PARAMETER SCANS IN TWO INTERESTING NMSSM SCENARIOS

I. Rottländer[1], *M. Schumacher*[2]
[1]Physikalisches Institut, University of Bonn, Nussallee 12, 53115 Bonn, Germany
[2]Fachbereich Physik, University of Siegen, Walter-Flex-Straße 3, 57068 Siegen, Germany

1. INTRODUCTION

In the past, proposals for interesting points in the parameter space of the *Next-to-Minimal Supersymmetric Standard Model* (NMSSM) [1, 2, 3, 4, 5, 6] have been made (see e.g. Refs. [7, 8, 9]). A new study proposes benchmark points for the constrained NMSSM [10]. To evaluate the discovery potential of NMSSM particles at collider experiments like the *Large Hadron Collider* (LHC)[1], it is furthermore desirable to define two-dimensional benchmark scans which include regions of typical and experimentally challenging NMSSM phenomenology. In the following, two such parameter scans over the Higgs sector of the NMSSM are proposed for this model. Both scans include a benchmark point from Ref. [9].

2. THE NMSSM

In the *Minimal Supersymmetric Standard Model* (MSSM), the value of the Higgs-Higgsino mass parameter μ is not confined by theory, but it is experimentally constrained to lie at the weak scale or else large fine-tuning is required (the so called μ-*problem*). In the NMSSM, an additional neutral singlet superfield S is added to the MSSM. After symmetry breaking, μ is then given by the product of the vacuum expectation value of the bosonic component of S ($\langle s \rangle$) and a new coupling constant λ. Constraints from the Higgs potential minimization strongly prefer $\langle s \rangle$ to lie at the weak scale. The right value of μ is thus obtained naturally.

The resulting model contains the whole particle spectrum of the MSSM with an additional neutral scalar boson, a pseudoscalar boson and a neutral fermion ("singlino"). The two additional neutral scalar bosons contained in S mix with the MSSM Higgs bosons to form the five neutral Higgs bosons of the NMSSM: three CP-even bosons H_1, H_2, H_3 and two CP-odd Higgs bosons A_1, A_2. The neutral fermion mixes with the four neutralinos of the MSSM, thus, the model contains in total five neutral fermion states. Since no charged particles are added, the features of the other MSSM particles, including the charged Higgs boson $H^{\pm}$, are only modified marginally. The maximally allowed mass of the lightest NMSSM scalar H_1 is about 10 GeV higher than the bound for h in the MSSM [11].

In the NMSSM, the Higgs sector can at tree level be described by six parameters. Usually, these are chosen to be the coupling parameters of S (λ, κ, A_λ, A_κ), μ and the ratio of the vacuum expectation values of the Higgs fields, $\tan\beta$. In the here defined two-dimensional parameter scans, λ and κ are varied. Variation of the other parameters also changes the features of the Higgs sector, however, a λ-κ variation was found to be sufficient to cover the most important phenomenology types in the two scans described here.

To calculate the NMSSM particle spectra and exclusion constraints from theory and LEP[2], the program NMHDECAY [12, 13, 14] was used. The mass parameters were chosen as $M_1 = 500$ GeV, $M_2 = 1$ TeV, $M_3 = 3$ TeV and $M_{susy} = 1$ TeV. The trilinear soft supersymmetry-breaking parameters were set to $A_t = A_b = A_\tau = 1.5$ TeV, the top quark mass to 172 GeV.

3. THE REDUCED COUPLINGS SCENARIO

Due to the mixing with the gauge singlet states, the NMSSM Higgs bosons can have reduced couplings to fermions and vector bosons and thus reduced production cross sections compared to the *Standard*

[1]A proton-proton collider with a design center-of-mass energy of 14 TeV. First physics runs are expected for 2008.
[2]The *Large Electron Positron Collider*, which ran until 2000 at center-of mass energies up to 209 GeV.

Table 1: Higgs sector parameters of the proposed scenarios

Scenario	λ-range	κ-range	A_λ [GeV]	A_κ [GeV]	μ [GeV]	$\tan\beta$
Reduced couplings	0 - 0.025	-0.005 - 0	-70	-54	-284	5.7
Light A_1	0 - 0.55	-0.2 - 0.6	-580	-2.8	-520	5.0

Model (SM) or the MSSM case. A light scalar with reduced couplings and a mass below 114 GeV is still unexcluded by LEP.

The here proposed scenario is a λ-κ scan with parameters given in Table 1. The point with $\lambda = 0.0163$ and $\kappa = -0.0034$ is described as having the lowest statistical significance found in a region without Higgs-to-Higgs decays in Ref. [9].

The masses of all six Higgs bosons in this scenario are smaller than about 300 GeV. The H_1 is very light, down to values of about 20 GeV in an unexcluded region with small negative κ (Fig.1). Since the H_2 has a SM-like mass around 120 GeV in the entire plane (Fig.2), there is a region where the decay $H_2 \rightarrow H_1 H_1$ is allowed with a small branching ratio of at maximum 6% in the unexcluded region (Fig.5). The A_1 mass ranges from about 55-100 GeV (Fig.3) in the allowed parameter region, whereas the H_3, A_2, and $H^\pm$ are approximately degenerate in the entire plane, but with small differences in mass for large negative κ. The mass of the H_3 ranges from about 150 to 300 GeV, the mass of the A_2 from about 140 to 300 GeV and the charged Higgs boson mass from about 165 to 300 GeV in the unexcluded region (Fig.4).

In Figures 6, 7 & 8, the vector boson couplings of the scalar bosons are given as an example coupling. Higgs boson couplings to gluons and up-type fermions vary similarly. The H_1 and H_3 couplings[3] are highly suppressed in most of the parameter plane, reaching sizeable values only in the LEP excluded region at large negative κ. The H_2 has SM-like couplings in large parts of the parameter plane. In the unexcluded region close to the benchmark point from Ref. [9], the vector boson couplings are reduced down to about 80% of their SM-value. The couplings of the A_1 and A_2 are highly suppressed for all considered parameter values.

To summarize, this scenario is characterized by a region with a very light H_1 close to the upper exclusion bound, where $H_2 \rightarrow H_1 H_1$ decays are possible, a region with a SM-like H_2 in the middle of the allowed parameter space, and a region with reduced couplings of the H_2 at large negative κ close to the lower exclusion bound.

4. THE LIGHT A$_1$ SCENARIO

Unlike in the MSSM, the mass of the lightest pseudoscalar A_1 is in the NMSSM not closely coupled to the masses of the scalar Higgs bosons and might thus lie well below the H_1/H_2 masses. In such a case, the decay chain $H_{1/2} \rightarrow A_1 A_1$ can be the dominant decay mode of the lightest scalars.

The here described scenario is also a λ-κ scan with parameters given in Table 1. The point with $\lambda = 0.22$ and $\kappa = -0.1$ has been described in Ref. [9].

Here, the lightest scalar H_1 has a mass around 120 GeV in the unexcluded region (Fig.9). The A_1 is very light with masses up to about 60 GeV (Fig.11), so that the decay $H_1 \rightarrow A_1 A_1$ is possible in the entire parameter plane with exception of a small region at very small λ and κ (Fig.13). In the unexcluded region with large λ and κ, this decay reaches branching ratios above 90%. Areas with a smaller branching ratio exists for smaller λ and κ. The other Higgs bosons are rather heavy (Figs.10,12), with the H_3, A_2 and $H^\pm$ being approximately degenerate in large parts of the parameter plane.

For A_1 masses larger than $2m_b$, about 90% of the lightest pseudoscalar bosons decay to bottom quarks.

[3]The term 'reduced couplings' here and in the following always excludes the Higgs boson coupling to down-type fermions which may be enhanced with respect to the SM-value, but are still too small to have an impact on the Higgs boson discovery potential with the here used $\tan\beta$ values around 5.

In these regions, the decay chains $H_1 \to A_1 A_1 \to b\bar{b}b\bar{b}$ and $H_1 \to A_1 A_1 \to b\bar{b}\tau\tau$ are important. In small regions at the borders of the unexcluded region, the A_1 is so light that the decay chain $H_1 \to A_1 A_1 \to \tau\tau\tau\tau$ prevails (Fig.14). In the narrow unexcluded band around $\lambda \approx 0.25$, the couplings of the A_1 to fermions are heavily suppressed. Here, the decay chain $H_1 \to A_1 A_1 \to \gamma\gamma\gamma\gamma$ is dominant.
The couplings of the H_1 are SM-like in the entire allowed parameter region (Fig.15). The couplings of the H_2 are sizeable only in a small excluded region with κ-values close to zero (Fig.16). All other Higgs bosons have highly suppressed couplings in the entire parameter plane.

CONCLUSIONS

Two interesting two-dimensional NMSSM scans were described and proposed as possible benchmarks for NMSSM Higgs boson searches. These two scans cover the four main, for the NMSSM typical phenomenology types, for which a discovery of Higgs bosons at future experiments like the LHC might be difficult:

- A region with very light scalar H_1.
- A region with reduced couplings of an otherwise SM-like scalar H_2.
- Regions with dominant $H_1 \to A_1 A_1 \to b\bar{b}b\bar{b}/b\bar{b}\tau\tau$ decays of an otherwise SM-like scalar H_1.
- Regions with dominant $H_1 \to A_1 A_1 \to \tau\tau\tau\tau$ decay of an otherwise SM-like scalar H_1.

Another example of an experimentally challenging phenomenology type not covered here is a dominant $H_1 \to c\bar{c}$ decay [8]. Also the region where the mass of the lightest scalar is maximal [11] could prove interesting for Higgs boson discovery .

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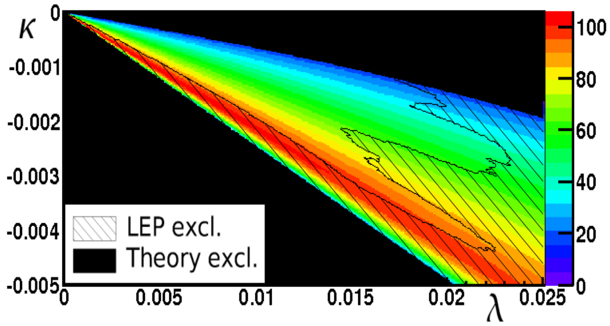

Fig. 1: H_1 mass [GeV] in the *Reduced Couplings Scenario*

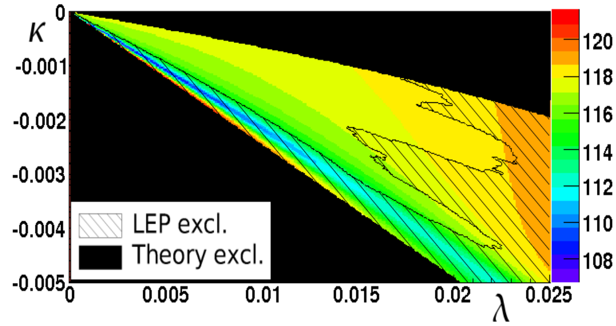

Fig. 2: H_2 mass [GeV] in the *Reduced Couplings Scenario*

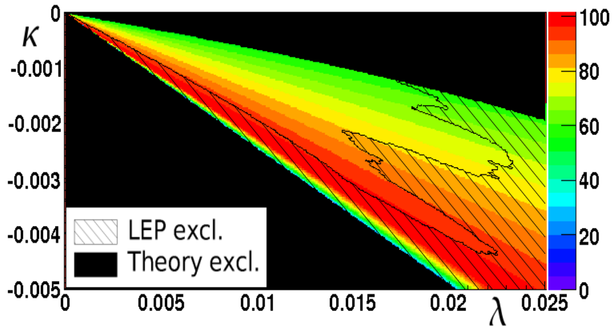

Fig. 3: A_1 mass [GeV] in the *Reduced Couplings Scenario*

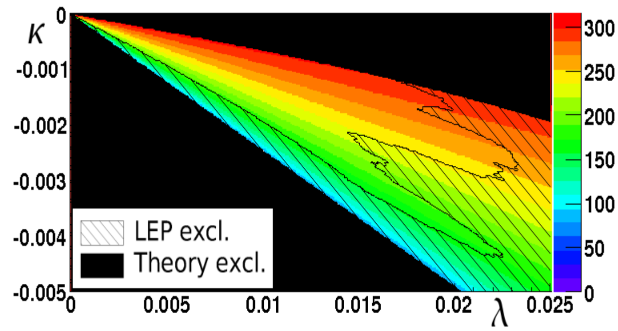

Fig. 4: $H^{\pm}$ mass [GeV] in the *Reduced Couplings Scenario*

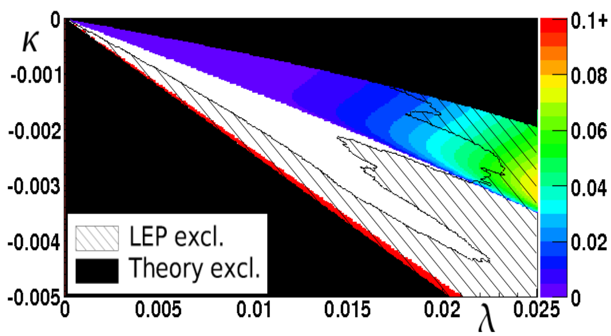

Fig. 5: $H_2 \rightarrow H_1 H_1$ branching ratio in the *Reduced Couplings Scenario*

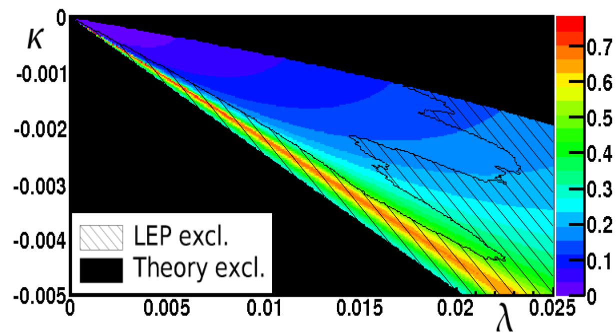

Fig. 6: H_1 vector boson coupling relative to its SM-value in the *Reduced Couplings Scenario*

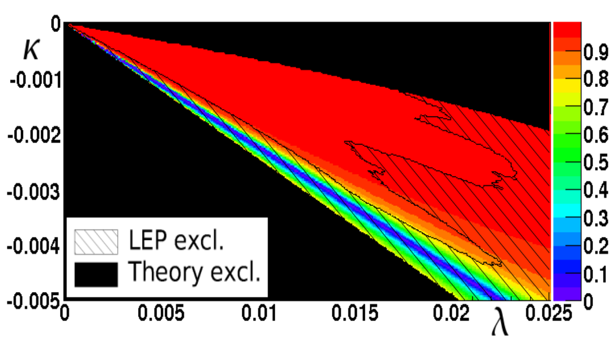

Fig. 7: H_2 vector boson coupling relative to its SM-value in the *Reduced Couplings Scenario*

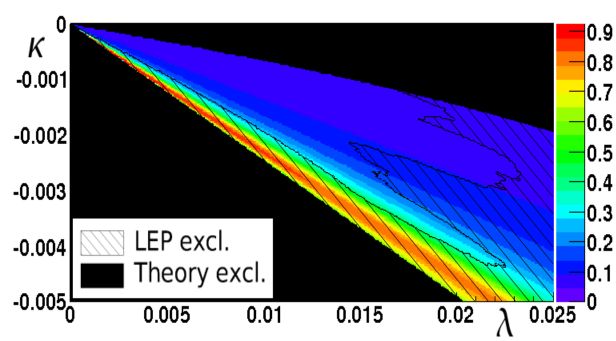

Fig. 8: H_3 vector boson coupling relative to its SM-value in the *Reduced Couplings Scenario*

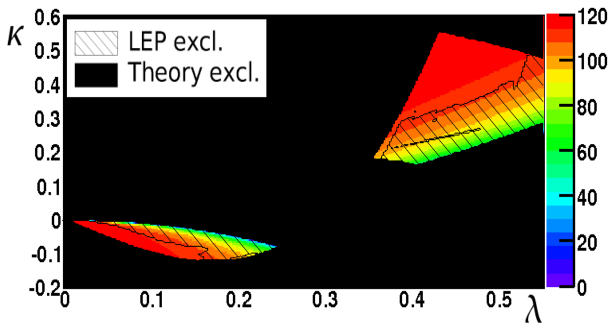

Fig. 9: H_1 mass [GeV] in the *Light* A_1 *Scenario*

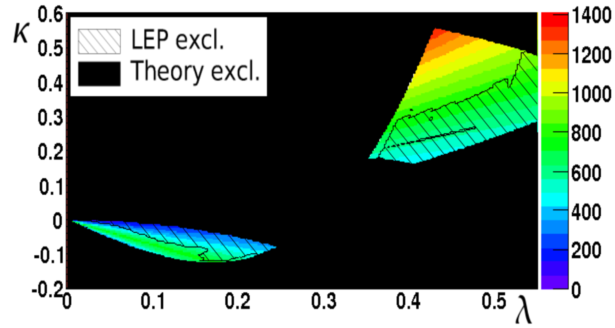

Fig. 10: H_2 mass [GeV] in the *Light* A_1 *Scenario*

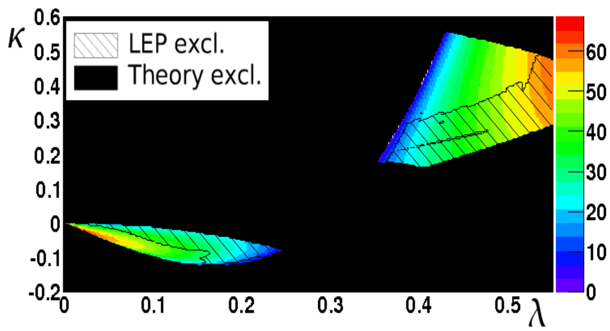

Fig. 11: A_1 mass [GeV] in the *Light* A_1 *Scenario*

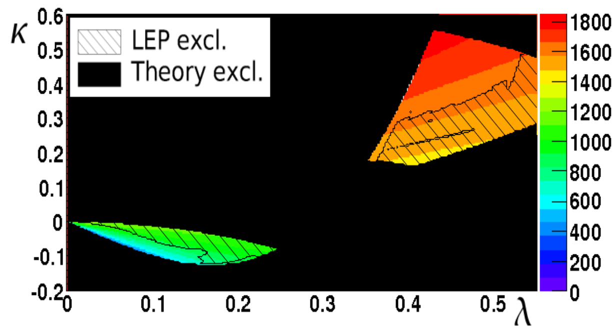

Fig. 12: $H^{\pm}$ mass [GeV] in the *Light* A_1 *Scenario*

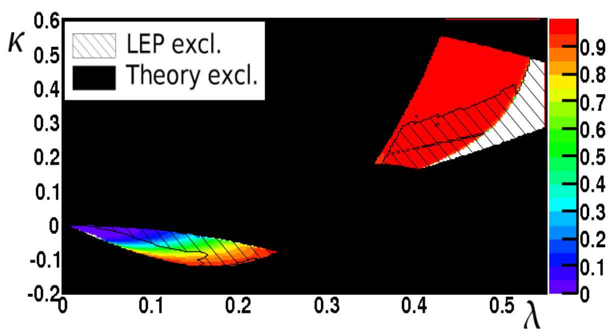

Fig. 13: $H_1 \to A_1 A_1$ branching ratio in the *Light* A_1 *Scenario*

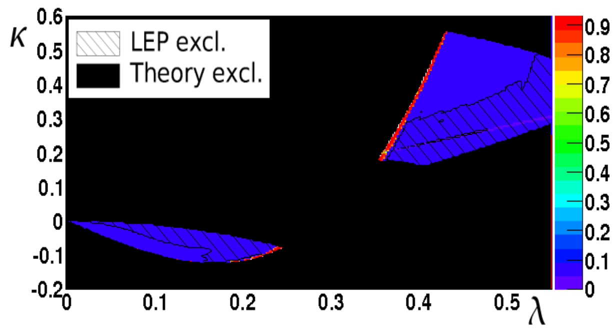

Fig. 14: $A_1 \to \tau\tau$ branching ratio in the *Light* A_1 *Scenario*

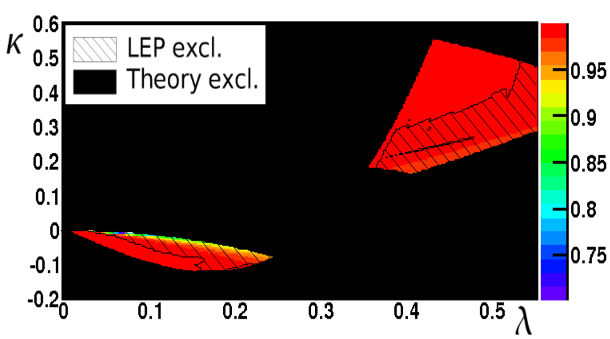

Fig. 15: H_1 vector boson coupling relative to its SM-value in the *Light* A_1 *Scenario*

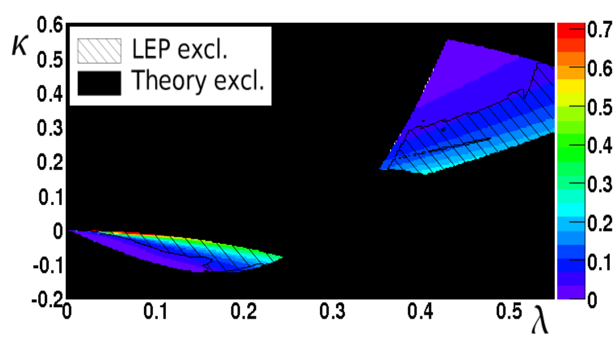

Fig. 16: H_2 vector boson coupling relative to its SM-value in the *Light* A_1 *Scenario*