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Searches for additional Higgs bosons in the ATLAS detector

Jeanette Miriam Lorenz[a,1,*]

[a] *LMU Munich,*
Am Coulombwall 1, 85748 Garching, Germany

E-mail: jeanette.miriam.lorenz@cern.ch

Since the discovery of the Higgs boson with the mass of about 125 GeV, much effort has been spent looking for further scalars, which are motivated in many scenarios. These proceedings report on searches for new neutral or charge heavy Higgs bosons decaying to tau leptons or top and b quarks, and on searches for high-mass resonances in di-photon or leptonic signatures. The searches are based on the full Run-2 dataset of the ATLAS experiment at the LHC.

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[1]On behalf of the ATLAS Collaboration
[*]Speaker

1. More Higgs bosons?

Since the discovery of the Higgs boson by the CMS and ATLAS Collaborations in 2012, the properties of this Higgs boson have been measured to increasing precision. So far, an excellent agreement with the predictions for a Standard Model (SM) Higgs boson are observed, as seen in e.g. precision measurements of the Higgs couplings.

Many extensions of the SM (beyond-the-SM, BSM) have been proposed to solve short-comings of the SM, like that it does not contain a Dark Matter candidate particle and offers no explanation for the matter-anti-matter-asymmetry in universe. In many BSM extensions additional neutral or charged Higgs bosons appear. Examples are the Two-Higgs-Doublet models (2HDM) which feature 5 Higgs bosons, among those two neutral CP-even Higgs bosons h, H, one CP-odd Higgs boson A, and two charged Higgs bosons $H^{\pm}$.

These proceedings highlight new results of direct searches for neutral or charged heavy Higgs bosons or scalars, using the full dataset of 139 fb^{-1} of Run-2 proton–proton collisions delivered by the Large Hadron Collider and recorded by the ATLAS detector [1].

2. Search for heavy neutral Higgs bosons decaying to taus

Decays of a new heavy (pseudo)scalar to final states with a tau pair are possibly enhanced with respect to other decay models in type-II 2HDM, especially at large $\tan(\beta)$ values. The $A/H \to \tau\tau$ analysis [2] searches for these signatures in final states with either one tau decaying leptonically and the other hadronically ($\tau_{\rm lep}\tau_{\rm had}$), or both taus decaying hadronically ($\tau_{\rm had}\tau_{\rm had}$). Here, the hadronically decaying tau is identified via a Boosted Decision Tree. The production mode of the heavy (pseudo)scalar may feature additional b-quarks. Therefore, the analyses uses two different search categories either requiring a b-tagged jet for the b-associated production mode, or a jet failing the b-tagging for the gluon-gluon-fusion (ggF) production. In both cases, the key discriminating variable is the reconstruction of the invariant mass of the tau pair via the total transverse mass $m_T^{\rm tot} = \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{\rm miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{\rm miss})^2}$, in which the signal peaks at higher values

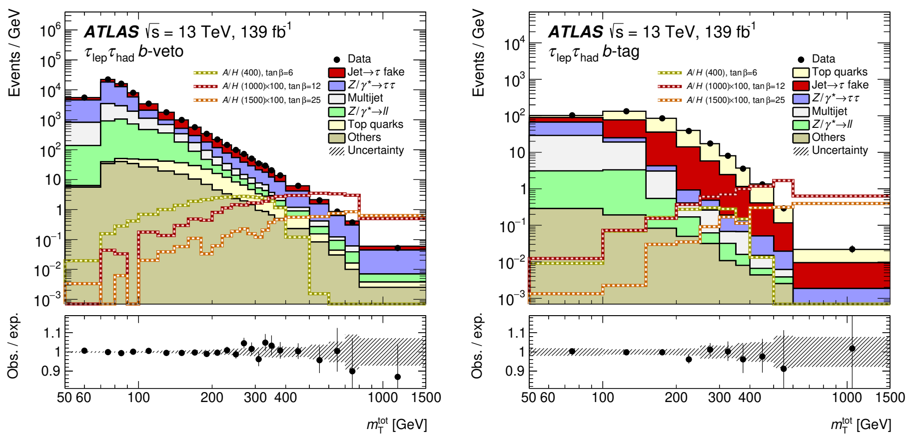

Figure 1: Distribution of $m_T^{\rm tot}$ in the $\tau_{\rm lep}\tau_{\rm had}$ regions in the category with jets failing the b-tagging (left) and b-tagged jets (right) [2]. The signal peaks at higher values.

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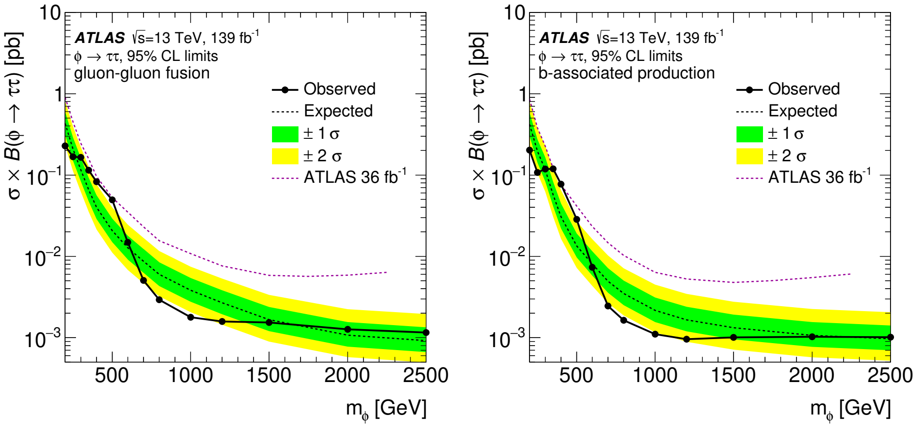

Figure 2: Exclusion upper limits for the ggF production mode (left) and the b-associated production (right) [2].

than the background. Example distributions in the $\tau_{\text{lep}}\tau_{\text{had}}$ regions are shown in Figure 1. The main backgrounds $t\bar{t}$ and W+jets, and multi-jet processes, are estimated by using data-driven methods.

No significant data excess with respect to the background estimates is observed. Exclusion limits at 95 % CL are set in different 2HDM variants including the benchmark model M_h^{125}. The upper limits on the signal strength assuming ggF or b-associated production are shown in Figure 2. Limits in the M_h^{125} extend e.g. for $\tan\beta > 8$ to $m_A = 1.0$ TeV, and for $\tan\beta > 21$ to $m_A = 1.5$ TeV.

3. Search for charged Higgs bosons decaying to top and bottom quarks

Charged Higgs bosons are equally predicted in many BSM scenarios. In 2HDM models with $\cos(\beta - \alpha) \sim 0$ the dominant decay mode of the positively charged Higgs H^+ is $H^+ \to tb$ for $m(H^+) > 200$ GeV. The $H^+ \to tb$ search [3] targets the production of H^+ in association with

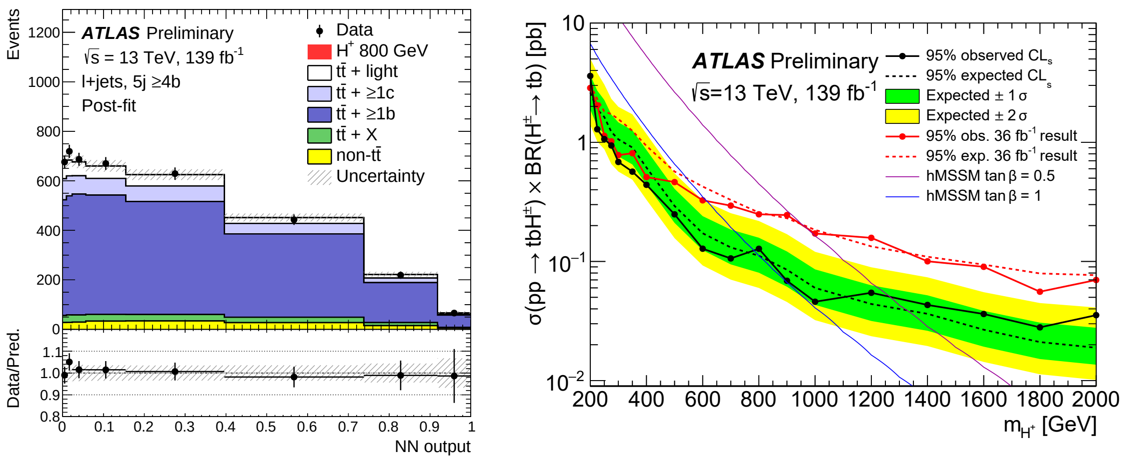

Figure 3: Output of the neural network trained in the $H^+ \to tb$ search [3] (left) and the upper limits obtained in this search (right).

additional top and bottom quarks in final states with an electron or muon, and thus selects b-jet-rich final states with three or at least four b-tagged jets in different jet multiplicities regions requiring either five or at least six jets. As the simulation of top-related backgrounds does not match the data well, a reweighting procedure has been developed, based on the jet multiplicities and the sum of the transverse momenta of the jets, to correct the simulation. The event selection in the search is achieved by a neural network trained on e.g. the (transverse) momenta, energies, mass and spatial separation of the jets. This training is performed for different H^+ masses. An example output distribution is shown in Figure 3. No significant data excess beyond the SM expectations is observed, and therefore, upper limits on $\sigma \times \mathrm{BR}$ are derived, as shown in Figure 3.

4. Search for high-mass resonances decaying to a pair of photons

Searches in final states with a photon pair profit from a particular clean signature with excellent mass resolution. The search for high-mass resonances with a mass above 160 GeV [4], where the resonance decays to photon pairs, addresses both spin-0 and spin-2 possibilities, and considers narrow and large width assumptions (NWA and LWA, respectively) for the spin-0 case. An example spectrum of the invariant di-photon mass is shown in Figure 4. In comparison to previous analyses iterations, the analysis of the full Run-2 dataset offers a common event selection for both spin hypotheses with an improved photon reconstruction and identification. Background and signal shapes are modeled by functional forms, where in the case of the signal a double-sided Crystal Ball function is used for the NWA case, convoluted with a relativistic Breit-Wigner function for the LWA case. The functional form for the backgrounds arise from templates built based on simulation for events with photon pairs and from data control regions for γ+jet events. The full spectrum of the invariant mass of the photon pair is scanned for deviations between the background estimates and the observed data. The largest deviation has a local significance of 3.29 σ, with a global significance of 1.3 σ, at a resonance mass of m_X = 684 GeV. Upper limits range from 12.5 fb for a resonance mass of 162 GeV to 0.03 fb for a mass of 3 TeV in case of the spin-0 hypothesis, as visualized in Figure 4.

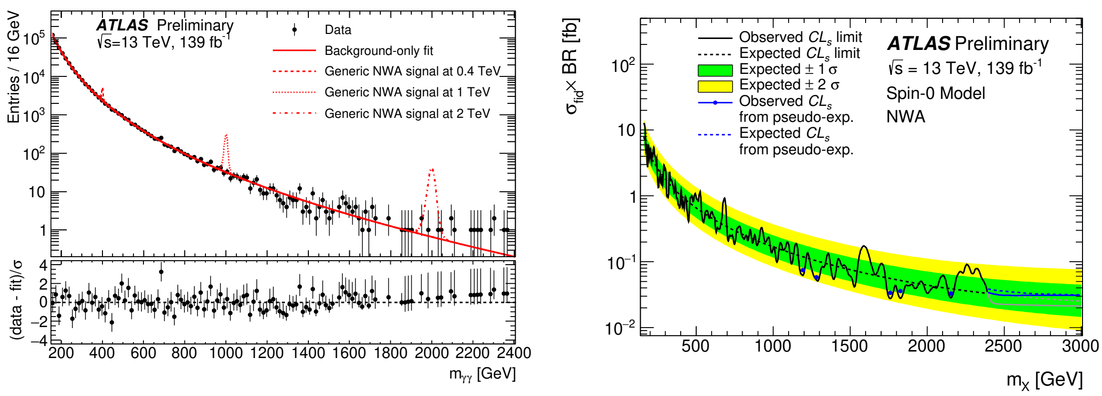

Figure 4: Invariant mass distribution of the photon pair, with example resonances of an heavy scalar overlaid (left). Exclusion limits at 95 % CL for the NWA and the spin-0 hypothesis (right) [4].

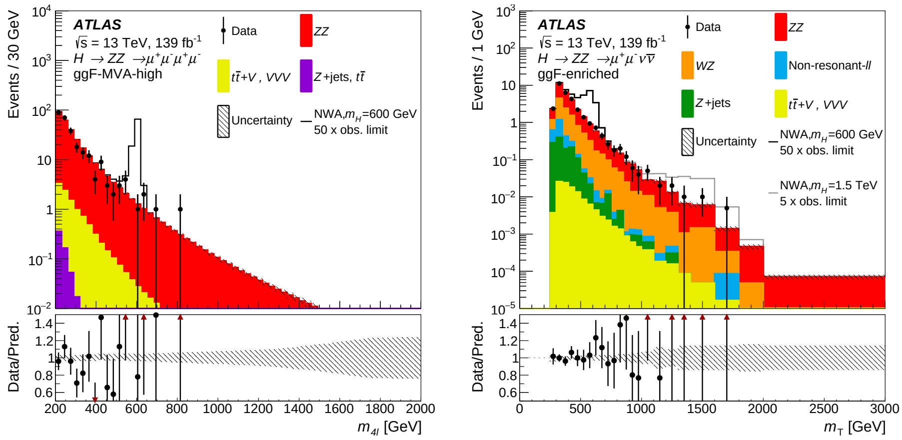

Figure 5: Invariant mass of the 4-lepton system (left) in the event category featuring $l^+l^-l^+l^-$ in the final state. This invariant mass cannot be constructed in the $l^+l^-\nu\nu$ event category, therefore a transverse mass used (right).[5]

5. Search for high-mass resonances decaying to a pair of Z bosons

Also the search for heavy resonances with decays to a pair of Z bosons [5] targets the spin-0 case (such as an heavy Higgs) or a spin-2 graviton. Two different event categories are considered, with either both Z bosons decaying into charged leptons ($l^+l^-l^+l^-$), forming lepton pairs with opposite charge, or one of them decaying into neutrinos ($l^+l^-\nu\nu$). The $l^+l^-l^+l^-$ category profits from a better resolution of the invariant mass due to the clean final state, while the $l^+l^-\nu\nu$ category offers the larger branching ratio. Thus, both categories are combined in this search. In the $l^+l^-l^+l^-$ category, the signal is separated from the background by a sequence of a recurrent network combined with multilayer perceptrons, where different classifiers are built for the ggF and the VBF production cases. The final score together with the lepton flavor is used to form five different search regions. The invariant mass of the 4-lepton system is used in addition as final discriminant, as shown exemplary in Figure 5.

In the $l^+l^-\nu\nu$ category, two close-by opposite-sign leptons are required, but because of the neutrinos the full invariant mass of all decay products cannot be constructed. Instead, the transverse mass of the system is built, using the leptons and the missing transverse momentum as input. This is used in addition to e.g. requiring high missing transverse momentum in opposite directions to the lepton system. Dominant backgrounds in this category are the WZ and ZZ processes, where the WZ background is estimated using control regions requiring three leptons, and the ZZ estimates are obtained from simulation with the normalization determined in a fit to data.

In neither of the two categories a significant data excess beyond the background estimates is observed. This result is interpreted in different models, e.g. 2HDM or a Randall-Sundrum graviton, and with different assumptions on the width of the hypothetical scalar in the spin-0 case. Example exclusion limits are shown for the narrow-width-approximation for the ggF and the VBF production modes in Figure 6. In this case, these two production mechanisms are considered separately to not assume a certain fraction of any of the two processes.

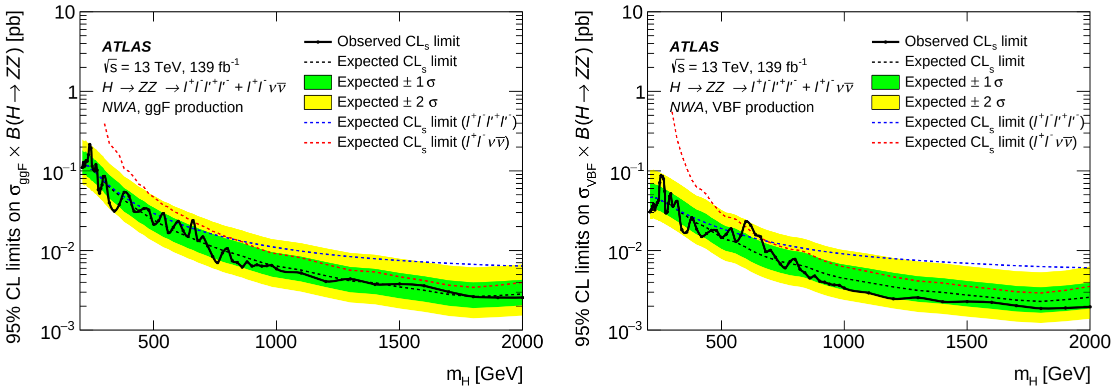

Figure 6: Exclusion limits for the NWA and the spin-0 assumption, for the ggF (left) and the VBF (right) production modes.[5]

6. Summary

Different searches for heavy neutral or charged Higgs boson are presented, all using the full dataset of 139 fb^{-1} recorded by the ATLAS detector at the LHC. The sensitivity of these searches not only profits from the increased data statistics with respect to previous iterations, but also from the use of sophisticated novel techniques. These include e.g. the identification of hadronic tau decays by Boosted Decision Trees, improved object reconstruction methods, and the use of functional forms to model the backgrounds. In none of the searches a significant data excess over background estimates was observed, but a significant update on the constraints in 2HDM is made.

References

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

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