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The Upper Bound on the Lightest CP Even Higgs Mass in the MSSM, NMSSM and ESSM

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Abstract: Recently a Higgs like particle is reported to be discovered at CMS and ATLAS experiments at CERN LHC with a mass of about 125 GeV. The aim of this paper is to study the theoretical upper bound of lightest CP even Higgs mass in MSSM, NMSSM and ESSM. Although at this moment it is not possible to conclude whether the observed Higgs like particle is Standard Model Higgs or Supersymmetric one, yet the present paper comes to the conclusion that it is possible to accommodate ~125 GeV Higgs mass within MSSM, NMSSM and ESSM.

Keywords: Higgs Mass, MSSM, NMSSM, ESSM

1. Introduction

The main reason for introducing low energy supersymmetric theories in particle physics was, in fact, their ability to solve the naturalness and hierarchy problems [1]. Supersymmetry prevents the Higgs boson mass from acquiring very large radiative corrections: the quadratic divergent loop contributions of the SM [2] particles to the Higgs mass squared are exactly cancelled by the corresponding loop contributions of their supersymmetric partners. This cancellation stabilizes the huge hierarchy between the GUT and electroweak scale and no extreme fine-tuning is required. In MSSM [3, 4, 5] every quark, lepton and gauge boson has a supersymmetric partner associated with it. MSSM requires two CP conserving Higgs doublets with opposite hypercharge so as to give masses to up-type and down-type fermions, by keeping consistency with supersymmetry and by avoiding gauge anomalies due to the fermionic super partners of the Higgs bosons. Recently a Higgs like particle is reported to be discovered at CMS and ATLAS experiments at CERN LHC with a mass of ~ 125 GeV. In the Standard Model, the Higgs boson mass is usually considered as an adjustable parameter because the quartic coupling of the Higgs potential is arbitrary. In the MSSM, an intrinsic upper bound on the lightest Higgs boson mass is obtained from the quartic Higgs couplings which is no longer arbitrary but is constrained by SUSY. But MSSM contains a μ-parameter in the superpotential where μ is a dimensionful parameter. It enters the Higgs potential with the soft scalar masses to determine the vacuum expectation value of the Higgs fields. This parameter has to be adjusted by hand to a value at the electroweak scale, in order to provide the correct pattern of electroweak symmetry breaking. This is a problem of the model and is called μ-problem [6]. In the NMSSM [7, 8, 9, 10] an additional gauge singlet S is introduced which generates the μ-term dynamically. In order to avoid a low energy global U(1) symmetry, the superpotential is also supplemented by a trilinear term S^3. However the super potential of the NMSSM remains invariant under a discrete Z_3 symmetry which, when broken at the weak scale, leads to the formation of domain walls in the early universe, which are inconsistent with modern cosmology. In an attempt to break the Z_3 symmetry, operators suppressed by powers of the Plank scale could be introduced. But these give rise to quadratically divergent tadpole contributions which would destabilize the mass hierarchy. The Exceptional Supersymmetric Standard Model (ESSM) [11, 12] is an E_6 inspired Supersymmetric model with an extra $U(1)_N$ gauge symmetry which solves the μ problem of the MSSM in a similar way to the NMSSM, but without the accompanying problems of singlet tadpoles or domain walls.

2. Upper Bound on the Lightest CP even Higgs Mass in the MSSM

The MSSM contains two Higgs doublets which give eight

independent states. After three of them are used to give longitudinal components of the W and Z bosons, we have five physical states: two neutral scalars h^0 and H^0 , a pseudoscalar A^0, and a pair of charged Higgs scalars $H^\pm$. At the tree level their masses and couplings are determined by

$$M_h^2 = \frac{1}{2} \left(M_A^2 + M_Z^2 + \varepsilon'\right) \left[1 - \sqrt{1 - \frac{4\{M_Z^2 M_A^2 cos^2 2\beta + \varepsilon'(M_A^2 Sin^2\beta + M_Z^2 cos^2\beta)\}}{(M_A^2 + M_Z^2 + \varepsilon')^2}}\right] \quad (1)$$

The neutral scalar gets a large radiative correction from the top quark loop along with the top squark (stop) loop. To a approximation this contribution is given by

$$\varepsilon = \frac{3g^2 m_t^4}{8\pi^2 M_W^2} ln\left(\frac{M_{\tilde{t}}^2}{m_t^2}\right) \quad (2)$$

Plus an additional contribution from the $\tilde{t}_{L,R}$ mixing, given by

$$\varepsilon_{mix} = \frac{3g^2 m_t^4}{8\pi^2 M_W^2} \frac{A_t^2}{M_{\tilde{t}}^2} \left(1 - \frac{A_t^2}{12 M_{\tilde{t}}^2}\right) \quad (3)$$

where

$$\varepsilon' = (\varepsilon + \varepsilon_{mix}) \frac{1 + tan^2\beta}{tan^2\beta} \quad (4)$$

The trilinear SUSY breaking parameter A_t is given by

$$A_t = \Pi \left[\frac{\alpha_i(\mu_t)}{\alpha_i(m_t)}\right]^{\frac{C_i}{2a_i}}$$

where $t = ln\beta$, $C_i = (\frac{17}{20}, \frac{9}{4}, 8)$; $i = Y, 2L, 3C$; $\mu_t > m_t$

$$\frac{1}{\alpha_i(\mu)} = \frac{1}{\alpha_i(m_t)} - \frac{a_i}{2\pi} ln\left(\frac{\mu_t}{m_t}\right)$$

$$i = 1,2,3; \ a_1 = \frac{21}{5}, \ a_2 = -3, a_3 = -7$$

$$\mu_t = \sqrt{m_t M_{SUSY}} = 418.33; \ m_t = 175 \ GeV, M_{SUSY}$$
$$= 1000 \ GeV, M_{\tilde{t}} = 1000 \ GeV, M_w$$
$$= 80 \ GeV, M_Z = 91 GeV \ and \ g = 0.65$$

Using equation (1) the variation of lightest Higgs boson mass M_h is studied with systematic variation of $tan\beta$ and M_A for three different values of m_t (= 172, 175 and 180 GeV) . The mass of M_h increases with increase of M_A, until at about 300 GeV for M_A, a maximum value of M_h is reached for each value of $tan\beta$. Beyond $M_A = 300 \ GeV$, M_h is almost independent of M_A. For large values of the pseudoscalar Higgs boson mass, $M_A \gg M_Z$, the lightest Higgs boson mass M_h reaches its maximum for a given value of $tan\beta$. I have also studied the variation of M_h with m_t as m_t varies from 172 GeV to 180 GeV. It is found that the value of M_h increases with the

increase of m_t. The value of M_h for $m_t = 180 \ GeV$ gives the maximum value of M_h which is ~ 135 GeV. This is interesting because MSSM gives the upper bound on the lightest Higgs boson mass as $M_h \leq 135 \ GeV$.

3. Upper Bound on the Lightest CP- even Higgs Mass in the NMSSM

The Higgs fields of the NMSSM consists of the usual two Higgs doublets as in the MSSM together with an extra Higgs singlet,

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, S$$

The extra singlet is allowed to couple only to the Higgs doublets of the model, and consequently the couplings of the new fields to gauge bosons will only be manifested via their mixing with the other Higgs fields.

The tree-level Higgs potential is composed of three parts [10],

$$V = V_F + V_D + V_{Soft} \quad (5)$$

with

$$V_F = |\lambda S|^2 (|H_u|^2 + |H_d|^2) + |\lambda H_u H_d + KS^2|^2 \quad (6)$$

$$V_D = \frac{g^2 + g'^2}{8} \left(|H_d|^2 - |H_u|^2 + \frac{1}{2} g^2 |H_u^+ H_d|^2\right) \quad (7)$$

$$V_{Soft} = m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_S^2 |S|^2 +$$
$$\left[\lambda A_\lambda S H_u H_d + \frac{1}{3} K A_K S^3 + h.c.\right] \quad (8)$$

Where g and g' being the gauge couplings of $SU(2)_L$ and U(1) interactions respectively. The Higgs potential contains seven parameters: λ and K from the superpotential and $A_K, A_\lambda, m_{H_u}, m_{H_d}$ and m_S from the soft supersymmetry breaking terms.

In the NMSSM seven Higgs bosons are created: 3 CP-even (H_1^0, H_2^0, H_3^0), two CP-odd (A_1^0, A_2^0) and two charged $(H^\pm)$.

The tree level lightest CP-even Higgs mass in NMSSM is given by [10].

$$M_{H_1}^2 = \frac{1}{2}\left\{ M_Z^2 + \frac{1}{2}Kv_S\left(4Kv_S + \sqrt{2}A_K\right) - \sqrt{\left[M_Z^2 - \frac{1}{2}Kv_S\left(4Kv_S + \sqrt{2}A_K\right)\right]^2 + cot^2\beta_S[2\lambda^2v_S^2 - M_A^2 sin^2 2\beta]^2} \right\} \qquad (9)$$

where $v = \sqrt{v_u^2 + v_d^2} = 246$ GeV, $tan\beta = \frac{v_u}{v_d}, tan\beta_S = \frac{v_S}{v}$ and negative value for A_K being preferred.

The upper bound of the lightest CP-even Higgs mass comes out to be ~140 GeV. It is reached for

$tan\beta \sim 2.2, \lambda \sim 0.677, k \sim 0.068, v_s = 15\, v, M_A = 1000\, GeV, m_Z$

$= 175\, GeV, \mu \sim 545\, GeV, A_\lambda \sim 1365\, GeV\, and\, A_K \sim 10\, GeV.$

4. Upper Bound on the Lightest CP- even Higgs Mass in the ESSM

The Exceptional Supersymmetric Standard Model (ESSM) represents a low energy alternative to the MSSM or NMSSM and provides a solution to the μ problem without domain wall problem. ESSM involves the low energy matter content of three 27 representations of E_6, which is broken at the GUT scale, and allows gauge coupling unification due to an additional pair of Higgs-like doublets. The ESSM predicts a $Z^/$ boson and exotic quarks which, if light enough, will provide spectacular new physics signals at the LHC. Within the E_6 inspired supersymmetric standard model there is a unique choice of Abelian gauge group, referred to as $U(1)_N$, which allows zero charges for right-handed neutrinos. This choice of $U(1)_N$ allows large right-handed neutrino Majorana masses and hence a high scale see-saw mechanism. A rich spectrum of new states at the TeV scale is predicted by E_6SSM corresponding the matter content of three 27 component families. Since each 27 includes a pair of Higgs doublets plus a SM singlet, the E_6SSM predicts a total three families of Higgs doublets and three families of Higgs singlets. The two Higgs doublets familiar from the MSSM are denoted as H_d and H_u, while the two further replicas of these Higgs doublets predicted by the E_6SSM are denoted as H_1^d, H_1^u and H_2^d, H_2^u. Each 27 representation also contains a separate SM singlet. There is the singlet S whose VEV yields an effective μ term, plus two further copies of this singlet, S_1 and S_2.

E_6SSM Higgs fields develop the VEVs $\langle H_d \rangle = \frac{v_d}{\sqrt{2}}, \langle H_u \rangle = \frac{v_u}{\sqrt{2}}$ and $\langle s \rangle = \frac{s}{\sqrt{2}}$, thus breaking the $SU(2)_w \times U(1)_Y \times U(1)_N$ symmetry to $U(1)_{EM}$. After Electro-Weak symmetry breaking two CP-odd and two charged Goldstone models in the Higgs sector are absorbed by the $Z, Z^/$ and $W^\pm$ gauge bosons so that only six physical degrees of freedom are left. They form one CP-odd, two charged and three CP-even Higgs states.

The tree-level upper bound on the lightest CP-even Higgs boson is given by,

$$m_{h_1}^2 \lesssim \frac{\lambda^2}{2} v^2 Sin^2 2\beta + M_Z^2 Cos^2 2\beta + \frac{M_Z^2}{4}\left(1 + \frac{1}{4}Cos2\beta\right)^2 \quad (10)$$

From equation (10) it is clear that, at tree level the theoretical upper bound on the lightest Higgs mass in the ESSM depends on λ and tanβ only. The requirement of validity of perturbation theory up to the Grand Unification Scale constrains the interval of variations of the Yukawa coupling λ for each value of tanβ. The resulting tree-level upper bound on the mass of the lightest Higgs particle in the ESSM attains a maximum value of 130 GeV at tanβ = 1.5 − 1.8.

5. Discussions and Conclusions

The theoretical upper bound on the lightest CP even Higgs mass in the MSSM, NMSSM, and ESSM comes out to be ~135 GeV, ~140 GeV and 130 GeV respectively. Recently ~125 GeV Higgs like particle has been discovered at CMS and ATLAS experiments at CERN. In this context a very important question arises: Is the scalar Higgs boson observed at the LHC, a supersymmetric Higgs boson or a Standard Model one? The present paper throws light on the fact that it is possible to accommodate ~125 GeV Higgs mass within MSSM, NMSSM, and ESSM. The problem of resolving the issue of newly discovered boson may be understood through independent discovery, with caution in accepting new ideas and after critical enquiry into the evidence of discovery of the Higgs boson.

References

[1] E. Witten, Nucl. Phys. B188 (1981) 513; *ibid* Nucl. Phys. B202 (1982) 253; N. Sakai, Z. Phys. C11 (1981) 153; S. Dimopoulos and H. Georgi, Nucl. Phys. B193 (1981) 150; R. K. Kaul and P. Majumdar, Nucl. Phys. B199 (1982) 36.

[2] Glashow S L, Nucl. Phys. 22, 1961, 579; Salam A and Ward J C, Phys. Lett. 13, 1964, 168; Weinberg S, Phys. Rev. Lett. 19, 1967, 1264.

[3] Veltman M, Acta Phys. Polon. B12 (1981) 437; Witten E, Nucl. Phys. B 188 (1981) 513 and Phys. Lett. B 105 (1981) 267.

[4] Gildener E and Weinberg S, Phys. Rev. D 13, 3333 (1976); Susskind L, Phys. Rev. D 20 (1979) 2619; Weinberg S, Phys. Lett. B 82 (1979) 387; t Hoof G, in Recent developments inGauge Theories, Proceedings of the NATO Advanced Study Institute, Cargese, 1979, eds., tHooft G et. al. (Plenum Press, NY, 1980).

[5] Gunion J F, Haber H E, Kane G and Dawson S, The Higgs Hunters' Guide (Addition-Weslay, Reading, MA, 1990);, Haber H E and Kane G, Phys. Rep. 117, 75 (1985). and references therein for SM; Introduction to supersymmetry (http://arxiv.org/pdf/hep-th/9612114) by Lykken J D, 1996; An introduction to supersymmetry (http://arxiv.org/pdf/hep-ph/9611409)by Drees M, 1996; A Supersymmetry Primer (http://arxiv.org/pdf/hep-ph/9709356) By Martin S, 1999; Introduction to Supersymmetry (http://arxiv.org/pdf/hep-ph/0101055) By Bilal A, 2001; An introduction to Global supersymmetry. (http://www.physics.uc.edu/~argyres/661/susy2001.pdf) By Philip Arygres, 2001.

[6] J. E. Kim and H. P. Nilles, Phys. Lett. B 138, 150 (1984).

[7]   M. Bastero-Gil, C. Hugonic, S. F. King, D. P. Roy and S. Vempati, Phys. Lett. B 489, 359 (2000); A. de Gouvea, A. Friedland and H. Murayama, Phys. Rev. D 57, 5676 (1998).

[8]   J. Ellis, J. F. Gunion, H. Haber, L. Roszkowski, F. Zwirner, Phys. Rev. D 39 (1989) 844.

[9]   J. P. Derendinger and C. A. Savoy, Nucl. Phys. B 237 (1984) 307; J. M. Frere, D. R. Jones and S. Raby, Nucl. Phys. B 222 (1983) 11.

[10]   P. P. Pal, Intertational Journal of High Energy Physics, 2015; 2 (3): 34-37, DOI: 10.11648/j.ijhep.20150203.11.

[11]   S. F. King, S. Moretti, R. Nevzorov, arXiv: hep-ph/0510419.

[12]   S. F. King, S. Moretti, R. Nevzorov, arXiv: hep-ph/0601269v2.

[13]   S. Chakrabarty and P. P. Pal, J. Assam Sc. Soc, Vol. 51, June 2010, pp. 18-26.