Status of low energy SUSY models confronted with the LHC 125 GeV Higgs data (Postprint)

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Abstract

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Full Text

Status of Low-Energy SUSY Models Confronted with the LHC 125 GeV Higgs Data

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Abstract

Confronted with LHC data indicating a Higgs boson around 125 GeV, different models of low-energy supersymmetry (SUSY) exhibit distinct behaviors: some are favored, some marginally survive, and some are strongly disfavored or excluded. In this note, we update our previous scans over the parameter spaces of various low-energy SUSY models by incorporating the latest experimental limits, including the LHCb data for $B_s \to \mu^+\mu^-$ and the XENON100 (2012) data for dark matter-nucleon scattering. We then confront the predicted properties of the SM-like Higgs boson in each model with the combined 7 TeV and 8 TeV Higgs search data from the LHC. For a SM-like Higgs boson around 125 GeV, we obtain the following observations: (i) The most favored model is the NMSSM, whose predictions about the Higgs boson can naturally (without any fine-tuning) agree with the experimental data at the 1σ level, performing even better than the SM; (ii) The MSSM can fit the LHC data quite well but suffers from some degree of fine-tuning; (iii) The nMSSM is excluded at the 3σ level after considering all available Higgs data; (iv) The CMSSM is quite disfavored since it is difficult to produce a 125 GeV Higgs boson mass while simultaneously enhancing the di-photon signal rate.

I. Introduction

The LHC experiments have reported compelling evidence for a Higgs boson around 125 GeV. Combining the 7 TeV and 8 TeV data, the ATLAS and CMS collaborations have separately obtained a 5σ local significance [?, ?, ?]. This observation is corroborated by Tevatron results showing a 2.5σ excess in the range 115–135 GeV [?]. Although the limited data show consistency with the SM prediction, the best-fit results nevertheless favor a non-standard Higgs [?, ?, ?]. In fact, ever since this 125 GeV particle was first hinted at last year, analyses of its properties were quickly performed in new physics models, such as low-energy SUSY models [?, ?, ?, ?, ?, ?, ?] and some non-SUSY models [?].

For SUSY models, the following observations were obtained: (i) The minimal gauge mediation SUSY breaking model (GMSB) and anomaly mediation SUSY breaking model (AMSB) cannot predict a SM-like Higgs boson as heavy as 125 GeV without incurring severe fine-tuning [?], while the constrained minimal supersymmetric standard model (CMSSM) and the minimal supergravity model (mSUGRA) can marginally accommodate a 125 GeV Higgs boson [?, ?]; (ii) The minimal supersymmetric standard model (MSSM), the nearly minimal supersymmetric model (nMSSM), and the next-to-minimal supersymmetric model (NMSSM) can readily predict a 125 GeV Higgs boson [?], but the MSSM suffers from some fine-tuning [?] and the nMSSM severely suppresses the di-photon signal rate [?, ?].

With the 8 TeV data, the statistics are much larger than last year' s 7 TeV data, enabling more accurate Higgs information to be extracted and allowing us to test different new physics models. Although one can roughly envisage that some models are (dis)favored by the data, it is necessary to directly confront the model predictions with experimental data and show in detail their extent of compatibility. For this purpose, we consider four low-energy SUSY models —the CMSSM, MSSM, NMSSM, and nMSSM—and compare the predictions of each model, such as Higgs signal rates, decay branching ratios, and couplings, with the latest data. These predictions are calculated in the parameter spaces obtained from our previous works [?, ?, ?], which satisfy various experimental constraints including precision electroweak data, B-decays, muon $g-2$, and dark matter relic density within the 2σ range. Since some experimental limits have recently been updated—for example, the latest LHCb data for $B_s \to \mu^+\mu^-$ [?] and the XENON100 (2012) data for dark matter-nucleon scattering [?]—we first update our scans and then present predictions in the allowed parameter space. Note that since GMSB and AMSB require scalar top partners (stops) as heavy as about 10 TeV to produce a 125 GeV Higgs boson [?], they can no longer be called low-energy SUSY and thus will not be analyzed in this work.

This work is organized as follows. In Sec. II, we recapitulate the four models and their Higgs sector features. In Sec. III, we calculate the Higgs couplings, decay branching ratios, and signal rates in comparison to experimental data. Finally, we draw our conclusions in Sec. IV.

II. Low-Energy SUSY Models and Their Features in the Higgs Sector

MSSM

As the most economical realization of SUSY in particle physics, the MSSM has the superpotential given by $W_F + \mu \hat{H}_u \cdot \hat{H}_d$, where $W_F = Y_u \hat{Q} \cdot \hat{H}_u \hat{U} - Y_e \hat{L} \cdot \hat{H}_d \hat{E} - Y_d \hat{Q} \cdot \hat{H}_d \hat{D}$, with $\hat{H}_u$ and $\hat{H}_d$ denoting the Higgs doublet superfields, $\hat{Q}$, $\hat{U}$, and $\hat{D}$ denoting the squark superfields, and $\hat{L}$ and $\hat{E}$ denoting the slepton superfields [?]. Since there are two Higgs doublets in the model construction, the MSSM predicts five physical Higgs bosons: two CP-even (h and H), one CP-odd (A), and a pair of charged ones ($H^{\pm}$). At tree level, this Higgs sector is determined by two parameters, usually taken as m_A and $\tan\beta \equiv v_u/v_d$, with v_u and v_d representing the vacuum expectation values of the two Higgs doublets.

In general, the lightest Higgs boson h is SM-like, and for moderate $\tan\beta$ and large m_A, its mass is given by [?]:

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{4\pi^2 v^2} \ln\left(\frac{M_S^2}{m_t^2}\right) + \frac{3m_t^4}{4\pi^2 v^2} \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)$$

where the first term on the right side is the tree-level mass and the last two terms are the dominant corrections from the top-stop sector, with $v = 174$ GeV, $X_t \equiv A_t - \mu \cot\beta$ denoting the scalar top mixing, and M_S representing the average stop mass scale defined by $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$. As indicated by numerous studies, to drive m_h as heavy as 125 GeV, M_S or X_t must be large, which induces some fine-tuning problem. The di-photon signal rate for such a boson at the LHC is usually less than its SM prediction except for a small fraction of the MSSM parameter space characterized by light $\tilde{\tau}$ and large $\mu \tan\beta$ [?], while the $pp \to h \to ZZ^* \to 4\ell$ and $pp \to h \to WW^* \to 2\ell + 2\nu$ signal rates can never be enhanced in the MSSM [?].

CMSSM

The CMSSM is identical to the MSSM except for the assumption of boundary conditions for its soft mass parameters. At the boundary (usually the GUT scale), the soft parameters are assumed to be m_0 for scalar masses, $m_{1/2}$ for gaugino masses, and A_0 for trilinear couplings. As a result, the parameter space of the CMSSM is rather limited compared to that of the MSSM. For example, it was found that m_h is upper bounded by about 124 GeV (126 GeV) before (after) considering its theoretical uncertainty if one takes into account experimental constraints on the model, especially those from muon $g-2$ and the decay $B_s \to \mu^+\mu^-$ [**?**]. This is because the SUSY explanation of muon $g-2$ at the 2σ level requires relatively light slepton and gaugino masses, which implies not-too-heavy m_0 and $m_{1/2}$. In this case, the only way to enhance m_h is through large X_t, which in return raises the branching ratio of $B_s \to \mu^+\mu^-$ [**?**]. Regarding this model, one should note that both the di-photon and ZZ^* signal rates cannot be enhanced.

NMSSM

The NMSSM extends the MSSM by introducing a gauge singlet superfield $\hat{S}$ with the Z_3-invariant superpotential given by $W_F + \lambda \hat{H}_u \cdot \hat{H}_d \hat{S} + \kappa \hat{S}^3/3$ [**?**]. As a result, the NMSSM predicts one additional CP-even Higgs boson and one additional CP-odd Higgs boson, and the μ-term is dynamically generated once the singlet scalar S develops a vev. Corresponding to the superpotential, new soft-breaking terms such as $\tilde{m}_S^2 |S|^2$, $A_\lambda \lambda S H_u \cdot H_d$, and $A_\kappa \kappa S^3/3$ appear, which complicate the dependence of the Higgs mass matrices on the model parameters. It has been shown that at tree level, the SM-like Higgs boson mass squared receives an additional term $\lambda^2 v^2 \sin^2(2\beta)$, which, together with the mixing effect among the doublet and singlet Higgs fields, may render large radiative corrections unnecessary, thus ameliorating the fine-tuning suffered by the MSSM [**?**]. Moreover, since the SM-like Higgs boson in this model has a singlet component, its coupling to $b\bar{b}$ can be suppressed, and so is its total decay width. This helps enhance the branching ratio of $h \to \gamma\gamma$ and its related di-photon signal rate at the LHC [**?**]. A similar situation applies to the $pp \to h \to ZZ^* \to 4\ell$ and $pp \to h \to WW^* \to 2\ell + 2\nu$ signals [**?**].

In the limit of vanishing λ and κ (but for fixed μ), the singlet field decouples from the doublet Higgs sector in the NMSSM and the MSSM phenomenology is recovered. This motivates us that to obtain Higgs properties significantly different from the MSSM prediction, one should consider the large λ case. For example, on condition that $\lambda > (m_Z/v \approx 0.53)$, the tree-level mass of the SM-like Higgs boson in the NMSSM is maximized at low $\tan\beta$, instead of large $\tan\beta$ as in the MSSM.

nMSSM

The nMSSM is identical to the NMSSM except that the cubic singlet term $\kappa\hat{S}^3$ in the superpotential is replaced by a tadpole term $\xi_F\hat{S}$ [?, ?]. Clearly this potential has no discrete symmetry and is thus free of the domain wall problem [?]. The unique feature of this model is that the lightest neutralino, as the lightest supersymmetric particle (LSP) and dark matter candidate, is singlino-dominated and must be light. This is because the singlino mass term in the neutralino mass matrix vanishes, and the LSP gets its mass only through mixing of the singlino with higgsinos. For such a dark matter candidate, it must annihilate through exchanging a resonant light CP-odd Higgs boson to obtain the correct relic density. As a result, although the structure of the Higgs sector in the nMSSM is quite similar to that of the NMSSM, the SM-like Higgs boson tends to decay dominantly into light neutralinos or other light Higgs bosons [?], so that its total width enlarges greatly. This greatly suppresses the di-photon signal rate as well as the WW^* and ZZ^* signal rates.

III. Higgs Properties in Confrontation with the LHC Data

First, we update our scans [?, ?, ?] by considering the latest experimental limits and enlarging the scan ranges for M_{Q3}, M_{U3}, and $|A_t|$. In our scan, we require SUSY to explain the muon $g-2$ anomaly at the 2σ level and simultaneously satisfy the following experimental constraints: (i) experimental bounds on sparticle masses; (ii) Higgs searches from LEP and LHC experiments [?, ?]; (iii) 2σ limits from precision electroweak data and various B physics observables such as the branching ratios of $B \to X_s\gamma$ and $B_s \to \mu^+\mu^-$ [?]; (iv) dark matter constraints including its relic density (the 2σ range given by WMAP) and direct search limits from the XENON100 (2012) experiment at 90% confidence level.

In our calculations, we use the packages NMSSMTools-3.2.0 [?] and HiggsBounds-3.8.0 [?]. For the cross section of dark matter-nucleon scattering, we use our own code by setting $f_{Ts} = 0.025$ [?]. Note that we check the MSSM results using the code FeynHiggs [?]. We find good agreement between NMSSMTools and FeynHiggs when m_h lies within 125 ± 2 GeV. For the CMSSM, we first use NMSPEC in NMSSMTools to run the soft-breaking parameters from the GUT scale down to the weak scale, then compute the couplings, branching ratios, and signal rates of the SM-like Higgs boson with FeynHiggs [?].

[Figure 1: see original paper] shows scatter plots of the samples surviving all constraints and predicting $m_h = 125 \pm 2$ GeV, projected on the plane of the di-photon signal rate versus m_h. The curves denote the central value and the 1σ region of the LHC data. The samples denoted by '+' (red) predict a SM-like Higgs boson in the best-fit range 125.5 ± 0.54 GeV (called 'golden samples' in the text).

The details of our scan are described in [?, ?, ?]. Here we only list the scan ranges of the NMSSM parameters (the scan ranges for M_{Q3}, M_{U3}, and $|A_t|$ are enlarged compared with our previous studies): $0.53 < \lambda \leq 0.7$, $0 < \kappa \leq 0.7$, 90 GeV $\leq M_A \leq 1$ TeV, $|A_\kappa| \leq 1$ TeV, 100 GeV $\leq M_{Q3}, M_{U3} \leq 2$ TeV, $|A_t| \leq 5$ TeV, $1 \leq \tan\beta \leq 60$, 100 GeV $\leq \mu, m_{\tilde{l}} \leq 1$ TeV, 50 GeV $\leq M_1 \leq 500$ GeV. We require a large λ because for a small λ the NMSSM is very similar to the MSSM.

In the following, we only keep the surviving samples which predict 123 GeV $\leq m_h \leq 127$ GeV and pay special attention to the 'golden samples' which predict m_h in the 1σ best-fit range 125.5 ± 0.54 GeV [?].

In [Figure 1: see original paper] and [Figure 2: see original paper], we project the surviving samples on the planes of the di-photon rate and the $pp \to h \to ZZ^* \to 4\ell$ rate versus the SM-like Higgs boson mass. For the experimental curves, we obtain them using the method introduced in [?] with the ATLAS and CMS data given in [?, ?, ?]. In combining the data from the two groups, we assume they are independent and Gaussian distributed. These figures have the following features: (1) For the CMSSM, m_h is upper bounded by about 124 GeV, significantly away from the 1σ best-fit region 125.5 ± 0.54 GeV [?]. Considering the theoretical uncertainty of m_h [?], the maximal value of m_h can be quite close to the best-fit values; but even so, the CMSSM is still disfavored because its di-photon rate is never enhanced. (2) For the nMSSM, although m_h can easily lie within the 1σ best-fit range, its severely suppressed di-photon and four-lepton rates deviate significantly from the experimental data (outside the 3σ range). (3) For the MSSM and NMSSM, the mass m_h and the signal rates of the two channels can agree with the data at the 1σ level (as shown later, for the samples in such 1σ region, the NMSSM is natural while the MSSM needs some degree of fine-tuning). (4) Comparing the di-photon data and the four-lepton data, we see that the former is now more powerful in constraining SUSY.

To further compare the SUSY models, we examine the fine-tuning extent and χ^2 values for each model. In [Figure 3: see original paper], we show the fine-tuning extent Δ defined in [?] versus the di-photon rate. As in [Figure 1: see original paper] and [Figure 2: see original paper], only the samples with $m_h = 125 \pm 2$ GeV are plotted. This figure indicates that the NMSSM with a large λ has the lowest tuning extent, with Δ as low as 4 for the golden samples with an enhanced di-photon rate. In contrast, Δ in the MSSM is larger than 7 and, in particular, exceeds 100 for the samples with an enhanced di-photon rate.

For the χ^2 values, we focus on the golden samples giving $m_h = 125.5 \pm 0.54$ GeV. In [Figure 4: see original paper], we project these samples on the plane of χ^2 (obtained with 16 degrees of freedom) versus m_h. We compute the χ^2 values using the method introduced in [?] with the experimental data for $m_h = 125.5$ GeV given in [?] and in [?] (for the latest CMS $\tau^+\tau^-$ channel). We assume that the data from different collaborations and for different search channels are independent of each other. This figure indicates that the minimal χ^2 in the MSSM and NMSSM are about 10, which means that both models can agree with the LHC data at the 1σ level, performing better than the SM. This figure also indicates that requiring $\chi^2 \leq 26.3$, which corresponds statistically to 95% probability for 16 degrees of freedom, will exclude some samples of the NMSSM and all samples of the nMSSM.

In our following discussions, we scrutinize the MSSM and NMSSM by classifying the golden samples into three categories: $\chi^2 < 16.5$ (better than SM), $16.5 < \chi^2 < 26.3$ (worse than SM but within the 2σ range), and $\chi^2 > 26.3$ (excluded at 95% CL). In [Figure 5: see original paper], we show the di-photon branching ratio and some couplings of the SM-like Higgs boson. The upper two panels indicate that, to achieve $\chi^2 < 16.5$, an enhanced di-photon signal rate is strongly preferred, which can be realized by a slightly reduced hgg coupling but a sizably enlarged $h \to \gamma\gamma$ branching ratio. The bottom panels indicate that the di-photon branching ratio is pushed up mainly by the enhanced $h\gamma\gamma$ coupling (through light $\tilde{\tau}$ loop [?]) in the MSSM, and by the suppression of the Higgs width (through suppression of the $hb\bar{b}$ coupling) in the NMSSM. This figure also indicates that in the NMSSM, the samples excluded by the Higgs data are usually characterized by $\sigma(gg \to h\gamma\gamma)/\mathrm{SM} \leq 70\%$, which is the consequence of the reduced hgg coupling and the suppressed $\mathrm{Br}(h \to \gamma\gamma)$ (through the enlarged $hb\bar{b}$ coupling or the opening of new invisible decay $h \to \chi_1^0$). Furthermore, combining [Figure 3: see original paper] and [Figure 5: see original paper], one can infer that in the MSSM, the samples with $\chi^2 < 16.5$ must correspond to $\Delta \gtrsim 100$, reflecting that the model suffers from some degree of fine-tuning to accommodate the Higgs data, while for the NMSSM with a large λ, it is free of such a problem.

In [Figure 6: see original paper], we show similar information for the 4ℓ signal. Three points should be noted. First, unlike the di-photon rate, an enhanced 4ℓ signal rate is unnecessary to obtain a low χ^2. In fact, from this figure one can infer that a slightly reduced 4ℓ signal seems to be more favored. Second, in contrast with the MSSM where the 4ℓ signal is always reduced, the signal in the NMSSM may be enhanced by the increase of $\mathrm{Br}(h \to ZZ^*)$ through the reduced $hb\bar{b}$ coupling. Finally, although the hZZ coupling in the MSSM remains almost the same as in the SM, $\mathrm{Br}(h \to ZZ^*)$ in this model is usually smaller than its SM value due to the enlargement of the Higgs boson width.

In [Figure 7: see original paper], we show the top and bottom quark Yukawa couplings. This figure indicates that the top quark Yukawa coupling in the MSSM is close to the SM value, while in the NMSSM it may be suppressed by a factor of 0.85 compared with the SM value. For the bottom Yukawa coupling, it tends to be enhanced (maximally by a factor of 1.25) in the MSSM, while in the NMSSM it can be either suppressed or enhanced (by a factor ranging from 0.5 to 1.3).

presents detailed information about two representative low-χ^2 samples for the MSSM and the NMSSM respectively. To illustrate how well these samples are compatible with experimental data, in [Figure 8: see original paper] we compare various signal rates with the experimental values given in [?]. For comparison, we also show the best-fit rates obtained by freely varying all Higgs couplings, including couplings with photons and gluons (free coupling scenario). We see that the rates predicted by these samples agree with the data at the 1σ level except for the channel $pp \to \gamma\gamma jj$. We should note that although the MSSM samples may have lower χ^2 than the NMSSM with a large λ, they suffer from the fine-tuning problem.

Finally, we study the direct detection of neutralino dark matter. In [Figure 9: see original paper], we display the spin-independent neutralino-nucleon scattering cross section. We find that although the recently released XENON100 (2012) data [?] have excluded a large portion of the golden samples, some samples remain with cross sections as low as 10^{-46} cm^2, both for the MSSM and NMSSM. Interestingly, we also find that for the samples with $\chi^2 \leq 16.5$, the allowed dark matter mass is tightly restricted, varying from 60 GeV to 140 GeV in the NMSSM with a large λ.

IV. Conclusion

In this note, we compared the properties of the SM-like Higgs boson predicted by low-energy SUSY models with the latest LHC Higgs search data. For a SM-like Higgs boson around 125 GeV, we obtained the following observations: (i) For the MSSM, although it can fit the LHC data quite well, it suffers from the fine-tuning problem; (ii) The most favored model is the NMSSM, whose predictions can naturally agree with the experimental data at the 1σ level; (iii) The nMSSM is excluded at the 3σ level due to its much-suppressed di-photon or four-lepton signal rates; (iv) The CMSSM is quite disfavored since it is hard to predict a 125 GeV Higgs boson while simultaneously enhancing the di-photon signal rate.

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