# CAN THE MSSM HIGGS BE DISCOVERED AT LHC?*

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This article presents a brief overview of the potential of the ATLAS detector at LHC for the detectability of the Higgs boson of the Minimal Supersymmetric Standard Model. The expected rates, backgrounds and significances are discussed channel by channel with the *realistic* assumptions for the detector performance. As final results the range of the MSSM parameter space where expected significances exceed $5\sigma$ value is shown on the $(m_A, \tan\beta)$ plane for the ATLAS detector alone and for combined results from ATLAS and CMS detectors. It is concluded, that potential of combined both LHC detectors will allow for the full coverage in the Higgs sector of the studied region of the MSSM parameter space. The direct impact of the SUSY particles sector on the Higgs observability is neglected so far.

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The ATLAS Collaboration [1] plans to study the $pp$ collisions at the Large Hadron Collider (LHC), approved to be built at CERN. The data-taking according to plans should start around the year 2004. Depending on the financial situation, the design centre-of-mass energy of 14 TeV will be reached at the machine start-up or a few years later. During the first three years of operation, the luminosity is expected to rise from $10^{33}$ cm$^{-2}$ $s^{-1}$ (low luminosity) to the design value of $10^{34}$ cm$^{-2}$ $s^{-1}$ (high luminosity).

One of the main physics goals of the LHC experiments is to explore the electroweak symmetry breaking sector of the Standard Model (SM) up to TeV energies. The present experimental knowledge leaves this sector of electroweak symmetry breaking largely unconstrained. There are various theoretical scenarios, all of which invoke the existence of new massive scalar

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bosons (or Higgs bosons). The SM predicts one unique scalar Higgs boson with a mass below $\sim 1$ TeV, whereas the Minimal Supersymmetric extension of the Standard Model (MSSM) predicts five physical states in a similar mass range. So far, no experimental evidence excludes nor confirms these theoretical scenarios.

To perform a systematic study of the Higgs sector of the MSSM [2] one has to deal with a rich spectrum of possible signals. The Higgs sector contains two charged ($H^{\pm}$) and three neutral (h, H, A) physical states. At the tree level, all Higgs boson masses and couplings can be expressed in terms of two parameters only, for example $m_A$, the mass of the CP-odd boson, and $\tan\beta$, the ratio of the vacuum expectation values of the Higgs doublets. However the radiative corrections from the t-quark and sparticles substantially modify the three level formulas for masses and mixing patterns in the Higgs sector [3]. It has important consequences for the strategies of MSSM Higgs boson searches as the non-observation of any signal from MSSM Higgs boson at LEP can no longer be used to put any limit on $\tan\beta$ or to exclude the MSSM model (the tree level inequality $m_h < m_Z \cos 2\beta$ is not valid [4]).

In the past years several theoretical groups have reevaluated prospects for the detection of MSSM Higgs bosons at future hadron colliders. Most studies have selected such set of parameters, that supersymmetric (SUSY) particle masses were large so that Higgs boson decays to SUSY particles were kinematically forbidden [5]. The interest was focused on various decay modes accessible also for SM Higgs: $h \to \gamma\gamma$, $h \to b\bar{b}$, $H \to ZZ^{(*)} \to 4\ell$, on modes strongly enhanced for large $\tan\beta$: $H/A \to \tau\tau$, $H/A \to \mu\mu$. Not that much attention was concentrated on other also potentially interesting channels like: $H/A \to t\bar{t}$, $A \to Zh$, $H \to hh$. The predictions given in the quoted papers evolved with time and improvements of the theoretical calculations, the most crucial effects come from theoretical uncertainties in predicting upper limit for the lightest Higgs mass. The conclusions that can be drawn from these studies was that the region of parameter space $m_A = 50 - 500$ GeV and $\tan\beta = 1 - 30$ should be accessible by LHC experiments for searching for one or more Higgs bosons at least in its large fraction, but the discovery by the LHC experiments is not guarantee.

In more recent studies it was rather emphasised that the effect of SUSY particles cannot be neglected in the consideration of prospects for the MSSM Higgs boson searches [6]. The impact of SUSY particles sector on the Higgs sector can be due to following effects: • Due to the radiative corrections the mass patern for the Higgs bosons is affected by the sparticle masses and mixing parameter in the stop-sbottom sector [4]. • If supersymmetric particles are not too heavy their contribution in loops can either enhance or suppress both the $gg \to h, H, A$ production and/or branching ratios for the $\gamma\gamma$ channel [7]. • There are regions in parameter space, where rates for Higgs boson decay to SUSY particles are large and dominant. These decays reduce rates for SM signatures opening however new mode for invisibly decaying Higgs [8] and new visible modes for Higgs detections [9, 10]. Of great interest is also Higgs decay to charginos or neutralinos ($H \to \chi\chi$) leading to the four-lepton finals state. • There are regions in parameter space where Higgs bosons are produced in decays of SUSY particles [9]. The most promising is neutralino decay to the lightest Higgs boson followed by $h \to b\bar{b}$ decay mode [1]. This option is even more interesting as the $b\bar{b}$ signature is enhanced by the typical SUSY inclusive signature (large missing energy, multi-jet final state).

In past two years the intensive work documented in [11] was done inside ATLAS Collaboration to understand better the detector potential for the discovering MSSM Higgs sector. Final results from [11] for the ATLAS potential alone Fig. 1 and Fig. 2 and also for the combined ATLAS+CMS potential Fig. 3 and Fig. 4 show that most of the MSSM parameter space can be probed at the LHC after the first three years of operation at low luminosity and the region $m_A = 50 - 500$ GeV and $\tan\beta = 1 - 50$ will be completely covered after combining results from both experiments after collecting $3 \cdot 10^5$ pb$^{-1}$ integrated luminosity. It will furthermore be possible to disentangle the SM Higgs sector from the MSSM one over more than 90% of the parameter space. The only remaining ambiguity would be located in a region where the only observable channel is $h \to \gamma\gamma$ with couplings essentially identical to the SM case. More than 85% of the parameter space will be covered by more than one signal channel at high luminosity.

Let us discuss first overall sensitivity and then turn to the specific channels.

## • Overall sensitivity

The MSSM Higgs sector is quite challenging experimentally for LHC as most often signal-to-background ratio is much smaller than one and the detector resolution in accessible channels quite large ($A \to t\bar{t}$, $H \to t\bar{t}$, $A \to \tau\tau$, $H \to \tau\tau$, $h \to b\bar{b}$). This puts stringent requirements on the detector performance in terms of energy and momentum resolution and particle identification, however the variety of channels give excellent benchmark to quantify potential of the detector. The very good performance of the EM calorimeter for $h \to \gamma\gamma$ and $H \to ZZ^{(*)} \to 4\ell$ channels, efficient tracker for the $b$-tagging for $Wh$, $H \to hh$ and $A \to Zh$ channels, good $E_T^{\rm miss}$ resolution and $\tau$ identification for $A, H \to \tau\tau$, $H^\pm \to \tau\nu$ are crucial to fully explore the MSSM Higgs sector.

Before the start of LHC the LEP2 experiment will cover ~10-20% parameter space on ($m_A$, $\tan\beta$) plane. The lightest Higgs can be observed

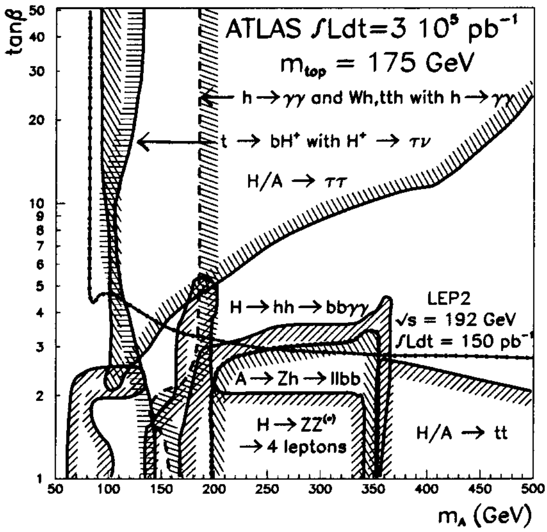


Fig. 1. For $m_t = 175$ GeV and an integrated luminosity of $3 \cdot 10^4$ pb$^{-1}$, ATLAS $5\sigma$-discovery contour curves in the ($m_A$, $\tan\beta$) plane for all discussed Higgs boson signals.

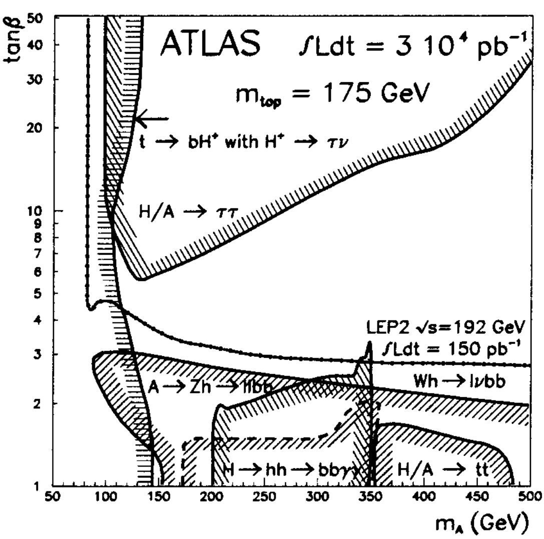


Fig. 2. For $m_t = 175$ GeV and an integrated luminosity of $3 \cdot 10^5$ pb$^{-1}$, ATLAS $5\sigma$-discovery contour curves in the ($m_A$, $\tan\beta$) plane for all discussed Higgs boson signals.

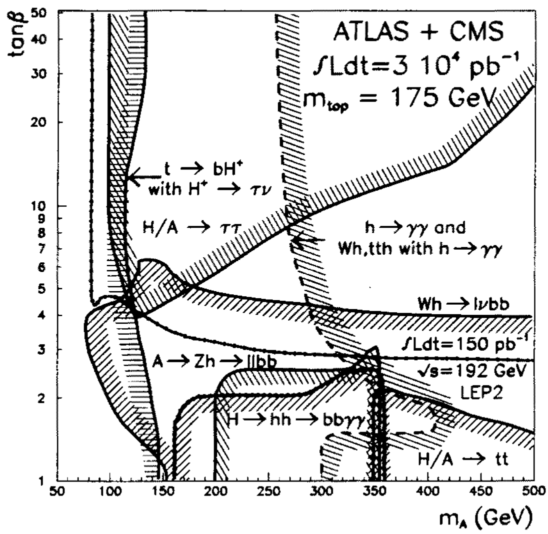


Fig. 3. For $m_t = 175$ GeV and an integrated luminosity of$3 \cdot 10^4$ pb$^{-1}$, combined ATLAS+CMS $5\sigma$-discovery contour curves in the ($m_A$, $\tan\beta$) plane for all discussed Higgs boson signals.

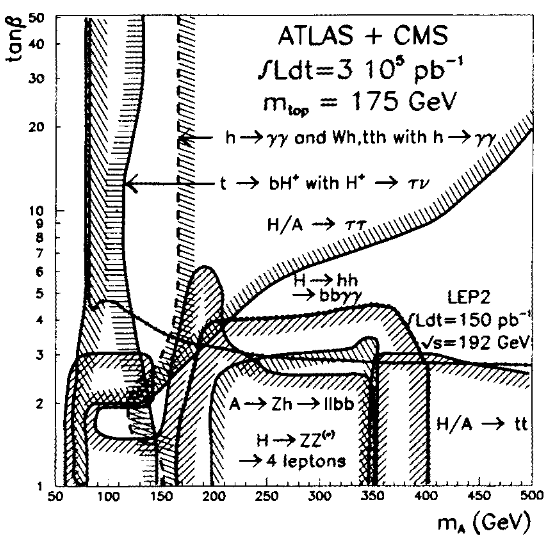


Fig. 4. For $m_t = 175$ GeV and an integrated luminosity of $3 \cdot 10^5$ pb$^{-1}$, combined ATLAS+CMS $5\sigma$-discovery contour curves in the ($m_A$, $\tan\beta$) plane for all discussed Higgs boson signals.

at LEP2 in two channels: $e^+e^- \to hA$ for $m_A < 90$ GeV, and $e^+e^- \to hZ$ for $m_A > 90$ GeV approximately. If $h$ is observed in the first mode and the $A$ boson is also seen then its supersymmetric nature can be unambiguously certified. If it is observed in the second mode, which is the same as for SM Higgs, then it will be difficult to disentangle between SM and MSSM as rates would be the same. If the $h$ will not be observed at LEP2, the region of the plane below LEP2 curve will be already excluded. The size of this region depends on top-quark mass also, the exclusion curve shifting towards larger values of $\tan\beta$ for smaller values of $m_t$.

After three years of LHC operating with low luminosity the large fraction of the parameter space will be already explored (see Fig. 1 and 3). In the low $\tan\beta$ range several channels ($A \to Zh$, $H \to hh$, $A \to t\bar{t}$, $H^\pm \to \tau\nu$) will cover region already tested by LEP2, and in case Higgs already have been found will help to disentangle between MSSM and SM sectors. The large $\tan\beta$ region will be partially explored by $A \to \tau\tau$ and $H \to \tau\tau$ and $H^\pm \to \tau\nu$ channels. Higgs discovery in these channels would confirm the MSSM Higgs sector (channels not accessible for SM Higgs), as well as observed rates would give indication on the value of the $\tan\beta$.

In the high luminosity operation mode the $h \to \gamma\gamma$ channel (inclusive and associated) would become accessible as well as with increasing integrated luminosity the parameter range covered by each channel separately would expand. After collecting $3 \cdot 10^5$ pb$^{-1}$ nearly whole parameter space can be already covered by the ATLAS detector (see Fig. 2). The coverage of the low $\tan\beta$ region ($\tan\beta = 1-4$) being shared by overlapping $h \to \gamma\gamma$(associated), $H \to ZZ^{(*)} \to 4\ell$, $A \to Zh$, $H \to hh$, $A \to t\bar{t}$ and $H \to t\bar{t}$ channels approximately up to the coverage by LEP2. The large $\tan\beta$ region would be covered by $A \to \tau\tau$, $H \to \tau\tau$ and $H^\pm \to \tau\nu$ as well as $h \to \gamma\gamma$(combined) channels. The moderate $\tan\beta$ range ($\tan\beta = 3-10$), where for $m_A > 100$ GeV only $h \to \gamma\gamma$ is accessible, might turn out to be the most difficult one. However discovery in this channel alone would allow neither to untangle between SM and MSSM sectors nor for good estimation of the corresponding $m_A$ and/or $\tan\beta$ value.

## The $h \to \gamma\gamma$ and $H \to \gamma\gamma$ channels

This is a rare decay mode, with a branching ratio of the order of $10^{-3}$ and an expected rate from direct production of about 1000 reconstructed events per year at high luminosity. It has the most promising signature in the mass region 80 GeV $< m_H <$ 130 GeV. The detector performance in terms of energy resolution and particle identification, is crucial to allow the observation of a possible Higgs-boson signal in this mass region. The final states of interest contain two high-$p_T$ photons, which produce a peak in the $\gamma\gamma$ invariant-mass distribution. The backgrounds to this channel are very large and therefore set stringent requirements on the performance of the detector, in particular of the electromagnetic calorimeter. A systematic study of the various backgrounds, irreducible $\gamma\gamma$, reducible $\gamma j$, $jj$ and resonant $Z \to ee$ (for $m_H \sim m_Z$), is presented in Ref. [13]. The search for the SM Higgs boson in $H \to \gamma\gamma$ decays can also be performed using $WH$ and $t\bar{t}H$ production, for events with a high-$p_T$ isolated lepton from $W$-decay in addition to the two photons from Higgs decay. The signal-to-background ratio is much higher [14] in this channel than in the inclusive $H \to \gamma\gamma$ channel. The signal rates, however, are too low in this channel for it to be observed with integrated luminosities much smaller than $3 \cdot 10^5$ pb$^{-1}$. Nevertheless, the expected sensitivity to this channel can be combined with that for the inclusive channel to improve the overall sensitivity to a possible signal.

The expected MSSM rates, for both $h \to \gamma\gamma$ and $H \to \gamma\gamma$ decays, are generally suppressed with respect to the SM case, and are only comparable to the SM rates over a very limited mass range for the Higgs boson under consideration. The so-called discovery potential of the combined $\gamma\gamma$ channel [1], is not overwhelming, slightly exceeding $5\sigma$ only, nevertheless allows to exclude region $m_A > 160$ GeV (for any $\tan\beta$) at high luminosity. The sensitivity to the exact value of the top mass would translate in a shift of the curve by $\pm 20$ GeV for $m_t$=150–200 GeV.

## The $h \to b\bar{b}$ channel

The SM $H \to b\bar{b}$ channel has recently been studied in [15], where both WH and $t\bar{t}H$ production were considered, with final states containing one high-$p_T$ lepton from W-boson decay for triggering and two (resp. three or four) reconstructed b-jets in the WH (resp. $t\bar{t}H$) case. The conclusions of [15] were that a signal from $H \to b\bar{b}$ decays may be observed above the background at the LHC for $m_H <$ 90-100 GeV and an integrated luminosity of $3 \cdot 10^4$ pb$^{-1}$, provided excellent b-tagging performance can be achieved with the detector. A signal from WH production can only be seen above the dominant $t\bar{t}$ background if tight veto cuts against additional jets and leptons are applied [15], what is certainly possible at low luminosity. It is however clear that further studies are needed to define efficient veto cuts at high luminosity and understand whether the signal sensitivity can be improved. A signal from $t\bar{t}H$ production could probably not be extracted

[1] The discovery potential is often expressed in terms of the signal significance, defined as the number of standard deviations ($\sigma$) with which the signal is observed above the background. It is usually assumed that a conclusive discovery can only be obtained for significances above $5\sigma$.

without a complete reconstruction of the top-quark decays to solve the large combinatorial problems arising from the presence of four b-quarks in the final state. Recent work on the b-tagging capabilities indicates that an overall b-tagging efficiency $\epsilon_b = 60\%$ can be achieved by the ATLAS detector with the combined use of vertexing and of soft-lepton tags and with the B-layer present in the Inner Detector.

In the MSSM case, the rates are somewhat suppressed with respect to the SM case. Although it provides limited coverage of the parameter space in the ($m_A$, $\tan\beta$) plane, especially for large values of $m_t$, this channel is quite important, since it provides additional sensitivity with respect to the $h \to \gamma\gamma$ channel for low values of $\tan\beta$. Future work will determine whether any improvement in the sensitivity can be expected at high luminosity.

## The $H \to ZZ^{(*)} \to 4\ell$ channel

For the intermediate mass range, 120 GeV$< m_H < 2m_Z$, the signal rates are small and the background rates are potentially very large. In particular, the reducible $t\bar{t}$ and $Zb\bar{b}$ backgrounds can only be brought down to a level well below the irreducible $ZZ^*/\gamma^*$ background by a combination of strong isolation and impact–parameter cuts. For this reason, the overall signal reconstruction efficiency is $\sim$ 40% at low luminosity, corresponding to a reconstruction efficiency of 90% per lepton, an efficiency of 85% for the lepton isolation cuts, an efficiency of 85% for the impact–parameter cuts, an efficiency of 95% for the four-lepton mass reconstruction in the chosen mass bin, and an efficiency of 90% for losses due to internal bremsstrahlung [16]. This overall efficiency of 40% drops to 24% at high luminosity, due to the lower efficiency of the lepton isolation cuts.

For the range of masses accessible in the MSSM case above the $ZZ$ threshold, $2m_Z < m_H <$ 400 GeV, the only significant background arises from irreducible ZZ continuum production. The overall signal reconstruction efficiency is thus significantly higher, $\sim$ 59%, corresponding to a reconstruction efficiency of 90% per lepton and an efficiency of 90% for the four-lepton mass reconstruction within the chosen mass bin. In the SM case, for which the Higgs-boson width increases rapidly as $m_H$ increases, this mass bin was chosen to be $m_H \pm 1.64\sqrt{(\Gamma_H^{\rm tot}/2.36)^2 + \sigma_m^2}$, where $\sigma_m$ is the expected experimental mass resolution [13]. Since, however, the MSSM H-boson width remains much narrower than the experimental resolution over the relevant region of parameter space, the mass bin chosen for the MSSM case is narrower, $m_H \pm 1.64\sigma_m$, where $\sigma_m/m_H \sim 1.5\%$ was estimated from recent studies using full simulation for the $H \to 4e$ channel and from updated detailed parametrisations of the overall muon momentum resolution for the $H \to 4\mu$ channel [17].

The MSSM $H \to ZZ^{(*)} \to 4\ell$ rates are strongly suppressed with respect to the SM case (except for values of $\tan\beta$ smaller than unity). This limits the observability of this channel to $m_H < 2m_t$ and to low values of $\tan\beta$. The highest possible integrated luminosity is needed in this channel. If a signal were to be observed in this channel, the measured signal rate would provide the best tool to understand its origin, since the $H \to ZZ^{(*)} \to 4\ell$ MSSM rates are suppressed by an order of magnitude with respect to the SM case over most of the parameter space, and would allow a measurement of the value of $\tan\beta$ with an accuracy of $\pm 10$ to 15%, for an integrated luminosity of $3 \cdot 10^5$ pb$^{-1}$. For values of $m_H$ larger than $\sim$ 250 GeV, the measured signal width would also provide a handle to disentangle the SM case ($\Gamma_H^{\rm tot} \sim 10$ GeV) from the MSSM case ($\Gamma_H^{\rm tot} < 1$ GeV).

### The $H/A \to \tau\tau$ channel

In the SM case, a signal from $H \to \tau\tau$ decays cannot be observed experimentally at the LHC because the signal rates are too low with respect to the large backgrounds [18]. However, the MSSM $H \to \tau\tau$ and $A \to \tau\tau$ rates are strongly enhanced with respect to the SM case over a large region of the parameter space. For low values of $\tan\beta$, the $gg \to A$, $A \to \tau\tau$ rates are dominant and significantly larger than in the SM case. For large values of $\tan\beta$, the production is dominated by $b\bar{b}H$ and $b\bar{b}A$, and the $H \to \tau\tau$ rates are very similar to the $A \to \tau\tau$ ones. For $m_A > 150$ GeV, the $H$- and $A$-bosons are degenerate in mass, so the signal rates in the $\tau\tau$ channel can be added, whereas a more complicated procedure depending on the experimental resolution and on the mass difference $m_H - m_A$ has to be applied for $m_A < 150$ GeV.

This channel requires excellent $\tau$ identification [19] to suppress the huge QCD-jet backgrounds from various sources, but also excellent $E_T^{\rm miss}$ resolution [20] for the reconstruction of the $\tau\tau$ invariant mass. One of the $\tau$ leptons is required to decay leptonically to trigger the experiment. The other $\tau$m lepton is then required to decay either to another lepton (lepton-lepton channel) or to a single charged hadron (lepton-hadron channel). The lepton-hadron channel turns out to provide the best sensitivity to a possible signal, due both to its larger rate and to the more favourable kinematics of the $\tau$ decay. The background, a mixture of $t\bar{t}$, $b\bar{b}$, W + jets and Z, can be significantly reduced by appropriate kinematic cuts based on the reconstructed lepton, on the $\tau$ jet and on $E_T^{\rm miss}$. After all cuts, $t\bar{t}$ decays amount to only 10 to 20% of the total background, which is dominated by W+jet and $b\bar{b}$ events (and Z-decays for the lower values of $m_H$ and $m_A$). Therefore, the background estimates in this channel were assumed to be independent of $m_t$, since the smaller $t\bar{t}$ cross-section is more or less compensated for by the larger acceptance of the selection cuts as $m_t$ increases.

At high luminosity, although the $\tau$ identification efficiency can be maintained at its low-luminosity value of $\sim 26\%$, the sensitivity to this channel is significantly degraded due to pile-up effects for the following two main reasons: • the fraction of cases where the neutrino system can be resolved [18] decreases by 30%; • the $\tau\tau$ mass resolution is degraded by a factor $\sim 1.5$. As a consequence, high-luminosity operation with $10^5$ pb$^{-1}$ is expected to only slightly improve the sensitivity to a possible signal with respect to low-luminosity operation with $3 \cdot 10^4$ pb$^{-1}$.

The expected $5\sigma$-discovery contour curves for the combined $H/A \to \tau\tau$ signal show that, even for a moderate integrated luminosity of $3 \cdot 10^4$ pb$^{-1}$, a signal should be observed over a large region of the ($m_A$, $\tan\beta$) plane. This region can be substantially increased only for the largest integrated luminosities achievable with high-luminosity operation, due to the degraded detector performance at high luminosity discussed above. The observability of this channel does not vary much as a function of $m_t$. As already mentioned, for low values of $\tan\beta$, the signal can be observed only in the $A \to \tau\tau$ channel, and the sensitivity to the signal disappears for $m_A > 2m_t$, where $A \to t\bar{t}$ decays become dominant.

As in the case of $H \to ZZ^{(*)} \to 4\ell$ decays, a measurement of the signal rate should provide good sensitivity to $\tan\beta$ in this channel. As an example, for $m_A = 150$ GeV and an integrated luminosity of $3 \cdot 10^5$ pb$^{-1}$, $\tan\beta$ can be measured to an accuracy of $\pm 5\%$ for $\tan\beta = 5$ and of $\pm 13\%$ for $\tan\beta = 40$ (a systematic uncertainty of $\pm 10\%$ was assumed for the measured signal rate).

### The $H/A \to \mu\mu$ channel

As for $H/A \to \tau\tau$, this channel cannot be observed in the SM case because of the limited expected rate and of the overwhelming backgrounds, but it can be observed in the MSSM case, due to the large enhancement of $H/A \to \mu\mu$ rates through $b\bar{b}H$ and $b\bar{b}A$ production expected for large values of $\tan\beta$. The rates for this channel are governed by the same couplings as for the $\tau\tau$ channel, but the branching ratio scales as $(m_\mu/m_\tau)^2$. This huge reduction in signal rate with respect to the $\tau\tau$ channel is however compensated to some extent by the much better experimental resolution achievable in the $\mu\mu$ mode.

### The $H \to hh$ channel

The observation of this channel would be particularly interesting, since it would correspond to the simultaneous discovery of two Higgs bosons. The studied channel, $H \to hh \to b\bar{b}\gamma\gamma$, can be easily triggered upon and it offers good kinematic constraints for the reconstruction of $m_H$. The signal was extracted by requiring two isolated photons, with $|\eta| < 2.5$ and $p_T > 20$ GeV, and two additional jets with $|\eta| < 2.5$ and $p_T > 15$ GeV (resp. $p_T > 30$ GeV) at low (resp. high) luminosity. At least one of these jets was required to be tagged as a b-jet with an assumed efficiency $\epsilon_b = 60\%$ (resp. 50%) at low (resp. high) luminosity. Events were accepted if the diphoton mass was within $\pm 2$ GeV of $m_h$, and if the dijet mass was within $\pm 20$ GeV of $m_h - 20$ GeV (no correction to the reconstructed dijet mass was applied in this study). Finally, after rescaling the photon and jet 4-momenta appropriately by applying a constraint on $m_h$, the $\gamma\gamma$jj invariant mass was required to be within $\pm 10$ GeV of $m_H$. Several background sources were considered: irreducible $b\bar{b}\gamma\gamma$ and reducible bj$\gamma\gamma$, $c\bar{c}\gamma\gamma$, cj$\gamma\gamma$ and jj$\gamma\gamma$, which were all estimated using PYTHIA. Large uncertainties apply to these background estimates, due to the poor knowledge of the total $b\bar{b}$, $c\bar{c}$ and jj cross-sections, and to the procedure used to simulate photon bremsstrahlung in these processes. The expected signal rates are very low, even when requiring only one of the two jets in the final state to be tagged as a b-jet. The $H \to hh$ channel can be observed only for low values of $\tan\beta$ and for $200 < m_H < 400$ GeV.

### The $H/A \to t\bar{t}$ channel

Because of the strong couplings of the SM Higgs boson to gauge boson pairs, the $H \to t\bar{t}$ branching ratio is too small for this channel to be observable in the SM case. In the MSSM case, however, the $H \to t\bar{t}$ and $A \to t\bar{t}$ branching ratios are close to 100% for $m_H$, $m_A > 2m_t$ and for $\tan\beta \sim 1$. The $H \to t\bar{t}$ and $A \to t\bar{t}$ decays cannot be distinguished experimentally from each other, since the H- and A-bosons are almost degenerate in mass in the relevant region of parameter space. As discussed in the literature [21], a signal from $H/A \to t\bar{t}$ decays would only appear as a peak in the $t\bar{t}$ invariant mass spectrum above the $t\bar{t}$ continuum background for values of $m_H$ and $m_A$ smaller than $\sim$ 500 GeV, due to negative interference effects between the signal and background amplitudes.

The signal was extracted by searching for $WWb\bar{b}$ final states, with one $W \to \ell\nu$ and one $W \to jj$ decay. The lepton was required to have $p_T > 20$ GeV and all the jets, *i.e.* those from W-decay and the two b-jets, were required to have $p_T > 40$ GeV. It was assumed that the experiment could trigger on such topologies and efficiently reconstruct them at low and high luminosities. Both b-jets were required to be tagged, with an assumed efficiency $\epsilon_b = 60\%$ (resp. 50%) at low (resp. high) luminosity. Both top-quark decays were fully reconstructed and a constraint on $m_t$ was used to improve the experimental resolution on the $t\bar{t}$ invariant mass. The expected mass resolution for $H/A \to t\bar{t}$ decays increases from 40 to 80 GeV as

$m_H$ and $m_A$ increase from 400 to 500 GeV. The background from continuum $t\bar{t}$ production is much larger than the W+jet background after these selection cuts, and is unfortunately also much larger than the signal. The signal-to-background ratio varies between 1.5% and 7% over the range of Higgs boson and top-quark masses considered. The mass resolutions quoted above imply that a typical mass window allowing to observe most of the signal would be between 150 and 300 GeV. With such wide mass windows, the signal can only be observed above the continuum background as an excess of events. This excess would be very significant statistically, but this significance would only be meaningful if the theoretical uncertainties on the continuum background shape were lower than a percent or so. With this optimistic scenario in mind, the $5\sigma$-discovery contour curves were extracted and they cover at best a limited region in parameter space, *i.e.* $m_H$, $m_A > 2m_t$ and $\tan\beta < 3$. For larger values of $\tan\beta$, the $H/A \to b\bar{b}$ branching ratios become dominant.

### The $A \to Zh$ channel

The observation of this channel would be particularly interesting, since it would correspond to the simultaneous discovery of two Higgs bosons. It is the dominant A-boson decay channel for low values of $\tan\beta$ and for $m_Z + m_h < m_A < 2m_t$. The $A \to Zh \to \ell\ell b\bar{b}$ channel has been studied as it can be easily triggered upon and it offers the large rates. The signal was extracted by requiring two isolated leptons, with $|\eta| < 2.5$ and $p_T > 20$ GeV, and two additional jets with $|\eta| < 2.5$ and $p_T > 15$ GeV (resp. $p_T > 30$ GeV) at low (resp. high) luminosity. Both jets were required to be tagged as b-jets with an assumed efficiency $\epsilon_b = 60\%$ (resp. 50%) at low (resp. high) luminosity. Events were accepted if the dilepton mass was within $\pm 6$ GeV of $m_Z$, and if the dijet mass was within $\pm 20$ GeV of $m_h -$ 20 GeV (no correction to the reconstructed dijet mass was applied in this study). Finally, after rescaling the lepton and jet 4-momenta appropriately by applying constraints on $m_Z$ and $m_h$, the $\ell\ell$jj invariant mass was required to be within $\pm 6$ GeV of $m_A$. Several background sources were considered: irreducible $Zb\bar{b}$ and $ZZ$, and reducible $ZW$, $Zjj$ and $t\bar{t}$. After the selection cuts, the $Zb\bar{b}$ and $t\bar{t}$ backgrounds are dominant. The expected signal rates decrease very rapidly as $\tan\beta$ increases. The $A \to Zh$ channel can therefore only be observed for low values of $\tan\beta$ and for 200 GeV $< m_A < 2m_t$.

### The $H^{\pm} \to \tau\nu$ channel

Charged Higgs boson production at the LHC can occur through $t\bar{t}$ production followed by $t \to H^{+}b$ decay or through Drell–Yan pair production. The latter is unfortunately much smaller in rate and much more difficult to extract from the huge QCD backgrounds. The study concentrated [22] on the search in $t\bar{t}$ events for an excess of $\tau$ leptons from $H^{\pm} \to \tau\nu$ decay with respect to the expected $\tau$ lepton rate from $W^{\pm} \to \tau\nu$ decay. The charged Higgs boson mass cannot be directly reconstructed, because several neutrinos are produced in the final states of interest.

Large samples of $t\bar{t}$ events can be triggered on by requiring one isolated high-$p_T$ lepton within $|\eta| < 2.5$. The additional requirement of at least three reconstructed jets with $p_T > 20$ GeV and $|\eta| < 2.5$, of which two are required to be tagged as b-jets, reduces the potentially large backgrounds from W + jet and $b\bar{b}$ production to a level well below the $t\bar{t}$ signal itself. The dominant background is then the combinatorial background from fake and real $\tau$-leptons in $t\bar{t}$ events. The selection cuts enhance the right-handed $\tau$-lepton signal from $H^{\pm}$ decays with respect to that from W decay, and select mostly single-prong $\tau$-decays. As for the case of the $H/A \to \tau\tau$ decays $\tau$ identification is a key element in extracting a possible signal from the large combinatorial background from jets.

After the selection cuts and the $\tau$ identification criteria have been applied, $t \to H^{+}b$ decays appear as final states with an excess of events with one isolated $\tau$ lepton compared to those with an additional isolated electron or muon. As in the case of $H/A \to \tau\tau$ decays, these results were obtained from full simulation of the signal and background processes. As an example, for $m_t = 175$ GeV, $m_{H^{\pm}} = 130$ GeV and $\tan\beta = 6$, an excess of $\sim 1000$ $\tau$ leptons is expected from the charged Higgs boson signal, above a background of $\sim 3000$ $\tau$ leptons from W decay, and of $\sim 4000$ fake $\tau$ leptons.

When measuring such an excess, systematic uncertainties have to be taken into account. They arise mainly from the imperfect knowledge of the $\tau$-lepton efficiency and of the amount of fake $\tau$ leptons present in the final sample. They were assumed to be $\sim \pm 3\%$ from past experience [23], and added to the statistical uncertainty to obtain the significances. These systematic uncertainties dominate the overall uncertainty, and the sensitivity to a charged Higgs boson signal would not improve significantly with integrated luminosity unless increased statistics would result in improved systematic uncertainties.in These results do not take into account recent calculations [24], which include possible decays of the charged Higgs boson to SUSY particles and show that the $H^{+} \to \tau\nu$ branching ratio may in some cases decrease significantly for low values of $\tan\beta$.

A signal from charged Higgs boson production in $t\bar{t}$ decays would be observed for all values of $m_{H^\pm}$ below the kinematical limit of $\sim m_t - 20$ GeV over most of the $\tan\beta$ range. For moderate values of $\tan\beta$, for which the expected signal rates are lowest, the accessible values of $m_{H^\pm}$ are lower than this kinematical limit by $\sim 20$ GeV. This effect becomes more pronounced as $m_t$ increases, due to the decrease in the $t\bar{t}$ production cross-section. One can note finally that, as for the $H/A \to \tau\tau$ channel, the fraction of parameter space covered by the $H^\pm \to \tau\nu$ channel in the ($m_h$, $\tan\beta$) plane is much larger than in the standard ($m_A$, $\tan\beta$) plane.

## Conclusions

- the LEP2 discovery potential corresponds to $\sim$ 10–20% of the parameter space in a linear ($m_A$, $\tan\beta$) plane. In most cases, the discovery of a Higgs boson at LEP2 would not in itself allow any discrimination between the SM case and the MSSM case;
- with a modest integrated luminosity of $3 \cdot 10^4$ pb$^{-1}$, the LHC discovery potential corresponds to $\sim$ 80% of the parameter space. For 80% to 90% of the cases, the discovery of a Higgs boson at the LHC would allow discrimination between the SM case and the MSSM case;
- with the very high integrated luminosity of $3\cdot 10^5$ pb$^{-1}$, the LHC discovery potential corresponds to the whole parameter space. For almost all cases, the experiments would be able to distinguish between the SM case and the MSSM case. In Fig. 4, the region with $m_A > 250$ GeV and $4 < \tan\beta <$ 5–10 is only covered by the $h \to \gamma\gamma$ channel. However, as discussed below, $h \to b\bar{b}$ decays from SUSY particle decays should be observable above background in this region for many cases, thus providing a direct evidence for SUSY. In the case of the simultaneous discovery of light $h$ and $A$ bosons at LEP2, essentially only the charged Higgs boson would be seen directly in top-quark decays at the LHC. In the more likely case of the discovery of one light $h$ boson at LEP2, several Higgs bosons would then be observed at the LHC;
- more generally, all three neutral Higgs bosons would be discovered at the LHC over $\sim$ 60% of the parameter space, *i.e.* for $m_A > 160$ GeV, but over most of this region the $H$ and $A$ bosons are degenerate in mass and would be very difficult to separate. Over $\sim$ 10% of the parameter space, *i.e.* for $\tan\beta > 2$ and $90 < m_A < 130$ GeV, the two heavy neutral Higgs bosons and the charged Higgs boson would be discovered at the LHC;
- over $\sim$ 5% of the parameter space, *i.e.* for $130 < m_A < 160$ GeV and $\tan\beta > 3$, only the $H/A \to \tau\tau$ channel seems to be observable

at the LHC at this stage. However, as can be seen from Fig. 3, the $Wh$ channel with $W \to \ell\nu$ and $h \to b\bar{b}$ decay provides sensitivity in this region for values of $\tan\beta$ as high as $\sim 5$ for an integrated luminosity of $3 \cdot 10^4$ pb$^{-1}$. Work is in progress to assess the observability of this channel at high luminosity, but also to determine whether the $t\bar{t}h$ channel could be useful to improve the sensitivity even further in this region of parameter space;

- the various channels have also been studied for values of $\tan\beta$ smaller than 1. Even if such values are disfavoured for theoretical reasons, it is important to assess the experimental sensitivity, and each channel was studied for $0.3 < \tan\beta < 2$. In contrast to LEP2, which has very little sensitivity to values of $\tan\beta$ below $\sim 0.8$, the sensitivity at LHC is quite good for most channels of interest in this region of very low values of $\tan\beta$;
- many Higgs boson couplings will be measured at LHC, but with an accuracy not likely to be better than 10–20%, since in most cases these measurements will be based on signal rates. A measurement of obvious interest will be that of the Higgs boson couplings to the top quark, either through the observation of $t\bar{t}h$ production with $h \to b\bar{b}$ decay, or through the observation of $H/A \to t\bar{t}$ decays;
- none of the above conclusions are strongly affected by changes in the model parameters, even if many of the discovery curves change significantly as a function of $m_t$. It is important to recall here that all SUSY particle masses were set to 1 TeV for this study. In some specific cases, the exact choice of the SUSY particle mass spectrum does affect the Higgs boson production cross-sections and/or decay branching ratios, and therefore the discovery potential, as discussed in [25]. In particular, preliminary studies based on Minimal Supergravity (SUGRA) Models [26] indicate that the two heavy neutral Higgs bosons and the charged Higgs boson will in many cases have masses larger than 500 GeV, *i.e.* outside the parameter space studied here, and that, for given values of $m_A$ and $\tan\beta$, many different values of $m_h$ are allowed, depending on the exact mass spectrum of SUSY particles.

In conclusion, it is clear that the MSSM Higgs sector is extremely challenging for the LHC experiments and therefore provides an excellent set of benchmark processes to optimise the detector design and performance. This is the case for the electromagnetic calorimeter and muon system resolution, for the b-tagging efficiency, for the $\tau$-lepton identification, the $E_T^{\rm miss}$ resolution and also for the hadronic calorimetry in the reconstruction of multijet final states.

The MSSM is however only one model among many and the theoretical predictions based on this model should not be the dominant input into the LHC detector design nor preclude the possibility of investigating other more exotic scenarios. In particular, the Higgs boson signals discussed throughout this study would not provide direct evidence for SUSY, which could only arise from the discovery of supersymmetric particles themselves.

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