PROCEEDINGS OF SCIENCE

Searches for singly- and doubly-charged Higgs bosons in ATLAS

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One doublet of complex scalar fields in the Standard Model is the minimal content of the Higgs sector in order to achieve spontaneous electroweak symmetry breaking. Several theories beyond the Standard Model predict a non-minimal Higgs sector and introduce charged scalar fields, that do not exist in the Standard Model. As a result, singly- and doubly-charged Higgs bosons would be a unique signature of new physics with a non-minimal Higgs sector. As such, they have been extensively searched for in the ATLAS experiment, using data samples of proton-proton collisions taken during the LHC Run 2. In this report, a summary is presented of the latest experimental results obtained in searches for both singly- and doubly-charged Higgs bosons.

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1. Introduction

The Higgs boson was observed in 2012, and the coupling measurements are consistent with the Standard Model (SM) predictions so far [1, 2]. The SM assumes one doublet of complex scalar fields, which is the minimal content of the Higgs sector for spontaneous electroweak symmetry breaking. The SM cannot explain all experimental results. Several theories beyond the SM predict a non-minimal Higgs sector and introduce charged scalar fields.

The most widely investigated extension is the two-Higgs-doublet models (2HDMs). Among the eight degrees of freedom of the two complex doublets, three are absorbed by the $W^{\pm}$ and Z bosons and five Higgs bosons are introduced, including the charged Higgs bosons $H^{\pm}$. Four types can be defined for the 2HDMs, depending on the coupling of the two Higgs doublets. The Type II assumes that the up-type quarks couple to a doublet and the down-type quarks and the charged leptons couple to the other doublet. The Type II of the Higgs sector is assumed in Minimal Supersymmetric Standard Model (MSSM). The hMSSM assumes Type II and the mass of the lighter CP-even Higgs h to be 125 GeV, and is described with the parameters entering the tree-level expressions for masses and mixing. This model is less model-dependent on the loops and is considered as a representative of the MSSM.

There are many other extensions of the Higgs sector. The three-Higgs-doublet models (3HDMs) allow relatively light charged Higgs bosons. The Georgi-Machacek (GM) model and the Type II seesaw model include Higgs triplet and doubly-charged Higgs bosons $H^{\pm\pm}$. A summary of the theories with extended Higgs sector is given in Ref. [3].

2. Production and the Concept of the Searches

Experimental signatures are defined by the charge, coupling, and mass of the charged Higgs bosons. Example diagrams are shown for singly-charged Higgs bosons in Figure 1. The high mass singly-charged Higgs bosons decaying into fermions are searched for in associated production with the top and bottom quarks. On the other hand, the low mass singly-charged Higgs bosons decaying into fermions are searched for in the top quark decays. The singly-charged Higgs bosons coupling to bosons can be searched for in the vector boson fusion production.

The searches at the ATLAS experiment are designed to enrich one or several signal regions in events with the expected signal signature. Multivariate analyses are used for the separation between the signal and the background in most searches.

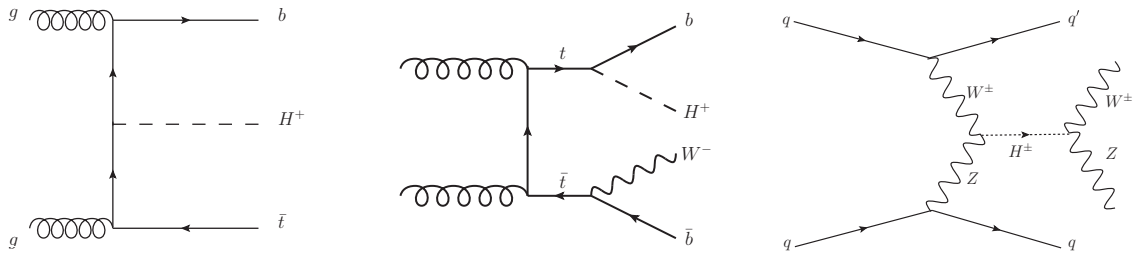

Figure 1: Example diagrams of singly-charged Higgs boson production in association with the top and bottom quarks (left), from the top quark decay (middle), and in the vector boson fusion (right).

3. Latest Results

The latest results on the charged Higgs searches at ATLAS are listed in Table 1. All of them were performed on data samples of pp collisions with a centre-of-mass energy of 13 TeV. For singly-charged Higgs bosons decaying into fermions, the searches were performed on the $\tau\nu$, tb, cb, and cs final states. For singly-charged Higgs bosons decaying into bosons, the searches were performed on the $W^{\pm}Z$ and $W^{\pm}a$ final states, where a indicates a new pseudoscalar boson. For doubly-charged Higgs bosons, the searches were performed on two charged leptons and $W^{\pm}W^{\pm}$ final states.

Charge	Coupling	Decay	Mass range	Integrated $\mathcal{L}$	Reference
Singly-charged	Fermions	$H^{\pm} \to \tau\nu$	90–2000 GeV	36 fb^{-1}	Ref. [4]
		$H^{\pm} \to tb$	200–2000 GeV	139 fb^{-1}	Ref. [5]
		$H^{\pm} \to cb$	60–160 GeV	139 fb^{-1}	Ref. [6]
		$H^{\pm} \to cs$	60–168 GeV	140 fb^{-1}	Ref. [7]
	Bosons	$H^{\pm} \to W^{\pm}Z$	200–1000 GeV	139 fb^{-1}	Ref. [8, 9]
		$H^{\pm} \to W^{\pm}a$	120–160 GeV	139 fb^{-1}	Ref. [10]
Doubly-charged	Fermions	$H^{\pm\pm} \to \ell\ell'$	400–1300 GeV	139 fb^{-1}	Ref. [11]
	Bosons	$H^{\pm\pm} \to W^{\pm}W^{\pm}$	200–600 GeV	139 fb^{-1}	Ref. [9]

Table 1: List of the latest searches for charged Higgs bosons at ATLAS. The charge, the coupling, the decay, and the mass range of the charged Higgs bosons assumed in the searches as well as the integrated luminosity for the data samples are shown. The symbols ℓ and ℓ' indicate e, μ, τ.

3.1 Searches for Singly-Charged Higgs Bosons Decaying into Fermions

Among the latest results listed in Table 1, we first focus on the charged Higgs boson decay into $\tau\nu$ [4]. The target was the production either in association with the top and bottom quarks, for high mass search, or in the top quark decays, for low mass search. A hadronically decaying tau lepton was required. The Boosted Decision Tree (BDT) was used for the separation between the signal and background. The inputs were kinematic variables, such as the transverse momentum p_{T} of reconstructed objects and the missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$ in the event. No evidence was found for the charged Higgs bosons, and upper limit was set to the product of the cross section and the branching ratio, for a range of the charged Higgs mass of 90–2000 GeV. The results were interpreted in the hMSSM and constraints were given on the plane of the charged Higgs mass m_{H^+} and the ratio of the two vacuum expectation values $\tan\beta$ (Figure 2, left).

The charged Higgs boson decay into tb includes a top quark in the final state, and the search targeted relatively high charged Higgs boson mass [5]. One electron or muon was required for better signal to background ratio, and the events were categorised according to the multiplicity of jets and b-tagged jets. Kinematic variables were used as the inputs to neural network, and the output was fitted for signal extraction. No evidence of the charged Higgs bosons was found and upper limit was set on the cross section times the branching ratio for a mass range of 200–2000 GeV. The results were interpreted in the hMSSM and constraints were given on m_{H^+} and $\tan\beta$ (Figure 2, right).

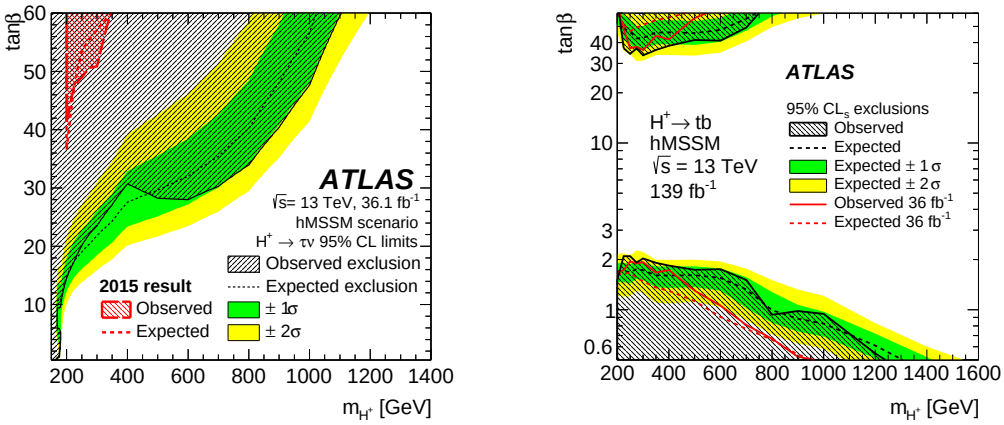

Figure 2: Expected and observed constraints (95% CL) on m_{H^+} and $\tan\beta$ in the hMSSM from the searches for the $\tau\nu$ (left) and tb (right) decays [4, 5].

Another search for the charged Higgs boson decays to fermions was performed on the decay into cb [6]. For MSSM, the mass scale up to several hundred GeV was excluded by the searches for charged and neutral Higgs bosons, but such constraints can be evaded or mitigated in other non-minimal extensions of the Higgs sector. The final states with lepton plus jets were analysed. Neural network score was fitted, and no evidence of the signal was found. Upper limit was set on the branching ratio for a mass range of 60–160 GeV and compared with the predictions from 3HDM (Figure 3, left). The global significance at 130 GeV was $(2.46 \pm 0.05)\sigma$.

A new search was performed for the charged Higgs boson decay into cs [7]. Low mass charged Higgs bosons produced in top quark decays were focused on, with lepton plus jet final state. The BDT was used for the signal and background separation, with the inputs including dijet mass, b-tagged jet p_{T}, and jet flavour-tagging variables. No excess on the BDT score was found. Upper limit was set on the branching ratio for a mass range of 60–168 GeV (Figure 3, right).

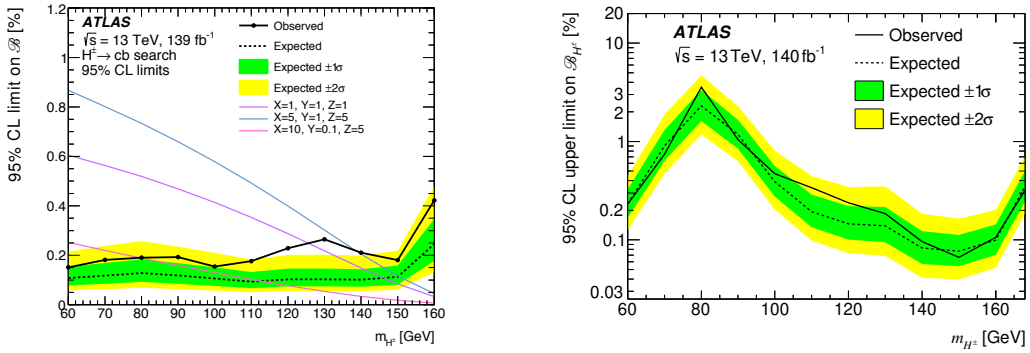

Figure 3: Expected and observed upper limits (95% CL) on the branching ratios of the charged Higgs boson decays into cb (left) and cs (right) [6, 7]. For the decay into cb, the predictions from three benchmark parameters of 3HDM are also shown. For the decay into cs, the sensitivity is worse at around 80 GeV due to the background from the SM top quark decay via the $W^{\pm}$ boson.

3.2 Searches for Singly-Charged Higgs Bosons Decaying into Bosons

The charged Higgs bosons decaying into $W^{\pm}$ and Z bosons were searched for with the fully leptonic final state [8]. The signal region was defined using the neural network output, and the signal was extracted with the invariant mass of the $W^{\pm}$ and Z system. No significant excess was observed, and upper limit was set for a mass range of 200–1000 GeV. The global significance at 375 GeV was 1.6σ. The results were interpreted in the GM model, and the parameters were constrained for a fiveplet mass m_5 and $\sin\theta_{\mathrm{H}}$, where $\sin\theta_{\mathrm{H}}$ determines the contribution of the triplets to the masses of the $W^{\pm}$ and Z bosons (Figure 4, left) [12].

The charged Higgs bosons decaying into $W^{\pm}$ and a bosons were searched for with the pseudoscalar a decay into two muons [10]. The search targeted the final state with $e\mu\mu$ or $\mu\mu\mu$. No significant excess was found by the fit to the $m_{\mu\mu}$ distributions. Upper limit was set to the branching ratio for a charged Higgs mass range of 120–160 GeV.

3.3 Searches for Doubly-Charged Higgs Bosons

Not only the singly-charged Higgs bosons but also the doubly-charged Higgs bosons were searched for. An example is on the decay into two leptons [11]. A pair production of the doubly-charged Higgs bosons was targeted. Lepton-flavor-violating decays were allowed. The regions were defined depending on the multiplicity of electrons and muons. No excess was observed and upper limit was set to the cross section for a mass range of 400–1300 GeV (Figure 4, right).

Another search for the doubly-charged Higgs bosons was performed with the $W^{\pm}W^{\pm}$ final state, including an associated production with singly-charged Higgs boson decay into $W^{\pm}Z$ [9]. The channels were defined for two same-charge leptons, three leptons, and four leptons. No excess was found and upper limit was set on the cross section for a doubly-charged Higgs mass range of 200–600 GeV. From the upper limit on the cross section, a limit was set in the Type II seesaw model, which is the doubly-charged Higgs mass of 350 GeV (95% CL). The result was also interpreted in the GM model, and m_5 and $\sin\theta_{\mathrm{H}}$ were constrained (Figure 4, left) [12].

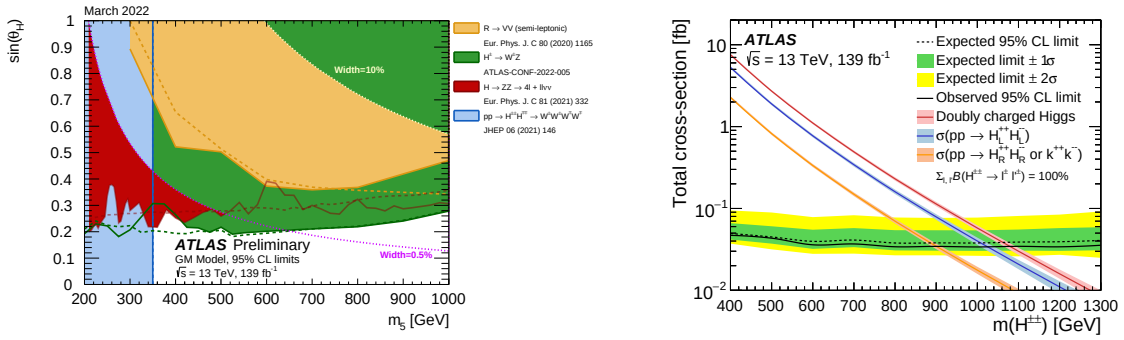

Figure 4: Summary plot of the constraints (95% CL) on the GM model (left) and the expected and observed upper limits (95% CL) on the cross section for the doubly-charged Higgs bosons in two lepton final state (right) [11, 12]. For the cross section plot, predictions from a left-right symmetric model are also shown.

4. Conclusion

Despite its tremendous success, the SM cannot be the final theory. Various models extend the Higgs sector, involving the charged Higgs bosons. Searches were performed with 13 TeV pp collision data taken at Run 2 of the ATLAS experiment. The results were reported for several production and decay channels of singly- and doubly-charged Higgs bosons. No significant excess over the SM expectation was found. Upper limits on the cross section and the branching ratio were set, and the parameters were constrained for extended models such as MSSM, 3HDM, the GM model, and the Type-II seesaw model.

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