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Towards discrimination of MSSM and NMSSM scenarios at colliders

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Abstract

One of the challenging tasks at future experiments is the clear identification of the underlying new physics model. In this study we concentrate on the distinction between different supersymmetric models, the MSSM and the NMSSM, exploring the gaugino/higgsino sector as an alternative to the Higgs sector. Under the assumption that only the light chargino and neutralino masses and polarized cross sections $e^+e^- \to \tilde{\chi}^0_i\tilde{\chi}^0_j$, $\tilde{\chi}^+_i\tilde{\chi}^-_j$ have been measured, we perform a fit of the fundamental MSSM parameters M_1, M_2, μ and $\tan\beta$ and study whether a model distinction is possible. We focus here on the challenging cases of scenarios with a relatively heavy singlino and address two classes of neutralino mixing, $\tilde{\chi}^0_1$ ∼higgsino-like versus $\tilde{\chi}^0_1$ ∼gaugino-like.

1 Introduction

Supersymmetry is an appealing candidate for physics Beyond the Standard Model (BSM): the introduction of a (broken) fermion-boson symmetry answers elegantly, for instance, the electroweak hierarchy puzzle, offers a dark matter candidate and is consistent with grand unification. The recent discovery of a Higgs-like particle with $m_h \sim 125.5$ GeV at the LHC [1, 2], together with the negative result of SUSY searches, however, is posing a challenge for theorists to conciliate supersymmetry.

Well motivated candidates for BSM are the Minimal Supersymmetric Standard Model (MSSM) and its minimal extension, the next-to-minimal Standard Model (NMSSM). The latter adds a gauge singlet chiral supermultiplet $\hat{S}$ and allows therefore a relaxation of the electroweak fine tuning and the naturalness conditions.

It is interesting to understand how, in case of a discovery of supersymmetry at the LHC and at a future linear collider, it would be possible to discriminate between these two models. They have, indeed, a very similar particle content but the NMSSM offers an enriched Higgs and higgsino spectrum: a CP-even Higgs, a CP-odd Higgs and a fifth neutralino in addition to the MSSM. In the literature mainly NMSSM scenarios are studied that have a singlino-like stable lightest supersymmetric particle (LSP). Due to the expected experimental accuracy in the Higgs measurements both at the LHC and the ILC [3, 4], and the additional two scalar states, a standard procedure to pinpoint the observed supersymmetry model is to study the Higgs sector. However, it could also well be that the additional Higgs bosons, are very heavy and not clearly detectable at the LHC/ILC. It is therefore important to find alternative and complementary tools to distinguish these models, for example addressing also the gaugino/higgsino sector.

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We follow such an alternative ansatz and assume that only the lightest states in this sector $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ are accessible, however contrary to [5], we focus on the heavy singlino case. Given the masses and production cross sections measured with a precision expected to be achievable at the linear collider, this method reconstructs the MSSM chargino and neutralino sector parameters M_1, M_2, $\mu = \mu_{\text{eff}}$, $\tan\beta$ in the philosophy of [6]. We perform a χ^2-fits and study whether a result non-compatible with the MSSM can be the smoking gun for the NMSSM.

In this proceeding, we shortly introduce the subject of an upcoming paper [7]. In particular, we address NMSSM scenarios with relatively heavy singlino ($\tilde{S}$), such that the detected spectra could be interpreted as an MSSM signal. We scan the (λ, κ)-plane applying the most recent phenomenological and experimental constraints from colliders and dark matter experiments in two cases. First we study a scenario with higgsino-like LSP and relatively heavy gauginos; then we look at a scenario with wino-like LSP ($M_1 > M_2$), expected in the context of minimal AMSB models [8,9].

In section 2 we briefly describe the strategy to discriminate the models; in section 3 we show the results of our analysis for different scenarios before we shortly summarize in section 4.

2 Strategy and MSSM parameter reconstruction

The $\mathbb{Z}_3$-invariant NMSSM, with the additional term in the superpotential

$$W_{\text{NMSSM}} = \lambda \hat{S}\hat{H}_u \cdot \hat{H}_d + \frac{\kappa}{3}\hat{S}^3\,, \tag{1}$$

features, with respect to the MSSM, a further gauge singlet superfield $\hat{S}$, consisting of a scalar Higgs singlet S and a neutralino $\tilde{S}$ that mixes due to electroweak symmetry breaking with the gaugino/higgsinos states. Therefore, looking for weakly coupling scalars or neutralinos is naïvely the first way to discriminate between NMSSM and MSSM, in particular promising in the light of the expected high accuracy in the Higgs sector measurements [4].

However, in case that the singlet states are relatively heavy in comparison with the SM-like Higgs, a discrimination could be more challenging since the observed Higgs sector can be interpreted within both the MSSM and the NMSSM. Signal strengths at the LHC would be very similar in both models with the heavier states decoupled from the spectrum and beyond the kinematic reach at the future linear collider.

The MSSM chargino and neutralino sectors are fully described by the parameters M_1, M_2, μ, $\tan\beta$. It has been shown in [10–12], that full tree-level determination of these parameters is possible at a linear collider, provided that $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ can be produced at the LC and their masses as well as the polarized cross sections $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$, $\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$ are precisely measured. A χ^2-minimisation selects parameters fitting the experimental results and provides a precise and rather model-independent determination of M_1, M_2, μ, $\tan\beta$. Such analysis can be strengthened if the mass of the heavier neutralino states can be inferred from combined analyses of LHC and LC data [6].

The possibility of reconstructing the MSSM chargino-neutralino sector parameters can then be enveloped in a strategy to discriminate between the MSSM and the NMSSM [5], complementary to looking only at the Higgs sectors. If the result of the χ^2-fit, based only on the measured $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^\pm$ sector, excludes the MSSM at 95% C.L., one should look for extended models as, for instance, the NMSSM.

In this study, we address in particular challenging NMSSM scenarios with relatively heavy singlino (and singlet) but a lower chargino-neutralino spectra that is approximately MSSM-like and proceed as follows:

- We choose an NMSSM scenario that presents low chargino-neutralino spectrum that is nearly indistinguishable with respect to the one of a corresponding MSSM scenario.
- The λ, κ parameters encode the pure NMSSM-behaviour in the neutralino sector and change the singlino admixtures in the different mass eigenstates. We scan a grid of ten thousand points in the (λ, κ)-plane for values $\lambda \in [0, 0.7]$ and $\kappa \in [0, 0.7]$. The singlino character of the neutralinos has a strong impact on the suitable strategy for the distinction of both models.

  Each point, in order to be further considered in the analysis, has to pass a series of phenomenological and experimental constraints implemented in `NMSSMTools-4.2.1`, that includes `NMHDECAY` [13–15] and `NMSDECAY` [16,17]. These tools calculate the Higgs sector parameters, SUSY particle masses at the loop level and their decays and test their agreement with limits from LEP and LHC and other EW precision constraints. Dark matter constraints, including the latest LUX and Planck results, are implemented through an interface to `MicrOMEGAS` [18]. We require the LSP relic density to be $\Omega_{\rm LSP}h^2 < 0.131$, where h is the Hubble constant in units of 100 km/(s·Mpc). A second test on the Higgs sector constraints is done with `HiggsBounds-4.0.0` [19] and `HiggsSignals-1.0.0` [20], and we accept only points compatible at 95% C.L. with the current data.

- For each point in the (λ, κ)-plane passing the tests mentioned above, we assume that the lower chargino/neutralino spectrum, namely $\tilde{\chi}^0_1$, $\tilde{\chi}^0_2$ and $\tilde{\chi}^\pm_1$, is observed at the ILC. We include the tree-level masses and production cross-sections for the processes $e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1$ and $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$ or $\tilde{\chi}^0_1\tilde{\chi}^0_3$ with electron and positron beam polarisation $(\mathcal{P}_{e^-}, \mathcal{P}_{e^+}) = (\pm 0.9, \mp 0.55)$ measured at $\sqrt{s} = 350$ GeV ($t\bar{t}$-threshold) and at $\sqrt{s} = 500$ GeV. A precision of uncertainty of 0.5% on the masses and 1% on the cross sections is assumed [21, 22].

- For each NMSSM point, the "measured" masses, cross-sections and respective uncertainties are used to perform the MSSM parameter determination through the χ^2-fit following the recipe in [6], using `Minuit` [23], minimizing

$$\chi^2 = \sum_i \left| \frac{\mathcal{O}_i - \bar{\mathcal{O}}_i}{\delta\mathcal{O}_i} \right|^2 . \tag{2}$$

  The $\mathcal{O}_i$ are the input observables, δO_i are the associated experimental uncertainties and $\bar{O}_i$ are the theoretical values of the observables on basis of the fitted MSSM parameters. If for a given point the fit is not consistent with the MSSM at the 95% C.L., it provides an experimental hint towards the NMSSM. In this way we can identify those parameter regions where the model distinction is possible in spite of the challenging assumption that only a very limited amount of experimental observables are accessible.

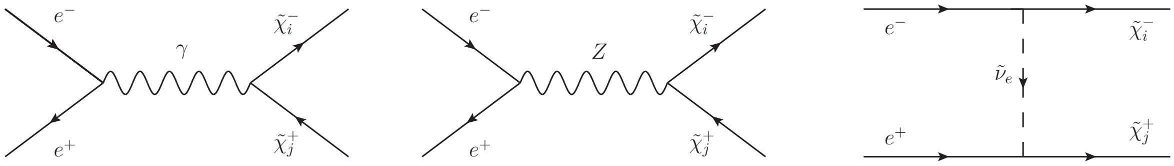


Figure 1: Feyman diagrams for $\tilde{\chi}^+_i\tilde{\chi}^-_j$ production at e^+e^- colliders.

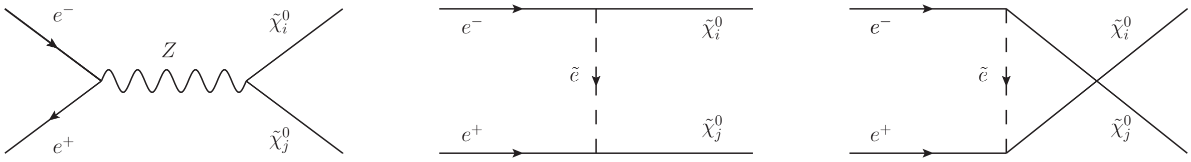


Figure 2: Feynman diagrams for $\tilde{\chi}^0_i\tilde{\chi}^0_j$ production at e^+e^- colliders.

3 Scenarios and analysis

In the NMSSM, the singlino ($\tilde{S}$) admixture of $\tilde{\chi}^0_1$ can be used to pinpoint two main classes of scenarios:

- High $\tilde{S}$ admixture in $\tilde{\chi}^0_1$ or $\tilde{\chi}^0_2$.

  Since we assume to detect the lightest neutralinos, a light singlino would be the smoking gun for a non-MSSM scenario, due to the different cross-sections and in consequence non-compatible fit.

Because of a high admixture of $\tilde{S}$ in $\tilde{\chi}_1^0$ and/or $\tilde{\chi}_2^0$, indeed, the higgsino and gaugino components in these lightest NMSSM neutralino states would be substantially different from those of the fit-reconstructed MSSM scenario. In such cases the distinction between the models through the outlined method is expected to be promising, see [5].

- High $\tilde{S}$ admixture mainly in the heavy neutralino states $\tilde{\chi}_3^0, \tilde{\chi}_4^0, \tilde{\chi}_5^0$.

  We will in particular focus on cases, where both the light spectra and the neutralino admixture are very similar between NMSSM and corresponding MSSM scenario. In this case it is likely that the fit is still compatible with the MSSM. We question how to integrate informations from heavier neutralino states at the LHC or TeV-LC, and/or from the Higgs sector in order to enable a model distinction.

  In particular we analyse an example for each of the following categories:

  1. $\mu_{\text{eff}} < M_1, M_2$: the LSP, $\tilde{\chi}_1^0$, is mainly higgsino-like in the whole studied (λ, κ)-plane, see subsection 3.1.
  2. $\mu_{\text{eff}} > M_1, M_2$: $\tilde{\chi}_1^0$ is mainly gaugino-like in the whole studied (λ, κ)-plane, see subsection 3.2.

3.1 Light higgsino scenario, $\mu_{\text{eff}} < M_1 < M_2$

The chargino/neutralino sector parameters for the light higgsino NMSSM scenario we consider are:

$$M_1 = 450 \text{ GeV}, \quad M_2 = 1600 \text{ GeV}, \quad \mu_{\text{eff}} = \lambda\, s = 120 \text{ GeV}, \quad \tan\beta = 27\,, \tag{3}$$

while $\lambda \in [0, 0.7]$ and $\kappa \in [0, 0.7]$ as prescribed above and μ_{eff} is kept fixed by varying s, the singlet vev. The singlet soft parameters are $A_\lambda = 3000$ GeV, $A_\kappa = -30$ GeV. The first generation sfermion masses, needed for the production cross sections, see Figures 1 and 2, are

$$m_{\tilde{e}_L} = 303.5 \text{ GeV}, \, m_{\tilde{e}_R} = 303 \text{ GeV}, \, m_{\tilde{\nu}_e} = 293.3 \text{ GeV}\,, \tag{4}$$

while squarks masses are > 1 TeV.

We now take a MSSM scenario with M_1, M_2, $\mu = \mu_{\text{eff}}$, $\tan\beta$ as in (3) and the same slepton masses as in (4). For the lightest neutralino and chargino states we have obtained, at the tree-level, masses and production cross sections that are very close to ones of the NMSSM scenario. The MSSM tree-level chargino/neutralino spectrum is given by:

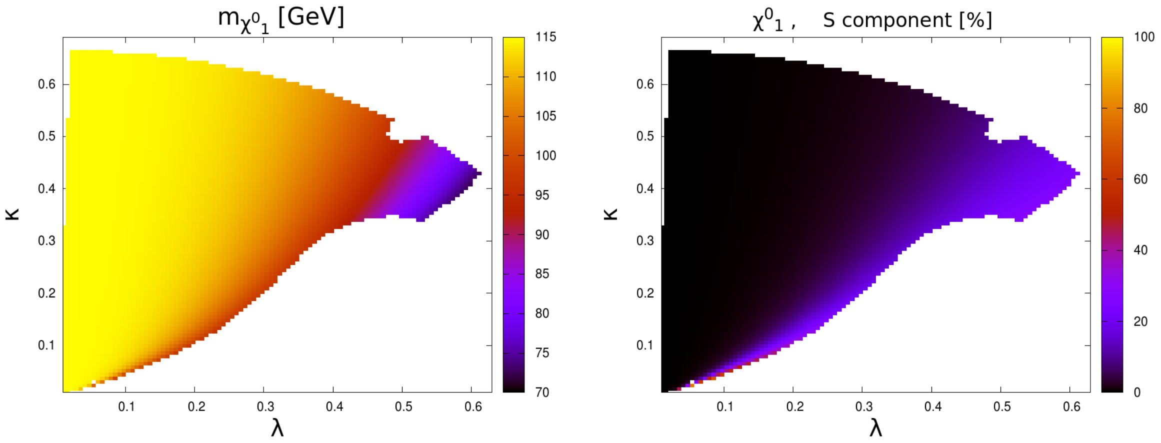
$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$
114.8 GeV	123.3 GeV	454.4 GeV	1604.1 GeV	119.4 GeV	1604.1 GeV

In Figure 3, the NMSSM $\tilde{\chi}_1^0$ mass and its singlino ($\tilde{S}$) component of are shown. One can clearly see that in the region where the singlino component is negligible, the NMSSM $m_{\tilde{\chi}_1^0}$ is very close to the MSSM value $m_{\tilde{\chi}_1^0} = 114.8$. In correspondence of higher singlino admixture, instead, NMSSM $m_{\tilde{\chi}_1^0}$ sensibly lowers.

The polarized tree-level production cross sections for the MSSM scenario are:

MSSM, $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$	$\sqrt{s} = 350$ GeV	$\sqrt{s} = 500$ GeV
$P = (-0.9, 0.55)$	791.7 fb	391.4 fb
$P = (0.9, -0.55)$	526.7 fb	261.7 fb

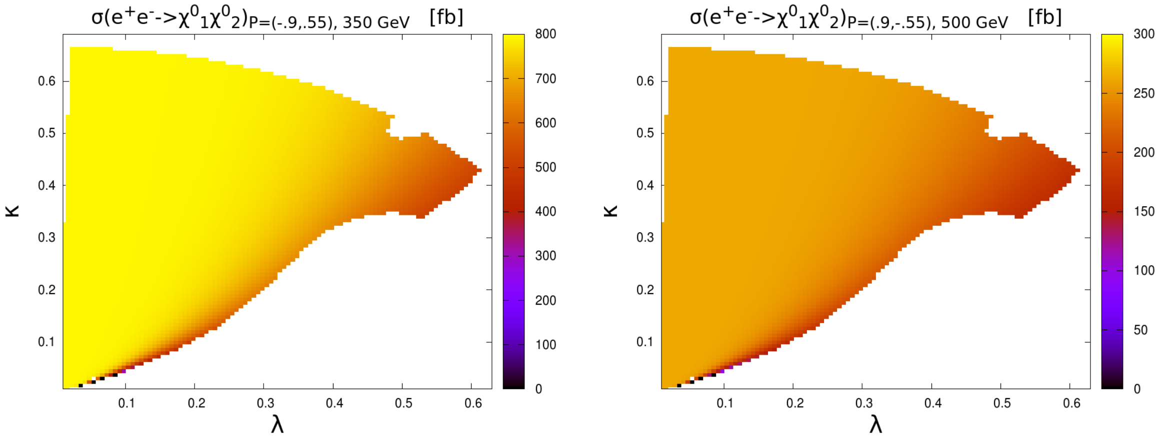
MSSM, $\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$	$\sqrt{s} = 350$ GeV	$\sqrt{s} = 500$ GeV
$P = (-0.9, 0.55)$	2348.8 fb	1218.9 fb
$P = (0.9, -0.55)$	445.1 fb	246.2 fb



(a) (b)

Figure 3: Light higgsino scenario: (a) the mass $m_{\tilde{\chi}^0_1}$, in GeV; (b) the $\tilde{S}$ component of $\tilde{\chi}^0_1$, in %.

At the tree-level, the NMSSM chargino masses and production cross-sections $\sigma(e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1)$ depend only on M_2, $\mu_{\rm eff}$, $\tan\beta$. Therefore, in the (λ, κ)-plane chargino production cross sections are identical to those of the MSSM scenario, since this has the same M_2, μ, $\tan\beta$ as in (3). Neutralino pair production $e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2$, instead, varies with λ and κ, see Figure 4, where it can be observed a lowering of the cross section following a higher singlino component in $\tilde{\chi}^0_1$.



(a) (b)

Figure 4: $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production cross sections in the ight higgsino scenario: (a) $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$ for $P = (-0.9, 0.55)$ at $\sqrt{s} = 350$ GeV, in fb; (b) $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$ for $P = (+0.9, -0.55)$ at $\sqrt{s} = 500$ GeV, in fb.

As described in Section 2 we now assume for each point in the (λ, κ)-plane experimental measurement of the corresponding lighter neutralino and chargino masses and associated production cross sections. Next, we perform the χ^2-fit to the MSSM, we assume for this scenario to detect at the ILC $m_{\tilde{\chi}^0_1}$, $m_{\tilde{\chi}^0_2}$ and $m_{\tilde{\chi}^\pm_1}$ with an uncertainty of 0.5%. Furthermore, we assume 1% uncertainty on the polarized cross sections $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$ and $\sigma(e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1)$, both at $\sqrt{s} = 350$ and 500 GeV, with polarizations $P = (-0.9, 0.55)$ and $P = (+.9, -.55)$.

In Figure 5 the result of the fit is shown: yellow areas correspond to regions in the (λ, κ)-plane that are compatible with the MSSM scenario, while the black areas are not compatible. We can observe two regions that, while allowed by the implemented phenomenological and experimental constraints, can definitely be distinguished from the MSSM using collider observables.

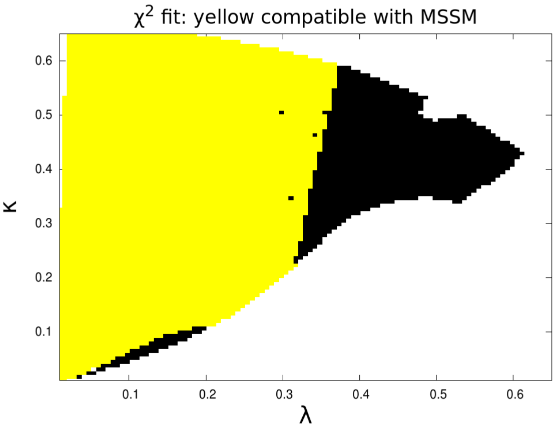


Figure 5: Light higgsino scenario: fit to the MSSM. Yellow areas are compatible with the MSSM, black areas are not compatible.

One can ask now how to integrate this result with additional information, further reducing the region that cannot be distinguished from the MSSM scenario. This information can be recovered from the heavier neutralino states, such as $\tilde{\chi}_3^0$. For example, given a set of M_1, M_2, μ, $\tan\beta$ reconstructed from the fit, one can derive $m_{\tilde{\chi}_3^0}$. Looking for such a state at the ILC or at the LHC, can either confirm the fit to the MSSM or even pinpoint the NMSSM. Further information can be given from the Higgs sector, in particular from the search of singlet states. Such questions will be addresses in the upcoming work [7].

3.2 Light gaugino scenario, $\mu_{\text{eff}} > M_1 > M_2$

We look at the light gaugino NMSSM scenario, whose neutralino/chargino sector parameters are:

$$M_1 = 240 \text{ GeV}, \quad M_2 = 105 \text{ GeV}, \quad \mu = \mu_{\text{eff}} = 505 \text{ GeV}, \quad \tan\beta = 9.2\,, \tag{5}$$

with $\lambda \in [0, 0.7]$ and $\kappa \in [0, 0.7]$. Moreover, $A_\lambda = 3700$ GeV, $A_\kappa = -40$ GeV. The first generation sfermion masses are

$$m_{\tilde{e}_L} = 303.5 \text{ GeV}, \, m_{\tilde{e}_R} = 303 \text{ GeV}, \, m_{\tilde{\nu}_e} = 293.3 \text{ GeV}\,, \tag{6}$$

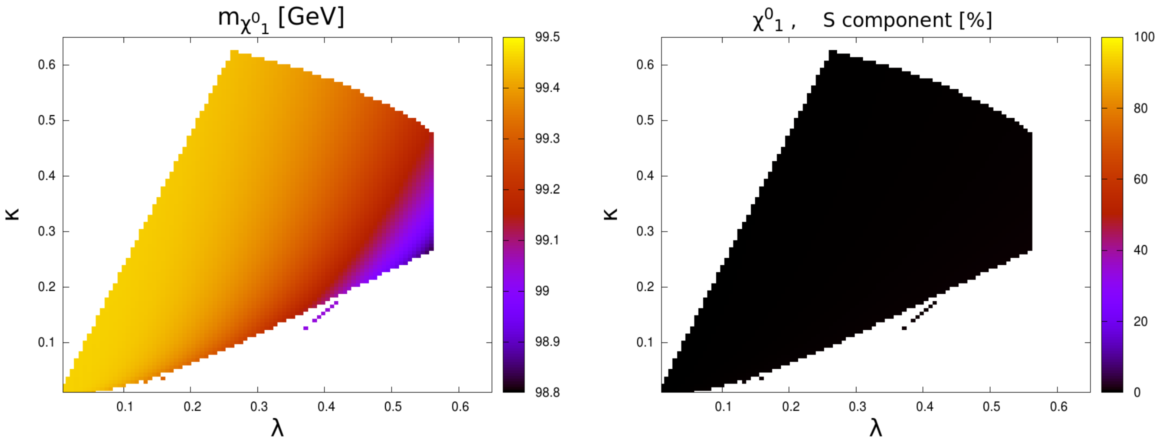
while squarks masses are > 1 TeV.

Choosing M_1, M_2, μ, $\tan\beta$ and the first generation slepton masses as in (5),(6) permits to find a MSSM scenario with an approximately indistinguishable lower neutralino/chargino mass spectrum with that of NMSSM along all the (λ, κ)-plane. The MSSM tree-level neutralino/chargino spectrum, is indeed given by:

$m_{\tilde{\chi}_1^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_2^\pm}$
99.5 GeV	237.0 GeV	510.1 GeV	518.7 GeV	99.6 GeV	518.7 GeV

In Figure 6 one can see that the NMSSM $m_{\tilde{\chi}_1^0}$ is very close to 99.5 GeV from the MSSM and varies very mildly in the allowed in the (λ, κ)-plane since the singlino component in $\tilde{\chi}_1^0$ is approximately zero. Also, the production cross sections $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$ are similar in the two models, while the $\sigma(e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-)$ are exactly identical at the tree-level as explained in Subsection 3.1.

MSSM, $\sigma(e^+e^- \to \tilde{\chi}_1^0\tilde{\chi}_2^0)$	$\sqrt{s} = 350$ GeV	$\sqrt{s} = 500$ GeV
$P = (-0.9, 0.55)$	7.3 fb	113.4 fb
$P = (0.9, -0.55)$	0.1 fb	1.8 fb



(a) (b)

Figure 6: The light gaugino scenario: (a) the mass $m_{\tilde{\chi}^0_1}$, in GeV; (b) the $\tilde{S}$ component of $\tilde{\chi}^0_1$, in %.

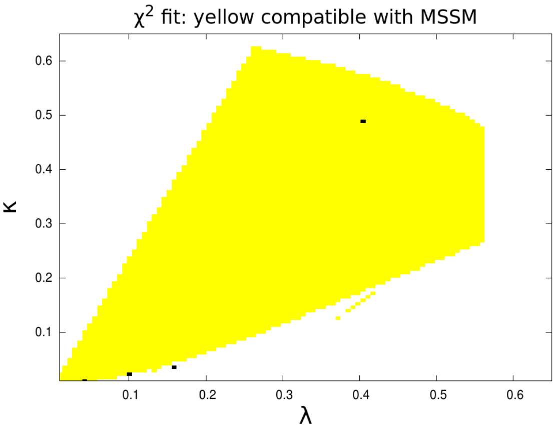


Figure 7: Light gaugino scenario: fit to the MSSM. Yellow areas are compatible with the MSSM, black areas are not compatible.

MSSM, $\sigma(e^+e^- \to \tilde{\chi}^+_1\tilde{\chi}^-_1)$	$\sqrt{s} = 350$ GeV	$\sqrt{s} = 500$ GeV
$P = (-0.9, 0.55)$	2692.1 fb	1252.6 fb
$P = (0.9, -0.55)$	44.5 fb	19.4 fb

For the χ^2-fit to the MSSM fit we use those cross sections that are large enough to be surely visible at the linear collider. We prefer to be conservative, so for $\tilde{\chi}^0_1\tilde{\chi}^0_2$ production we only use the $\sigma(e^+e^- \to \tilde{\chi}^0_1\tilde{\chi}^0_2)$ for $P = (0.9, -0.55)$ at 350 GeV, since the other cross sections are too small.

Figure 7 shows that our fit is not able to distinguish in this case between the two models. The physically allowed region is indeed basically everywhere compatible with the MSSM.

4 Conclusions and outlook

Supersymmetric models such as the MSSM and the NMSSM can lead to very similar light spectra. In case of SUSY discovery, methods to distinguish between the two models are needed. We addressed the study chargino and neutralino sectors alternatively to looking at the Higgs sector. It is proposed to distinguish between the MSSM and the NMSSM via M_1, M_2, $\mu = \mu_{\rm eff}$, $\tan\beta$ parameter reconstruction by fitting masses and cross sections from the chargino/neutralino sector. We have discussed two examples, the light higgsino and the light gaugino scenarios, where distinction could be possible.

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