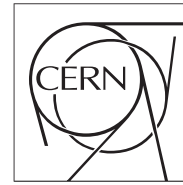




The Compact Muon Solenoid Experiment  
**Conference Report**

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# Discovery potential for Higgs bosons beyond the SM

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## Abstract

The discovery potential of the CMS detector for the MSSM neutral and charged Higgs bosons at the LHC is presented based on studies with full detector simulation and event reconstruction of the principal discovery channels.

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## 1. Higgs bosons in the MSSM

In the Minimal Supersymmetric Standard Model (MSSM) the electroweak symmetry is broken via the Higgs mechanism, leading to five physical scalars: three neutral ( $h$ ,  $H$ ,  $A$ ) and two charged ( $H^+$ ,  $H^-$ ) Higgs bosons. At tree level, two parameters, usually chosen to be the mass of the pseudo scalar Higgs boson ( $m_A$ ) and the ratio of the vacuum expectation values of the two Higgs fields ( $\tan\beta$ ), determine the masses and couplings in the Higgs sector. Radiative corrections, chiefly coming from the top-stop and, at large  $\tan\beta$ , from the bottom - sbottom sector, introduce further model parameters.

In the frequently studied decoupling limit ( $m_A \gg m_Z$ ), the lightest neutral Higgs boson is Standard Model-like, while  $H$  and  $A$  are close in mass and both couple with  $\tan\beta$  to down-type fermions and with  $\cot\beta$  to up-type fermions.

The dominant production mechanism for heavy neutral MSSM Higgs bosons at large  $\tan\beta$  is  $gg \rightarrow b\bar{b}H/A$  with negligible contributions from other processes. As the main decay mode  $H/A \rightarrow b\bar{b}$  suffers from high QCD background, the decay  $H/A \rightarrow \tau\tau$ , reaching about 10% rate for  $\tan\beta > 10$ , promises the most sensitivity.

Charged Higgs bosons couple to fermions as  $H^+ud \sim m_d \tan\beta + m_u \cot\beta$ . They are produced in top quark decay, if  $m_{H^\pm} < m_t$ , or in association with a top quark, if  $m_{H^\pm} > m_t$ . Light charged Higgs bosons decay almost exclusively to a tau lepton and a neutrino for  $\tan\beta \gtrsim 3$ . For  $m_{H^\pm} > m_t + m_b$ , the decay  $H^\pm \rightarrow tb$  dominates with an important contribution of  $H^\pm \rightarrow \tau\nu_\tau$  at large  $\tan\beta$ .

The following processes are considered here:

- associated  $b\bar{b}H/A$  production followed by  $H/A \rightarrow \tau\tau$  with all possible  $\tau\tau$  final states (jet jet,  $e$  jet,  $\mu$  jet and  $e\mu$ ) [1];
- production of a light charged Higgs boson in  $t\bar{t} \rightarrow H^\pm bWb$  with subsequent  $H^\pm \rightarrow \tau\nu_\tau$ ,  $\tau \rightarrow \text{jet}$  and  $W \rightarrow \ell\nu_\ell$  decays [2];
- associated  $H^\pm t(b)$  production of heavy charged Higgs boson with  $H^\pm \rightarrow \tau\nu_\tau$ ,  $\tau \rightarrow \text{jet}$  and hadronic top quark decays [3];
- associated  $H^\pm t(b)$  production of heavy charged Higgs boson with  $H^\pm \rightarrow tb$  and one of the top quarks decaying leptonically [4].

## 2. Experimental tools

The final states in the search for heavy MSSM Higgs bosons are complex: they typically contain leptons, b- and light-flavoured hadronic jets and missing transverse energy.

The selections rely on  $\tau$ -jet or lepton ( $e$ ,  $\mu$ ) triggers.  $\tau$ -identification based on vertex reconstruction and impact parameter measurements is powerful against hadronic jets. A single b-tag is sufficient to suppress events from Drell-Yan, QCD multi-jet and  $W$ +jets processes. Against the difficult  $t\bar{t}$  background a central jet veto is applied. Missing transverse energy ( $E_T^{\text{miss}}$ ) reconstruction is important to account for the neutrinos from the Higgs or the  $\tau$  decays. Top quark and  $W$  boson mass reconstruction provides a further handle on the background. For example, in the  $b\bar{b}H/A$ ,  $H/A \rightarrow \tau\tau \rightarrow \ell + \text{jet}$  searches, it is instrumental in vetoing leptons from  $W$  decay by reconstructing the transverse mass of the [lepton,  $E_T^{\text{miss}}$ ] system.

The main background comes from  $t\bar{t}$  events, with significant contribution from  $W$ +jets events in the  $H^\pm \rightarrow \tau\nu_\tau$  searches and Drell-Yan processes in the  $H/A \rightarrow \tau\tau \rightarrow \ell + \text{jet}$  searches. A major exception is the  $H/A \rightarrow \tau\tau \rightarrow \text{jet jet}$  analysis, where QCD events dominate the background. The typical selection efficiency is below 1%.

*Higgs boson mass reconstruction* does not only increases the sensitivity of the searches, but it will also play a crucial role in constraining the MSSM model parameters.

In the  $H/A \rightarrow \tau\tau$  selection the Higgs mass can be measured by the di-tau mass assuming that the  $\tau$  decay products are collinearly emitted. While the procedure has large inefficiency, it achieves a mass resolution of about 20%.

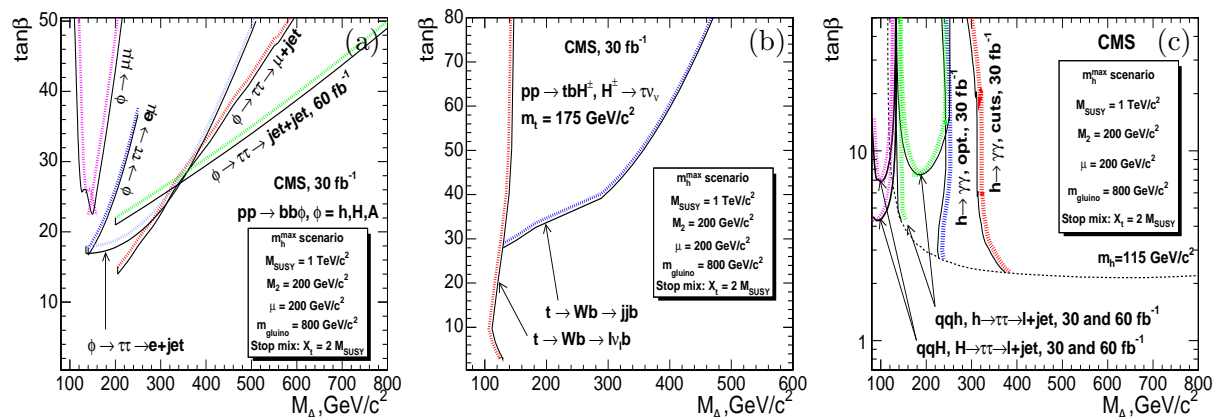
In the heavy charged Higgs search:  $H^\pm t \rightarrow \tau\nu_\tau bqq$ , the reconstruction of the top quark mass is instrumental in fully reconstructing the signal. The charged Higgs mass is then estimated by the transverse mass of the  $[\tau, E_T^{\text{miss}}]$  system ( $M_T$ ). By requiring  $M_T > 100$  GeV, an almost background-free selection is achieved.

### 3. Results

The results presented here are based on the full simulation of the CMS detector at low luminosity ( $\mathcal{L} = 2 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ ), assuming a total integrated luminosity of 30–60  $\text{fb}^{-1}$ . Pythia is used as the main Monte Carlo generator with notable exceptions (e.g. matrix element generators for multi-parton or Toprex for  $t\bar{t}$  final states in some cases). Background cross-sections are normalized to NLO calculations where available. Tau decays are modeled by Tauola.

For the numerical results, the minimal supergravity inspired  $m_h$ -max benchmark scenario is used, which maximises the theoretical upper bound on  $m_h$  for a given  $\tan\beta$ ,  $m_t$  and  $M_{\text{SUSY}}$ , the SUSY mass scale. Higgs boson masses, cross-sections and branching ratios are calculated by FeynHiggs 2.3.2.

The estimated 5-sigma discovery reach is shown on Figure 1(a) for the  $pp \rightarrow bbH/A$  searches and on Figure 1(b) for the  $H^\pm \rightarrow \tau\nu_\tau$  searches [5]. In all cases the systematic uncertainties are included in the calculation of signal significance.



**Figure 1.** 5-sigma discovery reach of searches for (a)  $bbH/A$  production with  $H/A \rightarrow \tau\tau$ , (b)  $H^\pm \rightarrow \tau\nu_\tau$  and (c) inclusive  $h \rightarrow \gamma\gamma$  and vector boson fusion  $qqh/H$  with  $h/H \rightarrow \tau\tau$ .

We also considered the extended  $m_h$ -max scenario, where the supersymmetric Higgs mass parameter can take different values:  $\mu = \pm 200, \pm 500, \pm 1000$ . The cross-section is enhanced for large negative and reduced for large positive values of  $\mu$ , but the change in the Higgs branching ratios due to decay modes to supersymmetric particles partially compensates this effect. In general, the default value of  $\mu = 200$  GeV gives the most conservative discovery reach. For a detailed discussion see [6].

*Systematic uncertainties* dominate these searches. Therefore, several methods are explored to measure them from collision data [7].

The main sources of uncertainty come from b-tagging,  $\tau$ - and lepton identification, missing energy measurement and energy scale calibration. Together with the theoretical uncertainties on the background production cross-sections, we estimate typically 12% error on the main  $t\bar{t}$

background, 9% on  $Z/\gamma$ , 16% on  $bbZ/\gamma$ , 10–14% on  $W+\text{jets}$  and 15% on  $tW$  processes. The QCD background will be measured from data with a 5–20% statistical error.

The inclusion of systematic uncertainties has a significant impact on the expected sensitivities. For example, in the charged Higgs boson  $H^\pm \rightarrow \tau\nu_\tau$  search, the 5-sigma reach is decreased from about 125 to 110 GeV at the most difficult value of  $\tan\beta \approx 10$ . At values of  $\tan\beta > 30$ , the downward shift is even larger ranging from about 30 to 80 GeV.

In the search for  $gg \rightarrow H^\pm tb$  with  $H^\pm \rightarrow tb$  and  $tt \rightarrow \ell\nu\ell b$  qqb requiring four b-tags, the main background comes from  $t\bar{t}bb$  and mistagged  $t\bar{t} + \text{jets}$  processes. With the simulation of the background processes by CompHEP (with the cross-section calculated by ALPGEN) and the inclusion of realistic experimental (about 5–5% on b-tagging efficiency and the mistag rate) and theory uncertainties, no discovery potential remains for this channel.

#### 4. Light neutral Higgs search in MSSM

The searches presented above for heavy Higgs bosons lose their sensitivity for small and intermediate  $\tan\beta$  and leave open the so-called LHC wedge region, where only a light neutral Higgs boson can be discovered. This is illustrated on figure 1(c), where the SM Higgs boson searches [5, 8] (for inclusive  $pp \rightarrow h+X$  production with  $h \rightarrow \gamma\gamma$  and for the vector boson fusion process  $qq \rightarrow qqh/H$  with  $h/H \rightarrow \tau\tau \rightarrow \ell + \text{jet}$ ) are reinterpreted in MSSM [5].

#### Acknowledgments

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