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Heavy MSSM Higgses at the LHC

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Abstract

This paper describes search strategies considered in the LHC collaborations ATLAS and CMS for the discovery of the heavy Higgs bosons A, H and $H^{\pm}$ of the Minimal Supersymmetric Standard Model. The emphasis is put on the channels that allow to cover a large fraction of the $(m_A, \tan\beta)$ parameter space.

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1 Introduction

Finding other Higgs bosons in addition to the neutral scalar postulated in the Standard Model would demonstrate the non-standard nature of the Higgs sector. If they are heavier than $\simeq 150$ GeV, the LHC experiments ATLAS and CMS will be the first to have a chance to discover them[1)]. This paper describes the search strategies for the heavy Higgs bosons of the Minimal Supersymmetric Standard Model (MSSM) in ATLAS and CMS.

In the MSSM two $SU(2)$ Higgs doublets are assumed to produce a spontaneous breakdown of the electroweak symmetry $SU(2) \times U(1)$. This leaves five physical degrees of freedom: two neutral CP-even Higgs bosons h and H, one neutral CP-odd A and two charged Higgs bosons $H^{\pm}$. The production mechanisms and decay channels which provide a detectable signature may vary depending on the values of the MSSM parameters. In this paper we concentrate on those channels which would allow to cover a large fraction of the $(m_A, \tan\beta)$ parameter space.

Section 2 discusses the dependence of the $A, H, H^{\pm}$ production cross-section and couplings on the MSSM parameters. Section 3 describes possible trigger and analysis for channels $gg \to A, H \to \tau^+\tau^-$, $gg \to b\bar{b}A, H \to b\bar{b}\tau^+\tau^-$, $A, H \to \chi^0\chi^0$, and $gb \to H^{\pm} \to \tau\nu$ or tb. Conclusions and perspectives are given in section 4.

2 Production mechanisms and decay channels

In the studies presented below the Pythia [3], HIGLU and HQQ [4] programs were used to simulate the signal events. HDECAY [4] is used to compute the Higgs branching ratios, as well as to correct the HIGLU and HQQ cross-sections for SUSY loop effects. Pythia was also used to simulate the backgrounds.

2.1 Heavy neutral Higgses A and H

As long as the superpartners are heavy enough to suppress SUSY loops and decays into sparticle pairs, the heavy MSSM Higgs masses, production cross-sections and couplings can be characterized in terms of only 2 parameters, m_A and $\tan\beta$.

In the region $m_A \gg m_Z$, A, H and $H^{\pm}$ are almost degenerate in mass. The coupling of the neutral bosons A and H to down-type quarks and charged leptons is enhanced by a factor $\simeq \tan\beta$ wrt. the Standard Model. Figure 1 shows the branching ratios of the heavy scalar as a function of m_A for a particular choice of MSSM parameters (see caption). The conclusions that can be drawn from the graph are however more general. For $m_A < 2m_\chi$, $BR(A, H \to b\bar{b}) \simeq 90\%$, $BR(A, H \to \tau^+\tau^-) \simeq 10\%$ for $\tan\beta > 10$, and $BR(A, H \to \mu^+\mu^-) \simeq 3.10^{-4}$. When kinematically allowed, $BR(A, H \to \chi\chi)$ is sizeable. Decays into $b\bar{b}$ are more difficult to see because of the huge background. Decays into $\tau^+\tau^-$ provide a detectable signature and sufficient statistics. This channel is detailed further in the text. Search through $A, H \to \mu^+\mu^-$,

[1)] Direct searches at LEP200 have set a limit on m_A at 91.9 GeV and excluded the region $0.5 < \tan\beta < 2.4$ in the maximal mixing scenario at 95% confidence level [1]. Tevatron experiments could discover one of the heavy MSSM Higgs bosons at 5σ significance if $m_A \leq 150$ GeV and if $\tan\beta$ is large [2].

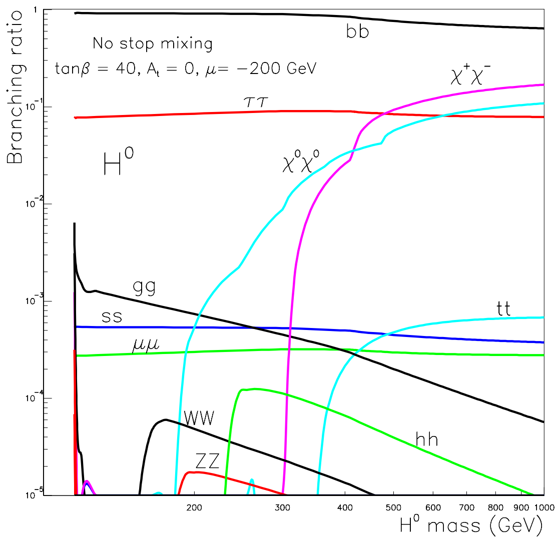

Figure 1: H branching ratios for $\tan\beta = 40$, $A_t = 0$ (no stop mixing), $M_2 = 200$ GeV, $\mu = -200$ GeV and $m_{\tilde{q},\tilde{l},\tilde{g}} = 1$ TeV.

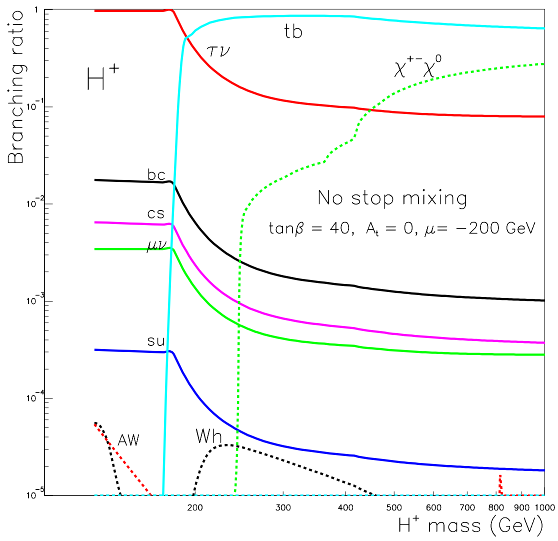

Figure 2: $H^{\pm}$ branching ratios for the same MSSM parameter values as in figure 1.

not discussed here, would allow an estimation of m_A with a precision of 2% [5, 6]. We will also show that $A, H \to \chi^0\chi^0$ provides a complementary coverage in the intermediate $\tan\beta$ region for some choices of MSSM parameters.

Production of A and H can occur through gluon fusion, $gg \to A, H$, or in association with a $b\bar{b}$ pair, $gg \to b\bar{b}A, H$. Figures 3 and 4 show the sum of the cross-sections σ_A^{prod} and σ_H^{prod} times the branching ratio into $\tau^+\tau^-$ for both processes as a function of m_A and for different values of $\tan\beta$. The sum of the cross-sections is the relevant number for evaluating the discovery potential since the mass peaks of the A and H cannot be separated experimentally. The associated production mechanism dominates for $m_A > 150$ GeV at $\tan\beta > 10$. Search for A, H in the $\tau^+\tau^-$ channel is insensitive to stop mixing effects since only the subdominant process $gg \to A, H \to \tau^+\tau^-$ is affected [7].

2.2 Charged Higgs $H^{\pm}$

We restrict our discussion to the case $m_{H^{\pm}} > m_t$. Computations of the $H^{\pm}$ production cross-section involve process $gb \to tH^-$, where the b-quark comes from the proton structure, and process $gg \to \bar{t}bH^+$. The second is included in the first as a NLO correction. As far as total σ^{prod} is concerned computations based on the first process yields a result accurate to better than 20% [8]. Analyses intending to make use of the associated b in $\bar{t}bH^+$ should use matrix elements for the second process, as only these would provide correct kinematics for the additional b-jet.

Decays into $t\bar{b}$ have a branching ratio $\simeq (m_t \cot\beta + m_b \tan\beta)^2$, which is large at high and low

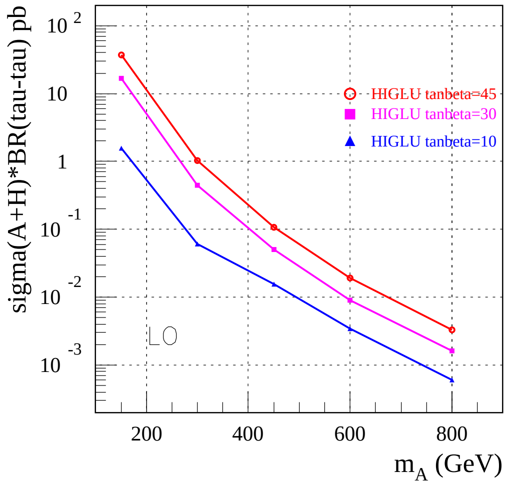

Figure 3: Sum of the production cross-sections times branching ratios $gg \to A \times BR(A \to \tau^+\tau^-)$ and $gg \to H \times BR(H \to \tau^+\tau^-)$, vs. m_A and $\tan\beta$.

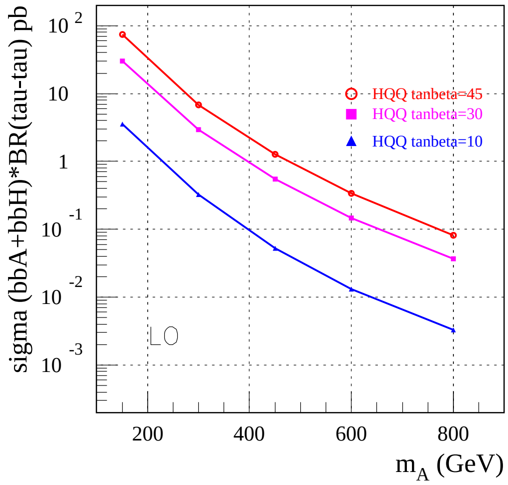

Figure 4: Sum of the production cross-sections $gg \to b\bar{b}A \times BR(A \to \tau^+\tau^-)$ and $gg \to b\bar{b}H \times BR(H \to \tau^+\tau^-)$, vs. m_A and $\tan\beta$.

$\tan\beta$ and minimum at $\tan\beta = \sqrt{m_t/m_b}$. $BR(H^\pm \to \tau\nu)$ is 1% for $\tan\beta = 3$ but increases to $\simeq$ 10% at high $\tan\beta$ (see figure 2). Analyses for other decay channels as well as for the case $m_{H^\pm} \leq m_t$ can be found in [5, 6, 9, 10].

3 Trigger and analysis

3.1 $A, H \to \tau^+\tau^-$

Different final states have been studied, each with slightly different backgrounds:

1. $l^+ + l'^- + \nu$'s, $BR \simeq 12\%$;
2. $l^\pm + \tau$-jet $+ \nu$'s, $BR \simeq 35\%$;
3. τ_1-jet $+ \tau_2$-jet $+ 2\nu$'s, $BR \simeq 25\%$ (both τ's decaying into 1 charged prong) and $\simeq 44\%$ (one 1-prong decay and one 3-prong decay).

Here τ-jet denotes a jet from a hadronic τ decay.

The first channel is easy to trigger on thanks to the high-energy isolated leptons. Irreducible backgrounds are $Z/\gamma^* \to \tau\tau$ and $t\bar{t}$ production with $W \to \tau\nu$. The background from $Z/\gamma^* \to l^+l^-$ is suppressed offline either by requiring leptons of different flavours, or by cutting on the lepton impact parameter. For the second channel, single lepton and lepton+τ-jet triggers are used. Additional backgrounds arise from W+jet and $t\bar{t}$ events with real or faked τ's, and from $b\bar{b}$ events.

As the Higgs decay products tend to be back to back, a cut on the angle between the lepton and the τ-jet, $60^o < \Delta\phi < 175^o$, can be applied. An angle $\neq 180^o$ is required to allow reconstruction of the Higgs mass (see below). E_T^{miss} cuts of 40 GeV or larger depending on the Higgs mass, can be applied offline for further background suppression, but are costly for the signal. In the $gg \to b\bar{b}A, H$ analysis the Z and $W+$ jet backgrounds can be suppressed by requiring one of the associated b-jets to be tagged. These b-jets are however soft and uniformly distributed in η. The tagging efficiency per jet is only about 35% due to the poor impact parameter resolution for soft and forward tracks. In the $gg \to A, H$ analysis a b-jet veto can be applied against the $t\bar{t}$ and $b\bar{b}$ backgrounds.

As to the third channel, the overwhelming QCD di-jet background renders triggering difficult. Standard single and di-jet trigger thresholds yield a low selection efficiency for low Higgs masses ($m_A = 200$ GeV). Both ATLAS and CMS have designed specific τ trigger paths based on the narrowness and isolation of calorimeter τ-jet candidates at first trigger level, isolation of the electromagnetic energy deposit at level 2, and isolation and track counting using the tracker at levels 2 and 3. The rejection factor per QCD jet varies with the jet energy and ranges between 2.10^3 and 10^4 for 1-prong decays (between 5.10^2 and 10^3 for both 1 and 3-prong decays). Trigger efficiencies of about 20% for $m_A = 200$ GeV are expected [11].

Mass reconstruction

The Higgs mass is reconstructed from the spectrum of invariant mass $m_{\tau\tau}$. The τ momenta are reconstructed in the approximation that the ν's are emitted parallel to the visible decay products of their respective parent τ. This approximation holds since the τ's from a heavy Higgs decay have a large boost. The E_T^{miss} vector is thus decomposed into 2 components by projection onto the visible τ momenta. In 50% of the cases, the projection leads to negative neutrino energy. These cases are rejected in the analysis.

The $m_{\tau\tau}$ resolution determines the signal visibility. It is proportional to $\sigma(E_T^{miss})/\sin\Delta\phi$. Figure 5 shows the mass resolution in the three channels, in both direct and associated production mechanisms, as estimated from a fast simulation of the ATLAS detector. Detailed simulations of the CMS detector yield resolutions ranging from 10% up to 25% depending on the channel. This poorer value as compared to ATLAS is attributed to a worse E_T^{miss} resolution.

Discovery reach

Figure 6 shows the expected discovery reach, defined as the parts of the $(m_A, \tan\beta)$ plane where the signal significance $S/\sqrt{N}$ is greater than 5, when combining the results of ATLAS and CMS for 30 fb^{-1} of integrated luminosity per experiment. The region $\tan\beta \geq 10$ is covered up to $m_A = 300$ GeV. At large m_A the all-hadronic channel allows to extend the coverage down to significantly lower $\tan\beta$ as compared to the other channels. The discovery limit is $\tan\beta \geq 15$ for $m_A = 500$ GeV and $\tan\beta \geq 40$ for $m_A = 800$ GeV.

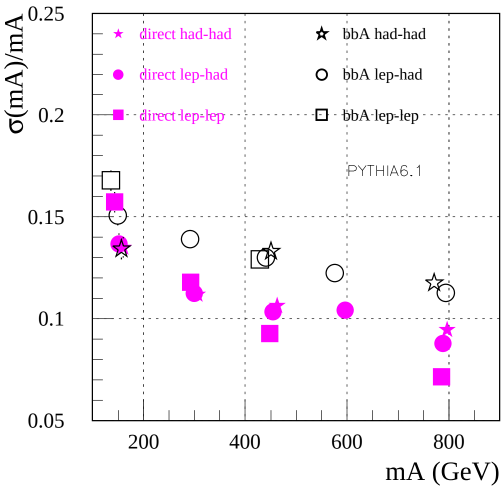

Figure 5: Mass resolution for the heavy neutral Higgses in the $\tau^+\tau^-$ decay channels (ATLAS study).

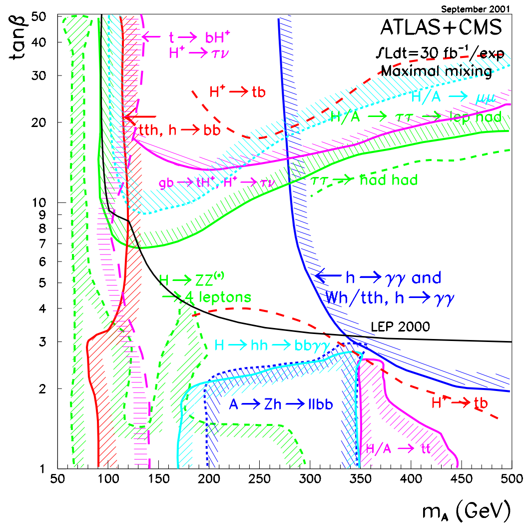

Figure 6: Combined ATLAS + CMS discovery reach ($S/\sqrt{N} \geq 5$) after 30 fb^{-1} of integrated luminosity per experiment.

3.2 $A, H \to \chi^0\chi^0$

Searches for heavy A, H through decays in Standard Model particles leave the intermediate $\tan\beta$ region uncovered, the couplings to the most visible signatures being suppressed. Studies have thus been performed in order to find visible signatures for A, H decaying into sparticles. An almost background-free signature could be observed in the $A, H \to \chi^0_2\chi^0_2$ channel if sleptons and neutralinos are light enough. Each χ^0_2 would decay into a lepton and a virtual slepton, decaying in turn into a lepton of opposite sign and a χ^0_1, leaving two pairs of opposite sign isolated leptons [5, 6, 12].

This search is model-dependent, but for favourable MSSM parameter values it provides a coverage complementary to SM decay searches. Figure 7 shows the 5σ discovery contours for the following choice of parameters: Higgsino mass parameter μ = -500 GeV, wino and bino mass parameters $M_2 = 2M_1 = 120$ GeV, $m_{\tilde{l}}$ = 250 GeV, squark and gluino masses around 1 TeV. Both SM and MSSM backgrounds giving rise to real or fake leptons in the final state have been considered: ZZ, ZW, $Zb\bar{b}$, $Zc\bar{c}$, $Wt\bar{b}$ and $t\bar{t}$, and the SUSY pair production processes involving $\tilde{q}$, $\tilde{g}$, $\tilde{l}$, $\chi^\pm$ and χ^0.

3.3 $gb \to tH^-$ with $H^- \to \tau^-\bar{\nu}$

The main background for this process originates from $t\bar{t}$ with one of the W's decaying into $\tau\nu$. To suppress it, we make use of polarisation effects in the τ decay [6, 13]. The charged Higgs being a scalar, the τ^- from $H^- \to \tau^-\bar{\nu}$ is produced in a right-handed helicity state. The π^- produced in 1-prong τ^- decays is emitted preferentially in the flight direction of the τ^-.

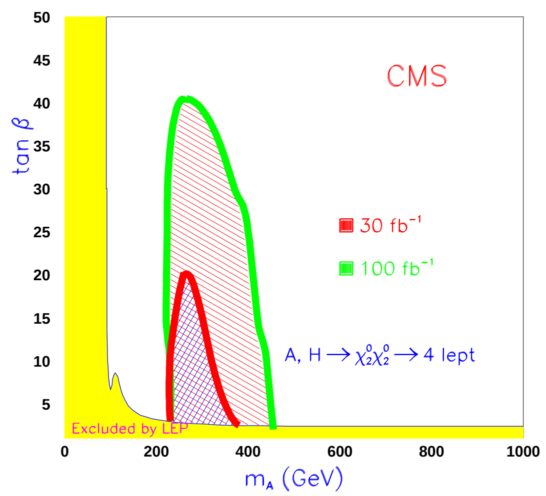

Figure 7: Discovery reach for $H, A \to \chi_2^0\chi_2^0 \to 4l^\pm$ for $M_1 = 60$ GeV, $M_2 = 120$ GeV, $\mu = -500$ GeV, $m_{\tilde{l}} = 250$ GeV, $m_{\tilde{q},\tilde{g}} = 1$ TeV, for 30 and 100 fb^{-1} (CMS study).

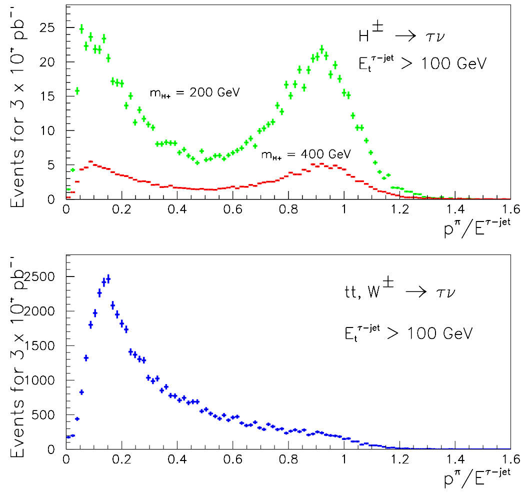

Figure 8: Fraction of the reconstructed τ-jet energy carried away by the charged pion, in $H^- \to \tau^-\bar{\nu}$ and in the main background channel $t\bar{t}$.

In W^- decays however the τ^- is produced left-handed due to the vector nature of W. Thus harder pions are expected from $H^\pm$ decays than from W decays in the case of τ's decaying into one charged pion. This is illustrated in figure 8 showing the fraction of the reconstructed τ-jet energy carried away by the charged pion, in signal and background events.

The trigger for this channel combines the multi-jet trigger and the single τ-jet trigger matched with 1 hard pion track reconstructed at high trigger level. The missing transverse energy due to the neutrino in $H^\pm \to \tau\nu$ is on average large. The E_T^{miss} distribution exhibits a peak characteristic of a two-body decay, with little dilution from the soft ν from the τ decay. The event selection proceeds as follows:

- one τ^--jet with the characteristics described above;
- $E_T^{miss} > 100$ GeV;
- at least three additional jets with $E_T > 20$ GeV, one of which being b-tagged.

At large $\tan\beta$ the signal shows up very clearly above the background in the spectrum of transverse mass $m_T^{\tau\nu}$ formed with the reconstructed τ-jet and E_T^{miss}. The discovery limit should extend up to 800 GeV at $\tan\beta \simeq 40$ with 100 fb^{-1} per experiment.

3.4 $gb \to tH^-$ with $H^- \to \bar{t}b$

This channel is characterized by the presence of at least three b-jets in the final state. It is triggered on thanks to the multi-jet signature and / or a high-energy lepton from one of the W's from top decays. The search is however difficult because it relies on efficient and pure b-tagging, and because the main backgrounds, $t\bar{t}b$ and $t\bar{t}j$ with a jet mistagged as b, have kinematics very comparable to the signal.

Studies have been performed with fast simulations in ATLAS and CMS [9, 14]. To reduce the number of combinations when reconstructing the top quarks, only events where one of the W's decays leptonically have been considered to date. We require:

- 1 isolated lepton with $p_T > 15$ GeV;
- at least five jets, three of which b-tagged.

Then reconstruction proceeds as follows:

- a combination of 2 non-b jets with mass closest to the W mass is formed;
- the reconstructed hadronic W is combined with the b-jet which leads to a mass closest to the top mass;
- the leptonically decaying W is reconstructed by fixing the longitudinal component of the ν using a W mass constraint;
- the second top is reconstructed in a similar way as the first one;
- the invariant mass of the $H^\pm$ candidates, made out of the remaining b-jet with the reconstructed top-quarks, is histogrammed.

The acceptance for the signal is of the order of 1%. The $S/\sqrt{N} = 5$ contours for this channel are shown in figure 6. Only the statistical error on the number of background events has been considered. It should be noted that the S/N ratio is small after event selection (0.2 for $m_A = 300$ GeV$, \tan\beta = 30$). This means that the background should be known theoretically with a precision better than 15%, which is quite challenging. The discovery reach shown in the figure should thus be regarded as optimistic.

4 Conclusions

At the LHC, the channel which provides the largest discovery region for the heavy neutral MSSM Higgs bosons A and H is $A, H \to \tau^+\tau^-$. Making use of the all-hadronic tau decays allows to extend the discovery reach till masses close to 1 TeV at large $\tan\beta$ (≥ 40 with 30 fb^{-1} per experiment). This is made possible thanks to the design, in both the ATLAS and CMS experiments, of specific trigger paths for jets from hadronic τ decays. In the difficult region

($m_A \gg m_Z,$ intermediate $\tan\beta$), decays into χ_2^0 pairs could lead to a striking discovery signature, provided that the MSSM parameter values are favourable (e.g. neutralinos and sleptons are light).

The most promising channel for discovering the charged MSSM Higgs is $H^- \rightarrow \tau^-\bar{\nu}$ followed by the 1-prong decay of the τ. Making use of polarisation effects in the τ decay allows to suppress the main background, due to $t\bar{t}$ with one of the W's decaying into $\tau\nu$. The decay channel $H^- \rightarrow \bar{t}b$ is much more probable but the $t\bar{t}b$ and $t\bar{t}j$ backgrounds are difficult to reduce. This channel requires precise theoretical knowledge of the background and improvements of the experimental analysis.

In the region ($m_A \gg m_Z,$ intermediate $\tan\beta$), disentangling between an SM Higgs and a richer Higgs sector is still problematic. If only the lightest MSSM Higgs boson is discovered, studies of its couplings as well as direct searches for supersymmetric particles should reveal which framework is realized in nature. Nevertheless the LHC collaborations continue to look for ways of seeing heavy SUSY Higgses in that region. Eventually, the MSSM Higgs masses and couplings would allow to constrain the SUSY model. ATLAS and CMS are actively investigating means of determining these parameters [5, 16].

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