The constrained NMSSM: mSUGRA and GMSB

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Abstract. We review different constrained versions of the NMSSM: the fully constrained cNMSSM with universal boundary conditions for gauginos and all soft scalar masses and trilinear couplings, and the NMSSM with soft terms from Gauge Mediated Supersymmetry Breaking. Regarding the fully constrained cNMSSM, after imposing LEP constraints and the correct dark matter relic density, one single parameter is sufficient to describe the entire Higgs and particle spectrum of the model, which then contains always a singlino LSP. The NMSSM with soft terms from GMSB is phenomenologically viable if (and only if) the singlet is allowed to couple directly to the messenger sector; then various ranges in parameter space satisfy constraints from colliders and precision observables. Motivations for and phenomenological features of extra $U(1)'$ gauge symmetries are briefly reviewed.

Keywords: Supersymmetry, NMSSM, Gauge Mediation
PACS: 12.60.Jv, 12.60.Fr, 12.10.-g

INTRODUCTION

The Next-to-Minimal Supersymmetric Standard Model (NMSSM) [1] solves in a natural and elegant way the so-called $\mu$-problem [2] of the MSSM: Within any supersymmetric (SUSY) extension of the Standard Model (SM), a supersymmetric Higgs(ino) mass term $|\mu| \gtrsim 100$ GeV is necessary in order to satisfy the LEP constraints on chargino masses, but $|\mu| \lesssim M_{\text{SUSY}}$ is required in order that the effective potential develops a non-trivial minimum with $\langle H_u \rangle, \langle H_d \rangle \neq 0$. (Here $M_{\text{SUSY}}$ denotes the order of magnitude of the soft SUSY breaking scalar masses as $m_{H_u}$ and $m_{H_d}$.) The question is, why a supersymmetric mass parameter as $\mu$ happens to be of the same order as $M_{\text{SUSY}}$.

In the NMSSM, an (effective) $\mu$-term is generated by the vacuum expectation value (VEV) of an additional gauge singlet superfield $S$ and a corresponding Yukawa coupling, similarly to the way how quark and lepton masses are generated in the SM by the VEV of a Higgs field. To this end, the $\mu$-term in the superpotential $W$ of the MSSM, $W_{\text{MSSM}} = \mu H_u H_d + \ldots$, has to be replaced by

$$W_{\text{NMSSM}} = \lambda S H_u H_d + \frac{1}{3} \kappa S^3 + \ldots$$

(1)

and the soft SUSY breaking term $\mu B H_u H_d$ by

$$\lambda A_3 S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3.$$  

(2)

Assuming that all soft SUSY breaking terms are of $\mathcal{O}(M_{\text{SUSY}})$, one obtains $\langle S \rangle \sim M_{\text{SUSY}}/\kappa$ and hence an effective $\mu$-parameter $\mu_{\text{eff}} \equiv \lambda \langle S \rangle / \kappa M_{\text{SUSY}}$, which is of the desired order if $\lambda / \kappa \sim \mathcal{O}(1)$. Instead of the two parameters $\mu$ and $B$ of the MSSM, the NMSSM contains four parameters $\lambda$, $\kappa$, $A_3$, and $A_\kappa$, and the spectrum includes one additional CP-even Higgs scalar, one CP-odd Higgs scalar and one additional neutralino from the superfield $S$. Generally, these states mix with the Higgs scalars and neutralinos of the MSSM. Then, each of the neutralino/CP-even/CP-odd sectors can give rise to a phenomenology different from that of the MSSM:

a) The Lightest Supersymmetric Particle (LSP) can be dominantly singlino-like (consistent with WMAP constraints on $\Omega h^2$ [3], if its mass is only a few GeV below the one of the Next-to-LSP (NLSP), see [4] and below) implying an additional contribution to sparticle decay chains; note that the NLSP could have a long life time leading to observable displaced vertices [5];

b) The SM-like CP-even Higgs scalar $h_1$ can be ~ 15 GeV heavier than in the MSSM (at low tan $\beta$!);

c) A CP-odd Higgs scalar $a_1$ can be (very) light (see also the talk by J. Gunion, these proceedings). A light CP-odd Higgs scalar can have an important impact on B physics (see the talk by M. Sanchis-Lozano, these proceedings), and can imply that the lightest CP-even scalar $h_1$ decays dominantly into $h_1 \rightarrow a_1 a_1$ [6, 7]. Then, LEP constraints on $a_1$ are less restrictive, but the search for $h_1$ at the LHC can become considerably more difficult.

Note that these are not “unavoidable” predictions of the NMSSM, but depend on the unknown parameters $\lambda$, $\kappa$, $A_3$, $A_\kappa$, $\tan \beta$ and $\mu_{\text{eff}}$. In the following we investigate, amongst others, the phenomenological consequences of particular boundary conditions on the param-
eters of the NMSSM at a high scale like mSUGRA (universal boundary conditions for gauginos and all soft scalar masses and trilinear couplings at the GUT scale), and GMSB (Gauge Mediated Supersymmetry Breaking).

The subsequent results are obtained with the help of the Fortran code NMHDECAY/NMSSMTools [8], which computes the Higgs and sparticle spectra and Higgs branching ratios including radiative corrections for general/mSUGRA/GMSB boundary conditions, and checks for constraints from colliders/B-physics/(g-2)μ/ dark matter (the latter via MicrOMEGAs [4]).

THE CNMSSM

By definition, the soft SUSY breaking gaugino, scalar masses and trilinear couplings in the fully constrained cN MSSM – including the singlet sector – are assumed to be universal (equal to m₀, M₁/₂ and A₀, respectively) at the scale M_GUT \sim M_{Planck} as generated via mSUGRA, i.e. minimal supergravity with flavour-blind kinetic functions [3]. As a result, the number of unknown parameters is reduced to 4. In the convention where κ is implicitly determined by M_2, these can be chosen as M₁/₂, m₀, A₀ and λ; one of these parameters can still be replaced by tan β. (A slightly less constrained version of the cN MSSM, where the SUSY breaking mass m_3 of the singlet is allowed to differ from m₀, has recently been studied in [10]; see also the talk by C. Balázs, these proceedings.)

First, it is useful to recall the constraints on these parameters which follow from a stable real (in order to avoid problems with CP-violating observables) VEV of \langle S \rangle of the NMSSM at a high scale like mSUGRA (un-)

First, for small values of m₀ (as the ones required by (4)), the lightest stau \tilde{\tau}_1 would be the LSP in the MSSM, which would be unacceptable due to its electric charge. In the NMSSM, the additional (singlet-like) neutralino \tilde{\chi}_1 (with a mass proportional to |A_K| \sim |A_0|) is lighter than the \tilde{\tau}_1, if |A_0| satisfies A₀ \lesssim \frac{1}{3} M₁/₂. Then (4) gives

m₀ \lesssim \frac{1}{10} M₁/₂ , (5)

which would lead to an unacceptable LSP within the MSSM.

Second, in order for a sufficiently rapid \tilde{\chi}_1\bar{\chi}_1 annihilation in the early universe (such that its relic density complies with WMAP constraints), the \tilde{\chi}_1 - \tilde{\tau}_1 mass difference must be relatively small (m_{\tilde{\chi}_1} - m_{\tilde{\tau}_1} \sim (1 - 8) \text{ GeV}), and both masses must not be too large (below \sim 600 \text{ GeV}). Together, these constraints imply

A₀ \sim \frac{1}{4} M₁/₂, M₁/₂ \lesssim 2 - 3 \text{ TeV} . (6)

Finally, the lower bound of \sim 100 \text{ GeV on } m_{\tilde{\tau}_1} from LEP requires

M₁/₂ \gtrsim 400 \text{ GeV} . (7)

Then we find that, for λ small enough (see below), the SM-like Higgs scalar H_{SM} has a mass m_{H_{SM}} = 115 - 120 \text{ GeV} (increasing with M₁/₂) in agreement with LEP constraints. However, for larger λ the mixing of H_{SM} with the singlet-like scalar increases leading to a decrease of its mass m_{H_{SM}}. Hence λ must be relatively small,

\lambda \lesssim 2 \times 10^{-2} . (8)

(The NMSSM specific positive contribution to m_{H_{SM}} proportional to λ^2 [11] is negligible here, since tan β turns out to be fairly large, see below.)

Hence, from (5) and (8), neither m₀ nor λ have an important effect on the Higgs- and sparticle spectrum; A₀ being determined by (6), the spectrum is practically completely fixed by M₁/₂.

In Fig. 1 we show acceptable points in the [M₁/₂, A₀] plane for m₀ \sim 0 and λ = 2 \times 10^{-3}, which satisfy theoretical and collider constraints; the blue line corresponds to the additional satisfaction of WMAP constraints. For points above this line the dark matter relic density comes out (far) too large. Also indicated are lines of constant tan β (in red), which is seen to vary between 25 and \sim 38 (for M₁/₂ below 1.5 TeV as required for a correct relic density for m₀ \sim 0).

Still for m₀ \sim 0 and λ = 2 \times 10^{-3} (and A₀ along the blue line in Fig. 1), we show in Figs. 2 the Higgs, neutralino and stau spectrum as function of M₁/₂. The

\footnote{The results of this section have been obtained in collaboration with A. Djouadi and A. M. Teixeira in [3].}
the dependency of observed by the E821 experiment at BNL [12]. In [13], all present collider- and it will be practically invisible at the LHC.

FIGURE 2. The Higgs (left) and neutralino plus stau (right) mass spectra in GeV as a function of $M_{1/2}$ along the dark matter line; the values of $A_0$ are indicated in the upper axis.

squark and gluino masses are (except for the somewhat lighter stop masses) of the order $2 \times M_{1/2}$.

Note that, for $M_{1/2} \lesssim 640$ GeV, the lightest CP-even scalar $h^0_1$ is singlet-like; however, due to the small value of $\lambda$, its couplings to SM particles (as the Z-boson) are so small that its mass is not constraint by LEP and, likewise, it will be practically invisible at the LHC.

Actually, the parameter regions shown above satisfy all present collider- and $B$-physics constraints, but do not necessarily describe the deviation $\delta a_{\mu}$ of the anomalous magnetic moment $a_{\mu} = (g_{\mu} - 2)/2$ from its SM value observed by the E821 experiment at BNL [12]. In [13], the dependency of $\delta a_{\mu}$ on $M_{1/2}$ (which is practically independent from $m_0$ and $\lambda$) has been studied with the result shown in Fig. 3.

From Fig. 3 one can conclude that values for $M_{1/2} \lesssim 1$ TeV are favored by this observable, $M_{1/2} \sim 500$ GeV giving the best fit.

Finally we note that not all observables are practically independent from $\lambda$: recall that within the present scenario, all sparticle decays will proceed via the stau NLSP, since the couplings of the true (singlino-like) LSP are of the order of $\lambda$ and hence small. Only at the end of each MSSM-like decay chain, the stau NLSP will decay into the singlino-like LSP, but its decay width can be tiny implying a possibly visible stau track length [5]. We find that this track length can be $\gtrsim 1$ mm at the LHC, if $\lambda \lesssim 10^{-3}$; this phenomenon can thus represent a possible “smoking gun” for the cNMSSM.

THE NMSSM AND GMSB

Supersymmetric extensions of the SM with Gauge Mediated Supersymmetry Breaking always involve messenger supermultiplets $\phi_i$ with a (supersymmetric) mass $M_{mess}$, whose CP-even and CP-odd scalar masses squared are split by $m^2$. Possible origins of the SUSY breaking parameter $m^2$ are

- Dynamical SUSY Breaking (non-perturbative) in a hidden sector containing a SUSY Yang-Mills theory plus matter, and couplings of $\phi_i$ to the hidden sector [14];
- O’Raifeartaigh-type models [15];
- models based on No-Scale supergravity [16] with Giudice-Masiero-like terms [17] for $\phi_i$ in the Kähler potential [18].

Since the messenger fields $\phi_i$ carry $SU(3) \times SU(2) \times U(1)_Y$ gauge quantum numbers, they generate gaugino masses (at 1 loop) and masses for all non-singlet scalars (at 2 loops) of the order $M_{SUSY} \sim \frac{m^2_{mess}}{16\pi^2 M_{mess}}$, but none of the phenomenologically required $\mu$- or $B$-terms of the MSSM – hence the $\mu$-problem is even more pressing in general GMSB-like models.

Again, the simplest solution of the problem is the introduction of a singlet $S$ together with its coupling $\lambda$
to $H_u$ and $H_d$ [4]. However, soft SUSY breaking terms in the potential for the singlet are necessary in order to generate a sufficiently large VEV of $S$. In order to generate such terms radiatively (of the desired order), it seems necessary to introduce a direct coupling $\sim \eta S\phi_1\phi_1$ of $S$ to the messenger sector.

Then, integrating out the messengers generates desired terms like $m_\lambda^2$ and $A_\lambda = \frac{1}{2}A_κ$; possibly, however, also terms linear in $S$ in the superpotential $W \sim \xi_F S$ and in the potential $V_{\text{soft}} \sim \xi_S S$, so-called “tadpole terms”. Such tadpole terms always trigger a non-vanishing $\langle S \rangle \neq 0$ but, if allowed at 1 loop order, the radiatively generated parameters $\xi_F, \xi_S$ tend to be somewhat large; one finds [18]

$$\xi_F \sim \eta M_{\text{mess}} M_{\text{SUSY}}, \quad \xi_S \sim 16\pi^2 \eta M_{\text{mess}} M^2_{\text{SUSY}},$$

and recall that we typically expect $M_{\text{mess}} > M_{\text{SUSY}}$. On the other hand, $\xi_S$ should not be larger than $M^3_{\text{SUSY}}$ which is the case if $\eta \lesssim \frac{1}{16\pi^2 M_{\text{SUSY}}}$ — typically implying $\eta \lesssim 10^{-3}$.

As investigated in [19], such models can be phenomenologically viable, if $\lambda > 0.5$ (and $\tan \beta \lesssim 2$); then the NMSSM specific contribution $\sim \lambda^2$ to the scalar Higgs mass matrix squared [1] pushes the lightest Higgs mass $m_{h_1}$ above the LEP bound. For the parameter choices $M_{\text{mess}} = 10^9$ GeV and $M_{\text{SUSY}} = 500$ GeV, we have varied the parameters $0.5 < \lambda < 0.6$ and $10^{-6} < \eta < 10^{-5}$; the resulting values for $m_{h_1}$ are shown in Fig. 4 as function of $\tan \beta$.

![FIGURE 4. $m_{h_1}$ as function of $\tan \beta$ in the scenario with tadpole terms.](image)

The other Higgs states are heavier than $\sim 600$ GeV, the bino, wino and slepton masses are in the range 110 to 290 GeV, and the squark and gluino masses in the range 640 to 890 GeV; hence the entire Higgs and sparticle spectrum satisfies all collider constraints for this class of models inspite of the presence of tadpole terms for $S$.

Tadpole terms for $S$ can also be forbidden by discrete symmetries, if the messenger sector is enlarged to $\phi_1, \phi_1, \phi_2, \phi_2$ [20] and the superpotential is chosen as

$$W = \eta S\phi_1\phi_2 + M_{\text{mess}}(\phi_1\phi_1 + \phi_2\phi_2).$$

The soft terms $m_\lambda^2$ (< 0), $A_\lambda$ are calculable in terms of $\eta$ and $M_{\text{SUSY}}$ as before. Phenomenologically viable regions in the parameter space $M_{\text{SUSY}}, m_\lambda, \tan \beta$ have been found in [21] (and confirmed in [19]) where, however, the sparticle spectrum turns out to be quite heavy: Bino, wino and slepton masses are in the range 450 to 1100 GeV, and the squark and gluino masses around 2 TeV.

In [19], we have also investigated scenarios where the soft terms $A_\lambda, A_κ$ are negligibly small at $M_{\text{mess}}$, i.e. where all soft terms for the singlet vanish at $M_{\text{mess}}$ except for $m_\lambda^2$ (a corresponding hidden sector remains to be constructed). Then, the scalar sector of the NMSSM has an R-symmetry ($M_{\text{mess}}$), which is, however, broken by radiative corrections to $A_\lambda, A_κ$ induced by the gaugino mass terms. Then, the explicit R-symmetry breaking at the weak scale by $A_\lambda, A_κ \sim$ a few GeV is small (if $M_{\text{mess}}$ is not too large), and the spontaneous R-symmetry breaking by $\langle H_a \rangle, \langle H_d \rangle, \langle S \rangle \neq 0$ generates a pseudo Goldstone Boson, the lightest CP-odd Higgs scalar $a_1$ [6]. Consequently, the lightest Higgs scalar $h_1$ can decay via $h_1 \rightarrow a_1 a_1$ escaping LEP constraints if $m_{h_1} \gtrsim 90$ GeV (depending on $m_{a_1}$) [22].

We have studied phenomenologically viable regions in the parameter space of such a scenario for $λ = 0.6, 10^3$ GeV $< M_{\text{mess}} < 5 \cdot 10^9$ GeV and 200 GeV $< M_{\text{SUSY}} < 280$ GeV as shown in Fig. 5 where, for $m_{h_1} < 114$ GeV, $m_{a_1}$ is below $m_{h_1}/2$.

![FIGURE 5. $m_{h_1}$ as function of $\tan \beta$ in the scenario with $A_κ, A_κ \sim 0$.](image)

Here the bino, wino and slepton masses are $\sim 100 – 200$ GeV, the squark and gluino masses $\sim 450 – 600$ GeV, and the masses of the additional Higgs bosons above $\sim 500$ GeV. The blue points satisfy also the 2$σ$ constraints on the muon anomalous magnetic moment.
Altogether a variety of NMSSM models with GMSB — with and without tadpole terms — is phenomenologically viable, provided that the singlet couples directly to the messengers such that destabilizing terms in the singlet potential can be radiatively generated.

**EXTRA $U(1)'$ GAUGE SYMMETRY**

A natural question is the one for a possible origin of a SM singlet superfield like the $S$ of the NMSSM. In fact, multiplets of large GUT gauge groups (like, e.g., $E_6$ [23]) typically contain singlets under the SM gauge groups which are, however, charged under one (or more) extra $U(1)'$ gauge group(s) (see [24] for a recent review). Quark, leptons as well as the MSSM doublets $H_u$ and $H_d$ carry such $U(1)'$ charges as well, as a consequence of which the MSSM $\mu H_u H_d$-term is forbidden and has to be generated by a VEV of $S$ (and a coupling $\lambda S H_u H_d$) as before.

Due to the $U(1)'$ charge of $S$, the $\kappa S^3$-term in the superpotential of the NMSSM is forbidden as well, but the $S$-dependent potential can still be stabilized for large $\langle S \rangle_0$ due to the $U(1)'$ $-$ D-term $\sim g'^2|\langle S \rangle_0|^4$. The $U(1)'$ $-$ D-term leads also to additional $g'^2|H_u, d|^4$-terms in the scalar potential, which imply heavier (SM-like) physical Higgs scalars which satisfy more easily the lower LEP bound of 114 GeV.

However, the cancellation of all anomalies (at scales $\sim M_{SUSY}$) usually requires additional exotic matter (and possibly several SM singlets) with masses of the order $M_{SUSY}$, as a consequence of which the unification of the SM gauge couplings at $M_{GUT}$ is no longer “automatic” as in the MSSM or in the NMSSM.

The most evident phenomenological implication of such models is the presence of at least one extra $Z'$ gauge boson; however, since it tends to mix with the $Z$ boson of the SM, one obtains constraints on its mass and the quantum numbers of matter whose loops are responsible for this mixing. Also the neutralino sector is enlarged [25], involving extra states from both $Z'$- and SM singlet matter supermultiplets.

**SUMMARY**

Under the assumption that the SUSY breaking scale $M_{SUSY}$ generates the weak scale $\sim M_Z$, and no other dimensionful parameters are present in the effective Lagrangian below the GUT scale, the NMSSM is the most natural supersymmetric extension of the Standard Model.

If one adds the assumption of universal soft SUSY breaking terms $M_{1/2}$, $m_0$ and $A_0$ one finds that the phenomenologically viable range — satisfying all present constraints from collider- and $B$-physics as well as the dark matter relic density — for $M_{1/2}$, $m_0$ and $A_0$ in the cNMSSM is very different from the cMSSM: it is characterized by $m_0 \ll M_{1/2}$ and $A_0 \sim \frac{1}{2} M_{1/2}$; the entire Higgs and sparticle spectrum can finally be parametrized by $M_{1/2}$ only. The most notable feature of this scenario is that the LSP is always singlino-like; depending on the Yukawa coupling $\lambda$, a large NLSP (stau) lifetime can lead to tracks of observable length at the end of sparticle decay chains at the LHC.

**ACKNOWLEDGMENTS**

It is a pleasure to thank the organisers of SUSY 08 for a very inspiring and fruitful conference.

This talk is based on work in collaboration with A. Djouadi, C.-C. Jean-Louis, F. Domingo and A.M. Teixeira. We acknowledge support from the French ANR project PHYS@COL&COS.

**REFERENCES**

1. H.P. Nilles, M. Srednicki and D. Wyler, Phys. Lett. B 120 (1983) 346; J.M. Frere, D.R. Jones and S. Raby, Nucl. Phys. B 222 (1983) 11; J. Ellis et al., Phys. Rev. D 39 (1989) 844; M. Drees, Int. J. Mod. Phys. A 4 (1989) 3635.

2. J.E. Kim and H.P. Nilles, Phys. Lett. B 138 (1984) 150.

3. D. N. Spergel et al. [WMAP Collaboration], Astrophys. J. Suppl. 170 (2007) 377.

4. G. Belanger et al., JCAP 0509 (2005) 001; G. Belanger et al., Comput. Phys. Commun. 174 (2006) 577; C. Hugonie, G. Belanger and A. Pukhov, JCAP 0711 (2007) 009.

5. F. Franke and H. Fraas, Z. Phys. C 72 (1996) 309; U. Ellwanger and C. Hugonie, Eur. Phys. J. C 5 (1998) 723 and Eur. Phys. J. C 13 (2000) 681;
V. Barger, P. Langacker and G. Shaughnessy, Phys. Lett. B 644 (2007) 361 and Phys. Rev. D 75 (2007) 055013.
6. B. A. Dobrescu, G. Landsberg and K. T. Matchev, Phys. Rev. D 63 (2001) 075003 [arXiv:hep-ph/0005308];
   B. A. Dobrescu and K. T. Matchev, JHEP 0009 (2000) 031 [arXiv:hep-ph/0008192];
   R. Dermisek and J. F. Gunion, Phys. Rev. D 75 (2007) 075019 [arXiv:hep-ph/0611142].
7. R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95 (2005) 041801 [arXiv:hep-ph/0502105] and Phys. Rev. D 73 (2006) 111701 [arXiv:hep-ph/0510122];
   U. Ellwanger, J. F. Gunion and C. Hugonie, JHEP 0507 (2005) 041 [arXiv:hep-ph/0503203];
   S. Chang, P. J. Fox and N. Weiner, JHEP 0608 (2006) 068 [arXiv:hep-ph/0511250];
   P. W. Graham, A. Pierce and J. G. Wacker, “Four taus at the Tevatron,” [arXiv:hep-ph/0605162];
   S. Moretti, S. Munir and P. Poulose, Phys. Lett. B 644 (2007) 241 [arXiv:hep-ph/0608233];
   S. Chang, P. J. Fox and N. Weiner, Phys. Rev. Lett. 98 (2007) 111802 [arXiv:hep-ph/0608310];
   T. Stelzer, S. Wiesenfeldt and S. Willenbrock, Phys. Rev. D 75 (2007) 077701 [arXiv:hep-ph/0611242];
   U. Aglietti et al., “Tevatron-for-LHC report: Higgs,” [arXiv:hep-ph/0612172].
8. E. Fullana and M. A. Sanchis-Lozano, Phys. Lett. B 653 (2007) 67 [arXiv:hep-ph/0702190];
   K. Cheung, J. Song and Q. S. Yan, Phys. Rev. Lett. 99 (2007) 031801 [arXiv:hep-ph/0703149];
   M. A. Sanchis-Lozano, “A light non-standard Higgs boson: to be or not to be at a (Super) B factory?,”
   [arXiv:0707.3647 [hep-ph]];
   M. Carena, T. Han, G. Y. Huang and C. E. M. Wagner, JHEP 0804, 092 (2008) [arXiv:0712.2466 [hep-ph]]; J. R. Forshaw et al., JHEP 0804, 090 (2008) [arXiv:0712.3510 [hep-ph]]; Z. Heng et al., Phys. Rev. D 77, 095012 (2008) [arXiv:0801.1169 [hep-ph]]; A. Djouadi et al., JHEP 0807 (2008) 002 [arXiv:0801.4321 [hep-ph]]; A. Belyaev et al., “The Scope of the 4 tau Channel in Higgs-strahlung and Vector Boson Fusion for the NMSSM: No-Lose Theorem at the LHC,” [arXiv:0805.3505 [hep-ph]]; D. E. Morrissey and A. Pierce, “Modified Higgs Boson Phenomenology from Gauge or Gaugino Mediation in the NMSSM,” [arXiv:0807.2259 [hep-ph]].
9. U. Ellwanger, J. F. Gunion and C. Hugonie, JHEP 0502 (2005) 066;
   U. Ellwanger and C. Hugonie, Comput. Phys. Commun. 175 (2006) 290 and Comput. Phys. Commun. 177 (2007) 399;
   see also the web site http://www.th.u-psud.fr/NMHEDECAY/nmssmtools.html.
10. A. Djouadi, U. Ellwanger and A. M. Teixeira, Phys. Rev. Lett. 101 (2008) 101802 [arXiv:0803.0253 [hep-ph]].
11. C. Balazs and D. Carter, “Discovery potential of the next-to-minimal supergravity motivated model,”
   [arXiv:0808.0770 [hep-ph]].
12. U. Ellwanger, M. Rausch de Traubenberg and C.A. Savoy, Phys. Lett. B 315 (1993) 331, Z. Phys. C 67 (1995) 665 and Nucl. Phys. B 492 (1997) 307.
13. G. W. Bennett et al. [Muon G-2 Collaboration], Phys. Rev. D 73 (2006) 072003 [arXiv:hep-ex/0602035].
14. F. Domingo and U. Ellwanger, JHEP 0807, 079 (2008) [arXiv:0806.0733 [hep-ph]].
15. I. Affleck, M. Dine and N. Seiberg, Nucl. Phys. B 241 (1984) 493, Phys. Lett. B 137 (1984) 187, Phys. Lett. B 140 (1984) 59 and Nucl. Phys. B 256 (1985) 557;
   Y. Meurice and G. Veneziano, Phys. Lett. B 141 (1984) 69;
   M. Dine and A. E. Nelson, Phys. Rev. D 48 (1993) 1277 [arXiv:hep-ph/9303230];
   M. Dine, A. E. Nelson and Y. Shirman, Phys. Rev. D 51 (1995) 1362 [arXiv:hep-ph/9408384];
   M. Dine, A. E. Nelson, Y. Nir and Y. Shirman, Phys. Rev. D 53 (1996) 2658 [arXiv:hep-ph/9507378];
   K. Intriligator, N. Seiberg and D. Shih, JHEP 0604 (2006) 021 [arXiv:hep-ph/0602239].
16. S. Chang, P. J. Fox and N. Weiner, Phys. Rev. Lett. 110 (2008) 227, Nucl. Phys. B 204 (1982) 346;
   L. Alvarez-Gaume, M. Claudson and M. B. Wise, Nucl. Phys. B 207 (1982) 96;
   S. Dimopoulos and S. Raby, Nucl. Phys. B 219 (1983) 479.
17. A. B. Lahanas and D. V. Nanopoulos, Phys. Rept. 145, 1 (1987); N. Dragon, U. Ellwanger and M. G. Schmidt, Prog. Part. Nucl. Phys. 18 (1987) 1.
18. G. F. Giudice and A. Masiero, Phys. Lett. B 206 (1988) 480.
19. U. Ellwanger, Phys. Lett. B 349 (1995) 57 [arXiv:hep-ph/9501227].
20. U. Ellwanger, C. C. Jean-Louis and A. M. Teixeira, JHEP 0805, 044 (2008) [arXiv:0803.2962 [hep-ph]].
21. G. F. Giudice and R. Rattazzi, Nucl. Phys. B 511 (1998) 25 [arXiv:hep-ph/9706540].
22. A. Delgado, G. F. Giudice and P. Slavich, Phys. Lett. B 653 (2007) 424 [arXiv:0706.3873 [hep-ph]].
23. S. Schael et al. [ALEPH, DELPHI, L3 and OPAL Collaborations], Eur. Phys. J. C 47 (2006) 547.
24. S. F. King, S. Moretti and R. Nevzorov, Phys. Lett. B 634, 278 (2006) [arXiv:hep-ph/0511256]; Phys. Rev. D 73, 035009 (2006) [arXiv:hep-ph/0510419];
   R. Howl and S. F. King, JHEP 0801, 030 (2008) [arXiv:0708.1451 [hep-ph]].
25. P. Langacker, “The Physics of Heavy ‘Z’ Gauge Bosons,” [arXiv:0801.1345 [hep-ph]].
26. S. Y. Choi, H. E. Haber, J. Kalinowski and P. M. Zerwas, Nucl. Phys. B 778, 85 (2007) [arXiv:hep-ph/0612218].