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ATLAS MSSM Higgs searches in SUSY cascades

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The neutral MSSM Higgs boson production and subsequent decay into heavy neutralino/chargino pairs has been studied for the ATLAS experiment. The final state with 4 leptons and missing energy is considered. The study has been performed using a realistic detector simulation of the signal and the SM and MSSM backgrounds for four benchmark scenarios. The discovery and exclusion sensitivity in the (m_A, $\tan\beta$) plane was discussed for different luminosity scenarios. An extension of the searches to the charged Higgs boson sector was explored.

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1. Introduction

The Minimal Supersymmetric Standard Model (MSSM) is the most investigated extension of the Standard Model (SM). The theory requires two Higgs doublets giving origin to five Higgs bosons: two CP-even neutral scalars, h and H (h is the lighter of the two), one CP-odd neutral scalar, A, and one pair of charged Higgs bosons, $H^{\pm}$. Their discovery is an irrefutable proof for physics beyond the SM. This is a key point in the physics program of future accelerators and in particular of the LHC.

After the conclusion of the LEP program in the year 2000, the experimental limit on the mass of the Standard Model Higgs boson was established at 114.4 GeV with 95% CL. Limits were also set on the mass of neutral and charged MSSM Higgs bosons for most of the representative sets of model parameters.

To achieve an uncontroversial proof of the existence of models beyond SM, the discovery of the heavier bosons H and A is demanded, being the light h indistinguishable from SM Higgs. Many signatures of MSSM neutral Higgs have been studied for decays into known SM particles, e.g. τ or μ pairs and $b\bar{b}$, by ATLAS [1], [7] and CMS experiments [2]. In this scenario the decay into sparticles is forbidden, if it is assumed that sparticles are too heavy to participate in the process.

If the MSSM Higgs decay in sparticles is kinematically allowed, decay channels involving neutralinos ($\widetilde{\chi}^0$), charginos ($\widetilde{\chi}^{\pm}_1$) and sleptons ($\tilde{\ell}$) can be considered, enlarging the possibilities of discovery. The decay of neutral [4] and charged Higgs [3] into neutralinos and charginos and the subsequent decay into sleptons have been studied. The focusing of these works are on the neutral Higgs decay via $\widetilde{\chi}^0_2\widetilde{\chi}^0_2$. In a recent study [5], the decay into a heavier neutralino pair as well as a chargino pair are also taken into account, extending the sensitivity of the discovery in (m_A, $\tan\beta$) plane.

The unconstrained MSSM has a huge number of parameters (105) in addition to SM ones, making any phenomenological analysis very complicated. A simplified version at some GUT (Grand Unification Theory) scale, mSUGRA, with fewer parameters is mostly used.

In this paper we discuss the potential of the ATLAS detector at LHC for the discovery of neutral MSSM Higgs bosons A and H in four different scenarios: two for MSSM and two for mSUGRA. The considered decays of A/H are into neutralino and chargino pairs, with subsequent decay into lighter neutralinos and leptons (Fig.1). An extension to charged Higgs sector is discussed. The experimental final state signature is four leptons and missing energy, due to the presence of $\widetilde{\chi}^0$-s.

2. Minimal Supersymmetric Standard Model

The decay processes involving light neutralinos, $A/H \to \widetilde{\chi}^0_2\widetilde{\chi}^0_2$, heavier neutralinos, $A/H \to$ $\widetilde{\chi}^0_2\widetilde{\chi}^0_3$, $\widetilde{\chi}^0_2\widetilde{\chi}^0_4$, $\widetilde{\chi}^0_3\widetilde{\chi}^0_3$, $\widetilde{\chi}^0_3\widetilde{\chi}^0_4$, $\widetilde{\chi}^0_4\widetilde{\chi}^0_4$, and chargino states, $A/H \to \widetilde{\chi}^{\pm}_1\widetilde{\chi}^{\mp}_2, \widetilde{\chi}^{+}_2\widetilde{\chi}^{-}_2$, with the subsequent $\widetilde{\chi}^0_2 \to \widetilde{\chi}^0_1\tilde{\ell}^+\tilde{\ell}^-$ decay, are investigated. All these processes are leading to a final state of four leptons and missing energy. The choice of parameters, in MSSM and mSUGRA frameworks has been dictated by the maximization of these signals e.g. by the leptonic branching ratio enhancement [5]. In the region with low M_2 values and moderate to high $|\mu|$, irrespective of heavier Higgs masses, the Higgs boson decays into $\widetilde{\chi}^0_2\widetilde{\chi}^0_2$ are the dominant source of signal events. For the low to moderate

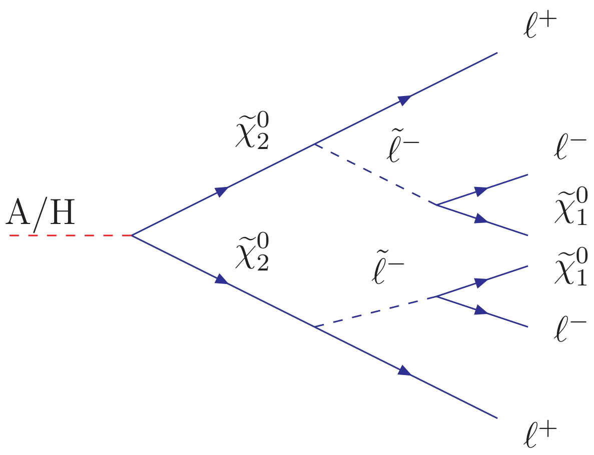

Figure 1: Example of *A/H* decay ($A/H \rightarrow \tilde{\chi}_2^0\tilde{\chi}_2^0$) with final state containing four leptons and undetectable particles.

M_2 values and low values of $|\mu|$, the dominant source of signal events is the decay into heavier neutralinos or charginos. Based on these considerations two sets of parameter values have been selected for the MSSM parameter space:

- **Set1** M_2 = 180 GeV, μ = -500 GeV, $m_{\tilde{\ell}\mathrm{soft}}$= $m_{\tilde{\tau}\mathrm{soft}}$=250 GeV, $m_{\tilde{g}}$=$m_{\tilde{q}}$= 1000 GeV,
- **Set2** M_2 = 200 GeV, μ = -200 GeV, $m_{\tilde{\ell}\mathrm{soft}}$= 150 GeV, $m_{\tilde{\tau}\mathrm{soft}}$=250 GeV, $m_{\tilde{g}}$= 800 GeV, $m_{\tilde{q}}$=1000 GeV,

where M_2 is the gaugino mass, μ, the strength of the supersymmetric Higgs mixing, $m_{\tilde{g}}$, the gluino mass, $m_{\tilde{q}}$ the $\tilde{q}$ mass, $m_{\tilde{\ell}}$ and $m_{\tilde{\tau}}$, the slepton and stau mass, respectively ($m_{\tilde{\ell}\mathrm{soft}} \equiv m_{\tilde{\ell}L,R}$). The scan is performed in the (tanβ, m$_A$) plane, where tanβ is the ratio of the vacuum expectation values of the two Higgs fields and m$_A$, the mass of the CP-odd Higgs boson. For all scenarios it has been used as value of *t* and *b* quark mass 175 GeV and 4.25 GeV, respectively .

Including additional assumptions on the unification of SUSY at very high mass scale (GUT) the free parameters are reduced to tanβ, M$_{1/2}$ (the universal gaugino mass), M$_0$ (the universal GUT-scalar mass), A$_0$ (the trilinear scalar mass), and the sign of μ. In this framework $|\mu|$ is not a free parameter, but is connected to the masses of scalar Higgs bosons via the M$_0$ input. In this framework the parameter set chosen are:

- **SetA** M$_0$ = 400 GeV, M$_{1/2}$=165 GeV, sgn(μ) =+1, A$_0$=0.
- **SetB** M$_0$ = 125 GeV, M$_{1/2}$=165 GeV, sgn(μ) =+1, A$_0$=0.

A search of *A/H* decays in a neutralino/chargino pair has been performed in the (tanβ, m$_A$) plane inside the interval 3 - 50 for tanβ (in steps of 5), and 375 - 900 GeV for m$_A$ (in steps of 250 GeV).

3. Analysis

For the event samples used in this analysis the full Monte Carlo simulation of the experiment (data generation, reconstruction and analysis) is used. The exploration of the unexcluded MSSM parameter space, with a view to either discovering a supersymmetric Higgs boson or excluding the model considered, constitutes the motivation of the analysis described in this paper.

The Higgs boson production modes considered herein are $gg \rightarrow H/A$ (gluon-fusion) and $q\bar{q} \rightarrow H/A$ (quark-fusion). To this purpose we have generated signal and MSSM background Monte Carlo events using the HERWIG MC package through ISAWIG and HDECAY (see reference in [5]) for a center-of-mass energy $\sqrt{s}$= 14 TeV and Standard Model background events as in Ref. [7]. The efficiency of the selection criteria, the detector acceptance and the purity of the data sample are estimated from these events and the ATLAS detector response [1].

The SM background sources are events originating from Z pair or $t\bar{t}$ pair or Z accompanied by $b\bar{b}$ pair. The MSSM background processes are from direct neutralino/chargino pair production (denoted as $\widetilde{\chi}^0\widetilde{\chi}^0$), from squark or gluino/neutralino ($\tilde{q}/\tilde{g}\widetilde{\chi}^0$) and from slepton pairs.

The number of events used in this analysis corresponds to an integrated luminosity $\int \mathscr{L}\, \mathrm{d}t =$ 300 fb^{-1} with the exception of the channel $t\bar{t}$. In this latter case a number of events corresponding to $\approx \frac{1}{3}$ the mentioned luminosity has been generated.

The signature of *A*/*H* channels decaying in $\widetilde{\chi}^0\widetilde{\chi}^0$ or $\widetilde{\chi}^{\pm}\widetilde{\chi}^{\mp}$ is 4 isolated leptons and missing energy. The event selection is based mainly on the following criteria:

- Four isolated leptons (pseudorapidity $|\eta_\ell| < 2.5$ and transverse momentum $P_{\mathrm{T}\ell}$ > 8 GeV), two positive and two negative, forming same flavor pairs.

- The invariant reconstructed mass of each lepton pair is outside a window around the Z mass, $|M^{\mathrm{inv}}_{\ell^+\ell^-} - m_{\mathrm{Z}}| > 6$ GeV, to suppress processes containing Z.

- The significance of the impact parameter determination is > 6 for electrons and > 4 for muons [7]. This cut is designed mainly to reduce $t\bar{t}$ background.

- The missing transverse energy, $E_{\mathrm{T}}^{\mathrm{miss}}$,is within a range e.g. 35 and 130 GeV, to remove ZZ, Z accompanied by a $b\bar{b}$ pair, and processes from direct $\tilde{q}/\tilde{g}\widetilde{\chi}^0$ pair production.

- Other cuts are applied on first and second lepton with highest transverse momenta (e.g. 100 and 60 GeV) which are reducing processes with slepton pairs and other MSSM backgrounds.

- The number of jets (with a transverse momentum e.g. P_{Tjet} > 20 GeV) is limited to $N_{\mathrm{jet}} \leq 5$ to reduce MSSM background.

For a given MSSM neutral Higgs boson (A, H), with Set1 parameters at the reference point (m$_A$=500 GeV, tanβ= 20), Table 1 shows the production cross section σ, the 4 ℓ decay branching ratio Br$_{4\ell}$, the number of signal events expected at $\int \mathscr{L}\, \mathrm{d}t$= 300 fb^{-1}, N$^{\mathrm{exp}}_{300}$, the number of Monte Carlo generated and selected events, N$^{\mathrm{MC}}$ and N$^{\mathrm{sel}}$.

Process	σ [pb]	$\mathrm{Br}_{4\ell}$	$\mathrm{N}^{\mathrm{exp}}_{300}$	N^{MC}	$\mathrm{N}^{\mathrm{sel}}$
A	1.18	0.0051	1800	2250	30
H	1.16	0.0049	1700	2500	14
$Zb\bar{b}$	60.5	0.00942	171000	44500	2
$t\bar{t}$	500.	0.00728	1092000	570555	82
ZZ	0.21	0.219	13500	1157000	10
$\tilde{q}/\tilde{g}$	1.49	0.034	15000	17000	1
$\tilde{\ell}/\tilde{\nu}$	0.15	0.15	1100	1500	44
$\widetilde{\chi}^0/\widetilde{\chi}^0$, $\tilde{q}/\tilde{g}\widetilde{\chi}^0$	2.97	0.019	1700	2500	7
$\mathrm{t}H^{\pm}$	0.136	0.0078	315	500	0

Table 1: Signal and background processes: cross section σ, branching ratio $\mathrm{Br}_{4\ell}$, number of events expected at $\int \mathscr{L}\,\mathrm{d}t = 300\ \mathrm{fb}^{-1}$, $\mathrm{N}^{\mathrm{exp}}_{300}$, number of Monte Carlo events generated and selected, N^{MC} and $\mathrm{N}^{\mathrm{sel}}$. The MSSM (Set1) signal and backgrounds are evaluated at the reference point (m_A = 500 GeV, tanβ=20).

4. Results

The significance of MSSM Higgs search is given using $\frac{S}{\sqrt{B}}$ as a statistical estimator, where S is the number of signal events (A/H or $A/H/H^{\pm}$), and B the number of background events. A search resulting in $\frac{S}{\sqrt{B}} \geq 5$ is interpreted as an indication of new physics, instead $\frac{S}{\sqrt{B}} \leq 2$ as its exclusion. The search significance for the A/H neutral boson is shown as a function of m_A, in Fig. 2 for all scanned values of tanβ and two luminosities $\int \mathscr{L}\,\mathrm{d}t = 300$ and $100\ \mathrm{fb}^{-1}$, for Set2. The values for the lower luminosity are derived from the first one, which corresponds to the highest statistics.

The charged Higgs decays in chargino and neutralino channels producing four leptons (three from neutralino/chargino) and a number of undetectable particles in the final state have been explored. The results on the $H^{\pm}$ boson search combined with the results from the A/H search enlarge the discovery range (Fig. 3). For the very high integrated luminosity, a *caveat* should be made because the event pile-up may have an effect on the selection efficiencies.

We could conclude that among the sets of parameters in MSSM and mSUGRA investigated (at $\int \mathscr{L}\,\mathrm{d}t = 300$ and $100\ \mathrm{fb}^{-1}$) the MSSM Set2 is the most promising scenario for a discovery reach in the first years of data taking either for MSSM neutral Higgs or for neutral and charged ones.

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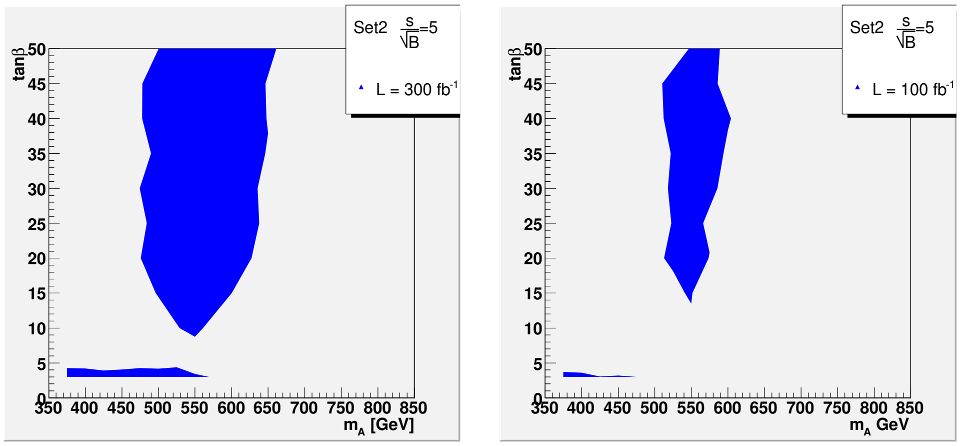

Figure 2: Discovery potential (for MSSM Set2) for a neutral Higgs boson A/H of mass m_A for final state with four leptons and missing transverse energy, as a function of m_A: contours are drawn for a search significance $\frac{S}{\sqrt{B}}$ = 5, for an integrated luminosity of $\int \mathscr{L}\,\mathrm{d}t = 300$ (left) and 100 fb^{-1} (right).

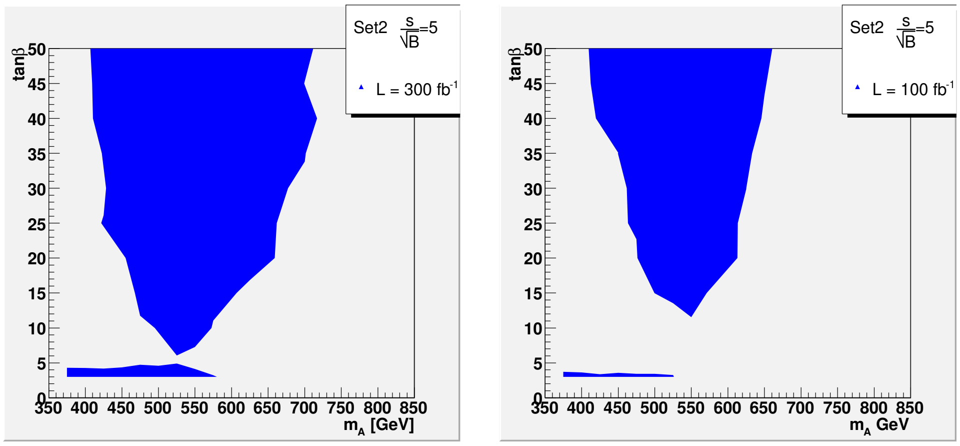

Figure 3: Discovery potential (for MSSM Set2) for Higgs boson A/H and $H^{\pm}$ of mass m_A for final states with four leptons and missing transverse energy, as a function of m_A: contours are drawn for a search significance $\frac{S}{\sqrt{B}}$ = 5 for an integrated luminosity of $\int \mathscr{L}\,\mathrm{d}t = 300$ (left) and 100 fb^{-1} (right).

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