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Searches for BSM Higgs bosons at ATLAS and CMS

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Several beyond-the-Standard-Model (BSM) theories predict an extended Higgs sector, which motivates searches for neutral and charged Higgs bosons in addition to the Higgs boson already observed at 125 GeV. Run 2 of the LHC was completed in 2018 and provided a total of 139 fb^{-1} of data giving an opportunity to further explore the BSM Higgs parameter space. This proceeding discusses searches for BSM Higgs bosons at the ATLAS and CMS experiments with either the early (36 fb^{-1}) or full LHC Run 2 dataset.

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1. Introduction

Several beyond-the-Standard-Model (BSM) theories predict an extended Higgs sector. Typically these are two Higgs doublet models (2HDM) [1], which predict a total of five Higgs bosons: two neutral CP even (h, H), one neutral CP odd (A), and two charged ($H^{\pm}$). A well-known 2HDM is the Minimal Supersymmetric Model (MSSM) [2]. The MSSM scenario can be described at the tree level in terms of the mass of the CP-odd neutral Higgs (m_A) and the ratio of the vacuum expectation values of the two Higgs doublets ($\tan\beta$). hMSSM [3, 4] and m_h^{mod} [5] are commonly used as benchmark scenarios, but new M_h^{125} benchmarks [6] were proposed in 2019, which were designed to be compatible with the Run 2 results up until that point. Analyses set model-independent limits on the Higgs boson production cross section times branching ratio and interpret results for particular MSSM models in the m_A-$\tan\beta$ plane.

Any BSM model must be compatible with the existence of the neutral 125 GeV Higgs boson discovered in 2012 [7, 8]. The additional neutral Higgs bosons can either be lighter or heavier than 125 GeV and searches are carried out for both cases.

Run 2 of the LHC data taking was completed at the end of 2018. Many analyses using the ATLAS [9] and CMS [10] experiments have results based on a partial Run 2 dataset, corresponding to 36 fb^{-1}. The complete dataset of 139 fb^{-1} is now available. Some analyses already use this dataset, which will allow more remaining 2HDM phase space to be explored.

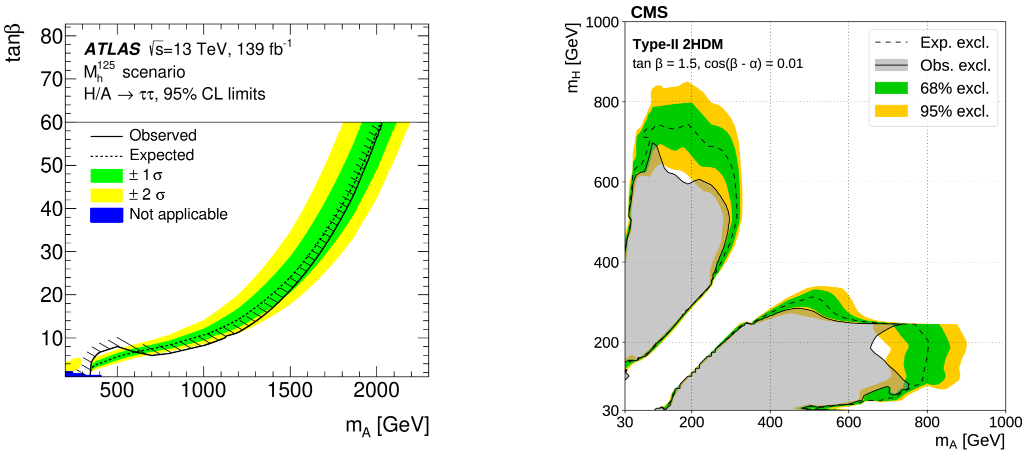
2. Neutral Higgs boson searches

An additional heavy neutral Higgs boson has many decays that can be studied at the LHC. Searches are either for the direct decay products of the Higgs bosons, or for decays via other Higgs and/or gauge bosons.

ATLAS published a search for $H/A \to \tau\tau$ with the full Run 2 dataset (139 fb^{-1}) [11]. In the MSSM for large $\tan\beta$ the couplings to both τ-leptons and b-type quarks are enhanced, meaning that this is a sensitive final state for that scenario. The analysis uses $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels, with electron/muon and single τ triggers respectively. Each is further split into a category containing a jet originating from a b-quark (b-tagged), and a category containing no b-associated jets (b-veto). This is to target each of the gluon fusion and b-associated production modes. In addition to the larger dataset, there were improvements in the Boosted Decision Tree (BDT) to distinguish τ_{had} from jets and in the background modelling when compared to the previous 36 fb^{-1} result [12]. Model independent limits were set on the b-associated and gluon fusion productions. For the MSSM, limits were set on both the hMSSM and the new M_h^{125} scenarios, the latter is shown in Figure 1a.

ATLAS and CMS both have results with 36 fb^{-1} for the $H \to \mu\mu$ channel [13, 14]. These search for a resonance in the observed di-μ spectrum. The analyses use a combination of a low-threshold trigger (20-26 GeV in ATLAS, 24 GeV in CMS) with a μ isolation requirement and a higher threshold (50 GeV) without the isolation. Similarly to $\tau\tau$, this also favours high $\tan\beta$ in the MSSM and is split into b-tagged and b-veto channels. The ATLAS analysis uses a looser event selection than CMS in order to not bias the search to a particular signal model. When assuming a narrow resonance, ATLAS sets upper limits at 95% confidence level on the cross section times branching ratio for b-associated and gluon fusion between masses of 200 GeV and 1000 GeV, with upper limits of 41 fb and 1.9 fb respectively. The CMS result extends the limits to 150 GeV and excludes down to 20 fb at 150 GeV and to 0.7 fb at 1000 GeV. The CMS analysis also includes results assuming an intrinsic width of 10% of the heavy Higgs boson mass and provides limits for the hMSSM and m_h^{mod} scenarios.

An example of a search for Higgs boson decays to bosons is the $H \to ZA \to \ell\ell b\bar{b}$ (or $A \to ZH$) channel, which has results with 36 fb^{-1} from both experiments [15, 16]. CMS presents results first assuming that m_H is greater than m_A, but then extends the result to the opposite case. ATLAS assumes that m_A is larger than m_H, which is motivated by the requirement for electroweak baryogenesis in 2HDM. The search combines the clean $\ell\ell$ final state with the large $b\bar{b}$ branching ratio and selects signals based on the dijet and dilepton masses. The CMS exclusion for type-II 2HDM is shown in Figure 1b.

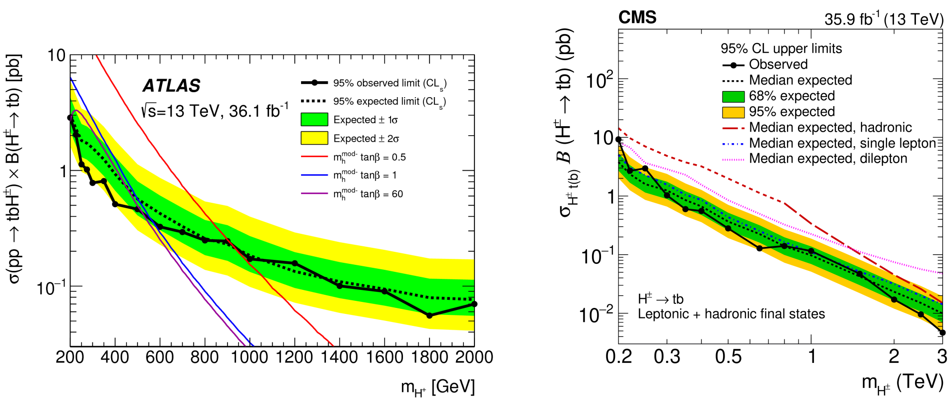


(a) **(b)**

Figure 1: Selected results from searches for heavy neutral BSM Higgs bosons. (a) Exclusion from the ATLAS $H/A \to \tau\tau$ search [11] for the M_h^{125} MSSM scenario. The blue region is where the mass splitting between the A and H bosons is significant when compared to the mass resolution, so the limit is not valid there. (b) Exclusion contours for type-II 2HDM with $\tan\beta = 1.5$ and $\cos(\beta - \alpha) = 0.01$ from the CMS $H \to ZA \to \ell\ell b\bar{b}$ analysis [16].

3. Charged Higgs boson searches

Any 2HDM contains only singly charged Higgs bosons, but other BSM theories can introduce doubly charged Higgs bosons. One of the main channels to search for a singly charged Higgs boson is $H^\pm \to tb$. Typically the charged Higgs boson is produced in association with an additional tb pair in these analyses, which leads to final states containing leptons, jets, b-jets, and missing transverse energy. Therefore, they are classified into several categories based on the number of jets and b-jets in the final state, all of which employ single lepton triggers. Both ATLAS and CMS have results with 36 fb^{-1} of data [17, 18]. Multi-variate analysis (MVA) techniques are employed with dedicated training in each category. Figure 2a shows the 95% confidence level limit on the production cross section derived from the ATLAS search. In addition to $H^\pm \to tb$ searches with leptons, CMS released a result in the all-hadronic final state [19]. Here, all final state objects can be reconstructed, enabling a search for an excess in the tb invariant mass. A specialised jet trigger was used in this analysis. The limits are combined with the other channels and shown in Figure 2b.



(a) **(b)**

Figure 2: Limits on $H^+ \to tb$ production in association with tb. (a) ATLAS limits from ℓ + jets and $\ell\ell$ final states [17]. Three predictions from benchmark $m_h^{\text{mod}-}$ scenarios are shown. (b) CMS upper limit from a combination of leptonic [18] and hadronic [19] final states.

Another CMS result uses a new channel to search for $H^+ \to cs$ in the $bcs - b\ell\nu$ final state [20]. The invariant mass of the two non-b-jets is used as an observable, which is reconstructed using a kinematic fit on the reconstructed objects taking the top-quark mass as a constraint.

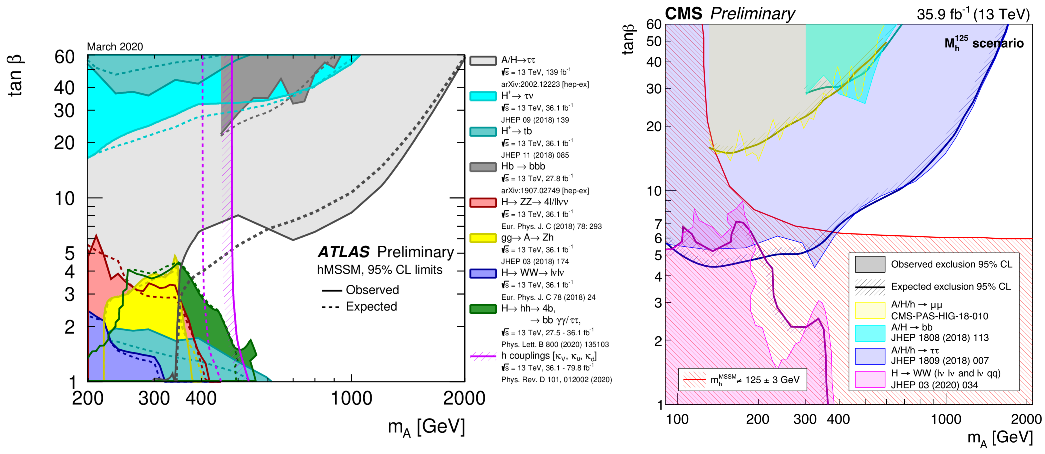
4. BSM Higgs bosons in di-Higgs searches

The Higgs self-coupling is an important aspect of the Standard Model, but the $pp \to HH$ production is predicted to have a small cross section. However, the presence of BSM physics can enhance the di-Higgs production via $gg \to X \to HH$. Therefore, analyses that set limits on the Standard Model process can also search for new BSM resonances in this channel.

The analyses generally have one Higgs boson decaying to $b\bar{b}$ thanks to its large branching ratio and combine this with another decay process. Both ATLAS and CMS have produced combinations of the different channels with 36 fb^{-1} of integrated luminosity [21, 22]. CMS includes the $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $b\bar{b}W^+W^-$, and $b\bar{b}b\bar{b}$ channels, ATLAS additionally includes $W^+W^-W^+W^-$ and $W^+W^-\gamma\gamma$. Upper limits on the $gg \to X \to HH$ production cross section range between ~700 fb at 300 GeV and ~0.6 fb at 3000 GeV. These channels set competitive limits on MSSM models at low $\tan\beta$.

5. Conclusion

There are 36 fb^{-1} searches for BSM Higgs bosons in many channels from both ATLAS and CMS. The full Run 2 dataset is now available, with a total of 139 fb^{-1} and the first analyses with the complete dataset are being released. It will take some time before enough Run 3 data is available to surpass these results. Figure 3 shows the current hMSSM limits for ATLAS and M_h^{125} limits for CMS.



(a) **(b)**

Figure 3: Excluded regions in the $\tan\beta$ versus m_A plane for MSSM scenarios. (a) Limits from ATLAS BSM Higgs searches for the hMSSM scenario [23]. (b) CMS limits on the M_h^{125} scenario [24].

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