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Supersymmetry and Higgs Sector*

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Abstract

Some issues on the Higgs sector in supersymmetric models are discussed. Especially, the neutral Higgs mass bounds in the minimal supersymmetric standard model and its extensions are given. Also, comments on the possible constraint on the charged Higgs mass from the $b \to s\gamma$ process are given in the model based on supergravity.

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Supersymmetry and Higgs Sector [1]

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Some issues on the Higgs sector in supersymmetric models are discussed. Especially, the neutral Higgs mass bounds in the minimal supersymmetric standard model and its extensions are given. Also, comments on the possible constraint on the charged Higgs mass from the $b \to s\gamma$ process are given in the model based on supergravity.

1. Introduction

Unified models based on Supersymmetry (SUSY) are now considered to be one of the most promising candidates beyond the standard model (MS). Theoretically, SUSY was discovered about 20 years ago [1] and since early 80's extensions of the SM and grand unified theories (GUT) based on SUSY [2] have been discussed in connection with naturalness problem of the Higgs sector in the SM [3]. Recently, it has been pointed out that the Weinberg angle determined at the LEP experiments remarkably coincides with the prediction of the SU(5) SUSY GUT [4] and this is one of the reasons for the recent renewed attention to the SUSY models.

In order to prove SUSY experimentally we need to discover superpartners of the ordinary particles. In addition to searching superpartners, however, there is one good experimental check point of the SUSY models. That is to explore the Higgs sector which has very special features in the models. First of all, any SUSY model has to contain at least two Higgs doublets which are required to give mass terms for both up-type and down-type quarks without conflicting the symmetry. Therefore, a physical charged Higgs particle is a general consequence of the SUSY Higgs sector. Moreover, SUSY models always include at least one light neutral Higgs. In fact we can determine the upper bound of the lightest neutral Higgs mass in the minimal supersymmetric standard model (MSSM) and its extensions. This is in contrast with the superpartners' masses which do not have a definite upper bound.

In this talk we first describe why and how the upper bound of the lightest neutral Higgs boson mass is obtained in the MSSM and then comment on the possible constraint on the charged Higgs mass from the $b \to s\gamma$ process. Finally, we show that how the upper bound of the Higgs particles is modified in extended versions of the supersymmetric standard model.

2. The upper bound of the lightest Higgs mass in MSSM

[1]Talk given at the 9th Topical Workshop on Proton-Antiproton Collider Physics, October 1993, Tsukuba.

In the minimal standard model the Higgs mass is determined by the strength of its self coupling constant. Since it is an independent coupling constant the Higgs mass is essentially a new free parameter. In the MSSM the situation is different. Here the Higgs sector consists of two Higgs doublets. Physical particles are two neutral scalars (h, H), one pseudo scalar (A), and one pair of charged Higgs $(H^{\pm})$. The tree level potential is given by

$$\begin{aligned} V &= m_1^2|H_1|^2 + m_2^2|H_2|^2 - m_3^2(H_1H_2 + H_1^*H_2^*) \\ &\quad + \frac{g^2}{8}(H_1^\dagger\tau^a H_1 + H_2^\dagger\tau^a H_2)^2 + \frac{g'^2}{8}(H_1^\dagger H_1 - H_2^\dagger H_2)^2. \end{aligned} \tag{1}$$

The remarkable feature of this model is that the quartic term in the Higgs fields is completely specified by the SU(2) and U(1) gauge coupling constants. This is the reason for the following mass relations valid at the tree level [5],

$$m_h \leq m_Z|\cos 2\beta| \leq m_Z \leq m_H, \tag{2}$$

$$m_{H^\pm}^2 = m_A^2 + m_W^2, \tag{3}$$

where β is a angle between two vacuum expectation values defined as $\tan\beta = \frac{<H_2^0>}{<H_1^0>}$. The most important relation is the first relation of the above equations which means that the lightest neutral Higgs boson is always lighter than the Z^0 boson.

It was however pointed out recently that this tree level mass relations are modified due to the loop corrections of top and stop since the top Yukawa coupling constant is now expected to be large[6]. This loop correction induces a new finite term to the Higgs effective potential which is proportional to the fourth order of the top quark mass. When the stop mass is larger than the top mass the upper bound of the lightest neutral Higgs boson mass increases compared to the tree level prediction. If we neglect the mixing effect of two stop states, the upper bound is given by the following simple formula.

$$m_h^2 \leq m_Z^2\cos^2 2\beta + \frac{6}{(2\pi)^2}\frac{m_t^4}{v^2}\ln\frac{m_{stop}^2}{m_t^2}. \tag{4}$$

Here, m_t, m_{stop} are the top mass and stop mass respectively and v=246 GeV. The upper bound of the lightest neutral Higgs mass is shown in figure 1 as a function of the top mass. The mass bound of this figure is calculated by the improved method using renormalization group equations as explained in ref. [7]. For the 150 GeV top mass, the maximum possible value of the lightest Higgs becomes approximately 120 GeV. Note that this correction term essentially represents a SUSY breaking effect as we can see from the fact that it vanishes in the case that the top and stop masses degenerate.

The modification of the upper bound gave an immediate impact on the Higgs search strategy for the MSSM. First of all, this bound exceeds the possible search limit of the LEP II experiment. MSSM cannot be excluded even if Higgs is not found there. This makes the Higgs search at future hadron colliders or e^+e^- linear colliders more important. The mass range of the lightest neutral Higgs enters into so-called intermediate mass region where the Higgs search is not so easy for hadron colliders because careful analysis using the rare two

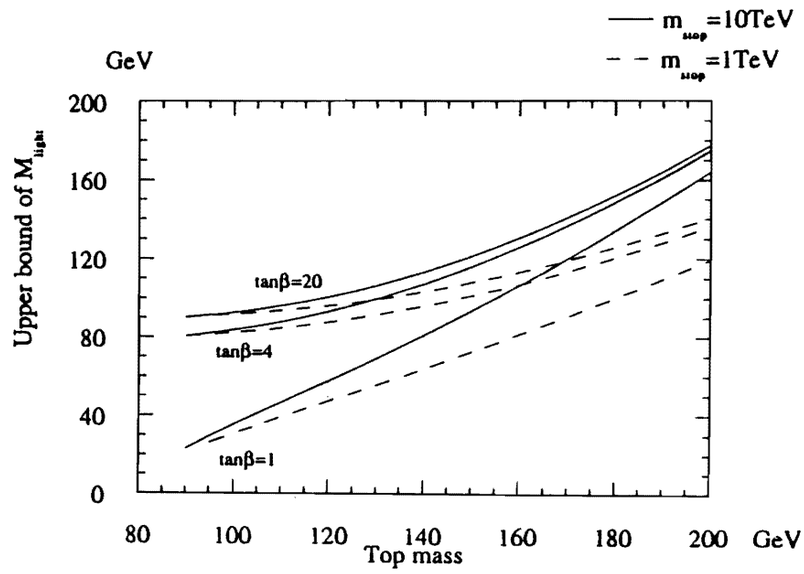

Figure 1: The upper bound of the lightest neutral Higgs mass in the MSSM for various $\tan\beta$ values and two extreme SUSY breaking scales. The solid line corresponds to the case that the stop mass is 10 TeV and the left-right stop mixing parameter (A term) is $\sqrt{6}$ and the dashed line the case that the stop mass is 1 TeV and A=0.

photon decay mode is required. Detailed investigations show that there remains a hole in the Higgs parameter space in terms of $(m_A, \tan\beta)$ where none of the Higgs particles is discovered in the future hadron collider like LHC, even if we assume that the detector is good enough to cover the standard model Higgs of intermediate mass region[8]. In such case, to explore the Higgs sector of the MSSM, an e^+e^- linear collider with a center of mass energy about 300 GeV is necessary and therefore the SUSY Higgs becomes one of the main targets for the project like JLC-I[9].

3. Charged Higgs and the $b \to s\gamma$ process

Recently, the $b \to s\gamma$ transition was reported from CLEO collaboration in the mode $B \to K^*(892)\gamma$ at the branching ratio of $(4.5 \pm 1.5 \pm 0.9) \times 10^{-5}$ and also the upper bound of the inclusive $b \to s\gamma$ branching ratio is given by 5.4×10^{-4} at 95% C.L[10]. Since this value is already close to the SM prediction $(3 \sim 4) \times 10^{-4}$ this process becomes very effective to put constraints on new physics beyond SM [11]. Especially, in a simple two Higgs doublet of the SUSY type the charged Higgs effect always gives a constructive interference with the SM contribution, and the charged Higgs mass less than about 200 GeV is almost excluded from the present experimental upper bound. Since this range of the charged Higgs mass corresponds to the hole of the parameter space of the MSSM from the Higgs search of hadron colliders [12], it is very important to see how the SUSY parameter space is constrained from this process.

In the SUSY standard model, the $b \to s\gamma$ transition is induced not only by the W

boson and the charged Higgs loops but also the following three new loop contributions; 1)charginos and up-type squarks, 2) gluino and down-type squarks, 3) neutralinos and down-type squarks. These contributions depend on the masses and the mixings of the particles inside the loop. For general SUSY models these parameters are free parameters. On the other hand if we consider models based on supergravity these parameters can be determined from the initial conditions at the GUT scale by solving the renormalization group equations for these masses and other relevant parameters. In this way the flavor changing neutral current (FCNC) processes like the $b \to s\gamma$ get connections with the mechanism of the SUSY breaking at very high energy. From the phenomenological side, the $K^0 - \bar{K}^0$ mixing puts severe constraints on the masses and the mixings of the squark sector[13]. This constraint is satisfied in the content of the minimal supergravity where the SUSY breaking effects at the GUT scale are universal for all scalar particles because we can show that the squarks of the first two generations are highly degenerate in this model. Since the $b \to s\gamma$ process depends on the squarks of the third generation the constraints from this process gives an independent informations on the squark mass matrices.

From this point of views many authors considered the constraints obtained from the $b \to s\gamma$ process in the supersymmetric standard model[14]. Since we have many free parameters even if the minimal supergravity is assumed it is still not easy to obtain general conclusions, but important observations are the followings. The chargino and gluino contributions can be sizable and have either sign compared to the SM and charged Higgs contributions whereas the neutralino contributions are very small. If their contributions are negative it is possible, after taking account of phenomenological constraints from superparticles' searches, that a positive charged Higgs contribution is completely cancelled by the other SUSY contributions even when the charged Higgs mass is less than 200 GeV. Therefore, the sensitivity to the charged Higgs mass is in general lost in the SUSY models. Since the chargino and stop loop contribution changes its sign for the different parameter regions of the higgsino mass parameter μ and the squark left-right mixing parameter it is difficult to specify its sign without any further input. On the other hand to cancel the positive charged Higgs contribution the relatively light chargino mass is required. Therefore if the $b \to s\gamma$ branching ratio turns out to be consistent with the SM prediction, we can say either that the chargino and charged Higgs are both relatively light and they cancel each other, or that the charged Higgs itself is heavy, if we assume the SUSY model. An interesting possibility is that the charged Higgs less than 200 GeV is in fact discovered in the top decay or even at LEP II which would strongly suggest that some other contribution like SUSY has to exist to cancel the charged Higgs contribution. Note that although the charged Higgs mass less than 90 GeV is not probable for the MSSM but can be realized in the extended versions of the SUSY standard model with a gauge singlet Higgs or extra matter multiplets [15]. Such models are considered in the next section.

4. The Higgs mass bound in extended SUSY models

Here we present the Higgs mass bound in the extended versions of SUSY models. In the MSSM, the bound of the lightest neutral Higgs boson is basically determined by the SU(2) and U(1) gauge coupling constants and, through the radiative correction, the top quark

mass. If the model is extended the lightest neutral Higgs mass in general depends on other coupling constants, therefore, without further assumption, no bound is obtained. On the other hand, if some coupling constants becomes large at the electroweak scale, we can show that such a model cannot be incorporated in the GUT scenario since some of the coupling constants becomes very large before reaching the GUT scale. Therefore, if we require that any coupling constant does not blow up below the GUT scale, we can determine the maximum possible value of the coupling constant and derive the upper bound.

If we want to keep the successful prediction of the Weinberg angle of the SUSY SU(5) GUT, we have only two possibilities to raise the upper bound. Firstly, we can add extra matter supermultiplets and introduce new Yukawa coupling constants[16, 17]. Then, the radiative correction due to these new coupling constants can increase the upper bound of the lightest neutral Higgs boson. Within the SU(5) GUT scenario we can list up all the possibilities for the numbers and representations of the matter multiplets. As explained in ref. [17] the maximum value for the lightest Higgs mass obtained in this way is, for the 1 TeV squark mass, about 180 GeV in a model with an extra family and its mirror partner. Interestingly, this bound is almost independent of the top quark mass.

The second possibility is to include a gauge singlet Higgs. In this case the tree level mass relation itself is modified due to a new coupling in the superpotential; $W \sim \lambda H_1 H_2 N$ where the N is a singlet and H_1 and H_2 are two doublet Higgses [18]. Including the top and stop loop effects the upper bound is given by

$$m_{h_1}^2 \leq \frac{\lambda^2}{2} v^2 \sin^2 2\beta + m_Z^2 \cos^2 2\beta + \frac{6}{(2\pi)^2} \frac{m_t^4}{v^2} \ln \frac{m_{stop}^2}{m_t^2}. \tag{5}$$

If we require that any of the dimensionless coupling constants do not blow up below the GUT scale we can determine the upper bound of the lightest neutral Higgs mass m_{h_1} as a function of m_t[17, 19]. Using the renormalization group approach described in ref. [17] the upper bound is calculated and the result is shown in figure 2. (An error in the calculation for the solid line with $a_{top} = \sqrt{6}$ in ref. [17] is corrected here.) This shows that for the stop mass 1 TeV the upper bound becomes about 140 GeV. For a relatively light top mass λ can be large then the first term of the right hand side of the above equation becomes larger than the last term, whereas if the top is as large as 180 GeV the top Yukawa coupling constant itself is close to the blow-up bound and there is little room for λ. Therefore, the resulting upper bound does not strongly depend on the top mass.

Since this model contains a singlet Higgs the upper bound of the lightest Higgs only does not guarantee the discovery of the Higgs below that energy since when the lightest one is an almost pure singlet it could easily escape detection. In such case the upper bound of the heavier Higgses becomes important. Fortunately, we can set a fairly strong upper bound in the region where a singlet component of the lightest Higgs is large[20]. The figure 3 shows the contour plot of the second lightest Higgs mass in the space of the lightest Higgs mass and the standard model Higgs component of the lightest Higgs, $|v_{11}|^2$. In fact, $|v_{11}|^2$ is proportional to the cross section of the $e^+e^- \to Z^0 h_1$ process normalized by the corresponding one of the

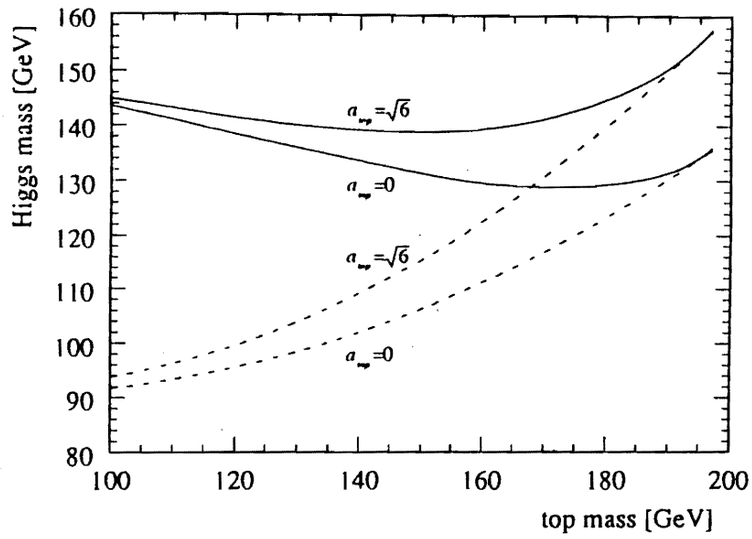

Figure 2: The upper bound of the lightest neutral Higgs boson mass in the model with a gauge singlet. The stop mass parameter is taken as 1 TeV and the stop left-right mixing parameter a_{top} is taken as 0 and $\sqrt{6}$. The solid line and the dashed line correspond to the upper bound for the model with a singlet and that for the MSSM, respectively.

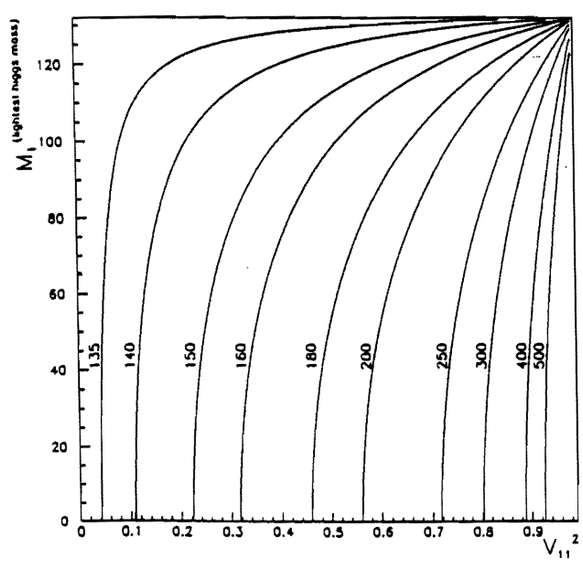

Figure 3: The contour plot for the upper bound of the second lightest neutral Higgs mass in the parameter space of the the lightest neutral Higgs mass and $|v_{11}|^2$. This figure corresponds to the case that the top mass is 150 GeV and the stop mass is 1 TeV. Numbers in GeV.

standard model Higgs, i.e,

$$|v_{11}|^2 = \frac{\sigma(e^+e^- \to Z^0 h_1)}{\sigma(e^+e^- \to Z^0 h_{SM})}, \tag{6}$$

where h_1 and h_{SM} represent the lightest Higgs and the standard model Higgs respectively. This figure corresponds to the case where the top mass is 150 GeV, the stop mass is 1 TeV, and the resulting upper bound of the lightest Higgs is 132 GeV. We can see that when the lightest Higgs becomes almost pure singlet, therefore $|v_{11}|^2$ is small, then the upper bound of the second lightest Higgs approaches to the value of the lightest mass bound. Therefore we can see that even in such case at least one doublet-like Higgs always exists in the intermediate mass region.

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