Neutralino Mass Bounds in the Next–To–Minimal Supersymmetric Standard Model

F. Franke and H. Fraas

Institut für Theoretische Physik, Universität Würzburg
D-97074 Würzburg, Germany

A. Bartl

Institut für Theoretische Physik, Universität Wien
A-1090 Wien, Austria

Abstract

We analyze the experimental data from the search for new particles at LEP 100 and obtain mass bounds for the neutralinos of the Next–To–Minimal Supersymmetric Standard Model (NMSSM). We find that for \( \tan \beta \gtrsim 5.5 \) a massless neutralino is still possible, while the lower mass bound for the second lightest neutralino corresponds approximately to that for the lightest neutralino in the Minimal Supersymmetric Standard Model (MSSM).

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email: fabian@physik.uni-wuerzburg.d400.de
1 Introduction

The Minimal Supersymmetric Standard Model (MSSM) technically solves the hierarchy problem of the standard model. However, the problem remains that one does not know why the $\mu$ parameter in the superpotential $W \ni \mu H_1 H_2$ should be of the electroweak scale. Supersymmetric models with an extended Higgs sector may provide a solution for this $\mu$ problem and, beyond that, avoid the strong mass bounds of the Higgs bosons and the neutralinos in the MSSM. Models of this kind are also motivated by GUT and string theories and were first developed in Refs. [1], [2], [3].

The Higgs sector of the MSSM [4] contains two Higgs doublets $H_1, H_2$ with vacuum expectation values $v_1$ and $v_2$ ($\tan \beta = v_2/v_1$) that lead to five physical Higgs particles, two CP-even and one CP-odd neutral scalars and a pair of charged scalars. Furthermore, there are four fermionic neutralino eigenstates being mixtures of photino, zino and the two neutral higgsinos. In this simplest supersymmetric model the mass of the lightest neutral Higgs boson $h$ is bounded at tree level by $m_h \leq m_Z |\cos 2\beta|$ (including radiative corrections this bound can be raised up to 130 GeV [5]). From Higgs search at LEP a neutral scalar lighter than 42 GeV and a neutral pseudoscalar with a mass less than 22 GeV is excluded [6]. Moreover, LEP data imply that the lightest neutralino in the MSSM has a lower mass bound of 20 GeV for $\tan \beta > 3$ and the second lightest is heavier than 40 GeV, a massless neutralino is only possible for $\tan \beta < 1.7$ [7].

In the Next-to-Minimal Supersymmetric Standard Model (NMSSM), the minimal extension of the MSSM by a gauge singlet superfield $N = (N, \psi_N, F_N)$ with the singlet Higgs $N$, the singlet higgsino $\psi_N$ and the auxiliary field $F_N$, the Higgs sector is extended to five physical neutral Higgs bosons, three Higgs scalars $S_a \ (a = 1, 2, 3)$ and two pseudoscalars $P_b \ (b = 1, 2)$ [8], [9]. The singlet higgsino enlarges the neutralino sector to five neutralinos. The NMSSM is fully determined by fixing the superpotential and the soft symmetry breaking potential. The terms relevant for the Higgs sector are

\begin{equation}
W = \lambda \varepsilon_{ij} H_1^i H_2^j N - \frac{1}{3} k N^3, \tag{1}
\end{equation}

\begin{equation}
V_{\text{soft}} = -\lambda A_\lambda \varepsilon_{ij} H_1^i H_2^j N - \frac{1}{3} k A_k N^2 + \text{h.c.}, \tag{2}
\end{equation}

where $H_1 = (H_1^0, H^-)$ and $H_2 = (H^+, H_2^0)$ are the $SU(2)$ Higgs doublets with hypercharge $-1/2$ and $1/2$, respectively, $N$ is the Higgs singlet with hypercharge 0, and $\varepsilon_{ij}$ is totally antisymmetric with $\varepsilon_{12} = -\varepsilon_{21} = 1$.

In the NMSSM the tree level bound on the lightest Higgs scalar is $m_{S_1}^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 (v_1^2 + v_2^2) \sin^2 2\beta$ [10], again it will be raised by radiative corrections [11], [12].

Experimental mass bounds from LEP data for the neutral Higgs scalars were found by Kim et al. [13] by studying the production of the lightest Higgs scalar in $e^+ e^- \rightarrow S_1 b \bar{b}$. Although the parameters $A_\lambda$ and $A_k$ in the soft symmetry breaking potential strongly determine the properties of the Higgs bosons, they do not influence the masses and mixing types of the neutralinos. Consequently, the Higgs mass bounds of Ref. [13] do not restrict the other parameters of the NMSSM and do not lead to neutralino mass bounds. Kim et al. [13], [14], [15] also calculate cross sections for the production of neutralinos for special values of the parameters of the NMSSM but leave the question open if and in which parameter region a massless neutralino is still compatible with experimental data.
In this letter we analyze the experimentally excluded domains of the parameter space and determine neutralino mass bounds in the NMSSM which originate from experimental data. The paper is organized as follows: In Sec. 2 we describe shortly the neutralino sector of the NMSSM. With the experimental constraints presented in Sec. 3 we then restrict in Sec. 4 the parameter space and derive in Sec. 5 bounds on the neutralino masses. Finally, their dependence on the parameters of this model are discussed.

2 The neutralino sector in the NMSSM

The NMSSM contains five neutral gauge and Higgs fermions $\tilde{\gamma}, \tilde{Z}, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{N}$. The mass eigenstates are the five neutralinos $\tilde{\chi}_i^0$ ($i = 1, \ldots, 5$) with masses and mixings determined by a $5 \times 5$ mass mixing matrix. The mass matrix depends on six parameters (compared to four in the MSSM [16]): the gaugino masses $M$ and $M'$, the ratio of the vacuum expectation values of the Higgs doublets $\tan \beta = v_2/v_1$, the vacuum expectation value of the Higgs singlet $x$, and the trilinear couplings in the superpotential $\lambda$ and $k$.

Taking as basis the two-component spinors of the photino, zino, and the neutral higgsinos

\[(\psi^0)^T = (-i\lambda_\gamma, -i\lambda_Z, \psi^a_H, \psi^b_H, \psi_N) \quad (3)\]

with

\[
\begin{align*}
\psi^a_H &= \psi_{H_1}^1 \cos \beta - \psi_{H_2}^2 \sin \beta, \\
\psi^b_H &= \psi_{H_1}^1 \sin \beta + \psi_{H_2}^2 \cos \beta,
\end{align*}
\]

the neutralino mass terms in the Lagrangian read

\[\mathcal{L} = -\frac{1}{2}(\psi^0)^T Y \psi^0 + \text{h.c.} \quad (6)\]

The mass matrix

\[
Y = \begin{pmatrix}
-M_{s_W^2} - M'_{c_W^2} & (M' - M) s_W c_W & 0 & 0 & 0 \\
(M' - M) s_W c_W & -M_{c_W^2} - M'_{s_W^2} & m_Z & 0 & 0 \\
0 & m_Z & -\lambda x \sin 2\beta & \lambda x \cos 2\beta & 0 \\
0 & 0 & \lambda x \cos 2\beta & \lambda x \sin 2\beta & \lambda v \\
0 & 0 & 0 & \lambda v & -2k x
\end{pmatrix}
\quad (7)
\]

with

\[
s_w \equiv \sin \theta_W, \quad c_w \equiv \cos \theta_W, \quad v \equiv \sqrt{v_1^2 + v_2^2}
\]

(8)

can be diagonalized by a unitary $5 \times 5$ matrix $N$

\[N_{im} Y_{mn} N_{kn} = \delta_{ij} m_{\tilde{\chi}_i^0}, \quad (9)\]

where $m_{\tilde{\chi}_i^0}$ is the mass eigenvalue of the neutralino state

\[\tilde{\chi}_i^0 = \left(\begin{array}{c}
\chi_i^0 \\
\overline{\chi}_i^0
\end{array}\right), \quad \chi_i^0 = N_{ij} \psi_j^0. \quad (10)\]

Note that with $\mu = \lambda x$ the upper $4 \times 4$ matrix reproduces the neutralino mass matrix of the MSSM, and the chargino sector is recovered.

Due to theoretical considerations we restrict the parameter space in the following way:
1. In order to avoid explicit CP violation in the scalar sector we choose \( \lambda k > 0 \) \[8\]. Because of the symmetries of the neutralino eigenvalue equation it is sufficient to consider \( \lambda, k > 0 \).

2. The vacuum state can be chosen such that \( v_1, v_2, x > 0 \) \[8, 17\].

3. The assumption of grand unification implies relations between the gaugino masses \( M \) and \( M' \) as well as between \( M \) and the gluino mass \( m_\tilde{g} \). At the electroweak scale one expects

\[
M' = \frac{5}{3} \frac{\alpha_1}{\alpha_2} M \simeq 0.5M, \quad |M| = \frac{\alpha_2}{\alpha_3} m_\tilde{g} \simeq 0.3m_\tilde{g},
\]

(11)

where \( \alpha_i = g_i^2/(4\pi), i = 1, 2, 3 \) and the \( g_i \) are the gauge couplings of the \( U(1)_Y, SU(2)_L \) and \( SU(3)_C \), respectively.

4. As suggested by naturalness arguments, by the hierarchy problem \[18\], and by fine tuning constraints \[19\], the gluino mass is assumed to be not much larger than 1 TeV.

Note that the sign of the gaugino mass parameter \( M \), however, remains arbitrary.

In the following, we obey the unitarity bounds on the couplings in the Higgs potential as worked out in \[20\], but we do not restrict ourselves to special solutions of renormalization group equations with fixed boundary conditions as discussed e. g. in \[8\] and \[21\]. We will not impose cosmological constraints obtained by assuming that the lightest neutralino is the main component of dark matter. As shown in \[22\], the lightest supersymmetric particle (LSP) of the NMSSM is most likely expected to lie in the mass range between 10 and 60 GeV in order to give a sufficient contribution to the relic density. This requirement would mean that the lower bounds on the mass of the lightest neutralino as derived in Sec. 5 have to be increased.

3 Experimental constraints

The parameter space of the NMSSM and the masses of the supersymmetric particles are constrained by the LEP results for

1. the upper limit of new physics contributing to the total \( Z \) width. The L3 Collaboration obtained \[6\]

\[
\Delta \Gamma_Z \leq 35.1 \text{ MeV}.
\]

(12)

2. the upper limit of the contribution of new physics to the invisible \( Z \) width \[6\]

\[
\Delta \Gamma_{\text{inv}} \leq 16.2 \text{ MeV}.
\]

(13)

3. limits from unsuccessful direct neutralino search in \( Z \) decays at LEP. The ALEPH Collaboration performed a detailed analysis of the search for the second lightest neutralino within the framework of the MSSM \[7\]. Taking into account the decay
channels $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^* \to \tilde{\chi}_1^0 f \bar{f}$, $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 \gamma$ (via loop diagrams) as well as $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 H^0$

we extract for the branching ratios of $Z$ decays into two neutralinos (not $\tilde{\chi}_1^0 \tilde{\chi}_1^0$)

$$B(Z \to \tilde{\chi}_i^0 \tilde{\chi}_j^0) < 5 \times 10^{-5} \quad (i, j) \neq (1, 1).$$

(14)

For special parameters of the MSSM the CDF Collaboration found a lower bound for the gluino mass $m_{\tilde{g}}$ (in a SUSY scenario with cascade decays of the gluino) [23]

$$m_{\tilde{g}} > 100 \text{ GeV}. \quad (15)$$

By eq. (11) this corresponds to

$$M > 30 \text{ GeV}. \quad (16)$$

Since in the NMSSM more cascade decays may be possible this limit could even be lower. Therefore we will not generally restrict the parameter $M$ by eq. (15), but will discuss its consequences in connection with Fig. 4.

4 Constraints on the parameter space in the NMSSM

We first show for various values of the parameters $\lambda$, $k$ and $\tan \beta$ the domain in the $M-x$ plane excluded by the experimental bounds presented in Sec. 3. They are determined by calculating for every set of parameters the masses and eigenstates of the neutralinos and charginos and, with the couplings given in [24], the $Z$ decay width. Since the $Z$ boson does not couple to the singlet higgsino, the differences between the MSSM and the NMSSM just arise by the explicit form of the diagonalization matrix $N_{ij}$. If the result violates one of the experimental constraints this parameter set is excluded.

For $\lambda = 0.5$, $k = 0.2$ and $\lambda = 0.2$, $k = 0.005$ the $M-x$ parameter space excluded by measurements of the total $Z$ width eq. (12) and direct neutralino search eq. (14) is depicted in Fig. 1 for $\tan \beta = 2$ and 20, respectively. The limit on the invisible $Z$ width eq. (13) does not further constrain the allowed region for the considered parameters.

While the shape of the excluded domain in the $M-x$ plane of the NMSSM resembles that in the $M-\mu$ plane of the MSSM [7], there are, however, some fundamental differences. Generally, the allowed parameter space shrinks for increasing values of $\tan \beta$ and with decreasing parameters $\lambda$ and $k$.

For all parameter values considered there exists an excluded $M$-region, and therefore by eq. (16) also gluino mass bounds are imposed by LEP data. For $\tan \beta \lesssim 4$ and $k \gtrsim 0.01$ a light gluino scenario even with $M = 0$ GeV, which also leads to a massless photino, is allowed in the range $x \leq 1000$ GeV while a certain domain of positive $M$ values is always excluded. In our example in Fig. 1 with $\lambda = 0.5$, $k = 0.2$, $\tan \beta = 2$ negative $M$-values are not restricted, but positive values 41 GeV $< M < 57$ GeV are excluded.

For $\tan \beta \gtrsim 4$ the LEP data entail a lower bound for $|M|$ of about 45 GeV corresponding to $m_{\tilde{g}} > 145$ GeV; the exact bound depends on the maximal $x$ value considered.
5 Neutralino mass bounds in the NMSSM

In this section we present bounds on the masses of the NMSSM neutralinos and discuss their dependence on the model parameters $M$, $x$, and $\tan \beta$. Our procedure is similar to that described in Sec. 4: We fix some parameters ($\tan \beta$, $M$ and $x$ in the case of Fig. 2, $\tan \beta$ and $M$ for Fig. 3 and $\tan \beta$ for Fig. 4) and vary the remaining parameters over the range $-400 \text{ GeV} \leq M \leq 400 \text{ GeV}$, $0 \leq x \leq 1 \text{ TeV}$, $0 \leq \lambda, k \leq 1$. Within the allowed parameter region we then search for maxima and minima of the neutralino masses.

Fig. 2 shows the lower and upper bounds on the neutralino masses as a function of the singlet vacuum expectation value $x$ for $M = 200 \text{ GeV}$ and $\tan \beta = 2$ and 20, respectively. Although the bounds look quite similar for both values of $\tan \beta$ there is a fundamental difference: for $\tan \beta = 20$ the lightest neutralino could be massless, while for $\tan \beta = 2$ the mass of $\tilde{\chi}_0^1$ has a lower limit which sometimes turns out to be very small. The precise dependence on $\tan \beta$ will be discussed in Fig. 4. Moreover, there exists a lower limit for the $x$-values being compatible with the LEP data. Whereas for $M = 200 \text{ GeV}$ $x$ must be larger than approximately 75 GeV, smaller values of $x$ are allowed for decreasing values of $M$. In the vicinity of this limit, the allowed neutralino mass spectrum is rather restricted, for increasing $x$ it becomes broader. For larger $x$-values ($x > M$) the dependence on $x$ of the lower mass bounds for all neutralinos is rather weak. The upper bounds are determined by the asymptotical behavior of the mass eigenvalues: for the two lighter neutralinos it is almost independent on the $x$-values (asymptotically $m_{\tilde{\chi}_0^1} = M'$ and $m_{\tilde{\chi}_0^2} = M$), while for the heavier neutralinos it is approximately $2kx$ for $m_{\tilde{\chi}_0^5}$ and $\lambda x$ for $m_{\tilde{\chi}_0^3}$ and $m_{\tilde{\chi}_0^4}$.

In Fig. 3 we show the dependence of the neutralino mass bounds on the gaugino mass parameter $M$. As discussed in Sec. 3, for $\tan \beta = 2$ the region $44 \text{ GeV} < M < 52 \text{ GeV}$ and for $\tan \beta = 20$ the region $-45 \text{ GeV} < M < 46 \text{ GeV}$ is excluded. Apart from $M = 0 \text{ GeV}$, for $\tan \beta = 20$ a massless neutralino could exist only for positive $M$, while for $M < -5 \text{ GeV}$ and $\tan \beta = 20$ there exists a lower mass bound of 1.5 GeV. Similarly, for $\tan \beta = 2$ a massless eigenstate is excluded except for $M = 0 \text{ GeV}$, and we found a lower bound of 2 GeV for $|M| > 5 \text{ GeV}$. The lower limit on $m_{\tilde{\chi}_0^2}$ is nearly constant over a wide range of $M$ values, it just decreases for small values of $M$. All upper limits have the same asymptotic behaviour as discussed above (the horizontal lines in Fig. 3 b) and d) correspond to the values $2kx$ and $\lambda x$, respectively, for the highest values of $x$, $\lambda$ and $k$ considered).

Finally, we present in Fig. 4 the lower mass bounds of the lightest and second lightest neutralino as a function of $\tan \beta$ for $M > 30 \text{ GeV}$. Taking into account only the LEP constraints and allowing small $M$ values, a massless neutralino would be possible for all values of $\tan \beta$. Therefore we assume in Fig. 4 that a lower bound for $M$ based on the CDF data according to eq. also holds in the NMSSM.

In contrast to the MSSM, the lower mass bounds then decrease with increasing $\tan \beta$, and for $\tan \beta \gtrsim 5.5$ a massless neutralino becomes compatible with the experimental data. For all values of $\tan \beta$, the mass of the LSP $m_{\tilde{\chi}_0^1}$ could be as small as a few GeV. Comparing our results with those of the ALEPH collaboration for the MSSM [7] we find that the mass bounds for the second lightest neutralino in the NMSSM correspond nearly to those for the lightest one in the MSSM, and so on for the next neutralinos, while the lightest neutralino of the NMSSM can be much lighter than in the MSSM or even massless for $\tan \beta \gtrsim 5.5$. 


Therefore in the NMSSM the neutralino spectrum is similar to that of the MSSM with the exception of an additional very light or even massless singlet like neutralino. This could lead to interesting phenomena for the production and decay of neutralinos at the next generation of high energy colliders.

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Figure captions

Figure 1: The excluded parameter space in the $M-x$ plane for various values of $\lambda$, $k$ and $\tan\beta$: from total $Z$ width measurements (bright shaded) and direct neutralino search (dark shaded).

Figure 2: Upper and lower bounds on the neutralino masses in the NMSSM for $M = 200$ GeV and $\tan\beta = 2$ (a,b) and $\tan\beta = 20$ (c,d).

Figure 3: Upper and lower bounds on the neutralino masses in the NMSSM for $\tan\beta = 2$ (a,b) and $\tan\beta = 20$ (c,d).

Figure 4: Lower mass bound for the lightest (a) and second lightest (b) neutralino in the NMSSM.
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