ATLAS SEARCHES IN THE HIGGS SECTOR*

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This document presents an overview of recent ATLAS searches in the Higgs sector using the full Run 2 dataset of proton–proton collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 140 fb^{-1}. The analyses include searches for additional scalars, charged Higgs bosons, and exotic decays.

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1. Introduction

The discovery of the Higgs boson in 2012 at the Large Hadron Collider (LHC) by the ATLAS [1] and CMS [2] collaborations marked a significant milestone in particle physics, confirming the last missing piece of the Standard Model (SM). However, many theoretical models predict the existence of additional Higgs-like states, which could provide insights into the nature of electroweak symmetry breaking and offer explanations for some of the outstanding questions in fundamental physics, such as the nature of dark matter, the hierarchy problem, and CP violation.

To address these questions, the ATLAS experiment has conducted extensive searches for beyond Standard Model (BSM) Higgs bosons using the full Run 2 dataset of proton–proton collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 140 fb^{-1}. These searches explore both neutral and charged Higgs bosons in a variety of decay modes, covering a broad mass range. The analyses employ state-of-the-art techniques, including machine learning-based classification, sophisticated background estimation strategies, and detailed detector calibrations to achieve optimal sensitivity.

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Among the key motivations for these searches is the possibility that the observed Higgs boson at 125 GeV may not be the only scalar particle but rather part of an extended Higgs sector, as predicted by theories such as Two-Higgs-Doublet Models (2HDM) [3, 4], Next-to-Minimal Supersymmetric Standard Model (NMSSM) [5], and other BSM scenarios [6]. Such extensions often introduce additional Higgs bosons that can be observed via their decays into SM particles or new exotic states.

The following sections present an overview of several ATLAS searches for additional scalar (S) and charged Higgs bosons ($H^{\pm}$).

2. Search for additional scalars

A search in the $\gamma\gamma$ final state was performed in the mass region of 66–110 GeV [7], where a background-dominated environment requires precise modelling. Both a model-independent search for a spin-0 particle (X) and a model-dependent search for an additional low-mass SM-like Higgs boson (H) are performed. The analysis exploits a boosted decision tree (BDT) to separate electrons from $Z \to ee$ and photons. Limits were set on the production cross section times branching ratio as shown in Fig. 1.

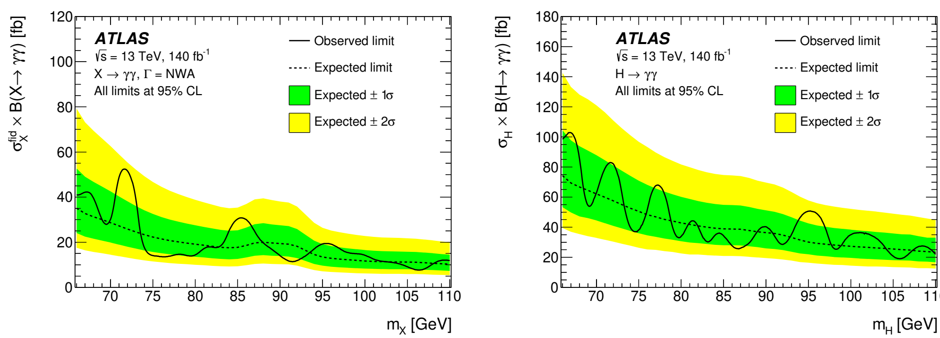

Fig. 1. 95% C.L. upper limits on the fiducial cross section times branching ratio as a function of (left) m_X for the model-independent search and (right) m_H for the model-dependent search. Taken from Ref. [7].

Another search investigated the $X \to S(b\bar{b})H(\gamma\gamma)$ process [8]. Parameterized neural networks (PNN) were employed to optimize sensitivity across the (m_X, m_S) plane. The most significant deviation was observed at $(m_X, m_S) = (575, 200)$ GeV with a local significance of 3.5σ (2.0σ global) as shown in Fig. 2, together with the observed limits on the signal cross section times branching fraction.

The $X \to S(VV) + H(\gamma\gamma)$ analysis [9] searched for new resonances in the $300 \leq m_X \leq 1000$ GeV and $170 \leq m_S \leq 500$ GeV mass ranges, complementing the boosted $b\bar{b}\gamma\gamma$ analysis. A PNN is used to suppress the

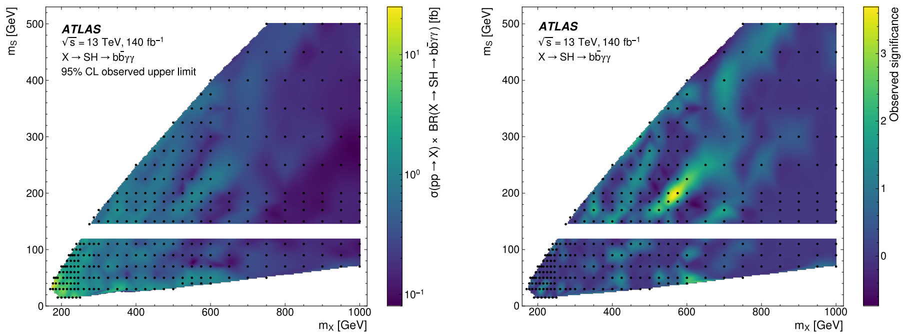

Fig. 2. Left: Observed 95% C.L. upper limits on the signal cross section times branching fraction for the $X \to SH$ signal, in the (m_X, m_S) plane. Right: Local observed significance for signal discovery at different (m_X, m_S). Taken from Ref. [8].

background from $\gamma\gamma + j$ and $V + \gamma\gamma$. Figure 3 shows the limits on $\sigma(gg \to X) \times \text{BR}(X \to SH)$ in three scenarios: assuming SM-like branching ratios for $S \to VV$, $\text{BR}(S \to ZZ) = 1$, and $\text{BR}(S \to WW) = 1$.

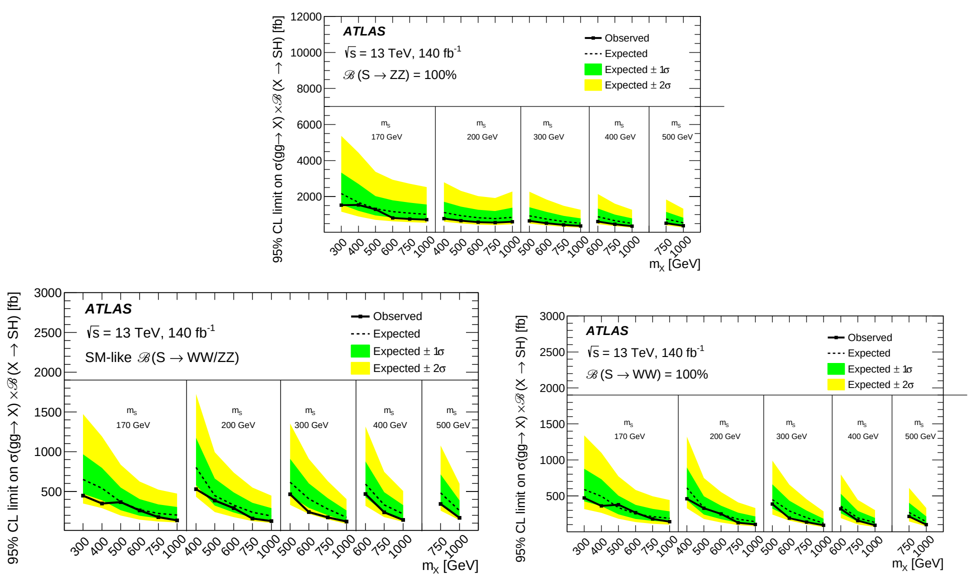

Fig. 3. 95% C.L. upper limit on $\sigma(gg \to X) \times \text{BR}(X \to SH)$ as a function of m_X and m_S under the assumption (top) SM-like $\text{BR}(S \to VV)$, (left) $\text{BR}(S \to WW) = 1$, (right) $\text{BR}(S \to ZZ) = 1$. Taken from Ref. [9].

For the first time, a direct search for $HHH \to 6b$ was performed [10], probing quartic Higgs couplings, using 126 fb^{-1} of data. The $6b$ final state presents a challenge due to the high combinatorial and large background from multijet events. The analysis set a limit on σ_{HHH} equal to 750 times the SM value, a first direct limit on $\kappa_4 = \lambda_4/\lambda_4^{\mathrm{SM}}$, shown in Fig. 4. The analysis also imposed limits on BSM scenarios with non-resonant production, where $m_S < 250$ GeV, and resonant production up to $(m_X, m_S) = (1500, 1000)$ GeV.

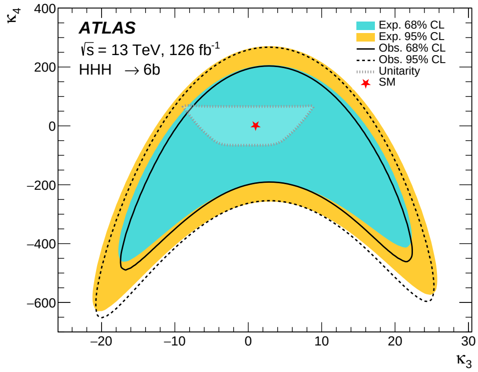

Fig. 4. Expected (filled regions) and observed (black solid and dashed lines) 95% and 68% C.L. constraints on κ_3 and κ_4. Taken from Ref. [10].

The analysis in the $S \to Z_d Z_d \to 4\ell$ channel [11], where Z_d is a new spin-1 boson, is based on the search for an excess in the $\langle m_{\ell\ell} \rangle$ distribution in bins of $m_{4\ell}$ for different m_S and m_{Z_d} hypotheses. In the first region ($m_{4\ell} < 115$ GeV), the limits on $\sigma(gg \to S) \times \mathrm{BR}(S \to Z_d Z_d \to 4\ell)$ range from 0.14 fb to 3.1 fb and in the second ($m_{4\ell} > 130$ GeV), from 0.05 fb to 0.60 fb. These represent stringent constraints on the dark sector described by the Hidden Abelian Higgs Model [12], and also apply to similar models resulting in a four-lepton final state.

3. Searches for charged Higgs bosons

The ATLAS experiment has also conducted searches for charged Higgs bosons ($H^\pm$), which arise in many BSM scenarios such as 2HDM and supersymmetry.

A novel search for $H^\pm \to Wh$ was performed [13]. The final state includes a Higgs boson decaying into $b\bar{b}$ and a W boson decaying either leptonically or hadronically. The analysis requires the presence of one lepton and targets both resolved and boosted topologies. In this second scenario, a recently developed boosted $h \to b\bar{b}$ tagging technique is used to identify the decay of boosted Higgs bosons. The $H^\pm$ mass resolution is expected to be 6–10%. A fit is performed on the m_{Wh} distribution. The upper limits on the production cross section times BR range from 2.8 pb for $m_{H^\pm} = 250$ GeV to 1.2 fb for $m_{H^\pm} = 3000$ GeV.

A search for $H^\pm \to \tau\nu$ is performed assuming $H^\pm$ produced either in top-quark decays or in association with top quarks [14]. The channel provides the best sensitivity for low and high masses. The analysis utilized recurrent neural networks (RNN) to identify hadronic τ decays and a likelihood fit of the output of a PNN to extract the signal. Upper limits on the production cross section times branching fraction are shown in Fig. 5 together, for the first time in the $\tau\nu$ channel, with an interpretation in the M_h^{125} scenario of the MSSM [15].

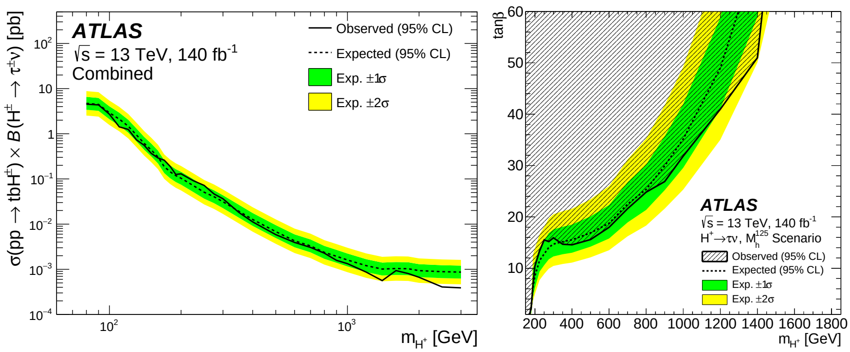

Fig. 5. Left: 95% C.L. exclusion limits on $\sigma(pp \to tbH^\pm) \times \mathrm{BR}(H^\pm\tau\nu)$. Right: Exclusion limits on $\tan\beta$ as a function of $m_{H^\pm}$ in the context of the M_h^{125} scenario of the MSSM. Taken from Ref. [14].

The first ATLAS search for $H^\pm$ in decays of the top quark $t \to H^\pm b$ with $H^\pm \to cs$ was conducted [16], relying on b- and c-tagging techniques in the mass range from 60 to 168 GeV. The analysis requires one lepton, from $W \to \ell\nu$, 2 b-jets and 4 jets. A likelihood fit to a BDT output was used to set limits on $\mathrm{BR}(t \to H^\pm b)$ assuming $\mathrm{BR}(t \to Wb) + \mathrm{BR}(t \to H^\pm(cs)b) = 1$ as shown in Fig. 6.

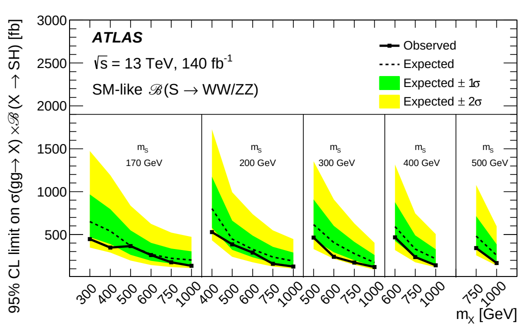

Fig. 6. Upper limits on $\mathrm{BR}(t \to H^\pm b)$ assuming $\mathrm{BR}(t \to Wb) + \mathrm{BR}(t \to H^\pm(cs)b) = 1$. Taken from Ref. [16].

4. Conclusion

The ATLAS Collaboration is continuing its investigation of the Higgs sector with full Run 2 proton–proton data. While no significant deviations from the Standard Model have been observed, the analyses have set stringent constraints on New Physics scenarios. Future improvements, including the use of Run 3 data and enhanced analysis techniques, will further refine these searches.

REFERENCES

[1] ATLAS Collaboration (G. Aad *et al.*), *J. Instrum.* **3**, S08003 (2008).
[2] CMS Collaboration (S. Chatrchyan *et al.*), *J. Instrum.* **3**, S08004 (2008).
[3] I.F. Ginzburg, M. Krawczyk, P. Osland, arXiv:hep-ph/0211371.
[4] M. Mühlleitner, M.O.P. Sampaio, R. Santos, J. Wittbrodt, *J. High Energy Phys.* **2017**, 094 (2017), arXiv:1612.01309 [hep-ph].
[5] U. Ellwanger, C. Hugonie, A.M. Teixeira, *Phys. Rep.* **496**, 1 (2010), arXiv:0910.1785 [hep-ph].
[6] T. Robens, T. Stefaniak, J. Wittbrodt, *Eur. Phys. J. C* **80**, 151 (2020), arXiv:1908.08554 [hep-ph].
[7] ATLAS Collaboration (G. Aad *et al.*), *J. High Energy Phys.* **2025**, 053 (2025), arXiv:2407.07546 [hep-ex].
[8] ATLAS Collaboration (G. Aad *et al.*), *J. High Energy Phys.* **2024**, 047 (2024), arXiv:2404.12915 [hep-ex].
[9] ATLAS Collaboration (G. Aad *et al.*), *J. High Energy Phys.* **2024**, 104 (2024), arXiv:2405.20926 [hep-ex].
[10] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. D* **111**, 032006 (2025), arXiv:2411.02040 [hep-ex].
[11] ATLAS Collaboration (G. Aad *et al.*), *Phys. Lett. B* **865**, 139472 (2025), arXiv:2410.16781 [hep-ex].
[12] S. Gopalakrishna, S. Jung, J.D. Wells, *Phys. Rev. D* **78**, 055002 (2008), arXiv:0801.3456 [hep-ph].
[13] ATLAS Collaboration (G. Aad *et al.*), *J. High Energy Phys.* **2025**, 143 (2025), arXiv:2411.03969 [hep-ex].
[14] ATLAS Collaboration (G. Aad *et al.*), *Phys. Rev. D* **111**, 072006 (2025), arXiv:2412.17584 [hep-ex].
[15] E. Bagnaschi *et al.*, *Eur. Phys. J. C* **79**, 617 (2019), arXiv:1808.07542 [hep-ph].
[16] ATLAS Collaboration (G. Aad *et al.*), *Eur. Phys. J. C* **85**, 153 (2025), arXiv:2407.10096 [hep-ex].