PROCEEDINGS OF SCIENCE

Searches for Extended Higgs Sectors at CMS

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The results of several searches for additional neutral and charged Higgs bosons are presented, using data collected with the CMS detector at $\sqrt{s}$ = 13 TeV, corresponding to an integrated luminosity of 138 fb^{-1}. The searches for neutral Higgs bosons target the decays into $\tau\tau$, WW, and pairs of lighter Higgs bosons. Each of these searches observes modest excesses of data with respect to the background expectation with local significances in the range of 3.1–3.8 standard deviations. The search for a charged Higgs boson targets its decay into a W and a neutral Higgs boson. No significant excess of data with respect to the background-only hypothesis was observed.

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1. Introduction

The standard model (SM) Higgs sector predicts exactly one neutral spin-0 particle, the Higgs boson (h). In 2012 a particle with a mass of around 125 GeV was discovered [1, 2] which has properties consistent with those predicted by the SM. However, many extensions of the SM require or allow a more complex Higgs sector. These extended Higgs sectors usually predict additional spin-0 states that can be searched for at the LHC. These additional states include neutral Higgs bosons with CP-even or CP-odd quantum numbers (referred to as H and A respectively or ϕ collectively in the following) and charged Higgs bosons ($H^{\pm}$). In these proceedings, the latest searches for additional Higgs bosons conducted by the CMS experiment [3] using 138 fb^{-1} of data at a centre-of-mass energy of 13 TeV are reviewed.

2. Searches for neutral Higgs bosons decaying into $\tau\tau$ or WW pairs

Extended Higgs sectors such as two Higgs doublet models predict the existence of additional H and A bosons. The couplings to down-type particles, including and τ leptons, are enhanced over a large proportion of the parameter space. The $\tau\tau$ channel is thus sensitive to these scenarios. The $\tau\tau$ pairs are reconstructed in final states where both decay hadronically ($\tau_h\tau_h$), one decays leptonically and the other hadronically ($e\tau_h$ and $\mu\tau_h$), and where one decays into an electron and the other to a muon ($e\mu$). The search targets masses between 60–3500 GeV, where different strategies are employed for the $m_\phi \leq 200$ GeV and $m_\phi > 200$ GeV ranges. The events are divided into "no b-tag" and "btag" categories requiring that exactly zero or at least one b-tagged jets are present in the event that target production via gluon-fusion (ggϕ) and in association with b quarks (bbϕ), respectively. For the $m_\phi \leq 200$ GeV search, a further categorisation based on the reconstructed ϕ transverse momentum p_T is used, and the di-τ mass $m_{\tau\tau}$ (estimated as described in Ref. [4]) is the discriminating variable used to extract the signal. For the $m_\phi > 200$ GeV search, the total transverse mass of the $\tau\tau$ pair m_T^{tot} [5] is used for signal extraction. An example $m_{\tau\tau}$ distribution is shown in Fig 1 (left). Full details of the analysis strategy can be found in Ref. [5].

The search reveals no significant excess with respect to the background prediction for the bbϕ process. For the ggϕ search, the largest deviation from the background expectation is observed at $m_\phi = 100$ GeV with a local (global) significance of 3.1 (2.7) standard deviations (s.d.). Exclusion limits at 95% confidence level (CL) are set on the product of the cross section and branching fraction, as displayed in Fig 1 (right).

A search is also presented for Higgs bosons decaying into WW pairs. This analysis reconstructs WW pairs in the leptonic final states. The search targets the mass region between 115–5000 GeV and H production via ggϕ and vector boson fusion (VBF). A deep neural network (DNN) is used to classify candidate events into "ggF", "VBF", and "background" categories depending on whether the events have a ggϕ-like, VBF-like, or background-like signature. The WW transverse mass m_T, regressed by a DNN-based algorithm, is used as the discriminating variable in each category. An example of the m_T distribution in the VBF category is shown in Fig 2 (left). Full details of the analysis strategy can be found in Ref. [6]. The largest deviation from the background expectation is observed for the VBF production with a local (global) significance of 3.8 (2.6) s.d. for a mass of

m_H = 650 GeV. Exclusion limits at 95% confidence level (CL) are set on the product of the cross section and branching fraction, as displayed in Fig 2 (right).

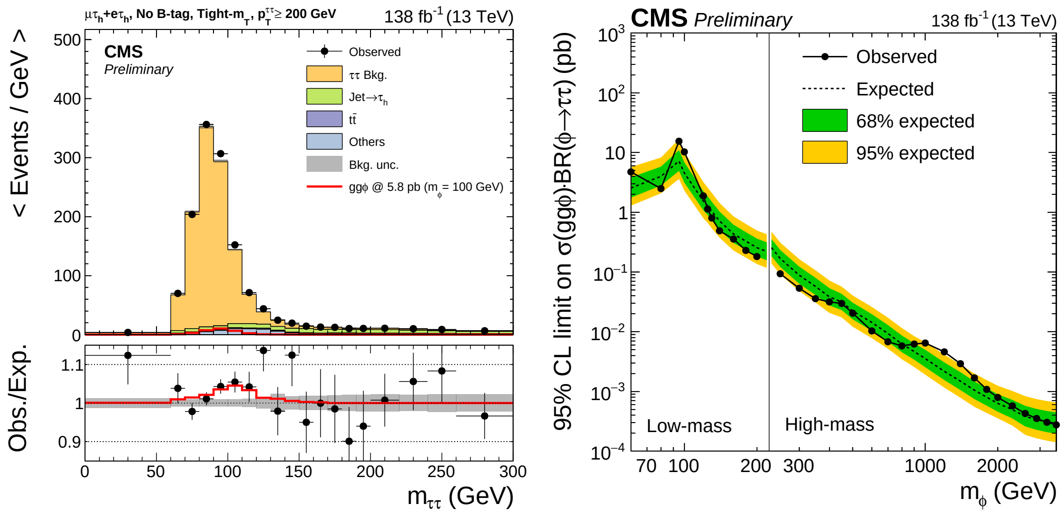

Figure 1: Left: The $m_{\tau\tau}$ distribution in the p_T > 200 GeV "no b tag" category for the $\mu\tau_h$ and $e\tau_h$ final states. Right: The observed and expected 95% CL exclusion limits on the product of the ϕ production cross section and the $\phi \to \tau\tau$ branching fraction for the ggϕ production processes. Figures taken from Ref. [5].

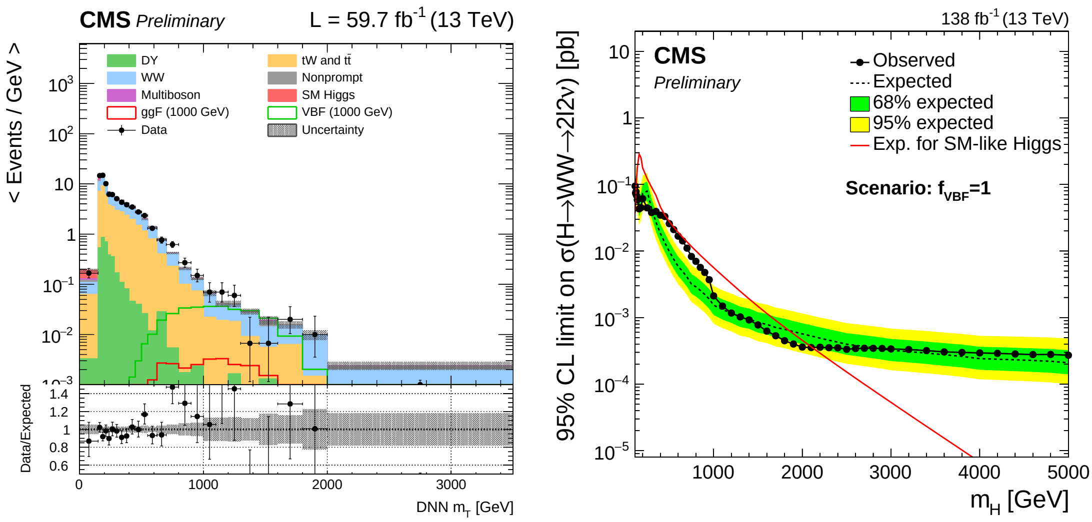

Figure 2: Left: The m_T distribution for the data collected in 2018 in the VBF category. Right: the observed and expected 95% CL exclusion limits on the product of the VBF H production cross section and the branching fraction for the H $\to$ WW $\to 2l2\nu$ decay process. Figures taken from Ref. [6].

3. Searches for heavy neutral Higgs bosons decaying into two lighter Higgs bosons

In models that include multiple Higgs bosons it is possible for the more massive bosons to decay into two lighter ones. The heavier boson, called "X" by convention, may decay into two

SM-like Higgs bosons (X → hh), or one SM-like Higgs boson and a new lighter (pseudo)scalar "Y" (X → Yh). Two searches are presented that search for the X → hh process in the bb$\gamma\gamma$ and "multi-lepton" final states. The bb$\gamma\gamma$ final state is also used to search for the X → Yh process.

The multi-lepton analysis targets hh pairs decaying into WWWW, WW$\tau\tau$, and $\tau\tau\tau\tau$, where final states with multiple reconstructed leptons are targeted. Events are selected and categorised based on the number of reconstructed light leptons (electron or muons), and hadronically decaying τ lepton candidates. In each category, a boosted decision tree (BDT) classifier is trained to separate the signal and background events. Events are binned into distributions of the BDT output score which is then fitted to extract the signal. An example of a BDT score distribution is shown in Fig. 3 (left). No significant excess of data with respect to the background prediction is observed and exclusion limits at 95% CL are set on the product of the cross section and branching fraction, as shown in Fig. 3 (right). Full details of the analysis strategy can be found in Ref. [7].

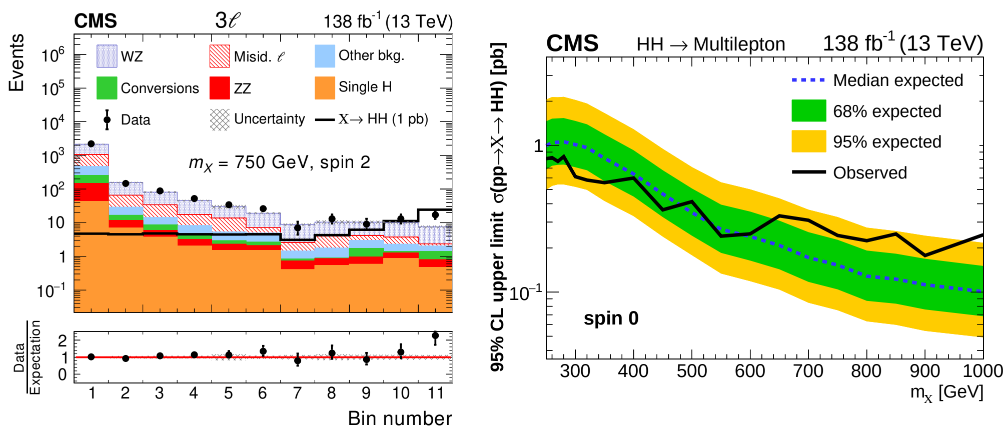

Figure 3: Left: Distribution of the BDT classifier output for a X resonance with a mass of 750 GeV in the $3l$ category. Right: The observed and expected 95% CL exclusion limits on the product of the X production cross section and the branching fraction for the X → hh decay process. Figures taken from Ref. [7].

The bb$\gamma\gamma$ search uses a BDT to reject the continuum background from γ + jets and $\gamma\gamma$ + jets events. Events are categorised based on the BDT output score. The search targets scenarios where a SM-like Higgs boson decay into photons (h → $\gamma\gamma$) and the other light Higgs boson decays into b quarks (h/Y → bb) producing two b-tagged jets in the final state. For each targeted X and Y hypothesis, the invariant masses of the bb$\gamma\gamma$ ($m_{\gamma\gamma\mathrm{jj}}$), $\gamma\gamma$ ($m_{\gamma\gamma}$), and bb (m_{jj}) systems, and the pole masses of the Y and h particles (m_{Y} and m_{h}), are used to reconstruct the variable $\tilde{M}_{\mathrm{X}} \equiv m_{\gamma\gamma\mathrm{jj}} - (m_{\gamma\gamma} - m_{\mathrm{h}}) - (m_{\mathrm{jj}} - m_{\mathrm{h,Y}})$, which is used to select events in a window around the target X mass. The signal is then extracted from an unbinned two-dimensional fit to the $m_{\gamma\gamma}$ and m_{jj} observables. Fig. 4 (left) displays the $m_{\gamma\gamma}$ distribution for the Y=h scenario. The largest deviation from the background expectation with a local (global) significance of 3.8 (2.8) s.d. occurs for m_{X} = 650 GeV and m_{Y} = 90 GeV. Exclusion limits at 95% confidence level (CL) are set on the product of the cross section and branching fraction as displayed in Fig 4 (right). Full details of the analysis strategy can be found in Ref. [8].

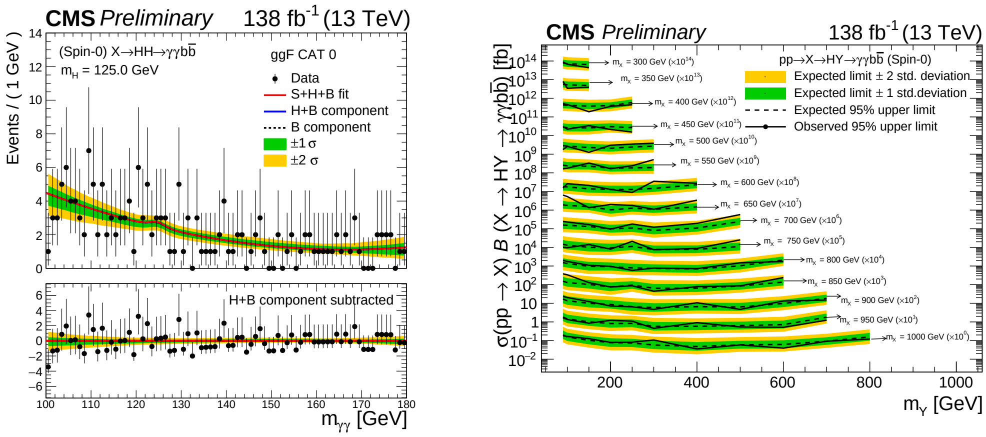

Figure 4: Left: The $m_{\gamma\gamma}$ distribution for a signal dominated category. Right: The observed and expected 95% CL exclusion limits on the product of the X production cross section and the branching fraction for the $\mathrm{X} \rightarrow \mathrm{hY} \rightarrow \mathrm{bb}\gamma\gamma$ decay process. Figures taken from Ref. [8].

4. Search for a charged Higgs boson

Finally, a search for a $\mathrm{H}^{\pm}$ decaying into a HW pair is presented. The $\mathrm{H}^{\pm}$ is produced in association with a t and b quark, leading to final states with additional b-tagged jets. The t quark is identified using a resolved top quark tagging algorithm based on a DNN. The H is assumed to have a mass of 200 GeV and is targeted via decay into $\tau\tau$ pairs in the $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$, $\mathrm{e}\tau_{\mathrm{h}}$, and $\mu\tau_{\mathrm{h}}$ final states. The W is reconstructed in both hadronic and leptonic decay channels. Several final states are possible depending on the W and $\tau\tau$ decays. The analysis targets the four most sensitive final states: $\mu\tau_{\mathrm{h}}\tau_{\mathrm{h}}$, $\mathrm{e}\tau_{\mathrm{h}}\tau_{\mathrm{h}}$, $\mu\tau_{\mathrm{h}}$, and $\mathrm{e}\tau_{\mathrm{h}}$. In the $\mu\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ and $\mathrm{e}\tau_{\mathrm{h}}\tau_{\mathrm{h}}$ channels, the reconstructed m_{T} of the $\mathrm{H}^{\pm}$ is used as the discriminating variable, while a BDT based discriminant is used for the $\mu\tau_{\mathrm{h}}$ and $\mathrm{e}\tau_{\mathrm{h}}$ channels. An example of the m_{T} distribution is shown in Fig. 5 (left). No significant excess of data with respect to the background prediction is observed and exclusion limits at 95% CL are set on the product of the cross section and branching fraction, as shown in Fig. 5 (right). Full details of the analysis strategy can be found in Ref. [9].

5. Summary

The results of several searches for additional neutral and charged Higgs bosons are presented, using data collected with the CMS detector at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 138 fb^{-1}. The searches for neutral Higgs bosons target the decays into $\tau\tau$, WW, and pairs of lighter Higgs bosons. Each of these searches observes modest excesses of data with respect to the background expectation with local significances in the range of 3.1–3.8 standard deviations, however, the results are largely consistent with the background-only hypothesis. The search for a charged Higgs boson targets its decay into a W and a neutral Higgs boson. No significant excess of data with respect to the background-only hypothesis was observed.

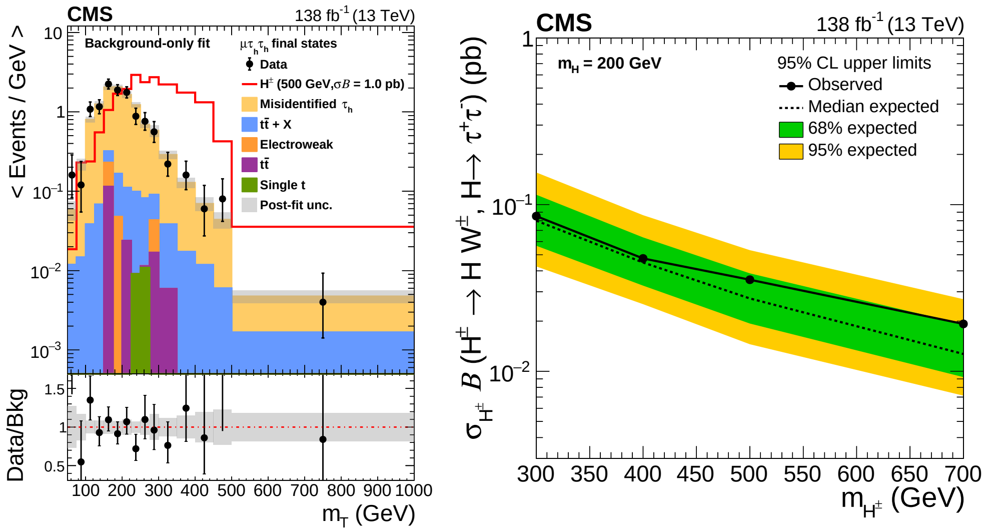

Figure 5: Left: The m_T distribution for the $\mu\tau_h\tau_h$ final state after a background-only fit to the data. Right: The expected and observed 95% CL exclusion limits on the product of the $H^\pm$ production cross section and the branching fraction for the $H^\pm \to H(\to \tau\tau)W^\pm$ decay process. Figures taken from Ref. [9].

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