The Next-to-Minimal Supersymmetric Standard Model

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1 The Higgs Sector in Supersymmetric Extensions of the Standard Model

First we recall why supersymmetric extensions belong to the most popular extensions of the Standard Model (SM) at scales beyond a TeV. As is well known, the electroweak scale M_{weak} is the only explicit mass scale in the SM. A priori, this scale could also be explained by new strong interactions at ~ 1 TeV, or compact (large) extra dimensions of a size ~ 1 TeV^{-1}. In supersymmetric (Susy) extensions of the SM, M_{weak} is of the order of the Susy breaking scale M_{Susy} which corresponds to the scale of the soft Susy breaking masses of squarks, sleptons, gauginos and Higgs bosons.

However, only with Susy the ratios of the three gauge coupling constants are naturally explained by the assumption of Grand Unification (GUT) with a simple GUT group as $SU(5)$ or $SO(10)$ at a reasonable scale 10^{16} GeV $\lesssim M_{GUT} \lesssim 10^{17}$ GeV! Moreover, Susy extensions of the SM (with unbroken R-parity) imply the existence of a stable particle (the Lightest Susy Particle, LSP) which can naturally explain the observed dark matter in the universe.

Any Susy extension of the SM requires a generalisation of the Higgs sector in the form of at least two $SU(2)$ doublets H_u and H_d, where H_u couples to up-type quarks and H_d to down-type quarks and leptons. The corresponding soft Susy breaking mass terms $m_{H_u}^2$, $m_{H_d}^2$ trigger $\langle H_u^0 \rangle$, $\langle H_d^0 \rangle \neq 0$ provided that at least $m_{H_u}^2 < 0$. This latter condition is satisfied naturally through radiative corrections, if the top quark Yukawa coupling is large enough implying $m_{top} \gtrsim 60$ GeV[1], which is obviously the case.

Once the Goldstone bosons are omitted, the physical states in the Higgs sector of this Minimal Susy extension of the SM (MSSM) consist in two CP-even neutral scalars h and H, one CP-odd neutral scalar A and a charged Higgs $H^{\pm}$. The higgsinos mix with the electroweak gauginos (bino and winos) and form 4 neutralinos and 2 charginos.

The masses and couplings of these states depend on undetermined parameters like $m_{H_u}^2$, $m_{H_d}^2$ and, via radiative corrections, on squark masses etc.. It is convenient to chose as undetermined parameters in the Higgs sector $\tan\beta = \langle H_u^0 \rangle / \langle H_d^0 \rangle$ and M_A, the mass of the CP-odd neutral scalar A. For $M_A \gg M_Z$ the extra Higgs states H, A and $H^{\pm}$ form a nearly degenerate $SU(2)$ doublet of a mass M_A. Then h couples to the electroweak gauge bosons similar to the SM Higgs boson.

The mass of the lighter Higgs state h is bounded from above in the MSSM, although this upper bound depends somewhat on the squark masses due to the radiative corrections. For reasonable squark masses below a few TeV one obtains $M_h \lesssim 130$ GeV. This implies that its detection at the LHC is guaranteed through one of the various production and decay modes once an integrated luminosity of 30 fb^{-1} at a c.m. energy of 14 TeV is achieved[2]. However, this "No-lose Theorem" is actually more difficult to satisfy for lighter Higgs masses ($M_h \lesssim 120$ GeV), since here it becomes more difficult to disentangle the signal from the background.

2 The NMSSM

We have noted above that the charged fermionic superpartners of $H_{u,d}$ mix with the charged $SU(2)$ gauginos (winos) to form two charginos. These have not been observed at LEP II, which implies that their mass is larger than ~ 103 GeV. This requires a *Susy* mass term μ for the higgsinos with $|\mu| \gtrsim 100$ GeV; note that masses for fermions are *not* soft Susy breaking parameters. This requirement in the MSSM spoils a nice relation: otherwise one could have $M_{weak} \sim M_{Susy}$ with M_{Susy} as the only dimensionful parameter below the Planck or GUT scale.

A non-vanishing μ-term is also required in the Higgs potential in order to make sure that *both* Higgs vacuum expectaion values $\langle H_u^0 \rangle$ *and* $\langle H_d^0 \rangle$ are non-vanishing. However, since the μ-term is supersymmetric, it implies a positive mass term $\sim \mu^2$ for both H_u and H_d which must *not* dominate the negative mass term $m_{H_u}^2 \sim -M_{Susy}^2$ in order to ensure the electroweak symmetry breaking. Hence the μ-term must satisfy $|\mu| \sim M_{Susy}$, which is *a priori* difficult to understand[3].

Mechanisms within supergravity exist (implying an *ad hoc* dependency of the Kähler potential on H_u, H_d[4]) which solve this so-called μ-problem of the MSSM, but a simpler solution consists in the generation of higgsino masses in a way similar to the generation of quark and lepton masses in the SM: introduce a (Susy) Yukawa coupling of the higgsinos to a scalar field S, where $\langle S \rangle \neq 0$. In fact, $\langle S \rangle \neq 0$ is easy to achieve with the help of a (negative) soft Susy breaking mass term and/or a trilinear self coupling for S implying automatically $|\mu| \sim \langle S \rangle \sim M_{Susy}$ as desired. Note that, since the μ-parameter is gauge invariant, S must be a gauge singlet (super-)field. The corresponding extension of the Higgs sector of the MSSM is denoted as the Next-to-Minimal Susy extension of the SM (NMSSM), for a recent review see[5].

In terms of the superpotential W the replacement of the μ-term of the MSSM by the singlet S corresponds to

$$W_{MSSM} = \mu H_u H_d \ + \ldots \ \rightarrow \ W_{NMSSM} = \lambda S H_u H_d + \frac{1}{3}\kappa S^3 \ + \ldots \ , \tag{1}$$

hence the superpotential W_{NMSSM} is scale invariant (without any Susy mass parameter); λ and κ denote two dimensionless Yukawa couplings. For the higgsino masses Eq. 1 implies

$$\mu \psi_u \psi_d \ \rightarrow \lambda S \psi_u \psi_d \qquad \text{or} \qquad \mu_{eff} = \lambda \langle S \rangle \ . \tag{2}$$

3 The Higgs sector of the NMSSM

Since the superfield S contains a CP-even and a CP-odd scalar as well as a fermion (the so-called singlino) which mix all with the Higgs and higgsino states of the MSSM, the physical states in the Higgs sector of the NMSSM consist in three CP-even neutral scalars H_i, two CP-odd neutral scalar A_i and a charged Higgs $H^{\pm}$. Now we find five neutralinos (but still 2 charginos).

It is important to note that the larger number of states in the Higgs sector does *not* imply that at least one Higgs boson is easier to detect at colliders! The reason is that the pure singlet states in S would decouple from gauge bosons and quarks/leptons, hence their mixing with the MSSM Higgs states will reduce the corresponding couplings of the physical eigenstates. Of course, this mixing can be very weak (if λ is very small), in which case the NMSSM becomes difficult to disentangle from the MSSM since the singlet-like states will hardly be produced. Otherwise, the phenomenology of the NMSSM can differ considerably from the MSSM in the CP-even and CP-odd Higgs sectors:

1. For large λ (but $\lambda \lesssim 0.7$ in order to avoid a Landau singularity below M_{GUT}), the SM-like CP-even scalar h can be ~ 10 GeV heavier than in the MSSM [6].
2. The lightest CP-even Higgs scalar can have a large singlet component, and satisfy the LEP II constraints with a mass well below 114 GeV due to its reduced couplings to the Z-boson.
3. The lightest CP-odd Higgs scalar A_1 can have a large singlet component, and can be very light in contrast to the MSSM (satisfying all phenomenological constraints, see the talk by F. Domingo [7]). In this case the SM-like CP-even scalar h can decay dominantly as $h \to A_1 A_1 \to 4b,\ 2b2\tau,\ 4\tau \ldots$ (depending on M_{A_1}), which modifies considerably the signal for h-detection.

In fact, both possibilities 1. and 3. above make it somewhat easier to satisfy the present constraints from LEP II on the SM-like Higgs sector. The results of the four LEP experiments searching for a Higgs scalar decaying into $H \to b\bar{b},\ \tau^+\tau^-$ (assuming SM branching fractions) have been combined by the LEP-Higgs Working Group [8] and are shown in Fig. 1. There, ξ denotes the reduced coupling of a Higgs scalar to the Z boson (compared to the coupling of the SM Higgs scalar), $\xi \equiv g_{HZZ}/g_{HZZ}^{SM}$. Shown are upper bounds on ξ^2 as function of a scalar Higgs mass M_H, which one can interpret as lower bounds on M_H at fixed ξ^2.

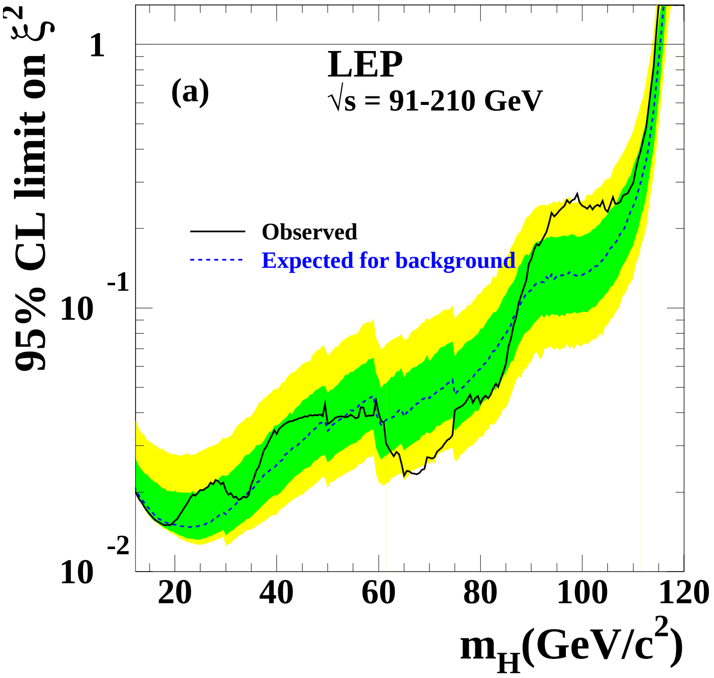

Figure 1: Upper bound on ξ^2 as function of a scalar Higgs mass H, where ξ denotes the coupling of the Higgs scalar to Z bosons (normalized w.r.t. the SM Higgs boson).

One can note a light excess of events for $h \sim 95-100$ GeV (of $\sim 2.3\,\sigma$ statistical significance), which is difficult to explain in the SM. The NMSSM offers two possible explanations for this excess of events: i) a Higgs scalar with a mass of $\sim 95-100$ GeV can have a reduced coupling to the Z boson ($\xi \lesssim 0.4-0.5$) due to its large singlet component; or ii) a Higgs scalar with a mass of $\sim 95-100$ GeV can have a reduced branching ratio into $b\bar{b}$, $\tau^+\tau^-$, since it decays dominantly into a pair of light CP-odd scalars with a $BR(h \to A_1 A_1) \sim 80-90\%$. In the latter case, the coupling of h to Z bosons can be SM-like. In[9,10] it has been argued that this scenario allows to alleviate the "little finetuning problem" of the MSSM (since $M_h \gtrsim 114$ GeV is not required).

However, the LEP experiments have also searched for $h \to A_1 A_1 \to 4b$[8], and the constraints are very strong for $M_h \sim 95-100$ GeV. On the other hand, if M_{A_1} is below the $b\bar{b}$ threshold of ~ 10.5 GeV, A_1 would decay dominantly into $\tau^+\tau^-$. If M_{A_1} is $9.5-10.5$ GeV, it satisfies constraints from CLEO and Babar and can solve a puzzle concerning the recently discovered η_b-mass, see the talk by F. Domingo[7,11,12].

The channel $h \to A_1 A_1 \to 4\tau$ has recently been re-investigated by the ALEPH collaboration[13], and is now also strongly constrained for $M_h \lesssim 107$ GeV (see the talk by K. Cranmer[14]). Still, for M_{A_1} in the $9.5-10.5$ GeV range and for small $\tan\beta$ (where the branching ratio $A_1 \to c\bar{c}$ is enhanced), $M_h \sim 95-100$ GeV could be possible[15], although now different more general Higgs search topologies can impose constraints[16].

In any case the dominant decay $h \to A_1 A_1 \to 4\tau$ remains a possibility in the NMSSM for $M_h \gtrsim 107$ GeV, which will be very challenging for Higgs searches at the Tevatron and the LHC: due to the (at least) four neutrinos in the final state, invariant masses of combinations of visible final state particles will not show strong peaks; the two τ leptons from the same A_1 will be nearly collinear with a low invariant mass, and without a large p_T; the SM provides backgrounds in the form of Υ-production and heavy flavour jets.

Several proposals have been made in order to circumvent these difficulties at the LHC: In[17] diffractive Higgs production $pp \to pp + h$ has been investigated, whose study would require the installation of additional forward proton detectors. Combining the vector-boson-fusion-channel and Higgs-Strahlung with $W^\pm$ bosons, the $4\tau \to 2\mu + 2$ jets and $4\tau \to 4\mu$ final states have been studied in[18,19]. In[20] it has been argued that the subdominant $A_1 \to \mu^+\mu^-$ decay (with a branching ratio of $\sim 3 \cdot 10^{-3}$) allows to see a peak in the $\mu^+\mu^-$ invariant mass, and hence to look for $h \to A_1 A_1 \to 2\tau + 2\mu$ with h produced via gluon fusion. These proposals still have to be investigated and confirmed by the LHC detector collaborations.

4 Possible implications of the extended neutralino sector in the cNMSSM

In the NMSSM, the LSP can be the additional singlino-like neutralino, i.e. $\chi_1^0 \sim \chi_S$ (the singlino mixes always somewhat with the other neutralinos as the bino). This is not a far-fetched scenario; it is even generic in the cNMSSM, where the soft Susy breaking scalar masses, trilinear couplings and gaugino masses are assumed to be universal (given by m_0, A_0 and $M_{1/2}$) at the GUT ($\sim$ Planck) scale[21,22]. (Note that here the singlet-dependent soft Susy breaking terms are assumed to be universal as well, as it would happen in minimal supergravity.)

The reason for a singlino-like LSP in the cNMSSM is fairly easy to understand: in order to obtain $\langle S \rangle \neq 0$, the Susy breaking singlet mass m_S^2 must not be large. Since m_S is hardly renormalized between the GUT and the weak scale, this implies a small value for m_0 (compatible with $m_0 = 0$). In the MSSM, $m_0 \sim 0$ leads to an intolerable stau ($\widetilde{\tau}$) LSP. In the cNMSSM, χ_S can be somewhat lighter than the $\widetilde{\tau}$ (which is now the NLSP), and give the correct dark matter relic density through co-annihilation with the $\widetilde{\tau}$. This implies $A_0 \sim -1/4 M_{1/2}$. Finally constraints from the Higgs sector require $\lambda \lesssim 0.02$, so that $M_{1/2}$ remains essentially the only undetermined parameter in the fully constrained cNMSSM[21,22]. For non-vanishing (but small) m_0, a singlet-like CP-even Higgs scalar with a mass of ~ 100 GeV might even explain the light excess of events in Fig. 1.

A singlino-like LSP will have important consequences for Susy particle (sparticle) searches, since it will appear in practically *every* sparticle decay cascade: since χ_S couples only weakly to all other sparticles, these prefer to decay first into the NLSP (the $\widetilde{\tau}$); only at the end of the cascade the $\widetilde{\tau}$ will decay into $\widetilde{\tau} \to \tau + \chi_S$. Hence a typical squark ($\tilde{q}$) decay cascade looks as

$$\tilde{q} \to q + \chi_2^0(\text{bino}) \to q + \tau + \tilde{\tau} \to q + \tau + \tau + \chi_1^0(\text{singlino}) \ , \tag{3}$$

which gives two τ's *per cascade*. However, only the first τ from $\chi_2^0 \to \tau + \widetilde{\tau}$ is hard and relatively easy to detect; the second τ from $\widetilde{\tau} \to \tau + \chi_S$ is relatively soft, since the mass difference $m_{\widetilde{\tau}} - m_{\chi_S}$ is only a few GeV in order to allow for successful co-annihilation. For very small λ and/or a small mass difference $m_{\widetilde{\tau}} - m_{\chi_S}$, the $\widetilde{\tau}$ life time can even become so long that the $\widetilde{\tau}$ decay vertices are visibly displaced, up to the order of several cm [22].

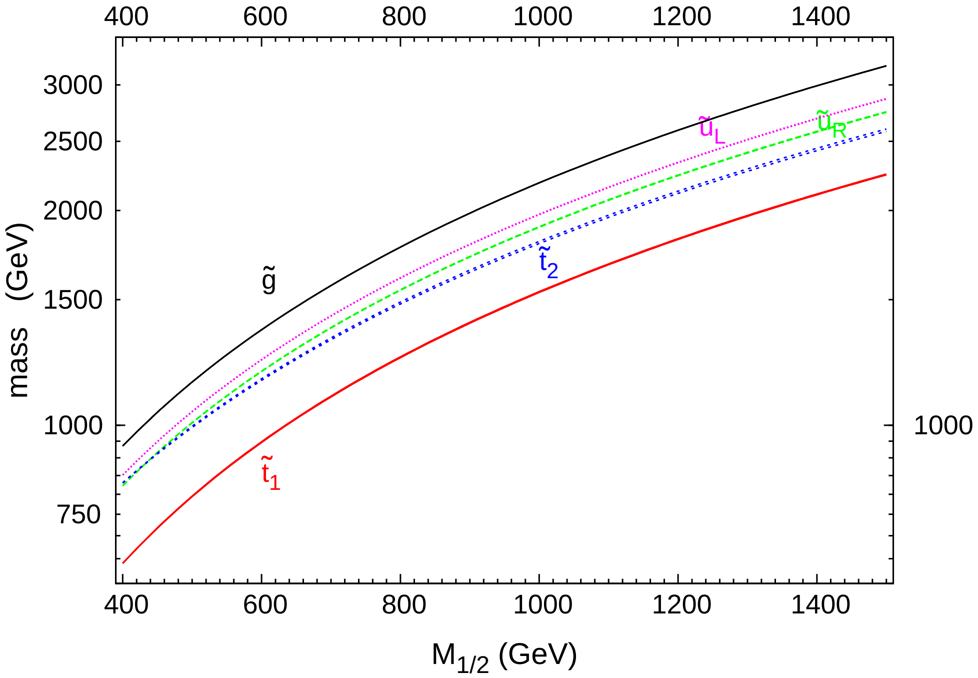

Figure 2: Gluino and squark masses as function of $M_{1/2}$ in the cNMSSM

The squark and gluino masses in the cNMSSM are displayed in Fig. 2 as function of $M_{1/2}$. One finds that the gluino is generally somewhat heavier than the squarks (due to $m_0 \sim 0$). For $M_{1/2} \gtrsim 500$ GeV, the cNMSSM satisfies all constraints from sparticle searches, Higgs searches at LEP II, B-physics etc. [21,22]. A preferred range for $M_{1/2}$ can be obtained if one requires that the Susy contribution to the anomalous magnetic moment of the muon explains the $\sim 3\sigma$ discrepancy with respect to the SM [23]: from Fig. 3 one deduces that $M_{1/2} \lesssim 1$ TeV is preferred by this observable, with $M_{1/2} \sim 500$ GeV giving the best fit. For this value of $M_{1/2}$ one has squark masses of ~ 1 TeV, and a gluino mass of ~ 1.2 TeV.

Of course it is interesting to ask whether this scenario is visible at the LHC. First, at 7 TeV c.m. energy, one expects $\sim$ 10 events/fb^{-1}. It is not excluded that, after 1 fb integrated luminosity, a few τ-rich events become visible above the background, but no definite conclusions could be drawn at this stage. At 14 TeV c.m. energy the signal gives ~ 1000 events/fb^{-1}. In [24] we propose dedicated cuts for the cNMSSM in the form of two jets with $p_T > 300/150$ GeV and $E_T(miss) > 350$ GeV; these cuts are quite hard, but appropriate for the heavy squark/gluino-spectrum. Since the τ-acceptance is only $\sim 30 - 40\%$ for hadronically decaying τ's (the leptonic

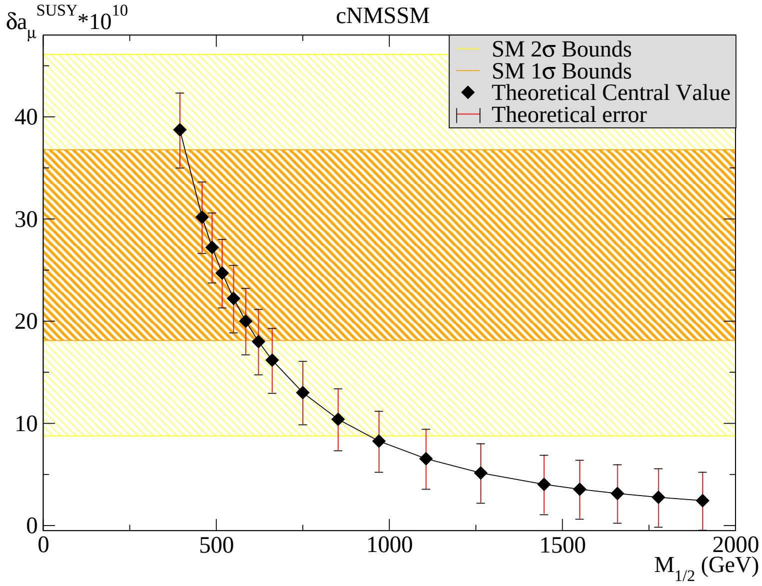

Figure 3: The Susy contribution δa_μ^{Susy} to the anomalous magnetic moment of the muon as function of $M_{1/2}$ in the cNMSSM.

τ decays are not useful) with $p_T \gtrsim 30$ GeV, it is not reasonable to require more than one reconstructed τ with $p_T \gtrsim 30$ GeV. Together with standard cuts on $\Delta\phi(jets - E_T(miss))$ and M_T these cuts still accept $\sim 10\%$ of the signal, but strongly suppress the SM background. (From the $t\bar{t}$ background we expect ~ 8 events/fb^{-1} after these cuts; τ-fakes from QCD-jets are under investigation.)

Hence the signal-to-background ratio looks quite promising. Moreover the τ p_T-spectrum is quite hard even after taking into account the τ-acceptance, since one has at least two energetic τ's per event. The τ p_T-spectrum would allow, in addition, to distinguish the cNMSSM from the stau-coannihilation-region of the cMSSM, where less energetic τ's per event are expected.

5 Conclusions

The NMSSM has several attractive features as compared to the MSSM: it solves the μ-problem, has a scale invariant superpotential and thus satisfies $M_{weak} \sim M_{Susy}$ without additional incredients. Its larger parameter space allows to satisfy constraints from LEP II on the Higgs sector more easily: the SM-like Higgs boson can be somewhat heavier, or mix with the singlet-like CP-even boson, or decay differently as into $A_1 A_1$.

The latter scenario (which is in any case possible for a heavier SM-like Higgs boson) can render the Higgs detection at the LHC quite difficult. As stated above, studies - also on $h \to A_1 A_1 \to 2b + 2\tau$ - are under way, but no “No-lose-Theorem” is confirmed at present for the NMSSM. Hence, in the worst case the non-detection of a Higgs signal at the LHC can be a signal for the NMSSM!

Also sparticle searches have possibly to rely on unconventional signals (as compared to the MSSM), if the scenario with a singlino-like LSP is realized in the NMSSM. As stated above, this scenario appears automatically in the fully constrained cNMSSM. With a stau NLSP, one will find ~ 4 τ leptons per Susy event and, possibly, displaced vertices from stau-decays.

Some aspects of these signals are currently under investigation, but more studies are required and should be ready when the LHC operates as originally forseen.

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