SEARCHES FOR BEYOND STANDARD MODEL HIGGS BOSONS WITH ATLAS*

Nikolaos Rompotis

on behalf of the ATLAS Collaboration

Department of Physics, University of Washington
Box 351560, Seattle WA 98195-1560, USA

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The search for evidence of beyond Standard Model Higgs bosons is an integral part of the Higgs boson studies at the LHC. This article reviews recent beyond Standard Model Higgs boson searches using 2–5 fb^{-1} of 7 TeV LHC proton–proton collision data recorded by the ATLAS detector. No significant deviations from the background expectations are found and corresponding constraints on physics beyond the Standard Model are obtained.

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1. Introduction

The recent observation of a new particle with mass 125–126 GeV at the LHC [1, 2] opens a new era for particle physics. The detailed study of the production and decay modes of the new particle provides invaluable input to answer the question of whether this is indeed the long-sought Standard Model (SM) Higgs boson [3–7]. The first measurements indicate that the new particle is indeed compatible with the SM Higgs boson [8], nevertheless, many more measurements and data will be needed to extract reliable conclusions. This task is further complicated by the fact that many beyond SM physics scenarios include an SM-like Higgs boson, which is part of an extended scalar sector. In that case, searches for beyond SM Higgs bosons are very interesting, since they provide direct information on a possibly extended scalar sector, and hence they are complementary to the precise measurements of the properties of the new particle.

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This article reviews some of the recent searches for beyond SM Higgs bosons in proton–proton collision data at 7 TeV centre-of-mass energy produced by the LHC [9] and recorded by the ATLAS detector [10].

2. Higgs bosons in beyond SM physics scenarios

The scalar sector of the SM is composed by a complex Higgs doublet, which after the electroweak symmetry breaking (EWKSB) leaves a single scalar boson in the theory. Possible extensions of the scalar sector are restricted, due to the fact that, in general, they violate the "custodial symmetry" of the SM[1]. The addition of doublets or singlets naturally conserves the custodial symmetry and hence it comprises an attractive idea on which beyond SM scenarios can be constructed.

The introduction of one additional Higgs doublet defines a class of models, which are collectively known as 2 Higgs doublet models (2HDM) [12]. The type II 2HDM, a 2HDM in which the first doublet couples to down-type fermions, *i.e.* quarks and charged leptons, and the second doublet couples to up-type quarks, has been extensively studied. One of the reasons is that the Minimal Supersymmetric Standard Model (MSSM) [13, 14] is a specific case of a type II 2HDM. Supersymmetric theories, like the MSSM, have been introduced to explain a number of problems of the SM (*e.g.* see [15]) and they enjoy high popularity among the high-energy physics community. In a 2HDM, there are five Higgs bosons after the EWKSB. More specifically, there is one CP-odd boson, A, two CP-even bosons[2], h and H, and two charged Higgs bosons $H^{\pm}$. The number of free parameters of the theory in the specific case of the MSSM are just two at tree level. These parameters are usually chosen to be m_A and $\tan\beta$ or $m_{H^{\pm}}$ and $\tan\beta$, where $\tan\beta \equiv u_1/u_2$ and u_1 (u_2) is the vacuum expectation value of the Higgs doublet coupling to up- (down-) type fermions. It is worth noting that the MSSM is compatible with the assumption that there is an SM-like Higgs boson with mass 125–126 GeV [16, 17]. In ATLAS, searches for $A/H/h \to \tau\tau/\mu\mu$ [18], $H^{\pm} \to \tau^{\pm}\nu$ [19] and $H^{\pm} \to cs$ [20] are inspired by the MSSM (and 2HDM in general) and the first two of these will be discussed in the next section.

More complicated choices for the scalar sector have also been studied and searches in ATLAS data are available for a variety of different signatures: scalar sector with light CP-odd particles [21, 22], doubly charged Higgs boson [23], "fermiophobic" Higgs bosons [24], Higgs boson in a model with a

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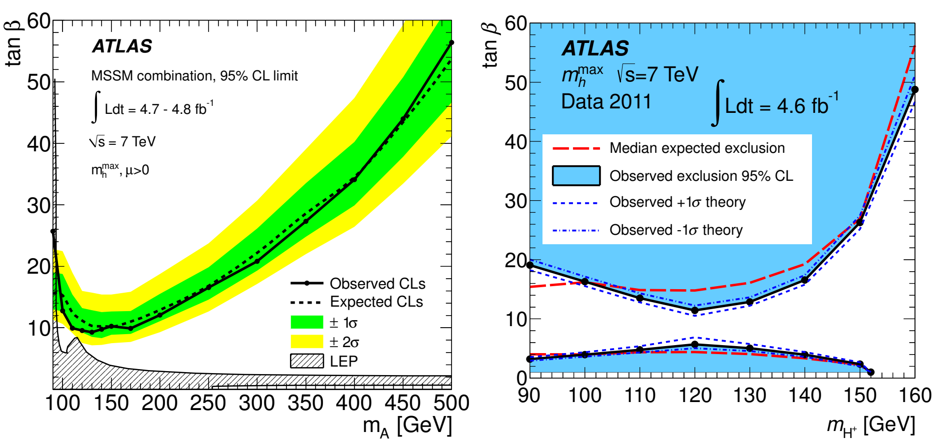
[1] The name "custodial symmetry" will be used to denote the experimental fact that the quantity $\rho \equiv m_W^2/(m_Z^2 \cos^2\theta) \simeq 1$, where $m_{W(Z)}$ is the W (Z) boson mass and θ the weak mixing angle, see also [11].

[2] The notation is such that $m_h < m_H$.

fourth generation of fermions [25], and Higgs bosons decaying to long-lived particles [26, 27]. In the following, only two of these more exotic cases will be discussed in more detail [22, 26].

3. MSSM-inspired searches

Over large part of the parameter space of a general 2HDM, and hence also the MSSM, the decays of the Higgs bosons to third generation fermions are enhanced [12, 15]. The neutral Higgs boson decays of $A/H/h \to \tau\tau$ are experimentally atractive, due to the progress in τ decays reconstruction and the fact that the branching fraction to $\tau\tau$ is about 10% for the parameter space that is relevant for this search. In a recent search using 4.7–4.8 fb^{-1} of data [18], neutral Higgs bosons decaying to a $\tau\tau$ pair are searched for, including cases where: both τs decay hadronically; one τ decays to an electron or muon plus neutrinos and the other hadronically; and finally, one τ decays to an electron plus neutrinos and the other τ to a muon plus neutrinos. In addition to the more sensitive $\tau\tau$ modes, the decay to a di-muon pair has been considered. This decay mode suffers from a very low branching fraction, which is about 10^{-4}, but profits from high mass resolution and high rejection of reducible backgrounds. No excess is observed with respect to the expectation from SM background processes. The results of the search can be interpreted in the $m_h^{\max}$ scenario of the MSSM [28] on the m_A–$\tan\beta$ space as shown in figure 1(a).



(a) $A/H/h \to \tau\tau/\mu\mu$ search

(b) $H^{\pm} \to \tau\nu$ search

Fig. 1. Interpretation of the $A/H/h \to \tau\tau/\mu\mu$ search [18] (a) and the $H^{\pm} \to \tau\nu$ search [19], (b) in the $m_h^{\max}$ scenario of the MSSM [28]. The 95% confidence level exclusion limits for the neutral and charged Higgs bosons are shown in the m_A–$\tan\beta$ and the $m_{H^{\pm}}$–$\tan\beta$ planes.

Searches for a light charged Higgs boson, produced in top quark decays ($t \to bH^{\pm}$) and decaying as $H^{\pm} \to \tau^{\pm}\nu$, with 4.6 fb^{-1} of ATLAS data are described in Ref. [19]. The final state $t\bar{t} \to b\bar{b}W^{\mp}H^{\pm}$ is characterised by the decay products of the W and the τ from the charged Higgs decay. More specifically, the following cases have been examined: "τ+jets": τ decaying hadronically and $W \to$ jets; "τ+lepton": τ decaying hadronically and $W \to e\nu/\mu\nu$; "lepton+jets": $\tau \to e$+neutrinos/μ+neutrinos and $W \to$ jets. The combination of all these three channels shows good agreement with the expectation from the SM processes. The results of the search can be interpreted[3] in the $m_h^{\max}$ scenario of the MSSM [28] on the $m_{H^{\pm}}$–$\tan\beta$ space as shown in figure 1(b).

4. Exotic signature searches

A number of beyond SM physics scenarios include light CP-odd scalar particles in which the Higgs boson can decay to, *e.g.* see [29]. A search for a Higgs boson decaying to a pair of light ($\sim$ 100 MeV), CP-odd particles, a, with each of them decaying to a di-photon pair: $H \to aa \to (\gamma\gamma)+(\gamma\gamma)$ with 4.9 fb^{-1} of data is described in Ref. [22]. The small mass of a particles with respect to the Higgs boson mass leads to highly boosted di-photon pairs, which are reconstructed as a single photon in the electromangetic calorimeter. The analysis follows the SM $H \to \gamma\gamma$ search [30], but with a modified photon identification to allow for the broader showers of the boosted di-photon pairs with respect to the shower of a single photon. No excess is observed with respect to the SM background processes and exclusion limits are extracted for the cross section of Higgs boson production times the branching fraction BR($H \to aa \to 4\gamma$) under various assumptions for the a particle mass, see figure 2 and Ref. [22].

In "hidden valley" models [31], there is a hidden sector, which communicates with the rest of the SM particles through a communicator particle. Assuming that the Higgs boson plays the role of the communicator particle it can decay to hidden sector particles. The search described in Ref. [26] looks for Higgs boson decays to long-lived hidden valley pions, $H \to \pi_{\rm V}\pi_{\rm V}$, in 1.9 fb^{-1} of data. These particles travel several metres inside the detector and they subsequently decay as $\pi_{\rm V} \to b\bar{b}/c\bar{c}/\tau\tau$. Their decay products are detected in the muon system using dedicated reconstruction algorithms. Triggering on such kind of events is highly non-trivial, since the usual reconstruction algorithms are designed to reject events with objects that do not originate from the interaction point. For this reason, a dedicated trigger was

[3] Both neutral and charged MSSM Higgs searches can have other, more general interpretations than the $m_h^{\max}$ scenario of the MSSM. For more details, see references [18, 19].

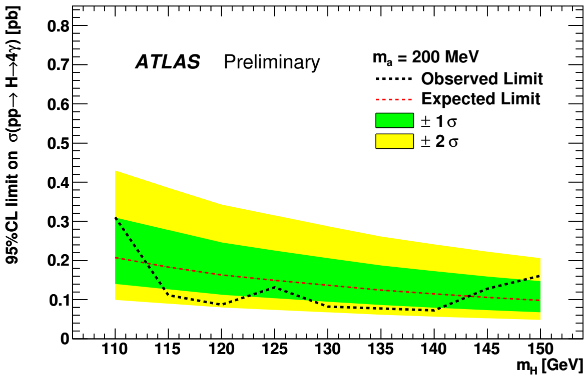


Fig. 2. Exclusion limits at the 95% confidence level (C.L.) for the Higgs boson cross section times BR($H \to aa \to 4\gamma$) assuming that the mass of the CP-odd particle a is 200 MeV [22].

developed, using muon system clusters only. No deviation is observed with respect to the SM background processes and exclusion limits for the Higgs boson production cross section are derived, which are shown in figure 3.

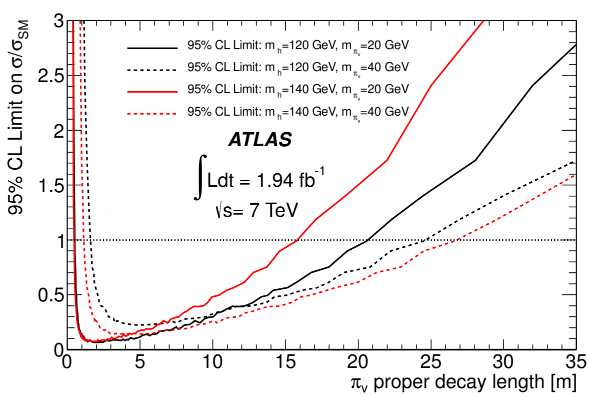


Fig. 3. Exclusion limits on the cross section of Higgs boson production divided by its value in the SM, assuming that the Higgs boson decays exclusively to $\pi_V\pi_V$, for various choices of Higgs boson and π_V masses [26].

5. Concluding remarks

ATLAS searches for beyond SM Higgs bosons increase the discovery potential of beyond SM physics at the LHC. Moreover, they contribute towards the effort to understand whether the recently observed 125–126 GeV particle is indeed the SM Higgs boson.

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