PROCEEDINGS OF SCIENCE

Searches for Resonances Decaying into Higgs Boson Pairs with the ATLAS Experiment

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This document summarizes recent searches for heavy resonances (X) decaying into pairs of Higgs bosons (HH) or a new scalar plus a Higgs boson (SH) using data from the ATLAS experiment at the Large Hadron Collider. The analyses utilize the full Run-2 data and, in some cases, partial Run-3 data, targeting various final states including $bb\tau\tau$, $bb\gamma\gamma$, $4b$, and $6b$. No significant excess over the Standard Model prediction is observed. Stringent upper limits are set on the production cross-section times branching ratio for a wide range of resonance masses and for various benchmark models. These results represent a significant improvement in sensitivity over previous searches.

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1. Introduction

The discovery of the Higgs boson at the Large Hadron Collider (LHC) completed the Standard Model (SM) particle content. However, many fundamental questions remain unanswered, motivating theories Beyond the Standard Model (BSM). Numerous BSM theories predict the existence of new heavy resonances that couple strongly to the Higgs boson, providing a compelling experimental signature. These include additional scalar states in models with extended Higgs sectors such as the Two-Higgs-Doublet Model (2HDM) [1], the Minimal Supersymmetric Standard Model (MSSM) [2], the Two Real Singlet Model (TRSM) [3], and the Next-to-Minimal Supersymmetric Standard Model (NMSSM). Furthermore, extra-dimensional models like Randall-Sundrum predict spin-2 Kaluza–Klein graviton excitations [4].

This proceeding summarizes recent searches conducted by the ATLAS experiment [5] for such resonances decaying into a pair of SM Higgs bosons ($X \to HH$) or into a new light scalar particle and a Higgs boson ($X \to SH$). The analyses leverage the full dataset collected during LHC Run-2 and mark the first forays into Run-3 data, significantly enhancing the discovery potential.

2. $X \to HH$ Searches

The non-resonant HH production cross-section in the SM is small, making this final state an excellent testbed for BSM physics. The analyses target different decay channels of the Higgs boson pair to maximize sensitivity across different mass ranges.

2.1 Combination of $bb\tau\tau$, $bb\gamma\gamma$ and $4b$ channels

A combination of searches in the $bb\tau\tau$, $bb\gamma\gamma$, and $4b$ final states has been performed using the full Run-2 dataset [6]. Major improvements over previous iterations include the use of advanced b-jet identification algorithms, optimized Higgs boson reconstruction techniques, enhanced background modeling, and a refined event categorization strategy.

The observed di-Higgs invariant mass spectrum is consistent with the SM background expectation. As shown in Figure 1, the largest local excess is observed at approximately 1.1 TeV with a significance of 3.3 σ, which reduces to 2.1 σ when considering the look-elsewhere effect. No significant excess is found in the analogous CMS search in this mass region [7].

The results are interpreted as exclusion limits in the context of heavy Higgs bosons in the Type-I 2HDM and the MSSM. For a Type-I 2HDM benchmark scenario with $\tan\beta = 10$ and $\cos(\beta - \alpha) = -0.1$, resonance masses between 270 GeV and 810 GeV are excluded at the 95% confidence level (CL).

2.2 Search for $X \to HH \to 4b$ via Vector-Boson Fusion Production

A first-of-its-kind search for $X \to HH$ produced via vector-boson fusion (VBF) was conducted in the $4b$ final state for masses between 1 TeV and 5 TeV [8]. The VBF signature includes two forward jets with large invariant mass and large separation in rapidity.

The analysis identifies the hadronically decaying Higgs bosons as large-radius jets, tagged using a dedicated Xbb algorithm. The dominant multi-jet background is estimated using a data-driven technique. A parameterized Boosted Decision Tree (pBDT) is trained to separate signal from background across the mass range and is used as the final discriminant.

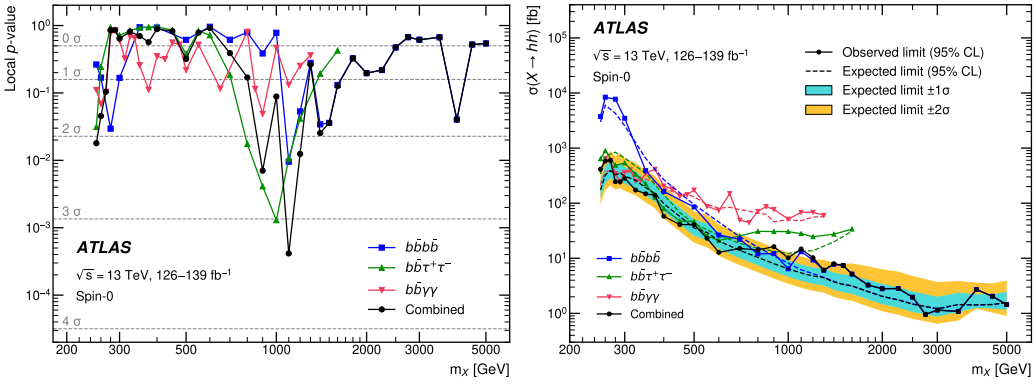

Figure 1: Local p-value (left) and observed and expected upper limits at the 95% CL on the resonant Higgs boson pair production cross section (right) as a function of the resonance mass m_X [6]. The symbol h denotes a SM Higgs boson with a mass 125 GeV.

No significant excess is observed. Upper limits are set on the product of the production cross-section and branching ratio for both narrow-width and broad-width resonance assumptions, both of which are shown in Figure 2. The observed (expected) limits range from 0.7 fb to 4.6 fb (1.2 fb to 3.1 fb) for a narrow resonance.

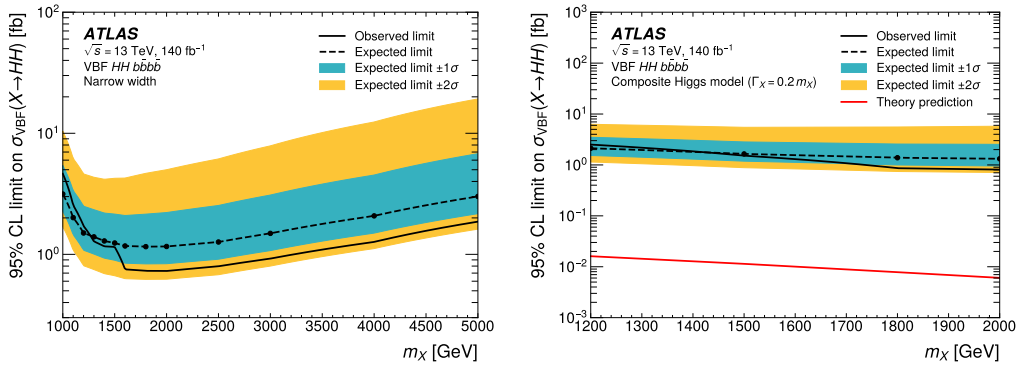

Figure 2: Expected (dashed black lines) and observed (solid black lines) 95% CL upper limits on the cross section of spin-0 heavy resonances with narrow-width (left) and broad-width (right) assumptions [8].

3. $X \to SH$ Searches

Searches for resonances decaying to a new scalar (S) and a Higgs boson probe different BSM parameter spaces, often where the new scalar S is lighter than the Higgs.

3.1 Search for $X \to S(\to bb)H(\to \gamma\gamma)$

This search targets a final state with a resolved diphoton peak from $H(\to \gamma\gamma)$ and a b-jet pair from $S(\to bb)$ [9]. It uses a combined dataset of 140 fb^{-1} from Run-2 and 58.6 fb^{-1} from early Run-3. Two signal regions are defined: one requiring two b-tagged jets (sensitive to larger m_S/m_X ratios) and one requiring a single b-tagged jet.

A Parametrized Neural Network (PNN) [10] is used to discriminate signal from the dominant $\gamma\gamma$+jets background. The background normalization is derived in control regions separately for Run-2 and Run-3 data. No significant deviation from the SM prediction is found. The sensitivity improved by 15-73% compared to the previous Run-2-only result, driven by the inclusion of Run-3 data, a tighter photon selection, an upgraded b-tagging algorithm, and an optimized PNN.

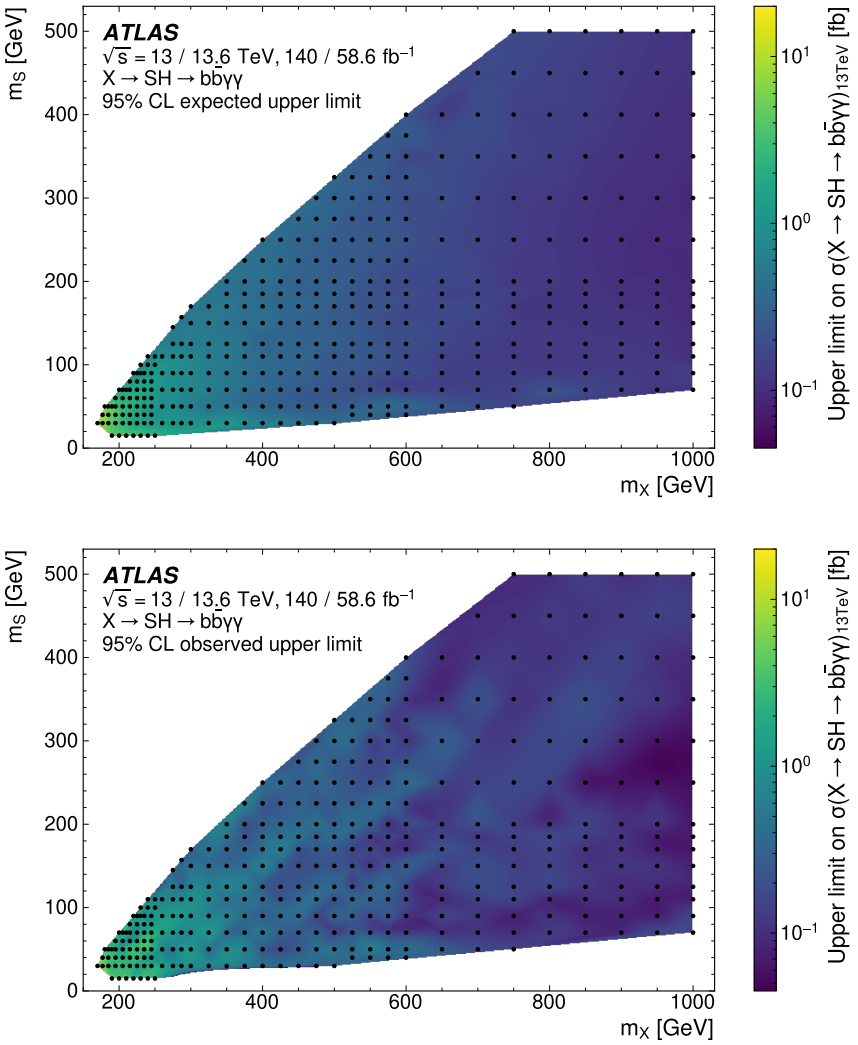

Figure 3: Expected (top) and observed (bottom) 95% CL upper limits on the $X \to S(\to bb)H(\to \gamma\gamma)$ cross-section at 13 TeV, in the full (m_X, m_S) plane, including both the 1 b-tagged and 2 b-tagged categories [9].

3.2 Search for $X \to S(\to WW/ZZ)H(\to \gamma\gamma)$

This search explores the decay of the scalar S into vector bosons for $300 < m_X < 1000$ GeV and $170 < m_S < 500$ GeV [11]. Four analysis regions are defined based on the decay products of the $S(\to WW/ZZ)$ decay (fully leptonic, semi-leptonic). A simultaneous fit to the $m_{\gamma\gamma}$ distribution in six signal regions is performed.

No evidence of a signal is found. Upper limits on the cross-section times branching ratio are set between 530 fb and 120 fb (observed) and between 800 fb and 170 fb (expected) as shown in Figure 4.

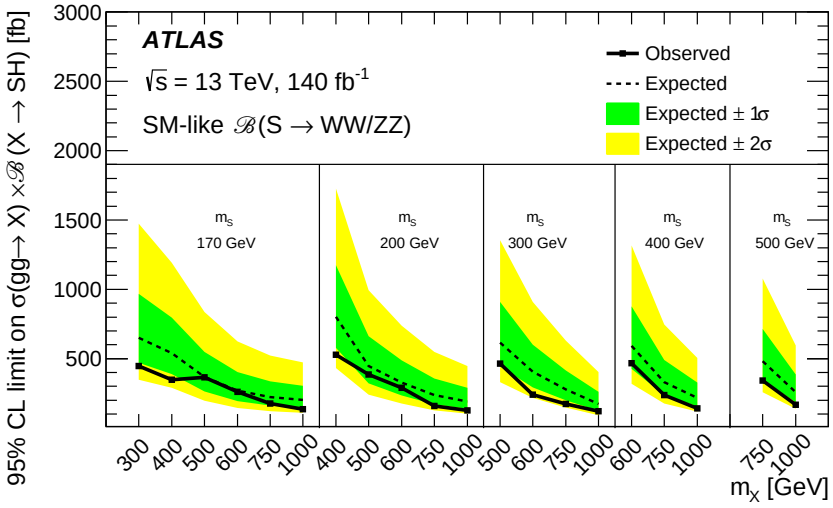

Figure 4: Observed (solid line) and expected (dashed line) 95% CL upper limits on $\sigma(gg \to X) \times \mathscr{B}(X \to SH)$ as a function of m_X and m_S, under the assumption of SM-like $\mathscr{B}(S \to WW/ZZ)$ [11].

3.3 Search for $X \to SH \to HHH \to 6b$

This search looks for a signature with six b-jets, arising from the decay chain $X \to SH$, followed by $S \to HH$ and the decay of all three Higgs bosons to bb pairs [12]. The search is performed for two benchmarks: a TRSM scenario ($325 < m_X < 575$ GeV, $200 < m_S < 350$ GeV) and a generic narrow-width scenario ($500 < m_X < 1500$ GeV, $275 < m_S < 1000$ GeV).

A deep neural network (DNN) is trained to separate the complex $6b$ signal from the multi-jet background and is used as the final discriminant. The observed data are consistent with the background prediction. As shown in Figure 5, for the TRSM scenario, cross-section limits between 48 fb and 310 fb are observed. For the generic narrow resonance, observed limits range from 5.7 fb to 38 fb.

4. Conclusion

The latest searches for resonances decaying to HH and SH pairs with the ATLAS experiment find no evidence for BSM physics. These results, based on the full Run-2 data and the early Run-3 data from the LHC, set the most stringent constraints to date on a wide variety of theoretical models, including the 2HDM, MSSM, and TRSM. The previously reported excess in the $X \to S(\to bb)H(\to \gamma\gamma)$ channel is not confirmed with the increased dataset and improved analysis. The ongoing collection of Run-3 data at higher luminosity and energy will provide further sensitivity to these compelling signatures, keeping the potential for discovery firmly on the horizon.

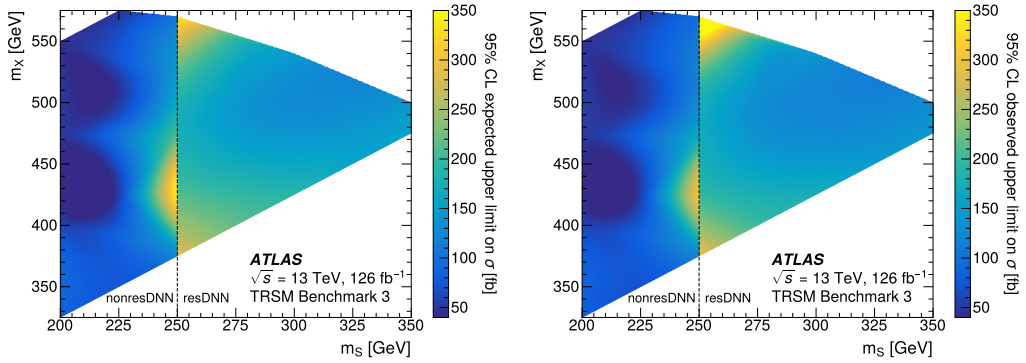

Figure 5: Expected (left) and observed (right) 95% CL HHH cross section upper limits for the phase space within the perturbative unitarity bounds of the TRSM [12].

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