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A general investigation of the Higgs boson and its properties.

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Bachelors of Science
Physics.

Submitted in partial fulfilment of the requirements for
Departmental Distinction in Physics

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A general investigation of the Higgs boson, and its properties.

Atul Rawal

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Introduction

“The quantity of any matter is the measure of it by its density and volume conjointly…This quantity is what I shall understand by the term mass or body in the discussions to follow. It is ascertainable from the weight of the body in question. For I have found pendulum experiments of high precision, that the mass of a body is proportional to its weight; as will hereafter be shown.” This was the definition of mass given by Isaac Newton. As time and physics progressed, the definition of mass progressed as well. Theorized in the 1960’s by François Englert, Peter W. Higgs and Robert Brout, the Higgs mechanism provides an explanation for why matters have mass and provides strong support for the legitimacy of the Standard Model.

The Standard Model of physics explains how the building blocks of matters interact, governed by the fundamental forces of nature. It is the best representation of particle physics that we have so far. On 4 July, 2012, the ATLAS (A Toroidal LHC ApparatuS) and CMS (The Compact Muon Solenoid) experiments at CERN's (European Organization for Nuclear Research) LHC(Large Hadron Collider) announced that they had each observed a new Higgs-like particle in the mass region around 126 GeV. This was consistent with the Higgs boson. The Higgs boson is one of the greatest discoveries of physics for our generation, which eluded particle physicists around the world for decades. This paper will examine the Higgs boson in a detailed manner and present a simpler formulation for the Higgs mechanism itself.

The Standard Model

Developed in the 1970’s, the Standard Model of physics is the most accurate and precise description of the subatomic nature. It is divided into three parts, quarks, leptons and gauge bosons. It describes how the most fundamental matter particles, quarks and leptons, interact with force carriers, photons, W& Z bosons and gluons. Three of the four fundamental forces of nature, electromagnetic force, weak nuclear force and strong nuclear force are represented through the Standard Model. Gravity is excluded in the Standard Model, as no proof of a corresponding force carrier exists.

Matter Particles

The matter particles that make up the Standard Model are called fermions. There are 12 types of fermions, classified into two groups, quarks and leptons. These are the most elementary particles in nature. They are the building blocks of matter. There are six different types of quarks and six different types of leptons which are divided into three generations each. The generations are arranged corresponding to the mass and the stability of the particle, with the first generation having the lightest and the most stable particles and the third generation consisting of the heaviest and the less stable particles.

There are six different types of quarks which are matched up into three pairs, the up and down quarks, charmed and strange quarks and the top and bottom quarks. The charge of the strong force, also called color, distinguishes them from other particles. They can either be red, green or blue color. The different quarks and their characteristics are presented below in Table 2.

First	Second	Third
u - **up**	*c* - **charmed**	*t* - **top**
d - **down**	*s* - **strange**	*b* - **bottom**

Table 1: The three generations with corresponding quarks.

Name	**Symbol**	**Charge**	**Generation**	**Mass**
Down	*d*	-1/3	First	0.0041 to
Up	*u*	+2/3	First	0.0017 to
Strange	*s*	-1/3	Second	0.80 to1.30
Charmed	*c*	+2/3	Second	1.18 to 1.34
Bottom	*b*	-1/3	Third	4.4
Top	*t*	+2/3	Third	172

Table 2: The six different quarks and their attributes, the charge in units of e and the approximate masses in GeV/c².

Leptons are the other six matter particles that make up the Standard Model. They are spin -1/2 fermions that don't have color charge due to the lack of their interactions with the strong force. Similar to the quarks, the leptons are classified into three generations with the lightest particle in the first generation and the heaviest in the third generation.

First	Second	Third
electron-neutrino	mu-neutrino	tau-neutrino
electron	muon	tauon

Table 3: The three generations with corresponding leptons

Name	Symbol	Charge	Generation	Mass
Electron-neutrino	ν_e	0	First	$< 2.2\times10^{-6}\ eV/c^2$
Electron	e^-	-1	First	$0.511\ MeV/c^2$
Mu-neutrino	ν_μ	0	Second	$<0.17\ MeV/c^2$
Muon	μ^-	-1	Second	$105.7\ MeV/c^2$
Tau-neutrino	ν_t	0	Third	$<15.5\ MeV/c^2$
Tauon	τ^-	-1	Third	$1776.8\ MeV/c^2$

Table 4: The six different leptons, their symbols and charges in units of e.

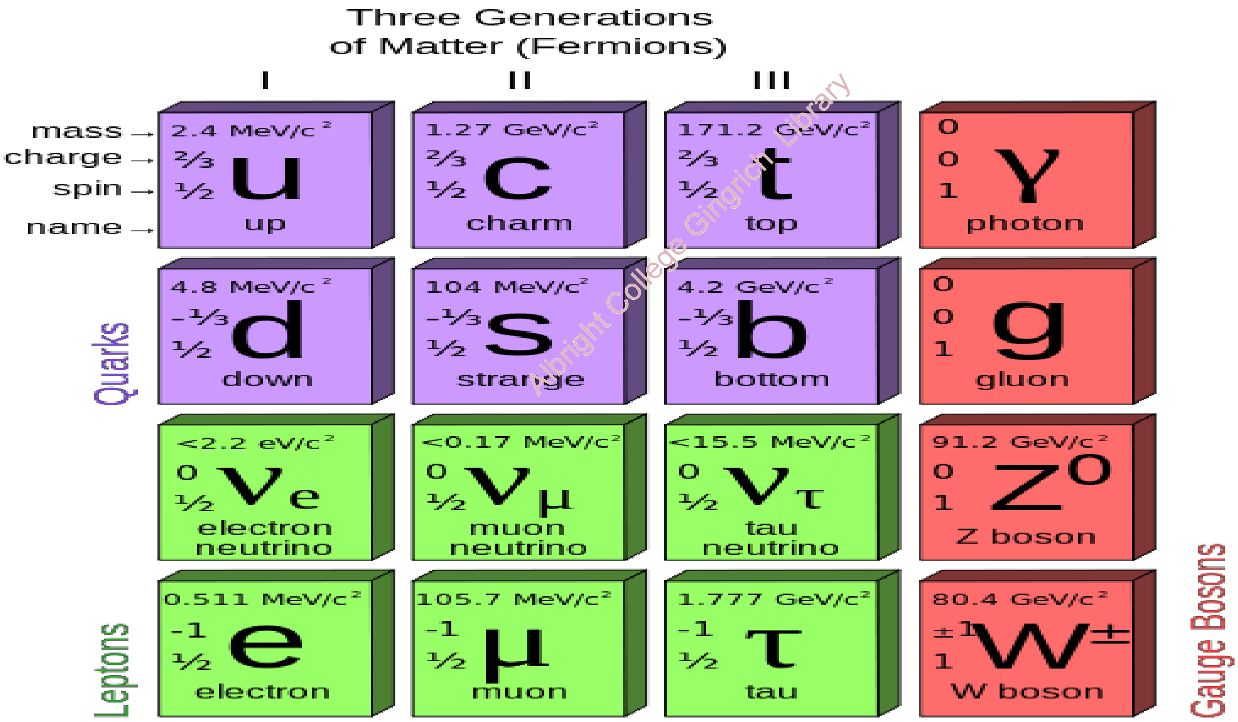

Figure 3: An illustration of the Standard Model and the three generations. [6]

Higgs boson

The Higgs boson is the last piece of the Standard Model. It gives mass to other particles and itself by permeating space-time. It is very critical to the understanding of and validation of the Standard Model. But, for the Standard Model to hold true the bosons y, Z^0 *and* $W^{\pm}$ have to be massless, but the Z^0 *and* $W^{\pm}$ bosons are actually heavy particles. The Higgs mechanism was introduced to explain the heavy masses of the $W^{\pm}$ and Z^0 bosons, and manifested the theorization of the Higgs boson and the Higgs field. The Higgs boson is a quantized manifestation of the Higgs mechanism, which explains how matters acquire mass by interacting with the Higgs field.

To explain it in simpler terms, the Einstein analogy can be used:

Imagine a room full of physicists. Suddenly Einstein enters and attempts to cross the room, but the star-struck physicists cluster around him and impede his movements, effectively increasing his mass. Now imagine that I enter the room. As a lowly undergraduate student, nobody wants to interact with me, so I pass through the physicists relatively unimpeded—no effective mass for me! Lastly, imagine that somebody

> whispers a rumor, causing the physicists to cluster together excitedly on their own. In this analogy, the room full of physicists represents the Higgs field in space, Einstein represents a particle with high mass, I represent a particle with low mass (or no mass), and a cluster of physicists represents an excitation of the field, which is effectively a Higgs boson. [8]

Another representation of the Higgs boson is the snow-field metaphor:

> A field covered in snow can be visualized as the Higgs field, but instead of snow, the Higgs field is made up of Higgs bosons. A skier, a man on snowshoes, a man in heavy boots and a bird are examples of particles that interact with the Higgs field. A skier barely interacts with the snowfield and can glide through the snow with ease. The man with the snowshoes has a higher interaction with the snowfield, and is slowed by the snow. The man with the heavy boots has an even higher interaction with the snowfield and is slowed at every step. The bird flying over the snowfield has no interaction with the field at all. How does this relate to the Higgs field? Well, particles that interact with the Higgs field have mass, and the ones that don't are massless. An electron is a very light particle. Just like the skier barely interacts with the snowfield, it barely interacts with the Higgs field and thus has very little mass. Like the snowshoer, a quark interacts more strongly with the field and thus has more mass than electrons. Bosons, like the man in the heavy boots have an even higher interaction with the Higgs field, thus have a lot more mass than other particles. Particles like photons and gluons are the metaphorical birds, that don't even interact with the field, so have zero mass. [22]

To find the Higgs boson, the decay products had to be detected. To detect the decay products of Higgs boson, particle accelerators are used. Particle accelerators accelerate particles to near light speed and attempt to recreate the big bang. These accelerators use magnets that are cooled to near absolute zero temperature. When the particles collide with each other they annihilate into energy and create new particles as predicted by Einstein, and the detectors detect the particles that are created as the result of the collision. Even though the properties and characteristics of the Higgs boson were known, the mass was the only unknown property of the particle. Other accelerators in the U.S, like the Tevatron accelerator at Fermilab in Batavia, Illinois were able to rule out various possible masses for the Higgs boson, allowing the L.H.C to experiment on the remaining possible masses.

CERN, which consists of the LHC, LHCb, ATLAS and CMS, is the largest physics laboratory in the world. It is the most expensive undertaking ever constructed by any government. Founded in 1954, and located over a 100 meters underground in Switzerland, LHC is the largest particle accelerator in the world. With energy of 7 TeV for each proton beam flying around the accelerator, the LHC is able to produce collision energy of 14 TeV.

After years of search, on July 4th 2012, the discovery of a Higgs particle with a mass near 125 GeV was made at LHC. The particle provided strong evidence for the Higgs mechanism that gives particles their mass. At first the term “Higgs-like boson” was used for the particle discovered in 2012, as its properties were yet to be fully investigated. Later in 2012, studies at LHC gave four times more data than before and were used to analyze the particle discovered earlier that year. With more data, in 2013 LHC was able to provide enough evidence to confirm that the particle found in 2012 was indeed a Higgs boson. [11]

When a new particle is found, we can conclude if it is indeed the Higgs boson based on its interactions with other particles and its quantum properties. For example, a Higgs boson is theorized to decay into fermions, have no spin and a positive parity. The experiments at ATLAS and CMS were able to confirm the properties of the new particle and its decay into two tau particles, which are fermions to conclude that they had indeed finally found the elusive Higgs boson.

Mathematical representation of the Higgs

The core research for the field of electroweak physics is the non-zero masses for the W and Z bosons. The W and Z bosons with masses of 80 GeV and 91 GeV respectively are too large to be neglected as small effects. Physicist Sally Dawson, from Brookhaven National Laboratory in her lecture, "Introduction to the physics of Higgs bosons" presents the Higgs mechanism as, "The Higgs mechanism can be summarized by saying that the spontaneous breaking of a gauge theory by a non-zero vacuum expectation value (VEV) results in the disappearance of a Goldstone boson and its transformation into the longitudinal component of a massive gauge boson." She presents the Lagrangian for a U(1) gauge theory with a single gauge field, the photon, with a mass term added [12]

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m^2 A_\mu A^\mu$$

where

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

The model is extended by adding a single complex scalar field,

$$\phi \equiv \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2).$$

The Lagrangian is now,

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} + \left|D_\mu \phi\right|^2 - V(\phi)$$

where,

$$D_\mu = \partial_\mu - ieA_\mu$$

$$V(\phi) = \mu^2 |\phi|^2 + \lambda(|\phi|^2)^2$$

For the case of $\mu^2 < 0$, the potential is written as

$$V(\phi) = -|\mu|^2 |\phi|^2 + \lambda(|\phi|^2)^2$$

which gives the Mexican hat shape for the curve, with the minimum energy state at

$$\langle\phi\rangle = \sqrt{-\frac{\mu^2}{2\lambda}}$$

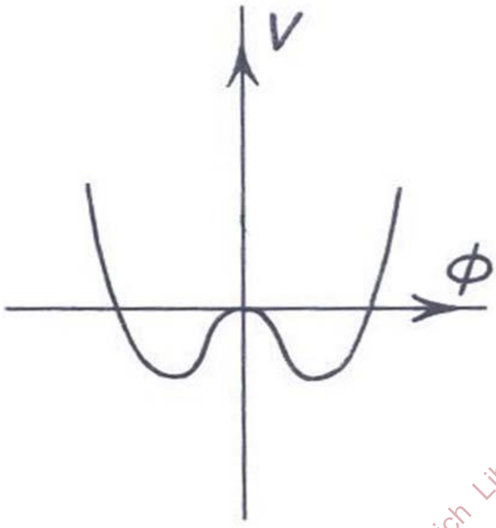

Figure 11: V is the Vacuum Expectation Value (VEV) of ϕ. The field ϕ is the Higgs field

The Lagrangian with interactions in terms of fields with no VEVs is given by [12],

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu}F^{\mu\nu} - evA_\mu\partial^\mu\chi + \frac{e^2v^2}{2} A_\mu A^\mu + \frac{1}{2}\left(\partial_\mu H\partial^\mu H + 2\mu^2 H^2\right) + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi + (H, \chi \text{ interactions})$$

It describes the photon with a mass $M_A = ev$, a scalar field H called a Higgs boson with mass-squared $-2\mu^2 > 0$, and a massless scalar field χ. By adding the gauge fixing term to the

Lagrangian, the more convenient R_ξ gauges are obtained. For calculations involving the Higgs boson, the Landau gauge, with $\xi = 0$ and the massless Goldstone bosons with no coupling to the physical Higgs boson, is the most convenient since there is no coupling to the unphysical χ field. Dawson presents this as [12]

$$\mathcal{L}_{GF} = -\frac{1}{2\xi}\left(\partial_\mu \mathrm{A}^\mu + \xi e v \chi\right)^2$$

where the gauge boson propagator is given by

$$\Delta_{\mu\nu}(k) = \frac{i}{k^2 - M_A^2}\left(g_{\mu\nu} - \frac{(1-\xi)k_\mu k_\nu}{k^2 - \xi M_A^2}\right).$$

The Lagrangian for the higgs is

$$\mathcal{L} = \tfrac{1}{2}\dot{\phi} - \mu^2\phi^2.$$

The 1-D Klien Gordon Equation gives us,

$$-\hbar^2\frac{\partial^2}{\partial x^2}\dot{\phi}(x) + m^2c^2\phi(x) = -\frac{\hbar^2}{c^2}\frac{\partial^2}{\partial t^2}\dot{\phi}(x)$$

$$h = c = 1$$

$$-\frac{\partial^2}{\partial x^2}\dot{\phi}(x) + m^2\phi(x) = -\frac{\partial^2}{\partial t^2}\dot{\phi}(x).$$

Transforming the equation with Euler's relation with respect to "t" gives us,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right) - \frac{\partial L}{\partial \phi} = 0$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{\phi}}\right) = \frac{\partial L}{\partial \phi}$$

$$\frac{d}{dt}(\dot{\phi}) = -\phi\mu^2$$

$$\ddot{\phi} = -\phi\mu^2$$

Transforming the equation with Euler's relation with respect to "x" gives us,

$$\frac{d}{dx}\left(\frac{\partial L}{\partial \dot{\phi}}\right) - \frac{\partial L}{\partial \phi} = 0$$

$$\frac{d}{dx}\left(\frac{\partial L}{\partial \dot{\phi}}\right) = \frac{\partial L}{\partial \phi}$$

$$\frac{d}{dx}(\dot{\phi}) = \phi\mu^2$$

$$\frac{\partial^2}{\partial^2 x}(\dot{\phi}) = \phi\mu^2$$

Subtracting the two equations we get,

$$\ddot{\phi} - \frac{\partial^2}{\partial^2 x}(\dot{\phi}) + 2\phi\mu^2 = 0$$

which gives

$$\mathcal{L} = T - V$$

$$E^2 = p^2c^2 + m^2c^4 .$$

Simplifying the Higgs mechanism

The Higgs boson is a paramount particle in Physics. The study and research associated with the Higgs boson is in the frontier of particle physics. It is an important concept for undergraduate students to comprehend to prepare them for graduate school or a career. Unfortunately, many colleges and universities either don't cover the Higgs boson in length or give only a very brief description of the particle. Most of the time the only introduction to Higgs is done in upper level physics classes to seniors. Even then, the introduction to the Higgs mechanism is just an introduction and students aren't exposed to the physics behind the Higgs. A simpler model is needed to help those without a substantial physics background conceptualize the Higgs boson and its properties. It will be helpful for undergraduate students in physics to further their understanding of a particle that is sure to be a focal point of physics for years to come. With a fundamental and simpler model of the Higgs boson presented to undergraduate students, we can expand their understanding of the particle and why it is so important for the physical laws of nature to hold true. A better understanding of the Higgs boson and its properties will allow us to better understand the physical laws of nature and either validate the predictions made by the Standard Model of Physics or move towards “new” physics.

A simpler explanation of the Higgs mechanism can be provided by introducing a pseudo symmetry, imitating what happens in Quantum Field Theory, as presented by Giovanni Organtini’s paper, "Unveiling the Higgs Mechanism to Students." It states that the classical expression of the energy of a particle in a field follows a particular symmetry, similar to the QFT’s weak interactions breaking the gauge symmetry causing flaws in the theory. The symmetry used, in principle, imitates what happens in QFT very well and allows us to derive a classical explanation of a quantitative effect, but is rather imaginative, so it is not recommended. The symmetry is broken by Special Relativity, similar to the breaking of the gauge symmetry by weak interactions in QFT. For this approach, we can maintain the validity of Special Relativity with what happens in QFT, by introducing a new field, helping us keep the original symmetry at the same time. We use the formalism of a charged particle in a parallel plate capacitor, which can be used for any system inside a conservative field. [21]

We consider the energy of a particle in an electric field *E*, with a mass *m*, charge *q*, and potential *V*, where the potential energy can be written as

$$U = qV.$$

Which can be rewritten for the energy contained in a vacuum as

$$U = \frac{\varepsilon_0}{2} E^2 \mathcal{V}$$

where ε_0 is the dielectric constant of the vacuum. The equation is rewritten to give us the energy density in a parallel plate capacitor as

$$u = \frac{U}{\mathcal{V}} = \frac{qV}{\mathcal{V}} + \frac{\varepsilon_0}{2} E^2$$

Here, the energy density expression follows a simple symmetry where all the terms are derived from multiplying a field by another field or the potential of the field times a property of the particle like the charge of the particle. This symmetry is followed by all conservative forces, where the energy density is derived as the sum of the two terms. Under Special Relativity, the symmetry is broken, so a mass term is introduced for a particle at rest with mass, mc^2 and the above equation is rewritten as,

$$u = \frac{U}{\mathcal{V}} = \frac{qV}{\mathcal{V}} + \frac{\varepsilon_0}{2}E^2 + \frac{mc^2}{\mathcal{V}}.$$

The minimal possible energy can be reached when E =0 and $m = 0$, which correlates to an empty volume, which is referred to as vacuum. The mass term breaks the symmetry under Special Relativity for the above equation, which suggests a difference between m and q such that m is the only variable that contributes to the energy of the particle. We can formulate an arbitrary concept, so that the energy contained in a given volume is always given in terms of a sum of products of either two fields, or a particle and a field. For this, we ignore the term mc^2 in the energy expression. [21]

The Higgs field

Ignoring the relativistic term, the energy density u is given as

$$u = \frac{U}{\mathcal{V}} = \frac{qV}{\mathcal{V}} + \frac{\varepsilon_0}{2}E^2.$$

We now introduce a field that couples with both matter and fields. Assuming the symmetry from the earlier section, the energy (using different variables than the original paper) is rewritten as,

$$u = \frac{qV}{\mathcal{V}} + \frac{\varepsilon_0}{2}E^2 + \frac{a}{\mathcal{V}}\Phi + bE\phi + b'\phi^2$$

where Φ is the potential of the field ϕ. The above equation is derived by noting all the possible particle-field and field-field pairs, each multiplied by a coupling constant. Where the first two terms follow the form

i. (Constant)(1/ $\mathcal{V}$)(Function of field)
ii. (Constant)(field)(field).

The terms q and $\frac{\varepsilon_0}{2}$ are the coupling constants that give the strength of the coupling between a particle and a field, or two fields, and (1/ $\mathcal{V}$) is the density of the particle in the volume. To complete the equation add

i. A term of form [i], where a is the constant, 1/ $\mathcal{V}$ is the particle, and Φ is the function of the higgs field ϕ
ii. A term of form [ii], where b is the constant acting on the fields E and ϕ
iii. A term of form [ii], where b' is the constant acting on the fields ϕ.

A simpler notation of the energy can be derived by substituting L for the 1/ $\mathcal{V}$, F_p as the potential of the field F, c_1 for q , c_2 for $\frac{\varepsilon_0}{2}$, and E_p for V. The energy of one particle and one field E is represented as,

$$u = c_1 L E_p + c_2 E E.$$

For one particle and two fields, we can follow the symmetry and write the energy as

$$u = c_1 L E_p + c_2 E E + c_3 L \phi_p + c_4 E \phi + c_5 \phi \phi.$$

When adding a term like ϕ^4 the energy density reaches its minimum for a field $\phi \neq 0$. The lowest possible energy is no longer when all the fields are zero, but when the field $\phi \neq 0$. Referring back to Figure 11, we see that the lowest energy is not reached when all the fields are zero, but when $\phi \neq 0$. We define a vacuum as a state where the energy reaches its minimum, i.e. when $\phi = \phi_0$. Therefore, a completely empty space, for which E = m = ϕ =0 does not necessarily correspond with a vacuum, as long as its energy is larger than the energy of the vacuum. Rewriting the energy density equation with $b' < 0$ and adding a ϕ^4 term, gives

$$u = \frac{qV}{\mathcal{V}} + \frac{\varepsilon_0}{2}E^2 + \frac{a}{\mathcal{V}}\Phi + bE\phi - b'\phi^2 + \phi^4.$$

This energy density defines vacuum as a state where $E = 0$ and $\phi = \phi_0$, i.e. vacuum is such that there is some field in the volume. [21]

Introducing the Higgs boson

Letting, $\phi = \phi_0 + \eta$, allows us to write its potential Φ as $\Phi = \Phi_0 + \Phi_1$, where Φ_0 is the vacuum potential, constant everywhere and $\Phi_0 \neq 0$. Following the new derivations the energy density in the capacitor is written as,

$$u = \frac{qV}{\mathcal{V}} + \frac{\varepsilon_0}{2}E^2 + \frac{a}{\mathcal{V}}(\Phi_0 + \Phi_1) + bE(\phi_0 + \eta) - |b'|\phi^2 + \phi^4$$

which is an interesting formulation, so we analyze it term by term starting with the third term as the first two terms are classical. [21]

The mass term is something of the form of a constant time L. In the above formulation, a mass term appears as the interaction of a massless particle with the vacuum potential. Which matches the one predicted by Einstein if we assume,

$$mc^2 = a\Phi_0$$
$$m = \frac{a}{c^2}\Phi_0.$$

Since, Φ_0 is constant, masses are also constant as well. Since the mass term is of the form $\frac{qV}{\mathcal{V}}$, it's concluded that it is due to an interaction. Similarly, we can also conclude that $\frac{a}{\mathcal{V}}(\Phi_0)$ represents the interaction of the same particle with the field ϕ, with potential Φ and coupling constant a. Another interaction term also appears as

$$\frac{a}{\mathcal{V}}(\Phi_1)$$

which represents the interaction of the particle with the field η, called the Higgs field, with potential Φ_1 and coupling constant

$$a = \frac{mc^2}{\Phi_0}$$

which shows that the intensity of the interaction is proportional to the particle mass.

In the equation the term $bE\eta$ causes the field E to interact with the Higgs field too. But if $b \neq 0$, E has a mass due to the term $bE\phi_0$, which contradicts the findings at LHC. Since a mass term is defined as one for which a particle or a field is multiplied by a constant, the term $bE\phi_0$ represents a mass for the field, similarly to the term $\frac{a}{v}(\Phi_0)$. To avoid that we let b =0.

Expanding the ϕ field in the last two terms gives,

$$-|b'|\phi_0^2 - 2|b'|\phi_0\eta - |b'|\eta^2 + (Higher\ order\ terms).$$

Where the first three terms are a constant, a mass term for the Higgs field and the self-interaction of the Higgs field, and the higher order terms are simply a combination of the first three terms, that represent more complex interactions that can be neglected. [21]

Consequently, with the hypothesis that the vacuum is not empty and defining the energy density in a region of the universe as a sum of products of at least two objects, the mass terms in the energy are explained, at the price of introducing a new field (Higgs), interacting in principle with both matter and fields and itself. [21]

Higgs Decay to Tau Pairs

One of the main properties of the Higgs boson is its decay pattern. Decay channels are the possible transformations a particle can undergo as it decays. Even fundamental particles decay into other particles. As explained by Kathryn Jepsen, when a particle decays, it changes into collections of less massive particles whose combined energy adds up to the energy of the original particle. For example, getting change for a dollar. Even though a dollar bill is not physically made up of coins, its value can be broken down into change. And just as many different combinations of coins add up to $1, many combinations of particles can add up to the energy of a massive particle. Each one of those particle combinations is called a decay channel.[23]

Heavy particles like the Higgs boson are more massive than electrons/protons and are unstable, so they decay into more stable particles shortly after they're produced. The experiments at CERN were able to present the most complete and comprehensive measurements of the decay patterns of the Higgs boson. These measurements included the studies of the Higgs' interactions with fermions and combined measurements from different decay channels. The analyses of the five main decay channels were combined together with the analyses targeting the rarest production mode. The results from the ATLAS experiment at CERN showed evidence of the Higgs boson decaying into Tau particles. The data in the Higgs decay to Tau analysis correspond to proton collisions of 8 TeV. Strong evidence for this is observed with a 4.1 standard deviation from the background-only hypothesis. The measured signal strength, normalized to the Standard Model expectation, is 1.4±0.4 which is consistent with the Standard Model prediction. A limiting factor of the measurement is the size of the available dataset. [24]

We can calculate how long a particle should last and the ways it should decay. Knowing a particles decay channel can help us spot massive particles created inside a particle collider (e.g. LHC), even if the particle decays before the detector can capture it. The five main decay channels of the Higgs boson are:

1. Higgs to B quark and its antiquark
2. Higgs to two Taus
3. Higgs to two Photons
4. Higgs to W boson and its antiparticle

5. Higgs to two Z bosons

We analyze the paper by Somnath Choudhary, "Higgs boson Decay to Tau Pairs at the CMS Experiment." in which he presents the results of the Standard Model Higgs decay into tau pairs. Using all possible decay channels in fully leptonic, semi-leptonic, and fully hadronic states using final-state signatures eμ, μμ, ee, $e\tau_h$, $\mu\tau_h$, and $\tau_h\tau_h$, where electrons and muons arise from leptonic τ- decays and τ_h represents the hadronic tau lepton decays, the decay search is performed. Maximum likelihood technique is used to reconstruct the tau-pair mass to separate the Higgs boson signal from background signals. By maximizing the likelihood with respect to free parameters corresponding to the missing neutrino momenta, subject to kinematic limitations, the algorithm presented estimates the original momentum components of the two taus. An almost Gaussian shape distribution is produced by the algorithm, which also gives a tau-pair mass with a mean consistent with the true value. A 10-20% resolution $m_{\tau\tau}$ mass is estimated from the simulation depending on the dual-tau decay channel and category. An improvement in the final expected significance of 40% is obtained using the likelihood based mass reconstruction for a better separation between simulated 125 GeV Higgs signal and $Z \to \tau\tau$ background than the visible mass alone. [19]

A search is performed in excess of events in the reconstructed dual-tau invariant and mass distribution, in each of the categories, where the $Z \to \tau\tau$, which is estimated using an observed sample of $Z \to \mu\mu$ events, is the largest source of irreducible background. Using the procedure of “embedding” the reconstructed muons are replaced by the reconstructed particles from simulated tau decays. Using the measurements of the CMS measure cross section, the process is normalized.

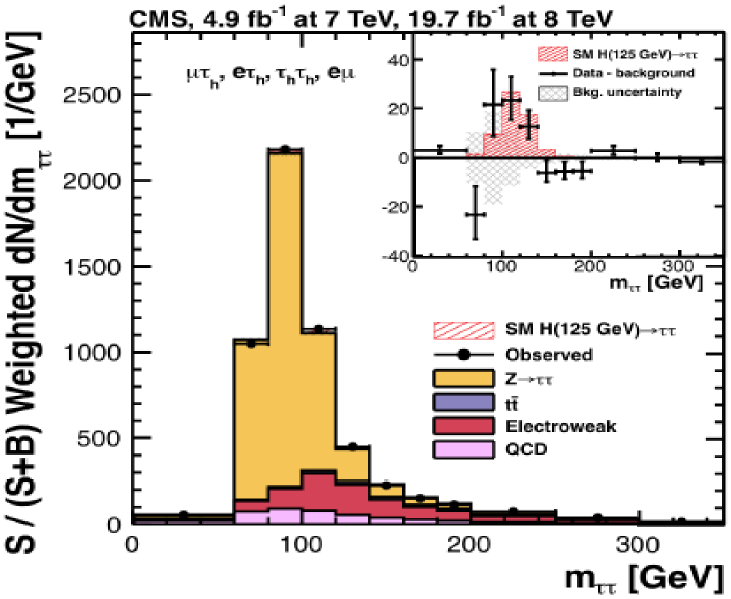

Figure 12: The di-tau invariant mass distribution combining all event categories.[19]

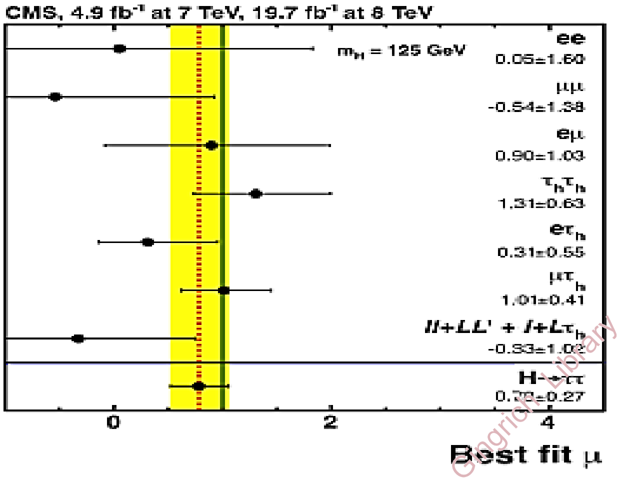

Figure 13: The signal strength with respect to SM expectation in different di-tau decay channels and result of the combination.[19]

A wide surplus of events is observed in the tau pair invariant mass distribution as seen in Figure 12 and Figure 13 over a range of the Higgs boson consistent with the 125 GeV scalar boson observed in the high resolution boson decay channels, after combining all event categories. With the observed significance of the excess at Higgs boson mass of 125 GeV at 3.2σ, a best-fit value of the signal strength at μ = 0.78±0.27is obtained in the global fit combining all channels included in the analysis where the H→WW process has been added as a background for the observed process. [19]

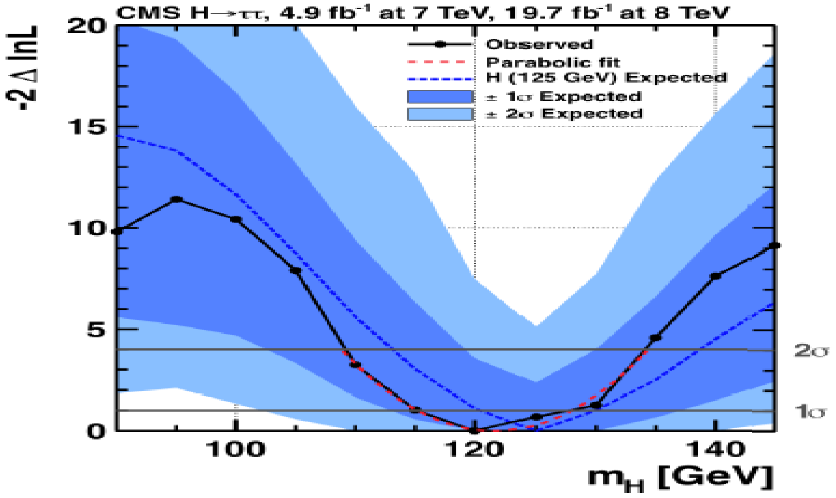

Figure 14: The measured mass from log-likelihood scan in di-tau channel. [19]

The results provide the proof of the Higgs boson coupling to leptons. The tau pair and bottom quark pair decay modes were combined at CMS and the significance for the Higgs boson decay to fermions at 125 GeV was 3.8 σ showing the first evidence of Higgs-Fermion coupling at the LHC. As shown in Figure 14, from a parabolic fit of the log likelihood scan of the observed mass points, the mass of the Higgs boson measured in this channel is 122±7 GeV. The measured couplings of the Higgs boson to vector bosons and fermions scaled with respect to SM, shows consistency within around one standard deviations from SM predictions where the H→WW process has been added as a signal component for this measurement. [19]

Conclusion

In conclusion, we present a better understanding of the Higgs boson, and its properties including its decay patterns. A simpler model of the Higgs mechanism is devised by creating a *pseudo* symmetry in a parallel plate capacitor and relating mass to the intensity of the interaction with the field. The Higgs to two taus decay mode was also interpreted and presented with datasets from CMS. We are now able to explain the Higgs mechanism, the Higgs boson and its properties at a fundamental level, for example, to freshmen students or to non-science majors. This will be very helpful for future students taking elementary physics here at Albright, as they will now be able to be introduced to and comprehend the physics behind one of the most fascinating particles in Physics.

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