Chapter 1

Introduction

1.1 History

In the 19^{th} century, scientists believed that atoms are the solid building blocks of the nature. But they soon discovered that atoms are not in fact the fundamental of nature, but there are even smaller particles such as electrons. Then they believed that all matter is composed of three fundamental particles named proton, neutron and electron till Murray Gellmann[1] and Zweigs[2] come up with the idea about sub atomic particles called quarks. In 1969 Jerome Friedman, Henry Kendall(from MIT) and Richard Taylor(from SLAC) provided the experimental evidences[3] for the quark model and 1990 Noble Prize in Physics was awarded for their contribution towards the development of quark model. All these concepts led to the formulation of Standard Model(SM) that established in mid 1970s. Standard Model is a mathematical formulation of the elementary particles and how they interact through electromagnetic, weak, and strong nuclear interactions. This model contains 17 fundamental particles, fermions or bosons, including 6 quarks, 6 leptons, 4 force carrying gauge bosons and a Higgs boson. Successful description of the particle phenomena by the Standard Model have already been evident by many experimental discoveries.

However, discovery of Higgs boson remained one of the most important experimental goal in high energy physics at the start of 21^{st} century. The search for Higgs boson was being motivated by the Large Hadron Collider(LHC), at CERN, with 14 TeV center of mass(CM) energy. Existence of a boson with mass 125 GeV was first announced on 4^{th} of July 2012 by ATLAS and CMS at Large Hadron Collider 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. In March 2013, it was tentatively confirmed as the Higgs boson.

In October 2013, the Royal Swedish Academy of Sciences awarded the 2013 Noble 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.*" [4]

The mass of the Higgs boson predicted by the SM has already been measured to a good precision by the ATLAS [5] and CMS[6] collaborations at LHC. The latest measurements have been made using pp collisions data at $\sqrt{s} = 7\ TeV$ and at $\sqrt{s} = 8\ TeV$. More precise measurements of Higgs production, decay rates, coupling and masses, new decay modes, measurements of Higgs self coupling and additional Higgs bosons beyond the standard model etc. are expected in the future LHC runs at 13-14 TeV.

1.2 Standard Model (Mathematical Formulation)

Standard Model combines all three fundamental interactions strong, weak and QED. The electroweak interaction is described by $SU(2) \otimes U(1)$ group while QCD is an SU(3)

Yang Mills theory [7]. So the standard model combines the strong interaction with the unified electroweak interaction through the symmetry group $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$. The Higgs sector of Standard Model Lagrangian can be written as,

$$\mathcal{L}_H = (\mathcal{D}^\mu \phi)^\dagger (\mathcal{D}_\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2 \tag{1.1}$$

$$\mathcal{D}^\mu = \partial^\mu + ig\frac{\tau_j}{2}W_j^\mu + ig'\frac{Y}{2}B^\mu \tag{1.2}$$

$\lambda>0$ and $\mu^2>0$, 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,

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

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

$$\phi = \begin{pmatrix} \phi_a \\ \phi_b \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix} \tag{1.3}$$

where, $v = \sqrt{\frac{\mu^2}{\lambda}} = 246\, GeV$ is vacuum expectation value (vev). Having all these facts, Higgs Lagrangian then changes to a form with terms which give masses of gauge bosons (See Appendix A) $m_W = \frac{gv}{2}$ and $m_Z = \frac{gv}{2\, Cos\theta_W}$. This is called well known Higgs mechanism. Fermion masses comes from the same mechanism with Yukawa part of the Lagrangian and can be given by, $m_i = \frac{\lambda_i\, v}{\sqrt{2}}$ where $i = e, u, d$ and λ_i are Yukawa couplings. In standard model nutrinos are usually treated as massless.

1.3 Physics beyond the Standard Model

Even though the standard model gives the currently available well tested best description for the subatomic world, there are topics, which cannot be explained by this theory. The parameters in SM like masses, mixing and couplings for leptons and quarks are experimentally proven, but still unable to explain why they are so and why there are three generations with such a different mass scale. SM does not provide explanations for cosmological parameters such as dark matter and dark energy. Having all these unanswered questions, it is clear that SM does not give a complete picture about the subatomic world. It seems the SM describes the physics for low energy scale (246 GeV) quite accurately but not at energies above the Plank scale (10^{19} GeV). 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. Supersymetry in fact provides solutions for most of these questions introducing a super partner for every particle. In supersymetry, a super partner for each particle in SM should be introduced whose spin differs by a 1/2 as well as both particle and its super partner should have the same transformation properties under the $SU(3) \times SU(2) \times U(1)$ gauge group [8] [9]. It also unifies the three forces weak, strong and electromagnetic. Fig. 1.1 shows the behavior of three forces for high energies in Standard model as well as minimal supersymetric standard model (MSSM).

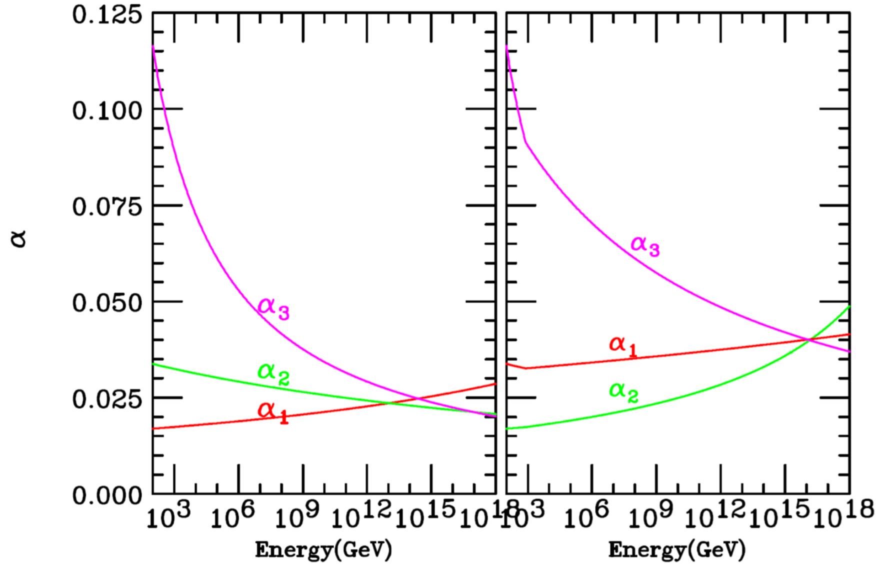

Figure 1.1: Three Guage Couplings a) in SM b) for MSSM generated using Isajet 7.8.1. Red curve represents gauge coupling of $SU(2)_L$, Green curve is for the gauge coupling of $U(1)_Y$ and color magenta represents strong SU(3) interaction

1.4 Minimal Supersymetric Standard Model

Most of the unanswered questions in the SM was able to solve introducing two Higgs doublets instead of one Higgs doublet in SM. Therefore, in the supersymetric models, two Higgs doublets are needed to give masses to both up-type and down-type quarks and the corresponding leptons. There are three famous sub catagories in 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 [10]. In type II one doublet couples to down flavor while the other doublet couples to up flavor fermions [11] [12] and in type III both doublets couple to both up and down flavored fermions [13]. MSSM is type II two Higgs doublet model which is considered to be the minimal extension to the standard model. MSSM has a second complex SU(2) Higgs-doublet field with hypercharge $Y = -1$ and both doublets acquire vacuum expectation values to break the $SU(2) \times U(1)$ symmetry. The general form of Higgs potential for MSSM can be written as,

$$\begin{aligned} V_{Higgs}(\phi_1, \phi_2) = m_1^2 \phi_1^\dagger \phi_1 + m_2^2 \phi_2^\dagger \phi_2 + m_{12}^2 (\phi_1^\dagger \phi_2 + \phi_2^\dagger \phi_1) + \lambda_1 (\phi_1^\dagger \phi_1)^2 + \lambda_2 (\phi_2^\dagger \phi_2)^2 \\ + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 [(\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1)] + \lambda_5 [(\phi_1^\dagger \phi_2)^2 + (\phi_2^\dagger \phi_1)^2] \end{aligned} \quad (1.4)$$

where Φ_1 and Φ_2 are two doublets in the Higgs sector of MSSM 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 MSSM 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 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 leads to the five physical Higgs bosons of MSSM. These five are two 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 leads to large variety of self couplings among them. At tree level, Higgs boson masses and couplings of MSSM Higgs 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 APPENDIX A and B in this thesis [9].

1.5 Outline

The Higgs production at LHC is expected to rely on a combination of several search mechanisms such as gluon fusion and weak boson fusion. Higgs boson pair production both in SM and MSSM have been studied by several groups before the Higgs was experimentally discovered as well as after. At the LHC, gluon fusion is the dominant source of Higgs boson pairs and this has been studied well in the past [14] [15] [16] [17] [18]. However in MSSM, the Yukawa coupling limit is enhanced by large value of $tan\ \beta$ and therefore Higgs production by b quark plays major role for this case. Once Higgs bosons are produced, they will decay into other particles such as quarks, tau leptons, W and Z bosons and so on. Branching ratio of Higgs decay provides important fact to choose probable decay channels. Fig. 1.2 shows the branching ratios for Standard Model Higgs and Fig. 1.3 shows the branching ratios of MSSM Pseudo scalar for two different $tan\ \beta$ values respectively. It is clear that Higgs dominantly decay in to $b\bar{b}$ pair both in SM (for Higgs mass of 126 GeV) as well as in MSSM for high $tan\beta$ regions. And second highest rate of decay goes to $\tau^+\tau^-$. Though $b\bar{b}$ is the dominant decay mode for neutral Higgs, not many have discussed this fact because the signal is overwhelmed by QCD backgrounds unless a special triggering is selected. However Kao et. al.[19] discuss the 3b final state in the neutral Higgs produced with one bottom quark and Yang[20] discuss the neutral Higgs production followed by one

Higgs decay into $b\bar{b}$ and the other decays into $\tau^+\tau^-$. Recently the Higgs bosson pair production in the $(b\bar{b})(b\bar{b})$ have been studied for SM given in [21].

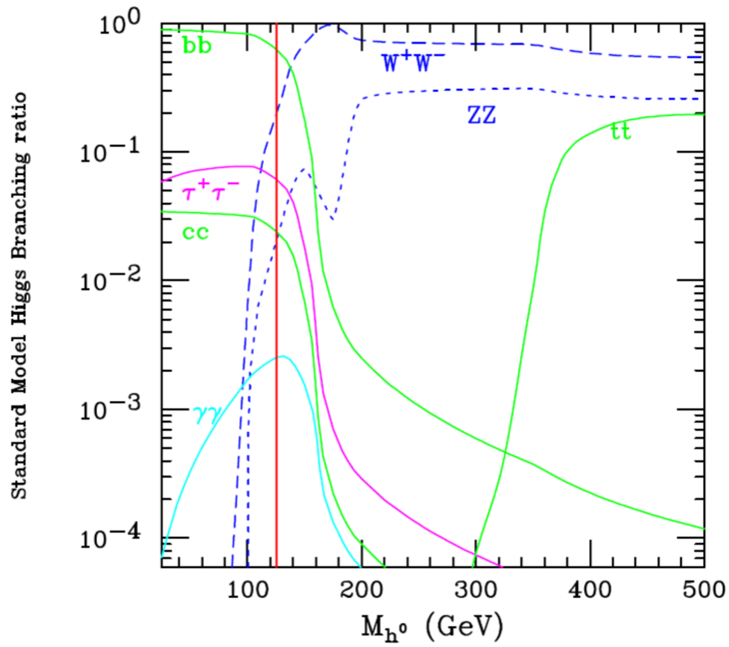

Figure 1.2: Branching Ratio for SM Higgs

This study basically includes the most important production cross sections of neutral Higgs at the LHC via gluon fusion, b quark fusion and Higgs decaying in to $b\bar{b}$ as well as one Higgs decaying into $b\bar{b}$ while other decays to $\tau^+\tau^-$. Chapter 2 of this thesis gives a complete study of Higgs cross sections for the process $gg \rightarrow \phi^0\, \phi^0 \rightarrow b\bar{b}b\bar{b}$, $gg \rightarrow \phi^0\, \phi^0 \rightarrow b\bar{b}\tau\tau$ and $\tau \rightarrow l, J_\tau$ for both SM and MSSM. In Chapter 3, Higgs cross sections for the processes $b\bar{b} \rightarrow \phi^0\, \phi^0 \rightarrow b\bar{b}b\bar{b}$ and $b\bar{b} \rightarrow \phi^0\, \phi^0 \rightarrow b\bar{b}\tau\tau$ and $\tau \rightarrow l, J_\tau$ will be discussed. Calculation tools, special selection of cuts will be discussed here along with the Numerical results and several distributions will be presented. Chapter 4 includes the calculation and results for dominant standard

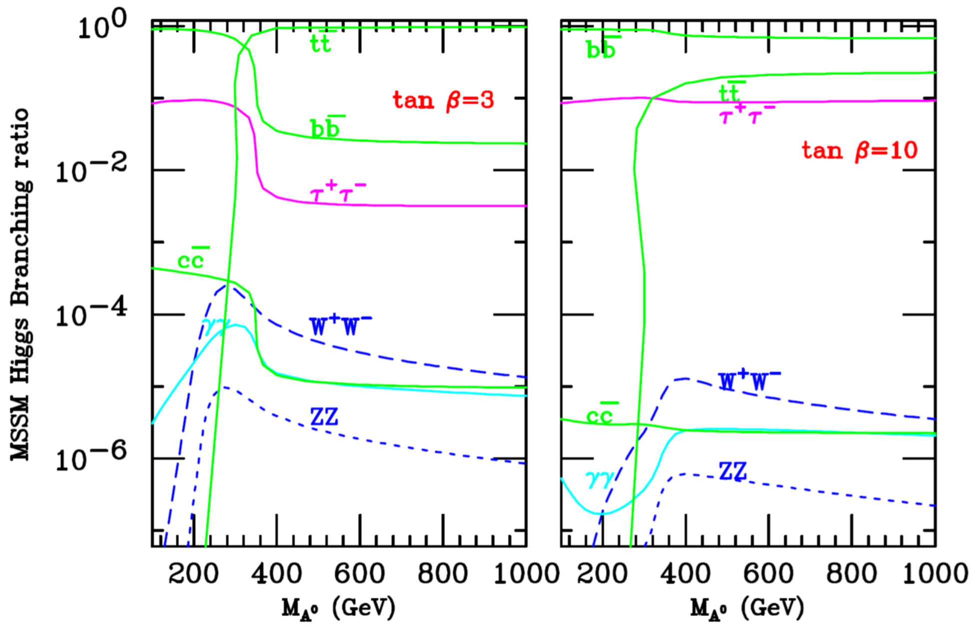

Figure 1.3: Branching Ratio for MSSM Higgs (a) for $tan\ \beta\ = 3$ and (b) for $tan\ \beta\ = 10$

Model backgrounds for the processes explained in chapter 2 and 3. Chapter 4 also presents the results analysis for the Higgs signal with background for the mentioned processes. 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 in terms of verifying actual Higgs boson as well as reproducing the correct Higgs potential and this will be focused specially in next runs at LHC. Chapter 5 includes a discussion about possibility of measuring trilinear Higgs coupling at LHC via the Higgs production processes discussed in Chapter 2 and 3. In Chapter 6, trilinear Higgs self couplings will be studied for the production of Higgs at ILC(International Linear Collider) via e^+e^- in SM.

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