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Searching for new symmetries in the Higgs sector with the ATLAS detector

Dominik Duda on behalf of the ATLAS Collaboration

School of Physics and Astronomy, University of Edinburgh,
Old College, South Bridge, Edinburgh EH8 9YL, United Kingdom

E-mail: dominik.duda@cern.ch

These proceedings give an overview of recent searches for additional low- and high-mass Higgs bosons, as well as direct searches for rare or exotic decays of the 125 GeV Higgs boson, using proton–proton collision data at 13 TeV collected by the ATLAS experiment in Run 2 of the LHC.

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1. Introduction

The discovery of the Higgs boson in 2012 by the LHC experiments confirmed the mass generation mechanism via spontaneous electroweak symmetry breaking (EWSB) and completed the particle content predicted by the Standard Model (SM). Even though the SM is well established and consistent with many experimental measurements, it is not capable of solely explaining some of the phenomena seen in nature. Extending the Higgs sector by introducing additional scalar fields to account for the electroweak symmetry breaking, promises to provide much desired solutions to some of the questions the SM fails to answer. In particular, an extended Higgs sector can provide new sources of CP violation, enhance vacuum stability, provide a dark matter candidate, or provide a solution to the strong CP problem (leading to axions). Furthermore, models of new physics beyond the SM (BSM) often explicitly require additional scalar fields: e.g. two Higgs doublets are required in the minimal supersymmetric extension of the SM, while Higgs triplets are required in models that predict the neutrino mass generation via a seesaw mechanism. Introducing additional scalar fields will necessarily lead to extra Higgs-like particles, which can be either neutral or charged.

These proceedings summarise the recent searches for additional low- and high-mass Higgs bosons, as well as direct searches for rare or exotic decays of the 125 GeV Higgs boson, using proton–proton (pp) collision data at 13 TeV collected by the ATLAS experiment [1] in Run 2 of the LHC.

2. Searches for additional Higgs bosons

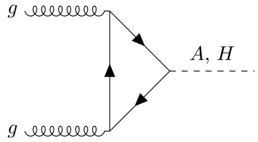
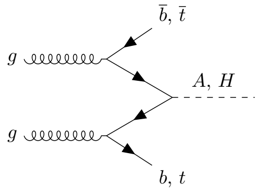
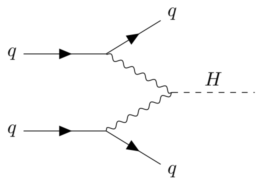
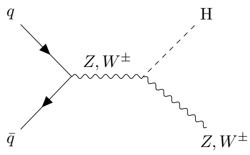
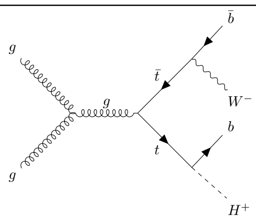
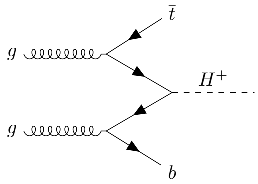
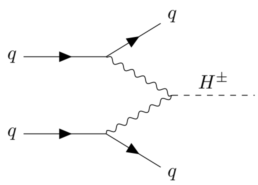
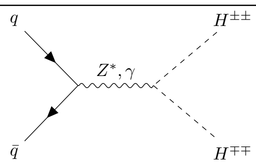
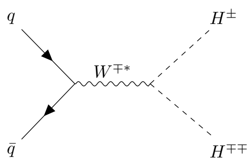
Direct searches for Higgs-like particles have always been a core component of the ATLAS physics programme. By now, the ATLAS Collaboration has performed a wide range of searches for extra Higgs bosons covering a large variety of different production and decay modes. The most recent searches for additional neutral, singly and doubly charged Higgs bosons based on data from pp collisions at $\sqrt{s} = 13$ TeV are summarised in Table 1. Examples of lowest order diagrams for the considered production modes are also presented.

Searches for additional Higgs bosons are typically designed to be as model independent as possible. This is achieved by probing for a localised excess in a characteristic distribution (such as the invariant mass of the relevant final state particles or the response of a machine learning algorithm). If no significant excess is found, upper limits at 95% confidence level (CL) are set on the production cross section and/or branching ratios of the extra Higgs boson. These upper limits are then interpreted in the context of specific benchmark models to set exclusion limits on relevant model parameters. Examples are shown in Figures 1 and 2, which show overlays of observed and expected exclusion limits at 95% CL on parameters of the hMSSM[1] and Georgi-Machacek model[2], respectively.

[1]The hMSSM scenario corresponds to a CP-conserving Two Higgs Doublet model and describes the Higgs sector of the Minimal Supersymmetric Standard Model. It contains five Higgs bosons (h, H, A, $H^{\pm}$), where h has the mass m_h = 125 GeV, and is effectively described by only two free parameters: the ratio of vacuum expectation values ($\tan\beta$) and the mass of the A boson (m_A) [2].

[2]The Georgi-Machacek model is a specific example of a Higgs triplet model, in which the Higgs sector contains two electroweak triplets and one doublet, leading to ten physical states after EWSB. These Higgs bosons are organised in custodial symmetry multiplets (i.e. one fiveplet, one triplet and two singlets) [3].

Table 1: Summary of recent direct searches for additional Higgs bosons by the ATLAS Collaboration based on data from pp collisions at $\sqrt{s} = 13$ TeV.

	Production modes	References	Diagrams
Neutral Higgs bosons	gluon–gluon fusion	[4–12]	
	b/t associated	[7–9, 15–17]	
	vector-boson fusion	[6, 11]	
	Higgs Strahlung	[10, 13]	
Singly-charged Higgs bosons	via Top-quark decays	[18, 19]	
	tb associated	[19, 20]	
	vector-boson fusion	[14]	
Doubly-charged Higgs bosons	pair production	[21, 22]	
	Higgs boson associated	[22]	

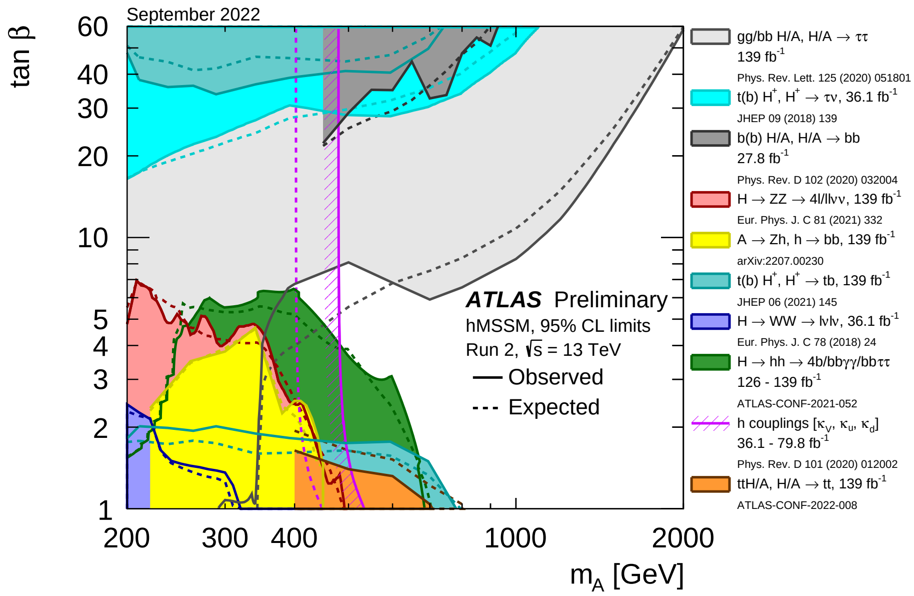


Figure 1: Overlay of observed (indicated as solid lines) and expected (indicated as dashed lines) exclusion limits at 95% CL on the hMSSM scenario presented as a function of the heavy Higgs boson mass m_A and the ratio of vacuum expectation values $\tan\beta$. The limits are obtained via direct searches for heavy Higgs bosons and via fits to the measured rates of the observed Higgs boson production and decays [23].

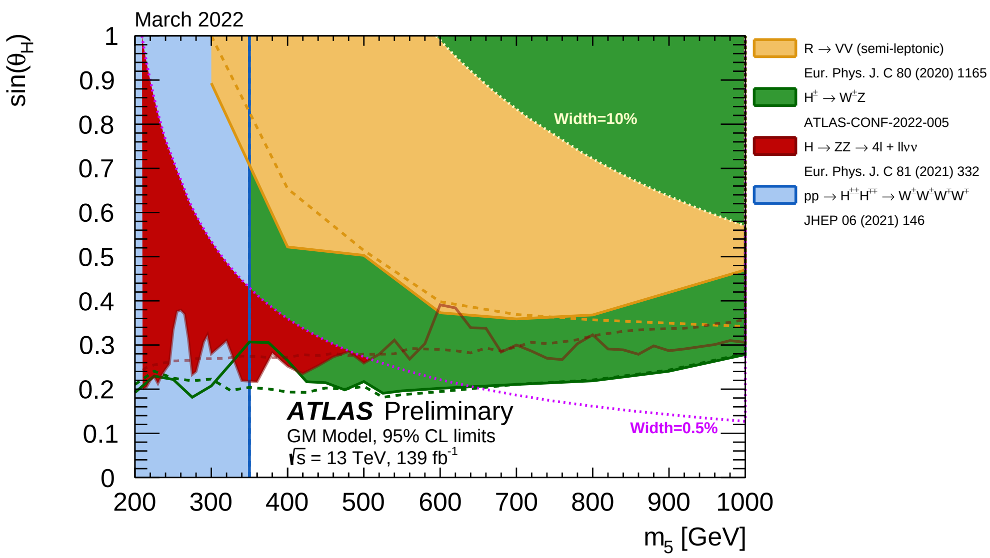


Figure 2: Overlay of observed (indicated as solid lines) and expected (indicated as dashed lines) exclusion limits at 95% CL on the H5 plane benchmark [3] of the Georgi-Machacek model presented as a function of the mass m_5 of the heavy Higgs bosons and the ratio of vacuum expectation values $\sin(\theta_H)$. The limits are obtained via direct searches for new, heavy, neutral or charged Higgs bosons [24].

3. Searches for exotic Higgs boson decays

Rare or exotic decays of the 125 GeV Higgs boson are excellent candidates to search for new light (pseudo) scalars, dark-matter candidates or new physics effects. Higgs boson decays are particularly sensitive to contributions from new physics owing to its narrow total width, which is three orders of magnitude smaller than that of the W and Z bosons as well as the top quark.

The ATLAS Collaboration has carried out numerous direct searches for new particles originating from the decay of the Higgs boson. Prominent examples are searches for Higgs boson decays to two pseudoscalars, $h \to aa$, which are performed in a large variety of different final states, such as $\mu\mu\tau\tau$, $\gamma\gamma\gamma\gamma$, $\mu\mu\mu\mu$, $bbbb$, $\gamma\gamma gg$, or $bb\mu\mu$. An overlay of the observed and expected 95% CL upper limits on $\frac{\sigma_h}{\sigma_{\text{SM}}} \times \mathcal{B}(h \to aa)$ resulting from these searches is presented in Figure 3. The limits are set as a function of the a boson mass m_a, covering a range from 1 GeV to 60 GeV.

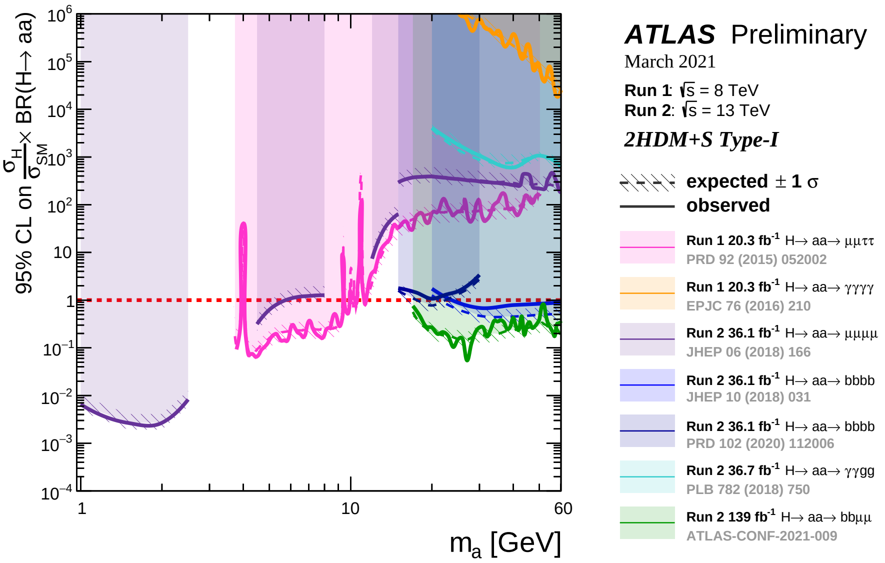


Figure 3: Overlay of observed and expected 95% CL upper limits on $\frac{\sigma_h}{\sigma_{\text{SM}}} \times \mathcal{B}(h \to aa)$ in the 2HDM+S type-I scenario [25] from a variety of different $h \to aa$ searches presented as a function of the a boson mass m_a. The limits are obtained from studies based on either 8 TeV or 13 TeV data [26].

The ATLAS Collaboration is also searching for flavour violation in decays of the Higgs boson to a pair of leptons with different flavours, i.e. $h \to e\mu$, $h \to e\tau$ and $h \to \mu\tau$ [27, 28]. These decays are forbidden in the SM, but occur naturally in models with more than one Higgs doublet [29]. Via a dedicated analysis, observed (expected) upper limits at 95% CL are set on the branching ratio of the $h \to e\mu$ decay, resulting in: $\mathcal{B}(h \to e\mu) < 6.2 \times 10^{-5}$ (5.9×10^{-5}). The branching ratios for $h \to \mu\tau$ and $h \to e\tau$ are constrained simultaneously via a combined fit, which yields branching ratio values compatible with zero within 2.2 standard deviations (as shown in Figure 4).

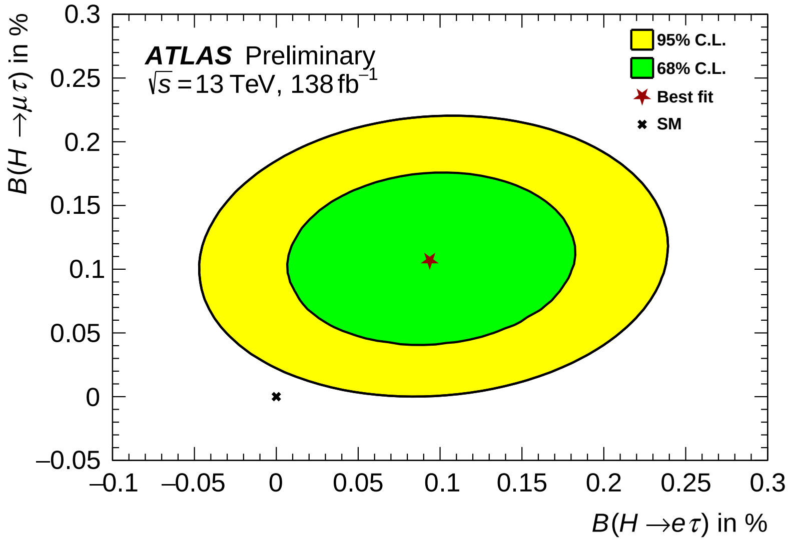


Figure 4: Best fit value (red star) of the branching ratios $\mathcal{B}(h \to e\tau)$ and $\mathcal{B}(h \to \mu\tau)$, given in %, and likelihood contours at 68% and 95% CL obtained from a simultaneous fit of $h \to e\tau$ and $h \to \mu\tau$ signals, compared to the SM expectation (black cross) [28].

4. Concluding remarks

Searches for additional Higgs bosons and rare or exotic decays of the 125 GeV Higgs boson are strongly motivated by theory, given that an extended Higgs sector can provide solutions to many of the questions the SM fails to answer. The ATLAS Collaboration has performed a wide range of such searches, covering a large variety of different production and decay modes. So far, no significant hint for physics beyond the SM has been observed and strong constraints are set on specific benchmark models. At the same time, a larger fraction of the theoretically allowed parameter space remains unconstrained given the limited statistical sensitivity of current BSM Higgs searches. Further scrutiny will be given to such searches based on data from Run-3 of the LHC (and eventually also the High-Luminosity phase of the LHC). With increasing dataset size, so far uncovered production and decay channels will become accessible [30] such that the ATLAS Collaboration will be able to extend its search programme.

References

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

[2] A. Djouadi et al., "Fully covering the MSSM Higgs sector at the LHC", JHEP 06 (2015) 168

[3] K. Hartling, K. Kumar and H. Logan, "The decoupling limit in the Georgi-Machacek model", Phys. Rev. D 90, 015007 (2014)

[4] ATLAS Collaboration, "Search for resonances decaying into photon pairs in 139 fb^{-1} of pp collisions at $\sqrt{s}$=13 TeV with the ATLAS detector", Phys. Lett. B 822 (2021) 136651

[5] ATLAS Collaboration, "Search for boosted diphoton resonances in the 10 to 70 GeV mass range using 138 fb^{-1} of 13 TeV pp collisions with the ATLAS detector", arXiv:2211.04172 [hep-ex]

[6] ATLAS Collaboration, "Search for heavy resonances decaying into a pair of Z bosons in the $\ell^+\ell^-\ell'^+\ell'^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states using 139 fb^{-1} of proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", Eur. Phys. J. C 81 (2021) 332

[7] ATLAS Collaboration, "Search for heavy Higgs bosons decaying into two tau leptons with the ATLAS detector using pp collisions at $\sqrt{s}$ = 13 TeV", Phys. Rev. Lett. 125 (2020) 051801

[8] ATLAS Collaboration, "Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the $\ell\ell bb$ and $\ell\ell WW$ final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", Eur. Phys. J. C. 81 (2021) 396

[9] ATLAS Collaboration, "Search for heavy resonances decaying into a Z or W boson and a Higgs boson in final states with leptons and b-jets in 139 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", arXiv:2207.00230 [hep-ex]

[10] ATLAS Collaboration, "Search for Higgs boson pair production in association with a vector boson in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", arXiv:2210.05415 [hep-ex]

[11] ATLAS Collaboration, "Search for heavy resonances in the decay channel $W^+W^- \to e\nu\mu\nu$ in pp Collisions at $\sqrt{s}$ = 13 TeV using 139 fb^{-1} of data with the ATLAS detector", ATLAS-CONF-2022-066

[12] ATLAS Collaboration, "Combination of searches for non-resonant and resonant Higgs boson pair production in the $b\bar{b}\gamma\gamma$, $b\bar{b}\tau^+\tau^-$ and $b\bar{b}b\bar{b}$ decay channels using pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", ATLAS-CONF-2021-052

[13] ATLAS Collaboration, "A search for heavy Higgs bosons decaying into vector bosons in same-sign two-lepton final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", arXiv:2211.02617 [hep-ex]

[14] ATLAS Collaboration, "Search for resonant $WZ \to \ell\nu\ell'\ell'$ production in proton−proton collisions at $\sqrt{\mathbf{s}}$ = **13** TeV with the ATLAS detector", arXiv:2207.03925 [hep-ex]

[15] ATLAS Collaboration, "Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ production in the multilepton final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", arXiv:2211.01136 [hep-ex]

[16] ATLAS Collaboration, "Search for heavy Higgs bosons from a g2HDM in multilepton plus b-jets final states in pp collisions at 13 TeV with the ATLAS detector", ATLAS-CONF-2022-039

[17] ATLAS Collaboration, "Search for heavy neutral Higgs bosons produced in association with b-quarks and decaying into b-quarks at $\sqrt{s}$ = 13 TeV with the ATLAS detector", Phys. Rev. D 102, 032004 (2020)

[18] ATLAS Collaboration, "Search for a light charged Higgs boson in t$\rightarrow$ $H^{+}b$ decays, with H^{+} $\rightarrow$cb, in the lepton+jets final state in proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", ATLAS-CONF-2021-037

[19] ATLAS Collaboration, "Search for charged Higgs bosons decaying via $H^{\pm} \rightarrow \tau^{\pm}\nu_{\tau}$ 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

[20] ATLAS Collaboration, "Search for charged Higgs bosons decaying into a top quark and a bottom quark at $\sqrt{s}$ = 13 TeV with the ATLAS detector", JHEP 06 (2021) 145

[21] ATLAS Collaboration, "Search for doubly charged Higgs boson production in multi-lepton final states using 139 fb^{-1} of proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector", arXiv:2211.07505 [hep-ex]

[22] ATLAS Collaboration, "Search for doubly and singly charged Higgs bosons decaying into vector bosons in multi-lepton final states with the ATLAS detector using proton-proton collisions at $\sqrt{s}$ = 13 TeV", JHEP 06 (2021) 146

[23] ATLAS Collaboration, "Summary plots for beyond Standard Model Higgs boson benchmarks for direct and indirect searches", ATL-PHYS-PUB-2022-043

[24] ATLAS Collaboration, "Summary plot for the interpretation of heavy Higgs boson searches in the Georgi-Machacek model", ATL-PHYS-PUB-2022-008

[25] U. Haisch, J. F. Kamenik, A. Malinauskas, and M. Spira, "Collider constraints on light pseudoscalars", JHEP 03 (2018) 178

[26] ATLAS Collaboration, "Summary of Exotic Higgs Boson Decays from the ATLAS Experiment", ATL-PHYS-PUB-2021-008

[27] ATLAS Collaboration, "Search for the Higgs boson decays $H \rightarrow ee$ and $H \rightarrow e\mu$ in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector",Phys. Lett. B 801 (2020) 135148

[28] ATLAS Collaboration, "Searches for lepton-flavour-violating decays of the Higgs boson into $e\tau$ and $\mu\tau$ in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector", ATLAS-CONF-2022-060

[29] J. L. Diaz-Cruz and J. J. Toscano,"Lepton Flavour Violating decays of Higgs bosons beyond the Standard Model", Phys. Rev. D62 (2000) 116005

[30] H. Bahl, T. Stefaniak and J Wittbrodt, "The forgotten channels: charged Higgs boson decays to a W and a non-SM-like Higgs boson", JHEP 06 (2021) 183