PROCEEDINGS OF SCIENCE

Searches for BSM Higgs bosons in ATLAS

Ljiljana Morvaj*, **on behalf of the ATLAS Collaboration**
Stony Brook University, USA
E-mail: ljiljana.morvaj@cern.ch

The discovery of the Higgs boson with a mass of about 125 GeV completed the particle content predicted by the Standard Model. Even though this model is well established and consistent with many measurements, it is not capable of explaining all observations. Many extensions to the Standard Model introduce additional Higgs-like bosons which can be either neutral, singly-charged or even doubly-charged. Other theories suggest that the Higgs boson may couple to light hidden-sector states, resulting in exotic decays of the Higgs boson. The current status of searches based on Run 2 data of the ATLAS experiment at the LHC is presented.

European Physical Society Conference on High Energy Physics - EPS-HEP2019 -
10-17 July, 2019
Ghent, Belgium

*Speaker.

PoS(EPS-HEP2019)584

1. Introduction

Extended Higgs sectors are common in many well-motivated Beyond-the-Standard-Model (BSM) theories. They appear in models offering a solution to the hierarchy and dark matter problems, such as Supersymmetry [1], in models containing axions [2], or models explaining baryogenesis [3]. One of the simplest extensions of the Standard Model (SM) Higgs sector involves adding another SU(2) Higgs doublet, resulting in a class of models called Two Higgs Doublet Models (2HDM) [4]. In the CP conserving case, 2HDM contain five physical states: two neutral CP even (the lighter of which is usually associated to the observed 125 GeV boson), one neutral CP-odd and two charged Higgs bosons. If another SM singlet (S) field is added to the theory, the resulting physical spectrum is enriched by additional two neutral bosons, one of which is CP-even and other that is CP-odd. The 2HDM+S scenario is realized, for example, in the Next-to-Minimal Supersymmetric SM (NMSSM) where the additional pseudoscalars can be lighter than the SM Higgs boson [5]. Light bosons have also been proposed as the mediators between the SM and dark sectors that are not charged under the SM gauge transformations [6]. Doubly charged Higgs bosons appear in, for example, left-right symmetric models [8], Higgs triplet models [9] or type-II seesaw models [10].

In the following, some of the recent searches for BSM Higgs bosons in the ATLAS experiment [11] at the LHC are presented.

2. Charged Higgs boson

The charged BSM Higgs boson produced in association with bottom and top quarks is searched for in $\tau\nu$ [14] and tb [15] final states. The $\tau\nu$ analysis is sensitive also to a Higgs boson that is lighter than the top quark. For this case, tau polarisation, defined as the energy asymmetry between charged and neutral pions from τ-decays, is used to discriminate between $t \to bH^+$ and $t \to bW$ decays. The top-quark pair production is the dominant background in both analyses, with the background from the single-top quark production being also significant in the $H \to \tau\nu$ channel. Both the $\tau\nu$ and tb analyses use a BDT discriminant to separate the signal from the background events. The data are found to be in good agreement with the SM expectation. Figure 1, left, shows the limits on $\mathscr{B}(t \to bH^+) \times \mathscr{B}(H^+ \to \tau\nu)$ in the charged Higgs boson mass range between 90 and 160 GeV. The limits from $\tau\nu$ and tb channels in the hMSSM scenario of the Minimal Supersymmetric SM (MSSM) [12, 13] are shown on the right hand side of Figure 1. The $H \to \tau\nu$ channel is sensitive to large values of $\tan\beta$[1], while the $H \to tb$ channel covers the low $\tan\beta$ region.

3. Neutral Higgs boson produced in association with b-quarks and decaying to b-quarks

The analysis looks for heavy neutral Higgs boson produced in association with b-quarks [16]. The final state consists of three or more b-quark initiated jets (b-jets). The b-jet tagging is used both for triggering and for the offline reconstruction of the events. The dominant multijet background is suppressed using a principal component analysis. The data are found to be in good agreement with

[1]The ratio of the vacuum expectation values of the two Higgs doublets is denoted as $\tan\beta$.

PoS(EPS-HEP2019)584

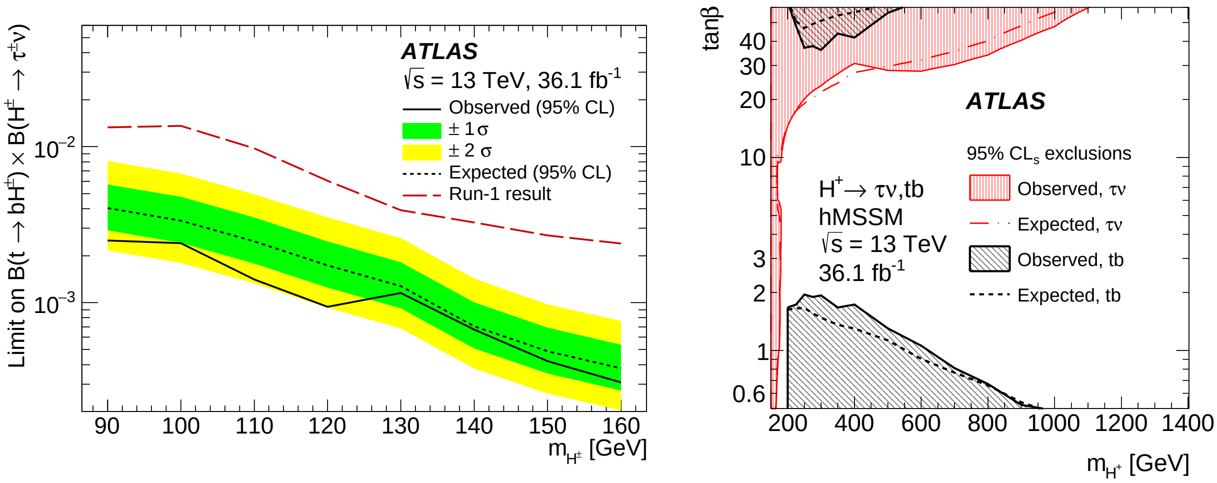

Figure 1: Observed and expected 95% CL exclusion limits on $\mathscr{B}(t \to bH^+) \times \mathscr{B}(H^+ \to \tau\nu)$ as a function of the charged Higgs boson mass [14] (left) and on tanβ as a function of m_{H^+} in the hMSSM scenario [15] (right).

the SM expectation. Figure 2, left, shows the limits for two MSSM scenarios in the tanβ versus Higgs boson mass plane.

4. Summary of limits in the hMSSM scenario

Figure 2, right, shows the summary of the searches for neutral and charged BSM Higgs bosons in the hMSSM scenario [17]. Constraints from the measurements of the SM Higgs boson production and decay rates [18] set a lower limit on the pseudoscalar mass (m_A) at around 540 GeV at 95% confidence level (CL), regardless of the value of tanβ. At large tanβ, due to the enhancement of the couplings to the down-type fermions, the best limits are set by $H \to \tau\nu$ and $H \to \tau\tau$ searches.

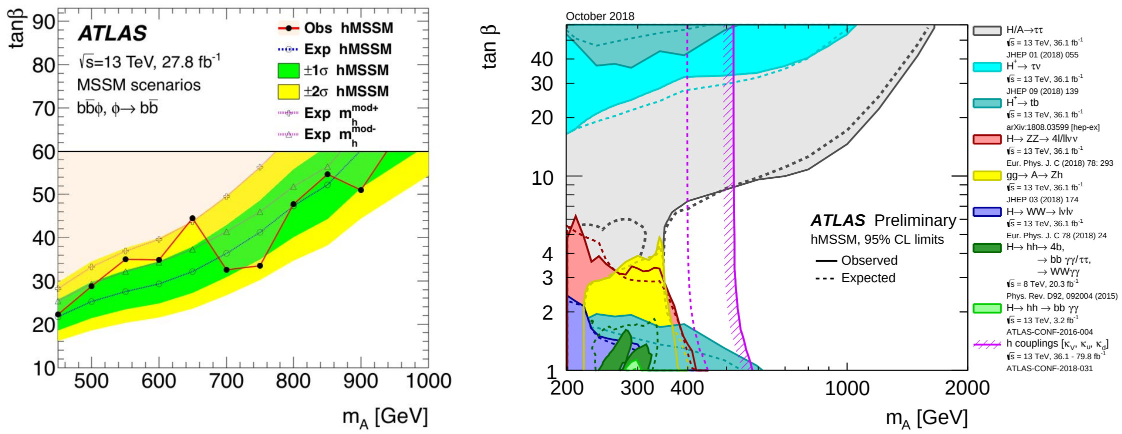

Figure 2: Observed and expected 95% CL exclusion limits on tanβ for MSSM scenarios as a function of m_A in $\Phi \to bb$ channel [16] (left) and an overlay of limits from searches in multiple channels [17] (right).

5. Light Higgs boson decaying to photons

This analysis looks for a BSM Higgs boson decaying to two photons in the 65< m_H <110 GeV mass range [19]. The main backgrounds are the continuum diphoton background consisting of $\gamma\gamma$, γ-jet and jet-jet events (where in the last two categories jets are misidentified as photons) and the $Z/\gamma* \to e^+e^-$ process where the electrons are misreconstructed as photons. A narrow diphoton excess is searched for on a smoothly falling background. The background shape is described by analytic functions validated on data. No significant deviation from the SM prediction is observed and the limits are set on the fiducial cross-section times the branching fraction to the diphoton state, as shown in Figure 3.

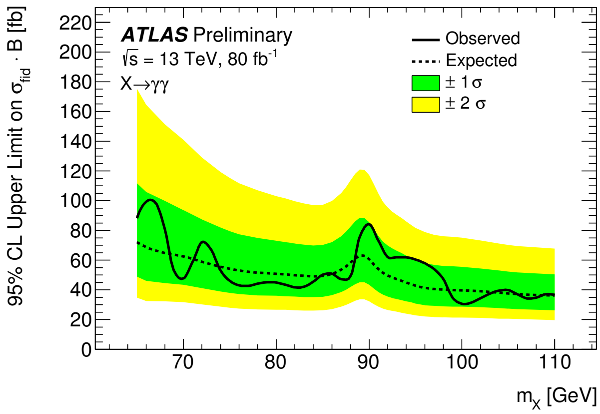

Figure 3: Upper limit on the fiducial cross-section times branching ratio $\mathscr{B}(X \to \gamma\gamma)$ as a function of m_X, where the solid (dashed) line corresponds to the observed (expected) limit and the green (yellow) band corresponds to one (two) standard deviation(s) from the expectation [19].

6. Doubly charged Higgs boson

The dominant production of doubly charged Higgs bosons at the LHC is through the Drell-Yan process. Pair-produced H^{++} and H^{--} are searched for in both the four-lepton [20] and the four-W-boson (with subsequent decays to leptons) [21] final states. Both analyses define multiple signal regions with varying numbers of leptons and differing lepton flavor and charge combinations. A binned maximum-likelihood fit is performed to obtain the numbers of signal and background events. The observed data are compatible with the SM prediction in all the signal regions. The limits on the production cross section of $pp \to H^{++}H^{--}$ for a particular choice of $H^{++/--}$ branching fractions to various lepton combinations and the limits on the production cross-section of $H^{++/--}$ times the branching fraction to a four-W final state are shown in Figure 4, as a function of the doubly-charged Higgs boson mass.

7. Exotic Higgs boson decays

7.1 $H \to aa \to 4b$

The analysis looks for the Higgs boson produced in association with a W- or a Z-boson and

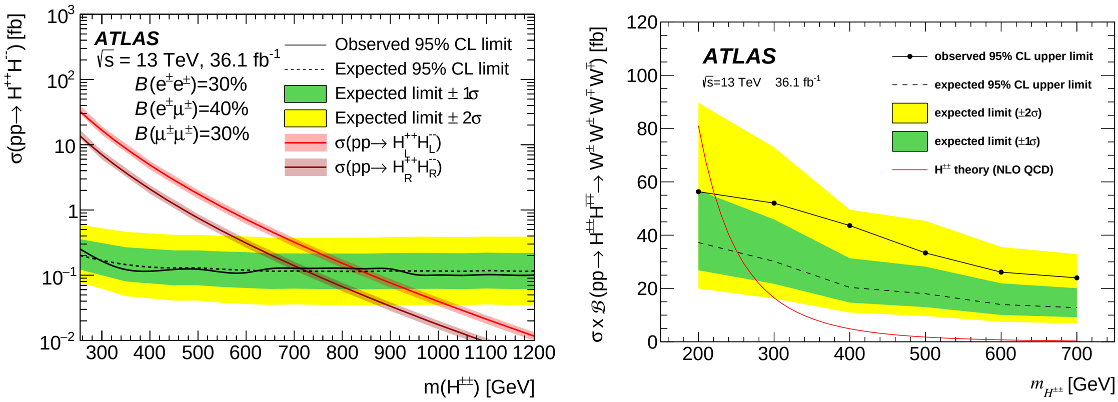

Figure 4: Observed and expected upper limits at 95% CL on the cross-section for $pp \to H^{++}H^{--}$ [20] (left) and on the $pp \to H^{++}H^{--} \to W^{\pm}W^{\pm}W^{\mp}W^{\mp}$ cross-section times branching fraction [21] (right).

decaying to two (pseudo)scalars [22]. The leptons from the vector-boson decays are used to trigger on the events and also help suppress the multijet background. The BDT discriminant is employed to separate the signal from the background processes dominated by the DY and the top-quark pair productions. The binned maximum-likelihood fit is performed simultaneously over all the control and signal regions. No significant deviation from the SM expectation is observed and the limits are set on $\sigma_{VH} \times \mathscr{B}(H \to aa \to 4b)$ as a function of the (pseudo)scalar mass m_a (see Figure 5, left). The limits deteriorate for values of m_a below 30 GeV due to jet merging – when the resonance a is light compared to the parent Higgs particle, it gets boosted and its decay products become collimated. For m_a <30 GeV, the two b-quarks will merge into a single reconstructed jet, requiring specialized analysis techniques in order to tag it as a signal jet.

7.2 $H \to aa \to 2b2\mu$

The final state with two muons and two b-jets [23] has two advantages – sensitivity to the dominant gluon-gluon fusion production mechanism thanks to triggering on the signal lepton and a clean final state containing a narrow dimuon resonance. The dominant backgrounds are coming from the top-quark pair production and the DY process. A series of maximum-likelihood fits is performed in $2-4$ GeV wide bins of the dimuon invariant mass spectrum. No significant deviation from the SM expectation is observed. The limits are set on $\sigma_H/\sigma_{SM} \times \mathscr{B}(H \to aa \to 2b2\mu)$ as a function of m_a (see Figure 5, right).

7.3 Summary plots for $H \to aa$

Limits from searches for exotic Higgs boson decays have been interpreted in terms of 2HDM+S scenarios for different values of the tanβ parameter [24]. Figure 6 shows the limits on $\sigma_H/\sigma_{SM} \times \mathscr{B}(H \to aa)$ as a function of m_a in a Type-II scenario with tan$\beta = 2$ and for $m_a = 40$ GeV as a function of tanβ in a Type-III scenario. Different channels dominate in different parts of the parameter space, demonstrating the importance of a diverse search program. Current measurements of the SM Higgs boson production and decay rates set the upper limit on the Higgs boson branching fraction to BSM states at 47% at 95% CL [18]. The analyses have started to probe ranges of $\mathscr{B}(H \to aa)$ where the effects of new physics could be observed.

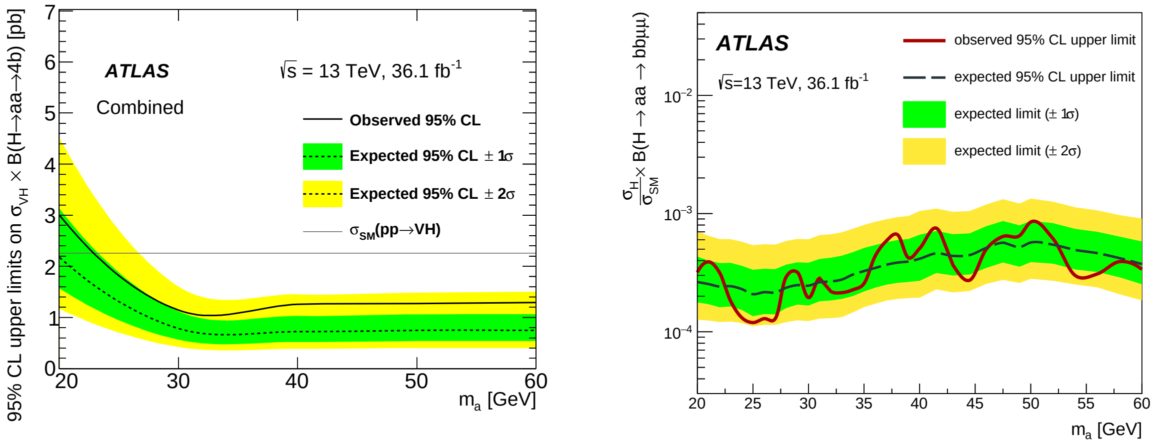

Figure 5: The observed and expected upper limits at the 95% CL on $\sigma_{VH} \times \mathscr{B}(H \to aa \to 4b)$ [22] (left) and on $\sigma_H/\sigma_{SM} \times \mathscr{B}(H \to aa \to 2b2\mu)$ [23] (right).

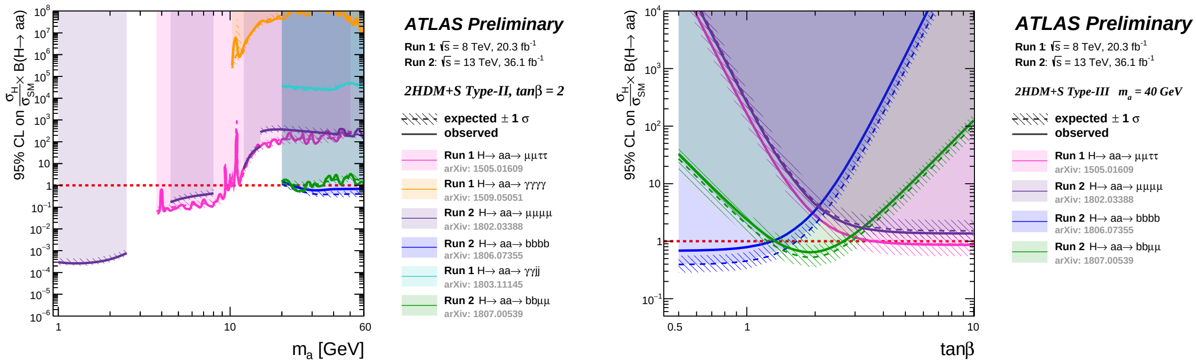

Figure 6: Observed and expected 95% CL upper limits on $\sigma_H/\sigma_{SM} \times \mathscr{B}(H \to aa)$ in Type-II scenario with $\tan\beta = 2$ (left) and in Type-III scenario as a function of $\tan\beta$ (right) [24].

8. Summary

Extensive searches for additional neutral, charged or doubly charged Higgs bosons have been performed using $\sqrt{s}$=13 TeV proton-proton collision data recorded by the ATLAS experiment at the LHC. No significant deviations from SM predictions have been observed in any of the search regions. Many results based on the full 140 fb^{-1} of the Run 2 data are in preparation.

References

[1] A. Djouadi, *The anatomy of electroweak symmetry breaking Tome II: The Higgs bosons in the Minimal Supersymmetric Model*, Phys. Rept. 459 (2008) 1, https://arxiv.org/abs/hep-ph/0503173

[2] B. A. Dobrescu and K. T. Matchev, *Light axion within the next-to-minimal supersymmetric standard model*, JHEP 09 (2000) 031, https://arxiv.org/abs/hep-ph/0008192

[3] M. Trodden, *Electroweak Baryogenesis: A Brief Review*, https://arxiv.org/abs/hep-ph/9805252

[4] G. C. Branco et al., *Theory and phenomenology of two-Higgs-doublet models*, Phys. Rept. 516 (2012) 1, https://arxiv.org/abs/1106.0034

[5] U. Ellwanger, J. F. Gunion, C. Hugonie and S. Moretti, *Towards a no lose theorem for NMSSM Higgs discovery at the LHC*, (2003), https://arxiv.org/abs/hep-ph/0305109

[6] D. Curtin et al., *Exotic decays of the 125 GeV Higgs boson*, Phys. Rev. D 90 (2014) 075004, https://arxiv.org/abs/1312.4992

[7] A. Martin, J. Shelton and J. Unwin, *Fitting the Galactic Center gamma-ray excess with cascade annihilations*, Phys. Rev. D 90 (2014) 103513, https://arxiv.org/abs/1405.0272

[8] R.N. Mohapatra, J.C. Pati, *Left-right gauge symmetry and an iso- conjugate model of CP violation*, Phys. Rev. D 11, 566 (1975)

[9] J.F. Gunion, R. Vega, J. Wudka, *Higgs triplets in the standard model*, Phys. Rev. D 42, 1673 (1990)

[10] P. Fileviez Perez, T. Han, G.-Y. Huang, T. Li, K. Wang, *Testing a neutrino mass generation mechanism at the large Hadron collider*, Phys. Rev. D 78, 071301 (2008), https://arxiv.org/abs/0803.3450

[11] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST 3 (2008) S08003

[12] A. Djouadi et al., *The post-Higgs MSSM scenario: habemus MSSM?*, Eur. Phys. J. C 73 (2013) 2650, https://arxiv.org/abs/1307.5205

[13] A. Djouadi, L. Maiani, A. Polosa, J. Quevillon and V. Riquer, *Fully covering the MSSM Higgs sector at the LHC*, JHEP 06 (2015) 168, https://arxiv.org/abs/1502.05653

[14] ATLAS Collaboration, *Search for charged Higgs bosons decaying via $H^{\pm} \to \tau^{\pm}\nu_{\tau}$ in the τ+jets and τ+lepton final states with 36 fb^{-1} of pp collision data recorded at $\sqrt{s}$=13 TeV with the ATLAS experiment*, JHEP 09 (2018) 139, https://arxiv.org/abs/1807.07915

[15] ATLAS Collaboration, *Search for charged Higgs bosons decaying into top and bottom quarks at $\sqrt{s}$=13 TeV with the ATLAS detector* JHEP 11 (2018) 085, https://arxiv.org/abs/1808.03599

[16] ATLAS Collaboration, *Search for heavy neutral Higgs bosons produced in association with b-quarks and decaying to b-quarks at $\sqrt{s}$ =13 TeV with the ATLAS detector*, submitted to Physical Review D, https://arxiv.org/abs/1907.02749

[17] ATLAS Collaboration, *BSM Higgs exclusion in the hMSSM*, https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/

[18] ATLAS Collaboration, *Combined measurements of Higgs boson production and decay using up to 80 fb^{-1} of proton-proton collision data at $\sqrt{s}$ = 13 TeV collected with the ATLAS experiment*, submitted to Phys. Rev. D, https://arxiv.org/abs/1909.02845

[19] ATLAS Collaboration, *Search for resonances in the 65 to 110 GeV diphoton invariant mass range using 80 fb^{-1} of pp collisions collected at $\sqrt{s}$ =13 TeV with the ATLAS detector*, ATLAS-CONF-2018-025, http://cdsweb.cern.ch/record/2628760

[20] ATLAS Collaboration, *Search for doubly charged Higgs boson production in multi-lepton final states with the ATLAS detector using proton-proton collisions at $\sqrt{s}$ = 13 TeV*, Eur. Phys. J. C (2018) 78:199, https://arxiv.org/abs/1710.09748

[21] ATLAS Collaboration, *Search for doubly charged scalar bosons decaying into same-sign W boson pairs with the ATLAS detector*, Eur. Phys. J. C (2019) 79: 58, https://arxiv.org/abs/1808.01899

PoS(EPS-HEP2019)584

[22] ATLAS Collaboration, *Search for the Higgs boson produced in association with a vector boson and decaying into two spin-zero particles in the $H \to aa \to 4b$ channel in pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector*, JHEP 10 (2018) 031, https://arxiv.org/abs/1806.07355

[23] ATLAS Collaboration, *Search for Higgs boson decays into a pair of light bosons in the $bb\mu\mu$ final state in pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector*, Phys. Lett. B 790 (2019) 1, https://arxiv.org/abs/1807.00539

[24] ATLAS Collaboration, *HBSM Working Group 2HDM+S Summary Plots*, ATL-PHYS-PUB-2018-045, https://cds.cern.ch/record/2650740/