PAIRS OF BOOSTED HIGGS
AND WHERE TO FIND THEM

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Abstract

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For Karen.

Wit beyond measure is man's greatest treasure.

Acknowledgements

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Chapter 1

The Standard Model of Particle Physics

The first recorded use of the word "elements" is by Empedocles in the 5th Century B.C. He proposed that 4 substances; earth air, fire, water, make up all of nature and can explain all the complexity of matter. This constitutes the first attempt at reductionist thinking in order to explain the world. Reductionist thinking has been very influential in modern physics, especially in the area of particle physics. The ability to break down what we previously thought were " elementary" particles into the constituent parts has led to many great discoveries. The electron, the first truly elementary particle to be discovered, was first hinted at in the 1869 discovery of cathode rays by Johann Wilhelm Hittorf. In 1897 , JJ. Thompson showed that cathode rays are streams of a previously unidentified negatively charged particle, which would later be named the electron. In 1911, Charles Wilson developed a cloud chamber which allowed for the first photographic evidence of electrons. Protons would be discovered in 1917 and then the neutron would be discovered in 1935. This launched a century of discovery that would culminate in 2012 with the discovery of the Higgs Boson, which was one of the last pieces of the puzzle in order to explain 3 of the 4 fundamental forces in nature. We call it the Standard Model of Particle Physics.

The Standard Model(SM) of Particle Physics is the theory that explains all the known particles and the forces that govern their behavior [1]. This is quite an astonishing statement because there are hundreds of known particles and to be able to explain them in a relatively succinct manner is quite the accomplishment of modern science. The theory is usually represented in two ways. One, the lagrangian form, see Figure 1-1 [2] and two, a useful diagram that has become popular in explaining the SM, see Figure 1-2.

1.1 Standard Model Particles

1.1.1 Leptons

Starting with the electron, we can begin to fill out the SM with two other particles that are in some sense just heavier version, the muon (μ) and the tau (τ). They all have charge of -1 [3]. One can see that the muon and the tau have masses roughly 200 and 4000 times that of the electron. There also exists a pair neutrino, denoted as ν, for each of these leptons which will complete our lepton table in the SM. The electron, muon, and tau neutrinos all have 0 charge and are supposed to be massless in the SM. You will see that on the table in Figure 1-2 each of the flavors of neutrino have a mass bound of less than some value. This is because various experiments have shown that the neutrinos have some mass. Since the mass of the neutrino is not predicted by the SM, we expect that some beyond Standard Model (BSM) explanation exists. Each of these particles has an anti-particle which is notated with a bar over the symbol. These are the $\bar{e}, \bar{\mu}, \bar{\tau}, \bar{\nu_e}, \bar{\nu_\mu}, \bar{\nu_\tau}$.

All the leptons also have other properties which are important to mention. The first is something called "spin", a vector quantity. This represents the intrinsic angular momentum of the particle. It is a purely quantum property so you should not think

[1] With the VERY notable exception of gravity

[2] This is the mathematical expression of the theory from which you can do precise theoretical calculations

[3] The unit of 1 here represents -1.602 x $10^{-19} Coloumbs$

$$
\begin{gathered}
-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu\partial_\mu A_\nu - \frac{1}{2}\partial_\mu H\partial_\mu H - \\
\frac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \frac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \\
\frac{2M}{g}H + \frac{1}{2}(H^2+\phi^0\phi^0+2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\frac{1}{8}g^2\alpha_h[H^4+(\phi^0)^4+4(\phi^+\phi^-)^2+4(\phi^0)^2\phi^+\phi^-+4H^2\phi^+\phi^-+2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2+(\phi^0)^2+2\phi^+\phi^-] - \\
\frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial+m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial+m_u^\lambda)u^\lambda_j - \\
\bar{d}^\lambda_j(\gamma\partial+m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \\
\frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - \\
1-\gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1-\frac{8}{3}s_w^2-\gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + \\
(\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+ \\
\gamma^5)u^\lambda_j)] + \frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \\
\frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + \\
m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1- \\
\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \\
\frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{X}^+(\partial^2-M^2)X^+ + \bar{X}^-(\partial^2-M^2)X^- + \bar{X}^0(\partial^2 - \\
\frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y} X^- - \\
\partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \\
\partial_\mu\bar{Y} X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \\
\frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \\
igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}
$$

Figure 1-1. The lagrangian form of the the Standard Model

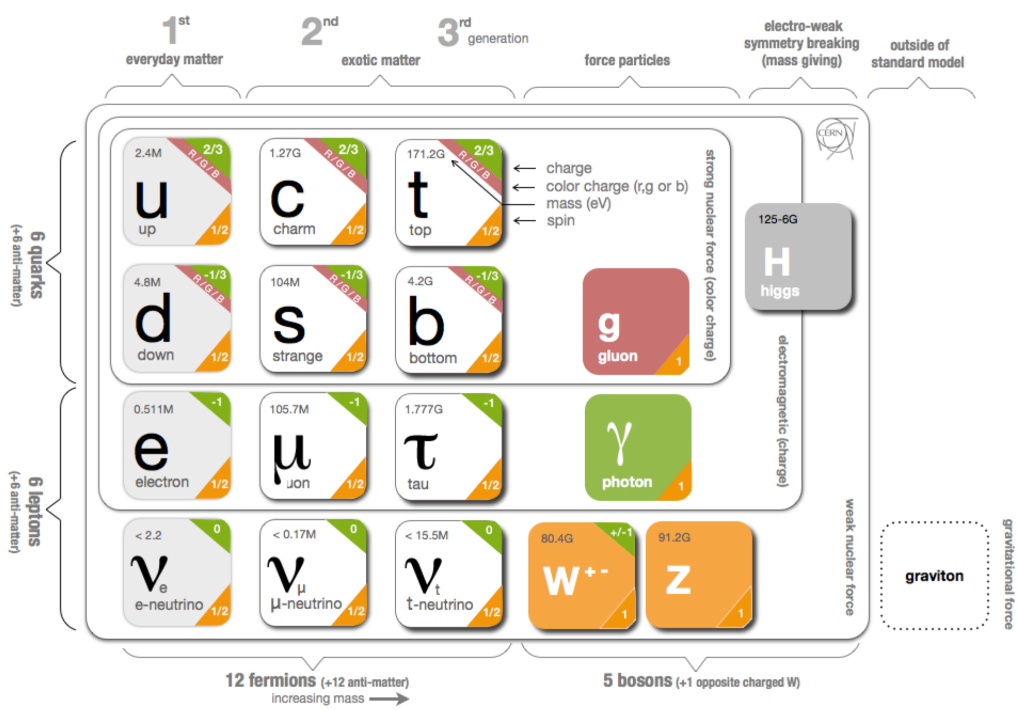


Figure 1-2. A graphical depiction of the Standard Model

of it as a measurement of how fast the particle rotates. Rather it is one component of the total angular momentum of the particle. However, the classical analogy is useful. Just as something can spin in multiple directions classically, this quantum notion of spin has two directions we denote as positive and negative. This spin can come in quantities of whole units, 0,1,2, and in half units of, $\frac{1}{2}$. The leptons mentioned above all have spin of positive or negative $\frac{1}{2}$, which means they are what we call fermions.

There is another important property which we call helicity (also called handedness). This is defined as the sign of the particles spin vector projected onto its momentum vector. Usually, negative helicity is referred to as left-handed and positive helicity is referred to as right-handed. This property plays an important part in the calculations of the SM and therefore is not a trivial quantity. Particles with different handedness can behave differently. For example, while the massive leptons can all be either left or right handed, the neutrinos all left handed and the anti-neutrinos are all right handed. This phenomenon currently has no explanation in the SM.

1.1.2 Hadrons

There are many more particles that have been discovered in the past 100 years. These have been meticulously detailed in a reference made by the Particle Data Group (PDG) and can be bought in a large textbook form or a small quick reference. However, the majority of these particles are composite particles, called Hadrons, that are made up of one of the six quarks seen in Figure 1-2. These quarks come in three groupings or "generations". [4] The quarks are the up (u) and down (d), stange (s) and charm (c), and bottom (b) and top (t). The u, c, and t quarks all have charge of $+\frac{2}{3}$ and the d, s, and b quarks all have charge of $-\frac{1}{3}$. They have their own masses, spins, and anti-particles (also denoted with a bar over the usual symbol), like the leptons do. They all have spin $\pm\frac{1}{2}$ so they are also fermions.

[4] Why only 3 and not 2 or 4? The SM theory requires 3 generations to preserve its symmetries and properties and indeed this requirement led to the discovery of the 3rd generation of quarks.

The quarks have an extra property that is unique, called color. This is another quantum property but unlike quantum spin, there is not a very good classical analogy. It can be thought of as a kind of "charge", but it has three different types, red, green, and blue. There also exists anti-red, anti-green, and anti-blue for the anti-quarks. Unlike electric charge, the color of a quark is not directly detectable and must be determined through the quarks interactions. It is also not possible for quarks to exists in anything but color neutral combinations. This will be further explained in the section on forces. These color neutral combinations make up a lot of the particles you think of today. For example, the proton is made of two u and one d quark. It has a charge of +1 because of this fact. The neutron on the other hand, is made of two d and one u quark. This combinations creates a neutral electric charge. Since the quarks always come in color neutral combinations, the fractional charges of the quarks also cannot be directly detected because all of the color neutral combinations also have whole numbers of electric charge.

1.1.3 Bosons

There are 5 bosons listed in figure 1-2. They are the photon, the gluon, the $W^{\pm}$, the Z and the Higgs bosons. Unlike the fermions, which all have spin $\pm\frac{1}{2}$, the bosons all have a unit spin of 1[5]. The photon and the gluon are massless, while the W, Z, and Higgs bosons have mass. This is not an accident and will be further explained in the following section on forces. So why do we distinguish fermions from bosons? The reason is that they fundamentally behave differently. The fermions are the stuff that everyday matter is made of but the bosons are what mediate the interactions between fermions. To put it simply, the bosons act on the fermions in what we call the forces of the SM.

[5] There exists the theoretical possibility of spin 0 or 2 bosons but none has been detected so far

1.2 Standard Model Forces

There are three fundamental forces that the SM explains, electromagnetism, the weak force, and the strong force. You will note the obvious absence of gravity. While gravity was the first force to be quantified in Newton's 3 Laws, it has resisted our attempts at understanding it at a quantum level. Many famous, and not famous, physicists have worked tirelessly to find a resolution to this problem. To date, our inability to reconcile the current theory of gravity with the quantum nature of the SM is one of the most vexing problems facing physics.

The forces of the SM are mediators between particles. It is therefore useful to discuss how this is done mathematically. We can consider a very basic situation where two particles are launched at each other. Let us consider like charges so that the two particles will repel each other. Then we can construct an infinite sum of all the possible interactions between the two particles that start in an initial state, i, and end in some final state f as:

$$S_{i \to f} = \sum_{n=0}^{\text{inf}} I^n \tag{1.1}$$

where each term I^n is a different possible interaction between the two particles. The first term is not interesting because it is the term that denotes the two particles not interacting. So the first interacting term is then:

$$I^2 = (\pm)^n \bar{\psi(x)} V \psi(x) \bar{\psi(x')} V \psi(x') \int (\frac{dk}{2\pi})^4 \frac{-g_{\mu\nu}}{k^2 - i0} e^{-ik(x-x')} \tag{1.2}$$

where the terms $\psi, \bar{\psi}$ refer to the two particles initial and final states and the V term is the interaction vertex. The $\frac{g_{\mu\nu}}{(k^2-i0)}$ term in the integral is propagator which denotes the force interaction between the two particles (in this case we are mediating the electromagnetic force with a photon). The integral is computed over all incoming and

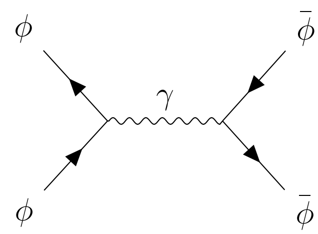
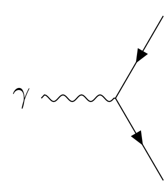


Figure 1-3. An example Feynman Diagram

outgoing momenta, k.

This equation, while precise and useful for direct computation, is not very instructive and can be put in a pictorial representation that is much easier to read. These representations are called Feynman Diagrams. Each term in the infinite sum above can be drawn with a Feynman diagram allowing us to see all the necessary components for the interaction. This allows us to look at specific physical processes without having to resort to long equations. More importantly, this representation does not lose any of the preciseness of the equations, they are essentially one and the same.



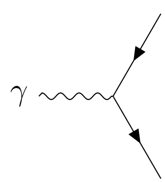
$$= V \tag{1.3}$$

Equation 1.3 is the mathematical expression for a vertex. A vertex is essentially the interaction point between two particles. One can build the diagram in Figure 1-3 by combining two vertices and correctly writing the corresponding propagator.

Physically, what is happening is that two particles are coming together, combining into an intermediate particles, and then that intermediate particle is decaying into two particles. This general description is actually very powerful. One can construct any number of particle combinations in such a way as they annihilate (or merge) into an intermediary particle and then decay into two (maybe even more) new particles. This ability to write down particle interactions based on a set of rules, which we will describe in following sections, is the foundation of the SM. We can classify three of the four fundamental forces of nature by constructing rules around the combination of vertex diagrams with particular intermediate particles. These intermediate particles are usually the bosons that govern a force that the particles are interacting with each other through.

1.2.1 Electromagnetic Force

Classically, Maxwell's equations do a very good job describing electromagnetism. However, in the quantum realm they do a poor job. The quantum theory of electromagnetism is called *quantum electrodynamics*. This theory governs all of the possible interactions between the photon, the propagating particle of the electromagnetic force, and any particle that interacts with the photon. Recall that the interaction vertex is the base of the rules for constructing Feynman diagrams and the interaction vertex for the photon is given in equation 1.4 as:



$$= ie\gamma^{\mu} \tag{1.4}$$

The equation for the propagating photon is:

$$\gamma = \frac{g_{\mu\nu}}{(k^2 - i0)} \tag{1.5}$$

which when combined together and integrated over all momenta, can be made into an equation which is similar in form to 1.2.

A quick example of how powerful these tools can be is electron-positron annihilation. If a positron and an electron interact through a photon we will get the diagram shown in Figure 1-4. We can also use some rules from classical electromagnetism, i.e charge is conserved, to tell us if this will actually happen in real life. In this example, the total charge of the incoming particles is $1 + (-1) = 0$. The photon has charge $= 0$ so then this will conserve charge and is possible in nature. Using charge conservation

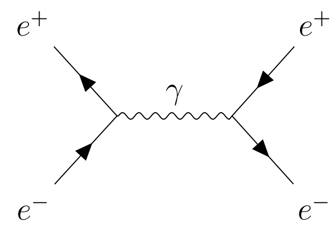


Figure 1-4. Electron positron annihilation.

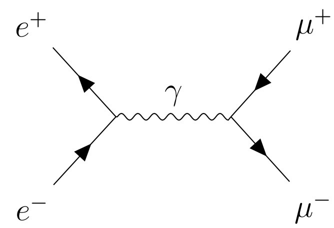


Figure 1-5. Electron positron annihilation into a muon and anti-muon pair.

as another rule we can construct other diagrams by just switching out the electron-positron pair with another lepton, anti-lepton pair. One classic example is to use the muon and anti-muon which yields the diagram seen in Figure 1-5. QED is very well tested in modern day experiments and there are no known expected differences between it and the SM.

1.2.2 Strong Force

The Strong Nuclear Force, or strong force for short, governs the interactions inside of hadrons like the proton and neutron. The mediator, or propagator, for the strong nuclear force is the gluon. The theory governing this force is called *Quantum Chromodynamics*. It can be said that QED is the theory of electrically charged interaction and the analogy for QCD is that it is the theory for colored interactions [6]. Unlike the photon, which since it has no charge it cannot couple to itself, the gluon has a color charge and so the interaction vertices possible to make Feynman diagrams are slightly more complicated and are shown in Figure 1-6. Just like in QED, if we apply a conservation law we can constrain what diagrams we can draw. However,

[6] recall that I described quarks as having a color charge.

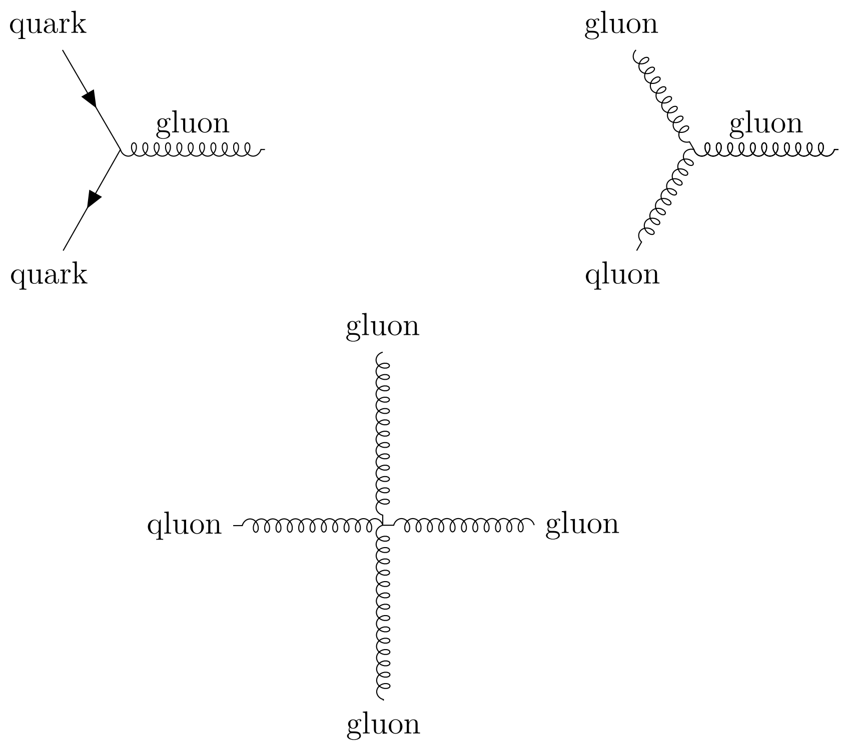


Figure 1-6. Strong force Vertices.

unlike with QED, the color charge is not as straight forward. For the diagrams in Figure 1-6 to work, we need each gluon to carry one color and one anti color since each quark carries only a color or anti color. Naively, one might think to just combine a color anti color pair like red anti-red, but gluons cannot carry both the color and corresponding anti color. This is due to the nature of the behavior of the strong force.

To give a little more context, protons and neutrons (sometimes called nucleons to refer to both of them) are confined to the nucleus by the strong force. However, they do not carry color charge in the same way that quarks do. The distinction here is that while the gluon is force carrier particle binding the quarks together inside the nucleons, it does not do that between nucleons. Two quark combinations called mesons are the mediators between nucleons. This difference is due to the emergent properties of complex systems of colored particles and is sometimes called the *residual strong force*. Since the mesons are not massless, the range for which the strong force can be felt is much smaller than say electromagnetism. In the case of these nucleons, they form what is called a color singlet. The color singlet is the superposition of quantum states as:

$$\frac{r\bar{r} + b\bar{b} + g\bar{g}}{\sqrt{3}} \tag{1.6}$$

Singlet states interact with each other. This allows us to make an empirically driven statement that since the gluon is massless, and force mediated by the singlet state has a range limit, no gluons will carry this color singlet state. This then allows us to construct the remaining color combinations for the gluons. There are eight of them and so they are called the color *octet*. The are as follows:

$$\begin{gathered} \frac{r\bar{b} + b\bar{r}}{\sqrt{2}} \quad \frac{r\bar{g} + g\bar{r}}{\sqrt{2}} \quad \frac{b\bar{g} + g\bar{b}}{\sqrt{2}} \quad \frac{r\bar{r} + b\bar{b}}{\sqrt{2}} \\ \frac{-i(r\bar{b} + b\bar{r})}{\sqrt{2}} \quad \frac{-i(r\bar{g} + g\bar{r})}{\sqrt{2}} \quad \frac{-i(b\bar{g} + g\bar{b})}{\sqrt{2}} \quad \frac{r\bar{r} + b\bar{b} - 2g\bar{g}}{\sqrt{6}} \end{gathered} \tag{1.7}$$

Interestingly, this is not just the only set of possible combinations, but it is also the least complex. One might ask, well what if I have sufficient energy to force something into a color singlet state? This becomes an interesting questions because physics not only prevents this from happening but does so in a way that allows us to further explore the SM.

For the sake of argument, lets say we smashed an electron and proton together with enough energy that one of the quarks in the proton was ejected. Any other parts of the proton that are ejected as well will interact through the strong force also. As the constituent quarks drift, the gluons that had bound them inside the proton form a web of self interacting connection called the color tube. These tubes exert constant force when stretched and increase in energy until they reach a characteristic size where it become more energetically favorable to create two new quarks out of the vacuum. This means that the lone quark that we ejected out of the proton will at the distance of about 10^{-15} meters, roughly the radius of atomic nuclei, become a new bound state meson because the lone quark cannot be in a color singlet state. If the quark still has too much energy to be bound in the meson, the process continues creating new quark anti quark pairs out of the vacuum until all free quarks are in bound states. This property is called *confinement* and the method by which the new quarks are produced in the vacuum is called *hadronization.* Hadronization in particular is important because it creates objects called “jets” which will be crucial to our experiment.

1.2.3 Weak Force

When we say the very early universe was very hot, what we mean is that the ambient temperature was extremely hot because of how energetic the particles were during that time. During this time, the electromagnetic force was unified with what we know as the weak nuclear force into what is called the Electroweak interaction. This force was mediated by 4 massless bosons named W_1, W_2,W_3, and B. Another field that matters in this story is the Higgs field which will be more completely described in the following section. At these high energies, the 4 original bosons did not interact with the Higgs field. However, as the universe cooled, this picture changed. As these original 4 bosons started interacting with the Higgs field, their interactions with the fermions changed. The fermions would no longer interact with the individual bosons but with superpositions of them. These superpositions give rise to 4 new bosons. The Z and γ bosons replaced the W_3 and B bosons. This is written as:

$$\begin{pmatrix} \gamma \\ Z \end{pmatrix} = \begin{pmatrix} cos(\theta_W) & sin(\theta_W) \\ -sin(\theta_W) & cos(\theta_W) \end{pmatrix} \begin{pmatrix} B \\ W_3 \end{pmatrix} \tag{1.8}$$

Here θ_W is called the Weinberg Angle or Mixing Angle and is a measurable parameter of the SM. The two remaining bosons combine to make two new bosons as:

$$W^{\pm} = \frac{W_1 \mp iW_2}{\sqrt{2}} \tag{1.9}$$

Figure 1-7. Weak force Vertices.

Now that we know where the three bosons of the weak force come from, their interaction vertices will be in Figure 1-7 These two bosons, the $W^{\pm}$ and Z are not massless like the other bosons. Their masses are 80.4 $\frac{GeV}{c^2}$ and 90.4 $\frac{GeV}{c^2}$[7] respectively. Each of these two bosons has a different effect on the particles in interacts with. The Z boson turns a particle into it's anti particle. So $Z \rightarrow \mu^- \mu^+$ is a valid interaction. This will work with quarks as well. W bosons also couples with pairs of fermions but exchanges them in terms of their flavor. For example, $W \rightarrow d\bar{u}$ is allowed. You can also have a W decay into an electron and its neutrino as $W^- \rightarrow e^- \nu_\mu$ as long as the charge matches. Since the W bosons is charged, decays like $Z \rightarrow W^- W^+$ are allowed.

If you recall that the proton and neutron are just combinations of up and down quarks, you might wonder why we don't see other combinations of quarks in nature. The reason is that the W boson can interact with quarks of different generations [8]. Through the W boson, all other quarks end up decaying to the lighter first generation of quarks. This process can be expressed mathematically as the CKM Matrix. The CKM Matrix encodes the probability of a W decaying into a pair of quarks.

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} = \begin{pmatrix} 0.974 & 0.225 & 0.004 \\ 0.225 & 0.973 & 0.041 \\ 0.009 & 0.040 & 0.999 \end{pmatrix} \tag{1.10}$$

where $|V_{ij}^2|$ is the probability of the ith quark decaying into the jth quark through emitting a W boson. It is through this mechanism that all the various other particles

[7]GeV stands for 10^9 eV which stands for electron volt. The unit eV/c^2 is equivalent to $1.78x10^{-36}$ kg. An electron has a mass of about 0.5 MeV/c^2 and a proton has a mass of about 1 MeV/c^2

[8]Recall Figure 1-2 and that there are 3 generations of particles.

that have been detected in the last century will decay into lighter ones, i.e., the proton and neutron.

1.2.4 The Higgs Boson and Mass

The Higgs Boson was discovered at the Large Hadron Collider at CERN in 2012. It's discovery rounded out the SM quite nicely because, as we mentioned previously, the Higgs Boson mediates the Higgs field and it is a particle's interaction with the Higgs Field that gives it mass. We said in the previous section that the Higgs Field interactions did not matter at high energies and now we will detail why. If you consider the form of the Higgs potential, $\approx (\phi^2 - \eta^2)^2$, where ϕ represents the Higgs field, you can see in Figure 1-8 that at high energies there is no interaction. As cooling happens, particles now may interact with the "bump" seen in the Higgs potential. When this happens, a choice needs to be made about which valley things must settle into. This is a phenomenon called *spontaneous symmetry breaking.*

Originally, there is a symmetry of the Higgs potential about the y-axis but the choice of valley or minima "breaks" that symmetry. This does not mean that the SM is asymmetric. It just means that there are energy ranges in the SM that give rise to asymmetric like behavior. Now that a choice has been made for a minima, this symmetry breaking causes the Higgs field to take a vacuum expectation value or VEV. This can be thought of as the average value of the field in empty space. When we say it "takes" a value for the VEV, what we mean is that it deviates from 0. In the case of the Higgs field, its VEV is 246 GeV. The VEV is what is coupling to the electroweak interactions creating the photon and weak force bosons we see today. Similarly, though definitely not identically, the Higgs field couples to weak bosons, quarks, electrons, muons, and tau particles and gives them mass. We cannot say that it couples to all fermions because the neutrino ends up being the odd particle out here and does not couple to the Higgs field. In order to finish off our rules for creating

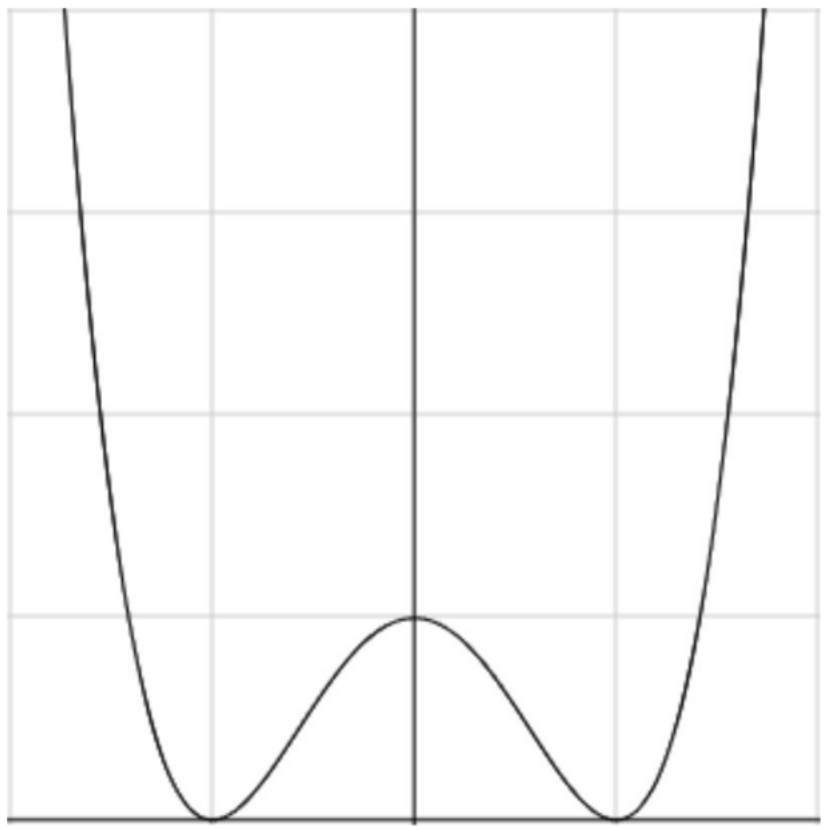


Figure 1-8. Higgs Potential where the y-axis has units of energy.

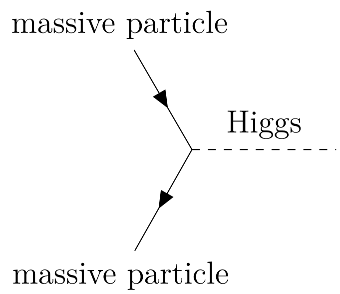


Figure 1-9. Higgs Boson Vertex.

Feynman diagrams we can draw the interaction vertex for the Higgs Boson in Figure 1-9. It can interact with any massive particle, including itself. The Higgs Boson has no charge, no spin and a mass of 126 $\frac{GeV}{c^2}$.

1.3 What's Left?

Now that we have a good understanding of the SM, what can we do with it? Well, to start, it isn't complete. Gravity is noticeably absent in the SM. This is possibly a little embarrassing for physics because gravity was the first fundamental force to be properly quantified when Newton wrote down his 3 laws. Our current understanding of gravity, through the theory of General Relativity, does not mesh nicely with the equations of the SM. Large and complicated theoretical efforts have been working very hard to try to reconcile this difference but it still remains today. The discovery of a graviton, thought to be a spin-2 boson, would aid physicists greatly in completing our understanding of the fundamental forces of nature.

Beyond that, the visible matter in our universe only makes up about 4% of the stuff in it. Physicists have good evidence that the universe is roughly 25% matter so what is the other 21%? This extra stuff is theorized to be “dark matter”, i.e. not interacting in a way we can directly detect, and is not currently included in the SM. There are many theories and experiments working on this question but no answer has come yet. Another problem is that we don't even fully understand the roughly 4% of baryonic matter we do know about. The majority of this matter is made of particles but why? Why are there not more anti particles? It is not clear why there would be an asymmetry to the amount of matter vs anti matter. Some progress has been made recently on this question but the answer is still incomplete.

So given that we seem to be missing many answers to questions about known measurable physical phenomenon, how do we explain them? Theorists spend their days creating answers for these questions in a manner that would be consistent with the current SM. These theories are know as “Beyond Standard Model” (BSM) and can address one or all of the known issues with the SM. Now we shall talk about a few BSM theories that will be relevant to this experiment.

Chapter 2

Beyond the Standard Model

In the last chapter we discussed the major parts of the SM, detailed some of the rules for working with it, and then talked briefly about what has been left out. The SM itself actually imposes many constraints, so any BSM theory must conform to those constraints. It should also be pointed out that there have been many searches, but very little evidence, of BSM physics. This does not exclude BSM physics, it just creates another set of constraints that must be satisfied along with the constraints already set by the SM. One of the most pressing questions about the SM, and one of the most relevant for the following experiment, is called the hierarchy problem.

2.1 The Hierarchy Problem

To understand the hierarchy problem, we need to revisit the Higgs boson feynman diagrams. If you recall, we can build up diagrams by adding vertices together. This then is a valid diagram between 4 particles that is mediated by a Higgs boson:

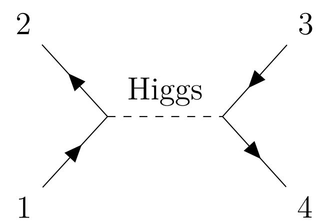


Figure 2-1. A tree level Higgs diagram

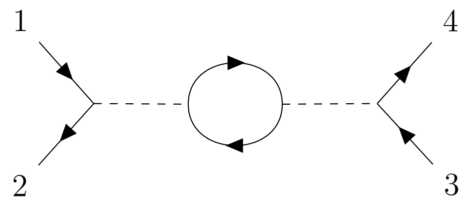


Figure 2-2. A loop level Higgs diagram

Figure 2-1 is what we call a “tree level” diagram. We can add possible interactions in the middle of the tree diagram creating what are called “loops”, like in figure 2-2.

Since all we do is measure the incoming and outgoing particles, we do not know which of the diagrams is physically happening. The SM starts with what we call a “bare” mass term, in this case m_H^{bare}, and then when adding loops[1], it makes quantum corrections to the bare mass. So, the mass we measure is actually:

$$m_H = m_H^{bare} \times (1 + \sum_{\text{all loops}} \text{quantum loop corrections}) \tag{2.1}$$

The Higgs boson is a scalar, which for our purposes, means that when adding up the corrective terms, they do not start cancelling each other out in a well controlled manner. Since we do measure a consistent Higgs mass, theoretically it is not satisfactory that we cannot predict this mass in the SM due to the lack of control of the quantum correction terms. The reason that this is a problem is that in the theoretical calculations of these quantum corrections, the Higgs mass is quadratically sensitive to any scale that you introduce to the theory. Energy scales are introduced to quantum corrections in order to carry out a process called renormalization. Simply stated, renormalization is the process by which we can remove any non-physical values, i.e infinities, that show up in our calculations. This happens frequently when calculating quantum corrections so if when we try to renormalize our quantum corrections but the terms only grow in relative size, there will be a problem when we try to take a large sum of ALL possible corrections to the Higgs bare mass. In this case, the infinities that we tried to regulate

[1]This process of adding loops can create some wacky looking diagrams. However, even wacky diagrams can be experimentally relevant.

will show up all over again. Again, since we can measure the Higgs mass, and it is definitely NOT infinity, we need to find a way to control these quantum corrections, which is where BSM physics comes in.

2.2 Possible Solutions to the Hierarchy Problem

There are several theoretical models that propose solutions that solve the hierarchy problem. We will not detail all of these proposals, as that would take a thesis of its own. Here we will give an overview of the two solutions that are most relevant to our experiment. They are Warped Extra Dimensions (WED) and Minimal Supersymmetric extensions to the SM (MSSM).

2.2.1 Warped Extra Dimensions

In classical physics, the notions of space and time are fixed to 4 dimensions, 3 space and 1 time. In quantum physics, there is no a priori reason we cannot consider additions to the amount of spacetime dimensions. After Einstein's newly introduced theory of 4-D spacetime, the General Theory of Relativity, researchers started asking if it was possible that what we see as 4-D spacetime is really 5-D, where the 5th dimension is compactified or warped in some way as to avoid easy detection. The first of these theories is called Kaluza-Klein Theory and was originally published by Kaluza in 1921. This theory was originally unused as it did not offer many testable predictions. However, there have been many improvements in recent decades.

One of the recent improvements, indeed the one that is most experimentally relevant to us, is WED. The WED models have an extra spatial dimension compactified between two branes, with the region between (called the bulk) warped via an exponential metric κl, κ being the warp factor and l the coordinate of the extra spatial dimension [1]. For our purposes, we can think of branes as the "boundaries" to the spacetime in which we live. They are lower dimensional spaces that are dynamic and can effect the fields that propagate the forces we see in nature. In these WED models, we can think of the "low energy" versions of our theories, i.e. the SM, as "living" on one brane. Here living on a brane means that the fields in the field theory do not propagate into all of the available spatial dimensions, in this case the bulk. Then the "high energy" versions will live on the other and the bulk will mediate between them. The original version of these theories had only gravity propagating in the bulk, but that it is not the only thing that may propagate in the bulk of a WED theory [2]. In the literature, the "low energy" brane is called the infrared (IR) brane and the "high energy" brane is called the ultraviolet (UV) brane. These two scales, UV and IR, are very important for theoretical discussions of the behavior of SM theories. Since we will not delve into those details, I described what they are for your future reference.

In WED models, there can exist excitations, which is the mathematical way we think of particles in their respective fields, that are of the type described in Kaluza-Klein theory, so called KK excitations, and which propagate in the bulk. The prediction from WED is that these excitations will be spin-2 bosons called KK gravitons. These would mediate gravity in the bulk and be a way to incorporate gravity into the SM. They also predict spin-0 particles, called radions, which are scalar versions of gravitons. These KK gravitons and radions are predicted to interact with the weak force which in turn allows them to interact with the SM Higgs boson and give them mass.

The radion serves another purpose. One question you might have thought to ask is, what is the size of the extra dimension that you keep talking about? If it is so small that we do not detect it, then how small is small enough to be undetectable? This is not currently known, however, the radion is produced from spontaneous symmetry breaking and therefore, takes a VEV. This radion VEV then sets the scale of the size of the extra dimension or bulk that is between the UV and IR branes.

[2] Other particles, namely SM fermions and bosons can propagate in the bulk.

2.2.2 Minimal Supersymmetry

Another way we can attempt to solve the hierarchy problem is to introduce a new class of theories called Supersymmetry. In supersymmetric theories, each particle has a superpartner particle that is different from the anti-particle. These extra particles would add cancelling terms to the equation in 2.1 which would allow the quantum correction terms to be controlled. There are many supersymmetric models, each with small differences to account for the issues seen in the SM. We will not be able to cover all of the known supersymmetry models and will focus on the MSSM models.

MSSM models make what is called the "minimal" extension to the standard model. These minimal extensions take each SM fermion and add a superpartner, known as a sfermion (squarks or sleptions). They also take each gauge field [3] and add a gaugino, which is a propagating fermion for the field. While this sounds overly simplistic, it adds its own version of complications after solving the hierarchy problem. For example, if these so called superpartners are just different version of their respective particles, and with the same mass, then we should have discovered them long ago. Since we haven't, we must assume that there is a mass scale above which all of these superpartners live.

Again, there are several ways to accomplish this addition of mass. However, they all involve a form of spontaneous symmetry breaking, recall how the Higgs field picks up a VEV, of the supersymmetry that generates all of these new particles. This symmetry breaking is the underlying cause of the masses that these superpartners have. This is also very similar to the case of the electroweak interaction. In both of these cases, in the UV limit of these theories, the symmetry is preserved. As soon as we move from the UV to the IR, the symmatry is broken. The mathematical details here are not necessary for this thesis, so we will skip them. They also contain

[3] A gauge field is the mathematical mechanism behind the SM forces. I do not introduce the machinery because it is quite extensive and would be a thesis in itself.

colloquial language that can be very confusing [4].

2.3 Predictions of WED and MSSM

In the standard model (SM), the pair production of Higgs bosons (H) [2–4] in proton-proton (pp) collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ is a rare process [5]. However, the existence of massive resonances decaying to Higgs boson pairs (HH) in many new physics models may enhance this rate to observable levels, even with current experimental data. For instance, WED models [6] contain new particles such as the spin-0 radion [7–9] and the spin-2 first KK excitation of the graviton [10–12], which have sizable branching fractions to HH.

In WED models, the reduced Planck scale ($\overline{M_{\mathrm{Pl}}} \equiv M_{\mathrm{Pl}}/8\pi$, M_{Pl} being the Planck scale) is considered a fundamental scale. The free parameters of the model are $\kappa/\overline{M_{\mathrm{Pl}}}$ and the UV cutoff of the theory $\Lambda_{\mathrm{R}} \equiv \sqrt{6}e^{-\kappa l}\overline{M_{\mathrm{Pl}}}$ [7]. In pp collisions, the graviton and the radion are produced primarily through gluon-gluon fusion and are predicted to decay to HH [13].

Other scenarios, such as the two-Higgs doublet models [14] (in particular, the minimal supersymmetric model [15]) and the Georgi-Machacek model [16] predict spin-0 resonances that are produced primarily through gluon-gluon fusion, and decay to an HH pair. These particles have the same Lorentz structure and effective couplings to the gluons and, for narrow widths, result in the same kinematic distributions as those for the bulk radion.

[4]For example, those of you who are theory inclined will recall that Goldstone bosons exist whenever a field breaks a symmetry and generates a VEV. When we promote that symmetry to a gauge symmetry, for some reason it is fashionable to say that the Goldstone boson is "eaten", which I found very confusing initially since it implies that the boson disappears instead transforming into the longitudinal polarization for the corresponding gauge field.

Chapter 3

The CMS Detector at the LHC, CERN

The way we probe the mysteries of particle physics has, in principle, not changed much since it started. The basic premise is what has been called the “reductionist” approach. This approach tries to reduce everything to its most fundamental parts. It has been very successful in the field of particle physics. We once thought of protons as fundamental particles, but were able to discover they are composite by continually smashing things together at higher energies.

The act of smashing particles together is the mechanism of particle physics. One needs to decide at what energies they will be smashed together, how the particles will be controlled, whether or not one is fixed in place initially, and a whole host of other factors. These will effect what particles you can smash and what new particles you might expect to see from this collision.

Nature itself actually provides a useful laboratory to start this type of research program. One of the early particles that started helping physicists start filling out the SM was the muon (μ). Muons are produced in nature when a positron is accelerated by the sun’s atmosphere and launched at earth. The positron then collides with one of the electrons in an atom. These two would then annihilate and become a very energetic photon. This photon will have so much energy that it is very likely to decay into something heavier than the electron/positron pair, a pair muons for example. Through this mechanism, muons actually are constantly being made in the upper atmosphere and shooting down to earth. We are able to detect them because they travel close enough to the speed of light that time dilation causes them to last long enough before they decay. In theory, other heavy particles could be produced this way but they do not last long enough in order for them to reach the surface [1].

Since we cannot rely on nature to make experimental labs for us, we need to make them ourselves. The first thing to consider is how to construct the collider. In linear colliders, one side fires a beam of particles at a beam of particles fired from the other side. The downside here is that the majority of the particles will pass by each other and not collide. The next thing we can do to alleviate this is to turn to circular colliders. In circular colliders, if some particles are not used in the initial collision, they can be recycled until they are used. This efficiency comes at a cost because particles radiate when being turned by an electromagnetic field. The equation for this is"

$$P = \frac{e^4}{6\pi m^4 c^5} E^2 B^2 \tag{3.1}$$

where E and B are the strengths of the respective electric and magnetic fields used to turn and focus the beams of particles. Since the power here is inversely proportional to mass, it is actually better to collide heavier particles rather than lighter ones [2]. This is the idea behind the Large Hadron Collider. By balancing the energy needed to collide a heavier particle with the energy saved by colliding a heavier particle, it was determined that colliding protons together would allow physicists to reach energies needed to probe the scale of physics that CERN was hoping to achieve.

[1] One can even turn a modern cell phone into a muon detector. There are apps that can register the passing of a muon through the CMOS sensor in your phone's camera.

[2] For example, if we collide protons instead of electrons, the power produced by radiation is reduced by 10^{13}

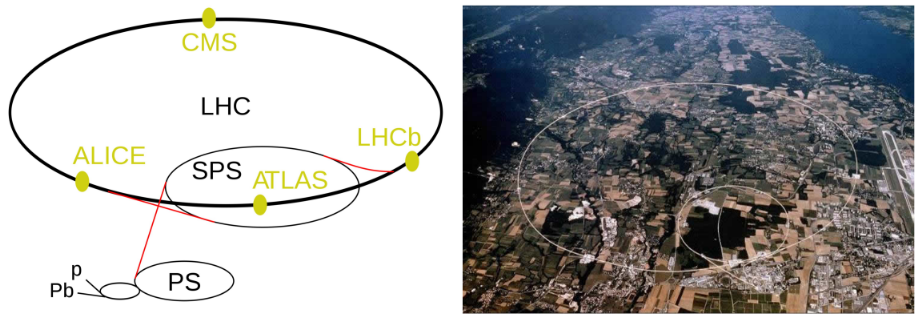


Figure 3-1. Left: A diagram of the LHC and its rings.
Right: An overhead picture of the LHC where you can see Lake Geneva on top of it.

3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) is the biggest particle collider, indeed the biggest machine, ever built. It has produced more data than all other particle experiments combined [3]. It is a 27 km ring with several smaller rings which feed the proton beams into the LHC in stages. The main ring has 1,232 dipole magnets that keep the protons in the ring and accelerate them. It also has 392 quadrupole magnets that focus the beams of protons. The magnetic fields needed to achieve this are some of the strongest ever made coming in at 7 Tesla. These can only be made by superconducting magnets that are cooled to below 2 Kelvin. This amount of cooling requires around 100 tonnes of superfluid liquid helium to achieve. The LHC currently collides protons at a center of mass energy of $13TeV$ but will be upgraded to achieve higher energies in the future. It should be noted that the beams of protons are not continuous. They come in "bunches" which consist of about 115 billion protons in each bunch. The bunches collide at 4 different points, corresponding to the 4 experiments that the LHC powers, and collide every 25 nanoseconds. This means there are roughly 40 Million collisions every second.

[3] The LHC has produced over 130 PB of data so far.

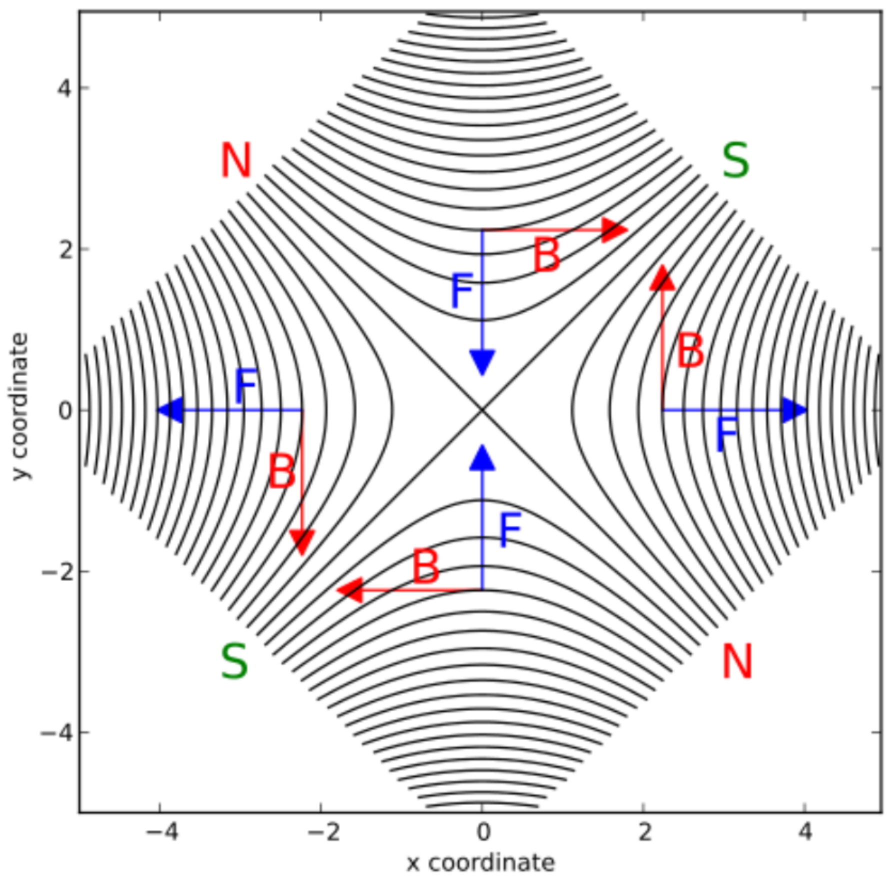


Figure 3-2. The quadrupole magnetic field that allows the proton beams to be focused in both horizontal and vertical directions.

3.1.1 Proton-Proton Collisions at the LHC

I previously had said that the proton was made up of a combination of up and down quarks. This is actually an oversimplification of the inside of a proton. In order for us to understand why one would want to smash protons together we need to get into some of the details about the proton. While it is true that the proton has two up and one down quark, the interactions between those quarks are dynamic and make up the rest of the picture of the inside of the proton. There is not actually one gluon per pair of quarks, as one might have thought, but a whole web of gluons that interact with each other and the up and down quarks. The gluons also interact with each other which creates pairs of quarks of all types that then decay back into gluons. This is a very important distinction because it powers the modern program of particle physics. When two protons collide, at the energies of the LHC, we are actually smashing together all of the quarks and gluons currently present in those protons. In this "soup" of interactions, we collectively call the gluons and quarks "partons".

The next important question is to ask what was actually collided in a given proton-proton collision. We just said that it can be a complicated interaction of quarks and gluons that is not predetermined so how do we solve this problem. What we end up doing is relying on something called the Parton Distribution Function[4]. Instead of trying to find out collision by collision what has happened, we use the PDF to create a statistical model that can give us an expectation. The PDF models are very important for discovering new physics because many predicted new particles happen under only specific interactions. Therefore, if we do not know what to expect coming out of a proton-proton collision at a given energy, then we cannot know where to look for any undiscovered particle. Unfortunately, PDFs are very hard to compute. What we end up doing is combining partial combinations with high precision measurements from fixed target colliders in order to approximate the true PDF. Since it is only an

[4]This is usually abbreviated as PDF.

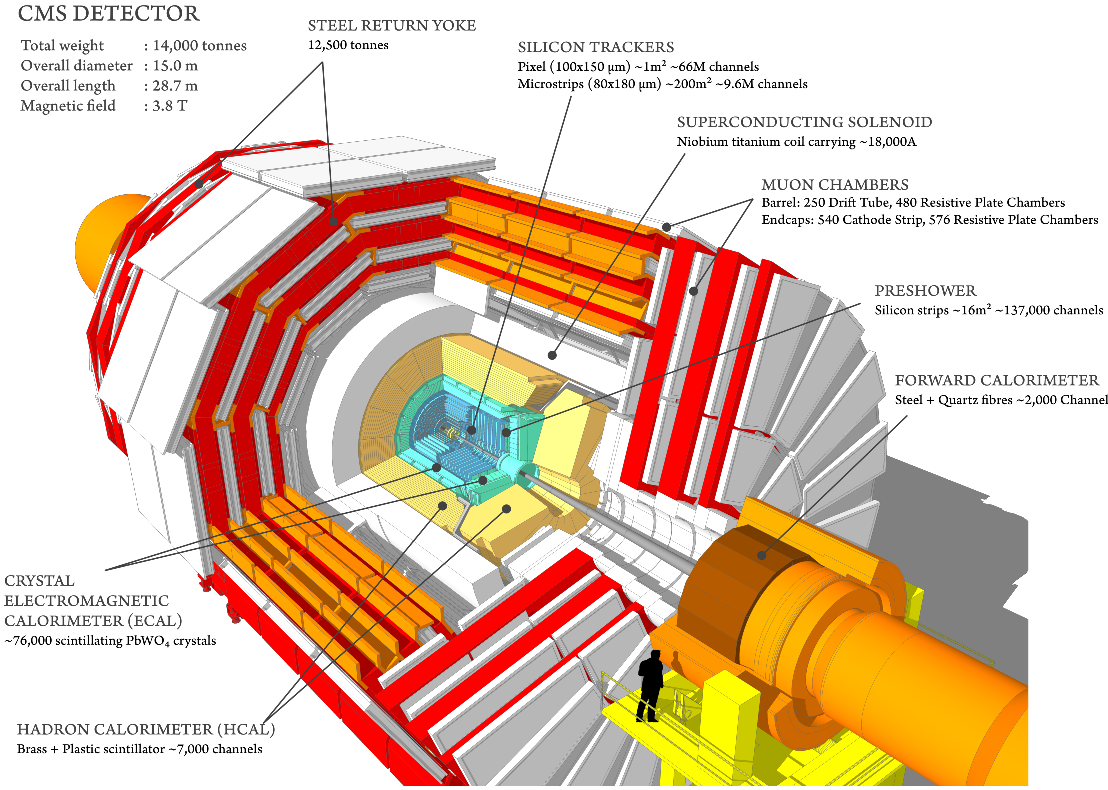


Figure 3-3. A detailed cross section of the CMS detector.

approximation, we end up have to assign a systematic error to the PDF based on the variance of likely PDFs. This will be a theme we revisit again and again. We will try to make a measurement, only be able to approximate it, and therefore we will need to assign systematic uncertainty.

3.2 The Compact Muon Solenoid Detector

There are 4 detector experiments at the LHC. The Compact Muon Solenoid (CMS), shown in Figure 3-3, is the detector that took the data we are using to perform this analysis. While it is quite massive compared to a human, weighing in at 14,000 tons, it is actually smaller than the other detectors. Once again, a full description of CMS and the work done by over 5000 scientists would take many more pages to write so we will confine our discussion to a small overview just to make sure the main parts of the detector are understood.

3.2.1 Coordinate System

CMS is essentially a large tube where both ends are covered. In order to describe this geometry, we use a modified spherical coordinate system. The angles used are η and ϕ where ϕ creates the circular component of the cylinder, and will always be perpendicular to the beam. η is defined as:

$$\eta = -ln\left(tan\frac{\theta}{2}\right) \tag{3.2}$$

and is also known as the *pseudorapidity*. Here θ is the usual angle from spherical coordinates. In these coordinates, $\eta = 0$ points straight out of the detector and $\eta = \inf$ points directly along the beampipe. One reason to use these coordinates is that η is approximately Lorentz invariant [5] This is necessary because while the protons themselves will have the same energy and likely be symmetric, there is no such guarantee with the partons. When we are talking about particles in the detector, we usually talk about them in terms of three values: radial angle ϕ, pseudorapidity η, and transverse momentum p_T. If one is interested in returning to Cartesian coordinates, which we are almost never going to do, the following equations will accomplish this task:

$$p_x = p_T cos(\theta) \quad p_y = p_T sin(\theta) \quad p_z = p_T cosh(\eta) \tag{3.3}$$

3.2.2 The Tracker

The first layer that a particle shot out of a proton-proton collision would encounter is called the Silicon Tracker. This layer is directly on the beampipe and consists of 13 individual layers surrounding the beampipe and 14 layers in the endcaps. These individual layers are bunched together and the first 4 are made up of 66 million silicon pixels that are 100 x 150 μm in area. The rest of the layers are made of strip pixels

[5] This means that it does not change depending on the reference frame in which we are looking at the interaction. It is always good to work with Lorentz invariant quantities in physics.

which are longer than the first set. All of this makes for 200 square meters of silicon that will measure the momentum of any charged particle moving through it.

A magnetic field is applied throughout the silicon tracker which causes any charged particle to curve. We can then measure the momentum because it will deposit charge on the way through each layer of the silicon tracker. With these “hits”, we can reconstruct the path and therefore the curvature which will allow us to calculate its charge and energy. The reconstruction of the hits in the silicon tracker of individual particles are called tracks and are determined to an accuracy of about 10 μm. The silicon tracker, unlike the rest of the detector, does not try to stop any particle, just measure it as it is shooting towards the calorimeters

3.2.3 The Calorimeters

After we get an idea of how a particle is moving through the detector, we need to start attempting to identify it. If you are thinking that the information from the tracker can be used to help identify any particle then you would be correct. However, we have seen that different types of particles will interact in different ways. Most notably, some particles are much heavier than others. The first layer outside of the tracker is called the Electromagnetic Calorimeter (ECAL) and is designed to allow photons and electrons to deposit their energy in this layer. Heavier particles, namely the hadrons, will move through this part of the detector and not deposit any energy. The Hadron Calorimeter (HCAL) is the next layer and is designed to stop the heavier particles.

The ECAL is composed of around 80,000 lead-tungstate ($PbWO_4$) crystals that are a type of scintillator. Scintillators emit light when a particle deposits energy into it. So the ECAL will scintillate when light charged particles impact with the crystals. Since photons have no mass, you might wonder how they interact. The photon can either produce a pair of electrons that will interact with the scintillator or interact with an electron in the crystal itself. Since these photons and electrons are typically very energetic, they can interact multiple times and create cascades of light or "showers" as byproducts of the initial interaction. The light that is produced is directly proportional to the energy of the initial particle and therefore gives us the missing piece of the puzzle to identify photons and electrons in the detector.

The HCAL is setup a little differently. Instead of crystal scintillators, it has plastic ones that are layered in between brass plates. The heavy particle will be stopped by the brass plate. This will cause a shower of secondary particles that are measured by the scintillators. Knowing what kinds of particles can decay to what final states, through the careful study of the rules of the SM, we can then reconstruct what particle hit the HCAL. It should be noted that the HCAL is the only part of the detector that can stop neutrally charged particles, like neutrons and some mesons, so it is very important for the CMS research program.

3.2.4 The Solenoid

All of the previous layers are contained in a large cylindrical electromagnet called the solenoid. This electromagnet provides a very large magnetic field (3.8 Tesla [6]) which causes electrically charged particles to bend due to the lorentz force. This effect is dependant on the energy of the particle so the information can be combined with the silicon tracker to measure the momentum of the particle. This magnetic field is strong enough to shift the alignment of the whole detector and this effect has to be accounted for. The last layer before the solenoid, the HCAL, uses brass specifically because it is non magnetic.

[6] A normal bar magnet is measured in millitesla!

3.2.5 The Muon Chambers

After the solenoid there is one final set of detectors. The issue these solve is due to muons[7] being too heavy to be stopped by the ECAL and not heavy enough to be stopped by the HCAL. Muons will go through both and then be stopped by the aptly named Muon Chambers. There are three kinds of muon chambers; drift tubes, cathode strip chambers, and resistive plate chambers, all of which work under the principle that as a muons traverses them, an electron is knocked off of gas atoms. The amount of electrons that a muon displaces is proportional to its energy and so we can measure the energy of muons with the muons chambers. Another important thing to note is that, due to the many layers of this detector and the specialities of each type, the muons chamber system is very good at reducing and filtering background noise.

3.3 Jets

In describing the strong force, I mentioned that colored particles cannot exist outside of a color singlet state, meaning they must be in pairs. In proton-proton collisions, bare quarks (quarks NOT in a color singlet state) can be produced. As soon as they are produced they begin the process of hadronization: creating new particles out of the vacuum until no bare quarks remain. Gluons may also be created in proton-proton collisions but they will decay to quarks which must then undergo hadronization. Due to hadronization, the LHC is not able to see individual quarks and gluons. All that can be seen is the shower of hadronized quarks in the direction that the quark or gluon was moving. The showers are called “Jets”. The jets are composed of constituent particles, which may in turn decay and leave traces in parts of the detector. These secondary particles are also considered constituents of the jet. The only particles that are not able to be counted as constituents are neutrinos as

[7] muons are always problematic!

their energy is lost in the detector.

3.3.1 The Particle Flow Algorithm

All of the information from the subdetectors is analyzed by the *Particle Flow Algorithm*. This algorithm allows us to reconstruct jets with a high degree of precision. It start in the silicon tracker. This subdetector is the crucial part of the algorithm because it makes the initial measurement. If it misses a charged particle, it will bias any reconstruction of that particle. Accordingly, great care has been taken to achieve high efficiencies. An iterative tracking strategy allows for extremely high efficiencies in the first pass with softer acceptance for follow up iterations. Next, a clustering algorithm is used in the calorimeters to detect and measure the energy of stable neutral particles, separate neutral from charged particles, reconstruct charged electromagnetically charged particles, and aid in the energy measurements for low-quality tracks. Finally, a link algorithm links the track detected in the silicon tracker with the appropriate clustering in the calorimeter if the extrapolation of the track fits within a given cluster's boundaries. This is a quick overview of the algorithm because, as is usual in most high energy physics topics, a full description would be beyond the scope of this thesis.

3.3.2 Anti-KT Algorithm

Since most of the events at CMS will generate more than one quarks or gluon, a number of algorithms exists to correctly "cluster" the constituents into the right jet. The one we use and will describe is called the *Anti-K_t* Algorithm. The algorithm is an iterative algorithm and runs in the following way. First, every PF (Particle Flow) candidate is compared against every other candidate with a distance like parameter, d_{ij}, given as:

$$d_{ij} = min(\frac{1}{p_{T,i}^2}, \frac{1}{p_{T,j}^2})\frac{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}{R^2} \tag{3.4}$$

where R is a predetermined distance parameter that sets the size of the jet. The two closest constituents are paired and become a new constituent. This process continues, generating new "pseudo-jets", until the distance of the pseudo-jet from the beam is $1/p_T^2$ of the pseudo-jet. It is then removed from consideration and the process starts again with the remaining constituents until none remain.

This algorithm creates what are called "conical" jets, with smooth, rounded edges[8]. We call these jets AKR jets, where we use the actual value of R in the naming. Accordingly, an AK8 jet is a jet constructed with the R value of 0.8. We use AK8 jets and AK4 jets in this analysis. For smaller particles, jets are useful for reconstructing kinematic properties. For the larger particles, heavy bosons and quarks, AKR jets can reconstruct the particle with a good degree of accuracy. A simplistic rule with this algorithm is the R value the larger the particle that can be reconstructed.

3.4 The Trigger

Each crossing of proton-proton bunches generates about 1 Megabyte of data. At the rate of 1 crossing every 25 nanoseconds, or 40 Megahertz, no modern computing system can actually keep up with this rate of data generation. This means the majority of the data is thrown out. The system responsible for filtering through all of the data is called the "trigger". The trigger operates in two stages, the Level 1 trigger and the High Level trigger.

The level 1 trigger is a hardware trigger. Output from the detector is stored in a buffer and then it is analyzed by custom circuits. These circuits look for "interesting" physics, such as especially large deposits in the calorimeters. This stage is very useful because it allows the rejection of all but about 0.1 % of all events. The rate of release to the next stage is around 50 kilohertz.

[8] This does not always happen, especially with jets that are very close to each other.

The High Level trigger takes the output from level 1 and analyzes the data further in order to find interesting events. At this level, there are many available triggers depending on what kind of event you are looking for. The selections are mostly kinematic differences. This is one of the first steps in conducting an analysis. One studies the available triggers in order to understand how your kinematic selections will effect the trigger efficiency.

For our analysis, the trigger algorithm used places requirements on the scalar sum of the jet transverse energy, H_t, jet p_T, and the jet groomed mass. We compensate for the difference in the trigger response between data and simulation by applying a trigger scale factor, defined as the ratio of trigger efficiency in data divided by the trigger efficiency in qcd, to simulated events. The trigger efficiency is defined as the ratio of the number of events passing the combined triggers and a pre-trigger to the number that pass the pre-trigger and is parameterized as a function of our measurement variable. The trigger efficiency in simulation is modeled by weighting simulated events by this data-derived trigger efficiency. We select events from the 2016 dataset that pass the `HLT_HT650` trigger, the `HLT_PFHT800` trigger or the `HLT_PFHT900` trigger, and the `HLT_AK8PFJet360_TrimMass30` trigger. For 2017 and 2018, we select events that pass the `HLT_PFHT1050` and the `HLT_AK8PFJet400_TrimMass30` trigger are used to select events for the trigger efficiency measurement. The pre-trigger for 2016, 2017, and 2018 is the `HLT_Jet260` trigger. Trigger scale factors are measured as a function of the reduced mass, which will be further discussed in Chapter 5. After passing the trigger, the events are required to have at least one reconstructed pp collision vertex satisfying the following criteria:

- Vertex number of degrees of freedom > 4;
- Absolute displacement from the beamspot position along the z direction < 4 cm;

- Absolute displacement from the beamspot position along the transverse direction < 2 cm.

Trigger scale factors are shown here in Figures 3-4, 3-5, 3-6.

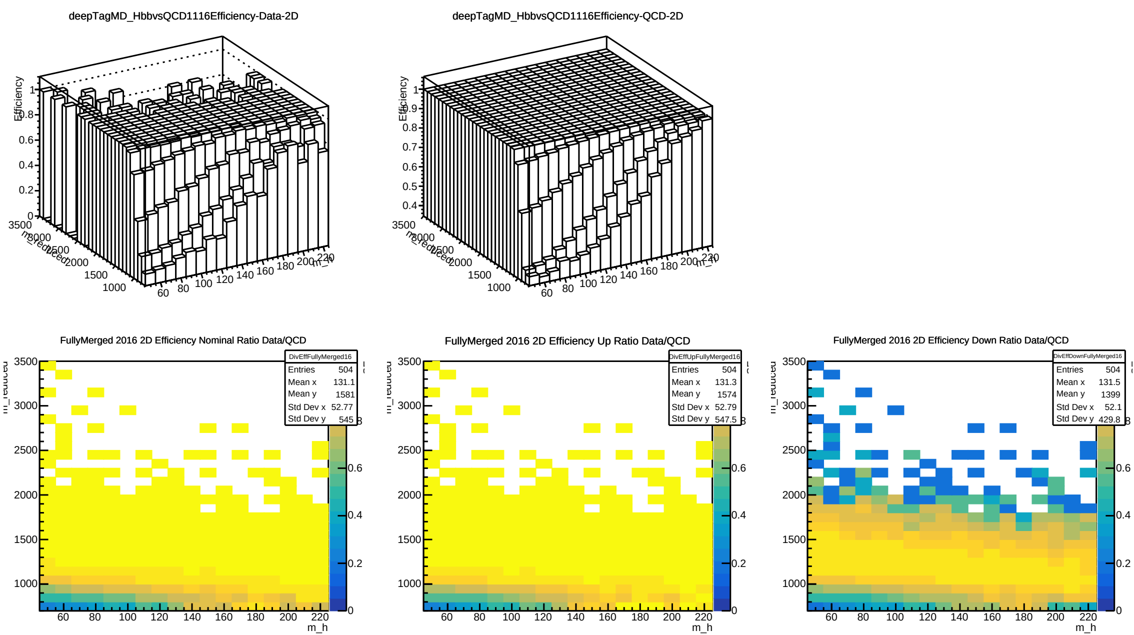


Figure 3-4. 2016 2-Dimensional Trigger Efficiency Scale Factor.

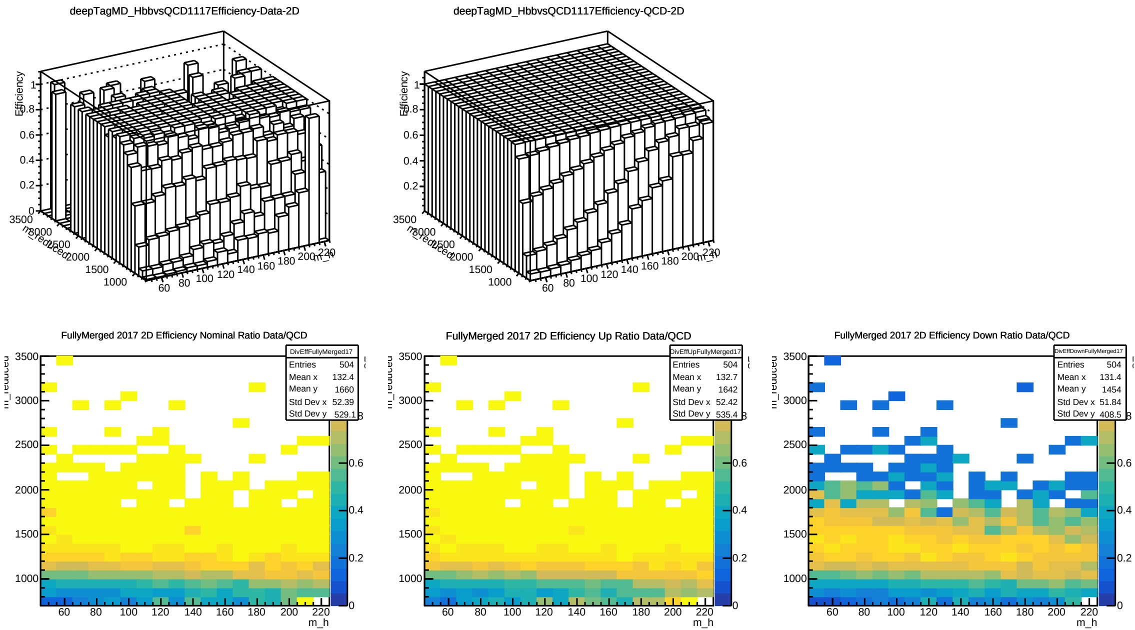


Figure 3-5. 2017 2-Dimensional Trigger Efficiency Scale Factor.

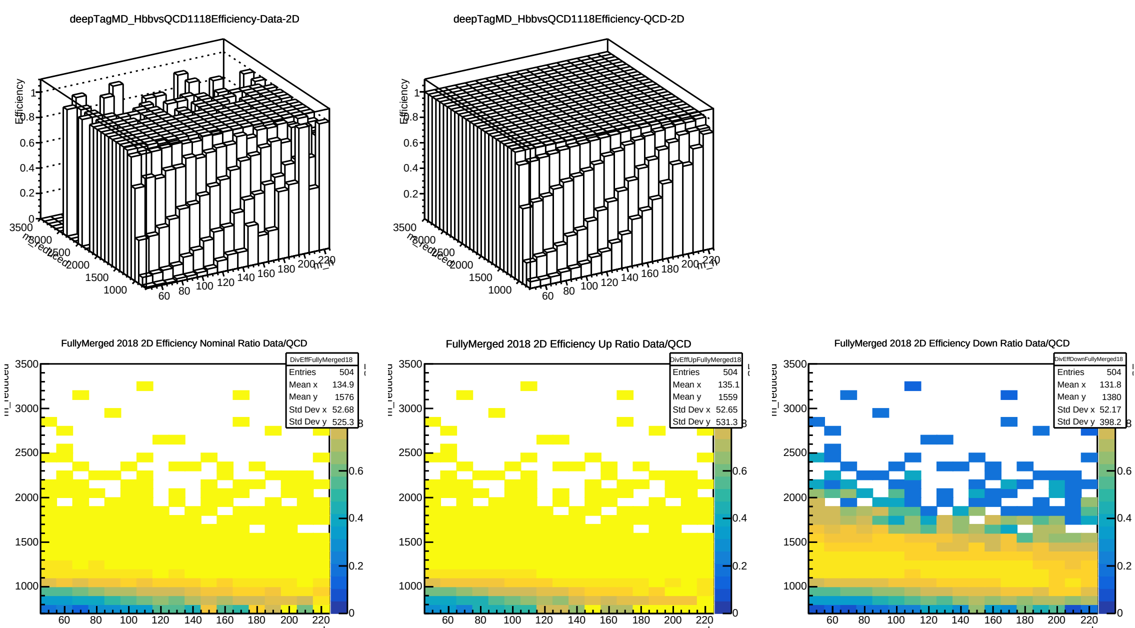


Figure 3-6. 2018 2-Dimensional Trigger Efficiency Scale Factor.

3.5 Pileup

Proton-proton collision events are ideally one proton colliding into one proton. However, since we collide them in bunches of protons, this is not the reality of what happens. Events may consist of up to 40 such proton-proton collisions. Therefore, we need to define the primary vertex. A vertex is a point along the beam from which some number of particle flow candidates originate from. The primary vertex is selected as the vertex with the highest value for the sum of the square of the transverse momenta of tracks and candidates associated.

Pileup is when the jets coming from the primary vertex contain particle flow candidates that actually originate from a different vertex. This effect ends up smearing the actual measurement of jet mass and momentum and so we must take this effect into account. The choice of the AK8 and AK4 clustering algorithm is partly motivated by the fact that the Anti-k_T algorithm resists these effects better than other jet clustering algorithms.

Chapter 4

Algorithms that Detect Interesting Higgs Boson Candidates

The analysis we perform will be looking for 2 Higgs bosons which decay into 4 total b quarks. The 4b final state will decay into jets. We are able to identify these jets resulting from pairs of b quarks because the parent Higgs jets are identifiable with a high degree of accuracy. The following sections will detail how we do this.

4.1 Soft-Drop Mass Algorithm

As we have stated, the decay signature of the Higgs boson we are looking for is a pair of b quarks. When heavy particles, like the Higgs boson, decay to a pair of quarks, the angle between those two quarks is dependant only on the velocity of the parent heavy particle[1]. Low energy Higgs will produced two distinct b quark jets where high energy Higgs will produce a collimated, also called "boosted", single jet. Since we then are concerned with the energy of the parent particle, it is important for us to accurately determine if we are looking at the parent particle or not. If you recall, pileup causes jets from background processes to appear to have the same mass[2] as a jet from a heavier particle. Of the grooming algorithms that exist to differentiate

[1] This is for the lab frame. In the rest frame of the parent particle the two quarks will decay back to back.

[2] We will sometimes substitute mass and energy freely since the lorentz invariant mass is also useful to measure as a proxy for energy.

these two cases, we will use the *Soft-Drop Mass Algorithm*.

The algorithm starts by unclustering the jet, recall we cluster jet with the Anti-k_T algorithm, and then categorizing the constituents as pseudo-jets. These pesudo-jets are then compared to each other using the formula:

$$\frac{min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,3}} > z \tag{4.1}$$

where z determines the strength of the cut. Our analysis uses $z = 0.1$**CHECK THIS** as the cut. If this condition is true, then the jet is kept. Otherwise, it is thrown out for consideration as a heavy particle jet. This helps mimic the conditions that a real heavy particle would cause rather than those that come from pileup. Since we use this as a discriminator for heavy particle jets and their decays, we will use it as a tagging variable in our analysis.

4.2 Deep AK8 Mass Decorrelated Tagger

The other way we will be tagging our Higgs bosons is through exploiting the information that is gained when creating particle flow candidates and using a machine learning algorithm to decay hadronically decaying heavy particles, like the Higgs boson. The algorithm also further delineates the decay product into decay modes, i.e. a Higgs to two b quarks. This algorithm is called *Deep-AK8*. The algorithm begins by defining two lists of inputs. The first list is a list of 100[3] jet constituent particles list in decreasing p_T. Measured properties of each particle, p_T, the energy deposit, the charge, the angular separation between the particle and the jet axis, etc., are used to help the algorithm extract features related to the substructure of the jet. Charged particle will also have information from tracking including track quality and displacement. These features are especially useful for identifying heavy flavour quarks,

[3] Typically, jets do not have more than 100 constituent particles so using this cap contributes to a negligible loss of information.

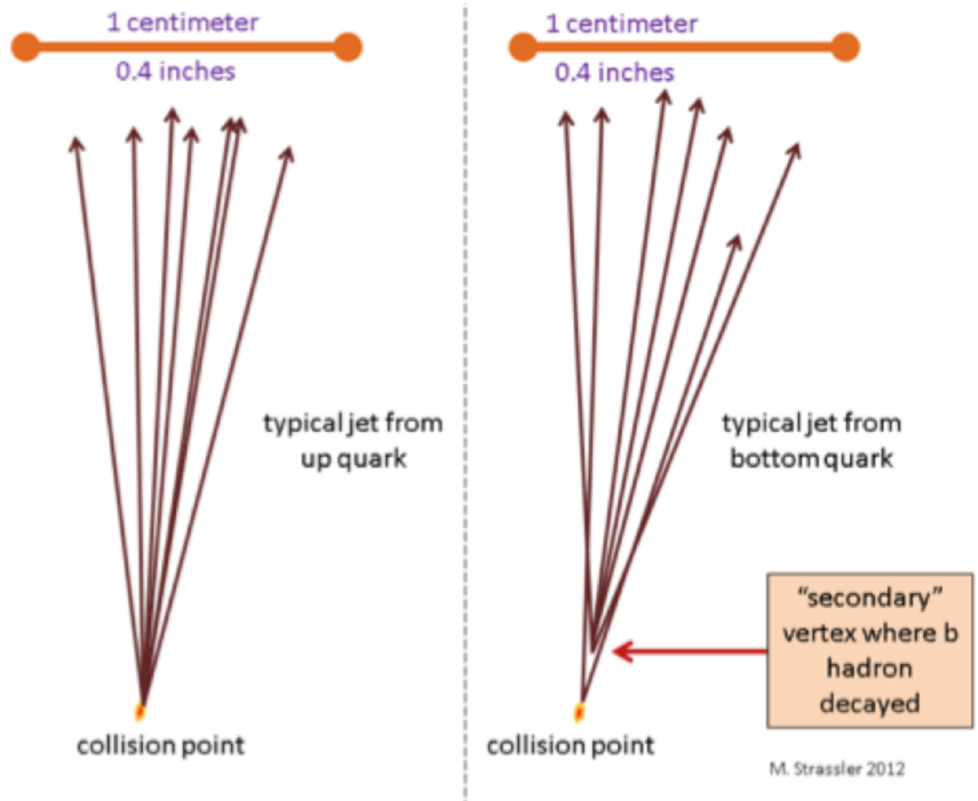


Figure 4-1. A diagram of how quarks behave in the detector.

like the b quark. In total there are 42 pieces of information for each particle in the list.

The second list is comprised of secondary vertex information. If you recall, the primary vertex relates to the location of the initial proton-proton collision. The secondary vertex relates to the location of the next decay. So then this can be useful for identifying decaying products. Notably, the b quark has a longer lifetime than other quarks, so its decay vertex, the secondary vertex, is very useful in its identification. This is shown pictorially in Figure 4-1. This list will contain up to 7 secondary vertices as well as kinematic information about the vertices, displacement, and quality of the vertices. Since this is a large amount of information, it poses a challenge to directly using it. The correlation between these inputs is very important for identifying particles so a custom neural network architecture is used.

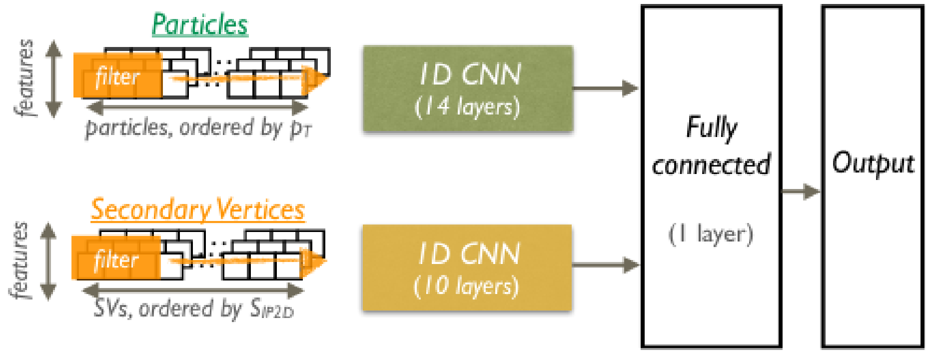


Figure 4-2. A diagram of the network architecture of the DeepAK8 Algorithm.

4.2.1 Custom Neural Network

A custom deep neural network (DNN) is constructed in order to handle the complicated correlations between inputs. This consists of two steps. The first step is to apply a convolutional neural network (CNN) is used to process each of the two lists in parallel. Then in the second step, the output of the CNN is combined by a simple, fully connected network to perform the classification of the jet. A re-weighting is used avoid any dependance on jet p_T that can occur when training the network with a mix of background and signal samples. The network architecture is shown in Figure 4-2.

4.2.2 Custom Neural Network

If, like we are, one wants to use mass as a discriminating variable, then a mass-decorrelated version of the DeepAK8 algorithm is used. This will add a feature to the network architecture that acts as a mass prediction score. This score then acts as a penalty weight to prevent the network from extracting features that correlate with mass. This allows the algorithm to become largely mass independent. This will decrease the power of the algorithm. The network architecture is shown in Figure 4-3. The training of the DeepAK8-MD tagger was conducted on jets with a softdrop mass (m_{SD}) between 30 and 250 GeV so any jet outside of that range should not be used in conjunction with this algorithm.

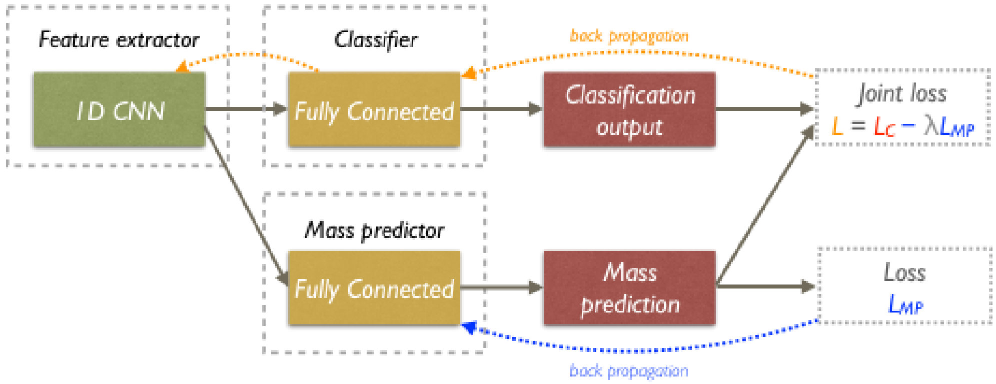


Figure 4-3. A diagram of the network architecture for the Mass-Decorrelated version of the DeepAK8 Algorithm.

4.2.3 Advantages

A similar analysis to the one we have done was performed with a different tagging algorithm and on only the 2016 data. This "Double B" tagger worked by using a boosted decision tree learning algorithm to assign a score to the jet measuring the likelihood that it contains two b quarks. It is also mass and p_T independent. At the time of that analysis, it was the best performing tagger available. However, it had drawbacks. The biggest drawback is that, while it attempted to use jet substructure information, it needed to be supplemented with directly measured substructure variables. The penalty is paid in the systematic uncertainty of those variables, which unfortunately is relatively high. The DeepAK8 tagger uses those substructure variables more efficiently so we can actually drop them as an extra discriminator and avoid paying the same penalty.

4.3 Deep Jet Tagger

The Deep Jet algorithm is used to find jets that are not pairs of b quarks but individual b quarks, i.e AK4 jets. It uses a similar two network structure like the DeepAK8 algorithm but substitutes a recurrent neural network (RNN) instead of using the simple fully connected network that DeepAK8 uses. It starts by training

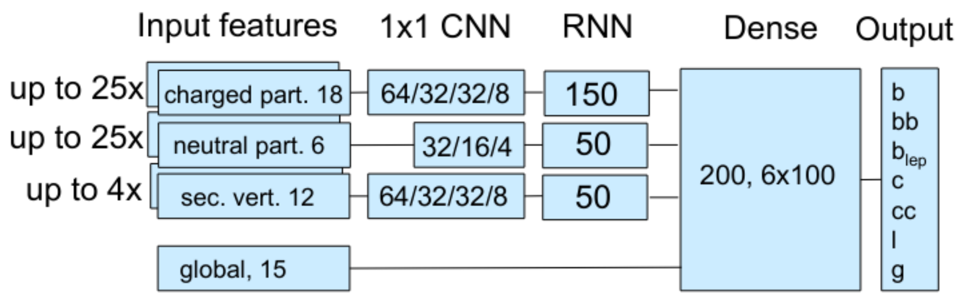


Figure 4-4. A diagram of the network architecture for the Deep Jet Algorithm.

the CNN on separate collections of charged and neutral jet particle flow candidates. The outputs are then fed into the RNN. After that training, the resultant output is combined with variables such as p_T and η of each jet and then processed by a dense layer with 7 hidden layers. The network architecture is shown in Figure 4-4 A score is then given based on the likelihood of the decay product being a heavy flavour quark. The improvement over the algorithm previously used to identify AK4 jets, called Deep CSV, is gained by using a larger set of inputs and a better neural network model.

Chapter 5

The Search for Massive Radion or Bulk Graviton Decaying to Two Boosted Higgs Bosons in the 4b Final State

Chapter 6

Extensions of the HH4b Search

Conclusions

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Appendix I

Oligonucleotide and probe sequences

Table I-I. Oligonucleotide and probe sequences

№	Name	Note	Sequence
		General	
1	SP6-F	*SP6 Promoter Primer*	GATTTAGGTGACACTATAG
2	T7-F	*T7 Promoter Primer*	TAATACGACTCACTATAGG
		qPCR oligos & probes	
3	EGFP-615F		GTCCGCCCTGAGCAAAGA
4	EGFP-668R		TCCAGCAGGACCATGTGATC
5	EGFP-634T	*EGFP probe*	CCCAACGAGAAGCG

Appendix II

A few scripts with syntax styling

A. Perl script

```perl
#!/usr/bin/perl

# The traditional first program.

# Strict and warnings are recommended.
use strict;
use warnings;

# Print a message.
print "Hello,␣World!\n";
```

B. R script

```r
# My first program in R Programming

# Store string in variable
myString <- "Hello,␣World!"

# Print variable
print (myString)
```