MSSM Higgs Searches with CMS

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12.44 Introduction

According to the Minimal Supersymmetric Standard Model (MSSM), two isospin Higgs doublets have to be introduced. After electroweak symmetry breaking, five Higgs scalar mass eigenstates remain: one CP-odd neutral scalar boson $A$, two charged scalars $H^\pm$, and two CP-even neutral scalars $h$ and $H$. At the tree level, the Higgs sector is completely defined by only two parameters: they are usually chosen as the ratio of the vacuum expectation values ($\tan \beta = v_2/v_1$) and the Higgs boson $A$ mass ($M_A$). The tree level hierarchies ($M_h < M_Z$, $M_A < M_H$ and $M_W < M_H$) are modified by large radiative corrections: the leading one-loop correction is proportional to $m_t^4$ and the upper bound of $M_h$ is shifted to $M_h \lesssim 135$ GeV/c$^2$.

Varying $M_A$ in the range $91$ GeV/c$^2 < M_A < 1$ TeV/c$^2$ we can distinguish three different regimes:

- **Decoupling regime.** If $M_A \gg M_h^{\text{max}}$ then the Higgs bosons $H$, $A$ and $H^\pm$ are very heavy and almost degenerate in mass, while $h$ has a mass very close to $M_h^{\text{max}}$ and becomes SM-like. $H$ and $A$, besides their masses, are degenerate also in width and cross section.

- **Low $M_A$ regime.** If $M_A < M_h^{\text{max}}$ the behavior of the two CP-even neutral Higgs bosons $h$ and $H$ is swapped with respect to the decoupling regime: $h$ is almost degenerate in mass, width and cross section with $A$, and $H$ is the SM-like Higgs, with a mass close to $M_h^{\text{max}}$.

- **Intense coupling regime.** This occurs for $M_A \sim M_h^{\text{max}}$ and high $\tan \beta$ [1, 2] and it leads to similar, but not degenerate, masses for the three neutral Higgs bosons. This property, in principle, allows to detect the three neutral Higgs separately.

The LEP experiments have excluded the Higgs masses $M_A < 91.9$ GeV/c$^2$, $M_{h,H} < 91$ GeV/c$^2$ [3] and $M_{H^\pm} < 78.6$ GeV/c$^2$ [4].

In this report the discovery potential of the MSSM neutral Higgs boson with the CMS detector at LHC is presented. These analysis are also described in [5].

12.45 Neutral Higgs bosons searches

The production cross-section for the MSSM neutral Higgs bosons is strongly dependent on the value of the $\tan \beta$ parameter. All neutral MSSM Higgs production cross sections including NLO QCD corrections are shown in Fig.12.51.
Figure 12.51: Neutral MSSM Higgs production cross sections at the LHC.
12.45.1 Large $\tan \beta$

In the region with large $\tan \beta$ values (> 15) the neutral Higgs bosons are mainly produced in association with b-quarks: $pp \rightarrow q\bar{q}/gg \rightarrow h/A/H + bb$. The presence of a $bb$ pair is important to suppress the very large background from Drell-Yan processes. The Higgs bosons mainly decay in a $bb$ pair (90%) and in a $\tau\tau$ pair (10%). In CMS six channels have been studied:

- $A/H \rightarrow \mu\mu$
- $A/H \rightarrow \tau\tau \rightarrow e + jet + X$
- $A/H \rightarrow \tau\tau \rightarrow \mu + jet + X$
- $A/H \rightarrow \tau\tau \rightarrow jet + jet + X$
- $A/H \rightarrow \tau\tau \rightarrow e + \mu + X$
- $A/H \rightarrow bb$

The muon final state, with respect to the other channels, has a much lower branching ratio ($\approx 3 \times 10^{-4}$), but the event is very clean and Higgs masses and widths can be reconstructed precisely. Moreover it is possible to exploit the theoretical relation between the Higgs decay width and $\tan \beta$ ($\Gamma_H \propto \tan^2 \beta$) to perform a direct measurement of this latter quantity.

The rejection strategy is mainly based on identification of isolated muons and on b-tagging. This latter selection is particular important: b jets from signal events are mainly produced in the forward region with lower $p_T$ with respect to the b jets coming from $t\bar{t}$ background. Figure 12.52 (left) shows the reconstructed dimuon invariant mass for signal and background.

The tau channels, on the other hands, have a better signal to background ratio and can reach larger discovery region in the plane ($M_A, \tan \beta$), as can be seen in Fig. 12.54 (left). Fig. 12.52 (right) shows the reconstructed invariant mass for signal and background that can be obtained with the $A/H \rightarrow \tau\tau \rightarrow e + jet$ channel. Indeed, despite the escaping neutrino, the Higgs boson mass can be reconstructed also for these channels, exploiting the collinearity approximation: the neutrino is assumed to be emitted along the $\tau$ direction.

Finally, the $bb$ channel must take into account the huge QCD background and, to perform a discovery, one needs to know in advance masses and widths of the Higgs bosons. Thus this channel can be considered mainly as a cross-check for the discovery.

12.45.2 Small $\tan \beta$

Concerning low $\tan \beta$ values, the dominant neutral MSSM Higgs production mechanism is the gluon fusion $gg \rightarrow h/A/H$, which can be mediated by top and bottom loops (as in the SM case), but also by stop and sbottom (Fig.12.51).

In CMS two channels have been investigated:

- $A \rightarrow Zh \rightarrow \ell^+\ell^-bb$
- $A/H \rightarrow \tilde{\chi}_2^0\tilde{\chi}_1^0 \rightarrow 4\ell + E_T^{\text{miss}}$

The first channel provides an interesting way to detect A and h simultaneously. The cross section increases with decreasing of $\tan \beta$, while the mass range is $m_Z + m_h \leq m_A \leq 2m_{1/2}$. However results are strongly dependent on the MSSM parameters $\mu$ and $M_2$, because the Higgs boson decay $A \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0$ may become dominant (the best results being...
obtained for large values of $\mu$ and $M_2$). Fig. 12.53 (left) shows the discovery region for this channel for 30 and 60 fb$^{-1}$ of integrated luminosity.

To increase the discovery region in the low and intermediate region of $\tan \beta$, the second channel has been studied which takes into account the decay modes of the neutral Higgs bosons to supersymmetric particles. The final state studied by this channel is particular clean (four leptons plus missing transverse energy). The analysis is performed in three benchmark points of the minimal Super Gravity constrained version of the MSSM (mSUGRA): these points are obtained varying the parameters $m_0$ and $m_1^2$ for $\tan \beta = 5, 10, \text{sign}(\mu) = +$ and $A_0 = 0$. Fig.12.53(right) shows the discovery region in the $(m_0, m_1^2)$ plane, for an integrated luminosity of 30 fb$^{-1}$.

Fig.12.54 summarize the 5$\sigma$ discovery region that can be obtained with 30 fb$^{-1}$ of integrated luminosity.

12.46 Charged Higgs bosons searches

Three channels, depending on the final state and on the Higgs boson mass, have been investigated for charged Higgs bosons:

- $H^\pm \rightarrow \tau \nu_\tau$, with $M_H < M_{\text{top}}$
- $H^\pm \rightarrow W^\pm \nu$, with $M_H > M_{\text{top}}$
- $H^\pm \rightarrow t \bar{b}$, with $M_H > M_{\text{top}}$

For Higgs boson masses below $M_{\text{top}}$, the main production mechanism is through top decay, $t \rightarrow H^\pm b$, and the branching ratio of the $\tau \nu$ channel is about 98% (Fig.12.55(left)). The study is performed considering the leptonic decay of the W: $t \bar{t} \rightarrow H^\pm W^\mp \bar{b}b \rightarrow \tau \nu_\tau \ell \nu_\ell \bar{b}b$, $\tau \rightarrow \text{hadrons}$. The discovery region, as can be seen in figure 12.55(right), covers almost the entire allowed region in the $(M_A, \tan \beta)$ plane.

If $M_H > M_{\text{top}}$, the charged Higgs bosons are mainly produced in association with a top-bottom pair, $gg \rightarrow t \bar{b}H^\pm$. The final state for this channel is very clean ($H^\pm \rightarrow \tau^\pm \nu$, $r \rightarrow \text{hadrons} + \nu$ and $W^\pm \rightarrow jj$) and, after the selection cuts, almost background free. The characteristics for this channel is the presence of large missing transverse energy and
Figure 12.53: (left) The 5\(\sigma\) discovery region contours for 30 and 60 fb\(^{-1}\) integrated luminosity for the \(A \rightarrow Zh\) channel. The effect of underestimation or overestimation of the background systematic uncertainty can be seen in the curve of 30 fb\(^{-1}\). (right) The 5\(\sigma\) discovery region contours for 30 fb\(^{-1}\) integrated luminosity for the \(A/H \rightarrow \tilde{\chi}^0_2\tilde{\chi}^0_2\) channel.

Figure 12.54: The 5\(\sigma\) discovery regions for the neutral Higgs bosons \(\phi\) (\(\phi = h, H, A\)) produced in the association with b quarks \(pp \rightarrow b\bar{b}\phi\) with the \(\phi \rightarrow \mu\mu\) and \(\phi \rightarrow \tau\tau\) decay modes (left plot) and for the light, neutral Higgs boson \(h\) from the inclusive \(pp \rightarrow h+X\) production with the \(h \rightarrow \gamma\gamma\) decay and for the light and heavy scalar Higgs bosons, \(h\) and \(H\), produced in the vector boson fusion \(qq \rightarrow qqh(H)\) with the \(h(H) \rightarrow \ell\ell+\text{jet}\) decay (right plot). The \(m^\text{max}_h\) scenario is used.
Figure 12.55: Branching ratios for charged Higgs boson decaying to different final states for $\tan \beta = 20$ (left). The $5\sigma$-discovery regions for the charged Higgs boson with the $\tau\nu$ decay mode with 30 fb$^{-1}$ of integrated luminosity (right).

The $\tau$ helicity correlations favouring the $H^{\pm} \to \tau^{\pm}\nu$ decay over the $W^{\pm} \to \tau^{\pm}\nu$ decay. A large sector of the ($M_A, \tan \beta$) plane can be covered (Fig. 12.55(right)).

Finally, for masses above $M_{top} + M_{bottom}$, the channel $H^{\pm} \to tb$ opens up. Two production mechanism are considered:

- $gb \to tH^{\pm} \to ttk \to W^{\pm}W^{-} bbb \to qq' \mu \nu_{\mu} bbb$
- $gg \to tH^{\pm}b \to ttkb \to W^{\pm}W^{-} bbbb \to qq' \mu \nu_{\mu} bbbb$

Unfortunately no sensitivity is obtained in the MSSM parameter space with this analysis, due to the large background and the resulting large effects of systematic uncertainties on its knowledge.

Fig.12.55(right) summarize the $5\sigma$ discovery region that can be obtained with 30 fb$^{-1}$ of integrated luminosity.

### 12.47 Conclusions

Many channels have been studied to estimate the discovery potential of MSSM Higgs bosons at CMS. A large area in the ($M_A, \tan \beta$) plane will be explored: the most promising channels are $\phi \to \tau \tau$ ($\phi = h, A, H$) and $H^{\pm} \to \tau \nu$. 

Bibliography


