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THE HIGGS BOSON WITHIN AND BEYOND THE STANDARD MODEL

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Declaration

I, **Vincent UZABAKIRIHO**, hereby declare and confirm that this research thesis entitled **THE HIGGS BOSON WITHIN AND BEYOND THE STANDARD MODEL** is my original work and it has never been submitted or published anywhere by any person to any University or other Institution of high learning for academic publication for any award. This Thesis was conducted under the supervision of **Dr. Shoaib MUNIR** from the East African Institute for Fundamental Research (ICTP-EAIFR),University of Rwanda, Rwanda.

January 14, 2022

Vincent UZABAKIRIHO

Dedication

To **Almight God**, for his blessings,
to my lovely wife **Leonille MUKANTIBIZERWA**,
to my supervisor **Dr.Shoaib MUNIR**,

This research is dedicated.

Approval

This dissertation was conducted under the guidance and supervision of

Supervisor name:...........................

Signature:.................................

Date:......................................

Abstract

The Standard Model (SM) of particle physics is based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, which requires the eletroweak (EW) gauge bosons $(W^{\pm}, Z)$ to be massless. However, the masses of these bosons have been experimentally measured, which implies that the EW symmetry is spontaneously broken. This is done by incorporating the Higgs mechanism into the SM, which in turn predicts the existence of a neutral scalar Higgs boson. In July 2012 the CMS and ATLAS collaborations of the Large Hadron Collider (LHC) experiment at CERN announced the discovery of this Higgs boson.

In this thesis, the SM, and the generation of fermion and gauge boson masses through the Higgs mechanism, is briefly reviewed. The properties of the Higgs boson as predicted by the SM, and the theoretical as well as the experimental limits on them from the Higgs boson searches at the Large Electron Proton (LEP) collider, the Tevatron, and the LHC are discussed in detail. Furthermore, since its discovery at the LHC, the subsequent developments in the measurements of the properties of the Higgs boson, such as its mass, interactions strengths and decay rates, are analysed.

Finally, several open questions in high energy physics, such as the nature of dark matter (DM) and the baryon asymmetry of the universe, among others, hint at physics beyond the SM, which almost always predicts additional Higgs bosons. As a case study for new physics, we briefly revisit how the additional scalar Higgs boson of the two-Higgs-doublet model (2HDM) can manifest itself at the LHC and what implication does its existence carry for the Higgs boson already discovered.

Contents

List of Figures

List of Tables

List of Abbreviations

SM: Standard Model
EWSB: Electroweak Symmetry Breaking
EW: Electroweak
CMS: Compact Muon Solenoid
ATLAS: A Toroidal LHC Apparatus
LHC: Large hadron Collider
CERN: European ouncil for Nuclear Research
LEP: Electron-Positron Collider
SSB: Spontaneous Symmetry breaking
2HDM: Two-Higgs Doublet Model
DM: Dark Matter
EM: Electron Magnetism
VEV: Vacuum Expectation Value
BSM: Beyond the Standard Model
LO: Leading Order
NLO: Next-to-Leading Order
NNLO: Next to Next-to-Leading Order
VBF: Vector Boson Fusion
QCD: Quantum Chromodynamics
BW: Breit-Wigner
ALEPH: Apparatus for LEP Physics
DELPHI: Detector with Lepton and Hadron Identification
L3: Letter of Intent 3
OPAL: Omnipurpose Aparatus for LEP
ALICE: A large Ion Collider Experment
ICHEP: International Conference on High Energy Physics
HL-HLC: High Luminosity LHC
CP: Charge conjugation and Parity operation
CKM: Cabbibo Cobayashi Masikawa
FCNC: Flavor Changing Neutral Current
IDM: Inert Double Model

1 General introduction

1.1 Brief review of the SM

The SM studies the electromagnetic and weak interactions according to [6], [7] through its $SU(2)_L \times U(1)_Y$ gauge groups. The $SU(3)_C$ gauge group [8] corresponds to the strong interaction. This theory can be briefly reviewed by dissecting it into two: the Standard model before and after symmetry breaking (SB).

1.1.1 The SM before Symmetry Breaking

Before symmetry breaking the SM has contained its untouched gauge group, as stated above.

a. The matter fields

Up to now, we have three generations of the matter fields, classified into left and right-handed Chiral fermions; $f_{L,R} = \frac{1}{2}(1 \mp \gamma^5)f$. In $SU(2)_L$, the left-handed particles are in its isodoublets, while right-handed are in isosinglets. The SM matter fields is summarized in a table below.

Table 1: The matter fields content of the SM [4]

Multiplets	Generation of particles	$SU(3)_C \times SU(2)_L \times U(1)_Y$
L_L	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(1, 2, -1)$
E_R	e^-_R, μ^-_R, τ^-_R	$(1, 1, -2)$
Q_l	$\begin{pmatrix} u \\ d \end{pmatrix}_L, \begin{pmatrix} c \\ s \end{pmatrix}_L, \begin{pmatrix} t \\ b \end{pmatrix}_L$	$(3, 2, +\frac{1}{3})$
U_R	u^-_R, c^-_R, t^-_R	$(3, 1, +\frac{4}{3})$
D_R	d^-_R, s^-_R, b_R	$(3, 1, -\frac{2}{3})$

One defines the hypercharge of fermions by using the third components of the weak isospin I^3_f, $Y_f = 2Q_f - 2I^{3R}_f$,with Q_f: charge of proton. Form the above table, it is directly identified that $Y_{L_L} = -1$, $Y_{E_R} = -2$, $Y_{Q_l} = \frac{1}{3}$, $Y_{U_R} = \frac{4}{3}$, $Y_{d_R} = -\frac{2}{3}$.

b. The gauge fields

The two types of gauge fields are massive for EW interactions and zero mass for EM and strong interactions. In the $SU(2)_L \times U(1)_Y$ there is first B_μ field with Y as generator of $U(1)$ and $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ as its fields strength tensor, and the second field is W^a_μ which has $T^a = \frac{1}{2}\sigma^a$,
$a = 1, .., 3$ are $SU(2)_L$ generators of and σ^a: Pauli matrices,

$W^a_{\mu\nu} = \partial_\mu W^a_\nu - \partial_\nu W^a_\mu + g_2\epsilon^{abc}W^b_\mu W^c_\nu$ field strength and g_2: coupling constant. The following commutation relations are verified for the electroweak sector $[T^a, T^b] = i\epsilon^{abc}T_c, [Y, Y] = 0$, where ϵ^{abc} is antisymmetric tensor [6].

In the $SU(3)_C$ there is gluonic field $G^a_\mu, a = 1, ..8$. This gauge group has eight generators $T^a = \frac{1}{2}\lambda^a$, λ^a, Gell-Mann matrices satisfying the following relations [6, 9]

$$[T^a, T^b] = if^{abc}T_c and Tr[T^aT^b] = \frac{1}{2}\delta_{ab}, \tag{1.1}$$

where f^{abc} is the structure constant and the field strength is given by $G^a_{\mu\nu} = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_3 f^{abc}G^b_\mu G^c_\nu$. The matter fields and gauge fields are mediated through the following covariant derivative $D_\mu\psi = (\partial_\mu - ig_sT^aG^a_\nu - ig_2W - \mu^a - ig_1\frac{Y_q}{2}B_u)\psi$.

There are trilinear and quartic interactions in both $SU(2)_L$ and $SU(3)_C$ gauge groups due to their non-abelian nature. The general Lagrangian which is invariant under the SM gauge group is

$$\begin{aligned} L_{SM} = &-\frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a - \frac{1}{4}W^a_{\mu\nu}W^{\mu\nu}_a - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \overline{L}_i iD_\mu\gamma^\mu L_i \\ &+ \overline{e}_{Ri}iD_\mu\gamma^\mu e_{Ri} + \overline{Q}_i iD_\mu\gamma^\mu Q_i + \overline{U}_{Ri}iD_\mu\gamma^\mu U_{Ri} + \overline{d}_{Ri}iD_\mu\gamma^\mu d_{Ri} \end{aligned} \tag{1.2}$$

This Lagrangian (1.2) is invariant under SM local transformations for both matter and gauge fields [6]. By inspection of this Lagrangian, you can see that there are no terms which could provide mass for any of the EW gauge bosons or fermions. It needed to introduce the mass term in the above Lagrangian which leads to the study of the SM after symmetry breaking.

1.1.2 The SM after Symmetry Breaking

We need to introduce the terms describing masses of both fields in the above Lagrangian. The mass terms of any of the stated fields disturb the invariance of SM gauge symmetry.

The photon must be massless under $U(1)$ local symmetry. The $SU(2)_L \times U(1)_Y$ need to break down so that the mass is generated in the standard model. The mechanism under which, this is done is described bellow [10].

a. The Higgs mechanism in abelian theory

In this section, we specify the Lagrangian with a specific potential, and invariant under $U(1)$ gauge transformation by introducing the vector potential $\phi \longrightarrow e^{i\alpha(x)}\phi(x)$, $A_\mu(x) \longrightarrow A_\mu(x) + \frac{1}{e}\partial\mu\alpha(x)$, where $\partial_\mu \longrightarrow D_\mu = \partial_\mu - ieA_\mu$, we get

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + (\partial_\mu\phi)^*(\partial^\mu\phi) - \mu^2\phi^*\phi - \lambda(\mu^2\phi^*\phi)^2. \tag{1.3}$$

If $\mu^2 > 0$, we identify that the Lagrangian represent the system of scalar particles of mass μ with ϕ^4 as self interaction. This theory has 4 degrees of freedom, 2 for the massless EM field vector A_μ and 2 for the complex scalar field.

If $\mu^2 < 0$, one minimizes the potential and get $\phi_0 = \langle 0|\phi|0\rangle = (-\frac{\mu^2}{2\lambda})^{\frac{1}{2}} \equiv \frac{\nu}{\sqrt{2}}$ and explores the spectrum of the system,

$$\phi(x) = \frac{1}{\sqrt{2}}(\nu + \eta(x) + i\xi(x)), \tag{1.4}$$

but this transformation induces a symmetry breaking of the $U(1)$ symmetry. We use Eq:(1.4) and the value of ∂_μ into Eq:(1.3) to get

$$\begin{aligned}\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2\nu^2}{2}A_\mu A^\mu + \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{2\nu^2\lambda}{2}\eta^2 + \frac{1}{2}\partial_\mu\xi\partial^\mu\xi - e\nu A^\mu\partial_\mu\xi + \\ + \frac{e^2}{2}A_\mu A^\mu(2\nu\eta + \eta^2 + \xi^2) + eA^\mu\eta\partial_\mu\xi - \frac{\lambda}{4}(\eta^2 + \xi^2)^2 - \nu\lambda\eta(\eta^2 + \xi^2) + \frac{\nu^4\lambda}{4}\end{aligned} \tag{1.5}$$

The observation made on this Lagrangian after its expansion around the minimum, one identifies that the mass term was generated for photon $m_A = e\nu = -\frac{e\mu^2}{2\lambda}$. The scalar particle η appears with mass $M_\eta = 2\nu^2\lambda = -2\mu^2$. We have also a massless particle ξ which is a Goldstone particle [11]. The propagation of the unphysical field ξ leads also to the transformation the vector field A_μ into a scalar field ξ as it highlighted in $e\nu A_\mu\partial_\mu\xi$. Now, the vector field A_μ is massive, and ξ behave as a longitudinal component. We now eliminate the unphysical field, by transforming as

$$\phi(x) = \frac{1}{\sqrt{2}}(\nu + \eta(x) + i\xi(x)) = \frac{1}{\sqrt{2}}(\nu + \eta(x)')\exp i\frac{\xi(x)'}{\nu}, \tag{1.6}$$

with $\xi = \xi'$, $\eta = \eta'$ to first order $(\nu + \eta)(1 + i\frac{\xi(x)}{\nu}) = \nu + \eta' + i\eta'$, $\alpha(x) = -\frac{\xi(x)}{\nu}$. In the unitary gauge

$$\phi(x) \longrightarrow e^{i\xi(x)'}\phi(x); A_\mu \longrightarrow A_\mu - \frac{1}{e\nu}\partial_\mu\xi(x)', \tag{1.7}$$

the phase factor disappears, so that the Lagrangian becomes

$$\begin{aligned}\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{e^2\nu^2}{2}A_\mu A^\mu + \frac{1}{2}e^2A_\mu A^\mu(2\nu\eta + \eta^2) + \\ \frac{1}{2}\partial_\mu\eta\partial^\mu\eta - \frac{1}{2}\lambda\nu^2\eta^2 - \lambda\nu\eta^3 - \frac{\lambda}{4}\eta^4 + \frac{1}{4}\lambda\nu_0^4.\end{aligned} \tag{1.8}$$

The $U(1)$ symmetry has been spontaneously broken; and this induces photon to absorb the would be one degree of freedom Goldstone boson and becomes massive with three degrees of freedom. It is in this process, the EW gauge bosons get their mass; this is known as **Higgs mechanism**.

One observes that we no longer have a massless photon, which is required by the EM theory. This problem is technically solved in the following section without losing possibility to generate mass of the EW gauge bosons.

b. The Higgs mechanism in the non-abelian theory

We focus now on the EW gauge group. We make a good choice of $SU(2)$ complex scalar field ϕ doublet, so that the mass of gauge bosons is generated while keeping the photon massless. One can take

$$\phi \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \tag{1.9}$$

In this context, the Lagrangian (1.3) can be written as

$$\mathcal{L} = (D^\mu\phi)^+(D_\mu\phi) - V(\phi), \tag{1.10}$$

where $V(\phi) = \mu^2\phi^+\phi + (\phi^+\phi)^2$. This Lagrangian has $U(1)$ local gauge invariance,

$$\phi(x) \longrightarrow \phi(X)' = e^{i\alpha_i(x)\frac{\tau_i(x)}{2}}\phi(x). \tag{1.11}$$

Where τ_i, with i=1,2,3 are Pauli matrices and $\alpha(x)$ is a transformation parameter.

If $\mu^2 < 0$, we minimize the potential and get the VEV $\phi = -\frac{\mu^2}{2\lambda} = \frac{\nu^2}{2}$ where $\langle 0|\phi|0\rangle_0 = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \nu \end{pmatrix}$, with $\nu = (-\frac{\mu^2}{\lambda})^{\frac{1}{2}}$. This breaks the $SU(2)_L$ and $U(1)_Y$ invariance, but $U(1)_{EM}$ invariance is preserved, which implies that electric charge is conserved. The original four generators, three $\frac{\tau_i}{2}$ and Y are broken which means that $\frac{\tau_i}{2}\langle 0|\phi|0\rangle_0 \neq 0$ [12]. The linear combination corresponding to electric charge is not broken, which implies that the photon remains massless where as $Y\langle 0|\phi|0\rangle_0 \neq 0$ implies that other gauge bosons acquires masses.

The expansion around the minimum in unitary gauge transformation.

$$\phi(x) \longrightarrow \phi(x)' = e^{-i\theta_a(x)\frac{\tau^a(x)}{2}}\phi(x) = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ \nu + h(x) \end{pmatrix}, \tag{1.12}$$

the parameter $\theta_a(x)$ is removed by the gauge transformation.

In the expansion of the kinetic term,
$|D_\mu\phi|^2 = \frac{1}{2}(\partial_\mu h)^2 + \frac{1}{8}g_2^2(\nu+h)^2|W_\mu^1 + iW_\mu^2|^2 + \frac{1}{8}(\nu+h)^2|g_2W_\mu^3 - g_1B_\mu|^2$, plus the potential up the to mass term

$$\begin{aligned} \mathcal{L} = &\frac{1}{8}g_2(\nu+h)^2|W_\mu^1 + iW_\mu^2|^2 + \frac{1}{8}(\nu+h)^2|g_2W_\mu^3 - g_1B_\mu|^2 + \\ &\frac{1}{2}[(\partial_\mu h)^2 + 2\mu^2h^2] + ... + \text{interaction terms.} \end{aligned} \tag{1.13}$$

Define the charged field $W^{\pm} = \frac{1}{\sqrt{2}}(W_{\mu}^{1} \mp iW_{\mu}^{2})$, and eliminate the field components W_{μ}^{1} and W_{μ}^{2} in favour of $W^{\pm}$. we identify the mass term to be $\frac{g_2^2\nu^2}{2}(|W_{\mu}^{+}|^2 + |W_{\mu}^{-}|^2)$, with

$$M_W \pm = \frac{g_2 \nu}{2}, \tag{1.14}$$

the Eq(1.14) define the mass $W^{\pm}$ gauge boson. We again define the orthogonal combination of the fields $Z_{\mu} = \frac{1}{\sqrt{g_1^2+g_2^2}}(g_2 W_{\mu}^3 - g_1 B_{\mu})$ and
$A_{\mu} = \frac{1}{\sqrt{g_1^2+g_2^2}}(g_2 W_{\mu}^3 + g_1 B_{\mu})$. By elimination of the vector field B_{μ} and the field components W_{μ}^3 one obtained the intermediate vector boson with acquired mass

$$M_Z = \sqrt{g_1^2 + g_2^2}\frac{\nu}{2}, \tag{1.15}$$

while the photon mass is zero as it was needed at the beginning of this section. This correspond to unbroken charge operator
$Q\langle 0|\phi|0\rangle_0 = \frac{1}{2}(\tau_3 + Y)\langle\phi\rangle_0 = 0$, where τ_3 is an isospin operator [12]. It is through this EWSB, $SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$, that the mass of $W^{\pm}$ and Z have been generated by absorbing the three Goldstone bosons which to form their orthogonal components.

The field $h(x)$ has acquired a mass

$$m_h^2 = -2\mu^2 > 0, \tag{1.16}$$

the Eq(1.16) defines mass of the physical Higgs boson particle. Normally, the mass term is forbiden by the SM gauge invariance, it is through this scalar field ϕ with hypercharge $Y = 1$ and the corresponding isodoublet $\Phi = i\tau_2\phi^*$, with $Y = -1$, with which successively we could generate mass of fermions and EW gauge bosons.

$$\begin{aligned}\mathcal{L}_{\{} &= -\lambda_e \overline{L}_e \phi e_R - \lambda_d \overline{Q}\phi d_R - \lambda_u \overline{Q}\Phi u_R + h.c \\ &= -\frac{1}{\sqrt{2}}\lambda_e(\nu + h)\overline{e}_L e_R - \frac{1}{\sqrt{2}}\lambda_d(\nu + h)\overline{d}_L d_R + h.c - \frac{1}{\sqrt{2}}\lambda_u \overline{u}_L u_R + h.c.\end{aligned} \tag{1.17}$$

The mass term for leptons, down and up quarks are identified to be [13]

$$m_e = \frac{\lambda_e \nu}{\sqrt{2}}, m_d = \frac{\lambda_d \nu}{\sqrt{2}}, m_u = \frac{\lambda_u \nu}{\sqrt{2}}. \tag{1.18}$$

The gauge and fermion masses have been generated through the interaction with Higgs field, and SM model gauge group is maintained invariant under gauge transformation. The mass of the fundamental particle is directly proportional to the coupling, this shows that Higgs boson is strongly coupled to the heavier particles than the lighter one.

2 Higgs boson in the SM

In this chapter we analyse the self interaction of Higgs boson and how it interacts with other SM particles.

2.1 The mass of the Higgs boson

The Higgs boson is a CP-even scalar of spin zero [14]. To study its mass, let's return to our Lagrangian Eq(1.13) and extract only terms corresponding to the kinetic term and potential for the Higgs field. One obtains

$$\mathcal{L} = \frac{1}{2}[(\partial_\mu H)^2 - (2\lambda\nu^2)H^2] - \lambda\nu H^3 - \frac{\lambda}{4}H^4 - \frac{\lambda}{4}\nu^4. \tag{2.1}$$

From the above Lagrangian Eq(2.1), one concludes that the mass of Higgs boson is

$$m_H^2 = 2\lambda\nu^2, \tag{2.2}$$

terms proportional to H^3 and H^4 respectively contribute to Higgs self interactions. As seen from Eq(2.2), the knowledge of Higgs boson mass requires first the information about Higgs self coupling constant λ and the vacuum expectation value ν. The VEV $\nu = 2\frac{M_W^\pm}{g_2} = 246$GeV was predicted in electroweak sector.

The Higgs potential at the minimum $V_{min}(\phi = \nu) = -\frac{\lambda\nu^4}{2}$, this privides the vacuum energy density of the universe from the SSB. In the SM, there is no fundamental justification of the origin of λ, and there's no other physical observables depending on it that can be measured [15]. Due to the fact that the Higgs mass was not predicted theoretically, but LHC has measured it to be $\lambda \approx 0.13$. However, there exist some theoretical constraints on mass of Higgs boson in the SM, which are discussed below.

2.1.1 The unitarity constraints

The scattering amplitude of the EW gauge bosons requires the unitary conservation of probabilities. The cross section of these processes increases with the increases in the energy and this leads to the violation of unitarity at a given level of energy.

The differential cross section is

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|M|^2, \tag{2.3}$$

with $M = 16\pi\sum_{l=0}^{\infty}(2l+1)p_l(\cos\theta)a_l$ [6, 16]. one can use partial wave decomposition, where a_l, p_l are spin partial wave and Legendre polynomials respectively.

$$\begin{aligned}\sigma &= \frac{8\pi}{s}\sum_{l=0}^{\infty}\sum_{l'=0}^{\infty}(2l+1)(2l'+1)a_l a_{l'}\int_{-1}^{1} d\mathrm{cos}\theta p_l(\cos\theta)p_{l'}(\cos\theta) \\ &= \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2.\end{aligned} \tag{2.4}$$

The use of optical theorem imposes

$$\sigma = \frac{1}{s}\mathrm{Im}[A(\theta=0)] = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)|a_l|^2 \tag{2.5}$$

This lead to the unitary condition $|a_l|^2 = \mathrm{Im}(a_l)$, implies that $|\mathrm{Re}(a_l)|^2 + |\mathrm{Im}(a_l)|^2 = \mathrm{Im}(a_l)$, with this in mind, one can solve it and get

$$|\mathrm{Re}(a_l)|^2 + [\mathrm{Im}(a_l - \frac{1}{2})]^2 = \frac{1}{4}. \tag{2.6}$$

This is the equation of a circle of radius $\frac{1}{2}$ and centred at $(0, \frac{1}{2})$ in the plane $(Re(a_l), \mathrm{Im}(a_l)$. the requirement of unitarity requires that

$$|Re(a_l)| < \frac{1}{2}. \tag{2.7}$$

We now consider a typical example of $W_L^+W_L^- \longrightarrow W_L^+W_L^-$ scattering for $J=0$ within the limits $M_W^2 << s$

$$\begin{aligned}a_0(W_L^+W_L^- \longrightarrow W_L^+W_L^-) &= \frac{1}{16\pi s}\int_{-s}^{0}|A|dt \\ &= -\frac{G_F M_H^2}{8\sqrt{2}\pi}\left[2 + \frac{M_H^2}{s-M_H^2} - \frac{M_H^2}{s}\log(1+\frac{s}{M_H^2})\right],\end{aligned} \tag{2.8}$$

then for $M_H^2 \ll$ limits

$$a_0(W_L^+W_L^- \longrightarrow W_L^+W_L^-) \longrightarrow -\frac{G_F M_H^2}{4\pi\sqrt{2}}. \tag{2.9}$$

The use of unitarity requirement Eq(2.9), one obtains $M_H < 860\mathrm{GeV}$. It is important to note that this doesn't means that the mass of the Higgs boson cannot be greater than 860GeV, it simply means that for heavier masses than the stated one, perturbation theory is not applicable [16].

The $W_L^+W_L^- \longrightarrow W_L^+W_L^-$ is also coupled to Z_LZ_L, HH and Z_LH channels as seen in [17] and we preferred to represent ϕ^0 by H [6]. The charge conservation requirements prohibit $W_L^+ H$ and $W_L^+ Z$ to be coupled to the charged channels. The base matrix is shown bellow, where are four charged channels and two neutral channels. The quartic coupling is dominant at high energy because $\lambda = \frac{M_H^2}{2\nu^2}$ and is represented in the basis $(W^+W^-, \frac{Z_L Z_L}{\sqrt{2}}, \frac{HH}{\sqrt{2}}, Z_L H, W_L^+ H, W_L^+ Z)$, with the factor of $\frac{1}{\sqrt{2}}$ to account for identical particles statistics. Then,

$$a_0 = \frac{M_H^2}{\nu^2} \begin{pmatrix} 1 & \frac{\sqrt{2}}{4} & \frac{\sqrt{2}}{4} & 0 & 0 & 0 \\ \frac{\sqrt{2}}{4} & \frac{3}{4} & \frac{1}{4} & 0 & 0 & 0 \\ \frac{\sqrt{2}}{4} & \frac{3}{4} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{2} \end{pmatrix} \tag{2.10}$$

The largest eigenvalue of a_0 is $\frac{3}{4}$ and thus respect unitarity. This requires $M_H \leq 710$GeV; for values above this; the unitarity is violated in the SM. The radiative correction is very large, this destroys the pertubativity of the theory. The need to set on Higgs boson mass requires the SM remains perturbative and higher order corrections do not have higher contributions. For $M_H >> \sqrt{s}$, and by considering all coupled channels; one obtains $\sqrt{s} \leq 1.2$TeV. This is an upper bound which calls for a new physics at TeV scale to restore unitarity if Higgs boson is too heavy.

2.1.2 Triviality constraint

The SM is a perturbative theory, which has bare parameter like m_0 and self coupling λ at tree level. The higher order corrections affect both parameters stated above, but we now focus on how self coupling is affected in this context. The value of λ need to be defined at a certain scale in a renormalizable theory, and the value at another scale is different (i.e λ runs) [18]. The λ value at a given energy scale is described by renormalization group equations [6]

$$\frac{d\lambda(Q^2)}{d(Q^2)} = \frac{3}{4\pi^2}\lambda^2(Q^2) + \text{higher order terms.} \tag{2.11}$$

The calculation up to one loop and by taking reference to the EWSB, $Q_0 = \nu$ gives

$$\lambda(Q^2) = \lambda(\nu^2)\left[1 - \frac{3}{4\pi^2}\lambda(\nu^2)\log(\frac{Q^2}{\nu^2})\right]^{-1}. \tag{2.12}$$

The clear observation highlights that λ varies with $\log(\frac{Q^2}{\nu^2})$. For $Q^2 \ll \nu^2$, the Higgs boson decouples and does not contribute to the RG runing. For $Q^2 \gg \nu^2$, the corrected λ increases monotonically with energy scale and the theory becomes non-pertribative (λ becomes infinite) at the so called Landau pole Λ_c, unless $\lambda = 0$, i.e the theory is "trivial", which means no interacting; from where the name of the constraint is coined. The energy at this point is

$$\Lambda_c = \nu \exp(\frac{4\pi^2\nu^2}{M_H}). \tag{2.13}$$

It is now of fundamental interest to fix the cut-off for a valid SM theory and for a finite λ.

For Λ_c very large, dictates Higgs mass to be very small so that the Landau pole is avoided, and $\Lambda_c \sim 10^{16}$GeV (i.e the Planck scale) implies $M_H \leq 200GeV$.

For Λ_c very small, the Higgs mass can be very large. The very large value case for λ is problematic, it breaks down the pertrubativity property of our theory. The $M_H < 640$GeV bound, is fixed by the technique which is not relying on pertribation.

2.1.3 The stability of vacuum

In this section, we analyse the behavior of the running self coupling constant (λ) by including EW gauge bosons and top quark only. The contribution of other fermions has been neglected due to their small masses. The coupling constant for one loop RGE, with fermions and gauge bosons is given [6]

$$\frac{d\lambda}{d\log Q} \simeq \frac{1}{16\pi^2}\left[12\lambda^2 + 6\lambda\lambda_t^2 - 3\lambda_t^4 - \frac{3}{2}\lambda(3g_2^2 + g_1^2) + \frac{3}{16}(2g_2^2 + (g_2^2 + g_1^2)^2)\right],$$

where λ_t is a Yukawa coupling of top quark. The triviality bound in this case for$\lambda \ll \lambda_t$,g_1, g_2, the use of this relation in Eq(2.14) and solved to get

$$\lambda(Q^2) = \lambda(\nu^2) + \frac{1}{16\pi^2}\left[-12\frac{m_t^4}{\nu^4} + \frac{3}{16}(2g_2^2 + (g_2^2 + g_1^2)^2)\right]\log(\frac{Q^2}{\nu^2}). \tag{2.14}$$

For λ very small, the term from the top quark dominates and drives ($\lambda(Q^2) < 0$) to negative value. The scalar potential is now energy dependent $V(Q^2) < V(\nu)$, smaller than that of SM, the vacuum has no minimum and it is not stable. The need for the potential which is bounded from bellow implies that $\lambda(Q^2) > 0$, or $M_H^2 > \frac{\nu^2}{8\pi^2}[-12\frac{m_t^4}{\nu^4} + \frac{3}{16}(2g_2^2 + (g_2^2 + g_1^2)^2)]\log(\frac{Q^2}{\nu^2})$. One can stand on the context of small self coupling (small Higgs mass) where the radiative correction are important, and fix the Higgs boson mass by requiring the the vacuum stability [19].

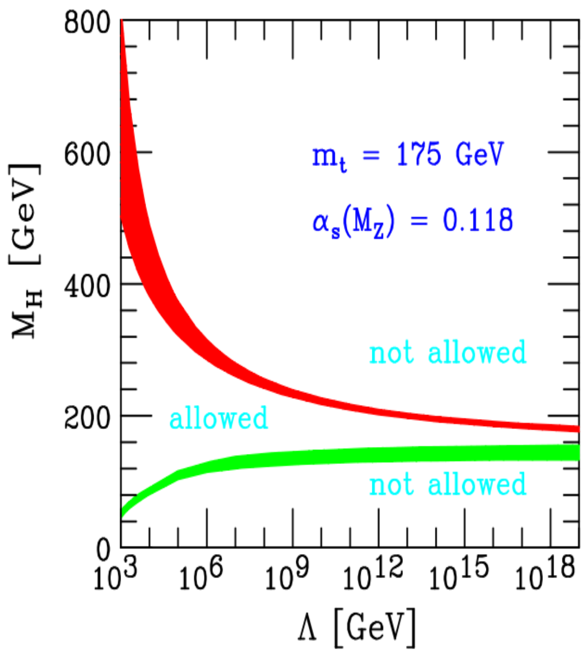

Figure 1: The lower bound is from vacuum stability, and upper bound is from triviality in function of the cut off, with $m_t = 176\text{GeV}$ [6, 19].

2.2 Production of Higgs boson

In this section, we explore the Higgs production and how it interacts within itself and with other fundamental particles, gauge bosons and fermions.

2.3 Higgs at the LHC

At LHC, the main Higgs production channels are: gluon-gluon fusion, fusion of EW gauge bosons and Higgs-Strahlung [1, 20].

2.3.1 Gluon-gluon fusion $gg \longrightarrow H + jets$

This is production mechanism has a very large cross section, at LHC machine. It is done through loops of all SM particles capable to couple both to gluons and and Higgs bosons, namely quarks [15]. The loop of top quark dominates, because as said in chapter one the coupling is directly proportional to the mass of the particle and this quark is heavier than other particles of the SM. The process describing this Higgs production is given Fig(2) The cross section corresponding

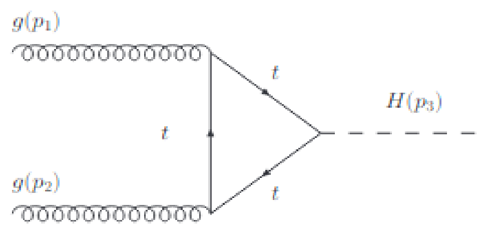

Figure 2: Gluon-gluon fusion diagram

to this process is given by

$$\sigma(gg \longrightarrow H) = \frac{\pi^2}{8M_H}\Gamma(H \longrightarrow gg)\delta(s - M_H^2) = \frac{M_H^2}{64\nu^2}(\frac{\alpha_s^2}{\pi})n^2|D(n)|^2\delta(s - M_H^2), \tag{2.15}$$

where Γ is the decay width, $n^2 = \frac{m^4}{M_H^4}$ and $D(n) = -2 + (4n - 1)\left[L_{i2}(\frac{-2}{\sqrt{1-4n}-1}) + L_{i2}(\frac{2}{\sqrt{1-4n}+1})\right]$. The Next to leading order (NLO)QCD corrections increase the leading order for the cross section by approximately 80%, and NNLO improve the cross section by 30% of the LO, plus NLO with at $\mu_f = mu_r = \frac{M_H}{2}$ [15, 21]. The improvement of cross section continue, now taking EW correction where the approximate improvement of 5% is obtained for the SM Higgs boson. The LO and NLO are diagramatically shown Fig(3)

2.3.2 The fusion of EW bosons, $qq \longrightarrow V^*V^* \longrightarrow Hqq$

This process is shown on the Fig(4) The weak-gauge boson is a colour singlet, so the VBF provides a well clean environment for Higgs searches and dermination of its couplings. The possible interference between $W^{\pm}$ and Z diagrams is negligible, less than 1% [6]. The coupling of W to fermions is stronger than that of Z boson, this leads to $\sigma(WW \longrightarrow H) \sim 3\sigma(ZZ \longrightarrow H)$ at LHC.

The total cross section is obtained by summing the parton cross section $\hat{\sigma}(qq \longrightarrow qqH) = \frac{d\mathcal{L}^{\nu\nu}}{d\tau_V}$ with $\tau_V = \frac{M_{VV}^2}{2}$ (Drell-Yan variable) over the flux of all possible pairs of quark-quark and antiquark-antiquark combinations,

$$\sigma(qq' \longrightarrow VV \longrightarrow H) = \int_{M_H^2}^{1} d\tau \sum_{qq'} \frac{d\mathcal{L}^{qq'}}{d\tau}\hat{\sigma}(qq' \longrightarrow qq'H; \hat{s} = \tau s). \tag{2.16}$$

This production mechanism is very important for heavy Higgs mass.

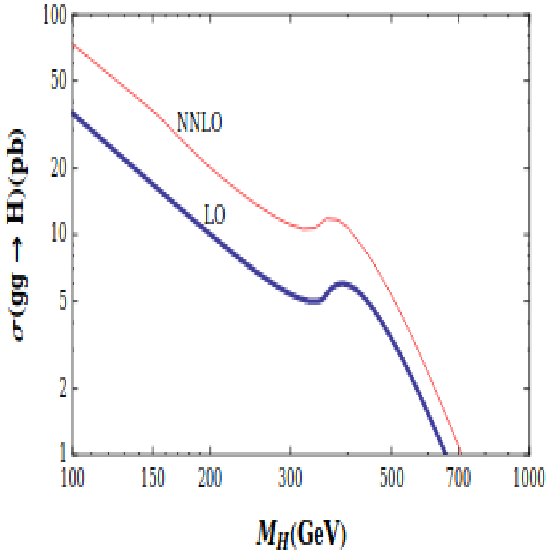

Figure 3: LO and NNLO $gg \longrightarrow H$ cross sections as functions of M_H at$\sqrt{s} = 14TeV$ [1]

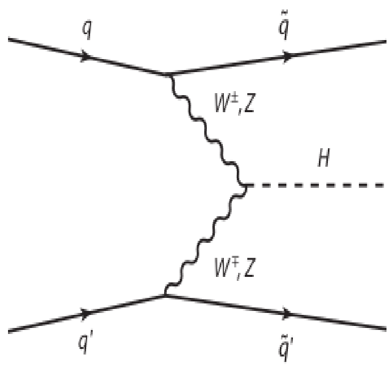

Figure 4: Feynman diagram for VBF

2.3.3 Higgs boson strahlung, $q\bar{q} \longleftarrow V^* \longrightarrow VH(V = W, Z)$

The third of the main Higgs boson production channels is the Higgs boson strahlung of vector boson, shown Fig(5). This mechanism is very important at LHC and at Tevatron in the search of light Higgs [2].For this process, the leptonic decays of the EW vector boson are used to filter out the Higgs events from the huge background.

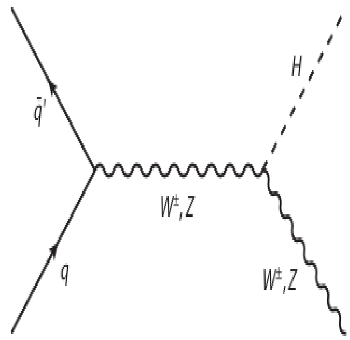

Figure 5: Feynaman diagram for higgs stahlung

2.3.4 Higgs boson Bremsstrahlung off top quarks, $qq \longrightarrow t\bar{t}H$

This process is usefull for small Higgs mass [2]. It finds use in determining top quark-Higgs Yukawa coupling [20]. Differents production mechanism at LHC are shown in Fig(6). The evaluation of LO and NLO QCD corrections yield an

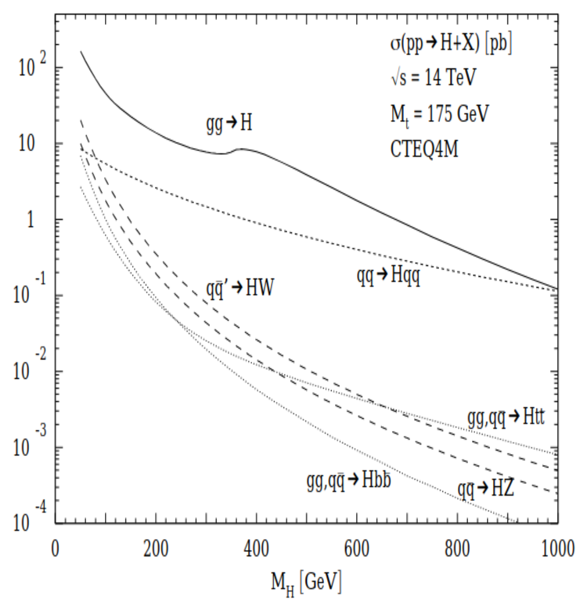

Figure 6: Higgs production of different processes at LHC, with QCD correction involved[2],[3]

increases in the total cross section of 20% at most, and significantly reduce the scale dependence of the inclusive cross section [20].

2.4 Production of Higgs boson at e^+e^- colliders

The mains production channels in e^+e^- scattering process are: Higgsboson strahlung, and WW fusion [6, 20, 21].

2.4.1 Higgs boson strahlung $e^+e^- \longrightarrow (Z^*) \longrightarrow ZH$

The Higgs strahlung is conducted according to the following diagram,

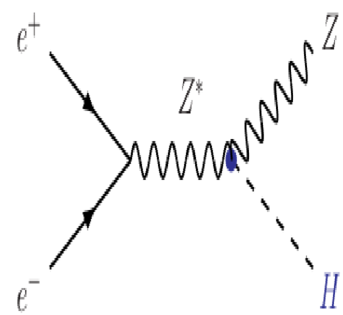

Figure 7: Feyman diagram for Higgs strahlung.

The cross section of this process is dominant at low energy and it scales as s^-1 [21], which means that for the squared energy, $\sigma \sim \frac{\alpha_W^2}{s}$ [2]. The cross section corresponding to this process is

$$\sigma(e^+e^- \longrightarrow ZH) = \frac{G_F^2 M_Z^4}{96\pi s}[\nu_e^2 + a_e^2]\lambda^{\frac{1}{2}} \frac{\lambda + \frac{12M_Z^2}{s}}{[1 - M_Z^2]^2}, \tag{2.17}$$

where $\nu_e = -1 + 4\sin^2(\theta)$ and $a_e = -1$ are vector and axial charge of the electron, $\lambda = [1 - \frac{(M_{H+M_Z})^2}{s}]$ is the two particle phase space function. The asymptotic behavior of this cross section shows that it vanishes.This process find use in constructing the Higgs mass as $M_H^2 = s - 2\sqrt{s}E_Z + M_Z^2$ without relying on Higgs decay products.

2.4.2 The fusion of WW gauge bosons, $e^+e^- \longrightarrow \bar{\nu}_e\nu_e W^* W^* \longrightarrow \bar{\nu}_e\nu_e H$

The cross section of this process scale as $\ln(\frac{s}{M_H^2})$ and is dominant at high energy [22]. This mechanism is schematically shown bellow.

The cross section in compact form is represented,

$$\sigma(e^+e^- \longrightarrow \bar{\nu}_e\nu_e H) = \frac{G_F^3 M_W^4}{4\sqrt{2}\pi^3} \int_{KH}^1 \int_x^1 \frac{dxdy}{[1 + (y - x)]^2} f(x, y), \tag{2.18}$$

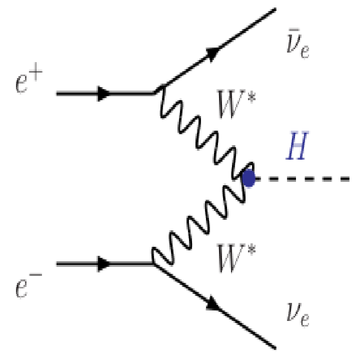

Figure 8: WW fusion in Higgs production

with $f(x,y) = (\frac{2x}{y^3} - \frac{1+3x}{y^2} + \frac{2+x}{y} - 1)[\frac{z}{1+z} - log(1+z)] + \frac{xz^2}{y^3}\frac{(1-y)}{1+z}$, $K_H = \frac{M_H^2}{s}$, $K_H = \frac{M_W^2}{s}$ and $z = \frac{y(x-K_H)}{K_W x}$.
At he asymptotic energies, σ is reduced to

$$\sigma(e^+e^- \longrightarrow \bar{\nu}_e\nu_e H) \longrightarrow \frac{G_F^3 M_W^4}{4\sqrt{2}\pi^3}\left[\log(\frac{s}{M_H^2}) - 2\right]. \qquad (2.19)$$

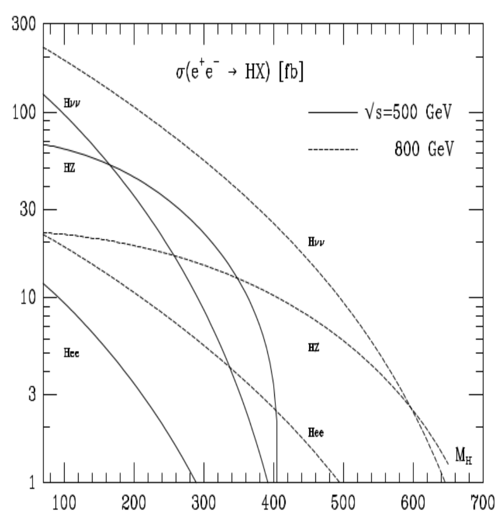

Figure 9: The cross section of Higgs -strahlung and WW fusion at $\sqrt{s} = 500$GeV for a solid curve and 800GeV for a dashed curve [2]

2.5 Higgs boson decays

In chapter one, it has been shown how Higgs boson couple to fermions and EW gauge bosons. The Higgs coupling to both fermions and gauges bosons is directly proportional to their masses, this implicates the way in which Higgs boson decays. It mainly decays into heavier particles it couples to, than the lighter ones. The Higgs boson is now studied by analysing its decay into fermions, EW gauge bosons and loop induced decays.

2.5.1 Higgs decay to fermions

The Higgs decay to both leptons and quark as it is shown on Fig(10) [2, 6, 23]. The decay rate corresponding to Fig(10) is

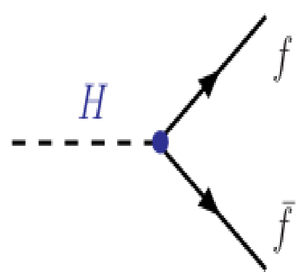

Figure 10: Feynman diagram for Higgs decay to fermions

$$\Gamma(H \longrightarrow \bar{f}f) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H m_f^2 \beta_f^3, \tag{2.20}$$

whith $\beta = (1 - \frac{4m_f^2}{M_H^2})^{\frac{1}{2}}$ being the velocity of fermions in final state and N_c is the colour factor 3 for quarks and 1 for leptons. This decay Eq(2.20) is strongly suppressed near the threshold, $\beta^3 \longrightarrow 0$ for $M_H 2m_f$. This is the case for scalar Higgs boson which is already discovered.
The QCD corrections to Γ is large, it need to be considered for $M_H \gg 2m_f$, is obtained to be

$$\Gamma_{\text{NLO}}(H \longrightarrow \bar{q}q) \simeq \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H m_q^2 \left[1 + \frac{4}{3}\frac{\alpha_s}{\pi}\left(\frac{9}{4} + \frac{3}{2}\log(\frac{m_f^2}{m_q^2})\right)\right], \tag{2.21}$$

the contribution of the logarithmic term in the above relation is large for very light quarks and may reduce Γ to negative value. This is solved by using $\overline{\text{MS}}$ renormalization where the running quark masses is redefined at the scale of the Higgs mass.

2.5.2 Higgs decay to EW gauge bosons

The analysis of the Higgs decay to EW gauge bosons is done by first dissecting the study into two body, three and four body decays. The calculation is given [1].

a. Higgs decay to two weak bosons, $H \longrightarrow ZZ/WW$

The decay width is proportional to the λ_{HVV} coupling constant. The partial

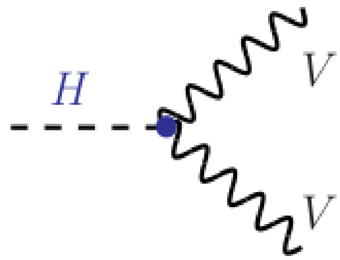

Figure 11: Feynman diagram for Higgs decay into real gauge bosons

decay rate to W is

$$\Gamma(H \longrightarrow WW) = \frac{1}{4\pi}\frac{M_W^2}{M_H V^2}\left(1 - \frac{4M_W^2}{M_H^2}\right)^{\frac{1}{2}}\left(3 + \frac{1}{4}\frac{M_H^4}{M_W^4} - \frac{M_H^2}{M_W^2}\right). \quad (2.22)$$

For the Z boson, we take M_W replace it by M_Z and just after, one finds the whole relation get multiplied by $\frac{1}{2}$ factor to account for identical particles.

$$\Gamma(H \longrightarrow ZZ) = \frac{1}{8\pi}\frac{M_Z^2}{M_H V^2}\left(1 - \frac{4M_Z^2}{M_H^2}\right)^{\frac{1}{2}}\left(3 + \frac{1}{4}\frac{M_H^4}{M_Z^4} - \frac{M_H^2}{M_Z^2}\right). \quad (2.23)$$

In the context of heavy Higgs masses, there is a longitudinal polarization of vector bosons [2]. The observation made on (2.22) and (2.23) reveals that $\Gamma(H \longrightarrow VV) \sim M_H^3$, which means that the wave functions of this state is linear in energy.

b. Three body decays, $H \longrightarrow VV^* \longrightarrow V\bar{f}f$

The decay process in which Higgs decay to two EW gauge bosons with one real W and other virtual W^*, and the virtual decays into f_u and f_d fermions. Where $f_u = u, c, t, e, \mu, \tau$ and $f_d = d, s, b, \nu_e, \nu_\mu, \nu_\tau$. The partial decay width of this process is given by

$$\Gamma(H \longrightarrow VV^*) = \frac{3G_F^2 M_V^4}{16\pi^3} M_H R(x)\delta'_V, \quad (2.24)$$

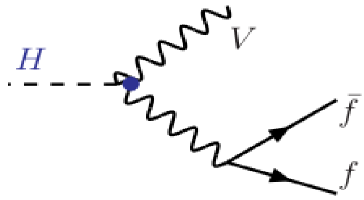

Figure 12: Feynman diagram of Higgs boson decay into real and virtual gauge bosons

where $\delta'_W = 1$, $\delta'_Z = \frac{7}{12} - \frac{10}{9}\sin^2\theta_W + \frac{40}{27}\sin^4\theta_W$ and
$R(x) = \frac{3(1-8x+20x^2)}{(4x-1)^{\frac{1}{2}}}\arccos(\frac{3x-1}{2x^{\frac{3}{2}}}) - \frac{1-x}{2x}(2-13x+47x^2) - \frac{3}{2}(1-6x+4x^2)$.
The processes where W^* is involved are considered important for low mass Higgs boson.

Then, for $H \longrightarrow ZZ^* \longrightarrow Z\bar{f}f$, this channel becomes relevant for the Higgs mass below ~ 180GeV and the corresponding decay with is

$$\Gamma(H \longrightarrow Zf\bar{f}) = \frac{g^2}{\nu^2}\frac{3M_Z^2}{256\pi^3}M_H R(x)\frac{\delta'_V}{\cos\theta_W^2}. \tag{2.25}$$

c. Four body decays

The four body decays process occurs when Higgs decays to two off-shell gauge bosons [24]. The partial decay width is represented by [6]

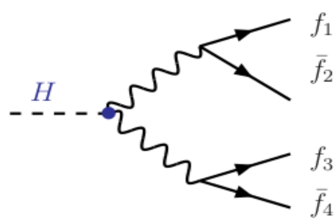

Figure 13: Feynamn diagram for Higgs boson decays into four body decays

$$\Gamma(H \longrightarrow V^*V^*) = \frac{1}{\pi^2}\int_0^{M_H^2}\frac{d^2q_1 M_V\Gamma_V}{(q_1^2-M_V^2)^2+M_V^2\Gamma_V^2}\int_0^{(M_H-q_1)^2}\frac{d^2q_2 M_V\Gamma_V}{(q_2^2-M_V^2)^2+M_V^2\Gamma_V^2}\Gamma_0, \tag{2.26}$$

with q_1^2, q_2^2 the squared invariant mass of the virtual gauge bosons, M_V and Γ_V their mass and total decay with width, and in terms of $\sigma = 2(1)$ for $W(Z)$, the matrix elements squared Γ_0 is given by

$\Gamma_0 = \frac{G_\mu M_H^3}{16\sqrt{2}\pi}\delta_V \sqrt{\lambda(q_1^2, q_2^2, M_H^2)}[\lambda(q_1^2, q_2^2, M_H^2) + \frac{12 q_1^2 q^2}{M_H^4}]$. The advanced and detailed computation on Higgs decay into vector bosons see [25].

2.5.3 Higgs boson decays into gg, $\gamma\gamma$, ang γZ

The SM do not allow the direct coupling of the $U(1)_{\mathrm{EM}}$ gauge boson (photon) and $SU(3)_{\mathrm{c}}$ gauge bosons, because they are massless. However the following $H \longrightarrow \gamma\gamma/\gamma Z/gg$ are observed. These decays are mediated by coloured or charged particles.

a. Higgs decay to gg and $\gamma\gamma$ pairs

The Higgs boson decay to gg is mainly mediated by top and bottom quarks in a loop as shown Fig(14).

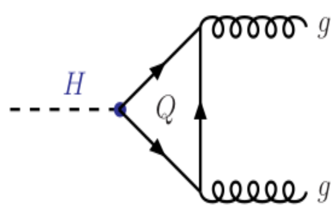

Figure 14: Higgs boson decay to gluons

The corresponding partial decay width is [2].

$$\Gamma(H \longrightarrow gg) = \frac{G_F \alpha_s^2(M_H)}{36\sqrt{2}\pi^3} M_H^3 \left[1 + \left(\frac{25}{4} - \frac{7}{6}N_F\right)\frac{\alpha_s}{\pi}\right]. \qquad (2.27)$$

For the $H \longrightarrow \gamma\gamma$ decay, the particle propagating in the loop is W And the

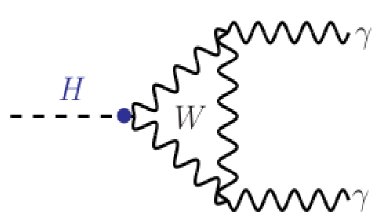

Figure 15: Feynman for Higgs decay to photons

corresponding decay width is

$$\Gamma(H \longrightarrow \gamma\gamma) = \frac{G_F \alpha^2(M_H)}{128\sqrt{2}\pi^3} M_H^3 |\frac{4}{3} N_c e_t^2 - 7|^2 \tag{2.28}$$

The relation Eq(2.27) and Eq(2.28) are valid only when $M^2 \ll 4M_W^2,\ 4M_t^2$ which means that they are valid below the top quark and W gauge boson threshold. Here, we note that quarks can also contribute to the loop, but not shown here for simplicity.

b. Higgs decay to γZ

This process and $H \longrightarrow \gamma\gamma$ have a very much smaller decay rates because of $\alpha \ll \alpha_s$, with α:EM coupling constant and α_s:strong force coupling constant. Thus, concluding this section the consideration of all processes discussed above are summarized in the following diagrams Fig(16)

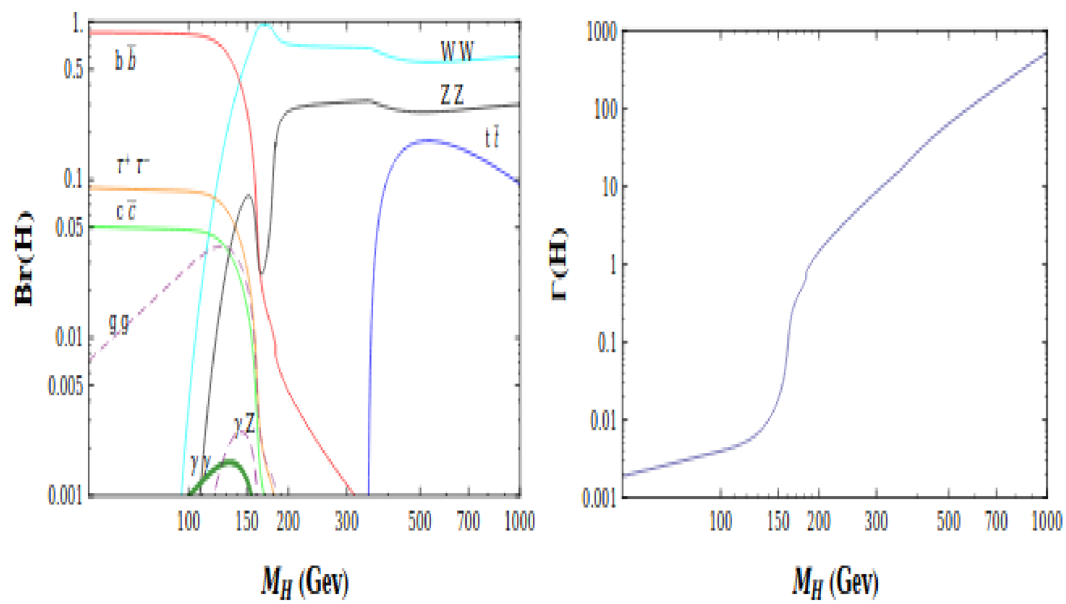

Figure 16: The left figure represent the Higgs branching ratio and the right represents the Higgs total decay width as function of M_H [1]

.

It is shown $H \longrightarrow \gamma Z$ and $H \longrightarrow \gamma\gamma$ have very small width than other channels. At low Higgs mass, $H \longrightarrow \bar{b}b$ is dominating, while $H \longrightarrow WW, ZZ, \bar{t}t$ are most important at higher Higgs mass. The measured branching ratios for channel shown Fig(16) [26].

3 Experimental history

The analysis made on chapter one and two reveals that the Higgs boson has been discovered after a long run of of both theoretical formulations and experimental researches. The study of experimental physics of Higgs boson is done by starting on potential key ingredient to Higgs physics, discoveries of $W^{\pm}$, Z gauge bosons and t, b quarks. The technical analysis of data and experimental progress toward Higgs discovery is highlighted in this chapter. The Higgs boson story after its discovery is then reviewed and compared to the expected data from SM.

3.1 Historical key ingredients to Higgs boson experimental history

3.1.1 Theoretical foundation of Higgs boson

The challenging problem of how fundamental particles get their masses, FranÇois, Robert Brout, Peter Higgs, Gerry Guralnik, Carl Hagen and Tom Kibble in 1964, had suggested a mechanism to accomplish this task, by standing on a mechanism provided in condensed matter by Philip Anderson and Yoichiriro Nambu [27].

It would be a bad starting point to deal with experimental history of Higgs boson without studying the electroweak gauge bosons and other heavy fundamental particles like top and bottom quarks, because they are tremendously implicated in its decay and production as it has been analysed in chapter 2. In 1964, Peter Higgs mentioned the existance of a massive scalar boson [28] and its decays are described into vector boson, in 1966 [29, 30]. It is in this context, one can think that Higgs boson's experimental discovery had to wait first for the production of $W^{\pm}$ and Z gauge boson.

The mechanism of SSB needed to be discussed as introduced in 1965 by Midgar and Polyakov, and highlighted in details in abelian case [29], and in 1967 in the non-abelian theory by Kibble [31]. This mechanism is also described in [32] and extended beyond standard model(BSM). This was strengthen by Salam and Weinberg who had incorporated SSB into the Glashow's unified $SU(2)U(1)$ model of EW as it is said in [33].

The renormalizabily of the theory was proven by Δ't Hooft and M.J.G. Veltman in 1972 [34], which makes the theory trustable one, by allowing to make differents calculations to be compared with experimental measurents [29].

The EW gauge bosons were theolised in 1968, by Glashow, Weinberg and Salam and have been discovered in 1983. These vector bosons constitute as discussed above, the main production channel through EW fusion process with a second rank after gluon fusion mechanism.

The first main production channel of Higgs boson involved heavy particles propagating virtually through the loop, there's no direct coupling of Higgs field with massless particles, like gluons and photons. The discovery of fundamental and heaviest fermion top quark, was made in 1995 at the FermiLab TeVatron collider [35]. This discovery was achieved through proton-antiproton collision, it was also used in gluon-gluon fusion $gg \longrightarrow H$ cahnnel [36], the most dominant channel with Higgs boson production at LHC. This is the reason why the top quark has been ranked as one of the potential key ingredient leading to Higgs detection.

The high energy scattering of electroweak gauge boson $W_L^+W_L^- \longrightarrow W_L^+W_L^-$, for example leads to the amplitude which grows with energy, this is violation of unitarity as studied in chapter 2, and this becomes worse for quantum corrections, because the corresponding loop diagrams which diverge. The introduction of scalar boson with g_{HWW} coupling to vector boson makes the integration over loop momentum controllable and the theory becomes renormalizable [30], such that the amplitude is asymptotically constant for g_{HWW} corresponding to the prediction of EWSB.

3.1.2 Experimental progress

The Higgs boson hunt started experimentally in 1976 [37], by a study group at LEP. In this section, the experimental progress is analysed by focusing to the research colliders like LEP, TEVATRON and LHC.

a. The LEP collider

The LEP collider started conclusively working with four detectors: ALEPH, DELPHI, L_3 and OPAL [38].

The main mechanism of Higgs production at LEP is $e^+e^- \longrightarrow HZ$ with Z being virtual (LEP1) and real (LEP2) [39]. The LEP research is sensitive to the center-of-mass energies, and its results are constantly improved by increasing energy up to $\sqrt{s} = 206\text{GeV}$, and Higgs boson mass of $M_H(\sqrt{s} - M_H) \simeq 116\text{GeV}$ is assumed. In parallel of of the above channel $Z \longrightarrow H + f\bar{f}$ at LEP_1 and $e^+e^- \longrightarrow Z + H$ at LEP_2, with the consideration of high precision data of EW sector, the SLC (Stanford Linear Collider) and elsewhere made it possible to make estimate of Higgs boson mass within the SM framework [33]

In the last two years of working until 2001, LEP group was determined to search for Higgs boson and start collecting data at high luminosity and at high energy than previous years [40]. The most exciting Higgs like events are shown in what they called spaghetti diagrams [40].

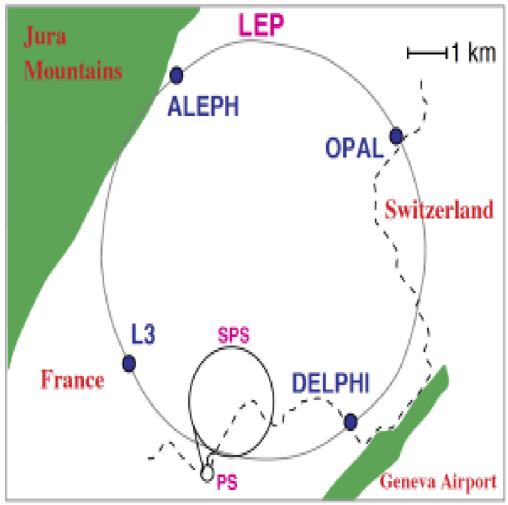

Figure 17: The four experiments at LEP and its pre-accelerators (PS and SPS)

Those diagrams are mainly random, and only results of ALEPH detector set a lower limit on Higgs boson mass of $115GeV/c^2$.

b. the Higgs boson at TeVatron at Fermilab

TeVatron, the protron-antiproton colliding accelerator operating at Fermilab in US since 1987. It could accelerate beam up to 0.98 TeV [41].
The focus of Higgs boson search is in RUN II, extended from 2001 up to its shutdown in Autumn 2011. This collider has two detectors CDF and DO, with capacity to collect $10fb^{-}1$ each. The combined results from the two detectors leads to an excess of data event with respect to the background estimation, in the mass range of 115GeV $< M_H <$ 135GeV [39], mainly in the $H \longrightarrow b\bar{b}$ channel.

c. The Higgs boson at LHC

It is proton-proton collider, and it is desined to use the LEP tunnel, which means that it started when LEP was shute down. Its design center of mass energy is 14TeV, and it started producing data in 2010 successively with $\sqrt{s}$ = 3.5TeV per beam. The LHC has four major experiments: ATLAS and CMS are large, while ALICE and

Higgs boson after its discovery is motivated by different key points like deviations of experimental observations from predicted results of the SM. The observation made on the above Fig(18), shows the $H \longrightarrow \gamma\gamma$ excess events than the one predicted by SM [41] and theoretically calculated [42] for the case of

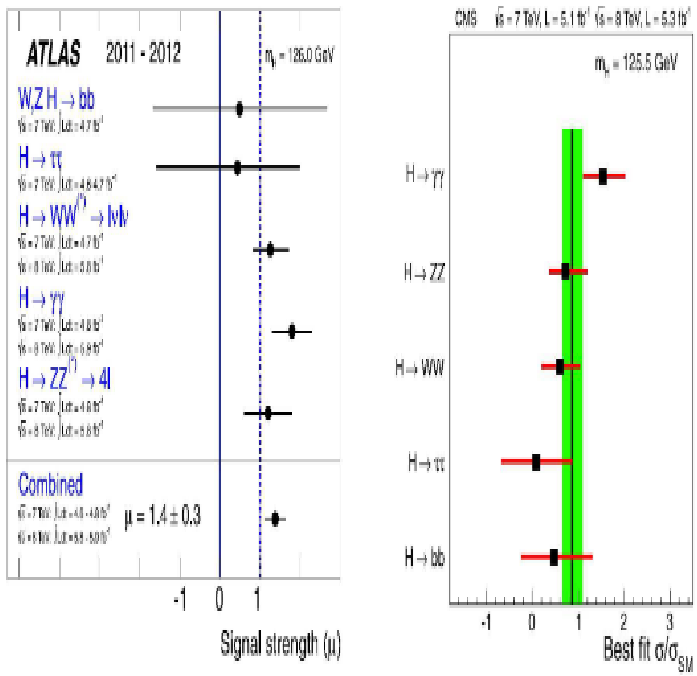

Figure 18: The measured signal strength $\mu = \frac{\sigma}{\sigma_{SM}}$ for both ATLAS and and CMS

W^+ virtually propagating in the loop. There are so many other reasons to deal with Higgs sector after its discovery, one can think about physics beyond SM as it will be motivated in the following chapter.

The search of the Higgs boson at LHC continue, and in 2018 the Higgs decay to bottom quark was recorded. Due to the upgrade of LHC to HL-LHC (High Luminosity extension) in its road to achieve a full potential which is 10 times the orginal design delivering a total of $3000fb^{-}$, with a target to measure all possible production and decay modes [43].

It is in this context the evidence for the Higgs boson to decay into muon is recorded and presented at the CMS dectector [44].

The Higgs pair production is of capital interest for Higgs self coupling, the Higgs rare decays and additional Higgs bosons are being searched. Many model which extend physics beyond standard model require more Higgs bosons like in 2HDM, there are three neutral(h,H,A) and two charged (H^+, H^-) bosons resulting from a two Higgs doublet model.

4 Higgs boson beyond the Standard Model

4.1 Motivation of Physics beyond the SM

The first key point to think about a new physics beyond SM is extracted from both chapter 2 by focusing the analysis loop induced decay and from chapter 3 by comparing the observed Higgs signal strengths and the expected one.

The constraint imposed by the ρ parameter to be $\rho \simeq 1$ shows new physics beyond SM, because at loop level is slightly different to one. The requirement of global custodial symmetry invariance allows additional scalar singlet and doublet extension of the SM scalar sector, while other representations induces strong constraints [45, 46].

Other reasons include another possible CP-violation [45], source beyond the one introduced in EW sector through the phase parameter δ in CKM matrix [47], the complex vacuum structure [48], the issue related to Dark Matter [49], and baryogenesis [50, 51].

The Two-Higgs doublet model (2HDM) is simple extension of the SM with two Higgs doublets. It is an extension which is compatible with gauge invariance, and with an extended mass spetrum.

4.2 Review of 2HDM

The general formulation of the two 2HDM as found in [52, 53, 54, 55] requires an additional Higgs doublet with the same quantum number, $Y = 1$ as the one in SM, so that

$$\phi_1 \equiv \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \longrightarrow \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_3 \\ \phi_4 \end{pmatrix}, \tag{4.1}$$

and

$$\phi_2 \equiv \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} = \begin{pmatrix} \phi_5 + i\phi_6 \\ \phi_7 + i\phi_8 \end{pmatrix} \longrightarrow \begin{pmatrix} \phi_5 \\ \phi_6 \\ \phi_7 \\ \phi_8 \end{pmatrix}. \tag{4.2}$$

In the SM there are two possible minima: the trivial one and the $\langle\phi\rangle = 0$ and the one which induces the EWSB $\langle\phi\rangle = \frac{\nu}{\sqrt{2}}$, while in 2HDM there are four possible vacua: trivial $\langle\phi_1\rangle = \langle\phi_2\rangle = 0$, normal (similar to that of the SM) $\langle\phi_1\rangle_N = \begin{pmatrix} 0 \\ \frac{\nu_1}{\sqrt{2}} \end{pmatrix}$ and $\phi_2\rangle_N = \begin{pmatrix} 0 \\ \frac{\nu_2}{\sqrt{2}} \end{pmatrix}$ for necessity if one the two zero VEV, CP-breaking $\langle\phi_1\rangle_{CP} = \begin{pmatrix} 0 \\ \frac{\nu_1}{\sqrt{2}}e^{i\theta} \end{pmatrix}$ and $\langle\phi_2\rangle_{CP} = \begin{pmatrix} 0 \\ \frac{\nu_2}{\sqrt{2}} \end{pmatrix}$ with ν_1 and ν_2 real and $0 \leq \theta < 2\pi$ and the fourth is charge-breaking vacua $\langle\phi_2\rangle_{CB} = \begin{pmatrix} \frac{\alpha}{\sqrt{2}} \\ \frac{\nu_1'}{\sqrt{2}} \end{pmatrix}$, $<\phi_2>_{CB} = \begin{pmatrix} 0 \\ \frac{\nu_2'}{\sqrt{2}} \end{pmatrix}$ with ν_1', ν_2' and α being real numbers. All these vacua are stable and there is no possible tunelling from one to another [55].

4.2.1 The potential of the 2HDM

The scalar potential of this theory $V(\phi_1, \phi_2)$, is shown bellow for general context and it contains 14 parameters which need to be fixed. The number of parameter in this theory can be reduced through manipulations imposed on Higgs doublets, and this leads to different potentials of the theory. There are six symmetries($U(2)$, CP_3, CP_2, $U(1)$, Z_2, CP_1) which can be applied to the scalar potential and each one has different effects [55] as it will be discussed below for some of them. We can write it by focusing on hermiticity and gauge invariance of each term [56]

$$\begin{aligned} V &= m_{11}^2(\phi_1^+\phi_1)^2 + m_{22}^2(\phi_2^+\phi_2)^2 - (m_{12}^2\phi_1^+\phi_2 + h.c) \\ &+ \frac{1}{2}\lambda_1(\phi_1^+\phi_1)^2 + \frac{1}{2}\lambda_2(\phi_2^+\phi_2)^2 + \lambda_3(\phi_1^+\phi_1)(\phi_2^+\phi_2) + \lambda_4(\phi_1^+\phi_2)(\phi_2^+\phi_1) \\ &+ [\frac{1}{5}\lambda_5(\phi_1^+\phi_2)^2 + \lambda_6(\phi_1^+\phi_1)(\phi_1^+\phi_2) + \lambda_7(\phi_2^+\phi_2)(\phi_1^+\phi_2) + h.c]. \end{aligned} \tag{4.3}$$

The six parameters m_{11}^2, m_{22}^2, λ_1,...,λ_4 are real while m_{12}^2 and λ_5,...,λ_7 are complex, forming a group of 14 real parameters, and they depend on the choice of basis (ϕ_1, ϕ_2).

One can solve for the physical degrees of freedom through a redefinition of the field $\phi_a \longrightarrow U_{ab}\phi_b$, under $U(2) \cong SU(2)U(1)$ group. $U(1)$ don't affect parameters of V while the transformation under $SU(2)$ requires three parameters which implies the removal of three degrees of freedom and leaves 11 physical degrees of freedom [57].

In this theory, there are dangerous flavour changing neutral current (FCNC) at tree level, to avoid this, the introduction of an appropriate discrete symmetry is necessary, which dictates that $m_{12}^2 = \lambda_6 = \lambda_7 = 0$ for Z_2 $\phi_1 \longrightarrow \phi_1$ and $\phi_2 \longrightarrow -\phi_2$. Under charge conjugation, $\phi_i \longrightarrow e^{i\alpha_i}\phi_i^*$, $\phi_i^+\phi_j \longrightarrow e^{i(\alpha_j-\alpha_i)}\phi_j^+\phi_i$, and by setting $\alpha_i = \alpha_j$ the operator $\hat{D} = -\frac{i}{2}(\phi_1^+\phi_2 - \phi_2^+\phi_1) = \mathrm{Im}(\phi_1^+\phi_2)$ changes sign and other terms remain invariant [52].

The 2HDM potential must be bounded from below so that it becomes stable to allow pertrubative calculations. For three types of non-trivial VEV, 2HDM requires that the quartic terms in the scalar potential be positive and the quadratic term may be negative for some values of the fields. Except for CP_1 symmetry, the following conditions on λ_i are valid for other five symmetries in the theory.

$$\lambda_1 \geq 0, \lambda_2 \geq 0, \lambda_3 \geq -\sqrt{\lambda_1\lambda_2}, \lambda_3 + \lambda_4 - |\lambda_5| \geq -\sqrt{\lambda_1\lambda_2}. \tag{4.4}$$

The consideration of λ_5 to be positive becomes necessary and sufficient for the case $\lambda_6 = \lambda_7 = 0$ in this theory.

To study the mass spectrum of theory, we now focus for simplicity on the normal minima, and not CP-violating and charge-violating (CB) minima. The square mass matrix is given by

$$M_{ij}^2 = \frac{1}{2}\frac{\partial^2 V}{\partial\phi_i\partial\phi_j}|_{<\phi_3>=\frac{\nu_1}{\sqrt{2}},<\phi_7>=\frac{\nu_2}{\sqrt{2}}}, \tag{4.5}$$

where ϕ_i(i=1,...8). The equation Eq(4.5) represent the (8×8) matrix, and its components can be found in the appendix of [55] for general 2HDM potential. From the minimum conditions $\frac{\partial V}{\partial\phi_i}|_{\langle\phi_3\rangle=\frac{\nu_1}{\sqrt{2}},\langle\phi_7\rangle=\frac{\nu_2}{\sqrt{2}}} = 0$ shows that $\nu = 0$ is a possible solution, with this $M_{11}^2 = M_{22}^2 = M_{12}^2 = 0$, $M_{15}^2 = M_{26}^2 = M_{34}^2 = M_{48}^2 = 0$ and terms M_{16}, M_{25},M_{34}, M_{38}, M_{47}, M_{78} mix real and imaginary in ϕ_1^0 and ϕ_2^0, so CP is violated in this case; the exact CP conserving mechanism reduce these CP-violating terms to zero, and requires the Lagrangian to be invariant under $\phi_1 \longrightarrow -\phi_1$ and $\phi_2 \longrightarrow \phi_2$ [53]. We decompose now the 8×8

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & M_{55}^2 & 0 \\ 0 & 0 & 0 & M_{66}^2 \end{pmatrix} \oplus \begin{pmatrix} M_{33}^2 & M_{37}^2 \\ M_{73}^2 & M_{77}^2 \end{pmatrix} \oplus \begin{pmatrix} 0 & 0 \\ 0 & M_{88}^2 \end{pmatrix}$$

. With $M_{55}^2 = M_{66}^2$, the first matrix is reduced to

$$\begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & M_{55}^2 & 0 \\ 0 & 0 & 0 & M_{55}^2 \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & M_{55}^2 \end{pmatrix} \otimes I_{22}$$

This correspond to the manipulation of indices 1, 2, 4 and 6 corresponds to the charged Higgs bosons [54].

We get a double degeneracy for both Goldstone and charged Higgs boson. There are two massless Goldstone $m_G^2{}^{\pm}$, $G^{\pm} = \phi_1^{\pm}\cos\beta + \phi_2^{\pm}\sin\beta$, and charged Higgs boson state $H^{\pm} = -\phi_1^{\pm}\sin\beta + \phi_2^{\pm}\cos\beta$ with mass of the charged is given by

$$m^2_{H^\pm} = -m^2_{22} + \frac{1}{2}\lambda_5\nu_1^2, \tag{4.6}$$

with $\tan(\beta) = \frac{\nu_2}{\nu_1}$, β is angle used in diagonalization of mass square matrix of charged Higgs bosons.

Then, for the indices 4 and 8, these correspond to the massive and neutral Higgs bosons and a massless Goldstone. We take the corresponding matrix

$$\begin{pmatrix} M^2_{44} & M^2_{48} \\ M^2_{84} & M^2_{88} \end{pmatrix} = \begin{pmatrix} 0 & 0 \\ 0 & -m^2_{22} + \frac{1}{2}(\lambda_4 + \lambda_5)\nu_1^2 \end{pmatrix},$$

and then, the corresponding mass eigenstates are $G^0 = \sqrt{2}(Im\phi_1^0 \cos\beta + Im\phi_2 \sin\beta)$ with mass $m_{G^0} = 0$. The the pseudoscalar Higgs boson state is $H_3^2 = \sqrt{2}(-Im\phi_1^0 sin\beta + Im\phi_2 cos\beta)$' the corresponding mass is

$$m_{A^0} = -m^2_{22} + \frac{1}{2}(\lambda_4 + \lambda_5)\nu_1^2. \tag{4.7}$$

Finally, we consider the indices 3 and 7 and this correspond to the neutral massive scalars and one massless Goldstone,

$$\begin{pmatrix} M^2_{33} & M^2_{37} \\ M^2_{73} & M^2_{77} \end{pmatrix} = \begin{pmatrix} 2\lambda_1\nu_1^2 & \frac{1}{2}\lambda_6\nu_1^2 \\ \frac{1}{2}\lambda_6\nu_1^2 & -m^2_{22} + \frac{1}{2}\nu_1^2\lambda_3\nu_1^2 \end{pmatrix}.$$

The mass eigenvalue obtained in this context are

$$m^2_{h^0,H^0} = (\lambda_1 + \frac{1}{2}\lambda_+) - \frac{1}{2}m^2_{22} \pm \sqrt{(\lambda_1 - \frac{1}{2}\lambda_+)}, \tag{4.8}$$

where $\lambda_+ = \frac{1}{2}(\lambda_3 + \lambda_5)$ and we can also write
$\begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} H^0 \\ h^0 \end{pmatrix}$, where α is defined to be the angle that diagonalises the square mass matrix of neutral scalars. In the unitary gauge, Goldstones are removed from the theory.

As it has been said just above, the analysis made on the scalar potential of the theory highlights the Higgs self interactions. There are of two possible type, the cubic and the quartic interactions, and their corresponding Feynman rules are studied in the Appendix of [58], the important triple-Higgs couplings is given as [59, 60]

$$\mathcal{L}_{3h} = -\frac{\nu}{\sqrt{2}} h_j h_k h_l [q_{j1} q_{k1} q_{l1} z_1 + q_{j2} q^*_{k2} q_{l1} (z_3 + z_4) + q_{j1} Re(q_{k2} q_{l2} z_5 e^{-2i\theta_{23}})$$
$$+ 3 q_{j1} q_{k1} Re(q_{l2} z_6 e^{-i\theta_{23}}) + Re(q^*_{j2} q_{k2} q_{l2} z_7 e^{-i\theta_{23}})]$$
$$- \sqrt{2}\nu H^+ H^- [q_{k1} z_3 + Re(q_{k2} z_7 e^{-i\theta_{23}})], \tag{4.9}$$

where $h_k = \frac{1}{\sqrt{2}}[q^*_{k1}(H^0 - \nu) + q^*_{k2} H^0_2 e^{-i\theta_{23}}]$ and $H^{\pm} = e^{-i\theta_{23}} H^{\pm}_2$ which is invariant under rephasing $H_2 \longrightarrow e^{-i\chi} H_2$, q_{k_1} and q_{k2} with $k = 1, 2, 3$ are invariant to be identified below.
The outcome from analysis of the scalar potential of 2HDM shows that from 8 physical degrees of freedom, one obtains five scalars: two neutral and CP-even Higgs bosons (H^0, h^0), two charged Higgs bosons$(H^{\pm})$ and one pseudoscalar Higgs boson (A^0).The three would be Goldstone bosons $(G^{\pm})$ and G^0 are eaten up to generate masses of the EW gauge bosons, as it is now going to be shown below.

4.2.2 The kinetic term of 2HDM

In this section, the information about mass of gauge bosons and its interactions with Higgs bosons are studied. From the Lagrangian Eq(3),

$$\mathcal{L} = \sum_{i,j=1,2} (D_\mu \phi_i)^+ (D_\mu \phi_i), \tag{4.10}$$

where

$$\phi_k \equiv \begin{pmatrix} Re\phi^+_k + Im\phi^+_k \\ Re\phi^0_k + Im\phi^0_k \end{pmatrix} \longrightarrow \begin{pmatrix} Re\phi^+_k \\ Im\phi^+_k \\ Re\phi^0_k \\ Im\phi^0_k \end{pmatrix} \tag{4.11}$$

where $k = 1, 2$. The matrix L_a, with i=1,...,4, in real representation are constructed in block form as [53], as below
$L_1 = \frac{1}{2}\begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \\ 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \end{pmatrix}$, $L_2 = \frac{1}{2}\begin{pmatrix} 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \\ 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{pmatrix}$, $L_3 = \frac{1}{2}\begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$
, $L_3 = \frac{1}{2}\begin{pmatrix} 0 & 1 & 0 & 1 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix}$,
such that $D\mu = \partial_\mu + g L_i W^i_\mu + g' L_4 W^4_\mu$ and $L_i \phi_i = -i\tau_i \phi_i$, now mass squared

of gauge bosons are found to be

$$m^2_{W\pm} = \frac{1}{2}g^2(\nu_1^2 + \nu_2^2) \tag{4.12}$$

$$m^2_Z = \frac{1}{4}(\nu_1^2 + \nu_2^2)(g^2 + g'2). \tag{4.13}$$

This was achieved through the calculations made on $\frac{1}{2}M^2_{ab}W^aW^b$, with $M^2_{ab} = 2\sum_{k=1}^{2}(g_aL_a\nu_k)(g_bL_b\nu_k)$. By identifying $\nu_1^2 + \nu_2^2 = 246GeV$ reduces the result of the above calculations to that of the SM.
The study of Higgs boson interactions in this section of kinetic term reveals that how Higgs boson interact with gauge bosons and it can be summarized as

$$\mathcal{L} = \mathcal{L}_{HHV} + \mathcal{L}_{HVV} + \mathcal{L}_{HHVV}, \tag{4.14}$$

where $H = H^0, h^0, A^0, H^{\pm}$ and $V = W^{\pm}, Z$. The above Lagrangian shows that there's an interaction of two Higgses bosons with one EW gauge boson, one Higgs with two EW gauge bosons and two Higgses with two Ew gauge bosons.

We now analyse the vertices which are not allowed by the theory, and those which are allowed. We first stand on the C and P theory for fundamental particles, and assume that fermions are absent which implies the separate conservation of both charge and parity. The table Tab(2) summarise the C and P assignments in this context.

Table 2: Assignments of C and P in the absence of fermions.

Fields	J^{PC}	Fields	J^P
γ	1^{--}	$W^{\pm}$	1^{-}
Z	1^{--}	$H^{\pm}$	0^{+}
H^0	0^{++}		
h^0	0^{++}		
A^0	0^{+-}		

The vertices $A^0W^+W^-$ and A^0ZZ are absent at tree level, and by standing on the information extracted from the above table the justification is given.

The Goldstone is produced from an imaginary component of the Higgs doublet in SM and is eaten to become a longitudinal component of Z, and one knowns that G and Z fields are coupled through derivative coupling which means that they are both CP-odd, then, to allow a separate conservation of C and P; $C = -1$ for both Z and G. The parity of G is +1 like other scalars, which is opposite to that of vector bosons. As it is shown above, there are two types of imaginary linear combinations in 2HDM, one of them produces G^0 and the other gives A^0, which means that $A^0(J^{PC}) = 0^{+-}$ the same as G^0. One can stand on the CP-invariance of the kinetic term to explain the absence of these vertices [58].

The coupling of H^0 and h^0 to a pair of massless vector bosons is also absent at tree level. We note that those vertices reappear at loop level, due to the Lorentz invariance of $\varepsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}A^0$ and $F_{\mu\nu}F^{\alpha\beta}h^0$ gauge terms which are present in dimension five.

The pair of identical Higgs bosons is forbiden by Bose symmetry to couple to Z, but it can couple to Higgs bosons with different CP-symmetry like ZA^0H^0 and ZA^0h^0.

The CP-invariance is broken in ZZA^0 and $W^+W^-A^0$ couplings, but they are allowed at loop level through the virtual fermions propagating through the loop.

The $H^+W^-\gamma$ is avoided by the requirement of EM conservation. The H^+W^-Z vertex also vanish at tree level, but this is highly dependent on the model discussed [61].

We first write the new invariant quantities $S_{\beta-\alpha} = \sin(\beta - \alpha)$ and $c_{\beta-\alpha} = \cos(\beta - \alpha)$, and then present in the CP conserving case, to show how each coupling depends on angle. where $\phi\phi = hh, HH, AA$ or H^+H^- and $V = W^+W^-$ or ZZ. The sum rule due to unitarity requirement at tree level imposes that the vertex with only one $(H, A, \mathrm{or} H\pm)$ Higgs bosons and with at least one vector boson to be proportional to $c_{\beta-\alpha}$ [62]

Table 3: Assignement of C and P when they are indivually violate, but CP conserved in presence of fermions.

Fields	J^{PC}	Fields	J^{P}
γ	$1^{--}, 1^{+}+$	$W^{\pm}$	$1^{-}, 1^{+}$
Z	$1^{--}, 1^{+}+$	$H^{\pm}$	$0^{+}, 0^{-}$
H^0	$0^{++}, 0^{--}$		
h^0	$0^{++}, 0^{--}$		
A^0	$0^{+-}, 0^{-+}$		

Table 4: Dependance of on angle EW gauge bosons coupling to 2HDM higgses

$c_{\beta-\alpha}$	$S_{\beta-\alpha}$	angle-independent
HW^+W^-	hW^+W^-	$-$
HZZ	hZZ	$-$
ZAh	ZAH	ZH^+H^-, γH^+H^-
$W^{\pm}H^{\mp}h$	$W^{\pm}H^{\mp}H$	$W^{\pm}H^{\mp}A$
$\gamma W^{\pm}H^{\mp}h$	$ZW^{\pm}H^{\mp}H$	$\gamma W^{\pm}H^{\mp}A$
$-$	$-$	$W\phi\phi\gamma H^+H^-, \gamma\gamma H^+H^-$

4.2.3 The Yukawa term

The present section deals with how scalar Higgs boson interact with fermions. The Weinberg and Glashow theorem is used to forbid this dangerous neutral flavour changing current.

The most general Higgs basis Yukawa Lagrangian in 2HDM in Higgs basis field H_1 and H_2 [56], is written as

$$\mathcal{L}_{\mathcal{Y}} = \bar{U}_L(\kappa^U H_1^{0+} + \rho^U H_2^{0+})U_R - \bar{D}_L(\kappa^U H_1^{-} + \rho^U H_2^{-})U_R$$
$$\bar{U}_L K(\kappa^{D+} H_1^{+} + \rho^D H_2^{+})D_R + \bar{D}_L(\kappa^{D+} H_1^{0} + \rho^D H_2^{0})D_R + \text{leptonic sector+h.c}, \tag{4.15}$$

with $U = (u, c, t)$ and $U = (d, s, b)$ mass eigenstate for quarks, the K: CKM matrix, ρandκ Yukawa coupling matrix of (3×3), R and L means Right and Left handed chiral states, and the quark masses matrices $M_U = \nu\kappa^U = \text{diag}(m_u, m_c, m_t)$ and $M_D = \nu\kappa^D = \text{diag}(m_d, m_s, m_b)$ in the basis $H_1 = \nu$ and $H_2^0 = 0$. The complex matrices ρ^F with $F = U, D, L$ are constrained, $\rho^F \longrightarrow e^{i\chi}\rho^F$, under rephasing of Higgs basis $H_2 \longrightarrow e^{i\chi}H_2$. The ρ^F indicates the FCNC in this sector of quarks, if its off diagonal terms are not suppressed, the dangarous FCNC is observed at tree level.
The coupling of the Higgs bosons are studied by the analogy made on Yukawa matrices for the Higgs doublets [63]

$$\mathcal{L}_y = \frac{1}{\sqrt{2}}\bar{D}[\kappa^D s_{\beta-\alpha}+\rho^D c_{\beta-\alpha}]Dh+\frac{1}{\sqrt{2}}\bar{D}[\kappa^D c_{\beta-\alpha}-\rho^D s_{\beta-\alpha}]DH+\frac{i}{\sqrt{2}}\bar{D}\gamma_5\rho^D DA$$
$$+\frac{1}{\sqrt{2}}\bar{U}[\kappa^U s_{\beta-\alpha}+\rho^U c_{\beta-\alpha}]Uh+\frac{1}{\sqrt{2}}\bar{D}[\kappa^U c_{\beta-\alpha}-\rho^U s_{\beta-\alpha}]UH-\frac{i}{\sqrt{2}}\bar{U}\gamma_5\rho^U A$$
$$+\frac{1}{\sqrt{2}}\bar{L}[\kappa^L s_{\beta-\alpha}+\rho^L c_{\beta-\alpha}]Lh+\frac{1}{\sqrt{2}}\bar{L}[\kappa^L c_{\beta-\alpha}+\rho^L s_{\beta-\alpha}]LH+\frac{i}{\sqrt{2}}\bar{L}\gamma_5\rho^L A$$
$$+[\bar{U}(V_{CKM}\rho^D P_R-\rho^U P_L)]DH^+\bar{\nu}P_R LH^+ + h.c, \quad (4.16)$$

where $P_{R,L}=\frac{1}{\sqrt{2}}(1\pm\gamma_5)$.

To attack the FCNC challenge, ρ^F must be diagonal, but sufficiently each fermion type couples to only one Higgs doublet [64], and ρ^F can be replaced by $\rho^F=\kappa^F\cot\beta$ or $\rho^F=-\kappa^F\tan\beta$, depending on the model. The introduction of a discrete symmetry remove the annoying couplings, there's six symmetries and one of them is Z_2 under which one Higgs doublet and Right hand field for fermions are odd.

It is in this context, that four models without FCNC at tree level are stated in the table bellow • Following the same steps as the one in SM, leads three neutral Higgses, h^0,

The SM has only one CP-even Higgs, with minimum SM scalar sector, the next to minimum scalar sector (2HDM) has five Higgses in its spetrum as reviewed above. In the search of Higgs boson, some of main channels have been studied like ggF, VBF, associated vector boson production (Wh,Zh) and $t\bar{t}$, we have noted that $h\longrightarrow\gamma\gamma$ signal strength present a higher deviation from the one predicted by SM, this stimulates one to think about a new physics BSM, by making a precise measurement on branching ratios. It is of capital interest to ask our self it the observed signal is identical to the one predicted by SM or it is from an other model. The analysis of how 2HDM manifest itself at LHC, and implications its spectrum has on the SM Higgs boson is made by focusing on studying Branching ratios, Higgs couplings, and decay width.

In the context of 2HDM the Higgs as

$$h_{SM}=h^0\sin(\alpha-\beta)-H^0\cos(\alpha-\beta), \quad (4.17)$$

, where $h^0=\sqrt{2}(H_d^0\sin\alpha-H_u^0\cos\alpha)$, $H^0=-\sqrt{2}(H_d^0\cos\alpha+H_u^0\sin\alpha)$,$A^0=\sqrt{2}(A_d^0\sin\beta-A_u^0\cos\beta$ [65]. In this theory, h_SM mixes as it is shown in equation Eq(4.17). By conforming our study to the h_SM, we get two case (i) $\beta-\alpha=\frac{\pi}{2}$: alignement limits and $\beta-\alpha=\frac{\pi}{2}$: the exact wrong sign(EWS) limits. Its corresponding coupling modifiers are shown bellow where $\kappa=\frac{g_{iih}}{g_{iih_{SM}}}$, $\xi=\frac{g_{iiH}}{g_{iih_{SM}}}$ for a specific Higgs and $k_\lambda=\lambda_{hhh}\lambda_{hhh}^{SM}$,$\xi=\lambda_{Hhh}/A_{hhh}^{SM}$. For $\sin(\alpha-\beta)=1$ or $K_{i,\lambda}$, we get a decoupling limits and $h=h^0$, H^0 decoupled, which means that

Table 5: The coupling modifiers for both H^0 and h^0 [5]

Limit	κ_V	ξ_V	κ_u	κ_d	κ_λ	ξ_λ
Alignement	1	0	1	1	1	0
EWS	$\frac{t_\beta^2-1}{t_\beta^2+1}$	$\frac{2t_\beta^2}{t_\beta^2+1}$	1	-1	$\frac{t_\beta^2-1}{t_\beta^2+1}$	$\frac{t_\beta^2}{t_\beta^2+1}[\frac{4}{3}-2(\frac{M_H^2-2M^2)}{3m_h^2}]$

its coupling is zero. The coupling of up and down type fermion posses opposite sign, and $k_v = k_\lambda$ deviate from the SM value. The parametrization of Yukawa term in the context of neutral Higgses

$$\mathcal{L}_Y uk = -\sum_{f=u,d,l} \frac{m_f}{\nu}\left(\hat{y}_f^{h^0}\overline{f}f + \hat{y}_f^{H^0}\overline{f}f - i\hat{y}_f^{A^0}\overline{f}\gamma_5 f A^0\right). \tag{4.18}$$

One noted that [66], how $\hat{y}^{h^0}$, $\hat{y}^{H^0}$, and $\hat{y}^{A^0}$ depend on the mixing angle α and β, this mixing phenomenon changed the properties of the 125GeV Higgs boson. This means that the lighter CP-even 2HDM higgs boson is not exactly identical to the SM Higgs boson. The extended SM scalars sector contain five Higgs bosons, this implies the probability to have more Higgs boson self couplings and Higgs boson to gauge bosons couplings which increase the probability to make precise measurements.

In SM Higgs theory, the ρ parameter ρ =1 at tree level, but the recent LCH measurement shows

$$\Delta\rho \equiv \rho^{obs} - \rho^{SM} \approx 0.002 \pm 0.007, \tag{4.19}$$

with $\Delta\rho$, the 2HDM contribution.

At LHC, they often parametrise the observed specific event of given channel with respect to the SM expectation [65].

$$R_{Decay}^{Production} = \frac{\sum_j \sigma(pp \to j \to h) \times Br(h \to decay)}{\sum_j \sigma(pp \to j \to h) \times Br(h \to decay)|SM}, \tag{4.20}$$

j stands for every event in Higgs decay and production channel.

One can define $\tilde{R}$ is observed Higgs rate,and R is the expected decay rate, the global fit χ^2 can be constructed

$$\chi^2 = \frac{\sum_i^N (R_i - \tilde{R}_i)^2}{\sigma_i^2}, \tag{4.21}$$

with i stands for all Higgs channels and σ_i is the error.

If the observed Higgs boson on the $h = h^0$ in senario 1, with $h = h^0$ or $h = H^0$ at $m_h = 125$GeV, the couplings in SM are given,

$$c_{v,SM} = c_{f,SM}|_{f=t,b,c,\tau} = 1, c_{g,SM} \approx 1, c_{\gamma,SM} - 0.81, \tag{4.22}$$

where v:stands for vector gauge boson, f:fermion , g:gluon, γ:photon respectively, and l:lepton. The effective observed coupling are

$$c_v = \sin(\beta - \alpha), c_b = \hat{y}_b^h, c_e = \hat{y}_e^h, c_t = c_c = \hat{y}_\mu^h. \tag{4.23}$$

The h^0VV coupling is shown to be smaller than SM value.

If the new Higgs boson is H^0 and heavy, and with h^0 missed in scenario 2 and the A^0 is heavy and degenerate with $H^{\pm}$.The observed parameters are

$$c_v = \cos(\beta - \alpha), c_b = \hat{y}_b^H, c_c = \hat{y_c^H}, \tag{4.24}$$

$c_v = \cos(\beta - \alpha)$, $c_b = \hat{y}_b^H$, $c_c = \hat{y_c^H}$. Let's $|\chi|^2$ be on the event rate,

$$|\xi|^2 = |C_v|^2 . \frac{B(h^{0 \to jj)}}{B(h_{SM} \to jj)} < 0.244, \tag{4.25}$$

is allowed by LEP. The Higgs couplings to fermions change.

The senario 3, $h^0 = A^0 = 125$GeV, the observed signal may shows that it is from the interplay resonance of h^0 and resonance of A^0. In explaining the signal of Higgs boson in this scenario concludes that this scenario is worse than the SM.

One can conclude this section by saying that the observed Higgs signal is a result of entangled information, possessed by LHC about: decays,productions and decay widths about the observed signal.

5 Discussion and Conclusion

The SM, one of the successful theory is stimulating scientists to explore its different sectors. The SSB applied in EW sector has reveals the existence of scalar particle, this is the Higgs boson, the particle which was hunted for around 50 years since 1964. This was made possible by both theoretical and experimental progress of different research centers mainly LEP, LHC and TeVatron. The experimental history of this institutions are a key ingredient in tracking the evolution, improvements and plan for the future researches. The puzzle of how fundamental particles get their masses is solved, they get their masses through the interaction of Higgs fields.

The Higgs boson mass was researched in a wide range because it was not known SM and different theoretical constraints are theorized, which fixed both lower bound and upper bound of Higgs boson mass. The main decay and production processes are studied, where cross sections (probability to produce a Higgs boson) and branching ratios(time taken for a Higgs boson to decay) have been considered. The first main production channel is gluon-gluon fusion which is being mediated at loop level. This channel excite the scientific curiosity, one can ask himself which particles are implicated in the loop.

It is not justified in SM, why it relays on a minimum scalar sector, it doesn't explain some other challenge like Dark Matter and matter-antimatter asymmetry. The need to introduce another CP-violating sources stimulated to slightly change the SM scalar sector to two doublet Higgs sector known as 2HDM. This new model came up with an exciting results, its mass spectrum contains Higgs bosons where one of them is identical to the discovered one in alignment limits.

The two 2HDM stongly implicates the SM, the observed Higgs signal is a result of entangled information, possessed by LHC about: Higgs decays, productions and decay widths about the observed signal. The coupling to fermions change with respect to those in SM, and are in good agreement with obsevations.

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