PROCEEDINGS OF SCIENCE

Searches for New Massive Scalars in ATLAS

Pawel Bruckman de Renstrom on behalf of the ATLAS Collaboration[a,b,*]

[a] *Institute of Nuclear Physics, Polish Academy of Sciences, Radzikowskiego 152, Cracow, Poland*

[b] *Partially supported by NCN grant nr. 2022/47/B/ST2/03059*

E-mail: pawel.bruckman.de.renstrom@cern.ch

The properties of the observed 125 GeV scalar suggest that, if an extended scalar sector exists, it is likely realised near the alignment limit in which one of the Higgs mass eigenstates aligns with the direction of the scalar field vacuum expectation values, and its couplings approach those of the Standard Model Higgs boson. Results of recent ATLAS searches for heavy (pseudo)scalar resonances decaying to either a top quark pair or lighter scalars are presented.

12th Large Hadron Collider Physics Conference (LHCP2024)
3-7 June 2024
Boston, USA

*Speaker

PoS(LHCP2024)020

1. Introduction

Since the discovery of the new scalar boson by the ATLAS and the CMS Collaborations in 2012 [1, 2], its properties have been measured to ever increasing precision. Thus far, its properties have shown excellent agreement with the predictions for the Standard Model (SM) Higgs boson. However, the SM, while highly successful, is not considered to be a complete theory as it is not capable of explaining some of the phenomena seen in nature. Key unresolved questions include the nature of dark matter, the electroweak hierarchy problem (Higgs mass fine-tuning), and the matter-antimatter asymmetry in the visible universe. Several beyond the Standard Model (BSM) scenarios predict an extended Higgs sector, with the lack of discoveries at low masses suggesting the possible existence of additional, heavier scalar resonances. The SM-like couplings of the observed 125 GeV scalar (H_{125}) require a hypothetical extended Higgs sector to remain close to the so-called alignment limit where H_{125} has SM Higgs properties. Consequently, the couplings of heavier neutral scalars to electroweak gauge bosons are expected to be suppressed. Extensive searches have been conducted for heavy scalars (H) and pseudoscalars (A) decaying into down-type fermions, particularly bottom quark pairs or tau lepton pairs [3, 4]; these are not discussed further in this report. In the high mass regime, probing for heavy Higgs coupling to $t\bar{t}$ pairs or a combination of lighter scalars (including H_{125}) remains promissing. In the following, three categories of search analyses are reported. The first category examines Higgs boson decays to $t\bar{t}$ pairs with leptonic final states. The gluon-gluon fusion or the top-associated productions are considered. The second category focuses on heavy (pseudo)scalar cascade decays involving H_{125} or other scalar states, probing generic scenarios. Finally, results of the combination of searches for resonant H_{125} pair production is reported. Unless otherwise stated, the presented searches rely on the narrow width approximation (NWA) for the sought for heavy (pseudo)scalar. The proceedings summarizes selected recent results, obtained using 140 fb^{-1} of proton–proton (pp) collision data at $\sqrt{s}$ = 13 TeV collected by the ATLAS experiment [5] at the LHC in the years 2015-2018.

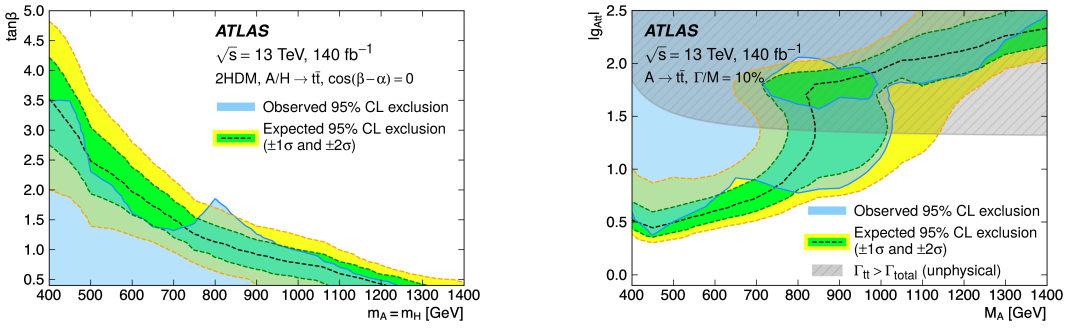
2. Heavy (pseudo)scalar decaying to a $t\bar{t}$ pair

The inclusive channel tagged by a top-quark pair in the final state is dominated by the gluon-gluon fusion production process and it is predicted to suffer from strong interference between the signal process and the irreducible background of the continuum $t\bar{t}$ production in the t-channel. As a result, the invariant mass peak at the resonance mass may by replaced by a dip accompanied by a wide excess at lower masses.

The reported analysis [6] searches for a massive H/A decaying into a top–antitop quark pair ($t\bar{t}$) in the mass range of $m_{H/A} \in [400, 1400]$ GeV. The search considers multiple BSM scenarios. These include Two-Higgs-Doublet-Model (2HDM) of type-II, the minimal supersymmetric SM with the lighter scalar h identified with the Higgs boson observed at the LHC (hMSSM), the dark matter-motivated 2HDM+a with an additional pseudoscalar, all parameterised by the H/A mass and the ratio of the two Higgs doublets vacuum expectation values, $\tan\beta$, as well as a simplified generic model parameterised by the H/A mass, width and coupling modifier to $t\bar{t}$ ($M_{A/H}, \Gamma_{A/H}, g_{A/Ht\bar{t}}$). The strong interference pattern precludes extraction of a simple limit on signal strength μ and requires a meticulous treatment of the signal model. The total production of the $t\bar{t}$ final state can

be described in terms of the contributions from the signal process (S), the background (B) and the interference term (I) as $(\mu - \sqrt{\mu})S + \sqrt{\mu}(S+I) + B_{t\bar{t}}$. The statistical analysis consists of two stages. In the first one, for each tested scenario, a fit of the best value of the $\sqrt{\mu}$ parameter is performed with the goal of potential rejection of the $\mu = 0$ hypothesis. In the absence of any significant deviation from the background-only hypothesis, in the second stage the level at which a given signal hypothesis is excluded by the data is quantified with the CLs frequentist formalism where the test statistic is defined as a simple ratio of the two likelihoods, for $\sqrt{\mu} = 1$ (signal hypothesis) and $\sqrt{\mu} = 0$ (background-only hypothesis). Here, the goal is to reject given scenario with $\mu = 1$. The quadratic dependence of the likelihood function on the signal strength leads to signal pattern shape dependence on $\sqrt{\mu}$. No unique upper limit can be established and even disjoined exclusion intervals may occur. Consequently, a full scan of the dense grid of points in the parameter space of the model in question is required.

The analysis defines two search channels. The **1-lepton** channel requires exactly one electron or muon with $p_{\mathrm{T}} > 28$ GeV, at least one jet identified as originating from a b-quark (b-tagged) and the missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV. Furthermore, two categories of reconstruction for the other top quark are defined. In the *merged topology* one large-radius jet with $p_{\mathrm{T}} > 200$ GeV and and $m > 100$ GeV is required. In the *resolved topology* at least four jets with $p_{\mathrm{T}} > 25$ GeV and at least one top candidate reconstructed with exactly one b-tagged jet are required. Additionally, the ortogonality of the two categories is assurred. The reconstructed mass of the $t\bar{t}$ system, $m_{t\bar{t}}$, serves as the final discriminant variable. The **2-lepton** channel requires exactly one opposite-sign lepton pair (e or μ) with one lepton of $p_{\mathrm{T}} > 28$ GeV and matched to the lepton object which fired the online trigger and at least two reconstructed jets. Additionally, at least one of the jets is required to be b-tagged. The mass of the lepton pair, $m_{\ell\ell}$, has to be larger than 15 GeV. For same flavour pairs (ee or $\mu\mu$) events with $m_{\ell\ell}$ consistent with the Z mass are rejected and $E_{\mathrm{T}}^{\mathrm{miss}} > 45$ GeV requiremnet is additionally imposed.



(a) **(b)**

Figure 1: Observed and expected (a) exclusion contours in the $m_{A/H} - \tan\beta$ plane for a type-II 2HDM in the alignment limit ($\cos(\beta - \alpha) = 0$) with mass-degenerate pseudoscalar and scalar states, $m_A = m_H$ (b) constraints on the coupling strength modifier $g_{A/Ht\bar{t}}$ in the generic scenario as a function of M_A for the relative width of the pseudoscalar A of 10% . [6]

No significant deviation from the SM prediction is observed. Example exclusions for type-II 2HDM model in the alignment limit and assuming mass-degenerate H and A states are shown in Figure 1(a). Data excludes at 95% confidence level (CL) $\tan\beta$ smaller than 3.49 (3.16) for $m_A =$

m_H = 400 GeV in the 2HDM (hMSSM). Masses up to 1240 GeV are excluded for the lowest tested $\tan\beta$ value of 0.4 in the 2HDM. In the hMSSM, masses up to 950 GeV are excluded for $\tan\beta = 1$. In addition, generic exclusion limits are derived separately for single scalar and pseudoscalar states for different choices of their mass and total width. Figure 1(b) shows example exclusions for the generic scenario assuming the relative width of the heavy pseudoscalar $\Gamma_A/M_A = 10\%$.

The top-associated production of a massive A/H is predicted to be considerably less abundant, however it does not suffer from any sizeable interference with the SM irreducible background. The SM $t\bar{t}t\bar{t}$ production has been recently established by both ATLAS [7] and CMS [8] with a mild excess of data over SM prediction observed by the earlier. The reported ATLAS analysis [9] searches for a heavy H/A predicted by the 2HDM, produced in association with a top quark pair and subsequently decaying into a pair of top quarks. ($t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$) in the H/A mass range of $m_{H/A} \in [400, 1000]$ GeV. The search uses events with exactly one lepton (**1L**) or two leptons with opposite electric charge (**2LOS**). These signatures complement an earlier search by ATLAS which used either two leptons with the same sign or multiple (>2) reconstructed leptons in the final state [10].

One of the principal experimental difficulties is modeling of the dominant $t\bar{t}$+jets background. The MC generated background is corrected in the procedure dubbed *flavor rescaling*, whereby rescaling factors are determined in the dedicated control regions as corrections to the overall normalisation of the $t\bar{t}$+light, $t\bar{t}$+$\geq 1c$ and $t\bar{t}$+$\geq 1b$ backgrounds. Additionally, in order to improve modeling the kinematics, corrections are derived using a feed-forward artificial neural network (NN) trained as a binary classifier between data and simulation. The NN score interpretted as a weight is then applied to $t\bar{t}$+jets simulation on event-by-event basis. Uncertainties of the analysis are dominated by the $t\bar{t}$+jets modelling and modelling of the SM $t\bar{t}t\bar{t}$ production.

Signal region (SR) is categorised into multiple bins depending on the reconstructed jet multiplicity and number of b-tagged jets. The multivariate discriminant built in this analysis is based on novel graph neural networks (GNN), which are trained separately for the 1L and 2LOS categories.

No significant excess over the SM background predictions is observed, hence 95% CL limits are set on the $\sigma \times BR(A/H \rightarrow t\bar{t})$ for 400 GeV $< m_{A/H} <$ 1000 GeV. In combination with the previous search performed by the ATLAS Collaboration [10], the observed 95% CL upper limit on the $\sigma \times BR(A/H \rightarrow t\bar{t})$ ranges from 14.2 fb at $m_{A/H} = 400$ GeV to 5.0 fb at $m_{A/H} = 1000$ GeV, as shown in Figure 2(a). When both H and A contribute to the $t\bar{t}t\bar{t}$ cross section, the exclusions on $\tan\beta$ range from below 1.7 down to 0.7 at masses of 400 GeV and 1000 GeV, respectively, as illustrated in Figure 2(b).

3. Heavy (pseudo)scalar cascade decays involving lighter scalar states

Two recent analyses are reported in this section. The first one tests either an extended 2HDM+S model, where a massive CP-even scalar R decays into a heavy Higgs boson and the additional scalar S which is a candidate for portal to the dark matter (DM) sector and hence decays invisibly or the 2HDM-based baryogenesis model where a massive CP-odd pseudoscalar A decays into a heavy Higgs boson and the Z boson [11]. In both cases H is assumed to decay to a ZZ pair. Assuming at least two Z bosons decaying leptonically, the selection requires two same-flavor opposite sign

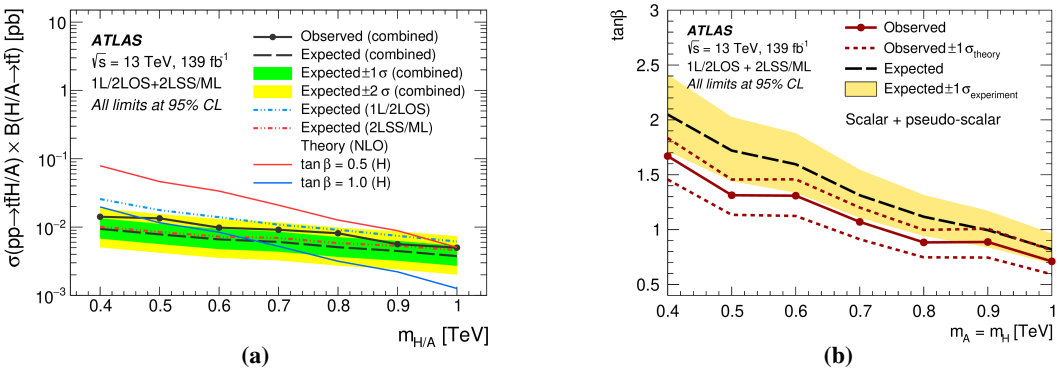


Figure 2: Expected and observed 95% CL upper limits on (a) $\sigma \times BR(A/H \to t\bar{t})$, as a function of $m_{A/H}$, obtained from the combination of the 1L/2LOS and 2LSS/ML final states. The expected limits from the individual 1L/2LOS and 2LSS/ML analyses are also shown. (b) $\tan\beta$ as a function of the $m_{A/H}$ mass obtained using the combination of 1L/2LOS and 2LSS/ML final states, assuming type-II 2HDM in the alignment limit and contribution from both mass-degenerate H and A states. [9]

(SFOS) reconstructed lepton pairs, both with the reconstructed mass consistent with m_Z. Seven signal regions are defined by the number of reconstructed jets, number of b-tagged jets and $E_{\mathrm{T}}^{\mathrm{miss}}$ significance. The main background to the search stems from the SM ZZ pair production. In order to probe the entire parameter space, a dense grid of mass points is generated. The final fit is performed simultaneously in all SR's to the invariant mass distribution of the four reconstructed leptons, $m_{4\ell}$. Presence of the signal would manifest by either a resonance in the $m_{4\ell}$ when the two leptonically decaying Z bosons originate from the decay of the heavy scalar H or as a wider excess if the reconstructed Z pair is non-resonant in the cascade decay of the pseudoscalar A.

No significant excess over the SM background is observed. Therefore, limits are set on the (m_H, m_R) and (m_H, m_A) planes assuming NWA for all concerned resonances. As dependence on the mass of S (the DM portal messenger) is found to be negligible, m_S is set to 160 GeV. The

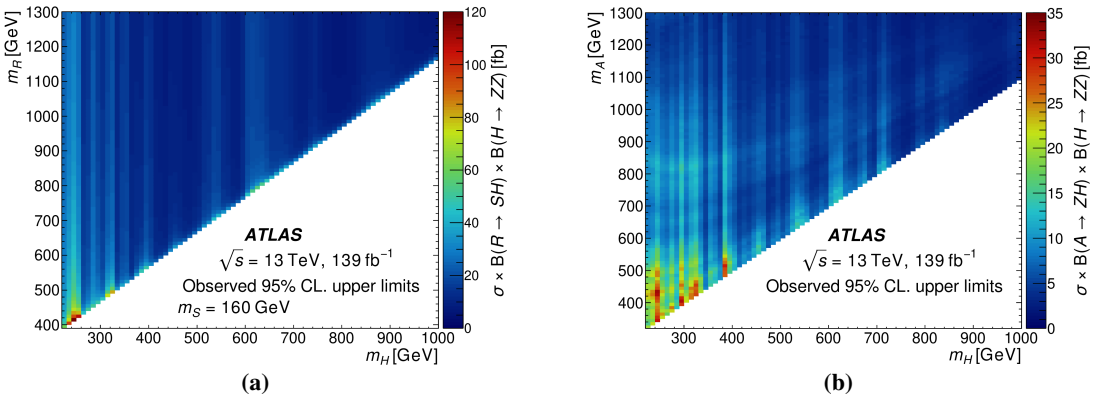


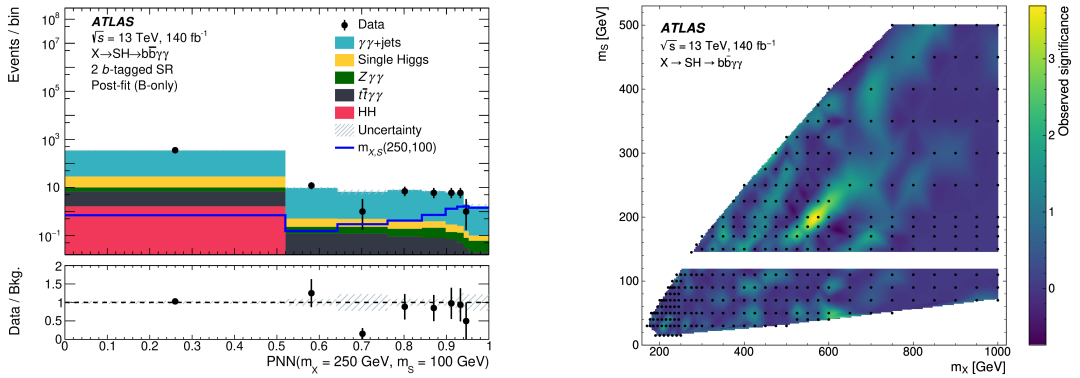
Figure 3: Observed 95% CL upper limits on (a) $\sigma(gg \to R) \times BR(R \to SH) \times BR(H \to ZZ)$ across the (m_H, m_R) plane with $m_S = 160$ GeV for the $R \to SH \to 4\ell + E_{\mathrm{T}}^{\mathrm{miss}}$ search, and on (b) $\sigma(gg \to A) \times BR(A \to ZH) \times BR(H \to ZZ)$ across the (m_H, m_A) plane for the $A \to ZH \to 4\ell + X$ search. [11]

resulting 95% CL upper limits on for the $R \to SH$ and $A \to ZH$ scenarios are shown in Figure 3.

The impact due to possible departure from the NWA is also studied and shows an almost factor two degradation of the sensitivity (a factor two higher limit) assuming 30% (10%) relative width for the A (H) resonance.

The second analysis looks for signature of either 2HDM type models or SM extended by singlets with at least two degrees of freedom, where a massive scalar X decays to a lighter one S and a SM Higgs (H_{125}), with subsequent decays of S (H_{125}) to a $b\bar{b}$ pair (a pair of photons) [12].

The event selection based on di-photon triggers requires a pair of reconstructed photons with invariant mass consistent with H_{125} ([120, 130]) and exactly one b-tagged jet (**1b SR**) or exactly two b-tagged jets (**2b SR**). Main background originates from $\gamma\gamma$+jets events and is normalised from $m_{\gamma\gamma}$ side bands. A simultaneous fit is performed to distributions of the NN score parameterised by m_X and (m_X, m_S) (PNN) in the 1b and 2b SR's, respectively. An example PNN score after the fit



(a) **(b)**

Figure 4: (a) Post-fit distributions of the PNN discriminant output in the 2 b-tagged signal region for $(m_X, m_S) = (250, 100)$ GeV after a background-only fit to data. The hypothetical signal normalised to a 1 fb cross section is illustrated for comparison. (b) Local observed significance for signal discovery at different (m_X, m_S). The points show where the significance was evaluated. [12]

for 2b SR and $(m_X, m_S) = (250, 100)$ GeV signal hypothesis is shown in Figure 4(a).

Data is found compatible with the SM prediction over the entire parameter space considered by the search. Figure 4(b) shows the significance of the signal over the SM background-only hypothesis on the (m_X, m_S) plane. m_S around 125 GeV is excluded as it is covered by dedicated searches of di-Higgs production. Largest deviation from the background-only hypothesis is observed for $(m_X, m_S) = (575, 200)$ GeV with the local (global) significance of $3.5(2.0)\sigma$.

The ATLAS result does not confirm the excess observed by the CMS experiment at $(m_X, m_S) = (650, 90)$ GeV with the local (global) significance of $3.8(2.8)\sigma$ [13].

4. Resonant H_{125} pair production

Search for the di-Higgs production is central for the LHC physics programme as cross-section enhancement over the SM-predicted may hint to new physics. At the same time the resonant production of a H_{125} pair would provide a direct evidence of extended scalar sector. Three complementary searches for resonant H_{125} (hereafter denoted as h) pair production are combined to

provide continuous exclusion limits on $\sigma(X \to hh)$ for m_X ranging from the kinematic limit of 251 GeV up to 5 TeV [14].

The $b\bar{b}b\bar{b}$ final state exploits both four b-tagged $R = 0.4$ jets (*resolved* channel) as well as two $R = 1.0$ jets tagged by constituent track jets (*boosted* channel) [15]. This channel uses $m_{b\bar{b}b\bar{b}}$ as the final variable and due to the highest branching fraction dominates the sensitivity for low masses.

The $b\bar{b}\tau^+\tau^-$ uses all-hadronic ($\tau_{\text{had}}\tau_{\text{had}}$ category) τ-lepton decays as well as semi-leptonic ones ($\tau_{\text{lep}}\tau_{\text{had}}$ category) and using PNN score as the final discriminant dominates the intermediate mass range [16].

The $b\bar{b}\gamma\gamma$ exploits the high mass resolution of the $\gamma\gamma$ system using $m_{\gamma\gamma}$ as the final variable [17]. This cannel is the most sensitive for high X mass hypotheses.

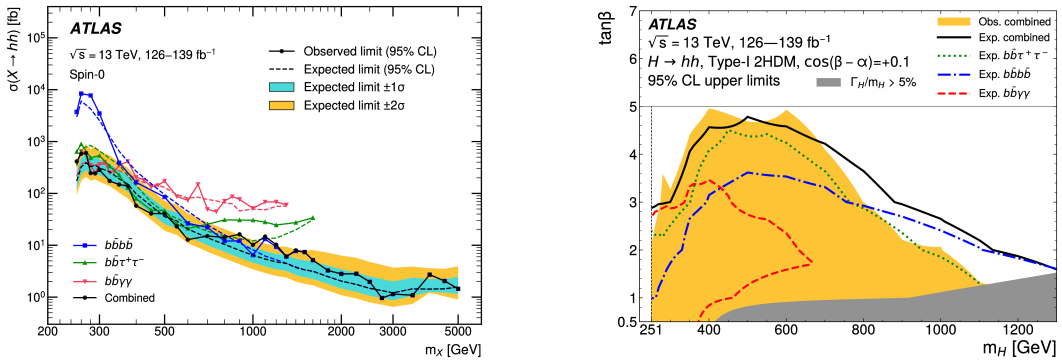


Figure 5: Expected and observed 95% CL upper limits on (a) the resonant Higgs boson pair production cross section as a function of the resonance mass m_X. (b) the Type-I 2HDM parameter space for $\cos(\beta - \alpha) = 0.1$. Observed and expected limits for the combination of all channels and expected limits for each of the individual channels are presented. [14]

The upper limits on the resonant $\sigma(X \to hh)$ are extracted from a simultaneous fit of all signal categories and shown in Figure 5(a). Data is found compatible with the SM background prediction over the entire mass range of 251GeV to 5 TeV. Largest excess is seen at 1.1 TeV with local (global) significance of $3.3(2.1)\sigma$. Obtained limits are additionally interpretted in the type-I 2HDM and MSSM models. Example exclusion for type-I 2HDM and $\cos(\beta - \alpha) = 0.1$ is shown if Figure 5(b).

5. Conclusion

So far, no new heavy scalar resonance has been observed by the ATLAS Collaboration. Searches using $t\bar{t}$ and di-Higgs final states extend existing exclusions on 2HDM-type models in the low and intermediate $\tan\beta$ range [18]. New exclusions on generic models with at least two additional heavy (pseudo)scalars have been obtained searching for cascade decays involving lighter scalar states by means of two-dimensional scans of the mass parameter space.

Acknowledgments

This work is supported in part by the Polish National Science Centre project no. 2022/47/B/ST2/03059.

References

[1] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B 716 (2012) 1.

[2] CMS Collaboration, *Observation of a new boson at a mass of* 125 *GeV with the CMS experiment at the LHC*, Phys. Lett. B 716 (2012) 30.

[3] 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.

[4] 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*, Phys. Rev. D 102 (2020) 032004.

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

[6] ATLAS Collaboration, *Search for heavy neutral Higgs bosons decaying into a top quark pair in* 140 fb^{-1} *of proton-proton collision data at $\sqrt{s}$ =* 13 TeV *with the ATLAS detector*, JHEP 08 (2024) 013.

[7] ATLAS Collaboration, *Observation of four-top-quark production in the multilepton final state with the ATLAS detector*, Eur. Phys. J. C 83 (2023) 496.

[8] CMS Collaboration, *Observation of four top quark production in proton–proton collisions at $\sqrt{s}$ =* 13 TeV, Phys. Lett. B 847 (2023) 138290.

[9] ATLAS Collaboration, *Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$ production in proton-proton collisions at $\sqrt{s}$ =* 13 TeV *with the ATLAS detector*, arXiv:2408.17164, submitted to EPJC.

[10] ATLAS Collaboration, *Search for $t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$ production in the multilepton final state in proton-proton collisions at $\sqrt{s}$ =* 13 TeV *with the ATLAS detector*, JHEP 07 (2023) 203

[11] ATLAS Collaboration, *Search for heavy resonances in final states with four leptons and missing transverse momentum or jets in pp collisions at $\sqrt{s}$ =* 13 TeV *with the ATLAS detector*, arXiv:2401.04742, submitted to JHEP.

[12] ATLAS Collaboration, *Search for a resonance decaying into a scalar particle and a Higgs boson in the final state with two bottom quarks and two photons in proton-proton collisions at a center of mass energy of* 13 TeV *with the ATLAS detector*, arXiv:2404.12915, submitted to JHEP.

[13] CMS Collaboration, *Search for a new resonance decaying into two spin-*0 *bosons in a final state with two photons and two bottom quarks in proton-proton collisions at $\sqrt{s}$ =* 13 TeV, JHEP 05 (2024) 316.

[14] ATLAS Collaboration, *Combination of searches for resonant Higgs boson pair production using pp collisions at* $\sqrt{s}$ = 13 TeV *with the ATLAS detector*, Phys. Rev. Lett. 132 (2024) 231801

[15] ATLAS Collaboration, *Search for resonant pair production of Higgs bosons in the* $b\bar{b}b\bar{b}$ *final state using* pp *collisions at* $\sqrt{s}$ = 13 TeV *with the ATLAS detector*, Phys. Rev. D 105 (2022) 092002.

[16] ATLAS Collaboration, *Search for resonant and non-resonant Higgs boson pair production in the* $b\bar{b}\tau^+\tau^-$ *decay channel using* 13 TeV pp *collision data from the ATLAS detector*, JHEP 07 (2023) 040.

[17] ATLAS Collaboration, *Search for Higgs boson pair production in the two bottom quarks plus two photons final state in* pp *collisions at* $\sqrt{s}$ = 13 TeV *with the ATLAS detector*, Phys. Rev. D 106 (2022) 052001.

[18] ATLAS Collaboration, *Summary plots for beyond Standard Model Higgs boson benchmarks for direct and indirect searches*, ATL-PHYS-PUB-2024-008, https://cds.cern.ch/record/2898861.