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Study of Decoupling Effects on SUSY Higgs Sector

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Abstract: The most likely scenario in the light of Higgs discovery is the decoupling limit in the MSSM Higgs sector. The decoupling limit in MSSM occurs when the pseudoscalar mass is large (i.e. $m_A \gg m_Z$), then the CP-even (H^0), CP-odd (A^0) and charged ($H^{\pm}$) Higgs are mass degenerate and the lightest CP-even Higgs boson (h) mimics the signature of the SM Higgs boson. In the decoupling limit of large m_A the couplings of the lightest CP-even MSSM Higgs boson h to pairs of SM particles approach their SM values. Moreover, in the decoupling limit there exists a value of $tan\beta$ which is independent of the value of m_A . 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. This estimate is only valid in the so called decoupling limit where all non-standard Higgs bosons are significantly heavier than the Z gauge boson.

Keywords: MSSM, Decoupling Limit, Lightest CP-Even Higgs Boson (h), LHC

1. Introduction

The Higgs mechanism plays a key role for spontaneous breaking of the electroweak symmetry not only in Standard Model (SM) [1] but also in the Minimal Supersymmetric Standard Model (MSSM) [2,3,4].The main reason for introducing low energy supersymmetric theories in particle physicswas, in fact, their ability to solve the naturalness and hierarchy problems [5] . Indeed, the new symmetry prevents the Higgs boson mass from acquiring very large radiative corrections: the quadratic divergent loop contributions of the SM particles to the Higgs mass squared are exactly canceled 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 every quark, lepton, and gauge boson has a supersymmetric partner associated with it. Moreover, the 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 withsupersymmetry and by avoiding gauge anomalies due to the fermionic super partners of the Higgs bosons.

In the SM, the Higgs boson mass is usually considered as an adjustable parameter because the quartic coupling of the Higgs potential is arbitrary. The requirement of the vacuum stability yields a severe lower bound on the Higgs boson mass which depends on the top quark mass and the cut-off scale beyond which the SM is no longer valid [6,7], while an upper bound follows from the requirement that no landau singularity appears up to a scale [8].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 [9].

Plenty of works have been done regarding the theoretical upper bounds on the lightest Higgs mass in MSSM giving the lightest Higgs mass in MSSM to be $< 130\ GeV$ [10]. A detailed work for Higgs mass in MSSM is given in [11] which shows that the maximum value of the lightest Higgs boson mass in MSSM is ~ 135 GeV. Recently discovered ~125 GeV Higgs like boson at the CERN LHC rises a question : Is the scalar Higgs boson observed at the LHC, a supersymmetric Higgs boson or a Standard Model one ?

The purpose of the present paper is to throw light on the fact that in the decoupling limit the lightest CP- even Higgs boson (h) mimics the signature of the SM Higgs boson and it is possible to accommodate m_h ~125 GeV within the MSSM.

The paper is organized as follows : The effect of decoupling on tree level mass and coupling of MSSM Higgs is given in section 2. m_A independent decoupling phenomenon is analyzed in section 3. Discussions and conclusions are given in section 4.

2. Effect of Decoupling on Tree Level Mass and Couplings of MSSM Higgs

The MSSM contains two CP-conserving Higgs doublets with opposite hypercharge, which correspond to 8 independent states. After 3 of them are absorbed by the W and Z bosons, one is left with 5 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 only two parameters- the ratio of the two vacuum expectation values $tan\beta$ and the mass of the CP-odd Higgs boson usually taken to be m$_A$. Although m$_A$ is essentially unconstrained, apart from naturalness arguments suggesting that it should not be much larger than Fermi scale, the range of $tan\beta$ favoured by model calculations is $1 < tan\beta < \frac{m_t}{m_b}$, where m$_t$ and m$_b$ are the running top and bottom masses evaluated near the Fermi scale. The remaining tree level mass eigenvalues are then given by :

$$m_{H^\pm}^2 = m_w^2 + m_A^2 \ , m_{h,H}^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 \mp \sqrt{(m_A^2 + m_Z^2)^2 - 4m_A^2 m_Z^2 cos^2 2\beta}\ \right] \quad (1)$$

Leading to stringent inequalities such as $m_W, m_A < m_{H^\pm}, \ m_h < m_Z|cos2\beta| < m_Z < m_H \ and \ m_h < m_A < m_H$, holding at the classical level.

The couplings of the three neutralMSSM Higgs bosons to vector boson and fermion pairs are easily obtained from the SM Higgs couplings, by multiplying the latter by the α and β dependent factors where the angleα describes mixing between the CP-even neutral Higgs bosons.

In particular, relative to their SM values, the couplings of h[H] to down-type fermions are multiplied by$-\frac{Sin\alpha}{Cos\beta}\left[\frac{Cos\alpha}{Cos\beta}\right]$, and those of h[H] to up-type fermionsare multiplied by$\frac{cos\alpha}{sin\beta}\left[\frac{sin\alpha}{sin\beta}\right]$. This is shown in Table-1.

Table 1. *Important couplings of MSSM neutral Higgs bosons to fermion and vector boson pairs relative to those of the SM Higgs boson :*

Channel	H$_{SM}$	H	H	A
$\bar{b}b(\tau^+\tau^-)$	$\frac{gm_b}{2M_W}(m_\tau)$	$\frac{-sin\alpha}{cos\beta}$	$\frac{cos\alpha}{cos\beta}$	$-i\gamma_5 tan\beta$
$\bar{t}t$	$\frac{gm_t}{2M_W}$	$\frac{cos\alpha}{sin\beta}$	$\frac{sin\alpha}{sin\beta}$	$-i\gamma_5 cot\beta$
$WW(ZZ)$	$gm_W(m_Z)$	$sin(\beta-\alpha)$l	$cos(\beta-\alpha)$	0

All tree-level Higgs boson couplings can be computed in terms of the mixing angle α that is required to diagonalize the mass matrix of the neutral CP-even Higgs bosons, and is given by

$$\cos 2\alpha = -\cos 2\beta \frac{m_A^2 - m_Z^2}{m_H^2 - m_h^2}\ , -\frac{\pi}{2} < \alpha \le 0 \quad (2)$$

It can be noted that

$$\alpha \xrightarrow{m_A \gg m_Z} \beta - \frac{\pi}{2} \quad (3)$$

It is interesting to notice that in parameter space the so-called decoupling limit corresponds to $m_A \gg m_Z$ and $\alpha \to \frac{\pi}{2}$.

Couplings of MSSM neutral Higgs boson to fermion and vector boson pairs in the decoupling limit is shown in Table 2 below:

Table 2. *Couplings of MSSM neutral Higgs boson to fermion and vector boson pairs in the decoupling limit :*

Channel	H$_{SM}$	H	H	A
$\bar{b}b(\tau^+\tau^-)$	$\frac{gm_b}{2M_W}(m_\tau)$	1	$tan\beta$	$-i\gamma_5 tan\beta$
$\bar{t}t$	$\frac{gm_t}{2M_W}$	1	$cot\beta$	$-i\gamma_5 cot\beta$
$WW(ZZ)$	$gm_W(m_Z)$	1	0	0

In the decoupling limit we get from equation (2) as

$$m_H, m_{H^\pm} \ \to m_A$$

Thus in the decoupling limit H, A, H$^\pm$ are much heavier and nearly degenerate, forming an isospin doublet that decouples at sufficiently low energy. Moreover, in the decoupling limit, the light Higgs boson (h) couplings approach the SM values. The other Higgs bosons are not only heavy, but their most important couplings are also suppressed. Thus in the decoupling limit the lightest neutral Higgs boson (h) behaves much as the SM Higgs boson i.e. in the decoupling limit the MSSM Higgs sector is phenomenologically indistinguishable from the SM.

3. m$_A$-Independent Decoupling Phenomenon

The squared mass matrix of the CP-even neutral MSSM Higgs bosons h and H(where $m_h < m_H$) is given by

$$M^2 \equiv \begin{pmatrix} M_{11}^2 & M_{12}^2 \\ M_{12}^2 & M_{22}^2 \end{pmatrix} =$$

$$\begin{pmatrix} m_A^2 S_\beta^2 + m_Z^2 C_\beta^2 & -(m_A^2 + m_Z^2)S_\beta C_\beta \\ -(m_A^2 + m_Z^2)S_\beta C_\beta & m_A^2 C_\beta^2 + m_Z^2 S_\beta^2 \end{pmatrix} + \delta M^2$$

$$= M_0^2 + \delta M^2 \quad (4)$$

Where the tree-level contribution is denoted by M_0^2 and δM^2 is the contribution from the radiative corrections. $[C_\beta = Cos\ \beta$ and $S_\beta = Sin\ \beta$]

The mixing angle α which diagonalizes the mass matrix in equation (4) can be expressed as :

$$S_\alpha C_\alpha = \frac{M_{12}^2}{\sqrt{(TrM^2)^2 - 4\ det\ M^2}}\ , C_\alpha^2 - S_\alpha^2 = \frac{M_{11}^2 - M_{22}^2}{\sqrt{(TrM^2)^2 - 4\ det\ M^2}} \quad (5)$$

Where $S_\alpha = Sin\ \alpha$ and $C_\alpha = Cos\ \alpha$
From equation (5) we can write

$$Cos(\beta - \alpha) = \frac{(M_{11}^2 - M_{22}^2)Sin2\beta - 2M_{12}^2 Cos2\beta}{2(m_H^2 - m_h^2)Sin(\beta - \alpha)} =$$

$$\frac{m_Z^2 Sin4\beta + (\delta M_{11}^2 - \delta M_{22}^2)Sin2\beta - 2\delta M_{12}^2 Cos2\beta}{2(m_H^2 - m_h^2)Sin(\beta - \alpha)} \qquad (6)$$

Since, $\delta M_{ij}^2 \sim \mathcal{O}(m_Z^2)$ and $m_H^2 - m_h^2 = m_A^2 + \mathcal{O}(m_Z^2)$, in the decoupling limit $(m_A \gg m_Z)$ we obtain from equation (6) as

$$Cos(\beta - \alpha) = C\left[\frac{m_Z^2 Sin4\beta}{2m_A^2} + \mathcal{O}\left(\frac{m_Z^4}{m_A^4}\right)\right] \qquad (7)$$

Where

$$C = 1 + \frac{\delta M_{11}^2 - \delta M_{22}^2}{2m_Z^2 Cos2\beta} - \frac{\delta M_{12}^2}{m_Z^2 Sin2\beta} \qquad (8)$$

Moreover, we have noted earlier that in the decoupling limit $(\beta - \alpha) = 0$. However, from equation (6) $Cos(\beta - \alpha) = 0$ can be achieved by equating the numerator of equation (6) equal to zero and we get

$$2m_Z^2 Sin2\beta = 2\, \delta M_{12}^2 - tan2\beta(\delta M_{11}^2 - \delta M_{22}^2) \qquad (9)$$

It is interesting to note that equation (9) is independent of m_A. By approximating $tan2\beta \simeq -Sin2\beta = -\frac{2}{tan\beta}$ equation (9) yields a solution at large $tan\beta$. One can determine the value of β at which decoupling occurs :

$$tan\beta \simeq \frac{2m_Z^2 - \delta M_{11}^2 + \delta M_{22}^2}{\delta M_{12}^2} \qquad (10)$$

Hence, there exists a value of $tan\beta$ where $Cos(\beta - \alpha) \simeq 0$ independently of the value of m_A. This phenomenon is refered to as m_A −independent decoupling.

4. Discussions and Conclusions

It is well known that the upper bound of the mass of the lightest Higgs is $\sim 135\ GeV$ in MSSM. Recently $\sim 125\ GeV$ Higgs like particle has been discovered at the CERN LHC. Here a confusion arises about the observed Higgs- is it MSSM Higgs or SM Higgs ? The present paper throws light on the fact that in the decoupling limit the MSSM Higgs sector is phenomenologically indistinguishable from the SM. In the decoupling limit the light Higgs boson couplings approach the SM values. Moreover, it is analyzed that in the decoupling limit there exists a value of $tan\beta$ independently of the value of m_A. On the basis of the above discussions I come to the conclusion that it is possible to accommodate $m_h \sim 125\ GeV$ within the MSSM. 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.In this case, the precision measurements of the Higgs couplings at the linear collider will be a powerful means to disentangle between the various possible scenarios.

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