Supersymmetry and the Higgs boson

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Abstract

This review investigates how the mass of the Higgs boson, m_h, measured at the Large Hadron Collider constrains the Minimal Supersymmetric Standard Model (MSSM). The natural ranges for the free parameters, M_S, X_t and tanβ, and the measured mass of the Higgs boson were used to assess if the lightest Higgs boson in MSSM could be the Higgs boson in the SM. The review found that the MSSM can remain a natural theory with $m_h \approx 125$ GeV for the energy of the Large Hadron Colliders first run but if no new physics is found on the second run the value for naturalness would be large enough that some would deem the theory to be unnatural.

Contents

1 Introduction

The Standard Model (SM) of particle physics is a theory which describes the electromagnetic, weak and strong interactions within the framework of Quantum Field Theory (QFT) [1]. QFT is a gauge theory, gauge theories are field theories which require the Lagrangian of the system to remain unchanged after gauge transformations [2]. This is due to the underlying symmetry of the field, these are known as gauge symmetry. Gauge theories are mathematically described by groups of these gauge symmetries. The SM brings together the symmetry groups of Quantum Chromodynamics (QCD), the theory explaining the strong interactions, and the theory which describes electromagnetic and weak interactions created by Glashow, Weinberg and Salam [3]. The symmetry group for the SM is $SU(3)_C \times SU(2)_L \times U(1)_Y$. $SU(3)_C$ is the symmetry group for QCD (the $_C$ is for color) and $SU(2)_L \times U(1)_Y$ (the $_L$ is for weak left-handed isospin and the $_Y$ is for hypercharge) is the symmetry group for electroweak interactions [4].

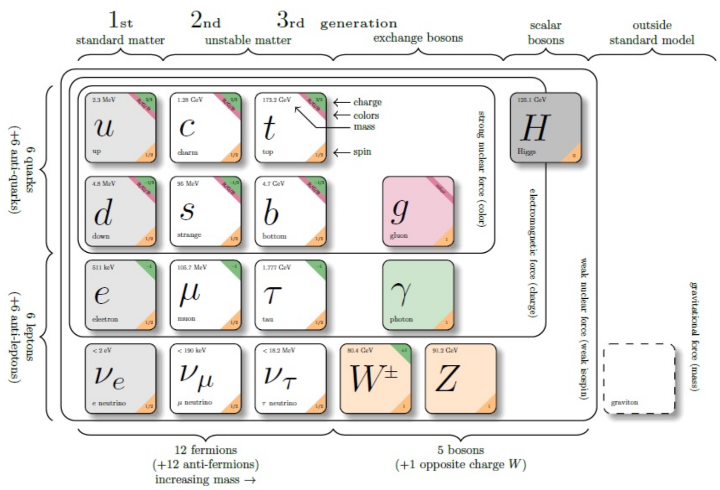

Figure 1.1: The Standard Model of Particle Physics [5].

Strong, electromagnetic and weak interactions are mediated by exchange bosons. The strong nuclear force acts between quarks, with gluons mediating this interaction. Gluons are excited states of the gluon field; this field dictates the movement of gluons between quarks. The electromagnetic force is much the same, instead of quarks there are charged particles, instead of the gluon field there is the electromagnetic field, and its exchange bosons (also known as gauge bosons) are the photon and the W$^\pm$ boson. The W$^\pm$ boson is also an exchange boson for weak interactions, with it, mediating these interactions is the Z boson. Weak interactions occur due to unstable states of particles, the transfer of W$^\pm$ and Z bosons allows a system to transition into a lower energy and more stable state. With this the SM includes information about the three generations of fundamental particles, exchange bosons and scalar bosons. The three generations are in order of stability, the lower the mass the more stable. Exchange bosons have spin 1 and scalar bosons have spin zero. The Higgs boson is the only scalar boson in the SM and it corresponds to excitations in the Higgs field.

1.1 Issues with the Standard Model

The SM is a very successful theory but it is incomplete, it does not include the theory of General Relativity (GR), theory of gravitation between massive objects on scales much greater than that of the quantum world. Gravitation is the fourth fundamental force of nature; any complete theory of the universe would need to include it. The SM has no candidates for dark matter, which is another key feature of the universe around us. To go with this, it is unable to explain dark energy, which is causing the acceleration of the universes expansion. The SM does not unify the strong, weak and electromagnetic forces at high energy, theories which do this are known as a Grand Unified Theory (GUT). GUT predicts that at high energies (grand unification energy), the strong and electroweak interactions will have the same coupling constant (parameter describing the interactions between particles and fields), combining $SU(3)_C$ and $SU(2)_L \times U(1)_Y$ into one grand symmetry group [2]. This is ideal for understanding the physics of the universe in a high-energy state such as just after the big bang.

There are a few key words and phrases which need explaining: Fine tuning, naturalness and the hierarchy problem. Fine tuning is the act of manipulating the parameters in a theory to agree with experimental data [4]. The formula for mass of the Higgs boson begins with a bare mass component and then to this quantum corrections are made. These quantum corrections have a momentum cut-off, Λ. The mass of the Higgs boson has a quadratic dependence to this cut-off, as the cut-off is increased, the mass of the Higgs boson diverges quadratically [4]. For the SM to remain consistent with experimental data, $m_h \approx 125$ GeV, the formula must be fine-tuned to cancel these quadratic divergences. The amount of fine tuning required is known as naturalness [6]. The hierarchy problem is to do with the vast difference between the electroweak scale and the GUT scale. Increasing Λ to the GUT scale these quantum corrections increase rapidly which leads to large amounts of fine tuning and an unnatural theory.

1.2 Supersymmetry

A symmetry which is trying to be a natural framework for the GUT is supersymmetry (SUSY). The idea put forward by the theory is that every fermion (half integer spin) and boson (integer spin) in the SM has a superpartner. By introducing superpartners (particles will a half integer spin difference while having all the same quantum numbers as their SM counterpart) SUSY has created a symmetry between fermions and bosons.

When first devised SUSY was unbroken, this meant the superpartners would have the same mass as the SM particles, meaning the masses of the particles and their superpartners would the same. Experiments like the Large Electron-Positron collider, Tevatron and the Large Hadron Collider (LHC) have shown us that this is not true. The theory was then updated to include soft symmetry breaking to give the superpartners greater mass than the SM equivalent, meaning that the cancellation is no longer exact, but the quantum corrections are still reduced.

The Renormalisation Group (RG), is a tool which relates parameters from one scale to another. It is used to relate the low energy scale of the SM and the high energy scale of GUT [2]. Applying RG to the SM the parameters nearly match leading to one grand symmetry group, but using SUSY the parameters match more accurately.

In the Minimal Supersymmetric Standard Model (MSSM, the theory will be discussed in the 2.1) there are suitable candidates for dark matter. Within this symmetry, a new parity was introduced, R-parity. The need for R-parity is to ensure baryon number and lepton number remain conserved. The particles in the SM all have even R-parity and the particles in the MSSM all have odd R-parity. Odd and even states do not mix, for the lightest supersymmetric particles, this leads to weak interactions with the particles of the SM [11]. The lightest particles in MSSM are called neutralinos, the MSSM predicts four possible candidates, these are the superpartners of the Z boson (zino), the neutral W boson (wino), the Higgs boson (higgsino) and the weak hypercharge gauge field (bino) [6]. These particles are all massive and neutral which makes the perfect candidates for dark matter. SUSY also solves the GR problem, by treating it as a local symmetry rather than a global symmetry, the theory of GR pops out, producing the theory known as supergravity [7].

2 Model

Model will be considering the MSSM, detailing some of its basic properties, setting the scene to start the discussion of the Higgs mechanism, the process by which the Higgs boson is derived in the SM and MSSM. The section will finish off by going into the mathematical process by which the MSSM formulates the mass of the lightest Higgs boson.

2.1 Minimal Supersymmetric Standard Model

MSSM is a SUSY model which incorporates the SM while having the smallest number of new particles and interactions. The supersymmetric partners are named in a way that separates fermions and bosons. The superpartners of fermions have the prefix s added to their names whereas the bosons have the suffix ino added to theirs [2].

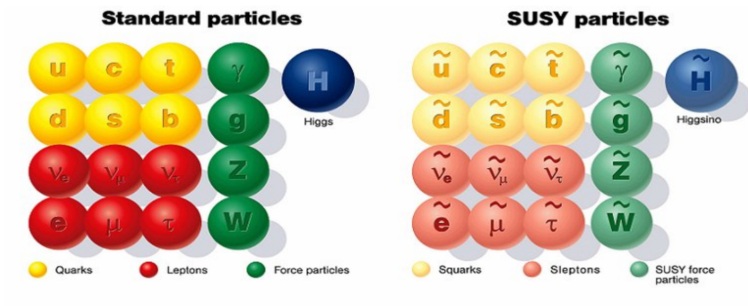

Figure 2.1: The SM and their supersymmetric counterparts [8].

2.2 Higgs Mechanism

As a gauge theory, the SM needs to be invariant under gauge transformations. This invariance means that the gauge bosons need to be massless [4]. This is in direction violation of the observed masses of the $W^{\pm}$ and Z bosons (80.4 GeV/c^2 and 91.2 GeV/c^2), and so the theory was altered, to incorporate a break in the symmetry for electroweak interactions. This is done through a process called the Higgs mechanism.

2.2.1 The Higgs Mechanism in the SM

The gauge bosons of the strong force and the electromagnetic force remain massless so only $SU(2)_L \times U(1)_Y$ needs to be broken. The symmetry is spontaneously broken to the $U(1)_{em}$ group, this is the Higgs mechanism. The Higgs mechanism starts with a SU(2) Higgs field doublet [4],

$$\Phi(x) = \frac{U(x)}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}. \tag{2.2.1}$$

The constant v is known as the vacuum expectation value (vev) and it is this which breaks the symmetry of the SU(2) doublet giving mass to the $W^{\pm}$ and Z bosons. U(x) is a unitary matrix, it is this matrix which acts as a SU(2) transformation. $h(x)$ is a scalar field which describes the spin-0 Higgs boson discovered in 2012 [4].

$$\mathcal{L} = |D_\mu \Phi|^2 + \mu^2 \Phi^\dagger \Phi - \lambda(\Phi^\dagger \Phi)^2 \tag{2.2.2}$$

This is the renormalized Lagrangian for the complex scalar doublet Eqn.(2.2.1) [4], where μ and λ are free parameters. To give mass to the $W^{\pm}$ and Z bosons the eigenvalues of the first term (kinetic term) in expression are derived. The last two terms will to the focus for this investigation as this is where the Higgs boson comes from. They are the potential term of the Lagrangian [4],

$$V_\Phi = const - \frac{\lambda}{4}\left(v^2 - \frac{\mu^2}{\lambda}\right) - v(\mu^2 - \lambda v^2)h + \frac{3\lambda v^2 - \mu^2}{2}h^2 + \lambda v h^3 + \frac{1}{4}h^4. \tag{2.2.3}$$

This is the Higgs potential; the minimum of this expression is vev. By analysing the quadratic term, the mass of the Higgs boson in the SM is found, see Appendix A.1.

$$m_h = \sqrt{2\lambda}v \tag{2.2.4}$$

2.2.2 The Higgs Mechanism in the MSSM

The Higgs Mechanism in MSSM follows the SM but with a few keys changes. For the MSSM Lagrangian to remain SUSY invariant two Higgs doublets are needed. Having two Higgs doublets is the only way to give up and down type quarks mass while having no complex conjugates in the superpotential, this lack of complex conjugates produces SUSY invariant Lagrangians [2],

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}; Y = \frac{1}{2}, \tag{2.2.5}$$

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}; Y = -\frac{1}{2}. \tag{2.2.6}$$

H_u and H_d are these doublets, they have hypercharge of Y=1/2 and Y=-1/2. A convenient way to describe MSSM interactions is to introduce a super potential (Eqn.(2.2.7)) [9]. Eqn.(2.2.5) and Eqn.(2.2.6) are places into the superpotential, as an invariant product (the product of the two scalar doublets omitting their complex conjugates) [4], this is because the superpotential must remain real,

$$W_{MSSM} = \bar{u}\lambda_u Q H_u - \bar{d}\lambda_d Q H_d - \bar{e}\lambda_e L H_d + \mu H_u H_d \tag{2.2.7}$$

Eqn.(2.2.7) is made up of chiral supermultiplets, these are the algebraic constructs used to explain supersymmetric models. The two Higgs doublets are in fact chiral supermultiplets. $\bar{u}$ and $\bar{d}$ are the multiplets for up and down type quarks, Q is for squarks. $\bar{e}$ and L are for sleptons and leptons respectively. $\lambda_{u,d,e}$ is the term used for Yukawa coupling parameter, this is the strength of an interaction between a scalar field and a fermion field, $_{u,d}$ are for Higgs-quark-quark and squark-Higgsino-quark interactions; whereas $_e$ is for Higgs-lepton-lepton couplings and slepton-Higgsino-lepton interactions [9]. The first three terms in the superpotential describe the Yukawa interactions of the SM, the last term is mixing between the two Higgs doublets [10]. The super potential is used to produce the scalar potential for MSSM, [4],

$$\begin{aligned}\mathcal{V} = &(|\mu|^2 + m_{H_u}^2)\left(\left|H_u^+\right|^2 + \left|H_u^0\right|^2\right) + (|\mu|^2 + m_{H_d}^2)\left(\left|H_d^-\right|^2 + \left|H_d^0\right|^2\right) \\ &+ \left[b(H_u^+ H_d^- - H_u^0 H_d^0) + h.c.\right] + \frac{g^2}{2}\left|H_u^{+*}H_d^0 + H_u^{0*}H_d^-\right|^2 \\ &+ \frac{g_U^2 + g_{SU}^2}{8}\left(\left|H_u^+\right|^2 + \left|H_u^0\right|^2 - \left|H_d^0\right|^2 - \left|H_d^-\right|^2\right)^2,\end{aligned} \tag{2.2.8}$$

where m_{H_u,H_d} are the masses of the two scalar complex doublets, Eqn.(2.2.5, 2.2.6), g_U, g_{SU} are the gauge couplings of the U(1) and SU(2) respectively. The parameter b needs a little more explaining, briefly mentioned early was the fact that the superpartners must have a greater mass than their SM counterparts. b with m_{H_u,H_d} break the gauge symmetry to give the superpartners a greater mass than their SM equivalent. The shape of the Higgs potential it is known as a Mexican hat function, Fig 2.2, it does not have a minimua at zero. Therefore the field has a vev, in the SM there is only one value for vev, just the same as Fig 2.2. In the MSSM two doublets are now used to describe both up and down type states are so this leads to an up and a down type vev, v_u and v_d [11],

$$v = \sqrt{v_u^2 + v_d^2}, \tag{2.2.9}$$

$$tan\beta = \frac{v_u}{v_d}. \tag{2.2.10}$$

2.3 Higgs Mass

In the SM, the single Higgs doublet has four degrees of freedom, two come from the real component of the doublet, the other two from the imaginary component. In MSSM there are two Higgs doublets, with 8 degrees of freedom, the $W^{\pm}$ and Z bosons are one degree of freedom each and the other five are for five physical Higgs bosons. The degrees of freedom are assigned as follows: 2 go to the charged Higgs bosons, $H^{\pm}$, two to the CP-even, H^0, h^0, and the last one goes to the CP-odd Higgs, A^0 [4]. Out of the five physical

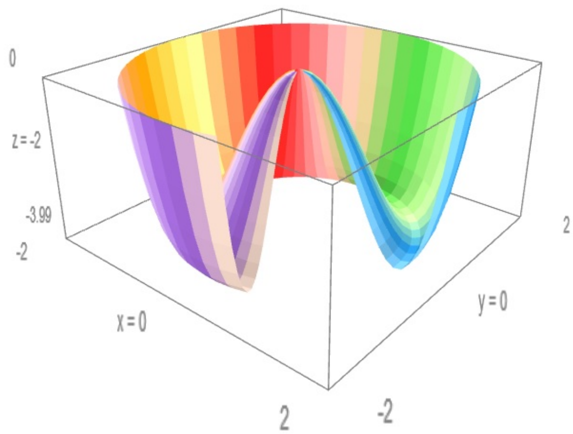

Figure 2.2: Surface of revolution of the function $f(x) = x^4 - 4x^2$ for θ between 0 to $\frac{3}{2}\pi$.

Higgs bosons, h^0 has the smallest mass and so is the best candidate for the Higgs boson discovered at the LHC [11].
For the electromagnetic gauge group to remain unbroken H_u^+ and H_d^- must both be equal to zero as they described changed interactions [11]. A substitution is made into the potential which separates the real and imaginary components of the complex doublets, as these states do not mix. When the real component of the substitution is placed into the Higgs potential the mass matrix for the CP-even Higgs bosons is formed. Finding the eigenvalues of this matrix produce the tree level masses of the h^0 and H^0 [11],

$$m^2_{h^0,H^0} = \frac{1}{2}\left[(m^2_{A^0} + m^2_Z) \mp \sqrt{(m^2_{A^0} + m^2_Z)^2 - 4m^2_{A^0}m^2_Z cos^2 2\beta}\right] \tag{2.3.1}$$

m_{A^0} is the mass of the CP-odd Higgs boson. The tree level mass (bare mass) of h^0 is Higgs mass with no quantum corrections, these corrections are known as loop corrections, the more loops considered the greater the accuracy of the mass. Using a one loop correction leads to an uncertainty of $\Delta m_h = \pm 3$ GeV [12] in the mass of the Higgs boson. These corrections come from how the Higgs boson couples with other particles. This effect is dependent upon mass, which means the one loop corrections from top and stop (the top quark supersymmetric counterpart) coupling has the greatest effect on the mass of h^0 [11],

$$m_h^2 = m_Z^2 cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2}\left[ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right]. \tag{2.3.2}$$

m_Z is the mass of the Z boson and m_t is the mass of the top quark. With any theory though there are parameters which are left as these are yet to be measured. M_S is the mass scale of the of the supersymmetric world, X_t is the stop mixing and β is found in Eqn.(2.2.10) [4]. Eqn.(2.3.1) is the mass of the lightest Higgs boson; the first term is the upper bound of the tree level mass and the second is the one loop correction for top and stop coupling [4]. The upper bound of the tree level mass has been used for the purposes of this review because it satisfies the decoupling limit, $m_{A^0} \ll m_Z$. In this limit, the lightest Higgs boson has more desirable properties, it couples to quarks, leptons and the electroweak gauge bosons the same way the Higgs boson in the SM [11]. Although this has led to a loss in generality, this investigation is into comparing the lightest Higgs boson of the MSSM and the Higgs boson of the SM so the more properties they share the better the comparison. In the MSSM the quantum corrections have a logarithmic dependence on M_S rather than a quadratic dependence on Λ. This is how the hierarchy problem is solved using in the MSSM. The difference between the GUT scale and the electroweak scale no longer matters. Instead the quantum corrections now depend on the scale of M_S which is many magnitudes less than the GUT scale. Quantum corrections are meant to be small corrections to a theory otherwise fine-tuned must be introduced. To reduce the size of these corrections M_S will have a maximum value 5 TeV when X_t and tanβ are examined.

3 Numerical Analysis

The mass of the Higgs boson at the LHC puts constraints on the formula for the mass of the lightest Higgs boson. Using this, code was produced to look at the free parameters (M_S, X_t and tanβ) of Eqn.(2.3.1). The numerical analysis will consist of looking at the how the m_h is effected by M_S, X_t and tanβ. The uncertainty of in m_h is shown for these graphs using horizontal lines at $\Delta m_h = \pm 3$ GeV. It will also be looking at the relationship between X_t and M_S for a constant mass of the Higgs boson, 125 GeV.

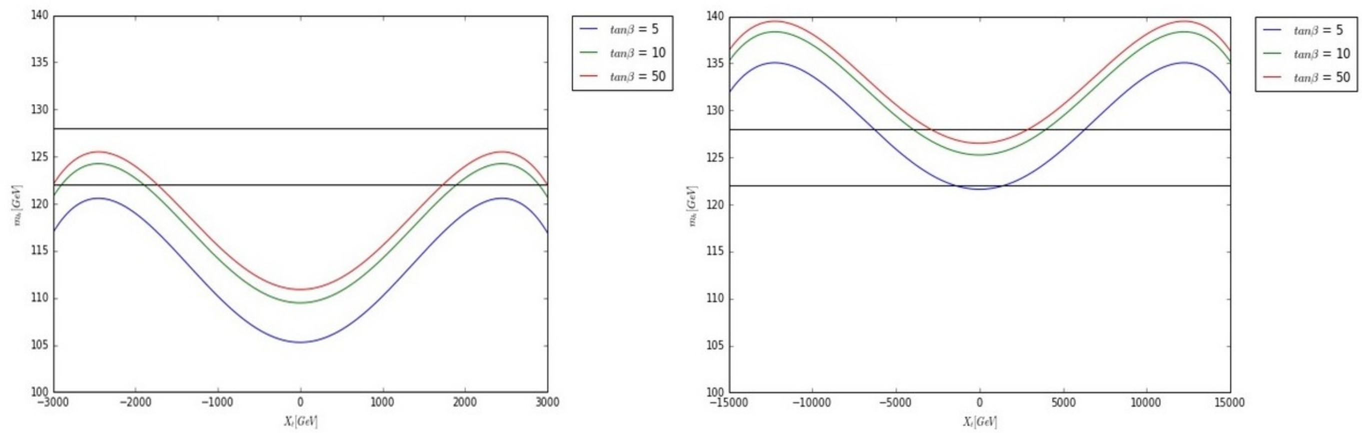

Figure 3.1: m_h against X_t for a range of tanβ. On the right M_S= 1 TeV and on the left is M_S= 5 TeV.

The graphs in Fig 3.1 both have a maximum value for the mass of the Higgs boson, beyond this maximum the mass of the Higgs boson becomes unbounded from below. This means it will continually decrease becoming negative values leading to an unphysical mass for the Higgs boson. This maximum is known as maximal mixing, analysing this maximum produces a value for maximal mixing of, X_t= $\sqrt{6}$ M_S, this will be discussed further in the discussion. For the $M_S = 1$ TeV graph the range of values for X_t that exist within the range of uncertainty is 1.75 TeV $\lesssim |X_t| \leqslant \sqrt{6}M_S$. Whereas for the $M_S = 5$ TeV graph this range is 0 Gev $\leqslant |X_t| \lesssim$ 6 TeV. The range of possible values for the 5 TeV graph has increased in magnitude and now incorporates the entire range of tanβ. In this range the values for stop mixing are much lower than maximal mixing compared with the 1 TeV graph.

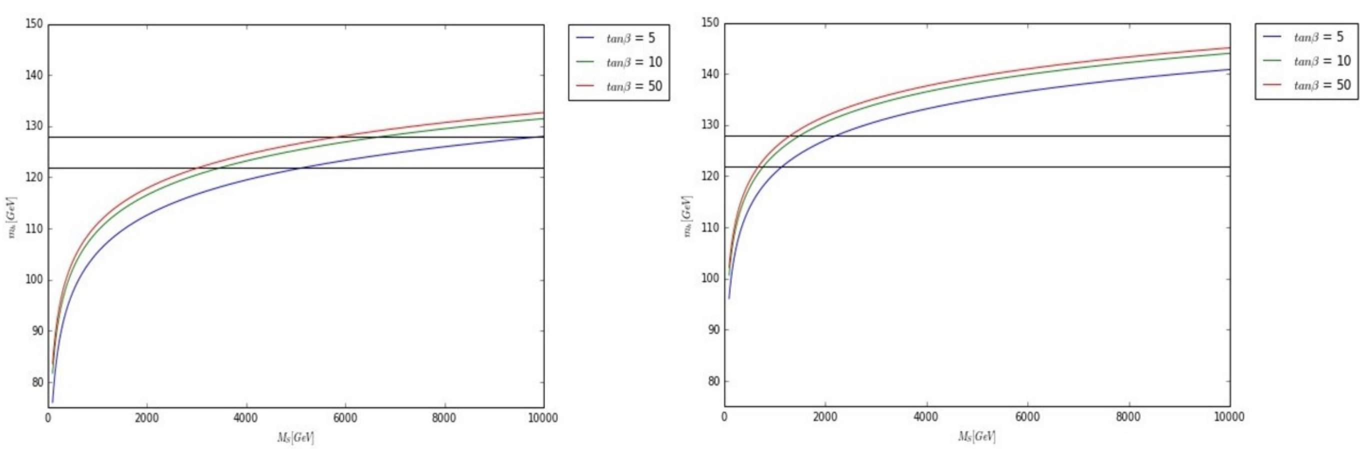

Figure 3.2: The relationship between m_h and M_S for a range of tanβ values. On the right is zero mixing and on the left is maximal mixing.

Fig 3.2 shows how m_h is effected by varying M_S for a range of tanβ values. On the left zero mixing has been implemented and on the right the maximal mixing. The range of M_S values for the minimal and maximal mixing graphs are 3 TeV $\lesssim |M_S| \lesssim$ 10 TeV and 1 TeV $\lesssim |M_S| \lesssim$ 2 TeV respectively, using the complete range of tanβ. The graphs highlight the fact that when maximal mixing is implemented the scale of the superpartner mass minimised, this means smaller quantum corrections are needed leading to a more natural theory.

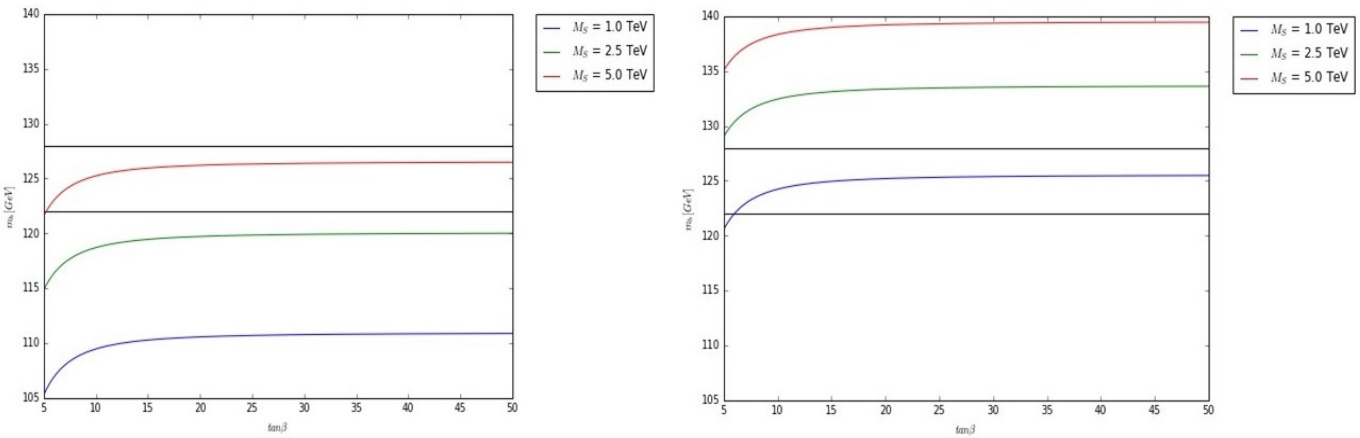

Figure 3.3: m_h against tanβ for a range of M_S. On the right X_t= 0 GeV and on the left is X_t= $\sqrt{6}M_S$ GeV.

As tanβ is increased there is great effect at first, but then its effect begins to plateau. After the point of plateau the effect becomes a small translation of the mass of the Higgs boson. When looking at the graph of maximal mixing, M_S must be minimised to counteract the effect of having of large X_t. With these input values, the entire range of tanβ produces values for the mass of the Higgs boson that are within the range of uncertainty. When X_t to set to be zero M_S is the counter balance, it must be increased to overcome the effect the mixing has.

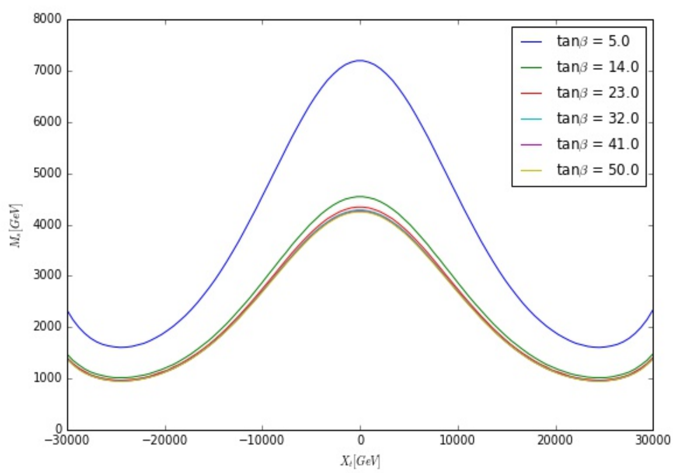

Figure 3.4: Keeping m_h = 125 GeV, to find the relationship between M_S and X_t for a range of tanβ.

The relationship between M_S and X_t gives an indication which parameter effects m_h the most, this helps work out the best ways to tweak the theory to gain the experimental value for the Higgs mass while still reducing the quantum corrections. tanβ has a big effect going from 5 to 14 after this tanβ becomes more like a translation due to the plateau. This graph is about how M_S and X_t interact to kept the mass of the Higgs boson at 125 GeV. M_S needs to be large when there is zero mixing, as X_t increases M_S can decrease. The graph reaches a minimum value of M_S and this is at maximal mixing from this point on M_S must increase rapidly to cancel the effect a change in X_t has.

4 Discussion

Any theory developed will have constraints, this ensures the theory remains physical. The discussion will be investigating these because the limits imposed by them either validate or terminate a theory. The discussion will be looking at the constraints on M_S, X_t and tanβ. After this there will be a discussion on the possibility of finding SUSY particles in the most recent run of the LHC.

4.1 Naturalness constrains on M_S

$$\mathcal{N} = max\{\mathcal{N}_i\}, \mathcal{N}_i = \left|\frac{\delta ln\Lambda^2}{\delta ln a_i^2}\right| \tag{4.1.1}$$

The way in which naturalness is quantified is Eqn.(4.2.1) where a$_i$ is a free parameter of a theory. $\mathcal{N}_i$ is known as the sensitivity parameter, in the equation above is shows how variation of a free parameter is related to the SM cut-off /citenatural. The larger this value the more unnatural a theory is because it relates to high orders of fine tuning. Naturalness places constraints on M_S because of the logarithmic dependence to the quantum corrections. To reduce the magnitude of fine tuning the magnitude of M_S must not become to large making the MSSM an unnatural theory and leading to a new smaller hierarchy problem between the electroweak scale and the supersymmetric scale.

4.2 CCB constrains on X_t

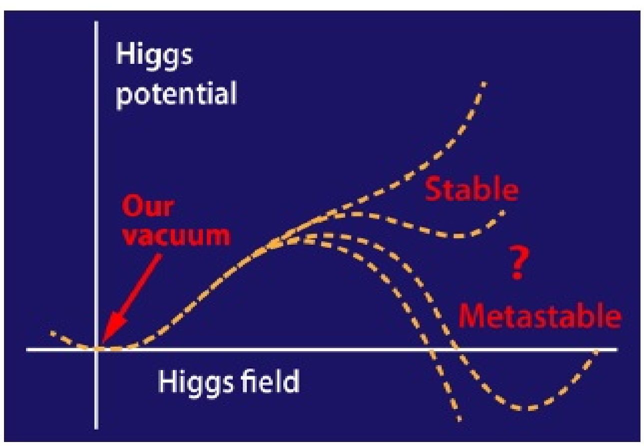

Figure 4.1: The various possible shape which the Higgs potential can take depending on what type of a universe we live in [13].

CCB is the breaking charge conversation or color conservation. Just like the electroweak symmetry breaking gives a non-zero vacuum expectation value. There could be other minima where charge and color particles gain a non-zero expectation value. Fig 4.1 shows a mock-up of the scalar potential, there are three possibilities, a stable, meta-stable or unstable universe. A stable universe has the electroweak symmetry breaking minimum as a global minimum. Meta-stable is a scenario where there are these CCB minima, but the decay time is greater than the age of the universe. The decay time is the time the universe will exist in this state before quantum tunnelling into the lower energy state. Finally, the unstable universe is one which is the same as a meta-stable universe expect the decay time is less than that of the age of the universe. This can be linked to the idea of maximal mixing. Around maximal mixing CCB minima are formed at first meta-stable, as X_t increases past maximal mixing there are CCB minima with decay times shorter than the age of the universe, this is reason why X_t was only considered up to maximal mixing [14].

4.3 Yukawa coupling constrains on tanβ

The masses of quarks and leptons in MSSM are dependent on tanβ and the Yukawa coupling. As one is increased the other decreases and vice versa. This effect is where the limits on tanβ arise, in the lower limit, the Yukawa coupling for the top quark increases to magnitudes beyond perturbation theory. The same dilemma occurs when looking at the Yukawa couplings for the tau lepton and the bottom quark, they become nonperturbatively large as tanβ reaches the upper limit. This is the reason for using the range 5 $\leqslant tan\beta \leqslant 50$.

4.4 SUSY at the LHC

The LHC was turned on for its second run in April of 2015, this run is now running at 13 TeV. This is 5 TeV greater than the last run, with this new increase it is still very possible that the ATLAS and CMS could see signals indicating new physics beyond the SM. Unfortunately, after the first year nothing new has been published. This run will last till 2018, which will be when the full analysis will be released. Taking the collisions up to this energy will mean that gluino and squarks masses will be pushed from 1 TeV to about 3 TeV [6]. This increase in energy leads to what some might think to be an unnatural theory as the value for naturalness will have greatly increased.

The lightest supersymmetric particles are the neutralinos, which are the candidates for dark matter. These come under the umbrella of weakly interacting massive particles (WIMPs), they are created in the early universe in a state of thermal equilibrium. This is not a permanent state, as time goes on the density decreases until the interaction are so infrequent that the particles freeze out. This density is called the thermal relic density, Ω_χ, and it is a way of analysing neutralinos as a candidate for dark matter. The requirement is that $\Omega_\chi \leq 0.23$, this puts limits on the masses of certain neutralinos [6],

$$m_{\tilde{B},\tilde{H}} < 1.0 \text{ TeV}, \tag{4.4.1}$$

$$m_{\tilde{W}} < 2.7 - 3.0 \text{ TeV}, \tag{4.4.2}$$

$m_{\tilde{B}-\tilde{H}}$ is the mass of the bino or higgino dark matter and $m_{\tilde{W}}$ is the mass of the wino. These values are within the react of the LHC, so the future of the MSSM is highly dependent upon what is found between now and the year 2018 [6].

5 Beyond the MSSM

The constrained MSSM is a theory that takes MSSM to the GUT scale, in doing so it restricts the parameters of the theory. The theory states that at the GUT scale there is one mass term for scalars, i.e. squarks, sleptons and Higgs bosons; that there is one mass term for gauginos and higginos and finally only one coupling term for all interactions [15].

$$m_{\frac{1}{2}}, \quad m_0, \quad A_0, \quad tan\beta, \quad sign(\mu) \tag{5.0.1}$$

$m_{\frac{1}{2}}$ is the gaugino and Higgsino mass term, m_0 is the scalar mass term and A_0 is the trilinear coupling term. μ and tanβ are the same as in MSSM, the magnitude of μ isnt a parameter of the theory merely the sign. With this small number of parameters, it becomes simpler to make predictions and this is the true power of CMSSM. Varying these parameters of CMSSM has an effect the mass of the lightest Higgs boson. When $m_{\frac{1}{2}}$ is increased, there is an increase in the mass of the lightest Higgs boson. Variations in m_0 only have a small effect on the mass. A_0 increases the mass as it is reduced. It has been shown how tanβ effects the lightest Higgs boson earlier in this paper. The effect of variation in the sign of μ is over shadowed by the effect of the other parameters [15].

6 Conclusion

The objective of this report was to investigate the Higgs boson in the SM discovered at the LHC in 2012, and relate it to the Higgs bosons found in the MSSM. The lightest of the five physical Higgs bosons in the MSSM was the main focus of the report as this is the best candidate. The report considered the limits of the free parameters in the MSSM. This numerical analysis was used to understand if the MSSM is still a natural theory after the first run of the LHC excluded more possible mass values for the superparticles. The report showed that the MSSM is still a natural theory within the limits of M_S, X_t and tanβ.
The theory will truly come to a head by 2018 when the LHC has analysed the data collected from the second run. Working at 13 TeV the LHC will test the limits of naturalness for the MSSM, and if no new physics is found then the situation for the MSSM does not look very good.

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A Appendix

A.1 Analysis of Higgs potential of the SM

Appendix A will be finding the minimum of the Higgs potential in order to produce a formula for the vacuum expectation value, this minimum is then used to find a formula for the mass of the Higgs boson in the SM. The minimum is found by differentiating Eqn.(2.2.3) with respect to the Higgs field (h) and setting this formula equal to zero,

$$\frac{\partial V_\Phi}{\partial h} = (\mu^2 - \lambda v^2) + \frac{3\lambda v^2 - \mu^2}{2} h + 3\lambda v h^2 + h^3 = 0 \tag{A.1.1}$$

To find the vacuum expectation value you need to set the Higgs field equal to zero and solve for v,

$$\left.\frac{\partial V_\Phi}{\partial h}\right|_{h=0} = \mu^2 - \lambda v^2, \tag{A.1.2}$$

$$v = \sqrt{\frac{\mu^2}{\lambda}}. \tag{A.1.3}$$

The quadratic term of a Lagrangian is known as the mass term, for a real scalar Lagrangian the coefficient is equal to $\frac{1}{2}m^2$ [16]. To produce a formula for the mass of the Higgs boson Eqn.(A.1.2) is substituted back into the quadratic term of the Higgs potential and set to equal $\frac{1}{2}m_h^2$,

$$m_h = \sqrt{2\lambda} v. \tag{A.1.4}$$