'} B_\mu Y_L - \frac{1}{2} i g_W \mathbf{W}_\mu \cdot \boldsymbol{\tau} \right) \boldsymbol{\Psi}_{\boldsymbol{L}} + i \bar{\Phi}_R \gamma^\mu \left(\partial_\mu - \frac{1}{2} i g^{'} B_\mu Y_R \right) \Phi_R \tag{2.6}$$

Next we must construct the gauge field self interaction and mass terms

$$\mathcal{L} = -\frac{1}{4} \boldsymbol{F}_{\mu\nu} \boldsymbol{F}^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \frac{1}{2} M_W^2 \boldsymbol{W}_\mu \boldsymbol{W}^\mu + \frac{1}{2} M_B^2 B_\mu B^\mu \tag{2.7}$$

where the field tensors $\boldsymbol{F}^{\mu\nu}$ and $B^{\mu\nu}$ are defined to be

$$\boldsymbol{F}^{\mu\nu} = \partial^{\mu}\boldsymbol{W}^{\nu} - \partial^{\nu}\boldsymbol{W}^{\mu} + g\boldsymbol{W}^{\mu} \times \boldsymbol{W}^{\nu} \tag{2.8}$$

$$B^{\mu\nu} = \partial^{\mu}\boldsymbol{B}^{\nu} - \partial^{\nu}\boldsymbol{B}^{\mu} \tag{2.9}$$

The field tensor terms in equation 2.7 are invariant under our gauge transformations, but simply plugging in equation 2.4 or equation 2.5 into the mass terms shows that these terms violate gauge invariance thus implying $M_W = 0$ and $M_B = 0$ in direct contradiction of the observed masses of the weak gauge bosons. This issue arises again for fermion mass terms as illustrated below for the elctron field (e)expanded in its chiral basis.

$$m\bar{e}e = m \begin{pmatrix} e_R^{\dagger} & e_L^{\dagger} \end{pmatrix} \begin{pmatrix} e_L \\ e_R \end{pmatrix} = m(e_R^{\dagger}e_L + e_L^{\dagger}e_R) \tag{2.10}$$

Remembering that the left and right handed spinors of the electroweak interaction transform differently we see that this mixture of right and left fields violates gauge invariance. This again forces us to conclude that $m = 0$ in contradiction to the observation that fermions do indeed have mass. As mentioned in section 2.1.1 the resolution to these mass mysteries lies in the Higgs mechanism discussed in section 2.4

2.3 Quantum Chromodynamics

Quantum Chromodynamics is the continuation of the mathematical framework established by Quantum Electrodynamics (section 2.2, this time for the strong force described by the $SU(3)_C$ gauge group where the C represents the "color" charge of QCD. This color charge doesn't imply actual visible color, but is useful as an anology to the visible spectrum where a combination of red, green, and blue generates white. For QCD the combination of red, green, and blue color charges results in a colorless object. As mentioned in section 2.1.2 the quarks will contain a color (anti-color) charge represented by a color triplet field which transforms under the general $SU(3)$ transformation as shown here

$$q = \begin{pmatrix} q_r \\ q_g \\ q_b \end{pmatrix} \rightarrow q^{'} = exp\left(ig_s \sum_{k=1}^{8} \eta_k(x) \frac{\lambda_k}{2} \right) q \tag{2.11}$$

Here the λ_k are the generators for $SU(3)$, $\eta(x)_k$ is the space-time dependancy for each generator, and g_s is the strong coupling constant. As with QED, the introduction of these space-time dependant terms introduces new terms into the kinematic portion of the lagrangian thus spoiling our gauge invairance. Again, we introduce a covariant derivative to restore invariance

$$D_\mu = \partial_\mu - i g_s G^k_\mu \frac{\lambda_k}{2} \tag{2.12}$$

Here the G^k_μ are the new fields introduced for the 8 gluons. These new fields transform under $SU(3)$ as shown in equation 2.13

$$G^k_\mu \rightarrow G'^k_\mu = G^k_\mu + \partial_\mu \eta_k(x) + g_s f_{klm} \eta_l(x) G^m_\mu \tag{2.13}$$

Given these definitions we can construct the QCD Lagrangian ($\mathcal{L}_{QCD}$) as shown in equation 2.14 where the gluon field tensor $G^{\mu\nu}_k$ is the one defined in equation 2.15

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma_\mu D^\mu - m_q)q - \frac{1}{4} G^{\mu\nu}_k G_{k\mu\nu} \tag{2.14}$$

$$G^{\mu\nu}_k = \partial^\mu G^\nu_k - \partial^\nu G^\mu_k + g_s f_{klm} G^\mu_l G^\nu_m \tag{2.15}$$

The strong force is peculiar in that we experimentally observe only colorless objects in the form of bound states of quarks known as hadrons. Qualitatively, when a bound state of quarks (meson or baryon) is given sufficeint energy to separate the strong force dramatically increases in strength. At the point where the objects would separate, and thus no longer be colorless, it becomes energetically favorable to produce a quark/anti-quark pair in a process known as hadronization. In other words, attempting to separate a bound quark state into its colored constituents simply results in new colorless bound states. This requirement of colorless objects by the strong force is known as color confinement. For highly energetic strong interactions at hadron colliders the result is an expanding chain of hadronizing quarks and gluons and their decay products known as a jet.

2.4 The Higgs Mechanism

The Higgs Mechanism is the system by which particles attain mass through the spontaneous breaking of the Higgs potential, thus causing all particles it interacts with to have mass.

2.4.1 Electroweak Symmetry Breaking

The Higgs field is expressed as a complex doublet, $\mathbf{\Phi}$, and thus has four components as shown in equation 2.16

$$\mathbf{\Phi}(x) = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1(x) + i\phi_2(x) \\ \phi_3(x) + i\phi_4(x) \end{pmatrix} \tag{2.16}$$

The four compoenents of this field each represent a degree of freedom which will be used to give the longitudinal polarizations of the gauge bosons $W^{\pm}, Z$ and the mass of the Higgs Boson. The resulting lagrangian for the higgs includes a kinetic term (K) as well as the Higgs potential (V) all of which are invariant under the Electroweak gauge symmetry $SU(2)_L \times U(1)_Y$

$$\mathcal{L}_{\text{Higgs}} = \underbrace{(D_\mu \mathbf{\Phi})^\dagger D^\mu \mathbf{\Phi}}_{\text{K}} - (\underbrace{\mu^2 \mathbf{\Phi}^\dagger \mathbf{\Phi} + \lambda(\mathbf{\Phi}^\dagger \mathbf{\Phi})^2}_{\text{V}}) \tag{2.17}$$

Here we constrain $\mu^2 < 0$ and $\lambda > 0$ such that the potential forms a stable minima. The shape of this potential is shown in figure 2.3 and is often refered to as the "Mexican-hat" or "Wine-bottle" potential.

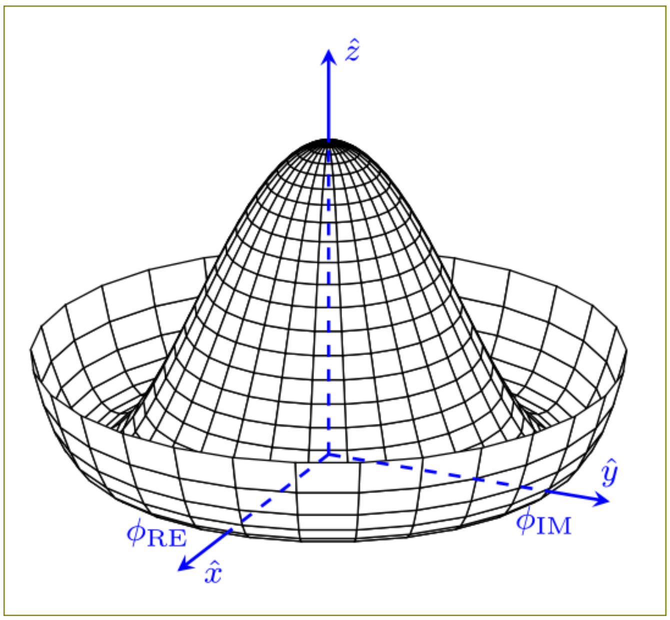


Figure 2.3: A lower dimensionality representation of the shape of the Higgs Potential. The central peak represents a $v = 0$ rotationally symmetric unstable state, while the trough represents the infinite choices of minima that can be selected upon the spontaneous breaking of symmetry.

Whatever you call it, this potential is significant in that its minimum is not at $\mathbf{\Phi} = 0$ but instead is symmetric around the origin thus defining an infinite number of states that minimize V. The value of this minima can be calculated by taking the derivative of V with respect to $\mathbf{\Phi}$ and setting it equal to 0. This value, also known as the vacuum expectation value (vev) has been found to be $v \equiv \sqrt{\mu^2/\lambda} = 246$ GeV. In order to reach this ground state energy, the Higgs field must spontaneously break this symmetry, and thus aquire an arbitrary single value. For ease of calculation we orient our coordinate system such that

$$\langle \mathbf{\Phi}(x) \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \tag{2.18}$$

Next we parameterize small perturbations around the minimum of the Higgs potential as

$$\langle \mathbf{\Phi}(x) \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \exp\left(i \frac{\tau^i}{2} \theta^i(x) \right) \tag{2.19}$$

Here the real scalar field $h(x)$ corresponds to radial perturbations of the minima and while the three $\theta^i(x)$ are the Nambu-Goldstone fields with values determined by your choice of gauge. Choosing the unitary gauge of $\theta^i(x) = 0$ and expanding the kinetic term around the vev we get

$$\mathcal{L}_{\text{Higgs},K} = \frac{g^2 v^2}{8}\left((W_\mu^-)^\dagger W^{-\mu} + (W_\mu^+)^\dagger W^{+\mu}\right) + \frac{1}{2}\begin{pmatrix} W_\mu^{3\dagger} & B_\mu^\dagger \end{pmatrix} \boldsymbol{M}^2 \begin{pmatrix} W^{3\mu} \\ B^\mu \end{pmatrix} + \dots \tag{2.20}$$

Here the first term is the physical mass term for the $W^\pm$ bosons where we have constructed their charge eigenstates ouf of the $W^{1,2}$ fields like this $W^\pm = \frac{1}{\sqrt{2}}(W^1 \mp iW^2$. The second term represents the mixture of the W^3 and B fields through the mass matrix $\boldsymbol{M}$. By diagonalizing this matrix and identifying the mass eigenstates we find the physical fields of the photon (γ) and the Z boson

$$\boldsymbol{M}^2_{Diagonalized} = \begin{pmatrix} 0 & 0 \\ 0 & \frac{v^2}{4}(g^2 + g^{'2}) \end{pmatrix} \tag{2.21}$$

The upper left diagonal element corresponds to the massless photon while the lower right diagonal element gives the mass of the massive Z boson. This leaves us with the following masses for the 4 Electroweak bosons

$$m_W = \frac{1}{2} g v \quad , \quad m_Z = \frac{1}{2} v \sqrt{g^2 + g^{'2}} \quad , \quad m_\gamma = 0 \tag{2.22}$$

The masses of the $W^\pm$ and Z gauge bosons can be related through the Wineberg angle or mixing angle which

$$\theta_W = cos^{-1}\left(\frac{g}{\sqrt{g^2 + g'^2}}\right) \rightarrow m_Z = \frac{m_W}{cos\theta_W} \tag{2.23}$$

Using this definition we can write out the exact mixture of B and W^3 that make up the photon and Z boson

$$\gamma = cos(\theta_W)B + sin(\theta_W W^3) \tag{2.24}$$

$$Z = -sin(\theta_W)B + cos(\theta_W W^3) \tag{2.25}$$

2.4.2 Fermion Mass Terms

2.4.3 The Higgs Boson

Part II

Experimental Apparatus and Associated Facilities

Chapter 3

The Large Hadron Collider

Located 100 meters under the Swiss / French boarder lies the 26.7 kilometer Large Hadron Collider (LHC) [1]. The culmination of a huge international collaboration, this apparatus is used to produce proton and heavy ion collisions for observation by the four major experiments at the LHC: ATLAS, CMS, LHCb, and ALICE. The system was designed for a maximum center-of-mass energy of $\sqrt{s} = 14$ TeV and a peak instantaneous luminosity of $L = 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The first LHC workshop was held in 1984 in Lausanne at the European Organization for Nuclear Reserach (CERN) [2]. The nearly 30 year old case for a machine that would push towards the discovery of the elusive Higgs Boson was presented using the existing CERN accerlerator facilities and the Large Electron Positron (LEP) collider tunnel. The proposal became reality on September 10, 2008 when the first proton beams were circulated, only to have calamity strike 9 days later in the form of a catastrophic electrical fault. The repairs and improvements lasted until November 2009 when the LHC restarted. Since then this modern marvel has worked wonderfuly and, as hoped, lead to the discovery of the Higgs Boson by the CMS and ATLAS collaborations July 4, 2013.

The following chapter provides a brief introduction to the worlds most powerful accelerator starting with the little red bottle of hydrogen in building XXX, and ending with the interaction point where protons collide at the highest energies ever produced.

3.1 Particle Incjecton Chain

We begin with the most common element in the Universe, hydrogen, as our source of protons. A bottle of hydrogen gas provides 100 microsecond pulses of raw H_2 which is then injected into a Duoplasmatron. There, a strong electric field and free elctrons from a cathode ionize the molecule into bare H^+ aka a proton! These protons are then accelerated by a 90kV field, leaving the Duoplasmatron with 1.4% speed of light ($\sim$4000km/s) or, in relativistic units, about 83KeV. The bare protons are then fed into the accelerating RadioFrequency (RF) cavities of Linear Accelerator 2 (LINAC2). Inside, conductors charged by a powerful oscillating electromagnetic field accelerate the protons resulting in a 50MeV energy. Along the way, small quadrupole magnets shape the proton packet insuring they remain in a tight beam. This pattern of accleration with RF cavities and shaping/turnig with magnets is then repeated with CERN's first

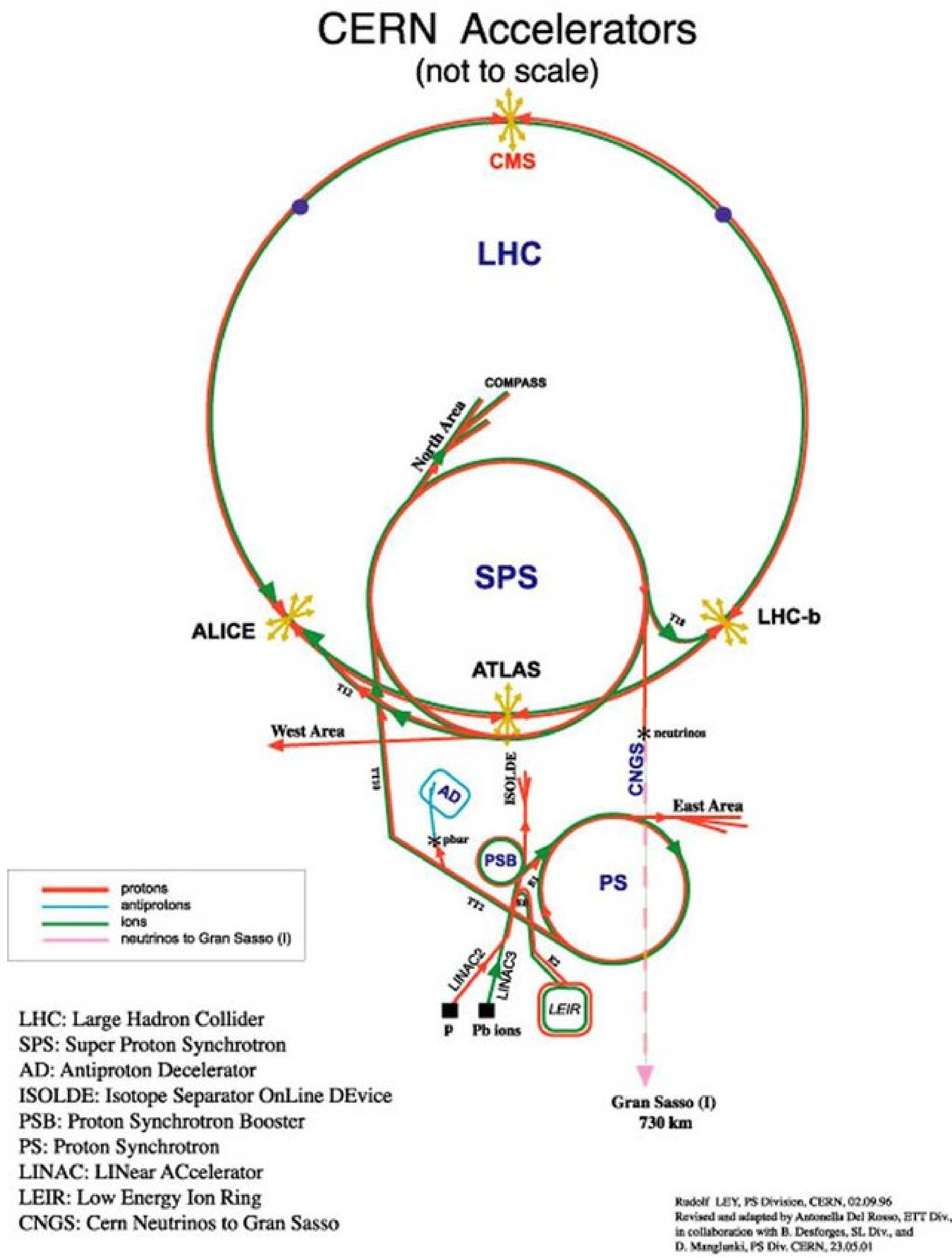


Figure 3.1: CERN accelerator complex

synchrotron, the Proton Synchrotron (PS) rendering a 1.4 GeV beam. The final step before the LHC comes with the Super Proton Synchrotron where the same technologies are implemented to produce 450 GeV protons, ready for injection into the LHC. A diagramatic representation of this chain can be seen in figure 3.1

In order to produce proton-proton collisions the LHC uses two beams circulating in opposite directions. The beams are not continuous, but instead consist of bunches, or buckets, of $\mathcal{O}(10^{11})$ protons with a spacing of 25ns. Given the LHC circumference this allows for 3564 buckets, however only 2808 are filled per beam due to safety requirements and injection limitations. Each beam takes 4 minutes and 20 seconds to fill and then an additional 20 minutes to for the protons to reach their maximum energy of 7 TeV TeV, or 99.99999991% the speed of light! Under normal operating conditions these beams can be used for many hours.

3.2 LHC layout and design

While often depicted as a perfect circle the LHC is in reality an octagon with rounded edges, called arcs, as can be seen in figure 3.2. Here you can see the counter circulating beams of protons depicted in red and blue. These beams are focused and collided at the 4 dedicated interaction points at rates of up to 40 MHz. Two of these points are occupoied by the ATLAS and CMS experiments, both of which are high luminosity, multi-purposed experiments.

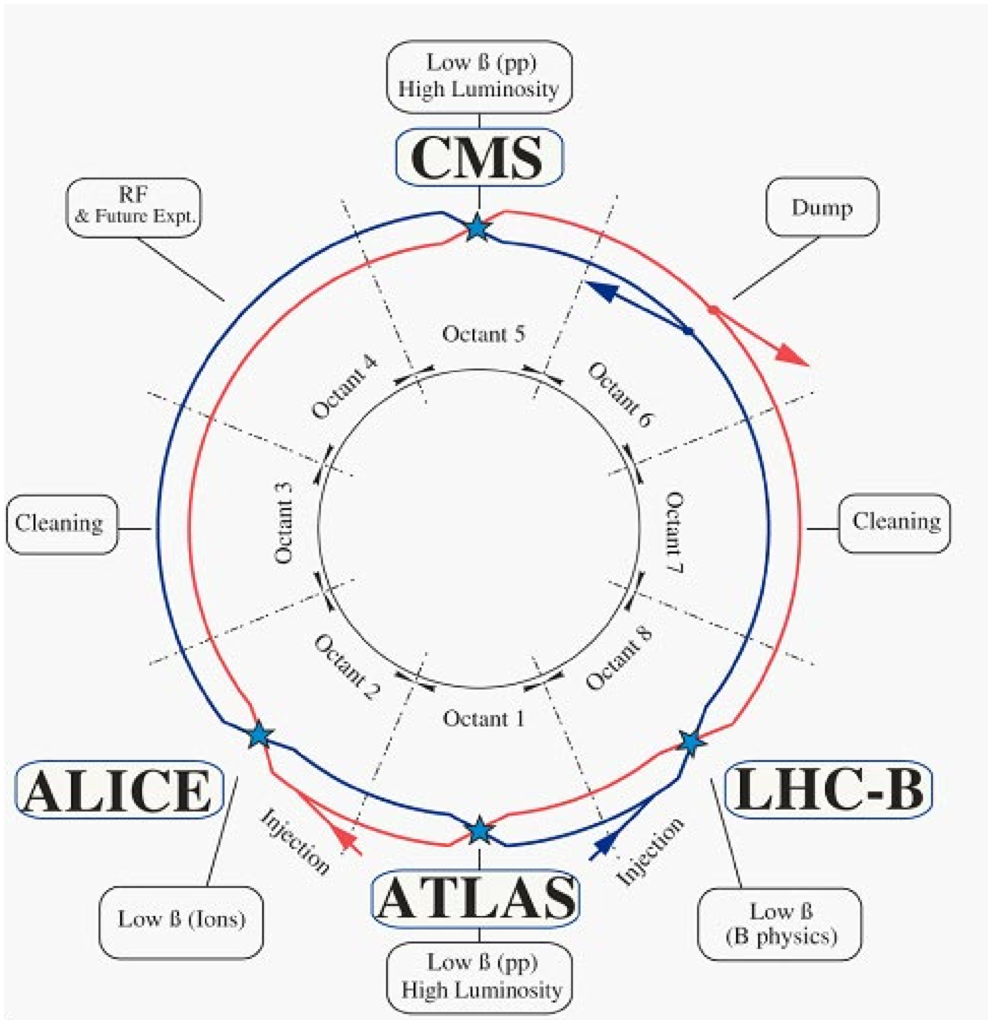


Figure 3.2: Labeled diagram of all the experiments at the LHC indicating the counter circulating beams and points of interest along the circumference of the accelerator.

The exact design of the tunnel is due to the experimental constraints of the original machine for which it was built, the Large Electron Positron (LEP) Collider. For the $\sim 2,000$ times lighter electron the maximum energy was limited by the synchrotron radiation, proportional to $\frac{1}{m^4}$, requiring long straight sections of accelerating RF cavities to recouperate the lost energy. Given that this effect is $\mathcal{O}(10^{13})$ times smaller for the proton the LHC is instead limited by our ability to design and construct magnets strong enough to bend the beam given the already determined curvature of the 8 arcs.

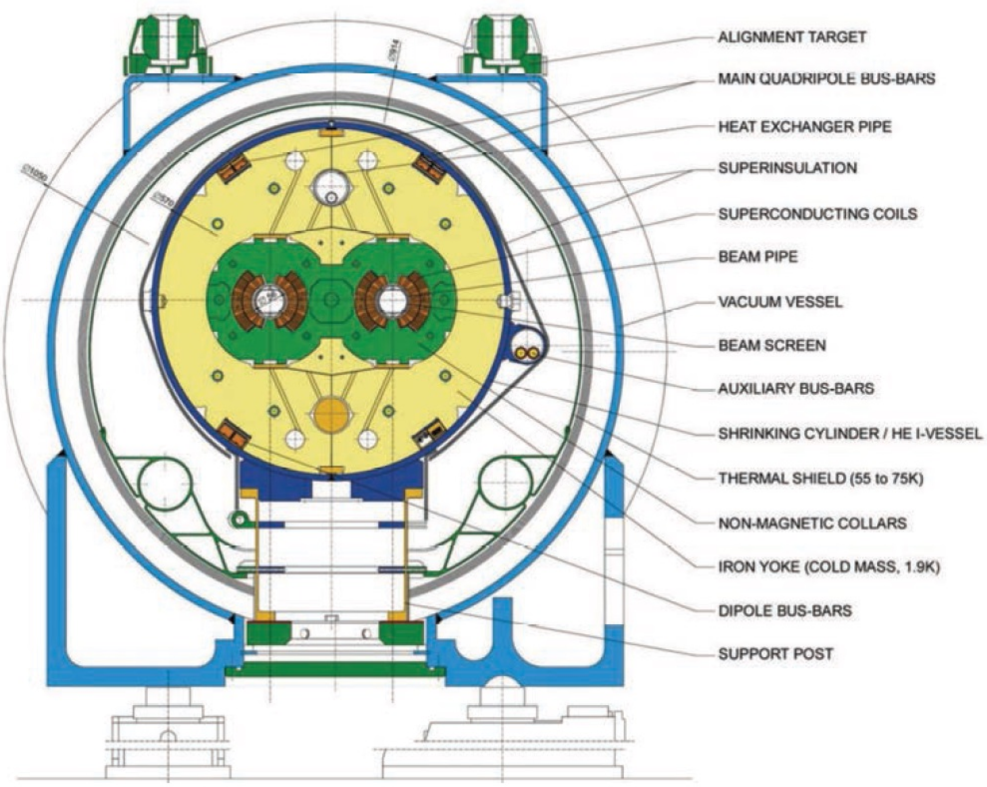


Figure 3.3: Depiction of a LHC dipole magnet 2-in-1 design labeling the major components

The oppositely circulating beams must each have their own ring and magnetic field which lead to the creation of a twin-bore (i.e. ”two-in-one”) magnet design, a cross section of which can be seen in figure 3.3. These magnets are constructed using NbTi superconductors which are cooled to 2K using superfluid helium. These magnets are designed to provide the needed 8.33 T magnetic field required to bend the beams at the design beam energy of 7 TeV. In total 1231 of these 15 m long bending dipole magnets are used, in association with 392 5-7m long quadrupole magnets which are responsible for keeping the proton bunches in a tight beam by squeezing them either horizontally or vertically.

3.3 Performance

Since the begining of its stable running in 2010 the LHC has performed well, even exceeding our expectations. While the experiment itself is incredibly complex, the performance of the machine, for the purposes of our analysis, can be reduced to two numbers; the familiar center of mass energy of the beams and a less common quantity known as the integrated luminosity.

For particle physics the integrated luminosity is proportional to the total number of collisions recorded during a specified time period, while the instantaneous luminosity is proportional to the bunch crossing rate along with the cross section of a proton-proton interaction and represents the potential number of collisions per second. Knowing this we can see that the integrated luminosity, L_{int} is simply the integral of the instantaneous luminosity $L_{inst.}$ for a choosen data period as seen in equation 3.1.

$$L_{int} = \int L_{inst.} dt \tag{3.1}$$

For a standard Gaussian beam, $L_{inst.}$ can be written as

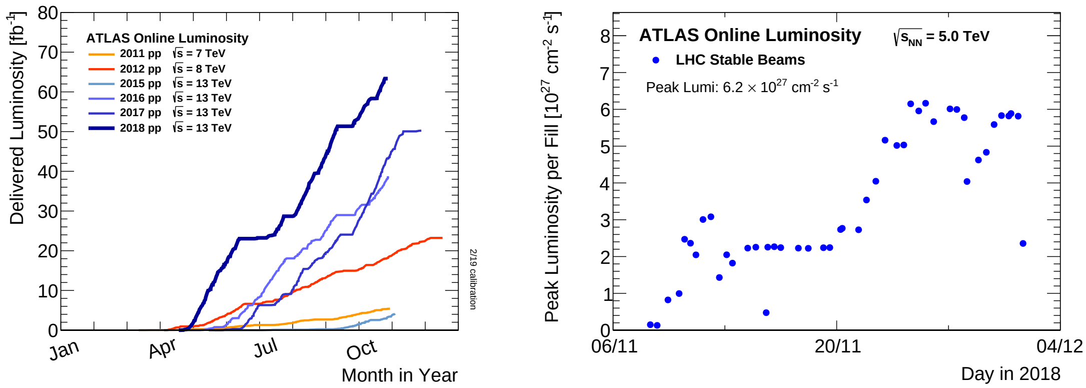
$$L = \frac{N_b^2 n_b f_{rev} \gamma_r}{4\pi \epsilon_n \beta^*} F \tag{3.2}$$

where N_b is the number of particles per bunch, n_b the number of bunches per beam, f_{rev} the revolution frequency, γ_r the relativistic gamma factor, ϵ_n the normalized transverse beam emittance, β^* the beta function at the collision point, and F the geometric luminosity reduction factor due to the crossing angle at the interaction point given by

$$F = \left(1 + \left(\frac{\theta_c \sigma_z}{2\sigma^*}\right)^2\right)^{-1/2} \tag{3.3}$$

where θ_c is the full crossing angle at the interaction point, σ_z is the RMS bunch length, and σ^* is the transverse RMS beam size at the interaction point.

For the ATLAS experiment the integrated luminosity for each year can be seen in figure 3.4a as well as an example of the instantaneous luminosity for the choosen year in figure 3.4b.



(a) Integrated Luminosity 2011 - 2018 (b) 2018 Peak Instantaneous Luminosity

Figure 3.4: Luminosity is monitored as both a runing total known as the Integrated Luminosity as depicted in (a) and as an instantaneous quanity as shown in (b)

3.4 Pile-up at the LHC

Given the large number of protons per bunch and the cross-section of a proton-proton interaction, the probability to observe multiple interactions per bunch crossing is quite high. These multiple-interaction are known as pile-up, μ or the time averaged representation $\langle\mu\rangle$, and come in two different forms:

1. **In-time pile-up:** These are the other proton-proton collisions that occur during the same bunch crossing as the primary interaction that cauesd the Data Aquisition (DAQ) system to trigger. These are the standard extra interactions we expect to observe as stated above.

2. **Out-of-time pile-up:** These are interactions that occur either before or after a

bunch crossing that causes the DAQ to trigger. This effect is generally due to the long integration times of some detector electronics.

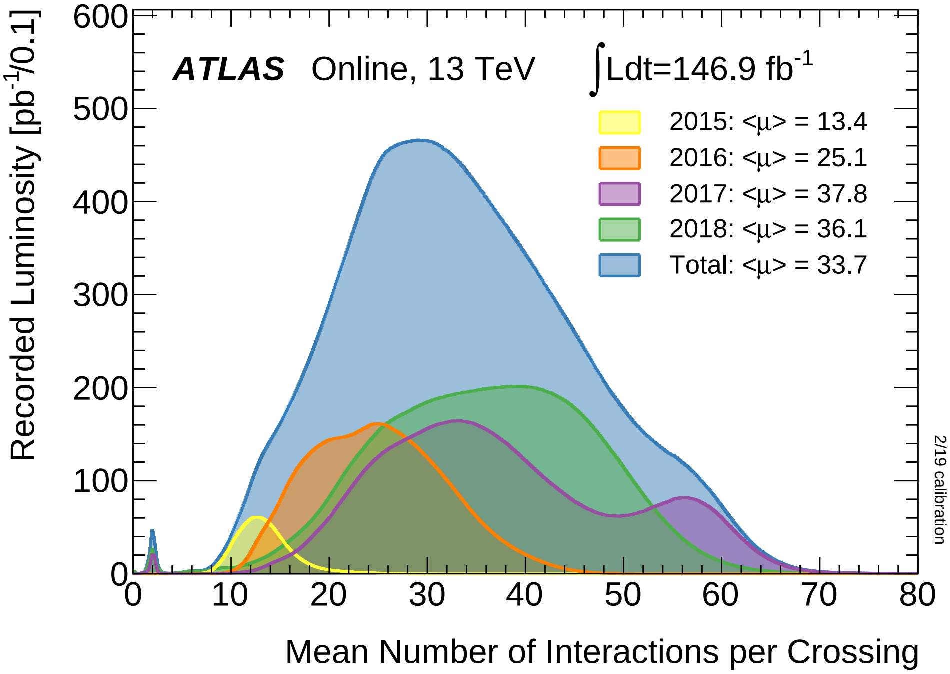


Figure 3.5: Pileup for data taking periods 2015 - 2018

The pile-up profile for past years can be seen in figure 3.5. The width of this distributino is due a combination of Poisonian statistics, the decrease in number of protons per bunch over the lifetime of a single run, and optimization tweaks to the beam's profile during runtime. Understanding and eliminating the noise from these pile-up events is crucial to reconstructing physics variables to represent the primary interaction we hope to observe.

Chapter 4

The ATLAS Detector

Given the immense energies availalbe at the LHC, and the veritable zoo of paricles we are trying to detect, we require a general-purpose experiment in order to fully exploit the full range of physics opportunities provided. Two international collaborations rose to this challenge, the CMS (Compact Muon Solenoid) and ATLAS (A Torroidal LHC ApparatuS) experiments. While both have similar physics goals and each of them strengths and weaknesses, this dissertation will focus on the ATLAS experiment and the intricacies of its three main sub-detectors and two massive magnet systems depicted in figure 4.1.

Originally proposed in 1994 the ATLAS experiment was completed in 2008. On July 4th, 2012 in a joint announcment the ATLAS and CMS experiments announced the discovery of the long predicted Higgs Boson. The collaboration now boasts over 3000 physicists from 175 instituations spread accross 38 countries and continues to probe

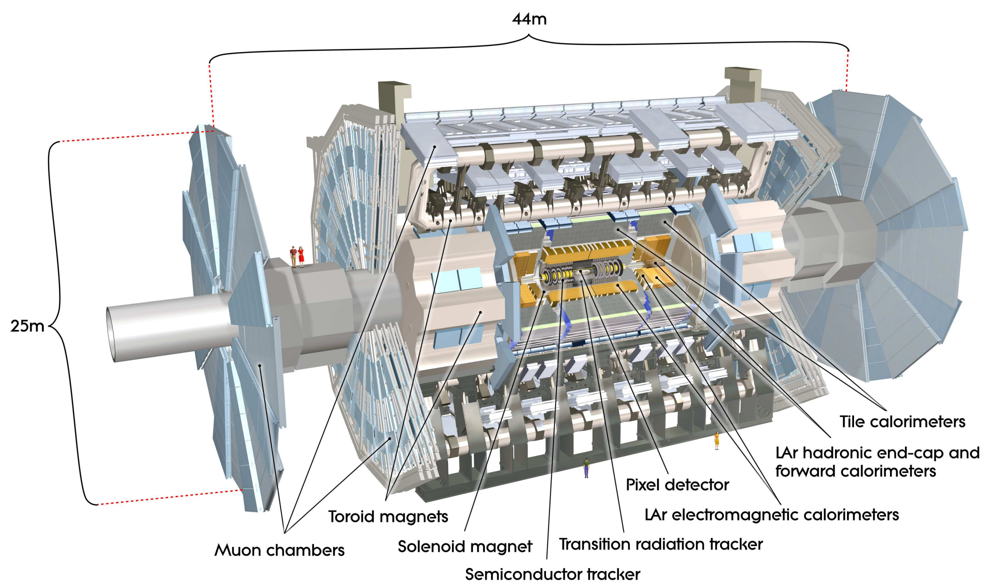


Figure 4.1: [3] Here we see a cut-away side view of the ATLAS detector with the major components labeled. Note that within each of these labeled components there may exist multiple different detector technologies. For scale two people in red are shown standing between the disk muon chambers on the left side of the figure.

the limits of the Standard Model in pursuit of answers to some of Humanities deepest questions.

Located approximately 100 meters underground in a vast excavated chamber, the ATLAS detector rests its 7000 metric tonnes on a bed of concrete reinforced steel. Out of it flows the signals of over 100 million electronic channels through a zip tied mass of greater than 3000 kilometers of cabling. At its very center is one of the four interaction points of the LHC, specifically Point 1, where the two counter circulating proton beams are skillfully shaped and then collided by a series of magnets. The energetic particles resultant from this collision then fly out in all directions into the bulk of the ATLAS detector.

The first sub-system they meet is the Inner Detector (ID) and its many layers of strip and pixel silcon detectors along with a transition radiation gaseous wire detector, all bathed in the 2T mangnetic field of the surronding superconducting solenoidal magnet. This system exploits the ionization of charged particles to track their curved trajectory through the magnetic field. This curvature gives us charge information, a momentum measurement, and precision 3D verticies crucial to the identification of the secondary verticies of a b-hadron decay.

Outside of the solenoid the particles are faced with first the Electromagnetic and then the Hadronic sampling calorimeters. Here, layers of scintillator and high radiation length materials are implemented to measure the energy of electrons, photons, and hadrons. As the goal is to completely absorb the energy of all outgoing particles the calorimeter has a nearly 4π solid angle coverage.

Finally we have the muon system surrounding the calorimeter and equipped with its own torroidal magnet system. Here the charged muon bends in the magnetic field while leaving a trail of ionization in the muon spectrometer before exiting the detector completely. Neutrinos are the only other standard model particle that leave the detector, however they do so without detection. A depiction of the various particle interactions with the different detector sub-systems can be seen in figure 4.2

In the following sections I will explain our choosen coordinate system and give a more detailed reveiw of these 3 detector sub-systems.

4.1 ATLAS Coordinate System

Using the nominal interaction point as the origin, ATLAS uses a right handed coordinate system where the positive x-axis points towards the center of the LHC ring, the positive y-axis points upwards, and the positive z-axis is defined by the counter clockwise circulating beam direction as viewed from above shown in figure 4.3 [3].

Using these coordinates we can define the physical momentum of the objects measured as $\vec{p} = (p_{\mathrm{T}}, p_z)$ with p_{T} being the momentum of the object in the transverse plane and p_z the momentum along the beam axis. Given the cylindrical symmetry of ATLAS it is desireable to define the polar angle θ from the beam axis with the $r - \phi$ plane being perpendicular to that axis. Since the particles we observe are relativistically boosted

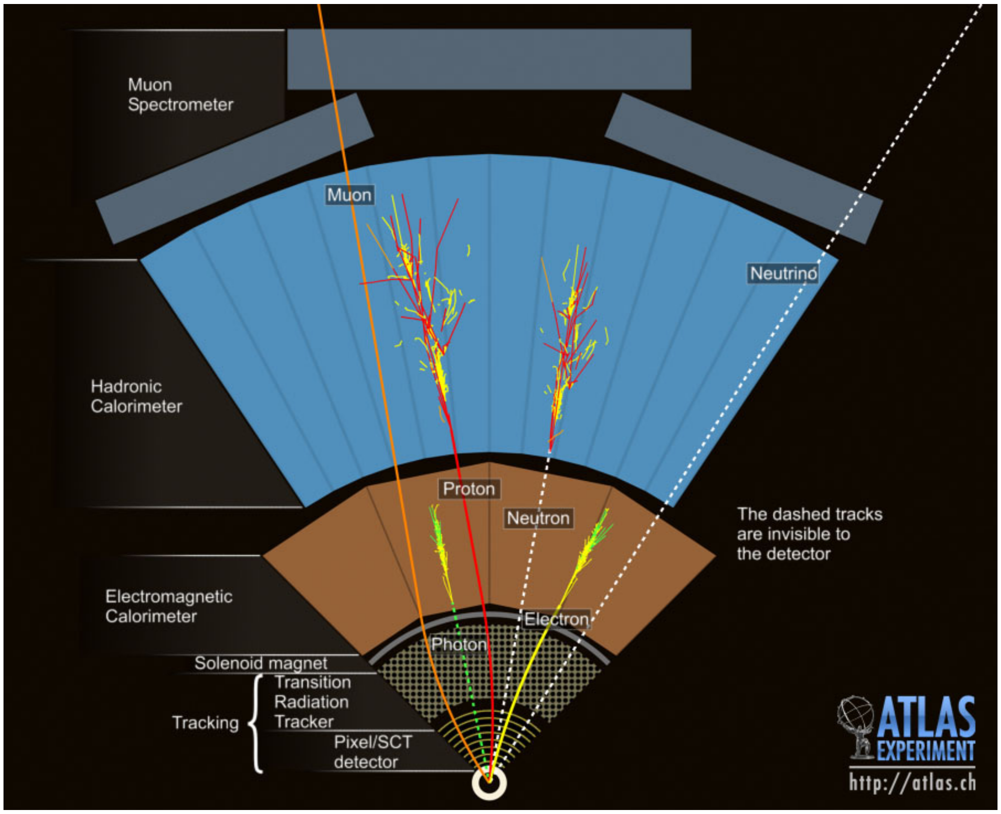


Figure 4.2: This slice of the ATLAS detector depicts how different particles interact with each component of the detector it crosses. A dashed line indicates no interaction while a solid line indicates interaction. Electrons (yellow/green) and charged hadrons (red) interact with the tracker and curve in the solenoid's magnetic field. Electrons and photons (yellow/green) are absorbed by the Electromagnetic calorimeter. All hadrons (red/yellow) are absorbed by the Hadronic calorimeter. The muons (orange) curve in both the solenoid and torroid magnetic fields before exiting the detector. Finally, the neutrinos (white) pass through the entire detector without interacting.

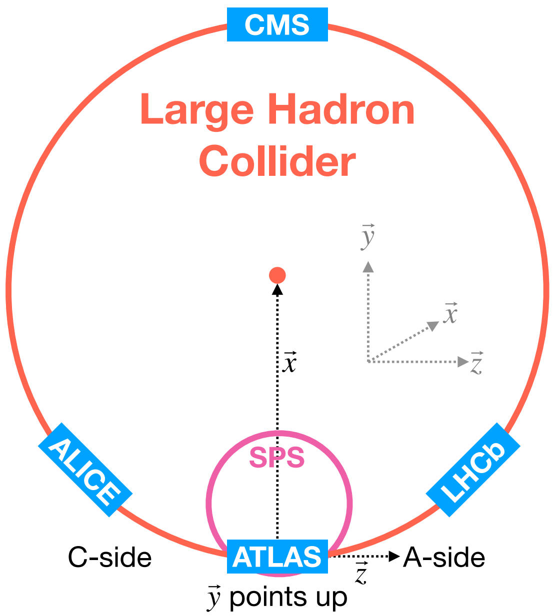


Figure 4.3: [4] A cartoon view of the the LHC from above showing the SPS, LHC and the four main experiments of the LHC: ATLAS, CMS, LHCb, and ALICE. The standard cartesian coordinate system is shown with its origin at the ATLAS interaction point, the positive x-axis towards the center of the LHC, the positive y-axis pointing upwards, and the positive z-axis pointing along the beamline towards the "A-side"

in the z-axis it is desireable to use the Lorentz invariant quantity pseudorapidity (η) defined in terms of the polar angle by

$$\eta = -\ln\tan\left(\frac{\theta}{2}\right). \tag{4.1}$$

where $\eta = 0$ is in the $x - y$ plane and larger values of $|\eta|$ being closer to the beam axis as can be seen in figure 4.4.

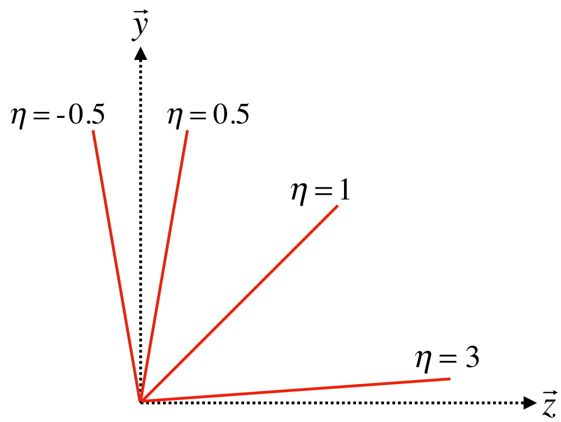


Figure 4.4: Modified from [4] this cartoon represents a selection of pseudorapiditity (η) values overlaid with some cartesian coordinates (dashed black lines). The redlines are drawn for $\eta = \pm 0.5, 1.0, 3.0$

In this analysis the angular separation between objects in the detector is calculated and represented using the geometric quantity

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \tag{4.2}$$

4.2 Tracking with the Inner Detector

With its closest component, the insertable b-layer (IBL) [5], only 3.3 cm from the interaction point The Inner Detector (ID), shown in figure 4.5 [6, 7], faces the incredible challenge of providing precision momentum resolution and identification of both primary and secondary vertex measurements of charged tracks all while recieving the highest fluence.

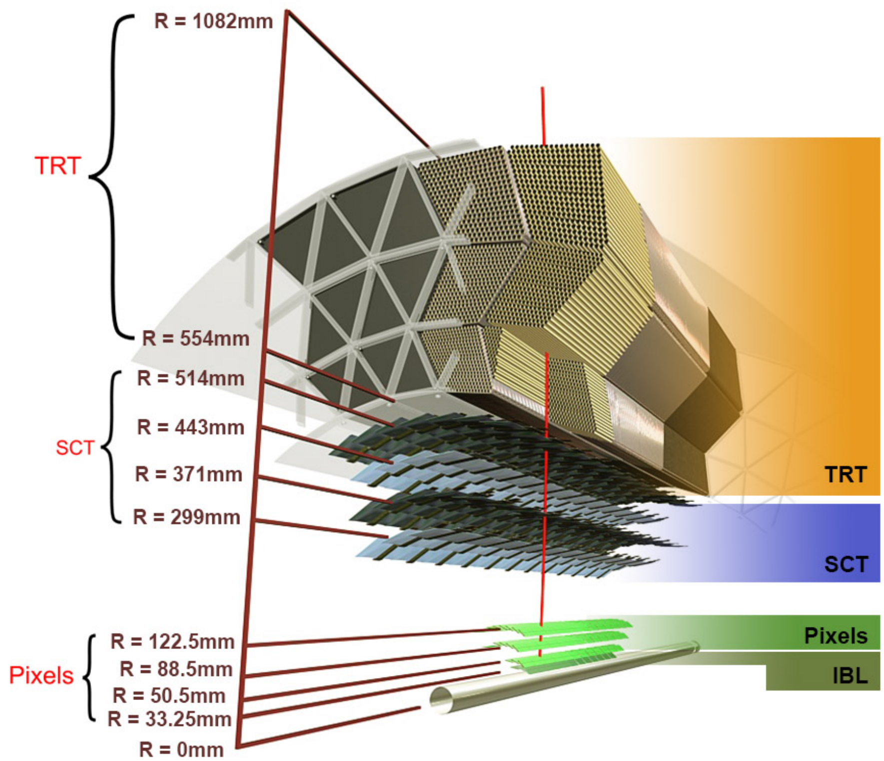


Figure 4.5: [5] Diagram of inner detector

It is designed to be very compact to reduce the probability of a particle decaying inside and to give precision measurements of the particles curvature in the 2T solenoidal magnetic field. This leades to excellent momentum resolution above the nominal p_{T} threshold of 0.5GeV and within the pseudorapidity range of $|\eta| < 2.5$ as shown in figure 4.6

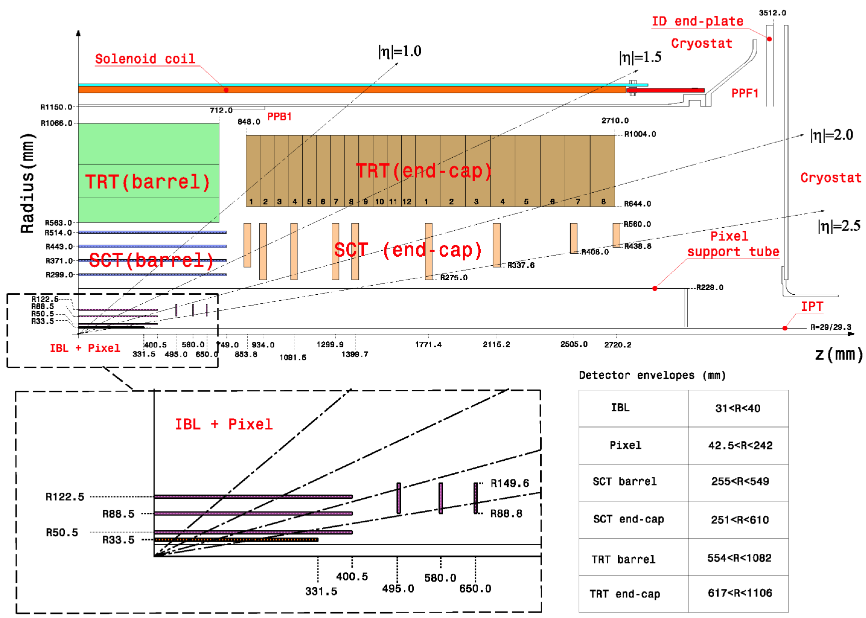


Figure 4.6: [8] Schematic of the Inner Detector including eta lines. Each component shown is cylindrically symmetric leading to a multi-layered detector.

The ID is composed of three different detector technologies for particle trajector reconstruction: The Pixel Detector, Semiconductor Tracker (SCT) and the Transition Radiation Tracker (TRT). These will be discussed in the following sections.

4.2.1 Pixel Detector

The ATLAS Pixel Detector [3], the innermost subdetector of the ID, is designed to give the best resolution possible as close as possible to the interaction point. This is accomplished using the 4 barrel layers and the 3 disks per endcap as indicated in figure 4.6. The inner most barrel layer, the IBL, has pixel dimensions of $50\mu\text{m}(\hat{\phi}) \times 250\mu\text{m}(\hat{z}) \times 200\mu\text{m}(\hat{r})$. For the other layers the dimensions are $50\mu\text{m}(\hat{\phi}) \times 400\mu\text{m}(\hat{z})$ for about 90% of the pixels and $50\mu\text{m}(\hat{\phi}) \times 600\mu\text{m}(\hat{z})$ for the others, all with a thickness of $250\mu\text{m}(\hat{r})$. This gives a total active area of 1.88m^2 collected through 92.4 million readout channels, more than half of the total number of channels for ATLAS. This detailed charged particle information very close to the interaction point is crucial not only for pattern recognition for track reconstruction, but also for the reconstruction of the primary and secondary verticies intrinsic to the decay of a b-hadrons, a critical element of the analysis presented in this thesis.

4.2.2 Semiconductor Tracker

Encompassing the Pixel Detector, the Semiconductor Tracker (SCT) [3] is composed of double sided silicon microstrips modules. Each side of the 4088 modules is constructed out of two silison strip sensors that are daisy chained togeather. The result is 768 composite strips each 12.6cm with an inter-strip pitch of 80μm. In the barrel the strips are alligned with the $\hat{z}$ direction, while in the end caps they are aligned with the $\hat{r}$ direction. In both cases the separation of the strips is constant in $\hat{\phi}$. The two sides are rotated with respect to eachother by 40μm to allow for position measurement along the length of the strip. These modules are then used to tile the 4 barrel layers and 9 disks per endcap (18 disks in total) as seen in figure 4.6. This design is choosen to ensure that each charged track interacts with 8 strip layers (equivalent to four space points). This information is used to further measure the momentum and impact parameter, and as well as vertex identification of charged particles.

4.2.3 Transition Radiation Tracker

The Transition Radiation Tracker [3], the outermoust subdetector of the ID, provides tracking through the detection of transition radiation from ultra-relativistic charged particles for $\eta < 2.0$ using 350,000 drift tube channels also known as straws. The 4mm diameter straws are filled with a 70% Xe, 27% CO_2, and 3% O_2 gas mixture and a 31μm diameter gold-plated tungsten wire anode at the center for the collection of the ionization signal. In the barrel 73 azimuthally symetric layers of 144cm straws are oriented parallel to the beam pipe with an electrical division in the center of each allowing the two sides to be read out separately. For each endcap the straws are radially oriented in 160 symmetric planes each containing 768 37cm long drift tubes showin in figure 4.6. In both the barrel and the end caps polypropylene fibers (barrel) or foils (encaps) function as the transition radiation material which causes the relativistic charged particles to radiate and thus ionize the gas in the straw. The ammount of transition radiation produced is proportional to the Lorentz factor meaning that lighter particles (e.g. electrons) will produce more radiation. Thus, by defining a high and low threshold, we can identify tracks belonging to electrons by requiring they register more high-threshold hits. There are typically 36 TRT hits per charged track.

4.3 Calorimetry

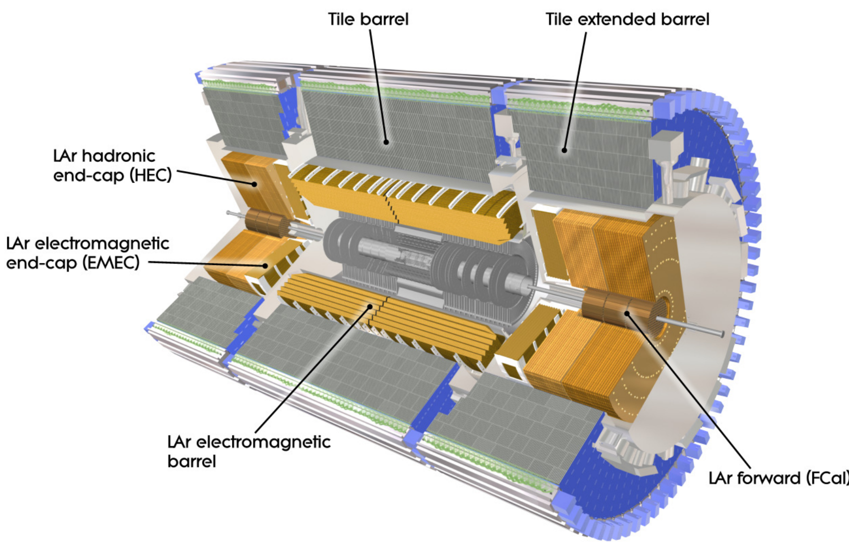


Figure 4.7: [3] A cutaway diagram of ATLAS's sampling calorimeters

Once the proton collision remnants have passed through the ID and it's surrounding solenoid they enter into the ATLAS calorimeters depicted in figure 4.7. Sampling calorimeter technologies were choosen for their compact geometry and lower cost point. These are constructed by alternating layers of absorber, a dense material which reduces the incedent particles energy, and active material which produces a detectible signal when a partilce passes through. This means that the detected signal is only a fraction of the total energy of the particle and thus requires a study of the calorimeter response for calibration purposes [9]. The first system, the Electromagnetic Calorimeter (EMC), is designed to measure the energy of electrons and photons which primarily lose their energy via bremstralung and pair production electromagnetic interactions. Outside of the EMC is the Hadronic Calorimeter (HC) which is designed to measure the energy of jets of hadrons through their electromagnetic and strong interactions. These detectors cover the entire $|\eta| < 4.9$ range and provide complete containment of both Electromagnetic and Hadronic showers with higher granularityi in the EMC for $|\eta| < 2.5$, the region matched to the ID, for precision measruements of electrons and photos. By instrumenting this huge space in $|\eta|$ we can search for events with asymetric energy deposits which imply the existence of a particle we didn't detect represented by missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$.

4.3.1 Electromagnetic Calorimeter

The innermost calorimeter, the Liquid Argon (LAr) Electromagnetic Calorimeter (EMC) [3], uses lead as the absorber and liquid argon as the active material in an "accordion geometry" as seen in figure 4.8. This geometry was choosen for uniform coverage in $\hat{\phi}$ due to its lack of un-instrumented cracks in the radial direction. The barrel region covers $|\eta| < 1.475$ and an end cap on each side covers $1.375 < |\eta| < 3.2$ each housed in their own cryostat. The barrel is composed of two half barrels with a 4mm gap at $z = 0$ and both end caps are divided into an intter wheel covering $2.5 < |\eta| < 3.2$ and an outer wheel covering $1.375 < |\eta| < 2.5$.

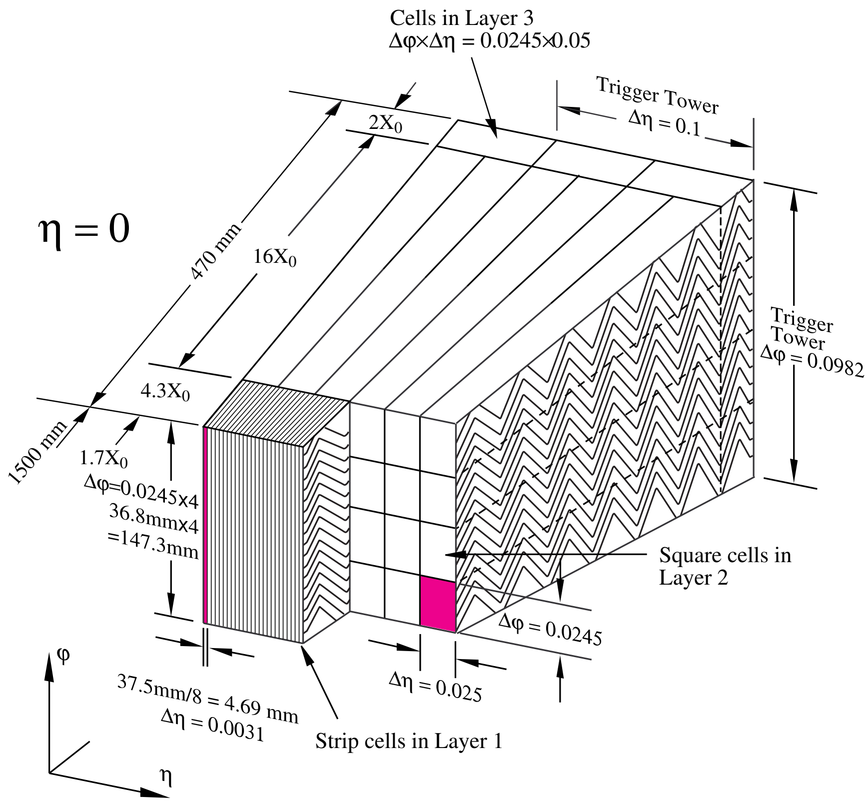


Figure 4.8: [3] Sketch of LAr EMC barrel module where the lead and liquid argon layers are visible in an accordion like geometry. Looking from the foreground to the back there are 3 different types of cells visible.

In the $|\eta| < 2.5$ region the EMC has 3 radial layers for precision physics measurements. Layer 1 consists of strip cells which are finely segmented with $\Delta\eta = 0.0031$ and $\Delta\phi = 0.0245$ allowing for precision position resolution which gives discrimination power between a single γ deposit and the π^0 characteristic $\gamma\gamma$ deposit. Layer 2 , which collects the largest fraction of energy from electromagnetic shower, is segmented with

$\Delta\eta = .025$ and $\Delta\phi = 0.0245$. Layer 3 collects the tail of the electromagnetic shower using a coarser segmentation of $\Delta\eta = .05$ and $\Delta\phi = 0.0245$. Additionally, in the region $|\eta| < 1.8$ a thin pre-sampler , which contains no lead absorber, was placed in front of Layer 1 to allow for energy corrections due to losses upstream of the EMC. Combined the EMC is > 22 radiation lengths (X_0) in the barrel and > 24 X_0 in the end-caps, where a radiation length is the average distance an electron travels in a given material before losing $1/e$ of its original energy E_0 via bremsstrahlung radiation.

4.3.2 Hadronic Calorimeter

Directly outside the EMC envelope is the Hadronic Calorimeter (HC) system [3] which consists of three sampling calorimeter technologies: the Tile calorimeter, the LAr hadronic end-cap calorimeter (HEC) and the LAr forward calorimeter (FCal). Combined, these three subsystems give measurements of hadronic jet energies in the $0 < |\eta| < 4.9$ range. The tile calorimeter uses steel as the absorber layer and scintillating tiles as the active material and covers the region $|\eta| < 1.7$ with a barrel section flanked by two barrel extensions each divided azimuthally into 64 modules. These scintillator tiles are read out on two sides by wave-length shifting fibers connected to photomultiplier tubes as seen in figure 4.9. At $\eta = 0$ the total tile calorimeter thickness is 9.7 nuclear interaction lengths (λ), where λ is the average distance a hadron travels before interacting inellastically with a nucleus.

The HEC is composed of two independent wheels per end-cap located just past the

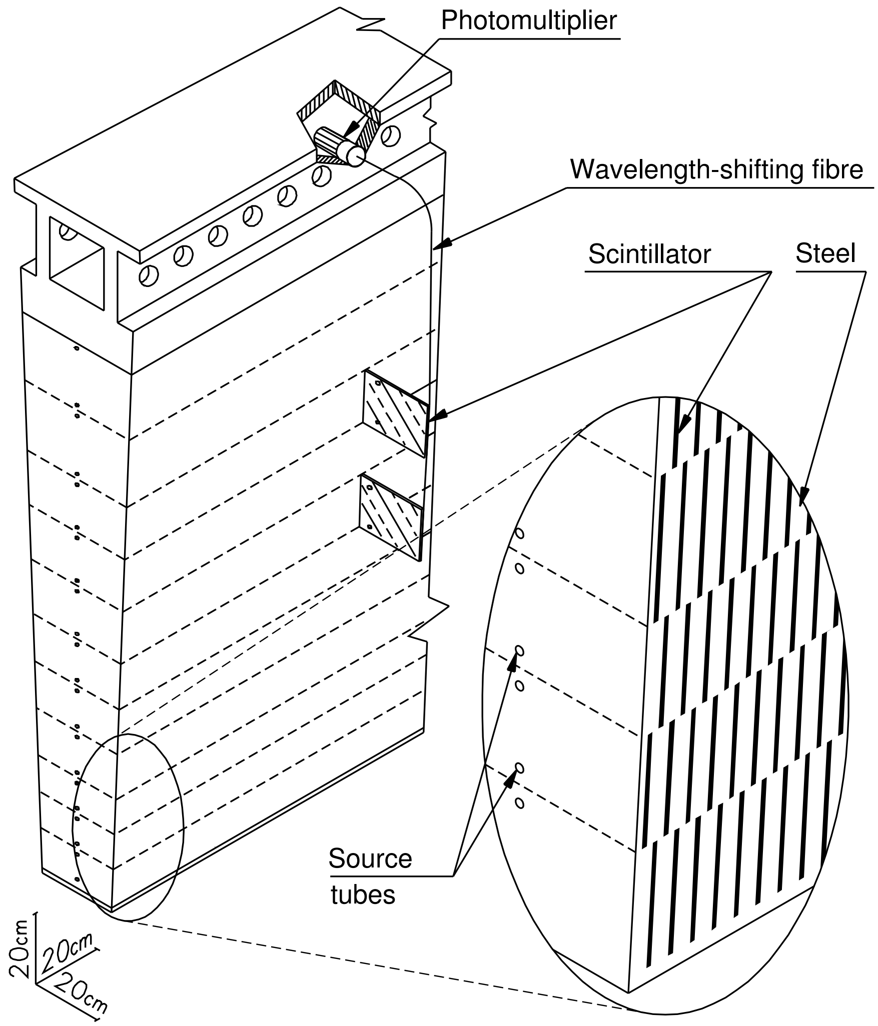


Figure 4.9: [3] Schematic of a tile calorimeter module including a depiction of the connection between the scintillator tile to the photomultiplier via a wavelength-shifting fibre.

EMC end-cap but sharing the same cryostat. This system uses copper as an absorber and liquid argon for the active material and covers the $1.5 < |\eta| < 3.2$ range using 32 wdge-shaped modules per wheel. Finally, the FCal shares the same cryostat as the EMC and HEC end-caps and acts to extend the coverage of the combined calorimeter system to include the $3.1 < |\eta| < 4.9$ range. Each endcap contains 3 modules, the first an electromagnetic module (Copper/Liquid-Argon) which is followed by two hadronic modules which use (Tungsten/Liquid-Argon.

4.4 Muon Spectrometer

The ATLAS Muon Spectrometer (MS) [3], see figure 4.10, accomplishes tracking of charged particles in the $|\eta| < 2.7$ region for momentum reconstruction while also providing triggering on charged particles in the $|\eta| < 2.4$ region. The magnetic field necessary for momentum reconstruction is provided by 3 air core torroid systems, one barrel torrioid covering $|\eta| < 1.4$ and two endcap torroid systems which are inserted into the inner radius of the the barrel torroid to cover the $1.6 < |\eta| < 2.7$. The so called transition region $1.4 < |\eta| < 1.6$ between these two magnet systems is covered by a combination of the barrel and endcap torroid magnets. Similar to the ID the resolution is inversely proportional to the particle's incident momentum. Any muon with pT lower than 3GeV will never make it to the MS and thus will not be detected.

Precision tracking measurements for momentum reconstruction is accomplished using

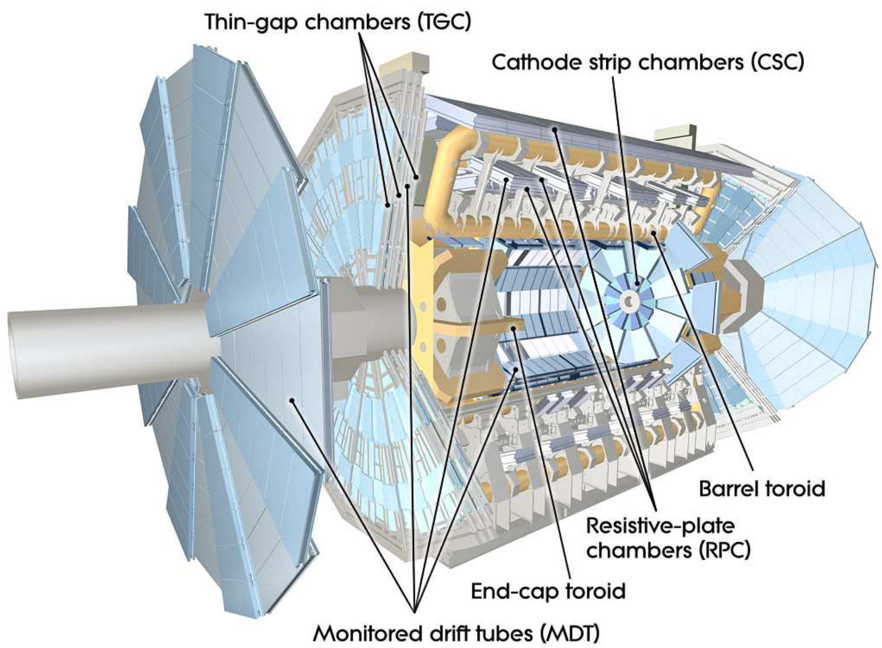


Figure 4.10: [3] A cut-away diagram of the ATLAS muon system and its many sub-detectors.

the Monitored Drift Tube chambers (MDTs) for $|\eta| < 2.0$ and using Cathode-Strip Chambers (CSCs) for $2.0 < |\eta| < 2.7$. The MDT system consists of 1163 drift tube chambers arranged in three to eight layers for varying η. The CSCs are designed to withstand the higher rate and retain good time resolution using multiwire proportional chambers with orthogonal segmented cathode planes.

The MS also gives nanosecond tracking information for triggering on muon tracks. This is accomplished using Resistive Plate Chambers (RPC) in the barrel region $|\eta| < 1.05$ and Thin Gap Chambers (TGC) in the end-cap $1.05 < |\eta| < 2.4$ region. Both chamber systems deliver a triggerable signal with a spread of $15-25$ ns, thus providing the ability to tag individual beam-crossings.

Chapter 5

Boosted Higgs at the LHC

Its July 4th, 2012 and the walls of building 500 are reverberating as Particle Physicists around the world rejoice the discovery of the particle that gives all things mass, the Higgs Boson.

5.1 Physics beyond the Stnadard Model

5.2 Higgs Production Mechanisms

5.3 Branching Ratios

5.4 Discovery

5.5 Fermion Decay Modes

5.6 Boosted Higgs

Part III

The HbbISR Analysis

Chapter 6

Data and Simulation Preparation

In order to compare data to theory ATLAS has developed an anlysis chain which runs both real data and simulated samples through the same processing, assuring a final result which is as comprable as possible.

6.1 Data Used

6.2 Monte Carlo Samples

Chapter 7

Physics Object Selection

After the ATHENA Digitization step both data and monte carlo have the same format, representing the three dimentional energy deposits. In order to analyze these deposits they are cleaned, clustered and checked for overlap resulting in physics objects useful for our specific analysis.

7.1 Calorimeter Jets

7.2 Track Jets

7.3 Fat Jets

7.4 B-tagged Jets

7.5 Muons

7.6 Overlap Removal

Chapter 8

Event Selection

Having created our physics objects we begin to make selections of what types of events we want to consider given the goal of our analysis. In our boosted topology this means considering things like momentum, jet collection efficiencies and background rejection.

8.1 Selected Triggers

8.2 Pre-selection Studies

8.3 Signal Selection

8.4 Optimisation

Chapter 9

Background Estimation

The dominant background was QCD. I worked on the ttbar control region. The Vqq and single top backgrounds were estimated from monte carlo.

9.1 Multi-jet QCD estimation

9.2 $t\bar{t}$ control region

9.3 Single top estimation

9.4 Hadronic vector boson channel

Chapter 10

Systematic Uncertanties

10.1 Theoretical Uncertanties

10.2 Experimental Uncertanties

Chapter 11

Statistical Fit

The statistical fit in our analysis was accomplished using a framework developed for Higgs searches.

11.1 Profile Likelihood Function

11.2 Fit Configruation

11.3 Statistical Tests

Chapter 12

Results

12.1 Expectations

12.2 Statistical Analysis Results

12.3 Measurements and Limits

Part IV

Conclusion

Chapter 13

Conclusion

I conclude that this secion is the conclusion

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Appendix A

Hadronic Vqq Sherpa Studies

Ancillary material should be put in appendices, which appear after the bibliography.