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Beyond-the-Standard Model Higgs Physics using the ATLAS Experiment

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Abstract. A summary of Beyond-the-Standard Model Higgs physics searches recently released by the ATLAS experiment at the Large Hadron Collider is presented.

1 Introduction

In the Standard Model (SM), the mass of elementary particles is generated by the Brout-Englert-Higgs (BEH) mechanism [1–3] which implies the existence of a scalar field and associated scalar boson called the Higgs boson. In July 2012, the ATLAS and CMS experiments at the Large Hadron Collider announced the observation of a scalar particle with a mass of about 125 GeV and properties consistent with those of the Higgs boson predicted by the SM [4, 5]. This led to the 2013 Nobel prize being awarded to Higgs and Englert. While this discovery is tremendously important for the whole field, several problems in particle physics remain to be addressed, among them the unnatural fine-tuning of the Higgs mass, the grand unification problem, and the absence of candidates for dark matter. The proposed theories that aim at solving these problems often imply the presence of additional Higgs fields and/or Higgs boson couplings different from the SM ones.

This paper summarizes recent results in searches for signs of Higgs physics beyond the Standard Model (BSM) obtained using the ATLAS experiment. An up-to-date list of the most recent ATLAS public results is maintained at [6].

2 Summary of BSM Higgs results with ATLAS

The two-Higgs doublet models (2HDM) [7] are a simple extension of the Standard Model Higgs sector made by adding a second Higgs doublet. These models are interesting from the phenomenological point of view since they are potentially able to explain the baryon asymmetry in the universe [8]. They also arise in axion models which could provide an insight into the origin of dark matter [9]. A particular example of the 2HDM model is the minimal supersymmetric model (MSSM) [10]. Depending on the coupling of the scalar fields h and H to fermions and gauge bosons, one can differentiate between various types of 2HDM. The presented results are interpreted in terms of Type-I (all quarks couple to only one of the two Higgs doublets) and Type-II (the right-handed up-type quarks couple to one Higgs doublet and the right-handed down-type quarks to the other doublet) 2HDM models.

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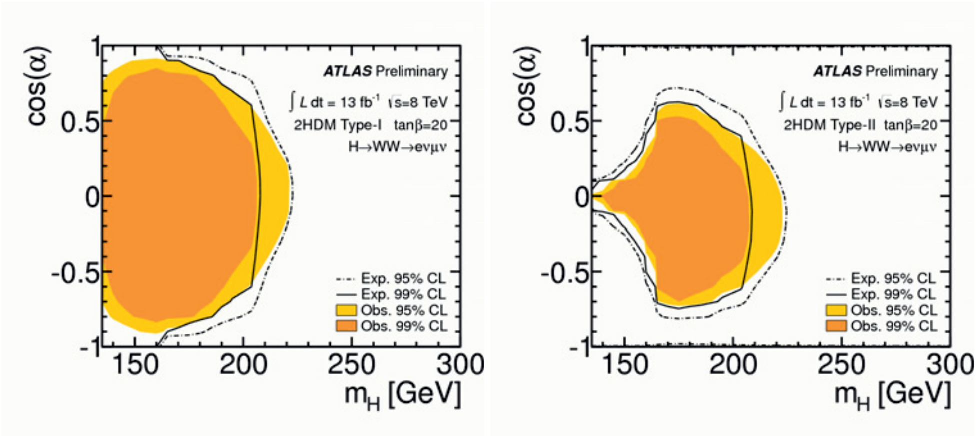

Figure 1. Exclusion contours in the $\cos\alpha - m_H$ plane for $\tan\beta = 20$ of the Type-I (left) and Type-II (right) 2HDM models [11].

ATLAS has searched for the 2HDM signal in the $H \to WW^* \to e\nu\mu\nu$ channel [11]. The reported result is based on 13 fb^{-1} of 8 TeV p-p data collected during the first half of ATLAS 2012 Run. The search probes the hypothesis that the observed boson is a part of a larger Higgs sector. In this scenario one can look for a heavier Higgs partner at various masses. As there are two dominant production mechanisms for Higgs – gluon fusion, resulting in production of the Higgs boson alone, and vector boson fusion, giving rise at tree level to a pair of additional jets – the analysis is split into two subchannels by requiring either zero or two additional jets in the final state. The dominant background in this analysis comes from non-resonant diboson production. The signal is separated from background using neural networks (NN). It has been found that the 0-jet channel has a better signal-to-background ratio but worse NN performance compared to the 2-jet channel. The range of masses $m_H = 135 - 300$ GeV has been probed. No evidence for the second Higgs boson production has been found, and the limits on the heavy scalar boson production are set for Type-I and Type-II 2HDM models in terms of excluded regions of the model parameters m_H and mixing angles of two doublets α and β. As an example, Fig. 1 shows the $\cos\alpha - m_H$ exclusion regions for $\tan\beta = 20$ for Type-I and Type-II models.

Besides looking into generic 2HDM models, ATLAS has searched for a MSSM neutral Higgs boson, φ, decaying into lepton pairs. The reported search [12] is based on 4.7–4.8 fb^{-1} of integrated luminosity data sample collected during the 2011 Run at the centre-of-mass energy of 7 TeV. Decays of the Higgs boson into a pair of muons or τ-leptons are considered, giving rise to two channels $\varphi \to \mu\mu$ and $\varphi \to \tau\tau$. The tau channel is further separated into cases when (a) both taus decay hadronically, (b) one tau decays hadronically and the other one decays into an electron or muon plus neutrinos, and (c) one tau decays into an electron and neutrinos and the other one decays into a muon and neutrinos. As the Higgs boson has two production mechanisms – gluon fusion and b-associated production – the data sample is separated into b-tagged (the event contains at least one identified b-jet) and b-vetoed (no b-jets are detected) subsets. The dominant backgrounds are $Z \to$dileptons, $t\bar{t}$, and multijet production.

The results of this search are interpreted in terms of a generic neutral Higgs boson production, as well as in the context of the MSSM m_h^{max} benchmark scenario [13]. Fig. 2 shows 95% CL limits on

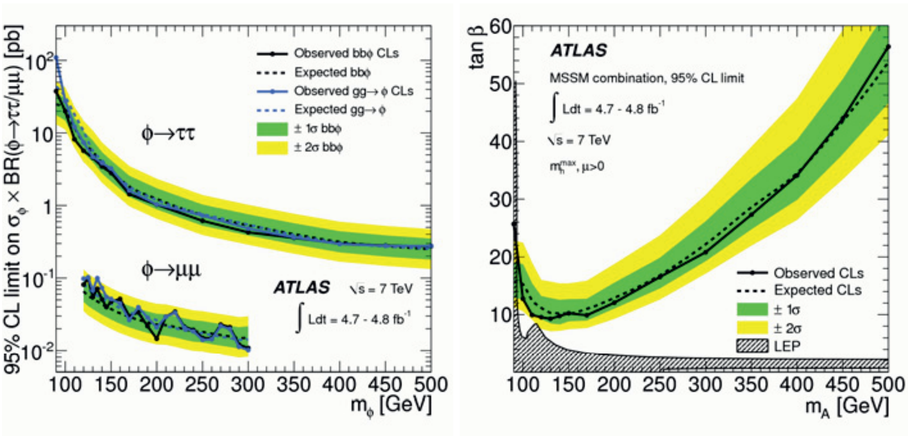

Figure 2. Expected (dashed line) and observed (solid line) 95% confidence level CL$_s$ limits on the cross-section for gluon-fusion and b-associated Higgs boson production times the branching fraction into τ and μ pairs, respectively (left), and on $\tan\beta$ as a function of m_A for the statistical combination of all channels (right) [12].

generic Higgs boson production cross section as a function of the Higgs mass, as well as 95% CL limits on $\tan\beta$ as a function of the neutral CP-odd Higgs boson mass m_A in the m_h^{max} scenario.

In some extensions of the Standard Model one of the neutral Higgs bosons may decay into stable or long-lived particles which interact only weakly with other elementary particles, making such a boson "invisible" for detection. The invisible Higgs boson is searched in the associated production channel $ZH, Z \to ll$ [14]. The final state is characterized by a Z boson reconstructed as a peak in the dielectron or dimuon invariant mass, and a large missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}} > 90$ GeV. This is a low statistics, low background analysis with most of the background originating from the ZZ production. The limits are set in two scenarios: on the invisible branching fraction of a 125 GeV SM Higgs boson, and on production cross section times branching fraction of a Higgs-like boson decaying into invisible particles. The search is done for both 7 TeV data (4.7 fb^{-1} of total integrated luminosity) and 8 TeV data (13.0 fb^{-1} of total integrated luminosity) and the results are reported for both samples as well as for their combination. The results for the combination are summarized in Fig. 3.

The SM Higgs discovery channel $H \to \gamma\gamma$ can be extended to study other models which can contribute to the $\gamma\gamma$ signal. In particular, in certain BSM models [15], the mass m_a of the CP-odd Higgs boson a can be low (few hundred MeV). If m_a is below the three π^0 mass threshold, a cannot decay into three π^0's, and since the $a \to 2\pi^0$ decay is forbidden by CP invariance, the $a \to \gamma\gamma$ becomes the dominant decay channel. The signal observed in the detector is similar to the one due to the regular $H \to \gamma\gamma$ decay but the clusters in the electromagnetic calorimeter are created by the photon pairs from the $H \to aa \to (\gamma\gamma)(\gamma\gamma)$ process. The ATLAS analysis [16] modifies the electromagnetic cluster reconstruction such that it becomes sensitive to collimated diphoton pairs. The analysis has been performed using 4.9 fb^{-1} of 7 TeV data. As no signal has been observed, the limits are set on the Higgs boson production cross section times branching fraction into four photons for three different a masses 100, 200, and 400 MeV. The results for $m_a = 400$ MeV are shown in Fig. 4.

While the neutral Higgs boson is a part of the SM, the observation of a charged Higgs boson H^+ would directly indicate the presence of BSM physics. Such particles are predicted by several models including 2HDM [7].

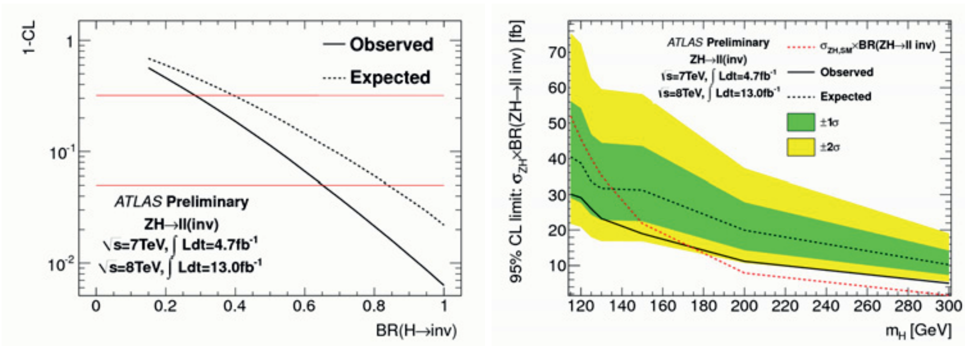

Figure 3. Confidence level scanned against the branching fraction BR(H→invisible) for the SM Higgs boson with 125 GeV mass (left) and 95% confidence level limits on the cross section times branching fraction of a Higgs-like boson decaying into invisible particles (right) [14].

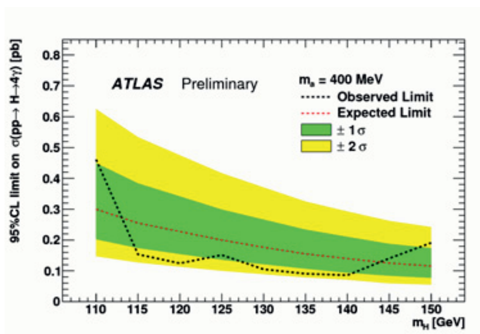

Figure 4. Observed and expected CL_s limit on the Higgs boson production cross section times branching fraction into four photons, mediated by 400 MeV CP-odd scalar coupling [16].

The phenomenology of charged Higgs depends on its mass m_H^+ compared to the top quark mass m_t. If the charged Higgs boson is "light" ($m_H^+ < m_t$) then it is mostly produced in top quark decays $t \rightarrow H^+ b$. Depending on the model, the dominant decay modes of the light charged Higgs boson are $H^+ \rightarrow \tau\nu$ (e.g. MSSM with low $\tan\beta$) and $H^+ \rightarrow cs$ (MSSM with high $\tan\beta$). If the charged Higgs boson is "heavy" ($m_H^+ > m_t$) then it predominantly decays into a top quark and a bottom quark. However the $H^+ \rightarrow \tau\nu$ decay mode is still of experimental interest. The heavy charged Higgs boson is produced in association with a top (and possibly bottom) quark in $gb \rightarrow H^+ t$ and $gg \rightarrow H^+ tb$ processes.

The ATLAS experiment has searched for the charged Higgs boson production in $H^+ \rightarrow \tau\nu$ and $H^+ \rightarrow cs$ decay channels. The former analysis [17] was performed for both light and heavy Higgs. In both cases only hadronically decaying τ's are considered. The event selection involves at least four jets (three for the heavy Higgs case), at least one of them being b-tagged, a large missing transverse energy cut, and topological cuts. No evidence for the existence of a charged Higgs boson was found in the data. Two interpretations of the result are provided. In a model independent approach, the 95% CL limits are set on the branching fraction $BR(t \rightarrow H^+ b)$ for the light charged Higgs boson search and

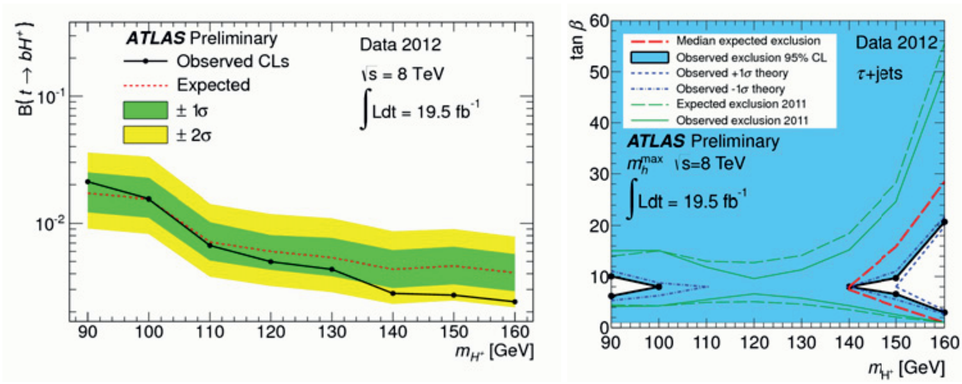

Figure 5. The expected and observed 95% CL upper limits for the light charged Higgs boson search, with the assumption that $BR(H^+ \to \tau\nu) = 1$ (left) and interpretation of the limits on the branching fractions of the light H^+, in the context of the MSSM m_h^{max} scenario with $\mu = 200$ GeV (right) [17].

on the production cross section $\sigma(pp \to t(b)H^+)$ for the heavy charged Higgs boson search assuming $BR(H^+ \to \tau\nu) = 1$ in both cases. These results are presented as a function of the H^+ mass between 90–160 GeV (light H^+ case) or 180–600 GeV (heavy H^+ case). The results are also interpreted in the MSSM m_h^{max} scenario [13] with $\mu = 200$ GeV as exclusion plots in the $\tan\beta - m_H^+$ plane. Some of these results are shown in Fig. 5.

Several exotic models consider Higgs multiplets which have more than two members. These models predict the existence of a doubly charged Higgs boson $H^{\pm\pm}$ [18, 19]. Doubly charged Higgs bosons also appear in Type-II see-saw models [20–23]. A $H^{\pm\pm}$-like singlet can occur in the Zee-Babu model [24–26]. If doubly charged Higgs bosons are discovered, this may offer a unique possibility to study the origin of neutrino masses and mixing.

The ATLAS analysis [27] performs a generic same-sign dilepton mass spectrum search in 4.7 fb^{-1} of 7 TeV data for doubly charged Higgs bosons decaying into $e^\pm e^\pm$, $e^\pm\mu^\pm$, or $\mu^\pm\mu^\pm$ pairs. The results are reported in terms of limits on generic $H^{\pm\pm} \to l^\pm l^\pm$ production cross section times branching fraction for each channel as a function of the $H^{\pm\pm}$ mass, as well as limits on the $H^{\pm\pm} \to l^\pm l^\pm$ branching fraction for pair production of doubly charged Higgs bosons coupled to left- and right-handed leptons as a function of the $H^{\pm\pm}$ mass. Two examples of the limits obtained in the analysis are shown in Fig. 6.

The Higgs boson's non-SM nature may manifest itself through anomalous couplings to elementary particles. These couplings are probed in the ATLAS analysis [28] via the search for the $t \to cH$ decay. Such decays are forbidden in the SM at tree level and are highly suppressed at higher orders due to the Glashow-Iliopoulos-Maiani (GIM) mechanism [29], so their observation would clearly indicate the presence of physics beyond the SM. The flavor changing neutral currents responsible for the $t \to cH$ decay appear in many BSM models, including quark-singlet and various 2HDM models [30].

ATLAS has searched for the $t \to cH$ process in $t\bar{t}$ events where one top quark decays into a c-quark and a Higgs boson, followed by the Higgs boson decaying to a pair of photons, and the other quark decays into a W and a b-quark. The final states are characterized by the presence of two energetic photons, at least one b-tagged jet, and (depending on the W decay mode) either an isolated lepton (electron or muon) or additional jets from the hadronic W decay. For the 7 TeV data sample (corresponding to 4.7 fb^{-1} of integrated luminosity), only the hadronic channel was studied. For the

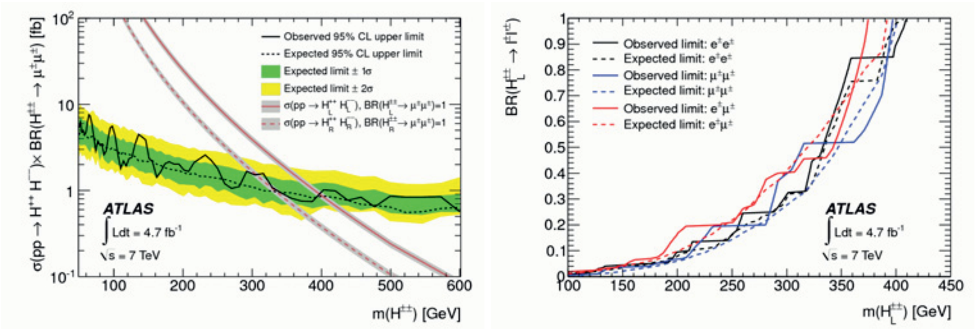

Figure 6. Upper limit at 95% CL on the cross section times branching fraction for pair production of $H^{\pm\pm}$ bosons decaying into $\mu^{\pm}\mu^{\pm}$ pairs and the mass limits as a function of the branching fraction for the $H_L^{\pm\pm}$ decaying into $l^{\pm}l^{\pm}$ pairs (right) [27].

8 TeV data sample (corresponding to 20.3 fb^{-1} of integrated luminosity), both hadronic and leptonic channels were analysed. The reported results correspond to a combination of the three analyses. As no signal is observed, the limits are set on the $t \to cH$ branching fraction to be 0.83% (0.53% expected) at the 95% CL. The corresponding limit on the tcH coupling is 0.17 (0.14 expected).

3 Conclusions

A summary of BSM Higgs physics searches recently released by the ATLAS experiment is presented. The list includes searches for neutral Higgs bosons predicted by 2DHM models (including MSSM), invisible Higgs, light Higgs decaying into diphoton pairs, charged and doubly charged Higgs, and Higgs produced in FCNC processes.

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