

My Thesis

by

Name

A dissertation submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
(Department)
in the University of Michigan
2020

Doctoral Committee:

Member 1, Chair
Member 2
Member 3
Member 4
Member 5

Name

name@umich.edu

ORCID ID: My Orcid ID

© Name 2020

Dedicated to...

ACKNOWLEDGEMENTS

I would like to acknowledge...

TABLE OF CONTENTS

LIST OF FIGURES

FIGURE

LIST OF TABLES

TABLE

LIST OF APPENDICES

APPENDIX

LIST OF ABBREVIATIONS

ABSTRACT

My Abstract.

CHAPTER 1

An Overview of the Standard Model

1.1 The Standard Model

The Standard Model of Particle Physics is arguably one of the crowning achievements of the last century of physics research. Though it is doubtless incomplete (it does not, for instance, explain the dark energy or dark matter observed in cosmological experiments, nor does it provide a satisfactory quantum-mechanical model of gravity), all predictions it has made have yet to be falsified ??, ??, ??.

The Standard Model is a quantum field theory, meaning that it describes the behavior of fields (physical quantities that are defined at all points in spacetime; common examples of fields include electric and magnetic fields) and their discrete, quantized excitations, referred to as particles (common examples of particles are the electron and the photon, which are excitations of the "electron field" and the electromagnetic field respectively). More about the mathematics of field dynamics will be discussed in section ??.

The Standard Model divides these fundamental particles (and their corresponding fields) into two major categories: the bosons and the fermions. Fermions carry half-integer spin, while bosons carry integer spin. In a general sense, the elementary fermions can be thought of as the particles that comprise matter, while the elementary bosons can be thought of as the particles that correspond to the behavior of the four fundamental forces (electromagnetism, the strong nuclear force, the weak nuclear force, and gravity).

The elementary fermions of the Standard Model all have spin 1/2. They are divided into two major subgroupings, quarks and leptons; each of these is further divided into three generations. Each generation of quarks contains one up-type quark (up, charm, or top) and one down-type quark (down, strange, and bottom), while each generation of leptons contains one charged lepton (electron, muon, or tau) and one neutrino (electron neutrino, muon neutrino, or tau neutrino). Fermions of successive generations behave similarly to each other, though those of each subsequent generation are more massive than the last.

The quarks are the only fermions that undergo both the strong and weak nuclear interactions, and are also the only particles in the Standard Model that have fractional electromagnetic charge (+2/3 for up-type quarks and -1/3 for down-type quarks). However, because quarks are never found in isolation and are always bound to other quarks in composite states called hadrons, all observable quark final states have integer charge. Conversely, the charged leptons all have an electromagnetic charge of -1, while neutrinos are chargeless. While the quarks and charged leptons have precisely-measured masses, the mass of the neutrinos is vanishingly small, and, to date, only the differences between the different neutrino masses have been conclusively measured.

In addition to these 12 fermion species, each fermion species has a corresponding antimatter "antifermion" species, which has the opposite charge and parity quantum numbers. This is discussed at length in section ??.

The bosons of the standard model are the "messengers" through which the fundamental forces operate (with the exception of the Higgs boson, which is detailed at length in section ??). The photon and the gluons are massless, while the two W-bosons, the Z-boson, and the Higgs boson are all massive. The photon is the mediator of the electromagnetic force and couples to charged particles; the gluon is the mediator of the strong nuclear force and couples to particles with "color charge", and the W and Z bosons are the mediators of the weak nuclear interaction, coupling to all fermions with left-handed parity and antifermions with right-handed parity. In addition, the three weak bosons (W^+ , W^- , and Z) can all couple to each other, as can the gluons.

The strong nuclear interaction binds quarks together, while the weak interaction governs the decay of one species of fermion into another. Weak interactions operate primarily on fermion doublets, coupling each up-type quark to its corresponding down-type quark and each charged lepton to its corresponding neutrino. However, some intergenerational coupling does occur, the rarity of which is governed by a matrix of coefficients called the Cabibbo-Kobayashi-Makasawa (or CKM) matrix.

The Higgs boson is the only scalar (spin-0) boson in the Standard Model. Though it does not mediate any force directly, its existence is a consequence of the unification of the electromagnetic and weak nuclear interactions into one "electroweak" interaction at high energy scales. Without the role of the Higgs boson in this process, the fermions, the W-bosons, and the Z-boson would all be massless; thus, the Higgs can be said to "give mass" to the particles of the Standard Model. It couples to all massive particles in the Standard Model, namely, the fermions and the W and Z bosons.

Standard Model of Elementary Particles

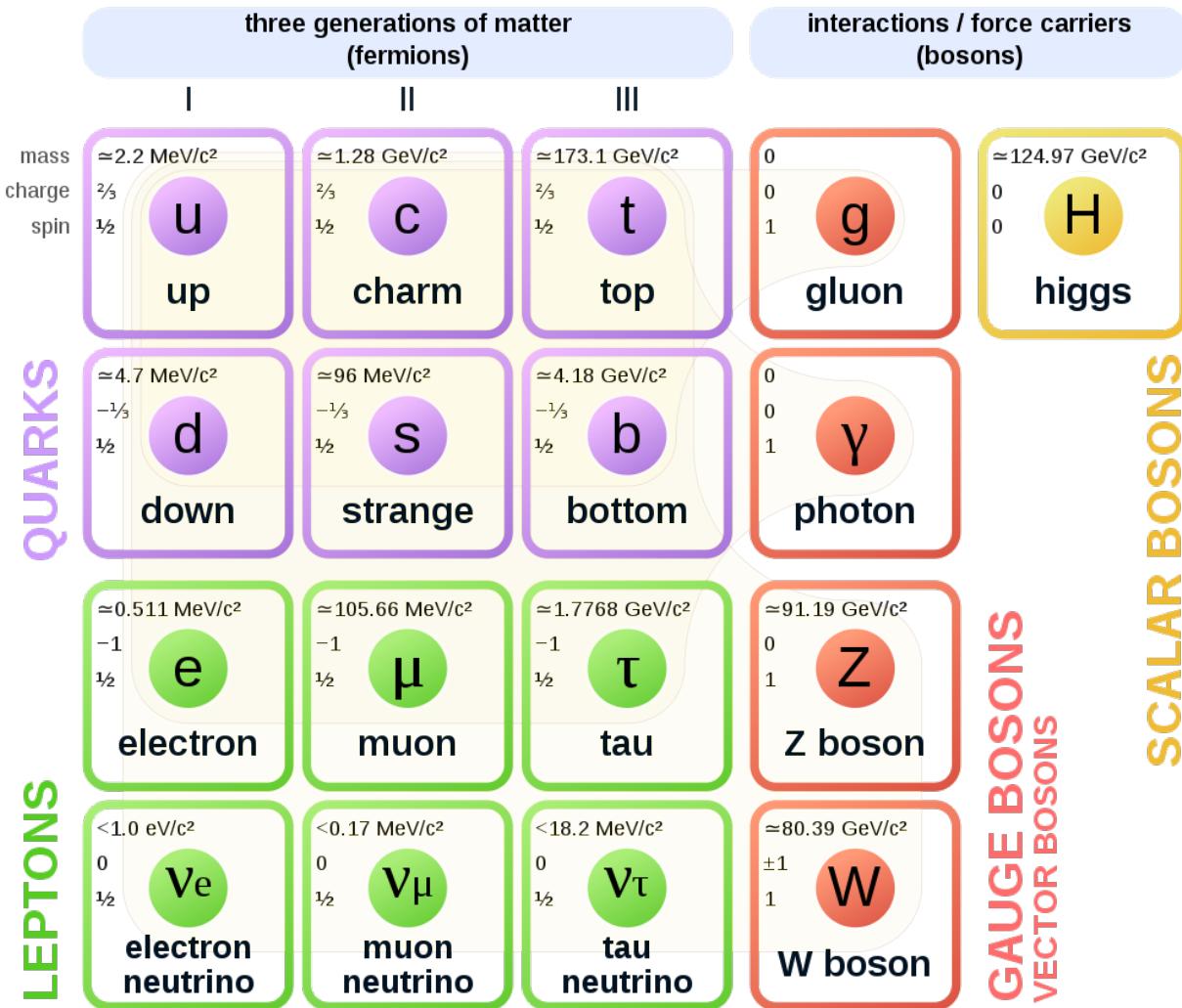


Figure 1.1: The "periodic table" of the Standard Model, depicting the three generations of fermions, the gauge bosons, and the Higgs. Taken from reference ??.

1.1.1 Lagrangians, Fields, and Gauge Transformations

In order to fully explain the Higgs mechanism, we must first discuss the mathematical language of quantum field theory. Both quantum and classical field theories are often discussed using Lagrangian dynamics, where the Lagrangian is defined as $\mathcal{L} = T - V$, the difference of the kinetic and the potential energy. Physical properties will always evolve in such a way that the integral of this property with respect to time, $S = \int \mathcal{L} dt$, called the action, is a constant. Lagrangians are also incredibly useful in that they give rise to conservation laws: Noether's Theorem states that operations performed on a system that do not change the Lagrangian are each associated to conserved quantities of a system (i.e., systems with translationally invariant Lagrangians must respect conservation of momentum, systems with temporally-invariant Lagrangians must respect conservation of energy, etc.).

A variety of types of fields exist, but we will discuss three at length: Klein-Gordon fields, which are scalar fields (single quantities defined everywhere), Dirac spinor fields (vector quantities defined everywhere), and gauge fields (additional vector fields that must be introduced in order to preserve certain physical symmetries). We begin with the Klein-Gordon field.

Klein-Gordon fields, one of the simplest examples of a field, are real scalar-valued quantities often denoted using the symbol ϕ . A non-interacting "free" Klein-Gordon field evolves according to the Lagrangian:

$$\begin{aligned} \mathcal{L} &= T - V \\ &= \frac{1}{2} \frac{\partial^2 \phi}{\partial t^2} - \frac{1}{2} (\nabla \phi)^2 - \frac{1}{2} m^2 \phi^2 \\ &= -\frac{1}{2} (\partial^\mu \phi) (\partial_\mu \phi) - \frac{1}{2} m^2 \phi^2 \end{aligned} \tag{1.1}$$

where we utilize Einstein sum notation in the last line to compress the four derivatives in the preceding expression into a single shorthand symbol. The Lagrangian of an interacting Klein-Gordon field would look similar, but would possess additional V potential terms depending on the nature of the interaction. As the only scalar in the Standard Model, the observable Higgs boson is the only elementary particle to follow an interacting Klein-Gordon field equation.

While the concept of a complex-valued scalar field does not directly correspond to any of the physical elementary particles that are present in the Standard Model, it plays an important role in the understanding of the Higgs mechanism. A complex-valued scalar field behaves similarly to a real-valued one, with the Lagrangian:

$$\mathcal{L} = (\partial^\mu \phi^*) (\partial_\mu \phi) - \frac{1}{2} m^2 \phi^* \phi \tag{1.2}$$

Where $*$ denotes the complex conjugate of the scalar field.

Finally, Dirac fields describe all Standard Model fermions (with the possible exception of neutrinos). They are vector fields as opposed to scalar fields, and behave according to the Lagrangian:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi \quad (1.3)$$

where γ^μ denotes the set of Dirac gamma matrices, and $\bar{\psi} = \psi^\dagger \gamma^0$ denotes the transpose of the complex conjugate of the vector field multiplied by one of these matrices, defined as such in order to preserve invariance under relativistic Lorentz boosts.

A four-component Dirac vector field can be written in a variety of representations, but one of the most useful is that of a doublet of two two-component Weyl spinors, one left-handed and one right-handed, that is, $\psi = \begin{pmatrix} \psi_L \\ \psi_R \end{pmatrix}$. Each of these components transforms differently under Lorentz boosts.

In order to discuss the gauge fields corresponding to the Standard Model bosons, we must first discuss the concept of gauge symmetries. Consider a single Dirac vector field described by equation ???. We transform the field by rotating it by a constant phase α : $\psi \rightarrow e^{i\alpha}\psi$, $\bar{\psi} \rightarrow e^{-i\alpha}\bar{\psi}$.

$$\begin{aligned} \mathcal{L} &= -(e^{-i\alpha}\bar{\psi})(i\gamma^\mu \partial_\mu - m)(e^{i\alpha}\psi) \\ &= -(e^{-i\alpha}e^{i\alpha})\bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi \\ &= -\bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi \end{aligned} \quad (1.4)$$

We see that we recover the original Dirac Lagrangian. Thus, the lagrangian is invariant under a constant phase rotation. A transformation of this character is called a global gauge transformation. A one-dimensional rotation is a unitary transformation, so we call this a global $U(1)$ gauge symmetry.

We next consider the concept of a local gauge transformation, that is, one in which the phase α may vary with position. The field transforms, as before, like $\psi \rightarrow e^{i\alpha(x)}\psi$, $\bar{\psi} \rightarrow e^{-i\alpha(x)}\bar{\psi}$. However, we note that the dependence on position means that we can no longer factor out the exponentials, and we thus have

$$\begin{aligned} \mathcal{L} &= -(e^{-i\alpha(x)}\bar{\psi})(i\gamma^\mu \partial_\mu - m)(e^{i\alpha(x)}\psi) \\ &= -ie^{-i\alpha(x)}\bar{\psi}\gamma^\mu(e^{i\alpha(x)}\partial_\mu\psi + ie^{i\alpha(x)}\psi\partial_\mu\alpha - m\bar{\psi}\psi) \\ &= -\bar{\psi}(i\gamma^\mu \partial_\mu + \gamma^\mu \partial_\mu\alpha - m)\psi \end{aligned} \quad (1.5)$$

i.e., the Lagrangian is not invariant under this sort of transformation. However, local gauge invariance is an important physical symmetry, so in order to attempt to preserve it, we add an additional term to the original Lagrangian: an extra vector field A_μ that transforms like $A_\mu \rightarrow A_\mu - \frac{1}{q}\partial_\mu\alpha(x)$ for a constant q . We also define a new operator, called the covariant derivative: $D_\mu = \partial_\mu + iqA_\mu$. Given how A_μ transforms, we see that D_μ transforms like

$$\begin{aligned}
D_\mu &= \partial_\mu + iqA_\mu \\
\rightarrow \partial_\mu &+ iq(A_\mu - \frac{1}{q}\partial_\mu\alpha(x)) \\
&= \partial_\mu + iqA_\mu - i\partial_\mu\alpha(x) \\
&= D_\mu - i\partial_\mu\alpha(x)
\end{aligned} \tag{1.6}$$

Let us replace the $\partial_\mu\phi$ terms in the initial Lagrangian with $D_\mu\phi$ and transform.

$$\begin{aligned}
\mathcal{L} &= -(e^{-i\alpha(x)}\bar{\psi})(i\gamma^\mu(D_\mu - i\partial_\mu\alpha(x)) - m)(e^{i\alpha(x)}\psi) \\
&= -(e^{-i\alpha(x)}\bar{\psi})(i\gamma^\mu(\partial_\mu + iqA_\mu - i\partial_\mu\alpha(x)) - m)(e^{i\alpha(x)}\psi) \\
&\quad = -\bar{\psi}(i\gamma^\mu D_\mu + \gamma^\mu\partial_\mu\alpha - \gamma^\mu\partial_\mu\alpha - m)\psi \\
&\quad = -\bar{\psi}(i\gamma^\mu D_\mu - m)\psi
\end{aligned} \tag{1.7}$$

Thus, by introducing an additional vector field that corresponds to the local U(1) gauge symmetry, we have restored the invariance of our lagrangian. Physically, this field is analogous to the introduction of electromagnetism to our single Dirac fermion model, with the A_μ field playing the role of the photon: it is a vector quantity and so has spin-1, it must be massless (as adding an A_μ mass term to the Lagrangian would violate the symmetry again), and couples to the fermion fields according to their electromagnetic charge. We note that we can also still preserve invariance if we add an additional term $L_{kin} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu}$ to the Lagrangian, where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$: this corresponds to the energy inherent in electromagnetic fields themselves.

Each of the fundamental forces in the Standard Model can be understood in terms of these sorts of gauge symmetries. The photon is the particle excitation of the electromagnetic field, which corresponds to a one-dimensional rotation "U(1)" transformation. In order to be invariant under three dimensional transformations of the type "SU(3)" (the set of all volume-preserving, $\bar{\psi}\psi$ -preserving transformations in a 3D vector space), we must add eight new vector fields (these are the eight gluons), leading to the incorporation of the strong interaction into the Standard Model.

Similarly, in order to be invariant under two-dimensional transformations of the type "SU(2)" (the set of all volume-preserving, $\bar{\psi}\psi$ -preserving transformations in a 2D vector space), we must add three new vector fields. However, these cannot be the observed weak-interaction bosons, the W^+, W^- and Z : as mentioned before, the new fields must be massless, as adding a mass term for these bosons would violate the local gauge symmetry. How, then, can the masses of the weak bosons fit into the Standard Model? The answer lies in the introduction of yet another field, called the Higgs field, the particle excitation of which is the much-lauded Higgs boson.

1.2 CP-Symmetry

In addition to the $SU(2)_L \times U(1) \times SU(3)$ gauge symmetry, the Standard Model also respects a discrete symmetry called CPT. This is the combined product of three separate symmetries: charge conjugation (C), parity inversion (P), and time reversal (T). While some interactions may respect a limited combination of these symmetries (i.e., just C, or the product CP), all Standard Model processes must respect the product of the three: that is, for a given physics process, if we invert all the charges, flip all the parities, and run the interaction backward, the resulting new process must also be physically allowed.

The strong nuclear, electromagnetic, and gravitational interactions are symmetric under C, P, and T individually. The weak nuclear interaction, however, is invariant only under the combination of all three: it violates C, P, and, in some cases, CP. The CP violation that occurs in the weak interaction is through the CKM off-diagonal quark-mixing matrix mentioned briefly in section ??.

A parity inversion is equivalent to reversing a particle's momentum without reversing its spin. For a fermion field $\psi(t, x)$, a parity transform P takes $\psi(t, x)$ to $\psi(t, -x)$, and looks like $P\psi(t, x)P = e^{i\theta}\gamma^0\psi(t, -x)$ for some constant matrix θ .

Given this, we find that the expression $P\bar{\psi}\psi P = \bar{\psi}\psi$, so $\bar{\psi}\psi$ is a *scalar* under parity, while the expression $iP\bar{\psi}\gamma^5\psi P = -i\bar{\psi}\gamma^5\psi$ acquires a minus sign, so $i\bar{\psi}\gamma^5\psi$ is a *pseudoscalar* under parity.

A time-reversal is equivalent to "running a process backward". For example, a swinging pendulum is a process that is approximately T symmetric, as it looks similar "played" in forward or reverse, while a plate shattering on the ground is not a T symmetric process, as reversing it does not make physical sense (broken plates do not spontaneously reform). For a fermion field $\psi(t, x)$, a time-reversal transform T takes $\psi(t, x)$ to $\psi(-t, x)$, and looks like $T\psi(t, x)T = -\gamma^1\gamma^3\psi(-t, x)$. Given this, we find that the expression $T\bar{\psi}\psi T = \bar{\psi}\psi$, so $\bar{\psi}\psi$ is a *scalar* under parity, while the expression $iT\bar{\psi}\gamma^5\psi T = -i\bar{\psi}\gamma^5\psi$ acquires a minus sign, so $i\bar{\psi}\gamma^5\psi$ is a pseudoscalar under time-reversal.

A charge conjugation is a reversal of all charges (electric charge, weak hypercharge, and strong-nuclear color charge). For a fermion field $\psi(t, x)$, a charge conjugation transform C takes ψ to $\bar{p}\bar{\psi}$, and looks like $C\psi C = -i(\bar{\psi}\gamma^0\gamma^2)^T$ (where T here denotes the matrix transpose). Given this, we find that the expression $C\bar{\psi}\psi C = \bar{\psi}\psi$, so $\bar{\psi}\psi$ is a *scalar* under charge conjugation, as is the expression $iC\bar{\psi}\gamma^5\psi C = i\bar{\psi}\gamma^5\psi$ as well. Thus, Lagrangians containing terms of the form $i\bar{\psi}\gamma^5\psi$ are invariant under C and CPT, but not P, T or CP.

Applying C and P together is equivalent to switching particles and antiparticles. However, we also know that our universe is composed almost entirely of matter, and not equal parts matter and antimatter (living in a universe in which matter and antimatter are equally abundant would be very unpleasant, as the two would be constantly annihilating each other, bathing us in a near-constant

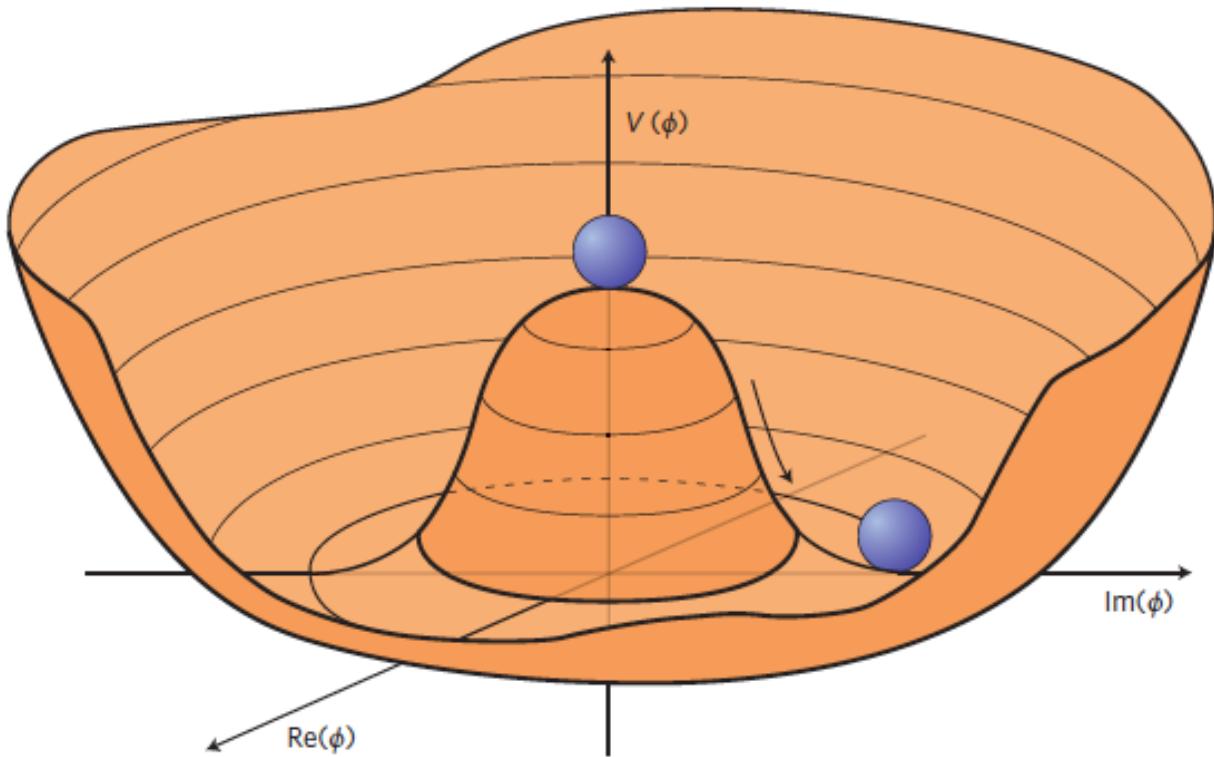


Figure 1.2: The "wine bottle" or "Mexican hat" potential hill, from reference ??

shower of gamma rays). Thus, some physics process that occurs in the high-energy regime near the Big Bang must violate CP in a substantial way. The CP-invariance that occurs through the CKM mixing is not enough to account for the matter-antimatter asymmetry, so searching for this source of CP violation is of pressing interest to experimental physicists.

1.3 The Higgs Mechanism and Electroweak Symmetry Breaking

Given the results of previous sections, it should be clear that the Higgs field is important not simply because it "gives particles mass" (an often-made claim which is, in a sense, true), but because it is a vital missing piece of the Standard Model that is necessary to reconcile the elegant mathematical language of the fundamental interactions with the particles we observe in real-world experiments.

To understand the Higgs mechanism, we must first devote a brief detour to the concept of spontaneous symmetry breaking. This occurs when an unstable, continuous symmetric state spontaneously changes into a more stable, asymmetric one. Consider, for example, the "wine-bottle" potential shape depicted in figure ??.

When the ball is balanced at the top of the potential "hill", the configuration is spatially symmetric: that is, no direction is privileged over any other. However, when this delicate balance is even slightly disturbed, the ball will roll down the hill in some direction, resulting in a final state that is *not* symmetrical. This is the phenomenon known as "spontaneous symmetry breaking".

Using the language of quantum field theory, we can easily add spontaneously-breakable symmetric potential terms to a Lagrangian. If we do so, the phenomenon of symmetry breaking allows us to rewrite these terms as a combination of massless fields (one for each "choice" the symmetry breaking must make) and massive fields (corresponding to the leftover degrees of freedom). If we rewrite the "wine-bottle" potential in this way, for example, the one new massless field corresponds to the ball's angular position along the circle at the base, while the massive field corresponds to the ball's radial position "up" or "down" the hill. The massless particles that arise from these massless fields are known as Goldstone bosons.

We are now ready to discuss the Higgs mechanism. We can combine the electromagnetic and weak nuclear forces as different manifestations of the same force, called the electroweak force, that transforms like $U(1) \times SU(2)$. We write the terms of the Standard Model electroweak Lagrangian, noting that, since the weak interaction is observed to be chiral, it couples differently to left- and right-handed fermions.

In this case, the generator of the $U(1)$ symmetry ($\alpha(x)$) is not the electric charge Q as in our previous example, but is instead the "Weak Hypercharge" $Y = 2(Q - I_3)$, where I_3 is the third component of the "Weak Isospin" I . For right-handed particles, $I_3 = 0$, for left-handed up/charm/top quarks and neutrinos, $I_3 = +\frac{1}{2}$, and for left-handed down/strange/bottom quarks and charged leptons, $I_3 = +\frac{1}{2}$. We will call our $U(1)$ boson B_μ rather than A_μ , to distinguish it from the photon. For a fermion ψ (u/c/s/e/ μ/τ) that couples weakly to another fermion ψ' , we can write the left-and-right-handed components of f as

$$L = \begin{pmatrix} \psi_L \\ \psi'_L \end{pmatrix}, R = \begin{pmatrix} \psi_R \end{pmatrix}.$$

Similarly, the generators of the $SU(2)$ symmetry are the three matrices τ_i , one corresponding to each weak boson W_i^μ . The self-interaction term for the weak interaction is $L_{kin} = -\frac{1}{4}G^{\mu\nu}G_{\mu\nu}$, where $G_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + \frac{g}{2}W_\mu \times W_\nu$.

We can define a new covariant derivative capturing the weak interaction terms as well: $D^\mu = \partial^\mu - \frac{1}{2}iYg_1B^\mu - \frac{1}{2}iIg_2\Sigma\tau_iW_i^\mu$. Thus, the full electroweak $SU(2)_L \times U(1)$ Lagrangian is:

$$\mathcal{L} = i\bar{R}\gamma^\mu D_\mu R + i\bar{L}\gamma^\mu D_\mu L - \frac{1}{4}G^{\mu\nu}G_{\mu\nu} - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} \quad (1.8)$$

However, we note that this Lagrangian does not allow for gauge boson mass or fermion mass, as a fermion mass term $m\bar{\psi}\psi = m(\bar{\psi}_R\psi_L + \bar{\psi}_L\psi_R)$ is not an $SU(2)$ singlet and would thus not be invariant under the $SU(2)$ symmetry.

To rectify this, we can introduce a new complex SU(2) doublet scalar field $\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$ called the *Higgs field*. It follows the Lagrangian

$$\mathcal{L} = T - V = (D^\mu \phi)^\dagger (D_\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2 \quad (1.9)$$

which, if $mu^2 < 0$ has a minimum at

$$\phi^\dagger \phi = \frac{-\mu^2}{2\lambda} = \frac{v^2}{2} \quad (1.10)$$

We note that the potential is symmetric, so we can pick a direction to "break the symmetry" in. Let us define the vacuum as $\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$. Then, for any arbitrary configuration of the field, we can expand the potential about the minimum as $\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ (v + h(x)) \end{pmatrix}$.

We can expand the kinetic term in the Lagrangian as

$$(D^\mu \phi)^\dagger (D_\mu \phi) = \frac{1}{2} (\partial_\mu h)(\partial^\mu h) + \phi^\dagger \left(\frac{1}{2} i Y g_1 B_\mu - \frac{1}{2} i I g_2 \sum \tau_i W_{i\mu} \right)^\dagger \left(\frac{1}{2} i Y g_1 B^\mu - \frac{1}{2} i I g_2 \sum \tau_i W_i^m u \right) \phi \quad (1.11)$$

Which, using the definitions of the three tau matrices, and putting $Y = I = 1$, becomes

$$\begin{aligned} & \frac{1}{2} (\partial_\mu h)(\partial^\mu h) + \frac{1}{8} \left| \begin{bmatrix} g_1 B_\mu + g_2 W_\mu^3 & g_2 (W_\mu^1 - i W_\mu^2) \\ g_2 (W_\mu^1 + i W_\mu^2) & g_1 B_\mu + g_2 W_\mu^3 \end{bmatrix} \begin{bmatrix} 0 \\ v \end{bmatrix} \right|^2 \\ &= \frac{1}{2} (\partial_\mu h)(\partial^\mu h) + \frac{1}{8} v^2 g_2^2 ((W_\mu^1)^2 + (W_\mu^2)^2) + \frac{1}{8} v^2 (g_1 B_\mu - g_2 W_\mu^3)^2 \end{aligned} \quad (1.12)$$

If we again define some new field combinations here: $W_\mu^+ = \frac{1}{\sqrt{2}} (W_\mu^1 - i W_\mu^2)$, $W_\mu^- = \frac{1}{\sqrt{2}} (W_\mu^1 + i W_\mu^2)$, $Z_\mu = \frac{g_1 B_\mu + g_2 W_\mu}{\sqrt{g_1^2 + g_2^2}}$ and $A_\mu = \frac{g_1 B_\mu - g_2 W_\mu}{\sqrt{g_1^2 + g_2^2}}$, then we get:

$$\frac{1}{2} (\partial_\mu h)(\partial^\mu h) + \left(\frac{1}{2} v g_2 \right)^2 W_\mu^+ W_\mu^- + \left(\frac{1}{2} v (\sqrt{g_1^2 + g_2^2}) \right)^2 Z_\mu \quad (1.13)$$

And we see that Z field and the two W fields have acquired mass terms, while the A field has remained massless. This corresponds to what we observe in the real world: the W bosons and the Z boson are massive, while the photon remains massless!

For fermions, the coupling to the Higgs field looks like $g_f (\bar{f}_L \phi f_R + \phi^\dagger \bar{f}_R f_L)$ (for some constant g_f).

We note that, if we expand $\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ (v + h(x)) \end{pmatrix}$ as before, we find that the coupling term now looks like $\frac{g_f v}{\sqrt{2}} (\bar{f}_L f_R + \bar{f}_R f_L) + \frac{g_f}{\sqrt{2}} (\bar{f}_L f_R + \bar{f}_R f_L)$. Thus, the presence of the Higgs field allows us to have fermion mass terms in our Lagrangians, where the masses are $m_f = \frac{g_f v}{\sqrt{2}}$. However, we note that, at the current time, there is no way to derive the g_f coupling theoretically: thus, while the Higgs mechanism now allows us to have massive fermions in our theory, it does not actually determine what the masses of these fermions are.

Finally, we note that if we expand the potential term in the complex Klein-Gordon Lagrangian for the Higgs field about the minimum, that is,

$$\begin{aligned} V &= \mu^2 \phi^\dagger \phi + \lambda(\phi^\dagger \phi)^2 = \frac{1}{2} \mu^2 (v + h)^2 + \frac{1}{4} \lambda (v + h)^4 \\ &\quad = -\frac{1}{2} \lambda v^2 (v + h)^2 + \frac{1}{4} \lambda (v + h)^4 \\ &= -\frac{1}{2} \lambda (v^4 + 2v^3 h + v^2 h^2) + \frac{1}{4} \lambda (v^4 + 4vh^3 + 6v^2 h^2 + 4v^3 h + h^4) \end{aligned} \tag{1.14}$$

we see a mass term of the form $(\frac{M_h^2}{2})h^2 = \frac{6}{4} \lambda v^2 h^2 - \frac{1}{2} \lambda v^2 h^2 = \lambda v^2 h^2$; That is, $M_h = v\sqrt{2\lambda}$.

In sum: without a Higgs field, in order for the Standard Model electroweak Lagrangian to preserve $SU(2)_L \times U(1)$ symmetry, we are forbidden from including mass terms for the fermions or the gauge bosons. However, by adding this additional field to the model and breaking its symmetry, we find that we can include fermion mass terms that do not violate the $SU(2)_L \times U(1)$ symmetry, and that the electroweak gauge bosons now acquire mass terms by default. Furthermore, this new field also has a mass. This is a remarkable result: by simply adding one extra field to the model, we have solved several different problems in one fell swoop!

1.4 The Higgs Boson and Its Couplings

As we have seen, the Standard Model Higgs is massive, and couples directly to all other massive particles (with the possible exception of neutrinos; this is an active area of research). However, the existence of the Higgs is clearly not all there is to the story: the Standard Model is noticeably incomplete (What are dark matter and dark energy? What determines the exact masses of each of the fermions? Why have we never observed right-handed neutrinos? Can we unify other forces like we have unified electromagnetism and the weak force?). In the majority of proposed Beyond-the-Standard Model extensions, other particles that would interact with the Standard Model Higgs are introduced, including additional Higgs fields, as well as new massive fermions and bosons.

With the discovery of the Higgs, it can be argued that we have now entered an era of precision-measurement in collider physics. By closely studying interactions that are very sensitive to the

injection of new physics, we can potentially detect deviations from the Standard Model: in many cases, we may see hints of the existence of new particles through changes to quantities of interest well before we are actually able to produce these particles in colliders directly. Due to the Higgs coupling to all massive particles, Higgs interactions are especially sensitive to new physics, and thus can serve as a useful bellwether for physics beyond the standard model.

The Large Hadron Collider is a proton-proton collider; as such, physics processes that occur in it are almost always initiated by quarks or gluons. The predominant production modes are, in order of frequency, gluon-gluon fusion (ggF), vector boson fusion (VBF), vector-boson associated (VH) and top-associated (ttH). The top-associated Higgs production mode is of particular interest to many experimentalists due to its direct dependence on the Higgs coupling to a fermion- by closely measuring the frequency and properties of the ttH mode, we can better understand the nature of this variety of couplings. Rarer production modes, such as single-top associated Higgs production (tH), can shed still more light on the nature of the top-quark/Higgs coupling (called the top quark Yukawa coupling), but are much more difficult to observe.

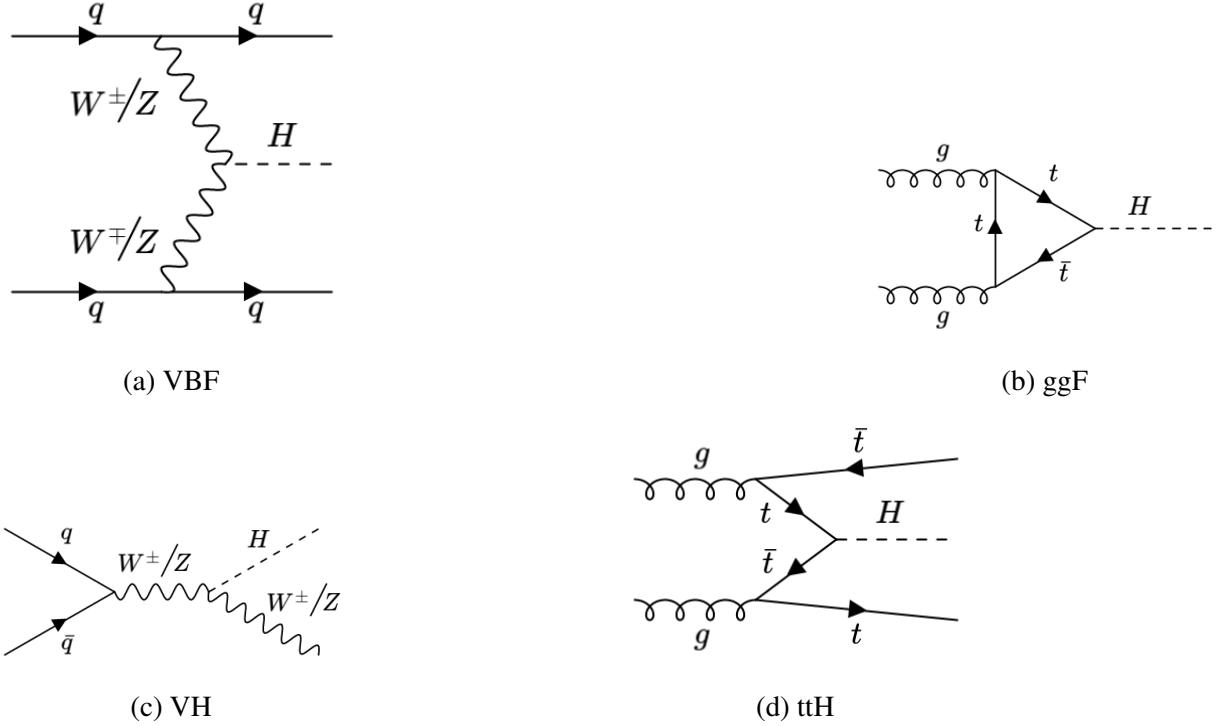
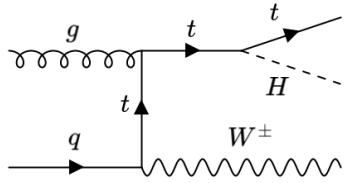
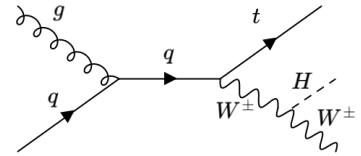


Figure 1.3: Feynman diagrams depicting the leading Higgs production modes.

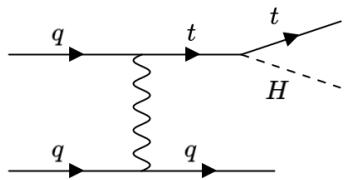
Similarly, the dominant decay mode of the Higgs is to bottom quarks ($H \rightarrow bb$), followed by to W bosons ($H \rightarrow WW$), gluons ($H \rightarrow WW$), tau leptons ($H \rightarrow \tau\tau$), charm quarks ($H \rightarrow bb$), Z bosons ($H \rightarrow ZZ$), photons ($H \rightarrow \gamma\gamma$), and a Z boson and a photon ($H \rightarrow Z\gamma$). Because the Higgs does not couple to massless particles directly, the decays to gg and $\gamma\gamma$ are mediated by loop



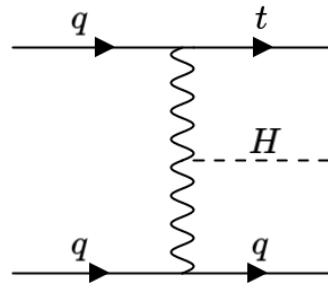
(a) A tWH mode



(b) A tWH mode

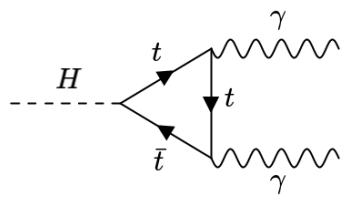


(c) A tqH mode

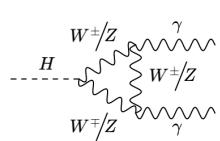


(d) A tqH mode

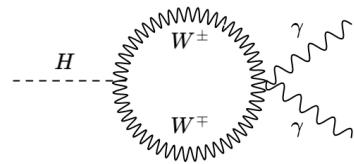
Figure 1.4: Feynman diagrams depicting single-top associated Higgs production modes.



(a) Top-mediated



(b) $W \rightarrow \gamma$



(c) $W \rightarrow \gamma\gamma$

Figure 1.5: Feynman diagrams depicting the leading-order processes contributing to the Higgs diphoton decay.

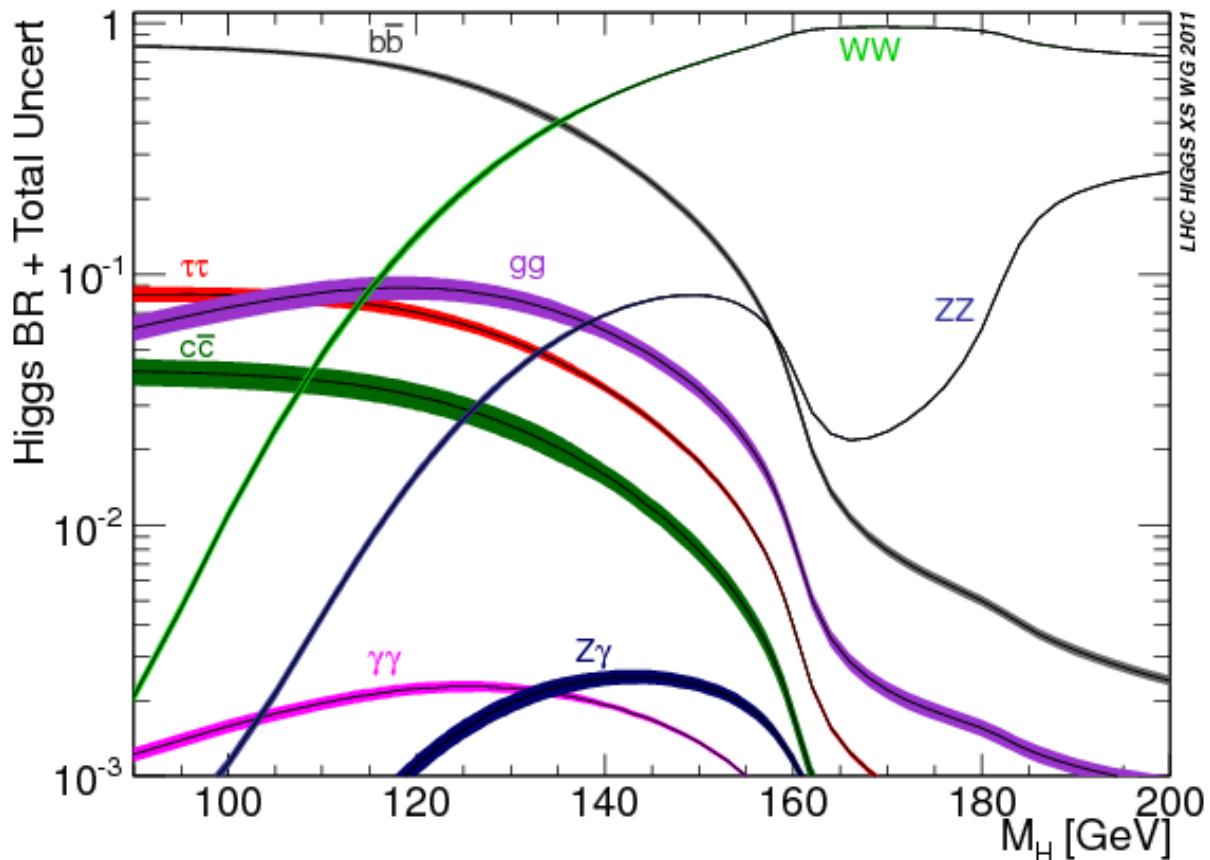


Figure 1.6: The branching ratio of the Higgs to various final state particles as a function of its mass (now known to be 125 GeV), from reference ??.

diagrams, most often involving top quarks.

Investigating each of these decay modes has different benefits and detriments. While the Higgs decay to bottom quarks is the most common, correctly identifying and accurately reconstructing quarks and gluons using the jets that they produce in detectors is often very difficult. Decays to W bosons, Z bosons, and τ leptons provide "cleaner" channels, but because the W, Z and τ decay dominantly to hadrons, similar reconstruction issues occur unless we restrict ourselves to the rarer leptonic subchannels of these decays. The Higgs to diphoton channel occurs very rarely, but offers a much more unambiguous signal, as the odds of misidentifying high-energy gamma rays are fairly low.

Additionally, we must consider combinatorics: in the ttH production mode, for instance, the final state contains two bottom quarks from the decay of the associated top quarks. If we choose to examine the subchannel in which the Higgs decays to bottom quarks as well, we find that we have at least four final-state bottom quark jets in the event, with 12 different unique assignments of bottom quark jets to parent particles. Correctly matching up which jet originated from which

parent particle thus further complicates the reconstruction problem.

This dissertation features two physics analyses from the ATLAS experiment. The first is a targeted attempt to measure whether the top quark Yukawa coupling is CP-even (respects CP symmetry) or CP-odd (violates it) by closely studying the $t\bar{t}H$ process. In the Standard Model Lagrangian, the top Yukawa coupling is purely CP-even, and can be written in the form $\kappa y_t \bar{t}h$. Adding a CP-odd component to the coupling adds an additional $\kappa y_t \bar{t}(i\gamma^5)th$ term to the Lagrangian; the total coupling can thus be parameterized as $\kappa y_t \bar{t}(\cos(\alpha) + \sin(\alpha)i\gamma^5)th$ for a "CP-mixing angle" α that governs the relative magnitude of the CP-even and CP-odd terms. Introducing this CP-odd term changes the kinematics of the process, and leads to events with different angular variable values (such as the angle between the two tops) as well as changing the energies and momenta of some decay products. By performing a fit on these variables to determine the relative agreement or disagreement with the standard model, we can extract a value for α .

The second analysis discussed here is a survey of a wide variety of Higgs-based physics processes using the Higgs-to-diphoton decay channel. A combined fit is performed in different regions of phase space that correspond to the ggH, VBF, VH, ttH, and tH processes; by doing this, we can extract limits on the individual Higgs couplings κ .

CHAPTER 2

The ATLAS Detector

2.1 The Large Hadron Collider

At roughly 27 kilometers in circumference, the Large Hadron Collider (LHC) at the Center for European Nuclear Research (CERN) is the largest machine ever built, slicing through the solid rock of the Jura mountains and running more than 100 meters beneath the Swiss-French border ???. It is a proton-proton collider operating at a center-of-mass energy of 13 TeV, circulating two beams of protons in opposite directions, each at more than 99% the speed of light ???. By utilizing a system of radiofrequency (RF) cavities and dipole magnets, protons are delivered to four primary collision points in bunches spaced 25 nanoseconds apart ??.

The LHC achieves such a powerful center-of-mass energy by repurposing a significant fraction of older collider physics infrastructure, including the Super Proton Synchrotron (SPS), which was itself one of the most powerful particle accelerators in the world at one time. In order to achieve collision, hydrogen atoms are first stripped of their electrons using an ionizing cathode filament in a device called a duoplasmatron; this produces a plasma that is filtered to produce beams of protons ???. The LINAC2, a linear accelerator, then accelerates the resultant proton beams to a collision energy of 50 MeV; the beams then move to the Proton Synchrotron Booster (PSB), a circular accelerator that accelerates them to an energy of 1.4 GeV, followed by the Proton Synchrotron (PS), a second circular accelerator that accelerates them to 25 GeV. Following this, beams enter the aforementioned Super Proton Synchrotron, where they are accelerated to a collision energy of 450 GeV before being injected into the Large Hadron Collider ring. This infrastructure is depicted in Figure ??.

The tight bunching of protons by the LHC ring allows the collider to deliver collisions at a high luminosity, a measure of the number of expected collision events per unit of beam area. Luminosity is measured in both instantaneous and integrated form (i.e., 'luminosity per unit time' and total luminosity delivered to date'); as of the end of the second major LHC run, the collider

CERN's Accelerator Complex

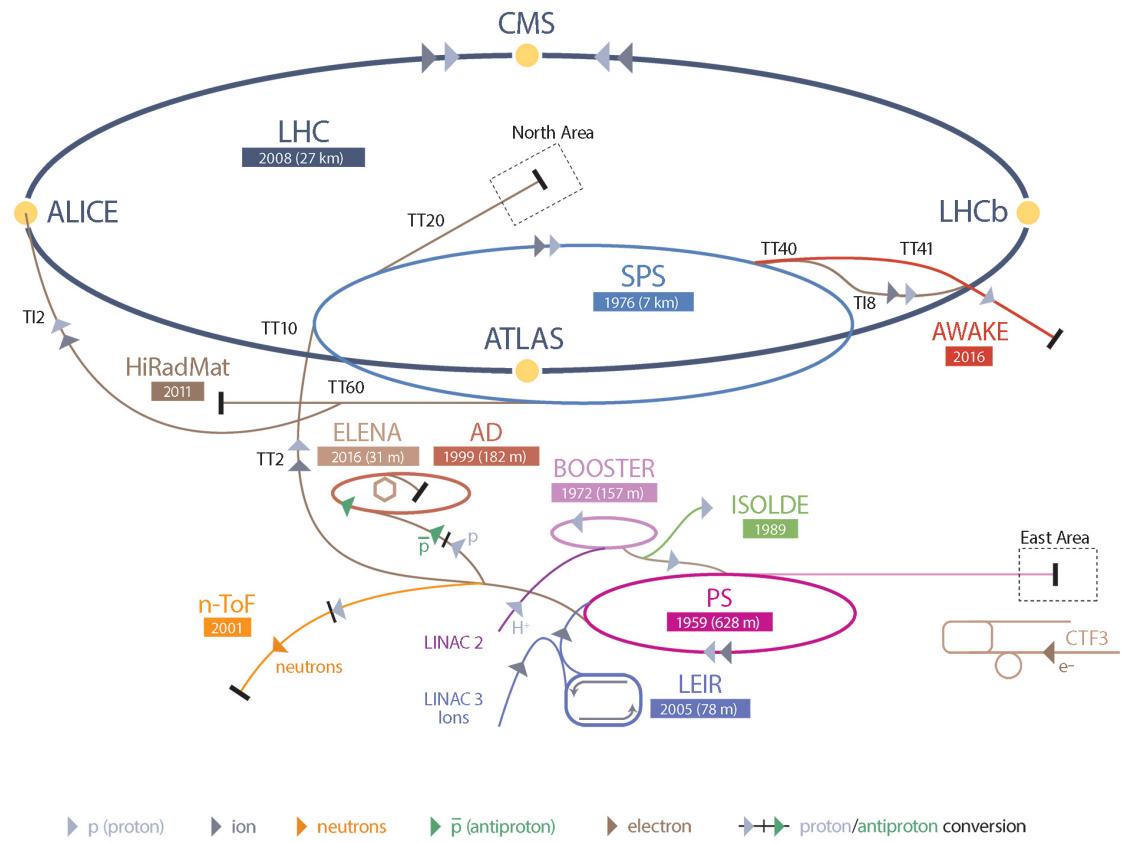


Figure 2.1: The infrastructure of the LHC accelerator ring, including the SPS and LINAC2. ??

has delivered a total integrated luminosity of 139 fb^{-1} , equivalent to approximately $1.39 * 10^{41}$ collisions per square centimeter ??.

At the time of this writing, the LHC is nearing the end of 'Long Shutdown 2' (LS2), a two-year long upgrade period designed to increase detector performance and lay the groundwork for the upcoming high-luminosity LHC (HL-LHC) upgrade, which is slated to begin in approximately 2027 and aims to increase the design luminosity of the LHC by at least a factor of 5 ??HL-LHC. Higher luminosity allows for the production of more rare physics events, but also dramatically increases the incidence of unwanted "pileup" events; mitigating this is one of the major efforts of the CERN physics community during the lead-up to the HL-LHC run.

The LHC ring accelerates beams to a center-of-mass collision energy of 13 TeV. The ring consists of two primary beam pipes, one containing a "clockwise" beam and the other containing a "counterclockwise" beam, which overlap at the four primary collision points. These correspond to the four major LHC physics experiments: ATLAS ?? and CMS ??, which are "general purpose" physics detectors, LHCb ??, which is specialized to study the physics of hadrons containing bottom (or "beauty") quarks, and ALICE ??, which is primarily designed for heavy-ion physics. Due to the highly sensitive nature of their instrumentation, these detectors are buried approximately 100 meters underground to avoid interference from high-energy cosmic rays.

2.2 The ATLAS Detector

The work contained in this dissertation was performed using the ATLAS (A Large Toroidal LHC ApparatuS) detector. Together with its "sibling detector" CMS (the Compact Muon Solenoid), the ATLAS detector is one of CERN's two "general purpose" detectors, so-called because it is designed to observe a wide variety of high-energy physics phenomena. The ATLAS detector is cylindrical, with a diameter of 25 meters and a length of 44 meters ???. Upon colliding at the interaction point in the center of the detector, the constituent particles of each proton will interact with one another through a host of different physical processes, producing a variety of new particles traveling at high velocities. The ATLAS detector is comprised of several specialized subsystems, each of which is responsible for logging different properties of these decay products. Each of these subsystems is optimized to detect specific properties of a collision event; taken together, they provide a detailed snapshot of the moment of interaction. The Inner Detector (ID), a high-resolution detector composed of primarily of silicon, measures the tracks of particles close to the primary vertex. It is encased within a 2T solenoidal magnetic field that bends the tracks of charged particles produced at the collision point, allowing particle momenta to be measured as a function of the curvature of their trajectories. Enclosing the Inner Detector are two nested calorimeter systems: a liquid-argon-and-lead electronic calorimeter (ECAL) that measures the energy of incident photons

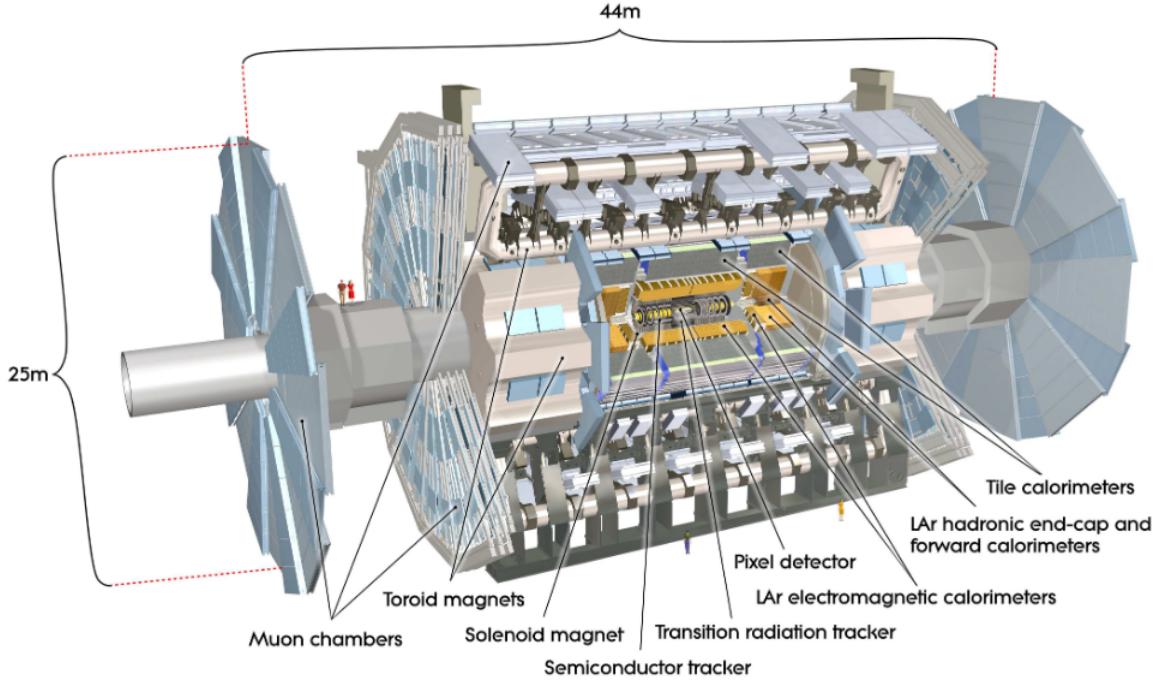


Figure 2.2: A diagram of the various subsystems of the ATLAS detector. ??

and electrons, and a primarily scintillator-tile-and-steel hadronic calorimeter (HCAL) that measures the energy of hadronic showers. Finally, a muon spectrometer composed of gas-filled tubes and chambers records the tracks of muons, which do not decay in the calorimeters like most other particles ???. The entirety of the muon spectrometer is suffused with magnetic field generated by 24 toroidal magnets, eight of which lie in the barrel, generating a field of 1T and eight of which lie in each endcap, generating a field of 0.5T ???. These magnets bend the trajectories of muons in a manner similar to the inner solenoidal magnet system, allowing the momenta of particles to be measured based on the track curvature. The ATLAS detector is also equipped with a highly sensitive trigger system, which uses a wide variety of physics signatures in each of these detector subsystems to determine which collision events to store for later analysis ???. A diagram of the ATLAS detector is shown in figure ??.

The ATLAS detector uses a right-handed coordinate system, with the central interaction point at $z = 0$. The x -axis points from the interaction point to the center of the LHC ring, while the y -axis points upward. However, particle trajectories are more commonly measured not in (x,y,z) coordinate space but utilizing angular variables (r and ϕ) in the transverse plane and pseudorapidity η in the longitudinal plane, where $\eta = -\ln(\tan(\theta/2))$. This is illustrated in figure ??.

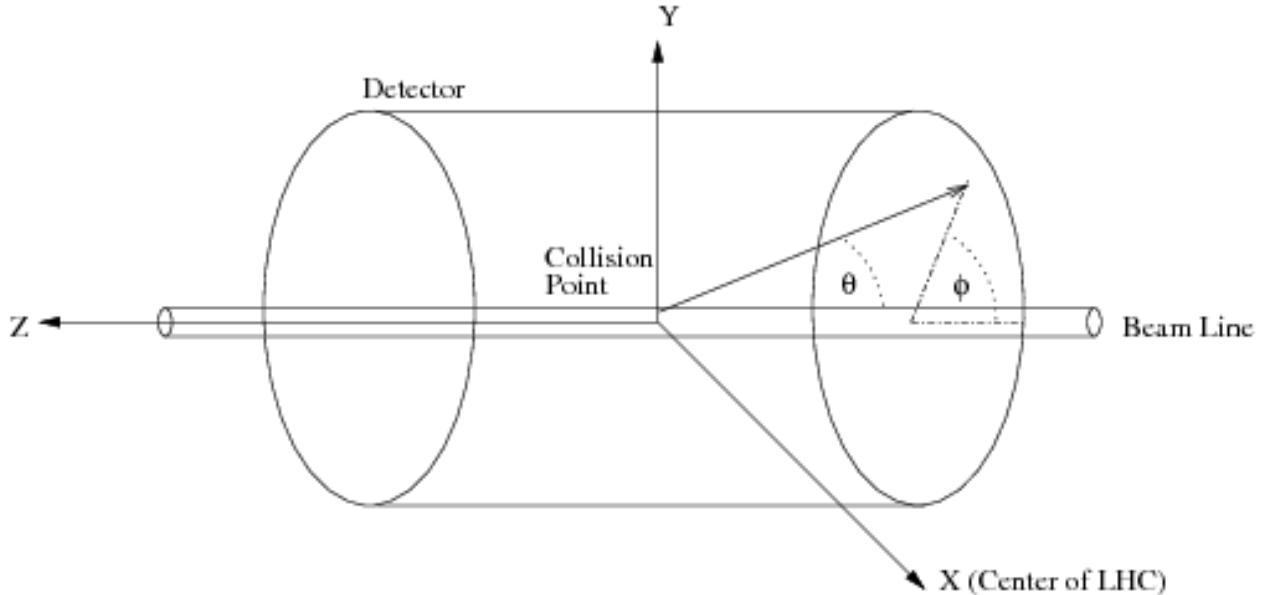


Figure 2.3: The coordinate system used to define the ATLAS detector geometry. ??

2.2.1 Inner Detector

The Inner Detector is composed of five highly granular subdetectors. The closest to the beam, the silicon-based Insertable B-Layer, was added between the LHC’s first and second runs in order to improve precision track-vertex measurement for tasks such as b-hadron tagging and tau lepton identification ??, methods discussed more in section ?? . Proceeding outward from the IBL are the silicon-based Pixel detector and Semiconductor Tracker (SCT), followed by the gas-based Transition Radiation Tracker (TRT) ?? . The inner detector is encased within a solenoidal magnetic field which causes charged particle tracks to bend according to their charge, as detailed in ?? .

The IBL is composed of 26,880 $25050 \mu\text{m}^2$ silicon pixels arranged in an 80 column by 336 row geometry. The pixel modules are supported by 14 support staves, tilted at approximately 14 degrees from the nominal to achieve near-complete cylindrical coverage of the barrel region. The IBL is approximately 33.25 mm from the beam axis, necessitating a replacement of the beryllium beam-pipe with a smaller-radius one for detector reintegration ?? .

Silicon is an optimal material for precision trackers due to its status as a semiconductor. Silicon wafers can be easily ”doped” with atoms of other elements, leading them to carry either an excess of electrons (n-type semiconductors) or a deficit of electrons (p-type semiconductors). By putting the two together, an n-p junction is formed, leading to a one-way current gate known as a diode. A voltage is then applied to the diode to halt current flow (”reverse biasing”). When ionizing particles such as those produced in collisions pass through the silicon, they will produce a cascade of charge carriers that will induce a current in the diode, which can then be measured by the precision front-

end electronics attached to the silicon wafers ??.

The pixel detector is similarly composed of silicon pixels, each of which is either $50 \times 400 \mu\text{m}^2$ (nominal) or $50 \times 600 \mu\text{m}^2$ (near the front-end readout electronics due to spatial constraints). The detector contains 1744 identical pixel sensors, each of which contains 47232 pixels. Three layers of pixels in the barrel region sit at $r = 50.5, 88.5$ and 122.5 mm from the beam axis, while three layers of pixels in the endcap region sit at $r = 495, 580$, and 650 mm from the beam axis. The silicon wafers in the pixel detector are "n+ type" strips (n-type semiconductors with extra doping) embedded in an n-type bulk, rather than the traditional n-type and p-type semiconductors due to the fact that excessive radiation from the beam can cause standard n-and-p-type semiconductors to change into one another ??.

The SCT is composed of longer silicon microstrip wafers made out of standard n-p type semiconductors. It consists of four layers of 2112 total silicon microstrip modules in the barrel region and 1976 microstrip modules in the endcap regions, with 770 microstrips per sensor module. The strips are 12cm long and 80 m wide; the distance of modules from the beam pipe ranges from radii of $r = 299$ mm to $r = 514$ mm in the barrel and $r = 852.8$ mm to $r = 2720.2$ mm in the endcaps. The SCT is designed using less-costly materials than the TRT and IBL, but serves a valuable complementary function ??.

Finally, the TRT consists of polyimide "straws" filled with a gas mixture (70% Xenon, 27% Carbon Dioxide, and 3% Carbon Tetrafluoride), each 4mm in diameter and 144 cm long. In the center of each straw tube is a 31 m in diameter grounded gold-plated tungsten wire filament that serves as an anode. Charged particles travelling through the gas medium will ionize it, producing a cascade of ions that will drift to the anode wire. The TRT is uniquely designed to detect low-energy X-ray transition radiation photons, which allows for better identification of electron candidates ?? . The barrel region consists of 73 layers of sensor modules ranging from $r = 554$ mm to $r = 1082$ mm from the beam pipe, while the endcaps straws, arranged in a "wheel" shape, stretch from $r = 852.8$ mm to $r = 2720.2$ mm from the beam pipe.

Additionally, two Minimum Bias Trigger Scintillators, composed of plastic scintillator tiles, sit on the circular endcaps of the ID in order to provide trigger capabilities in the forward region $|\eta| > 2.5$. The MBTS endcap scintillator consists of 2 cm thick polystyrene scintillator disks mounted on each endcap at a distance of 3.6m from the collision point at .

Together, these subsystems form the ATLAS detector's Inner Detector. Each subdetector has a different spatial resolution- the IBL has a resolution of approximately $10 \mu\text{m}$, the pixel detector has a resolution of $12 \mu\text{m}$, the SCT has a resolution of $16 \mu\text{m}$, and the TRT has a resolution of $130 \mu\text{m}$. The combined effect of these subdetectors is thus to record particle tracks produced in collisions with very high granularity within the range $|\eta| < 2.5$, allowing for sophisticated physics analyses to be performed.

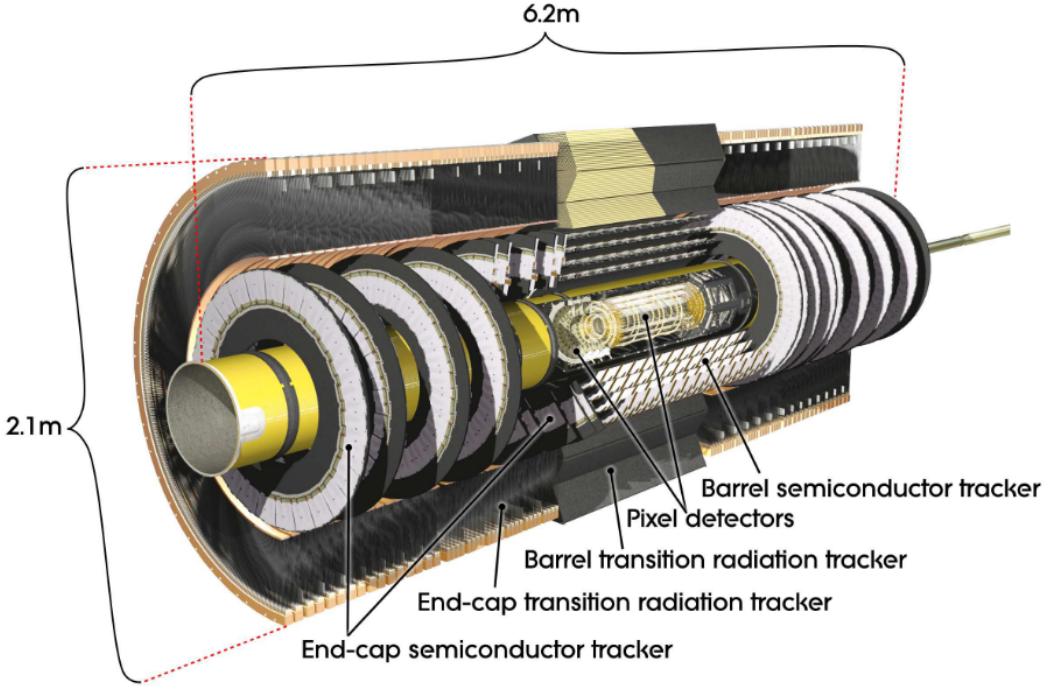


Figure 2.4: An illustration of the Inner Detector. ??

2.2.2 Solenoid Magnet

Track-bending in the Inner Detector is performed by a solenoid magnet providing a field of 2T throughout the ID bulk. The solenoid magnet is constructed of a single layer of high-strength aluminum-stabilized Nb/Ti conductor. The magnetic field it provides is axial (in the z direction), and thus the direction of bending of charged tracks in the ID is in the ϕ direction.

2.2.3 Calorimeters

Measurement of particle energies is performed by the ATLAS detector's two calorimeters. Both calorimeters provide a wider η coverage than the Inner Detector, allowing for measurement of hadronic jets and electromagnetic showers that fall outside the $|\eta| < 2.5$ precision tracking range. The liquid-argon based calorimeters function differently than the silicon-based tracking Inner Detector: they do not require the incident particles to be charged, and record energies of particles as they shower (decay) in the calorimeter material rather than simply recording their tracks as they pass through. Broadly speaking, there are two types of calorimeters: homogeneous calorimeters, which are composed entirely of active "measuring" material such as liquid argon or polystyrene scintillator tile, and sampling calorimeters, which interleave layers of this active material with slabs of material designed to cause the incident particles to shower ?? . Both the electronic and hadronic

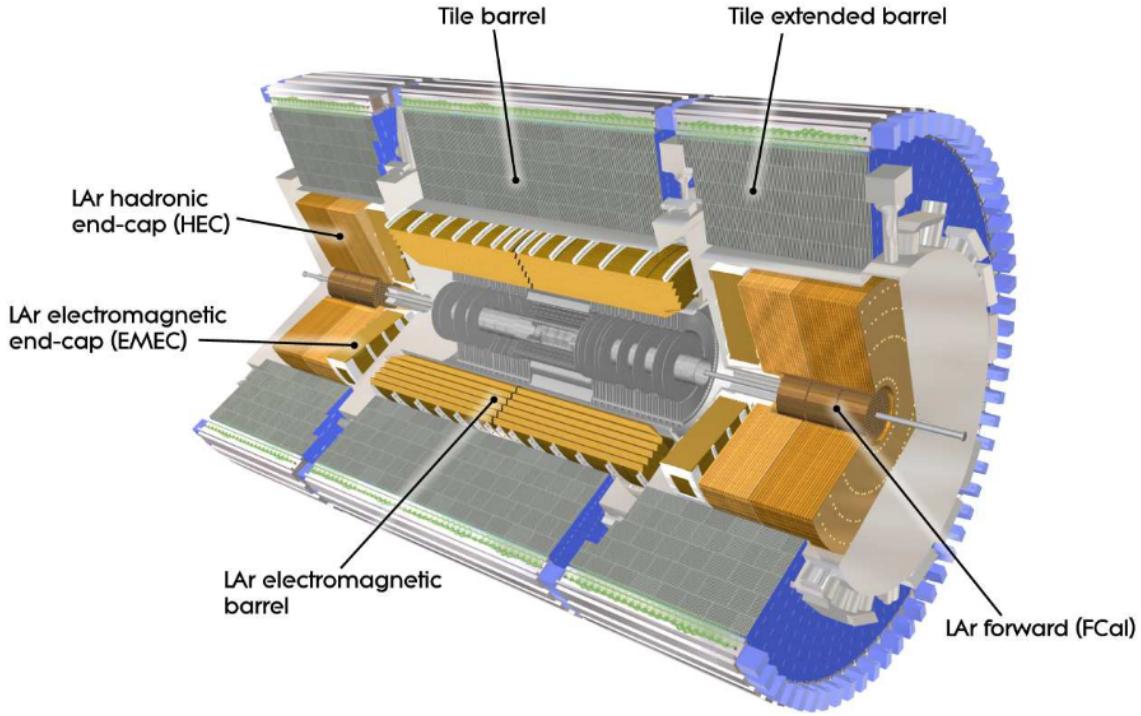


Figure 2.5: An illustration of the ATLAS calorimeter systems. ??

calorimeters are sampling calorimeters; however, they utilize different materials in both the active and non-active layers of the calorimeter. A diagram of the calorimeter system is shown in figure ??.

2.2.3.1 ECAL

When electrons and photons enter the non-active layer of a sampling calorimeter, they interact with the electric fields produced by the atoms of the layer material and produce showers of bremsstrahlung photons and electron-positron pairs, which then produce electrical signals in the Liquid Argon active layers that are read out by specialized electrodes. The depth of the electronic calorimeter thus must be chosen carefully in order to capture the entirety of a typical EM shower (measured in "radiation lengths" X_0 , this varies depending on the absorber material). All ECAL subsystems are made of the same materials: liquid Argon (LAr) sampling layer with lead-plate absorber layers, arranged in a unique "accordion" geometry that gives the ECAL complete coverage in ϕ . Due to the high atomic number of lead, the electron clouds of the atoms of the absorber plates are well-populated, thus leading to a high likelihood that photons or electrons will shower within the calorimeter bulk.

The ATLAS electronic calorimeter consists of two primary subsystems: one barrel calorime-

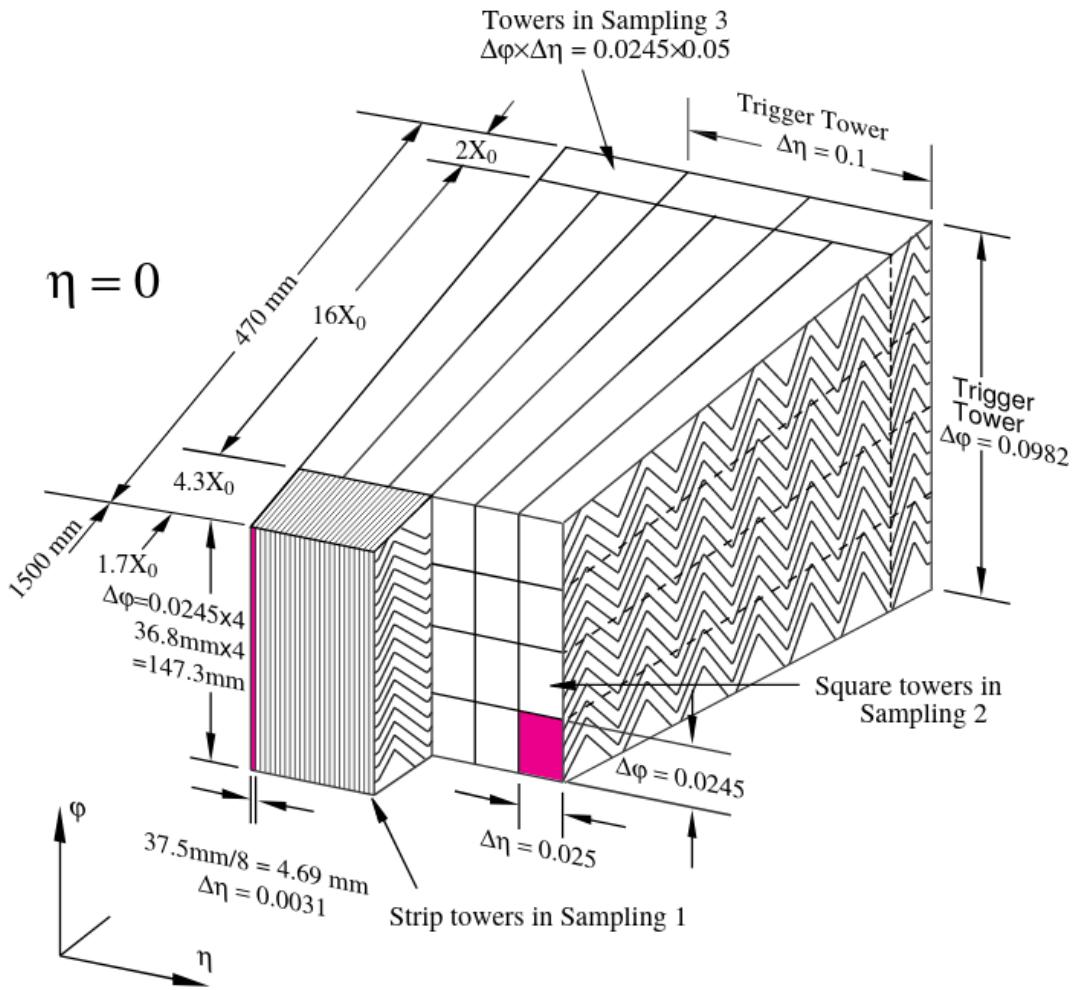


Figure 2.6: A cutaway diagram of the barrel ECAL depicting the "accordion" absorber geometry ??

ter, covering $|\eta| < 1.475$, and two end-cap calorimeters, covering $1.375 < |\eta| < 3.2$. The barrel calorimeter is composed of two identical half-barrels, separated by a 4mm horizontal gap at $z=0$, along the plane of the beam pipe. The lead absorber plates, readout electrodes, and "honeycomb" spacers that form the cavities for the liquid argon layer are all zigzag-shaped and arranged in a circular "starburst" pattern around the barrel ??, as depicted in figures ?? and ???. Each half-barrel consists of 1024 accordion absorbers with their associated interleaved spacers and electrodes, weighs 57 tons, and is 3.2 m long, with an inner radius of 2.8 m and an outer radius of 4.0 m. There are three layers of absorbers in the inner precision-measurement region ($0 < |\eta| < 1.35$) of the barrel and two in the higher- η region ($1.35 < |\eta| < 1.475$), each with a different segmentation; the angle, lateral orientation and length of the accordion waves varies with η .

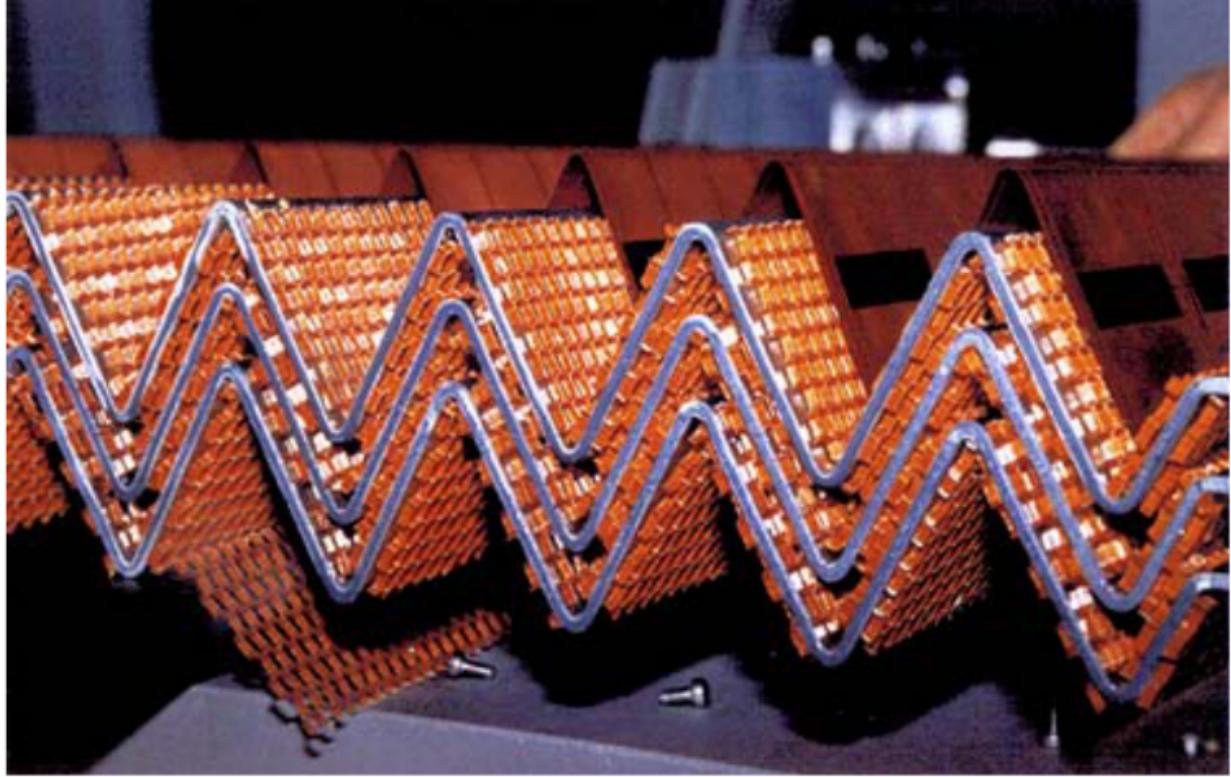


Figure 2.7: A photograph of an ECAL absorber. ??

Each end-cap calorimeter is composed of two wheels, one large outer wheel covering $1.375 < |\eta| < 2.5$, and one smaller inner wheel covering the range $2.5 < |\eta| < 3.2$. Each endcap is 63 cm thick, weighs 27 tons, and contains 768 accordion absorbers in the outer wheel and 256 absorbers in the inner wheel. Like the barrel, the calorimeter structure in the endcaps consists of three layers of absorber modules in the region nearest the beam pipe in the outer wheel ($1.5 < |\eta| < 2.5$) and only two layers both nearest the edges of the outer wheel ($1.375 < |\eta| < 1.5$) and in the entirety of the inner wheel. In the endcaps, the "zigzag" accordion folds are oriented longways, in the z-direction ??.

In the barrel, each absorber is at minimum 22 radiation lengths thick (though this varies up to 33 radiation lengths as a function of pseudorapidity η), thus ensuring that electromagnetic showers are contained within the calorimeter bulk. In the endcaps (except for the outer wheel edge region $1.375 < |\eta| < 1.475$), the calorimeter systems are at minimum 24 radiation lengths thick.

In addition to the accordion sampling layer folds of the ECAL bulk, a presampler detector composed of 64 modules in the barrel and 32 in each endcap provides information about electromagnetic objects before they enter the sampling calorimeter. The presampler modules consist of interleaved electrodes between glass-fiber composite plates, filled with liquid argon in the gaps. In the barrel, the presampler is 11mm thick and covers the entire barrel range; in the endcaps, the

presampler is 4mm thick and covers the range ($1.5 < |\eta| < 1.8$) ??.

2.2.3.2 HCAL

Hadronic showers typically have both electromagnetic and non-electromagnetic components, and, as such, are typically much larger than electromagnetic showers. As such, the hadronic calorimeter is required to be much deeper than the electronic calorimeter, in order to longitudinally contain hadronic showers in their entirety. The characteristic length scale for hadronic showers is the nuclear interaction length (λ_{int}), which can be up to 30 times larger than the radiation length X_0 . The ratio λ_{int}/X_0 is proportional to atomic number; thus, placing at least one layer at the front of a hadronic calorimeter that uses a high-atomic number material such as lead in its absorbers is essential in order to distinguish between purely electromagnetic showers and the electromagnetic components of hadronic showers. For the ATLAS detector, this purpose is served by the ECAL: a significant fraction of the energy of hadronic jets is deposited in the ECAL as electromagnetic activity due to the presence in jets of charged hadrons such as pions. In deeper layers, calorimeter absorbers should be constructed of a dense material such as iron or steel, so that hadrons are able to interact with the nuclei of absorber-layer atoms and produce signals in the active layers ??.

The ATLAS HCAL is composed of three major subsystems: the TileCal, which uses polystyrene scintillator tiles in the active layer and steel in the absorber layer; the LAr endcap calorimeters, which use liquid argon as the active layer and copper as the absorbers; and the LAr forward calorimeters, which use liquid argon as the active layer and contains both copper and tungsten absorber layers.

The TileCal is located immediately behind the electronic calorimeter, and covers the pseudorapidity range $|\eta| < 1.7$. It consists of a central barrel region and two extended barrel regions, one on each side of the detector cylinder, as depicted in figure ?? . The central barrel is 5.8 m long and each extended barrel is 2.6m long; all three have an inner radius of 2.28m and an outer radius of 4.25m. This corresponds to a total radial depth of approximately $7.4 \lambda_{int}$. Additionally, each subsystem is composed of 64 wedge modules, each spanning 5.625° in ϕ . Each wedge consists of a series of trapezoidal scintillator tiles (3mm thick, but varying in width and height depending on position in the wedge) interleaved with steel absorber; two fiber-optic cables connect each scintillator tile to two photomultiplier tubes in order to enable accurate readout. Each tube connects to multiple tiles; these readout channels are structured in order to form a system of calorimeter cells.

When ionizing particles produced by interactions in the steel absorber reach the scintillator tiles, they produce ultraviolet light. The scintillator tiles are composed of polystyrene doped with 1.5% p-terphenyl (PTP) and 0.044% 1,4-bis(5-phenyloxazol-2-yl) benzene (POPOP), which serve to shift the ultraviolet photons into visible light. These are then read out through the photomultiplier tubes ??.

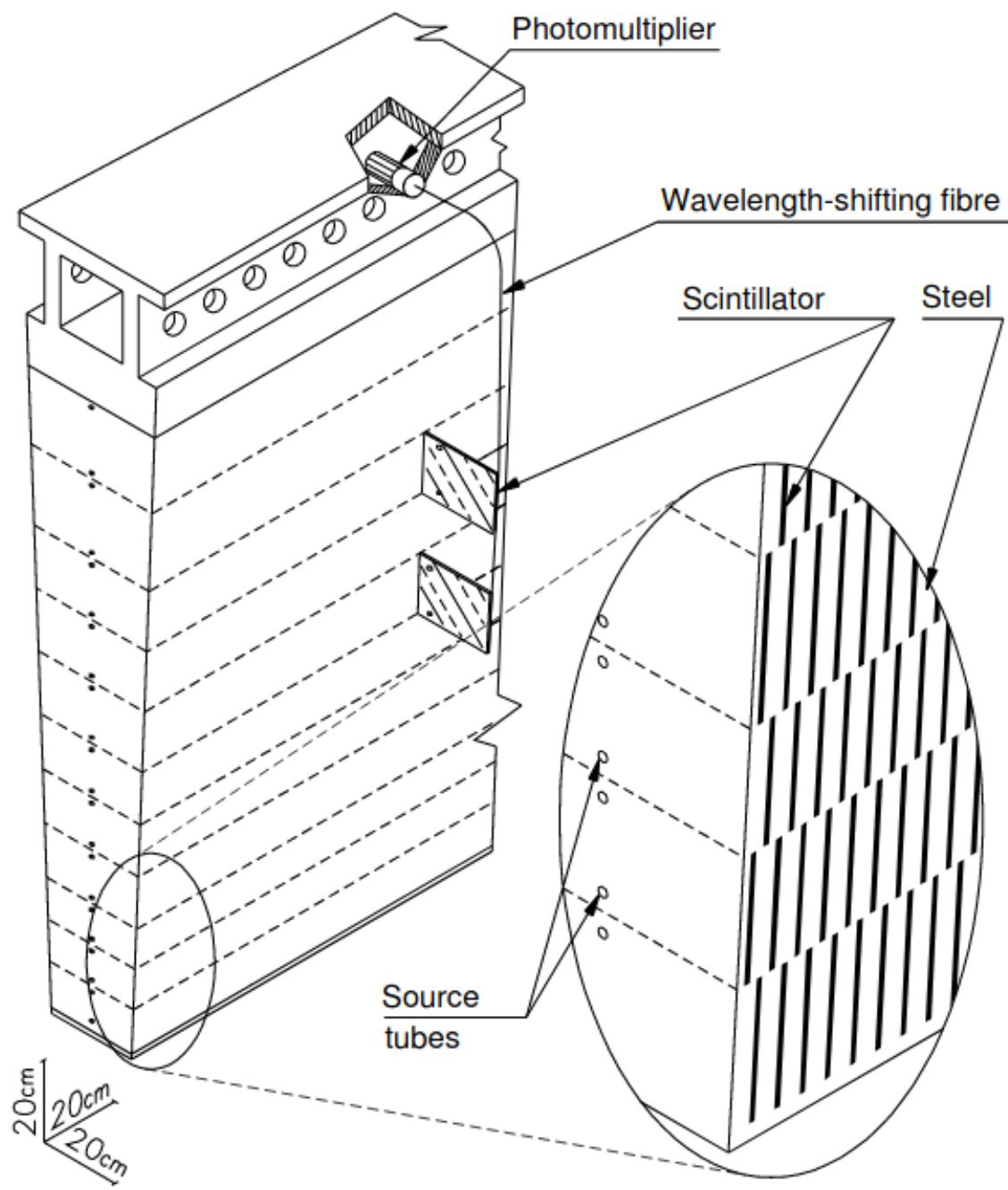


Figure 2.8: A diagram of the TileCal geometry ??

The Hadronic Endcap Calorimeter (HEC) uses flat copper plates as the absorber layer and liquid argon as the active material, and covers the range $1.5 < |\eta| < 3.2$. It consists of two wheels in each endcap, each wheel containing two longitudinal sections. Each wheel is cylindrical with an outer radius of 2030 mm, and consists of 32 identical wedge modules. The front wheels contain 24 copper plates each; the rear wheels contain 16 each.

Finally, the LAr forward calorimeters (FCAL) sit in the very forward region closest to the beamline, $3.1 < |\eta| < 4.9$, and are designed to measure the energy of very forward, often low-energy hadronic jets. The FCAL is unique in that, due to its forward position, it experiences a very large particle flux; it uses very thin active layers in order to mitigate the potential ion buildup this may cause. The FCAL contains three subdetectors, labelled FCAL1, FCAL2 and FCAL3 proceeding outward from the beamline.

Because it lies outside the eta range of the electromagnetic calorimeter, the FCAL must also contain an electronic calorimeter component in order to capture the electronic components of hadronic showers. FCAL1 is this electronic calorimeter, and uses copper as its active material. It is composed of a matrix of copper plates with circular holes in them, through which are pushed copper electrode rods utilized for readout. The gap between these rods and the plates is then filled with LAr; this setup offers very fine control over the active layer thickness. This can be seen in figure ??.

FCAL2 and 3, however, are optimized for the much longer characteristic shower scales of hadronic interactions. They are set up identically to FCAL1, but use tungsten readout electrode rods instead of copper ??.

2.2.4 Toroid Magnets

A series of three large toroid magnets (one in the barrel and one in each endcap) are designed to curve the tracks of muons in the muon spectrometer, allowing for their momentum to be measured using their curvature. Each toroid consists of eight rectangular air-core coils, wound in the $R - z$ plane. Barrel and endcap toroids are rotated at an angle of 22.5° with respect to each other in order to provide maximal coverage. Because the toroidal magnets are toroids and lie in the $R - z$ plane, they curve tracks in this plane as well; this is distinct from the solenoid, which curves tracks in ϕ .

Each barrel toroid magnet consists of a "racetrack-style" Aluminum-stabilized Nb/Ti/Cu conductor wound into two double pancakes; together, these supply a field bending-power ranging from 1.5 to 5.5 Tm in the pseudorapidity range $0 < |\eta| < 1.4$?. Endcap toroids are similarly constructed racetrack-style magnets, but are bolted and glued together with eight keystone wedges in order to withstand the Lorentz forces and hold the magnets together. Endcap toroids supply a bending-power of 1 Tm to 7.5 Tm in the range $1.6 < |\eta| < 2.7$??.

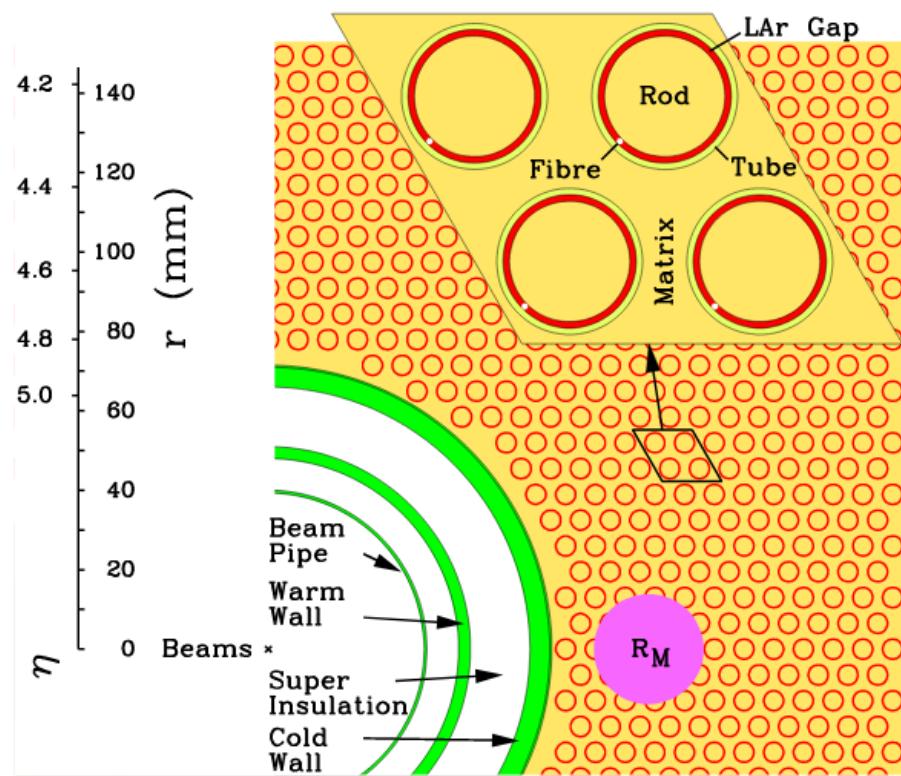


Figure 2.9: A diagram of the FCAL geometry ??

2.2.5 Muon Spectrometer

Unlike electrons and photons, muons are not stopped by the electronic calorimeter. This is due to the fact that a charged particle's energy loss as a function of unit distance due to bremsstrahlung is proportional to its energy and inversely proportional to the square of its mass; because muons are much heavier than electrons, this energy loss drops off substantially at the energies seen at the LHC. While at very high energies, muons again begin to lose most of their energy due to radiation, this occurs at muon energies exceeding a few hundred GeV. Thus, while muons may lose some energy in the electronic calorimeter, and at high energies may be slowed substantially, it is typically not enough to cause them to come to a stop ??.

Similarly, because muons do not interact through the strong nuclear interaction, like pions and other hadrons, they are not stopped by the high-Z material of the hadronic calorimeter. Thus, muons in ATLAS are "minimum ionizing particles", that is, particles that lose energy when travelling through material primarily through the process of ionization ?? . Therefore, a specialized detector subsystem must be built to measure the energies of muons exiting the detector.

The Muon Spectrometer, is, as its name suggests, not a calorimeter, but a device designed to measure the momentum spectra of outgoing muons (from which their energies can be calculated). It consists of four major types of detector chambers, two designed for muon tracking and two designed for triggering. A cutaway diagram of the full Muon Spectrometer is shown in figure ??.

The primary tracking detectors are the Monitored Drift Tube (MDT) chambers. A single MDT is an aluminum tube 29.970 mm in diameter, threaded through with a $50 \mu\text{m}$ radius tungsten-rhenium wire that is affixed with a stopper at each ends. The tube is pumped through with a mixture of 93% argon gas and 7% carbon dioxide, held at a pressure of three bars. Each anode wire is held at a potential of 3080 V, while each tube exterior serves as a cathode, and is grounded. As a muon passes through the tube, it will ionize the gas within; the electrons thus produced will drift to the high-voltage wire and produce electrical signals that can be read out by the specialized boards to which the tubes are attached. Because a muon passing through the tube will leave a trail of ions in its wake, each tube is able to record the minimum radius at which the track passes through the wire, as depicted in figure ?? . However, because this in itself is not enough to reconstruct a track, multiple layers of tubes must be placed together to form a chamber module.

There are 18 varieties of MDT chamber modules, each containing a different number of MDT tubes. Each chamber module consists of one or more "multilayers" of tubes, which consist of either three or four layers of tubes vertically separated by 6.5, 170, or 317 mm, depending on their position in the muon spectrometer. In the barrel, chambers are arranged in three concentric rings around the beam axis, at radii approximately 5m, 7.5m, and 10m from the beamline. In the end-cap region, chambers are arranged in large wheels perpendicular to the beam at approximately 7.4m,

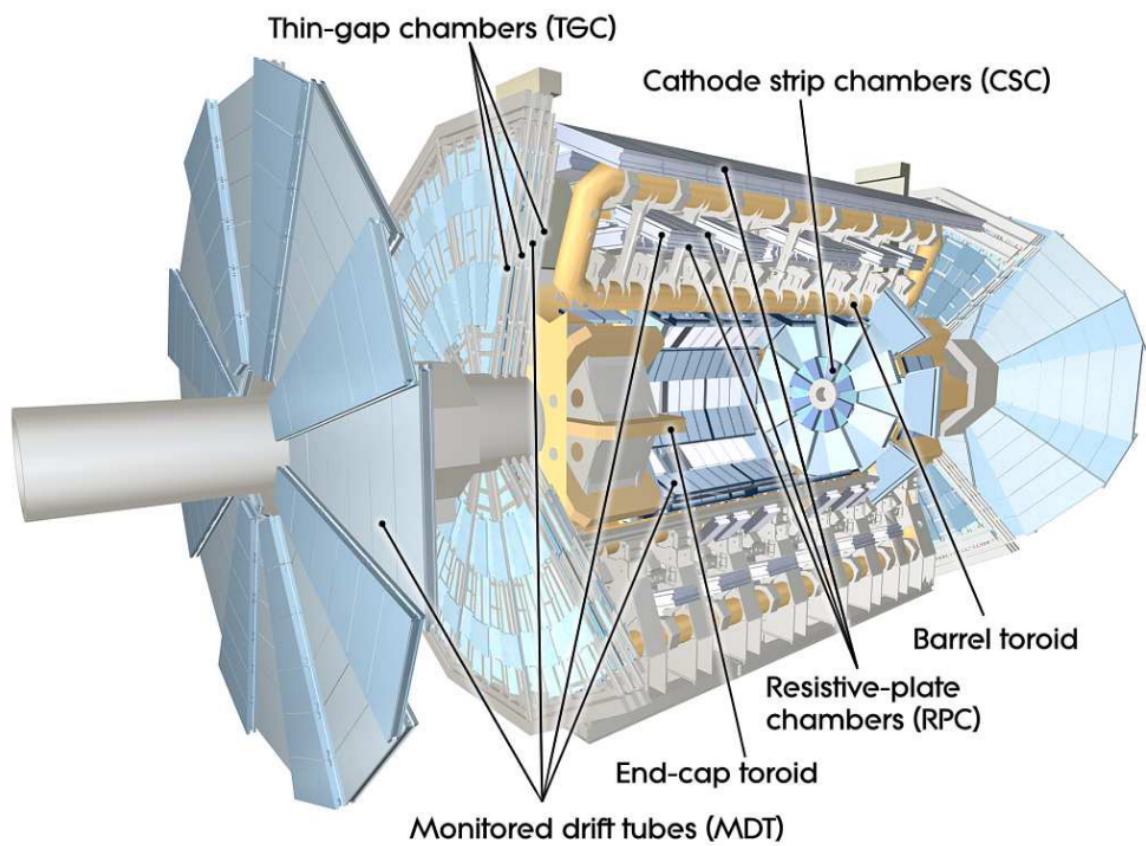


Figure 2.10: A diagram of the Muon System ??

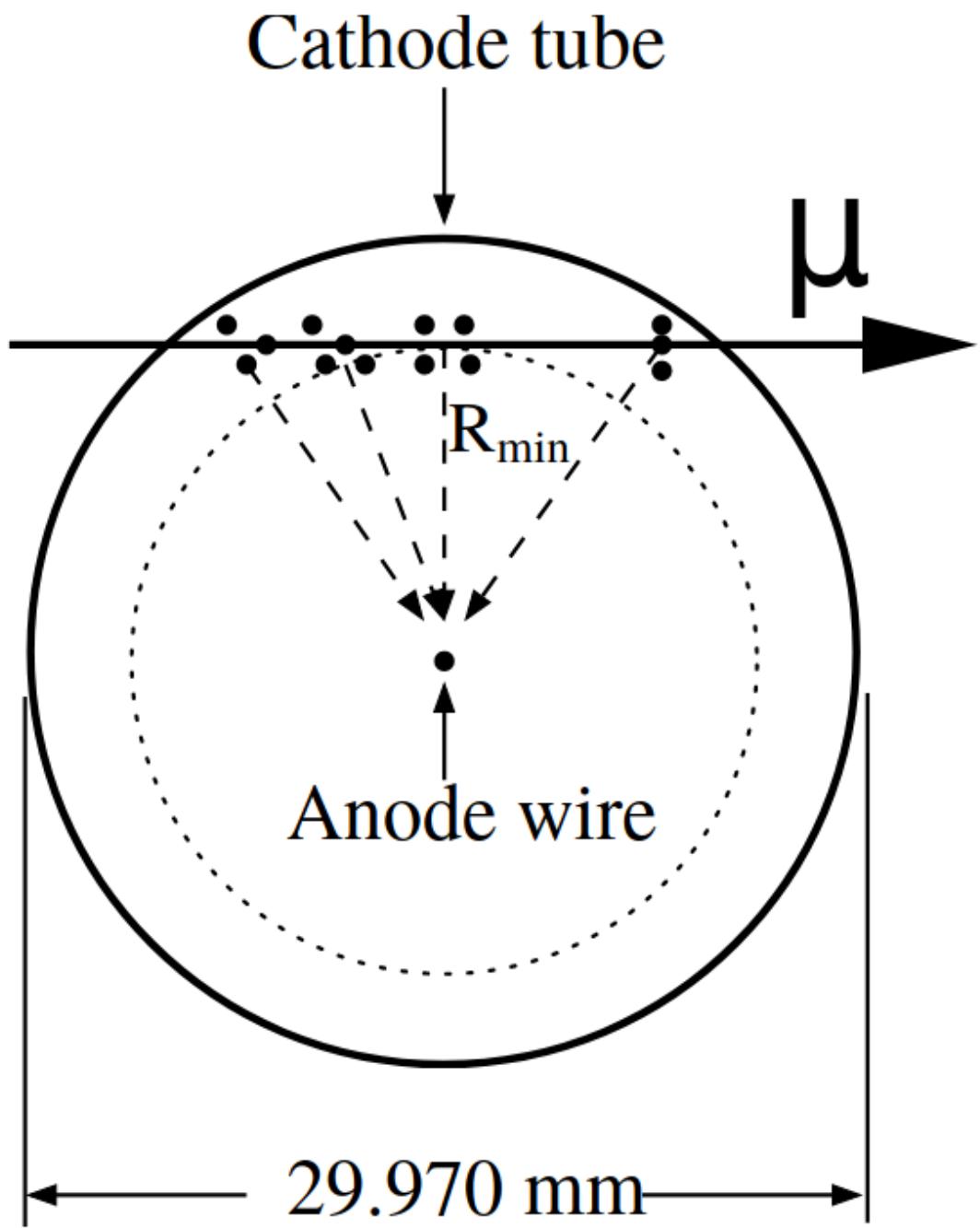


Figure 2.11: A diagram of a Monitored Drift Tube ??

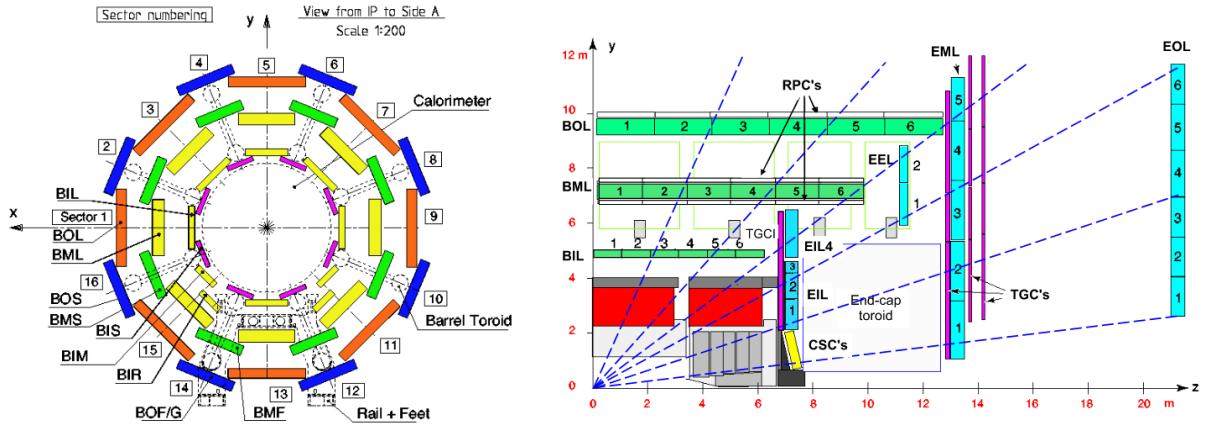


Figure 2.12: A diagram of the MDT chamber geometry from two positions, one looking down the beam pipe and one alongside the detector. ??

10.8m, 14m, and 21.5m from the interaction point. Each MDT chamber has a spatial resolution of approximately $35 \mu\text{m}$. Overall, MDT chambers cover the region $|\eta| < 2.7$, though the number of chambers intersected varies as a function of η ???. The MDT system geometry is shown in figure reffig:MDTChamber.

Closer to the beam, the event rate is higher due to beam halo effects caused by protons decaying into pions (and in turn, muons) in the beam pipe???. Because the expected rate exceeds the tolerance of the MDT chambers, a different type of muon chamber is situated closer to the beam pipe in order to safely deal with the larger event rate. Cathode Strip Chambers (CSCs), are used in the inner endcap chambers in the range $2 < |\eta| < 2.7$.

Each CSC endcap consist of two circular disks, one containing eight large chambers and one containing eight small chambers. A CSC is a type of multiwire proportional chamber that functions similarly to an MDT: muons passing through the CSC will ionize the $\text{Ar} - \text{CO}_2$ gas within; electrons will then drift to anode wires and produce a current. Unlike MDTs, however, CSCs are flat, and threaded through with multiple anode wires. Unlike an MDT, a CSC utilizes cathode strips for readout, rather than reading from the anode wire directly: electrons produced during ionization will float to the anode wire; this will produce a charge screening effect that induces a current in the cathode strips. These are then read out; the strength of the current on each strip can be used to determine the path of the muon track.

Each chamber contains eight layers of cathode strips crisscrossed with anode wires and filled with a mixture of 80% argon gas and 20% CO_2 . Four of these layers are segmented in the η direction and four segmented in the ϕ direction, enabling spatial determination of both coordinates of a muon track. Each CSC chamber has a spatial resolution of approximately $40 \mu\text{m}$ in the "bending" η plane and 5 mm in the "non-bending" ϕ plane. The CSC endcaps are angled slightly

toward the interaction point in order to improve resolution; the readout pitch is 5.31mm for the large chambers and 5.66mm for the small ones ??.

In addition to the precision MDT and CSC chambers, the muon system contains a series of chambers designed explicitly for quickly triggering on muon events. These are the Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs). These provide cursory information about the tracks of muons passing through the detector in order to rapidly determine whether an event should be stored for later analysis.

In the barrel region ($|\eta| < 1.05$), the trigger chambers are Resistive Plate Chambers (RPCs). RPCs are gas-filled detectors, like MDTs and CSCs, but do not contain a wire. Instead, in each RPC gas-gap module, two resistive plates made of plastic laminate are held 2mm from one another and suffused with a large electric field of 4.9 kV/mm. Incoming muons will then produce ionization avalanches that will induce a current on copper anode strips on the outside of the module through capacitive coupling. RPCs are filled with a gas mixture of 94.7% 1,1,2,2-Tetrafluoroethane (C₂H₂F₄), 5 % Isobutane (Iso-C₄H₁₀) and 0.3% Sulfur Hexafluoride (SF₆). Each RPC chamber consists of four gas-gap modules, segmented in ϕ in a manner similar to the CSCs. RPCs follow the same naming scheme as the MDT chambers, and are arranged in three concentric layers around the detector, one small at radii of 7.820 m, 8.365 m, and 10.229m, and one large at radii of 6.800m, 7.478m, and 9.832m.

In the endcaps ($1.05 < |\eta| < 2.4$), the trigger chambers are Thin Gap Chambers (TGCs). TGCs serve two purposes: first, to provide trigger capabilities, and second, to complement the radial measurement of the endcap MDT chambers by providing a precision measurement of the ϕ coordinate of incoming muon tracks. TGCs are structured very similarly to CSCs, as they are also multiwire proportional chambers. However, TGCs are designed so the wire-to-cathode distance (1.4mm) is smaller than the wire-to-wire distance (1.8mm). TGCs are filled with 50% CO₂ and 45% n-pentane (n-C₅H₁₂); the choice of this gas in addition to the chamber geometry substantially increases the ratio of charges reaching the wire to ionizations produced by the incident particle. Two layers of copper strips in each chamber are segmented in ϕ and used as readout channels.

One set of doublet TGC chambers is placed just inside the inner MDT endcap, covering the range $1.05 < |\eta| < 1.92$ (divided radially into two concentric non-overlapping "Endcap" and "Small Wheel" regions); three others (one triplet and two doublets) are placed with the middle MDT endcap to form the "Big Wheel" (covering the range $1.92 < |\eta| < 2.4$). On the Big Wheel, TGC chambers are arranged in two circular wheels, each split into 12 segments. The outer wheel (further from the interaction point) contains 48 modules, each subtending 7.5 °, while the inner wheel (closer to the interaction point) contains 24 modules each subtending 15 °. Each module contains between 3 and 12 TGCs, depending on its position in the wheel. Similarly, the inner TGC layer is also arranged in a wheel shape, and contains a total of 180 TGCs refTGCs. The TGC

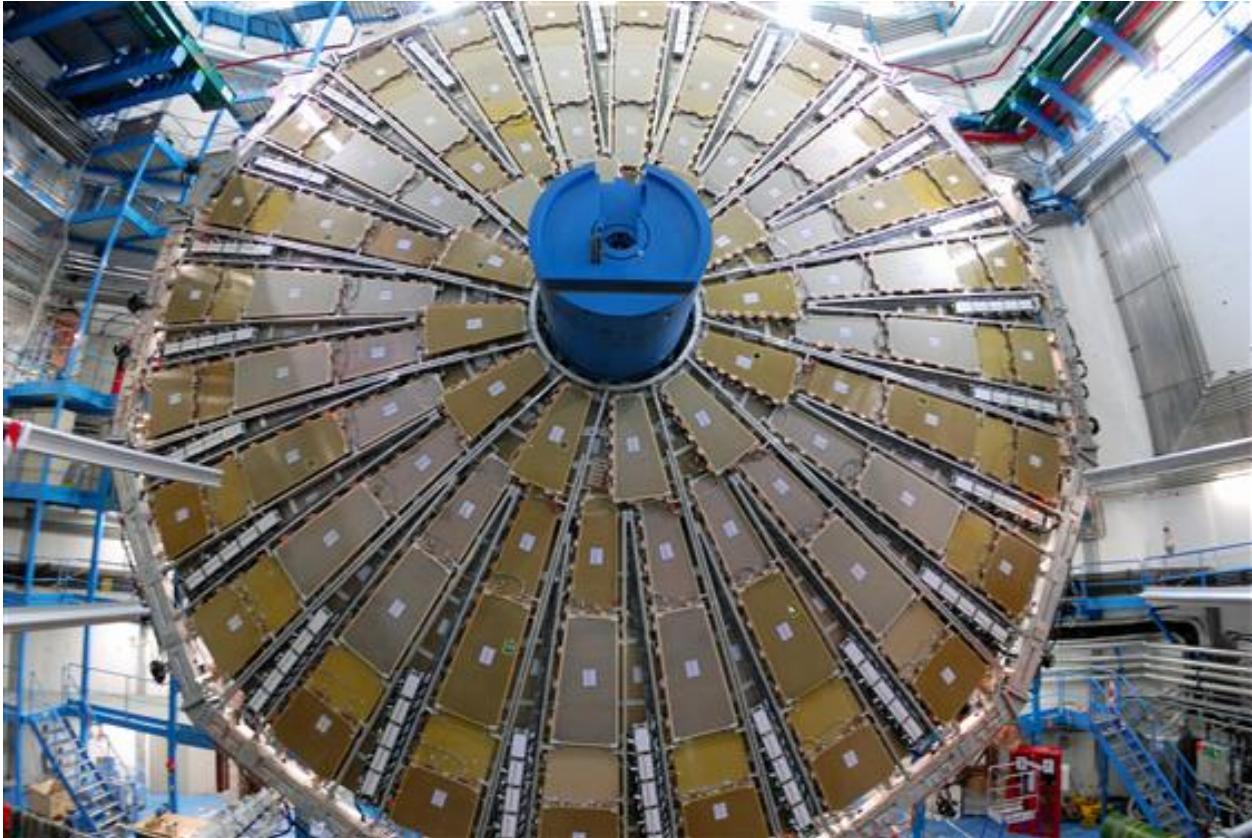


Figure 2.13: A photograph of the TGC wheels. ??

wheels are depicted in figure ??.

2.2.6 Trigger

Due to the high rate of collision events delivered by the accelerator, it is impossible to save the data from every single collision produced in the detector. Luckily, only a subset of these are relevant for physics analysis; indeed, the majority of events produced in the detector are "minimum bias" events caused by low-energy interactions between beam protons that are useful only for performance studies ???. A three-leveled system of triggers is therefore implemented in order to reduce the event rate from 40 MHz to a more manageable 200 Hz. The trigger system is a mix of both hardware and software based subsystems, and is optimized to balance the demands of complexity and speed: more sophisticated algorithms take more time to run, but this cannot get in the way of more data-taking. Each successive trigger is thus more complex than the last, with the lower-level trigger systems applying coarser selections and the higher-level triggers applying finer ones ??.

The first tier of trigger systems, called the L1 trigger, is hardware-based. It utilizes information directly received from the detector subsystems to search for a variety of noteworthy physics

objects: high-transverse-momentum muons (transverse momentum here meaning the component of the momentum in the radial coordinate, denoted by p_T) are identified using the RPC and TGC chambers discussed in section ??, while photons, electrons, tau leptons, and hadronic jets are identified using coarse calorimeter information. These triggers form the "L1Muon" and "L1Calo" trigger menus; this information in addition to that of other subsystems such as the MBTS are then sent to the Central Trigger Processor (CTP). The CTP then combines the information from these trigger systems and sends it to the L2 trigger; it also indicates spatial regions of interest using a third trigger called "L1Topo" and calculates quantities of interest such as missing transverse energy (here denoted E_T^{miss} , defined as the negative vector sum of the p_T of all objects in the event. E_T^{miss} serves as an indicator of the presence of unobserved neutrinos or other "invisible" decay products in the event). The combined activity of the L1 triggers serve to reduce the event rate to less than 1kHz.

After passing the hardware-based L1 trigger, events then proceed to the software based L2 trigger and Event Filter, which are known together as the High Level Trigger (HLT). HLT triggers utilize a full-granularity event display in order to perform trigger calculations, analyzing the regions of interest marked by the L1 trigger. It is at the HLT stage that reconstruction and matching of tracks using Inner Detector information, as well as jet, photon and electron object identification and tagging of objects such as b-jets and tau leptons is performed. All events that pass one or more triggers in the HLT menu are recorded, reducing the event rate to the aforementioned 200 Hz. Triggers may also be 'prescaled' (for which only a set fraction of the events that pass are recorded); this allows analyzers to explore properties of events that normally occur at a rate much higher than can be handled by the trigger system. The triggers utilized in the analyses described in this dissertation are detailed in section ?? and ??.

CHAPTER 3

Experimental Methods

3.1 Experimental Methods

It is not possible to induce a particular interaction in a particle collider: every physics process that *can* occur from the collision of two protons at 13TeV *will* occur in the ATLAS detector. Thus, the process of studying rare Higgs interactions is not one of determining how to produce them in a laboratory setting, but of determining whether or not they are being produced in our detector at all. Because physics 'signal' processes are fundamentally indistinguishable from unwanted 'background' processes, ATLAS studies are statistical counting experiments which test the compatibility of the observed numbers of events with different detector signatures against the event counts that are predicted to occur under different physics hypotheses.

Performing these experiments effectively in the data-rich environment of the LHC requires many clever statistical and computational tools, which vary from analysis to analysis. However, in all analyses, it is vitally important both to accurately model what the physics processes of interest may look like in the ATLAS detector and to translate observed detector signals into high-level physics objects. The Monte Carlo simulation method is used for the former, while the latter is performed by the variety of identification and reconstruction techniques detailed in this chapter.

3.1.1 Monte Carlo

The Monte Carlo simulation method is a way of modelling how a given physics process that may occur at the point of collision may translates into signatures in the ATLAS detector. For a given physics process, say, $gg \rightarrow t\bar{t}H$, we must model both the initial process (i.e., what is the likelihood two gluons will interact to make a $t\bar{t}H$ event? What properties of the gluons make this more or less likely to occur? How will the top quarks and Higgs boson decay, and what might their decay products look like?), and the detector stage (how will the hadronic jets produced by decaying top quarks and the photons produced by a decaying Higgs look in the ATLAS detector?).

In order to make this problem computationally tractable, each stage is performed separately. In the first stage, the *generator* stage, physics events for a given process are generated according to their cross-sections σ (a measure of how likely they are to occur that is calculated using perturbation theory). A variety of different generator packages are used to produce events for different processes; common generator packages include PYTHIA ??, HERWIG ??, and aMCatNLO ?? . In many cases, intermediate decays are also performed by the generator software. Meanwhile, detector-level simulation is performed using the GEANT4 (GEometry ANd Tracking 4) package ??, which models the signatures of different particles produced in a collision as they pass through detector material.

Simulated events are then reconstructed in the same manner as real events. Because, unlike data events, Monte Carlo events include a "truth record" of what particles they contain, Monte Carlo simulations enable us to perform a number of useful tasks, including training machine learning algorithms to search for specific processes, model the relative contributions of various signal and background processes, and calculate various statistical and systematic uncertainties on our measurements ??.

3.1.2 Reconstruction and Tagging

Objects produced in the ATLAS detector produce a wide variety of signatures, many of which can be difficult to distinguish from one another. For this reason, dedicated algorithms and criteria are employed to reconstruct and identify the particles used in ATLAS analyses. A sample illustration of the ATLAS detector showing typical shapes of a variety of physics objects is shown in Figure .

3.1.3 Tracks

Track reconstruction is essential for identifying and measuring the properties of a wide variety of physics objects, including both muons and hadronic jets.

Initially, the "space points" (spatial coordinates) of potential particle hits are reconstructed using clusters of energy deposits in both the Pixel and SCT detectors. Track candidates are then identified combinatorially using this space-point information (with a minimum of three space-points per track candidate); these track candidates are then passed through an analytic weight-based "ambiguity solver" designed to weed out unphysical track candidates. To aid the ambiguity solver, a neural network is implemented in order to distinguish between isolated and merged clusters of energy deposits. After this, a neural network-based procedure is used to fit the identified tracks. ??.

Fitted tracks from the Pixel detector and SCT can be extended into the TRT if nearby TRT hits are identified. In addition, tracks that are seeded by TRT hits can also be identified and recon-

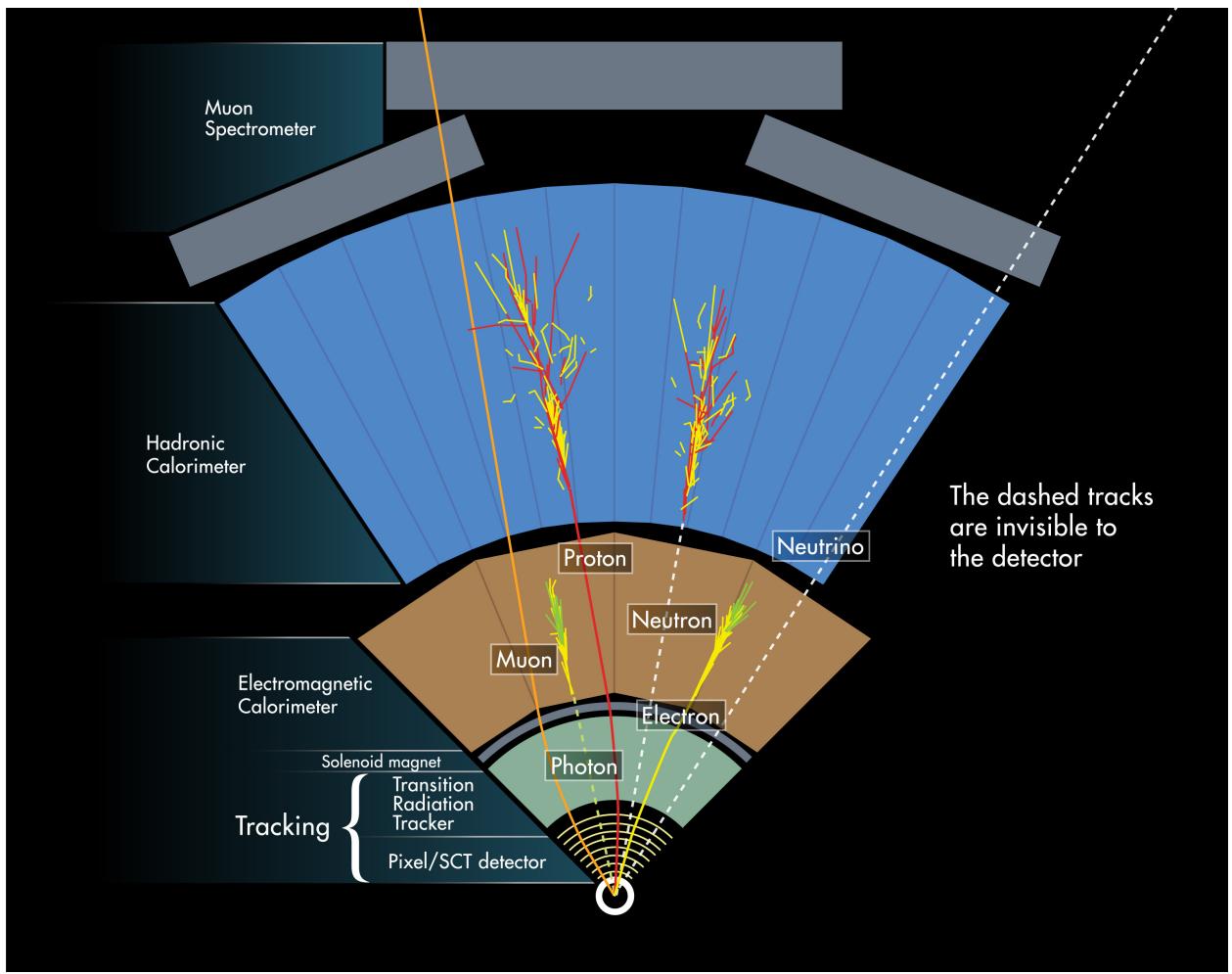


Figure 3.1: Shapes and signatures of a variety of objects in the detector ??

structed using an "outside-in" approach; this helps mitigate the potential loss of real tracks at the ambiguity-solver stage ??.

After tracks are identified and reconstructed, they are used to identify interaction vertices in the event. Each vertex candidate must contain at least two tracks, each with transverse momentum $p_T > 400$ MeV and $|\eta| < 2.5$, at least nine hits in the Pixel or SCT detector for tracks with $|\eta| < 1.65$ or at least eleven hits for tracks with $|\eta| > 1.65$, at least one hit in the first two pixel layers (i.e., the IBL and the inner b-layer), no more than one shared module (i.e. one shared pixel hit or two shared SCT hits), no holes in the Pixel detector, and no more than one hole in the SCT. An iterative combinatorial procedure is then used to fit all compatible tracks to vertex candidates; the primary vertex (PV) representing the initial protom-proton collision is chosen as the vertex with the greatest Σp_T^2 ??.

However, we note that, for $H \rightarrow \gamma\gamma$ events, a potential lack of charged particles in the final state means that a different primary-vertexing method utilizing ECAL clusters must be considered. This is detailed at length in section ??.

3.1.4 Clusters

Photons, electrons and jets are reconstructed using topological clusters of hits ("topo-clusters") in the electromagnetic and hadronic calorimeters. Clusters are reconstructed using a "seed-and-collect" method, where cluster-initiating "seeds" are defined as calorimeter cells with an energy four times greater than the expected noise threshold for that cell ??, ??.

After the identification of seed cells, calorimeter cells neighboring the seed cell with recorded energy greater than twice their noise threshold are added to the proto-cluster. If proto-clusters contain more than two local maxima with energy greater than 500 GeV in a single cell, the proto-cluster is split into two in order to account for potential overlap. Initially, seed cells in these split clusters may reside only in the ECAL sampling layers EMB2, EMB3, EME2 and EME3, or the forward calorimeter module FCAL0, after this splitting, clusters are then iteratively split again, with maxima now allowed in the other HCAL and FCAL layers (The first layer of the ECAL is not used to seed topo-clusters in order to reduce the likelihood of producing clusters of noise). In the case of overlap between multiple clusters, cells are assigned to the two cluster candidates with the largest maxima.

3.1.4.1 Electrons and Photons

Electrons and photons are defined using tracks that are matched to topo-clusters in the ECAL. Topo-clusters compatible with EM showers are selected and used to define Regions of Interest; those Regions of Interest are then matched to tracks in the ID. Track candidates are extrapolated

into the Regions of Interest using both the measured track momentum and the rescaled momentum measured in the relevant topo-cluster (the latter of which allows for accounting of radiative energy loss in the calorimeter).

For a track to be considered matched to a topo-cluster, under either momentum-definition-extrapolation, it must fall within $|\Delta\eta| < 0.05$ of its relevant topo-cluster and satisfy $-0.10 < q \times (\phi_{track} - \phi_{cluster}) < 0.05$, where q is the charge of the incident particle.

Topo-clusters matched to a single charged track are considered to be electron candidates, topo-clusters matched to two oppositely-charged tracks forming a vertex consistent with a photon are considered to be "converted" photon candidates (i.e., clusters resulting from a photon converting into an electron-positron pair in the ID), and topo-clusters matched to no tracks are considered to be "unconverted" photon candidates. In addition, single tracks that have no hits in the innermost layers of the ID are also considered as potential converted photon candidates??.

Since the start of Run 2, combined topo-clusters called "superclusters" have been implemented in the EM clustering process in order to capture bremsstrahlung photons and other energy lost in the calorimeter ???. For electrons, a supercluster seed must be a cluster with momentum $p_T > 1\text{GeV}$ matched to a track with at least four hits, while for photons, a supercluster seed must be a cluster with momentum $p_T > 1.5\text{GeV}$. Satellite clusters are then added to the seed to form a supercluster if they fall into a window $\Delta|\eta| \times \Delta\phi = 0.075 \times 0.125$ around the center of the seed cluster. For electrons, an additional satellite cluster search is performed, adding clusters that fall into the window $\Delta|\eta| \times \Delta\phi = 0.075 \times 0.125$ that are matched to the same track as the seed. For converted photons, the $\eta - \phi$ window is not used: all satellite clusters matched to one of the tracks of the converted photon vertex are added to the supercluster.

Following the identification of superclusters and tracks, energy calibration corrections are applied (determined using Monte Carlo simulation for photons and $Z \rightarrow ee$ decays for electrons)??, and the photon and electron candidate objects are passed to cluster-shape-based identification algorithms. For both electrons and photons, three identification working points are defined using cut-based multivariate discriminants based on the shower-shape variables.

For photons, the *loose* ID threshold is determined based on the following variables:

- Acceptance: $|\eta| < 2.37$, excluding the calorimeter crack at $1.37 \leq |\eta| < 1.52$
- R_{had} : the ratio of transverse energy deposited in the HCAL to transverse energy deposited in the ECAL for clusters with $0.8 \leq |\eta| < 1.37$
- R_{had1} : the ratio of transverse energy deposited in the first layer of the HCAL to transverse energy deposited in the ECAL for clusters with $0.8 \leq |\eta| < 1.37$
- R_{eta} : the ratio of the energy deposited in the ECAL in a 3×7 rectangle in the $\eta \times \phi$ plane

to the energy deposited in the ECAL in a 7×7 rectangle in the $\eta \times \phi$ plane, both centered on the calorimeter cell with the most deposited energy.

- Lateral shower width w_{eta2} : $\sqrt{\frac{\sigma E_i \eta_i^2}{\sigma E_i} - \frac{\sigma E_i \eta_i^2}{\sigma E_i}}$ (where E is the energy and η is the pseudo-rapidity of cell 'i', summed over all cells in a 3×5 rectangle centered around the most energetic calorimeter cell).

The *medium* photon ID threshold is determined based on both passage of the loose threshold and the variable $E_{ratio} = \frac{E_1 - E_2}{E_1 + E_2}$, where E_1 and E_2 are the leading and subleading energies deposited in calorimeter cells, respectively.

The *tight* photon ID threshold is determined based on passage of the medium ID threshold and the following shape variables in the strip layer of the ECAL

- Lateral Shower Width: $w_{s3} = \sqrt{\frac{\sigma E_i (i - i_{max})^2}{\sigma E_i}}$ (where E is the energy of a strip, ' i_{max} ' is the index of the highest-energy strip, and 'i' is the index of each strip with respect to i_{max} calculated in a $3 \times 2\eta - \phi$ rectangle centered around the strip with the maximum energy deposit)
- Total Lateral Shower Width: $w_{stot} = \sqrt{\frac{\sigma E_i (i - i_{max})^2}{\sigma E_i}}$ (where E is the energy of a strip, ' i_{max} ' is the index of the highest-energy strip, and 'i' is the index of each strip with respect to i_{max} calculated in a $20 \times 2\eta - \phi$ rectangle centered around the strip with the maximum energy deposit)
- ΔE_s : the difference between the second-largest strip energy and the minimum energy in the strips that lie between the largest- and second-largest strip energies
- f_1 : The ratio of the energy in the first layer to the energy in the whole EM cluster.
- f_{side} : the total energy outside the three central strips but within seven strips, divided by the energy of the three central strips

Each working-point threshold varies in bins of η . For loose and medium working points, converted and unconverted photons are not treated differently, but for tight working points, they are determined separately. ??

For electrons, the identification process proceeds similarly: working-points are defined using shower-shape variables $f_1, E_{ratio}, w_{stot}, R_{eta}, w_{eta2}, f_3, R_{had}$, and R_{had1} , as well as R_{phi} (the ratio of the energy deposited in the ECAL in a 3×3 rectangle in the $\eta \times \phi$ plane to the energy deposited in the ECAL in a 3×7 rectangle in the $\eta \times \phi$ plane, both centered on the calorimeter cell with the most deposited energy). Electron ID working-points also include the following track variables:

- n_{Blayer} : Number of hits in the B-layer

- n_{Pixel} : Number of hits in the Pixel
- n_{Si} : Number of hits in the silicon detectors (ID and SCT)
- d_0 : the transverse impact parameter relative to the beamline
- $|d_0/\sigma(d_0)|$: the impact parameter significance relative to its uncertainty
- $\Delta(p)/p = (p - p_{last})/p$: the momentum difference between the track perigee and its endpoint, divided by the momentum at perigee
- $eProbabilityHT$: the electron probability based on TRT radiation
- $\Delta\eta_1$: the difference in pseudorapidity between the cluster position in the first layer and the matched track
- $q \times (\phi_{track} - \phi_{cluster})$: where ϕ_{track} is the momentum-rescaled track extrapolated from the perigee and $\phi_{cluster}$ is the cluster position in the second ECAL layer.
- E/p : ratio of the cluster energy to the track momentum (used for $E_T > 150GeV$ only)

However, the photon identification is a cut-based process, while the electron identification process relies on a likelihood-based discriminant. For the analyses discussed in subsequent chapters, we utilize the *Medium* electron working point, with an efficiency of approximately 88% ?? . Electrons are also required to satisfy $p_T > 10GeV$, $|\eta| < 2.47$ (excluding the calorimeter crack at $(1.37 < |\eta| < 1.52)$), have track impact parameter significance $|d_0/\sigma(d_0)| < 5$, and satisfy $z_0 \times \sin(\theta) < 0.5mm$ with respect to the primary vertex ?? .

To aid in modelling, additional photon ID working points are created. These "LoosePrimeN" working points involve photons that pass the 'loose' identification criteria, but fail one or more of N 'tight' identification criteria. The analyses discussed in this dissertation use the LoosePrime4 working point, which is defined as photons passing the Loose identification but failing one or more of the w_{s3} , f_{side} , ΔE_s , and E_{ratio} criteria ?? .

To distinguish between photons originating from the hard scatter (i.e., the process of interest in an event) and photons radiated off of other final-state objects, we consider the relative isolation of identified photons. Photons near large amounts of calorimeter activity are likely to be radiative photons ('non-prompt') radiated from final-state particles after the hard-scatter event, while photons that are isolated are more likely to originate from the hard-scatter.

Two types of isolation variables are considered: calorimetric and track-based.

The calorimetric isolation variable employed in the analyses discussed here is $E_T^{coneXX} = E_{T,raw}^{isolXX} - E_T^{core} - C$, where $E_{T,raw}^{isolXX}$ is the total calorimeter energy in a cone of $\Delta R = XX/100$

around the electron or photon of interest, E_T^{core} is the total calorimeter energy in a 5×7 rectangle in $\Delta\eta \times \Delta\phi$ around the barycenter of the electron or photon of interest, and C is a correction for pileup and leakage.

The photon track isolation variable employed in the analyses discussed here is $p_T^{cone20} = p_T^{cone} - p_T^{core}$, where p_T^{cone} is the total track momentum of all tracks with $p_T > 1\text{GeV}$ in a cone of $\Delta R = 0.2$ around the photon of interest and p_T^{core} is the total track momentum of all tracks with $p_T > 1\text{GeV}$ matched to the photon candidate. In addition to satisfying $p_T > 1\text{GeV}$, all tracks considered for this metric must also fall within $z = 3\text{mm}$ of the diphoton vertex and have $|\eta| < 2.5$.

The electron track isolation variable considered is $p_T^{varcone20}$, identical to p_T^{cone20} except for the fact that, rather than consider a constant-radius cone of $\Delta R = 0.2$, we consider a cone of radius $\Delta R = \max(\frac{10}{p_T[\text{GeV}]}, 0.2)$??.

Unlike in Run 1, photon isolation cut thresholds are defined as a function of photon energy rather than being fixed. The isolation thresholds used are *FixedCutLoose* ($E_T^{cone20} < 0.065E_T^\gamma$ and $p_T^{cone20} < 0.05E_T^\gamma$) and *FixedCutTight* ($E_T^{cone40} < 0.022E_T^\gamma + 2.45\text{GeV}$ and $p_T^{cone20} < 0.05E_T^\gamma$) for photons and *FCLoose* ($E_T^{cone20} < 0.2p_T$ and $p_T^{cone20} < 0.15p_T$) for electrons ??.

In analyses discussed in this dissertation, the diphoton vertex originating from the Higgs decay is often not the hardest vertex. This is because, in processes such as gluon-gluon fusion (ggF), many events contain a low final-state track multiplicity ?. The diphoton vertex is therefore identified using a Neural Network, trained on variables including the *photonpointing* (that is, the vertex position in z most compatible with the shower-shapes observed in the ECAL), the $\Delta\phi$ between the vector sum of the track momenta and the diphoton system (as determined by the ECAL), and the scalar momentum sums p_T and p_T^2 for the tracks in each diphoton vertex candidate ?. Photon energies and pseudorapidities are corrected to reflect this new vertexing procedure.

The efficiency of the Neural Network diphoton vertex compared to the hardest vertex for a number of targeted physics processes ("STXS bins") for the full Run-2 Couplings analysis is shown in Figure .

3.1.4.2 Jets

Hadronic jets are identified from topo-clusters using the $anti-k_t$ algorithm. Clustering algorithms iteratively follow the following procedure: for each topo-cluster i , calculate the distance between both the topo-cluster and every other topo-cluster j and between the topo-cluster and the beam B :

$$d_{i,j} = \min(p_{T,i}^{2k}, p_{T,j}^{2k}) \frac{((y_i - y_j)^2 - (\phi_i - \phi_j)^2)}{R^2} d_{i,B} = p_{T,i}^{2k} \quad (3.1)$$

Where y_i is the rapidity of particle i , defined as $y = \frac{1}{2}\ln(\frac{E+p_L}{E-p_L})$ (where p_L is the particle's momentum in the beam direction), $R = 0.4$ (the jet radius), and k is some constant. For the $anti-k_t$

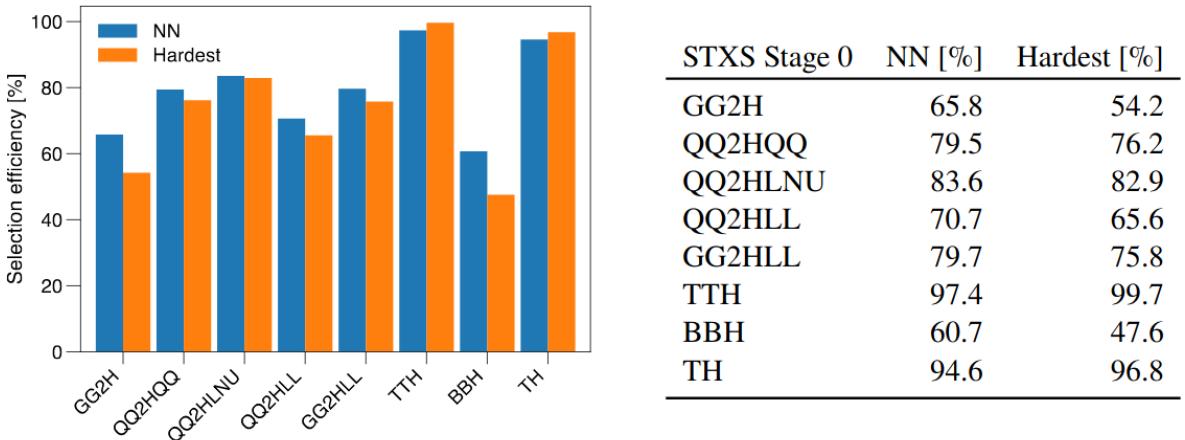


Figure 3.2: Shapes and signatures of a variety of objects in the detector ??

algorithm, $k = -1$; other common clustering algorithms use $k = 1$ (k_t) or $k = 0$ (Cambridge-Aachen).

After calculating these metrics, combine the two cluster objects that are the smallest distance apart and re-calculate the distance metrics for the combined object. If a cluster object is closer to the beam than to another object, it is considered a jet and is removed from the list of objects for potential combination.

The algorithm is both infrared safe, meaning that very-low- p_T objects do not appreciably impact the jet-finding algorithm results, and collinear safe, meaning that splitting one high- p_T object into two collinear ones does not impact the results. Compared to other jet-finding algorithms, the anti- k_T algorithm is more robust to the effects of low-energy radiation ??.

For the Run-2 Couplings analysis detailed in section ??, the ParticleFlow algorithm detailed in ref ?? is implemented. This helps to provide clearer pictures of the individual constituents of a jet. The ParticleFlow algorithm is an intermediate step in jet reconstruction, which subtracts off energy deposits not associated with the primary vertex and replaces energy deposits that are associated with the primary vertex with the momenta of the relevant tracks. This is done using the modified diphoton vertex discussed previously.

The collection of jets is "cleaned" to remove jets that have signatures consistent with calorimeter noise, and jets that do not satisfy $|y| < 4.4$ and $p_T > 25\text{GeV}$ are rejected as well.

A Jet Vertex Tagger (JVT) multivariate discriminant is also used to reject pileup jets. This utilizes variables such as Jet Vertex Fraction (the p_T in a given jet that is track-associated to the primary vertex divided by the p_T in a given jet that is track-associated to all vertices) and R_{pT} (the fraction of the p_T in a given jet that is track-associated to the primary vertex divided by the total jet p_T). Different JVT thresholds are used for PFlow Jets and the standard "EMTopo" jets that do

not use the ParticleFlow algorithm ??.

3.1.4.3 b-jets

While in general it is very difficult to identify the type of particle that seeded a hadronic jet, jets originating from hadrons containing bottom quarks are often identifiable with some degree of accuracy. This is due to their long lifetimes compared to other hadrons, meaning that they will travel a short distance in the inner detector ($450\mu m$) before hadronizing into jets.

For EMTopo jets, the Boosted Decision Tree-based Mv2c10 algorithm is used, while for ParticleFlow jets, the Neural Network-based DL1r algorithm is used. The Mv2c10 algorithm is based on a Boosted Decision Tree trained on variables such as impact parameter significance, the presence and properties of a secondary vertex, and jet kinematic variables such as p_T and η ??; the DL1r algorithm is based on a Deep Neural Network ?? trained on the same input variables as the Mv2c10 tagger, with additional vertex variables included to allow for charm-quark jet discrimination. The DL1r tagger also features a recurrent neural network trained to take advantage of correlations between track impact parameters in discrimination. The Mv2c10 tagger has an efficiency of approximately 77%, while the DL1r has an efficiency of approximately 70%.

3.1.4.4 Muons

Muons are reconstructed using tracks from either the muon spectrometer and inner detector or the muon spectrometer only.

In the muon spectrometer, segments of hits along the bending plane in the MDT chambers are identified using a Hough transform ??, an image-processing technique from the field of edge-detection that maps observed line segments into a polar-coordinate feature space. The coordinate orthogonal to the bending plane is found using TGC and RPC hits, while segments in the CSC detectors are reconstructed using a separate combinatorial algorithm. Muon tracks are then reconstructed from the segments using a χ^2 algorithm- a track must contain at least two segments, except in the barrel-endcap transition region, where one segment is sufficient to build a track.

Tracks are used to define four types of muons: Combined Muons, for which a track is fitted using both the Inner Detector and Muon Spectrometer, Segment-Tagged, for which a track in the ID is matched to a segment (but not a full track) in the Muon Spectrometer, Calorimeter-Tagged for which a track in the ID is matched to a calorimeter deposit compatible with a muon, and Extrapolated Muons, reconstructed using segments in the Muon Spectrometer that are not associated with any ID tracks but are compatible with the primary vertex. For all muons using the ID, criteria on the number of hits in each ID subsystem are employed to ensure track quality.

Muons must also pass identification criteria to distinguish them from potential fake muons

(usually pions or kaons). Three main criteria are used:

- The charge-to-momentum ratio significance, defined as the absolute value of the difference between the ratio of the charge and momentum of the muons measured in the ID and MS divided by the sum in quadrature of the corresponding uncertainties
- ρ' , defined as the absolute value of the difference between the transverse momentum measurements in the ID and MS divided by the p_T of the combined track
- the normalized χ^2 of the combined track fit

The analyses detailed in this thesis use the Medium identification working point, which allows only Combined and Extrapolated muons. Medium Combined Muons require at least 3 hits in at least two MDT layers, except for tracks in the $|\eta| < 0.1$ region, where tracks containing at least one MDT layer but no more than one MDT hole layer are allowed. Medium Extrapolated muons require at least three MDT or CSC hits, and are only used in the region $2.5 < |\eta| < 2.7$. Additionally, the q/p significance is required to be less than 7 ??.

Like other objects, we require isolated muons. Muon isolation variables are defined identically to those of electrons for the ttH-CP analysis, while for the Couplings analysis, the ParticleFlow algorithm is used to augment the isolation procedure with a new isolation variable called $neflowiso$, corresponding to the energy deposited in neutral reconstructed ParticleFlow objects rather than raw calorimeter clusters ??.

For the standard isolation, we use the *FixedCutLoose* working point, corresponding to $E_T^{cone20} < 0.30 \times p_T^\mu$ and $p_T^{varcone30} < 0.15 \times p_T^\mu$. For the ParticleFlow isolation, we use $(ptvarcone30 + 0.4 \times neflowisol20) < 0.16 \times p_T$ for muons with $p_T < 50\text{GeV}$ and $(ptvarcone20 + 0.4 \times neflowisol20) < 0.16 \times p_T$ for muons with $p_T > 50\text{GeV}$.

Additionally, muons are required to satisfy $p_T > 10\text{GeV}$, $|\eta| < 2.7$, have track impact parameter significance $|d_0/\sigma(d_0)| < 3$, and satisfy $z_0 \times \sin(\theta) < 0.5\text{mm}$ with respect to the primary vertex ?. Muon momentum and energy scale and resolution calibrations are determined using $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ decays ?. A charge-dependent sagitta bias calibration is also applied to correct for a slight observed misalignment of the muon system and inner detector.

3.1.4.5 Overlap Removal

An overlap removal procedure is employed to avoid double-counting objects. It proceeds in the following order:

- Remove electrons within $\Delta R = 0.4$ of any photon

- Remove muons within $\Delta R = 0.4$ of any photon
- Remove jets within $\Delta R = 0.4$ of any photon
- Remove jets within $\Delta R = 0.2$ of any electron
- Remove electrons within $\Delta R = 0.4$ of any jet
- Remove muons within $\Delta R = 0.4$ of any jet

3.1.4.6 MET

The initial momentum of protons approaching the collision point is almost entirely in the beam direction, that is, there is no appreciable momentum component in the transverse direction. Thus, by conservation of momentum, we expect that, when we sum the momenta of all particles produced in the event, we should not see an appreciable momentum excess in the transverse direction. However, often such an excess does occur, indicating the presence of undetected particles that have caused the visible transverse momentum imbalance. Missing Transverse Energy, or MET, is something of a misnomer, as it is missing *momentum*, not energy, but it is one of the most valuable tools for studying rarely-interacting particles such as neutrinos in the ATLAS detector.

The MET is defined as the negative vector sum of the transverse momenta of all objects associated with the diphoton vertex, including electrons, photons, muons, jets, and any additional low- p_T tracks. For the purpose of MET reconstruction in $H \rightarrow \gamma\gamma$ events, τ leptons are treated as jets; this is allowable because they occur rarely in the parameter spaces studied and decay dominantly to hadrons ??.

3.1.4.7 taus

We note that, though many physics analyses use τ leptons, they are not considered in any of the event signatures discussed in this thesis, so we refrain from discussing their reconstruction at length. However, we note that tau leptons can decay both hadronically and leptonically; as a result of this, their reconstruction depends on the reconstruction of electrons, muons, and jets.

APPENDIX A

An Appendix

This is an appendix. To start the appendices, use the `\appendix` command in the `thesis.tex` file.