# Search for Higgs Bosons Beyond the Standard Model with the CMS Detector

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After a Higgs boson with a mass near 125 GeV has been discovered, it is still unclear whether this is the Higgs boson predicted by the standard model (SM). Various models with extended Higgs sectors are being considered, such as the minimal supersymmetric extensions of the SM. Recent results of searches for non-SM Higgs bosons with the CMS detector are presented, which are based on pp collision data collected at centre-of-mass energies of 7 and 8 TeV corresponding to integrated luminosities of about 5 and 20 $\mathrm{fb}^{-1}$.

While the recently discovered Higgs boson with a mass near 125 GeV [1] is consistent with the standard model (SM) expectations, non-SM couplings are only excluded up to branching ratios of $\approx 30\%$ with the current data [2]. Furthermore, numerous BSM models predict extended Higgs sectors. The minimal supersymmetric extension (MSSM) [3], for example, requires two complex Higgs doublets, one of which couples to the u-type and one to the d-type fermions. After electroweak symmetry breaking, five physical states remain: a light and a heavy CP-even boson h and H, an CP-odd boson A, all of which are neutral and collectively denoted $\Phi$, and two charged bosons $\mathrm{H}^{\pm}$. At tree level, the MSSM Higgs sector is completely defined by two parameters, conventionally chosen as the mass $m_{\mathrm{A}}$ of the CP-odd boson and the ratio $\tan\beta$ of the vacuum expectation values of the two doublets.

In this article, recent results of direct searches both for additional Higgs bosons and for non-SM decays of the 125 GeV boson conducted by the CMS experiment [4] at the LHC are reviewed: a search for a heavy neutral Higgs boson $\Phi \to \tau\tau$, for a light charged Higgs boson $\mathrm{H}^{+} \to \mathrm{c\bar{s}}$, and for lepton-flavour violating Higgs boson decays $\mathrm{H} \to \mu\tau$. The analyses are performed with 4.9 and 19.7 $\mathrm{fb}^{-1}$ of data collected at centre-of-mass energies $\sqrt{s}$ of 7 and 8 TeV, respectively. A particle-flow algorithm [5] is used to reconstruct the individual particles in the events, from which hadronically decaying taus $\tau_{\mathrm{h}}$, the missing transverse momentum $\not\!\!E_{\mathrm{T}}$, and jets are clustered. Jets initiated by b-quarks are identified (b-tagged) with a likelihood discriminant combining track-based lifetime and secondary-vertex information [6].

## 1 Searches for heavy neutral Higgs bosons

At the LHC, the neutral MSSM Higgs bosons $\Phi$ are expected to be predominantly produced either in gluon-gluon fusion or in b-quark associated production. For larger values of $\tan\beta$, the latter mode dominates, and at the same time, the branching fraction ($\mathcal{B}$) to $\tau$ leptons is also enhanced relative to the SM over the whole $m_{\mathrm{A}}$ range. CMS has performed a search for $\Phi \to \tau\tau$ using the full 25 $\mathrm{fb}^{-1}$ of the 7 and 8 TeV data and considering five $\tau\tau$ final-states, $\mathrm{e}\tau_{\mathrm{h}}$, $\mathrm{e}\mu$, $\mu\tau_{\mathrm{h}}$,

$\mu\mu$, and $\tau_h\tau_h$ [7]. Events are collected using a combination of e, $\mu$, and $\tau_h$ triggers, whose criteria varied during the data-taking periods. Offline, events are further selected requiring two oppositely charged, well isolated leptons. Additional channel-dependent selection criteria are applied to suppress contributions from SM background processes; for example, in the $\mu\tau_h$ channel the transverse mass of the $\mu$ and the $\not{E}_T$ is required to be less than 30 GeV to reject W+jets events. Moreover, the selected events are split into two categories of either 0 or $\geq 1$ b-tagged jets to enhance the sensitivity to the different production modes.

The invariant mass $m_{\tau\tau}$ of the di-$\tau$ system is reconstructed from the leptons and $\not{E}_T$ in the event using a maximum-likelihood technique based on a model of the $\tau$-decay phase-space and the $\not{E}_T$ resolution, which results into a relative mass resolution of typically 20% at 90 GeV. The $m_{\tau\tau}$ distribution observed in the $\mu\tau_h$ 0-b-tag channel is shown in Fig. 1 (left). The dominant SM background contribution arises from $Z \to \tau\tau$ events and is determined from data with an embedding technique, where the muons in $Z \to \mu\mu$ events are replaced by simulated $\tau$-decay products. Further important backgrounds are due to W+jets and QCD-multijet events with jets mis-identified as $\tau_h$ and $\mu$ and are estimated from signal-depleted control regions in data.

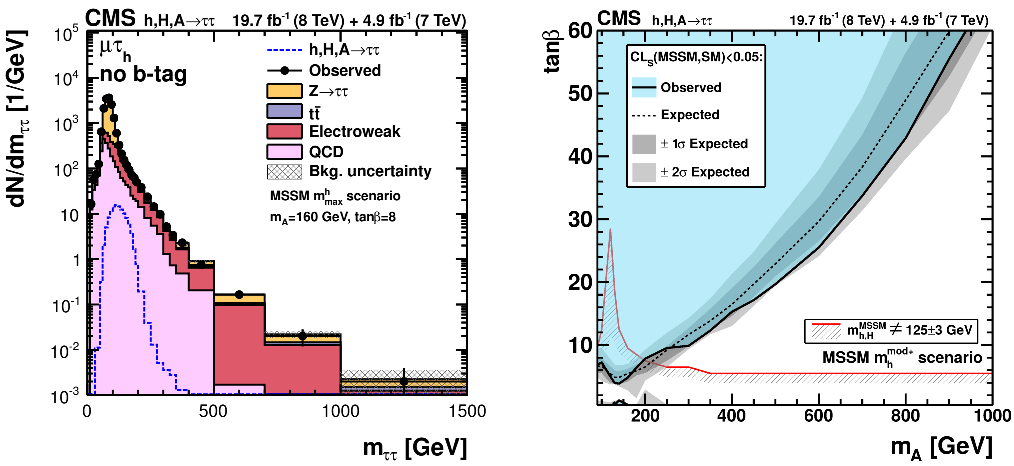


Figure 1: $m_{\tau\tau}$ distribution in the $\mu\tau_h$ 0-b-tag channel (*left*) and 95% C. L. exclusion limits on the MSSM parameters $m_A$ and $\tan\beta$ (area above the black lines is excluded) in the $m_h^{mod+}$ scenario (*right*); the region above the red line is compatible with a 125 GeV Higgs boson.

In all channels, the observed data agree well with the SM-only expectation. Thus, model-independent upper limits are derived on the resonance production rate $\sigma \times \mathcal{B}(\Phi \to \tau\tau)$. The results are also interpreted as constraints on the MSSM parameters, expressed as limits at 95% confidence level (C. L.) in $(\tan\beta, m_A)$ space assuming the other MSSM parameters to be fixed at certain benchmark values. In all cases, the signal hypothesis is tested against a background plus SM-Higgs hypothesis, thus taking into account the Higgs boson at 125 GeV. Likewise, the MSSM interpretation is not only performed in the traditionally used $m_h^{max}$ benchmark scenario but also in several other recently proposed scenarios [8] that are compatible with either h or H having a mass of 125 GeV in most parts of the parameter space. This is not the case in the $m_h^{max}$ scenario, which is therefore disfavoured by data. The sensitivity in the $m_h^{mod+}$ scenario [8], for example, reaches up to $m_A = 1$ TeV and down to $\tan\beta = 5$ at low $m_A$, cf. Fig. 1 (right).

## 2 Search for light charged Higgs bosons

If the charged Higgs boson $H^+$ predicted by the MSSM is lighter than the mass difference of the t- and b-quarks, t quarks can decay as $t \rightarrow H^+b$, and if $\tan\beta < 1$, the $H^+$ decays predominantly to a $c\bar{s}$-quark pair (charge conjugation is implied). CMS has performed a search for light $H^+$ bosons in $t\bar{t} \rightarrow H^+(\rightarrow c\bar{s})bW^-(\rightarrow \mu\nu)b$ events in 19.7 $\mathrm{fb}^{-1}$ of data at $\sqrt{s} = 8$ TeV [9].

Events are collected triggering on an isolated $\mu$ with $p_T > 24$ GeV. Offline, exactly one $\mu$ is required to suppress contributions from Z+jets and $t\bar{t}$ events. Furthermore, four central jets with $p_T > 30$ GeV, two of which are b-tagged, and $\not{E}_T > 20$ GeV are required. After this selection, the expected SM contributions arise almost exclusively from $t\bar{t}$ events in the semi-leptonic decay channel. Assuming that the $t\bar{t}$ production cross-section remains un-altered, a signal would manifest in the invariant dijet-mass distribution of the two non-b-tagged jets as a deficit of events at the W mass and an excess at the $H^+$ mass compared to the SM expectation due to the additional decay-channel. The mass resolution is significantly improved using a kinematic fit to reconstruct the $t\bar{t}$ event, where the t-quark mass is constraint to 172.5 GeV.

Since no significant deviation is observed, model-independent upper limits at 95% C. L. on $\mathcal{B}(t \rightarrow H^+b)$ are derived assuming $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 100\%$, cf. Fig. 2 (left). The limits range from 2 to 7% for $H^+$ masses between 90 and 160 GeV.

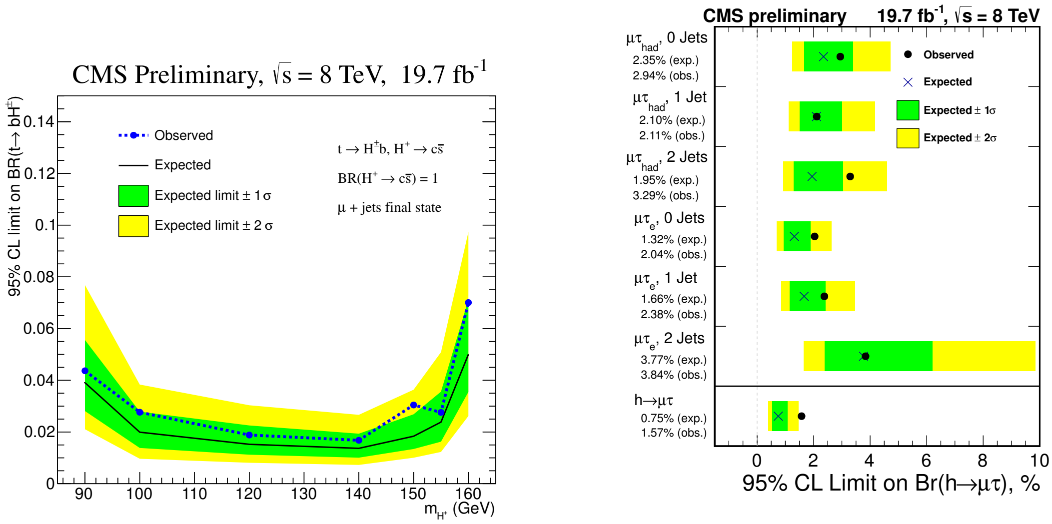


Figure 2: Upper limits at 95% C. L. on $\mathcal{B}(t \rightarrow H^+b)$ assuming $\mathcal{B}(H^+ \rightarrow c\bar{s}) = 100\%$ (*left*) and on $\mathcal{B}(H \rightarrow \mu\tau)$ in the different channels and their combination (*right*).

## 3 Search for lepton-flavour violating Higgs boson decays

While lepton-flavour violating (LFV) Higgs boson decays are not allowed in the SM, they can occur naturally in various BSM models such as composite-Higgs and Randall-Sundrum models. CMS has performed the first direct search for LFV decays $H \rightarrow \mu\tau$ of the 125 GeV Higgs boson in the $\mu\tau_e$ and $\mu\tau_h$ final states using 19.7 $\mathrm{fb}^{-1}$ of 8 TeV data [10].

Events are collected triggering on an isolated $\mu$ and e with $p_\mathrm{T}$ above 17 and 8 GeV, respectively, in the $\mu\tau_\mathrm{e}$ channel and an isolated $\mu$ with $p_\mathrm{T} > 17\,\mathrm{GeV}$ in the $\mu\tau_\mathrm{h}$ channel. Offline, the leptons are required to have opposite charge, and events are further divided into jet-multiplicity categories to enhance the sensitivity to different production modes. Further selection criteria to suppress SM contributions exploit that the $\mu$ in signal events stems promptly from the LFV decay and thus tends to have larger $p_\mathrm{T}$ than in SM $\mathrm{H} \to \tau_\mu\tau_{\mathrm{e/h}}$ events for example. An important residual background arises from $\mathrm{Z} \to \tau\tau$ and is estimated from data using the aforementioned embedding technique. Depending on the channel, further main backgrounds are due to W+jets, QCD-multijet, and $\mathrm{t\bar{t}}$ events, in which jets are mis-reconstructed as leptons or $\tau_\mathrm{h}$ and which are determined from control regions in data using estimates of the mis-reconstruction rate. The invariant $\mu\tau$ mass is approximated from the $\mu$, the visible $\tau$ decay products $\tau_\mathrm{vis}$, and the $\not\!\!E_\mathrm{T}$ component along $\tau_\mathrm{vis}$, which is assumed to be collinear to the $\nu$ due to the high boost of the $\tau$.

No significant excess of events above the SM expectation is observed in the mass distributions. The combined upper limit at 95% C. L. on the LFV $\mathcal{B}(\mathrm{H} \to \mu\tau)$ is $(0.75 \pm 0.38)\%$ expected and 1.57% observed, cf. Fig. 2 (right). Interpreted as signal, it corresponds to $\mathcal{B}(\mathrm{H} \to \mu\tau) = (0.89^{+0.40}_{-0.37})\%$, i. e. a significance of 2.5 standard deviations. The limit is also translated into constraints on $\mu\tau$ Yukawa couplings, improving earlier results from indirect measurements by an order of magnitude.

# 4 Conclusions

CMS has performed a wide variety of searches both for non-SM properties of the 125 GeV Higgs boson and for additional Higgs bosons. In this article, searches for heavy neutral and for light charged Higgs bosons as well as for lepton-flavour violating decays have been discussed, which have been performed with up to $25\,\mathrm{fb}^{-1}$ of 7 and 8 TeV data. No significant deviation from the SM is observed, and the results are used to derive valuable constraints on the BSM-Higgs parameter space, which mostly exclude for example the low-$\mathrm{m_A}$ region of the MSSM.

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