Results on the Search for MSSM Neutral and Charged Higgs bosons (CMS)

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Abstract. In the minimal super-symmetric extension of the Standard Model (MSSM), the Higgs sector contains two Higgs boson doublets, including, after electroweak symmetry breaking, the CP-odd neutral scalar $A^0$, the two charged scalars $H^\pm$, and the two CP-even neutral scalars $h$ and $H^0$. The neutral Higgs boson is searched in the $\mu^+\mu^-$, $\tau^+\tau^-$, and recently also in the $b\bar{b}$, channels, whereas the charged Higgs state is searched in top quark decays with at least one $\tau$ in the final state. This report reviews the current status of searches for MSSM Higgs bosons with the data collected by the CMS experiment at LHC in the 2011 and 2012 operations.

1. Introduction
The precise nature of the boson recently discovered [1, 2] at the Large Hadron Collider remains open. In addition to measuring its properties to determine whether it is the quantum of the field that breaks electroweak symmetry and gives mass to the fundamental particles, the search for other Higgs particles predicted by models beyond the Standard Model (SM), has intensified. In this report, results are presented from searches for Higgs-like particles predicted within the minimal super-symmetric extension of the Standard Model (MSSM) framework [3].

The MSSM requires the presence of two Higgs doublets, which turn to five massive Higgs bosons: a light neutral scalar ($h$), two charged scalars ($H^\pm$), a heavy neutral CP-even state ($H$) and a neutral CP-odd state ($A$). At the tree level the Higgs sector is controlled by two parameters, conventionally chosen as the mass of the pseudoscalar Higgs boson, $m_A$, and the ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta = v_2/v_1$. For $\tan\beta$ larger than unity, the Higgs field couplings to up-type particles are suppressed relative to the SM, while the couplings to down-type particles are enhanced by a factor of $\tan\beta$. Therefore, the combined cross section of Higgs boson production in association with b quarks is effectively enhanced by a factor $\approx \tan^2\beta$. In addition, the mass $m_A$ is expected to be nearly degenerate with either $m_h$ or $m_H$ within the experimental resolution.

This report presents the searches for MSSM neutral and charged Higgs particles in pp collisions at a center of mass energy of both 7 and 8 TeV, using data recorded by the Compact Muon Solenoid (CMS) experiment in 2011 and 2012 with an integrated luminosity of 4.8 and 12 fb$^{-1}$, respectively.
2. The CMS detector and the event reconstruction

Details of the CMS detector and its performance can be found elsewhere [4]. The CMS particle-flow event reconstruction [5, 6] is used for optimizing the reconstruction and the identification of all particles in the event, i.e. electrons, muons, photons, charged hadrons, and neutral hadrons, with an extensive combination of all CMS sub-detectors.

The reconstructed primary vertex [7] with the largest $p_T^2$-sum of its associated tracks is selected and used as reference for the other physics objects. Muons are reconstructed [8, 9] with a simultaneous global fit performed on hits in the tracker and the muon system. Electrons are reconstructed [10] from clusters of energy deposits in the electromagnetic calorimeter that are matched to tracker hits. Jets and the missing transverse energy ($E_T$) are reconstructed using PF objects. Jets are clustered with the anti-kT algorithm [11] from particle-flow objects with a distance parameter of 0.5. The tagging of jets originating from the hadronization of a b quark (b jet) is performed using several algorithms [12], which, relying on the characteristic of the b quark, provide a good separation between b jets and jets of other flavors. The identification and reconstruction of hadronically decaying τ candidates [14], is accomplished, using tracking and calorimeter information, applying the Hadron plus Strips (HPS) algorithm, which considers candidates with one or three charged pions and up to two neutral pions. The missing transverse energy vector is calculated as the negative vector sum of all particle transverse momenta, and its magnitude is referred to as $E_T$ [15].

3. Search for neutral MSSM Higgs bosons

The most interesting production processes of MSSM neutral Higgs bosons at the LHC, are the gluon-gluon fusion, for small and moderate values of tan $\beta$ and the production in association with bottom quarks, which constitutes the dominant mechanism for large values of tan $\beta$. In the latter case there is a significant probability to observe a jet from the hadronization of the b-quark in association with the Higgs boson in the detector.

CMS has studied the production of neutral MSSM Higgs bosons in three complementary channels: $\phi \rightarrow b\bar{b}$ [16, 17, 18], $\phi \rightarrow \tau^+\tau^-$ [19] and $\phi \rightarrow \mu^+\mu^-$ [20]. The decay to $b\bar{b}$ provides the largest branching fraction ($\approx 90\%$), but suffers from an overwhelmingly large background of QCD multi-jet production. The branching fraction for the decay to $\tau^+\tau^-$ is approximately one order of magnitude lower, but the presence of two electrons, muons or hadronically decaying taus in the event provides a large signal to background ratio. The decay to $\mu^+\mu^-$ has a very small branching fraction ($\approx 10^{-4} \div 10^{-5}$), offset by the advantages of very low background, high reconstruction efficiency for the muons, and excellent mass resolution.

3.1. MSSM neutral Higgs into $\tau^+\tau^-$

The search for $\phi \rightarrow \tau^+\tau^-$ is performed in four final states: $\tau_h e\tau_h$, $\tau_h \mu\tau_h$, $e\mu$ and $\mu\mu$, where the electrons and muons arise from leptonic $\tau$ decays, and where $\tau_h$ denotes hadronic $\tau$ decays.

The Higgs boson signal would appear as a broad excess in the distribution of the full mass of the tau pair, $M_{\tau^+\tau^-}$. In this analysis the $M_{\tau^+\tau^-}$ reconstruction is done by a novel likelihood technique, combining the visible $\tau$ decay products and the missing transverse energy, achieving a resolution of about 20% on $M_{\tau^+\tau^-}$. The observed reconstructed tau-pair mass distribution for the $\tau_h e$ channel is shown in Figure 1 (left).

The search sensitivity is improved by classifying the events in two distinct event categories: events in the first category are required to contain a b-tagged jet with $p_T > 20$ GeV and $|\eta| < 2.4$, while events without such a jet are in the second category. Events with b-tagged jets are more likely to come from b-association production process, while the other events are candidates for gluon-gluon fusion production.
Figure 1. Left: the reconstructed tau-pair full mass distribution in the b-tag category for the $\tau\bar{\tau}e$ final states, comparing the observed distributions (points with error bars) to the sum of the expected backgrounds (shaded histograms). The contribution from a Higgs boson signal ($m_A=160\,\text{GeV}$) is also shown, for the hypothesis $\tan\beta = 8$. Right: region in $\tan\beta$ versus $m_A$ parameter space excluded at 95% CL in the context of the MSSM $m_{\text{max}}$ scenario, by the $17\,\text{fb}^{-1}$ of data collected by CMS in 2011 and 2012. The exclusion limits from the LEP experiments are also shown.

The online selections require the presence of an electron and/or a muon trigger object, and also special triggers requiring the presence of both a lepton and a charged track with an accompanying calorimeter pattern consistent with a $\tau$ decaying hadronically were adopted for the $\tau\bar{\tau}e$ and $\tau\bar{\tau}\mu$ channels.

In all final states $W$+jets and $t\bar{t}$ background events are reduced by requiring that the reconstructed $E_T$ points in the direction of the visible tau decay products. Events with additional leptons are rejected to suppress $Z/\gamma^*$ processes. The contributions of QCD multi-jet, $W$+jets and the dominant irreducible $Z \rightarrow \tau^+\tau^-$ background are determined using data, while predictions for other background processes, such as $t\bar{t}$ and di-boson processes, are obtained from Monte Carlo (MC) simulation.

The event yields observed in the distributions of $M_{\tau\tau}$, in a dataset corresponding to an integrated luminosity of $17\,\text{fb}^{-1}$, with and without b-tagged jets, is in agreement with the expectation for SM background processes, and no evidence for a MSSM Higgs signal is seen.

Therefore, an upper bound on the product of the MSSM Higgs boson cross-section and the tau-pair branching fraction, $\sigma_{\Phi} \cdot BR_{\tau\tau}$, is set. The limit is computed as function of the mass of the pseudoscalar Higgs, $m_A$, by fitting the $M_{\tau^+\tau^-}$ distribution observed in all decay channels with shape templates for different Higgs mass hypotheses, obtained from MC simulation. These upper limits, interpreted in the MSSM parameter space of $\tan\beta$ versus $m_A$ in the $m_{\text{max}}$ scenario [21, 22], provide stringent bounds on $\tan\beta$, shown in Figure 1 (right).

3.2. Higgs into $b\bar{b}$
A search for MSSM neutral Higgs bosons produced in association with at least one $b$ quark, and decaying into a pair of $b$ quarks is performed using $2.7 - 4.8\,\text{fb}^{-1}$ of proton-proton collisions collected by CMS in 2011 with a center-of-mass energy of 7 TeV.

A signal is searched for in final states characterized either purely by jets (“all-hadronic”)
or with an additional non-isolated muon ("semileptonic"). Events are selected by specialized triggers that exploit online algorithms for the identification of b jets to tackle the large hadronic interaction rate at the LHC. The selected data sets are largely exclusive, and the small overlap (of the order of 2.3%) is removed for the combined results.

The dominant background is the production of heavy-flavor multijet events, while other background processes, such as $t\bar{t}+\text{jets}$ and $Z\rightarrow b\bar{b}+\text{jets}$, are predicted by the MC simulation to be less than 1% of the total background.

The common analysis strategy is to search, in events identified as having at least three b jets, for an excess of events in the invariant mass distribution of the two leading b jets, $M_{12}$, over the large multi-jet background. The QCD multi-jet background is not fully reducible nor well described by MC simulations, therefore a key point of both analyses is the estimation of the background using control data samples.

In the all-hadronic analysis the background modeling is done with a method similar to the one used in Ref. [23]. Two-dimensional (2D) templates on $M_{12}$ and EvtBTag (variable which reflects the b-jet content of the event) of the different flavour compositions of the background are constructed from a double-b-tag data sample. Signal templates are built using MC simulations. A 2D fit of a linear combination of the background-only templates shows good agreement between data and the background estimation. According to the fit the three b-jets production is dominant contribution to the background. The signal yield is extracted by fitting a linear combination of signal and background templates. The result of the fit projected on the $M_{12}$ variable for a Higgs boson mass hypothesis of 200 GeV is shown in Figure 2 (left).

![Figure 2](image-url)

Figure 2. Left: results from the all-hadronic analysis. Di-jet mass distribution resulting from the fit with an additional signal template for a MSSM Higgs boson ($m_A = 200$ GeV). The fitted mass distribution of the Higgs contribution is shown a second time as the dashed histogram at the bottom of the figure. Right: results from the semileptonic analysis. Data (red point) and predicted background (blue line) in the signal region; the expected signal for different $m_A$ and for $\tan\beta = 30$ is also plotted. The difference between data and predicted background is also shown: the blue area represent the systematical and statistical uncertainties on the background prediction.
Figure 3. Observed upper limits at 95% CL on $\tan\beta$ as a function of $m_A$, including the statistical and systematic uncertainties, in the $m_{h_{\text{max}}}^{\text{max}}$ scenario with $\mu = -200$ GeV for the combined all-hadronic and semileptonic results. One- and two-standard deviation ranges for the expected upper limit are represented by the gray bands. Previous exclusion regions from LEP [?] and Tevatron the multi-b jet channel [?] are overlaid.

In the semileptonic analysis two methods have been developed to predict the expected background. The first one, using double-b-tag samples (bbj), is based on the computation of b-tagging probabilities of the third jet to predict the background in the signal region; and the second one, which makes use of the bjj and bib samples, is based on a nearest-neighbor-in-parameter-space technique. Because the two methods use exclusive data samples, their results is combined by performing a weighted average of their bin-by-bin predictions. The predicted background is shown in Figure 2 together with the expected signal for two Higgs boson masses at $\tan\beta = 30$. A binned likelihood fit to the invariant mass distribution of the two leading jets in the event is used in order to extract a possible MSSM Higgs contribution.

No significant deviation from the SM background is observed in neither the all-hadronic nor the semileptonic analysis. Both analysis are combined and the 95% CL upper limit on the signal contribution in the data, in terms of cross section times branching fraction, is extracted. Figure 3 (left) presents the results in the MSSM framework as a function of the MSSM parameters $m_A$ and $\tan\beta$, in the $m_{h_{\text{max}}}^{\text{max}}$ scenario [? ,?], with $\mu = +200$ GeV. Figure 3 (right) shows the results in the scenario with $\mu = -200$ GeV, together with previous limit set by LEP [24] and Tevatron [25].

3.3. Higgs into $\mu^+\mu^-$

Events in the $\phi \rightarrow \mu^+\mu^-$ channel are selected by requiring two isolated muons of opposite charge, with $p_T > 30$ GeV and 20 GeV for the leading and the subleading muon, respectively, within the pseudo-rapidity range $|\eta| < 2.1$.

In order to enhance the sensitivity of the search, the statistical analysis is performed in three distinct event categories: events in the first category are required to contain a b-tagged jet of $p_T > 20$ GeV and $|\eta| < 2.1$; the second category is defined by events with at least three muons in the final state, in this case the selection on the third muon is relaxed ($p_T > 3$ GeV and $|\eta| < 2.4$); while events which satisfy neither requirement enter the third category. Events with b-tagged jets and enriched by soft muon are more likely to come from b-associacion
production process, while the other events are candidates for gluon-gluon fusion production.

The events coming from $t\bar{t}$ processes are suppressed by cutting on the $E_T$. DrellYan muon pair production $Z/\gamma^* \rightarrow \mu^+\mu^-$ is the dominant background. The contribution of this irreducible background is estimated by fitting the distribution of the leading two muon mass, $M_{\mu\mu}$, in sidebands of the region where the signal is expected. The result of the fit is then extrapolated into the signal region.

The distribution of $M_{\mu\mu}$ observed in data is shown in Figure 4 (left), as well as for the expected backgrounds and signal sample. The shape of the signal exhibits two peaks: one representing the light scalar $h$ and the other representing heavy scalar $H$ plus pseudoscalar $A$. The contribution of individual Higgs bosons can be resolved owing to the excellent mass resolution, about $2 \div 3\%$ in this channel.

No evidence for a signal is observed in the analyzed dataset corresponding to an integrated luminosity of $5.0 \, fb^{-1}$ and therefore an upper limit at 95% CL is set on the cross section times the branching fraction into two muons as function of the pseudoscalar Higgs bond mass. Such a limit is interpreted within the MSSM framework in the $m_{h}^{max}$ scenario and the region in MSSM $\tan \beta - m_A$ parameter space excluded by this analysis is shown in Figure 4 (right).

**Figure 4.** Left: di-muon invariant mass distribution for the sum of the different categories. The expected $M_{\mu\mu}$ distribution for the decay $\phi \rightarrow \mu^+\mu^-$, with the hypothesis $m_A = 150 \, GeV$ and $\tan \beta = 30$ is superimposed. The different background contributions are reported as well. Right: the combined exclusion limit for the MSSM production cross-section times the BR at 95% CL projection in the ($m_A - \tan \beta$) plane (b).

4. **Search for charged MSSM Higgs in top quark events**

In CMS, the search for the charged Higgs boson is done in the low $H^\pm$ mass regime, when $m_{H^\pm} < m_{top}$ [26]. In such a scenario, the Higgs boson may be produced in top quark decays, $t \rightarrow H^\pm b$, and then, for $\tan \beta$ greater than 5, it preferentially decays to a $\tau$ lepton and a neutrino, $H^\pm \rightarrow \tau \nu_{\tau}$. The presence of such a decay mode process alters the $\tau$ lepton yield in the decay products of $t\bar{t}$ pairs compared to the SM predictions. The search for an excess of tau lepton events in the $t\bar{t}$ sample is, therefore, a direct way to search for beyond SM physics.

The upper limit on the branching fraction, $BR(t \rightarrow H^\pm b) < 0.2$, has been set by the
CDF and D0 experiments at the Tevatron for $m_{H^\pm}$ between 80 and 155 GeV, assuming $BR(H^\pm \to \tau \nu_{\tau}) = 1$. More recently, the ATLAS experiment at the LHC has set the upper limit on the $BR(t \to H^\pm b)$ between 5% and 1% for charged Higgs boson masses in the range $90 \div 160$ GeV.

CMS has studied three final states separately, using a dataset at 7 TeV corresponding to an integrated luminosity of $2.0 \div 2.3 \text{ fb}^{-1}$, all requiring presence of a $\tau$ lepton from $H^\pm$ decays, missing transverse energy, and multiple jets: (1) a $\tau$ lepton that decays to hadrons accompanied by jets ($\tau_h$+jets), (2) $\tau_h$ produced in association with an electron or a muon ($\tau_e\mu$ or $\tau_\mu\mu$), and (3) an electron and a muon ($e\mu$).

The largest background contributions in these analyses come from the irreducible $t\bar{t}$ di-tau channel, and from tau fakes, where one jet fakes the tau. The main background ($\tau$-fake) is from events where one W boson is produced in association with jets, and from $t\bar{t} \to W^- bW^+ b \to l\nu qq' b\bar{b}$ events. The data driven method used in the estimate of the $\tau$-fake background is described in Ref.[27]. The non-$\tau$-fake backgrounds, like $Z/\gamma^* \to \tau^+\tau^-$, single top production, di-bosons, and the part of the SM $t\bar{t}$ background not included in the $\tau$-fake background are estimated from MC.

A good agreement between data and SM expectations is found at various levels of the events selections. Therefore, an upper limit on the branching fraction $BR(t \to H^\pm b)$ is set using the CLs method, assuming $BR(H^\pm \to \tau \nu_{\tau}) = 1$. The inputs to the limit computation are: the number of observed and expected events in the $\tau_h e$ and $\tau_h \mu$ as well as the $e\mu$ channels; and the observed and expected distribution of the transverse mass (built by the $\tau_h$ candidate and the $E_T$) in the $\tau_h$+jets channel. The upper limit on $BR(t \to H^\pm b)$ as a function of $m_{H^\pm}$ obtained from the combination of all final states is shown in Figure 5 (left). Figure 5 (right) shows the exclusion region in the MSSM $m_H^\mp - \tan \beta$ parameter space obtained from the combined analysis for the MSSM $m_h^{max}$ scenario.

**Figure 5.** Left: the upper limit on $BR(t \to H^\pm b)$ as a function of $m_{H^\mp}$, assuming $BR(H^\pm \to \tau \nu_{\tau}) = 1$, obtained from the combination of the all final states. The green and yellow bands show the ±1 and ±2σ bands, respectively, around the expected limit. Right: the exclusion region in the MSSM $m_H^\mp - \tan \beta$ parameter space obtained from the combined analysis for the MSSM $m_h^{max}$ scenario. The ±1 and ±2 sigma bands around the expected limit are also shown.
5. Conclusion

The production of neutral and charged MSSM Higgs bosons in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV has been studied using data recorded by the CMS experiment. No evidence for a signal is found in a dataset corresponding to an integrated luminosity of $2.0_{-0.17}^{+1.0}$ fb$^{-1}$. The non-observation of a signal excludes previously unexplored regions of MSSM parameter space.

In particular, the $\phi \rightarrow \tau^+\tau^-$ analysis sets stringent new bounds in the parameter space, excluding at 95% CL values of $\tan\beta$ as low as 6 up to $m_A=250$ GeV in the $m_{h_{\text{max}}}$ benchmark scenario.

Moreover, the $\phi \rightarrow b\bar{b}$ channel provides the most stringent limits on neutral Higgs boson production and decay in multi-$b$-jet mode and exclude the 2$\sigma$ excess reported by CDF [23].

The $\phi \rightarrow \mu^+\mu^-$ analysis which has an excellent mass resolution (2 ÷ 3%) does not see any tension with respect to SM predictions.

Finally, the search for a light charged Higgs boson provides stringent upper limits on the branching fraction $BR(t \rightarrow H^\pm b)$ in the range of 2 ÷ 4% for charged Higgs boson masses between 80 and 160 GeV, under the assumption that $BR(H^\pm \rightarrow \tau\nu_\tau) = 1$.

References