Searches for neutral and charged Higgs bosons in the ATLAS experiment as a test of physics beyond the Standard Model

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Abstract. In several theories beyond the Standard Model, the Higgs sector consists of more than one complex scalar doublet. For instance, supersymmetric models such as the MSSM have five physical Higgs states: two charged and three neutral. In this paper, a review of the searches for new neutral and charged Higgs bosons at the Large Hadron Collider, with the ATLAS experiment, is presented.

1. Introduction
In the Standard Model (SM), only one doublet of Higgs complex scalars is responsible for the electroweak symmetry breaking. Since three degrees of freedom are used in order to give mass to the $Z$, $W^+$ and $W^-$ gauge bosons, there can be only one Higgs physical state, $h^0$. Recently, a new neutral boson with Higgs-like properties has been observed by both the ATLAS and CMS experiments at the Large Hadron Collider (LHC), with a mass of 125–126 GeV [1, 2]. The remaining mass range is meanwhile excluded with a high confidence level. Detailed investigations are now conducted in order to determine whether this new particle is the SM Higgs boson, or a Higgs boson. Indeed, additional Higgs bosons are predicted by several non-minimal Higgs scenarios, such as Two Higgs Doublet Models (2HDM) [3]. In a type-II 2HDM, such as the Higgs sector of the Minimal Supersymmetric extension of the Standard Model (MSSM), five physical Higgs states are predicted [4]: the neutral CP-even $h^0$ and $H^0$, the neutral CP-odd $A^0$, and the charged $H^\pm$ Higgs bosons. At tree level, the MSSM Higgs sector is fully defined by the mass of one of the Higgs bosons and $\tan \beta$, the ratio of the two Higgs vacuum expectation values. In this paper, the searches for neutral and charged Higgs bosons using the LHC proton-proton collision data recorded by the ATLAS [5] experiment in 2011 are reviewed.

2. The ATLAS experiment
The ATLAS detector consists of an inner tracker with coverage in pseudorapidity up to $|\eta| = 2.5$, surrounded by a thin 2 T superconducting solenoid, a calorimeter system up to $|\eta| = 4.9$ for the detection of electrons, photons and hadronic jets, as well as a large muon spectrometer extending up to $|\eta| = 2.7$, which measures the deflection of muon tracks in the field of three superconducting toroid magnets. A three-level trigger system is used, which reduces the recorded event rate to about 300 Hz.
Electrons are reconstructed by matching energy deposits in the electromagnetic calorimeter (except in the pseudorapidity range $1.37 < |\eta| < 1.52$) to tracks reconstructed in the inner detector [6]. Muons are required to contain matching inner detector and muon spectrometer tracks [7]. The combination of all sub-systems provides precise lepton measurements within $|\eta| < 2.5$. The jets, as well as the magnitude of the missing transverse momentum $E_T^{\text{miss}}$, are reconstructed using energy deposits over the full coverage of the calorimeters, i.e. up to $|\eta| = 4.9$. The anti-$k_T$ algorithm [8] with a radius parameter value of $R = 0.4$ is used for the jet reconstruction, taking three-dimensional noise-suppressed clusters of calorimeter-cell energy deposits as input [9]. In order to select jets originating from the hard-scatter interaction, at least 75% of the tracks associated to a jet (weighted by their transverse momenta $p_T$) must point to the primary vertex. A multivariate algorithm combining information from the impact parameter of associated tracks and the reconstruction of $b$- and $c$-hadron decay vertices is used in order to identify jets initiated by $b$-quarks, within $|\eta| < 2.5$. The $b$-jet identification has an efficiency of about 70% in $t\bar{t}$ events. In order to reconstruct hadronically decaying $\tau$ leptons, anti-$k_T$ jets with either one or three associated tracks are considered as $\tau$ candidates, however, with a different calibration than hadronic jets. The $\tau$ candidates are required to have a visible $p_T > 20$ GeV and to be within $|\eta| < 2.5$. Dedicated algorithms are used to reject electrons and muons. The hadronic $\tau$ decays are identified using either a likelihood criterion or a boosted-decision-tree (BDT) discriminant, with “loose”, “medium” and “tight” selections depending on the efficiency for hadronically decaying $\tau$ leptons and on the rejection factor against quark- and gluon-initiated jets [11]. Selected $\tau$ candidates fulfilling the identification criteria are referred to as “$\tau$ jets”.

3. Search for new neutral Higgs bosons in ATLAS

In the MSSM, the couplings of neutral Higgs bosons to $\tau$ leptons and $b$-quarks are strongly enhanced for a large part of the parameter space, especially at large $\tan \beta$. The most common production mechanism for MSSM neutral Higgs bosons at the LHC are the $b$-quark associated production and the $gg$ fusion (primarily through a $b$-quark loop), with cross sections increasing with $\tan \beta$. In this paper, searches for new neutral Higgs bosons in the $A^0/H^0/h^0 \to \tau\tau$ mode using 4.7 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 7$ TeV are presented. This review is divided into separate search channels, according to the lepton decay modes. More details can be found in Ref. [12]. The direct decay into a $\mu\mu$ pair occurs rarely (its branching ratio is 0.04%), however it offers a clean signature. It was also considered in Ref. [12], but is not detailed in the present review.

3.1. Common aspects

**Missing Mass Calculator:** The full reconstruction of the $A^0/H^0/h^0 \to \tau\tau$ events requires solving equations with more unknowns than constraints. Hence, a technique known as the Missing Mass Calculator (MMC) is used to reconstruct the neutral Higgs boson candidate mass [13]. Assuming that the missing transverse momentum is entirely due to the neutrinos, the algorithm scans over the angles between the neutrinos and the visible $\tau$ lepton decay products. At each point, the $\tau\tau$ invariant mass is calculated, and the most likely value is chosen by weighting each solution according to probability density functions derived from simulated $\tau$ lepton decays. This method finds a solution in 99% of the cases, with a 13–20% mass resolution.

**$\tau$-embedding for the $Z/\gamma^* \to \tau\tau$ background estimation from data:** $Z/\gamma^* \to \tau\tau$ events are a largely irreducible background in the search for neutral Higgs bosons $A^0/H^0/h^0 \to \tau\tau$, in all final states. In order to estimate this background from data, the $\tau$-embedding technique is used. It consists in selecting $Z/\gamma^* \to \mu\mu$ events in data and in replacing the detected muon signature (muon track hits and associated calorimeter cells) by the response of a simulated $\tau$ lepton decay. After selection of the $\tau$ decay products, the embedded sample is normalised to the event yield obtained with simulated $Z/\gamma^* \to \tau\tau$ events.
3.2. $A^0/H^0/h^0 \rightarrow \tau\tau \rightarrow e\mu$  

Events in this channel must fire a single-lepton or electron+muon trigger and they must contain exactly one electron and one muon, with $E_T^e > 24$ GeV and $p_T^\mu > 20$ GeV for events selected by a single-lepton trigger, or $E_T^e > 10$ GeV and $p_T^\mu > 6$ GeV for events selected by the electron+muon trigger. The invariant mass of the electron and the muon must satisfy $m_{e\mu} > 30$ GeV. The selected sample is then split according to the flavor content:

- **$b$-tagged:** exactly one $b$-jet, $H_T = \sum_j E_T(j) < 100$ GeV (using only jets with $E_T > 20$ GeV and $|\eta| < 4.5$), $E_T^{\text{miss}} + E_T^e + p_T^\mu < 125$ GeV, $\Delta\phi_{e\mu} > 2.0$, $\sum_{e\mu} \cos \Delta\phi_{e\mu}^{\text{miss}} > -0.2$;
- **$b$-vetoed:** no $b$-jet, $E_T^{\text{miss}} + E_T^e + p_T^\mu < 150$ GeV, $\Delta\phi_{e\mu} > 1.6$, $\sum_{e\mu} \cos \Delta\phi_{e\mu}^{\text{miss}} > -0.4$,

where $\phi$ stands for the azimuthal angle. The selections above allow to reduce the top quark, diboson and $W \rightarrow \ell\nu$ backgrounds, as well as processes with a higher jet multiplicity or containing jets with higher transverse energies than the signal. The irreducible $Z/\gamma^* \rightarrow \tau\tau$ background is estimated with the $\tau$-embedding technique. The contribution from $t\bar{t}$ events is extrapolated from control regions, which have the same selection criteria as for the signal, except that two $b$-jets are required and $H_T < 100$ GeV is not applied. Finally, the multi-jet background is determined with a so-called ABCD method by splitting the event sample into four regions according to the charge product of the $e\mu$ pair and the isolation requirements on the electron and muon. The signal region is labelled A, and the other regions (B, C, D) are dominated by the background from multi-jet processes. One variable separates A and B from C and D. After correcting the event yields $n_B$, $n_C$ and $n_D$ in, respectively, the regions B, C and D by subtracting (simulated) processes other than the multi-jet background, an estimate of the multi-jet background in the signal region, $n_A$, is:

$$n_A = n_B \times (n_C/n_D).$$

The observed event yields in the 2011 data, as well as the MMC distributions of the selected events, are compatible with the SM predictions within uncertainties, see Figure 1.

**Figure 1.** MMC mass distributions for the $A^0/H^0/h^0 \rightarrow \tau\tau \rightarrow e\mu$ final state, shown for the $b$-tagged (left) and $b$-vetoed (right) samples, extracted from Ref. [12]. The data are compared to the SM background expectation and an added hypothetical MSSM signal ($m_A = 150$ GeV and $\tan\beta = 20$). The contributions of $Z/\gamma^* \rightarrow e\mu$ and $W^+j$ are labelled as “Other electroweak”. For the $b$-tagged sample, the diboson background is included as well. Background contributions from top quarks are included in “Other electroweak” for the $b$-vetoed sample.
3.3. $A^0/H^0/h^0 \rightarrow \tau\tau \rightarrow \ell\tau_{\text{had}}$ with $\ell = e, \mu$

Events in this channel must fire a single-lepton trigger and they must contain one isolated electron with $E_T > 25$ GeV or one isolated muon with $p_T^\mu > 20$ GeV. Events containing additional electrons or muons with transverse energies or momenta greater than 15 GeV or 10 GeV, respectively, are rejected. One $\tau$, with $p_T^\tau > 20$ GeV, $|\eta| < 2.5$, a medium BDT identification and a charge of opposite sign to the selected electron or muon is required. A cut on the transverse mass of the lepton $\ell$ and the missing transverse momentum is then applied to reduce the $W$+jets and $t\bar{t}$ backgrounds:

$$m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos \Delta\phi_{\ell,E_T^{\text{miss}}})} < 30 \text{ GeV}.$$  

At this stage, events are included in the $b$-tagged sample if the leading jet within $|\eta| < 2.5$ is identified as a $b$-jet and if its $E_T$ is in the range of 20–50 GeV. Events are included in the $b$-vetoed sample if the leading jet fails the $b$-jet identification criterion and the event has $E_T^{\text{miss}} > 20$ GeV. After the event selection up to the $m_T$ requirement, the $W$+jets background consists primarily of events in which a jet is misidentified as a $\tau$. The jet $\rightarrow \tau_{\text{had}}$ misidentification rates are corrected in simulated $W$+jets events, separately for $e\tau_{\text{had}}$ and $\mu\tau_{\text{had}}$, using control regions enriched with $W$+jets events in data, selected by requiring $70 \text{ GeV} < m_T < 110$ GeV. The $Z/\gamma^* \rightarrow \tau\tau$ background is estimated with the $\tau$-embedding technique. The contribution from $t\bar{t}$ events is extrapolated from control regions, which have the same selection criteria as for the signal, except that there is no requirement on $m_T$, the leading jet must be $b$-tagged, with $E_T$ in the range 50–150 GeV, and a second highest-$E_T$ jet must satisfy the same $b$-jet identification requirement. Finally, the ABCD method is used in order to estimate the multi-jet background. The four regions are defined according to whether the charges of the jet and the lepton have opposite or same sign, and whether the selected lepton passes or fails isolation criteria. The observed event yields in the 2011 data, as well as the MMC distributions of the selected events, are compatible with the SM predictions within uncertainties, see Figure 2.

Figure 2. MMC mass distributions for the $A^0/H^0/h^0 \rightarrow \tau\tau \rightarrow \ell\tau_{\text{had}}$ final state, shown for the $b$-tagged (left) and $b$-vetoed (right) samples, extracted from Ref. [12]. The data are compared to the SM background expectation and an added hypothetical MSSM signal ($m_A = 150$ GeV and $\tan\beta = 20$). The diboson and $W$+jets backgrounds are combined and labelled as “Other electroweak”.
3.4. $A^0/H^0/h^0 \to \tau\tau \to \tau_{\text{had}}\tau_{\text{had}}$

Events in this channel must fire a $\tau_{\text{had}}$ trigger and contain two $\tau_{\text{had}}$ candidates matched to the trigger objects (one passing the tight BDT identification requirement and the second one passing the medium criteria), with opposite-sign charges and with transverse momenta larger than 45 GeV and 30 GeV. Corrections for the $\tau_{\text{had}}$ trigger and identification efficiencies, as well as for the jet $\to \tau_{\text{had}}$ misidentification rate, are derived from data and applied in the simulation. Events containing identified electrons or muons with $E_T > 15$ GeV or $p_T > 10$ GeV, respectively, are vetoed. The missing transverse momentum is required to be larger than 25 GeV to account for the presence of neutrinos originating from the $\tau$ decays and to suppress the multi-jet background. At this stage, events are included in the $b$-tagged sample if the leading jet within $|\eta| < 2.5$ is identified as a $b$-jet and if its $E_T$ is in the range of 20–50 GeV. Events are included in the $b$-vetoed sample if no jet is found or if the leading jet fails the $b$-jet identification criterion. Because of higher background levels in this sample, the leading jet must have $p_T > 60$ GeV.

Since the di-$\tau_{\text{had}}$ trigger cannot be modelled in embedded $Z/\gamma^* \to \tau\tau$ events, this background is estimated with simulation, and validated using a $-\text{embedded}$ $Z/\gamma^* \to \mu\mu$ sample. Similarly, simulation is used to estimate the $W \to \tau\nu$ background and a $-\text{embedded}$ $W \to \mu\nu$ sample from data is used for validation purposes. For both backgrounds, correction factors for the efficiency of the $b$-jet identification requirement on the leading jet are applied. The ABCD method is used in order to estimate the multi-jet background. The four regions are defined according to the charge product of the two leading $\tau_{\text{had}}$ candidates, and whether their nominal identification requirements are met.

The observed event yields in the 2011 data, as well as the MMC distributions of the selected events, are compatible with the SM predictions within uncertainties, see Figure 3.

![Figure 3](image_url)

**Figure 3.** MMC mass distributions for the $A^0/H^0/h^0 \to \tau\tau \to \tau_{\text{had}}\tau_{\text{had}}$ final state, shown for the $b$-tagged (left) and $b$-vetoed (right) samples, extracted from Ref. [12]. The data are compared to the SM background expectation and an added hypothetical MSSM signal ($m_A = 150$ GeV and tan $\beta = 20$).

3.5. Exclusion limits

The statistical analysis of the data employs a binned likelihood function. Each one of the $e\mu$, $e\tau_{\text{had}}$, $\mu\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ final states is split into $b$-tagged and $b$-vetoed samples. In each category, the likelihood is a product over bins of the MMC distributions in the signal and control regions. Signal and background predictions depend on systematic uncertainties that are listed in Ref. [12] and parameterised by nuisance parameters. Correlations of the systematic uncertainties across
categories are taken into account. Since no significant excess of events above the background-only expectation is observed in the considered channels, using 4.7 fb⁻¹ of 7 TeV LHC data, 95% confidence level (CL) limits are set on the production cross section for a single scalar boson \( \phi \), produced in either the gluon fusion or \( b \)-associated production mode, times the branching ratio into \( \tau \tau \) pairs, see the left-hand plot of Figure 4. In the \( m_A^{\text{max}} \) scenario with \( \mu > 0 \) [14], 95% CL upper limits can be placed on \( \tan \beta \) for each \( m_A \) point, see the right-hand plot of Figure 4. In all plots, limits are also shown for \( A^0/H^0/h^0 \to \mu \mu \).

Figure 4. Left: expected (dashed line) and observed (solid line) 95% CL limits on the cross section for gluon fusion and \( b \)-associated Higgs boson production times the branching ratio into \( \tau \tau \) and \( \mu \mu \), along with the 1\( \sigma \) (green) and 2\( \sigma \) (yellow) bands for the expected limit. Right: expected (dashed lines) and observed (solid lines) 95% CL limits on \( \tan \beta \) as a function of \( m_A \) for each of the \( \mu \mu, e\mu, e\tau_\text{had}, \mu\tau_\text{had} \) and \( \tau_\text{had}\tau_\text{had} \) channels and their statistical combination (the 95% CL exclusion region from neutral MSSM Higgs boson searches performed at LEP [15] is shown in a hatched style). Both figures are extracted from Ref. [12].

4. Search for light charged Higgs bosons in ATLAS

The main production mode for charged Higgs bosons (referred to as \( H^+ \) in the following) at the LHC is through top quark decays \( t \to bH^+ \), for charged Higgs boson masses smaller than the top quark mass \( (m_{H^+} < m_{t\text{top}}) \). The dominant source of top quarks at the LHC is through \( tt \) production. For \( \tan \beta > 2 \), the charged Higgs boson decay via \( H^+ \to \tau \nu \) is dominant. At lower \( \tan \beta \) values, the decay into a \( c\bar{s} \) pair also becomes sizeable. In this paper, searches for charged Higgs bosons using 4.6 fb⁻¹ of \( pp \) collisions at \( \sqrt{s} = 7 \) TeV are presented. With the assumption that the branching ratio \( \text{Br}(H^+ \to \tau \nu) \) is 100\%, \( H^+ \) is searched for in \( tt \) events with a \( \tau \) lepton in the final state. More details can be found in Refs. [16] and [17]. On the other hand, if the branching ratio \( \text{Br}(H^+ \to c\bar{s}) \) is assumed to be 100\%, \( H^+ \) is searched for in semi-leptonic decays of \( t\bar{t} \) pairs [18].

4.1. Search for charged Higgs bosons in the \( \tau_\text{had}+\text{jets} \) final state

Using 4.6 fb⁻¹ of \( pp \) collision data at \( \sqrt{s} = 7 \) TeV, three final states were analysed by the ATLAS collaboration in Ref. [16], in order to search for charged Higgs bosons in the \( H^+ \to \tau \nu \) decay mode. The most sensitive channel, \( t\bar{t} \to bbWH^+ \to bb(q\bar{q}')(\tau_\text{had}\nu) \), is reviewed here. This analysis uses events which pass a \( \tau + E_{\text{T}}^{\text{miss}} \) trigger and which contain four or more jets with \( p_T > 20 \) GeV, of which at least one is \( b \)-tagged, as well as one \( \tau \) jet with \( p_T > 40 \) GeV and...
$|\eta| < 2.3$ (the tight likelihood criterion is used for $\tau$ identification), matched to the corresponding trigger object. Events with identified electrons and muons are vetoed. With $p_T^{PVtrk}$ being the transverse momentum of a track originating from the primary vertex, the following requirements are then applied:

$$E_{T}^{\text{miss}} > 65 \text{ GeV and } \frac{E_{T}^{\text{miss}}}{0.5 \cdot \sqrt{\sum p_{T}^{PVtrk}}} > 13 \text{ GeV}^{1/2}.$$ 

Finally, in order to enrich the sample with $t\bar{t}$ events, the $jjb$ candidate with the highest $p_{T}^{jjb}$ value is requested to satisfy $m(jjb) \in [120, 240] \text{ GeV}$. The transverse mass of the $\tau$ jet and the missing transverse momentum is used as a discriminating variable:

$$m_T = \sqrt{2p_T^{\tau}E_{T}^{\text{miss}} \left(1 - \cos \Delta\phi_{\tau, E_{T}^{\text{miss}}}\right)}.$$ 

In order to estimate the contribution of the multi-jet background in terms of event yield, a fit of the $E_{T}^{\text{miss}}$ distribution in the signal region is performed, using a multi-jet $E_{T}^{\text{miss}}$ template from a control region in data and simulated events for all other processes. The $m_T$ shape for the multi-jet background is also measured in data, in the same control region as the $E_{T}^{\text{miss}}$ template, and is then normalised using the result of the $E_{T}^{\text{miss}}$ fit. The electroweak backgrounds with misidentified $\tau$ jets are first estimated using simulations and later adjusted using data-driven correction factors. In the case of an electron misidentified as $\tau_{\text{had}}$, scale factors are derived with a tag-and-probe method in $Z \rightarrow ee$ events from data, and they are then applied to all simulated events. Jet $\rightarrow \tau_{\text{had}}$ misidentification rates are measured in a data sample enriched with $W$+jets events, and then applied in the simulation. Finally, the electroweak backgrounds with true $\tau$ jets is estimated using a $\tau$-embedded sample of $t\bar{t}$-like $\mu$+jets events from the data, which is then normalised using simulation.

The $m_T$ distribution for the $\tau_{\text{had}}$+jets channel, after all selection cuts are applied, is shown in Figure 5. The data are found to be consistent with the SM background expectation.

![Figure 5](image-url)

**Figure 5.** Distribution of $m_T$ after all selection cuts in the $\tau_{\text{had}}$+jets channel, extracted from Ref. [16]. The dashed line corresponds to the SM-only hypothesis and the hatched area around it shows the total uncertainty. The solid line is the predicted contribution of signal+background with a charged Higgs boson with $m_{H^+} = 130$ GeV, assuming that $\text{Br}(t \rightarrow bH^+) = 5\%$ and $\text{Br}(H^+ \rightarrow \tau\nu) = 100\%$. The contributions of $t\bar{t} \rightarrow b\bar{b}W^+W^-$ events in the backgrounds with misidentified objects are scaled down accordingly.
4.2. Search for charged Higgs bosons via the violation of lepton universality in $t\bar{t}$ events

While $W$ bosons decay equally to all lepton families, $H^\pm$ mostly decays to $\tau$ leptons, which would lead to an excess of $t\bar{t}$ events in $\ell + \tau_{\text{had}}$ final states ($\ell = e, \mu$). In order to cancel several systematic uncertainties in the analysis presented here, and detailed in Ref. [17], event yield ratios are computed between $\ell + \tau_{\text{had}}$ and dilepton ($e\mu$) final states, again using 4.6 fb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 7$ TeV. Events in this channel must fire a single-lepton trigger and contain one isolated lepton with $E_T > 25$ GeV or $p_T > 25$ GeV, matched to the corresponding trigger object. In addition, at least two jets with $p_T > 20$ GeV and $|\eta| < 2.4$ must be found, with two $b$-tags. Then, events are split into two categories ($\ell + \tau_{\text{had}}$ and $\ell\ell'$), depending on whether they contain either exactly one $\tau$ jet with $p_T > 25$ GeV and $|\eta| < 2.3$, as well as no other lepton, or exactly one other lepton with $E_T$ or $p_T$ above 25 GeV and a different flavor than the trigger-lepton. Finally, all events are required to have $E_T^{\text{miss}} > 40$ GeV.

The backgrounds with misidentified leptons are estimated using a data-driven method based on events containing tight or loose leptons (those differ only in lepton identification criteria). The efficiencies $p_r$ and $p_m$ for a real or misidentified lepton, respectively, to be detected as a tight lepton, are determined from data. Based on these efficiencies, the number of misidentified leptons passing the final requirements can be calculated by weighting events in the data sample with one loose lepton, according to the following per-lepton weights: for a loose but not tight lepton, $w_{\text{LL}} = p_m p_r / (p_r - p_m)$, while for a tight lepton $w_{\text{LT}} = p_m (p_r - 1) / (p_r - p_m)$. About 51% of the simulated $t\bar{t}$ events in the $\ell + \tau_{\text{had}}$ final state contain a $\tau$ jet matched to a true hadronically decaying $\tau$ lepton. For the small background where an electron is misidentified as $\tau_{\text{had}}$, scale factors are used, as in the analysis of the $\tau_{\text{had}}+\text{jets}$ channel. For the background where a hadronic jet is misidentified as $\tau_{\text{had}}$, it was noticed that giving a negative weight to same-sign (SS) events cancels the gluon and $b$-quark jet contributions of opposite-sign (OS) events, leaving only light quark jets misidentified as $\tau$ objects. The misidentification rate of light quark jets to $\tau_{\text{had}}$ is derived from a control region in data enriched with OS-SS events. It is then applied to simulated events, prior to the OS-SS subtraction. Having computed OS-SS event yields $N$ in the $\ell + \tau_{\text{had}}$ and $\ell\ell'$ final states, ratios are determined as follows:

$$R_\ell = \frac{N(bb + \ell\tau_{\text{had}} + E_T^{\text{miss}})}{N(bb + \ell\ell' + E_T^{\text{miss}})}.$$ 

As shown in Table 1, the measured event yield ratios $R_e$ and $R_\mu$ are compatible with those predicted in the SM-only hypothesis, within uncertainties.

Table 1. Predicted and measured ratios of event yields in the $\ell + \tau_{\text{had}}$ and $\ell\ell'$ final states [17]. For the values of the ratios predicted using simulation, the statistical and systematic uncertainties are combined.

<table>
<thead>
<tr>
<th>Event yield ratio</th>
<th>SM-prediction</th>
<th>Data 2011</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_e$</td>
<td>0.105 ± 0.012</td>
<td>0.115 ± 0.010 (stat)</td>
</tr>
<tr>
<td>$R_\mu$</td>
<td>0.166 ± 0.017</td>
<td>0.165 ± 0.015 (stat)</td>
</tr>
</tbody>
</table>

4.3. Exclusion limits for $H^+ \rightarrow \tau\nu$

In the two searches reviewed above, the data are found to be consistent with the SM prediction. Assuming $\text{Br}(H^+ \rightarrow \tau\nu) = 100\%$, 95% CL upper limits are placed on $\text{Br}(t \rightarrow bH^+)$, see the left-hand plot of Figure 6. The combined limit on the product $\text{Br}(H^+ \rightarrow \tau\nu) \times \text{Br}(t \rightarrow bH^+)$ is then interpreted in the $m_h^{\text{max}}$ scenario, see the right-hand plot of Figure 6.
Figure 6. Left: 95% CL upper limits on $\text{Br}(t \rightarrow bH^+)$ derived from the transverse mass distribution of $\tau_{\text{had}} + \text{jets}$ events and the combined event yield ratio $R_{e+\mu}$, as a function of the charged Higgs boson mass, obtained for an integrated luminosity of 4.6 fb$^{-1}$, assuming $\text{Br}(H^+ \rightarrow \tau \nu) = 1$. Right: limits for charged Higgs boson production from top quark decays in the $m_{H^+}$-$\tan\beta$ plane, in the context of the $m_h^{\text{max}}$ scenario of the MSSM. The 1$\sigma$ band around the observed limit (dashed lines) shows the theoretical uncertainties. Values below $\tan\beta = 1$, where the calculations in the MSSM become non-perturbative, are not considered, as the results become unphysical. Both figures are extracted from Ref. [17].

4.4. Search for charged Higgs bosons in the $c\bar{s}$ decay mode

The decay mode $H^+ \rightarrow c\bar{s}$ may have a significant branching ratio at low $\tan\beta$ values. It was searched for in ATLAS, using 4.6 fb$^{-1}$ of $pp$ collision data [18]. In order to select a sample enriched with $pp \rightarrow t\bar{t} \rightarrow b\bar{b}WH^+$ events, with $W \rightarrow \ell\nu$ and $H^+ \rightarrow c\bar{s}$, a single-lepton trigger is required. The events used for this analysis must contain one trigger-matched electron or muon with $E_T > 25$ GeV or $p_T > 20$ GeV, respectively, and at least four jets with $p_T > 25$ GeV and $|\eta| < 2.5$ (including two $b$-tags). After some requirements on both $E_T^{\text{miss}}$ and the transverse mass of the lepton and the missing transverse momentum, $t\bar{t}$ is the dominant background. At this stage, a kinematic fit is applied on the top quark decay products. Among all jet combinations, the one with the smallest $\chi^2$ value is selected as the best assignment:

$$\chi^2 = \sum_{i=\ell, A\text{jets}} \frac{(p_T^{i,\text{fit}} - p_T^{i,\text{meas}})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_T^{j,\text{SEJ,fit}} - p_T^{j,\text{SEJ,meas}})^2}{\sigma_{\text{SEJ}}^2} + \sum_{k=j,jb,bb\nu} \frac{(M_k - m_t)^2}{\Gamma_t^2},$$

where $\text{SEJ}$ is the vector sum of the energy of the remaining jets in the event. The fitter constrains the invariant mass of the two systems ($b\ell\nu, bj$) to be within $\Gamma_t = 1.5$ GeV of the top quark mass 172.5 GeV. With the requirement $\chi^2_{\text{min}} < 10$, the fit results in a 20–30% improvement in the resolution of the dijet mass, which is the discriminating variable for this analysis.

The left-hand plot of Figure 7 shows the dijet mass distribution in data and simulated events. The data are found to be in good agreement with the SM-only hypothesis. Hence, with the assumption $\text{Br}(H^+ \rightarrow c\bar{s}) = 100\%$, 95% CL upper limits are placed on $\text{Br}(t \rightarrow bH^+)$, see the right-hand plot of Figure 7.
Figure 7. Left: Dijet mass distribution from data and expectation from the SM, with the corresponding uncertainties (the first and last bins contain the underflow and overflow events, respectively). Right: 95% CL upper limits on Br($t \to bH^+$) for charged Higgs boson masses ranging from 90 GeV to 150 GeV, with the assumption Br($H^+ \to c\bar{s}$) = 100%. Both figures are extracted from Ref. [18].

5. Conclusion
Using LHC proton-proton collision data recorded in 2011, the ATLAS collaboration has searched for new neutral and charged Higgs bosons, as a test of physics beyond the Standard Model. This paper reports on the search for $A^0/H^0/h^0 \to \tau\tau$ events, as well as $t \to bH^+$ decays of the top quark in $t\bar{t}$ events, with subsequent $H^+ \to \tau\nu$ or $H^+ \to c\bar{s}$ decays. In all analyses, the data are found to agree with the SM-only hypothesis, hence 95% CL exclusion limits are set on the production for new neutral and charged Higgs bosons.

References