Current Experimental Constraints on NMSSM with Large (Postprint)

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Full Text

Preamble

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Current Experimental Constraints on NMSSM with Large

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Abstract

The next-to-minimal supersymmetric model (NMSSM) with a large (the mixing parameter between the singlet and doublet Higgs fields) is well motivated since it can significantly push up the upper bound on the SM-like Higgs boson mass to solve the little hierarchy problem. In this work we examine the current experimental constraints on the NMSSM with a large , which include the direct search for Higgs bosons and sparticles at colliders, the indirect constraints from precision electroweak measurements, the cosmic dark matter relic density, the muon anomalous magnetic moment, as well as the stability of the Higgs potential. We find that, with the increase of , parameters like tan , M_A, and M_2 are becoming more stringently constrained. It turns out that the maximal

reach of is limited by the muon anomalous magnetic moment, and for smuon masses of 200 GeV (500 GeV) the parameter space with 1.5(0.6) is excluded.

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Introduction

Since the minimal supersymmetric standard model (MSSM) suffers from the -problem and the little hierarchy problem, some non-minimal supersymmetric models have recently attracted much attention, among which the most intensively studied is the next-to-minimal supersymmetric standard model (NMSSM). In the NMSSM there are no dimensionful parameters in the supersymmetry-conserving sector and the term is dynamically generated through the coupling between the two Higgs doublets and a newly introduced singlet Higgs field which develops a vacuum expectation value of the order of the SUSY breaking scale.

The NMSSM provides two ways to alleviate the little hierarchy problem. One is to relax the LEP II lower bound on the mass of the SM-like Higgs boson, h, by diluting the ZZh coupling through the singlet component of h and/or by suppressing the visible decay h → b¯b through introducing new decay modes of h. The other is to push up the Higgs boson mass with a large , which can be seen from the tree-level upper bound of the Higgs boson mass:

$$h_{\max} \simeq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta$$

where tan = H_u / H_d , v² = H_u ² + H_d ² and is the mixing parameter between the singlet and doublet Higgs fields defined in Eq.(2).

Note that the choice of a large to solve the little hierarchy problem may be limited by the perturbativity of the theory at the scale Λ since the value of increases with the energy scale. If this scale Λ is the grand unification (GUT) scale, should be less than about 0.7 at the weak scale, leading to an upper bound on the Higgs boson mass of about 150 GeV. However, the bound on from perturbativity considerations can be relaxed by embedding the NMSSM in some more complex frameworks. For example, in the Fat Higgs model, by completing the NMSSM (or NMSSM-like models) with an appropriate strong dynamics at an intermediate scale (much lower than the GUT scale), can be as large as 2 at the weak scale and the Higgs boson mass can be pushed up to about 400 GeV.

In this work, regardless of the detailed forms of the ultraviolet physics, we treat the NMSSM as an effective theory and examine the current experimental constraints on its parameter space. Such phenomenological studies on the Higgs boson and supersymmetry are pressing since the mystery of the Higgs sector will be unveiled at the LHC in the near future. If the SM-like Higgs boson is discovered with a mass above the MSSM upper bound, the NMSSM (or other NMSSM-like models) with a large , generally called SUSY, will be immediately favored since it not only inherits all the advantages of the MSSM, such as unifying gauge couplings and providing a dark matter candidate, but also is free from the -problem and the little hierarchy problem.

For the phenomenological studies of these models, a primary work is to examine the current experimental constraints on their parameter space. We note that various constraints on the NMSSM have been studied in the literature, but different constraints were considered in different papers. For example, in some works the authors mainly considered the LEP II constraints and put emphasis on the small case. The package NMSSMTools encodes various constraints (like the LEP II searches for the Higgs boson, the cosmic dark matter relic density, and the stability of the Higgs potential), but it is still not complete since it does not include the indirect constraints from precision electroweak measurements and the muon anomalous magnetic moment. In this work we consider all these constraints and especially focus on the case with a large . As will be shown from our study, with the increase of , the parameter space becomes more stringently constrained. To figure out the allowed parameter space is helpful for exploring such low-energy supersymmetry at the LHC and may also shed some light on constructing the ultraviolet physics from a bottom-up perspective.

This paper is organized as follows. In Sec. II we briefly describe the structure of the NMSSM with emphasis on its differences from the MSSM. In Sec. III we summarize the constraints considered in this work and briefly discuss their characteristics. In Sec. IV we scan over the NMSSM parameter space and display the region allowed by all these constraints. In Sec. V we give our conclusions.

II. About the NMSSM

The NMSSM extends the matter fields of the MSSM by adding one gauge singlet superfield Ŝ, and its superpotential takes the form:

$$W = \lambda \varepsilon_{ij} \hat{H}_u^i \hat{H}_d^j \hat{S} + \frac{\kappa}{3} \hat{S}^3 + Y_u \varepsilon_{ij} \hat{Q}^i \hat{U} \hat{H}_u^j - Y_d \varepsilon_{ij} \hat{Q}^i \hat{D} \hat{H}_d^j - Y_e \varepsilon_{ij} \hat{L}^i \hat{E} \hat{H}_d^j$$

where $\hat{Q}, \hat{U}$ and $\hat{D}$ are squark superfields, $\hat{L}$ and $\hat{E}$ are slepton superfields, and $\hat{H}_u$ and $\hat{H}_d$ are Higgs doublet superfields. The soft SUSY breaking terms are given by standard expressions involving mass terms and trilinear couplings.

Note that just like the MSSM, the NMSSM has the feature that SUSY breaking induces electroweak symmetry breaking. Before SUSY breaking (i.e., without the soft breaking terms), the Higgs scalars have zero vevs in the supersymmetric vacuum of the scalar potential and thus the electroweak symmetry is not broken. After SUSY breaking (i.e., with the soft breaking terms), the Higgs scalars develop non-zero vevs in the physical (non-supersymmetric) vacuum of the scalar potential and hence the electroweak symmetry is spontaneously broken and the parameter is generated as = S . Since both the electroweak symmetry breaking and the parameter generation are induced by SUSY breaking, their scales should naturally be at the SUSY breaking scale (the scale of soft breaking mass parameters).

The differences between the NMSSM and MSSM come from the Higgs sector and the neutralino sector. In the Higgs sector of the NMSSM there are three CP-even and two CP-odd Higgs bosons. In the basis [Re(H_d^0), Re(H_u^0), Re(S)], the mass-squared matrix elements for CP-even Higgs bosons are given by standard expressions. In the basis [Ã, Im(S)] with Ã = cos Im(H_u^0) + sin Im(H_d^0), the mass-squared matrix elements for the CP-odd Higgs bosons are similarly defined. As shown in Eq.(10), we can choose m_A instead of A_ as a free parameter. So compared with the MSSM, the NMSSM has three additional parameters: , and A_ . Conventionally, is chosen to be positive while and A_ can be either positive or negative. Note that the parameters and affect the mixings between doublet and singlet Higgs fields, while A_ only affects the squared-mass of the singlet Higgs field.

In the neutralino sector, the NMSSM predicts one extra neutralino. In the basis (−i _1, −i _2, _u^0, _d^0, _s) the neutralino mass matrix is given by standard expressions. This mass matrix is independent of A_ , and the role of is to introduce the mixings of _s with _u^0 and _d^0, while affects the mass of _s. In the limit , → 0, the singlet field has no mixing with the doublet fields and thus is decoupled. In this case, the NMSSM can recover the MSSM.

III. Constraints on the NMSSM Parameters

Before we proceed to discuss experimental constraints on the parameters of the NMSSM, we examine the bounds on and from the requirement that the theory should remain perturbative up to a certain scale Λ. The renormalization group equations (RGEs) for and under the scale Λ take the following form:

$$\frac{d\lambda}{d\ln\mu} = \frac{1}{16\pi^2}\left(4\lambda^2 + 2\kappa^2 + 3Y_t^2 + 3Y_\tau^2 - 3g^2 - g'^2\right)\lambda$$

$$\frac{d\kappa}{d\ln\mu} = \frac{1}{16\pi^2}\left(6\lambda^2 + 6\kappa^2\right)\kappa$$

where g and g are the SU(2)_L and U(1)_Y gauge couplings. These RGEs indicate that the values of and increase with the energy scale. The requirement of perturbativity up to the cutoff scale Λ, i.e., (Λ) 2 and (Λ) 2 , will set upper bounds on and at the weak scale (throughout this paper, without specification all input parameters are defined at the weak scale). For example, if we assume that new dynamics appears at Λ = 10 TeV, we get ² + ² 4.2 and for > 1.5, must be less than 1.2; while if Λ is chosen to be the GUT scale, a stringent bound ² + ² 0.5 is obtained. In our numerical study we let and vary below 2 and 1, respectively, and this corresponds to setting Λ 10 TeV.

In our study we consider the following constraints on the parameters of the NMSSM:

1. **Constraints on the neutralino and chargino sector**, which include: the bound from invisible Z decay Γ(Z → _1^0 _1^0) < 1.76 MeV; the upper bounds on neutralino pair production at LEP II (e e → _i^0 _j^0) < 10 2 pb (i > 1) and (e e → _1^0 _i^0) < 10 1 pb; and the LEP II bound on the lightest chargino mass m_ ^+ > 103.5 GeV. These bounds mainly constrain the parameters M_1, M_2 and .
2. **Lower bounds on sparticle masses** from LEP and Tevatron experiments: m_ẽ > 73 GeV, m_˜ > 94 GeV, m_˜ > 81.9 GeV, m_q̃ > 250 GeV, m_t̃ > 89 GeV, m_b̃ > 95.7 GeV, m_g̃ > 195 GeV, where m_q̃ denotes the masses for the first two generation squarks. These constraints put lower bounds on the soft breaking masses for sleptons and squarks.
3. **The LEP II lower bound on the charged Higgs boson mass**, m_H > 78.6 GeV, which gives a lower bound on m_A through the relation m_H ² = m_W² - ½ ²v².
4. **Constraints from the direct search for Higgs bosons at LEP II**, which include various channels of Higgs boson productions. They constrain the parameters m_A, tan , as well as the masses and the chiral mixing of top squarks in a complex way.
5. **Constraint from the relic density of cosmic dark matter**, i.e., 0.0945 < Ωh² < 0.1287, assuming the lightest neutralino is the dark matter particle. The relic density constrains the parameters M_1, M_2, , m_A, tan and in a complex way.
6. **Constraint from the stability of the Higgs potential**, which requires that the physical vacuum of the Higgs potential with non-vanishing vevs of Higgs scalars should be lower than any local minima. Also, the scale of the Higgs soft breaking parameters should not be much higher than the electroweak scale to avoid the fine-tuning problem. Here we set 1 TeV as the upper bound of the soft breaking parameters in the Higgs sector. This constrains the parameters m_A, , A_ , and tan .
7. **Constraints from precision electroweak observables** such as _lept, sin² _eff^lept and M_W, or their combinations _i(i = 1, 2, 3). We require the predicted _i in the NMSSM to be compatible with the LEP/SLD data at 95.6% confidence level or equivalently ²/dof 8.1/3. We take the correlation coefficient of _i from the literature in calculating ². This requirement constrains the parameters tan , m_A as well as the soft breaking parameters in the third generation squark sector.
8. **Constraint from R_b = Γ(Z → b¯b)/Γ(Z → hadrons)**, whose measured value is R_b^exp = 0.21629 ± 0.00066 and the SM prediction is R_b^SM = 0.21578 for m_t = 173 GeV. In our analysis we require R_b^SUSY to be within the 2 range of its experimental value. It has

been shown that the SUSY contribution to R_b might be sizeable for large tan .

9. **Constraint from the muon anomalous magnetic moment a_ .** Now both the theoretical prediction and the experimental measurement of a_ have reached remarkable precision, but they show a significant deviation a_ ^exp - a_ ^SM = (29.5 ± 8.8) × 10^{1} . In our analysis we require the SUSY effects to account for such deviation at the 2 level. The character of the SUSY contribution to a_ is that it is suppressed by smuon masses but enhanced by tan .

Among the above constraints, (1-6) and (9) have been encoded in the package NMSSMTools. In our calculations we extend it by including constraints (7) and (8). The analytic expressions of _i and R_b in the NMSSM were given in our recent work. We also calculated the NMSSM contribution to a_ (when we started that work, the results in some references had not yet been published), where we extended the neutralino- and chargino-mediated MSSM contributions to the NMSSM and also considered the contributions from the Higgs-mediated diagrams and from the Barr-Zee diagrams. We checked that our a_ results agree with those in the literature.

Note that in our analysis we did not include the constraints from various B-decays because they are dependent on squark flavor mixings and thus involve additional parameters.

IV. Allowed Regions of the NMSSM Parameters

In this section, we scan over the NMSSM parameter space to identify the region allowed by the constraints in the preceding section. Since we are interested in the parameters sensitive to the constraints, we make some assumptions (as conservative as possible) for the other parameters such as soft breaking parameters in the squark, slepton and gaugino sectors.

For the parameters in the squark sector, we assume the so-called m_max scenario, which can maximize the lightest Higgs boson mass. This scenario assumes all the soft breaking masses in the squark sector to be degenerate M_q = M_Qi = M_Ui = M_Di with i being the generation index. It also assumes the trilinear couplings to be degenerate A_ui = A_di with (A_ui - cot)/M_q = 2. We fix M_q = 1 TeV in our analysis since large M_q can not only enhance the lightest Higgs boson mass, but also decrease the contribution of the third generation squarks to the electroweak parameters, which has the same sign as the Higgs contributions.

For the parameters in the slepton sector, we note that the slepton masses affect little the constraints except for the muon anomalous magnetic moment. In our calculation we assume all the soft breaking parameters in the slepton sector are degenerate and take a value of 200 GeV (we will discuss the effects of its variation). For the gaugino mass parameters, we assume the grand unification relation M_1 = (5/3)(g' ²/g²)M_2.

With the above assumptions, the free parameters are reduced to seven (, , A_ , tan , m_A, , M_2) and within the capability of our computer to perform a scan. During our scan, we first divide the varying range of into bins with each bin width being 0.1 and then we vary the values of other parameters in the following ranges:

$$-1 \leq \kappa \leq 1, \quad 1 \leq \tan\beta \leq 60, \quad -1 \text{ TeV} \leq A_\kappa < 1 \text{ TeV},$$

$$50 \text{ GeV} \leq M_A, \mu, M_2 \leq 1 \text{ TeV}.$$

With two hundred million samples in each bin and keeping the points satisfying the constraints, we finally obtain the allowed regions of these parameters. Our scan results indicate that the number of survived samples for < 0.5 is much larger than that for > 0.5, which means that the parameters for small are much less constrained than the case with large . Since we are interested in large , here we only show our scan results for > 0.5.

In Fig.1 we display the parameters (scatter plots) satisfying all the constraints (1-9) in the plane of versus tan . Also, we present a curve which is the upper bound on tan without considering the muon g-2 constraints. To obtain this curve, we fix and scan over the parameters in the allowed ranges. We adopt the important sampling method to optimize the varying range of tan .

Fig.1 shows that the upper bound on tan gets stronger as gets large, and when all constraints are considered, is upper bounded by about 1.5. The underlying reason for this is that constraints (1-8), especially constraint (7), have limited the maximal value of tan , which decreases with the increase of . Since a large tan is needed to explain the deviation of the muon g-2, must terminate at a certain value where the corresponding tan value is too small to explain the muon g-2. We have checked that the maximal value of depends on the slepton mass. For example, for slepton masses of 100 GeV, 280 GeV and 500 GeV, the bounds on are 2, 1 and 0.6, respectively.

In Fig.2 we display the NMSSM parameters satisfying all the constraints in different planes. We see that for a large the parameters m_A, , M_2 and A_ are also bounded in certain regions. For $= 1$, these bounded regions are:

$$400 \text{ GeV} \lesssim M_A \lesssim 800 \text{ GeV},$$

$$150 \text{ GeV} \lesssim \mu \lesssim 250 \text{ GeV},$$

$$150 \text{ GeV} \lesssim M_2 \lesssim 300 \text{ GeV},$$

$$A_\kappa \lesssim 600 \text{ GeV}.$$

From the figure of M_A versus in Fig.2 one can see that the lower bound of M_A increases as becomes large. The reason is that the LEP II direct search for Higgs bosons mainly limits the mass and couplings of the light CP-even Higgs boson whose component is dominated by the doublet Higgs field H_u or H_d. For tan > 1, this Higgs boson should be dominantly composed of the H_u field since M_{S,11}² is smaller than M_{S,22}², and its mass is reduced by the off-diagonal elements M_{S,12}² and M_{S,13}². As gets larger, these off-diagonal elements get larger and hence reduce the mass of the light CP-even Higgs boson, which then requires a larger M_A to compensate in order to satisfy the LEP II lower bound.

The figure of versus in Fig.2 indicates that with the increase of , the upper bound of decreases. This is because in the off-diagonal elements M_{S,13}² and M_{S,23}² (which reduce the light CP-even Higgs boson mass), is always associated with , and to meet the LEP II bound a large must be accompanied by a small .

The figure of M_2 versus in Fig.2 shows that M_2 is also bounded in a narrow region. This is because the relic density of dark matter correlates the parameters m_A, , M_2, and tan in a complex way, and a large value for any of these parameters will severely limit the region of other parameters.

The figure of A_ versus in Fig.2 shows that the trilinear soft breaking parameter A_ for the singlet field is also limited. This can be understood from the expressions of M_{P,11}² and M_{P,22}². The stability of the Higgs potential requires both of them to be positive, which sets a double-sided bound on A_ .

We also studied the relationship between the Yukawa couplings and , and we found no correlation between them. Even for = 1.5, the value of can still vary from 0.3 to 1.

Next, we examine the Higgs boson masses allowed by the constraints. Since a large can enhance the lightest CP-even Higgs boson mass and thus avoid the little hierarchy problem, it is interesting to look at the dependence of the Higgs boson masses on the parameter .

In Figs.3 and 4 we show our scan results in the versus m_h plane and versus m_a plane, with m_h being the lightest CP-even Higgs boson mass and m_a the lighter CP-odd Higgs boson mass. From Fig.3 one can learn that the upper bound of m_h increases with , which is expected from Eq.(1), and for = 1.5 the value of m_h can reach 210 GeV. From Fig.4 one can learn that with the increase of , a super-light CP-odd Higgs boson is gradually ruled out, and for > 1 it is bounded in the range 100 GeV m_a 600 GeV. The properties of these Higgs bosons can be quite different from those in the MSSM, and their phenomenology at the LHC was discussed in the literature.

Finally, in order to understand the mechanism used to reproduce the correct dark matter abundance, we consider the properties of the neutralino sector. In the NMSSM with large tan , the component of the lightest neutralino is either higgsino-dominant or bino-dominant for a light mass below 80 GeV, but for a heavier mass it is bino-dominant. In Fig.5 we show our scan results in the plane of m_˜ versus . We see that with the increase of , the upper bound on m_˜ becomes stringent and eventually it is constrained in the range of 50-100 GeV. Regarding the next lightest neutralino ˜ , we find that its mass is constrained in the range of 100-160 GeV for > 1.2.

In order to figure out the annihilation mechanism of ˜ in providing the dark matter relic density, we compare the masses of ˜ and the CP-odd Higgs boson a with m_˜ in Fig.6. This figure indicates that ˜ is significantly heavier than ˜ , and since in our scan the slepton masses are fixed to 200 GeV, they are also significantly heavier than ˜ . We conclude that the coannihilation of ˜ with ˜ or with sleptons is generally Boltzmann-suppressed and plays an unimportant role in accounting for the dark matter relic density. Note that, as shown in Fig.6, there are some samples around the funnel region 2m_˜ m_a, and in this case the annihilation of ˜ through the s-channel exchange of a light a becomes dominant.

V. Conclusion

The NMSSM with a large is an attractive scenario since it can push up the upper bound on the SM-like Higgs boson mass to solve the little hierarchy problem. We examined the current experimental constraints on this scenario, which include the direct experimental bounds, the indirect constraints from precision electroweak measurements, the cosmic dark matter relic density, the muon anomalous magnetic moment, as well as the stability of the Higgs potential. Our results showed that for a large the parameter space is severely constrained. For example, for a smuon mass of 200 (500) GeV the parameter space with 1.5(0.6) is excluded, and for = 1 the allowed ranges are 2.5-4 for tan , 400-800 GeV for M_A, 150-250 GeV for , 150-300 GeV for M_2 and 0-600 GeV for A_ .

Finally, we would like to point out that our conclusion may be qualitatively applicable to other NMSSM-like models such as the Minimal Non-minimal Supersymmetric Standard Model (MNMSSM), which has a similar structure to the NMSSM and can be viewed as the low-energy realization of the Fat Higgs model. For example, it has been pointed out that for any singlet extensions of the MSSM, regardless of the form of its superpotential, a large is always accompanied by a small tan . This property, as shown in our paper, can either limit the smuon mass or limit if we require the theory to explain the deviation of the muon anomalous magnetic moment. Another example is about the constraint from dark matter. In the MNMSSM we expect that the constraint can limit the relevant parameters in a more stringent way than in the NMSSM since the neutralino sector in the MNMSSM is exactly the same as in the NMSSM but with fixed = 0.

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Note: Figure translations are in progress. See original paper for figures.