INVESTIGATION OF THE LHC DISCOVERY POTENTIAL FOR HIGGS BOSONS IN THE NMSSM

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1. INTRODUCTION

The *Large Hadron Collider* (LHC) will deliver proton-proton collisions at a center-of-mass energy of 14 TeV. First physics runs are expected for 2008. First, the LHC will operate at low luminosity ($2 \cdot 10^{33}\text{cm}^{-2}\text{s}^{-1}$). Later, the luminosity will be increased to its design value of $10^{34}\text{cm}^{-2}\text{s}^{-1}$. One of the main aims of the ATLAS [1] and CMS [2] experiments at the LHC is the search for the Higgs boson. In the Standard Model (SM) electroweak symmetry breaking is achieved via the introduction of one Higgs doublet. Only one neutral Higgs boson is predicted. Extended Higgs sectors with additonal Higgs doublets and Higgs singlets give rise to several neutral and charged Higgs bosons, e.g. the two Higgs doublets of the Minimal Supersymmetric Extension of the SM (MSSM) yield three neutral and two charged Higgs bosons. Detailed studies have shown that the SM Higgs boson will be observable at ATLAS and CMS [1, 2, 3]. The discovery of one or more Higgs bosons of the CP-conserving MSSM will be possible [4]. Previous studies claim that at least one Higgs boson of the Next-to-Minimal Supersymmetric Standard Model (NMSSM) will most likely be observable at the LHC [5, 6]. Here, we present an evaluation of the discovery potential for NMSSM Higgs bosons based on current ATLAS studies [1, 3, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16].

2. THE NMSSM HIGGS SECTOR

In the framework of the NMSSM, the μ-*problem* of the MSSM is solved by the introduction of an additional neutral singlet superfield S [17]. 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 phenomenology of the charged Higgs boson $H^\pm$ is only modified marginally with respect to the MSSM. The Higgs sector of the NMSSM at Born level is determined by the four coupling parameters of the singlet superfield, λ, κ, A_λ, A_κ, and the two parameters μ and $\tan\beta$. For a more detailed description of the NMSSM Higgs sector see e.g. Refs. [17, 18].

3. EVALUATION OF THE DISCOVERY POTENTIAL

Two two-dimensional benchmark scenarios are investigated in this study: the *Reduced Couplings Scenario* and the *Light* A_1 *Scenario* which were proposed during this workshop (for details see these proceedings). The parameters λ and κ are varied in meaningful ranges whereas the other parameters are fixed as described previously in this report. The method of evaluation of the discovery potential is similar to the study performed for the MSSM in Ref. [4].

3.1 Calculation of masses and events rates in the NMSSM

NMHDECAY [19, 20] was used to calculate the masses, branching ratios and decay widths of the NMSSM Higgs bosons and the couplings of the neutral Higgs bosons to fermions and gauge bosons, relative to the respective SM couplings. Couplings to gluons relative to the SM couplings were calculated from the ratio of partial widths of $H \rightarrow gg$ in the NMSSM and the SM [21] as in Eq.1.

$$\frac{g^2_{Hgg,NMSSM}}{g^2_{Hgg,SM}} = \frac{\Gamma(H \rightarrow gg)_{NMSSM}}{\Gamma(H \rightarrow gg)_{SM}} \tag{1}$$

Table 1: Included search topologies with allowed mass ranges.

Search Channel	**Mass Range [GeV]**	**Refs.**
VBF, $H\to\tau\tau$	110-150	[3]
VBF, $H\to WW\to ll\nu\nu$	110-200	[3]
VBF, $H\to WW\to l\nu h$	130-200	[3]
VBF, $H\to\gamma\gamma$	110-160	[7]
ttH, $H\to b\bar{b}$	70-150	[8]
GGF, $H\to ZZ\to 4l$	120-420	[1]
GGF, $H\to WW\to ll\nu\nu$	140-200	[9]
WH, $H\to WW\to ll\nu\nu$, W→lν	150-190	[1]
Inclusive $H\to\gamma\gamma$	70-160	[1]
Inclusive $A\to\gamma\gamma$	200-450	[1]
WH, ZH, ttH, $H\to\gamma\gamma$	70-150	[1]
bbH, $H/A\to\tau\tau\to$hh	450-800	[10]
GGF, bbH, $H/A\to\tau\tau\to l\nu$h	150-800	[11]
GGF, bbH, $H/A\to\mu\mu$	70-450	[12, 13]
GGF, $H\to hh\to\gamma\gamma$bb	230-270 / 70-100	[1]
GGF, $H\to ZA\to llb\bar{b}$	200-250 / 70-100	[1]
$gb\to H^{\pm}t$, $H^{\pm}\to\tau\nu$	175-600	[14]
$gb\to H^{\pm}t$, $H^{\pm}\to tb$	190-400	[15]
$t\bar{t}\to H^{\pm}bWb\to\tau\nu l\nu b\bar{b}$	90-165	[1]
$t\bar{t}\to H^{\pm}bWb\to\tau\nu q\bar{q}b\bar{b}$	80-165	[16]

For the neutral Higgs bosons, leading order SM cross sections [22] were scaled according to Eq.2.

$$\sigma_{NMSSM} = \sigma_{SM} \cdot \frac{g^2_{NMSSM}}{g^2_{SM}} \tag{2}$$

The charged Higgs boson $gb\to tH^{\pm}$ cross sections in leading order were taken from Ref.[23] and were modified according to the $H^{\pm}tb$-couplings obtained with NMHDECAY. The branching ratio $t\to H^{\pm}b$ was calculated with Feynhiggs [24]. For $t\bar{t}$-production, a leading order cross section of 482 pb was assumed. The top quark mass was set to 172 GeV. Theoretical and LEP[1] exclusion criteria (bounds from hZ and hA searches) were calculated by NMHDECAY.

3.2 Significance Calculation

The expected number of signal events is derived from the above discussed NMSSM cross sections. Signal efficiencies are taken from published ATLAS Monte-Carlo studies (Table 1). The expected numbers of background events are also taken from published ATLAS MC studies. If MC studies at design luminosity exist, a data volume of 300 fb^{-1} is assumed; if only low luminosity studies are available, 30 fb^{-1} are used, and if both scenarios have been investigated, 30 fb^{-1} taken at low luminosity and 270 fb^{-1} taken at design luminosity are assumed. The current results only include SM background processes. Systematic uncertainties are neglected. For the significance calculation, the profile likelihood method [25] with asymptotic approximation [26] is used. To claim a discovery, a significance of at least 5σ is required. The number of expected signal events is corrected for the effects of increased Higgs boson decay widths and the possibility of degenerate Higgs boson masses as described in the following.

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[1] The *Large Electron Positron Collider*, which ran until 2000 at center-of mass energies up to 209 GeV.

Corrections for large Higgs bosons widths
In the NMSSM, the natural line width of the Higgs boson may be enhanced relative to the SM case. Thus, a larger fraction of signal events may lie outside a mass window cut than in the SM. To correct for this, the Higgs boson peak was described by a Voigt-function whose Breit-Wigner part is given by the natural line width, the Gaussian part by the detector resolution. The ratio of the integral values over the mass window for the SM and the NMSSM case was used as a correction factor.

Corrections for degenerate Higgs boson masses
Higgs boson peaks were described by a Voigt function as previously. The peaks were assumed to be indistinguishable if their separation was smaller than 2·FWHM/2.355. In case of negligible Higgs boson width, this corresponds to a 2σ separation of two Gaussians. Higgs bosons with overlapping mass windows were also considered indistinguishable to avoid double counting of events. In case of inseparable peaks, contributions from all Higgs bosons were added up for each boson's mass window. Only the highest observed significance was kept and assigned to the Higgs boson with the largest fraction of signal events in that mass window.

3.3 Search Topologies

The combinations of production mechanisms and decay modes considered in the evaluation of the discovery potential and the considered mass ranges are summarised in Table 1.[2] Within the scenarios examined here, only the VBF, $H\to\tau\tau$; ttH, $H\to b\bar{b}$ and $H\to\gamma\gamma$ channels show significances greater 5σ at the given integrated luminosities in the theoretically allowed and yet unexcluded regions (see section 4.).

4. RESULTS

4.1 The Reduced Couplings Scenario

In the *Reduced Couplings Scenario*, the H_2 with a mass of about 120 GeV is SM-like in large parts of the parameter space. In an unexcluded region with large negative κ close to the lower exclusion bound, the couplings of H_2 are reduced to about 80% of their SM-value. The H_1 gets very light at the region close to the upper exclusion bound, so that the decay $H_2\to H_1H_1$ is kinematically allowed. However, due to the small branching ratio for this decay mode of at maximum 6%, its effect on the discovery potential is negligible. The discovery potential for the H_2 is shown in Fig.1. The entire unexcluded region is covered by the ttH, $H_2\to b\bar{b}$ channel despite the coupling reduction. The inclusive $H_2\to\gamma\gamma$ and the

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[2] Production modes are abbreviated GGF for gluonfusion, VBF for vector boson fusion and ttH, bbH, WH and ZH for associated production with top quarks, bottom quarks and vector bosons.

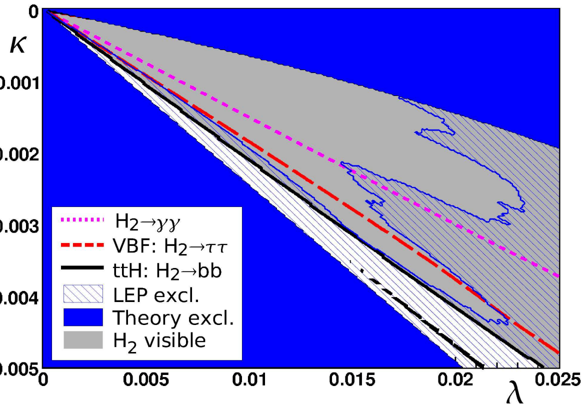

Fig. 1: 5σ discovery contours of the H_2 in the λ-κ plane for the *Reduced Couplings Scenario*

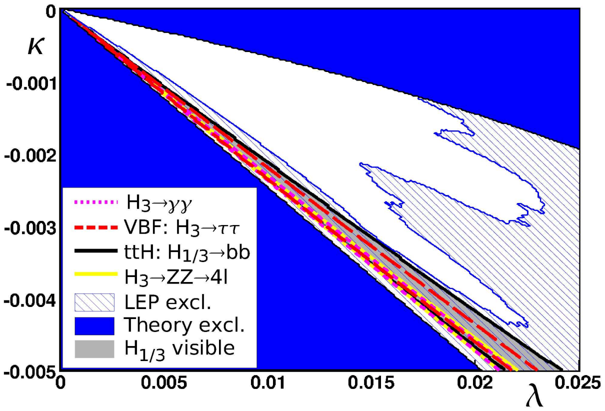

Fig. 2: 5σ discovery contours of the H_1 and H_3 in the λ-κ plane for the *Reduced Couplings Scenario*

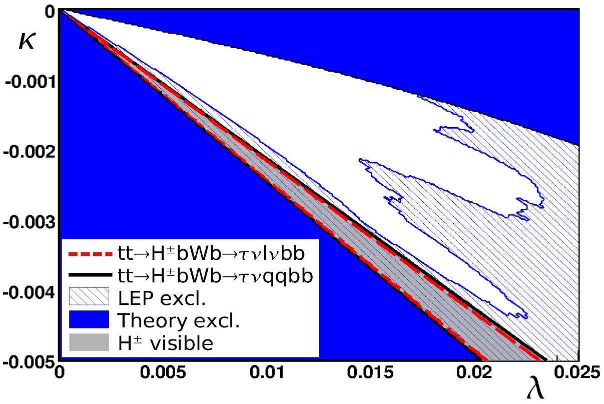

Fig. 3: 5σ discovery contours of the $H^{\pm}$ in the λ-κ plane for the *Reduced Couplings Scenario*

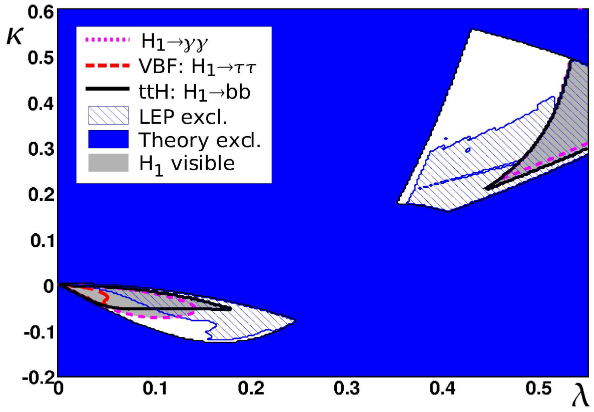

Fig. 4: 5σ discovery contours of the H_1 in the λ-κ plane for the *Light A_1 Scenario*

VBF, $H_2 \to \tau\tau$ channels also contribute. With 30 fb^{-1}, the search for $H_2 \to \tau\tau$ will be the only sensitive channel. The region with reduced couplings will not be covered in that case. The couplings of the H_1 and H_3 are sizable only at large negative κ. Here, the channels $H_3 \to \gamma\gamma$; VBF, $H_3 \to \tau\tau$; ttH, $H_{1/3} \to b\bar{b}$ and GGF, $H_3 \to ZZ \to 4l$ contribute in a region ruled out by LEP (Fig.2). Since the charged Higgs boson is lighter than the top quark in the same region, it can be detected via the $t\bar{t} \to H^{\pm}bW^{\pm}b \to \tau\nu l\nu b\bar{b}$ and $t\bar{t} \to H^{\pm}bW^{\pm}b \to \tau\nu q\bar{q}b\bar{b}$ searches only in the LEP excluded region also (Fig.3). All other Higgs bosons have highly reduced couplings and are therefore unobservable.

4.2 The Light A_1 Scenario

In this scenario, the H_1 has a mass of about 120 GeV and SM-like couplings. Since the A_1 is light, $H_1 \to A_1A_1$ decays are kinematically possible and often dominant. In the upper right unexcluded region, the branching ratio of $H_1 \to A_1A_1$ is larger than 90%. Here, the H_1 cannot be observed (see Fig.4). The branching ratio of $H_1 \to A_1A_1$ drops for small λ and κ. Therefore, a discovery via the inclusive and associated $H_1 \to \gamma\gamma$; VBF, $H_1 \to \tau\tau$ and ttH, $H_1 \to b\bar{b}$ modes is possible in that region (Fig.5). The outermost discovery contour of $H_1 \to \gamma\gamma$ follows approximately the 60% line of the branching ratio of $H_1 \to A_1A_1$. The H_2 has contributions from the channels $H_2 \to \gamma\gamma$; VBF, $H_2 \to WW$; GGF, $H_2 \to ZZ \to 4l$ and GGF, $H_2 \to WW \to 2l2\nu$ in the excluded region where it is light enough to be accessible (Fig.6). All other Higgs bosons have either highly reduced couplings or are too heavy to be observed in this scenario.

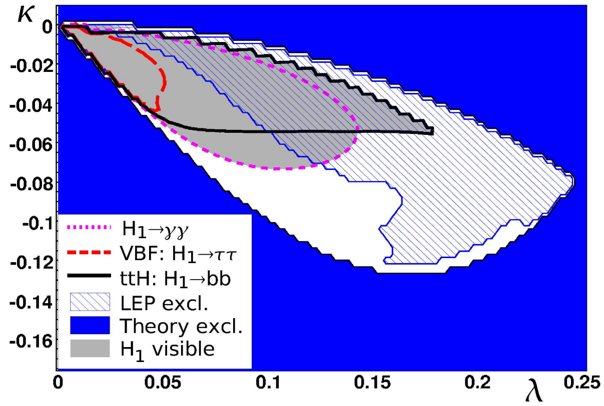

Fig. 5: 5σ discovery contours of the H_1 in the λ-κ plane for the *Light A_1 Scenario*, restricted to low λ and κ values.

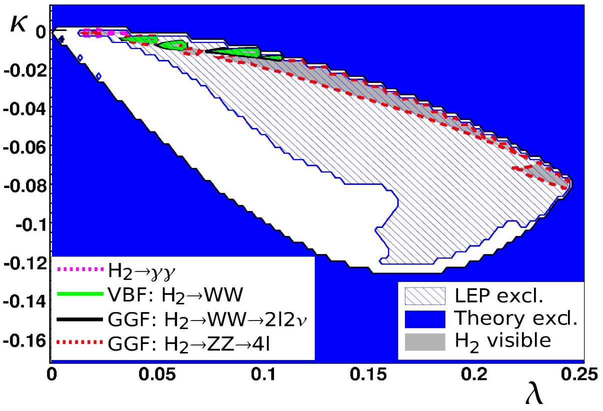

Fig. 6: 5σ discovery contours of H_2 in the λ-κ plane for the *Light A_1 Scenario*, restricted to low λ and κ values.

CONCLUSIONS

An evaluation of the ATLAS discovery potential for NMSSM Higgs bosons within two benchmark scenarios was performed. At least one Higgs boson was found to be observable in regions without a light A_1 or where the branching ratio of $H_{1/2}{\rightarrow}A_1A_1$ is smaller than about 60%. In the other cases, searches for the decay chains $H_{1/2}{\rightarrow}A_1A_1{\rightarrow}\tau\tau b\bar{b}$ or $H_{1/2}{\rightarrow}A_1A_1{\rightarrow}4\tau$ could be considered.

ACKNOWLEDGEMENTS

The authors thank U. Ellwanger, E. Gross, S. Heinemeyer, T. Plehn and M. Spira for helpful discussions.

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