Current Experimental Constraints on the Lightest Higgs Boson Mass in the Constrained MSSM (Postprint)

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Full Text

Preamble

Current Experimental Constraints on the Lightest Higgs Boson Mass in the Constrained MSSM

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Abstract

We examine the parameter space of the constrained MSSM by considering various experimental constraints. For the dark matter sector, we require the neutralino dark matter to account for the relic density measured by WMAP and satisfy the XENON limits on its scattering rate with nucleons. For the collider constraints, we consider all relevant direct and indirect limits from LEP, Tevatron, and LHC, as well as the muon anomalous magnetic moment. Especially, for the limits from $B_s \to \mu^+\mu^-$, we either directly consider its branching ratio with the latest LHC data or alternatively consider the double ratio of the purely leptonic decays defined by $R \equiv \frac{\mathrm{Br}(B_s\to\mu^+\mu^-)/\mathrm{Br}(B_u\to\tau\nu_\tau)}{\mathrm{Br}(D_s\to\tau\nu_\tau)/\mathrm{Br}(D\to\mu\nu_\mu)}$. We find that under these constraints, the mass of the lightest Higgs boson (h) in both the CMSSM and NUHM2 is upper bounded by about 124 GeV (126 GeV) before (after) considering its theoretical uncertainty. We also find that for these models, the di-photon Higgs signal at the LHC is suppressed relative to the SM prediction, and that the lower bound of the top-squark mass increases with m_h, reaching 600 GeV for $m_h = 124$ GeV.

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As a cornerstone of the Standard Model (SM), the Higgs boson is now being exhaustively hunted at the LHC. Very recently, both the CMS and ATLAS collaborations reported hints for a relatively light Higgs boson with mass around 124 GeV [**?**] and 126 GeV [**?**], respectively. Such a light Higgs boson can be neatly accommodated both in the SM (the electroweak precision data require a Higgs boson lighter than about 160 GeV) and in low-energy supersymmetric models, which predict a rather light Higgs boson below 135 GeV. Due to the large number of free parameters, the Minimal Supersymmetric Standard Model (MSSM) can easily predict a Higgs boson with mass around 125 GeV [**?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**, **?**]. The constrained MSSM, however, may not be so easy to produce such a mass due to its rather restrictive parameter space [**?**]. In this note, we examine the Higgs boson mass in the constrained MSSM by considering various experimental constraints on its parameter space.

We begin our analysis with a description of the constraints we investigate, which arise from both dark matter experiments and collider experiments. For the dark matter sector, we require the neutralino dark matter to account for the relic density measured by WMAP ($0.1053 < \Omega_{\mathrm{CDM}} h^2 < 0.1193$) [**?**] and satisfy the XENON limits (90% C.L.) on its scattering rate with nucleons [**?**]. As shown in [**?**, **?**, **?**], a large part of the parameter space in low-energy SUSY models can be excluded by such limits. For the collider constraints, we consider the following as in [**?**]: (1) The LEP search for Higgs bosons; (2) The LEP limits on the masses of sparticles such as charginos, sleptons, and third-generation squarks [**?**], and the limits on the production of charginos and neutralinos; (3) The Tevatron limits on charged Higgs bosons in top quark decays [**?**, **?**]. We do not consider the Tevatron limits on sparticle masses because they are generally weaker than the LHC limits in the constrained MSSM [**?**]; (4) The LHC search for SUSY Higgs bosons via $H/A \to \tau^+\tau^-$ (95% C.L.) [**?**]; (5) The latest SUSY search results (95% C.L.) at the LHC [**?**]; (6) The limits from electroweak precision observables including R_b at 2σ [**?**]; (7) The discrepancy between the SM prediction of muon $g-2$ and its experimental value, $\delta a_\mu = 25.5 \times 10^{-10}$ [**?**]. We require SUSY to explain this discrepancy at the 2σ level; (8) The limits from various low-energy processes [**?**, **?**, **?**]: $10^{-7} < \mathrm{Br}(B \to X_s \mu^+\mu^-) < 6.8 \times 10^{-7}$, $10^{-4} < \mathrm{Br}(B \to X_s \gamma) < 4.93 \times 10^{-4}$, $10^{-2} < \mathrm{Br}(B_u \to \tau\nu_\tau) < 6.1 \times 10^{-2}$, $10^{-4} < \mathrm{Br}(D_s \to \tau\nu_\tau) < 2.57 \times 10^{-2}$, $10^{-4} < \mathrm{Br}(D \to \mu\nu_\mu) < 4.6 \times 10^{-4}$; (9) Because $\mathrm{Br}(B_s \to \mu^+\mu^-) \propto \tan^6\beta/m_A^4$ with $M_{\tilde{t}}$ and m_A denoting the mass scale of top-squark and the CP-odd Higgs boson mass respectively [?, ?], and thus it serves as a sensitive probe of SUSY with large $\tan\beta$, and also because recently the experimental upper bound on $\mathrm{Br}(B_s \to \mu^+\mu^-)$ was greatly improved [?, ?], we pay special attention to this quantity. Noting that $\mathrm{Br}(B_s \to \mu^+\mu^-)$ involves the decay constant f_{B_s} subject to large theoretical uncertainty, we consider the double ratio of purely leptonic decays defined by [?]:

$$R \equiv \frac{\mathrm{Br}(B_s \to \mu^+\mu^-)/\mathrm{Br}(B_u \to \tau\nu_\tau)}{\mathrm{Br}(D_s \to \tau\nu_\tau)/\mathrm{Br}(D \to \mu\nu_\mu)}$$

As pointed out in [?], the quantity R is quite theoretically clean, and after considering the latest LHC upper bound on $\mathrm{Br}(B_s \to \mu^+\mu^-)$ ($< 1.26 \times 10^{-8}$ at 95% C.L. [?, ?]), R should be less than 2.3 at 95% C.L. In our analysis, we will require either $\mathrm{Br}(B_s \to \mu^+\mu^-) < 1.26 \times 10^{-8}$ (see the manual of the package SuperIso [?, ?, ?], which has considered the theoretical uncertainties of $\mathrm{Br}(B_s \to \mu^+\mu^-)$), or $R < 2.3$ to take into account the constraint from $B_s \to \mu^+\mu^-$.

In the following, we first consider the simplest version of the constrained MSSM called CMSSM. This model is motivated by the paradigm of minimal supergravity [?, ?, ?, ?], and its free parameters consist of M_0, $M_{1/2}$, A_0, $\tan\beta$, and $\mathrm{sign}(\mu)$, where M_0 and $M_{1/2}$ are the common scalar mass and gaugino mass respectively, A_0 is a common trilinear soft SUSY breaking parameter, and all of them are defined at the GUT scale. The parameter $\tan\beta$ represents the ratio of the Higgs field vacuum expectation values, and μ is the Higgsino mass. For comparison, we also consider a more general 2-parameter non-universal Higgs model (NUHM2) inspired by SU(5) grand unification [?, ?, ?]. This model assumes that, besides the input parameters for the CMSSM, the Higgs soft breaking masses M_{H_u} and M_{H_d} are free parameters. In our analysis, we set $\mathrm{sign}(\mu) = +1$ and vary the CMSSM parameters in the following ranges: $100\,\mathrm{GeV} < M_0, M_{1/2} < 2\,\mathrm{TeV}$, $1 < \tan\beta < 60$, and $-3\,\mathrm{TeV} < A_0 < 3\,\mathrm{TeV}$. We emphasize that based on our numerous scan results, only samples within these regions may survive the constraints. For the NUHM2, motivated by the naturalness of electroweak symmetry breaking, we also require $|M_{H_u}|, |M_{H_d}| \leq 1\,\mathrm{TeV}$.

In our calculation, we fix $m_t = 172.9$ GeV [?] and $f_{T_s} = 0.02$ [?, ?, ?] (f_{T_s} denotes the strange quark fraction in the proton mass). We use the package NMSSMTools [?] in the MSSM limit (i.e., by choosing very small λ and κ [?, ?]) to run the soft breaking parameters from the GUT scale down to the weak scale and implement all constraints other than (5), (8), and (9). During the RGE running, vacuum stability at the weak scale is checked, and only parameter samples that do not spoil stability are kept for further study.

To implement constraint (5), we note that in the LHC search for SUSY, the 0-lepton analyses are generally relatively insensitive to the $\tan\beta$ and A_0 parameters in the CMSSM and also insensitive to the amount of Higgs non-universality in the NUHM [?]. Therefore, we omit the dependence of the exclusion bound on parameters other than M_0 and $M_{1/2}$ and take the red lines in the right panels of Fig. 3 and Fig. 4 in [?] as the 95% C.L. exclusion limits [?, ?]. For constraints (8) and (9), we use the package SuperIso [?, ?, ?] to study them. After obtaining parameter points that survive the constraints, we calculate the mass of the lightest Higgs (h) and its production rate with the code FeynHiggs [?, ?, ?, ?].

In our random scan, we have 9.6×10^8 (8×10^8) samples for the CMSSM (NUHM2), and obtain 50,936 (43,194) samples surviving the constraints except (9). This number is further reduced to 20,477 (25,978) if the constraint from the latest measurement of $\mathrm{Br}(B_s \to \mu^+\mu^-)$ is added, or alternatively reduced to 6,749 (14,549) once $R < 2.3$ is considered. This fact reflects that $B_s \to \mu^+\mu^-$ can significantly limit the constrained MSSM (especially the CMSSM), and the constraint from R is more stringent than that from $\mathrm{Br}(B_s \to \mu^+\mu^-)$. In the following, we will project the surviving samples onto different planes, and to show how strong the constraints from $B_s \to \mu^+\mu^-$ are, we will display samples both without and with constraint (9).

In Figs. 1-2, we show the surviving samples of the CMSSM on the planes of M_0 versus $M_{1/2}$, A_0 versus $\tan\beta$, and μ versus $\tan\beta$, respectively. These figures indicate that significant parameter regions are excluded by the process $B_s \to \mu^+\mu^-$, especially samples with $\tan\beta > 52$ are completely excluded if the constraint $\mathrm{Br}(B_s \to \mu^+\mu^-) < 1.26 \times 10^{-8}$ is considered, and samples with $\tan\beta > 45$ are strongly disfavored once we require $R < 2.3$. For samples with $R < 2.3$, $\mathrm{Br}(B_s \to \mu^+\mu^-)$ is usually less than 0.8×10^{-8}, which explains why the constraint from R is tighter than that directly from $\mathrm{Br}(B_s \to \mu^+\mu^-)$. In these figures, we also show the surviving samples predicting $123\,\mathrm{GeV} < m_h < 127\,\mathrm{GeV}$. Taking into account the theoretical uncertainty in calculating m_h and the experimental error, this mass range is favored by the latest Higgs search at the LHC [?]. In this case, the favored parameter regions have moderate M_0 and $M_{1/2}$ but large $\tan\beta$. Since in our scan we only obtain 166 (upper panel) and 153 (bottom panel) points with $123\,\mathrm{GeV} < m_h < 127\,\mathrm{GeV}$, we conclude that the CMSSM will be tightly constrained once $m_h \sim 125$ GeV is experimentally confirmed in the near future.

In Fig. 3, we show the correlations of the lighter top-squark mass and the LHC di-photon rate with m_h in the CMSSM. We see that after including the constraints from $B_s \to \mu^+\mu^-$, the upper bound of m_h is reduced from 132 GeV to 124 GeV. We will discuss the underlying reason below. We can also see that for $m_h \geq 120$ GeV, the lower bound of $m_{\tilde{t}_1}$ increases while the upper bound decreases as m_h becomes heavier. This can be well understood by the approximate formula for radiative corrections to m_h [?]:

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

where $v = 246$ GeV and $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$. This formula tells us that a heavy top-squark (corresponding to the increase of the lower bound) or a large X_t

(corresponding to the decrease of the upper bound) is necessary to push up the Higgs boson mass. Fig. 3 also shows that for $m_h = 124$ GeV, the value of $m_{\tilde{t}_1}$ varies from 600 GeV to 1 TeV. In this case, the induced fine-tuning problem is not so severe.

From Fig. 3, we also find that the di-photon Higgs signal at the LHC is suppressed relative to the SM prediction. We checked that such suppression mainly comes from the enhanced $h\bar{b}b$ interaction that enlarges the total width of h [?, ?]. So far, the di-photon signal reported by the ATLAS and CMS experiments is consistent with its SM prediction [?, ?], but due to their large experimental uncertainties, it is too early to use the di-photon signal rate to exclude the CMSSM.

Since the CMSSM has difficulty predicting a Higgs boson with mass indicated by the ATLAS and CMS experiments, we consider the NUHM2. This model is a more general constrained MSSM with two additional free parameters compared to the CMSSM, allowing one to tune the value of m_A to escape the limit from $B_s \to \mu^+\mu^-$. In Figs. 4-6, we show our results for the NUHM2. From these figures, one can see that in the NUHM2, the constraint from $\mathrm{Br}(B_s \to \mu^+\mu^-)$ allows for relatively heavy SUSY and m_h can be as large as 130 GeV. However, the constraint from R remains stringent, requiring $m_h < 124$ GeV. For this case, other features such as the lighter stop mass, the di-photon rate, and the parameter regions predicting $123\,\mathrm{GeV} < m_h < 127\,\mathrm{GeV}$ are quite similar to those of the CMSSM.

Regarding these results, we have further explanations. First, in calculating the scattering rate of neutralino dark matter with nucleons, we choose a relatively small $f_{T_s} = 0.02$, given by recent lattice computations [?, ?, ?]. In this case, the contribution of the strange quark in the nucleon to the scattering rate is less important. Since a larger f_{T_s} usually enhances the scattering rate [?], our choice of f_{T_s} actually leads to a conservative constraint from the XENON100 experiment. Second, we note that so far the top quark mass has sizable experimental uncertainty. We checked that changing m_t from 172.9 GeV to 173.9 GeV will increase m_h by less than 0.8 GeV. We also examined the theoretical uncertainty of m_h from FeynHiggs, which may arise from variation of the renormalization scale from $m_t/2$ to $2m_t$, the use of m_t^{pole} instead of m_t^{run} in two-loop corrections, and the exclusion of higher-order resummation effects in m_b [?, ?, ?, ?]. We found the uncertainty δm_h is usually less than 2.5 GeV, and for the sky-blue samples shown in the bottom panel of Fig. 1 (Fig. 4), only about 110 (90) points predict $m_h + \delta m_h$ exceeding 125 GeV, but no point exceeds 126 GeV. This again reflects the difficulty of the CMSSM (NUHM2) in predicting $m_h \simeq 125$ GeV. Third, we note that at LHCb with 3 fb^{-1} integrated luminosity, the rare decay $B_s \to \mu^+\mu^-$ can be discovered for rates down to 10^{-9} [?]. This will provide a good opportunity in the near future to further test the constrained MSSM. Finally, we provide an intuitive understanding of why the Higgs boson mass m_h is so severely constrained by the process $B_s \to \mu^+\mu^-$, emphasizing two facts. One is that in the constrained MSSM, the sfermions have a common boundary mass, so slepton masses are correlated with squark masses. Since we require SUSY effects to explain the muon $g-2$ discrepancy at 2σ level, the sleptons (and thus the squarks) cannot be too heavy given $\tan\beta < 60$ as required by perturbativity. This means that heavy squarks must be accompanied by large $\tan\beta$ to explain the muon $g-2$. Since $\mathrm{Br}(B_s \to \mu^+\mu^-)$ is very sensitive to $\tan\beta$ (proportional to $\tan^6\beta A_t^2/m_A^4$), the constraint from $B_s \to \mu^+\mu^-$ can tightly restrict the value of $\tan\beta$ and consequently further restrict the squark masses. Given limited top-squark masses, the only way to enhance m_h is through large A_t, which, however, enhances $\mathrm{Br}(B_s \to \mu^+\mu^-)$ and thus gets constrained.

In summary, under current experimental constraints at 2σ level (except constraints from the XENON experiment which are at 90% C.L.), we performed a random scan in the parameter space of the constrained MSSM and obtained the following observations: (i) the mass of the lightest Higgs boson (h) in the CMSSM and NUHM2 is upper bounded by about 124 GeV (126 GeV) before (after) considering its theoretical uncertainty; (ii) the di-photon Higgs signal at the LHC is suppressed relative to the SM prediction; (iii) the lower bound of the top-squark mass increases with m_h, and for $m_h = 124$ GeV, the top-squark must be heavier than 600 GeV. Therefore, if the ATLAS (CMS) Higgs hint around 125 GeV is confirmed, these models will be tightly constrained.

Note added: While preparing this manuscript, we found similar works appeared on arXiv [**?**, **?**, **?**, **?**]. Let us clarify the main differences. In [**?**], the authors build a likelihood function by incorporating relevant experimental data to find parameter regions favored by experiments in the CMSSM framework, while in [**?**, **?**], the authors investigate how large m_h can reach in the CMSSM without seriously considering the constraint from muon $g-2$. Compared with [**?**], where the authors investigate m_h in the same models as our work, we considered more constraints.

We emphasize again that although a small $\mathrm{Br}(B_s \to \mu^+\mu^-)$ can be easily accommodated in heavy SUSY, the latest experimental results on $\mathrm{Br}(B_s \to \mu^+\mu^-)$ can severely constrain the CMSSM parameter space. This is because we require SUSY effects to explain the muon $g-2$ discrepancy, which favors SUSY at moderate scale and large $\tan\beta$. We also stress again that our observation of the upper bound of 124 GeV on m_h is obtained by scanning about 10^9 random samples under various experimental constraints listed at the beginning of this paper.

Finally, during the revision of this manuscript, updated information on $B_s \to \mu^+\mu^-$ from CMS appeared as $\mathrm{Br}(B_s \to \mu^+\mu^-) < 0.94 \times 10^{-8}$ [**?**]. We checked that with such a new limit, the $\mathrm{Br}(B_s \to \mu^+\mu^-)$ constraint will be comparable with the R constraint presented in our results.

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References

[1] CMS Physics Analysis Summary, CMS PAS HIG-11-032.
[2] ATLAS Collaboration, ATLAS-CONF-2011-163.
[3] S. Heinemeyer, O. Stål and G. Weiglein, arXiv:1112.3026; M. Carena et al., arXiv:1112.3336; P. Draper et al., arXiv:1112.3068; A. Arbey, M. Battaglia and F. Mahmoudi, arXiv:1112.3032; A. Arbey et al., arXiv:1112.3028; L. J. Hall, D. Pinner and J. T. Ruderman, arXiv:1112.2703; J. L. Feng, K. T. Matchev and D. Sanford, arXiv:1112.3021; T. Li et al., arXiv:1112.3024; T. Moroi and K. Nakayama, arXiv:1112.3123; T. Moroi, R. Sato and T. T. Yanagida, arXiv:1112.3142; U. Ellwanger, arXiv:1112.3548; J. Cao et al., arXiv:1202.5821 [hep-ph].
[4] I. Gogoladze, Q. Shafi and C. S. Ün, arXiv:1112.2206 [hep-ph].
[5] J. Dunkley et al. [WMAP Collaboration], Astrophys. J. Suppl. 180, 306 (2009).
[6] E. Aprile et al. [XENON100 Collaboration], Phys. Rev. Lett. 107, 131302 (2011).
[7] J. Cao et al., JHEP 1007, 044 (2010); Phys. Lett. B 703, 292 (2011); Phys. Lett. B 706, 72 (2011).
[8] K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010).
[9] T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 103, 101803 (2009); V. M. Abazov et al. [D0 Collaboration], Phys. Lett. B 682, 278 (2009).
[10] P. Wittich [ATLAS Collaboration and CMS Collaboration and CDF Collaboration], arXiv:1111.1169 [hep-ex].
[11] CMS Collaboration, CMS PAS HIG-11-029.
[12] J. Cao and J. M. Yang, JHEP 0812, 006 (2008).
[13] M. Davier et al., Eur. Phys. J. C 66, 1 (2010).
[14] F. Mahmoudi, Comput. Phys. Commun. 178 (2008) 745; Comput. Phys. Commun. 180 (2009) 1579; D. Eriksson, F. Mahmoudi and O. Stål, JHEP 0811 (2008) 035.
[15] C. Bobeth et al., Phys. Rev. D64, 074014 (2001); A. J. Buras et al., Phys. Lett. B 546, 96 (2002).
[16] CMS and LHCb Collaborations, LHCb-CONF-2011-047, CMS PAS BPH-11-019.
[17] A. G. Akeroyd, F. Mahmoudi, D. M. Santos, arXiv:1108.3018.
[18] A. H. Chamseddine, R. Arnowitt and P. Nath, Phys. Rev. Lett. 49 (1982) 970; R. Barbieri, S. Ferrara and C. Savoy, Phys. Lett. B119 (1982) 343; L. Hall, J. Lykken and S. Weinberg, Phys. Rev. D27 (1983) 2359; N. Ohta, Prog. Theor. Phys. 70 (1983) 542.
[19] J. Ellis, K. Olive and Y. Santoso, Phys. Lett. B 539, 107 (2002); J. Ellis, T. Falk, K. Olive and Y. Santoso, Nucl. Phys. B 652, 259 (2003); H. Baer, et al., Phys. Rev. D 71, 095008 (2005).
[20] H. Ohki et al., Phys. Rev. D 78, 054502 (2008); D. Toussaint and W.

Freeman, Phys. Rev. Lett. 103, 122002 (2009); J. Giedt, A. W. Thomas and R. D. Young, Phys. Rev. Lett. 103, 201802 (2009).
[21] U. Ellwanger, J. F. Gunion and C. Hugonie, JHEP 0502, 066 (2005).
[22] U. Ellwanger and C. Hugonie, Comput. Phys. Commun. 177, 399 (2007); U. Ellwanger, C. Hugonie and A. M. Teixeira, Phys. Rept. 496, 1 (2010).
[23] O. Buchmueller et al., arXiv:1110.3568 [hep-ph].
[24] O. Buchmueller et al., arXiv:1112.3564.
[25] G. Degrassi et al., Eur. Phys. J. C 28 (2003) 133; S. Heinemeyer, W. Hollik and G. Weiglein, Eur. Phys. J. C 9 (1999) 343; S. Heinemeyer, W. Hollik and G. Weiglein, Comput. Phys. Commun. 124 (2000) 76; M. Frank et al., JHEP 0702 (2007) 047.
[26] J. Cao, Z. Heng, T. Liu, J. M. Yang, Phys. Lett. B 703, 462 (2011); L. Wang, J. M. Yang, Phys. Rev. D 84, 075024 (2011).
[27] J. Cao et al., Phys. Rev. D 82, 051701 (2010).
[28] S. Akula, et al., arXiv:1112.3645; M. Kadastik et al., arXiv:1112.3647.
[29] H. Baer, V. Barger, A. Mustafayev, arXiv:1112.3017.
[30] U. Langenegger [the CMS collaboration], talk at CERN, 28 Feb. 2012, http://indico.cern.ch/conferenceDisplay.py?confId=178806

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