Chapter 1

Introduction

1.1 Discovery of the Higgs Boson

The existence of a boson with mass 125 GeV was first announced on 4 of July 2012 by ATLAS and CMS at the Large Hadron Collider (LHC), and physicists suspected at the time that it was the Higgs boson. This particle had been proven to behave, interact and decay as predicted by the Standard Model (SM). In March 2013, it was tentatively confirmed as the Higgs boson.

In October 2013, the Royal Swedish Academy of Sciences awarded the 2013 Nobel prize in Physics, jointly, to Francois Englert and Peter W. Higgs for the, "*theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider.*" [1]

The mass of the SM Higgs boson has been measured to good precision by the ATLAS [2] and CMS [3] collaborations at the LHC. These measurements have been made using proton-proton (pp) collision data at $\sqrt{s} = 7$ TeV and at $\sqrt{s} = 8$ TeV. More precise measurements of Higgs production, decay rates, couplings, masses, new decay modes, measurements of Higgs self coupling and additional Higgs bosons beyond the Standard Model are expected in LHC Run2 which is currently $\sqrt{s} = 13$ TeV and will be upgraded to $\sqrt{s} = 14$ TeV in the future.

1.2 Standard Model

The Standard Model is a gauge theory which combines all three fundamental interactions strong, weak and electromagnetic. The electroweak interaction is described by the $SU(2)_L \otimes U(1)_Y$ group while QCD is an SU(3) Yang Mills theory [4]. Since the mass terms of gauge bosons violate the gauge invariance of $SU(2)_L \otimes U(1)_Y$ theory, the masses are set to be zero, though in reality they are observed to have mass. This led theorists to introduce a realistic and renormalizable mechanism to give masses to fermions and gauge bosons. Though it is often called the Higgs Mechanism, several groups also contributed to the development of this mechanism in 1964, [5][6][7]. Therefore, in history, it is called Englert-Brout-Higgs-Guranlik-Hagen-Kibble mechanism which explains how the vector bosons acquire non zero masses through spontaneous symmetry breaking.

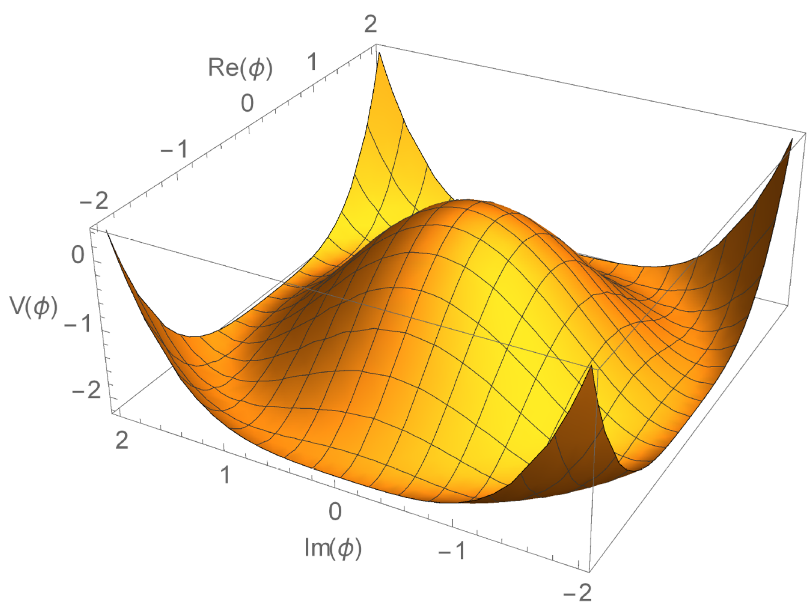

Figure 1.1: 3D plot of Higgs potential vs Real and Imaginary parts of complex Φ.

The Higgs potential can be written as,

$$V(\Phi) = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2 \tag{1.1}$$

Fig. 1.1 shows a plot of Higgs potential; $\Phi = 0$ is an unstable maximum while its minimum is at $\Phi = \sqrt{\mu^2/2\lambda}$.

The Higgs sector of the Standard Model Lagrangian can be written as,

$$\mathcal{L}_H = (\mathcal{D}^\mu \Phi)^\dagger (\mathcal{D}_\mu \Phi) + \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2 \tag{1.2}$$

$$\mathcal{D}^\mu = \partial^\mu + ig\frac{\tau_j}{2} W_j^\mu + ig'\frac{Y}{2} B^\mu \tag{1.3}$$

λ>0 and μ^2>0, Y is weak hyper-charge and +1 for the Higgs field, or can be written in matrix form $Y = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$.

$\tau_j = \frac{1}{2}\sigma_j$ and σ_j denotes the Pauli matrices,

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \ , \ \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \ , \ \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

and $B(x)$ is the gauge boson corresponding to the $U(1)_Y$ group. This Lagrangian is invariant under $SU(2)_L \otimes U(1)_Y$ gauge transformations. Φ is the Higgs field and is given by,

$$\Phi = \begin{pmatrix} \phi_a \\ \phi_b \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \tag{1.4}$$

where, $v = \sqrt{\mu^2}/\lambda = 246\, GeV$, is the vacuum expectation value (vev). Incorporating all these facts, the Higgs Lagrangian changes to a form containing terms that give masses to the gauge bosons; $m_W = gv/2$ and $m_Z = gv/2\ cos\theta_w$. Fermion masses come from the same mechanism with Yukawa part of the Lagrangian; $m_i = \lambda_i \, v/\sqrt{2}$ where $i = e, u, d$, and λ_i are Yukawa couplings. In the SM, neutrinos do not interact with the Higgs boson so they are massless. The mass of the Higgs boson is a free parameter in the SM and is given by $M_H = \sqrt{2\lambda v^2} = \sqrt{2\mu^2}$. This is called the well known Higgs mechanism.

1.3 Physics beyond the Standard Model

Even though the SM gives the currently available, well tested, best description for the subatomic world, there are topics, that cannot be explained by this theory. The parameters in the SM like masses, mixing and couplings for leptons and quarks are experimentally proven. The SM also does not provide explanations for cosmological parameters such as dark matter and dark energy. Having all these unanswered questions, it is clear that the SM does not give a complete picture about the subatomic world and the universe. So one might say the Standard Model is a small part of a bigger story that explains the whole world. Furthermore, the SM does not show a grand unification of strong and electroweak forces at very high energy scale indicating the necessity of a theory beyond the SM. Supersymmetry provides solutions for most of these questions by introducing a super partner for every particle. In supersymmetry, super partners for each particle in the SM whose spin differs by a 1/2 are introduced as well as both particle and its super partner should have the same transformation properties under the $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge group [8] [9]. It also unifies the three forces weak, strong and electromagnetic. Fig. 1.2 shows the behavior of three forces for high energies in the Standard Model as well as Minimal Supersymmetric Standard Model (MSSM).

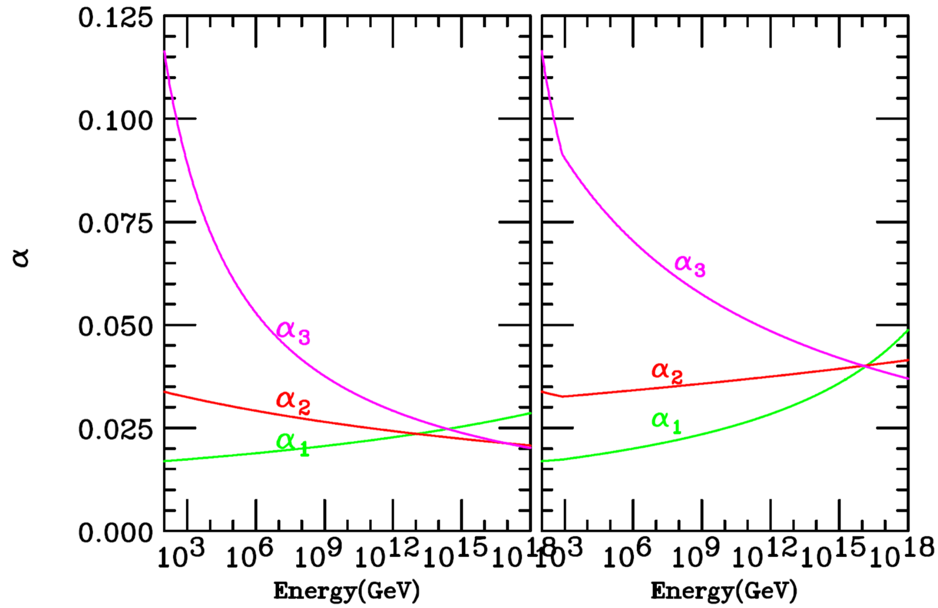

Figure 1.2: Three Gauge Couplings a) in the SM b) for the MSSM (generated using Isajet 7.8.1). Red curve represents the gauge coupling of $SU(2)_L$. Green curve is for the gauge coupling of $U(1)_Y$, and color magenta represents strong $SU(3)_C$ interaction.

1.4 Minimal Supersymmetric Standard Model

Some of the unanswered questions in the SM can be explained introducing two Higgs doublets instead of a single Higgs doublet in the SM. Therefore, in the supersymmetric models, two Higgs doublets are needed to give masses to both up-type and down-type quarks and the corresponding leptons[9] [10] [11]. There are three famous subcatagories in the two Higgs doublet models (2HDM) based on their couplings to leptons. In Type

1, one doublet couples to both up-and down type fermions whereas the other does not couple to any fermions [12] [13]. In Type II, one doublet(Φ_1) couples to down flavor while the other doublet(Φ_2) couples to up flavor fermions [14] [15] [13] and in Type III, both doublets couple to both up and down flavored fermions. The MSSM is Type II two Higgs doublet model which is considered to be the minimal extension to the Standard Model. The MSSM has a second complex SU(2) Higgs-doublet field with hypercharge $Y = -1$ and both doublets acquire vacuum expectation values to break the $SU(2)_L \times U(1)_Y$ symmetry. The general form of the Higgs potential for 2HDM can be written as,

$$V_{Higgs}(\phi_1, \phi_2) = m_1^2 \phi_1^\dagger \phi_1 + m_2^2 \phi_2^\dagger \phi_2 + m_{12}^2(\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1) + \lambda_1(\phi_1^\dagger \phi_1)^2 + \lambda_2(\phi_2^\dagger \phi_2)^2 + \lambda_3(\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4[(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1)] + \lambda_5[(\phi_1^\dagger \phi_2)^2 + (\phi_2^\dagger \phi_1)^2] \quad (1.5)$$

where Φ_1 and Φ_2 are two doublets in the Higgs sector of 2HDM which are,

$$\Phi_1 = \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} v_2 \\ 0 \end{pmatrix}$$

v_1 and v_2 are vacuum expectation values in the Higgs field, $v = \sqrt{v_1^2 + v_2^2} \approx 246\ GeV$, and there is no CP violation in the Higgs sector. In the 2HDM Higgs potential, there are 8 unknowns namely $m_1,\ m_2,\ m_{12},\ \lambda_1,\ \lambda_2,\ \lambda_3,\ \lambda_4$ and λ_5 all of which are real in this case. Three of them are Goldstone modes and are absorbed by $W^\pm$ and Z bosons. The remaining five degrees of freedom lead to the five physical Higgs bosons of the MSSM. In these five, two are CP even neutral Higgs bosons, the h^0(lighter) and

H^0(heavier), one CP odd neutral pseudo scalar A^0 and a pair of singly charged Higgs bosons $H^{\pm}$, and these lead to a large variety of self couplings among them. At tree level, Higgs boson masses and couplings of the MSSM Higgses are determined by two free parameters, the mass of the CP odd pseudo scalar (m_A) and the ratio of vacuum expectation values ($tan\beta = v_1/v_2$) where $0 \leq \beta \leq \frac{\pi}{2}$. Higgs self couplings as well as tree level Higgs-Fermion Yukawa couplings are given in the appendix of this thesis.

1.5 Outline

After the discovery of Higgs, now it is necessary to investigate its properties to verify that it is exactly the SM Higgs boson. Towards this goal, measurement of Higgs self coupling is really important to reproduce the correct Higgs potential, and this will be focused on the next runs at the LHC. Our main focus in this study is to explore the possibilities of measuring the trilinear Higgs couplings in future experiments. We first study the dominant Higgs production processes which provide a way to measure the Higgs coupling. Gluon fusion is the dominant source of Higgs boson pair production via box and triangle diagrams, and it has been studied by several groups in the past [16],[17],[18],[19] and [20]. The distructive interference between two diagrams provides a path to measure the trilinear Higgs couplings at the LHC. Chapter 2 of this thesis discusses the production cross section of the Higgs bosons via gluon fusion at the LHC. Once Higgs bosons are produced, they will decay into other particles such as quarks, tau leptons, W and Z bosons and so on. The branching ratio of Higgs decays provides important facts that allow us to choose probable decay channels. Fig. 1.3

shows the branching ratios for the Standard Model Higgs, and Fig. 1.4 shows the branching ratios of the MSSM pseudo scalar for two different $tan\ \beta$ values. It is clear that the Higgs dominantly decays into $b\bar{b}$ pair both in the SM (for Higgs mass of 126 GeV) as well as in MSSM for high $tan\beta$ regions. The second highest rate of decay is $h^0 \to \tau^+\tau^-$.

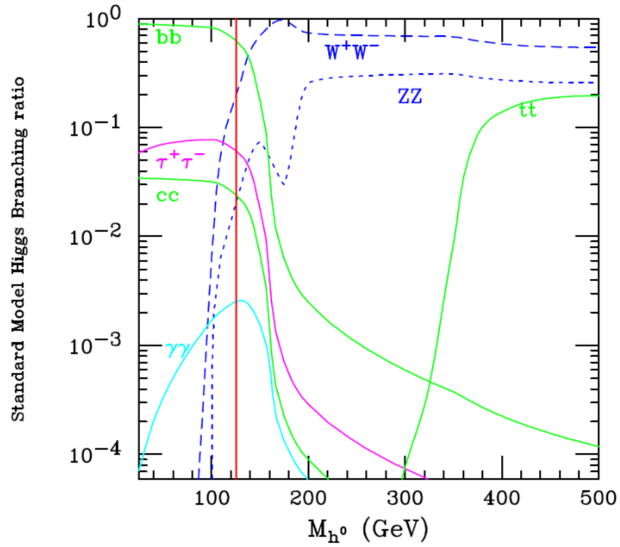

Figure 1.3: Branching Ratio for SM Higgs.

Though $b\bar{b}$ is the dominant decay mode for the neutral Higgs, not many studies have been conducted because the signal is overwhelmed by QCD backgrounds unless a special triggering is selected. We study the production cross sections for the process $gg \to \phi^0\phi^0 \to b\bar{b}b\bar{b}$, $gg \to \phi^0\phi^0 \to b\bar{b}\tau^+\tau^-$ and $\tau^\pm \to l, j_\tau$ for both the SM and the MSSM in Chapter 2. In the MSSM, the Yukawa coupling is enhanced by large value of $tan\ \beta$ and therefore Higgs production by b quarks plays a major role here. In Chapter 3, Higgs cross sections for the processes $b\bar{b} \to \phi^0\phi^0 \to b\bar{b}b\bar{b}$ and $b\bar{b} \to \phi^0\phi^0 \to b\bar{b}\tau^+\tau^-$ and $\tau^\pm \to l, J_\tau$ are discussed. The choice of selection cuts and numerical results for

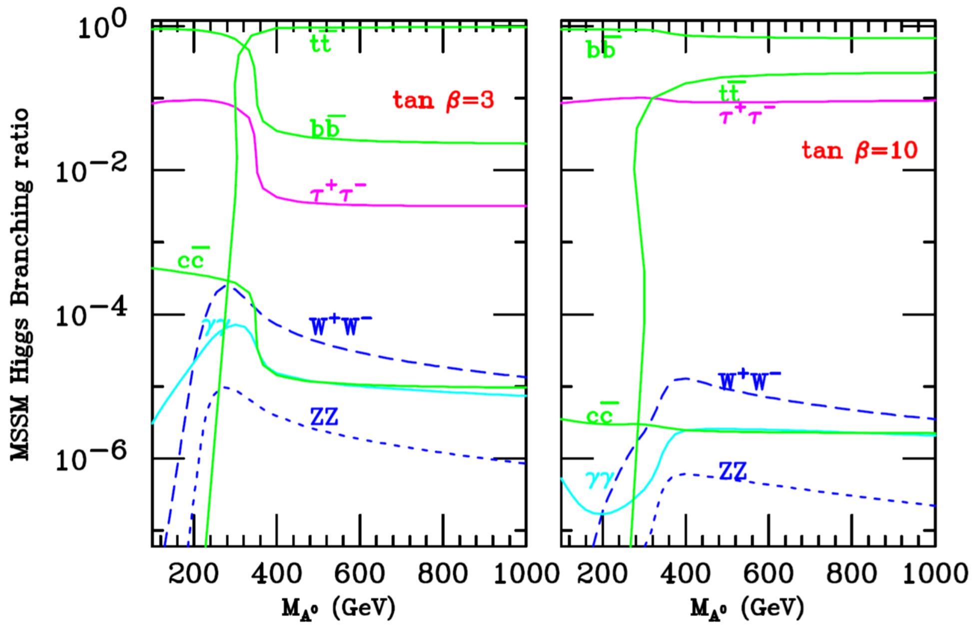

Figure 1.4: Branching Ratio for the MSSM pseudoscalar Higgs (a) with $tan\ \beta\ = 3$ and (b) with $tan\ \beta\ = 10$.

several distributions is presented in 'Calculation tools'. The dominant Standard Model background for the mentioned processes was discussed in Chapter 4 with analysis of statistical significance. Chapter 5 includes a discussion about measuring the trilinear Higgs coupling at the LHC via the Higgs production processes discussed in Chapter 2 and 3. However, measuring the Higgs self coupling is not an easy task at the LHC due to small cross sections and large backgrounds in the $gg \to hh$ process. Lepton colliders are well known for high precision measurements and measuring the trilinear Higgs coupling will be one of the main focuses of next e^+e^- machine that has been proposed, International Linear collider(ILC). The trilinear Higgs self coupling is discussed in Chapter 6, for the production of the SM Higgs at ILC via e^+e^- collisions.

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