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CMS NOTE 2001/042

The Compact Muon Solenoid Experiment

CMS Note

Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

October 23, 2001

Observability of MSSM Higgs bosons via sparticle decay modes in CMS

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Abstract

We discuss the possibilities to observe the decays of heavy SUSY Higgs bosons into supersymmetric particles at the LHC. Such an observation would be of interest either in a discovery search if sparticle modes are the dominant ones, or in a study of additional decay modes, bringing information on the SUSY scenario potentially at work. We will focus on the most promising channel where the heavy neutral Higgses decay into a pair of next-to-lightest neutralinos χ_2^0, followed by $\chi_2^0 \to l^+l^-\chi_1^0$, thus leading to four isolated leptons + E_T^{miss} as the main final state signature. A study with the CMS detector shows that the background (SM + SUSY) can be sufficiently suppressed and that in the mass region between $m_{A,H} \sim 230$ and 450 GeV, for low and intermediate values of $\tan\beta$, the signal would be visible provided neutralinos and sleptons are light enough.

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1 Introduction

While the problem of electroweak symmetry breaking can be solved in the Standard Model (SM) by introducing one Higgs boson, the Minimal Supersymmetric Standard Model (MSSM) requires five physical Higgses: a light CP-even (h^0), a heavy CP-even (H^0), a heavy CP-odd (A^0) and two charged Higgs bosons ($H^{\pm}$). Therefore, the discovery of heavy neutral Higgs bosons would be a major breakthrough in verifying the supersymmetric nature of the fundamental theory, which is one of the main physics goals of the Large Hadron Collider project.
The most promising channel to discover the heavy SUSY Higgses is the $A^0, H^0 \rightarrow \tau\tau$ [1] channel, where both the leptonic and hadronic decays of the tau can be exploited. This channel has been shown to cover large parts of the intermediate and high $\tan\beta$ region of the MSSM parameter space for an integrated luminosity of 30 fb^{-1}. For low values of $\tan\beta$, the coupling of the Higgs bosons to taus is not sufficiently enhanced and therefore this region is inaccessible for the $\tau\tau$ channel.
In all studies of the SM channels (meaning that the SUSY Higgses decay into Standard Model particles), it is assumed that sparticles are too heavy to participate in the decay process. One should ask what would happen if some of the sparticles would be light and the decays of Higgs bosons into these SUSY particles would be kinematically allowed. Indeed, the existence of light neutralinos (χ^0), charginos ($\chi^{\pm}$) and sleptons ($\tilde{l}$) seems favoured by a large number of supersymmetric models in order to explain electroweak symmetry breaking without large fine-tuning [2]. Also recent experimental results (precision measurements at LEP2 [3], muon $g-2$ [4]) may point towards the existence of light gauginos and sleptons.
Light SUSY particles may jeopardize the Higgs discovery potential of the SM channels, since their presence can drastically decrease the branching ratios of the Higgses into SM particles. Furthermore, pair and cascade production of light sparticles becomes an extra background to the Higgs searches. On the other hand, Higgs bosons decaying into sparticles might open new possibilities to explore regions of parameter space where SM decays would not be accessible [6]. In this note we report on a study of this type of decay with the CMS detector.
We will focus on the decay of the heavy neutral Higgses H^0 and A^0 into two next-to-lightest neutralinos, with each of the neutralinos in turn decaying as $\chi^0_2 \rightarrow l^+l^-\chi^0_1$, i.e. into two (isolated) leptons + E_T^{miss}, so we get

$$A^0, H^0 \rightarrow \chi^0_2\,\chi^0_2 \rightarrow 4\,l^{\pm} \;+\; X \qquad\qquad (l \;=\; e,\, \mu) \tag{1}$$

This results in a clear four lepton final state signature. We will show that, as is often the case for supersymmetric channels, SUSY backgrounds are more difficult to suppress than the SM backgrounds. Of the latter, basically only ZZ survives after requiring four isolated leptons. Of the SUSY backgrounds, sneutrino pair production and sparticle cascade decay production of neutralinos are the most dangerous processes. Using a set of selection criteria as described in section 5, we can clearly distinguish the signal from the background in the intermediate mass range 230 GeV $\lesssim m_A \lesssim$ 450 GeV and for low and intermediate values of $\tan\beta$, depending on the values of the other MSSM parameters.

The remainder of this note is organised as follows: first we study the behaviour of the relevant branching ratios. Then we describe the event generation, the signal versus background discrimination methods, and the discovery potential of the channel in the m_A - $\tan\beta$ plane. As a next step we investigate the effects of varying the other MSSM parameter values. In the last section the results are summarized.

2 Framework

The main difficulty in studying decay modes involving supersymmetric particles is the large amount of free parameters in the MSSM. Therefore most studies are carried out in the mSUGRA or GMSB context in order to reduce the number of free parameters; we will however stick to the more general MSSM framework, to avoid too many model dependent assumptions. As free parameters, we take the mass of the CP-odd Higgs m_A, the Higgs VEV ratio $\tan\beta$, the Higgsino mass parameter μ, the bino mass parameter M_1, the wino mass parameter M_2, the slepton mass $m_{\tilde{l}}$ and the squark/gluino mass $m_{\tilde{q},\tilde{g}}$. As a starting point for our studies, we will adopt the following framework:

- we consider light neutralinos and charginos, above the LEP2 limits. Initially, we fix M_1 at 60 GeV, and using the renormalisation group relation $M_2 \approx 2\ M_1$, we can set M_2= 120 GeV. We take $M1 < M2 < |\mu|$. This large μ scenario is favoured in models where χ^0_1 is the dark matter candidate, like mSUGRA. In low μ scenarios, the decay of χ^0_2 into leptons will be strongly suppressed. For large values of $|\mu|$, χ^0_2 is rather wino and χ^0_1 is bino-like. Therefore it approximately holds that $m_{\chi^0_1} \approx M_1$ and $m_{\chi^0_2} \approx M_2$. The effects of varying these parameters will be discussed later on.

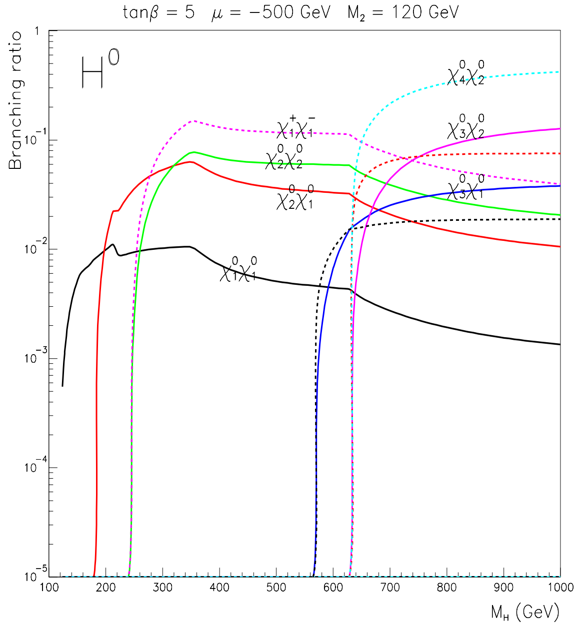

Figure 1: Branching ratios of H^0 into neutralinos and charginos.

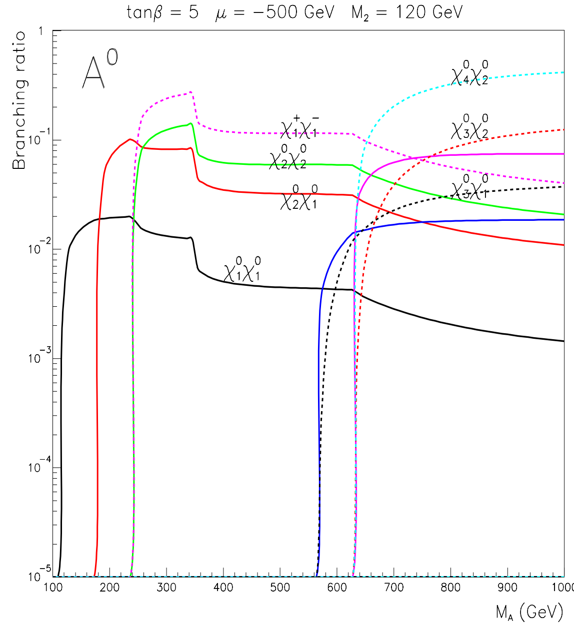

Figure 2: Branching ratios of A^0 into neutralinos and charginos.

- we also take sleptons to be light. In the most favourable case they would be lighter than χ_2^0, thereby allowing two-body decays into leptons. We will consider two scenarios: $m_{\tilde{l}} < m_{\chi_2^0}$, where real decays of neutralinos into sleptons are allowed and $m_{\tilde{l}} > m_{\chi_2^0}$, where only the virtual exchange is possible.
- the masses of squarks and gluinos are kept at the 1 TeV scale. In the MSSM, it is natural that these sparticles are heavier than neutralinos and sleptons. In section 7, we will investigate the effect of lowering the masses of squarks and gluinos.

These parameter values and domains for μ, M_1, M_2, $m_{\tilde{l}}$ and $m_{\tilde{q},\tilde{g}}$ will be used as default throughout this note. The exact values for μ and $m_{\tilde{l}}$ will be chosen after analysing and optimizing the $A^0, H^0 \rightarrow 4\,l$ cross sections through the MSSM parameter space. After establishing the visibility in this optimal point, we will scan the area in $m_A - \tan\beta$ around it to see how far the discovery region reaches. Effects of varying the initial SUSY parameter values will be discussed.

3 Branching ratios in the MSSM parameter space

In order to determine the regions in MSSM parameter space where sparticle decay modes may be accessible, we will first discuss the behaviour of the relevant branching ratios.

3.1 Decay of the heavy Higgs bosons into neutralinos and charginos

The package HDECAY [7] is used to study the supersymmetric decay modes $H^0, A^0 \rightarrow \chi\chi$ of the heavy Higgses. The H^0 and A^0 couple preferably to mixtures of gauginos and higgsinos. The dominant MSSM parameters controlling this process are m_A, $tan\beta$, M_2 and μ.
Figs. 1 and 2 show the decays of H^0 and A^0 into neutralinos and charginos, in the case where M_1 = 60 GeV, M_2 = 120 GeV, μ = -500 GeV and $\tan\beta$ = 5. For $M_A \lesssim 500$ GeV, the probability for the heavy Higgses to decay into SUSY particles can be as high as 20 %. In this mass region, the decay mode to $\chi_1^+\chi_1^-$ has the highest branching ratio (BR), however it produces a final state with only two leptons. This mode would be in competition with numerous SM and SUSY backgrounds. The second best sparticle mode is $\chi_2^0\chi_2^0$. This channel can provide four leptons and is thus a priori more appropriate for obtaining a good signal to background ratio. The $\chi_2^0\chi_2^0$ threshold is determined by our choice of M_2 ($\approx m_{\chi_2^0}$) = 120 GeV; the fall in BR at $M_A > 350$ GeV is caused by the opening of the $t\bar{t}$ mode. The partial decay widths into supersymmetric particles remain the same as for lower

values of M_A, but due to the opening of the $t\bar{t}$ mode, the total decay width increases and the branching ratio into charginos/neutralinos decreases. For values of $M_A < 350$ GeV, the BR of the CP-odd Higgs (A^0) into gauginos is substantially higher than in the CP-even (H^0) case. This is due to the fact that for the CP-even Higgs more couplings to SM particles are allowed, thus leading to a larger total decay width and smaller BR's to sparticles. For high values of m_A the BR's are about the same for H^0 and A^0 since one reaches the decoupling regime. Also for higher masses, other neutralino modes like $\chi_3^0\chi_2^0$, $\chi_4^0\chi_2^0$ or $\chi_2^+\chi_1^-$ may open up which will contribute to the four lepton signal.

3.2 Decays of the next-to-lightest neutralino into leptons

The next-to-lightest neutralino χ_2^0 will decay into two fermions and the lightest neutralino: $\chi_2^0 \to f\bar{f}\chi_1^0$. These fermions will most often be quarks, leading to two jets and missing E_T in the final state. To obtain a clean signature, we will only focus on the case where the neutralino decays into two leptons $\chi_2^0 \to l^+l^-\chi_1^0$, where l = e or μ. This process is determined by the bino, wino and higgsino mass parameters M_1, M_2, μ, by $\tan\beta$ and by the slepton masses $m_{\tilde{l}}$. If sleptons are heavier than the χ_2^0, and as long as direct decays into a Z^0 boson are not allowed (or suppressed), only three-body decays $\chi_2^0 \to l^+l^-\chi_1^0$ will contribute. These decays are mediated by virtual slepton and Z^0 exchange [8]. Therefore it is more favourable to have light sleptons in order to have larger BR's. The decay branching ratios can be rather sensitive to the MSSM parameters due to the fact that the Z^0 and slepton exchange amplitudes may interfere positively as well as negatively.

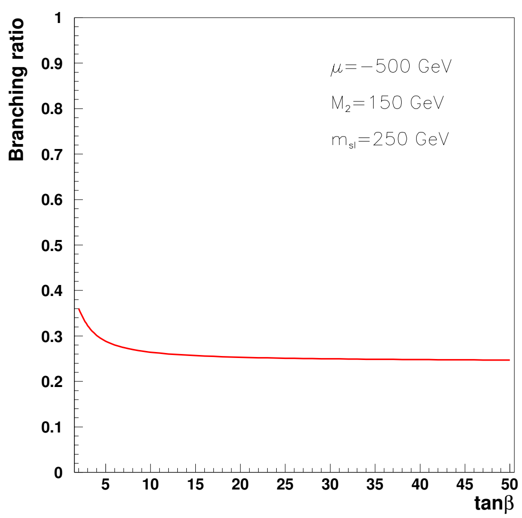

Figure 3: Branching ratio of $\chi_2^0 \to l^+l^-\chi_1^0$ as a function of $\tan\beta$, in the case of $m_{\tilde{l}} > m_{\chi_2^0}$. ($l$ = e + μ)

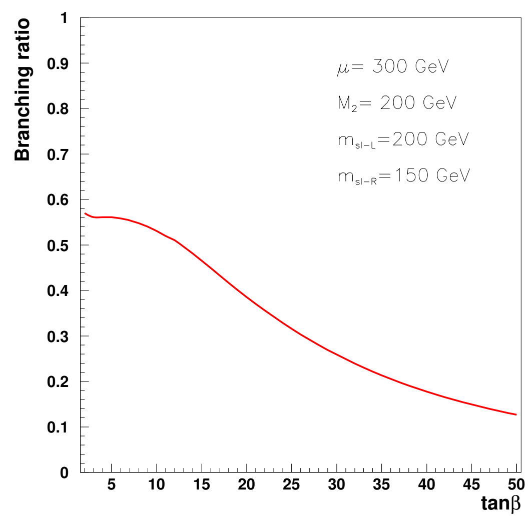

Figure 4: Branching ratio of $\chi_2^0 \to l^+l^-\chi_1^0$ as a function of $\tan\beta$, in the case of $m_{\tilde{l}} < m_{\chi_2^0}$. ($l$ = e + μ)

In fig. 3 we show the BR as a function of $\tan\beta$. Sleptons (including staus) are taken at 250 GeV and μ = -500 GeV. χ_2^0 is then rather wino and χ_1^0 is bino-dominated. Because of this, their coupling to the Z^0 is dynamically suppressed, and the $\chi_2^0 \to l^+l^-\chi_1^0$ branching ratio will depend strongly on slepton masses.

If sleptons are lighter than the χ_2^0, direct two-body decays of the neutralino into a slepton-lepton pair are allowed, which may lead to large branching ratios. In fig. 4 the evolution of the BR with $\tan\beta$ is shown for M_2 = 200 GeV, μ = 300 GeV, $m_{\tilde{l}_L}$ = 200 GeV, $m_{\tilde{l}_R}$ = 150 GeV. This is however only valid in a rather limited region of the MSSM parameter space, since often sneutrinos will be lighter than sleptons, causing the neutralinos to decay purely into invisible particles.

The fall of BR($\chi_2^0 \to l^+l^-\chi_1^0$) with $\tan\beta$ in fig. 4 is compensated by a rise in BR($\chi_2^0 \to \tau^+\tau^-\chi_1^0$). This means that allowing taus in the final state could possibly extend our discovery reach towards higher $\tan\beta$ values. However, taus decay into leptons (e, μ) in only $\sim$35% of the cases, whilst the hadronic decay modes have detection efficiencies of $\sim$30% [5]. This, together with the fact there are up to four taus in the final state, makes that there is only a limited hope for a large improvement by including taus in the final state, but a dedicated study is needed.

4 Event generation

The signal events are generated with SPYTHIA [9]. For low $\tan\beta$ values ($\tan\beta \sim 1$), the gluon-gluon fusion mechanism $gg \to A^0, H^0$ dominates the production. Due to the large coupling of the Higgses to $b\bar{b}$, the associated production $gg \to b\bar{b}A^0, H^0$ dominates for $\tan\beta > 5$ [10]. The CP-odd Higgs is produced more than the CP-even one because the $A^0 b\bar{b}$ coupling is directly proportional to $\tan\beta$, whilst the $H^0 b\bar{b}$ coupling is proportional to $\frac{\cos\alpha}{\cos\beta}$. In the decoupling regime (i.e. high values of m_A), both couplings become equal. Besides these two main processes, we also included the WW/ZZ fusion and Higgsstrahlung processes.

We scanned the $A^0, H^0 \to \chi_2^0\chi_2^0 \to 4l$ cross section in the (m_A, $\tan\beta$) plane for different values of μ and $m_{\tilde{l}}$. M_1 and M_2 were initially kept on 60 and 120 GeV respectively, and no direct decays of neutralinos in sleptons were allowed. In figs. 5 and 6, the plot of $\sigma\times$ BR for μ = -500 GeV and $m_{\tilde{l}}$ = 250 GeV is shown. Values of $\tan\beta \lesssim$ 30 - 40 and $m_A \lesssim$ 400 - 500 GeV seem to be favoured. One also notices that the pseudoscalar Higgs gives much higher cross sections than the scalar one.

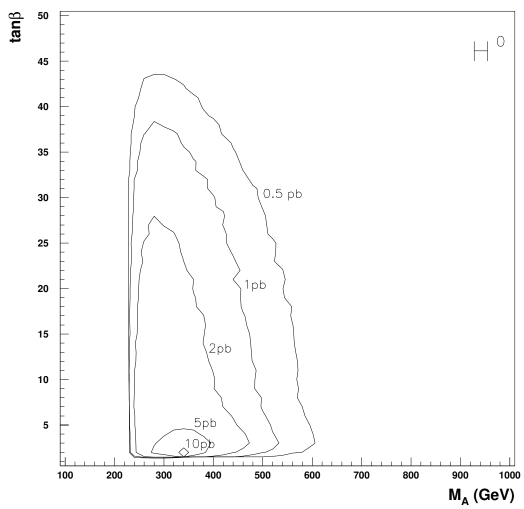

Figure 5: $\sigma\times$ BR contours for H^0 in the $m_A - \tan\beta$ plane. Parameter values as described in the text.

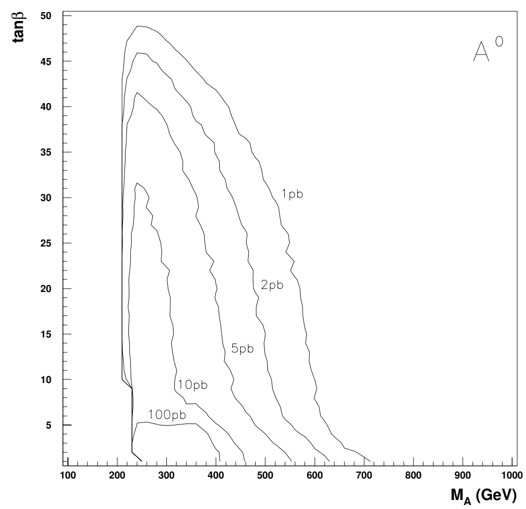

Figure 6: $\sigma\times$ BR contours for A^0 in the $m_A - \tan\beta$ plane. Parameter values as described in the text.

For the background processes, PYTHIA 6.136 [11] was used with a few bugs fixed both in the SUSY and general code. The following SM backgrounds giving rise to four (real or fake) leptons in the final state have been generated: ZZ, ZW, $Zb\bar{b}$, $Zc\bar{c}$, $Wt\bar{b}$ and $t\bar{t}$. Decays of Z into τ's have been included, since they might be dangerous due to their non-zero E_T^{miss}. For the SUSY backgrounds, we generated all pair production processes involving squarks, gluinos, sleptons, charginos and neutralinos.

The CMS detector response is simulated using the CMSJET fast Monte Carlo [12]. The effects of pile-up at high luminosity running of LHC have not been included yet, but are expected to be minor in the four-lepton final state.

5 Signal versus background discrimination

In order to obtain a clear signal, we will have to discriminate between the signal events and background events that contain a similar four lepton final state. Two categories of background have to be considered: Standard Model processes and SUSY backgrounds.
The main SM backgrounds are ZZ and $t\bar{t}$ production. They are dangerous because of their large cross sections at the LHC. In order to distinguish between events coming from the signal and from the SM background, we apply the following selection criteria:

- we require two pairs of isolated leptons with opposite sign and same flavour, with a P_T larger than 10 GeV and within $|\eta| < 2.4$. The isolation criterion demands that there are no charged particles with $P_T > 1.5$ GeV in a cone of R = 0.3 rad around each lepton track, and that the sum of the transverse energy in the crystal towers between R = 0.05 and R = 0.3 rad is smaller than 3 GeV.

- all dilepton pairs of opposite sign and same flavour that have an invariant mass in the range $m_Z \pm 10$ GeV are rejected (Z veto).

Demanding four tightly isolated leptons with a transverse momentum higher than 10 GeV is a powerful requirement in fighting the $t\bar{t}$ and $Wt\bar{b}$ background. An explicit Z veto eliminates the ZZ, WZ, $Zb\bar{b}$ production and all other backgrounds containing a Z boson. Furthermore, to reduce ZZ we also require a minimal missing transverse energy of 20 GeV. ZZ events where one of the Z's decays into taus, with the taus decaying leptonically, can however pass this criterion.

The SUSY background is more complex. Squark/gluino production is characterised by a large jet multiplicity (5 jets on average), a significant E_T^{miss} ($\gtrsim$ 100 GeV) and jet transverse momenta that are large compared to the expectations for the signal. Selecting events with few, rather soft jets (e.g. $\leq$ 2 jets, E_T of the hardest jet below 100 GeV) and with $E_T^{miss} <$ 130 GeV allows us to eliminate most of these events. The E_T^{jet} threshold can be lowered to 50 GeV if necessary. The squark/gluino - gaugino associated production can be eliminated this way too. If we assume $m_{\tilde{q},\tilde{g}}$ = 1000 GeV as in our default scenario, no squark/gluino events will survive the selection. In paragraph 7, the effects of lighter masses will be discussed.
Slepton-slepton production predominantly ends up in a 2-lepton final state. Sneutrino-sneutrino production remains however as the dominant SUSY background. It could possibly be distinguished from the signal because of larger E_T^{miss} and larger p_T of the leptons, as sneutrinos either decay into $\chi_2^0 + \nu$ (leading to extra E_T^{miss}) or into $\chi_1^+ + l^-$ (leading to harder leptons).
Pair production of heavier neutralinos and charginos will lead to more and harder jets and will often contain Z bosons in the final state. Direct χ_2^0-χ_2^0 production gives the same signature as the signal, but the production cross section is much smaller due to the strongly suppressed coupling of gauginos to the Z/γ intermediate state.

In figures 7 - 14, the distributions of the different kinematical variables for the signal and the total background (SM + SUSY) are plotted. The parameters of the considered case are: m_A = 350 GeV, $\tan\beta$ = 5, M_1 = 60 GeV, M_2 = 120 GeV, μ = -500 GeV, $m_{\tilde{l}}$ = 250 GeV, $m_{\tilde{q},\tilde{g}}$ = 1000 GeV. The dark shaded (blue) area is the part of the spectrum that is retained in the event selection.
In view of these distributions, we will apply the following search strategy: events are selected with E_T^{miss} smaller than 130 GeV (to suppress the SUSY background), but larger than 20 GeV (to suppress ZZ background). The P_T of the hardest lepton should be less than 80 GeV. The E_T of the harderst jet in the event is taken smaller than 100 GeV. In addition, we could also make a jet multiplicity requirement ($\leq$ 2 jets), but this seems to be needed only if squarks and/or gluinos would be light (cfr. paragraph 7). The four lepton invariant mass of the signal events should not exceed m_A - $2m_{\chi_1^0}$. If the mass of the lightest neutralino is approximately known at the time of the analysis, one could set a limit at $m_{llll} \leq$ 230 GeV.
The number of signal and background events remaining after applying this selection is, for the considered case, given in table 1.

Table 1: Number of events after successive cuts (at 100 fb^{-1}). As parameters were used: m_A = 350 GeV, $\tan\beta$ = 5, M_1 = 60 GeV, M_2 = 120 GeV, μ = -500 GeV, $m_{\tilde{l}}$ = 250 GeV, $m_{\tilde{q},\tilde{g}}$ = 1000 GeV.

Process	4l events (isol.)	Z-veto	P_T^{lept} cut	E_T^{miss} cut	E_T^{jet} cut	4l inv. mass
$\tilde{q}, \tilde{g}$	421	206	60	8	1	1
$\tilde{t}\tilde{t}$	10	4	2	0	0	0
$\tilde{l}$,$\tilde{\nu}$	191	92	20	15	15	11
$\tilde{q}\tilde{\chi}$	41	23	7	0	0	0
$\tilde{\chi}\tilde{\chi}$	40	20	13	5	4	3
total SUSY bkg.	703	345	102	28	20	15
ZZ	2106	80	79	10	10	2
total bkg.	2809	425	181	38	30	17
H, A signal	268	232	218	179	164	164

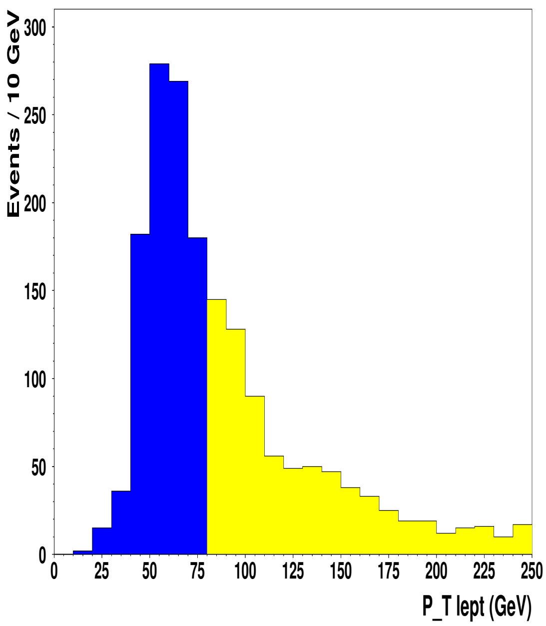

Figure 7: P_T spectrum of the hardest lepton in the event for the total background (SM + SUSY) at 100 fb^{-1}.

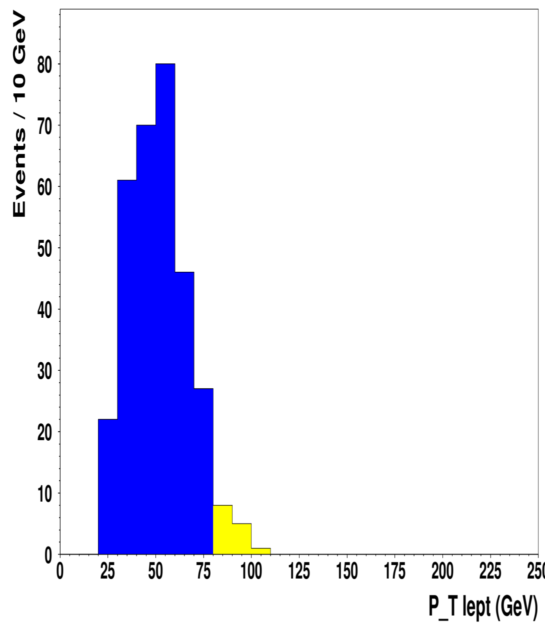

Figure 8: P_T spectrum of the hardest lepton in the event for the signal at 100 fb^{-1}.

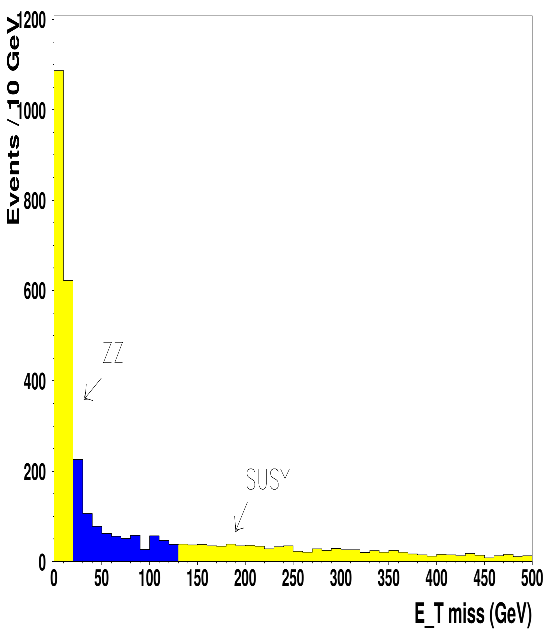

Figure 9: Missing E_T distribution for the total background (SM + SUSY) at 100 fb^{-1}.

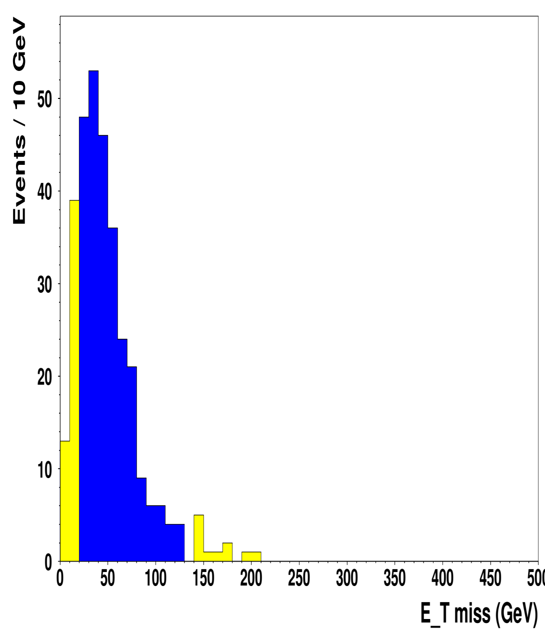

Figure 10: Missing E_T distribution for the signal at 100 fb^{-1}.

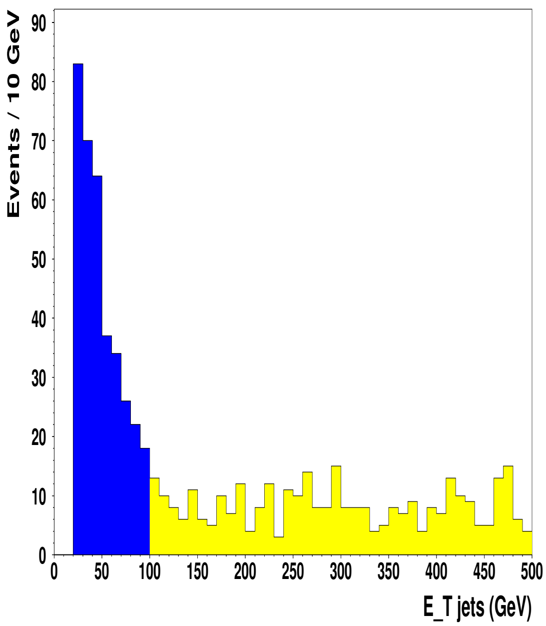

Figure 11: Transverse energy distribution of the hardest jet in the event for the total background (SM + SUSY) at 100 fb^{-1}.

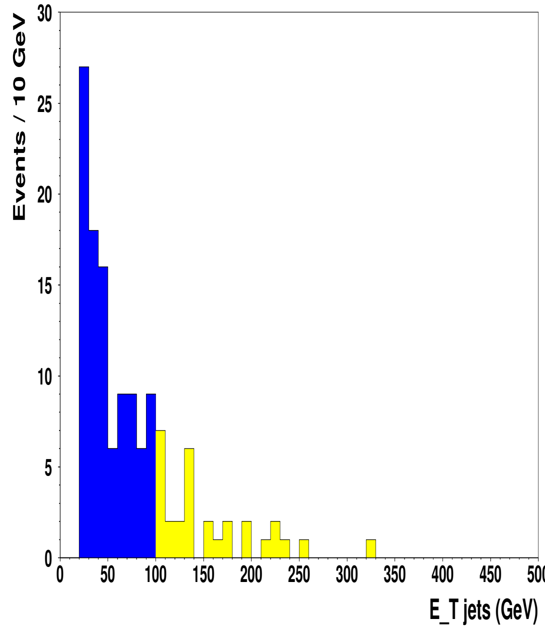

Figure 12: Transverse energy distribution of the hardest jet in the event for the signal at 100 fb^{-1}.

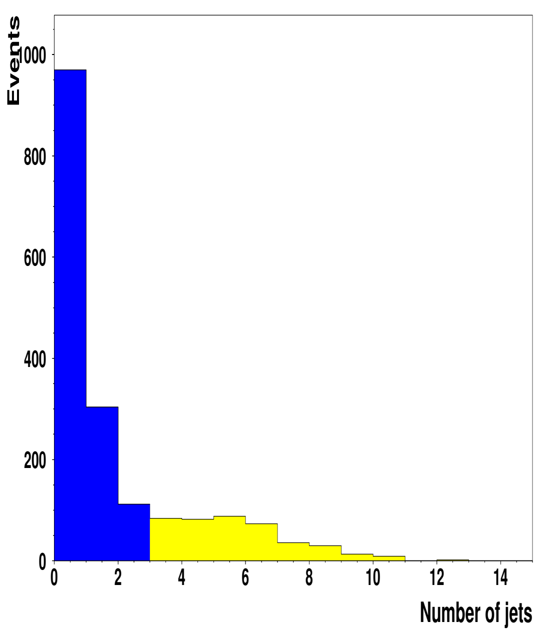

Figure 13: Jet multiplicity for the total background (SM + SUSY) at 100 fb^{-1}.

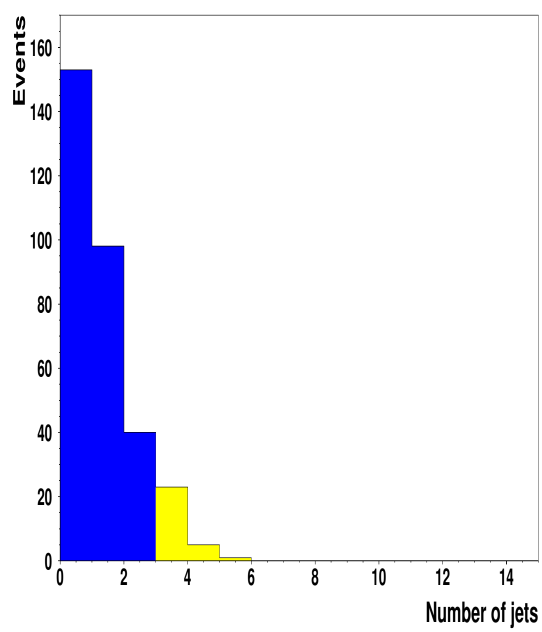

Figure 14: Jet multiplicity for the signal at 100 fb^{-1}.

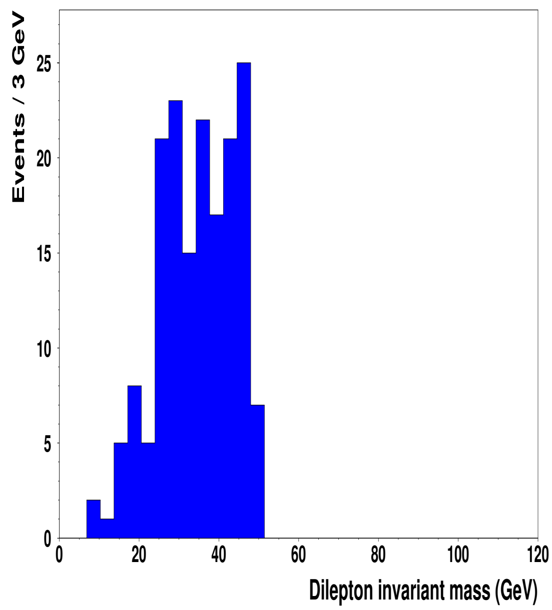

Figure 15: Kinematical edge in the dilepton (opposite sign - same flavour) invariant mass distribution.

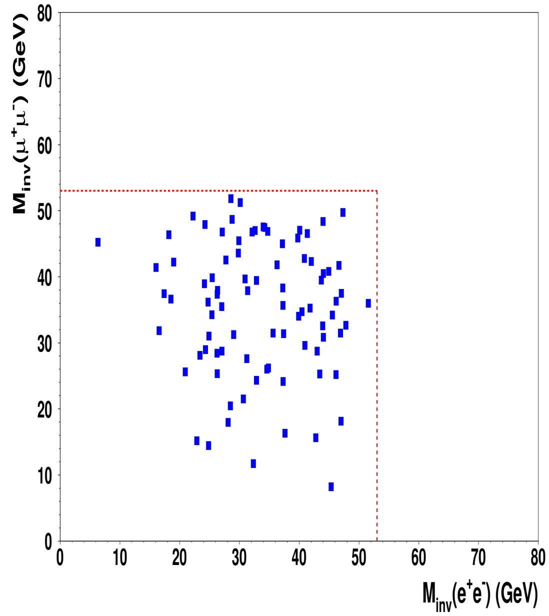

Figure 16: Double kinematical edge in the di-electron versus dimuon invariant mass.

An extra feature that can be exploited in the signal versus background discrimination is the shape of the dilepton invariant mass spectrum. For signal events both $\chi_2^0 \to l^+l^-\chi_1^0$ decays will result in a kinematical edge at $m_{\chi_2^0}$ - $m_{\chi_1^0}$ in the dilepton invariant mass. In figs. 15 and 16, this edge can be seen for our case where $m_{\chi_2^0}$ - $m_{\chi_1^0} \approx$ 50 GeV. To avoid improper combinations of leptons, one can use selected events where one neutralino decays to electrons and the other one to muons. Selecting events in which both dilepton pairs are close to the kinematical edge may allow for the direct reconstruction of the A^0 / H^0 mass, if the statistics are sufficient.

After this selection, we can plot the four lepton invariant mass of the events. In fig. 17, we show the case of m_A = 350 GeV and $\tan\beta$ = 5, M_1 = 60 GeV, M_2 = 120 GeV, μ = -500 GeV, $m_{\tilde{l}}$ = 250 GeV, $m_{\tilde{q},\tilde{g}}$ = 1000 GeV (point A). In fig. 18, we present a case where direct decays of neutralinos into right-handed sleptons is allowed: m_A = 350 GeV, $\tan\beta$ = 10, M_1 = 100 GeV, M_2 = 200 GeV, μ = 350 GeV, $M_{\tilde{l_L}}$ = 200 GeV, $M_{\tilde{l_R}}$ = 150 GeV, $M_{\tilde{q},\tilde{g}}$ = 550 GeV (point B). At these chosen points in parameter space, the signal entirely dominates the 4-lepton sample, with less than 10 percent of background events.

6 Discovery reach in the m_A - $\tan\beta$ plane

As a next step, we investigated the domain of m_A - $\tan\beta$ parameter space where the $A/H \to \chi_2^0\chi_2^0 \to 4l + E_T^{miss}$ final states would be detectable. We tried to optimize our selection criteria to get the best S/B ratio and best signal observability by sliding upper and lower cuts on selection variables.
As a criterion for discovery, we require the significance $\sigma \geq 5$, with σ defined conservatively as $\sigma = S/\sqrt{S+B}$. S and B are the number of signal and background events respectively.
In fig. 19 the region in the $m_A - \tan\beta$ plane is plotted where a 5σ-discovery could be made for an integrated luminosity of 30 and 100 fb^{-1}, provided we understand the nature of both SM and SUSY backgrounds in the final state topology. For this plot, the other MSSM parameters were chosen as μ = -500 GeV, M_1 = 60 GeV, M_2 = 120 GeV, $m_{\tilde{l}}$ = 250 GeV, $m_{\tilde{q},\tilde{g}}$ = 1000 GeV, so direct decays of neutralinos into sleptons are not allowed. The discovery region starts where the $\chi_2^0\chi_2^0$ decay becomes kinematically accessible, $m_A \geq 2m_{\chi_2^0} \approx$ 230 GeV; the upper reach in m_A is, for high values of $|\mu|$, mainly determined by the A^0, H^0 production cross section, which drops with m_A as a power law. The reach in $\tan\beta$ is determined by the branching ratio of $A^0, H^0 \to \chi_2^0\chi_2^0$ and $\chi_2^0 \to l^+l^-\chi_1^0$.
At 30 fb^{-1}, the discovery region reaches $m_A \approx$ 350 GeV and $\tan\beta \approx$ 20. For 100 fb^{-1}, values of $\tan\beta \approx$ 40

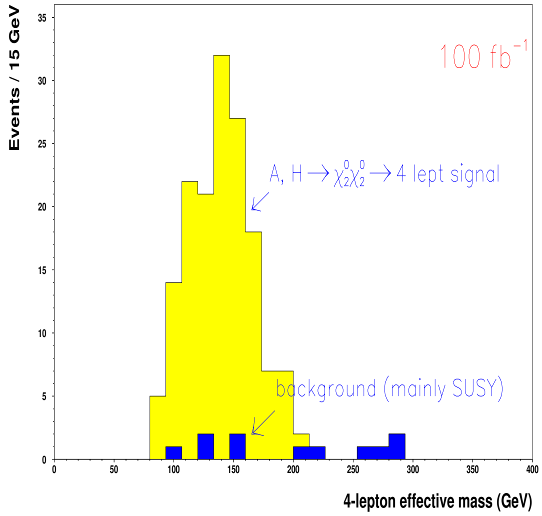

Figure 17: Four lepton invariant mass for signal versus background (SM + SUSY) for point A: m_A = 350 GeV, $\tan\beta$ = 5, M_1 = 60 GeV, M_2 = 120 GeV, μ = -500 GeV, $m_{\tilde{l}}$ = 250 GeV, $m_{\tilde{q},\tilde{g}}$ = 1000 GeV (100 fb^{-1}).

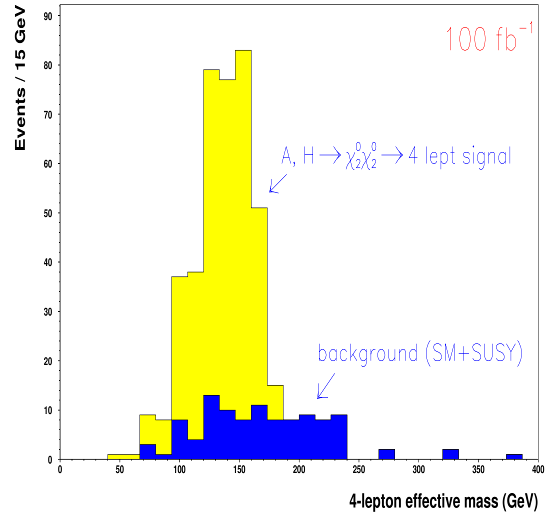

Figure 18: Four lepton invariant mass for signal versus background (SM + SUSY) for point B: m_A = 350 GeV, $\tan\beta$ = 10, M_1 = 100 GeV, M_2 = 200 GeV, μ = 350 GeV, $m_{\tilde{l}_L}$ = 200 GeV, $m_{\tilde{l}_R}$ = 150 GeV, $m_{\tilde{q},\tilde{g}}$ = 550 GeV (100 fb^{-1}).

and masses up to $m_A \approx$ 450 GeV are accessible. In the case that $\chi_2^0 \rightarrow \tilde{l}l$ decays are dominating, even higher values of m_A may be observable, but the reach in $\tan\beta$ will be lower.
These areas are covering the otherwise difficult region (partly at 30 fb^{-1} and fully at 100 fb^{-1}) of MSSM parameter space that is not easily accessible for SM decays of SUSY Higgses - except for the $h \rightarrow b\bar{b}$ mode.

7 Dependence of the discovery potential on the other MSSM parameters

Since the discovery reach depends strongly on the nature of the $\chi_2^0\chi_2^0$ intermediate state, we have to investigate the effect of varying - apart from m_A and $\tan\beta$ - also the other important MSSM parameters μ, $m_{\tilde{l}}$, M_1, M_2 and $m_{\tilde{g},\tilde{q}}$.
There are two main aspects to investigate: the μ - $m_{\tilde{l}}$ dependence of the discovery potential, which will be crucial for the signal; and the effect of light squarks and gluinos, leading to additional large SUSY backgrounds. The impact of the M_1 and M_2 parameters is discussed too.

Discovery potential in the μ - $m_{\tilde{l}}$ plane

The Higgsino mass parameter μ (together with the wino mass M_2) determines the gaugino/higgsino composition of the neutralinos in the intermediate state. For low values of $|\mu|$, the χ_2^0 is rather higgsino-like and it will preferably decay into jets rather than into leptons. For higher values of $|\mu|$, the gaugino content will dominate and they will prefer to decay into leptons. In fig. 20, the 5σ-discovery contours in the μ - $m_{\tilde{l}}$ plane are shown for $\tan\beta$ = 5, m_A = 350 GeV, M_1 = 80 GeV, M_2 = 150 GeV, $m_{\tilde{g},\tilde{q}}$ = 1000 GeV. The indicated slepton mass is the right-handed slepton mass, the left-handed slepton mass is assumed to be $m_{\tilde{l}_R}$ + 50 GeV. This is done to avoid very light sneutrinos.
Within the discovery contours, one can distinguish two regimes. If $m_{\tilde{l}} <$ 150 GeV ($\approx M_2$), decays of neutralinos in real sleptons are allowed. This results in very high branching ratios in the range 200 $\lesssim \mu \lesssim$ 500 GeV (-250 $\lesssim \mu \lesssim$ -100 GeV for negative values); for μ values outside this range or if the splitting between $m_{\tilde{l}_R}$ and $m_{\tilde{l}_L}$ is not sufficient, the neutralinos will preferably decay into sneutrino-neutrino pairs rather than into slepton-lepton pairs, thus leading to pure E_T^{miss}.
For $m_{\tilde{l}} >$ 150 GeV ($\approx M_2$), only virtual slepton exchange is allowed. In this case, the branching ratio decreases steadily with the mass of the sleptons. Negative values of μ seem slightly more favourable.

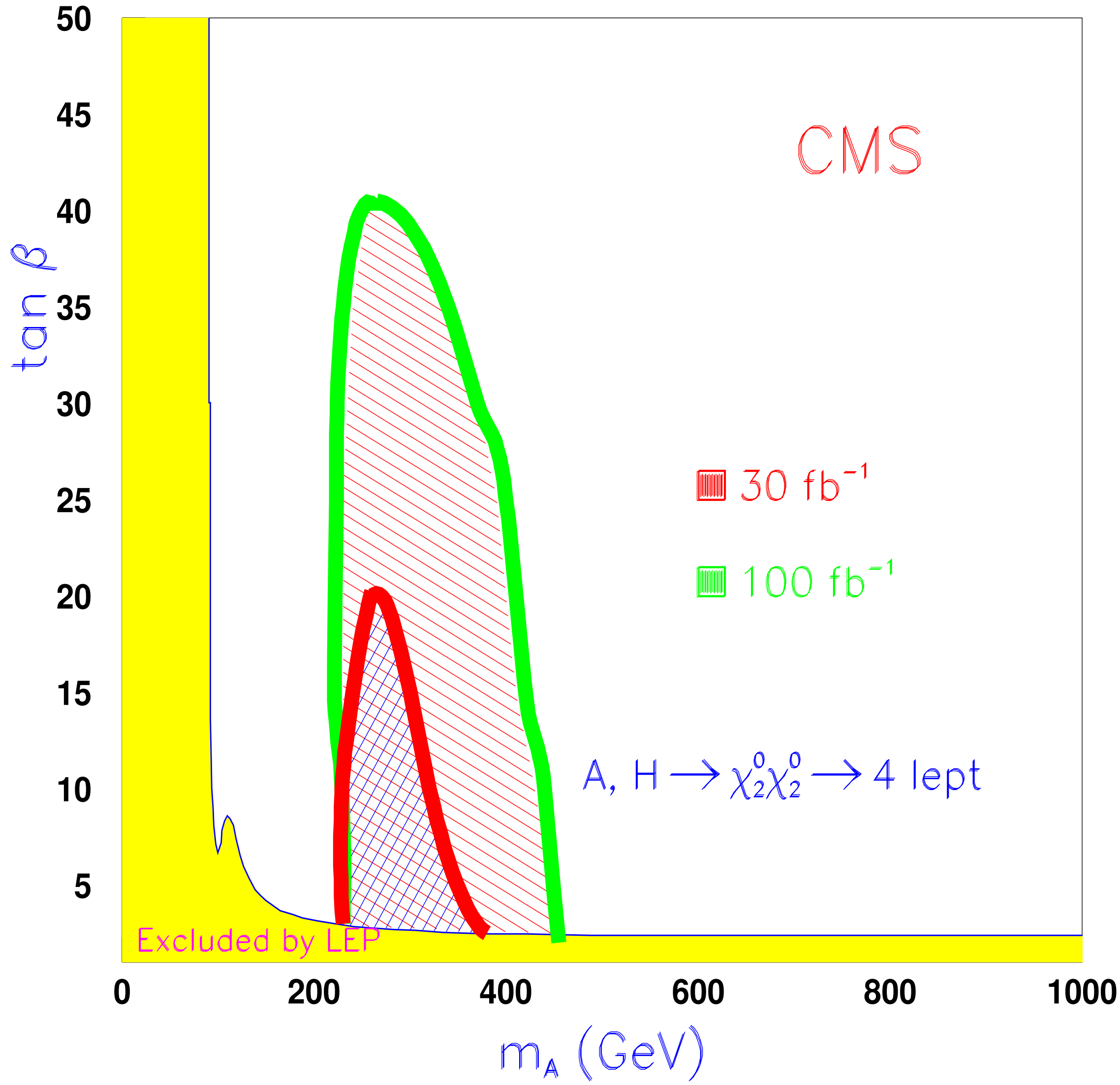

Figure 19: 5σ-discovery contours in the $m_A - \tan\beta$ plane for 30 and 100 fb^{-1}. The other MSSM parameters are μ = -500 GeV, M_1 = 60 GeV, M_2 = 120 GeV, $m_{\tilde{l}}$ = 250 GeV, $m_{\tilde{q},\tilde{g}}$ = 1000 GeV.

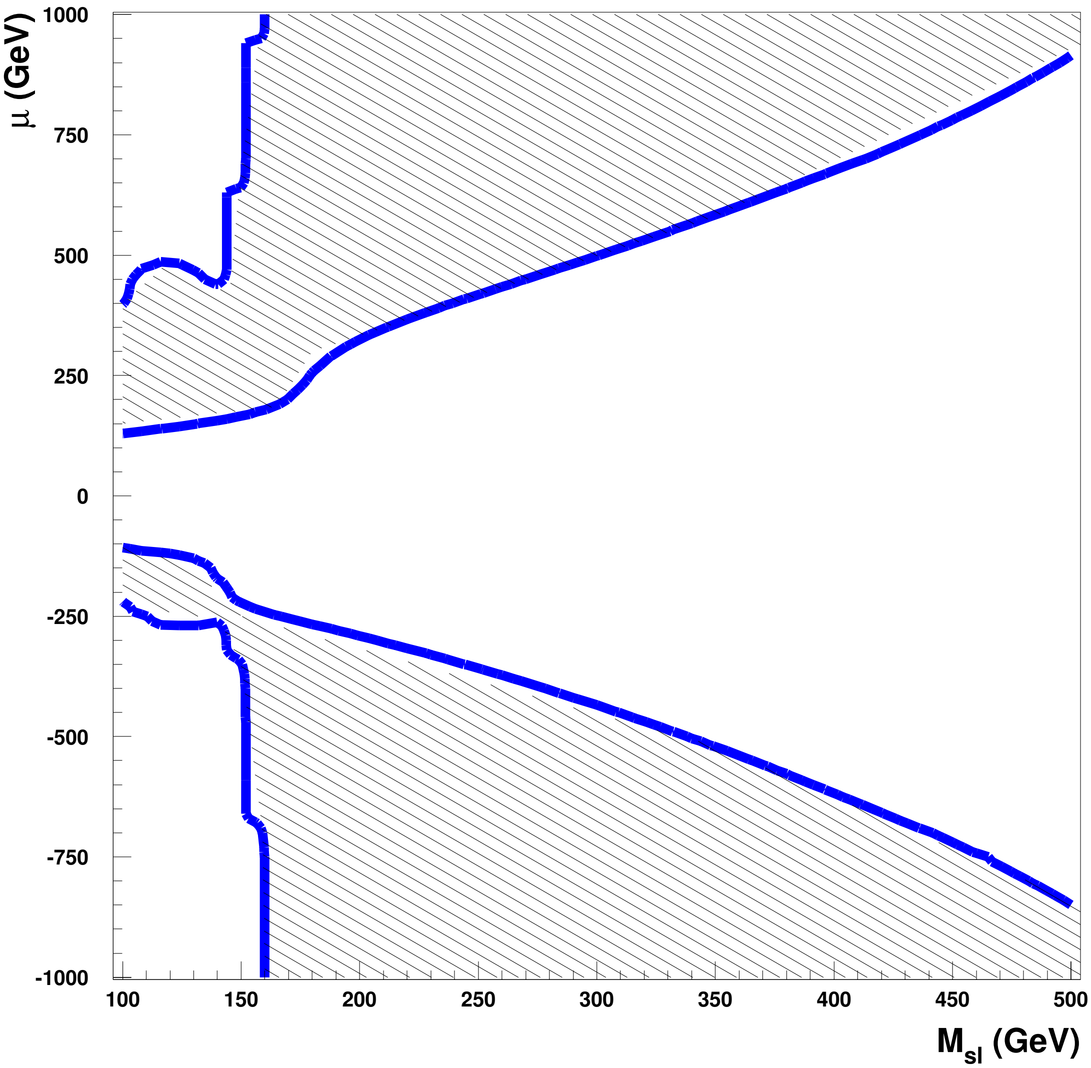

Figure 20: 5σ-discovery contour in the $\mu - m_{\tilde{l}}$ plane for 100 fb^{-1}. The other MSSM parameters are $\tan\beta$ = 5, m_A = 350 GeV, M_1 = 80 GeV, M_2 = 150 GeV, $m_{\tilde{g},\tilde{q}}$ = 1000 GeV.

The bino mass M_1 and wino mass M_2

If neutralinos are gaugino-like (large $|\mu|$ regime), the mass of the χ_1^0 will approximately be equal to the bino mass parameter M_1 and the mass of the χ_2^0 will be about the same as the wino mass parameter M_2. Therefore, M_2 will determine the kinematic threshold from where the discovery reach starts: $m_A \geq 2M_2$. It is clear that low values of M_1 and M_2 are much more favourable in order to obtain a large discovery region in m_A.
The analysis presented in the previous paragraphs assumed that $M_2 - M_1 < m_{Z^0}$. If this is not the case, the Z veto would also reject dileptons coming from the neutralinos. We can estimate the upper limits on M_1 and M_2 for this relation to be valid using the gaugino mass unification relation $M_2 = 1.8M_1$, so we find the assumption to be valid up to M_1 = 100 GeV, M_2 = 180 GeV. If $M_2 - M_1 \geq m_{Z^0}$, we will be forced to omit the Z veto, leading to a larger Standard Model ZZ background since it can now only be rejected using the E_T^{miss} requirement. Furthermore, it is also necessary that M_1 and M_2 are not to close to each other ($M_1 \lessapprox M_2$) to allow for leptons with $P_T >$ 10 GeV.

Effects of light squarks and gluinos

If squarks and gluinos are light, they will be copiously produced at the LHC, thus providing a large extra background due to the cascade decays of the squarks and gluinos into next-to-lightest neutralinos. However, the neutralinos produced in these cascade decays will be accompanied with a large number of jets and a large amount of E_T^{miss}. The signal, often produced in association with a $b\bar{b}$ pair, will contain not more than these two soft, rather forward jets (plus eventual initial/final state radiation jets). This feature allows us to discriminate between the signal and the squark/gluino background. Therefore, if this background would become important, it can be drastically reduced by selecting events with not more than two jets with $E_T \lesssim$ 50 GeV and putting an upper limit on E_T^{miss}. Nevertheless, since the production cross section rises steeply with decreasing squark/gluino mass, one can see from table 2 that for masses lower than 500 GeV, the squark/gluino background starts to become comparable to the sneutrino pair production background and the discovery contours will shrink accordingly. In table 2, the squark/gluino pair production is estimated for different values for $m_{\tilde{q},\tilde{g}}$ and compared with a 350 GeV Higgs signal, after applying the extra cuts. MSSM parameters are taken the same as in table 1.

Table 2: Number of surviving background and signal events after successive selection cuts (for 100 fb^{-1}).

Process	800 GeV $\tilde{q}$ & $\tilde{g}$	600 GeV $\tilde{q}$ & $\tilde{g}$	500 GeV $\tilde{q}$ & $\tilde{g}$	400 GeV $\tilde{q}$ & $\tilde{g}$	350 GeV H^0/A^0
cuts as in table 1	0	12	94	670	164
$E_T^{jet} < 50 GeV$	0	3	6	25	133
max. 2 jets	0	1	2	8	130

8 Conclusion

The sparticle decay modes of the heavy neutral SUSY Higgs bosons have been investigated.
The channel $A^0, H^0 \rightarrow \chi_2^0\,\chi_2^0 \rightarrow 4\,l^{\pm}$ (l = e, μ) seems the most promising. In a rather large region of the MSSM parameter space, a clean signal can be observed by selecting events with 4 isolated leptons in the final state. The main backgrounds are ZZ and sparticle pair production (sneutrino, neutralino), but they can be sufficiently suppressed using appropriate selection criteria. Extra backgrounds due to light squark/gluino production can also be kept under control by applying additional cuts.
In the most common case where direct decays of neutralinos to sleptons are not allowed, the $\chi_2^0\,\chi_2^0$ channel seems to provide a detectable signal in the region between $m_A \approx$ 230 and 450 GeV and for $\tan\beta \lesssim$ 40 (at 100 fb^{-1}), in a scenario where $M_2 \approx$ 120 GeV, $\mu \approx$ -500 GeV and $m_{\tilde{l}} \approx$ 250 GeV.
Since the branching ratio of the A^0, H^0 into four leptons is determined by the interplay between a number of MSSM parameters, the observability will also depend strongly on the values of μ, $m_{\tilde{l}}$, M_1 and M_2. Large values of $|\mu|$ and low values of $m_{\tilde{l}}$ are favourable since they enhance the decay rate of the neutralinos into leptons.

Motivated by the low $\tan\beta$ discovery potential of the $A^0, H^0 \rightarrow \chi_2^0\,\chi_2^0 \rightarrow 4\,l$ channel, we also plan a similar study of the sparticle decay modes of the charged Higgs bosons $H^{\pm}$.

9 Acknowledgements

The authors would like to thank Abdel Djouadi for helpful discussions.

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