Search for Heavy Neutral MSSM Higgs Bosons with CMS: Reach and Higgs-Mass Precision

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Abstract

The search for MSSM Higgs bosons will be an important goal at the LHC. We analyze the search reach of the CMS experiment for the heavy neutral MSSM Higgs bosons with an integrated luminosity of 30 or 60 fb⁻¹. This is done by combining the latest results for the CMS experimental sensitivities based on full simulation studies with state-of-the-art theoretical predictions of MSSM Higgs-boson properties. The results are interpreted in MSSM benchmark scenarios in terms of the parameters tan β and the Higgs-boson mass scale, M_A. We study the dependence of the 5σ discovery contours in the M_A–tan β plane on variations of the other supersymmetric parameters. The largest effects arise from a change in the higgsino mass parameter µ, which enters both via higher-order radiative corrections and via the kinematics of Higgs decays into supersymmetric particles. While the variation of µ can shift the prospective discovery reach (and correspondingly the “LHC wedge” region) by about Δ tan β = 10, we find that the discovery reach is rather stable with respect to the impact of other supersymmetric parameters. Within the discovery region we analyze the accuracy with which the masses of the heavy neutral Higgs bosons can be determined. We find that an accuracy of 1–4% should be achievable, which could make it possible in favourable regions of the MSSM parameter space to experimentally resolve the signals of the two heavy MSSM Higgs bosons at the LHC.

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1 Introduction

Identifying the mechanism of electroweak symmetry breaking will be one of the main goals of the LHC. Many possibilities have been studied in the literature, of which the most popular ones are the Higgs mechanism within the Standard Model (SM) and within the Minimal Supersymmetric Standard Model (MSSM) [1]. Contrary to the case of the SM, in the MSSM two Higgs doublets are required. This results in five physical Higgs bosons instead of the single Higgs boson of the SM. These are the light and heavy $C\!P$-even Higgs bosons, $h$ and $H$, the $C\!P$-odd Higgs boson, $A$, and the charged Higgs boson, $H^\pm$. The Higgs sector of the MSSM can be specified at lowest order in terms of the gauge couplings, the ratio of the two Higgs vacuum expectation values, $\tan \beta \equiv v_2/v_1$, and the mass of the $C\!P$-odd Higgs boson, $M_A$. Consequently, the masses of the $C\!P$-even neutral Higgs bosons and the charged Higgs boson are dependent quantities that can be predicted in terms of the Higgs-sector parameters. Higgs-phenomenology in the MSSM is strongly affected by higher-order corrections, in particular from the sector of the third generation quarks and squarks, so that the dependencies on various other MSSM parameters can be important.

After the termination of LEP in the year 2000 (the final LEP results can be found in Refs. [2,3]), and the (ongoing) Higgs boson search at the Tevatron [4–6], the search will be continued at the LHC [7–9] (see also Refs. [10,11] for recent reviews). The current exclusion bounds within the MSSM [3–5] and the prospective sensitivities at the LHC are usually displayed in terms of the parameters $M_A$ and $\tan \beta$ that characterize the MSSM Higgs sector at lowest order. The other MSSM parameters are conventionally fixed according to certain benchmark scenarios [12–14].

The most prominent one is the “$m^\text{max}_h$ scenario”, which in the search for the light $C\!P$-even Higgs boson allows to obtain conservative bounds on $\tan \beta$ for fixed values of the top-quark mass and the scale of the supersymmetric particles [15]. Besides the “no-mixing scenario”, which is similar to the $m^\text{max}_h$ scenario, but assumes vanishing mixing in the stop sector, other $C\!P$-conserving scenarios that have been studied in LHC analyses (see e.g. Ref. [11]) are the “gluophobic Higgs scenario” and the “small $\alpha_{\text{eff}}$” scenario [13].

For the interpretation of the exclusion bounds and prospective discovery contours in the benchmark scenarios it is important to assess how sensitively the results depend on those parameters that have been fixed according to the benchmark prescriptions. While in the decoupling limit, which is the region of MSSM parameter space with $M_A \gg M_Z$, the couplings of the light $C\!P$-even Higgs boson approach those of a SM Higgs boson with the same mass, the couplings of the heavy Higgs bosons of the MSSM can be sizably affected by higher-order contributions even for large values of $M_A$. The kinematics of the heavy Higgs-boson production processes, on the other hand, is governed by the parameter $M_A$, since in the region of large $M_A$ the heavy MSSM Higgs bosons are nearly mass-degenerate, $M_A \approx M_H \approx M_{H^\pm}$. In Ref. [14] it has been shown that higher-order contributions to the relation between the bottom-quark mass and the bottom-Yukawa coupling have a dramatic effect on the exclusion bounds in the $M_A$–$\tan \beta$ plane obtained from the $b\bar{b}\phi, \phi \rightarrow b\bar{b}$ channel at the Tevatron.

In this article we investigate how the $5\sigma$ discovery regions in the $M_A$–$\tan \beta$ plane for the heavy neutral MSSM Higgs bosons (a corresponding analysis for the charged Higgs-boson

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1 We focus in this paper on the case without explicit $C\!P$-violation in the soft supersymmetry-breaking terms.
search will be presented elsewhere) obtainable with the CMS experiment at the LHC depend on the other MSSM parameters. For the experimental sensitivities achievable with CMS we use up-to-date results based on full simulation studies for 30 or 60 fb$^{-1}$ (depending on the channel) [9]. This information is combined with precise theory predictions for the Higgs-boson masses and the involved production and decay processes incorporating higher-order corrections at the one-loop and two-loop level. In our analysis we investigate the impact on the discovery reach arising both from higher-order corrections and from possible decays of the heavy Higgs bosons into supersymmetric particles.

The search for the heavy neutral MSSM Higgs bosons at the LHC will mainly be pursued in the $b$ quark associated production with a subsequent decay to $\tau$ leptons [7–9]. In the region of large $\tan\beta$ this production process benefits from an enhancement factor of $\tan^2\beta$ compared to the SM case. The main search channels are (here and in the following $\phi$ denotes the two heavy neutral MSSM Higgs bosons, $\phi = H, A$):

$bb\phi, \phi \to \tau^+\tau^- \to 2\text{ jets}$ (1)

$bb\phi, \phi \to \tau^+\tau^- \to \mu + \text{ jet}$ (2)

$bb\phi, \phi \to \tau^+\tau^- \to e + \text{ jet}$ (3)

$bb\phi, \phi \to \tau^+\tau^- \to e + \mu$ . (4)

For our numerical analysis we use the program FeynHiggs [19–22]. We study in particular the dependence of the “LHC wedge” region, i.e. the region in which only the light $\mathcal{CP}$-even MSSM Higgs boson can be detected at the LHC at the 5$\sigma$ level, on the variation of the higgsino mass parameter $\mu$. The dependence on $\mu$ enters in two different ways, on the one hand via higher-order corrections affecting the relation between the bottom mass and the bottom Yukawa coupling, and on the other hand via the kinematics of Higgs decays into supersymmetric particles. We analyze both effects separately and discuss the possible impact of other supersymmetric parameters.

Our results for the discovery reach of the heavy neutral MSSM Higgs bosons extend the known results in the literature in various ways. In comparison with Refs. [23, 24], where the prospective 5$\sigma$ discovery contours for CMS in the $M_A$–$\tan\beta$ plane of the $m_h^{\text{max}}$ benchmark scenario were given for three different values of $\mu$, the results in the present paper are based on full simulation studies and make use of the most up-to-date CMS tools for triggering and event reconstruction. Furthermore, in the analysis of Refs. [23, 24] relevant higher-order corrections, in particular those depending on $\Delta_b$ (see Sect. 2.2 below), have been neglected. The effects induced by the $\Delta_b$ corrections have been investigated in Ref. [14], where the results were obtained by a simple rescaling of the experimental results given in Refs. [7, 23–25]. Our present analysis, on the other hand, makes use of the latest CMS studies and provides a separate treatment of the different $\tau$ final states, channels (1)–(4).

As a second step of our analysis we investigate the experimental precision that can be achieved for the determination of the heavy Higgs-boson masses in the discovery channels (1)–

\footnote{We restrict our analysis to the impact of supersymmetric contributions. For a discussion of uncertainties related to parton distribution functions, see e.g. Ref. [16].}

\footnote{In our analysis we do not consider diffractive Higgs production, $pp \to p \oplus H \oplus p$ [17]. For a detailed discussion of the search reach for the heavy neutral MSSM Higgs bosons in diffractive Higgs production we refer to Ref. [18].}
We discuss the prospective accuracy of the mass measurement in view of the possibility to experimentally resolve the signals of the heavy neutral MSSM Higgs bosons.

The paper is organized as follows: Sect. 2 introduces our notation and gives a brief summary of the most relevant supersymmetric radiative corrections to the Higgs-boson masses, production cross sections and decay widths at the LHC. The relevant benchmark scenarios are briefly reviewed. In Sect. 3 the experimental analysis is described. The results for the variation of the $5\sigma$ discovery contours, obtainable at CMS with 30 or 60 fb$^{-1}$ are given in Sect. 4, where we also discuss the achievable experimental precision in the Higgs mass determination. The conclusions can be found in Sect. 5.

2 Phenomenology of the MSSM Higgs sector

2.1 Notation

The MSSM Higgs sector at lowest order is described in terms of two independent parameters (besides the SM gauge couplings): $\tan \beta \equiv v_2/v_1$, the ratio of the two vacuum expectation values, and $M_A$, the mass of the $\mathcal{CP}$-odd Higgs boson $A$. Beyond the tree-level, large radiative corrections can occur from the $t/\tilde{t}$ sector, and for large values of $\tan \beta$ also from the $b/\tilde{b}$ sector.

Our notations for the scalar top and scalar bottom sector of the MSSM are as follows: the mass matrices in the basis of the current eigenstates $\tilde{t}_L, \tilde{t}_R$ and $\tilde{b}_L, \tilde{b}_R$ are given by

$$
M^2_{\tilde{t}} = \begin{pmatrix}
M^2_{\tilde{Q}} + m_t^2 + \cos 2\beta \left( \frac{1}{2} - \frac{2}{3}s_w^2 \right) & m_t X_t \\
M^2_{\tilde{t}} + m_t^2 + \frac{2}{3} \cos 2\beta s_w^2 & M^2_{\tilde{t}} + m_t^2
\end{pmatrix},
$$

(5)

$$
M^2_{\tilde{b}} = \begin{pmatrix}
M^2_{\tilde{Q}} + m_b^2 + \cos 2\beta \left( -\frac{1}{2} + \frac{1}{3}s_w^2 \right) & m_b X_b \\
M^2_{\tilde{b}} + m_b^2 & M^2_{\tilde{b}} + m_b^2 - \frac{1}{3} \cos 2\beta s_w^2
\end{pmatrix},
$$

(6)

where

$$
m_t X_t = m_t (A_t - \mu \cot \beta), \quad m_b X_b = m_b (A_b - \mu \tan \beta).
$$

(7)

Here $M_{\tilde{Q}}, M_{\tilde{t}R}$ and $M_{\tilde{b}R}$ are the diagonal soft SUSY-breaking parameters, $A_t$ denotes the trilinear Higgs–stop coupling, $A_b$ denotes the Higgs–sbottom coupling, and $\mu$ is the higgsino mass parameter.

For the numerical evaluation, it is often convenient to choose

$$
M_{\tilde{Q}} = M_{\tilde{t}R} = M_{\tilde{b}R} =: M_{\text{SUSY}}.
$$

(8)

Concerning analyses for the case where $M_{\tilde{t}R} \neq M_{\tilde{Q}} \neq M_{\tilde{b}R}$, see e.g. Refs. [20,26,27]. It has been shown that the upper bound on the mass of the light $\mathcal{CP}$-even Higgs boson, $M_h$, obtained using eq. (8) is the same as for the more general case, provided that $M_{\text{SUSY}}$ is identified with the heaviest mass of $M_{\tilde{Q}}, M_{\tilde{t}R}, M_{\tilde{b}R}$ [20].

Accordingly, the most important parameters entering the Higgs-sector predictions via higher-order corrections are $m_t, M_{\text{SUSY}}, X_t, X_b$ and $\mu$ (see also the discussion in Sect. 2.2.2 below). The Higgs-sector observables furthermore depend on the SU(2) gaugino mass parameter, $M_2$, the U(1) parameter $M_1$ and the gluino mass, $m_{\tilde{g}}$ (the latter enters the predictions
for the Higgs-boson masses only from two-loop order on). In numerical analyses the $U(1)$ gaugino mass parameter, $M_1$, is often fixed via the GUT relation

$$M_1 = \frac{5}{3} s_w^2 M_2. \tag{9}$$

We will briefly comment below on the possible impact of complex phases entering the Higgs-sector predictions via higher-order contributions.

### 2.2 Higher-order corrections in the Higgs sector

In the following we briefly summarize the most important higher-order corrections affecting the observables in the MSSM Higgs-boson sector. As mentioned above, we focus on the MSSM with real parameters. For our numerical analysis we use the program *FeynHiggs* [19–22][4], which incorporates a comprehensive set of higher-order results obtained in the Feynmandiagrammatic approach [20–22, 28–30].

#### 2.2.1 Higgs-boson propagator corrections

Higher-order corrections to the Higgs-boson masses and the wave function normalization factors of processes with external Higgs bosons arise from Higgs-boson propagator-type contributions. These corrections furthermore contribute in a universal way to all Higgs-boson couplings. For the propagator-type corrections in the MSSM the complete one-loop results [31–34], the bulk of the two-loop contributions [20, 27–29, 35–39] and even leading three-loop corrections [40] are known. The remaining theoretical uncertainty on the light $\mathcal{CP}$-even Higgs-boson mass has been estimated to be below $\sim 3$ GeV [21, 41]. The by far dominant contribution is the $\mathcal{O}(\alpha_t)$ term due to top and stop loops ($\alpha_t \equiv h^2_t/(4\pi)$, where $h_t$ denotes the top-quark Yukawa coupling). Effects of $\mathcal{O}(\alpha_b)$ can be important for large values of $\tan\beta$.

#### 2.2.2 Corrections to the relation between the bottom-quark mass and the bottom Yukawa coupling

Concerning the corrections from the bottom/sbottom sector, large higher-order effects can in particular occur in the relation between the bottom-quark mass and the bottom Yukawa coupling (which controls the interaction between the Higgs bosons and bottom quarks as well as between the Higgs and scalar bottoms), $h_b$, for large values of $\tan\beta$. At lowest order the relation reads $m_b = h_b v_1$. Beyond the tree level large radiative corrections proportional to $h_b v_2$ are induced, giving rise to $\tan\beta$-enhanced contributions [36–38, 42]. At the one-loop level the leading terms proportional to $v_2$ are generated either by gluino–sbottom one-loop diagrams of $\mathcal{O}(\alpha_s)$ or by chargino–stop loops of $\mathcal{O}(\alpha_t)$.

The leading one-loop contribution $\Delta_b$ in the limit of $M_{\text{SUSY}} \gg m_t$ and $\tan\beta \gg 1$ takes the simple form [36]

$$\Delta_b = \frac{2\alpha_s}{3\pi} m_{\tilde{g}} \mu \tan\beta \times I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, m_{\tilde{g}}) + \frac{\alpha_t}{4\pi} A_t \mu \tan\beta \times I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu), \tag{10}$$

4 The code can be obtained from [www.feynhiggs.de](http://www.feynhiggs.de).
where the function $I$ is given by
\[ I(a, b, c) = \frac{1}{(a^2 - b^2)(b^2 - c^2)(a^2 - c^2)} \left( a^2b^2 \log \frac{a^2}{b^2} + b^2c^2 \log \frac{b^2}{c^2} + c^2a^2 \log \frac{c^2}{a^2} \right) \] (11)
\[ \sim \frac{1}{\max(a^2, b^2, c^2)}. \]

The leading contribution can be resummed to all orders in the perturbative expansion [36–38]. This leads in particular to the replacement
\[ m_b \rightarrow \frac{m_b}{1 + \Delta_b}, \] (12)
where $m_b$ denotes the running bottom quark mass including SM QCD corrections. For the numerical evaluations in this paper we choose $m_b = m_{b_l}(m_t) \approx 2.97$ GeV.

The $\Delta_b$ corrections are numerically sizable for large $\tan\beta$ in combination with large values of the ratios of $\mu m_{\tilde{b}}/M_{\text{SUSY}}$ or $\mu A_t/M_{\text{SUSY}}$. Negative values of $\Delta_b$ lead to an enhancement of the bottom Yukawa coupling as a consequence of eq. (12) (for extreme values of $\mu$ and $\tan\beta$ the bottom Yukawa coupling can even acquire non-perturbative values when $\Delta_b \to -1$), while positive values of $\Delta_b$ give rise to a suppression of the Yukawa coupling. Since a change in the sign of $\mu$ reverses the sign of $\Delta_b$, the bottom Yukawa coupling can exhibit a very pronounced dependence on the parameter $\mu$.

For large values of $\tan\beta$ the correction to the production cross sections of the Higgs bosons $H$ and $A$ induced by $\Delta_b$ enters approximately like $\tan^2\beta/(1 + \Delta_b)^2$, giving rise to potentially large numerical effects. In the case of the subsequent Higgs-boson decay $\phi \to \tau^+\tau^-$, however, the $\Delta_b$ corrections in the production and the decay process cancel each other to a large extent. The residual $\Delta_b$ dependence of $\sigma(b\bar{b} \phi) \times \text{BR}(\phi \to \tau^+\tau^-)$ is approximately given by $\tan^2\beta/((1 + \Delta_b)^2 + 9)$, which has a much weaker $\Delta_b$ dependence (see Ref. [14] for a more detailed discussion).

In the numerical analysis below the $\Delta_b$ corrections, which have been discussed in this section in terms of simple approximation formulae, will be supplemented by other higher-order corrections as implemented in the program FeynHiggs (and possible decay modes into supersymmetric particles are taken into account). Higher-order corrections to Higgs decays into $\tau^+\tau^-$ within the SM and MSSM have been evaluated in Refs. [34, 43].

### 2.2.3 Corrections to the Higgs production cross sections

For the prediction of Higgs-boson production processes at hadron colliders SM-type QCD corrections in general play an important role. The SM predictions for the process $b\bar{b} \rightarrow \phi + X$ at the LHC are far advanced. In the five-flavor scheme the SM cross section is known at NNLO in QCD [44]. The cross section in the four-flavor scheme is known at NLO [45, 46]. Results obtained in the two schemes have been shown to be consistent [47–49] (see also Refs. [48, 50] and Refs. [45, 46] for results with one and two final-state $b$-quarks at high-$p_T$, respectively).

The predictions for the $b\bar{b} \rightarrow \phi + X$ cross sections in the MSSM have been obtained with FeynHiggs [19–22]. The FeynHiggs implementation\(^5\) is based on the state-of-the-art

\(^5\)The inclusion of the charged Higgs production cross sections is planned for the near future.
SM prediction, namely the NNLO result in the five-flavor scheme [44] using MRST2002 parton distributions at NNLO [51], with the renormalization scale set equal to \( M_{\text{HSM}} \) and the factorization scale set equal to \( M_{\text{HSM}}/4 \). In order to obtain the MSSM prediction the SM cross section is rescaled with the ratio of the partial widths in the MSSM and the SM,

\[
\frac{\Gamma(\phi \rightarrow bb)_{\text{MSSM}}}{\Gamma(\phi \rightarrow bb)_{\text{SM}}}. \tag{13}
\]

The evaluation of the partial widths incorporates one-loop SM QCD and SUSY QCD corrections, as well as (in the SUSY case) the resummation of all terms of \( \mathcal{O}((\alpha_s \tan \beta)^n) \) [34,37,43] and the proper normalization of the external Higgs bosons as discussed in Refs. [22,52]. Since the approximation of rescaling the SM cross section with the ratio of partial widths does not take into account the MSSM-specific dynamics of the production processes, the theoretical uncertainty in the predictions for the cross sections will in general be somewhat larger than for the decay widths. It should be noted that in comparison with other approaches for treating the SM and SUSY contributions, for instance the program \( \text{HQQ} \) [53], sizable deviations can occur as a consequence of differences in the scale choices and the inclusion of higher-order corrections.

### 2.3 The \( m_h^{\text{max}} \) and no-mixing benchmark scenarios

While the phenomenology of the production and decay processes of the heavy neutral MSSM Higgs bosons at the LHC is mainly characterised by the parameters \( M_A \) and \( \tan \beta \) that govern the Higgs sector at lowest order, other MSSM parameters enter via higher-order contributions, as discussed above, and via the kinematics of Higgs-boson decays into supersymmetric particles. The other MSSM parameters are usually fixed in terms of benchmark scenarios. The most commonly used scenarios are the "\( m_h^{\text{max}} \)" and "no-mixing" benchmark scenarios [12–14]. According to the definition of Ref. [13] the \( m_h^{\text{max}} \) scenario is given by

\[
\text{\( m_h^{\text{max}} \):} \quad M_{\text{SUSY}} = 1000 \, \text{GeV}, \quad X_t = 2 M_{\text{SUSY}}, \quad A_b = A_t, \\
\mu = 200 \, \text{GeV}, \quad M_2 = 200 \, \text{GeV}, \quad m_\tilde{g} = 0.8 M_{\text{SUSY}}. \tag{14}
\]

The no-mixing scenario differs from the \( m_h^{\text{max}} \) scenario only in that it has vanishing mixing in the stop sector and a larger value of \( M_{\text{SUSY}} \)

\[
\text{\text{no-mixing}:} \quad M_{\text{SUSY}} = 2000 \, \text{GeV}, \quad X_t = 0, \quad A_b = A_t, \\
\mu = 200 \, \text{GeV}, \quad M_2 = 200 \, \text{GeV}, \quad m_\tilde{g} = 0.8 M_{\text{SUSY}}. \tag{15}
\]

The value of the top-quark mass in Ref. [13] was chosen according to the experimental central value at that time. For our numerical analysis below, we use the value, \( m_t = 171.4 \, \text{GeV} \) [54].

In Ref. [14] it was suggested that in the search for heavy MSSM Higgs bosons the \( m_h^{\text{max}} \) and no-mixing scenarios, which originally were mainly designed for the search for the light \( \mathcal{C}\mathcal{P} \)-even Higgs boson \( h \), should be extended by several discrete values of \( \mu \),

\[
\mu = \pm 200, \pm 500, \pm 1000 \, \text{GeV} . \tag{16}
\]

6 Most recently the central experimental value has shifted to \( m_t = 170.9 \pm 1.8 \, \text{GeV} \) [55]. This shift has a negligible impact on our analysis.
As discussed above, the variation of $\mu$ in particular has an impact on the correction $\Delta_b$, modifying in this way the bottom Yukawa coupling. For very large values of $\tan{\beta}$ and large negative values of $\mu$ the bottom Yukawa coupling can be so much enhanced that a perturbative treatment is no longer possible. We have checked that in our analysis of the LHC discovery contours the bottom Yukawa coupling stays in the perturbative regime, so that all values of $\mu$ down to $\mu = -1000$ GeV can safely be inserted.

The variation of the parameter $\mu$ also modifies the mass spectrum and the couplings in the chargino and neutralino sector of the MSSM. Besides the small higher-order corrections induced by loop diagrams involving charginos and neutralinos, a change in the mass spectrum of the chargino and neutralino sector can have an important effect on Higgs phenomenology because decay modes of the heavy neutral MSSM Higgs bosons into charginos and neutralinos open up if the supersymmetric particles are sufficiently light (the mass spectrum in the $m_h^{\text{max}}$ and no-mixing scenarios respects the limits from direct searches for charginos at LEP [56] for all values of $\mu$ specified in eq. (16)).

Differences between the $m_h^{\text{max}}$ and no-mixing scenarios in the searches for heavy neutral MSSM Higgs bosons are induced in particular by a difference in the $\Delta_b$ correction. While in the $m_h^{\text{max}}$ scenario both the $\mathcal{O}(\alpha_s)$ and $\mathcal{O}(\alpha_t)$ contributions to $\Delta_b$ can be sizable, see eq. (10), in the no-mixing scenario the $\mathcal{O}(\alpha_t)$ contribution is very small because $A_t$ is close to zero in this case. The larger value of $M_{\text{SUSY}}$ in the no-mixing scenario gives rise to an additional suppression of $|\Delta_b|$ compared to the $m_h^{\text{max}}$ scenario.

3 Experimental analysis

In this section we briefly review the recent CMS analysis of the $\phi \to \tau^+\tau^-$ channel, see Ref. [9], yielding the number of events needed for a 5 $\sigma$ discovery (depending on the mass of the Higgs boson). The analysis was performed with full CMS detector simulation and reconstruction for the following four final states of di-$\tau$-lepton decays: $\tau^+\tau^- \to \text{jets}$ [57], $\tau^+\tau^- \to e + \text{jet}$ [58], $\tau^+\tau^- \to \mu + \text{jet}$ [59] and $\tau^+\tau^- \to e + \mu$ [60].

The Higgs-boson production in association with $b$ quarks, $pp \to b\bar{b}\phi$, has been selected using single $b$-jet tagging in the experimental analysis. The kinematics of the $gg \to b\bar{b}\phi$ production process ($2 \to 3$) was generated with PYTHIA [61]. It has been shown that in this way the NLO kinematics is better reproduced than using the PYTHIA $gb \to b\phi$ process ($2 \to 2$) [62]. The backgrounds considered in the analysis were QCD multi-jet events (for the $\tau\tau \to \text{jets}$ mode), $tt, bb$, Drell-Yan production of $Z, \gamma^*$, $W + \text{jet}, Wt$ and $\tau\tau b\bar{b}$. All background processes were generated using PYTHIA, except for $\tau^+\tau^- b\bar{b}$, which was generated using CompHEP [63].

The results for the various channels, eqs. (1) – (4), are given in Tabs. 1 – 4. For every Higgs-boson mass point studied we show the number of signal events needed for 5 $\sigma$ discovery, $N_S$, the total experimental selection efficiency, $\varepsilon_{\text{exp}}$, and the ratio of the di-$\tau$ mass resolution to the Higgs-boson mass, $R_{M_\phi}$. The last row in Tabs. 1 – 4 shows the expected precision of the Higgs-boson mass measurement, evaluated as explained below, for parameter points on the 5 $\sigma$ discovery contour. Detector effects, experimental systematics and uncertainties of the background determination were taken into account in the evaluation of the $N_S$. These effects reduce the discovery region in the $M_A$–$\tan{\beta}$ plane as shown in previous analyses [9].
\[ \phi \rightarrow \tau^+\tau^- \rightarrow \text{jets}, \ 60 \text{ fb}^{-1} \]

| \( M_A \) [GeV] | 200 | 500 | 800 |
|------------------|-----|-----|-----|
| \( N_S \)       | 63  | 35  | 17  |
| \( \varepsilon_{\exp} \) | \( 2.5 \times 10^{-4} \) | \( 2.4 \times 10^{-3} \) | \( 3.6 \times 10^{-3} \) |
| \( R_{M_\phi} \)  | 0.176 | 0.171 | 0.187 |
| \( \Delta M_\phi/M_\phi \) [%] | 2.2 | 2.8 | 4.5 |

Table 1: Required number of signal events, \( N_S \), with \( \mathcal{L} = 60 \text{ fb}^{-1} \) for a 5\( \sigma \) discovery in the channel \( \phi \rightarrow \tau^+\tau^- \rightarrow \text{jets} \). Furthermore given are the total experimental selection efficiency, \( \varepsilon_{\exp} \), the ratio of the di-\( \tau \) mass resolution to the Higgs-boson mass, \( R_{M_\phi} \), and the expected precision of the Higgs-boson mass measurement, \( \Delta M_\phi/M_\phi \), obtainable from \( N_S \) signal events.

\[ \phi \rightarrow \tau^+\tau^- \rightarrow e + \text{jet}, \ 30 \text{ fb}^{-1} \]

| \( M_A \) [GeV] | 200 | 300 | 500 |
|------------------|-----|-----|-----|
| \( N_S \)       | 72.9 | 45.5 | 32.8 |
| \( \varepsilon_{\exp} \) | \( 3.0 \times 10^{-3} \) | \( 6.4 \times 10^{-3} \) | \( 1.0 \times 10^{-2} \) |
| \( R_{M_\phi} \)  | 0.216 | 0.214 | 0.230 |
| \( \Delta M_\phi/M_\phi \) [%] | 2.5 | 3.2 | 4.0 |

Table 2: Required number of signal events, \( N_S \), with \( \mathcal{L} = 30 \text{ fb}^{-1} \) for a 5\( \sigma \) discovery in the channel \( \phi \rightarrow \tau^+\tau^- \rightarrow e + \text{jet} \). The other quantities are defined as in Tab. 1.

\[ \phi \rightarrow \tau^+\tau^- \rightarrow \mu + \text{jet}, \ 30 \text{ fb}^{-1} \]

| \( M_A \) [GeV] | 200 | 500 |
|------------------|-----|-----|
| \( N_S \)       | 79  | 57  |
| \( \varepsilon_{\exp} \) | \( 7.0 \times 10^{-3} \) | \( 2.0 \times 10^{-2} \) |
| \( R_{M_\phi} \)  | 0.210 | 0.200 |
| \( \Delta M_\phi/M_\phi \) [%] | 2.4 | 2.6 |

Table 3: Required number of signal events, \( N_S \), with \( \mathcal{L} = 30 \text{ fb}^{-1} \) for a 5\( \sigma \) discovery in the channel \( \phi \rightarrow \tau^+\tau^- \rightarrow \mu + \text{jet} \). The other quantities are defined as in Tab. 1.
\[ \phi \rightarrow \tau^+ \tau^- \rightarrow e + \mu, \ 30 \text{ fb}^{-1} \]

| \(M_A\) [GeV] | 200 | 250 |
| \(N_S\)     | 87.8 | 136.7 |
| \(\varepsilon_{\text{exp}}\) | \(6.4 \times 10^{-3}\) | \(1.1 \times 10^{-2}\) |
| \(R_{M_{\phi}}\) | 0.262 | 0.412 |
| \(\Delta M_{\phi}/M_{\phi}\) [%] | 2.8 | 3.5 |

Table 4: Required number of signal events, \(N_S\), with \(L = 30 \text{ fb}^{-1}\) for a 5 \(\sigma\) discovery in the channel \(\phi \rightarrow \tau^+ \tau^- \rightarrow e + \mu\). The other quantities are defined as in Tab. 1.

(see in particular Fig. 5.6 of Ref. [9] for the \(\tau^+ \tau^- \rightarrow \mu + \text{jet mode}\)).

Now we turn to the evaluation of the expected precision of the Higgs-boson mass measurement. In spite of the escaping neutrinos, the Higgs-boson mass can be reconstructed in the \(H, A \rightarrow \tau \tau\) channel from the visible \(\tau\) momenta (\(\tau\) jets) and the missing transverse energy, \(E_T^{\text{miss}}\), using the collinearity approximation for neutrinos from highly boosted \(\tau\)'s. In the investigated region of \(M_A\) and \(\tan \beta\) the two states \(A\) and \(H\) are nearly mass-degenerate. For most values of the other MSSM parameters the mass difference of \(A\) and \(H\) is much smaller than the achievable mass resolution. In this case the difference in reconstructing the \(A\) or the \(H\) will have no relevant effect on the achievable accuracy in the mass determination. In some regions of the MSSM parameter space, however, a sizable splitting between \(M_A\) and \(M_H\) can occur even for \(M_A \gg M_Z\). We will discuss below the prospects in scenarios where the splitting between \(M_A\) and \(M_H\) is relatively large. The precision \(\Delta M_{\phi}/M_{\phi}\) shown in Tabs. 1 – 4 is derived for the border of the parameter space in which a 5 \(\sigma\) discovery can be claimed, i.e. with \(N_S\) observed Higgs events. The statistical accuracy of the mass measurement has been evaluated via

\[ \frac{\Delta M_{\phi}}{M_{\phi}} = \frac{R_{M_{\phi}}}{\sqrt{N_S}}. \tag{17} \]

A higher precision can be achieved if more than \(N_S\) events are observed. The corresponding estimate for the precision is obtained by replacing \(N_S\) in eq. (17) by the number of observed signal events, \(N_{\text{ev}}\). It should be noted that the prospective accuracy obtained from eq. (17) does not take into account the uncertainties of the jet and missing \(E_T\) energy scales. In the \(\tau^+ \tau^- \rightarrow \text{jets mode}\) these effects can lead to an additional 3% uncertainty in the mass measurement [57]. A more dedicated procedure of the mass measurement from the signal plus background data still has to be developed in the experimental analysis. However, we do not expect that the additional uncertainties will considerably degrade the accuracy of the Higgs boson mass measurement as calculated with eq. (17).
4 Results

The results quoted in Sect. 3 for the required number of signal events depend only on the Higgs-boson mass, i.e. the event kinematics, but are independent of any specific MSSM scenario. In order to determine the 5σ discovery contours in the $M_A$–$\tan \beta$ plane these results have to be confronted with the MSSM predictions. The number of signal events, $N_{ev}$, for a given parameter point is evaluated via

$$N_{ev} = \mathcal{L} \times \sigma_{bb\phi} \times \text{BR}(\phi \rightarrow \tau^+\tau^-) \times \text{BR}_{\tau\tau} \times \varepsilon_{\text{exp}} .$$  \hspace{1cm} (18)

Here $\mathcal{L}$ denotes the luminosity collected with the CMS detector, $\sigma_{bb\phi}$ is the Higgs-boson production cross section, $\text{BR}(\phi \rightarrow \tau^+\tau^-)$ is the branching ratio of the Higgs boson to $\tau$ leptons, $\text{BR}_{\tau\tau}$ is the product of the branching ratios of the two $\tau$ leptons into their respective final state,

$$\text{BR}(\tau \rightarrow \text{jet} + X) \approx 0.65 , \hspace{1cm} (19)$$

$$\text{BR}(\tau \rightarrow \mu + X) \approx \text{BR}(\tau \rightarrow e + X) \approx 0.175 , \hspace{1cm} (20)$$

and $\varepsilon_{\text{exp}}$ denotes the total experimental selection efficiency for the respective process (as given in Tabs. 1–4). The Higgs-boson production cross sections and decay branching ratios have been evaluated with FeynHiggs as described in Sect. 2.2.

4.1 Discovery reach for heavy neutral MSSM Higgs bosons

The number of signal events, $N_{ev}$, in the MSSM depends besides the parameters $M_A$ and $\tan \beta$, which govern the MSSM Higgs sector at lowest order, in principle also on all other MSSM parameters. In the following we analyze how stable the results for the 5σ discovery contours in the $M_A$–$\tan \beta$ plane are with respect to variations of the other MSSM parameters. We take into account both effects from higher-order corrections, as discussed in Sect. 2.2, and from decays of the heavy Higgs bosons into supersymmetric particles. As starting point of our analysis we use the $m_{h}^{\text{max}}$ and no-mixing benchmark scenarios, where we investigate in detail the sensitivity of the discovery contours with respect to variations of the parameter $\mu$. We then discuss the possible impact of varying other MSSM parameters.

We have evaluated $N_{ev}$ in the two benchmark scenarios as a function of $M_A$ and $\tan \beta$. For fixed $M_A$ we have varied $\tan \beta$ such that $N_{ev} = N_S$ (as given in Tabs. 1–4). This $\tan \beta$ value is then identified as the point on the 5σ discovery contour corresponding to the chosen value of $M_A$. In this way we have determined the 5σ discovery contours for the $m_{h}^{\text{max}}$ and the no-mixing scenarios for $\mu = \pm 200, \pm 1000$ GeV.

In Figs. 1–3 we show the 5σ discovery contours obtained from the process $b\bar{b}\phi$, $\phi \rightarrow \tau^+\tau^-$ for the final states $\tau^+\tau^- \rightarrow \text{jets}$, $\tau^+\tau^- \rightarrow e + \text{jet}$ and $\tau^+\tau^- \rightarrow \mu + \text{jet}$. As can be seen from Tab. 4 the fourth channel discussed above, $\tau^+\tau^- \rightarrow e + \mu$, contributes for 30 fb$^{-1}$ only in the region of relatively small $M_A$ values and has a lower sensitivity than the other three channels. We therefore omit this channel in the following discussion. The discovery contours in Figs. 1–3 are given for the $m_{h}^{\text{max}}$ and no-mixing benchmark scenarios with $\mu = \pm 200, \pm 1000$ GeV. As explained above, the 5σ discovery contours are affected by a change in $\mu$ in two ways. Higher-order contributions, in particular the ones associated with $\Delta_b$,
Figure 1: Variation of the 5σ discovery contours obtained from the channel $b\bar{b}\phi$, $\phi \rightarrow \tau^+\tau^-$ $\rightarrow$ jets in the $m_h^{\text{max}}$ (left) and no-mixing (right) benchmark scenarios for different values of $\mu$.

Figure 2: Variation of the 5σ discovery contours obtained from the channel $b\bar{b}\phi$, $\phi \rightarrow \tau^+\tau^-$ $\rightarrow$ $e +$ jet in the $m_h^{\text{max}}$ (left) and no-mixing (right) benchmark scenarios for different values of $\mu$. 

modify the Higgs-boson production cross sections and decay branching ratios. Furthermore
the mass eigenvalues of the charginos and neutralinos vary with $\mu$, possibly opening up the
decay channels of the Higgs bosons to supersymmetric particles, which reduces the branching
ratio to $\tau$ leptons.

The results for the 5$\sigma$ discovery contours for the final state $\tau^+\tau^- \rightarrow$ jets are shown in
Fig. 1 for the $m_h^{\text{max}}$ (left) and the no-mixing (right) scenario. As expected from the discussion
of the $\Delta_b$ corrections in Sect. 2.2, the variation of the 5$\sigma$ discovery contours with $\mu$ is more
pronounced in the $m_h^{\text{max}}$ scenario, where a shift up to $\Delta \tan \beta = 12$ can be observed for
$M_A = 800$ GeV. For low $M_A$ values (corresponding also to lower $\tan \beta$ values on the discovery
contours) the variation stays below $\Delta \tan \beta = 3$. In the no-mixing scenario the variation does
not exceed $\Delta \tan \beta = 5$. The $\tau^+\tau^- \rightarrow$ jets channel has also been discussed in Ref. [14]. Our
results, which are based on the latest CMS studies using full simulation [57], are qualitatively
in good agreement with Ref. [14], in which the earlier CMS studies of Refs. [23, 24] had been
used. The 5$\sigma$ discovery regions are largest for $\mu = -1000$ GeV and pushed to highest $\tan \beta$
values for $\mu = +200$ GeV. In the low $M_A$ region our discovery contours are very similar
to those obtained in Ref. [14]. In the high $M_A$ region, $M_A \sim 800$ GeV, corresponding to
larger values of $\tan \beta$ on the discovery contours, our improved evaluation of the 5$\sigma$ discovery
contours gives rise to a shift towards higher $\tan \beta$ values compared to Ref. [14] of about
$\Delta \tan \beta = 8$ (mostly due to the up-to-date experimental input). Accordingly, we find a
smaller discovery region compared to Ref. [14] and therefore an enlarged “LHC wedge”
region where only the light $CP$-even MSSM Higgs boson can be detected at the 5$\sigma$ level.

The results for the channel $\tau^+\tau^- \rightarrow e +$ jet are shown in Fig. 2. Again the $m_h^{\text{max}}$ scenario
shows a stronger variation than the no-mixing scenario. The resulting shift in $\tan \beta$ reaches
up to $\Delta \tan \beta = 8$ for $M_A = 500$ GeV in the $m_h^{\text{max}}$ scenario, but stays below $\Delta \tan \beta = 4$ for the no-mixing scenario. Finally in Fig. 3 the results for the channel $\tau^+ \tau^- \rightarrow \mu + \text{jet}$ are depicted. The level of variation of the $5\sigma$ discovery contours is the same as for the $e + \text{jet}$ final state.\footnote{Since the results of the experimental simulation for this channel are available only for two $M_A$ values, the interpolation is a straight line. This may result in a slightly larger uncertainty of the results shown in Fig. 3 compared to the other figures.}

![Figure 4](image-url)  

\textbf{Figure 4:} Variation of the $5\sigma$ discovery contours obtained from the channel $b\bar{b}\phi, \phi \rightarrow \tau^+ \tau^- \rightarrow \text{jets}$ in the $m_h^{\text{max}}$ (left) and no-mixing (right) benchmark scenarios for different values of $\mu$ in the case where no decays of the heavy Higgs bosons into supersymmetric particles are taken into account (see text). In order to gain a better understanding of how sensitively the discovery contours in the $M_A$–$\tan \beta$ plane depend on the chosen SUSY scenario, it is useful to separately investigate the different effects caused by varying the parameter $\mu$. For simplicity, we restrict the following discussion to the $b\bar{b}\phi, \phi \rightarrow \tau^+ \tau^- \rightarrow \text{jets}$ channel. In Fig. 4 we show the same results as in Fig. 1 but for the case where no decays of the heavy Higgs bosons into supersymmetric particles are taken into account. As a consequence, the variation of the $5\sigma$ discovery contours with $\mu$ shown in Fig. 4 is purely an effect of higher-order corrections, predominantly those entering via $\Delta_b$. The difference between Fig. 1 and Fig. 4, on the other hand, is purely an effect of the change in BR($\phi \rightarrow \tau^+ \tau^-$) caused by the variation of the partial Higgs-boson decay widths into supersymmetric particles arising from a shift in the masses of the charginos and neutralinos.

In Fig. 4 the dependence of the $5\sigma$ discovery contours on $\mu$ significantly differs from the case of Fig. 1. While in Fig. 1 the inclusion of decays into supersymmetric particles gives
rise to the fact that the smallest discovery region is found for small \( \mu \) values, \( \mu = +200 \text{ GeV} \) (with the exception of the region of very small \( M_A \)), in Fig. 4 the 5\( \sigma \) discovery contours are ordered monotonously in \( \mu \): the largest (smallest) 5\( \sigma \) discovery regions are obtained for \( \mu = -(+)1000 \text{ GeV} \), i.e. for the largest (smallest) values of the bottom Yukawa coupling. As expected, the effect of the higher-order corrections is largest in the high \( \tan \beta \)-region (corresponding to large values of \( M_A \) on the discovery contours). In this region the variation of \( \mu \) shifts the discovery contours by up to \( \Delta \tan \beta = 11 \) for the case of the \( m_h^{\text{max}} \) scenario (left plot of Fig. 4), i.e. the effect is about the same as for the case where decays into supersymmetric particles are included. For lower values of \( \tan \beta \) (corresponding to smaller values of \( M_A \) on the discovery contours), on the other hand, the modification of the Higgs branching ratio as a consequence of decays into supersymmetric particles yields the dominant effect on the 5\( \sigma \) discovery contours. Accordingly, the observed variation with \( \mu \) in this region is significantly smaller in Fig. 4 as compared to the full result of Fig. 1. The reduced sensitivity of the discovery contours on \( \mu \) can also clearly be seen for the case of the no-mixing scenario (right plot), where as discussed above the \( \Delta_b \) correction is smaller than in the \( m_h^{\text{max}} \) scenario.

A parameter affecting the \( \Delta_b \) corrections, see eq. (10), but not the kinematics of the Higgs-boson decays is the gluino mass, \( m_{\tilde{g}} \). We now investigate the impact of varying this parameter, which is normally fixed to the values \( m_{\tilde{g}} = 800, 1600 \text{ GeV} \) in the \( m_h^{\text{max}} \) and no-mixing benchmark scenarios, respectively. The results for four different values of the gluino mass, \( m_{\tilde{g}} = 200, 500, 1000, 2000 \text{ GeV} \), are shown in Fig. 5. The \( \mu \) parameter has been set to \( \mu = +1000 \text{ GeV} \) in Fig. 5 such that the Higgs decay channels into charginos and neutralinos are suppressed. As one can see from eq. (10), the change of \( m_{\tilde{g}} \) affects the \( \mathcal{O}(\alpha_s) \) part of \( \Delta_b \) and corresponds to a monotonous increase of \( \Delta_b \). As an example, this yields for

\begin{align*}
\text{Figure 5: Variation of the 5}\sigma \text{ discovery contours obtained from the channel } & b\bar{b}\phi, \phi \to \tau^+\tau^- \to \text{jets in the } m_h^{\text{max}} \text{ (left) and no-mixing (right) benchmark scenarios with } \mu = +1000 \text{ GeV for different values of } m_{\tilde{g}}. \\
\end{align*}
\( \mu = 1000 \text{ GeV}, \tan \beta = 50 \) in the two scenarios:

\[
\begin{align*}
\text{no-mixing, } & m_h^{\text{max}}, \ m_{\tilde{g}} = 200 \text{ GeV} : \Delta_b = 0.06 \\
\text{no-mixing, } & m_h^{\text{max}}, \ m_{\tilde{g}} = 2000 \text{ GeV} : \Delta_b = 0.29.
\end{align*}
\]

In the no-mixing scenario the \( A_t \) value is close to zero, suppressing the \( m_{\tilde{g}} \)-independent contribution to \( \Delta_b \), while the higher SUSY mass scale results in an overall reduction of \( \Delta_b \) in this scenario. The value of \( \Delta_b \) in the no-mixing scenario would slightly increase if \( m_{\tilde{g}} \) were raised to even larger values, but this effect would not change the qualitative behaviour.

Fig. 5 shows that the results for the discovery reach in the \( M_A-\tan \beta \) plane are relatively stable with respect to variations of the gluino mass. The shift in the discovery contours remains below about \( \Delta \tan \beta = 4 \) for the \( m_h^{\text{max}} \) scenario (left plot) and \( \Delta \tan \beta = 1 \) for the no-mixing scenario (right plot). For the positive sign of \( \mu \) chosen in Fig. 5 where the \( \Delta_b \) correction yields a suppression of the bottom Yukawa coupling, the largest discovery reach is obtained for small \( m_{\tilde{g}} \), while the smallest discovery reach is obtained for large \( m_{\tilde{g}} \). This behaviour would be reversed by a change of sign of \( \mu \).

We have also investigated the possible impact of other MSSM parameters (besides \( \mu \) and \( m_{\tilde{g}} \)) on the 5\( \sigma \) discovery contours in the \( M_A-\tan \beta \) plane. The \( \Delta_b \) corrections depend also on the parameters in the stop and sbottom sector, see eq. (10). While the formulas in Sect. 2.2.2 have been given for the region where \( M_{\text{SUSY}} \gg m_t \), the qualitative effect of reducing the stop and sbottom masses can nevertheless be inferred. Sizable \( \Delta_b \) corrections require relative large values of \( \mu \) and \( m_{\tilde{g}} \). If these parameters are kept large while the stop and sbottom masses are reduced, the \( \Delta_b \) corrections tend to decrease. It is obvious from eq. (10) that reducing the absolute value of \( A_t \) decreases the electroweak part of the \( \Delta_b \) correction. As discussed above, this effect of the \( \Delta_b \) corrections manifests itself in the comparison of the \( m_h^{\text{max}} \) and no-mixing scenarios, see Figs. 1–5. Concerning the possible impact of the \( \Delta_b \) corrections on the 5\( \sigma \) discovery contours for the \( b\bar{b}\phi, \phi \to \tau^+\tau^- \) channel in the \( M_A-\tan \beta \) plane we conclude that larger effects than those shown in Figs. 1–5 (where we have displayed the discovery contours up to \( \tan \beta = 50 \)) would only arise if the variation of \( \mu \) were extended over an even wider interval than \(-1000 \text{ GeV} \leq \mu \leq +1000 \text{ GeV} \) as done in our analysis above.

We now turn to the possible effects of other higher-order corrections beyond those entering via \( \Delta_b \) on the 5\( \sigma \) discovery contours for the \( b\bar{b}\phi, \phi \to \tau^+\tau^- \) channel. These effects are in general non-negligible, see the discussions in Sect. 2.2 and in Sect. 4.2 below, but smaller than those induced by \( \Delta_b \). As a consequence, the impact on the 5\( \sigma \) discovery contours in the \( M_A-\tan \beta \) plane of other supersymmetric parameters entering via higher-order corrections is in general much smaller than the effect of varying \( \mu \) in the high-\( \tan \beta \) region of Fig. 4.

As an example, the difference observed in Figs. 1–5 between the \( m_h^{\text{max}} \) and no-mixing scenarios arising from the different values of \( A_t \) and \( M_{\text{SUSY}} \) in the two scenarios (see eqs. (13), (15)) is mainly an effect of the \( \Delta_b \) corrections, while the impact of other higher-order corrections involving \( A_t \) and \( M_{\text{SUSY}} \) is found to be small.

Also the decays of the heavy neutral MSSM Higgs bosons into supersymmetric particles are in general affected by other supersymmetric parameters in addition to the dependence
on $\mu$, $M_A$ and $\tan \beta$. The resulting effects on $\text{BR}(\phi \to \tau^+\tau^-)$ turn out to be rather small, however. We find that sizable deviations from the values of $\text{BR}(\phi \to \tau^+\tau^-)$ occurring in the $m^\text{max}_h$ and no-mixing scenarios for $-1000 \text{ GeV} \leq \mu \leq +1000 \text{ GeV}$ are only possible in quite extreme regions of the MSSM parameter space that are already highly constrained by existing experimental data.

Our discussion above has been given in the context of the MSSM with real parameters. Since the sensitivity of the $5\sigma$ discovery contours in the $M_A$–$\tan \beta$ plane on the other supersymmetric parameters can mainly be understood as an effect of higher-order corrections to the bottom Yukawa coupling and of the kinematics of Higgs-boson decays into supersymmetric particles, no qualitative changes of our results are expected for the case where complex phases are taken into account.

### 4.2 Higgs-boson mass precision

The discussion in the previous section shows that the prospective discovery reach of the $b\bar{b}\phi$, $\phi \to \tau^+\tau^-$ channel in the $M_A$–$\tan \beta$ plane is rather stable with respect to variations of the other MSSM parameters. We now turn to the second part of our analysis and investigate the expected statistical precision of the Higgs-boson mass measurement. The expected statistical precision is evaluated as described in Sect. 3, see eq. (17). In Figs. 6–7 we show the expected precision for the mass measurement achievable from the channel $b\bar{b}\phi$, $\phi \to \tau^+\tau^-$ using the final states $\tau^+\tau^- \to \text{jets}$ and $\tau^+\tau^- \to e + \text{jet}$. Within the $5\sigma$ discovery region we have indicated contour lines corresponding to different values of the expected precision, $\Delta M/M$.

The results are shown in the $m^\text{max}_h$ benchmark scenario for $\mu = -200 \text{ GeV}$ (left plots) and $\mu = +200 \text{ GeV}$ (right plots).

We find that experimental precisions of $\Delta M_\phi/M_\phi$ of 1–4% are reachable within the discovery region. A better precision is reached for larger $\tan \beta$ and smaller $M_A$ as a consequence of the higher number of signal events in this region. The other scenarios and other values of $\mu$ discussed above yield qualitatively similar results to those shown in Figs. 6–7.

As discussed above, for large values of $M_A$ the heavy neutral MSSM Higgs bosons are nearly mass-degenerate, $M_H \approx M_A$. The experimental separation of the two states $H$ and $A$ (or the corresponding mass eigenstates in the $CP$-violating case) will therefore be challenging. The results shown in Figs. 6–7 have been obtained using the combined sample of $H$ and $A$ events. It is important to note, however, that even in the region of large $M_A$ the mass splitting between $M_H$ and $M_A$ can reach the level of a few %. An example of such a scenario is (as above, we consider the $CP$-conserving case, i.e. the MSSM with real parameters; the corresponding scenario in the case of non-vanishing complex phases has been discussed in Ref. [22])

$$M_{\text{SUSY}} = 500 \text{ GeV}, \quad A_t = A_b = 1000 \text{ GeV}, \quad \mu = 1000 \text{ GeV},$$
$$M_2 = 500 \text{ GeV}, \quad M_1 = 250 \text{ GeV}, \quad m_\tilde{g} = 500 \text{ GeV}. \quad (22)$$

In Fig. 8 the mass splitting

$$\frac{\Delta M_{HA}}{M} \equiv \frac{|M_H - M_A|}{\min(M_H, M_A)} \quad (23)$$

is given as a function of $X_t$ for $\tan \beta = 40$ and two $M_A$ values, $M_A = 300 \text{ GeV}$ (solid line) and $M_A = 500 \text{ GeV}$ (dashed line). The dot-dashed and dotted parts of the contours for
Figure 6: The statistical precision of the Higgs-boson mass measurement achievable from the channel $b\bar{b}\phi, \phi \rightarrow \tau^+\tau^- \rightarrow$ jets in the $m_h^{\text{max}}$ benchmark scenario for $\mu = -200$ GeV (left) and $\mu = +200$ GeV (right) is shown together with the $5\sigma$ discovery contour.

Figure 7: The statistical precision of the Higgs-boson mass measurement achievable from the channel $b\bar{b}\phi, \phi \rightarrow \tau^+\tau^- \rightarrow e +$ jet in the $m_h^{\text{max}}$ benchmark scenario for $\mu = -200$ GeV (left) and $\mu = +200$ GeV (right) is shown together with the $5\sigma$ discovery contour.
Figure 8: The mass splitting between the heavy neutral MSSM Higgs bosons, $\Delta M_{HA}/M \equiv |M_H - M_A|/\min(M_H, M_A)$, is shown as a function of $X_t$ for $M_A = 300, 500$ GeV in a scenario with $M_{SUSY} = 500$ GeV, $\mu = 1000$ GeV and $\tan\beta = 40$. The other parameters are given in eq. (22). The dot-dashed (dotted) parts of the contours for $M_A = 300$ GeV ($M_A = 500$ GeV) indicate parameter combinations that are excluded by the search for the light $CP$-even Higgs boson of the MSSM at LEP [3].

$M_A = 300, 500$ GeV, respectively, in the region of small $|X_t|$ indicate parameter combinations that result in relatively low $M_h$ values that are excluded by the search for the light $CP$-even Higgs boson of the MSSM at LEP [3]. One can see in Fig. 8 that the mass splitting between $M_H$ and $M_A$ shows a pronounced dependence on $X_t$ in this scenario. Mass differences of up to 5% are possible for large $X_t$ (while the widths of the Higgs bosons are at the 1–1.5% level in this parameter region).

The example of Fig. 8 shows that a precise mass measurement at the LHC may in favourable regions of the MSSM parameter space open the exciting possibility to distinguish between the signals of $H$ and $A$ production. In confronting Fig. 8 with the expected accuracies obtained in Figs. 6 – 7 one of course needs to take into account that a separate treatment of the $H$ and $A$ channels in Figs. 6 – 7 would reduce the number of signal events by a factor of 2, resulting in a degradation of the expected accuracies (for the same luminosity) by a factor of $\sqrt{2}$. A more detailed analysis of the potential for experimentally resolving two mass peaks would furthermore have to include effects arising from overlapping Higgs signals.
5 Conclusions

We have analyzed the reach of the CMS experiment with 30 or 60 fb$^{-1}$ for the heavy neutral MSSM Higgs bosons, depending on $\tan\beta$ and the Higgs-boson mass scale, $M_A$. We have focused on the channel $b\bar{b}H/A, H/A \rightarrow \tau^+\tau^-$ with the $\tau$’s subsequently decaying to jets and/or leptons. The experimental analysis, yielding the number of events needed for a 5 $\sigma$ discovery (depending on the mass of the Higgs boson) was performed with full CMS detector simulation and reconstruction for the final states of di-$\tau$-lepton decays. The events were generated with PYTHIA.

The experimental analysis has been combined with predictions for the Higgs-boson masses, production processes and decay channels obtained with the code FeynHiggs, taking into account all relevant higher-order corrections as well as possible decays of the heavy Higgs bosons into supersymmetric particles. We have analyzed the sensitivity of the 5 $\sigma$ discovery contours in the $M_A$-$\tan\beta$ plane to variations of the other supersymmetric parameters. We have shown that the discovery contours are relatively stable with respect to the impact of additional parameters. The biggest effects, resulting from higher-order corrections to the bottom Yukawa coupling and from the kinematics of Higgs decays into charginos and neutralinos, are caused by varying the absolute value and the sign of the higgsino mass parameter $\mu$. The corresponding shift in the 5 $\sigma$ discovery contours amounts up to about $\Delta \tan\beta = 10$. The effects of other contributions to the relation between the bottom-quark mass and the bottom Yukawa coupling, arising from the gluino mass and the parameters in the stop and sbottom sector, are in general smaller than the shifts induced by a variation of $\mu$. The same holds for the impact of higher-order contributions beyond the corrections to the bottom Yukawa coupling and for the possible effects of other decay modes of the heavy Higgs bosons into supersymmetric particles. The results of our analysis, which was carried out in the framework of the $CP$-conserving MSSM, should not be substantially affected by the inclusion of complex phases of the soft-breaking parameters.

We have analyzed the prospective accuracy of the mass measurement of the heavy neutral MSSM Higgs bosons in the channel $b\bar{b}H/A, H/A \rightarrow \tau^+\tau^-$. We find that statistical experimental precisions of 1–4% are reachable within the discovery region. These results, obtained from a simple estimate of the prospective accuracies, are not expected to considerably degrade if further uncertainties related to background effects and jet and missing $E_T$ scales are taken into account. We have pointed out that a %-level precision of the mass measurements could in favourable regions of the MSSM parameter allow to experimentally resolve the signals of the two heavy MSSM Higgs bosons.

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References

[1] H. Nilles, *Phys. Rept.* **110** (1984) 1;  
H. Haber and G. Kane, *Phys. Rept.* **117** (1985) 75;  
R. Barbieri, *Riv. Nuovo Cim.* **11** (1988) 1.

[2] [LEP Higgs working group], *Phys. Lett.* **B 565** (2003) 61, [hep-ex/0306033]

[3] [LEP Higgs working group], *Eur. Phys. J.* **C 47** (2006) 547, [hep-ex/0602042]

[4] V. Abazov et al. [D0 Collaboration], *Phys. Rev. Lett.* **95** (2005) 151801, [hep-ex/0504018]  
*Phys. Rev. Lett.* **97** (2006) 121802, [hep-ex/0605009]; D0 Note 5331-CONF.

[5] A. Abulencia et al. [CDF Collaboration], *Phys. Rev. Lett.* **96** (2006) 011802,  
[hep-ex/0508051]; CDF note 8676.

[6] A. Abulencia et al. [CDF Collaboration], *Phys. Rev. Lett.* **96** (2006) 042003,  
[hep-ex/0510065];  
R. Eusebi, Ph.d. thesis: “Search for charged Higgs in $t\bar{t}$ decay products from proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV”, University of Rochester, 2005.

[7] ATLAS Collaboration, *Detector and Physics Performance Technical Design Report*, CERN/LHCC/99-15 (1999), see:  
atlasinfo.cern.ch/Atlas/GROUPS/PHYSICS/tdr/access.html;

[8] K. Cranmer, Y. Fang, B. Mellado, S. Paganis, W. Quayle and S. Wu, [hep-ph/0401148]

[9] *CMS Physics Technical Design Report, Volume 2. CERN/LHCC 2006-021*, see:  
cmsdoc.cern.ch/cms/cpt/tdr/.

[10] V. Büscher and K. Jakobs, *Int. J. Mod. Phys.* **A 20** (2005) 2523, [hep-ph/0504099]

[11] M. Schumacher, *Czech. J. Phys.* **54** (2004) A103; [hep-ph/0410112]

[12] M. Carena, S. Heinemeyer, C. Wagner and G. Weiglein, [hep-ph/9912223]

[13] M. Carena, S. Heinemeyer, C. Wagner and G. Weiglein, *Eur. Phys. J.* **C 26** (2003) 601,  
[hep-ph/0202167]

[14] M. Carena, S. Heinemeyer, C. Wagner and G. Weiglein, *Eur. Phys. J.* **C 45** (2006) 797,  
[hep-ph/0511023]

[15] S. Heinemeyer, W. Hollik and G. Weiglein, *JHEP* **0006** (2000) 009, [hep-ph/9909540]

[16] A. Belyaev, J. Pumplin, W. Tung and C. Yuan, *JHEP* **0601** (2006) 069,  
[hep-ph/0508222]
[17] M. Albrow and A. Rostovtsev, hep-ph/0009336; V. Khoze, A. Martin and M. Ryskin, *Eur. Phys. J. C* 23 (2002) 311, hep-ph/0111078; A. De Roeck, V. Khoze, A. Martin, R. Orava and M. Ryskin, *Eur. Phys. J. C* 25 (2002) 391, hep-ph/0207042; B. Cox, *AIP Conf. Proc.* 753 (2005) 103, hep-ph/0409144; J. Forshaw, hep-ph/0508274.

[18] S. Heinemeyer, V. Khoze, M. Ryskin, W. Stirling, M. Tasevsky and G. Weiglein, *in preparation.*

[19] S. Heinemeyer, W. Hollik and G. Weiglein, *Comput. Phys. Commun.* 124 (2000) 76, hep-ph/9812320, hep-ph/0002213; see: www.feynhiggs.de.

[20] S. Heinemeyer, W. Hollik and G. Weiglein, *Eur. Phys. J. C* 9 (1999) 343, hep-ph/9812472.

[21] G. Degrassi, S. Heinemeyer, W. Hollik, P. Slavich and G. Weiglein, *Eur. Phys. J. C* 28 (2003) 133, hep-ph/0212020.

[22] M. Frank, T. Hahn, S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, *JHEP* 02 (2007) 047, hep-ph/0611326.

[23] S. Abdullin et al., *Eur. Phys. J. C* 39S2 (2005) 41.

[24] R. Kinnunen and A. Nikitenko, CMS note 2003/006.

[25] J. Thomas, ATL-PHYS-2003-003; D. Cavalli and D. Negri, ATL-PHYS-2003-009.

[26] M. Carena, P. Chankowski, S. Pokorski and C. Wagner, *Phys. Lett. B* 441 (1998) 205, hep-ph/9805349.

[27] J. Espinosa and I. Navarro, *Nucl. Phys. B* 615 (2001) 82, hep-ph/0104047.

[28] S. Heinemeyer, W. Hollik and G. Weiglein, *Phys. Rev. D* 58 (1998) 091701, hep-ph/9803277; *Phys. Lett. B* 440 (1998) 296, hep-ph/9807423.

[29] G. Degrassi, A. Dedes and P. Slavich, *Nucl. Phys. B* 672 (2003) 144, hep-ph/0305127.

[30] M. Carena, H. Haber, S. Heinemeyer, W. Hollik, C. Wagner, and G. Weiglein, *Nucl. Phys. B* 580 (2000) 29, hep-ph/0001002.

[31] J. Ellis, G. Ridolfi and F. Zwirner, *Phys. Lett. B* 257 (1991) 83; Y. Okada, M. Yamaguchi and T. Yanagida, *Prog. Theor. Phys.* 85 (1991) 1; H. Haber and R. Hempfling, *Phys. Rev. Lett.* 66 (1991) 1815.

[32] A. Brignole, *Phys. Lett. B* 281 (1992) 284.

[33] P. Chankowski, S. Pokorski and J. Rosiek, *Phys. Lett. B* 286 (1992) 307; *Nucl. Phys. B* 423 (1994) 437, hep-ph/9303309.
[34] A. Dabelstein, *Nucl. Phys.* B 456 (1995) 25, hep-ph/9503443; *Z. Phys.* C 67 (1995) 495, hep-ph/9409375.

[35] R. Hempfling and A. Hoang, *Phys. Lett.* B 331 (1994) 99, hep-ph/9401219; J. Casas, J. Espinosa, M. Quirós and A. Riotto, *Nucl. Phys.* B 436 (1995) 3, E: *ibid.* B 439 (1995) 466, hep-ph/9407389; M. Carena, J. Espinosa, M. Quirós and C. Wagner, *Phys. Lett.* B 355 (1995) 209, hep-ph/9504316; M. Carena, M. Quirós and C. Wagner, *Nucl. Phys.* B 461 (1996) 407, hep-ph/9508343; H. Haber, R. Hempfling and A. Hoang, *Z. Phys.* C 75 (1997) 539, hep-ph/9609331; R. Zhang, *Phys. Lett.* B 447 (1999) 89, hep-ph/9808299; J. Espinosa and R. Zhang, *JHEP* 0003 (2000) 026, hep-ph/9912236; G. Degrassi, P. Slavich and F. Zwirner, *Nucl. Phys.* B 611 (2001) 403, hep-ph/0105096; J. Espinosa and R. Zhang, *Nucl. Phys.* B 586 (2000) 3, hep-ph/0003246; A. Brignole, G. Degrassi, P. Slavich and F. Zwirner, *Nucl. Phys.* B 631 (2002) 195, hep-ph/0112177; A. Brignole, G. Degrassi, P. Slavich and F. Zwirner, *Nucl. Phys.* B 643 (2002) 79, hep-ph/0206101; S. Heinemeyer, W. Hollik, H. Rzehak and G. Weiglein, *Eur. Phys. J.* C 39 (2005) 465, hep-ph/0411114, hep-ph/0506254.

[36] R. Hempfling, *Phys. Rev.* D 49 (1994) 6168; L. Hall, R. Rattazzi and U. Sarid, *Phys. Rev.* D 50 (1994) 7048, hep-ph/9306309; M. Carena, M. Olechowski, S. Pokorski and C. Wagner, *Nucl. Phys.* B 426 (1994) 269, hep-ph/9402253.

[37] M. Carena, D. Garcia, U. Nierste and C. Wagner, *Nucl. Phys.* B 577 (2000) 577, hep-ph/9912516.

[38] H. Eberl, K. Hidaka, S. Kraml, W. Majerotto and Y. Yamada, *Phys. Rev.* D 62 (2000) 055006, hep-ph/9912463.

[39] S. Martin, *Phys. Rev.* D 65 (2002) 116003, hep-ph/0111209; *Phys. Rev.* D 66 (2002) 096001, hep-ph/0206136; *Phys. Rev.* D 67 (2003) 095012, hep-ph/0211366; *Phys. Rev.* D 68 (2003) 075002, hep-ph/0307101; *Phys. Rev.* D 70 (2004) 016005, hep-ph/0312092; *Phys. Rev.* D 71 (2005) 016012, hep-ph/0405022; *Phys. Rev.* D 71 (2005) 116004, hep-ph/0502168; S. Martin and D. Robertson, *Comput. Phys. Commun.* 174 (2006) 133, hep-ph/0501132.

[40] S. Martin, hep-ph/0701051.

[41] S. Heinemeyer, W. Hollik and G. Weiglein, *Phys. Rept.* 425 (2006) 265, hep-ph/0412214.

[42] J. Guasch, P. Häftiger and M. Spira, *Phys. Rev.* D 68 (2003) 115001, hep-ph/0305101.

[43] S. Gorishny, A. Kataev, S. Larin and L. Surguladze, *Mod. Phys. Lett.* A 5 (1990) 2703; *Phys. Rev.* D 43 (1991) 1633; A. Kataev and V. Kim, *Mod. Phys. Lett.* A 9 (1994) 1309;
L. Surguladze, *Phys. Lett.* B 338 (1994) 229, hep-ph/9406294; *Phys. Lett.* B 341 (1994) 60, hep-ph/9405325
K. Chetyrkin, *Phys. Lett.* B 390 (1997) 309, hep-ph/9608318
K. Chetyrkin and A. Kwiatkowski, *Nucl. Phys.* B 461 (1996) 3, hep-ph/9505358
S. Larin, T. van Ritbergen and J. Vermaseren, *Phys. Lett.* B 362 (1995) 134, hep-ph/9506465
P. Chankowski, S. Pokorski and J. Rosiek, *Nucl. Phys.* B 423 (1994) 497;
S. Heinemeyer, W. Hollik and G. Weiglein, *Eur. Phys. J.* C 16 (2000) 139, hep-ph/0003022

[44] R. Harlander and W. Kilgore, *Phys. Rev.* D 68 (2003) 013001, hep-ph/0304035
[45] S. Dittmaier, M. Kramer and M. Spira, *Phys. Rev.* D 70 (2004) 074010, hep-ph/0309204
[46] S. Dawson, C. Jackson, L. Reina and D. Wackeroth, *Phys. Rev.* D 69 (2004) 074027, hep-ph/0311067
[47] K. Assamagan et al. [Les Houches 2003 Higgs Working Group], hep-ph/0406152
[48] S. Dawson, C. Jackson, L. Reina and D. Wackeroth, *Phys. Rev. Lett.* 94 (2005) 031802, hep-ph/0408077
[49] S. Dawson, C. Jackson, L. Reina and D. Wackeroth, *Mod. Phys. Lett.* A 21 (2006) 89, hep-ph/0508293
[50] J. Campbell, R. Ellis, F. Maltoni and S. Willenbrock, *Phys. Rev.* D 67 (2003) 095002, hep-ph/0204093
[51] A. Martin, R. Roberts, W. Stirling and R. Thorne, *Eur. Phys. J.* C 28 (2003) 455, hep-ph/0211080
[52] T. Hahn, S. Heinemeyer and G. Weiglein, *Nucl. Phys.* B 652 (2003) 229, hep-ph/021204
[53] See: people.web.psi.ch/spira/hqq.
[54] E. Brubaker et al. [Tevatron Electroweak Working Group], hep-ex/0608032 see: tevewwg.fnal.gov/top/.
[55] [Tevatron Electroweak Working Group], hep-ex/0703034.
[56] G. Abbiendi et al. [OPAL Collaboration], *Eur. Phys. J.* C 35 (2004) 1, hep-ex/0401026
[57] S. Gennai, A. Nikitenko and L. Wendland, CMS Note 2006/126.
[58] R. Kinnunen and S. Lehti, CMS Note 2006/075.
[59] A. Kalinowski, M. Konecki and D. Kotlinski, CMS Note 2006/105.
[60] S. Lehti, CMS Note 2006/101.
[61] T. Sjostrand et al., *Comput. Phys. Commun.* **135** (2001) 238; [hep-ph/0010017](https://arxiv.org/abs/hep-ph/0010017).

[62] J. Campbell, A. Kalinowski and A. Nikitenko, “Comparison between MCFM and Pythia for the $gb \rightarrow bh$ and $gg \rightarrow bbh$ processes at the LHC” in C. Buttar et al., *Les Houches Physics at TeV Colliders 2005*, “Standard Model and Higgs working group: Summary report”, [hep-ph/0604120](https://arxiv.org/abs/hep-ph/0604120).

[63] E. Boos et al. [CompHEP Collaboration], *Nucl. Instrum. Meth.* **A 534** (2004) 250, [hep-ph/0403113](https://arxiv.org/abs/hep-ph/0403113).