PROCEEDINGS OF SCIENCE

Searches for additional neutral Higgs bosons in ATLAS

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The discovery of the Higgs boson with a mass of about 125 GeV completed the observation of the particle content predicted by the Standard Model. Even though this model is well established and consistent with many measurements, it is not considered complete as it is not capable of explaining some experimental observations. Many extensions of the Standard Model addressing such shortcomings introduce additional Higgs-like bosons. A selection of searches for additional high- and low-mass neutral Higgs bosons based on the full LHC Run 2 dataset of the ATLAS experiment at 13 TeV is presented in this contribution.

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PoS(EPS-HEP2023)434

1. Introduction

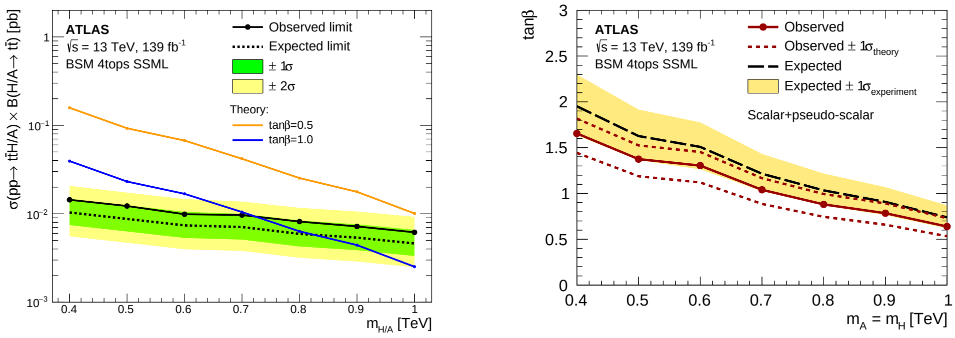
The discovery of the Higgs boson with a mass of about 125 GeV in 2012 by the ATLAS [1] and CMS [2] Collaborations completed the observation of the particle content predicted by the Standard Model (SM). Since the discovery, its properties have been measured with increasing precision and so far all measurements are in agreement with the SM predictions. However, the SM, while being well established and consistent with many measurements, is not considered to be a complete theory because it is not capable of explaining some experimental observations. Many theories beyond the Standard Model (BSM) extend the Higgs sector by introducing additional scalar fields to provide solutions to some of the questions that the SM fails to answer. Introducing additional scalar fields leads to extra Higgs-like particles, which can be either neutral or charged and can be directly searched for at the LHC in various final states. This contribution presents a selection of the searches for additional neutral Higgs bosons performed using 140 fb^{-1} of 13 TeV proton–proton collision data collected by the ATLAS experiment during the Run 2 of the LHC.

2. Search for heavy Higgs bosons produced in association with a top-quark pair and decaying into a top-quark pair ($ttH/A \to tttt$)

This search is motivated by the Two-Higgs-Doublet-Model (2HDM) of Type-II [3] and looks for a heavy scalar (H) or pseudo-scalar (A) with a mass in the range 400 − 1000 GeV produced in association with a top-quark pair and decaying into a top-quark pair ($ttH/A \to tttt$) [4] . The analysis is performed in final states with exactly 2 leptons with same-sign electric charge or at least three leptons, at least 6 jets and at least 1 b-tagged jet. A Boosted Decision Tree (BDT) classifier is used to distinguish the SM events with four top-quarks from the rest of the SM backgrounds and it is used to define the analysis signal region. In the signal region, a mass-parameterised BDT is used to distinguish between the signal and the total SM background and the output of this BDT is used as final discriminant. No significant excess of data events over the SM prediction is observed and thus upper limits are set on the ttH/A production cross section times the branching ratio of $H/A \to tt$ as a function of $m_{H/A}$ and on the parameter $\tan\beta$ as a function of $m_{H/A}$ in the 2HDM Type-II, as shown in Figure 1.

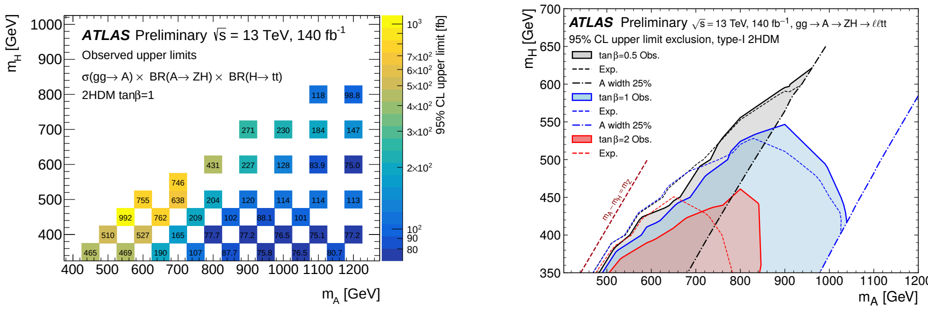
3. Search for a heavy CP-odd Higgs boson decaying to a heavy CP-even Higgs boson and a Z boson in the $\ell\ell tt/\nu\nu bb$ final states ($A \to ZH \to \ell\ell tt/\nu\nu bb$)

This search is inspired by the Two-Higgs-Doublet-Model [3] and looks for a heavy CP-odd scalar (A) with a mass in the range 450−1200 GeV produced via gluon-gluon fusion or in association with a b-quark pair and decaying into a Z boson and a heavy CP-even scalar (H) with a mass in the range 350 − 800 GeV ($A \to ZH$) [5]. The analysis considers the Z boson decaying in two leptons or two neutrinos and the H boson decaying into a pair of top-quarks or a pair of b-quarks, leading to the $\ell\ell tt$ and $\nu\nu bb$ channels, analysed in final states with exactly three leptons, at least four jets and two b-tagged jets or zero leptons, missing transverse energy and at least three b-tagged jets. The mass difference between the reconstructed A and H bosons and the transverse mass of the reconstructed ZH system are used as final discriminants in the two channels respectively. No



(a) **(b)**

Figure 1: Upper limits on the ttH/A production cross section times the branching ratio of $H/A \to tt$ as a function of $m_{H/A}$ (a) and upper limits on the parameter $\tan\beta$ as a function of $m_{H/A}$ in the 2HDM Type-II (b) [4].



(a) **(b)**

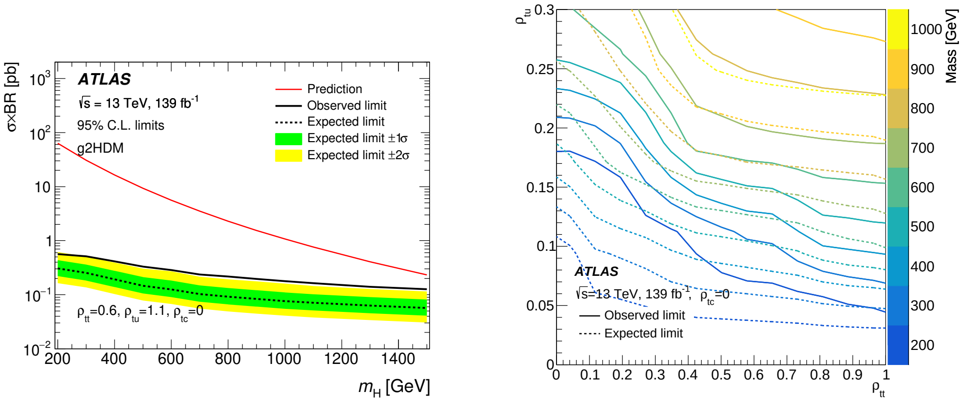
Figure 2: Observed upper limits on the A production cross section times the $A \to ZH$ and the $H \to tt$ branching ratios as a function of m_A and m_H (a) and expected and observed exclusion regions in the $(m_A - m_H)$ plane for different values of the parameter $\tan\beta$ in the 2HDM Type-I (b) for the $\ell\ell tt$ channel [5].

significant excess of data events over the SM prediction is observed. Thus, upper limits are set on the A production cross section times the $A \to ZH$ and the $H \to tt$ or $H \to bb$ branching ratios as a function of m_A and m_H and are interpreted as constraints on the 2HDM Type-I and Type-II in the $(m_A - m_H)$ plane for different values of the parameter $\tan\beta$, as shown in Figure 2 with an example for the $\ell\ell tt$ channel.

4. Search for heavy Higgs bosons in multilepton plus b-jets final states

This search is motivated by the Two-Higgs-Doublet-Model with extra flavor-changing neutral Higgs interactions (g2HDM) [6] and looks for heavy Higgs bosons (H) with a mass in the range 200 – 1500 GeV with BSM couplings of the Higgs involving the top-quark and the up and charm quarks ($\rho_{tt}, \rho_{tc}, \rho_{tu}$) [7]. The targeted signals lead to final states with a same-sign top-quark pair, three top-quarks, or four top-quarks, and the analysis is performed in final states with two leptons

PoS(EPS-HEP2023)434



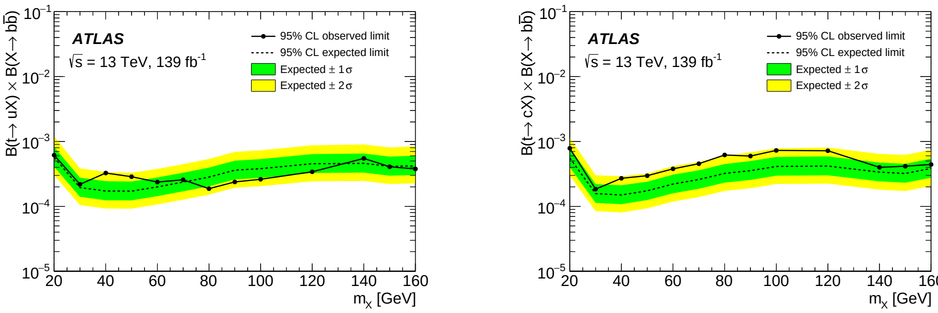
(a) **(b)**

Figure 3: Upper limits on the heavy Higgs boson production cross section times branching ratio as a function of its mass assuming ($\rho_{tt} = 0.6, \rho_{tc} = 0, \rho_{tu} = 1.1$) (a) and upper limits on the couplings in the (ρ_{tt}, ρ_{tu}) plane as a function of the heavy Higgs boson mass assuming $\rho_{tc} = 0$ (b) [7].

with same-sign electric charge, three leptons or four leptons and b-tagged jets. A Deep Neural Network (DNN) trained to distinguish between the five different production modes considered for the signal is used to define separate analysis signal region categories to enhance the sensitivity to each possible production mode and the output of a second DNN trained in each signal region to separate the signals from the background is used as final discriminant. No significant excess of data events over the SM prediction is observed, thus, upper limits are set on the heavy Higgs boson production cross section times branching ratio as a function of its mass for different values of the BSM couplings ($\rho_{tt}, \rho_{tc}, \rho_{tu}$) and on the values of the couplings ($\rho_{tt}, \rho_{tc}, \rho_{tu}$) as a function of the heavy Higgs boson mass, as shown in the examples in Figure 3.

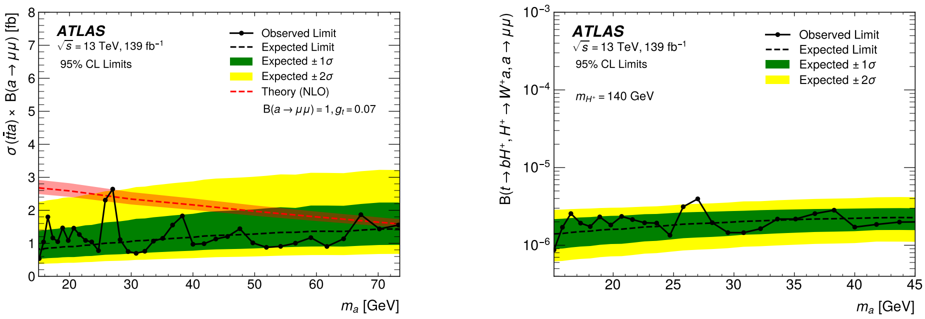
5. Search for light scalars produced in the decay of a top-quark and decaying into a b-quark pair

This search is motivated by the Flavon Model with flavor-changing-neutral-current top-decays [8] and looks for a light scalar (X) with a mass in the range 20 – 160 GeV produced from the BSM decay of the top-quark $t \to Xq(u/c)$ in top-quark pair production events and decaying into a pair of b-quarks ($X \to bb$) [9]. The analysis is performed in final states with one lepton, at least four jets and three b-tagged jets and uses as final discriminant the output of a mass-parameterised Neural Network trained to separate the signals with different masses of the X from the background. No significant excess of data events over the SM prediction is observed, thus, upper limits are set on the $t \to Xq(u/c) \times X \to bb$ branching ratio as a function of the X mass, as shown in Figure 4.



(a) **(b)**

Figure 4: Upper limits on the $t \to Xu \times X \to bb$ branching ratio (a) and upper limits on the $t \to Xc \times X \to bb$ branching ratio (b) as a function of the X mass [9].



(a) **(b)**

Figure 5: upper limits on the tta production cross section times the $a \to \mu\mu$ branching ratio as a function of the mass of the a (a) and upper limits on the $t \to H^{\pm} \times H^{\pm} \to W^{\pm}a \times a \to \mu\mu$ branching ratio as a function of the mass of the a for $m_{H^{\pm}}$ = 140 GeV [10].

6. Search for light pseudo-scalar Higgs bosons decaying into a pair of muons in events with a top-quark pair

This search is inspired by the 2HDM+a extended Higgs sector model and looks for a light pseudo-scalar (a) with a mass in the range 15 – 72 GeV produced in association with a top-quark pair (tta) or produced from the decay of a charged Higgs coming from the top-quark decay ($t \to H^{\pm} \to W^{\pm}a$) and decaying into a pair of muons ($a \to \mu\mu$) [10]. The analysis is performed in final states with exactly three leptons ($e\mu\mu$ or $\mu\mu\mu$), at least three jets and at least one b-tagged jets and uses the di-muon mass in the range 12 GeV < $\mathrm{m}^{\mathrm{a}}_{\mu\mu}$ < 77 GeV as final discriminant. No significant excess of data events over the SM prediction is observed, thus, upper limits are set on the tta production cross section times the $a \to \mu\mu$ branching ratio as a function of the mass of the a and on the $t \to H^{\pm} \times H^{\pm} \to W^{\pm}a \times a \to \mu\mu$ branching ratio as a function of the mass of the a for different values of the mass of $H^{\pm}$, as shown in Figure 5.

7. Conclusions

Extensive searches for additional neutral Higgs bosons have been performed using 140 fb^{-1} of 13 TeV proton–proton collision data collected by the ATLAS experiment during the Run 2 of the LHC. Several different production and decay modes of the searched BSM Higgs bosons have been probed over a wide mass range and no significant deviations from SM predictions have been observed in data.

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