PROCEEDINGS OF SCIENCE

Searches for singly- and doubly-charged Higgs bosons with the ATLAS detector

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In the Standard Model, one doublet of complex scalar fields is the minimal content of the Higgs sector needed to achieve the 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. They have been extensively searched for in the ATLAS experiment, using proton-proton collision data at 13 TeV during the LHC Run 2. In this document, a summary of the latest experimental results obtained in searches for both singly- and doubly-charged Higgs bosons is presented.

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PoS(EPS-HEP2023)433

1. Introduction

The Standard Model of particle physics (SM) does not predict any Higgs boson with non-zero charge. However, several models beyond the Standard Model (BSM) predict additional singly- and additional doubly-charged Higgs bosons or similar scalar boson particles. They have rich final state topologies that can be probed at collider experiments. In this document, several searches using full Run 2 dataset of proton–proton collisions collected by the ATLAS [1] detector at the Large Hadron Collider (LHC) are presented.

2. Searches for singly-charged Higgs bosons

In scenarios beyond the Standard Model, the Higgs sector is typically extended to incorporate new degrees of freedom. A popular and minimal extension of the SM paradigm is provided by two-Higgs-doublet models (2HDM) [2], where the Higgs sector consists of two complex doublets. A mixture of the two doublets fulfils the same role as the SM Higgs field and generates a Higgs boson (h) similar to that in the SM, and the other mixture gives rise to a neutral CP-even Higgs boson (H), a neutral CP-odd Higgs boson (A), and a charged Higgs boson ($H^{\pm}$). Constraints from existing searches and measurements suggest that the natural mass scale for additional Higgs bosons should be above several hundred GeV. Other non-minimal extensions of the SM Higgs sector do not have such limitations, such as the three Higgs doublets (3HDM) [3], which feature three CP-even and two CP-odd neutral Higgs bosons, as well as two charged Higgs bosons.

The lightest charged Higgs boson can be lighter than the top quark, so it can be produced as a top-quark decay product, and has a sizeable decay branching ratio into a charm quark and a bottom quark. This is investigated by an ATLAS search [4], motivated by a small yield of the irreducible SM background originating from the $t\bar{t}$ production in this final state. The charged Higgs boson $H^{\pm}$ is produced when one of the top quarks in the $t\bar{t}$ pair-production decays into $H^{\pm}$ and a b-quark. The final state consists of exactly one electron or muon, non-zero missing transverse momentum due to a neutrino, and at least four jets. A dedicated tagging is used to separate jets originating from b-quarks, so-called b-jets, and jets originating from light quarks. Several thresholds on the likelihood of being a result of the hadronisation of a b-quark are defined and at least two jets should satisfy the tight threshold.

To improve the modelling of the leading background, $t\bar{t}$, data-driven corrections are derived as a function of scalar sum of all momenta $H_{\mathrm{T}}^{\mathrm{all}}$ of all jets and the lepton in a region where requirements on the b-jet identification for the third jet are relaxed. The corrections are smoothened to avoid fluctuations and take values between 1.0 and 1.2. Events with at least three tight b-jets are used for the training of neural-networks, one for each jet multiplicity between total of four and six jets. These networks are used to discriminate between the expected $H^{\pm}$ signal and the large SM background.

A profile likelihood fit of the neural network score is performed. No significant excess of data events above the background expectation is observed, and 95 % confidence level limits are set on the product of branching fractions $\mathcal{B}(t \to H^{\pm}b) \times (H^{\pm} \to cb)$, shown in Figure 1. They vary between 0.15 % and 0.42 % for $m_{H^{\pm}}$ between 60 and 160 GeV. The largest excess in data has a local significance of about $3\,\sigma$ ($2.5\,\sigma$ global) for $m_{H^{\pm}} = 160$ GeV.

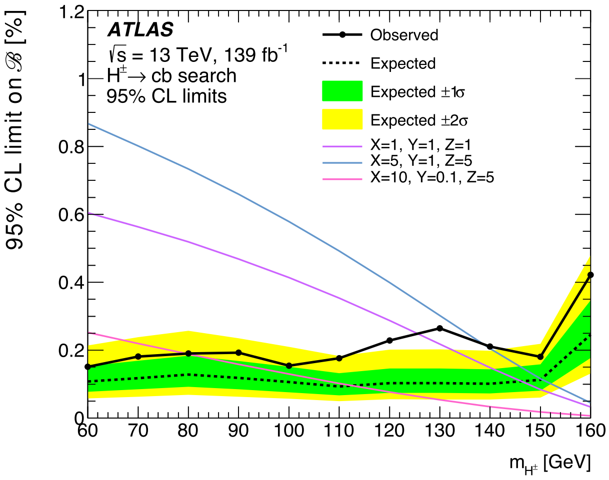


Figure 1: The observed (solid) 95 % CL upper limits on $\mathcal{B}$ as a function of $m_{H^{\pm}}$ and the expectation (dashed) under the background-only hypothesis. Superimposed on the upper limits, the predictions from the 3HDM are shown, corresponding to three benchmark values for the parameters X, Y, and Z, which are functions of the Higgs-doublet vacuum expectation values and the mixing angle between the charged Higgs bosons. Taken from Ref. [4].

Alternatively the charged Higgs boson can also decay into a W boson and a new light pseudo-scalar particle a, also searched for by the ATLAS experiment [5]. Such new particles are well motivated phenomenologically and have been proposed as an explanation for the excess of γ-ray emissions from the center of our galaxy [6] in the context of Coy Dark Matter models [7]. They can also be colourless solutions of the naturalness problem [8] or explain electroweak baryogenesis [9].

The ATLAS search considers two scenarios: one where the $H^{\pm}$ decays into the pseudo-scalar a and one where the pseudo-scalar is produced directly in the association with the top quark pair. In both cases a decays into a pair of muons, and the high mass resolution achievable for muon pairs provides a distinctive signature to search for and excellent discrimination against most of the background sources. The search targets final states with three leptons, including an electron or muon from a top-quark decay in addition to the two muons from the light pseudo-scalar decay. Additionally, at least three jets are required, of which at least one should be classified as a b-jet.

The presence of a signal consistent with the production of the pseudo-scalar particle is tested by comparing the expected background with data in narrow bins of the reconstructed $m_{\mu\mu}$ using a profile-likelihood fit. In the tri-muon final state, the pair with the invariant mass closer to the hypothesised mass is chosen. A total of 43 bins between 12 GeV and 77 GeV are used. A bin width proportional to the expected width of a detected signal, illustrated in Figure 2, ensures that any signal contribution is highly concentrated in a few bins, while keeping the analysis largely independent of the specific signal mass distribution.

No significant excess is observed, the largest with local significance of about 2.4 σ at m_a = 27 GeV. Limits are set on the $t\bar{t}a$ production cross section, with a decaying into two muons, between 0.5 − 3 fb at 95 % confidence level. Upper limits on the branching ratio $\mathcal{B}(t \rightarrow bH^{\pm}) \times \mathcal{B}(H^{\pm} \rightarrow W^{\pm}a) \times \mathcal{B}(a \rightarrow \mu\mu)$ are in the range $(0.9 - 3.9) \times 10^{-6}$ at 95 % confidence level for $m_{H^{\pm}}$ between 120 GeV and 160 GeV and m_a between 15 GeV and 72 GeV.

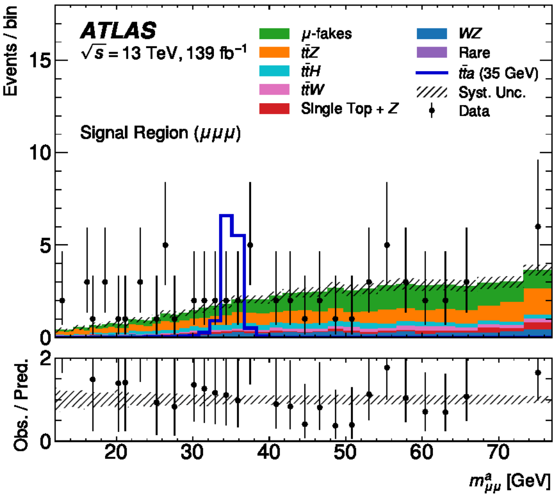


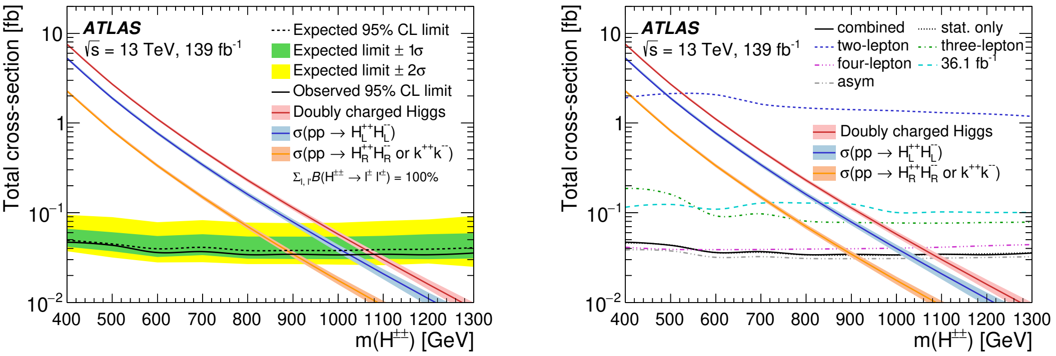
Figure 2: Di-muon mass distributions for data and expected background in the $\mu\mu\mu$ signal regions for the $m_a = 35\,\text{GeV}$ hypothesis. Taken from Ref. [5].

3. Searches for doubly-charged Higgs bosons

Various theories beyond the Standard Model predict the existence of doubly-charged bosons, such as type-II seesaw models [10], left-right symmetric models (LRSM) [11], the Zee–Babu neutrino mass model [12, 13], and the Georgi–Machacek (GM) model [14]. In the case of type-II seesaw and LRSM models, the particles are called doubly charged Higgs bosons. The left-handed $H_L^{\pm\pm}$ is common for both, while the right-handed $H_R^{\pm\pm}$ is only present in LRSMs. They are produced via Drell–Yan production $H^{\pm\pm}H^{\mp\mp}$. In the Zee–Babu case, the scalar particle is usually denoted by $k^{\pm\pm}$ and has the same quantum number and electroweak production as $H_R^{\pm\pm}$, while differing by the cross-section normalisation.

The decay channels of the first three model types depend on the vacuum expectation value, which is a free parameter of the model. In the ATLAS search presented in Ref. [15], this is chosen to be smaller than 10^{-8} GeV, making $H^{\pm\pm}$ decay exclusively in lepton pairs. The analysis regions are split by lepton multiplicity into di-, tri- and four-lepton signal regions. The final state is expected to be fully leptonic and lepton pairs originating from the decays of SM Z boson are rejected. Same-charge lepton pairs are reconstructed as $H^{\pm\pm}$ candidates, and in case of three leptons the pair with the highest mass is considered.

The main backgrounds of the analysis are the SM di-boson production processes (ZZ, WZ, WW), electron charge misidentification and fake and non-prompt leptons. The normalisation of the di-boson processes is extracted from control regions, one for each lepton multiplicity. The electron charge is often misidentified, mainly due to bremsstrahlung emission from the electrons as they propagate through the detector material. The charge misidentification probability is extracted from $Z \to e^+e^-$ events in data, where both of the leptons are reconstructed with the same charge, and used to correct any mis-modelling in simulation. Fake and non-prompt leptons are estimated using the fake-factor method [16] on single-lepton fake-enriched control regions and propagated to the



(a) **(b)**

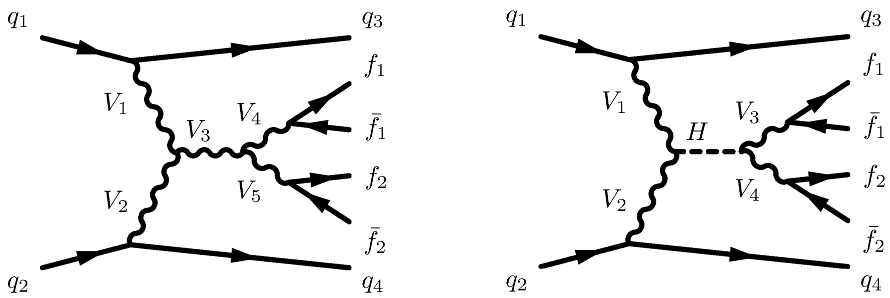
Figure 3: Upper limits on the $H^{\pm\pm}$ pair production cross-section as a function of $m_{H^{\pm\pm}}$: (a) as a result of the combination of all three lepton multiplicities, where the solid line represents observed and the dashed line expected limits, and (b) as observed limit broken down by lepton multiplicity. The grey line shows the limit using the asymptotic approximation and the cyan line compares the result with the 36.1 fb^{-1} ATLAS search [17]. The theoretical signal cross-section predictions are shown as blue, orange and red lines for the left-handed $H_L^{\pm\pm}$, right-handed $H_L^{\pm\pm}$, and a sum of the two chiralities, respectively. Taken from Ref. [15].

signal regions.

While good sensitivity to the signal is obtained, the analysis is statistically limited. In the four-lepton signal region, no data event is observed, which is consistent with the expected yield. A profile-likelihood fit is performed using the leading lepton pair's invariant mass distribution. No significant excess from the SM is observed and limits are set on the production cross-section of the doubly-charged scalar particles, illustrated in Figure 3. These vary between 520 GeV and 1050 GeV for LRSM and type-II seesaw models and between 410 GeV and 880 GeV for the Zee–Babu model, depending on the lepton multiplicity channel. The four-lepton channel is the most sensitive of the three probed. The observed combined lower limit on the $H^{\pm\pm}$ mass is 1080 GeV within LRSM and type-II seesaw models and 900 GeV within the Zee–Babu model.

The doubly charged Higgs boson $H_5^{\pm\pm}$ that is part of the Georgi–Machacek model is fermiophobic, meaning it only interacts with vector bosons. The additional scalar fields in the model contribute to the masses of of SM W and Z bosons, characterised by the $\sin\theta_H$ parameter. ATLAS investigated this model as a reinterpretation of the SM production of a same-charge W pair in association with two jets ($W^\pm W^\pm jj$) [18]. The W bosons are produced in the interaction of two initial electroweak bosons, also called the vector boson scattering (VBS). In the presence of BSM physics instead a doubly charged Higgs boson can be produced in vector boson fusion (VBF) processes and decay into same-charge W bosons. The Feynman diagrams comparing representative diagrams of the two processes are shown in Figure 4. To fit the GM model a benchmark 100 % branching fraction of $H_5^{\pm\pm}$ into same-charge W boson pairs is chosen. The VBF production and decays of the $H_5^{\pm\pm}$ depend on the mass of the new Higgs boson and the $\sin\theta_H$ parameter. The GM model signal contribution is proportional to $\sin^2\theta_H$.

The characteristic signature of $W^\pm W^\pm jj$ events is the presence of two energetic forward jets in opposite hemispheres with large invariant mass m_{jj}, the presence of a same-charge lepton pair, and missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$). The two jets have large absolute value of rapidity difference,



(a) **(b)**

Figure 4: Representative s-channel Feynman diagrams for electroweak $VVjj$ production with a scattering topology including either (a) a triple gauge boson vertex with production of a W/Z boson or (b) the exchange of a Higgs boson. Taken from Ref. [18].

$\Delta y_{jj} = |y_{j_1} - y_{j_2}|$. In addition, the two leptons from the decay of the two W bosons tend to lie between the two jets in rapidity.

The transverse mass of the di-lepton and $E_\mathrm{T}^\mathrm{miss}$ system m_T is used for the fit, defined as

$$m_\mathrm{T} = \sqrt{\left(E_\mathrm{T}^{\ell\ell} + E_\mathrm{T}^\mathrm{miss}\right)^2 - \left|\vec{p}_\mathrm{T}^{\,\ell\ell} + \vec{E}_\mathrm{T}^\mathrm{miss}\right|^2},$$

where $E_\mathrm{T}^{\ell\ell}$ is the transverse energy of the lepton pair, and $\vec{p}_\mathrm{T}^{\,\ell\ell}$ is the vectorial sum of the lepton transverse momenta. No significant excess over the SM is observed, with the largest one observed at a resonance mass of around 450 GeV, corresponding to a local significance of $3.2\,\sigma$ ($2.5\,\sigma$ global). The observed 95 % confidence level limits exclude $\sin\theta_H$ parameter values greater than 0.11-0.41 for the $m_{H_5^{\pm\pm}}$ range from 200 to 1500 GeV. Additionally, model-independent upper limits on the product of the cross-section and branching fraction for VBF production of doubly-charged Higgs bosons are set.

4. Conclusions

The ATLAS experiment at the LHC has performed many searches for additional Higgs bosons, both with single and double charge. No significant excess from the Standard Model has been observed and limits on production cross sections or other model parameters of various theories beyond the Standard Model have been set.

References

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

[2] G.C. Branco, P.M. Ferreira, L. Lavoura, M.N. Rebelo, M. Sher and J.P. Silva, *Theory and phenomenology of two-Higgs-doublet models*, *Phys. Rept.* **516** (2012) 1 [`1106.0034`].

[3] A.G. Akeroyd, S. Moretti, K. Yagyu and E. Yildirim, *Light charged Higgs boson scenario in 3-Higgs doublet models*, *Int. J. Mod. Phys. A* **32** (2017) 1750145 [`1605.05881`].

[4] ATLAS Collaboration, *Search for a light charged Higgs boson in $t \to H^\pm b$ decays, with $H^\pm \to cb$, in the lepton+jets final state in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *JHEP* **09** (2023) 004 [`2302.11739`].

[5] ATLAS Collaboration, *Search for a new pseudoscalar decaying into a pair of muons in events with a top-quark pair at $\sqrt{s} = 13$ TeV with the ATLAS detector*, `2304.14247`.

[6] L. Goodenough and D. Hooper, *Possible Evidence For Dark Matter Annihilation In The Inner Milky Way From The Fermi Gamma Ray Space Telescope*, `0910.2998`.

[7] C. Boehm, M.J. Dolan, C. McCabe, M. Spannowsky and C.J. Wallace, *Extended gamma-ray emission from Coy Dark Matter*, *JCAP* **05** (2014) 009 [`1401.6458`].

[8] Z. Chacko, H.-S. Goh and R. Harnik, *The Twin Higgs: Natural electroweak breaking from mirror symmetry*, *Phys. Rev. Lett.* **96** (2006) 231802 [`hep-ph/0506256`].

[9] S. Profumo, M.J. Ramsey-Musolf and G. Shaughnessy, *Singlet Higgs phenomenology and the electroweak phase transition*, *JHEP* **08** (2007) 010 [`0705.2425`].

[10] Y. Cai, T. Han, T. Li and R. Ruiz, *Lepton Number Violation: Seesaw Models and Their Collider Tests*, *Front. in Phys.* **6** (2018) 40 [`1711.02180`].

[11] J.C. Pati and A. Salam, *Lepton Number as the Fourth Color*, *Phys. Rev. D* **10** (1974) 275.

[12] A. Zee, *Charged Scalar Field and Quantum Number Violations*, *Phys. Lett. B* **161** (1985) 141.

[13] K.S. Babu, *Model of 'Calculable' Majorana Neutrino Masses*, *Phys. Lett. B* **203** (1988) 132.

[14] H. Georgi and M. Machacek, *Doubly Charged Higgs Boson*, *Nucl. Phys. B* **262** (1985) 463.

[15] ATLAS Collaboration, *Search for doubly charged Higgs boson production in multi-lepton final states using 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, *Eur. Phys. J. C* **83** (2022) 605 [`2211.07505`].

[16] ATLAS Collaboration, *Tools for estimating fake/non-prompt lepton backgrounds with the ATLAS detector at the LHC*, `2211.16178`.

[17] ATLAS Collaboration, *Search for doubly charged Higgs boson production in multi-lepton final states with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13$ TeV*, *Eur. Phys. J. C* **78** (2018) 199 [`1710.09748`].

[18] ATLAS Collaboration, *Measurement and interpretation of same-sign W boson pair production in association with two jets in pp collisions at 13 TeV with the ATLAS detector*, ATLAS-CONF-2023-023, 2023, https://cds.cern.ch/record/2859330.