PROCEEDINGS OF SCIENCE

# Searches for Heavy Resonances: New Scalars and BSM Higgs Decays with ATLAS Run-2 Data

**Marzieh Bahmani, on behalf of the ATLAS Collaboration**[a,*]

[a] *Humboldt University of Berlin, Germany*

*E-mail:* marzieh.bahmani@cern.ch

The Standard Model (SM) has been remarkably successful, yet several key questions remain open, including the nature of dark matter, the matter–antimatter asymmetry, and the origin of neutrino masses. Many extensions of the SM predict additional heavy particles, such as neutral scalars ($H$, $S$), pseudoscalars ($A$), and charged Higgs bosons ($H^{\pm}$, $H^{\pm\pm}$), as realised for example in Two-Higgs-Doublet Models, Supersymmetry, or hidden-sector Higgs models. We summarise ATLAS Run-2 searches for heavy resonances in these scenarios. Using 140 fb$^{-1}$ of proton-proton collisions at $\sqrt{s} = 13$ TeV, we present representative results in four channels: (i) $H^{\pm} \to W^{\pm}h \to \ell\nu b\bar{b}$, (ii) $H^{\pm} \to \tau\nu$, (iii) exotic decays $S \to Z_d Z_d \to 4\ell$, and (iv) model-independent dijet resonance searches using weakly supervised anomaly detection. No significant excess is observed. Limits are set in benchmark frameworks (2HDM, hMSSM/MSSM, HAHM) and on generic resonance cross sections, with notable sensitivity gains driven by advanced machine-learning techniques.

*The European Physical Society Conference on High Energy Physics (EPS-HEP2025)*
*7–11 July 2025*
*Marseille, France*

*Speaker

 ISSN 1824-8039 . Published by SISSA Medialab.



PoS(EPS-HEP2025)417

## 1. Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC) [1] in 2012 marked a cornerstone in particle physics, confirming the Brout–Englert–Higgs mechanism as the origin of electroweak symmetry breaking. Since then, the ATLAS and CMS experiments [2, 3] have measured Higgs boson properties with increasing precision, finding them broadly consistent with Standard Model (SM) predictions. There are some phenomena that SM does not explain such as the nature of dark matter, the matter–antimatter asymmetry, or the origin of the scalar sector itself. These open questions motivate a wide range of searches for new scalar states, additional Higgs bosons, and other exotic resonances.

Many extensions of the SM predict charged Higgs bosons ($H^{\pm}$), as realized in two-Higgs-doublet models (2HDM) and supersymmetric theories. Two complementary ATLAS searches have recently targeted these states. The first [4] investigates heavy $H^{\pm}$ bosons produced in association with a top quark and decaying via $H^{\pm} \to W^{\pm}h$, where $h$ is the observed 125 GeV Higgs boson. The analysis uses both resolved and merged final states, depending on the boost of the Higgs boson decay products, and sets upper limits on $\sigma(pp \to tbH^{\pm}) \times \mathcal{B}(H^{\pm} \to W^{\pm}h) \times \mathcal{B}(h \to b\bar{b})$ across a mass range from 250 GeV to 3 TeV. The second [5] searches for $H^{\pm} \to \tau\nu$ decays, both in top-quark decays for light $H^{\pm}$ and in associated production with top-quark for heavy $H^{\pm}$. The results cover a wide mass range (80–3000 GeV) and provide the most stringent limits to date on $\mathcal{B}(t \to bH^{\pm}) \times \mathcal{B}(H^{\pm} \to \tau\nu)$ and on $\sigma(pp \to tbH^{\pm}) \times \mathcal{B}(H^{\pm} \to \tau\nu)$.

Beyond charged Higgs bosons, ATLAS has also explored models predicting additional neutral scalars. A dedicated search [6] investigates the decay of a new scalar $S$ into pairs of light vector bosons $Z_d$, $S \to Z_d Z_d \to 4\ell$, motivated by hidden-sector models such as the Hidden Abelian Higgs Model. Using the full Run 2 dataset, the analysis probes scalar masses between 30 and 800 GeV and $Z_d$ masses between 15 and 300 GeV, setting strong limits on $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$.

In parallel, new approaches that go beyond model-specific searches are being developed. A recent ATLAS study [7] applies weakly supervised anomaly detection techniques to dijet final states. By exploiting machine learning strategies, the analysis searches for localized excesses in dijet invariant mass spectra without relying on specific signal hypotheses. Taken together, these four analyses illustrate the breadth of the ATLAS new physics programme. These analyses extend the ATLAS sensitivity both to heavy resonances in the multi-TeV mass range and to processes with increasingly smaller production cross sections at lower masses.

## 2. Dataset

All four analyses use the full Run 2 dataset of proton–proton collisions at $\sqrt{s} = 13$ TeV recorded by ATLAS during 2015–2018, corresponding to an integrated luminosity of about 140 fb$^{-1}$ after data-quality requirements. Object reconstruction follows standard reconstruction, calibrations and uncertainties (electrons, muons, electrons, muons, small-radius (small-$R$) and large-radius (large-$R$) jets, $b$-tagging, reconstructed $\tau$ candidates, corresponding to the visible part of a hadronic $\tau$-lepton decay, $\tau_{\text{had-vis}}$ and missing transverse momentum, $E_{\text{T}}^{\text{miss}}$), with per-analysis optimizations (e.g. boosted $h \to b\bar{b}$ tagging in merged topologies, Recurrent Neural Network (RNN)-based $\tau$ identification, and jet substructure for large-$R$ jets). Simulated samples (where used) employ state-

of-the-art generators and tunes, with pile-up reweighting to data; purely data-driven references are used in the weakly supervised anomaly detection analysis.

## 3. Analysis strategy

**$H^{\pm} \to W^{\pm}h$ ($h \to b\bar{b}$) (associated $tbH^{\pm}$ production).** Events with one lepton, jets (including multiple $b$-tags), and $E_{\mathrm{T}}^{\mathrm{miss}}$ are categorized into *resolved* and *merged* regimes depending on the boost of the $h$ and $W$ candidates. Dedicated reconstruction builds $Wh$ candidates and targets a narrow excess in the reconstructed mass. Signal regions (SRs) are complemented by control regions (CRs) that constrain the dominant backgrounds (e.g. $t\bar{t}$, $W$+jets). A simultaneous profile-likelihood fit across SRs and CRs extracts limits on $\sigma(pp \to tbH^{\pm}) \times \mathcal{B}(H^{\pm} \to W^{\pm}h) \times \mathcal{B}(h \to b\bar{b})$ over $m_{H^{\pm}}$ from a few hundred GeV to multi-TeV. The resulting observed and expected 95% CL upper limits are shown in Figure 1.

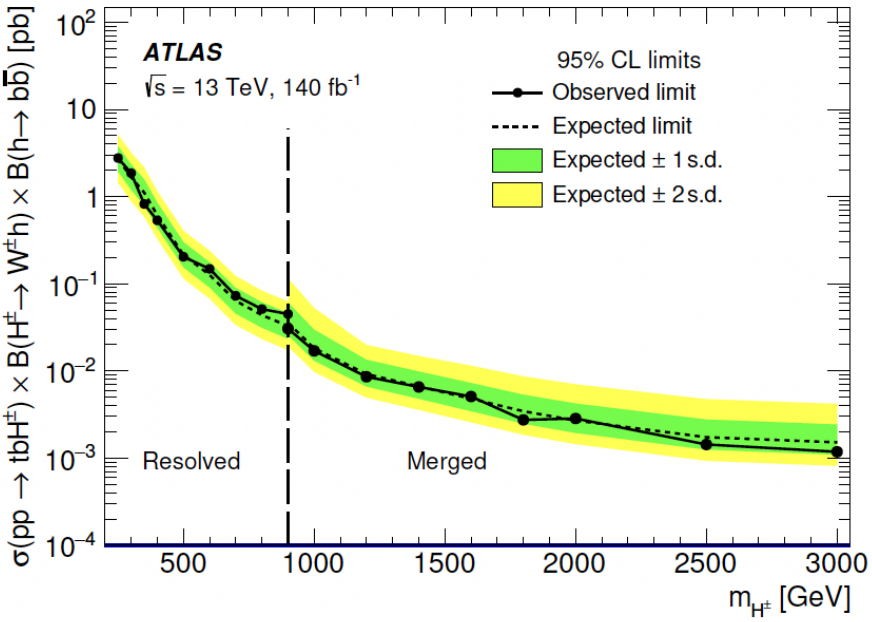


**Figure 1:** Upper limits at 95% CL on $\sigma(pp \to tbH^{\pm}) \times \mathcal{B}(W^{\pm}h) \times \mathcal{B}(h \to b\bar{b})$ from the combined fit to signal and control regions of the resolved and merged analyses. Bands show the ±1 and ±2 standard deviation intervals. Resolved results are used up to 900 GeV and merged results at higher masses. Adapted from Ref. [4]

**$H^{\pm} \to \tau\nu$ (low/intermediate/high mass).** Two complementary channels are used depending on the $W$ from the associated top: $\tau_{\text{had-vis}}$+jets and $\tau_{\text{had-vis}}$+lepton. Mass-sensitive, parameterized neural-network (PNN) discriminants separate signal from $t\bar{t}$ and $W$+jets; misidentified $\tau$ backgrounds are constrained with improved data-driven fake factor methods. A combined fit across channels provides 95% CL limits on $\mathcal{B}(t \to bH^{\pm}) \times \mathcal{B}(H^{\pm} \to \tau\nu)$ (for light $H^{\pm}$) and on $\sigma(pp \to tbH^{\pm}) \times \mathcal{B}(H^{\pm} \to \tau\nu)$ (for heavy $H^{\pm}$), with interpretations in benchmark 2HDM and

Minimal Supersymmetric Standarm Model (MSSM) scenarios (e.g. habemus MSSM (hMSSM)). The combined exclusion limits on cross-section and on ratio of the vacuum expectation values of the two Higgs doublets, $\tan\beta$ are presented in Figure 2.

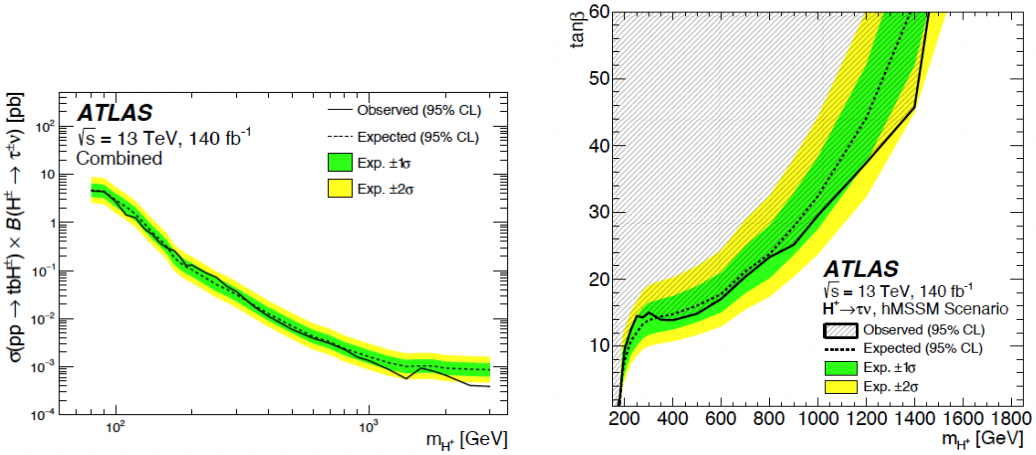


**Figure 2:** Observed and expected 95% CL exclusion limits: (a) on $\sigma(pp \to tbH^+) \times \mathcal{B}(H^+ \to \tau\nu)$ as a function of $m_{H^+}$, from the combined $\tau_{\text{had-vis}}$+jets and $\tau_{\text{had-vis}}$+lepton channels; (b) on $\tan\beta$ as a function of $m_{H^+}$ in the hMSSM for $m_{H^+} > 150$ GeV and $1 \leq \tan\beta \leq 60$. The shaded bands show the $\pm 1\sigma$ and $\pm 2\sigma$ intervals around the expected limits. Adapted from Ref. [5]

**$S \to Z_d Z_d \to 4\ell$ (hidden-sector scalar).** Events with exactly four isolated leptons are selected using single-/di-lepton triggers. Pairs of opposite-sign, same-flavour leptons form two $Z_d$ candidates are selected. Kinematic selections and lepton-quality criteria suppress SM $ZZ^{(*)}$, $H \to ZZ^{(*)}$, and reducible backgrounds. The four-lepton invariant mass spectrum is scanned for localized excesses over backgrounds predicted by simulation and validated in data control samples. No deviations are observed, and 95% CL upper limits on $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$ are set, as shown in Figure 3.

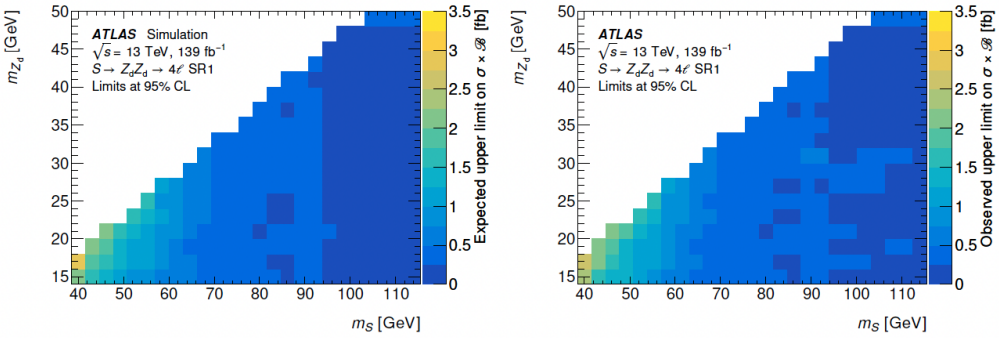


**Figure 3:** Expected and observed 95% CL limits on $\sigma(gg \to S) \times \mathcal{B}(S \to Z_d Z_d \to 4\ell)$. (a) SR1 expected limit; (b) SR1 observed limit. Adapted from Ref. [6]

**Dijet weakly supervised anomaly detection.** A model-agnostic search targets narrow resonances in dijet events with two high-$p_{\mathrm{T}}$ large-$R$ jets and $m_{JJ} > 1.3$ TeV. Two complementary weakly supervised strategies build background *reference* samples without relying on a specific signal model: *SALAD* (simulation-assisted reweighting) and *CURTAINs* (normalizing-flow morphing). Classifiers trained in the CWoLa paradigm enhance potential signal-like regions; the post-selection dijet mass, $m_{JJ}$ spectrum is scanned for bumps. Figure 4 compares the resulting 95% CL upper limits from both methods with previous ATLAS dijet and diboson searches [8]. While no significant excess is observed, these techniques demonstrate strong potential for model-independent discovery.

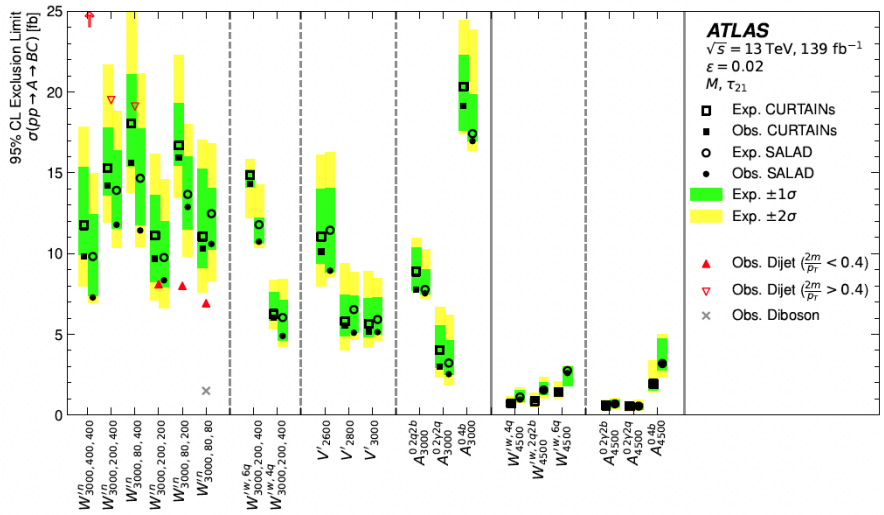


**Figure 4:** 95% CL upper limits on $\sigma(pp \to A \to BC)$ set by SALAD and CURTAINs at $\epsilon = 0.02$ with $T = M, \tau_{21}$. Shaded bands indicate the $\pm 1\sigma$ and $\pm 2\sigma$ variations. Observed limits from the ATLAS dijet search [9] (red triangles) and all-hadronic diboson search [10] (grey X) are overlaid, derived in the previous weakly supervised ATLAS study [11]. For comparison, the $W'$ acceptance in this work is 86% of that in Ref. [10]. The inclusive dijet limit exceeding the shown range is marked with a red arrow. Adapted from Ref. [7]

**Statistical treatment and systematics.** All targeted searches use profile-likelihood fits with nuisance-parameter constraints for experimental and modelling systematics (jet energy/mass scales and resolutions, $b/\tau$ ID, luminosity, background normalizations and shapes). Expected and observed 95% CL limits are derived using the asymptotic approximation [12], with $\pm 1\sigma$ and $\pm 2\sigma$ uncertainty bands shown on each plot.

## 4. Summary and outlook

Across four representative channels in the ATLAS heavy-resonance program using the complete Run-2 dataset, we find no evidence for BSM signals. The analyses set stringent limits on extended-Higgs-sector scenarios and generic resonance production, with substantial sensitivity gains driven by improved reconstruction and modern ML (including weakly supervised approaches). Run 3

(2022-2026 data taking) and High-Luminosity (HL)-LHC data will further enhance coverage, particularly in boosted topologies and rare/exotic signatures.

**Data and software availability** Results summarized here are based on published ATLAS analyses. Public documentation and HEPData entries (where applicable) provide detailed selections, background estimates, and limit-setting configurations.

## Acknowledgments

The author thanks the ATLAS Collaboration and the EPS-HEP 2025 organizers. Support from the University of Berlin is gratefully acknowledged.

## References

[1] L. Evans and P. Bryant, JINST **3** (2008) S08001.

[2] ATLAS Collaboration, JINST **3** (2008) S08003.

[3] CMS Collaboration, JINST **3** (2008) S08004.

[4] ATLAS Collaboration, JHEP **02** (2025) 143, arXiv:2411.03969[hep-ex].

[5] ATLAS Collaboration, Phys. Rev. D **111** (2025) 072006,arXiv:2412.17584 [hep-ex].

[6] ATLAS Collaboration, Phys. Lett. B **865** (2025) 139472, arXiv:2410.16781 [hep-ex].

[7] ATLAS Collaboration,Phys. Rev. D **112** (2025), 072009, arXiv:2502.09770 [hep-ex].

[8] ATLAS Collaboration, Phys. Rev. Lett. **125** (2020) 131801,arXiv:2005.02983 [hep-ex]

[9] ATLAS Collaboration, JHEP **03** (2020) 145, arXiv:1910.08447 [hep-ex].

[10] ATLAS Collaboration, JHEP **09** (2019) 091, arXiv:1906.08589 [hep-ex].

[11] ATLAS Collaboration, *Phys. Rev. Lett.* **125** (2020) 131801, arXiv:2005.02983 [hep-ex].

[12] G. Cowan *et al.*, Eur. Phys. J. C **71** (2011) 1554, arXiv:1007.1727 [physics.data-an]